Cross section and double helicity asymmetry for eta mesons and their comparison to pi(0) production in p plus p collisions at root s=200 GeV

Andrew Adare  
*University of Colorado, Boulder*

Nathan C. Grau  
*Iowa State University*

John C. Hill  
*Iowa State University, jhill@iastate.edu*

Todd Kempel  
*Iowa State University, todd.kempel@gmail.com*

John G. Lajoie  
*Iowa State University, lajoie@iastate.edu*

*See next page for additional authors*

Follow this and additional works at: [http://lib.dr.iastate.edu/physastro_pubs](http://lib.dr.iastate.edu/physastro_pubs)

Part of the [Elementary Particles and Fields and String Theory Commons](http://lib.dr.iastate.edu/physastro_pubs)

The complete bibliographic information for this item can be found at [http://lib.dr.iastate.edu/physastro_pubs/291](http://lib.dr.iastate.edu/physastro_pubs/291). For information on how to cite this item, please visit [http://lib.dr.iastate.edu/howtocite.html](http://lib.dr.iastate.edu/howtocite.html).

This Article is brought to you for free and open access by the Physics and Astronomy at Iowa State University Digital Repository. It has been accepted for inclusion in Physics and Astronomy Publications by an authorized administrator of Iowa State University Digital Repository. For more information, please contact [digirep@iastate.edu](mailto:digirep@iastate.edu).
Cross section and double helicity asymmetry for eta mesons and their comparison to pi(0) production in p plus p collisions at root s=200 GeV

Abstract
Measurements of double-helicity asymmetries in inclusive hadron production in polarized p + p collisions are sensitive to helicity-dependent parton distribution functions, in particular, to the gluon helicity distribution, Delta g. This study focuses on the extraction of the double-helicity asymmetry in eta production ((p) over right arrow + (p) over right arrow -> eta + X), the eta cross section, and the eta/pi(0) cross section ratio. The cross section and ratio measurements provide essential input for the extraction of fragmentation functions that are needed to access the helicity-dependent parton distribution functions.

Disciplines
Elementary Particles and Fields and String Theory | Physics

Comments

Authors
Andrew Adare, Nathan C. Grau, John C. Hill, Todd Kempel, John G. Lajoie, Alexandre Lebedev, Craig Ogilvie, H. Pei, Marzia Rosati, Alexey Yu. Semenov, S. Skutnik, Carla Vale, Feng Wei, et al., and PHENIX Collaboration

This article is available at Iowa State University Digital Repository: http://lib.dr.iastate.edu/physastro_pubs/291
Cross section and double helicity asymmetry for $\eta$ mesons and their comparison to $\pi^0$ production in $p + p$ collisions at $\sqrt{s} = 200$ GeV

L. Aphicetche,55 R. Armendariz,24 S. H. Aronson,6 J. Asai,47,48 E. T. Atomssa,31 R. Averbeck,54 T. C. Awes,43
B. Azmoun,6 V. Babintsev,21 M. Bai,2 G. Baksay,57 L. Baksay,17 A. Baldissieri,14 K. N. Barish,7 P. D. Barnes,53
B. Bassalleck,41 A. T. Basye,1 S. Bathe,7 S. Batsouli,33 V. Baublis,46 C. Baumann,37 A. Bazilevsky,6 S. Belikov,6,*
R. Bennett,54 A. Berdnikov,50 Y. Berdnikov,50 A. A. Bickley,11 J. G. Boissevain,33 H. Borel,14 K. Boyle,54 M. L. Brooks,33
H. Buesching,6 V. Burnazhnov,21 G. Bunce,6,48 S. Butsyk,35,44 C. M. Camacho,33 S. Campbell,54 B. S. Chang,62
T. Chjuo,58,59 P. Chung,53 A. Churyu,21 V. Cianciolo,43,50 Z. Citron,54 C. R. Cleven,9 A. B. Cole,12 M. P. Comets,44
P. Constantin,33 M. Csanád,16 T. Csörgő,27 T. Dahms,54 S. Dairaku,30,47 K. Das,18 G. David,6 M. B. Deaton,1 K. Dehmelt,17
H. Delagrange,55 A. Denisov,21 D. d’Enterría,12,31 A. Deshpande,48,45 E. J. Desmond,6 O. Dietzsch,51 A. Dion,54
Y. V. Efremenko,33 J. Egdemir,54 F. Ellinghaus,11 W. S. Emmam,7 T. Engelmore,12 A. Enokizono,32 H. En’yo,47,48
S. Esumi,58 K. O. Eyser,7 B. Fadem,38 D. E. Fields,41 M. Finger,9,8 S. D. Rolnick,7 A. Romana,31,* M. Rosati,24 S. S. E. Rosendahl,35
B. K. Singh,3 C. P. Singh,3 V. Singh,3 S. Skutnik,24 M. Slunceka,8,25 A. Soldatov,21 R. A. Soltz,32 W. E. Sondheim,33
T. Sugitate,20 C. Suire,44 A. Sukhanov,6 J. Sziklai,27 T. Tabaru,58 S. Takagi,58 E. M. Takagui,51 A. Takeda,57,47,48

PHYSICAL REVIEW D 83, 032001 (2011)

2011 American Physical Society
I. INTRODUCTION

Until recently, the knowledge about helicity-dependent parton distribution functions (PDFs) in the nucleon mainly came from next-to-leading order (NLO) QCD fits (see, e.g., [1]) to the helicity-dependent structure function $g_1$, as measured in fixed-target polarized inclusive deep-inelastic scattering (DIS) experiments (see, e.g., [2,3]). The resulting helicity-dependent PDF for the gluon has rather large uncertainties due to the fact that the exchanged virtual photon does not couple directly, i.e., at leading order, to the gluon, and that an indirect way of accessing it via NLO fits to $g_1$ suffers from the limited kinematic reach of the fixed target experiments. Accessing the helicity-dependent gluon PDF via the so-called photon-gluon-fusion process in semi-inclusive DIS has not yet resulted in better constraints, see Refs. [4,5] and references therein for details. Thus, additional data from polarized $p + p$ collisions are needed in the case of longitudinally polarized gluons and quarks. This is especially true for the fragmentation functions, which are sensitive to helicity-dependent parton helicity distributions, the fragmentation functions are assumed to be spin independent.

The double-helicity asymmetry in inclusive hadron production is given as

\[
A_{LL} = \frac{\sigma^{++} - \sigma^{-+}}{\sigma^{++} + \sigma^{-+}} = \sum_{abc} \Delta f_a \otimes \Delta f_b \otimes \Delta \tilde{\sigma}^{ab-c\Xi} \otimes D_h^c / 2\sigma,
\]

where the cross section $\sigma^{++}$ ($\sigma^{-+}$) describes the reaction where both protons have the same (opposite) helicity. The helicity-independent cross section is defined as $\sigma = (\sigma^{++} + \sigma^{-+})/2$. The helicity-dependent decomposition of the numerator is given on the right-hand side of Eq. (1), where $\Delta f_a$, $\Delta f_b$ represent the helicity-dependent PDFs for quarks or gluons, and $\Delta \tilde{\sigma}$ are the helicity-dependent hard scattering cross sections calculable in perturbative QCD (pQCD). The kinematic dependences of these terms are omitted for simplicity. At leading order (LO) the fragmentation functions $D_h^c$ can be interpreted as the probability for a certain parton $c$ to fragment into a certain hadron $h$ and thus they are not needed in the case of jet and direct photon production. In current global fits of parton helicity distributions, the fragmentation functions are assumed to be spin independent.

This study focuses on the midrapidity cross section and double-helicity asymmetry in inclusive $\eta$ production ($\bar{p} + \bar{p} \rightarrow \eta + X$) as a function of transverse momentum ($p_T$) and the $\eta/\pi^0$ cross section ratio at $\sqrt{s} = 200$ GeV measured at the PHENIX experiment at RHIC. The measurement of the $\eta$ double-helicity asymmetry adds independent data with different systematics to the present set of polarized data available to PDF fits. Even when compared to a closely related data set, e.g., the PHENIX $\pi^0$ data on double-helicity asymmetries, the difference in the
fragmentation functions can lead to a different sensitivity to certain helicity-dependent PDFs. In contrast to the \(p^0\), the experimental data available to extract \(\eta\) fragmentation functions is rather limited. The existing \(\eta\) cross section measurements from the charged-particle collider data can constrain the quark fragmentation functions to some degree, but the extraction of gluon fragmentation functions requires either rather precise \(e^+ + e^-\) data taken in a wide range of center of mass energies, or cross section measurements from processes where gluons are directly involved, e.g., \(p + p\) scattering. Therefore, the data on cross sections and cross section ratios presented here serve as important input for the extraction of fragmentation functions, in particular, as the measurement has been performed over a wide range of \(p_T\).

II. EXTRACTION OF \(\eta\) AND \(p^0\) YIELDS

The \(\eta\) (\(p^0\)) meson is reconstructed through its main decay channel, \(\eta(p^0) \rightarrow \gamma\gamma\), with a branching ratio (BR) of about 39% (99%) [11]. The data were taken at the PHENIX [12] experiment in 2005 and 2006. After data quality and vertex cuts, 2.5 pb\(^{-1}\) from the 2005 data and 6.5 pb\(^{-1}\) from the 2006 data are used for the analysis. The data sets from both years are used for the extraction of the statistics-limited double-helicity asymmetry in \(\eta\) production while only the larger data set from 2006 is used for the extraction of the predominantly systematics-limited cross section measurements. Note that the analysis described in the following, including all cuts, is done in the exact same way for the \(\eta\) and the \(p^0\) meson in order to minimize the systematic uncertainties on the \(\eta/p^0\) cross section ratio presented below.

Two data sets have been analyzed, collected by requiring two different trigger selections. The minimum bias (MB) trigger requires coincident signals in two beam-beam counters (BBCs) [13], which are arrays of quartz-radiator Čerenkov counters providing full azimuthal coverage at pseudorapidities of \(3.0 < \eta < 3.9\). Based on the timing of the signals from the two BBCs, the event vertex is reconstructed and required to be within 30 cm of the nominal interaction point. In addition to the MB trigger, the high-\(p_T\) triggered data set requires an energy deposition larger than approximately 1.4 GeV in an area of \(4 \times 4\) towers in the electromagnetic calorimeter (EMCal) [14].

The EMCal is the primary detector used in this analysis, located at a radial distance of about 5 m from the beam pipe. It covers the pseudo-rapidity range \(|\eta| < 0.35\) and has an azimuthal acceptance of \(\Delta \phi = \pi\). The EMCal comprises eight sectors, six of which are composed of a total of 15 552 lead-scintillator sandwich towers (5.5 cm \(\times 5.5\) cm \(\times 37.5\) cm), and two sectors of leadglass Čerenkov calorimeters, consisting of a total of 9216 towers (4 cm \(\times 4\) cm \(\times 40\) cm). For the cross section measurements only the lead scintillator was used.

A cluster in the EMCal is assumed to originate from a photon if the following criteria are met. First, since showers in the EMCal are not confined to a single tower, a shower profile analysis can be used to reject hadrons, which usually produce broader showers than photons. Since hadrons are slower than photons, an additional time of flight cut is used for photon identification. Furthermore, the cluster must not be associated with a hit from a charged particle in the pad chamber (PC3) just in front of the EMCal; an exception is made if the hit position in the EMCal and that in the PC3 are aligned in such a way that the particle could have come from the vertex on a straight line, i.e., it was not bent in the central magnetic field. In this case, the cluster is accepted as a photon candidate since it is likely that the original photon converted into an \(e^+e^-\) pair before the PC3 but outside the magnetic field. The latter two selection cuts are used in the analysis of the double-helicity asymmetry but not in the extraction of the cross sections, leading to a smaller signal to background ratio in the cross section measurements. In order to exclude clusters with potentially incorrectly reconstructed energies due to leakage effects, the tower with the largest energy deposition in a cluster must not be in the outermost two columns or rows of an EMCal sector. In addition, there must not be a noisy or dead tower in the eight towers surrounding the central one.

Using all possible pairs of photon candidates, the two-photon invariant mass spectrum is calculated. An upper limit of 0.7 is placed on the energy asymmetry, \(|E_1 - E_2|/(E_1 + E_2)|\) of the two cluster energies, \(E_1\) and \(E_2\), in order to reduce the combinatorial background due to numerous low-energy background clusters. It is also checked that either of the two clusters coincides with an area in the EMCal that caused a high-\(p_T\) trigger. Finally, the \(p_T\) of the diphoton is required to be larger than 2 GeV/c. At smaller \(p_T\), the uncertainties in the cross section extraction become too large due to large backgrounds and limited acceptance.

The \(\eta\) and \(p^0\) cross sections and the \(\eta\) double-helicity asymmetry are extracted in bins of \(p_T\). Using the selection cuts for the cross section extraction on the high-\(p_T\) triggered data set, the resulting invariant mass distributions in the vicinity of the \(\eta\) peak are shown in Fig. 1 for three different bins of \(p_T\). For bins at small \(p_T\), the signal extraction is based on fits to the invariant mass distributions using a Gaussian for the signal plus a second-order polynomial for the background that describe the vicinity of the \(\eta\) and \(p^0\) peaks very well. For \(p_T \gtrsim 10\) GeV/c the signal extraction based on fits becomes unreliable as limited statistics leads to large fluctuations in the fit results for the mean and width of the peaks. Therefore, the mean and width are taken from a Monte-Carlo simulation, which describes the mean and width of the \(\eta\) and \(p^0\) peaks as a function of \(p_T\) very well for bins in the mid-\(p_T\) range between 3 GeV/c and 10 GeV/c, giving confidence in
using them for the bins above. This is demonstrated in Fig. 2 for the case of $/C^{17}$ production. The small discrepancies at $p_T < 3$ GeV/c are due to the large background underneath the peak, as can be seen in the top panel of Fig. 1, which is not modeled in the MC. Thus, above $p_T = 3$ GeV/c the number of background counts under the signal peak can be estimated by using the number of counts in the sidebands. The sidebands are on both sides of the mean of the peak, between 4 and 7 (4 and 6) times the Gaussian width of the peak for the cross section (double-helicity asymmetry) analysis. However, the exact position and width of the sidebands are varied and possible effects are taken into account in the systematic uncertainty. In the mid-$p_T$ range between 3 GeV/c and 10 GeV/c, where statistics is sufficient for the fit results to be stable and the background in the vicinity of the peaks is approximately linear so that the sideband subtraction is applicable, both methods agree as expected.

III. THE $\eta$ CROSS SECTION AND $\eta/\pi^0$ CROSS SECTION RATIO

The $\eta$ and $\pi^0$ meson cross sections are calculated from

$$E \frac{d^4\sigma}{d^3p} = \frac{1}{2\pi p_T} \frac{1}{BR} \frac{1}{L} \frac{1}{A\epsilon_{\text{trig}}\epsilon_{\text{rec}}} N(\Delta p_T, \Delta y),$$

where $L$ denotes the integrated luminosity, $A$ the acceptance, $\epsilon_{\text{trig}}$ the trigger efficiency, $\epsilon_{\text{rec}}$ the reconstruction efficiency, and $N$ the number of reconstructed mesons.

The luminosity is calculated from the number of MB events divided by the cross section for events selected by the MB trigger. For the latter, a value of 23.0 mb with a systematic uncertainty of 9.7% has been derived from Vernier scan results [15] and an extrapolation for subsequent years. The acceptance is calculated from a Monte Carlo simulation using, as an input, the map of

![FIG. 1](image1.png)

FIG. 1. The invariant mass distributions in the vicinity of the $\eta$ peak for the high-$p_T$ triggered data set and for three different bins of $p_T$. The selection cuts for the cross section extraction are used.

![FIG. 2](image2.png)

FIG. 2 (color online). The mean and width of the $\eta$ peaks as a function of $p_T$ for the high-$p_T$ triggered data set and the MC. The selection cuts for the cross section extraction are used.
noisy and dead cells also used in the data analysis. The systematic uncertainty on the acceptance calculation is 3.6% (3%) for the \( \eta \) (\( \pi^0 \)) meson. The trigger efficiency for the MB data is given by the MB trigger efficiency for \( \eta \) and \( \pi^0 \) production. The trigger efficiency for the high-\( p_T \) triggered data set is given by the MB trigger efficiency times the efficiency of the high-\( p_T \) trigger. The MB (high-\( p_T \)) trigger efficiency is determined by the ratio of the number of reconstructed \( \pi^0 \) or \( \eta \) mesons in a high-\( p_T \) (MB) triggered sample in coincidence with the MB (high-\( p_T \)) trigger divided by the number of reconstructed \( \pi^0 \) or \( \eta \) events without the coincidence. The MB trigger efficiency is 0.78 for both \( \pi^0 \) and \( \eta \) mesons over the whole range of \( p_T \) considered, with a systematic uncertainty of 3%. The high-\( p_T \) trigger efficiency reaches a plateau at a level of 0.90 for \( p_T > 4.5 \text{ GeV}/c \) and is also very similar for both mesons. Because of the fact that the turn-on curve of the high \( p_T \) trigger is very steep and reaches an efficiency of about 0.80 in the \( 3 < p_T < 3.5 \text{ GeV}/c \) bin, the efficiency for \( p_T < 3 \text{ GeV}/c \) has a large systematic uncertainty. Therefore, the cross section calculation is based on the smaller MB triggered data set for \( p_T < 3 \text{ GeV}/c \) and on the high-\( p_T \) triggered data set for larger transverse momenta. The reconstruction efficiency accounts for the loss of photons due to conversion (6% \( \pm 2\% \)) and due to the cut on the shower shape discussed above (4% \( \pm 2\% \)). In the case of \( \pi^0 \) production, merging of the two decay photons into a single cluster is considered for \( p_T > 10 \text{ GeV}/c \).

The \( \eta \) cross section as a function of \( p_T \) between 2 and 20 \( \text{ GeV}/c \) is shown in Fig. 3 and tabulated in Table I. Note that a bin-shift correction is applied in order to be able to plot each data point at the center of each given \( p_T \) bin, which, due to the exponentially falling spectrum, does not represent the true physical value of the yield in that bin [16]. This, in particular, facilitates the calculation of the \( \eta/\pi^0 \) cross section ratio.

The \( \eta \) cross section is consistent with an earlier PHENIX measurement [17] covering a smaller range in \( p_T \) from 2.5 to 12 \( \text{ GeV}/c \). The error bars shown in Fig. 3 are the statistical and systematic uncertainties added in quadrature. Not included is an overall normalization uncertainty of 9.7% due to the uncertainty in the luminosity measurement. The other dominant systematic uncertainties are an approximately \( p_T \)-independent uncertainty of about 8% due to the uncertainty on the global energy scale of 1.2%, possible nonlinearities in the energy scale affecting mainly points with \( p_T > 10 \text{ GeV}/c \), and uncertainties from the signal extraction affecting principally the two lowest \( p_T \) points, which have a large background underneath the \( \eta \) peak. The systematic uncertainties are subdivided into uncertainties that are uncorrelated between \( p_T \) bins (type-A), correlated between \( p_T \) bins (type-B), and overall normalization uncertainties (type-C). As described above, the peak extraction is based on different methods depending on \( p_T \). Thus, the \( p_T \) bins in certain regions are correlated, but there is no full correlation over the whole range. This kind of uncertainty is subcategorized as type-\( B_1 \), in order to distinguish from those correlated over all \( p_T \) bins (type-\( B_2 \)). All other uncertainties, except the one from the luminosity measurement (type-\( C \)), are assumed to be in this category.

The \( \eta \) cross section from \( p + p \) scattering presented here, together with the above mentioned earlier PHENIX data [17], and various \( \eta \) cross section measurements from \( e^+ e^- \) scattering have been used in a global fit to extract new fragmentation functions for \( \eta \) production at NLO [18]. The wide \( p_T \) range of this measurement, as compared to the earlier PHENIX measurement, which covers a range in \( p_T \) from 2.5 to 12 \( \text{ GeV}/c \), is important, because it allows for a much more stringent constraint on the \( \eta \) fragmentation function, as can be seen in Figs. 6 and 8 of Ref. [18].

Earlier determinations of \( \eta \) fragmentation functions based on SU(3) model estimates at LO and normalizations taken from a Monte Carlo event generator at NLO are described in Refs. [19–21], respectively. Because of the absence of data on semi-inclusive \( \eta \) production the fragmentation functions can only be extracted separately for each quark flavor with additional assumptions. The assumption that all light quark fragmentation functions are
the same, i.e., $D_\eta^\eta = D_\eta^\eta = D_\eta^\eta = D_\eta^\eta = D_\eta^\eta$, has been used in Ref. [18].

Using these new fragmentation functions and the CTEQ6M [22] PDFs as an input to the NLO code of Ref. [23], pQCD calculations at three different scales $\mu$ are carried out. Here, $\mu$ represents the factorization, renormalization and fragmentation scales, i.e., the three scales are set equal in each separate calculation. With these new fragmentation functions, for which the present data constitute nearly 20% of the input experimental data points, the cross section is described well.

The contributions of the various scattering subprocesses, gluon-gluon ($gg$), quark-gluon ($qg$), and quark-quark ($qq$), to the $\eta$ production as a function of $p_T$, are shown in Fig. 4. For comparison, they are also shown in the case of $\pi^0$ production [24]. While the corresponding uncertainties are difficult to quantify, it is clear that the subprocess contributions to the $\eta$ and $\pi^0$ production are, within uncertainties, identical up to a $p_T$ of approximately 10 GeV/$c$. This is the kinematic range of the $\eta$ and $\pi^0$ double-helicity asymmetries presented below and published in Refs. [7,8], respectively. Consequently, these measurements have approximately the same sensitivity to the gluon helicity distribution accessible via the $gg$ and $qg$ subprocesses. The differences at larger values of $p_T$ are mostly related to uncertainties in the fragmentation functions and thus do not necessarily indicate different sensitivities to polarized PDFs.

Constraining the fragmentation function further should be possible by including precise $\eta$ to $\pi^0$ cross section ratios in the extraction. The cross section ratio, as a function of $p_T$, is given in Fig. 5 and Table II. The ratio has been extracted in a single pass over the same data set, thus minimizing systematic uncertainties. In particular, the large normalization uncertainty of 9.7% arising from the luminosity calculation cancels completely. Also all other systematic uncertainties are assumed to either cancel or be reduced to a negligible amount with the exception of the following. The systematic uncertainties due to the $\eta$ and $\pi^0$ peak extraction (type-$B_1$) and due to the correction for possible merging of the two $\pi^0$ decay photons into a single cluster (type-$B_2$) do not cancel. Furthermore, while the uncertainties on the high-$p_T$ trigger efficiency (type-$B_2$) are assumed to cancel above $p_T = 4.5$ GeV/$c$ where the
efficiency is flat, a remaining 2\% uncertainty on the ratio is assigned for differences in the trigger turn-on curve for $3 < p_T < 4.5$ GeV/c. Finally, the systematic uncertainty on the acceptance (type-$B_2$) is reduced to a $p_T$ independent contribution of 2\%. The ratio is presented up to $p_T = 14$ GeV/c only, as beyond this point the statistical and systematic uncertainties become rather large. The latter is due to the fact that for increasing transverse momenta the two photons from the $\pi^0$ have a strongly increasing probability of being reconstructed as only a single cluster in the calorimeter, leading to a rather large systematic uncertainty arising from the correction for this effect.

**FIG. 4** (color online). The fractional contribution of gluon-gluon ($gg$), quark-gluon ($qg$), and quark-quark ($qq$) scattering to the $\eta$ production in the pQCD calculation of Fig. 3, and to the $\pi^0$ production [24], as a function of $p_T$.

**FIG. 5**. The cross section ratio for the midrapidity production of inclusive $\eta$ to $\pi^0$ mesons at $\sqrt{s} = 200$ GeV as a function of $p_T$. The error bars show the statistical and systematic uncertainties added in quadrature. The solid curve shows the ratio of the NLO pQCD calculations shown in Fig. 3 and the corresponding one for the $\pi^0$. The dashed curve shows the result of a PYTHIA Monte Carlo simulation. See text for details.

### Table II

<table>
<thead>
<tr>
<th>$p_T$ (GeV/c)</th>
<th>$\eta/\pi^0$</th>
<th>Stat</th>
<th>Type-$B_1$</th>
<th>Type-$B_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.25</td>
<td>0.369</td>
<td>0.020</td>
<td>0.078</td>
<td>0.007</td>
</tr>
<tr>
<td>2.75</td>
<td>0.462</td>
<td>0.024</td>
<td>0.065</td>
<td>0.009</td>
</tr>
<tr>
<td>3.25</td>
<td>0.482</td>
<td>0.002</td>
<td>0.022</td>
<td>0.013</td>
</tr>
<tr>
<td>3.75</td>
<td>0.485</td>
<td>0.003</td>
<td>0.022</td>
<td>0.014</td>
</tr>
<tr>
<td>4.25</td>
<td>0.497</td>
<td>0.004</td>
<td>0.022</td>
<td>0.014</td>
</tr>
<tr>
<td>4.75</td>
<td>0.525</td>
<td>0.005</td>
<td>0.023</td>
<td>0.010</td>
</tr>
<tr>
<td>5.25</td>
<td>0.528</td>
<td>0.007</td>
<td>0.024</td>
<td>0.011</td>
</tr>
<tr>
<td>5.75</td>
<td>0.539</td>
<td>0.009</td>
<td>0.024</td>
<td>0.011</td>
</tr>
<tr>
<td>6.25</td>
<td>0.536</td>
<td>0.012</td>
<td>0.024</td>
<td>0.011</td>
</tr>
<tr>
<td>6.75</td>
<td>0.555</td>
<td>0.015</td>
<td>0.025</td>
<td>0.011</td>
</tr>
<tr>
<td>7.25</td>
<td>0.491</td>
<td>0.019</td>
<td>0.022</td>
<td>0.010</td>
</tr>
<tr>
<td>7.75</td>
<td>0.544</td>
<td>0.024</td>
<td>0.024</td>
<td>0.011</td>
</tr>
<tr>
<td>8.25</td>
<td>0.530</td>
<td>0.029</td>
<td>0.024</td>
<td>0.011</td>
</tr>
<tr>
<td>8.75</td>
<td>0.518</td>
<td>0.035</td>
<td>0.023</td>
<td>0.010</td>
</tr>
<tr>
<td>9.25</td>
<td>0.448</td>
<td>0.030</td>
<td>0.020</td>
<td>0.009</td>
</tr>
<tr>
<td>9.75</td>
<td>0.488</td>
<td>0.045</td>
<td>0.022</td>
<td>0.014</td>
</tr>
<tr>
<td>10.25</td>
<td>0.511</td>
<td>0.058</td>
<td>0.023</td>
<td>0.023</td>
</tr>
<tr>
<td>10.75</td>
<td>0.441</td>
<td>0.058</td>
<td>0.020</td>
<td>0.024</td>
</tr>
</tbody>
</table>

Except for an initial increase due to the different meson masses, the data do not exhibit a strong dependence on $p_T$. This hints towards a similar dependence of the $\eta$ and $\pi^0$ fragmentation functions on the energy fraction of the parton carried by the hadron. Fitting the cross section ratio, including its statistical and type-$B_1$ systematic uncertainty, to a constant, gives $R_{\eta/\pi^0} = 0.51 \pm 0.01$ ($\chi^2/\text{ndf} = 18.3/17$), with a remaining systematic uncertainty of 0.01 from the type-$B_2$ systematic uncertainty. This result does not change when fitting the data above $p_T = 3$ GeV/c ($\chi^2/\text{ndf} = 14.9/15$) instead of fitting the full range.

Within the uncertainties, the present measurement of $\eta/\pi^0$ is consistent with all previous measurements in $p + p$ collisions, going back to the measurement reported in Ref. [25]. A detailed comparison of subsequent measurements is summarized in Ref. [17]. The observed ratio is in good agreement with a PYTHIA 6.131 [26] calculation shown in the same figure, which is using the default settings and the Lund string fragmentation model [27]. The solid line in Fig. 5 shows the ratio of the NLO pQCD calculations at a scale $\mu = p_T$ (see Fig. 3) and the corresponding one for the $\pi^0$ using the same PDF but the $\pi^0$ fragmentation function of Ref. [24]. Note that the shape of this calculated cross section ratio is not necessarily well determined as the statistical uncertainty on the $\eta$ fragmentation function, defined by $\Delta \chi^2 = 2\%$, results in an uncertainty on the $\eta$ cross section between about 5\% and 9\%, depending on $p_T$ [18].

The calculated ratio underestimates the data even though the $\eta$ cross section presented in this paper and earlier
Possible transverse components of the beam polarizations are present within four consecutive bunch crossings.

The degree of polarization is determined from the combined information of a polarized-proton on carbon (\(\vec{p}C\)) polarimeter [28], using an unpolarized ultra-thin carbon ribbon target, and from elastic \(\vec{p} + \vec{p}\) scattering, using a polarized atomic hydrogen gas-jet target [29]. The average polarization value for the data from 2005 (2006) is 0.49 (0.57). There is a relative uncertainty of 4.8% in the product of the beam polarizations, correlated between the 2005 and 2006 data sets, which is a scale uncertainty on the vertical scale due to uncertainty in the beam polarizations that is correlated between years.

It is consistent with zero. The resulting background corrected asymmetry for \(\eta\) production as a function of \(p_T\) from the combined 2005 and 2006 data is shown in Fig. 6 and tabulated in Table III. It is consistent with zero over the measured range as can be expected based on the similar contributions of the various scattering subprocesses to the \(\eta\) and \(\pi^0\) production shown in Fig. 4 and the fact that the double-helicity asymmetry for \(\pi^0\) production [8] is consistent with zero as well.

As can be seen in Fig. 6, the \(\eta\) double-helicity asymmetry is in agreement with NLO pQCD calculations using the above mentioned fragmentation functions and two different sets of polarized PDFs [6,32] as an input to the code of Ref. [23].

### TABLE III. The double-helicity asymmetry values and uncertainties vs \((p_T)\) for the combined 2005 and 2006 data sets.

<table>
<thead>
<tr>
<th>((p_T)) (GeV/c)</th>
<th>(A_{LL}^{\eta})</th>
<th>(\sigma_{stat})</th>
<th>(\sigma_{syst}^0)</th>
<th>(\sigma_{syst}^R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.33</td>
<td>-0.0073</td>
<td>0.0055</td>
<td>0.0006</td>
<td>0.0004</td>
</tr>
<tr>
<td>3.35</td>
<td>0.0000</td>
<td>0.0070</td>
<td>0.0000</td>
<td>0.0004</td>
</tr>
<tr>
<td>4.38</td>
<td>-0.0026</td>
<td>0.0124</td>
<td>0.0002</td>
<td>0.0004</td>
</tr>
<tr>
<td>5.40</td>
<td>0.0137</td>
<td>0.0228</td>
<td>0.0016</td>
<td>0.0004</td>
</tr>
<tr>
<td>6.74</td>
<td>-0.0111</td>
<td>0.0320</td>
<td>0.0021</td>
<td>0.0004</td>
</tr>
</tbody>
</table>
momentum these data serve as important input for the extraction of fragmentation functions. The $\eta$ to $\pi^0$ cross section ratio as a function of $p_T$ has been extracted in a single pass over the same data set, thus minimizing systematic uncertainties. A fit to a constant above $p_T = 2$ GeV/$c$ or $p_T = 3$ GeV/$c$ yields a value of $R_{\eta/\pi^0} = 0.51 \pm 0.01_{\text{stat}} \pm 0.01_{\text{syst}}$. The inclusion of these data on the ratio in future fragmentation function extractions should allow for more precise results for both particle species. This opens up the possibility to include the data on the double-helicity asymmetry in future NLO pQCD fits in order to further constrain the polarized parton distribution functions, in particular, the helicity-dependent gluon distribution function.

ACKNOWLEDGMENTS

We thank the staff of the Collider-Accelerator and Physics Departments at Brookhaven National Laboratory and the staff of the other PHENIX participating institutions for their vital contributions. We also thank M. Stratmann and R. Sassot for fruitful discussions. We acknowledge support from the Office of Nuclear Physics in the Office of Science of the Department of Energy, the National Science Foundation, a sponsored research grant from Renaissance Technologies LLC, Abilene Christian University Research Council, Research Foundation of SUNY, and Dean of the College of Arts and Sciences, Vanderbilt University (U.S.), Ministry of Education, Culture, Sports, Science, and Technology and the Japan Society for the Promotion of Science (Japan), Conselho Nacional de Desenvolvimento Científico e Tecnológico and Fundação de Amparo à Pesquisa do Estado de São Paulo (Brazil), Natural Science Foundation of China (People’s Republic of China), Ministry of Education, Youth and Sports (Czech Republic), Centre National de la Recherche Scientifique, Commissariat à l’Énergie Atomique, and Institut National de Physique Nucléaire et de Physique des Particules (France), Ministry of Industry, Science, and Technologies, Bundesministerium für Bildung und Forschung, Deutscher Akademischer Austausch Dienst, and Alexander von Humboldt Stiftung, and the Wallenberg Foundation (Sweden), the U.S. Civilian Research and Development Foundation for the Independent States of the Former Soviet Union, the U.S.-Hungarian Fulbright Foundation for Educational Exchange, and the U.S.-Israel Binational Science Foundation.

V. SUMMARY

The double-helicity asymmetry in $\eta$ production is measured and found to be consistent with zero in the transverse momentum range between 2 GeV/$c$ and 9 GeV/$c$. The $\eta$ cross section is determined over 7 orders of magnitude between 2 GeV/$c$ and 20 GeV/$c$ in transverse momentum. In particular due to the wide range in transverse

These data can be used in global fits in order to further constrain polarized PDFs, in particular, the helicity-dependent gluon PDF. In the future, with improved statistics and the availability of flavor-separated fragmentation functions, double-helicity asymmetries in $\eta$ production can potentially constrain the polarized strange quark PDF ($s$) due to the additional $s$-quark contribution in the $\eta$ wave function. Special interest in $s$ arises from the fact that its value is negative, when extracted from analyses of inclusive DIS data, using hyperon decay data and assuming SU(3) flavor symmetry [2,3], but consistent with zero, when directly extracted from semi-inclusive DIS data [33–35]. Global fits can constrain PDFs by simultaneously describing a wide variety of experimental channels over a range of kinematics with different sensitivities, different experimental systematic uncertainties, and different sources of theoretical uncertainty. Thus, the data presented here open up a valuable new channel to improve knowledge of polarized PDFs.

FIG. 6. The double-helicity asymmetry for midrapidity inclusive $\eta$ production from the combined 2005 and 2006 data at $\sqrt{s} = 200$ GeV as a function of $p_T$. The gray boxes are point-to-point systematic uncertainties due to polarization and relative luminosity uncertainties and are correlated point-to-point, moving all points in the same direction but not by the same factor. An additional systematic uncertainty of 4.8% on the vertical scale due to the uncertainty in the beam polarizations is not shown. The results are compared to NLO pQCD calculations using two different sets of polarized PDFs [6,32]. See text for details.