Cross section and double helicity asymmetry for $\eta$ mesons and their comparison to $\pi^0$ production at PHENIX

Frank Ellinghaus (for the PHENIX Collaboration)

University of Mainz, Staudinger Weg 7, 55128 Mainz, Germany
and
University of Colorado, Boulder, CO 80309, USA

E-mail: Frank.Ellinghaus@uni-mainz.de

Abstract.

The $\eta$ cross section and double helicity asymmetry ($\vec{p}+\vec{p} \rightarrow \eta+X$) as a function of transverse momentum have been measured at $\sqrt{s} = 200$ GeV at the PHENIX experiment at RHIC. The cross section data serve as important input to the extraction of $\eta$ fragmentation functions, which were essentially unknown before. With the availability of fragmentation functions the asymmetry data can be included in future pQCD fits in order to further constrain the polarized parton distribution functions, in particular the helicity–dependent gluon distribution function. In addition, the $\eta$ to $\pi^0$ cross section ratio as a function of transverse momentum has been extracted in a single pass over the same data set, thus minimizing systematic uncertainties. The inclusion of these data in future fragmentation function extractions should allow for more precise results for both particle species.

1. Introduction

In contrast to the case of the $\pi^0$ meson, the experimental data available to extract $\eta$ fragmentation functions is rather limited. The existing $\eta$ cross section measurements from $e^+e^-$ 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 $p_T$.

Present knowledge about helicity–dependent parton distribution functions (PDFs) in the nucleon mainly comes from next-to-leading order (NLO) QCD fits to polarized data. The data comprises inclusive deep–inelastic scattering (DIS) data on the helicity–dependent structure function $g_1$, as measured in fixed–target polarized inclusive DIS experiments (see, e.g., [1, 2]), as well as semi-inclusive DIS data in which, in addition to the scattered lepton, at least one more particle is detected. Recently, data from polarized $pp$ scattering from RHIC became available. The results of a NLO QCD fit, using, for the first time, the available inclusive and semi-inclusive polarized DIS data together with the $pp$ data are described in Ref. [3]. The $pp$ data included...
were the double helicity asymmetries in inclusive $\pi^0$ [4, 5, 6] and jet [7] production from the PHENIX and STAR experiments, respectively.

The measurement of the $\eta$ double helicity asymmetry presented here adds independent data with different systematics to the present set of polarized data. 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.

2. Extraction of $\eta$ and $\pi^0$ yields

After applying data quality criteria, the analysis is based on $2.5\,pb^{-1}$ and $6.5\,pb^{-1}$ of data taken at the PHENIX [8] experiment in 2005 and 2006, respectively. 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. In addition, a preliminary result for the double helicity asymmetry using data from 2009 is available. The $\eta$ ($\pi^0$) meson is reconstructed through its main decay channel, $\eta$ ($\pi^0$) $\to \gamma\gamma$, with a branching ratio (BR) of about 39% (99%) [9].

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) [10], 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) [11].

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 consists of eight sectors, six of which are composed of a total of 15552 lead–scintillator (PbSc) sandwich towers ($5.5 \times 5.5 \times 37.5$ cm), and two sectors of lead-glass (PbGl) Čerenkov calorimeters, consisting of a total of 9216 towers ($4 \times 4 \times 40$ cm). For the cross section measurements only the PbSc was used.

Clusters in the EMCal have to pass a number of requirements in order to most likely originate from a photon, see Ref. [12] for details. Using all possible pairs of photon candidates, the two–photon invariant mass can be 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. 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 transverse momentum $p_T$ of the di–photon is required to be larger than 2 GeV/c.

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. At large $p_T$ where limited statistics leads to large fluctuations in the fit results, the number of background counts under the signal peak can be estimated by using the number of counts in the sidebands. 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.

3. The $\eta$ cross section and $\eta/\pi^0$ cross section ratio

The $\eta$ and $\pi^0$ cross sections can be calculated as

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

(1)
Figure 1. Cross section for midrapidity inclusive $\eta$ production at $\sqrt{s} = 200$ GeV as a function of $p_T$ and its comparison to NLO pQCD calculations at three different scales $\mu$. The error bars shown are the statistical and systematic uncertainties added in quadrature. Not included is the overall normalization uncertainty of 9.7%. Note that the fragmentation functions used in the calculations are partially constrained by this data. Figure taken from Ref. [12].

where $\mathcal{L}$ 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 $\eta$ cross section as a function of $p_T$ between 2 and 20 GeV/$c$ is shown in Fig. 1. It is consistent with an earlier PHENIX measurement [13] covering a smaller range in $p_T$ from 2.5 to 12 GeV/$c$. The error bars shown in Fig. 1 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 non-linearities in the energy scale affecting mainly points with $p_T > 10$ 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 $\eta$ cross section from $p+p$ scattering presented here, together with the above mentioned earlier PHENIX data [13], 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 [14]. The wide $p_T$ range of this measurement, as compared to the earlier PHENIX measurement,
Figure 2. Profiles of $\chi^2$ for the NLO eta fragmentation fit as a function of the truncated second moments $\xi^\eta_{u+d}$ ($z_{\text{min}} = 0.2, Q = 5 \text{ GeV}$) for different flavors (solid lines). In each case, the moments are normalized to the value $\xi_0$ they take in the best fit to data. The other lines indicate the partial contributions to $\Delta \chi^2$ of the individual data sets used in the fit. Figure taken from Ref. [14].

which covers a range in $p_T$ from 2.5 to 12 GeV/c, is important as it allows for a much more stringent constraint on the $\eta$ fragmentation function, as can be seen in Fig. 2. A detailed discussion on the impact of the various data sets on the $\eta$ fragmentation functions can be found in Ref. [14].

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. [15, 16] and Ref. [17], respectively. Due to 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., $D^\eta_{u} = D^\eta_{d} = D^\eta_{s} = D^\eta_{\bar{u}} = D^\eta_{\bar{d}} = D^\eta_{\bar{s}}$, has been used in Ref. [14].

Using these new fragmentation functions and the CTEQ6M [18] PDFs as an input to the NLO code of Ref. [19], 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. The results are in good agreement with the data as can be seen in Fig. 1. However, note that these data play a decisive role in the extraction of the fragmentation functions as discussed above and thus provide part of the input to the calculation.

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. 3. The ratio is presented up to $p_T = 14 \text{ GeV/c}$ 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.

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...
Figure 3. Cross section ratio for the midrapidity production of inclusive η to π⁰ mesons at √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. 1 and the corresponding one for the π⁰. The dashed curve shows the result of a PYTHIA Monte-Carlo simulation. Figure taken from Ref. [12].

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 η and π⁰ peak extraction and due to the correction for possible merging of the two π⁰ decay photons into a single cluster do not cancel. Furthermore, while the uncertainties on the high-p_T trigger efficiency 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 is reduced to a p_T independent contribution of 2%.

Except for an initial increase due to the different meson masses, the data do not exhibit a strong dependence on p_T. Fitting the cross section ratio to a constant, gives R_η/π⁰ = 0.51 ± 0.01 (χ²/ndf = 18.3/17), with a remaining systematic uncertainty of 0.01. This result does not change when fitting the data above p_T = 3 GeV/c (χ²/ndf = 14.9/15) instead of fitting the full range.

Within the uncertainties, the present measurement of η/π⁰ is consistent with all previous measurements in p + p collisions, going back to the measurement reported in Ref. [20]. A detailed comparison of subsequent measurements is summarized in Ref. [13]. The observed ratio is in good agreement with a PYTHIA 6.131 [21] calculation [13] shown in the same figure, which is using the default settings and the Lund string fragmentation model [22]. The solid line in Fig. 3 shows the ratio of the NLO pQCD calculations at a scale µ = p_T (see Fig. 1) and the corresponding one for the π⁰ using the same PDF but the π⁰ fragmentation function of Ref. [23]. Note that the shape of this calculated cross section ratio is not necessarily well determined as the statistical uncertainty on the η fragmentation function, defined by Δχ² = 2%, results in an uncertainty on the η cross section between about 5% and 9%, depending on p_T [14].

The calculated ratio underestimates the data even though the η cross section presented in this paper and earlier PHENIX π⁰ data are part of the input in the extraction of the fragmentation functions. This indicates that the constraints from the separate fits are less stringent than fitting the cross section ratio directly. This is obvious from the fact that some of the experimental
systematic uncertainties cancel in the ratio as already discussed above, in particular the overall normalization uncertainty of 9.7% due to the uncertainty in the luminosity measurement. For example, the earlier PHENIX data, used in the extraction of the $\pi^0$ fragmentation functions, was scaled by a factor of 1.09 [23] in the fit, which is within the experimental normalization uncertainty, but leads to a smaller calculated cross section ratio as can be seen in Fig. 3. Also, the dependence of the calculated $\eta$ and $\pi^0$ cross sections on the theoretical scale, as shown in, e.g., Fig. 1, largely cancels in the calculation of the ratio [16]. Hence it appears that improved constraints on $\eta$ and $\pi^0$ fragmentation functions can be derived by directly including the data on the $\eta/\pi^0$ cross section ratio in the fit.

4. Double Helicity Asymmetry for $\eta$ Mesons

The double helicity asymmetry is given as

$$A_{LL} = \frac{1}{|P_B||P_Y|} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}, \quad \text{with} \quad R \equiv \frac{L_{++}}{L_{+-}},$$

where $N_{++}$ ($N_{+-}$) is the experimental yield for the case where the beams have the same (opposite) helicity. The polarizations of the two colliding beams at RHIC are denoted by $P_B$ and $P_Y$. The relative luminosity $R$ is measured by a coincident signal in the two BBCs that satisfies the vertex cut.

The double helicity asymmetry for $\eta$ production,

$$A_{LL}^\eta = A_{LL}^{\eta+BG} - r A_{LL}^{BG}, \quad \text{with} \quad r \equiv \frac{N_{BG}}{N_{\eta} + N_{BG}},$$

can be calculated by separately measuring the asymmetry in the $2\sigma$ window around the mean of the $\eta$ peak ($A_{LL}^{\eta+BG}$) and in the sidebands ($A_{LL}^{BG}$). The latter 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 the left panel of Fig. 4. A preliminary result
including data from 2009 is shown in the right panel. The data taken in 2009 has a slightly higher luminosity than the combined data taken in 2005 and 2006 and about the same degree of polarization. The results are consistent with zero over the measured range. As can be seen, 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 [24, 3] as an input to the code of Ref. [19].

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 $\Delta s$ due to the additional $s$-quark contribution in the $\eta$ wave function. Special interest in $\Delta s$ 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 [1, 2], but consistent with zero, when directly extracted from semi-inclusive DIS data [25, 26, 27]. 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.

5. Summary
The $\eta$ cross section is determined over seven orders of magnitude between 2 GeV/$c$ and 20 GeV/$c$ in transverse momentum. In particular due to the wide range in transverse momentum these data have proven essential for the extraction of the $\eta$ fragmentation functions. 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/$c$. With the availability of $\eta$ fragmentation functions the data on the double helicity asymmetry can now be used in future NLO pQCD fits in order to further constrain the polarized parton distribution functions, in particular the helicity–dependent gluon distribution function. 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. The inclusion of these data in future fragmentation function extractions should allow for more precise results for both particle species.

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