Measurements of the Direct Photon Cross Section and Double Longitudinal Spin Asymmetry in $\sqrt{s} = 200$ GeV pp Collisions at PHENIX

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Spin, like mass and charge, is a fundamental property of all matter. Understanding how the spin of the proton is distributed amongst its internal parts – quarks and gluons – is a fundamental concern of modern physics. Polarized deep inelastic scattering experiments in the late 1980’s showed that quarks only contribute a small percentage to the total spin of the proton, $\approx 25\%$. Since then, a significant international effort has been put forth to measure how the gluon spin is distributed inside the proton. A major focus of the PHENIX spin program of the Relativistic Heavy Ion Collider
(RHIC) at Brookhaven National Laboratory (BNL) is to access the gluon contribution to the spin of the proton, \( \Delta G \), through measurements of the double longitudinal spin asymmetry \( A_{LL} \) in proton-proton \((p+p)\) collisions.

One of the channels which PHENIX employs to measure \( \Delta G \) is the direct photon. The direct photon has been called the "Golden Channel" for accessing the gluon. It has earned this title due to the small number of theoretically clean subprocesses whose kinematics are well understood which produce these photons. Also, at leading order, the direct photon \( A_{LL} \) is linear in the gluon polarization, and therefore sensitive to both the sign and magnitude of \( \Delta G \).

Interpretation of PHENIX results relies on perturbative Quantum Chromodynamics (pQCD). The applicability of pQCD must be verified for each channel by comparing the measured cross section with theoretical predictions. Measurements of the direct photon cross section, from the 2006 (Run 6) data set, and double longitudinal spin asymmetry, from the 2005 (Run 5) and 2006 data sets, are presented in this work. Novel techniques developed to calculate the absolute luminosity normalization at PHENIX, a necessary quantity for all cross section analyses, will be shown. The cross section from the Run 6 data set will be compared with previous PHENIX results and theoretical calculations. Finally an extraction of \( \Delta G \) at leading order from Run 5 and Run 6 direct photon ALL measurements is examined.
### Contents

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>List of Figures</td>
<td>xxiii</td>
</tr>
<tr>
<td></td>
<td>List of Tables</td>
<td>xxvi</td>
</tr>
<tr>
<td></td>
<td>Acknowledgements</td>
<td>xxvii</td>
</tr>
<tr>
<td>1</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1</td>
<td>Spin</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>The Quark Model</td>
<td>3</td>
</tr>
<tr>
<td>1.2.1</td>
<td>The Color Charge</td>
<td>6</td>
</tr>
<tr>
<td>1.3</td>
<td>Probing the Structure of the Proton</td>
<td>8</td>
</tr>
<tr>
<td>1.3.1</td>
<td>Deep Inelastic Scattering and the Parton Model</td>
<td>11</td>
</tr>
<tr>
<td>1.3.2</td>
<td>Parton Model</td>
<td>12</td>
</tr>
<tr>
<td>1.3.3</td>
<td>Bjorken Scaling</td>
<td>12</td>
</tr>
<tr>
<td>1.3.4</td>
<td>The Quark Parton Model</td>
<td>15</td>
</tr>
<tr>
<td>1.3.5</td>
<td>Sum Rules</td>
<td>16</td>
</tr>
<tr>
<td>1.4</td>
<td>Quantum Chromodynamics</td>
<td>18</td>
</tr>
<tr>
<td>1.4.1</td>
<td>Renormalization</td>
<td>21</td>
</tr>
<tr>
<td>1.4.2</td>
<td>Factorization and Universality</td>
<td>23</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>1.4.3 Parton Distribution Functions in QCD</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>1.5 Spin Structure of the Proton</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>1.5.1 Naive Quark Model</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>1.5.2 Sum Rules</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>1.5.3 EMC Experiment</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>1.5.4 Spin Crisis to Spin Puzzle</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>1.6 Hadron-Hadron Scattering</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>1.6.1 PP-Cross Section</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>1.6.2 Accessing ΔG in Polarized Proton-Proton The Collisions</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>1.6.3 Measuring $A_{LL}$</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>2 Direct Photons</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>2.1 Photon Production</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>2.1.1 Leading-order Processes $O(\alpha_s)$</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>2.1.2 Beyond Leading Order</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>2.2 Experimental Techniques</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>2.2.1 Direct Method</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>2.2.2 Conversion Method</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>2.2.3 Comparison of Methods</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>2.3 Early Measurements of Direct Photons</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>2.4 Relation to Spin</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>3 BNL Collider Accelerator Facility</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>3.1.1 Polarized Source</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>3.2 Pre-RHIC Acceleration</td>
<td>52</td>
<td></td>
</tr>
</tbody>
</table>
3.2.1 LINAC and Booster ........................................ 52
3.2.2 Alternating Gradient Synchrotron ....................... 53
3.3 Relativistic Heavy Ion Collider ............................. 53
3.4 Spin Specific Equipment ...................................... 54
  3.4.1 Siberian Snakes ......................................... 54
  3.4.2 Spin Rotators ............................................ 56
  3.4.3 Polarimetry .............................................. 56
  3.4.4 Spin Pattern .............................................. 58

4 PHENIX Detector .................................................. 59
  4.1 Beam Beam Counter ......................................... 59
  4.2 Zero Degree Calorimeter and Shower Maximum Detector ... 61
  4.3 Electromagnetic Calorimeter ................................ 62
    4.3.1 PbSc .................................................. 63
    4.3.2 PbGl .................................................. 63
  4.4 Charged Particle Tracking ................................... 64
    4.4.1 Central Magnets ....................................... 64
    4.4.2 Drift Chamber ........................................ 64
    4.4.3 Pad Chamber ......................................... 65
    4.4.4 Track Quality ......................................... 66
  4.5 Ring Imaging Čerenkov Detector ............................ 67
  4.6 Triggers ..................................................... 68
    4.6.1 BBCLL1 ............................................... 68
    4.6.2 ZDCLL1 ............................................... 69
    4.6.3 EMCal RICH Trigger ................................. 69
5 Luminosity Measurement

5.1 Introduction .................................................. 71
5.2 Vernier Scans .................................................. 73
5.3 Data Collection .................................................. 75
  5.3.1 Rates .................................................. 76
  5.3.2 Beam Position Monitors .................................. 78
  5.3.3 Beam Intensity ........................................... 78
5.4 Data set .................................................. 80
5.5 Analysis .................................................. 81
  5.5.1 Gaussian fitting ........................................... 81
  5.5.2 Luminosity calculation .................................... 84
  5.5.3 Z-vertex cut efficiency .................................... 84
5.6 Summary of Run5 and Run6 scans at $\sqrt{s} = 200$ GeV ........... 90
5.7 Statistical Uncertainties and Systematic Error Estimation ........ 91
  5.7.1 Crossing-by-Crossing Uncertainty ....................... 91
  5.7.2 Run-by-run Variation ..................................... 93
5.8 Hour-glass effect correction .................................. 96
  5.8.1 Simulation ............................................... 98
  5.8.2 Simulation of Detector Resolution ..................... 99
  5.8.3 Comparison of Simulations and Data .................. 100
5.9 Final result of Run5 and Run6 Vernier Scans .................... 105

6 Data Quality Assurance ........................................ 108

6.1 Run Veto .................................................. 109
6.2 Trigger Selection ........................................... 109
C Cross Section Data Tables

D $A_{LL}$ and $\Delta G/G$ Data Tables

D.1 Results
List of Figures

1.1 World data on the total cross section of $e^+ e^- \rightarrow \text{hadrons}$ and the ratio $R(s) = \sigma(e^+ e^- \rightarrow \text{hadrons})/\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)$[1].......................6

1.2 A schematic representation of lepton-nucleon scattering............................9

1.3 Compiled world data for the proton structure function, $F_2^p$. Plot is a reproduction of the original found in the Review of Particle Physics[1].........................................................14

1.4 Plotted is the ratio $2x F_1/F_2$ against x. Data was collected by A. Bodek et.al[2]..........................................................15

1.5 A schematic representation of charge screening of an electron in QED.................................................................19

1.6 Higher order diagrams involved in the screening of the electron in quantum electrodynamics..............................20

1.7 Higher order diagrams involved in the screening of the color charge in QCD, this is the direct analog of the QED diagram in Figure 1.4.........................................................20

1.8 In addition to the diagrams shown in Figure 1.7 the above diagram also contributes to color charge screening. The gluon loops are responsible for the anti-screening...............................20
1.9 $\alpha_s$ Fill in caption...[3] .................................................. 23

1.10 Proton structure function $g_1^p$ measured by polarized DIS for $Q^2 > 1$. This figure was originally shown in a paper by S. Bass[4] 37

1.11 The above diagram is a schematic of factorization in hadronic collisions. ................................................................. 38

2.1 Quark-gluon Compton scattering process .............................. 41

2.2 Quark-Antiquark annihilation process ................................. 41

2.3 Relative signal fraction of direct photon production by $qq$ and quark-gluon Compton scattering in NLO pQCD calculations . 42

2.4 Examples of bremsstrahlung photon emission ....................... 43

2.5 Differential cross sections for direct photon production from several CERN experiments at various center mass energies compared with theoretical calculations provided by Contogouris et al. [5]. The plot was originally shown in the same article. Circles are data from R806 [6], squares from R108 [7] and triangles from R107 [8] .................. 45

2.6 Data from various experiments compared with NLO pQCD calculations compiled by Aurenche et al.[9]. The scale has been set to $\mu = p_T/2$ and CTEQ6M PDFs were used ....................... 46

2.7 Two examples of soft gluon exchange ................................. 47

3.1 BNL Collider Accelerator Facility ........................................ 51
3.2 View of the CNI polarimeter along the beam axis with the vertical carbon target inserted into the beam path (blue). Recoiled carbon atoms are measured in the 6 silicon strip detectors (red) spaced around the inside of the beam pipe.

4.1 PHENIX detector setup during the 2006 run. Top drawing shows the PHENIX central arm as seen along the beam line. Bottom Drawing is a cross section of the detector as seen from the side.

4.2 Collisions measured by the BBC. The drawing schematic of a collision at PHENIX and the position and timing measurements using the BBC.

4.3 Collisions measured by the BBC. The drawing schematic of a collision at PHENIX and the position and timing measurements using the BBC.

4.4 Schematic of charged track momentum determination in the central arm.

4.5 Diagram of the circuit logic for summing overlapping 2x2 and 4x4 tiles in the EMCal.

5.1 A schematic of a single test particle interacting with a proton bunch. Protons may have a nonuniform distribution inside the bunch.

5.2 BBC rates vs event number.

5.3 Positions measured by the BPM vs time on either side of the PHENIX IR. Red is North and Green South. Black is the mean.
5.4 Gaussian + constant fit to the transverse beam profiles measured for each bunch crossing by the horizontal (left) and vertical (right) scans.

5.5 Comparison of the peak rate of horizontal and vertical scans after position and WCM corrections: correlation (left) and ratio (right). From top to bottom: run5 run175928, run6 run200257.

5.6 Peak rate (after correction, left) and luminosity (right) of each crossing. From top to bottom: run5 run175928, run6 run200257.

5.7 Correlation of the peak rate (after correction) and luminosity: correlation (left) and ratio (right). From top to bottom: run5 run175928, run6 run200257.

5.8 Z-vertex cut position by BBCLL1. From top to bottom: run5 run175928 (ZDCNS trigger, because BBCLL1 no-vertex-cut trigger was not available), run6 run200257 (BBCLL1 no-vertex-cut trigger).

5.9 Z-vertex of run6, run200257. From top to bottom: BBC vertex with BBCLL1 no-vertex-cut trigger (Gaussian fit width 57.34 cm), BBC vertex with ZDCNS trigger (Gaussian fit width 57.07 cm), ZDC vertex ZDCNS trigger (Gaussian fit width 63.40 cm), ZDC vertex ZDCNS trigger with BBC vertex reconstructed (Gaussian fit width 58.84 cm), and ratio of 4th and 3rd histogram which shows BBC efficiency (Gaussian fit width 172 cm).
5.10 Z-vertex of run5, run175928 From top to bottom: BBC vertex with BBCLL1 no-vertex-cut trigger (No good data because of an incorrect setting of the BBCLL1), BBC vertex with ZDCNS trigger, ZDC vertex ZDCNS trigger, ZDC vertex ZDCNS trigger with BBC vertex reconstructed, and ratio of 4th and 3rd histogram which shows BBC efficiency.

5.11 BBC trigger cross section of each crossing (left) and profile (right). From top to bottom: run5 run175928, run6 run200257.

5.12 BBC Cross section run-by-run after the hourglass correction is applied.

5.13 $\chi^2$ distribution for Gaussian + polynomial fits.

5.14 $\sigma_{BBC}$ crossing by crossing fit with weighted errors and weighted errors plus a constant systematic for 200GeV run 170055.

5.15 $\sigma_{BBC}$ crossing by crossing fit with weighted errors and weighted errors plus a constant systematic for 200GeV run 171623.

5.16 $\sigma_{BBC}$ crossing by crossing fit with weighted errors and weighted errors plus a constant systematic for 200GeV run 174762.

5.17 $\sigma_{BBC}$ crossing by crossing fit with weighted errors and weighted errors plus a constant systematic for 200GeV run 174762.

5.18 $\sigma_{BBC}$ crossing by crossing fit with weighted errors, unweighted errors and weighted errors plus a constant systematic for 200GeV run 175928.

5.19 $\sigma_{BBC}$ crossing by crossing fit with weighted error and weighted errors plus a constant systematic for 200GeV run 200257.
5.20 $\sigma_{BBC}$ crossing by crossing fit with weighted errors and weighted errors plus a constant systematic for 62GeV scan run 205866.

5.21 Hourglass shape of the beams due to focusing

5.22 Hourglass shape of the beams due to focusing and large crossing angle

5.23 Beam longitudinal profiles measured by WCM (in m) for yellow (left) and blue (right) beams, from run-200257.

5.24 Z-vertex distribution measured by PHENIX ZDC (in cm), data from run-200257 (black) vs calculations (red).

5.25 Z-vertex distribution measured by PHENIX BBC (in cm), data from run-200257 (black) vs calculations (red).

5.26 Z-vertex distribution measured by PHENIX BBC in cm, data is from run-200257 (black) vs calculations (red); for $\sigma_{eff}^{BBC}=1m$ (left), 1.4m (middle) and 2m (right).

5.27 Z-vertex distribution measured by PHENIX ZDC (in cm), data from run-200257 (black) vs calculations for $\beta^* = 0.5m$ (blue), 1m (red) and 2m (green); four plots correspond to different shift of one beam relative the other in vertical direction: 0mm, 0.3mm, 0.6mm and 0.9mm, from left to right.

5.28 Z-vertex distribution measured by PHENIX ZDC in cm from PHENIX run 200257 (black). Calculations of the distribution assuming a crossing angle 0.03 mrad (blue), 0.13 mrad (red) and 0.23 mrad (green) are shown. The four sets of plots correspond to different shift of one beam relative the other in horizontal direction: 0mm, 0.3mm, 0.6mm and 0.9mm, from left to right.
5.29 Z-vertex distribution measured by PHENIX BBC (in cm), data from run-205866 (black) vs calculations (red), for $\sigma_{eff}^{BBC} = 85 \text{cm}$ (left), 95cm (middle), 105cm (right) ............................................. 104

5.30 $\eta$ production cross section extracted from Run 6 $\sqrt{s} = 200 \text{GeV}$ pp collisions. Plot is originally shown in the thesis of J. Seele[10] 106

5.31 $\pi^0$ production cross section extracted from Run 6 $\sqrt{s} = 62.4 \text{GeV}$ pp collisions. .......................................................... 107

6.1 EMCal warn map (Left-right: west-east, Bottom-top: sector 0-3). Towers numbered 0 (=white) are used in the analysis. The colored towers are hot, dead, uncalibrated, a 3 x 3 neighbor, or some combination of the four. ............................................. 111

6.2 EMC sdphi parameter, with $|emcsdz| < 2$ ............................................. 112

6.3 EMC sdz parameter, with $|emcsdphi| < 2$ ............................................. 112

6.4 $\alpha$ (momentum) vs board number ($\phi$ angle) for the North West sector of the drift chamber in Run 190454. Run 190454 is used as the reference run. ............................................. 112

6.5 $\alpha$ (momentum) vs board number ($\phi$ angle) for the South West sector of the drift chamber in Run 190454 ................................. 112

6.6 $\alpha$ (momentum) vs board number ($\phi$ angle) for the North West sector of the drift chamber in Run 204363. A lost wire can be clearly seen compared to the reference run ............................. 113

6.7 $\alpha$ (momentum) vs board number ($\phi$ angle) for the South West sector of the drift chamber in Run 204353. A lost wire can be clearly seen compared to the reference run ............................. 113
6.8 The number of DC charged tracks normalized to minimum bias counts vs run number in the North West portion of the DC. A clear dip can be seen after the wire was lost near Run 204353.

6.9 The number of DC charged tracks normalized to minimum bias counts vs run number in the South West portion of the DC. A clear dip can be seen after the wire was lost in Run 204353.

6.10 The number of DC charged tracks normalized to minimum bias counts vs run number in the South East portion of the DC.

6.11 The number of DC charged tracks normalized to minimum bias counts vs run number in the South West portion of the DC.

6.12 An example of the asymmetry measured in the beginning of a run while the beams are transversely polarized.

7.1 Two photon invariant mass distribution (west $E_{\text{min}} = 0.5\text{GeV}$).
Each panel shows different photon $p_T$. The top-left is for $5 < p_T < 5.5\text{GeV}$.

7.2 Two photon invariant mass distribution (east $E_{\text{min}} = 0.5\text{GeV}$).
Each panel shows different photon $p_T$. The top-left is for $5 < p_T < 5.5\text{GeV}$.

7.3 Isolated pair photon invariant mass distribution (west $E_{\text{min}} = 0.5\text{GeV}$).
Each panel shows different photon $p_T$. The top-left is for $5 < p_T < 5.5\text{GeV}$.

7.4 Isolated pair photon invariant mass distribution (east $E_{\text{min}} = 0.5\text{GeV}$).
Each panel shows different photon $p_T$. The top-left is for $5 < p_T < 5.5\text{GeV}$.
7.5 Two photon invariant mass distribution of photons which pass the isolation cut (west $E_{\text{min}} = 0.5\text{GeV}$). Each panel shows different photon $p_T$. The top-left is for $5 < p_T < 5.5\text{GeV}$.

7.6 Two photon invariant mass distribution of photons which pass the isolation cut (east $E_{\text{min}} = 0.5\text{GeV}$). Each panel shows different photon $p_T$. The top-left is for $5 < p_T < 5.5\text{GeV}$.

7.7 $\pi^0$ peak position vs $P_T$ in the east arm Red:Data Black:MC

7.8 $\pi^0$ peak width vs $P_T$ in the east arm Red:Data Black:MC

7.9 $\pi^0$ peak position vs $P_T$ in the west arm Red:Data Black:MC

7.10 $\pi^0$ peak width vs $P_T$ in the west arm Red:Data Black:MC

7.11 (MC) photon acceptance and smearing estimation. Shown is the ratio of photons in the east are to all photons simulated.

7.12 (MC) photon acceptance and smearing estimation. Shown is the ratio of photons in the east are to all photons simulated.

7.13 Minimum bias trigger efficiency measured in Run 6

7.14 ERT4x4a bias trigger efficiency measured in Run 6

8.1 $\pi^0$ Photon Asymmetry $P_t =5-6\text{GeV}$

8.2 $\pi^0$ Photon Asymmetry $P_t =6-7\text{GeV}$

8.3 $\pi^0$ Photon Asymmetry $P_t =7-8\text{GeV}$

8.4 $\pi^0$ Photon Asymmetry $P_t =8-10\text{GeV}$

8.5 $\pi^0$ Photon Asymmetry $P_t =10-12\text{GeV}$

8.6 $\pi^0$ Photon Asymmetry $P_t =12-15\text{GeV}$

8.7 Isolated Photon Asymmetry $P_t =5-6\text{GeV}$

8.8 Isolated Photon Asymmetry $P_t =6-7\text{GeV}$
8.9 Isolated Photon Asymmetry $P_T = 7-8\text{GeV}$ .................................. 140
8.10 Isolated Photon Asymmetry $P_T = 8-10\text{GeV}$ ................................. 140
8.11 Isolated Photon Asymmetry $P_T = 10-12\text{GeV}$ ............................... 141
8.12 Isolated Photon Asymmetry $P_T = 12-15\text{GeV}$ ............................... 141
8.13 Direct photon asymmetry as a function of $P_T$ with several model
curves included. The first three bins have a width of 1 GeV.
The finals bin is 2,2, 3 GeV wide respectively. The Run5 data
are shown in black while the Run6 in Blue .................................. 143
8.14 Bunch shuffling $\chi^2$ distribution for the $P_T = 5-6\text{GeV}$ bin ........ 143
8.15 Bunch shuffling $\chi^2$ distribution for the $P_T = 6-7\text{GeV}$ bin ........ 143
8.16 Bunch shuffling $\chi^2$ distribution for the $P_T = 7-8\text{GeV}$ bin ........ 144
8.17 Bunch shuffling $\chi^2$ distribution for the $P_T = 8-10\text{GeV}$ bin ........ 144
8.18 Bunch shuffling $\chi^2$ distribution for the $P_T = 10-12\text{GeV}$ bin ...... 144
8.19 Bunch shuffling $\chi^2$ distribution for the $P_T = 12-15\text{GeV}$ bin ...... 144
8.20 Distribution of $x_b(juglon)$ for $p_T = 5-6\text{GeV}$ direct-$\gamma$ ........ 147
8.21 Distribution of $x_b(juglon)$ for $p_T = 6-7\text{GeV}$ direct-$\gamma$ ........ 147
8.22 Distribution of $x_b(juglon)$ for $p_T = 7-8\text{GeV}$ direct-$\gamma$ ........ 147
8.23 Distribution of $x_b(juglon)$ for $p_T = 8-10\text{GeV}$ direct-$\gamma$ ........ 147
8.24 Distribution of $x_b(juglon)$ for $p_T = 10-12\text{GeV}$ direct-$\gamma$ ........ 148
8.25 Distribution of $x_b(juglon)$ for $p_T = 12-15\text{GeV}$ direct-$\gamma$ ........ 148
8.26 $A_L^p$ with fit to data $f(x) = 1.04 \times x^{0.16} \times (1 - e^{-2.9x})$. Data
is collected and stored at the Durham HEP database. scale
uncertainties not shown ......................................................... 148
8.27 The partonic asymmetry $\hat{a}_{LL}$ ........................................... 149
9.1 Isolated direct photon cross section for Run-6 in the east arm (red) and west arm (blue) compared with the Run-5 preliminary result (green) and theoretical predictions.

9.2 The direct photon cross section measured via the statistical subtraction Method for Run-6 in the east arm (red) and west arm (blue) compared with the Run-5 preliminary result (green) and theoretical predictions.

9.3 Contributions to the inclusive photon cross section (red) separated into direct photon (black) and fragmentation photons (blue) with out isolation cut.

9.4 Contributions to the isolated photon cross section (red) separated into isolated direct photons (black) and isolated fragmentation photons (blue) with the isolation cone size set to 0.5mrad.

9.5 Direct Photon $A_{LL}$ measured in Run-5 and Run-6 with model predictions from the GRSV model.

9.6 $\Delta G/G$ including Run-5 and Run-6 PHENIX direct photon data.

9.7 Published $\pi^0 A_{LL}$ measured in Run-5 and Run-6 with model predictions from GRSV.

9.8 $\eta A_{LL}$ measured in Run-5 and Run-6 with model predictions from GRSV.

9.9 $\chi^2$ profile from several fits used to extract $\Delta G/G$ from the $\pi^0$ asymmetry.

9.10 A summary measurements of $\Delta G/G$ from several DIS experiments. This plot originally appeared in a paper by G. Mallot.
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.11</td>
<td>Open charm production in DIS. Figure originally appeared the book by S. Bass.</td>
</tr>
<tr>
<td>9.12</td>
<td>A summary of $\Delta G/G$ measurements from PHENIX and several DIS experiments. PHENIX data is from Run-5 and Run-6 combined (Blue circle).</td>
</tr>
<tr>
<td>9.13</td>
<td>Projections of statistical uncertainties for Run-9 (red) direct photon $A_{LL}$ based upon Run-6 (blue) values.</td>
</tr>
<tr>
<td>9.14</td>
<td>Projections of statistical uncertainties for total integrated luminosity direct photon $A_{LL}$.</td>
</tr>
<tr>
<td>9.15</td>
<td>Projections of statistical uncertainties on $\Delta G/G$ from Run-9 (blue) and total integrated luminosity (black).</td>
</tr>
</tbody>
</table>
List of Tables

1.1 10 3-quark combinations of the light quarks, known as the \textit{Baryon Decuplet} ........................................ 4

1.2 Summary of kinematic variables in lepton-proton scattering .................................................. 10

3.1 Run 5 and Run 6 Polarization values ..................................................................................... 58

4.1 Summary Drift Chamber Quality Bits .................................................................................. 67

5.1 Dataset table: analyzed vernier scan runs at PHENIX from 2005 and 2006 .......................... 80

5.2 Summary of Run5 and Run6 scan at $\sqrt{s}$ = 200 GeV, $\delta \sigma_{BBC}$ shows uncertainty from a constant fit of crossing-by-crossing $\sigma_{BBC}$ ................................................................. 91

5.3 Summary of Run6 scan at $\sqrt{s}$ = 62.4 GeV, $\delta \sigma_{BBC}$ shows crossing-by-crossing deviation of $\sigma_{BBC}$ from fits before the hourglass correction ................................................................. 91

5.4 Summary of statistical uncertainty in Run6 scan at $\sqrt{s}$ = 62.4 GeV. Shows mean values and uncertainty obtain for an individual crossing from fits crossing-by-crossing ......................................................... 92

5.5 Summary of corrections ........................................................................................................ 105
D.4 Summary of Run5 dilution factors
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the data looked at first, Mike reminded me that this analysis is important to spin.

Lastly, I would like to thank my family for their unconditional support. I would not be where I am today if it were not for the nurturing environment they created. I am fortunate to have such wonderful parents to guide me, teach me and love me.
Chapter 1

Introduction

The topic of this thesis covers the measurement of the direct photon cross section and double longitudinal spin asymmetry ($A_{LL}$) taken with the PHENIX detector at the Relativistic Heavy Ion Collider (RHIC) located at Brookhaven National Laboratory (BNL).

This chapter will discuss the history and scientific advances which led up to the initial studies of the structure of the proton. The quark model will be introduced and the interpretations of quarks in the parton model will be discussed. The convergence of these two ideas along with guidance from experimental results led to the formulation of Quantum Chromodynamics (QCD), the full field theoretical description of the interactions of quarks and gluons, the force carriers which bind quarks together. Early results of the spin structure of the proton from the Yale-SLAC and European Muon Collaboration (EMC) experiments, which are the impetus for this work, will be shown. Finally, the current research being conducted at the PHENIX experiment at BNL, in which the spin structure of the proton is being explored in proton-proton collisions, will be presented. Chapter 2 contains a brief discussion of direct photons and their
relationship to the gluon contribution to the spin of the proton. Chapters 3 will introduce the the major components of the Brookhaven National Laboratory Collider-Accelerator facility dedicated to provided polarized protons to the experiments. The detector systems pertinent to the direct photon measurement at PHENIX are explained in Chapter 4. Chapter 5 will present a new measurement of the the absolute luminosity calibration of the PHENIX collision counters. The details of the of the event selection and techniques for measuring the direct photon cross section and double longitudinal spin asymmetry measurement are presented in Chapters 6-8. Finally Chapter 9 will present the results of the direct photon cross section from the 2006 data set along with the first measurement of the direct photon double longitudinal spin asymmetry and resulting constraints on the gluon contribution to the spin of the proton.

### 1.1 Spin

Spin, like mass and charge, is a fundamental property of all elementary particles. It has important theoretical and practical applications in all areas of physics. Spin is essential to explain topics ranging from fundamental ideas of modern physics, like the Pauli Exclusion Principle, to the landscape of the periodic table of elements to even our understanding of the properties of neutron stars in distant galaxies.

It was in 1925 that Goudsmit and Uhlenbeck introduced the concept of an intrinsic, purely quantum mechanical angular momentum of an electron–dubbed spin, thus imparting a non-zero angular momentum on the particle,
even in its rest frame. This quantum mechanical spinning of the particle gives rise to an intrinsic magnetic moment

\[ \mu_e = \frac{2e\vec{s}}{m_e} \]  

(1.1)

Two years later, in 1927, Dennison showed that the proton is a spin \( \frac{1}{2} \) particle. Six years later, Stern and Esterman measured the anomalous magnetic moment of the proton, \( \kappa_p = 1.79 \). This large deviation from the magnetic moment of a Dirac point particle (i.e. \( \kappa_{Dirac} = 1 \)) reveals that the proton is, in fact, not an elementary particle and it has some internal substructure. In the next half a century much of physics has been devoted to understanding the internal workings of the proton. It was the convergence of two new ideas used to describe the inner working of the proton, the quark model proposed by Gell-Mann and Zweig and the parton model posited by Feynman and Bjorken, which began our modern theoretical understanding of the proton. The theoretical work was driven by advances in accelerator technology, and the seminal scattering experiments conducted at the Stanford Linear Accelerator Center (SLAC). This large effort culminated in the forming of the modern field theoretical description of the strong nuclear force, Quantum Chromodynamics.

1.2 The Quark Model

By the early 1960’s what seemed to be an incomprehensible zoo of particles emerged from experiments performed over the previous two decades. It was thought that order could be made of this multitude of particles if they were
composed of a smaller number of more elementary particles, similar to how the periodic table of elements can be made sense of using only protons, neutrons and electrons.

In 1964, Murray Gell-Mann and George Zweig independently went on to postulate the existence of quarks, a set of fermions that possess fractional charge and when taken in the proper combinations could reproduce the plethora of newly discovered particles. Initially, these quarks came in three types, or *flavors*; *up*(u), which held an electric charge (\(q_u\)) of +2/3; *down*(d) (\(q_d = -1/3\)); and *strange* (s) (\(q_s = -1/3\)). The strange quark came with an additional quantum number called strangeness, S. The three quarks – up, down and strange– when combined with their anti-particles, could describe all known hadrons at that time (see in Table 1.1). Lighter particles called mesons were represented by quark-anti-quark pairs (\(q\bar{q}\)). Heavier combinations called Baryons were described by three quarks (\(qqq\)) or anti-quarks (\(q\bar{q}\bar{q}\)).

<table>
<thead>
<tr>
<th>Quark Content</th>
<th>Charge</th>
<th>Baryon</th>
</tr>
</thead>
<tbody>
<tr>
<td>uuu</td>
<td>2</td>
<td>(\Delta^{++})</td>
</tr>
<tr>
<td>uud</td>
<td>1</td>
<td>(\Delta^+)</td>
</tr>
<tr>
<td>udd</td>
<td>0</td>
<td>(\Delta^0)</td>
</tr>
<tr>
<td>ddd</td>
<td>-1</td>
<td>(\Delta^-)</td>
</tr>
<tr>
<td>uus</td>
<td>1</td>
<td>(\Sigma^{++})</td>
</tr>
<tr>
<td>uds</td>
<td>0</td>
<td>(\Sigma^+)</td>
</tr>
<tr>
<td>dds</td>
<td>-1</td>
<td>(\Sigma^-)</td>
</tr>
<tr>
<td>uss</td>
<td>0</td>
<td>(\Xi^0)</td>
</tr>
<tr>
<td>dss</td>
<td>-1</td>
<td>(\Xi^-)</td>
</tr>
<tr>
<td>sss</td>
<td>-1</td>
<td>(\Omega^-)</td>
</tr>
</tbody>
</table>

Table 1.1: 10 3-quark combinations of the light quarks, known as the *Baryon Decuplet*

This list would later be extended to include three other quarks the *charm*
(c) \((q_c = +2/3)\), posited by Bjorken, Sheldon Glashow, John Iliopoulos and Luciano Maiani\[16\] in order to better describe phenomenon associated with weak interactions. The existence of the charm was confirmed with the discover of the \(J/\psi\) particle in 1974 \[17\] \[18\]. Later the bottom \((q_b = -1/3)\) and top \((q_t = +2/3)\), proposed by Makoto Kobayashi and Toshihide Maskawa\[19\] based, on symmetry arguments, were predicted. The bottom quark was discovered by the E288 experiment at Fermilab in 1977 when collisions produced bottomonium, \(\Upsilon\) \[20\]. Experimental confirmation of the top quark did not occur until 1995, when it was seen at the CDF and \(D\bar{O}\) experiments at Fermilab\[21\] \[22\] \[23\] \[24\].

An interesting feature arises when one compares the total elastic cross section for the production of \(\mu^+ + \mu^-\) pairs, \(\sigma_{e^+e^-\rightarrow\mu^+\mu^-}\), to that of hadron production in \(e^+ + e^-\), \(\sigma_{e^+e^-\rightarrow q_a\bar{q}_a}\) annihilation at leading order

\[
\sigma_{e^+e^-\rightarrow\mu^+\mu^-} = \frac{4\pi\alpha^2}{3Q^2} \tag{1.2}
\]

\[
\sigma_{e^+e^-\rightarrow q_a\bar{q}_a} = \left(\frac{4\pi\alpha^2}{3Q^2}\right) \sum_a e_a^2 \tag{1.3}
\]

where \(e_q\) is the charge of the quark flavor \(q\). The extra term in equation \[1.3\] is summed over the kinematically accessible quarks. This leaves us with a simple ratio.

\[
R = \frac{\sigma(e^+ + e^- \rightarrow \text{hadrons})}{\sigma(e^+ + e^- \rightarrow \mu^+ + \mu^-)} = 3 \sum_q e_q^2 \tag{1.4}
\]

For the light quarks u,d, s this ratio predicts \(R = 3\left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2\right] = 2\), or \(R = \frac{10}{3}\) above the charm quark threshold but below the bottom. Though this does not tell us whether or not we will find more quarks at higher energies,
this ratio can be used to identify the energies where new quark final states become accessible. This general structure can be seen in a plot of the world data on measurements of $R$ in Figure 1.2.

![Graph showing $\sigma_{\text{hadrons}}$ and $R$ as functions of $\sqrt{s}$ (GeV)]

Figure 1.1: World data on the total cross section of $e^+e^- \rightarrow \text{hadrons}$ and the ratio $R(s) = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$[1].

### 1.2.1 The Color Charge

The introduction of quarks gave physicists a way to understand the multitude of particles that had just been discovered, a way to explain the anomalous
magnetic moment of the proton and perhaps a simple way to build up the properties of the proton from its constituent quarks\footnote{1}. For example the proton charge could simply be recovered by summing the charges of the two up quarks and the one down quark, $e_q$.

\[
+1 = \sum q e_q \\
= \left( \frac{2}{3} \right) + \left( \frac{2}{3} \right) + \left( -\frac{1}{3} \right) \\
\]

or the spin of the proton might be a simple superposition of the spins of the quarks:\footnote{1}

\[
\frac{1}{2} = \frac{1}{2} + \frac{1}{2} - \frac{1}{2} \\
\]

Though the quark model was quite successful in corraling the massive herd of hadrons, there was a notable objection. The quarks were believed to be fermions, thus subject to the Pauli Exclusion Principle. If the three quarks inside a baryon are assumed to be in an s-wave state, an assumption supported by data on the ratio of magnetic moments of baryons, one of the states of the baryonic decuplet, found in Table \ref{table}, the $\Delta^{++}$, should not be allowed. But it had been observed experimentally. The problem is as follows, the $\Delta^{++}$ consists of three identical u quarks, in an s-wave state, a state which seems to violate the Pauli Exclusion Principle, since the total wave function was not anti-symmetric under exchange of particles. In 1964 Greenberg\footnote{25} proposed a new quantum number, color, which all quarks were to carry. So now not only do quarks have a flavor (u,d,s,c,b & t) but also a color charge, usually
denoted red, green and blue. Though this may seem like an ad hoc solution, the introduction of color plays an important role in our understanding of the dynamics of quarks, as will be discussed in Section 1.4.

1.3 Probing the Structure of the Proton

As these theoretical advances were gaining traction, experimental physicists, taking their cue from Rutherford, Marsden, and Geiger, began performing scattering experiments to study the structure of the proton. The best way to do this is to probe it with something simple and well understood. To this end, the immediate choice would be light.

Starting in the 1950’s Hofstadter and collaborators at SLAC[26] began a series of experiments in which a beam of electrons is scattered off of a fixed nuclear target. In an electron-proton scattering experiment, or in any lepton-nucleon scattering experiment for that matter, the lepton with incoming (out-going) energy \(E\) (\(E’\)), 4-momentum \(k^\mu = (E, \vec{k})\) (\(k'^\mu = (E’, \vec{k’})\)) and helicity \(\lambda\) (\(\lambda’\)) emits a virtual photon in the electromagnetic field of the nucleon with a 4-momentum \(q^\mu\), which interacts with the nucleon with 4-momentum \(P^\mu\) and spin \(\sigma\), similar to the arrangement in Figure 1.2.

A summary of the relevant variables in a lepton-nucleon scattering experiment is available in Table 4.1. A more detailed explanation will follow.

The differential cross section for such a process can be written in terms of two tensors, \(L_{\mu\nu}\) and \(W_{\mu\nu}\), which describe the leptonic and hadronic coupling to the photon:

\[
\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{Q^4} \frac{E'}{E} L^{\mu\nu}(k, q, \lambda) W_{\mu\nu}(P, q, \sigma) \tag{1.7}
\]
where $\alpha$ is the fine structure constant ($\alpha \approx 1/137$). It is also convenient to define the virtuality $Q^2$,

$$- Q^2 \equiv q^\mu q_\mu$$  \hspace{1cm} (1.8)

The wavelength, and thus the resolving power given by the de Broglie relationship $\lambda = h/p$, is proportional to $\frac{1}{Q}$. The leptonic tensor in equation [1.7] can be written out exactly, since the electron is a point-like object, so the Feynman rules of QED are straightforward:

$$L_{\mu\nu}(k, k') = 2(k_\mu k'_{\nu+} + k'_\mu k_{\nu} - Q^2 g_{\mu\nu})$$  \hspace{1cm} (1.9)

$W_{\mu\nu}(P, q, \sigma)$ is the hadronic tensor which describes the coupling of the photon to the hadron, and depends on the 4-momentum of the nucleon, $P$, the 4-momentum transfer $q$, and the spin of the nucleon, $\sigma$ Hadronic tensor, in contrast to the leptonic tensor, can not be written down so simply. The
Table 1.2: Summary of kinematic variables in lepton-proton scattering

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M )</td>
<td>The mass of the target hadron.</td>
</tr>
<tr>
<td>( E )</td>
<td>The energy of the incident lepton.</td>
</tr>
<tr>
<td>( k )</td>
<td>The 4-momentum of the initial lepton. ( k = (E, 0, 0, E) ) if the lepton mass is neglected.</td>
</tr>
<tr>
<td>( \Omega )</td>
<td>The solid angle into which the outgoing lepton is scattered.</td>
</tr>
<tr>
<td>( E' )</td>
<td>The energy of the scattered lepton.</td>
</tr>
<tr>
<td>( k' )</td>
<td>The momentum of the scattered lepton. ( k' = (E', E'\sin\theta \cos\phi, E'\sin\theta \sin\phi, E'\cos\theta) ).</td>
</tr>
<tr>
<td>( p )</td>
<td>The momentum of the target, ( p = (M, 0, 0, 0) ) for a fixed target experiment.</td>
</tr>
<tr>
<td>( q )</td>
<td>The momentum transfer in the scattering process. ( q = k - k' ).</td>
</tr>
<tr>
<td>( \nu )</td>
<td>The energy loss of the lepton. ( \nu = E = E' = \frac{\nu q}{M} ).</td>
</tr>
<tr>
<td>( y )</td>
<td>The fractional energy loss of the lepton. ( y = \nu / E = \frac{\nu q}{\nu k} ).</td>
</tr>
<tr>
<td>( Q^2 )</td>
<td>( Q^2 = -q^2 = 2EE'(1 - \cos\theta) = 4EE'\sin^2\theta/2 ).</td>
</tr>
<tr>
<td>( x )</td>
<td>Bjorken x. The momentum fraction of the proton carried by a given parton. ( x = \frac{Q^2}{2M\nu} = \frac{Q^2}{2\nu q} = \frac{Q^2}{2M\nu y} ).</td>
</tr>
</tbody>
</table>

The hadronic tensor, which describes protons, describes a complex object.\(^2\) The spin independent and spin dependent components of the hadronic tensor are,

\(^2\)In the modern interpretation, the proton is a bound state of several more elementary objects, the quarks and gluons, and is governed by confinement, and other non-perturbative effects.
respectively,

\[ W^S_{\mu\nu}(p, q, \sigma) = (g_{\mu\nu} + \frac{1}{Q^2} q_{\mu} q_{\nu}) W_1(\nu, Q^2) + \frac{1}{M^2} (p_{\mu} + \frac{p \cdot q}{Q^2} q_{\mu}) (p_{\nu} + \frac{p \cdot q}{Q^2} q_{\nu}) W_2(\nu, Q^2) \]  

(1.10)

and

\[ W^A_{\mu\nu}(p, q) = \frac{i}{M^2} \epsilon_{\mu\nu\lambda\sigma} q^{\lambda} [s^\sigma \left( G_1(\nu, Q^2) + \frac{\nu}{M} G_2(\nu, Q^2) \right) - \frac{1}{M^2} s \cdot q p^\sigma G_2(\nu, Q^2)] \]  

(1.11)

Where \( W_1(\nu, Q^2) \) and \( W_2(\nu, Q^2) \) (\( G_1(\nu, Q^2) \) and \( G_2(\nu, Q^2) \)) are the spin independent (spin dependent) structure functions which contain all of the target-specific information. In unpolarized collisions, spins are summed over and the spin dependent part does not contribute. We have also made use of another invariant, \( \nu \)

\[ \nu = \frac{p \cdot q}{M} \]  

(1.12)

which, in the target rest frame, simplifies to the lepton energy loss \((E - E')\)

The differential cross section can be written as

\[ \left( \frac{d^2\sigma}{d\Omega dE'^2} \right)_{lab} = \left( \frac{4\alpha^2 E'^2}{Q^2} \right) [2W_1(\nu, Q^2) + W_2(\nu, Q^2)(\frac{\theta}{2})] \]  

(1.13)

1.3.1 Deep Inelastic Scattering and the Parton Model

By the 1960's accelerator technology had advanced to the point where the resolving power of the photon probe could "see" the substructure of the proton. Unlike in the elastic regime the virtual photon does not interact with the proton as a whole, but instead it only interacts with a portion of the proton. In
these types of experiments the proton is blown apart. This type of experiment, where the target nucleon does not remain intact has come to be known as *deep inelastic scattering.*

1.3.2 Parton Model

At the same time that Gell-Mann and Zweig were working on the quark model, Richard Feynman was studying the physics of high energy hadron collisions. It was during this time he proposed the parton model of the nucleon. The parton model provides a simple physical picture that helps to interpret results from DIS experiments. In this model, the nucleon is composed of a number of free on-shell particles, called partons. The scattering cross section is then computed in terms of incoherent scattering of the virtual photon with these partons.

1.3.3 Bjorken Scaling

Bjorken introduced the scaling variable $x$, which became crucial in understanding DIS results.

$$x_{bj} \equiv \frac{Q^2}{2p \cdot q} = \frac{Q^2}{2\nu M}$$ (1.14)

In limit where $Q^2$ becomes very large, such that the transverse momentum and mass of the partons can be neglected, $x_{bj}$ can be interpreted as the fraction of the protons momentum carried by the parton, ranging from 0 to 1. This can be seen most readily by considering the virtual photon scattering off an
on mass-shell parton, i, carrying a fraction, $\xi_i$ of the protons momentum, P.

$$0 \approx (\xi_i P + q)^2 = \xi_i^2 M_i^2 + 2\xi_i P \cdot q + q^2$$

$$\rightarrow \xi = \frac{Q^2}{2P \cdot q} = x_{bj}$$

Deep inelastic scattering is the study of lepton-hadron scattering in the limit that $x_{bj}$ is fixed and $Q^2 \rightarrow \infty$. In most cases, the ”bj” subscript is dropped and the Bjorken scaling variable is simply called $x_F$. This convention will be used from here on out.

*Form factors*, which describe how charge is distributed through the proton as a whole, show a strong dependence on the ratio $Q^2/M^2$. It was thought that the same behavior would persist in the structure functions in deep inelastic scattering. Bjorken discovered that if the constituents of the hadrons were in fact free point-like objects at high energies, then the hadronic scale, M, would become irrelevant, and the structure functions only depend on $x$, and must be independent of $Q^2$. In other words, the proton “looks” the same at a given $x$ no matter how close you look at it.

In the Bjorken limit, the spin independent structure functions, $W_1$ and $W_2$ are usually express as

$$F_1(x) = MW_1(\nu, Q^2)$$

$$F_2(x) = \nu W_2(\nu, Q^2)$$

There is copious amounts of data on the $F_1$ and $F_2$ structure functions. A sum-

---

3 Another common scaling variable used in the description of high energy hadron–hadron collisions is Feynman $x$, $x_F$. It is the ratio of the longitudinal momentum of an outgoing particle to the maximum momentum accessible to the particle. When ambiguity may arise the subscripts are used.
mary of the world data of the $F_2$ structure function can be found in Figure 1.3.3. The scaling property is seen to hold approximately. These small logarithmic deviations are due to higher order corrections, which are introduced by QCD. Fortunately these scaling violations are predictable from QCD and are governed by the DGLAP equations, which will be discussed in section 1.4.3.

Figure 1.3: Compiled world data for the proton structure function, $F_2^p$. Plot is a reproduction of the original found in the Review of Particle Physics.\[1\]
1.3.4 The Quark Parton Model

In 1969, Callan and Gross\textsuperscript{28} suggested that if the partons were to carry spin-$\frac{1}{2}$, the structure functions in the Bjorken limit are related, i.e.:

\[
2xF_1(x) = F_2(x)
\]

(1.19)

If the partons were spin-0, their prediction was that $xF_1(x)/F_2(x) = 0$, though this would be inconsistent with the data shown in Figure 1.3.4 This provided the first compelling evidence that Feynman’s charged partons were actually quarks. It is important to note the cross section for a photon interacting with a gluon is suppressed. Since photon is colorless and the gluon has no electric charge, they cannot couple directly to each other.

![Figure 1.4: Plotted is the ratio $2xF_1/F_2$ against $x$. Data was collected by A. Bodek et.al\textsuperscript{2}](image)

If we define a quantity $q_f(x)$, known as the \textit{parton distribution function}
(PDF), to be the probability of finding a parton of flavor $f$ and momentum fraction $x$ inside the nucleon we can write the spin independent structure functions as [4]

$$F_1(x) = \frac{1}{2} \sum_f e_f^2 [q_f(x) + \bar{q}_f(x)]$$  \hspace{1cm} (1.20)

$$F_2(x) = \sum_f e_f^2 x [q_f(x) + \bar{q}_f(x)]$$  \hspace{1cm} (1.21)

### 1.3.5 Sum Rules

Now that partons have been linked to quarks and it is assumed the proton is composed of only two up and a down quark along with possible quark-antiquark pairs of any flavor (u,d,s,c,b or t), known as *sea quarks*, one arrives at the following relations.

$$\int_0^1 dx \ u(x) - \bar{u}(x) = 2$$  \hspace{1cm} (1.22)

$$\int_0^1 dx \ d(x) - \bar{d}(x) = 1$$  \hspace{1cm} (1.23)

$$\int_0^1 dx \ s(x) - \bar{s}(x) = 0$$  \hspace{1cm} (1.24)

Since the sea quarks only appear as $q\bar{q}$ pairs it should be expected that they exist in equal amounts in the proton so the difference integrated over all values of $x$ should be zero. The surplus $u$ and $d$ quarks, are termed *valence quarks*.

With the merger of the quark model and the parton model, one can begin to derive fundamental quantities, which characterize the proton, by summing up its parts. Since it is perhaps the most basic, or at least well know, property,
the simplest of these quantities would be the charge of the proton. So we sum over all quark flavors, $q_f$, spanning all ranges in $x$ values and weight by the quark charge of flavor $f, e_f$

$$+ 1 = \sum_f e_f \int_0^1 dx \ q_f(x) - \bar{q}_f(x)$$

$$= \frac{2}{3} \int_0^1 dx \ u(x) - \bar{u}(x) - \frac{1}{3} \int_0^1 dx \ u(x) - \bar{u}(x)$$

$$+ \sum_{f=s,c,b,t} e_f \int_0^1 dx q_f(x) - \bar{q}_f(x)$$

$$= 2 \times \frac{2}{3} - 1 \times \frac{1}{3} + 0 \quad (1.25)$$

Similarly, the momentum sum over all partons can be calculated. Again, summing over the quark flavors, spanning the entirety of $x$ and weighting by the momentum fraction another sum rule is arrived at.

$$1 = \sum_f \int_0^1 dx \ x \ [q_f(x) + \bar{q}_f(x)] \quad (1.26)$$

However, this sum rule does not agree with experiment. Using PDFs mostly derived from DIS data it was discovered that quarks and anti-quark account for only about 50% of the proton momentum. This missing momentum, as it turns out, can be attributed to the existence of gluons, which are the force carrier that appear when one tries to write down a description of the strong nuclear force using quantum field theory.
1.4 Quantum Chromodynamics

In light of the theoretical work by Bjorken and the results coming out of DIS experiments, a full field theoretical description of the interactions of partons inside the nucleon was sought after. What follows can be found in most standard text on QCD. Theorists were burdened by two unorthodox ideas. First unlike the most successful theory known to physics, Quantum Electrodynamics (QED), the coupling strength in this new theory had to become weaker as the interaction distance became smaller. Second, the fundamental particles of the theory seemed to be stuck inside the nucleon. The solution came in the form of a non-Abelian gauge theory being studied by Gross, Politzer and Wilczek which we now call Quantum Chromodynamics (QCD). A byproduct of the non-Abelian gauge theory was a new kind of force carrier, the gluon, which is the QCD equivalent of the photon in QED. These gluons had the added complexity that there were 8 of them. The gluon, though electrically neutral, did carry the strong force charge, color. Meaning that, unlike photons, gluons will couple directly to other gluons. This peculiar property of the force carriers in the theory had some very beneficial byproducts.

In QED, one sees that there is a variation in some physical coupling constants under a change of scale. Qualitatively, this can be understood by thinking of the action of the field on virtual particles in the vacuum. For example, when measuring the charge of an electron in the laboratory, in the vicinity of the charge, the vacuum becomes polarized; virtual particles of like sign are repelled, unlike sign are attracted and the net result is a screening of the charge. As one gets closer and closer to the charge one sees less of this vacuum effect.
and the effective charge increases. An intuitive picture is shown below. In

\[ \text{\includegraphics[width=0.5\textwidth]{figure.png}} \]

Figure 1.5: A schematic representation of charge screening of an electron in QED

QCD, each gluon carries a color charge, the net effect of polarization of virtual

\[ \text{gluons in the vacuum is not to screen the field, but to enhance it. This is some-}\]
\[ \text{times called anti-screening. "Looking" closer (higher } Q^2 \text{) at quark diminishes}\]
\[ \text{the anti-screening effect of the surrounding virtual gluons, so the contribution}\]
\[ \text{of this effect would be to weaken the effective charge with decreasing distance.}\]
\[ \text{This is the behavior that had been observed in experiment. This phenomena}\]
\[ \text{goes by the name } asymptotic \text{ freedom and was discovered by Gross, Wilczek}\]
\[ \text{and Politzer } [31,32]. \text{ The converse of this, i.e. enhancement of the coupling}\]
\[ \text{as the distance increases, solved another problem. In QCD, the strengthening}\]
\[ \text{of the coupling meant that, if one were to try to pull a single quark out of}\]
\[ \text{a proton there becomes a point where it is more energetically favorable to}\]
\[ \text{create a } q\bar{q} \text{ pair from the vacuum than to separate the quarks any farther.}\]
\[ \text{This describes the lack of observation of free quarks. This property has been}\]

19
termed *color confinement.* As we will see, in QCD there exists a delicate

![Diagram](https://via.placeholder.com/150)

**Figure 1.6:** Higher order diagrams involved in the screening of the electron in quantum electrodynamics

![Diagram](https://via.placeholder.com/300)

**Figure 1.7:** Higher order diagrams involved in the screening of the color charge in QCD, this is the direct analog of the QED diagram in Figure 1.4

![Diagram](https://via.placeholder.com/300)

**Figure 1.8:** In addition to the diagrams shown in Figure 1.7, the above diagram also contributes to color charge screening. The gluon loops are responsible for the anti-screening

interplay between the virtual quarks and the virtual gluons. Each contribute with opposite effects, which effect prevails depends on the number of quark flavors. For standard QCD with three colors, as long as there are no more than 16 flavors of quark, anti-screening dominates and the theory is asymptotically free.
1.4.1 Renormalization

In order to compare quantities measured in the laboratory to theory, the physical quantities must be renormalized. Renormalization is a systematic method for determining the relationship between what is measured in laboratory to what we call "bare" quantities, values of parameters in the Lagrangian, when the parameters change with scale. In e-p scattering the most natural choice would be related to the resolving power of the photon, Q.

The relevant parameter of QCD is the strong coupling constant, $\alpha_s$. It is analogous to the fine structure constant $\alpha$ in QED. QCD does not predict an absolute size of the coupling constant, this must be extracted from experimental data, but its evolution with scale can be calculated. Renormalization at a scale $\mu$ essentially accounts for the fact that the quantum vacuum is not empty when we "look" at it close enough. When we probe the proton, the bare color charges (i.e. the parameters we see in the Lagrangian) of the theory are not seen. Instead, charges will be surrounded by a fluctuating cloud of virtual gluons and $q\bar{q}$ pairs and it is the sum of these components which is "seen" at a given resolution. The evolution of the coupling constant obeys the renormalization group equations which dictate that the coupling, $\alpha_s$, should vary as

$$\frac{d\alpha_s(\mu)}{d\mu} = \beta(\alpha_s(\mu)) \tag{1.27}$$

where $\beta(\alpha_s(\mu))$ can be calculated order by order in a perturbative expansion,

$$\beta(\alpha_s(\mu)) = -\beta_0 \alpha_s^2(\mu^2) - \beta_1 \alpha_s^3(\mu^2) + \ldots \tag{1.28}$$
Where the first few terms of the expansion are \[31\] 32

\[
\begin{align*}
\beta_0 &= \frac{33 - 2N_f}{12\pi} \\
\beta_1 &= \frac{153 - 19N_f}{24\pi^2}
\end{align*}
\] (1.29) (1.30)

Measurements of the coupling, \(\alpha_s\), as a function of the scale, \(Q\), are plotted in figure \[1.4.1\] with a fit superimposed. At leading order, the evolution of the coupling constant in equation \[1.27\] can be solved analytically and it is found to be related to the number of flavors kinematically accessible, \(N_f\).

\[
\alpha_s(\mu) = \frac{\alpha_s(\mu_0)}{1 + \left(\frac{\beta_0}{4\pi}\right) \ln \left(\frac{\mu^2}{\mu_0^2}\right) \alpha_s(\mu_0)}
\] (1.31)

where \(\mu_0\) is the initial scale, where the value of the coupling constant is known, \(\mu\) is the scale where the value would like to be known and \(\alpha_s(\mu_0)\) is the value of the coupling constant at the initial scale. the number of different flavors of quarks that are assumed to exist. The leading order result for the coupling constant decreases logarithmically as \(\mu \to \infty\). This behavior of tending to zero is the desired quality that the partons look free on the time scales over which the photon is scattering, asymptotic freedom. Thus at larger and larger energies, the quarks and gluons begin to look as though they are non-interacting particles. The small value of the coupling is what allows theorist to apply perturbative techniques to calculations.
1.4.2 Factorization and Universality

We found in the previous section that the strong coupling constant, $\alpha_s$, is small at short distances, or equivalently large momentum transfer, but can grow to be quite large. As a result, in order to do calculations, the problem may need to be broken into parts. In DIS, the cross section, $\sigma_{DIS}$ might be separated into a part describing the elastic scattering of the lepton off of the parton, $\hat{\sigma}$ and a part handles the fact that the proton is a composite particle. $\hat{\sigma}$ is a quantity calculable via perturbative QCD. The second part was mentioned earlier, this is the parton distribution function $q_f(x)$. This procedure is called factorization. Factorization now introduces another scale into the description.
of scattering experiment with the proton. This is known as the factorization scale $\mu_F$. $\mu_F$ sets the point below which, soft physics, i.e. the radiation and absorption of gluons, is absorbed into the PDF, and above which pQCD calculations are applicable. The total cross section is then the convolution of these two terms.

$$\sigma_{DIS} = \sum_{f=q,g} \int_0^1 dx \ \sigma_{ep}(x, q, \mu_F^2, \mu_R^2) q_f(x, \mu_F^2)$$  \hspace{1cm} (1.32)

Along with factorization, another assumption must be made, and that is the *universality* of the parton distribution functions. Universality that the parton distribution function must be independent of the reaction used to measure it. This would allow the use of PDFs measured in lepton proton collisions in a cross section calculation of proton on proton collisions. Universality and factorization are assumptions made to facilitate calculations. Their validity must be tested by comparing measured cross sections with theoretical predictions. We shall see this is a prerequisite for interpreting experimental results in terms of QCD.

### 1.4.3 Parton Distribution Functions in QCD

The parton distribution functions, like the coupling constant, are not calculable in QCD, so they must be determined empirically from experiment. However, their dependence on the factorization scale and renormalization scale is governed by the DGLAP evolution equations, which are named after five physicists, all of whom independently derived them, Dokshitzer, Gribov, Lipatov, Altarelli and Parisi. \[33\] \[34\] \[35\] The DGLAP equations, shown in Equation
are a set of coupled differential integral equations that describe the $Q^2$ dependence of the quark and gluon distribution functions:

$$
\mu^2 \frac{d}{d\mu^2} q_i(x, \mu_F, \mu_R) = \int_x^1 \frac{d\xi}{\xi} \sum_{j=f, g} P_{ij} \left( \frac{x}{\xi}, \alpha_s(\mu) \right) q_j(\xi, \mu_F, \mu_R)
$$

(1.33)

where $\mu_R$ is the renormalization scale and $\mu_F$ is the factorization scale described in the previous sections. The functions $P_{ij}$ are known as the splitting functions and they represent the probability that parton $j$ in the initial state with momentum fraction $\xi$ radiates parton $i$ in the final state with momentum fraction $x$. The splitting functions are calculable quantities in pQCD. The DGLAP equations tell us how quarks radiate gluons and how the $q\bar{q}$ sea quark pairs originate from gluons. They also, perhaps more importantly, allow PDFs measured at one scale at one experiment to be used to predict the results of experiments at other scales.

1.5 Spin Structure of the Proton

Guided by the idea that the charge and momentum of the proton could now be understood as the sum of its parts, we look to understand the origin or the proton spin by mapping out how spin and orbital angular momentum are distributed amongst the partons. In this section, the Naïve Quark Model is presented, in which one assumes most, if not all, the spin of the proton is due to the quarks. Next, results of the spin structure of the proton using deep-inelastic scattering techniques will be reviewed. These experiments show, like before, there will be corrections to our simple models once we include QCD
effects.

1.5.1 Naïve Quark Model

Our understanding of the spin structure of the proton follows a similar trajectory to our understanding of the quark parton model. Initial assumptions were that the spin of the proton should be describable in terms of the quarks alone. With that in mind two spin dependent quark parton distribution function may be defined as \( q_+(x) \) and \( q_-(x) \). These represent the probability of finding a quark with momentum fraction \( x \) and helicity aligned with proton and anti-aligned with the proton respectively. The quark contribution to the spin of the proton is now reasoned to be proportional to a new quantity, \( \Delta \Sigma \), defined by:

\[
\Delta \Sigma \equiv \sum_{q=u,d,s,c,b,t} \int_0^1 dx \ [q_+(x) - q_-(x) + \bar{q}_+(x) - \bar{q}_-(x)]
\]  

(1.34)

Neglecting contributions due to the gluons, one arrives at a new sum rule relating the spin of the proton to the spins of the quarks and anti-quarks, i.e.:

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma
\]  

(1.35)

In the naïve quark model, \( \Delta \Sigma \) is the spin dependent structure function \( g_1(x) \).

1.5.2 Sum Rules

In 1974, Ellis and Jaffe [36] derived a sum rule which relates the spin dependent structure function of the proton, \( g_1^p \) to linear combinations of matrix elements
of axial currents, where we have made use of the three linear combinations of the axial charges.

\[ \int_0^1 dx \ g_1^p(x, Q^2) = \left( \frac{1}{12} g_A^{(3)} + \frac{1}{36} g_A^{(8)} + \frac{1}{9} g_A^{(0)} \right) [1 + O(\alpha_s(Q^2))] \quad (1.36) \]

In the quark-parton model these charges are interpreted in terms of the polarized quark distributions.

\[
\begin{align*}
g_A^{(3)} &= \Delta u - \Delta d \\
g_A^{(8)} &= \Delta u + \Delta d - 2\Delta s \\
g_A^{(0)} &= \Delta u + \Delta d + \Delta s
\end{align*}
\]

These combinations were chosen because of the availability of data from other experiments. \( g_A^{(3)} \) is the axial decay constant in neutron beta decay and is measured to be \( g_A^{(3)} = 1.2695 \pm 0.0029 \)\(^4\). \( g_A^{(8)} = 0.58 \pm 0.03 \)\(^4\) is extracted from hyperon semileptonic decay. The objective of the polarized DIS experiment is to extract the quark contribution to the spin of the proton \( g_A^{(0)} \).

### 1.5.3 EMC Experiment

The first polarized DIS experiments were performed at SLAC by the Yale-SLAC group. The collaboration looked to measure the spin dependent part

\(^4\)In QCD the matrix elements of the axial current comes from the interactions of a virtual photon with the quark spin. For proton with momentum \( p \) and spin \( s \) the matrix elements are given: \( \mathcal{M} \equiv (p, s) \frac{i}{2} \bar{u} \gamma^\mu \gamma_5 u + \frac{i}{2} \bar{d} \gamma^\mu \gamma_5 d + \frac{i}{2} \bar{s} \gamma^\mu \gamma_5 s(p, s) \) where \( (p, s) \) is the proton wave function, \( \gamma^\mu \) and \( \gamma_5 \) are the Dirac matrices and \( u, d \) and \( s \) are the quark wave functions and \( \bar{u}, \bar{d} \) and \( \bar{s} \) their adjoints.
of the electron-proton cross section, found in Equation 1.11. In order to do this, both the proton and the incident electron must be polarized. One then measures the difference between the cross sections when the electron spin is aligned and when it is anti-aligned with the proton. The spin independent part, found in Equation 1.10 will cancel in the numerator and one is left with,

\[
\frac{d^2\sigma^{++}}{d\nu dQ^2} - \frac{d^2\sigma^{+-}}{d\nu dQ^2} = \frac{4\pi\alpha^2}{E^2Q^2} \left( M(E + E'\cos\theta)G_1(\nu, Q^2) - Q^2G_2(\nu, Q^2) \right) \tag{1.40}
\]

This should be compared with the total differential cross section in Equation 1.13, recalling that \( G_1 \) and \( G_2 \) are the spin dependent analog of the spin independent structure functions \( F_1 \) and \( F_2 \). Similarly, in the Bjorken limit, they can be written down as functions of \( x \) alone.

\[
\frac{\nu}{M} G_1(\nu, Q^2) \rightarrow g_1(x) \tag{1.41}
\]
\[
\frac{\nu^2}{M^2} G_2(\nu, Q^2) \rightarrow g_2(x) \tag{1.42}
\]

We define the quark asymmetry, \( A_1^p \) as the ratio of the \( g_1 \) and \( F_1 \) structure functions of the proton

\[
A_1^p = \frac{g_1^p}{F_1^p} \tag{1.43}
\]

In practice, what is measured is

\[
A_1^p = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \tag{1.44}
\]

\(^5\)The naming convention puts the type of structure function in the subscript and the hadron in the superscript. Hence, the quark asymmetry in the neutron would be called \( A_1^n \).
where \( \sigma^{++} (\sigma^{+-}) \) signifies the electron-proton cross section when the electron and proton polarizations are aligned (anti-aligned). This, of course, can be generalized to any lepton-hadron scattering experiment.

Combining the EMC measurement with the values of \( g_A^{(3)} \) and \( g_A^{(8)} \) the value of \( \Delta q \) is obtained for all three flavors. 

\[
\begin{align*}
\Delta u &= 0.74 \pm 0.10 \quad (1.45) \\
\Delta d &= -0.54 \pm 0.10 \quad (1.46) \\
\Delta s &= -0.20 \pm 0.10 \quad (1.47) \\
\end{align*}
\]

The first thing one notices is that not only do they conclude that the strange quark contribution, which only appears as the result of the sea quarks, was non-zero, but it is also negative. Next, the quark contribution to the spin of the proton can be calculated,

\[
\Delta \Sigma = \Delta u + \Delta d + \Delta s \\
= 0.01 \pm 0.29 \quad (1.49)
\]

This is an even more shocking result. The quarks only contribute to a small fraction of the spin of the proton. The measurement of the \( g_1^p \) structure function was repeated several times by collaborations at CERN, DESY and SLAC. A summary of the world data of \( g_1^p \) is shown in Figure 1.5.2. They all confirm the EMC result. Recent results of \( \Delta \Sigma \) have the value measured a value of \( 0.120 \pm 0.094[\text{stat}] \pm 0.138[\text{sys}] \).
1.5.4 Spin Crisis to Spin Puzzle

The EMC experiment showed that quarks alone could not account for the spin of the proton. In our modern view of the proton, one must include not only the contribution from quark spins (\(\Delta \Sigma\)), but also the contribution from spin of the gluons (\(\Delta G\)), and perhaps even orbital angular momentum of the two. We could then consider the following sum rule.

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + \Delta G + L_g
\]  

(1.50)

There have been attempts to measure the gluon contribution, \(\Delta G\). These types of measurements are quite difficult since the probe in DIS, the photon, does not couple directly to the gluon. This is because gluon is electrically neutral and the photon does not carry a color charge.

1.6 Hadron-Hadron Scattering

One is also able to obtain information about the structure of the nucleon via hadron-hadron collisions. The upshot of these types of experiments is that because hadrons are strongly interacting particles, the gluons are able to interact at leading order. Though, Hadron-Hadron Collision come with the added difficulty, as compared to DIS, that the probe is no longer point-like. Instead of having just one PDF, a convolution of two parton distribution functions, each representing one of the colliding hadrons, must be taken. Interpreting results, again, relies on the applicability of factorization to the processes at hand. In the most general case, in the framework of pQCD, one expects that
the description of hadron-hadron collisions can be separated into three distinct parts. One short range part, due to elastic scattering between partons, which is calculable in pQCD and two long distance parts the PDFs and the fragmentation functions (FF). The PDFs describe the state of the partons in the hadrons before the collision. The fragmentation functions are due to the fact that partons liberated from the hadron during the collision will form a spray of hadrons, commonly called a jet. Like the PDFs, the fragmentation functions are expected to be universal, so they may be measured in \( e^+ + e^- \) collisions, and their \( Q^2 \) evolution is governed by a set of DGLAP equations such that measurements at one scale may be translated to another. The cross section is represented schematically as

\[
\sigma = \sum_{f_a, b = q, \bar{q}, g} f_a \otimes f_b \otimes \hat{\sigma} \otimes D^h_c z_c \tag{1.51}
\]

where \( f_a \) (\( f_b \)) is the PDF of hadron A (B). \( \hat{\sigma} \) is the partonic cross section and \( D^h_c \) is the fragmentation function, which describes how parton c forms hadron h. In the case of jets and direct photons, with a shrewd choice of cuts to isolate the photon, the fragmentation function can be set to unity. The functional dependence of the PDFs and FFs on the factorization and renormalization scales has been suppress for ease of reading.

### 1.6.1 PP-Cross Section

Verification that factorization is applicable at the energies studied is required. This is done by comparing measured cross sections to theoretical calculations. The single particle differential cross section, for the process \( p + p \rightarrow h + X \),
where the final states $X$ are summed over, is given by

$$
\frac{d\sigma_{p_1 p_2 \rightarrow h X}}{dp_T d\eta} = \sum_{abc} \int dx_a dx_b dz_c \ f^A_a(x_a, \mu_R) f^B_b(x_b, \mu_R) \frac{d\hat{\sigma}^{ab \rightarrow cd}}{d\hat{p}_T d\eta}(x_a P_a, x_b P_b, P^h / z_c, \mu_R, \mu_F) D^h_c(z_c, \mu_R')
$$

(1.52)

Where $p_T$ is the transverse momentum of the particle of interest, and $\eta$ its pseudorapidity. The PDFs $f^A_a(x_a, \mu_R)$ ($f^B_b(x_b, \mu_R)$) represents the probability of finding parton $a$ ($b$) in proton $A$ ($B$), with momentum fraction $x_a$ ($x_b$). $D^h_c$ is the fragmentation function for parton $c$ to hadronize to hadron $h$. Variables with hats, $\hat{\sigma}$ and $\hat{p}_T$ are partonic counterparts to the unhatted variables. So $\hat{p}_T$ is the parton transverse momentum and $\hat{\sigma}^{ab \rightarrow cd}$ is the partonic cross section for the process $ab \rightarrow cd$. $\mu_R$ and $\mu_F$ are the renormalization and factorization scales respectively. One of the main disadvantages of pp collisions is that direct measurements of $x$ and $Q^2$ are usually not feasible. The most natural choice of scale is then the transverse momentum. Calculations are traditionally carried out using a single scale $\mu_R = \mu_F = \mu = Q^2 = p_T$. Theoretical uncertainties are usually attained by comparing results with the scale set to $2p_T$ and $p_T/2$.

Cross sections have been measured at PHENIX for several channels at both $\sqrt{s} = 200 GeV$ and $\sqrt{s} = 62.4 GeV$. Next to leading order (NLO) and next to leading log (NLL) pQCD calculations and their comparison to PHENIX data will be shown in later chapters.
1.6.2 Accessing $\Delta G$ in Polarized Proton-Proton The Collisions

Once agreement between data and theoretical calculations is established in the unpolarized case, one can then begin applying factorization techniques to polarized quantities as well. Suppose pairs of protons are collided while keeping track of their helicity. The difference in production cross sections during collisions when the two proton helicities are aligned and anti-aligned can be written as

$$\Delta \sigma = \sum_{f_{a,b} = q, g} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{ab \rightarrow cd} \otimes D^h_c$$  \hspace{1cm} (1.53)

where $\Delta f_a$ ($\Delta f_b$) is a polarized parton distribution function for proton A (B), $\Delta \hat{\sigma}$ is a polarized hard partonic cross section difference for the process $ab \rightarrow cd$ and $D^h_c$ is the same fragmentation function described in the previous section. The goal is to measure the polarized gluon distributions, $\Delta f_g$, or $\Delta G$, which could be achieved by measuring helicity dependent cross sections and including data for fragmentation functions, collected from $e^+ - e^-$ data, when needed.

Equation 1.53 can be written in terms of the helicity configurations of the colliding protons.

$$\Delta \sigma = [\sigma^{++} + \sigma^{--}] - [\sigma^{+-} + \sigma^{-+}]$$  \hspace{1cm} (1.54)

where $\sigma^{++}$ and $\sigma^{--}$ are cross sections measured during collisions of protons with like helicities, and $\sigma^{+-}$ and $\sigma^{-+}$ unlike helicities. The dominant mechanism for interaction at the partonic level in proton proton collision at
\[ \sqrt{s} = 200 \text{GeV} \] is the strong interaction, in which parity conserved. Therefore the following simplification may be made,

\[
\sigma^{++} = \sigma^{--} \\
\sigma^{+-} = \sigma^{-+} \\
\sigma^{+} = \sigma^{-}
\]

(1.55) (1.56) (1.57)

For the rest of this discussion "++" ("+-") will represent both like (unlike) helicity configurations "++ and - -" ("+- and +- "). Because of inherent difficulties in measuring absolute cross sections, due to large systematic uncertainties and fluctuations in detector efficiencies, a ratios of cross sections is often taken. When the ratio is taken many of these uncertainties and effects due to efficiencies will cancel. Therefore we will define a quantity the double longitudinal spin asymmetry, \( A_{LL} \), as the ratio of equations [1.53] and .

\[
A_{LL} = \frac{\sum_{f_a,b=q,\bar{q}} \Delta f_a \otimes \Delta f_b \otimes \Delta \hat{e}_{ab} \otimes \Delta D^h_c}{\sum_{f_a,b=q,\bar{q}} f_a \otimes f_b \otimes \hat{e} \otimes D^h_c} \]

(1.58)

\[
= \frac{[\sigma^{++} - \sigma^{+-}]}{[\sigma^{++} + \sigma^{+-}]} \\
= \frac{\Delta \sigma}{\sigma}
\]

(1.59) (1.60)

Like the single particle inclusive cross section, extracting \( \Delta G \) from \( A_{LL} \) in the most general case may require incorporating FF’s and PDFs from \( e^+ + e^- \) and DIS data.
1.6.3 Measuring $A_{LL}$

When measuring quantities like cross sections, it is important to have a good handle on efficiencies in the detector. One of the benefits of a collider experiment, as we will see in Chapter 3, is that the time difference between collisions of different helicity configurations is on the order of $\approx 100\text{ns}$. This means that changes in detector efficiencies due to gain drifts in power supplies, for example, will cancel in the ratio of $\Delta\sigma/\sigma$, since they vary on a much larger time scale. The cross section for a given process can be written as the ratio of the particle yield correct for efficiencies, $N'$ to the luminosity, $L$.

$$\sigma = \frac{N'}{L}$$ (1.61)

These corrections may include trigger bias efficiencies ($\epsilon_{\text{trigger}}$), reconstruction efficiencies ($\epsilon_{\text{reco}}$), and detector acceptance efficiencies ($\epsilon_{\text{acc}}$). We will represent the total correction as a single quantity.

$$\epsilon_{\text{corr}} = \epsilon_{\text{trigger}} \otimes \epsilon_{\text{reco}} \otimes \epsilon_{\text{acc}}$$ (1.62)

Then, the corrected yield, $N'$, is related to the raw yield by.

$$N = \epsilon_{\text{corr}} N'$$ (1.63)

We can now rewrite the double longitudinal spin asymmetry in equation
as a function of raw yields,

\[
A_{LL} = \frac{N^{++}}{\epsilon_{\text{corr}} L^{++}} - \frac{N^{+-}}{\epsilon_{\text{corr}} L^{+-}} = \frac{\epsilon_{\text{corr}} (N^{++} - \frac{L^{+}}{L^{++}} N^{+-})}{\epsilon_{\text{corr}} (N^{++} + \frac{L^{+}}{L^{++}} N^{+-})} = \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}}
\]  \hspace{1cm} (1.64)

where we have made use of the fact that the efficiencies will fluctuate on a time scale much larger than the rate at which different helicity collisions occur, and set \(\epsilon_{\text{corr}}^{++} = \epsilon_{\text{corr}}^{+-}\). Also a quantity called the relative luminosity is defined \(R \equiv L^{+}/L^{++}\). This will account for any false asymmetries which may occur due to differences in luminosity between beams of like helicity protons and unlike helicity protons.

Finally, \(A_{LL}\) is usually normalized to the beam polarization. This allows us to measure a true physics asymmetry,

\[
A_{LL} = \frac{1}{P_B P_Y} \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}}
\]  \hspace{1cm} (1.65)

where \(P_B\) and \(P_Y\) are the polarization of the two proton beams. In the next chapter, we will discuss the measurement of the cross section and \(A_{LL}\) of a special channel, called the direct photon.
Figure 1.10: Proton structure function $g_1^p$ measured by polarized DIS for $Q^2 > 1$. This figure was originally shown in a paper by S. Bass[4]
Figure 1.11: The above diagram is a schematic of factorization in hadronic collisions.
Chapter 2

Direct Photons

Hadron-hadron collisions are very complicated at the level of the constituent quarks and gluons. For most channels ($\pi^0$, $\eta$, ...) in order to calculate the most fundamental result from any collider experiment, the production cross section, many subprocesses must be disentangled and summed over. With this in mind, we look for a large momentum transfer hadron-hadron scattering process which, at the partonic level, one can directly constrain the kinematics of a small number of underlying subprocesses. The production of direct photons is one such process and because of this, the direct photon has been called the ”golden channel”. Here direct photon it taken to mean photons originating from the original hard scattering process. This excludes decay photons from hadronic decays. Since the direct photon originates in the hard-scattering process, one has a more direct probe of the interaction and the gluon spin than say, the $\pi^0$ channel.
2.1 Photon Production

2.1.1 Leading-order Processes $O(\alpha\alpha_s)$

At leading order two diagrams and their cross terms contribute to the production of direct photons. These are the quark-gluon Compton scattering process and $q\bar{q}$ annihilation. Following the standard prescription, the differential cross section for direct photon production is written in its factorized form as

$$E_\gamma \frac{d\sigma^{AB \rightarrow \gamma + X}}{dp_\gamma} = \int dx_d dx_b F(A, x_d) F(B, x_b) \frac{\hat{s}}{\pi} \frac{d\sigma}{dt} \delta(\hat{s} + \hat{t} + \hat{u})$$  \hspace{1cm} (2.1)

Where $\hat{s}$, $\hat{t}$, and $\hat{u}$ are the three Mandelstam variables for the subprocess. In the case of the quark-gluon Compton scattering process, the partonic cross section is,

$$\frac{d\sigma}{dt}(qg \rightarrow q\gamma) = -\frac{\pi\alpha\alpha_s}{3\hat{s}^2} e_q^2 \hat{u}^2 + \hat{s}^2 \frac{\hat{s}}{\hat{s} \hat{u}}$$  \hspace{1cm} (2.2)

and the $q\bar{q}$ annihilation process,

$$\frac{d\sigma}{dt}(q\bar{q} \rightarrow g\gamma) = \frac{8\pi\alpha\alpha_s}{9\hat{s}^2} e_q^2 \hat{u}^2 + \hat{t}^2 \frac{\hat{t}}{\hat{t} \hat{u}}$$  \hspace{1cm} (2.3)

The relative contribution of the two subprocesses are shown below in Figure 2.1.1 In PP collisions the Compton process dominates.

2.1.2 Beyond Leading Order

The simple leading order description of the direct photon is complicated by the addition of bremsstrahlung processes, examples are shown in figure 2.4. In practice, these photons may be removed from the data sample by a judicious
choice of isolation cut. Theoretical calculations must also take the isolation cut into account.

2.2 Experimental Techniques

The detection of direct photons requires the suppression of background from non-prompt sources, decays of short-lived particles. The primary source of background photons in hadron-hadron interactions arise from the decay of $\pi^0$ and $\eta$ mesons and, to a lesser extent from $\eta'$ and $\omega$ decays. Meson decays give rise to background photons in one of two ways: (1) one of the $\gamma$’s from a $\pi^0 \rightarrow \gamma\gamma$ or $\eta \rightarrow \gamma\gamma$ decay may not be detected, due to dead regions of the detector or small detector acceptance, thus imitating an isolated photon or
Figure 2.3: Relative signal fraction of direct photon production by $q\bar{q}$ and quark-gluon Compton scattering in NLO pQCD calculations

(2). The two decay photons may merge. Historically the two commonly used techniques for detecting prompt photons have emerged. The direct method and the conversion method.

2.2.1 Direct Method

The direct method relies on simultaneously measuring the prompt photon signal along with all decay photons and then systematically removing measured backgrounds. This method puts certain technical constraints on the detector used. First, the detector must have fine segmentation. In order to separate the photon pairs from a $10\, GeV\pi^0$, a segmentation of less than 15cm is required for distance of 5 meters from the interaction point. Secondly, good capability for detecting low energy photons is required in order to detect the low energy partner photons in very asymmetric meson decays. Third, a large solid angle would be desirable, in order to minimize the occurrence of events in which on $\gamma$ from a $\pi^0$ decay misses the detector. Lastly, linearity in the energy response,
since both the direct photon and $\pi^0$ production spectrum falls quickly with $P_T$. The fast falling spectrum, means that small uncertainties in the energy can result in very large accidental subtractions.

2.2.2 Conversion Method

In the conversion method, $\pi^0$’s and direct–$\gamma$’s are also measured simultaneously, but separated statistically. In this method a thin converter is placed between the interaction region and the detector. Since the most probable decay channel for the $\pi^0$ is $\pi^0 \rightarrow \gamma\gamma$, the likelihood of seeing a conversion from a $\pi^0$ is greater than that of a single $\gamma$. Comparisons of the inclusive photon yields with and without the converter in place will show an enhancement of the yield at low $p_T$ when the converter is present, which is due to the loss of one of the photons, and hence a portion of the total energy, from the $\pi^0$ in the converter.
2.2.3 Comparison of Methods

The advantage of the direct method is that one can directly detect and remove ground decay photons, but the catch is that the detector resolution must be fine enough with a reasonably good sized acceptance. The better the resolution and the larger the acceptance, undoubtedly implies the higher the cost of building and maintaining the detector. Any holes that exist in the acceptance must be understood and accounted for by a well tuned Monte-Carlo. The upshot of the conversion method is that it specifically does not require very fine granularity of the detector. Though, the conversion method requires a very good knowledge of the absolute conversion probability and nonlinearities as a function of photon energy of the conversion material used. This method also requires a very well tuned Monte-Carlo simulation.

The PHENIX detector, as will be discussed in Chapter \[4\] has a very finely segmented detector for photons and a well understood acceptance. The method used in this analysis found in Chapter \[7\] will more closely follow the direct method.

2.3 Early Measurements of Direct Photons

The R412 experiment, performed at the Intersecting Storage Rings (ISR), at the European Organization for Nuclear Research, CERN\[1\] produced the first published results on direct photons, though it was dominated by large systematic uncertainties\[38\]. The results were confirmed by later experiments

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\[1\]The acronym is based upon the original name of the laboratory in French: Conseil Européen pour la Recherche Nucléaire
at the CERN ISR (R107, R108, and R806) experiments and at the Fermi National Accelerator Laboratory (Fermilab) E629 experiment. Comparisons of several of the results from the ISR are shown in Figure 2.3.

![Differential cross sections for direct photon production from several CERN experiments at various center mass energies compared with theoretical calculations provided by Contogouris et al. The plot was originally shown in the same article. Circles are data from R806, squares from R108 and triangles from R107.](image)

Figure 2.5: Differential cross sections for direct photon production from several CERN experiments at various center mass energies compared with theoretical calculations provided by Contogouris et al. The plot was originally shown in the same article. Circles are data from R806, squares from R108 and triangles from R107.

Despite its standing as the "golden channel", direct photon measurements are not without controversy. Results from fixed target experiments have shown
large discrepancy between measured cross sections and NLO pQCD calculations. This disagreement is most pronounced in the E706 data from Fermilab. A compilation of the most recent direct photon data is shown in Figure 2.3. A proposed explanation for the discrepancy is initial-state soft gluon radiation, which introduces a transverse component to the initial parton momentum, $k_T$. It should be noted that this is a separate phenomenon from what is called "intrinsic" transverse momentum, which is due to the partons being confined to a finite space in the hadron. Apanasevich et al. found that by including a Gaussian smearing to the proton PDFs of the form

$$dx_a F(A, x_a) \to dx_a dk_T g(k_T) F(A, x_a)$$

(2.4)
where, $g(k_T)$ parametrizes the Gaussian smearing, the theory could be made to fit the world data. An alternative explanation was also proposed by Aurenche et. al. [9]. In their prescription the world data, aside from the E706 results, can be fit with the theory via a proper choice of PDFs and factorization scale. Of course, at the end of the day, the only true test of whether or not the theory is applicable to PHENIX data is a comparison of the measured cross section to pQCD calculations.

### 2.4 Relation to Spin

The direct photon $A_{LL}$ measurement is the most direct measurement of the gluon contribution to the spin of the proton. Though, the direct photon measurement is made difficult by the copious amount of decay photons one finds in the detector, as mentioned earlier, at leading order there are only two, theoretically well understood, subprocesses that contribute to the direct photon production. Recalling equation [1.53] With a smart choice of an isolation cut, some theoretical complications may be avoided. At leading order, the direct photon will be emitted back-to-back with a jet. Thus there should be minimal
activity in the detector surrounding the direct photon. If one only considers isolated photons, the fragmentation function, $D_c^b$ may be set to unity. The double longitudinal asymmetry may then be written down as a simple product of the gluon contribution, $\Delta G/G$, to the proton spin, a quark contribution, $\Delta \Sigma/\Sigma$, and the partonic asymmetry, $\Delta \hat{a}_{pp-\gamma X}$, which is calculable in pQCD

$$A_{LL} = \frac{\Delta G}{G} \frac{\Delta \Sigma}{\Sigma} \Delta \hat{a}_{pp-\gamma X}$$  \hspace{1cm} (2.5)$$

Where the $\Delta \Sigma/\Sigma$ is measured in DIS experiments and the partonic symmetry is defined as $\Delta \hat{a}_{pp-\gamma X} \equiv \Delta \sigma/\sigma$ The main benefit to using direct photons to understanding the spin structure of the proton is that, unlike the jet, $\pi^0$ and $\eta$ asymmetries [10] [11], the direct photon asymmetry is linear in $\Delta G$ thus providing information of both the sign and the magnitude of the gluon contribution to the spin of the proton. Also, since the fragmentation function can be neglected at leading order, the theoretical uncertainties associated with the FFs, which can be as large as 30% [11] and are present in the $\pi^0$ and $\eta$ asymmetries, do not appear in the direct photon extraction of $\Delta G/G$. Compared with the jet, the photon does not require complicated jet reconstruction algorithms.

**Key points of the direct photon:**

§1. Known point-like interaction.

§2. The most direct probe of $\Delta G/G$ available.

§3. Provides information that complements the $\pi^0$ asymmetry since it does not require a fragmentation function and model dependent fits at leading order.
§4. Provides a complementary measurement to the jet asymmetry since it does not require a complications arising from jet finding.
Chapter 3

BNL Collider Accelerator Facility

3.1 Introduction

The Brookhaven National Laboratory Collider Accelerator Facility provides high energy beams of different species for several scientific programs. These include the acceleration of Au and Cu for the study of the hot dense state of matter created in these heavy ion collisions and polarized protons to study the spin structure of the proton. Of interest to the present work are the facilities and equipment which provide the polarized protons to the Relativistic Heavy Ion Collider (RHIC), the world first and currently only polarized proton collider. A diagram of the facility can be seen in Figure 3.1

3.1.1 Polarized Source

Polarizing protons for acceleration are provided by an Optically Pumped Polarized Ion Source (OPPIS). These protons begin their lives at RHIC as unpolarized atomic Hydrogen gas ($H_2$). The atomic hydrogen is ionized by a strong microwave source. The resulting beam of unpolarized $H^+$ ions are removed
through a hole in a plate at one end of the source. The unpolarized protons are passed through a cell of optically pumped rubidium vapor in a 2.5 T field. The unpolarized protons capture a polarized electron from the vapor. The ground state of atomic Hydrogen is split into eigenstates $|s, m>$ of total spin by the hyperfine interaction. The spin states are separated into a spin triplet:

$$|1, 1\rangle = |\uparrow_e \uparrow_p\rangle$$  \hspace{1cm} (3.1)

$$|1, 0\rangle = \frac{1}{\sqrt{2}}[|\uparrow_e \downarrow_p\rangle + |\downarrow_e \uparrow_p\rangle]$$  \hspace{1cm} (3.2)

$$|1, -1\rangle = |\downarrow_e \downarrow_p\rangle$$  \hspace{1cm} (3.3)

and spin singlet state:

$$|0, 0\rangle = \frac{1}{\sqrt{2}}[|\uparrow_e \downarrow_p\rangle - |\downarrow_e \uparrow_p\rangle]$$  \hspace{1cm} (3.4)

Since the magnetic moment of the electron is $\approx 1000$ times greater than

51
the magnetic moment of the proton, interactions of the atom with an external magnetic field will be largely controlled by the electron. Hydrogen atoms are passed through a Stern-Gerlach-like apparatus. States of definite electron spin are then chosen, $|s, m\rangle = |\uparrow_{e\downarrow_p}\rangle$ and $|s, m\rangle = |\uparrow_{e\downarrow_p}\rangle$. This beam is then passed through a uniform magnetic field and an RF field that induces a Sona transition from $|\uparrow_{e\downarrow_p}\rangle \rightarrow |\downarrow_{e\uparrow_p}\rangle$. This transition leaves the protons, now polarized. The polarized hydrogen atoms are then exposed to sodium vapor, from which they pick up an extra, unpolarized electron. The $H^-$ ions are now ready to be accelerated by the LINAC. The design specification of the BNL source are to provide $\approx 10^{12}$ polarized protons per pulse with $\approx 85\%$ polarization to the LINAC

3.2 Pre-RHIC Acceleration

3.2.1 LINAC and Booster

Polarized $H^-$ from the source are accelerated to 200 MeV in the BNL Linear Accelerator (LINAC). At the end of the LINAC a stripping foil removes the 2 extra electrons from the hydrogen atoms and injects 200MeV polarized protons into the booster. The booster which was completed in 1991 serves as a preaccelerator for particles entering the AGS ring. It’s purpose is to help increase the intensity of the bunched proton beams generated for RHIC. Beam leaves the booster at 1.5 GeV, bound for the AGS.
3.2.2 Alternating Gradient Synchrotron

The Alternating Gradient Synchrotron (AGS) has a long history of scientific discovery, in its own right. It was at the AGS where the technique of strong-focusing was conceived by BNL physicists Ernest Courant and Hartland Snyder [42]. This critical leap in the development of modern particle accelerator design allowed scientists to accelerate protons to energies that would have been otherwise unattainable. In the 1960, the AGS became the world’s premiere accelerator and since its inception research at the AGS had been responsible for three Nobel prizes in physics. The primary function of the AGS in the spin physics program is as a pre-accelerator to the RHIC. Bunched beam is injected into the AGS at 1.5 GeV. The AGS then accelerates beams to 25GeV, an injects them into RHIC six bunches at a time.

3.3 Relativistic Heavy Ion Collider

RHIC is composed of two counter circulating storage rings each with a 3.8 km circumference capable of accelerating proton beams to center of mass energies ranging from $\sqrt{s} = 62$ GeV to $\sqrt{s} = 500$ GeV. Storage rings, like RHIC, use radio frequency (RF) electromagnetic pulses to accelerate the beam. In order for the beam to stay inside the accelerator, in the presence of these (RF) kicks, it must remain in a confined area of phase space, called a RF bucket. The beam is therefore, not a continuous ribbon, but rather, it is grouped together into collections of particles called bunches. The current RHIC setup allows for 360 RF buckets. Typically, only 1/3 of the buckets is filled leaving neighboring bunches, called satellite bunches, empty. Each bunch is approx-
imately 3 meters in length and containing $\sim 10^{11}$ protons. RHIC is capable of storing beam for time periods upwards of 12 hours, though in practice it is usually refilled every 8. These periods of stored beam are called fills.

Collisions at RHIC occur at specified interaction regions (IR). These interaction regions, which are labeled by there position on a clock face, are intervals along the ring in which the beams are crossed. They are spaced regularly about the ring, though only four of these crossings housed major experiments: PHENIX (8 o’clock), PHOBOS (10 o’clock), BRAHMS (4 o’clock) and STAR (6 o’clock). The smaller of these experiments PHOBOS and BRAHMS completed their data taking in 2005 and 2006 respectively. Currently only PHENIX and STAR are operational, both of which have very active spin programs. The PHENIX experiment, which was used in this work, is described in the next chapter.

### 3.4 Spin Specific Equipment

Accelerating protons to over 99.9% of the speed of light is difficult on its own. Polarized proton experiments at RHIC have the added complexity that comes with maintaining and monitoring the direction and degree of polarization of the accelerated beam. These tasks require specialized equipment not usually found in most accelerator facilities.

#### 3.4.1 Siberian Snakes

During the acceleration of polarized protons, special magnets are required in order to manipulate the polarization direction of the protons. The charged
particles are accelerated via pulsed RF, and the motion is governed by the Lorentz force:

\[ \frac{dv}{dt} = \frac{e}{m\gamma}[E + v \times B] \]  

(3.5)

where \(v\) is the proton velocity, \(e\) the particles charge and \(m\) is the mass. \(E\) and \(B\) are the electric field and magnetic field perpendicular to the direction of motion, respectively.

This means the polarized protons are immersed in a multitude of electric and magnetic fields, which will not only accelerate the proton but perturb the direction of its spin. During acceleration, the direction of the protons spin will begin to precess according to the Thomas-BMT equation.

\[ \frac{dS}{dt} = -\frac{e}{m\gamma}[(1 + G\gamma)B_{\perp} + (1 + G)B_{\parallel} + \gamma(G + \frac{1}{1 + \gamma})\frac{E_{\perp} \times \mathbf{v}}{c^2}] \times S \]  

(3.6)

\(S\) is the polarization vector in the protons moving frame. \(G\) is the anomalous magnetic moment. \(G = 1.7928\) for the proton. Ignoring the \(E\) field component, for the moment, and comparing equations 3.5 and 3.6 we see the spin vector rotates \(G\gamma\) times faster than the orbital motion. Thus, \(G\gamma\) gives the number of spin precessions for every revolution, which in accelerator jargon is call the \textit{spin tune} \((v_{sp})\). When the spin precession frequency equals the frequency at which spin perturbing magnetic fields are encountered this is referred to as a depolarizing resonance. The two main types of depolarizing resonances are imperfection resonances, which are the result of misalignment or errors in the magnets, and intrinsic resonances which are the byproduct of strong focusing magnets.

Helical magnets, called \textit{Siberian Snakes} help to preserve the proton beam
polarization through the acceleration process. The Siberian snakes induce a spin flip each time the beam passes through. When the beam passes through magnet lattice during the next loop, spins which have advanced relative to the bulk will now be behind in phase and vise versa. This is analogous to the spin echo phenomena seen in nuclear magnetic resonance. Two Siberian Snakes are installed in RHIC. In addition 3 partial Snakes can be found in the AGS.

### 3.4.2 Spin Rotators

The magnets which bend the stored beam around its circular orbit in the accelerator are strong dipole magnets with their fields aligned in the vertical direction. The stable spin direction for protons in the ring, would be in the same direction as these field lines, i.e. transverse to the direction of motion. Double longitudinal spin asymmetry measurements require longitudinally polarized beam. Special dipole magnets located at either end of the major spin experiments at RHIC, STAR and PHENIX, called *Spin Rotators* allow each experiment to independently choose the spin orientations – transverse, longitudinal or radial – needed for their specific measurement. Techniques for verifying the spin direction at PHENIX will be explained in the next chapter.

### 3.4.3 Polarimetry

To extract a physical asymmetry from measurements at PHENIX, results must be normalized to the beam polarization. RHIC utilizes two separate polarimeters to measure the magnitude of the beam polarization. The first being the CNI polarimeter, which which allows for fast, high statistics measurements.
The CNI only measures relative polarization. An absolute determination is provided by the second polarimeter, the HJet.

**CNI Polarimeter**

The Coulomb-Nuclear Interference (CNI) polarimeter accesses the beam polarization by inserting a thin carbon target, about 25 nm thick, into the path of the beam. Carbon atoms which are elastically scattered by the transversely polarized proton beam are measured in six silicon strip detectors spaced regularly about the inside of the beam pipe, see figure 3.2. Left-Right, or up-down depending on the orientation of the beam and target, asymmetries resulting from the interference between the electromagnetic and strong scattering amplitudes is measured. A more complete description of the CNI polarimeter can be found in [13].

![Diagram of CNI polarimeter](image)

**Figure 3.2:** View of the CNI polarimeter along the beam axis with the vertical carbon target inserted into the beam path (blue). Recoiled carbon atoms are measured in the 6 silicon strip detectors (red) spaced around the inside of the beam pipe.
**HJet Polarimeter**

The hydrogen jet polarimeter (HJet), described in [14], introduces a stream of polarized hydrogen gas into the path of the RHIC beam. The hydrogen nuclei are elastically scattered out of the beam pipe and the polarization is measured with a Breit-Rabi[15] polarimeter.

<table>
<thead>
<tr>
<th>Year</th>
<th>Run</th>
<th>Polarization [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Run5</td>
<td>49</td>
</tr>
<tr>
<td>2006</td>
<td>Run6</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 3.1: Run 5 and Run 6 Polarization values

### 3.4.4 Spin Pattern

The pattern of the train of bunches traveling through RHIC is dictated by the source. Since the major spin experiments are looking to measure spin dependent asymmetries, the pattern should allow for every helicity combination available $-++, +-, --, --$. The spin pattern at RHIC is chosen such that different helicities pairings collide with in a few hundred nanoseconds of each other. As will be shown later, this allows the cancellation of many of the systematic uncertainties and detector efficiencies in $A_{LL}$ measurements.
Chapter 4

PHENIX Detector

The PHENIX Detector is one of the two large experiments at RHIC. Located at the 6 o’clock region, PHENIX is designed to specialize in the measurement of rare probes. PHENIX utilizes it’s high trigger rates and excellent energy and mass resolution to identify photons, leptons and hadrons in the detector. The experimental setup described in this chapter will cover the 2005 (Run-5) and 2006 (Run-6) RHIC data taking runs.

4.1 Beam Beam Counter

The Beam Beam Counters (BBC) provide four main functions.

§1. Minimum bias trigger

§2. Collision Vertex

§3. PHENIX $T_0$

§4. Absolute luminosity determination
Figure 4.1: PHENIX detector setup during the 2006 run. Top drawing shows the PHENIX central arm as seen along the beam line. Bottom Drawing is a cross section of the detector as seen from the side.

The BBC consists of an array of two arrays of 64 quartz capped photomultiplier tubes (PMT) located 1.44 to either side of the central collision vertex. This is the inner most detector at PHENIX and thus provides minimum collision requirement. Each BBC covers a rage in pseudorapidity of $3.0 < |\eta| < 3.9$ and a full $2\pi$ coverage in $\phi$. The BBC timing resolution for a single PMT is $52 \pm 4$ pico seconds. The good timing resolution allows for a precise measurement of both the collision vertex position ($Z_{BBC}$) and $T_0$, see Figure 4.2. These two
quantities are calculated as follows:

\[ z_{BBC} = \frac{c \times (T_S - T_N)}{2} \]  \hspace{1cm} (4.1)

\[ T_0 = \frac{(T_S + T_N)}{2} \]  \hspace{1cm} (4.2)

This corresponds to a position resolution of 5cm online and 2cm offline.

The BBCs also play a crucial role in the Absolute and Relative luminosity determinations.

![Diagram](image)

Figure 4.2: Collisions measured by the BBC. The drawing schematic of a collision at PHENIX and the position and timing measurements using the BBC.

### 4.2 Zero Degree Calorimeter and Shower Maximum Detector

The Zero Degree Calorimeters (ZDC) are a pair of hadronic calorimeters located at either end of each of the four interaction regions approximately 14m from the nominal collision vertex. Like the BBCs, the ZDCs can provide information about the z-vertex position and timing, but with much poorer
resolution. Because of their location downstream of the $D_X$ magnets\footnote{The $D_X$ magnets are a pair of large dipole magnets which bend the proton beam into and out of the PHENIX IR.} only neutral hadrons will reach the ZDC. Figure 4.3 shows the three separate modules of the ZDC. Each module consists of alternating layers of tungsten alloy, which provides a large cross section for neutrons, and scintillators, which provide the signal measured by the photomultiplier tubes, shown at the top of the diagram.

Between the first and second modules of the ZDC is the Shower Maximum Detector (SMD). The SMD is a pair of scintillating paddles which provide rough position measurements for hits in the ZDC.

![Figure 4.3: Collisions measured by the BBC. The drawing schematic of a collision at PHENIX and the position and timing measurements using the BBC.](image)

### 4.3 Electromagnetic Calorimeter

The PHENIX Electromagnetic Calorimeter (EMCal) is located 5 meters from the beam axis and is the most exterior of the PHENIX detectors. The primary function of the EMCal is to measure the energy and spatial position of photons
and electrons in the PHENIX central arm. The EMCal has a pseudo rapidity coverage of $|\eta| = 0.35$ and is separated into east and west arms each with a $\phi$ coverage of $\phi = 90^0$.

Each arm is further divided in to four sectors. Theses sectors are labeled W0 through W3 and E0 through E3 for the West and East arms respectively. Six of these eight sectors, W0-W3 and E2-E3, make up the Lead Scintillator (PbSc) EMCal. The remaining two sectors, E0 and E1, comprise the Lead Glass (PbGl) EMCal. The two different types of EMCal allow PHENIX analyzers to cross check measurements in the EMCal, since systematics in the two types are expected to be different.

4.3.1 PbSc

Each sector of the PbSc contains $36 \times 72$ towers. A tower has a cross sectional area of $5.52 \times 5.52cm^2$ and is $33cm$ deep. Each tower is compromised of 66 alternating slabs of $1.5mm$ lead and $4mm$ scintillating material. The PbSc excels in timing, and the response to hadrons is better understood than in the PbGl. The energy resolution was measured with an electron test data[46]:

$$\frac{\sigma_E}{E} = 2.1\% \oplus \frac{8.1\%}{\sqrt{E}}$$

4.3.2 PbGl

The PbGl EMCal is a Čerenkov calorimeter. Charged particles which enter the tower faster than the speed of light in the tower material emit Čerenkov photons. It only comprises $1/4$ of the total EMCal but, each sector contains
48 \times 96 \text{ towers. The finer granularity allows the PbGl EMCal to have photon separation in neutral meson decays to higher energies than the PbSc. The energy resolution was also checked with the electron test beam:} [46]:
\[
\frac{\sigma_E}{E} = 0.8\% \oplus \frac{5.9\%}{\sqrt{E}} \tag{4.4}
\]

## 4.4 Charged Particle Tracking

Aside from measuring the energy and spacial separation of photons and electrons in the EMCal, PHENIX is also capable of tracking and identifying charged particles produced in collisions.

### 4.4.1 Central Magnets

The PHENIX Central Magnet(CM)\(^2\) consist of two independent concentric coils which provide a 1.15 T magnetic field parallel to the beam direction. The field strength falls off to less than 0.01T at a radius of 2 m from the nominal beam axis.

### 4.4.2 Drift Chamber

The Drift Chamber (DC) system consists of a pair of multiwire gas chambers which provides a precise measurement of charged particle momentum and tracking at PHENIX. Like EMCal, the DC is split into two arms, each covering

\(^2\)The term "Central" is used to distinguish these magnets from Muon Arm magnets. The Muon Arm magnets are located to either side—north and south—of the Central Magnets. They are used to track and identify charged particles in the forward and backward direction at PHENIX. They are required for some channels of interest at PHENIX, but are beyond the scope of the current work.
$|\eta| \leq 0.35$ and $\phi = 90^\circ$. Either arm of the DC is located $2.02 < R < 2.48$ meters from the beam axis. The chambers are filled with mixture of 50% Argon and 50% Ethane gas. There are 6 sets of wire nets called modules. These modules are labeled X1, X2, U1, U2, V1, and V2. The wires of the X1 and X2 modules are aligned along the beam axis and provide position measurements in the $r - \phi$ plane with a spacial resolution of $0.15mm$. The two U and V modules are at a $6^\circ$ angle with respect to the X wires and make measurements of the position along the beam axis. The spatial resolution in Z direction (along the beam axis) better than $2mm$. Momentum and tracking measurements require additional information provided by the Pad Chambers.

### 4.4.3 Pad Chamber

The Pad Chambers (PC) are comprised of three layers of multiwire proportion chambers, referred to as PC1, PC2 and PC3. PC1 is located directly behind the DC. The next layer radially outward, PC2, is placed behind the Ring-Imaging Cerenkov detector in the West arm. The second PC layer is missing from the East arm. The final layer, PC3 is just before the EMCal. Each PC layer covers the full PHENIX central arm acceptance ($90^\circ \times 2$ and $|\eta| < 0.35$), except for the missing layer in the East Arm.

The pad chambers provide entrance and exit points for the RICH and EMCal. PC1 is particularly indispensable since it gives Z coordinate in the charge track reconstruction. This will play an important role in the removing electrons, which have a similar signal to photons in the EMCal, and in applying an isolation cut in the direct photon analysis.
Figure 4.4: Schematic of charged track momentum determination in the central arm

4.4.4 Track Quality

Tracks in PHENIX are defined using hits from the PC1 and the X, U and V wire nets. Since the CM field strength is quite weak at the radius of the drift chamber tracks in the DC are nearly straight. Track momentum determination relies on measuring two vectors in the $r - \phi$ plane, show in the schematic in Figure 4.4.4. The first is the path which best matches the hits in the DC and PC1 associated with the track. The second being the straight line from the collision vertex through the midpoint in the radial direction of the DC. The angle between these two lines, $\alpha$ indicates the degree of curvature of the particle, and thus the momentum of the particle. Momentum in the
z direction requires a hit in the PC1. Since the field lines of the CM are pointing in the z direction the paths of particles traveling in that will not bend. The momentum is extracted from the collision vertex and the PC1 hit alone. For each subsystem/module there is an associated bit pattern. For particle identification and momentum determination a quality bit of 63

<table>
<thead>
<tr>
<th>Bit Pattern</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X1 Available</td>
</tr>
<tr>
<td>2</td>
<td>X2 Available</td>
</tr>
<tr>
<td>4</td>
<td>UV UV Available</td>
</tr>
<tr>
<td>8</td>
<td>UV Available and associated with a Unique track</td>
</tr>
<tr>
<td>16</td>
<td>PC1 Available</td>
</tr>
<tr>
<td>48</td>
<td>PC1 Available and associated with a unique track</td>
</tr>
</tbody>
</table>

is usually desired. Since the DC is only used as a charge veto in the direct photon analysis, only quality > 3 is required. This minimum requirement gives enough information to extrapolate a charged track to a position in the EMCal.

### 4.5 Ring Imaging Čerenkov Detector

A Ring Imaging Čerenkov Detector is placed just beyond PC1 in either arm of PHENIX. The RICH is backfilled with \( CO_2 \) gas. Čerenkov radiation is produced in a conical shape when a charged particle transverses a medium with index of refraction, \( n \), faster than the phase velocity of light in that medium. The RICH is built such that Čerenkov photons will shine in a ring shaped pattern on a set of PMTs. The detector is mainly used to separate
charged pions from electrons. It is not used in the direct photon analysis.

4.6 Triggers

Because of financial and physical limits on the amount of computer disk space available to PHENIX, online electronics based triggers have been implemented to decide if an event is likely to contain a particle of interest or not. This system is called the Level-1 trigger system (LVL1)\(^3\). The main triggers applicable to the current work are the BBC Local Level-1 (BBCLL1) triggers, the ZDC Local Level-1 (ZDCLL1) and the EMCal-RICH triggers (ERT).

4.6.1 BBCLL1

The BBCLL1 triggers are the main triggers for events at PHENIX. As a minimum requirement, a trigger from the BBC requires at least one PMT to fire on each side. This trigger is called BBC\textit{wide}. A more restrictive trigger can be defined by requiring that the reconstructed z-vertex \((z_{BBC})\) position be within a certain range. Because of the location of a pair of pole tips of the PHENIX magnets, most PHENIX analyses require that only collisions with \(|z_{BBC}| < 30\) cm be considered, where \(z_{BBC} = 0\) corresponds to the center of the detector along the beam axis. The BBC trigger with this added stipulation is called the BBCLL1 trigger. It serves as the minimum bias (minbias) trigger condition for all events of the current analysis. The rate of BBCLL1 triggers may be used to calculate the beam luminosity at PHENIX, though and absolute luminosity

\(^3\)There exist a set of online software triggers, called Level-2 (LVL2) triggers. Since, primarily the LVL-1 triggers are used in the direct photon analysis, the LVL2 triggers will not be discussed here.
normalization is required. The procedure for this calibration will be described in Chapter 5.

### 4.6.2 ZDCLL1

Like the BBC a pair of triggers may be derived from coincident events in the ZDCs. These triggers like the BBC triggers, include additional requirements of the z-vertex position, but measured with the ZDC \( z_{ZDC} \). The two triggers are ZDC\text{narrow} and ZDC\text{wide}. ZDC\text{narrow} and ZDC\text{wide} require coincident events in the north and south arms of the ZDC and \( |z_{ZDC}| < 30 \) and \( |z_{ZDC}| < 150 \), respectively. The ZDCLL1 triggers are not directly used in most PHENIX analysis, but they are essential for the BBCLL1 absolute luminosity measurement, as they are used to measure geometric acceptance inefficiencies in the BBC. A more detailed explanation of this procedure will be given in Chapter 5.

### 4.6.3 EMCal RICH Trigger

The EMCal RICH Trigger (ERT) is the primary trigger for most \( p+p \) analyses at PHENIX which look for particles at mid-rapidity. The ERT provides a trigger for rare, high transverse momentum \( (p_T) \) particles at PHENIX. The ERT will trigger on events with large localized energy deposits in the EMCal. Energy deposited in the EMCal will typically be shared by several neighboring towers. There for two sets of overlapping tile triggers are defined, ERT2x2 and ERT4x4. Like their names suggest, the ERT2x2 and ERT4x4 triggers sum the energy in groups of 4 and 16 square-tiles. For the direct photon analysis, only
the ERT4x4 trigger will be used.

The ERT4x4 trigger is further refined by defining three versions of the trigger with different minimum energy thresholds. The three version ERT4x4a, ERT4x4b and ERT4x4c require an energy deposit of 2.1, 2.8 and 1.4 GeV respectively. The ERT4x4c trigger was used for the Run-5 direct photon analysis but switched to the ERT4x4a in Run-6 due to a large number of noisy towers in the PbGIs. This will not have a visible effect on the measurement since, both years only events with an energy deposit well above the thresholds, > 5 GeV, were considered.

![Diagram of the circuit logic for summing overlapping 2x2 and 4x4 tiles in the EMCal](image)

Figure 4.5: Diagram of the circuit logic for summing overlapping 2x2 and 4x4 tiles in the EMCal
Chapter 5

Luminosity Measurement

5.1 Introduction

For the past 150 years, since the first collision experiments of Lord Rutherford, nuclear and particle physicists have essentially been performing the same experiment and asking the same question: *When I collide two pieces of matter together, what comes out? and how much?* In order to extract a physical quantity, the cross section, the "how much?" must be normalized by the luminosity, \( \mathcal{L} \). Aside from the center of mass energy of the collisions, this is the most important parameter at any collider facility experiment. The Luminosity, is defined as the interaction rate per unit cross section of the beam.

In the case of RHIC, the beam of particles is not a continuous stream, but rather a train of bunches. Figure 5.1 shows a schematic of a test particle interacting with a bunched beam. The rate at which collisions occur is given by,

\[
R = \frac{fN\sigma_{\text{Int}}}{A}.
\]

(5.1)

Where \( N \) is the number of scattering centers (i.e. protons) in a given bunch,
Figure 5.1: A schematic of a single test particle interacting with a proton bunch. Protons may have a nonuniform distribution inside the bunch.

A is the cross sectional area of the beam, f is the frequency at which test particles are incident on the bunch and $\sigma_{int}$ is the interaction cross section of the scattering centers. If instead of a single test particle, one imagines a two bunches colliding, the rate is simply scaled by the number of particles in the second bunch. Using the definition above, the luminosity of two colliding bunches of beam, one with $N_1$ protons and the other with $N_2$ is

$$\mathcal{L} = \frac{fN_1N_2}{A}. \tag{5.2}$$

Implicit in the above discussion is that the beams are uniformly populated with protons. In reality, the beam has somewhat of a Gaussian distribution in both the longitudinal and transverse directions. The equation for the lumi-
nosity must then be modified to reflect this.

\[
\mathcal{L} = \frac{f N_1 N_2}{2\pi \sqrt{(\sigma_{x1} + \sigma_{x2})^2(\sigma_{y1} + \sigma_{y2})^2}}
\]  \quad (5.3)

Where \(\sigma_{x1}(\sigma_{y1})\) and \(\sigma_{x2}(\sigma_{y2})\) are the transverse beam widths of the two beams in the radial (vertical) direction. Further, more complicated, corrections could be made for the non-uniform longitudinal distribution of the beam, a non-zero crossing angle, and focusing effects. These corrections will be discussed later in this chapter.

The luminosity measurement gives PHENIX an absolute calibration for the Beam-Beam Counters. The determination of the the transverse extent of the beam and the resulting absolute luminosity measurement is the subject of this chapter. Measurements made in Run-5 and Run-6 will be presented. Novel methods, developed for this measurement, for determining the beam crossing angle and corrections to the beam shape due to beam focusing will be discussed. Finally absolute luminosity calibrations of the beam beam counters at two center of mass energies, \(\sqrt{s} = 200\) GeV and \(\sqrt{s} = 62.4\) GeV will be shown.

### 5.2 Vernier Scans

The absolute luminosity at PHENIX is determined from the number of events triggered by the BBCs, \(N_{BBC}\), using an absolute calibration of the BBC trigger cross section \(\sigma_{BBC}\):

\[
\mathcal{L} \equiv \frac{N_{BBC}}{\sigma_{BBC}}.
\]  \quad (5.4)
As discussed in Chapter 4.1, the BBC trigger is a minimum-bias trigger of the PHENIX trigger system. $\sigma_{BBC}$ is the ratio of the BBC trigger rate when the beams are overlapping maximally ($R_{\text{max}}$) to the effective machine luminosity observable by the BBC trigger.

$$\sigma_{BBC} = \frac{R_{\text{max}}}{L_{\text{machine}} \cdot \epsilon_{\text{vertex}}},$$

(5.5)

where $\epsilon_{\text{vertex}}$ is the vertex selection efficiency obtained by the vertex reconstruction analysis of the BBC detector. Once properly calibrated, $\sigma_{BBC}$ allows PHENIX to easily convert rates measured in the BBC to beam luminosities, necessary for cross section normalizations.

The absolute calibration of the $\sigma_{BBC}$ is obtained via the vernier scan (or van der Meer scan) technique [47]. During a vernier scan, the transverse profile of the beam overlap is measured by sweeping one beam across the face of the other in steps of a few hundred microns while monitoring the BBC trigger rate. Once the transverse extent of the beam is measured, they are combined with the with the bunch intensities of the two beams, $N_b$ and $N_y$, and the revolution frequency for one bunch in the accelerator ring, $f_{\text{rev}}$, to compute the machine luminosity:

$$L_{\text{machine}} = \frac{f_{\text{rev}}}{2\pi\sigma_x^v\sigma_y^v} \sum_{i=\# \text{ of bunch crossings}} (N_b \cdot N_y)_i,$$

(5.6)

where $\sigma_x^v$ and $\sigma_y^v$ are transverse widths of the beam overlap as measured by the vernier scan in the horizontal and vertical directions. Equation 5.6 assumes

\[\text{The bunch intensities are provided by two pieces of equipment built into the RHIC, the Wall Current Monitors and the DCCT. Their function will be discussed later in this chapter.}\]
the beams are of a constant transverse extent along the beam direction and the angle which the beams cross is small. It should be noted that the widths in Equation 5.6 are not the widths of the distributions of single beams, but the width of the the overlap.

During the vernier scan, the number of BBC-trigger events in each bunch crossing is recorded by a special set of crossing-sorted scaler, called the Global Level-1 physics scalers (GL1P scalers). The GL1P scalers are capable of simultaneously measuring live events in four detector systems. By including the RHIC clock as one of the recorded scalers, crossing sorted rates of the BBC trigger can be measured. In essence, with standard operating conditions (i.e. \( \sim 100 \) bunch’s circulating in each ring ), \( \sim 100 \) separate vernier scan measurements are made in a single fill and any crossing-by-crossing dependence’s can be identified. During the 2005 and 2006 runs, more than ten vernier scans were performed. By analyzing multiple scans, effects from fluctuations in accelerator conditions at RHIC (e.g. variations in bunch shape, non-zero crossing angle between beams, beam intensity, and beam blow-up) can be studies.

### 5.3 Data Collection

Because of the nature of the vernier scan, cooperation between PHENIX and the RHIC-AGS Main Control Room (MCR) is essential. The acquisition of the rates at PHENIX must be coordinated with the beginning of the steering sequence initiated by the MCR. Beside the trigger rates acquired with PHENIX detectors, the measurement also makes use of special monitoring devices, which are maintained by the Collider Accelerator Department. The
procedures for obtaining these data and some of the specialized accelerator equipment will be discussed in this section.

5.3.1 Rates

During a Vernier scan, the event rates in the BBC and ZDC are typically measured. For beams with finite transverse extent, rates in these detectors will fall off as the translated beam moves further and further from the central position, during the scan.

The trigger rates are obtained using the GL1P scaler boards. The GL1P scalers can take up to 4 different signal inputs. During the Vernier Scans the following triggers were used:

1. BBCLL1
2. ZDC Wide Cut
3. ZDC NS
4. Clock

Once the GL1P scaler boards begin acquiring data, the Main Control Room begins using the steering magnets on either side of the PHENIX IR to step one of the beams in the transverse direction. Typically the beam is moved every thirty seconds by a few hundred microns. The decrease and subsequent increase in the rates in the BBC, as the beams are steered away from and back towards the center can be seen in Figure 5.2
Figure 5.2: BBC rates vs event number.
5.3.2 Beam Position Monitors

The beams positions shown in Figure [5.3] are recorded by the Beam Position Monitors (BPMs) and stored in a database maintained by the MCR. The BPMs essentially consist of a two pairs of parallel plate electrodes, one pair for vertical position measurements the other for horizontal. Beam positions are calculated by measuring the difference between the induced current in each pair of plates. The design specifications require the BPMs be accurate to within 130 microns [18]. The BPMs used to monitor the beam at PHENIX are located inside the final set of steering magnets, so there is only a single aperture which both the blue and yellow beams must pass through. In order to distinguish between the two beams, the triggering of the BPMs with respect to the RHIC RF must be tuned properly by the MCR.

5.3.3 Beam Intensity

The number of ions circulation through RHIC is kept track of by two pieces of equipment, the Wall Current Monitor (WCM) and the Direct Current Current Transformer (DCCT). The DCCT measures the current induced in a large copper coil wrapped around the beam pipe. It measures the average current induced during a $\sim 1$ second sample period. This large sample time allows the DCCT to measure the total number of ions in RHIC to $\approx 0.2\%$ accuracy [49]. The main drawback of the DCCT is that, because of its large integration time, it is unable to distinguish between bunched and debunched beam, beam that has "leaked" into a neighboring RF bucket. Only bunched beam should be included in the calculation.

78
Figure 5.3: Positions measured by the BPM vs time on either side of the PHENIX IR. Red is North and Green South. Black is the mean
To remedy this, the DCCT is used in tandem with the WCM. The WCM measures the induced voltage across a large RLC circuit placed in a cut-out section of the beam pipe. The WCM samples at ~0.25\(\text{nsec}\) and is insensitive to the debunched beam. Just after flat top, when the RHIC beam has just completed it’s final acceleration no debunched beam will have survived. At this point, the WCM is calibrated by comparing its sum to the DCCT value.

### 5.4 Data set

During Runs 5 and 6 vernier scans were taken on approximately a weekly basis. Several of these PHENIX runs\(^2\) were not used in the analysis due to problems ranging from failures of the PHENIX DAQ during scans to inconsistent reading from the BPMs. Beside the scans take at \(\sqrt{s} = 200\text{GeV}\), a pair of scans at \(\sqrt{s} = 62.4\) GeV were taken. A summary of the runs used in the analysis is found on Table 5.1.

\(^2\)A PHENIX run is an ~ one hour data taking time period at PHENIX. Not to be confused with RHIC Runs (e.g. Run-5 and Run-6) which are severl month long beam programs at BNL.

<table>
<thead>
<tr>
<th>Run</th>
<th>Run number</th>
<th>Fill number</th>
<th>(\sqrt{s}) (GeV)</th>
<th>Date</th>
<th>Scan</th>
<th>Step size ((\mu)m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run5</td>
<td>170055</td>
<td>6972</td>
<td>200</td>
<td>Apr.26, 2005</td>
<td>Yellow</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>171623</td>
<td>7028</td>
<td>200</td>
<td>May.6, 2005</td>
<td>Yellow</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>174762</td>
<td>7123</td>
<td>200</td>
<td>May.22, 2005</td>
<td>Yellow</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>175928</td>
<td>7164</td>
<td>200</td>
<td>May.29, 2005</td>
<td>Blue</td>
<td>250</td>
</tr>
<tr>
<td>Run6</td>
<td>192680</td>
<td>7673</td>
<td>200</td>
<td>Mar.31, 2006</td>
<td>Blue</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>200257</td>
<td>7847</td>
<td>200</td>
<td>May.12, 2006</td>
<td>Yellow</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>205863+5</td>
<td>8036</td>
<td>62.4</td>
<td>Jun.15, 2006</td>
<td>Yellow</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>205866</td>
<td>8036</td>
<td>62.4</td>
<td>Jun.15, 2006</td>
<td>Yellow</td>
<td>350</td>
</tr>
</tbody>
</table>

Table 5.1: Dataset table: analyzed vernier scan runs at PHENIX from 2005 and 2006.
Step sizes of these runs are summarized on Table A.1. An analysis of the BPM data, revealed the step size of some of the runs showed a significant deviation from the set-point. Since the set-points and BPMs were consistent in most runs and because acceleration of the beams requires that the magnet settings be reliable, it was decided that the set-point values be used.

5.5 Analysis

From the data available, several quantities can be extracted. The machine Luminosity is the first, and most involved quantity. Once the machine luminosity is found, the z vertex distribution is measured. Combining the machine luminosity and the z vertex, we get the more pertinent quantity, the Effective Luminosity. The effective luminosity is, again, the constant of proportionality between the peak event rate of a process and the cross section. Knowing this along with the peak event rate we obtain a value for the absolute BBC cross section.

5.5.1 Gaussian fitting

The BBC trigger rates from the GL1P boards are combined with the BPM data, to produce plots of rates vs. beam position. The beam width is obtained from a four parameter Gaussian plus constant fit to the data

\[ F(x) = P_0 e^{-\frac{1}{2}((x-P_1)/P_2)^2} + P_4 \]  

(5.7)
Figure 5.4: Gaussian + constant fit to the transverse beam profiles measured for each bunch crossing by the horizontal (left) and vertical (right) scans.

Examples of the data and fits are shown in Figure 5.4. The horizontal and vertical overlap widths obtained from the fits are then used in the luminosity calculation.

In the horizontal vernier scan, the vertical position was fixed, and vise versa. By the Gaussian + constant fitting, we can find how much these fixed positions were shifted from the real peak-rate position of the other direction. In order to evaluate the real peak rates, the peak rate obtained by the Gaussian + constant fitting in each scan was corrected for the shift.

A second correction was made for the beam current. Usually the vertical
Figure 5.5: Comparison of the peak rate of horizontal and vertical scans after position and WCM corrections: correlation (left) and ratio (right). From top to bottom: run5 run175928, run6 run200257.

Scans were made after the horizontal scan, and the beam current in the vertical scan is, as a result, a little lower than that in the horizontal scan. The ratio can be evaluated with the WCM data, and corrected. These corrections are summarized in Table A.2. After these corrections, Figure 5.5 shows the correlation of the peak rates measured in the horizontal scan and the vertical scan, and the ratio between them. These ratios are very close to one, within 3% level. An average of the peak rate of the two directional scans was used in the final analysis.
Figure 5.6: Peak rate (after correction, left) and luminosity (right) of each crossing. From top to bottom: run5 run175928, run6 run200257.

5.5.2 Luminosity calculation

5.5.3 Z-vertex cut efficiency

In order to calculate the BBC Cross-section the Effective Luminosity is needed, $L_{\text{eff}}$

$$L_{\text{eff}} = L_{\text{machine}} \times \epsilon$$  \hspace{1cm} (5.8)

Where, $\epsilon$ is the fraction of the vertex distribution triggered on by the detector. The fraction of the vertex seen by the detector is found by dividing the number
Figure 5.7: Correlation of the peak rate (after correction) and luminosity: correlation (left) and ratio (right). From top to bottom: run5 run175928, run6 run200257.
of counts inside ±30 cm cut by the total counts in the detector.

\[ \epsilon_{BBC} = \frac{N_{BBC}^{±30\text{cm}}}{N_{\text{Total}}^{BBC}} \] (5.9)

During the run, the trigger setting for the BBCLL1 were set slightly wider then ±30 cm. As a result, to obtain the true \( \epsilon_{BBC} \) we must measure and use this wider value. To obtain the wider value, we divide the BBCLL1 distribution by the BBC no-vertex distribution. The resulting ratio is shown on the right hand side of the figure below (Figure 5.8). As would be expected the ratio of the two distributions has a plateau at 1 inside the BBCLL1 cut, with very sharp tails. The resulting shape is fit by a Gauss error function.

The efficiency of the BBC is dependent upon the position of the collision along the beam axis. This position dependent efficiency will result in a narrowing of the vertex position distribution. To account for this effect, we examine the BBC vertex distribution in coincidence with the ZDCNS trigger, and compare this shape to that of the Z vertex measured by the ZDC with the ZDCNS trigger. The ZDCs located 14 meters from the center of PHENIX, do not suffer from the same z position dependence in the efficiency. The ratio of these two distributions will give us the z position dependency of the BBC efficiency as shown in the bottom panels of Figures 5.9 and 5.10.

The true BBC vertex distribution with no z-vertex dependence of the BBC efficiency can be evaluated by two ways. One is by smearing by the ZDC resolution, the other applying the BBC efficiency shown on Table A.5 to the measured BBC vertex distribution. In the final calculation the mean value of 152.5 is used for all runs.
Figure 5.8: Z-vertex cut position by BBCLL1. From top to bottom: run5 run175928 (ZDCNS trigger, because BBCLL1 no-vertex-cut trigger was not available), run6 run200257 (BBCLL1 no-vertex-cut trigger).
Figure 5.9: Z-vertex of run6, run200257. From top to bottom: BBC vertex with BBCLL1 no-vertex-cut trigger (Gaussian fit width 57.34 cm), BBC vertex with ZDCNS trigger (Gaussian fit width 57.07 cm), ZDC vertex ZDCNS trigger (Gaussian fit width 63.40 cm), ZDC vertex ZDCNS trigger with BBC vertex reconstructed (Gaussian fit width 58.84 cm), and ratio of 4th and 3rd histogram which shows BBC efficiency (Gaussian fit width 172 cm).
Figure 5.10: Z-vertex of run5, run175928 From top to bottom: BBC vertex with BBCLL1 no-vertex-cut trigger (No good data because of an incorrect setting of the BBCLL1), BBC vertex with ZDCNS trigger, ZDC vertex ZDCNS trigger, ZDC vertex ZDCNS trigger with BBC vertex reconstructed, and ratio of 4th and 3rd histogram which shows BBC efficiency.
Figure 5.11: BBC trigger cross section of each crossing (left) and profile (right). From top to bottom: run5 run175928, run6 run200257.

5.6 Summary of Run5 and Run6 scans at $\sqrt{s} = 200$ GeV

Figure 5.11 shows $\sigma_{BBC}$ obtained in each crossing and crossing by crossing distribution for typical runs in Run-5 and Run-6. Table 5.2 shows a summary of the vernier scan result at $\sqrt{s} = 200$ GeV. The RMS of $\sigma_{BBC}$ in each crossing shown in the profile of Figure 5.11 is listed as $\delta \sigma_{BBC}$. 1
Table 5.2: Summary of Run5 and Run6 scan at $\sqrt{s} = 200$ GeV. $\delta\sigma_{BBC}$ shows uncertainty from a constant fit of crossing-by-crossing $\sigma_{BBC}$.

<table>
<thead>
<tr>
<th>Run</th>
<th>$\sigma_H$ ($\mu$m)</th>
<th>$\sigma_V$ ($\mu$m)</th>
<th>$N_b \times N_y$ ($\times 10^{18}$)</th>
<th>$R_{max}$ (Hz)</th>
<th>luminosity (mb$^{-1}$s$^{-1}$)</th>
<th>z-vertex cut</th>
<th>$\sigma_{BBC}$ (mb)</th>
<th>$\delta\sigma_{BBC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>170055</td>
<td>339.0</td>
<td>342.1</td>
<td>2849</td>
<td>252</td>
<td>30.7</td>
<td>0.457</td>
<td>17.89</td>
<td>0.04</td>
</tr>
<tr>
<td>171623</td>
<td>304.5</td>
<td>301.5</td>
<td>7308</td>
<td>839.5</td>
<td>99.0</td>
<td>0.487</td>
<td>17.53</td>
<td>0.02</td>
</tr>
<tr>
<td>174762</td>
<td>252.2</td>
<td>253.7</td>
<td>5707</td>
<td>863.6</td>
<td>111.7</td>
<td>0.440</td>
<td>17.54</td>
<td>0.02</td>
</tr>
<tr>
<td>175928</td>
<td>301.4</td>
<td>288.1</td>
<td>3973</td>
<td>491.5</td>
<td>54.9</td>
<td>0.481</td>
<td>18.34</td>
<td>0.03</td>
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<td>257.4</td>
<td>254.0</td>
<td>5098</td>
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<td>96.8</td>
<td>0.423</td>
<td>18.90</td>
<td>0.02</td>
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<td>200257</td>
<td>270.8</td>
<td>268.9</td>
<td>10459</td>
<td>1337.4</td>
<td>178.4</td>
<td>0.436</td>
<td>17.31</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 5.3: Summary of Run6 scan at $\sqrt{s} = 62.4$ GeV. $\delta\sigma_{BBC}$ shows crossing-by-crossing deviation of $\sigma_{BBC}$ from fits before the hourglass correction.

<table>
<thead>
<tr>
<th>Run</th>
<th>$\sigma_H$ ($\mu$m)</th>
<th>$\sigma_V$ ($\mu$m)</th>
<th>$N_b \times N_y$ ($\times 10^{18}$)</th>
<th>$R_{max}$ (Hz)</th>
<th>luminosity (mb$^{-1}$s$^{-1}$)</th>
<th>z-vertex cut</th>
<th>$\sigma_{BBC}$ (mb)</th>
<th>$\delta\sigma_{BBC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>205863+5</td>
<td>1009</td>
<td>1143</td>
<td>3622</td>
<td>18.4</td>
<td>3.9</td>
<td>0.36</td>
<td>12.53</td>
<td>0.12</td>
</tr>
<tr>
<td>205866</td>
<td>1089</td>
<td>1069</td>
<td>3614</td>
<td>19.6</td>
<td>3.9</td>
<td>0.36</td>
<td>12.67</td>
<td>0.14</td>
</tr>
</tbody>
</table>

5.7 Statistical Uncertainties and Systematic Error Estimation

5.7.1 Crossing-by-Crossing Uncertainty

The statistical uncertainties of the values which are used in the luminosity calculation are obtained from the Gaussian + polynomial fits. First the $\chi^2$ distribution is checked to see if the fits seem reasonable. Uncertainties in the number of ions is simply taken from the RMS spread in WCM measurements taken during the scan. Uncertainties for each of these quantities is taken in quadrature. A summary of the uncertainties obtained in the fits is show in Table 5.4. The resulting $\sigma_{BBC}$ is plotted as a function of crossing id. For most runs the $\chi^2/d.o.f.$ is larger then unity, suggesting there may be some
unknown systematic error. To estimate the size of this systematic error we examined two methods. In the first method the uncertainty of each point is scaled until the $\chi^2/d.o.f.$ reaches unity. The second is to assign a constant uncertainty to each point until the $\chi^2/d.o.f.$ approaches 1. The second method was chosen for the analysis since it seems more reasonable that any systematic uncertainty would not depend on the statistical error bar. Though, the two methods yield nearly identical central values (< 0.3% difference) and point by point uncertainties. For the two 62GeV runs using the constant systematic uncertainty, the point by point uncertainty is 7.78% and 9.55% for, 205866 and 205863 + 5 respectively. Since these crossing-by-crossing uncertainties are uncorrelated, the uncertainty for a given run will be decreased by a factor of $\sim 1/10$, $(1/\sqrt{\text{#of crossings}})$.

A summary of the 200GeV results is found in Table 5.2 and 62GeV in Table 5.3.
Figure 5.12: BBC Cross section run-by-run after the hourglass correction is applied.

Figure 5.13: $\chi^2$ distribution for Gaussian + polynomial fits.

### 5.7.2 Run-by-run Variation

Fluctuations in the 200GeV scans are used understand any run-by-run systematics which may occur. The final crossing-by-crossing value of the 200GeV scans are fit with a constant. Similar to the crossing-by-crossing case, the fit over runs yield a $\chi^2/d.o.f.$ larger then unity. The size of the systematic uncertainty is estimated by adding a constant systematic error to the run-by-run uncertainty. This yield a 4.1% run-by-run systematic uncertainty. The results of these fits are seen in Figure 5.12. It should be noted that this uncertainty is obtained after the hourglass correction, described below in Section 5.8, since it is run dependent.
Figure 5.14: $\sigma_{BBC}$ crossing by crossing fit with weighted errors and weighted errors plus a constant systematic for 200GeV run 170055.

Figure 5.15: $\sigma_{BBC}$ crossing by crossing fit with weighted errors and weighted errors plus a constant systematic for 200GeV run 171623.

Figure 5.16: $\sigma_{BBC}$ crossing by crossing fit with weighted errors and weighted errors plus a constant systematic for 200GeV run 174762.

Figure 5.17: $\sigma_{BBC}$ crossing by crossing fit with weighted errors and weighted errors plus a constant systematic for 200GeV run 174762.
Figure 5.18: \( \sigma_{BBC} \) crossing by crossing fit with weighted errors, unweighted errors and weighted errors plus a constant systematic for 200GeV run 175928.

Figure 5.19: \( \sigma_{BBC} \) crossing by crossing fit with weighted error and weighted errors plus a constant systematic for 200GeV run 200257.

Figure 5.20: \( \sigma_{BBC} \) crossing by crossing fit with weighted errors and weighted errors plus a constant systematic for 62GeV scan run 205866.
5.8 Hour-glass effect correction

The vernier scan method involves calculating the luminosity from beam characteristics –intensity, transverse size etc–. In the above discussion it was assumed that the transverse extent of the beam remained constant along the beam axis and that the beams collided precisely head on. In reality, the beam profile converges and diverges due to strong focusing effects of the magnets, forming an hour glass shape along the beam direction. This is analogous to the phenomena seen in laser and optical physics. In addition there may also be a non-zero crossing angle between the beams. The derivation above does not directly take into account hour glass effect due to beam focusing and beam crossing angle. The accelerator parameter which quantifies the severity of the hourglass shape, $\beta^*$, defines the radius of curvature of the beam. Hence, the smaller the value of $\beta^*$, the more pronounced the hourglass shape becomes. An effect of this hourglass shape, which may be observed in PHENIX, is a double peaked z vertex distribution when one of the beams has been moved off of center. An exaggerated picture of this scenario is shown in Figure 5.21. In this example the focusing is so strong and the beams are displaced enough such that they do not collide in the center of the interaction region where the beams are narrowest, but they do collide at either extreme along the z axis. An asymmetry in the double peaked vertex distribution may indicate a large crossing angle as seen in Figure 5.22. In this section we discuss calculations which verify that PHENIX data is in fact sensitive to both the value of $\beta^*$ and the crossing angle. Corrections due to the measured hour glass effect and non-zero beam crossing angles will be discussed.
Figure 5.21: Hourglass shape of the beams due to focusing

Figure 5.22: Hourglass shape of the beams due to focusing and large crossing angle
5.8.1 Simulation

The $z$ vertex distribution resulting from the collision of two non uniformly distributed bunches of beam is estimated by taking the convolution of two 3-dimensional beam densities, defined for the blue beam as,

$$D^B(x, y, z, t) = D^B(x) \otimes D^B(y) \otimes D^B(z - ct) \quad (5.10)$$

and

$$D^Y(x, y, z, t) = D^Y(x) \otimes D^Y(y) \otimes D^Y(z + ct) \quad (5.11)$$

for yellow beam. Last term accounts for the beams move towards each other along $Z$-axis.

The resulting luminosity is then proportional to four-dimensional integral

$$L \sim \int \int \int D^B(x, y, z, t) \cdot D^Y(x, y, z, t) \cdot dx dy dz dt \quad (5.12)$$

and the collision $z$-vertex distribution can be calculated by

$$V(z) \sim \int \int \int D^B(x, y, z, t) \cdot D^Y(x, y, z, t) \cdot dx dy dt \quad (5.13)$$

The longitudinal beam profiles, $D(x, y, z)$, are taken from WCM measurements. Since the WCM sample every 0.25ns, it is capable of resolving internal bunch structure. The transverse beam size is estimated to be a normalized Gaussian shape;

$$D(x) = \frac{1}{\sigma_x \sqrt{2\pi}} e^{-\frac{(x-x_0)^2}{2\sigma_x^2}}, \quad D(y) = \frac{1}{\sigma_y \sqrt{2\pi}} e^{-\frac{(y-y_0)^2}{2\sigma_y^2}} \quad (5.14)$$
When performing calculations it is assumed that both beams have the same transverse profiles: $\sigma^B_x = \sigma^Y_x$ and $\sigma^B_y = \sigma^Y_y$. Unfortunately there is no definitive way to confirm this assumption. Though, a 10% difference in beam sizes in one dimension (either X or Y) gives corrections to calculated luminosity in vernier scan analysis of < 1%.

Incorporating the hourglass effect into the simulation consists of the changing the transverse beam sizes as a function of z position according to:

$$\sigma^2_{X,Y}(z) = \sigma^2_{X,Y}(0) \cdot (1 + \frac{z^2}{\beta^*})^2,$$  \hspace{1cm} (5.15)

where $\beta^*$ is beam focusing parameter. $\beta^*$ is assumed to be the same for both transverse directions.

The nonzero crossing angle is easily introduced by making densities $D(x)$ and $D(y)$ angle dependent: $D(x + \alpha_x z)$ and $D(y + \alpha_y z)$, where $\alpha_x$ and $\alpha_y$ are beam crossing angles in X and Y directions.

### 5.8.2 Simulation of Detector Resolution

BBC and ZDC position resolution is implemented in the simulation. Smearing in the ZDC measurement was set to $\sigma^{ZDC}_Z = 15cm$. BBC smearing was set to $\sigma^{ZDC}_Z = 2cm$. These values were taken from the offline calibrations of the two detectors. The BBC has an additional z position dependent efficiency which must be accounted for. This is simply due to the geometry of the apparatus, collisions occurring closer to one side of the BBC are more likely to interact with that side than the far side. The z position dependence is assumed to have a Gaussian shape with sigma $\sigma^{BBC}_{z\text{eff}}$. 

99
Figure 5.23: Beam longitudinal profiles measured by WCM (in m) for yellow (left) and blue (right) beams, from run-200257.

5.8.3 Comparison of Simulations and Data

This subsection will demonstrate that the calculations shown above describe PHENIX data well and therefore can be used to extract corrections to the BBC cross section measurements due to non-zero crossing angle and hourglass effects in both $\sqrt{s} = 200GeV$ and $\sqrt{s} = 62.4GeV$ collisions at PHENIX.

Figure 5.23 shows longitudinal beam profiles for the blue and yellow beams as measured by WCM for PHENIX run 200257. A comparison of the measured $z$-vertex distribution in the ZDC, and the results of the calculations using Equation 5.13 including ZDC position smearing, and $\beta^* = 1$ is shown in Figure 5.24. The calculation shows good agreement with data.

The BBC $z$-vertex distribution for the same run is shown in Figure 5.25 along with calculations using Equation 5.13. Both BBC position resolution and efficiency dependence vs $z$ are included. Here we used $\sigma_{eff}^{BBC} = 140cm$. 

100
Figure 5.24: Z-vertex distribution measured by PHENIX ZDC (in cm), data from run-200257 (black) vs calculations (red).

Again, the agreement between data and calculations is good.

The calculations are sensitive to $\sigma_{\text{eff}}^{\text{BBC}}$. Figure 5.25 shows Z-vertex distribution measured by PHENIX BBC for several values of $\sigma_{\text{eff}}^{\text{BBC}}$, 1m, 1.4m and 2m. The best fit value is consistent with $\sigma_{\text{eff}}^{\text{BBC}}=1.4m$. This value is very reasonable and consistent with previous PYTHIA+PISA simulations[19].

As mentioned earlier, one of the ways in which the effects of beam focusing may manifest itself at PHENIX is via a double peaked in the z vertex distribution when one of the beams is displaced from the center position. Figure 5.27 shows Z-vertex distribution measured by PHENIX ZDC for different shifts of one beam relative the other in vertical direction. Note that beam transverse size in this run was about 0.2mm (at z~0). The drastic shape change at large beam displacement is directly due to hour glass effect: Also shown in the figure are curves from calculations using several values of $\beta^*$ to test the sensitivity of the data to $\beta^*$. A value of $\beta^*=1$ m is most consistent with data. 

101
Figure 5.25: Z-vertex distribution measured by PHENIX BBC (in cm), data from run-200257 (black) vs calculations (red).

Figure 5.26: Z-vertex distribution measured by PHENIX BBC in cm, data is from run-200257 (black) vs calculations (red); for $\sigma_{eff}^{BBC} = 1$m (left), 1.4m (middle) and 2m (right).
Figure 5.27: Z-vertex distribution measured by PHENIX ZDC (in cm), data from run-200257 (black) vs calculations for $\beta^* = 0.5$ m (blue), 1m (red) and 2m (green); four plots correspond to different shift of one beam relative the other in vertical direction: 0mm, 0.3mm, 0.6mm and 0.9mm, from left to right.

Similarly Figure 5.28 shows Z-vertex distribution measured by PHENIX ZDC for different shift of one beam relative the other in the horizontal direction. In addition to hour glass effect, the asymmetric double peak is seen. The asymmetry is due to the non-zero beam crossing angle. Also show in this figure are calculations of the z distribution with several values of the crossing angle, with $\beta^* = 1$ m. A crossing angle of 0.13 mrad are best fits the data. Analogous measurements and calculations for $\sqrt{s} = 62.4$ GeV collisions are shown in Figure 5.29.

In order to extract the $\beta^*$ correction to the luminosity, the luminosity obtained from calculations using Equation (5.12) with $\beta^* = 1$ is compared with the calculation when $\beta^* = \infty$. Similarly comparisons of luminosity calculations with and without the crossing angle are used to extract those corrections due to the non-zero crossing angle. A summary of the values of $\beta^*$ and the crossing angles found in all analyzed runs along with the associated corrections are summarized in Table 5.5.
Figure 5.28: Z-vertex distribution measured by PHENIX ZDC in cm from PHENIX run 200257 (black). Calculations of the distribution assuming a crossing angle 0.03 mrad (blue), 0.13 mrad (red) and 0.23 mrad (green) are shown. The four sets of plots correspond to different shift of one beam relative the other in horizontal direction: 0mm, 0.3mm, 0.6mm and 0.9mm, from left to right.

Figure 5.29: Z-vertex distribution measured by PHENIX BBC (in cm), data from run-205866 (black) vs calculations (red), for $\sigma_{eff}^{BBC} = 85$cm (left), 95cm (middle), 105cm (right)
Table 5.5: Summary of corrections.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Sample/Year</th>
<th>Nominal $\beta^*$ (m)</th>
<th>Cross angle Y (mrad)</th>
<th>Cross angle X (mrad)</th>
<th>Correction due to $\beta^*$</th>
<th>Correction due to cross angle</th>
<th>Final correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>170055</td>
<td>200 GeV Run5</td>
<td>1</td>
<td>0.00</td>
<td>0.17</td>
<td>$1.335 \times 0.945$</td>
<td>1.02</td>
<td>1.29</td>
</tr>
<tr>
<td>175928</td>
<td>200 GeV Run5</td>
<td>1</td>
<td>-0.02</td>
<td>-0.15</td>
<td>$1.415 \times 0.94$</td>
<td>1.02</td>
<td>1.36</td>
</tr>
<tr>
<td>178765</td>
<td>200 GeV Run5</td>
<td>1</td>
<td>0.12</td>
<td>-0.18</td>
<td>$1.400 \times 0.93$</td>
<td>1.05</td>
<td>1.37</td>
</tr>
<tr>
<td>192680</td>
<td>200 GeV Run6</td>
<td>1</td>
<td>0.02</td>
<td>-0.03</td>
<td>$1.465 \times 0.935$</td>
<td>1.00</td>
<td>1.37</td>
</tr>
<tr>
<td>200257</td>
<td>200 GeV Run6</td>
<td>1</td>
<td>0.00</td>
<td>0.13</td>
<td>$1.475 \times 0.935$</td>
<td>1.02</td>
<td>1.41</td>
</tr>
<tr>
<td>205866</td>
<td>62 GeV Run6</td>
<td>3</td>
<td>**</td>
<td>**</td>
<td>$1.075 \times 0.995$</td>
<td>**</td>
<td>1.07</td>
</tr>
</tbody>
</table>

5.9 Final result of Run5 and Run6 Vernier Scans

The Run5 and 6 vernier scan analysis yields a mean value of the BBC crosssection, after hour glass effect correction, of 24.5mb at $\sqrt{s} = 200GeV$. The statistical uncertainty in the measurements in small compared to systematics from the hourglass corrections ($\approx 2\%$) and BBC trigger efficiency corrections ($\approx 10\%$). The final obtained is $\sigma_{BBC} = 24.5 \pm 0.009$ [stat] $\pm 2.49$ [sys] at $\sqrt{s} = 200GeV$ Similar uncertainties yield a final value of 13.5 mb $\pm 0.09$ [stat] $\pm 1.49$ [sys] at $\sqrt{s} = 62.4GeV$. These values are used in all PHENIX cross section measurements including recent results for $\eta$ production at $\sqrt{s} = 200GeV$, shown in Figure 5.30 and $\pi^0$ production at $\sqrt{s} = 62.4GeV$ shown in
Figure 5.30: $\eta$ production cross section extracted from Run 6 $\sqrt{s} = 200\,\text{GeV}$ pp collisions. Plot is originally shown in the thesis of J. Seele\cite{10}.
Figure 5.31: $\pi^0$ production cross section extracted from Run 6 $\sqrt{s} = 62.4$GeV pp collisions.
Chapter 6

Data Quality Assurance

At PHENIX, several terabytes of data are typically recorded within a single RHIC run. In order to efficiently handle such a large amount of data, certain global and analysis specific cuts must be applied. These cuts are intended to reduce the data set to a more manageable size by only including those data which are likely to contain events of interest. The two guiding principles in this procedure are to (1) maximize the signal to background ratio and (2) ensure detector conditions are consistent and reliable.

In this chapter the systematic processes for eliminating unreliable data will be discussed. This will include trigger selections used to maximize the likelihood of measuring a direct photon and criteria which will guarantee a stable detector conditions. Finally cuts used to eliminate backgrounds specific to the direct photon analysis will be presented.
6.1 Run Veto

During a given RHIC run inevitably a handful of PHENIX runs will be excluded in whole from analyses. These are typically runs in which some subset of the PHENIX detectors are no operating correctly or beam conditions are not ideal for data taking. A summary of the vetoed runs can be found in Appendix B.

6.2 Trigger Selection

The trigger level cuts are to ensure the collision occurred within the PHENIX IR and the event is likely to contain a particle of interest. To this end, the ERT4x4a triggered events with at a cluster energy above 5GeV were chosen. In addition the BBCLL1(> 0 Tubes) trigger is imposed. This insures the collision occurred $|z_{BBC}| < 30$ cm, well away from the magnet pole tip.

6.3 EMCal Warn map

Over time certain towers or the EMCal may begin to function improperly. Errors may range from returning the wrong energy for an event to being completely inoperable. These towers must be identified and removed from the analysis. It is especially important to know the location of these towers since this will have an effect on the size of the detector acceptance and hence the calculation of the differential cross section.

Towers are calibrate by measuring the signal of the $\pi^0$ mass peak for each individual tower. The tower gains are adjusted to center this peak around the
accepted value of the $\pi^0$ mass. This processes is repeated several times with the goal of improving the peak resolution with each iteration. Towers in which the $\pi^0$ peak can not be seen are ignored.

Besides uncalibrated towers, hot towers and dead towers must be identified. Hot towers are found by looking at ERT triggered events and measuring the hit distribution amongst the towers. Towers with a number of event over 5 standard deviations more than the mean are considered hot and removed. Towers are considered dead if there are zero hits found. Around each hot, dead or uncalibrated tower the surrounding $3 \times 3$ towers are also excluded. Figure 6.1 shows the warn map used in the Run-6 analysis. In addition to the hot, dead and uncalibrated towers mentioned above, a 10 (12) tower fiducial cut is made around the edge of the PbSc (PbGl) sectors.

6.3.1 Central Track-EMCal cluster matching parameters

In the direct photon analysis, the DC is used to both veto charged track clusters in the EMCal and to calculate the charged particle energy deposited inside the isolation cut cone used in the isolation cut method described in section 7.3.2. The CNT-EMCal matching parameters, emcsdphi and emcsdz, give the distance, in number of standard deviations, between an extrapolated track in the DC and a hit in the EMCal. To check these parameters are properly tuned their value is plotted for ERT4x4a triggered events, with a track quality $> 3$. If the parameters are set properly the mean of the distribution is centered around zero with a width of one. The distribution of the emcsd-
Figure 6.1: EMCal warn map (Left-right: west-east, Bottom-top: sector 0-3). Towers numbered 0 (=white) are used in the analysis. The colored towers are hot, dead, uncalibrated, a $3 \times 3$ neighbor, or some combination of the four.

phi parameter given that $|emcsdz| < 2$ is plotted in Figure 6.2. The emcsdz parameter distribution with $|emcsdhi| < 2$ is shown in Figure 6.3. In Run-5 a small correction was to emcsdphi and emcsdz was required. In Run-6 no such correction was needed.

### 6.3.2 Run Dependence of the Drift Chamber Charge Veto

Since the DC is used for the charge veto, it is important to check the run dependence. Over time, wires of the DC may break, this will result in holes
in the DC acceptance. To make certain the conditions in the DC remain reasonably unchanged over the run, the number of tracks with a quality $> 3$ in each section of the drift chamber are plotted, normalized to the number of minbias events and compared to a reference "good" run. Examples are shown in Figures 6.5-6.7.

Figure 6.2: EMC $sdphi$ parameter, with $|emcsdz| < 2$

Figure 6.3: EMC $sdz$ parameter, with $|emcsdphi| < 2$

Figure 6.4: $\alpha$ (momentum) vs board number ($\phi$ angle) for the North West sector of the drift chamber in Run 190454. Run 190454 is used as the reference run.

Figure 6.5: $\alpha$ (momentum) vs board number ($\phi$ angle) for the South West sector of the drift chamber in Run 190454

Runs which contain a number of tracks $> 5$ standard deviations from the
normalized mean number of tracks per run are excluded from the analysis. A
Plot of the run dependence of the number of tracks in the DC are shown in
Figures 6.8,6.11

6.4 Photon Probability Cut

An independent method for reducing the hadron contamination in the data
sample is the photon probability, also called the shower shape, cut. Since,
photons and electrons interact with matter via the electromagnetic force, they will deposit energy in the EMCal in a very similar manner. Hadrons,
on the other hand, interact with the material via the strong force. Therefor,
showers in the EMCal due to hadrons will have a different longitudinal and
transverse extent than showers due to photons and electrons. To determine
the type of shower a candidate cluster shower shape of a hit in the EMCal is compared to known electromagnetic shower shapes. The known shower
shapes were obtained via the application of $E = 1GeV$ photons $^{[46]}$ to a set of sample PHENIX EMCal towers. In the test beam studies, the fractional energy per tower deposited by the 1 GeV photon was calculated and an average distribution was determined. The likelihood that a given hit in the EMCal is in fact an electromagnetic shower is from the $\chi^2$ from fitting the the candidate clusters distribution with the known electromagnetic shower shapes.

### 6.5 Local Polarimetry

Double longitudinal spin asymmetry measurements require the proton spin to be along the beam axis. Though, the stable direction of the proton spin is aligned with the RHIC bending magnets, transverse to the direction of the protons motion. Spin Rotators located at either end of the PHENIX IR rotate the spins along to the longitudinal direction. At PHENIX it was found that the production of neutrons in the forward direction was dependent upon the
Figure 6.10: The number of DC charged tracks normalized to minimum bias counts vs run number in the South East portion of the DC.

Figure 6.11: The number of DC charged tracks normalized to minimum bias counts vs run number in the South West portion of the DC.

direction the the proton spin. Left-Right asymmetries of neutron production in the ZDCs were observed when the beams are transversely polarized, see Figure 6.12. This asymmetry disappears when the spins are rotated into the longitudinal direction. Only fills with reliable local polarimeter measurements are use in the $A_{LL}$ measurements.

Figure 6.12: An example of the asymmetry measured in the beginning of a run while the beams are transversely polarized
Chapter 7

Direct Photon Cross Section

The invariant direct photon production cross section is given by the formula,

\[
E \frac{d^3 \sigma}{dp^3} = \frac{1}{\mathcal{L}} \frac{1}{2\pi p_T} \frac{N_{\gamma_{\text{dir}}}(\Delta p_T, \Delta y)}{\Delta p_T \Delta y} \frac{1}{f_{\text{acc}}} \frac{1}{\epsilon_{\text{bias}}}.
\]

(7.1)

\( \mathcal{L} \) is the integrated luminosity, derived from the total number of BBC triggers scaled by the BBC cross section, obtained in the vernier scan analysis. \( f_{\text{acc}} \) and \( \epsilon_{\text{bias}} \) are the acceptance correction and trigger efficiency, respectively. \( N_{\gamma_{\text{dir}}}(\Delta p_T, \Delta y) \) is the direct photon yield binned in transverse momentum, \( p_T \), and pseudorapidity, \( y \). This chapter will discuss the measurement of the direct photon cross section from the Run 6 data set. Two methods of extracting the direct photon yield will be introduced. Background and uncertainty estimates will be explained. Finally, a comparison between PHENIX data and Next to Leading Order pQCD calculations will be presented.

7.1 Photon Selection

Photons are defined by any particle which passes the following six cuts:
§1. **Warnmap Veto:** Events in EMCal towers which have been excluded from the analysis due to lack of calibrations are thrown out.

§2. **Fiducial Veto:** Direct photon candidates in a 10 (12) tower edge around the PbSc (PbGl) sectors of the EMCal are ignored. Partner photons while tagging $\pi^0$’s may be found in this region.

§3. **Photon Probability:** Photon probability $> 0.02$ is required for photons in both PbSc and PbGl sectors of the EMCal.

§4. **ERT bit:** Direct photon candidates require an ERT4x4c (ERT4x4a) trigger bit in Run 5 (Run 6).

§5. **Charge Veto:** 3 $\sigma$ matching cut of CNT tracks with quality $> 3$

§6. **Minimum Energy** Photon candidates must have a minimum energy of 5GeV. partner photons for $\pi^0$ tagging may be as low as 0.5 GeV.

### 7.2 Integrated luminosity

The luminosity is calculated based on the number of BBC events scaled by $\sigma_{BBC}$. In total, 6.55pb$^{-1}$ were analyzed using $\sigma_{BBC} = 24.5$mb.

### 7.3 Yield Extraction

The direct photon yield will be obtained via two methods, the *Statistical Subtraction Method* and the *Isolation Cut Method*. The Statistical Subtraction Method relies on measuring the inclusive photon yield and subtracting off
known backgrounds from hadronic decays. The Isolation Cut method uses a geometric cut to reduce the contribution from decay and fragmentation photons, before removing the remaining hadronic decay contributions. This geometric cut must be incorporated into the NLO pQCD calculations. In both cases the largest background is expected to come from the copious amounts of $\pi^0$'s produced in pp collisions at RHIC. The most favored decay mode for the neutral pion is $\pi^0 \to \gamma\gamma$, with a 98.798\% branching ratio\(^1\). The majority of the work in both of these analysis methods is the understanding and removal of these decay photons.

### 7.3.1 Statistical Subtraction Method

In the subtraction method, the number of inclusive photons is simply counted and then known hadronic decay photon contributions are subtracted off. The hadronic decay background is obtained by first measuring the number of $\pi^0$'s, in which both photons are inside the PHENIX acceptance. In this analysis, these are refereed to as two-tag $\pi^0$'s and denote there number by $N_{\pi^0}$. The two-tag $\pi^0$ yield is obtained by pairing photons in an event and calculation the invariant mass associated with the two photons. A full description of the $\pi^0$ tagging procedure is giving in Section 7.4.1. Because PHENIX is not a hermetic detector, a certain number of $\pi^0$'s will be produced in which only one of the photons appear in the PHENIX acceptance. The frequency of this occurrence must be estimated, so that these single photons may be removed from the sample. The ratio of the number of $\pi^0$'s where only one photon is inside the PHENIX acceptance to the number of $\pi^0$'s where both photons in the
acceptance is called the ”one-miss ratio” (R). This ratio is gotten from a single particle Monte-Carlo simulation. The MC takes as an input the EMCal warn map, the minimum energy cut, and the functional form of the $\pi^0$ spectrum measured from previous data. The total number of pions is then simply the sum of the number of two-tag pions, $N_{\pi^0}$, plus the number of one-miss points, which is just the number of two-tag pions times the one miss ratio, $R \times N_{\pi^0}$.

The Further hadronic contributions, from $\eta, \omega, \ldots$, are then estimated by scaling the total $\pi^0$ count, $(1 + R) \times N_{\pi^0}$, by production branching ratios, A. For each photon $p_T$ bin, the direct photon signal yield ($N_s$) is obtained by Equation 7.2

$$N_s = N_{incl} - (1 + A)(1 + R)N_{\pi^0},$$

(7.2)

where

$N_{incl}$: All photon corrected by non-photon background contributions.

$N_{\pi^0}$: Tagged $\pi^0$ photon in this photon $p_T$ bin corrected by the $\pi^0$ efficiencies.

$R$: The ratio of missing $\pi^0$ photons to two tagged $\pi^0$ photons. (From MC)

$A$: The ratio of all hadron to $\pi^0$ photon contribution. (From branching ratios)

### 7.3.2 Isolation Cut Method

Production of direct photons at PHENIX is dominated by the quark-gluon Compton scattering process. At leading order, the quark absorbs a gluon, and later emits an isolated photon and a jet back to back, assuming there is negligible intrinsic momentum of the partons inside the proton. In the
Isolation Cut Method method, the photon sample is purified by drawing a cone around a candidate direct photon and requiring that there be minimal activity in the vicinity of this photon for it to remain in the direct photon sample. In practice, what is demanded is that the sum of the neutral energy, measured in the EMCal, and the charged particle momentum, measured in the DC, be less than some fraction, $f$, of the candidate photon. It is also convenient to introduce the isolated pair, which similarly requires minimal activity in the detector around a pair of photons. The two concepts introduced (1) the ”isolated photon”, and (2) ”isolated pair”, defined in Equation 7.4 and Equation 7.6 respectively.

\[
E_\gamma \times f > E_{cone} \quad \quad (7.3)
\]
\[
> \sum E_{\text{neutral}} + P_{\text{charged}} - E_{\text{gamma}} \quad \quad (7.4)
\]

\[
E_\gamma \times f > E_{cone} - E_{\text{pair}} \quad \quad (7.5)
\]
\[
> \sum E_{\text{neutral}} + P_{\text{charged}} - E_{\text{pair}} \quad \quad (7.6)
\]

In this analysis the fraction ($f$) is set at 10%. $E_{cone}$ is calculated by the sum of energies of photons and momentum of charged tracks in the fixed cone around the target photon (or pair). A maximum momentum cut is applied to reduce the momentum misreconstructed backgrounds. The cone radius is set to 0.5$mrad$
There will remain a hadronic contribution inside the isolated sample which must be accounted for. The two main ways in which a hadronic decay might pass the isolation cut are:

§1. **Missing Partner Photon:** As in the subtraction method, this is when one photon is in the PHENIX acceptance while the partner photon has landed in a dead/masked region of the detector or has completely missed the the PHENIX acceptance.

§2. **Asymmetric Decay:** In this case the hadron has decayed very asymmetrically, leading to a very high energy photon and Partner photon below the 10% energy cut.

To deal with these hadronic decay photon backgrounds, two other quantities are defined (1) $N^{i}_{\pi^{0}}$, the two tagged isolated pair $\pi^{0}$’s, and (2) $n^{i}_{\pi^{0}}$, the two tagged isolated photon $\pi^{0}$’s. There is a subtle difference between the two. $N^{i}_{\pi^{0}}$ are the Isolation Cut methodology of the two tagged $\pi^{0}$’s of the Subtraction method. These are $\pi^{0}$ pairs with an isolation cone drawn around them. $n^{i}_{\pi^{0}}$ do not have an analogous Partner in the subtraction method. These correspond to $\pi^{0}$ pairs created by photons which have passed the isolation cut. These are the second item, ”Asymmetric Decay” in the list above.

$N^{i}$: Number of all isolated photon corrected by non-photon background contributions.

$n^{i}_{\pi^{0}}$: Tagged $\pi^{0}$ photon in the isolated photons corrected by the $\pi^{0}$ efficiencies. These are $\pi^{0}$ pairs which pass the isolation cut.
$N^i_{\pi^0}$: Tagged $\pi^0$ photon in the isolated pairs corrected by the $\pi^0$ efficiencies.

Analogous to the two tagged photons in the Subtraction Method.

$R$: The ratio of missing $\pi^0$ photons to tagged $\pi^0$ photons, from single particle MC.

$A^{n'}$: The ratio of all hadron to $\pi^0$ photon contribution, from branching ratios.

In the isolation cut method, the same $R$ is used in the subtraction method. The factor to calculate the other hadron contribution ($A^{n'}$) additionally includes a correction of isolation cut effect due to the decay partner energy. For $\eta'$s and heavier particles, it is less likely to have the partner photon in the isolated cone than $\pi^0$'s in low energy region. The isolated direct photon yield is given by,

$$N^i_s = N^i - (n^i_{\pi^0} + N^i_{\pi^0} R) - A^{n'}(1 + R)N^i_{\pi^0} \quad (7.7)$$

The statistical uncertainty is calculated according to Eq. 7.8

$$\delta N^i_s = \delta N^i_{\pi^0} - \{ R + A^{n'}(1 + R) \} \delta N^i_{\pi^0} \quad (7.8)$$

### 7.4 Summary of Photon Selection

Photon clusters are selected by applying cuts in Table 7.1 to EMCal clusters.

#### 7.4.1 $\pi^0$ Tagging in the Method

To extract the number $\pi^0$ photons in the inclusive or isolated photon sample, the invariant mass spectrum is plotted. When plotted, a peak at the neutral...
pion mass ($\approx 135\,MeV$) becomes clearly visible. To maximize the detection efficiency, the partner photons are selected only by applying the warn map and a minimum partner energy cut of 0.5GeV, the fiducial cut is not required for the partner photon. Figure 7.1 $\sim$ 7.2 show the invariant mass plots, each plot is binned in the $\pi^0$ photon $p_T$. Naturally, there will be a combinatorial background in the spectrum. This is removed by fitting the peak and the background with a Gaussian plus a polynomial function. The Gaussian will represent the peak and the polynomial should be indicative of the background. Integration of the Gaussian peak will yield $N_{\pi^0}$. The correction of combinatorial background was checked in three ways, by Gauss+pol1 fit, Gauss+pol2 fit, and by sideband subtraction, where the counts inside a $\pm 30$ MeV window around the $\pi^0$ mass peak were counted. The counts inside two 30 MeV sidebands were subtracted from the peak, to give a $\pi^0$ signal yield. All three methods yielded similar results for low $p_T$ $\pi^0$ photon bins, where low statistics are not a problem for the fitting procedure. So as not to switch methods between low and high $P_T$ points, the sideband method was used through out the

<table>
<thead>
<tr>
<th>Subtraction Method</th>
<th>Warn map veto</th>
<th>Guard veto</th>
<th>Photon shape cut</th>
<th>Charge track veto</th>
<th>ERT bit match</th>
<th>10(12) towers of PbSc(PbGl)</th>
<th>$prob &gt; 0.02$ for both PbSc and PbGl</th>
<th>$3\sigma$ matching of CNT tracks of quality $&gt;3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation Cut Method</td>
<td>Warn map veto</td>
<td>Guard veto</td>
<td>Photon shape cut</td>
<td>Charge track veto</td>
<td>ERT bit match</td>
<td>Isolation Cut</td>
<td>$10(12)$ towers of PbSc(PbGl)</td>
<td>$prob &gt; 0.02$ for both PbSc and PbGl</td>
</tr>
</tbody>
</table>

Table 7.1: photon cluster cuts
rest of the analysis. A summary of the three methods is found in Table 7.2

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauss+pol1 fit</td>
<td>((0.105 \leq M_{\gamma\gamma} \leq 0.165) - \int_{0.105}^{0.165} (pol1) dM_{\gamma\gamma})</td>
</tr>
<tr>
<td>Gauss+pol2 fit</td>
<td>((0.105 \leq M_{\gamma\gamma} \leq 0.165) - \int_{0.105}^{0.165} (pol2) dM_{\gamma\gamma})</td>
</tr>
<tr>
<td>Sideband subtraction</td>
<td>((0.105 \leq M_{\gamma\gamma} \leq 0.165) - (0.075 \leq M_{\gamma\gamma} &lt; 0.105) + (0.165 &lt; M_{\gamma\gamma} \leq 0.195))</td>
</tr>
</tbody>
</table>

Table 7.2: Cuts for \(\pi^0\) yield extraction

Show in Figures 7.1 and 7.2 are the invariant two photon mass distributions used to measure \(N_{\pi^0}\) in the subtraction method, in the west and east arms of the EMCal, respectively.

As described above, in the isolation cut method, two \(\pi^0\) photon samples are extracted, one for isolated \(\pi^0\), shown in Figures 7.3 and 7.4, and the other for \(\pi^0\) pairs of isolated photons, show in Figures 7.5 and 7.6. These two sets correspond to \(N_{\pi^0}\) and \(n_{\pi^0}\) of Equation 7.7, respectively.

### 7.4.2 Monte-Carlo Tuning

In the single particle Monte Carlo (MC), homogeneous and isotropic decays of \(\pi^0\)'s are simulated, with the stipulation that the production spectrum follow the know \(\pi^0\) spectrum from previous PHENIX data. The MC then uses PHENIX geometry, the warmmap, the \(E_{\text{min}}\) cut and the \(\pi^0\) to calculate several useful quantities in this analysis. These include the one miss ratio \(R\), and acceptance and smearing corrections. In order to use it, the MC must first be tuned to PHENIX data. This is done by comparing the \(\pi^0\) peak position...
Figure 7.1: Two photon invariant mass distribution (with $E_{min} = 0.5\,\text{GeV}$). Each panel shows different photon $p_T$. The top-left is for $5 < p_T < 5.5\,\text{GeV}$.

and width in from data to that of the simulation. Parameters of the MC are adjusted, so that the two are in agreement. Figures 7.7-7.10 below, show the results of several iterations of tuning the MC to PHENIX data.

### 7.5 $\pi^0$ photon merge

In the analysis the contributions due to the decay of heavier hadrons is obtained by scaling the total number of $\pi^0$’s in our acceptance. Since the merged $\pi^0$’s will be excluded by the photon probability cut, while pairs from heavier particles will not have merged yet, the $\eta$ and $\omega$ contributions will be undercount. The probability of merged clusters passes the probability cut was estimated via Monte Carlo simulations.
Figure 7.2: Two photon invariant mass distribution (east $E_{\text{min}} = 0.5\text{GeV}$). Each panel shows different photon $p_T$. The top-left is for $5 < p_T < 5.5\text{GeV}$.

### 7.6 Acceptance and smearing

By the same MC tuned to reproduce $\pi^0$ mass peak positions and widths, the acceptance and smearing correction was obtained. For the input photon spectra, we used $f = 0.1506 * p_T/(p_T^{7.047})$, which is from the fit to the Run3 preliminary spectra. Figure 7.11 and Figure 7.12 show the ratio of photons in the PHENIX acceptance to photons simulated. The ratios give a value or 0.0922 for the East are and 0.103 for the west.
Figure 7.3: Isolated pair photon invariant mass distribution (with \( E_{\text{min}} = 0.5\text{GeV} \)). Each panel shows different photon \( p_T \). The top-left is for \( 5 < p_T < 5.5\text{GeV} \).

### 7.7 Trigger Efficiencies

PHENIX relies on triggers to select collisions which are most likely to contain events of interest. Physical quantities, like cross sections, should not depend on the triggers used to collect data. Therefore, the yield must be corrected for the efficiencies of these triggers. In order to measure the efficiency of the trigger, two independent trigger selected data sets are needed. One then calculates the probability of measuring one type of trigger in the other triggered data set. For two triggers, A and B, the efficiency of trigger A is given by,

\[
\epsilon_A = \frac{N(A\&\&B)}{N(B)} \tag{7.9}
\]
Figure 7.4: Isolated pair photon invariant mass distribution (east $E_{\text{min}} = 0.5\text{GeV}$). Each panel shows different photon $p_T$. The top-left is for $5 < p_T < 5.5\text{GeV}$.

where $N(A\&\&B)$ is the number of particles –direct photons, $\pi^0$, etc – when both triggers A and B are present. $N(B)$ is the number of particles when trigger B is present irrespective of A. The two triggers used in the direct photon analysis are the Minimum Bias Trigger (MB) $BBCLL1(> 0\text{ Tubes})$ and $ERT4x4c\&\&BBCLL1(> 0\text{Tubes})$.

The minimum bias trigger efficiency and ERT trigger efficiency were measured during the Run-6 $\eta$ cross section analysis [10].

The minimum bias trigger efficiency was found to be $p_T$ dependent in Run-6. This will require further investigation for the cross section analysis. For the rest of the analysis I will assume a flat dependence with $MB_{\text{eff}} = 0.784$ with a large uncertainty.
Figure 7.5: Two photon invariant mass distribution of photons which pass
the isolation cut (with \(E_{\text{min}} = 0.5\text{GeV}\)). Each panel shows different photon \(p_T\).
The top-left is for \(5 < p_T < 5.5\text{GeV}\).

7.8 Uncertainties

7.8.1 Statistical error propagation

In order to calculate the propagation of the statistical uncertainties of the
direct photon signal, \(\delta N_s\), two extreme cases are are considered. The fist
being a 100% correlation between inclusive photons, \(N\), and \(\pi^0\) photons, \(n\pi^0\),
Equation 7.10 The other being zero correlation between them 7.11

\[
\delta N_s = \delta N_{\text{not}\pi^0} + (1A(1 + R))\delta n\pi^0
\]  

(7.10)
Figure 7.6: Two photon invariant mass distribution of photons which pass the isolation cut (with $E_{\text{min}} = 0.5\text{GeV}$). Each panel shows different photon $p_T$. The top-left is for $5 < p_T < 5.5\text{GeV}$.

$$\delta N_s = \delta N A (1 + R) \delta n \pi^0$$

(7.11)

Uncorrelated errors will give a larger uncertainty. The correlated error method was chosen since it yielded a better $\chi^2$ when fit with theory curves.

### 7.8.2 Systematic Uncertainties

In the direct photon cross section calculation systematic effects enter into the measurement due the properties inherent to the detector and the method of analysis. These are summarized below.
Figure 7.7: $\pi^0$ peak position vs $P_T$ in the east arm Red:Data Black:MC

Figure 7.8: $\pi^0$ peak width vs $P_T$ in the east arm Red:Data Black:MC

Figure 7.9: $\pi^0$ peak position vs $P_T$ in the west arm Red:Data Black:MC

Figure 7.10: $\pi^0$ peak width vs $P_T$ in the west arm Red:Data Black:MC

**Vernier Scan:**

A $\sim 10\%$ uncertainty is inherited directly from the vernier scan measurement. The details of this uncertainty are contained in Chapter 5. This is one of the largest sources of systematic uncertainty in the measurement.

**Global Energy Scale:**

Because of the steep falling slope of most yields, small uncertainties in the energy measurement will result in large discrepancies in the cross section at a given $p_{TT}$. A 10% global energy scale uncertainty is assigned to the cross
Figure 7.11: (MC) photon acceptance and smearing estimation. Shown is the ratio of photons in the east are to all photons simulated

Figure 7.12: (MC) photon acceptance and smearing estimation. Shown is the ratio of photons in the east are to all photons simulated

Figure 7.13: Minimum bias trigger efficiency measured in Run 6

This was obtained from studies of the $\pi^0$ peak width in the EMCal.

**Photon Conversion:**

The direct photon measurement relies on the DC to remove electrons from the sample. Comparing the photon yield when using the DC charge veto to the yield when using PC3 to veto on charged particles will give an estimate
on the number of photons which convert on the back face of the DC. A 1% uncertainty is assigned.

**Shower Shape Cut:**

A 1% uncertainty is obtained for the shower shape cut by comparing the $\pi^0$ yield with and without the cut.

**Background Subtraction:**

A 3% uncertainty is assigned to the $\pi^0$ yield. This was obtained by comparing the yield of $\pi^0$'s in the Gaussian plus first order polynomial fit method, the Gaussian plus second order polynomial fit method and side band method.

**$\pi^0$ Merging:**

A 1% uncertainty was estimated in GEANT simulations.
**BBC Trigger Efficiency:**

An unexplained run dependence in the BBC trigger efficiency appeared in Run-6. A constant value was assumed in the calculation and a 5% uncertainty is assigned to the value above $p_T = 8$ GeV.
Chapter 8

Direct Photon $A_{LL}$ and Extraction of $\Delta G/G$

This chapter details the double longitudinal spin asymmetry calculation for mid-rapidity direct photons in the PHENIX experiment and the leading order extraction of the gluon contribution to the spin of the proton $\Delta G/G$.

8.1 Double Longitudinal Spin Asymmetry ($A_{LL}$)

The double longitudinal spin asymmetry($A_{LL}$) was defined in Equation 1.59 as the difference in helicity dependent production cross sections over the sum.

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$  \hspace{1cm} (8.1)

As was discussed in chapter[1] this could be reduced to a difference in luminosity normalized yields over their sum.

8.1.1 Photon Selection

The cuts below are applied to the isolated photon sample:
§1. Photon Probability cut $i \geq 0.02$

§2. Charge veto via drift chamber EMC matching

§3. $e_{\text{core}} > 5$ GeV

§4. Minimum neutral energy cut 0.5 GeV

§5. Minimum charged momentum cut 0.5 GeV

§6. 10 tower edge for PbSc

§7. 12 tower edge for PbGl

### 8.1.2 Direct Photon $A_{LL}$ Calculation

The measurement of the direct photon $A_{LL}$ starts by considering an isolated photon sample, as described in Chapter 7. Decay photons, which remain in the isolated photon sample must either be removed or the asymmetry associated with them must be corrected for. The majority of decay photons will come from $\pi^0 \rightarrow \gamma\gamma$ decays. Similar to the cross section measurement, decay photons enter the sample in two ways (1) very asymmetric decays, whereby the partner photon is well below the 10% cone cut and (2) if one of the decay photons were to land in PHENIX acceptance and the partner photon were to hit a masked tower or completely miss the the calorimeters. Following the naming convention of the previous chapter these $\pi^0$ yields will be called $n_{\pi^0}$ and $N_{\pi^0}$, respectively.

$\pi^0$ pairs which pass the isolation cut due to a large asymmetry in their energies, $n_{\pi^0}$ are simply removed. These are identified by photon pairs from
the isolated sample which produce an invariant mass inside a 60MeV mass window around the $\pi^0$ (135MeV ± 30). This window corresponds to $\approx 3$ standard deviations of the peak width. These events are so rare that it is reasonable to assume no combinatorial background exists. The photons which remain, $N_{iso} - n_{\pi^0}$, are used to calculate the foreground asymmetry, $A_{LL}^{iso-n_{\pi^0}}$. Still left behind are the isolated $\pi^0$ photon pairs in which one photon is within PHENIX acceptance and the other has missed. The invariant mass spectrum of these $\pi^0$ photons sit on a small combinatorial background. Therefore these pions are not identified on an event by event basis. A Gaussian plus second order polynomial is fit to the distribution. The number of isolated $\pi^0$'s is the number of counts inside a 3$\sigma$ mass window minus the area under the polynomial. The asymmetry of these isolated pairs, $A_{LL}^{Background}$, is calculated and the foreground asymmetry is corrected for this background asymmetry. The direct photon asymmetry is then calculated using Equation (8.2) below.

$$A_{LL}^{direct-\gamma} = \frac{A_{LL}^{iso-n_{\pi^0}} - r A_{LL}^{Background}}{1 - r}$$  \hspace{1cm} (8.2)

The quantity $r$, called the dilution factor, describes the degree to which the background dilutes the foreground asymmetry, and is defined by

$$r = \frac{N^{BG}}{N^{iso}}$$  \hspace{1cm} (8.3)

where,

$$N^{BG} = N^{iso} - n_{\pi^0} - N^{direct-\gamma}.$$  \hspace{1cm} (8.4)

The dilution factor is extracted from the yields in the cross section analysis.
\[
\delta A_{LL}(\text{sig})^2 = \frac{\delta A_{LL}^2(\text{iso}) + r^2 \delta A_{LL}^2(\text{bg})}{(1 - r)^2}
\]  

(8.5)

### 8.2 Background Asymmetry

The isolated photon asymmetry must be corrected for using the \(\pi^0\) photon asymmetry. As with the Isolated photon asymmetry, we run out of \(\pi^0\) for our background asymmetry estimations.

**Figure 8.1**: \(\pi^0\) Photon Asymmetry \(P_t = 5-6\text{GeV}\)

**Figure 8.2**: \(\pi^0\) Photon Asymmetry \(P_t = 6-7\text{GeV}\)

**Figure 8.3**: \(\pi^0\) Photon Asymmetry \(P_t = 7-8\text{GeV}\)

**Figure 8.4**: \(\pi^0\) Photon Asymmetry \(P_t = 8-10\text{GeV}\)
We can represent $A_{LL}$ in the following way:

$$A_{LL} = \frac{1}{|P_1| |P_2|} \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}$$

(8.6)

where $P_1$ and $P_2$ are the beam polarizations, $N_{++}(N_{+-})$ represent the number of observed photons during like (unlike) helicity collisions, and R is the Relative Luminosity as measured by the beam beam counters.

$$R = \frac{N_{++}}{N_{+-}}$$

(8.7)

The statistical uncertainty on $A_{LL}$ can then be calculated as follows:

$$\delta A_{LL} = \frac{1}{P_1 P_2 N_{++} + R N_{+-}} \sqrt{\left( \frac{\delta N_{++}}{N_{++}} \right)^2 + \left( \frac{\delta N_{+-}}{N_{+-}} \right)^2 + \left( \frac{\delta R}{R} \right)^2}$$

(8.8)
Figure 8.7: Isolated Photon Asymmetry $P_t = 5\text{-}6\text{GeV}$

Figure 8.8: Isolated Photon Asymmetry $P_t = 6\text{-}7\text{GeV}$

Figure 8.9: Isolated Photon Asymmetry $P_t = 7\text{-}8\text{GeV}$

Figure 8.10: Isolated Photon Asymmetry $P_t = 8\text{-}10\text{GeV}$

### 8.3 Average $P_T$

The average direct photon $P_T$ in each $P_T$ bin was calculated using [8.9]

$$
\langle P_T^{\text{direct}} \rangle = \frac{\langle P_T^{\text{iso}} \rangle - r \langle P_T^{\text{BG}} \rangle}{1 - r}
$$

(8.9)

again

$$
r = \frac{N^{BG}}{N^{iso}}
$$

(8.10)

Since the isolated $\pi^0$ pairs are obtained by a statistical subtraction, three
Figure 8.11: Isolated Photon Asymmetry $P_T = 10-12\,\text{GeV}$

Figure 8.12: Isolated Photon Asymmetry $P_T = 12-15\,\text{GeV}$

<table>
<thead>
<tr>
<th>Bin $P_T$</th>
<th>$\langle P_T^{BG} \rangle$ ($m_{\gamma\gamma} &lt; m_{\pi^0} \pm 50,\text{MeV}$)</th>
<th>$\langle P_T^{BG} \rangle$ ($m_{\gamma\gamma} &gt; m_{\pi^0} \pm 50,\text{MeV}$)</th>
<th>$\langle P_T^{BG} \rangle$ ($m_{\gamma\gamma} &lt; 20,\text{GeV}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 – 6</td>
<td>5.40</td>
<td>5.40</td>
<td>5.40</td>
</tr>
<tr>
<td>6 – 7</td>
<td>6.40</td>
<td>6.42</td>
<td>6.42</td>
</tr>
<tr>
<td>7 – 8</td>
<td>7.42</td>
<td>7.43</td>
<td>7.43</td>
</tr>
<tr>
<td>8 – 10</td>
<td>8.73</td>
<td>8.75</td>
<td>8.75</td>
</tr>
</tbody>
</table>

Table 8.1: Summary of the mean $P_T$ calculation for each $P_T$ bin

regions were examined, to estimate the mean $P_T$ for that bin. First a $100\,\text{MeV}$ region around the $\pi^0$ mass peak, second, outside this mass window, and lastly the entire range of available photos. A summary of the mean $P_T$ of the background can be found in Table. 8.1

### 8.4 Combined Fills

In order for the $\chi^2$ fitting method to be valid, there must be enough events, in a given fill, typically ten or more, to apply the basic rules of Gaussian statistics. At high $P_T$ there are several fills which do not meet the minimum requirement.
Normally these fills would be excluded from the analysis. When looking for particularly rare probes such as direct photons, the number of usable fills falls off very quickly. A mathematically consistent way to include these fills in the analysis is desired. It has been shown, that fills may be combined if the efficiencies and relative luminosities remain fairly constant through the entirety of the fill [30]. A spread in the relative luminosity of 0.02 was allowed during the combining process. This was the minimum spread which allowed all fills to be utilized. In Table D.3 are listed the Combined fill $A_{LL}$’s. No bunch shuffling is show since, there are no degrees of freedom left if we sum over fills.

Figure 8.13 shows the result of the $A_{LL}$ for direct photons as a function of $P_T$. Included on the plot are the theoretical curves, GRSV-max, GRSV-std and GRSV-0. At the current level of statistics these data are still unable to rule out any of the models. In future runs with higher statistics and increased polarization we hope to be able to do so. Though it is interesting to see the effectiveness of the isolation cut on the high $P_T$ points.

### 8.5 Bunch Shuffling

The bunch shuffling technique is used to ensure that any systematic uncertainties which have not been accounted for are negligible with respect to the current level of the statistical uncertainty of the measurement. The technique relies on randomly assigning spin orientations to the bunch crossings in a spin analysis, effectively simulating an unpolarized beam. Asymmetries are then calculated, fit and the resulting $\chi^2$ per degree of freedom is recorded. The
Figure 8.13: Direct photon asymmetry as a function of $P_T$ with several model curves included. The first three bins have a width of 1 GeV. The finals bin is 2.2, 3 GeV wide respectively. The Run5 data are shown in black while the Run6 in Blue

resulting $\chi^2$ distribution is then compared to the expected distribution for the number of degrees of freedom in the fits. If the distribution deviates significantly from the expected distribution it signifies that there is some systematic uncertainty which is unaccounted for. The results of the bunch shuffling for the foreground and background for the 6 $P_T$ bins used in this analysis.

Figure 8.14: Bunch shuffling $\chi^2$ distribution for the $P_t = 5$-6GeV bin

Figure 8.15: Bunch shuffling $\chi^2$ distribution for the $P_t = 6$-7GeV bin
8.6 Leading Order Extraction of $\Delta G/G$

As mentioned in Chapter 2, one of the main advantages of the direct photon measurement is that at leading order, the direct photon double longitudinal helicity asymmetry is linear in the gluon contribution to the spin of the proton $\Delta G/G$. In this section the method for calculating $\Delta G/G$ using $A_{1T}$ data from DIS will be explained. Also, a simple Monte Carlo for estimating the most probable gluon $x$ associated with a direct photon of a given $p_T$ will be shown.
8.6.1 $A_{LL}$ to $\Delta G/G$

To leading order the following reordering of Equation 2.5 may be used to calculate $\Delta G/G$ from the direct photon $A_{LL}$

$$\frac{\Delta G(x)}{G(x)} = \frac{A_{LL}(p+p \to \gamma + X)|_{\theta=90^\circ}}{A_1^p(x) \times \hat{a}_{LL}(g + q \to \gamma + q)|_{\theta^*=90^\circ}}$$

(8.11)

$A_1^p(x)$ is the quark spin contribution, which has been well constrained by DIS experiments. $\hat{a}_{LL}(g + q \to \gamma + q)|_{\theta^*=90^\circ}$ is the partonic asymmetry for the hard scattering subprocess, which is calculable in pQCD.

8.6.2 Average $x_{bj}$

In proton-proton collisions, the underlying kinematics are not completely constrained. A Monte Carlo simulation must be used to calculate the most probably $x_{gluon}$ for a given direct photon $P_T$.

The differential cross section in p+p collisions can be represented as a convolution of PDF’s with the appropriate hard scattering subprocess and the cross terms $(1,2 \to 2,1)$.

$$\frac{d\sigma}{dx_1dx_2d\cos(\theta^*)} = \sum_{a,b} f_a(x_1) \otimes f_b(x_2) \otimes \frac{d\sigma}{dt} + (1,2 \to 2,1)$$

(8.12)

For direct photon production the two leading order subprocesses are quark-gluon Compton scattering and $q\bar{q} - annihilation$. The quark-gluon Compton scattering and $q\bar{q} - annihilation$ partonic cross sections may be written as,

$$\frac{d\sigma}{dt}(gq \to \gamma q) = e_q^2(-2)\frac{\pi \alpha_s}{6s^2}\left(\frac{\hat{u}}{\hat{s}} + \frac{\hat{s}}{\hat{u}}\right)$$

(8.13)
\[
\frac{d\sigma}{dt}(q\bar{q} \rightarrow \gamma g) = e_q^2(8) \frac{\pi\alpha\alpha_s}{9s^2} (\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}})
\]

(8.14)

where, \(e_q\) is the quark charge and \(\alpha\) and \(\alpha_s\) are the fine structure and strong coupling constants, respectively. The Mandelstam variables, \(\hat{s}\), \(\hat{t}\) and \(\hat{u}\) defined as follows:

\[
\hat{s} = x_1x_2s
\]

(8.15)

\[
\hat{u} = -\frac{\hat{s}(1 + \cos(\theta^*))}{2}
\]

(8.16)

\[
\hat{t} = -\frac{\hat{s}(1 - \cos(\theta^*))}{2}
\]

(8.17)

\(s\) is the center of mass of the proton-proton collision and \(\theta^*\) is the angle of the outgoing direct photon. In the simulation \(x_1\), \(x_2\) and \(\theta^*\) are chosen at random. The hard scattering cross section is calculated using Equations 8.13 and 8.14 and weighted by the appropriate PDFs. The PDFs chosen for this analysis are CTEQ6M. Momentum conservation is applied between the incoming and outgoing particles \((x_1 + x_2 = x_3 + x_4)\). Only mid-rapidity photons are chosen using,

\[
y = \ln(\frac{x_1}{x_2}).
\]

(8.18)

Finally, the x distribution of the gluons are plotted in bins of the transverse momentum of the direct photon,

\[
p_T = \frac{\sqrt{s}}{2}\sin(\theta^*)
\]

(8.19)

Plots of the x distribution of gluons for several direct photon \(p_T\) bins are
shown in in Figures 8.20-8.25

Figure 8.20: Distribution of $x_{bj}(gluon)$ for $p_T = 5-6$GeV direct-$\gamma$

Figure 8.21: Distribution of $x_{bj}(gluon)$ for $p_T = 6-7$GeV direct-$\gamma$

Figure 8.22: Distribution of $x_{bj}(gluon)$ for $p_T = 7-8$GeV direct-$\gamma$

Figure 8.23: Distribution of $x_{bj}(gluon)$ for $p_T = 8-10$GeV direct-$\gamma$

8.6.3 $A^p_1(x)$

The values $A^p_1(x)$ is obtained from DIS data. A large database of the world data is stored by Durham University.

http://durpdg.dur.ac.uk/hepdata/online/f2/structindex.html

Plotted in Figure 8.26 are several more recent measurements of $A^p_1$ obtained from the database along with a fit to the data.
Figure 8.24: Distribution of $x_{bj}(\text{gluon})$ for $p_T = 10-12\text{GeV}$ direct-$\gamma$

Figure 8.25: Distribution of $x_{bj}(\text{gluon})$ for $p_T = 12-15\text{GeV}$ direct-$\gamma$

Figure 8.26: $A_F^p$ with fit to data $f(x) = 1.04 \times x^{0.16} \times (1 - e^{-2.9x})$. Data is collected and stored at the Durham HEP database. Scale uncertainties not shown.

### 8.6.4 Partonic Asymmetry $\hat{a}_{LL}$

The partonic asymmetry for various hard scattering QCD processes have been calculated numerous times\cite{51}. The analyzing power for lowest order reactions in $p + p$ collisions are shown in Figure 8.27. Of particular interest are curves for quark-gluon Compton Scattering, curve ”C”, and that for $q\bar{q}$–annihilation, curve ”E”. 

148
Figure 8.27: The partonic asymmetry $\hat{a}_{LL}$
Chapter 9

Results & Discussion

This chapter will present and discuss the results from the previous two chapters: the cross section for mid-rapidity direct photon production and the double longitudinal spin asymmetry for direct photons. These results will be compared with theoretical expectations. Implications for $\Delta G$ will be discussed and compared to expectations from other measurements. Lastly, the outlook on future measurements of $\Delta G$ will be presented. Tables of the cross section and $A_{LL}$ results are contained in appendices C and D.

9.1 Results for the Direct Photon Cross Section

The direct photon cross section at mid-rapidity in $\sqrt{s} = 200 \text{ GeV} \ p + p$ collisions was measured in Run-6 using both the Isolation Cut Method and the Statistical Subtraction Method. Figures 9.1 and 9.2 show the Run-5 preliminary cross section (green) and the Run-6 cross sections separated by arm – east arm(red) and west arm(blue) – for the Isolation cut method and sub-
traction method respectively. Theory curves for both were provided by W. Vogelsang\cite{52}.

Figure 9.1: Isolated direct photon cross section for Run-6 in the east arm (red) and west arm (blue) compared with the Run-5 preliminary result (green) and theoretical predictions

In both cases the Run-6 measurement shows good agreement with previous data. It can be seen from the two figures that, pQCD calculations describe the data well over several orders of magnitude. The implications of this agreement are threefold. First, it shows that NLO calculations describe the data well and that Next to Leading Log terms which are required to describe cross section measurements at PHENIX in $\sqrt{s} = 62.4$ GeV collisions\cite{53} have less of an effect in $\sqrt{s} = 200$ GeV collisions. Next, it gives confidence that the calculations of the relative contributions of the sub processes ($\sim 80\%$ $gq$-Compton and $\sim 20\%$ $q\bar{q}$ annihilation) are reliable. Lastly, the two methods have a different
Figure 9.2: The direct photon cross section measured via the statistical subtraction Method for Run-6 in the east arm (red) and west arm (blue) compared with the Run-5 preliminary result (green) and theoretical predictions.

Admixture of direct photons and fragmentation photons, shown in Figures 9.3 and 9.4. Agreement of the theory in both methods indicate the isolation cut method is very effective in removing the fragmentation photon contribution. Together they show that if a direct photon is found at mid-rapidity in the measured transverse momentum range \( 5 < P_T < 30 \), then there is a high probability that it came from the \( qg \to \gamma + X \) subprocess. This strengthens the validity to the leading order extraction of \( \Delta G \) from the direct photon \( A_{LL} \), described in the previous chapter.
Figure 9.3: Contributions to the inclusive photon cross section (red) separated into direct photon (black) and fragmentation photons (blue) with out isolation cut.

Figure 9.4: Contributions to the isolated photon cross section (red) separated into isolated direct photons (black) and isolated fragmentation photons (blue) with the isolation cone size set to 0.5mrad.

9.2 Results for $A_{LL}$ and $\Delta G/G$

The direct photon double helicity asymmetry at mid rapidity was measured in both Run-5 and Run-6. The asymmetry vs $p_T$ is shown in figure 9.5. This is the first measurement of the direct photon $A_{LL}$. Also shown in the figure are several theoretical curves from the GRSV model. These curves correspond to the maximum allowable value of $\Delta G$; GRSV-Max, $\Delta G = 0$ labeled GRSV - 0 and GRSV - G, which corresponds to the largest negative value allowable. Unfortunately the current measurements are dominated by statistical uncertainty and are unable to make a meaningful constraint of the models. $\Delta G/G$ was extracted from the direct photon $A_{LL}$ using the leading order analysis described in Chapter 8. This is also the first extraction of this quantity. Figure 9.6 shows the calculated value of $\Delta G/G$ vs $x_{gluon}$. The central point of in $x$ is predicted from the Monte Carlo simulation. The $x_{gluon}$ distribution for the single point is peaked at $x = 0.086^{+0.85}_{-0.09}$ with asymmetric uncertainties. The
Figure 9.5: Direct Photon $A_{LL}$ measured in Run-5 and Run-6 with model predictions from the GRSV model.

The value of $\Delta G/G = -0.52 \pm 0.45$ at a single point is measured by taking the weighted mean of all available PHENIX data.

### 9.3 Comparison with Other PHENIX Data

Currently there are two double helicity asymmetry measurements which have been released by the PHENIX experiment, the $\pi^0$ [10] – Figure 9.7 and $\eta$ [10] – Figure 9.8 measurements. The motivation for continuing to pursue the direct photon measurement in light of the small statistical uncertainties of these two measurements seems unclear at first glance. Though, there remain several advantages to looking at the direct photon channel as compared to these other channels. First, both of the other measurements suffer from the fact that there are terms which are quadratic in $\Delta G$ which contribute to the double
Figure 9.6: $\Delta G/G$ including Run-5 and Run-6 PHENIX direct photon data

longitudinal spin asymmetry. This means that these channels are less sensitive to negative values of $\Delta G$. This fact becomes particularly striking when looking at Figures [9.9] Which show a $\chi^2$ minimization analysis for the extraction of $\Delta G$ from the $\pi^0$ asymmetry. These two channels also rely on model dependent fits to extract $\Delta G$. The theoretical uncertainties from these fits are not show [10][10].

The $\pi^0$ and $\eta$ measurements have the added complication of having to include fragmentation functions along with the theoretical and experimental uncertainties associated with them. As the integrated luminosity increases and statistical errors no longer overshadow these systematic uncertainties, the direct photon will be the premier channel for constraining the gluon spin in the proton at RHIC.
Figure 9.7: Published $\pi^0 A_{LL}$ measured in Run-5 and Run-6 with model predictions from GRSV.

Figure 9.8: $\eta A_{LL}$ measured in Run-5 and Run-6 with model predictions from GRSV.

### 9.4 Comparison with DIS Data

Several results from DIS experiments have constraining $\Delta G$ have been published. These include results from HERMES, COMPASS and the SMC collaborations. These results are summarized in Figure 9.10. The difficulty with measuring the gluon via DIS is that the virtual photon probing the proton does not directly couple to the gluon at leading order. These measurements also require complicated model dependent fits in order to extract $\Delta G/G$ from their data.\textsuperscript{54} The "golden channel" to constrain the gluon in DIS experiments is the open charm measurement. It has the most direct access to the gluon, and thus the least amount of added systematic uncertainties from theoretical models. As of the completion of this work the most precise measurement of $\Delta G$ from the open charm channel has come from the COMPASS experiment. Currently the value coming out of COMPASS stands at $-0.57 \pm 0.41$. The
Figure 9.9: $\chi^2$ profile from several fits used to extract $\Delta G/G$ from the $\pi^0$ asymmetry.

Uncertainties from the direct photon measurement from PHENIX are on the same level. Figure 0.12 shows the PHENIX data with current DIS data. The curves are theoretical calculations of the gluon polarization provided by W. Vogelsang. The values range from $\Delta G/G = -1.05$ to $\Delta G/G = 0.70$. At the time of the writing of this thesis, COMPASS does not plan to have another spin dependent data taking run for at least another year. In this time, PHENIX plans to complete its ninth year of running. This run promises to have a long highly polarized longitudinal data set.

9.5 Outlook for the Direct Photon

Both the cross section and the first double longitudinal spin asymmetry for direct photons at mid-rapidity in $\sqrt{s} = 200$ GeV $p + p$ collisions have been measured and a leading order extraction of $\Delta G/G$ has been performed. With the current data the cross section is limited mostly by systematic uncertainties. Future measurements at $\sqrt{2} = 200$ are not likely to make much of an impact.
Figure 9.10: A summary measurements of $\Delta G/G$ from several DIS experiments. This plot originally appeared in a paper by G. Mallot [12].

The double longitudinal spin asymmetry, on the other hand is dominated by statistical uncertainties. The upcoming Run-9 data set could provide significant improvements in this measurement. The proposed luminosity for Run-9 200GeV pp run is $25pb^{-1}$ with 70% polarization. These figures would correspond to a factor of 2 reduction in the statistical uncertainty. Figure 9.13 shows projections for the for the asymmetry measurement with these parameters. Figure 9.13 shows projected statistical errors for the total expected luminosity for the lifetime of PHENIX. 100$pb^{-1}$ with 70%. Similar gains can be expected in the $\Delta G/G$ measurement. Figures 9.15 shows projections of the uncertainties of this measurement with the same expected luminosity and polarizations.

There are plans for $\sqrt{s} = 500$ GeV $p + p$ collisions at RHIC in the near future. This will expand the allowable x range which PHENIX may probe.
and allow PHENIX to begin a program in which the $W^+$ and $W^-$ boson asymmetries are measure, giving PHENIX access to flavor dependent spin in the proton. A new silicon vertex detector will also be installed in the coming runs. This new device will facilitate $\gamma - Jet$ measurements, thus giving PHENIX the ability to pin down the underlying kinematics of the subprocesses in a $p + p$ collision. By the end of the RHIC spin program the value of $\Delta G$ should be well constrained by the tremendous effort put forth by the spin collaborations.
Figure 9.12: A summary of $\Delta G/G$ measurements from PHENIX and several DIS experiments. PHENIX data is from Run-5 and Run-6 combined (blue circle).

Figure 9.13: Projections of statistical uncertainties for Run-9 (red) direct photon $A_{LL}$ based upon Run-6 (blue) values

Figure 9.14: Projections of statistical uncertainties for total integrated luminosity direct photon $A_{LL}$
Figure 9.15: Projections of statistical uncertainties on $\Delta G/G$ from Run-9 (blue) and total integrated luminosity (black)
Bibliography


[43] I. Nakagawa et al., RHIC/CAD Accelerator Physics Note.


[49] S. Belikov et al., Determination of the absolute luminosity for the proton-proton data at $\sqrt{s} = 200\text{ gev}$ recorded by phenix during rhic run-02, (2003).


Appendix A

Vernier Scan Data

A.1 Beam Position Monitors
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<tr>
<th>Run</th>
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Table A.1: BPM Step sizes.
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Table A.2: Mean peak offset in the horizontal and vertical direction based upon scans in the orthogonal direction.

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Table A.3: Mean peak offset in the horizontal and vertical direction based upon scans in the orthogonal direction.

## A.2 Peak Correction
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Table A.4: Summary of Z-vertex width calculated by the Gaussian fitting.

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Table A.5: Mean BBC efficiency and ZDC resolution at $\sqrt{s} = 200$ GeV.

### A.3 BBC Efficiency
Appendix B

Run & Fill level Cuts

The following runs were removed from the run 6 data set for the cross section analysis:

§1. No ERT Triggers: 198061, 198137, 198138

§2. HBD: 200582

§3. Field Off Runs: The central arm magnets were off. We are unable to calculate the charged particle momentum for the isolation cut. 198167, 198490, 198491, 198982, 199136, 199248, 199368, 199503, 199666, 199754, 200255, 200403, 201476, 201489, 201504, 201537, 202716, 203367

Along with the above runs, the runs below were removed from the asymmetry analysis only.

§4. STAR Magnet Trips: Trips of the STAR magnet during the run may have caused changes in magnitude or direction of the initial proton spin: 198136, 198383, 198569, 198560, 201872, 201876, 201880, 201881, 201883, 201885, 201886, 203463, 204356, 204357, 204358, 204491, 204492, 204494, 204495, 204497, 204625
§5. **No STAR Magnet info**: Runs were excluded due to lack of STAR magnet information: 201476, 201489, 201504

§6. **Relative Luminosity**: The following runs were excluded by the relative luminosity analysis: 198167, 198490, 198491, 199136, 199368, 199503, 199666, 198484, 199544, 199754, 200240, 200585, 200697

§7. **Rotator Magnet Currents**: The rotator magnet currents were not set properly for several runs in the beginning of Run 6 198063, 198064, 198134
## Appendix C

### Cross Section Data Tables

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<th>$p_T$ [GeV/c]</th>
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Table C.1: Run 5 Cross section via the subtraction method
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Table C.3: Run 6 Cross section via Subtraction method
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Table C.4: Run 6 Cross section via Subtraction method
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Table C.5: Yield in the west arm in the subtraction method ($E_{min} = 0.5$GeV)
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\hline
$p_T[\text{GeV/c}]$ & $N$ & $N_{n0}$ & $R$ & $A$ & $N_s$ \\
\hline
5.25 & 49970 & 12617 & 1.54 & 0.23 & 10589.68 \\
5.75 & 26746 & 7018 & 1.32 & 0.23 & 6689.76 \\
6.25 & 14868 & 4021 & 1.27 & 0.23 & 3637.53 \\
6.75 & 8903 & 2503 & 1.1 & 0.23 & 2424.39 \\
7.25 & 5332 & 1500 & 1.05 & 0.23 & 1542.11 \\
7.75 & 3304 & 912 & 0.93 & 0.24 & 1125.43 \\
8.25 & 2224 & 594 & 0.9 & 0.24 & 829.58 \\
8.75 & 1487 & 401 & 0.85 & 0.24 & 568.58 \\
9.25 & 1049 & 283 & 0.82 & 0.24 & 411.09 \\
9.75 & 767 & 214 & 0.83 & 0.24 & 281.69 \\
10-12 & 1365 & 337 & 0.71 & 0.25 & 648.07 \\
12-14 & 463 & 108 & 0.61 & 0.26 & 244.63 \\
14-16 & 142 & 20 & 0.51 & 0.27 & 103.7 \\
16-18 & 69 & 10 & 0.48 & 0.29 & 49.96 \\
18-20 & 38 & 9 & 0.4 & 0.31 & 21.51 \\
20-22 & 12 & 1 & 0.38 & 0.33 & 10.16 \\
22-24 & 13 & 0 & 0.36 & 0.34 & 13 \\
24-30 & 3 & 0 & 0.3 & 0.35 & 3 \\
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Table C.6: Yield in the east arm in the subtraction method ($E_{\text{min}} = 0.5\text{GeV}$)
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<th>$N_{\pi^0}^i$</th>
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Table C.7: Yield in the west arm in the isolation cut method ($E_{\text{min}} = 0.5\text{GeV}$)
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Table C.8: Yield in the east arm in the isolation cut method ($E_{min} = 0.5$GeV)
Appendix D

$A_{LL}$ and $\Delta G/G$ Data Tables

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Table D.1: Summary of $\Delta G/G$ calculation

D.1 Results
Table D.2: Summary of Combined Isolated Photon and $\pi^0$ photon asymmetry

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<th>Bin $P_T$</th>
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<th>$A_{LLIso}$</th>
<th>$\delta A_{LLIso}$</th>
<th>$A_{LL\pi^0}$</th>
<th>$\delta A_{LL\pi^0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 – 6</td>
<td>0.68</td>
<td>-0.016</td>
<td>0.015</td>
<td>0.011</td>
<td>0.025</td>
</tr>
<tr>
<td>6 – 7</td>
<td>0.58</td>
<td>0.014</td>
<td>0.026</td>
<td>0.018</td>
<td>0.044</td>
</tr>
<tr>
<td>7 – 8</td>
<td>0.46</td>
<td>0.021</td>
<td>0.042</td>
<td>0.038</td>
<td>0.073</td>
</tr>
<tr>
<td>8 – 10</td>
<td>0.34</td>
<td>0.025</td>
<td>0.050</td>
<td>0.036</td>
<td>0.097</td>
</tr>
<tr>
<td>10 – 12</td>
<td>0.20</td>
<td>0.017</td>
<td>0.093</td>
<td>0.022</td>
<td>0.22</td>
</tr>
<tr>
<td>12 – 15</td>
<td>0.10</td>
<td>0.120</td>
<td>0.139</td>
<td>0.052</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Table D.3: Summary of Combined Isolated Photon and $\pi^0$ photon asymmetry

<table>
<thead>
<tr>
<th>Bin $P_T$</th>
<th>$A_{LLdirect} - \gamma$</th>
<th>$\delta A_{LLdirect} - \gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 – 6</td>
<td>-0.070</td>
<td>0.071</td>
</tr>
<tr>
<td>6 – 7</td>
<td>0.058</td>
<td>0.087</td>
</tr>
<tr>
<td>7 – 8</td>
<td>-0.006</td>
<td>0.100</td>
</tr>
<tr>
<td>8 – 10</td>
<td>-0.056</td>
<td>0.091</td>
</tr>
<tr>
<td>10 – 12</td>
<td>-0.027</td>
<td>0.113</td>
</tr>
<tr>
<td>12 – 15</td>
<td>-0.139</td>
<td>0.161</td>
</tr>
</tbody>
</table>

Table D.4: Summary of Run5 dilution factors

<table>
<thead>
<tr>
<th>Bin $P_T$</th>
<th>$r$</th>
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</thead>
<tbody>
<tr>
<td>5 – 6</td>
<td>0.68</td>
</tr>
<tr>
<td>6 – 7</td>
<td>0.58</td>
</tr>
<tr>
<td>7 – 8</td>
<td>0.46</td>
</tr>
<tr>
<td>8 – 10</td>
<td>0.34</td>
</tr>
</tbody>
</table>