



sPHENIX Conference Note

Transverse Single-Spin Asymmetry in Isolated Photon Production in $\sqrt{s} = 200$ GeV $p^\uparrow + p$ Collisions with sPHENIX

sPHENIX Collaboration

Abstract

Isolated photon transverse single-spin asymmetries, A_N , provide a clean probe of spin-momentum correlations in the proton, because photons are insensitive to strong final-state effects. The dominant hard-scattering channel at the Relativistic Heavy Ion Collider (RHIC) energies is quark-gluon Compton scattering. As a result, isolated photons are sensitive to both quark-gluon-quark and tri-gluon correlation functions. This conference note presents the sPHENIX measurement of A_N in isolated photon production in $\sqrt{s} = 200$ GeV transversely polarized $p + p$ collisions with an integrated luminosity of approximately 58 pb^{-1} and an average beam polarization of approximately 52% (7% relative systematic uncertainty). The polarization uncertainty contributes a common scale uncertainty to A_N . Photon candidates are reconstructed with the Electromagnetic Calorimeter (EMCal). An isolation requirement is applied using both electromagnetic and hadronic calorimeter information. The asymmetry is reported for the transverse energy range $5 < E_T^\gamma < 30$ GeV and the pseudorapidity range $|\eta| < 0.7$.

1 Introduction

The transverse single-spin asymmetry A_N probes spin-momentum correlations in the proton. The photon A_N quantifies the asymmetry of the yield of photons moving to the left versus the right of the polarized proton spin. At the Relativistic Heavy Ion Collider (RHIC) [1] energies, direct-photon production is dominated by the quark-gluon Compton process $qg \rightarrow \gamma q$ [2], providing sensitivity to both the quark and gluon distributions within the polarized proton. Because photons in general do not participate in strong interactions, photon production provides a relatively clean probe of initial-state spin-dependent effects.

Prompt photons include photons produced either directly from parton-parton scattering, so-called direct photons, or from the collinear fragmentation of a final-state parton, so-called fragmentation photons. In experimental measurements, a major background arises from photons produced in hadron decays. This background, as well as part of the fragmentation-photon contribution, can be reduced by applying an isolation requirement. The isolation requirement selects photon candidates with a small amount of transverse energy deposited around the photon within a cone defined in azimuthal angle (ϕ) and pseudorapidity (η). In this note, photon candidates passing this requirement are referred to as isolated photons.

Large transverse single-spin asymmetries have long been observed in hadron production off transversely polarized nucleons or nuclei, from fixed-target energies to RHIC energies [3, 4, 5]. Their interpretation has motivated theoretical descriptions based on transverse momentum-dependent effects such as the Sivers and Collins mechanisms [6, 7], as well as the collinear twist-3 framework for multi-parton correlations [8, 9]. These approaches are related in the appropriate kinematic limits [10, 11]. In this context, isolated photons are particularly valuable because they provide direct sensitivity to initial-state spin-transverse momentum correlations.

The first isolated photon A_N was measured by the E704 experiment at Fermilab, with a 200 GeV polarized proton beam on an unpolarized proton target [12]. Previously, the PHENIX collaboration measured the isolated photon A_N in $p^\uparrow + p$ collisions at RHIC with $\sqrt{s} = 200$ GeV [13].

This note presents the sPHENIX measurement of A_N for isolated photons in $p^\uparrow + p$ collisions at $\sqrt{s} = 200$ GeV over the range $5 < E_T^\gamma < 30$ GeV and $|\eta| < 0.7$.

2 sPHENIX Detector

sPHENIX [14] is designed to measure jets, heavy-flavor probes, and direct photons created in $p + p$ and Au+Au collisions at RHIC. A precision tracking system enables measurements of heavy-flavor and jet substructure observables, while the electromagnetic and hadronic calorimeter system is crucial for measuring the energy of jets and identifying direct photons and electrons.

Going outwards starting from the beam line, sPHENIX comprises the following subsystems [15]: the MAPS-based Vertex Detector (MVTX); the INTermediate Tracker (INTT) [16, 17]; the Time Projection Chamber (TPC) [18]; the Time Projection Chamber Outer Tracker (TPOT) [19]; the Electromagnetic Calorimeter (EMCal) [20, 21]; the Inner Hadronic Calorimeter (IHCAL) [21]; the 1.4 T superconducting solenoid magnet [22] and the Outer Hadronic Calorimeter (OHCAL) [21]. Except for TPOT, all detectors have full azimuthal coverage and span $|\eta| < 1.1$ in pseudorapidity.

sPHENIX also includes a number of forward detectors, namely the Minimum Bias Detectors (MBD) which previously served as the PHENIX Beam-Beam Counters [23, 24], the sPHENIX Event Plane Detectors (sEPD), and the Zero Degree Calorimeters (ZDC) which include the Shower Maximum Detector (SMD).

sPHENIX began its commissioning process in RHIC Run-2023 with Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. During RHIC Run-2024, sPHENIX collected a large sample of polarized $p + p$ physics data at $\sqrt{s} = 200$ GeV, along with a smaller sample of Au+Au data to complete its commissioning phase in that collision system. Additional polarized $p + p$ data at $\sqrt{s} = 200$ GeV were collected during RHIC Run-2025 and are available for future analyses.

3 Data and Event Selection

For this analysis, the EMCal is used to reconstruct photon clusters, the IHCAL and OHCAL are used in the isolation-energy calculation, and the MBD is used for the primary-vertex measurement and luminosity monitoring. The photon fiducial acceptance is restricted to $|\eta| < 0.7$ so that the full isolation cone with $R = 0.4$ remains inside the detector acceptance. The data used in this analysis were collected during the RHIC Run-2024, when transversely polarized proton beams at a center-of-mass energy of $\sqrt{s} = 200$ GeV were collided. The average transverse polarizations of both beams were approximately 52%. The approximate integrated luminosity used in this analysis is 58 pb^{-1} . Events are required to satisfy a photon trigger and to have a reconstructed primary vertex within $|z_{\text{vtx}}| < 60$ cm, where the vertex position is measured with the MBD.

Monte Carlo samples are used to optimize the photon identification, study the calorimeter shower-shape observables, and validate the photon purity estimate. The simulated events are generated with PYTHIA8 [25] using the Detroit tune [26] and reconstructed with a GEANT4-based simulation [27] of the sPHENIX detector. Inclusive jet samples, including photons from neutral-meson decays, are used to optimize the photon identification and sideband requirements and are referred to as inclusive MC. Prompt-photon samples are generated using both direct-photon and fragmentation-photon production channels and are referred to as signal MC. Photon filters select events containing photons in the relevant kinematic region.

4 Analysis Procedure

4.1 Photon Reconstruction and Identification

Photon candidates are reconstructed by clustering EMCal towers. A major source of photon background arises from neutral-meson decays, such as $\pi^0/\eta \rightarrow \gamma\gamma$. At lower transverse momentum, the two photons from neutral-meson decays are often reconstructed as separate EMCal clusters. A meson-tagging veto is applied to reject such resolved decay-photon candidates by pairing each photon candidate with other clusters in the same event and rejecting candidates that form an invariant mass within the π^0 mass window $0.1 \leq m_{\gamma\gamma} \leq 0.2 \text{ GeV}/c^2$ or the η mass window $0.45 \leq m_{\gamma\gamma} \leq 0.65 \text{ GeV}/c^2$. The partner cluster must have energy above 0.5 GeV for both mesons. At higher transverse momentum, the opening angle between the two photons from a meson decay

decreases, causing the decay photons to be reconstructed as a single merged EMCal cluster. These merged clusters exhibit broader shower shapes than those of single photons, providing effective discrimination between isolated photon candidates and merged-photon backgrounds.

The photon identification, denoted as γ^{ID} , is therefore optimized with a boosted decision tree (BDT). The BDT uses variables characterizing the EMCal cluster kinematics, event vertex, and calorimeter shower shape. The input variables used in the BDT training are summarized in Table 1. The training prescription and input variables follow the sPHENIX isolated-photon cross-section analysis [28, 29], with additional low- E_T samples lowering the minimum training E_T from 6 to 3 GeV. The training range for this analysis is $3 < E_T < 35$ GeV. Signal candidates are clusters matched to truth-level direct or fragmentation photons in signal MC. Background candidates are clusters in inclusive MC after truth-matched direct and fragmentation photons are removed.

Table 1: Input variables used in the photon-identification BDT training.

Variable	Description
E_T	Transverse energy of the EMCal cluster.
η	Pseudorapidity of the EMCal cluster.
z_{vtx}	Primary-vertex position along the beam axis.
$w_{\eta(\phi)}^{\text{COGX}}$	Energy-weighted second moment in η (ϕ), excluding the tower containing the cluster center of gravity.
$E_{1 \times 1} / E_{3 \times 3}$	Ratio of the central-tower energy to that in the surrounding 3×3 tower region.
$E_{3 \times 2} / E_{3 \times 5}$	Ratio of the energy in the 3×2 tower region to that in the 3×5 tower region.
E_{t1}	$(E_1 + E_2 + E_3 + E_4) / E_{\text{tot}}$, the fraction of cluster energy in the 2×2 block around the center of gravity.
E_{t2}	$(E_1 + E_2 - E_3 - E_4) / E_{\text{tot}}$, an η -direction energy-asymmetry observable.
E_{t3}	$(E_1 - E_2 - E_3 + E_4) / E_{\text{tot}}$, a ϕ -direction energy-asymmetry observable.
E_{t4}	E_3 / E_{tot} , the diagonal-corner tower fraction.

After shower-shape preselection, the trained BDT model is applied to data, and each cluster is assigned a shower-shape BDT score, S_{BDT} , with larger values being more signal-like and smaller values being more background-like. The nominal photon sample is defined by a tight γ^{ID} requirement,

$$S_{\text{BDT}} > 0.8156 - 0.00156 \cdot E_T^\gamma. \quad (1)$$

A non-tight γ^{ID} control region is defined by

$$0.7333 - 0.01333 \cdot E_T^\gamma < S_{\text{BDT}} < 0.6844 + 0.00156 \cdot E_T^\gamma, \quad (2)$$

where E_T^γ is expressed in GeV. This region is used to estimate the remaining background contribution described in Sec. 4.2.

To further suppress background photons, primarily from neutral-meson decays, the isolation energy is computed from EMCal, IHCAL, and OHCAL topological clusters inside an $R = 0.4$ cone,

$$E_T^{\text{iso}} = \sum_{\Delta R < 0.4} E_{T,i} - E_T^{\text{cluster}}, \quad (3)$$

where $E_{T,i}$ is the transverse energy of topological cluster i , E_T^{cluster} is the transverse energy of the photon candidate cluster, and the sum runs over topological clusters passing the standard quality selection inside the isolation cone. The same E_T^γ -dependent isolation requirement used in the sPHENIX isolated-photon cross-section measurement [28] is applied here,

$$E_T^{\text{iso}} < 0.490 \text{ GeV} + 0.037 \cdot E_T^\gamma, \quad (4)$$

with a gap separating the isolated and non-isolated control regions. The BDT-based photon identification and the isolation requirement define the isolated photon candidate sample used for the asymmetry measurement.

4.2 Photon Purity and Background Estimation

Even after the tight photon-identification, isolation, and meson-tagging veto requirements, a residual background contribution remains. The photon purity is estimated using two complementary methods: a tagging-based method following the PHENIX direct-photon measurements [30, 13] and a leakage-corrected double-sideband method used in the sPHENIX isolated-photon cross-section measurement [28]. The latter assumes approximate independence between the shower-shape and isolation selections for background clusters. At low E_T^γ , the larger opening angles of π^0 decays can introduce correlations between these selections, limiting the applicability of this assumption. Therefore, the tagging-based method is used in the 5–6 and 6–8 GeV bins, while the double-sideband method is used at and above 8 GeV. In the intermediate region, $8 \leq E_T < 10$ GeV, the two purity estimation methods are found to agree with each other.

The tagging-based method estimates the untagged π^0 and η contributions. For each meson species h , inclusive MC provides the ratio

$$R_h = \frac{N_{\text{miss}}^h}{N_{\text{tag}}^h}, \quad h \in \{\pi^0, \eta\}. \quad (5)$$

Here N_{miss}^h counts selected truth- h decay candidates remaining after the tagging veto, and N_{tag}^h counts tagged truth- h decay candidates. For tagged candidates, isolation is evaluated after excluding the partner photon from the isolation energy.

The purity is estimated from the corresponding data counts as

$$P = 1 - \frac{R_{\pi^0} N_{\pi^0, \text{tag}}^{\text{data}} + R_\eta N_{\eta, \text{tag}}^{\text{data}}}{N_A}. \quad (6)$$

Here N_A is the isolated tight-candidate yield after the meson veto, and $N_{h, \text{tag}}^{\text{data}}$ is the corresponding pair-isolated mass-window tag yield measured in data.

In the double-sideband method, two observables define the sidebands: the shower-shape BDT and the isolation energy. Four regions are then formed: Region A (tight, isolated), Region B (tight, non-isolated), Region C (non-tight, isolated), and Region D (non-tight, non-isolated). The tight and non-tight categories are defined from the shower-shape BDT score assigned to each cluster. Region A is the signal-enriched region, while Regions B, C, and D are used to estimate the background contamination, as illustrated in Fig. 1.

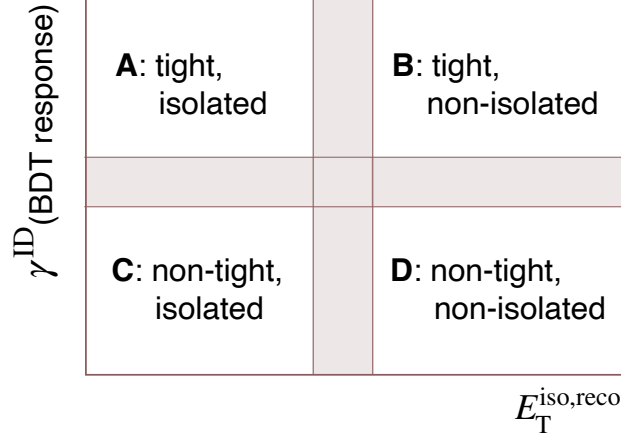


Figure 1: Schematic illustration of the double-sideband method in the plane of photon-identification and isolation selections. Region A is the signal-enriched region, while Regions B, C, and D are used to estimate the residual background contribution. Figure adapted from Ref. [29].

Under the background-factorization assumption introduced above, the background transfer factor from Region C to Region A is the same as that from Region D to Region B, so the background yield in Region A can be estimated as $N_B N_C / N_D$ in the absence of signal leakage. Signal MC provides the leakage fractions $f_X = N_{X,\text{sig}} / N_{A,\text{sig}}$ for $X = B, C, D$. The signal yield in Region A is obtained by solving

$$N_{\text{sig}}^A = N_A - \frac{(N_B - f_B N_{\text{sig}}^A)(N_C - f_C N_{\text{sig}}^A)}{N_D - f_D N_{\text{sig}}^A}, \quad (7)$$

where N_X denotes the number of photon candidates in Region X, and N_{sig}^A is the signal yield in the nominal signal region. The corresponding purity is

$$P = \frac{N_{\text{sig}}^A}{N_A}. \quad (8)$$

Since the double-sideband estimate relies on the candidate yields in the background control regions as well as in the signal region, an additional selection is applied to suppress beam-induced non-collision background (NCB) using the BDT classifier described in Ref. [28]. The classifier distinguishes collision-produced clusters from beam-induced backgrounds using their shower shapes and kinematics. For $E_T^\gamma \geq 8$ GeV, clusters are required to have an NCB BDT score greater than 0.5. No additional NCB selection is applied below 8 GeV.

Figure 2 shows the data-driven photon purity obtained with the tagging method below 8 GeV and the leakage-corrected double-sideband method at and above 8 GeV.

Simulation studies indicate that the residual background at low E_T^γ is dominated by photons from π^0 decays with a missing partner. In asymmetric decays, the lower-energy photon may fall below the tagging threshold or fail to form a reconstructed cluster, while the higher-energy photon produces a shower similar to that of a prompt photon. These configurations can survive both photon identification and isolation. Even when a partner cluster is reconstructed, the pair can escape tagging if its reconstructed invariant mass lies outside the tagging window. Lowering the

partner-energy threshold or widening the mass window improves background rejection, but also increases accidental tagging of prompt photons, limiting the benefit of these changes.

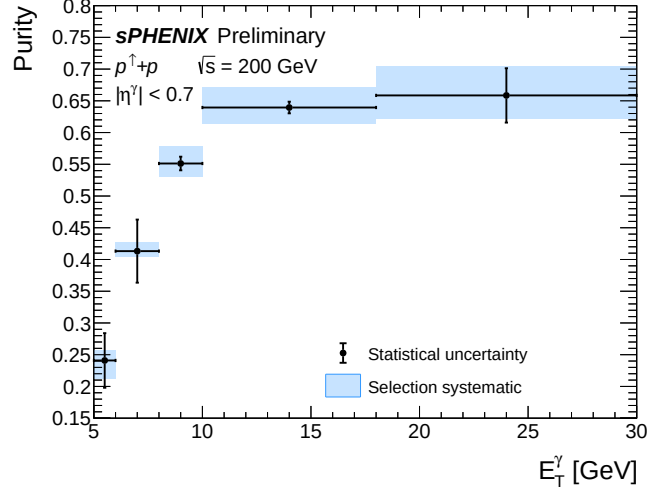


Figure 2: Data-driven photon purity in the signal region, using the tagging method below 8 GeV and the leakage-corrected double-sideband method at and above 8 GeV. Error bars include statistical uncertainties from data and simulation. The shaded band shows the systematic uncertainty from variations of the photon-identification, isolation, sideband, and tagging mass-window selections.

4.3 Asymmetry Extraction

The isolated photon asymmetry is then extracted from the yields in each spin state and azimuthal bin. The purity P is obtained with the procedure described above. The measurement uses five E_T^γ bins: 5–6, 6–8, 8–10, 10–18, and 18–30 GeV.

The spin-up and spin-down yields are first combined with the relative-luminosity correction,

$$A(\phi) = \frac{N^\uparrow(\phi) - R N^\downarrow(\phi)}{N^\uparrow(\phi) + R N^\downarrow(\phi)}, \quad R = \frac{L^\uparrow}{L^\downarrow}. \quad (9)$$

Here $N^\uparrow(\phi)$ and $N^\downarrow(\phi)$ are the spin-up and spin-down yields in a given azimuthal angle ϕ relative to the spin axis, and R is the relative luminosity defined from the corresponding spin-dependent integrated luminosities $L^\uparrow$ and $L^\downarrow$. RHIC collides two independently polarized proton beams, commonly referred to as the clockwise and counterclockwise beams. The asymmetry is therefore extracted separately for each beam. When one beam is used as the polarized beam of interest, the spin states of the other beam are averaged over. This gives two measurements of the same physics asymmetry, one from each beam, which are found to be consistent. The two measurements are then combined after applying the polarization correction.

An alternative and robust estimator of the asymmetry is provided by the square-root (geometric-

mean) formula,

$$A(\phi) = \frac{\sqrt{N^\uparrow(\phi) N^\downarrow(\phi + \pi)} - \sqrt{N^\downarrow(\phi) N^\uparrow(\phi + \pi)}}{\sqrt{N^\uparrow(\phi) N^\downarrow(\phi + \pi)} + \sqrt{N^\downarrow(\phi) N^\uparrow(\phi + \pi)}}. \quad (10)$$

This expression combines yields at opposite azimuthal angles and largely eliminates luminosity effects together with most acceptance effects.

For the chosen azimuthal convention, each method is fit with a $\sin \phi$ modulation,

$$A(\phi) = -\epsilon_N \sin \phi, \quad (11)$$

where ϵ_N is the amplitude of the raw transverse-spin modulation. The raw asymmetry is then corrected by the beam polarization,

$$A_{N,\text{raw}} = \frac{\epsilon_N}{\mathcal{P}_{\text{beam}}}. \quad (12)$$

Here $\mathcal{P}_{\text{beam}}$ denotes the beam polarization for the corresponding sample. The clockwise- and counterclockwise-beam results are combined with inverse-variance weighting. The relative-luminosity method provides the nominal result. The square-root method provides a consistency check.

The fully corrected isolated photon asymmetry is obtained by correcting the raw asymmetry in the nominal signal region for the residual background fraction, with zero background asymmetry assumed in the nominal result:

$$A_N^{\gamma,\text{iso}} = \frac{A_{N,\text{raw}}^A}{P}, \quad r = 1 - P. \quad (13)$$

In this expression, $A_{N,\text{raw}}^A$ is the polarization-corrected asymmetry measured in Region A before the purity correction, P is the signal purity in Region A, and r is the corresponding background fraction. The background asymmetry is set to zero for the nominal result based on the sPHENIX preliminary neutral-meson asymmetry measurement [31]. The effect of nonzero neutral-meson background asymmetries is evaluated as a systematic uncertainty in Sec. 5.

Bin-by-bin t -scores are used to compare the two beam results and the two extraction methods. The differences are consistent with statistical fluctuations, and no additional systematic uncertainty is assigned.

5 Systematic Uncertainties

Systematic uncertainties are evaluated by changing one analysis choice at a time, recalculating the corrected A_N , and taking its difference from the nominal central value.

The uncertainty associated with photon identification is evaluated by varying the tight BDT requirement. The photon purity and asymmetry are re-evaluated to account for changes in the selected sample. This contribution reaches approximately 47% of the statistical uncertainty in the 8–10 GeV bin and is lower in the other bins.

The sensitivity of the double-sideband purity estimate to the background control region is evaluated by varying the non-isolated sideband selection. The resulting change in purity is

propagated to the corrected asymmetry. This contribution remains below approximately 3.2% of the statistical uncertainty in the bins where the double-sideband method is used.

The signal isolation requirement is varied separately to evaluate its effect on the photon selection. The purity and asymmetry are re-evaluated with the modified isolation selection. This contribution reaches approximately 26% of the statistical uncertainty.

The uncertainty from residual background asymmetry is evaluated using the measured π^0 and η asymmetries from sPHENIX together with their estimated background fractions. This accounts for possible nonzero asymmetries of the neutral-meson background. This is the largest systematic contribution in the two lowest-energy bins, corresponding to approximately 60–68% of the statistical uncertainty.

The difference between the data purity estimate and the truth prompt-photon fraction in inclusive MC is also considered. Its effect on the corrected asymmetry is assigned as a purity-related systematic uncertainty. This contribution reaches approximately 23% of the statistical uncertainty in the highest-energy bin.

Selection variations are treated asymmetrically, while the background asymmetry and data–MC purity contributions are treated symmetrically. The total uncertainty is obtained by adding the source contributions in quadrature separately for the upward and downward directions. The common beam-polarization scale uncertainty is quoted separately.

Possible false asymmetries are checked by randomly shuffling the spin labels. The pull distributions show no significant bias or broadening requiring an additional systematic uncertainty. The clockwise–counterclockwise and extraction-method comparisons described above likewise require no additional contribution.

The source-by-source contributions and their totals are summarized in Fig. 3. Their combined effect is represented by the systematic-uncertainty boxes in Fig. 5.

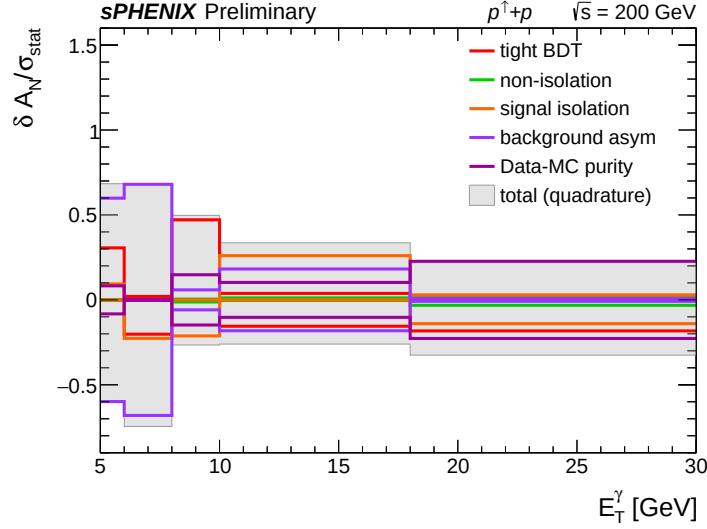


Figure 3: Upward and downward systematic uncertainty contributions, normalized to the statistical uncertainty, for the purity-corrected isolated photon asymmetry. The grey band shows the total, evaluated in quadrature separately on each side.

6 Results

Figure 4 shows the measured isolated-photon asymmetry, and Figure 5 shows the measured asymmetry together with the published PHENIX result [13]. The result is consistent with zero within uncertainties across the measured range $5 < E_T^\gamma < 30$ GeV, and is consistent with the PHENIX measurement within the quoted uncertainties.

Compared to the previous PHENIX measurement [13], this measurement has comparable integrated luminosity while sPHENIX has much larger acceptance. However, the statistical uncertainty is comparable with PHENIX. The precision depends on the selected candidate yield, photon purity, and beam polarization, rather than on integrated luminosity and acceptance alone.

As a cross-check, we extracted the isolated-photon cross section using the analysis method described in this note. The extracted cross section in the overlapping energy range agrees with the sPHENIX measurement [28] within 5%, which is much smaller than the experimental uncertainty. It differs from the PHENIX reference [30] by at most 16% over $5 < E_T < 12$ GeV, within the quoted PHENIX systematic uncertainties.

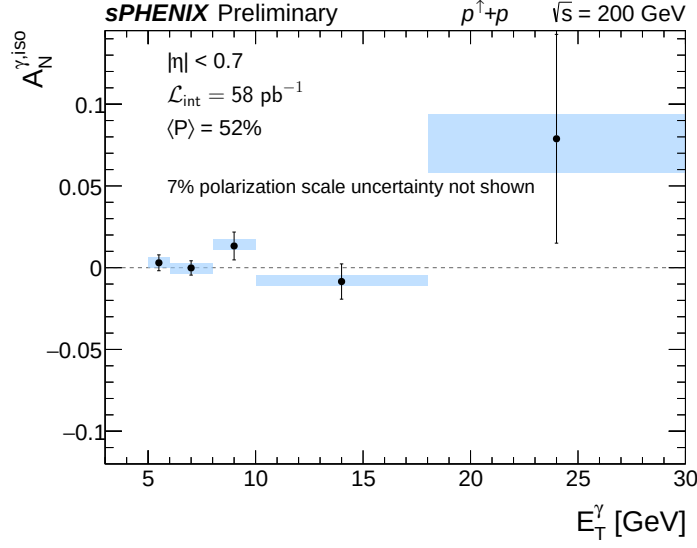


Figure 4: Isolated photon asymmetry. Vertical bars show statistical uncertainties; blue boxes show the point-to-point systematic uncertainties. The 7% global polarization scale uncertainty is shown separately.

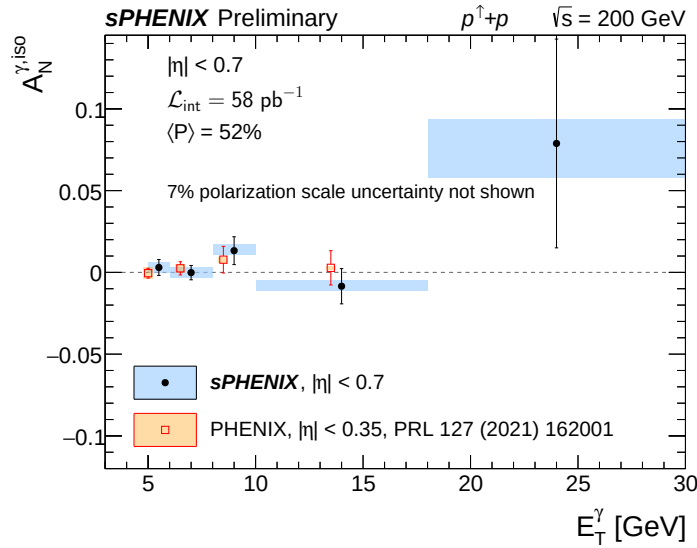


Figure 5: Isolated photon asymmetry compared with the published PHENIX result [13]. Vertical bars show statistical uncertainties; blue and orange boxes show the point-to-point systematic uncertainties of sPHENIX and PHENIX, respectively. The 7% global polarization scale uncertainty of sPHENIX is shown separately. The PHENIX points are shifted by 0.5 GeV to the left for visual clarity.

7 Summary

The transverse single-spin asymmetry A_N for isolated photons produced in $\sqrt{s} = 200$ GeV $p^\uparrow + p$ collisions at sPHENIX has been measured. The result is consistent with zero over the measured transverse energy range $5 < E_T^\gamma < 30$ GeV and is consistent with the published PHENIX result within uncertainties. Further studies will explore an extended pseudorapidity acceptance and refinements to the meson-tagging selection. These studies will assess the balance between photon purity and signal retention, with the aim of improving the statistical precision.

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