Accessing Gluon Polarization in the Proton with Direct Photons at PHENIX

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Abstract. Direct photon production in polarized pp collisions serves as an excellent probe of the spin structure of the proton. Gluon-quark scattering, \( g + q \rightarrow \gamma + q \), dominates direct photon production for p+p collisions. This channel is theoretically clean as it requires no fragmentation function for the photon. In addition, the double longitudinal asymmetry \( A_{LL} \) is directly proportional to the quark and gluon polarizations, giving access to both the magnitude and sign of the polarized gluon distribution since the polarized quark distributions are known from polarized DIS. The status of the direct photon cross section measurement and \( A_{LL} \) for center of mass energies 200 and 500 GeV at midrapidity (\( |\eta| < 0.35 \)) will be presented.

1. Introduction
The structure of the proton can be encoded in parton distribution functions (PDFs) which give the probability of finding a given parton (quark or gluon) with a given fraction of the proton’s momentum \( x_{Bj} \). These functions have been well measured in deep inelastic scattering (DIS) of leptons on protons. Further, the spin of the proton can be encoded in polarized PDFs which give the probability of finding a parton with its spin aligned or anti-aligned with the spin of the proton. The total spin of the proton can be written in the following heuristic way:

\[
S_P = 1/2 = 1/2\Delta\Sigma + \Delta G + L_Q + L_G
\]

where \( S_P \) is the spin of the proton, \( \Delta\Sigma \) is the total number of quarks with spin aligned with the proton’s minus those anti-aligned, \( \Delta G \) is the corresponding quantity for gluons, and \( L_Q \) and \( L_G \) are the orbital momentum contributions from quarks and gluons, respectively.

While leptons couple directly to quarks since they both carry electric charge, they do not couple directly to the gluons which are electrically neutral. One goal of the PHENIX spin program at the Relativistic Heavy Ion Collider (RHIC) is to measure the contribution of the gluon spin to the proton spin via polarized proton-proton collisions.

2. Direct Photon Production and the Double Longitudinal Spin Asymmetry \( A_{LL} \)
Direct photon production, in which a photon is produced by hard scattering of partons, in proton-proton collisions occurs through quark-gluon Compton scattering, \( g + q \rightarrow \gamma + q \), and quark-anti-quark annihilation, \( q + \bar{q} \rightarrow \gamma + g \). The quark gluon Compton scattering process dominates in proton-proton collisions giving direct access to the gluon distribution in the proton.
Polarized PDFs are measured through asymmetries in polarized proton collisions at PHENIX. The double longitudinal asymmetry $A_{LL}$ is given by the difference in cross sections when the colliding protons have like and unlike polarization.

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\Delta\sigma}{\sigma} \tag{2}$$

The superscript ++ refers to collisions where the proton helicities (defined in the lab center of mass frame) are the same, and the superscript +- refers to when they are not the same. The experimentally measured quantity is

$$A_{LL} = \frac{1}{P_Y P_B} \frac{N^{++} - R N^{+-}}{N^{++} + R N^{+-}} \tag{3}$$

where $P_Y$ and $P_B$ are the polarization of the proton beams at RHIC, $N$ is the yield of direct photons, and $R$ is the ratio of the luminosity in like polarized collisions to that in unlike polarized collisions.

Parton distribution functions can be extracted from experimental data through the use of factorization. Factorization allows the separation of the hadronic cross section into a convolution over a partonic cross section, $\hat{\sigma}$, calculable in perturbative Quantum Chromodynamics (pQCD) and the PDFs which describe the non-perturbative distribution of partons in the proton. Thus, the cross section for the semi-inclusive production of a particle $C$ with unmeasured $X$, $p_A + p_B \rightarrow C + X$, is written as

$$d\sigma_{p_A p_B \rightarrow C X} = \sum_{abc} dx_a dx_b dz_c f^A_a(x_a) f^B_b(x_b) d\hat{\sigma}^{ab-c} D^c_C(z_c) \tag{4}$$

Uppercase letter refer to hadrons and lowercase letter refer to partons. The functions $f^A_a$ and $f^B_b$ are the PDFs for the incoming protons for parton types $a$ and $b$, and the function $D^c_C$ is the fragmentation function which describes the probability for a parton of type $c$ to produce a hadron of type $C$ with a fraction $z$ of the parton’s momentum. Dependencies on energy scales have been suppressed. In order to obtain information on the polarized PDFs, $\Delta f$, through $A_{LL}$ measurements it must be shown that pQCD is applicable. This is done by comparing pQCD predictions to the measured cross section.

Since photons do not fragment into hadrons and are directly observed, the fragmentation function can be set to unity. The direct photon channel is not subject to uncertainties in the non-perturbative process of fragmentation as are other channels where hadrons are observed. Also, since the quark-gluon Compton process couples a quark to a gluon, direct photons are sensitive to both the magnitude and the sign of the polarized gluon distribution.

### 3. Statistical Subtraction Method

Photons are measured with the electromagnetic calorimeter at midrapidity ($|\eta| < 0.35$). The main challenge is to remove the copious background of decay photons from $\pi^0$, $\eta$, and other mesons, of which $\pi^0$s dominate at about 80%. The statistical subtraction method defines a sample of candidate direct photons $N_{incl}$ and subtracts the decay photon component. The inclusive sample contains all energy clusters that fire the high $p_T$ trigger, are not associated with a charged track in the tracking system, and pass a shower shape cut which rejects neutral hadron backgrounds. Candidate direct photons are not accepted in hot or dead towers of the electromagnetic calorimeter.

The invariant mass spectrum of di-photons is produced by matching candidate photons with all other clusters in the event. The number of $\pi^0$s is measured by fitting its mass peak with
a Gaussian plus a second order polynomial to describe the combinatorial background. The number of tagged π0's in the sample, \( N_{\pi^0} \), is given by the number of candidate direct photons reconstructed to the \( \pi^0 \) mass range of 105-165 MeV minus the integral of the background polynomial in the same range. Some \( \pi^0 \) contamination remains due to partner decay photons hitting outside of the acceptance or in masked regions of the electromagnetic calorimeter. This contribution is estimated in simulation using the PHENIX measured \( \pi^0 \) spectrum and is given by the miss ratio \( R \). Contributions from heavier mesons such as the \( \eta \) are also estimated in simulation as a ratio \( A \) to the number of \( \pi^0 \) s.

The yield of direct photons, \( N_{dir\gamma} \), is then

\[
N_{dir\gamma} = N_{incl} - (1 + R)(1 + A)N_{\pi^0} \tag{5}
\]

4. Isolated Photon Method

Midrapidity photons originating from hard scattering exit nearly back-to-back with the outgoing parton. The sample of direct photons can be purified by requiring the candidate photons to have minimal charged track momentum and energy deposited in the calorimeter in a cone surrounding them. The requirement is

\[
0.1 \times E_\gamma > \sum E_{\text{neutral}} + \sum P_{\text{charged}} \tag{6}
\]

where \( E_\gamma \) is the energy of the candidate photon and the sums are over all neutral energy and charged track momenta measured in a 0.5 radian cone around the candidate. Photonic meson decays still contribute to the sample in two ways. Asymmetric decays of \( \pi^0 \)s, where the partner photon is below the threshold for the isolation cut, can be directly subtracted off. They are measured by forming invariant mass spectra of candidate isolated photons with all clusters and counting the number, \( n_{\pi^0}^{\text{asym}} \), that are in the 105-165 MeV mass region. The combinatorial background for these decays is negligible.

Decays of \( \pi^0 \)s in which the partner photon falls out of the acceptance or into a masked calorimeter region constitute another background. These are estimated by first creating an isolated \( \pi^0 \) sample. The yield, \( N_{\pi^0}^{\text{iso}} \), is measured by first forming the invariant mass of photon pairs that satisfy

\[
0.1 \times E_\gamma > \sum E_{\text{neutral}} + \sum P_{\text{charged}} - E_{\text{pair}} \tag{7}
\]

where \( E_{\text{pair}} \) is the energy of the cluster paired with the isolated photon candidate. Pairs reconstructing to the \( \pi^0 \) mass range are then removed from the sample as the combinatorial background is again very small. The miss ratio remains the same, but the heavy meson ratio must be corrected for the larger probability of the decay photons falling outside the isolation cone due to their wider opening angle. The isolated direct photon yield \( N_{dir\gamma} \) is then

\[
N_{dir\gamma}^{\text{iso}} = N_{incl}^{\text{iso}} - (n_{\pi^0}^{\text{asym}} + RN_{\pi^0}^{\text{iso}}) - A^{\text{iso}}(1 + R)N_{\pi^0}^{\text{iso}} \tag{8}
\]

where \( A^{\text{iso}} \) is the isolated heavy meson ratio.

5. Direct Photon Cross Section and \( A_{LL}(dir\gamma) \)

The cross section for direct photon production at \( \sqrt{s} = 200 \) GeV, after correcting the yield for efficiencies, acceptance, and energy smearing, is shown for the statistical subtraction and isolated photon methods in figure 1 as a function of \( p_T \). As discussed above, the agreement of the cross section with pQCD predictions allows for the extraction of the polarized gluon distribution.

The asymmetry \( A_{LL} \) is calculated by equation 3. Isolated \( \pi^0 \) decays in which the partner photon is missed constitute an irreducible background. The direct photon asymmetry is calculated as

\[
A_{LL}(dir\gamma) = \frac{A_{LL}(N_{incl}^{\text{iso}} - n_{\pi^0}^{\text{asym}}) - rA_{LL}(RN_{\pi^0}^{\text{iso}})}{1 - r} \tag{9}
\]

where \( r = \frac{RN_{\pi^0}^{\text{iso}}}{N_{incl}^{\text{iso}} - n_{\pi^0}^{\text{asym}}} \) is the dilution factor. Results from the 2006 run are shown in figure 2.
Figure 1. Direct photon cross section from the statistical subtraction method on the left and the isolated photon method on the right.

Figure 2. The direct photon double longitudinal asymmetry compared to theory predictions for various values of $\Delta G$.

6. Results Summary
The $A_{LL}(\text{dir}\gamma)$ measurement is currently statistics limited and does not yet provide a direct constraint. The 2009 polarized proton run at RHIC at $\sqrt{s} = 200$ GeV doubled the delivered luminosity of the 2006 run. The 2009 run also included collisions at $\sqrt{s} = 500$ GeV which pushes the probed $x_{Bj}$ range to lower values. Further running at $\sqrt{s} = 500$ GeV will take place during the 2011 run. These data sets will improve the direct photon constraint on the polarized gluon distribution both directly and via inclusion in a global analysis of world data on polarized scattering experiments.