

Cross sections of η mesons in $p + p$ collisions at forward rapidity at $\sqrt{s} = 500$ GeV and central rapidity at $\sqrt{s} = 510$ GeV

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We present the first measurements of the forward and midrapidity η -meson cross sections from $p + p$ collisions at $\sqrt{s} = 500$ and 510 GeV, respectively. We also report the midrapidity η/π^0 ratio at 510 GeV. The forward cross section is measured differentially in η -meson transverse momentum (p_T) from 1.0 to 6.5 GeV/ c for pseudorapidity $3.0 < |\eta| < 3.8$. The midrapidity cross section is measured from 3.5 to 44 GeV/ c for pseudorapidity $|\eta| < 0.35$. Both cross sections serve as critical inputs to an updated global analysis of the η -meson fragmentation functions.

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I. INTRODUCTION

Experimental measurements from hadronic collisions have served as an invaluable tool in the development of quantum chromodynamics (QCD). While quarks and gluons, together known as partons, are the fundamental particles of QCD, the experimentally relevant degrees of freedom are their hadronic bound states. The relationship between the partons and hadrons is contained in non-perturbative functions that rely on experimental input for their description. Take, for example, the inclusive production of hadrons from proton collisions, $p + p \rightarrow h + X$. At short distance scales, the partonic hard scattering matrix elements are calculable in fixed-order perturbative QCD (pQCD). However, the long-distance initial- and final-state descriptions are nonperturbative. The initial state is described by the parton distribution functions (PDFs) $f(x, Q^2)$ which, to leading order in α_s , give the number density of a parton in the proton at a given collinear momentum fraction x and squared momentum transfer scale Q^2 . In the final state, the scattered partons undergo hadronization, where they evolve from the hard scattering to the observable hadronic-QCD bound states. This process is described by fragmentation functions (FFs) $D(z, Q^2)$, which, to leading order, give the probability density that a struck parton will fragment into a given final state hadron with collinear momentum fraction z at Q^2 . QCD factorization enables the separation of the nonperturbative functions from the perturbative physics [1]. Hadronic-level

observables can then be calculated by convoluting the initial-state PDFs, final-state FFs, and the partonic scattering cross section described by pQCD. The PDFs and FFs, which are usually assumed to be universal, are determined through global fits to an array of experimental results.

Fragmentation into the lightest QCD bound state, the pion, has been thoroughly studied with spectra of π^0 and $\pi^\pm$ from hadron-hadron collisions [2–12], $\pi^\pm$ from electron-positron annihilation [13–17] and $\pi^\pm$ from semi-inclusive deep-inelastic scattering (SIDIS) [18,19]. Global analyses of these results have constrained the pion FFs to high precision [20–22]. In contrast, the Aidala-Ellinghaus-Sassot-Seele-Stratmann (AESSS) (2011) [23] η -meson FFs from over a decade ago are the one global analysis available for η mesons and are significantly less constrained. In the time since these FFs were initially determined, more measurements of η meson production have been made over a wide range of energies in hadronic collisions [9–11,24–26] and in electron-positron annihilation [27]. Large deviations from predictions using the AESSS FFs have been found in the high-energy data at the Large Hadron Collider (LHC), motivating an update to the η meson FF global fits. The measurements of the η -meson cross sections in the forward region at $\sqrt{s} = 500$ GeV and central region at $\sqrt{s} = 510$ GeV presented here serve as two principal inputs in a newly released global analysis of the η meson FFs, denoted the Aidala-Loomis-Martinez-Sassot-Stratmann (ALMSS) (2025) FFs [28]. The cross sections are the first of their kind at $\sqrt{s} = 500$ GeV and $\sqrt{s} = 510$ GeV, providing an important intermediate energy input into the ALMSS FFs between the lower-energy data at the Relativistic Heavy Ion Collider (RHIC) and higher-energy data at the LHC. The cross sections are compared to next-to-leading-order (NLO) pQCD predictions utilizing the earlier AESSS (2011) FFs [23,29,30] and the newer ALMSS (2025) FFs [28].

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II. THE PHENIX EXPERIMENT AT RHIC

A. PHENIX detector

The PHENIX experiment [31], shown in Fig. 1, was located in the 8 o'clock interaction region of RHIC at Brookhaven National Laboratory and operated from 2000-2016. The detector comprised two central-arm spectrometers covering pseudorapidity $|\eta| < 0.35$, two muon arms covering $1.2 < |\eta| < 2.4$, two global detectors, which are the beam-beam counters (BBC) and zero-degree calorimeters, plus a forward electromagnetic calorimeter covering $3.1 < |\eta| < 3.9$.

The central-arm spectrometers each covered $\pi/2$ in azimuth and comprised (i) a high-granularity electromagnetic calorimeter (EMCal) [32], (ii) drift and pad chambers for charged-track reconstruction [33], and (iii) a

ring-imaging Čerenkov detector for charged-particle identification [34]. The muon arms [35] had a combination of tracking and identification capabilities and were used primarily for detecting vector mesons through their dimuon decays. The BBC [36] was an array of quartz Čerenkov radiators covering $3.0 < |\eta| < 3.9$ used for minimum-bias (MB) triggering on inelastic proton collisions. It also served to measure luminosity and determine the event vertex position along the beam axis (z vertex) to ± 2 cm.

B. Muon-piston calorimeter

The muon-piston calorimeter (MPC) was a forward electromagnetic calorimeter primarily used for measurements of π^0 and η mesons through their diphoton decay. The MPC had two arms with full azimuthal acceptance that

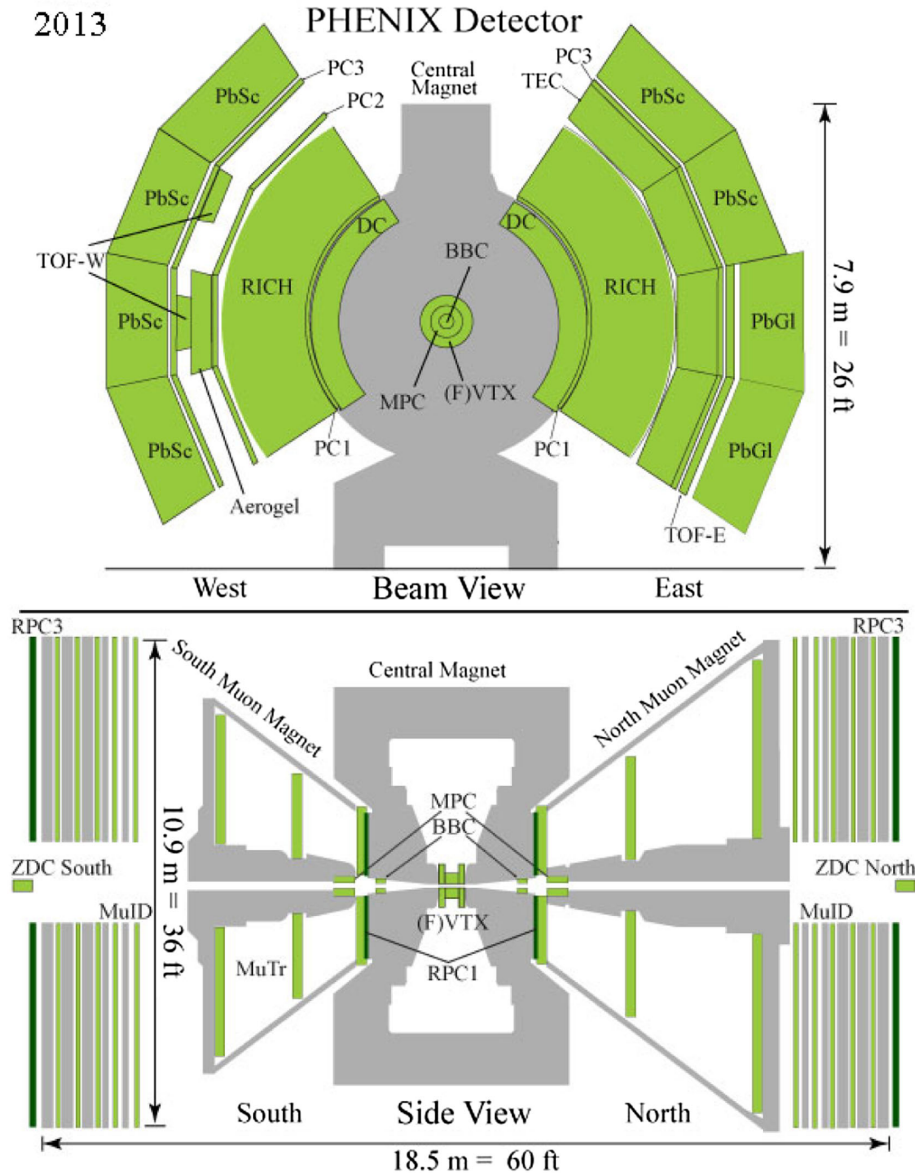


FIG. 1. The PHENIX detector during the 2013 RHIC run.

were each located ± 220 cm away from the nominal PHENIX interaction point. The south MPC covered $-3.8 < \eta < -3.1$ and the north MPC covered $3.1 < \eta < 3.9$. The south (north) MPC comprised 196 (220) $2.2 \times 2.2 \times 18$ cm³ PbWO₄ crystal towers read out by Hamamatsu S8664-55 avalanche photodiodes. Tower-by-tower gain variations in time were tracked and corrected by an LED calibration system. An absolute calibration was performed using an iterative algorithm to match the π^0 invariant-mass peak position of diphoton clusters. The nominal relative energy resolution of the MPC was $\sigma(E)/E = 13\%/\sqrt{E[\text{GeV}]} \oplus 8\%$ with an energy scale uncertainty of 2% [24,37]. A dedicated MPC trigger was utilized for high- p_T η mesons that required the energy sum of a 4-by-4 group of towers (tile) to exceed a certain threshold, which at $\sqrt{s} = 500$ GeV corresponds to approximately 40 GeV. The set of 56 (61) 4-by-4 tiles in the south (north) MPC are in general nondisjoint, overlapping by up to two towers in both the horizontal and vertical directions to reduce the impact of a position-dependent threshold tied to cluster showers that can spread their energy across multiple tiles.

C. Central electromagnetic calorimeter

The PHENIX central EMCal provided highly segmented detection of photons and electrons in two nearly back-to-back arms each covering a pseudorapidity of $|\eta| < 0.35$ and $\phi \approx \pi/2$ in azimuth. The EMCal comprised 8 sectors with 24,768 calorimeter towers of two different calorimeter technologies, with 75% of the acceptance (six sectors; four in the west arm and two in the east arm) covered by a lead scintillator (PbSc) sampling calorimeter and the remaining 25% (two sectors in the east arm) covered by a lead glass (PbGl) Čerenkov calorimeter. The EMCal granularity was $\Delta\phi \times \Delta\eta = 0.011 \times 0.011$ (0.008×0.008) and the nominal relative-energy resolution for the PbSc (PbGl) calorimeters [32] was $\sigma(E)/E = 8.1\%/\sqrt{E[\text{GeV}]} \oplus 2\%$ ($5.9\%/\sqrt{E[\text{GeV}]} \oplus 0.8\%$). The EMCal also provided particle time-of-flight (ToF) measurements, an essential tool for reducing the impact of out-of-time pileup that could accrue over integration time. The energy calibration of the EMCal was performed by matching the reconstructed π^0 mass for each calorimeter tower. The ToF calibration was performed on a run-by-run basis by fitting to the peak of the photon time-of-flight distribution on a given tower. A dedicated EMCal high-momentum photon (HPP) trigger, similar to the MPC 4-by-4 trigger, required the energy deposition in a group of 4-by-4 towers to exceed a threshold corresponding to approximately 4 GeV for $\sqrt{s} = 510$ GeV collisions. This trigger enabled the measurement of high- p_T mesons and contained information on which photon clusters and calorimeter sectors in an event fired the trigger.

III. THE η -MESON CROSS SECTION

The invariant cross section of inclusive η meson production $p + p \rightarrow \eta + X$ was measured by

$$E \frac{d^3\sigma}{dp^3} = \frac{1}{\mathcal{L}} \frac{1}{\text{BR}_{\eta \rightarrow \gamma\gamma}} \frac{1}{2\pi p_T} \frac{\Delta N^{\text{meas}}}{\epsilon_{\text{trig}} \epsilon_{\text{reco}} \Delta p_T \Delta \eta}, \quad (1)$$

where ΔN^{meas} is the measured η meson yield in a given bin of p_T and pseudorapidity, ϵ_{trig} is the efficiency with which the MB or dedicated high p_T trigger will fire when an η meson is produced, ϵ_{reco} is the efficiency of the detector to reconstruct an η meson through its decay to diphotons, $\mathcal{L}$ is the integrated luminosity of the dataset, and $\text{BR}_{\eta \rightarrow \gamma\gamma} = 0.3936$ is the branching ratio (fraction) of the $\eta \rightarrow \gamma\gamma$ decay [38].

The integrated luminosity is determined as the number of sampled events in the dataset divided by the cross section of inelastic $p + p$ collisions that the BBCs detected. The BBC cross section at $\sqrt{s} = 500$ GeV was 32.5 mb with a 9.3% systematic uncertainty, as measured by a Vernier scan of events within ± 30 cm from the nominal interaction point [8].

For the forward η -meson cross section, a subpercent level correction was applied to account for the more lenient BBC vertex cut of ± 70 cm, leading to a final BBC cross section of 32.25 mb. The integrated luminosities of the MB and MPC-triggered datasets used in the analysis were $\mathcal{L}_{\text{MB}} = 5.56 \times 10^{-3}$ pb⁻¹ and $\mathcal{L}_{\text{MPC}} = 9.33$ pb⁻¹. Any multiple-collision effects on the luminosity counting were found to be negligible with the relatively small number of interactions per BBC triggered event, $\langle n_{\text{coll}} \rangle \approx 1.1$.

For the midrapidity η meson cross section, the integrated luminosities of the MB and HPP trigger datasets used in the analysis were $\mathcal{L}_{\text{MB}} = 8.45 \times 10^{-3}$ pb⁻¹ and $\mathcal{L}_{\text{HPP}} = 13.77$ pb⁻¹. Large instantaneous luminosities meant that up to one third of all bunch crossings contained more than one $p + p$ collision. Luminosity corrections for multiple collisions of up to 15% were calculated independently for the PbSc and PbGl calorimeters in MB and HPP datasets. This was done by studying the behavior of the ratio of the π^0 yield to the number of MB triggers as a function of the instantaneous MB trigger rate [8].

A. The forward η -meson cross section at $\sqrt{s} = 500$ GeV

In 2009, PHENIX collected data from proton-proton collisions at $\sqrt{s} = 500$ GeV. The cross section was measured independently in the south and north MPCs in MB and MPC-triggered datasets. In events that satisfied the MB requirement, the cross section was measured differentially in p_T from 1.0 to 4.5 GeV/ c . Events that fired the MPC trigger provided a high p_T sample from 3.5 to 6.5 GeV/ c .

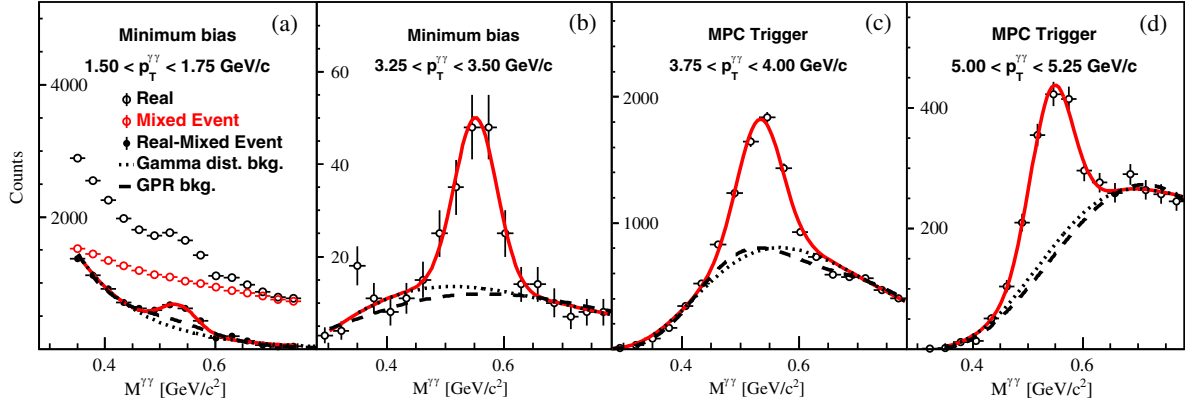


FIG. 2. Examples of two-photon invariant-mass distributions in the MPC from the 2009 $\sqrt{s} = 500$ GeV run in MB [(a),(b)] and MPC-triggered data [(c),(d)]. The black open circles represent the real diphoton cluster pairs, the red open circles represent diphoton cluster pairs from the mixed-event background, and the black closed circles represent the real cluster pairs with the mixed-event background subtracted. The red solid curves show the combined fit of the gamma-distribution background and signal while the gray dotted curves show only the gamma-distribution background fit. The black dashed curves show the background description from Gaussian process regression.

1. Yields

The raw yields of η mesons are extracted from the invariant-mass distributions of photon cluster pairs as shown in Fig. 2. The invariant mass is given by

$$M_{\gamma\gamma} = \sqrt{E_{\gamma\gamma}^2 - \vec{p}_{\gamma\gamma} \cdot \vec{p}_{\gamma\gamma}} = \sqrt{4E_1 E_2} \sin \frac{\theta}{2}, \quad (2)$$

where the E_1 , E_2 are the cluster energies and θ is the opening angle between the cluster momentum vectors. A cut on the cluster energy asymmetry $\alpha = |E_2 - E_1|/(E_2 + E_1) < 0.6$ is used to reduce the background from mismatched photon clusters. Additionally, cluster pairs are required to be separated by at least 2.6 cm in the MPC to lessen the impact of high-momentum η mesons whose photon daughters have an opening angle small enough to be reconstructed in the same cluster, known as a merged cluster.

For cluster-pair transverse momentum $p_T^{\gamma\gamma}$ below 2.25 GeV/c in the MB dataset, a mixed-event background subtraction is used to reject pairs from combinatorial background sources. The mixed-event distribution is formed by pairing clusters from distinct events with one another, removing any likelihood of creating correlated pairs. Above 2.25 GeV/c, the impact of any mixed event background subtraction is minimal, so yields were determined by directly fitting to the real pairs.

The raw η meson yields are determined using two independent fitting methods. First, the background with the signal region removed ($0.45 < M_{\gamma\gamma} < 0.65$ GeV/c²) is fit to a gamma-distribution function. In the case of the MPC-triggered data, the functional form of the background also includes a Gaussian centered at 0.78 GeV/c² to describe a small resonance from $\omega(782) \rightarrow \pi^0 + \gamma$ decays where the π^0 has decayed into two photons which merge

into a single cluster. The signal region is then included back into the invariant-mass distribution and a simultaneous fit of the background fixed with the previously determined parameters and the signal, described by a Gaussian, was used to extract the raw yields. The second method fitted the background distributions with the signal region removed using Gaussian process regression (GPR) [39] with a radial-basis-function kernel. The yields are extracted as the difference of integrals in the signal region of the total invariant-mass distribution and the GPR fit of the background. The final raw yields in Fig. 3(a) are the weighted mean of those found between the two methods, and a systematic uncertainty is taken as their relative difference. The yield extraction was found to be stable across small changes in the mass fit region.

2. Efficiencies and corrections

The raw yields must be corrected by the fraction of produced η mesons that are detected by the MPC. This fraction was encoded in two efficiencies: a trigger efficiency, which represents the probability that an event with an η meson was successfully triggered, and the reconstruction efficiency, which represents the probability that the produced η meson will be in the acceptance of the MPC and could have been reconstructed as a diphoton decay within the η meson signal region, accounting for smearing effects due to the finite energy and spatial resolution of the detector and the selection requirements used to identify diphoton candidates. The reconstruction efficiency also accounted for any cluster-merging effects.

To help calculate these corrections, a set of simulated single η mesons was generated in Monte Carlo as a flat distribution in p_T from 0.5 to 8.5 GeV/c and pseudorapidity for $2.5 < |\eta| < 4.5$, passed through a Geant3 [40] description of the PHENIX detector, and embedded into

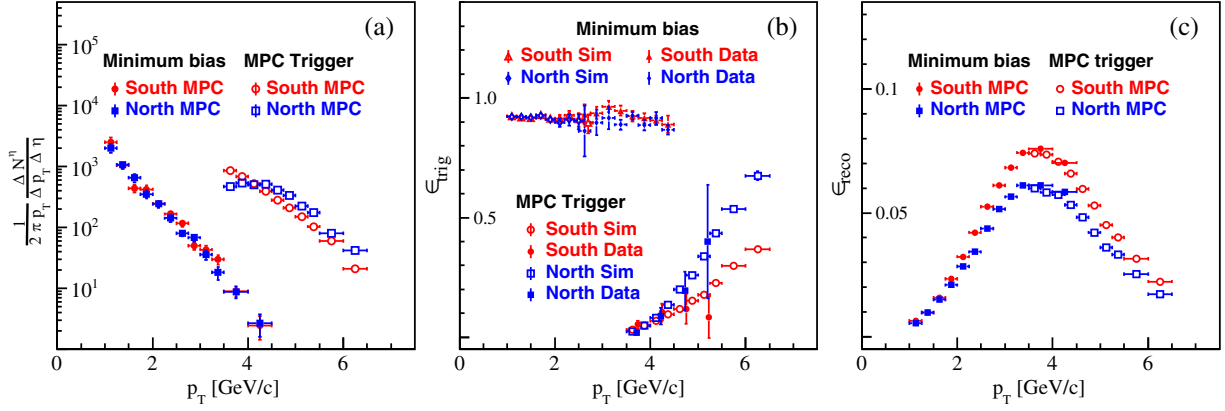


FIG. 3. The inputs to the forward η meson cross section at $\sqrt{s} = 500$ GeV for both the MB and MPC-triggered dataset at pseudorapidities $3.0 < |\eta| < 3.8$. (a) The raw yields as a function of η meson p_T , (b) the trigger efficiency as a function of η meson p_T , and (c) the reconstruction efficiency as a function of η meson p_T .

real MB events. Photon cluster pairs are identified from these simulated η mesons with the same reconstruction work flow and cluster kinematic cuts as real data. The simulations are weighted to match the real event z-vertex distribution and the variations of tower gain over time.

For $p_T > 2.5$ GeV/c, the MB trigger efficiency was calculated in a data-driven manner by finding the fraction of η mesons that fire the MB trigger in the MPC-triggered dataset. This value was found to be uniform in p_T at $0.92 \pm 0.01(\text{stat}) \pm 0.04(\text{syst})$ where the systematic uncertainty is assigned for the small difference between the constant values found in the south and north MPCs, as seen in Fig. 3(b). This efficiency agrees with a previous PHENIX midrapidity π^0 analysis at 510 GeV [8], which measured the efficiency down to 1 GeV/c. We confirmed this uniform behavior of the efficiency at low $p_T < 2.5$ GeV/c by finding the fraction of charged particles from Pythia6 (TuneA) [41–43] simulations that fall into the BBC acceptance.

Insufficient statistics at high p_T in the MB dataset prevent a fully data-driven estimation of the MPC trigger efficiency. Instead, a technique for simulating the trigger was utilized [24]. First, trigger efficiencies as a function of raw ADC were gathered for each MPC 4-by-4 tile from data throughout the entire data-taking period. At any given time, these efficiencies are a step function of the ADC, but variations in gain over time spread the step functions to some extent. The time-integrated tile efficiencies were then fitted by a sigmoidlike double error function

$$f(x) = \int_{-\infty}^x [a\mathcal{N}_1(x'; \mu_1, \sigma_1) + b\mathcal{N}_2(x'; \mu_2, \sigma_2)] dx', \quad (3)$$

where $\mathcal{N}_{1,2}$ are Gaussian distributions. To find the ADC thresholds (ADC_{thresh}) that correspond to the turn-on value of the step functions associated with each tile, candidate values of $\theta_{\text{thresh}} = f(ADC_{\text{thresh}})$ were tested by matching

single cluster trigger efficiencies from full Pythia6 (TuneA) + Geant3 simulations and data. A simulated cluster is considered to have fired the trigger if at least one of its associated tile ADCs exceeds the ADC value that maps to the chosen θ_{thresh} determined by the tile fit parameters from Eq. (3). The optimal threshold for matching the simulation to the data was determined to be $\theta_{\text{thresh}} = 0.73$ which for 500 GeV $p + p$ collisions in 2009 corresponds to the 4-by-4 tile thresholds of ≈ 40 GeV. A trigger efficiency systematic was taken for slight differences in the threshold determination between the south and north MPCs. The final MPC trigger efficiency binned in η meson p_T was found by examining whether any of the tiles associated with either of the reconstructed photon clusters from the single η meson simulations exceeded the optimal ADC threshold. At low p_T where MB data can be used, the resulting trigger efficiency shown in Fig. 3(b) agrees with that of real photon clusters from the data.

The calculation of the reconstruction efficiency relies on an iterative weighting procedure of the simulated η meson sample to replicate realistic p_T and pseudorapidity distributions. On an initial pass, the reconstruction efficiency was calculated as the fraction of reconstructed to generated η mesons where each η meson has been weighted for its p_T and pseudorapidity from Pythia6 (TuneA) truth spectra. This weighted efficiency is then used as a correction to measured yields from real data. The resulting corrected real spectra are used as the weights to the efficiency calculation of the next iteration. After several iterations, the reconstruction efficiencies converge to the stable result shown in Fig. 3(c). The decrease in reconstruction efficiency at $p_T \gtrsim 4$ GeV/c stems from enhanced cluster merging of the diphoton clusters from boosted η mesons. Differences between the south and north MPC reconstruction efficiencies are due to the larger number of towers in the north MPC that are removed in quality assurance due to an anomalous driver board and beam pipe support blockage.

3. Systematic uncertainties

Systematic uncertainties for the forward cross section are determined independently for the south and north arms of the MPC, and then averaged for the final systematic uncertainty. Three types of systematic uncertainties are considered for this measurement. The first type is point-to-point uncorrelated uncertainties across p_T bins. These include contributions from the choice of the invariant-mass fitting method for yield extraction (2%–10%) and the choice of mixed event background normalization (5%–10% for $p_T < 2.25$ GeV/ c). The second type of systematic uncertainties are correlated across p_T bins. These include uncertainties due to the MPC energy scale (5%–35%, increasing with p_T due to the convolution of the intrinsic 2% energy-scale uncertainty with bin smearing from the physical p_T spectrum), MB-trigger-efficiency (4%), MPC-trigger-efficiency thresholds (5%–30%, decreasing in p_T), η meson reconstruction efficiency (8%), and high-energy cluster merging studied with the fully reconstructed single η meson simulations (3%–10%, increasing in $p_T > 3.5$ GeV/ c). Finally, a global-scale uncertainty of 9.3% comes from the Vernier-scan measurement needed for the integrated-luminosity determination. Correlated systematic uncertainties are treated as fully correlated across p_T bins. The global-scale uncertainty is treated separately from the other correlated systematic uncertainties but is fully correlated between this forward measurement and the midrapidity measurement discussed in Sec. III B. The correlation matrix of the systematic uncertainties is included in HEPData [44].

4. Cross-section results

The final invariant cross section of inclusive η mesons for $1.0 < p_T < 6.5$ GeV/ c and $3.0 < |\eta| < 3.8$ is shown in Fig. 4 and listed in Table I. The cross section was measured independently in the south and north MPCs and agrees within 4%. The final cross section is taken as the weighted mean of the cross sections in each MPC arm. In the p_T region where the MB and MPC-triggered datasets overlap ($3.5 < p_T < 4.5$ GeV/ c), the cross sections are consistent within the statistical uncertainties and only the MPC-triggered cross section, being significantly more precise, is included in the final cross section. A final correction must be applied because the cross sections are reported at their bin centers in a steeply falling distribution. The correction follows a standard procedure [25,45], in which a smooth function is fit to the cross section and is then used to scale the cross section in each p_T bin by the ratio of its average value in the bin to its value at the bin center. In this analysis, the MB and MPC-triggered cross sections were fit with separate exponential distributions which provided a good description of the data points. As the bin widths are relatively narrow, the corrections are correspondingly small, ranging from 1% for the bins with widths of 0.25 GeV/ c to 4% for the bins with widths of 0.5 GeV/ c .

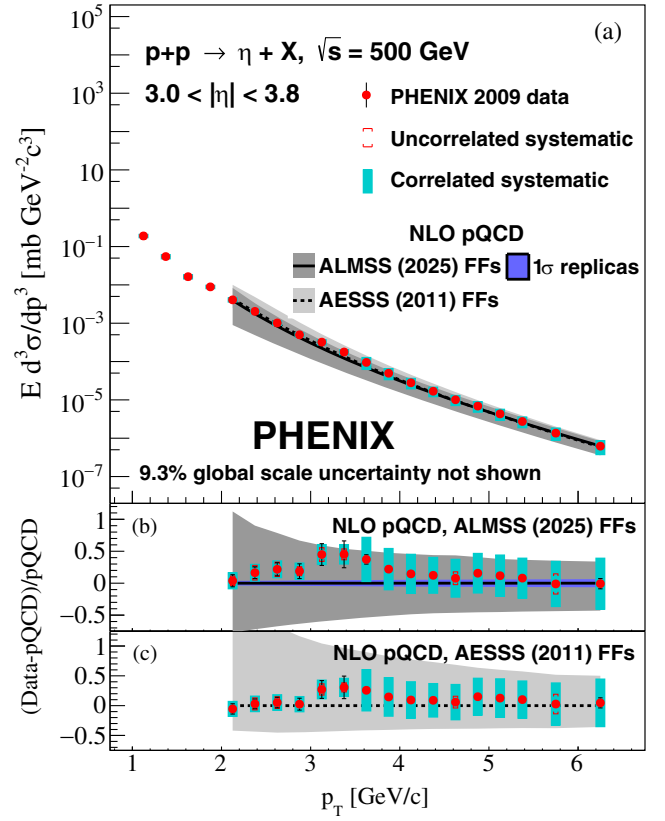


FIG. 4. (a) Invariant cross section of inclusive η mesons at forward rapidity in $\sqrt{s} = 500$ GeV $p + p$ collisions. Statistical uncertainties are shown in black uncertainty bars, systematic uncertainties uncorrelated across p_T are shown in red uncertainty bars, and systematic uncertainties correlated across p_T are shown in blue uncertainty boxes. A global 9.3% systematic uncertainty is not shown. NLO-pQCD predictions using the AESSS (2011) [23] η FFs and the ALMSS (2025) [28] η FFs are shown as the dashed and solid line, respectively, and their corresponding theoretical scale uncertainties are displayed as the gray uncertainty bands. The blue uncertainty band shows the 1σ standard deviation of the cross section predictions across the final set of ALMSS η FF replicas. The bottom two panels show the ratios of data to pQCD predictions (Data-pQCD/pQCD) using the (b) ALMSS (2025) [28], and (c) AESSS (2011) [23] η FFs.

The cross section is compared to two NLO-pQCD calculations. The first uses the new ALMSS η -meson FFs [28] along with the MSHT20 PDFs [46]. The second [30] uses the old AESSS η meson FFs [23] together with the CTEQ18 PDFs [47]. In both cases, the calculations agree well with the data within statistical, systematic, and theoretical uncertainties in the perturbative regime above $p_T > 2$ GeV/ c . As this measurement was itself included in the ALMSS analysis, it is natural that the prediction using the ALMSS FFs matches nicely with the data. To test the actual predictive capability of the ALMSS FFs, the calculation was repeated with a modified FF fit that excluded the forward η -meson cross section reported here from the fit data. In this case, the predictions remain consistent with the

TABLE I. The invariant cross section of inclusive forward η mesons at $\sqrt{s} = 500$ GeV, as shown in Fig. 4. A global 9.3% scale systematic uncertainty is not included.

p_T bin [GeV/c]	p_T [GeV/c]	$E \frac{d^3\sigma}{dp^3}$ [mb GeV $^{-2}$ c ^{3}]	σ_{stat}	σ_{syst} (Uncorrelated)	σ_{syst} (Correlated)	σ_{syst} (Total)
1.00 to 1.25	1.125	1.89×10^{-1}	2.42×10^{-2}	3.57×10^{-2}	1.94×10^{-2}	4.07×10^{-2}
1.25 to 1.50	1.375	5.48×10^{-2}	5.05×10^{-3}	7.76×10^{-3}	7.09×10^{-3}	1.05×10^{-2}
1.50 to 1.75	1.625	1.64×10^{-2}	1.79×10^{-3}	2.73×10^{-3}	2.16×10^{-3}	3.46×10^{-3}
1.75 to 2.00	1.875	8.88×10^{-3}	9.93×10^{-4}	1.34×10^{-3}	9.21×10^{-4}	1.63×10^{-3}
2.00 to 2.25	2.125	4.07×10^{-3}	3.70×10^{-4}	2.87×10^{-4}	5.14×10^{-4}	5.88×10^{-4}
2.25 to 2.50	2.375	2.04×10^{-3}	1.61×10^{-4}	2.00×10^{-4}	2.67×10^{-4}	3.34×10^{-4}
2.50 to 2.75	2.625	1.02×10^{-3}	8.57×10^{-5}	9.40×10^{-5}	1.34×10^{-4}	1.64×10^{-4}
2.75 to 3.00	2.875	4.98×10^{-4}	4.84×10^{-5}	2.97×10^{-5}	6.40×10^{-5}	7.05×10^{-5}
3.00 to 3.25	3.125	3.21×10^{-4}	3.78×10^{-5}	2.40×10^{-5}	5.06×10^{-5}	5.60×10^{-5}
3.25 to 3.50	3.375	1.77×10^{-4}	2.57×10^{-5}	1.05×10^{-5}	2.71×10^{-5}	2.91×10^{-5}
3.50 to 3.75	3.625	9.50×10^{-5}	5.06×10^{-6}	2.14×10^{-6}	3.29×10^{-5}	3.30×10^{-5}
3.75 to 4.00	3.875	4.96×10^{-5}	2.39×10^{-6}	2.77×10^{-6}	1.61×10^{-5}	1.64×10^{-5}
4.00 to 4.25	4.125	2.79×10^{-5}	1.30×10^{-6}	1.30×10^{-6}	8.58×10^{-6}	8.68×10^{-6}
4.25 to 4.50	4.375	1.68×10^{-5}	7.68×10^{-7}	8.86×10^{-7}	4.73×10^{-6}	4.81×10^{-6}
4.50 to 4.75	4.625	1.01×10^{-5}	4.92×10^{-7}	9.40×10^{-7}	3.00×10^{-6}	3.14×10^{-6}
4.75 to 5.00	4.875	6.89×10^{-6}	3.55×10^{-7}	1.13×10^{-7}	2.14×10^{-6}	2.14×10^{-6}
5.00 to 5.25	5.125	4.31×10^{-6}	2.29×10^{-7}	1.40×10^{-7}	1.40×10^{-6}	1.41×10^{-6}
5.25 to 5.50	5.375	2.73×10^{-6}	1.55×10^{-7}	1.10×10^{-7}	8.55×10^{-7}	8.62×10^{-7}
5.5 to 6.0	5.750	1.36×10^{-6}	7.66×10^{-8}	2.17×10^{-7}	4.82×10^{-7}	5.29×10^{-7}
6.0 to 6.5	6.250	6.20×10^{-7}	5.01×10^{-8}	6.62×10^{-9}	2.48×10^{-7}	2.49×10^{-7}

measurement, indicating both that the ALMSS FFs are able to describe the forward η meson cross section at 500 GeV in a fully predictive manner and that the PHENIX measurement is consistent with other world data. An additional theoretical uncertainty is included in the ALMSS predictions related to the fact that the uncertainties on the ALMSS FFs were estimated using Monte-Carlo replicas rather than the Lagrange-multiplier method used in the AESSS FFs. The 1σ standard deviation of the cross section predictions across the final set of

ALMSS η FF replicas are shown in Fig. 4. This uncertainty band represents the statistical dispersion of the fit ensemble rather than a fixed tolerance interval in χ^2 . The replica-based method more naturally reflects correlated uncertainties among fit parameters but should not be directly compared in magnitude to an uncertainty derived from the Lagrange-multiplier method. In either case, the replica uncertainty and the Lagrange multiplier uncertainty are quite small in comparison with the theoretical uncertainty from the renormalization scale.

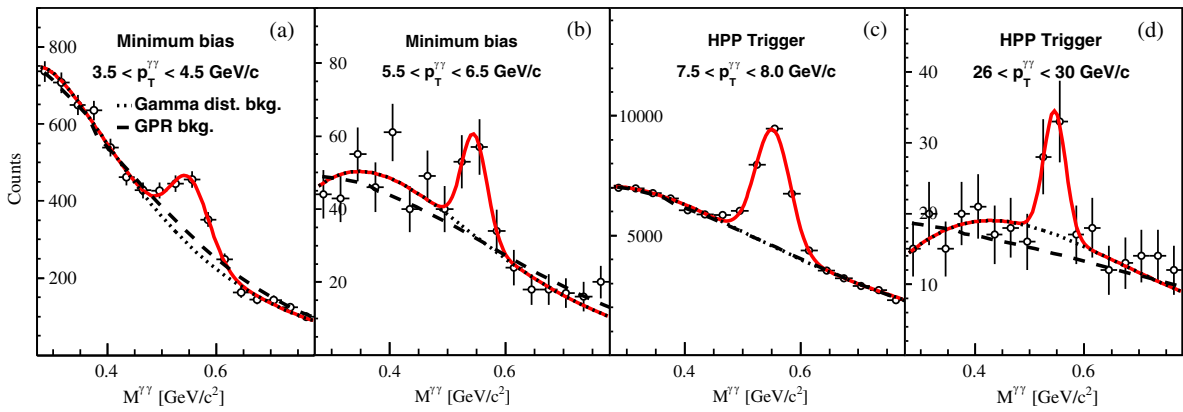


FIG. 5. Examples of two-photon invariant-mass distributions in the central EMCAL from the 2013 $\sqrt{s} = 510$ GeV run in (a),(b) MB and (c),(d) HPP-triggered data. The black open circles represent the real diphoton cluster pairs while the red solid curves show the combined fit of the gamma-distribution background and signal while the gray dotted curves show only the gamma-distribution-background fit. The black dashed curves show the background description from Gaussian process regression.

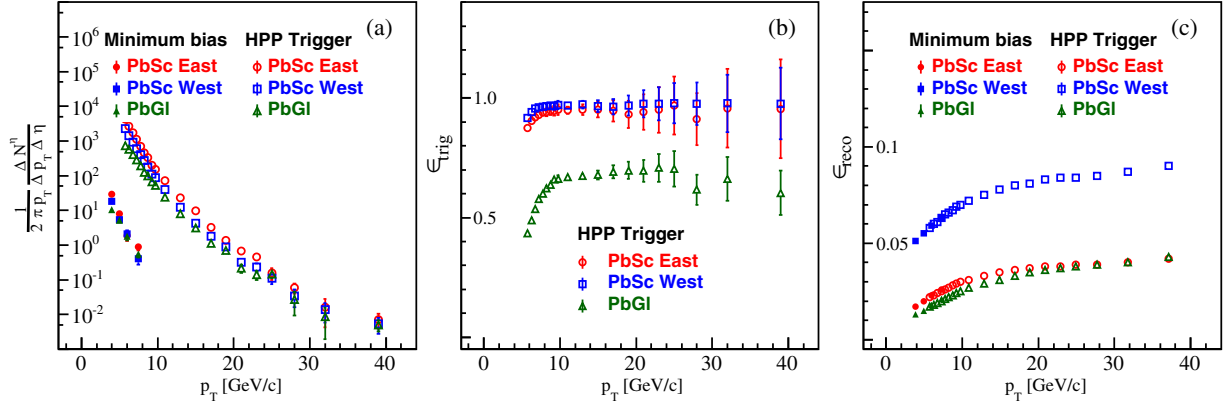


FIG. 6. The inputs to the midrapidity η meson cross section at $\sqrt{s} = 510$ GeV for both the MB and HPP-triggered dataset at pseudorapidities $|\eta| < 0.35$. (a) The raw yields as a function of η meson p_T , (b) the trigger efficiency as a function of η meson p_T , (c) the reconstruction efficiency as a function of η meson p_T .

B. The midrapidity η meson cross section at $\sqrt{s} = 510$ GeV

In 2013, PHENIX collected a high luminosity dataset of proton collisions at $\sqrt{s} = 510$ GeV. The cross section of η mesons is measured independently in each arm and calorimeter type: PbSc west, PbSc east, and PbGl. It is also measured independently in events satisfying only the MB narrow event vertex ($|z| < 10$ cm) condition and events that are required to have fired the HPP trigger with an additional offline vertex cut of 10 cm. The MB cross section is measured differentially in p_T from 3.5 to 8.0 GeV/c. The HPP cross section is measured in p_T from 5.5 to 44 GeV/c.

1. Yields

The invariant-mass distributions of photon cluster pairs in the central EMCAL are formed in the same manner as Eq. (2). The cluster-energy asymmetry requirement is loosened to 0.8 and the cluster separation cut that was present in the forward cross section is removed as cluster merging is negligible for η mesons in the kinematic range measured. A ToF requirement of $|\text{ToF}| < 10$ ns was applied to reduce the impact of out-of-time pileup events. As was done in the forward analysis, the raw η -meson yield for each p_T bin is determined from a simultaneous signal and background fit described by a Gaussian signal and multiple choices for a description of a background. The background is found to be well described across the entire p_T range by a gamma-distribution function, which is thus taken as nominal. Invariant-mass distributions of photon cluster pairs from several representative p_T regions are shown in Fig. 5. The resulting yield distribution, shown in Fig. 6(a), is robust to small variations in the invariant-mass fit region. A systematic uncertainty on the yield extraction is defined as the relative difference of the yield determined from the nominal background description and the yield determined with a 2nd-order-polynomial

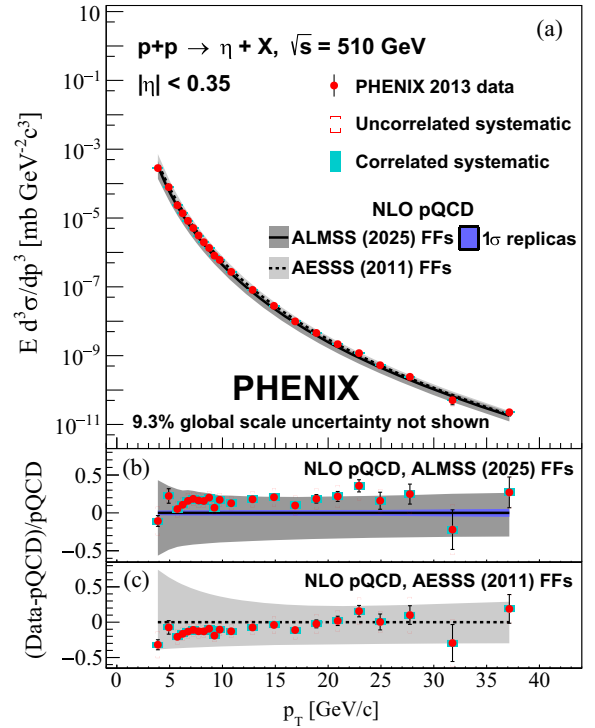


FIG. 7. (a) Invariant cross section of inclusive η mesons at midrapidity in $\sqrt{s} = 510$ GeV $p + p$ collisions. Statistical uncertainties are shown in black uncertainty bars, systematic uncertainties uncorrelated across p_T are shown in red uncertainty bars, and systematic uncertainties correlated across p_T are shown in blue uncertainty boxes. A global 9.3% systematic uncertainty is not shown. NLO-pQCD predictions using the AESSS (2011) [23] η FFs and the ALMSS (2025) [28] η FFs are shown as the dashed and solid line, respectively, and their corresponding theoretical uncertainties are displayed as the gray uncertainty bands. The blue uncertainty band shows the 1σ standard deviation of the cross section predictions across the final set of ALMSS η FF replicas. The bottom two panels show the ratios of data to pQCD predictions (Data-pQCD/pQCD) using the (b) ALMSS (2025) [28], and (c) AESSS (2011) [23] η FFs.

TABLE II. The invariant cross section of inclusive midrapidity η mesons at $\sqrt{s} = 510$ GeV, as shown in Fig. 7. A global 9.3% scale systematic uncertainty is not included.

p_T bin [GeV/ c]	p_T [GeV/ c]	$E \frac{d^2\sigma}{dp^2} [\text{mb GeV}^{-2} c^3]$	σ_{stat}	σ_{syst} (Uncorrelated)	σ_{syst} (Correlated)	σ_{syst} (Total)
3.5 to 4.5	3.89	2.827×10^{-4}	2.005×10^{-5}	5.297×10^{-5}	1.138×10^{-5}	5.42×10^{-5}
4.5 to 5.5	4.91	7.912×10^{-5}	7.584×10^{-6}	6.907×10^{-6}	3.320×10^{-6}	7.66×10^{-6}
5.5 to 6.0	5.73	2.345×10^{-5}	1.774×10^{-7}	2.489×10^{-6}	1.062×10^{-6}	2.71×10^{-6}
6.0 to 6.5	6.23	1.375×10^{-5}	1.181×10^{-7}	1.323×10^{-6}	6.273×10^{-7}	1.46×10^{-6}
6.5 to 7.0	6.73	8.283×10^{-6}	9.354×10^{-8}	8.149×10^{-7}	3.801×10^{-7}	8.99×10^{-7}
7.0 to 7.5	7.23	5.122×10^{-6}	5.987×10^{-8}	4.630×10^{-7}	2.361×10^{-7}	5.18×10^{-7}
7.5 to 8.0	7.74	3.109×10^{-6}	4.378×10^{-8}	2.994×10^{-7}	1.438×10^{-7}	3.33×10^{-7}
8.0 to 8.5	8.24	1.981×10^{-6}	3.215×10^{-8}	1.667×10^{-7}	9.193×10^{-8}	1.92×10^{-7}
8.5 to 9.0	8.74	1.351×10^{-6}	2.466×10^{-8}	1.163×10^{-7}	6.288×10^{-8}	1.32×10^{-7}
9.0 to 9.5	9.24	8.056×10^{-7}	1.859×10^{-8}	7.069×10^{-8}	3.757×10^{-8}	7.98×10^{-8}
9.5 to 10.0	9.74	6.064×10^{-7}	1.456×10^{-8}	5.374×10^{-8}	2.833×10^{-8}	6.09×10^{-8}
10 to 12	10.82	2.724×10^{-7}	4.618×10^{-9}	2.433×10^{-8}	1.277×10^{-8}	2.73×10^{-8}
12 to 14	12.85	8.120×10^{-8}	2.161×10^{-9}	8.427×10^{-9}	3.820×10^{-9}	9.28×10^{-9}
14 to 16	14.88	2.801×10^{-8}	7.052×10^{-10}	3.275×10^{-9}	1.321×10^{-9}	3.53×10^{-9}
16 to 18	16.88	9.913×10^{-9}	3.704×10^{-10}	1.278×10^{-9}	4.683×10^{-10}	1.36×10^{-9}
18 to 20	18.89	4.569×10^{-9}	2.555×10^{-10}	6.198×10^{-10}	2.161×10^{-10}	6.57×10^{-10}
20 to 22	20.91	2.157×10^{-9}	1.416×10^{-10}	3.203×10^{-10}	1.021×10^{-10}	3.36×10^{-10}
22 to 24	22.92	1.183×10^{-9}	9.528×10^{-11}	2.224×10^{-10}	5.604×10^{-11}	2.29×10^{-10}
24 to 26	24.92	5.264×10^{-10}	5.920×10^{-11}	7.977×10^{-11}	2.494×10^{-11}	8.36×10^{-11}
26 to 30	27.74	2.427×10^{-10}	3.201×10^{-11}	6.191×10^{-11}	1.151×10^{-11}	6.30×10^{-11}
30 to 34	31.77	5.068×10^{-11}	1.326×10^{-11}	1.685×10^{-11}	2.404×10^{-12}	1.70×10^{-11}
34 to 44	37.15	2.263×10^{-11}	4.594×10^{-12}	4.757×10^{-12}	1.074×10^{-12}	4.88×10^{-12}

background fit and a GPR background fit with a radial-basis-function kernel.

2. Efficiencies and corrections

The MB-trigger efficiency is determined by finding the likelihood that an event containing an η meson reconstructed in the EMCal within a HPP-trigger sample also fired the MB trigger. It is found to be 0.91 ± 0.01 , consistent with the value used in the forward cross section measurement in Sec. III A 2. For the HPP trigger efficiency, a set of events uncorrelated with the η meson photon clusters was obtained by requiring the opposite arm to have fired the trigger. Among these events, the fraction of η mesons that had at least one of their underlying photon clusters also fire the HPP trigger defines the trigger efficiency. The efficiency reaches a plateau value of 0.95 at $p_T \gtrsim 8$ GeV/ c for the PbSc calorimeter and 0.67 at $p_T \gtrsim 9.5$ GeV/ c for the PbGl, as seen in Fig. 6(b). The difference in efficiencies between calorimeter types arises from a more-restrictive trigger masking in the case of the PbGl calorimeter. The efficiencies in the low p_T turn-on region were found to be consistent with an independent method of determining the efficiency using MB events.

The reconstruction efficiency was calculated using a well-validated PHENIX fast-Monte-Carlo framework [8,48] that contains a realistic description of the detector geometry with known smearing and inefficiency effects

[32]. A sample of single η mesons was generated flat within $1 < p_T < 50$ GeV/ c , weighted by the η meson p_T spectrum determined from a NLO-pQCD + AESSS calculation, and then fed into the detector simulation. The total reconstruction efficiency accounts for corrections stemming from acceptance, smearing due to imperfect detector resolution, and the cluster-energy-asymmetry cut, which is shown in Fig. 6(c). In the acceptance of the west(east) EMCal, an additional correction is needed for the 28%(8%) chance that either of the η -meson decay photons convert to e^+e^- in detector material near the beam pipe and are unable to be reconstructed in the EMCal.

3. Systematic uncertainties

Systematic uncertainties for the midrapidity cross section are determined independently for the PbSc west, PbSc east, and PbGl, and then averaged for the final systematic uncertainty. The uncorrelated systematic uncertainties for the midrapidity cross section include the description of the combinatorial background used in the yield extraction (2%–10%), the description of detector resolution (1.5%) and acceptance (3%) in the Monte Carlo, the EMCal energy nonlinearity (1%–10% increasing in p_T), the HPP trigger efficiency in the turn-on region (6%–3% decreasing in p_T), the multiple collision correction (2%), and the photon-conversion correction (4.3%). Correlated uncertainties are due to the EMCal energy scale (4%), and MB-trigger

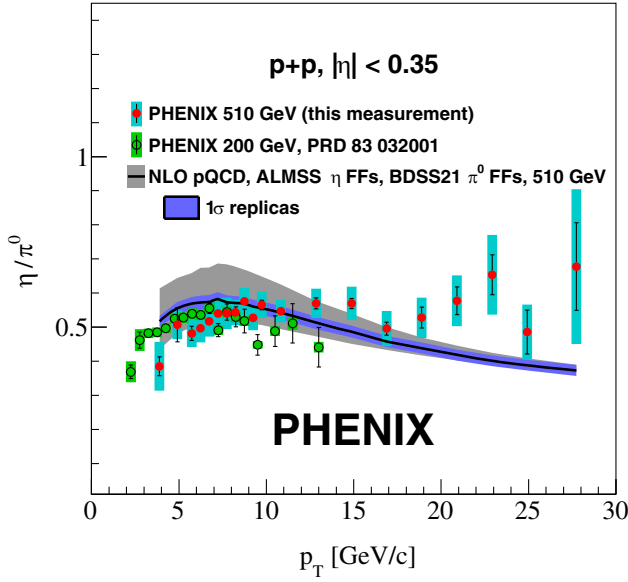


FIG. 8. The η/π^0 ratio at midrapidity in $\sqrt{s} = 510$ GeV $p + p$ collisions. Statistical uncertainties are shown in black uncertainty bars and systematic uncertainties in blue uncertainty boxes. NLO-pQCD predictions at $\sqrt{s} = 510$ GeV using the ALMSS (2025) η FFs [28] and BDSS21 π^0 FFs [22] are shown as the solid black line. The ratio measured by PHENIX at $\sqrt{s} = 200$ GeV [50] is shown with the open black circles, where statistical uncertainties are represented by the black uncertainty bars and systematic uncertainties by the green uncertainty boxes. The theoretical scale uncertainty is represented by the gray uncertainty band while the blue uncertainty band shows the 1σ standard deviation of the η/π^0 predictions across the final set of ALMSS η FF replicas.

efficiency coupled with the normalization of the HPP and MB datasets due to trigger scale downs (1%–2%). As in the forward cross section, correlated systematic uncertainties are treated as fully correlated across p_T bins and a 9.3% global scale uncertainty is fully correlated with the forward measurement.

4. Cross section results

The final invariant cross section of inclusive η mesons for $3.5 < p_T < 44$ GeV/ c and $|\eta| < 0.35$ is shown in Fig. 7 and listed in Table II. The cross section has been measured independently in the PbSc west, PbSc east, and PbGl calorimeters, which agree within the statistical and systematic uncertainties. The final cross section is calculated as the weighted average of these independent cross-section measurements and is reported at the mean- p_T value in each bin, so the bin shift correction introduced in the forward cross section was not applied. In the p_T overlap region of the MB and HPP-triggered data between 5.5 and 8.0 GeV/ c , the independently determined cross sections based on the two datasets agree with one another. Only the HPP-triggered cross section is included in the final cross section within this overlap region. Figure 7 shows the

TABLE III. The midrapidity η/π^0 at $\sqrt{s} = 510$ GeV, as shown in Fig. 8.

p_T bin [GeV/ c]	p_T [GeV/ c]	η/π^0	σ_{stat}	σ_{syst} (Uncorrelated)
3.5 to 4.5	3.89	3.851×10^{-1}	2.791×10^{-2}	7.027×10^{-2}
4.5 to 5.5	4.91	5.068×10^{-1}	5.040×10^{-2}	4.054×10^{-2}
5.5 to 6.0	5.73	4.816×10^{-1}	2.086×10^{-2}	3.846×10^{-2}
6.0 to 6.5	6.23	4.967×10^{-1}	4.398×10^{-3}	3.997×10^{-2}
6.5 to 7.0	6.73	5.167×10^{-1}	5.986×10^{-3}	4.319×10^{-2}
7.0 to 7.5	7.23	5.395×10^{-1}	6.522×10^{-3}	4.272×10^{-2}
7.5 to 8.0	7.74	5.407×10^{-1}	7.867×10^{-3}	4.454×10^{-2}
8.0 to 8.5	8.24	5.431×10^{-1}	9.122×10^{-3}	3.627×10^{-2}
8.5 to 9.0	8.74	5.755×10^{-1}	1.091×10^{-2}	3.841×10^{-2}
9.0 to 9.5	9.24	5.276×10^{-1}	1.259×10^{-2}	3.500×10^{-2}
9.5 to 10.0	9.74	5.651×10^{-1}	1.412×10^{-2}	3.635×10^{-2}
10 to 12	10.82	5.465×10^{-1}	9.602×10^{-3}	3.122×10^{-2}
12 to 14	12.85	5.694×10^{-1}	1.587×10^{-2}	4.153×10^{-2}
14 to 16	14.88	5.693×10^{-1}	1.486×10^{-2}	4.738×10^{-2}
16 to 18	16.88	4.956×10^{-1}	1.917×10^{-2}	4.985×10^{-2}
18 to 20	18.89	5.278×10^{-1}	3.064×10^{-2}	5.735×10^{-2}
20 to 22	20.91	5.774×10^{-1}	4.054×10^{-2}	7.302×10^{-2}
22 to 24	22.92	6.538×10^{-1}	5.836×10^{-2}	1.155×10^{-1}
24 to 26	24.92	4.856×10^{-1}	6.449×10^{-2}	7.901×10^{-2}
26 to 30	27.74	6.776×10^{-1}	1.285×10^{-1}	2.250×10^{-1}

comparison of the cross section to NLO-pQCD calculations [28,49] with the ALMSS η meson FFs and AESSS FFs, showing good agreement with both predictions within statistical, systematic, and theoretical uncertainties. As in the case of the forward cross section, the ALMSS FF fit was repeated excluding this specific measurement and the corresponding predicted cross section utilizing the modified FFs was found to be consistent with the prediction from the full ALMSS FFs.

C. The midrapidity η/π^0 ratio at $\sqrt{s} = 510$ GeV

Using the midrapidity π^0 cross section at $\sqrt{s} = 510$ GeV [8] from the same 2013 dataset as the η meson cross section, we report the measurement of the η/π^0 ratio with the highest recorded p_T to date at RHIC. Figure 8 and Table III show the midrapidity η/π^0 ratio. The ratio can serve as a powerful input to FF global fits as any shared systematic uncertainties between the cross sections cancel. However, as cautioned in [28], care must be taken because inaccuracies in the individual η and π^0 FFs can be obscured when looking at the ratio alone. Figure 8 shows the ratio along with an earlier PHENIX measurement of the midrapidity ratio at $\sqrt{s} = 200$ GeV [50] compared to a NLO-pQCD calculation at $\sqrt{s} = 510$ GeV that uses the ALMSS η FFs and the BDSS21 π^0 FFs [22].

At $p_T > 8$ GeV/ c , the ratio saturates at 0.54 ± 0.03 , consistent with the behavior observed at lower energy from ISR [51], PHENIX [50] and STAR [25,52] and higher

energy results from ALICE [53]. This saturation of the ratio at high p_T has been found across a wide range of additional measurements with different energies and collision systems [54]. This suggests that η and π^0 production at high p_T is generated through some universal fragmentation mechanism that is relatively robust to differences in energy, p_T , and the nuclear medium. Any difference between η and π^0 production at high p_T originating from the enhanced contribution of strange quark and gluon fragmentation into η mesons appears to be limited. The high p_T saturation behavior is consistent with empirical models of simple transverse-mass scaling of the π^0 spectrum. Recent ALICE results [53] have shown the breakdown of transverse mass scaling at low p_T , suggesting a more complicated interplay of fragmentation contributions at p_T below the reach of this measurement.

IV. SUMMARY

The forward η -meson cross section at $\sqrt{s} = 500$ GeV, as well as the midrapidity η -meson cross section and η/π^0 ratio at $\sqrt{s} = 510$ GeV, were measured at PHENIX. Utilizing the cross sections, a new global η -meson-FF fit reported in Ref. [28] has been performed at NLO accuracy, with improved constraints compared to the previous η -meson FFs [23] and the ability to simultaneously describe η -meson production from RHIC, the LHC, and high-statistics e^+e^- data from Belle. Theoretical predictions at NLO, utilizing both the updated FFs as well as the previous set of FFs, are consistent with the cross section measurements reported in this article within theoretical uncertainties.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The values in the plots and tables associated with this article are stored in HEPData [44].

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- [1] J. C. Collins, D. E. Soper, and G. F. Sterman, Factorization of hard processes in QCD, *Adv. Ser. Dir. High Energy Phys.* **5**, 1 (1989).
 - [2] J. Adams *et al.* (STAR Collaboration), Identified hadron spectra at large transverse momentum in $p + p$ and $d + \text{Au}$ collisions at $\sqrt{s} = 200$ GeV, *Phys. Lett. B* **637**, 161 (2006).
 - [3] J. Adams *et al.* (STAR Collaboration), Forward neutral pion production in $p + p$ and $d + \text{Au}$ collisions at $\sqrt{s} = 200$ GeV, *Phys. Rev. Lett.* **97**, 152302 (2006).
 - [4] B. I. Abelev *et al.* (STAR Collaboration), Longitudinal double-spin asymmetry and cross section for inclusive neutral

- pion production at midrapidity in polarized proton collisions at $\sqrt{s} = 200$ GeV, *Phys. Rev. D* **80**, 111108 (2009).
- [5] G. Agakishiev *et al.* (STAR Collaboration), Identified hadron compositions in $p + p$ and $\text{Au} + \text{Au}$ collisions at high transverse momenta at $\sqrt{s_{NN}} = 200$ GeV, *Phys. Rev. Lett.* **108**, 072302 (2012).
- [6] L. Adamczyk *et al.* (STAR Collaboration), Neutral pion cross section and spin asymmetries at intermediate pseudorapidity in polarized proton collisions at $\sqrt{s} = 200$ GeV, *Phys. Rev. D* **89**, 012001 (2014).
- [7] A. Adare *et al.* (PHENIX Collaboration), Inclusive cross-section and double helicity asymmetry for π^0 production

- in $p + p$ collisions at $\sqrt{s} = 200$ GeV: Implications for the polarized gluon distribution in the proton, *Phys. Rev. D* **76**, 051106 (2007).
- [8] A. Adare *et al.* (PHENIX Collaboration), Inclusive cross section and double-helicity asymmetry for π^0 production at midrapidity in $p + p$ collisions at $\sqrt{s} = 510$ GeV, *Phys. Rev. D* **93**, 011501 (2016).
- [9] B. Abelev *et al.* (ALICE Collaboration), Neutral pion and η -meson production in proton-proton collisions at $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 7$ TeV, *Phys. Lett. B* **717**, 162 (2012).
- [10] S. Acharya *et al.* (ALICE Collaboration), π^0 and η -meson production in proton-proton collisions at $\sqrt{s} = 8$ TeV, *Eur. Phys. J. C* **78**, 263 (2018).
- [11] S. Acharya *et al.* (ALICE Collaboration), Production of π^0 and η mesons up to high transverse momentum in pp collisions at 2.76 TeV, *Eur. Phys. J. C* **77**, 339 (2017).
- [12] S. Acharya *et al.* (ALICE Collaboration), Production of light-flavor hadrons in pp collisions at $\sqrt{s} = 7$ and $\sqrt{s} = 13$ TeV, *Eur. Phys. J. C* **81**, 256 (2021).
- [13] K. Abe *et al.* (SLD Collaboration), Production of π^+ , K^+ , K^0 , K^{*0} , ϕ , p , and Λ^0 in hadronic Z^0 decays, *Phys. Rev. D* **59**, 052001 (1999).
- [14] D. Buskulic *et al.* (ALEPH Collaboration), Inclusive $\pi^\pm$, $K^\pm$, p , and $\bar{p}$ differential cross-sections at the Z resonance, *Z. Phys. C* **66**, 355 (1995).
- [15] P. Abreu *et al.* (DELPHI Collaboration), $\pi^\pm$, $K^\pm$, p , and $\bar{p}$ production in $Z^0 \rightarrow q\bar{q}$, $Z^0 \rightarrow b\bar{b}$, $Z^0 \rightarrow u\bar{u}$, $d\bar{d}$, and $s\bar{s}$, *Eur. Phys. J. C* **5**, 585 (1998).
- [16] R. Seidl *et al.* (Belle Collaboration), Update of inclusive cross sections of single and pairs of identified light charged hadrons, *Phys. Rev. D* **101**, 092004 (2020).
- [17] J. P. Lees *et al.* (BABAR Collaboration), Production of charged pions, kaons, and protons in e^+e^- annihilations into hadrons at $\sqrt{s} = 10.54$ GeV, *Phys. Rev. D* **88**, 032011 (2013).
- [18] A. Airapetian *et al.* (HERMES Collaboration), Multiplicities of charged pions and kaons from semi-inclusive deep-inelastic scattering by the proton and the deuteron, *Phys. Rev. D* **87**, 074029 (2013).
- [19] C. Adolph *et al.* (COMPASS Collaboration), Multiplicities of charged pions and charged hadrons from deep-inelastic scattering of muons off an isoscalar target, *Phys. Lett. B* **764**, 1 (2017).
- [20] D. de Florian, R. Sassot, and M. Stratmann, Global analysis of fragmentation functions for pions and kaons and their uncertainties, *Phys. Rev. D* **75**, 114010 (2007).
- [21] D. de Florian, R. Sassot, M. Epele, R. J. Hernández-Pinto, and M. Stratmann, Parton-to-pion fragmentation reloaded, *Phys. Rev. D* **91**, 014035 (2015).
- [22] I. Borsa, D. de Florian, R. Sassot, and M. Stratmann, Pion fragmentation functions at high energy colliders, *Phys. Rev. D* **105**, L031502 (2022).
- [23] C. A. Aidala, F. Ellinghaus, R. Sassot, J. P. Seele, and M. Stratmann, Global analysis of fragmentation functions for Eta mesons, *Phys. Rev. D* **83**, 034002 (2011).
- [24] A. Adare *et al.* (PHENIX Collaboration), Cross section and transverse single-spin asymmetry of η mesons in $p^\uparrow + p$ collisions at $\sqrt{s} = 200$ GeV at forward rapidity, *Phys. Rev. D* **90**, 072008 (2014).
- [25] B. I. Abelev *et al.* (STAR Collaboration), Inclusive π^0 , η , and direct photon production at high transverse momentum in $p + p$ and $d + \text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV, *Phys. Rev. C* **81**, 064904 (2010).
- [26] R. Aaij *et al.* (LHCb Collaboration), Production of η and η' mesons in pp and $p\text{Pb}$ collisions, *Phys. Rev. C* **109**, 024907 (2024).
- [27] R. Seidl *et al.* (Belle Collaboration), Production cross sections of light and charmed mesons in e^+e^- annihilation near 10.58 GeV, *Phys. Rev. D* **111**, 052003 (2025).
- [28] C. A. Aidala, D. A. Loomis, R. T. Martinez, R. Sassot, and M. Stratmann, companion article, Eta fragmentation functions revisited, *Phys. Rev. D* **113**, 092012 (2026).
- [29] B. Jager, A. Schafer, M. Stratmann, and W. Vogelsang, Next-to-leading order QCD corrections to high $p(T)$ pion production in longitudinally polarized pp collisions, *Phys. Rev. D* **67**, 054005 (2003).
- [30] W. Vogelsang, (private communication).
- [31] K. Adcox *et al.* (PHENIX Collaboration), PHENIX detector overview, *Nucl. Instrum. Methods Phys. Res., Sect. A* **499**, 469 (2003).
- [32] L. Aphecetche *et al.* (PHENIX Collaboration), PHENIX calorimeter, *Nucl. Instrum. Methods Phys. Res., Sect. A* **499**, 521 (2003).
- [33] K. Adcox *et al.* (PHENIX Collaboration), PHENIX central arm tracking detectors, *Nucl. Instrum. Methods Phys. Res., Sect. A* **499**, 489 (2003).
- [34] M. Aizawa *et al.* (PHENIX Collaboration), PHENIX central arm particle ID detectors, *Nucl. Instrum. Methods Phys. Res., Sect. A* **499**, 508 (2003).
- [35] H. Aikawa *et al.* (PHENIX Collaboration), PHENIX muon arms, *Nucl. Instrum. Methods Phys. Res., Sect. A* **499**, 537 (2003).
- [36] M. Allen *et al.* (PHENIX Collaboration), PHENIX inner detectors, *Nucl. Instrum. Methods Phys. Res., Sect. A* **499**, 549 (2003).
- [37] A. Adare *et al.* (PHENIX Collaboration), Measurement of transverse-single-spin asymmetries for midrapidity and forward-rapidity production of hadrons in polarized $p + p$ collisions at $\sqrt{s} = 200$ and 62.4 GeV, *Phys. Rev. D* **90**, 012006 (2014).
- [38] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [39] C. E. Rasmussen and C. K. I. Williams, *Gaussian Processes for Machine Learning* (MIT Press, Boston, USA, 2006).
- [40] S. Agostinelli *et al.* (Geant4 Collaboration), Geant4- A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [41] T. Sjostrand, S. Mrenna, and P. Z. Skands, Pythia 6.4 Physics and Manual, *J. High Energy Phys.* **05** (2006) 026.
- [42] R. D. Field (CDF Collaboration), The underlying event in hard scattering processes, *eConf* **C010630**, P501 (2001).
- [43] M. G. Albrow *et al.* (TeV4LHC QCD Working Group), Tevatron-for-LHC Report of the QCD Working Group (2006).
- [44] <https://www.hepdata.net/record/166316>.
- [45] G. Lafferty and T. Wyatt, Where to stick your data points: The treatment of measurements within wide bins, *Nucl. Instrum. Methods Phys. Res., Sect. A* **355**, 541 (1995).

- [46] S. Bailey, T. Cridge, L. A. Harland-Lang, A. D. Martin, and R. S. Thorne, Parton distributions from LHC, HERA, Tevatron and fixed target data: MSHT20 PDFs, *Eur. Phys. J. C* **81**, 341 (2021).
- [47] T.-J. Hou *et al.*, New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC, *Phys. Rev. D* **103**, 014013 (2021).
- [48] U. Acharya *et al.* (PHENIX Collaboration), Measurement of direct-photon cross section and double-helicity asymmetry at $\sqrt{s} = 510$ GeV in $p \rightarrow +p \rightarrow$ collisions, *Phys. Rev. Lett.* **130**, 251901 (2023).
- [49] W. Vogelsang (private communication).
- [50] A. Adare *et al.* (PHENIX Collaboration), Cross section and double helicity asymmetry for η mesons and their comparison to neutral pion production in $p + p$ collisions at $\sqrt{s} = 200$ GeV, *Phys. Rev. D* **83**, 032001 (2011).
- [51] C. Kourkouvelis *et al.*, Inclusive η production at high p_T at the ISR, *Phys. Lett.* **84B**, 277 (1979).
- [52] L. Adamczyk *et al.* (STAR Collaboration), Transverse single-spin asymmetry and cross section for π^0 and η mesons at large feynman x in $p^\uparrow + p$ collisions at $\sqrt{s}=200$ GeV, *Phys. Rev. D* **86**, 051101 (2012).
- [53] S. Acharya *et al.*, π^0 and η meson production in proton-proton collisions at $\sqrt{s} = 8$ TeV, *Eur. Phys. J. C* **78**, 263 (2018).
- [54] Y. Ren and A. Drees, Examination of the universal behavior of the η -to- π^0 ratio in heavy-ion collisions, *Phys. Rev. C* **104**, 054902 (2021).

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