PROCEEDINGS OF SCIENCE

Measurement of Direct-Photon Cross Section and Double-Helicity Asymmetry at $\sqrt{s}$ = 510 GeV in $\vec{p} + \vec{p}$ Collisions at PHENIX

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Longitudinal polarized $\vec{p} + \vec{p}$ collisions provide a leading-order probe of the gluon spin contributions to the proton spin. The direct-photon production is named the "golden" channel due to its "cleanliness" and sensitivity to the sign of the gluon spin. The PHENIX measurement at the Relativistic Heavy-Ion Collider performed the first published direct-photon double-helicity asymmetry (A_{LL}) measurement. Our data indicate the gluon spin has a large probability of aligning with the proton spin. I will show the direct-photon cross sections and A_{LL} measurements at PHENIX.

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1. Introduction

Understanding the quarks' and gluons' contributions to the proton spin provides important information for its structure. According to [1], the proton spin can be decomposed as

$$\frac{1}{2} = \frac{1}{2}\Delta q + \Delta g + L_q + L_g, \tag{1}$$

where $\frac{1}{2}\Delta q$ and Δg are spin contributions from quarks and gluons, respectively, L_q and L_g are their orbital momentum contributions.

Since the late 80s, the European Muon Collaboration (EMC) discovered that only about 30% of the proton spin comes from the quarks' spin [2, 3]. The remaining part comes from the gluon spin and partons' orbital angular momentum. Various deep-inelastic scattering (DIS) experiments provide constraints on the Δq [4]. However, constraints on the Δg are poor since gluons do not have an electric charge and only interact through a higher-order effect in DIS.

At the Relativistic Heavy-Ion Collider (RHIC), we collide two longitudinal polarized proton beams ($\vec{p} + \vec{p}$) and measure the double-helicity asymmetries (A_{LL}) of final-state particles. These measurements probe the Δg at the leading order in the perturbative quantum chromodynamics (pQCD). The existing RHIC data mainly probe the gluon momentum fraction x_g from 0.05 to 0.2. The PHENIX π^0 A_{LL} at $\sqrt{s} = 510$ GeV confirms a nonzero Δg and extend x_g to 0.01 [5]. The STAR jet data clearly imply a polarization of gluons in this range [6]. However, the existing inclusive DIS data and jet A_{LL} measurements in polarized $\vec{p} + \vec{p}$ collisions cannot decide the sign of Δg. Unlike jet production, where both quark-gluon and gluon-gluon scatterings contribute, direct photon production mainly gets contributions from quark-gluon scattering and is sensitive to the sign of Δg. In addition, there is little fragmentation contribution involved in direct photon production, making this the "cleanest" channel and thus designated the "golden" channel for gluon parton distribution functions (PDF). However, direct-photon measurement is very challenging due to limited statistics and large backgrounds from π^0 decay photons [7, 8]. These obstacles were overcome by the PHENIX detector at the 2013 year run of RHIC. which provide the largest integrated luminosity (155 pb^{-1}) in polarized $\vec{p} + \vec{p}$ collisions. The Electromagnetic Calorimeter (EMCal) at PHENIX has a fine angular resolution and is capable of separating the π^0 decay photons up to transverse momentum (p_T) of 30 GeV/c with a shower-profile analysis. I will show the measurement of direct-photon cross section and double-helicity asymmetry (A_{LL}) and its role in deciding the sign of Δg.

2. PHENIX detector

The PHENIX detector is shown in Fig. 1 [9]. The Beam-Beam Counters (BBC) [10] served as the minimum-bias trigger and the luminosity counter, which are located at ±144 cm from the beam interaction point (IP) with a pseudorapidity coverage $3.0 < |\eta| < 3.9$. The primary detector for the photon measurement is the EMCal [11], which covers $|\eta| < 0.35$ and π radians in azimuthal angle. EMCal also includes high-energy photon triggers. The Drift Chamber (DC) [12] measures charged particles and is used to veto an EMCal cluster if it is too close to a track in DC. DC is also used in the isolated direct-photon measurement to measure the other particles' energy near the signal photon.

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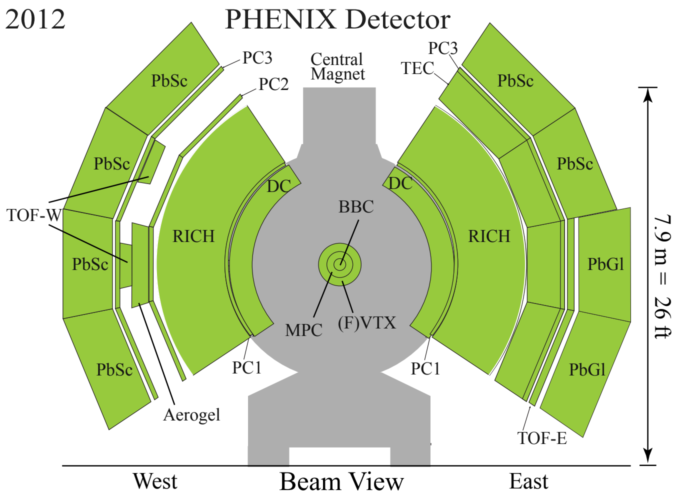


Figure 1: The PHENIX detector.

3. Direct-photon cross sections

The PHENIX experiment measured the direct-photon cross section in p+p collisions at $\sqrt{s}$ = 510 GeV. Most direct photons at 6 GeV/c $< p_T <$ 30 GeV/c are produced by quark-gluon Compton scatterings, $q + g \rightarrow q + \gamma$. A small portion comes from the $q\bar{q}$ annihilation, $q + \bar{q} \rightarrow g + \gamma$. For the PHENIX measurements, the main backgrounds are from the hadron decay photons, among which most are $\pi^0 \rightarrow \gamma\gamma$ decays, but there are also decay photons from η, ω, and η' mesons. The π^0 decay photons can be reconstructed by the two-photon invariant mass. There is a chance that we missed one of the π^0 decay photons but measured the other, we used simulations to estimate the portion of this situation. The number of decay photons from other mesons is estimated by their ratios with π^0 decay photons, which are obtained from previous 200 GeV p+p data and simulations. The number of direct photons is thus the number of total photons subtracting the number of decay photons. To improve the signal-to-background ratio, in addition to the inclusive direct-photon measurement, we also applied isolation criteria, which require the sum of energy from other particle inside a cone with radius $r_{\text{cone}} = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} = 0.5$ is less than 10% of the energy of the photon candidate, i.e. $\sum E_{\text{in cone}} < 0.1 E_\gamma$ (Fig. 2). In this way, we reduced the contributions from decay and fragmentation photons.

We measured the inclusive and isolated direct-photon cross sections [13] (Fig. 3) and the ratio of isolated over inclusive cross sections (Fig. 4a). The next-to-leading order (NLO) pQCD calculation [14, 15] agrees well with the isolated direct-photon cross section but underestimates the inclusive cross section and overestimates their ratio. The POWHEG + PYTHIA8 calculation [16–18] agrees better with data than the NLO pQCD for the inclusive cross section due to the inclusion of parton showers. Without multiparton interactions (MPI), it gives a similar prediction as the NLO pQCD calculations for the ratio. The POWHEG + PYTHIA8 calculation with MPI agrees best with our measurements for the ratio of cross sections.

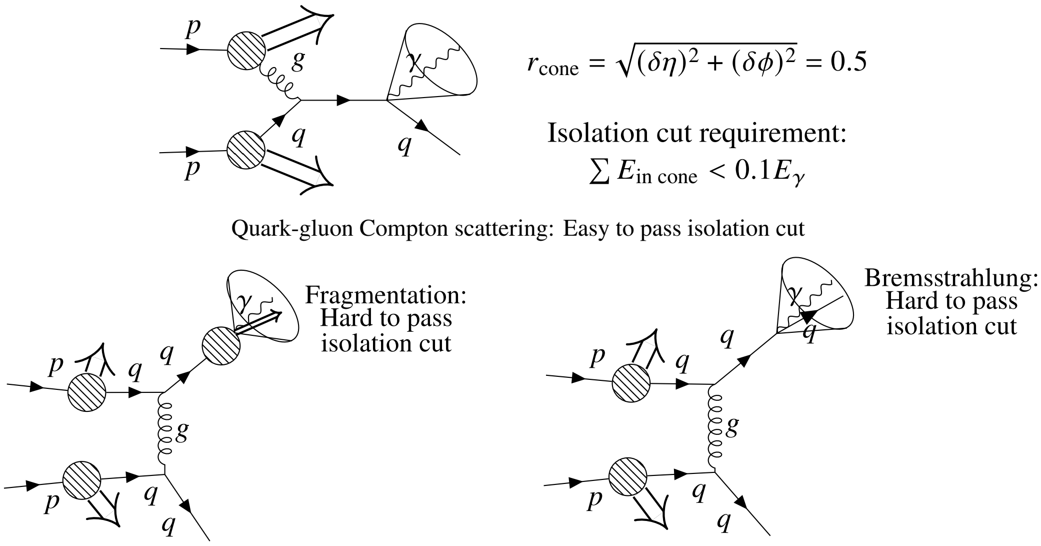


Figure 2: Isolation criteria on a photon candidate.

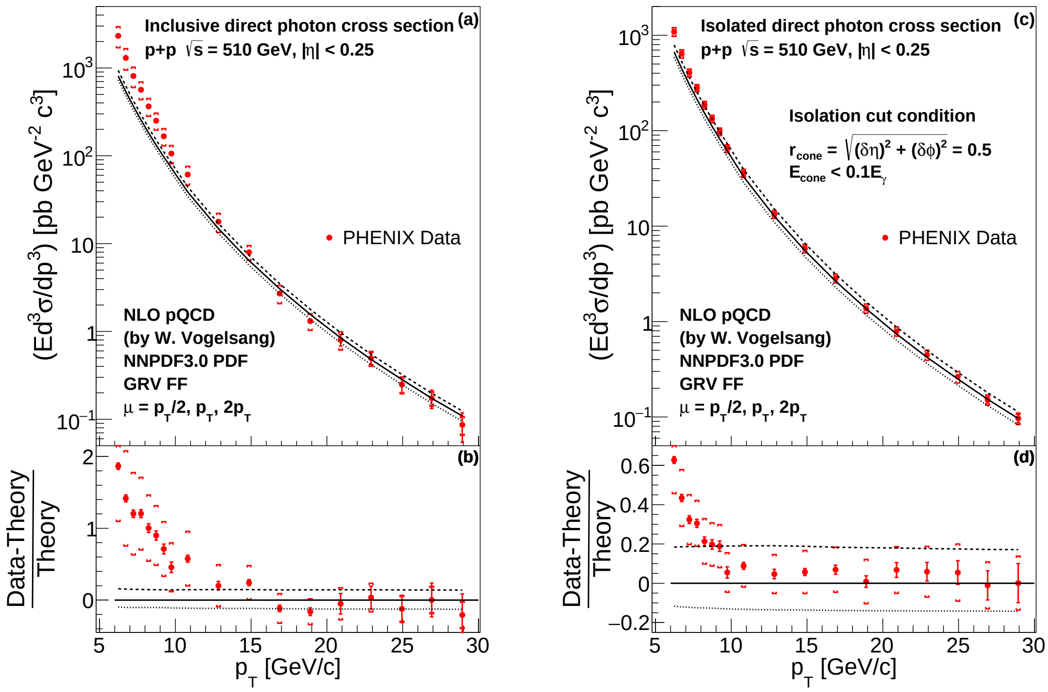
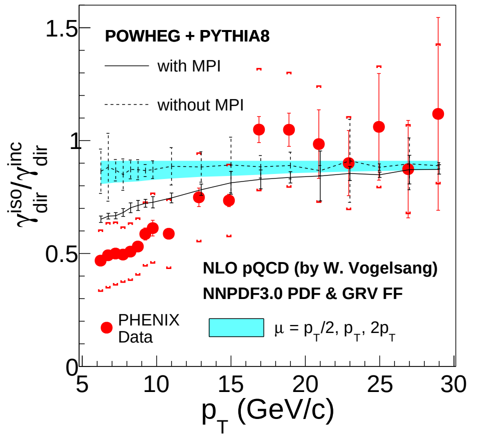
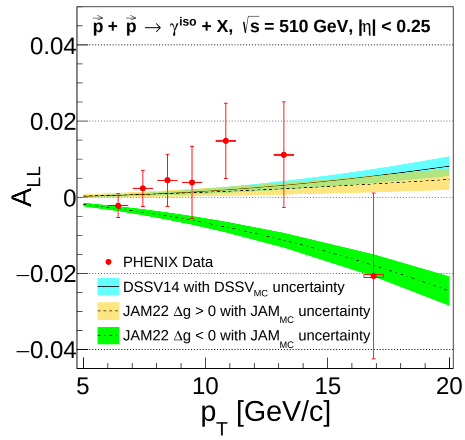


Figure 3: Cross sections for (a) inclusive and (c) isolated direct photons as a function of p_T compared with NLO pQCD calculations [14, 15] for different renormalization and factorization scales $\mu = p_T/2$ (dashed line), p_T (solid line), $2p_T$ (dotted line). The vertical bars show statistical uncertainties and the square brackets are for systematic uncertainties. Not shown are 10% absolute luminosity uncertainties. Panels (b) and (d) show comparisons of data and calculations.



(a) Ratio of isolated over inclusive direct-photon cross sections. The band is from the NLO pQCD calculations as in Fig. 3. The solid and dotted lines are from the POWHEG + PYTHIA8 with and without the MPI configuration, respectively.



(b) Double-helicity asymmetry A_{LL} *vs* p_T for isolated direct-photon production. Vertical error bars (boxes) represent the statistical (systematic) uncertainties. Not shown is a $3.9{\times}10^{-4}$ shift uncertainty from relative luminosity and a 6.6% scale uncertainty from polarization. The DSSV14 and JAM22 calculations are shown with 1σ uncertainty bands obtained from MC replicas [19–23]. JAM22 calculations are based on PDF sets from the global analysis of the JAM Collaboration [23], and the code to calculate the asymmetries was provided by W. Vogelsang.

Figure 4: Ratio of cross sections and A_{LL}.

4. Isolated direct-photon A_{LL}

The A_{LL} can be calculated by

$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_B P_Y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}, \tag{2}$$

where the ++ and +− signs represent the same and opposite helicities of the beam, respectively. σ means the cross section and N is the yield. $R = L_{++}/L_{+-}$ is the relative luminosity with L_{++} and L_{+-} represent the luminosity of the corresponding beam helicities. $P_B \approx 0.55$ and $P_Y \approx 0.57$ are the blue and yellow beam polarizations at RHIC, respectively [24]. We measured the total photon A_{LL}^{total}, the isolated π^0 decay photon $A_{LL}^{\pi^0}$ and its fraction in total photons r_{π^0}, and the isolated other hadron decay photon A_{LL}^{h} and their fraction r_h. The isolated direct photon A_{LL} is calculated by

$$A_{LL}^{\text{dir}} = \frac{A_{LL}^{\text{total}} - r_{\pi^0} A_{LL}^{\pi^0} - r_h A_{LL}^{h}}{1 - r_{\pi^0} - r_h}. \tag{3}$$

Fig. 4b shows the isolated direct-photon A_{LL} in polarized $\vec{p} + \vec{p}$ collisions at $\sqrt{s} = 510$ GeV [13]. The Jefferson Lab Angular Momentum (JAM) Collaboration found there are two possible solutions for the polarized gluon parton distribution functions (PDF) with $\Delta g > 0$ and $\Delta g < 0$

[22, 23]. Even though the $\Delta g < 0$ solution violates the positivity assumption, $|\Delta g| < g$, previous data from jet A_{LL}'s and inclusive DIS cannot exclude those solutions due to the mixed contributions from quark-gluon and gluon-gluon interactions. However, the direct-photon A_{LL} comes mainly from the quark-gluon interactions and has $\chi^2 = 4.7$ and 12.6 for 7 data points for the $\Delta g > 0$ and $\Delta g < 0$ solutions, respectively, with the difference of 7.9 between χ^2 values implying that the negative solution is disfavored at more than 2.8σ level.

5. Conclusions

We present the inclusive and isolated direct-photon cross sections and the isolated direct-photon A_{LL} in polarized $\vec{p}+\vec{p}$ collisions at $\sqrt{s} = 510$ GeV. The measurement of inclusive and isolated cross sections and their ratios shows the importance of including parton shower and MPI in the relatively low p_T range. The A_{LL} result is the first published direct-photon A_{LL} measurement and provides a "clean" probe of the gluon spin Δg. Our data agree with the positive Δg solutions and disfavor the negative Δg solutions by 2.8σ.

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