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Inclusive Photoproduction of Neutral Pions in the Photon Hemisphere at HERA

H1 Collaboration

Abstract

The recently installed high resolution backward calorimeter SpaCal of H1 allows the reconstruction of neutral pions through their decays into two photons. The SpaCal covers the rapidity range $-1.4 < y < -3.5$. This paper presents measurements of the inclusive cross section for π^0 photoproduction at an average photon - proton centre - of - mass energy $W = 200$ GeV, in dependence on transverse momentum $p_\perp$ and rapidity y of the pion. The predictions of the PHOJET and PYTHIA models are compared with the measurements and show good agreement, with a slight preference for PYTHIA. A measurement of pion production in this rapidity range, which partly covers the phase space available for the photon remnant, is a potential source of information on intrinsic transverse momenta of partons inside the photon. Plotting the invariant differential cross section as a function of $p_\perp$, one observes the characteristic exponential behaviour at lower $p_\perp$, and the deviation thereof at higher transverse momenta, due to hard interactions. The results extend those previously obtained by the H1 and ZEUS Collaborations on charged particle spectra measured in the central region.

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1 Introduction

Inclusive spectra of identified particles in high energy reactions represent a basic tool to derive global features of the physics processes involved, and allow a comparison of model predictions, generally available from Monte Carlo simulation programs, with measured quantities. While H1, as most multipurpose detectors, has easy access to charged particle momentum spectra over a wide phase space range, the reconstruction of neutral mesons from their decay photons is possible only in limited phase space regions covered by calorimeters with sufficient spatial granularity and energy resolution.

H1 is equipped with two main calorimeters, the Liquid Argon calorimeter covering the forward and central regions, and the lead - scintillator backward calorimeter SpaCal. Either calorimeter has an electromagnetic and a hadronic section. The basis of the analysis presented here is the reconstruction of neutral pions through their decay photons detected in the SpaCal.

The collision of positrons with an energy of 27.5 GeV and protons of 820 GeV at HERA is a source for photoproduction ($Q^2 \approx 0$) processes with a total cross section of about 165 μb, for an average γp CM energy of 200 GeV. Photoproduction is generally labelled as either "direct" or "resolved"; the former means the interaction of the photon with a charged parton of the "target" particle (at HERA: the proton), while the latter refers to a photon fluctuating into parton pairs which in turn interact with partons from the target.

Photoproduction events used in this study are distinguished from deep inelastic scattering (DIS) events by the detection of the scattered positron in a special detector, thus ensuring their kinematical properties, namely vanishing Q^2 ("tagged photoproduction").

The study presented in this paper is based on the reconstruction and measurement of neutral pions through their decays to two photons. The kinematical range of measurement is dictated by the region covered by the SpaCal. Inclusive meson cross sections are determined in dependence on transverse momentum $p_\perp$ and rapidity y of the π^0. The results are compared to predictions of the PYTHIA and PHOJET models, as outlined in Section 4 below.

2 Detector description

A detailed description of the H1 detector is given in [1]. The analysis presented here relies on the new backward calorimeter SpaCal which has been installed in 1995. In addition, the small angle electron[1] detector ("Electron tagger") is used; it is located[2] at z = -33m upstream of the main detector and the interaction point.

The SpaCal is a lead - scintillating fibre calorimeter which covers the polar angular range $153° \leq \theta \leq 178°$, where θ is measured with respect to the proton beam direction. For pions, this corresponds to a rapidity range of $-1.4 < y < -3.5$. It is separated into an electromagnetic (EM) and a hadronic section of equal size. The EM section consists

[1] In the 1996 running period, HERA was operated with a positron beam. We will nevertheless use the term "electron" in technical contexts.

[2] The z - axis is defined by the proton beam direction

of 1192 cells with a cross section of 40.5×40.5 mm^2, each read out by a photomultiplier tube. The hadronic section consists of 128 cells with a cross section of 120×120 mm^2. The EM section has a depth of 27 radiation lengths; EM and hadronic section each has a "nuclear" depth of one interaction length.

The energy resolution of the EM Spacal section, for electromagnetically interacting particles, is described by

$$\frac{\sigma(E)}{E} = \frac{(0.075 \pm 0.002)}{\sqrt{E/\mathrm{GeV}}} \oplus (0.01 \pm 0.001).$$

The angular resolution is better than 2 mrad. A complete technical description of the SpaCal and of its performance is found in [2].

The spatial and energy resolution capability of the SpaCal transforms directly into mass resolutions of π^0's, whose masses are reconstructed from energies and opening angle of the decay photons according to

$$m_{\gamma\gamma}^2 = 2E_1E_2(1 - \cos\alpha_{1,2}),$$

where E_1 and E_2 are the energies of the decay photons, and $\alpha_{1,2}$ their opening angle.

Figure 1 shows two photon invariant mass distributions, as measured with the SpaCal (Fig. 1a - 1d), in phase space regions as indicated in the figures. Reconstructed photons are required to have energies larger than 0.1 GeV. The transverse momentum $p_\perp$ is defined as the momentum component perpendicular to the z - axis. One observes a dramatic change of background behaviour between the SpaCal diagrams which leads to a high sensitivity of fit results to background parametrizations.

An essential detector component for photoproduction measurements is the small angle electron detector ("electron tagger"), a device belonging to the luminosity determination system [1]. It consists of a TlCl/TlBr crystal calorimeter with an energy resolution of $\sigma(E)/E = 0.1/\sqrt{E/\mathrm{GeV}}$, located at z = -33 m. It accepts positrons from photoproduction processes with energy fractions between 0.2 and 0.8 with respect to the beam energy, and scattering angles $\theta' < 5$ mrad with respect to the incoming positron beam direction.

3 Data selection and analysis

The data sample used for this analysis was collected in the 1996 running period and corresponds to an integrated luminosity of 6.6 events/pb. The trigger condition required was a positron seen in the 33m tagger, and an energy deposition in the SpaCal of at least 2 GeV (so called $IET > 1$ condition). The radial distance between SpaCal cluster, i.e. isolated energy deposition, and beam axis was required to be larger than 20 cm. The trigger reached its maximum efficiency of 97% at energies larger than 2.6 GeV.

In the further data selection an event was accepted if a vertex could be reconstructed from the tracker information, and its position along the z -axis was $|z| < 30$ cm . In addition, the most energetic SpaCal cluster was required to have an energy above 2.2 GeV, with a distance from the beam axis of at least 16 cm, corresponding to a trigger efficiency larger than 40 %. The value of $y_{Bjorken}$[3] had to be in the interval 0.35 to 0.65, in order to ensure reasonable tagger efficiency. Roughly half a million events survived these trigger and selection criteria.

A SpaCal cluster was regarded as a single photon's energy deposition if it was reconstructed as an isolated energy deposition over at least two SpaCal cells. The cluster energy had to exceed 0.2 GeV. A cluster distance between 8 cm and 75 cm from the beam axis was required to ensure full energy containment.

The procedure of reconstructing and counting π^0's was as follows: Any pair of two photons satisfying the above quoted criteria was labelled according to an interval in transverse momentum $p_\perp$ with respect to the z - axis, and laboratory frame rapidity $y = 1/2 \cdot \ln((E + p_z)/(E - p_z))$, where $p_\perp$ and y were calculated from the sum of the four - momenta of the two photons. In the above formula, E denotes the energy, and p_z the momentum component parallel to the proton beam axis, of the two photon system. Photon four - momenta were derived from the cluster energy, the cluster coordinates, and the interaction vertex coordinates.

For any such pair of photons, the invariant mass $m_{\gamma\gamma}$ was calculated and entered into a histogram. Since the signal shape can be satisfactorily described by a Gauss function (see Fig. 1), a Gaussian together with a combinatorial background parametrized by a threshold function times a polynomial was used in the fit. The fact that the π^0 peak is so close to threshold makes the determination of the signal somewhat difficult in cases where the background is steeply rising. To estimate the uncertainty introduced by this behaviour, repeated fits have been performed by varying especially the fit ranges. Systematic uncertainties are therefore in some kinematical intervals considerably larger than the statistical errors emerging from the fits.

For the efficiency calculations, the following procedure has been applied, using the full detector simulation only in the backward hemisphere of H1 where the neutral pions are reconstructed: The generator PHOJET (see Section 4) is used to model the photoproduction interactions. Events with at least one track in the pseudorapidity[4] range $-2 < \eta < 2$ are marked as "events with a vertex". On the generator level, particles emitted into the forward hemisphere have been excluded from the subsequent simulation procedure in order to save computing time. Next, the H1 detector simulation program H1SIM [3] which is based on the CERN program package GEANT [4] is used to model the detector response. Control distributions of kinematical quantities for data and simulation show very good agreement. A survey of the π^0 reconstruction efficiencies and their uncertainties in the different kinematical intervals is given in Table 1, while Table 2 shows the reduction factors imposed by the trigger. The procedure was cross checked using the PYTHIA generator; the slight deviations due to the different generators enter the systematic uncertainties.

Cross sections shown refer to positron - proton, not γ - proton interactions.

4 Monte Carlo models

Photoproduction, comprising the interactions sketched above, is modelled by various Monte Carlo generators as e.g. "PHOJET" [5] and "PYTHIA" [6]. Since the pion di-

[3] Expressed in terms of electron variables, the definition is $y_{Bjorken} = 1 - (E'_e/E_e)\sin^2\theta_e/2$.

[4] The pseudorapidity is defined as $\eta = -\ln \tan \theta/2$, where θ is the polar angle w.r.t. the proton beam direction

rection is about the same as that of the photon, the measurement potentially gives new information on the intrinsic parton transverse momenta in the photon.

The PHOJET (Version 1.04) generator is based on the “Two component Dual Parton Model (DPM)”; for a review, see [7]. It calculates hard scattering processes from perturbative QCD and soft processes from Regge phenomenology, where the connection between hard and soft regimes is established using unitarity corrections [5]. PHOJET generally includes multiple interactions (MIAs).

The generator PYTHIA (Version 5.722) uses lowest order perturbative QCD matrix elements for hard processes plus a parton shower mechanism to describe soft interactions. PYTHIA can optionally be run with and without MIAs.

In both PHOJET and PYTHIA, the fragmentation of partons into hadrons follows the Lund string model [8], as implemented in JETSET [9].

5 Results

The numbers of π^0's derived from the fits in the $p_\perp$- and rapidity intervals were converted into a twofold differential cross section $\frac{d^2\sigma}{dp_\perp dy}$, using the relation

$$\sigma = \frac{N(\pi^0)_{Signal} - N(\pi^0)_{BG}}{\mathcal{L}\epsilon},$$

where $\mathcal{L}$ is the integrated luminosity and ϵ the efficiency. $N(\pi^0)_{Signal}$ is the number of π^0's from genuine positron - proton interactions reconstructed inside the vertex fiducial region, and $N(\pi^0)_{BG}$ the number of π^0's generated in beam - gas interactions. The number of background π^0's has been estimated from a vertex side band, where the number of π^0's has been determined and extrapolated to the vertex region.

The results are listed in Table 3, and displayed in Figure 2, as function of transverse momentum, in three intervals of rapidity y. The model predictions according to PHOJET and PYTHIA are shown in the same diagram. The agreement is satisfactory. Figure 3 shows the π^0 cross section as function of rapidity, for four transverse momentum intervals, again together with the PHOJET and PYTHIA predictions.

The PYTHIA model delivers a better description of the data than PHOJET. The two models give slightly different predictions with respect to the influence of multiple interactions at the parton level. The accuracy reached in this analysis is, however, not sufficient to distinguish between the predictions.

It is interesting to show the transverse momentum spectrum in the invariant representation, i.e. as function of $p_\perp^2$, using the relation

$$dp_\perp^2 = 2\pi \cdot p_\perp dp_\perp.$$

We thus plot in Figure 4 the distribution

$$\frac{1}{N_{events}} \frac{dN}{dp_\perp^2 \Delta y} \approx \frac{1}{N_{events}} \frac{1}{2\pi p_\perp \Delta y} \frac{\Delta N}{\Delta p_\perp}.$$

The $p_\perp^2$ spectrum for particles emitted in soft hadronic interactions is satisfactorily described by a steep exponential function, as predicted e.g. by the Thermodynamic Model of Hagedorn [10]. The contribution of hard scattering processes dominates at higher $p_\perp$ and follows a power law. This behaviour is clearly seen in Figure 4.

Fitting a function

$$\frac{1}{N_{events}} \frac{dN}{dp_\perp^2 \Delta y} = exp(a - b \cdot \sqrt{p_\perp^2 + m_{\pi^0}^2}),$$

in the range up to $p_\perp = 1.3$ GeV/c, where m_{π^0} is the π^0 mass, yields a slope $b = (5.80 \pm 0.20)(\mathrm{GeV/c})^{-1}$. This value is derived for the backward phase space region, i.e. the laboratory frame rapidity range from -1.5 to -3.5.

Fitting a power law function of the form

$$\frac{1}{N_{events}} \frac{dN}{dp_\perp^2 \Delta y} = A \cdot (1 + (p_\perp / p_\perp^0)^{-n}),$$

yields the values $p_\perp^0 = (1.3 \pm 0.4)$ GeV/c and $n = 12.3 \pm 2.0$.

The ZEUS Collaboration have measured charged particle transverse momentum spectra in a more central region, namely in the pseudorapidity range $-1.2 < \eta < 1.4$ [11]. They are able to distinguish between non - diffractive and diffractive events with masses of the diffractively excited proton of 5 GeV and 10 GeV. The slopes they determine for these event classes are (4.94 ± 0.09) GeV/c^{-1}, (5.91 ± 0.17) (GeV/c)$^{-1}$, and (5.28 ± 0.10) (GeV/c)$^{-1}$, respectively. In our analysis, no attempt has been made to distinguish between diffractive and non - diffractive events.

Inclusive charged particle cross sections for γp events in the central region ($|\eta| < 1.5$) have also been determined by the H1 Collaboration [12], where, however, the main emphasis was put on the behaviour of the cross section at higher transverse momenta ($p_\perp > 2$ (GeV/c)). Here, a power law fit yielded the results $p_\perp^0 = (0.63 \pm 0.20)$ GeV/c and $n = 7.1 \pm 2.0$.

6 Summary and conclusions

Inclusive π^0 photoproduction in the photon hemisphere, that is in the H1 backward region, has been studied for the first time. Differential cross sections with respect to transverse momentum and rapidity are presented and compared to model (PHOJET 1.04, PYTHIA 5.722) predictions which show satisfactory agreement, with a slight preference for PYTHIA.

Displaying the transverse momentum spectrum as invariant differential cross section in $p_\perp$ shows the typical exponential fall at lower $p_\perp$ values, and the power law behaviour at higher $p_\perp$ which is expected for hard scattering processes. The fitted parameters are compared with the results of the H1 and ZEUS Collaborations who have measured charged particle transverse momentum spectra in a more central region.

7 Acknowledgements

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$y \in$	$p_\perp$ [GeV/c] $\in$			
	$[0.2, 0.6]$	$[0.6, 0.8]$	$[0.8, 1.0]$	$[1.0, 2.0]$
$[-2.8, -2.4]$	$(42 \pm 1)\,\%$	$(54 \pm 2)\,\%$	$(50 \pm 4)\,\%$	$(32 \pm 4)\,\%$
$[-2.4, -2.0]$	$(42 \pm 2)\,\%$	$(47 \pm 1)\,\%$	$(56 \pm 4)\,\%$	$(55 \pm 4)\,\%$
$[-2.0, -1.4]$	$(21 \pm 1)\,\%$	$(27 \pm 1)\,\%$	$(31 \pm 1)\,\%$	$(37 \pm 1)\,\%$

Table 1: Efficiencies for the π^0 reconstruction in different bins of the pion transverse momentum $p_\perp$ and rapidity y.

$y \in$	$p_\perp$ [GeV/c] $\in$			
	$[0.2, 0.6]$	$[0.6, 0.8]$	$[0.8, 1.0]$	$[1.0, 2.0]$
$[-2.8, -2.4]$	2.6	1.0	1.0	1.0
$[-2.4, -2.0]$	4.2	1.6	1.0	1.0
$[-2.0, -1.4]$	3.7	3.9	2.2	1.1

Table 2: Trigger suppression factors in different bins of the pion transverse momentum $p_\perp$ and rapidity y.

$y \in$	$p_\perp$ [GeV/c] $\in$			
	$[0.2, 0.6]$	$[0.6, 0.8]$	$[0.8, 1.0]$	$[1.0, 2.0]$
$[-2.8, -2.4]$	922 ± 92	207 ± 21	73 ± 8	6 ± 1
$[-2.4, -2.0]$	1310 ± 141	414 ± 40	136 ± 14	14 ± 2
$[-2.0, -1.4]$	1430 ± 210	428 ± 42	205 ± 20	31 ± 3

Table 3: Measured cross sections (nb/(GeV/c)) in different bins of the pion transverse momentum $p_\perp$ and rapidity y.

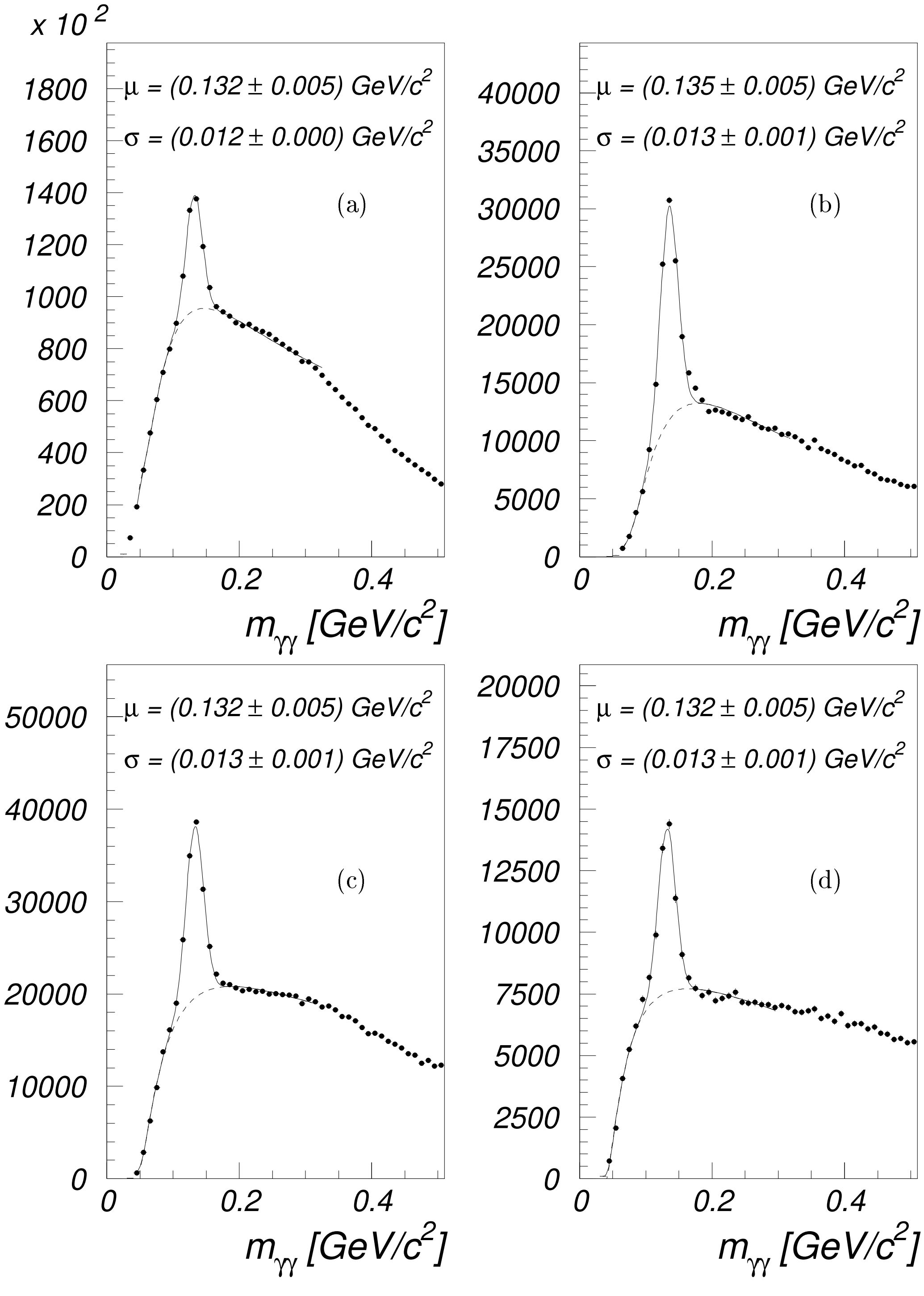

Figure 1: $m_{\gamma\gamma}$ - spectra, measured in the SPACAL, in bins of the π^0 transvers momentum $p_\perp$ and the rapidity y: (a) $p_\perp \in [0.2, 0.6]$ GeV, $y \in [-2.8, -2.4]$, (b) $p_\perp \in [0.6, 0.8]$ GeV, $y \in [-2.4, -2.0]$, (c) $p_\perp \in [0.6, 0.8]$ GeV, $y \in [-2.4, -2.0]$, (d) $p_\perp \in [0.8, 1.0]$ GeV, $y \in [-2.0, -1.4]$.

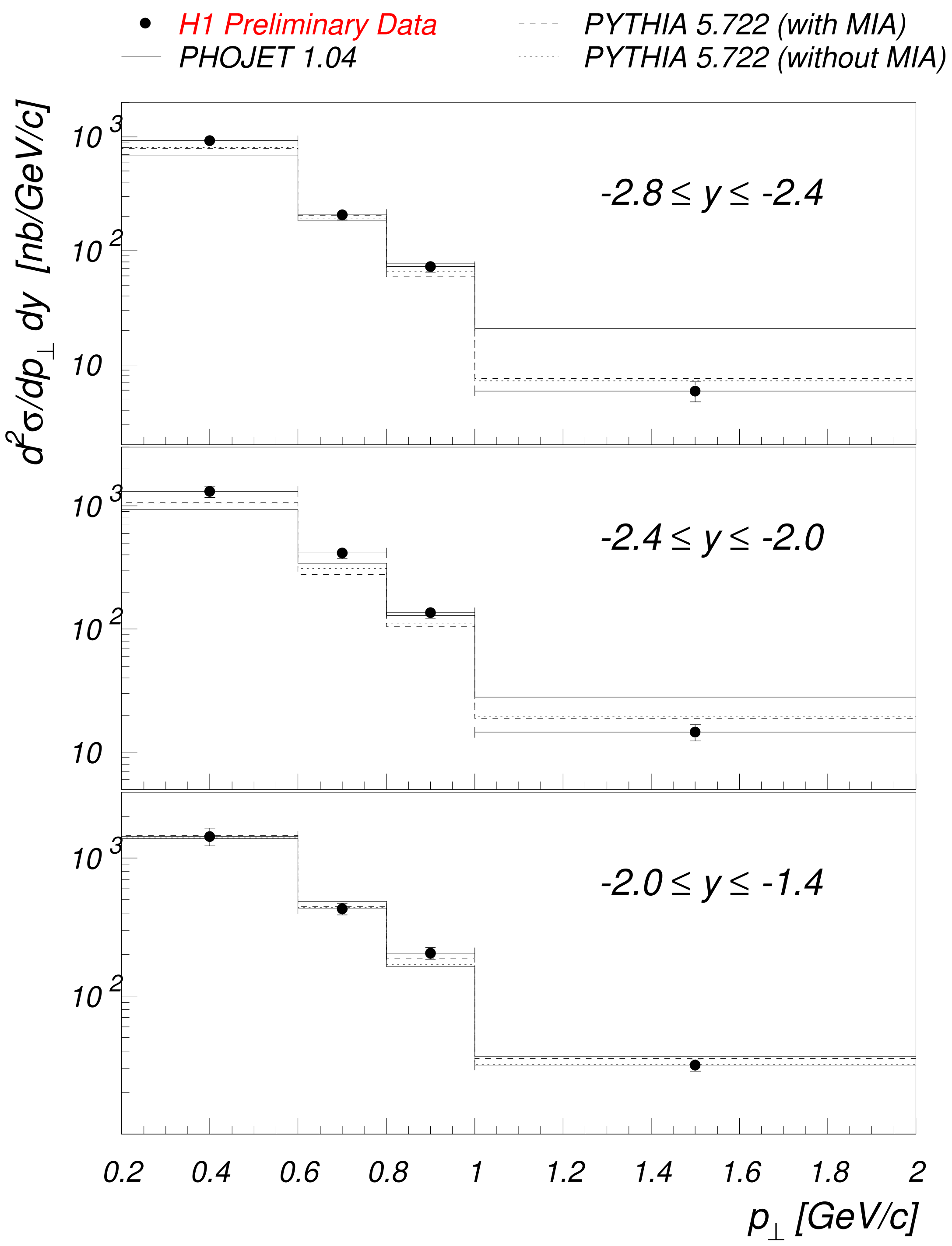

Figure 2: Measured π^0 cross section shown in dependence on the pion transverse momentum $p_\perp$, in comparison with different model predictions.

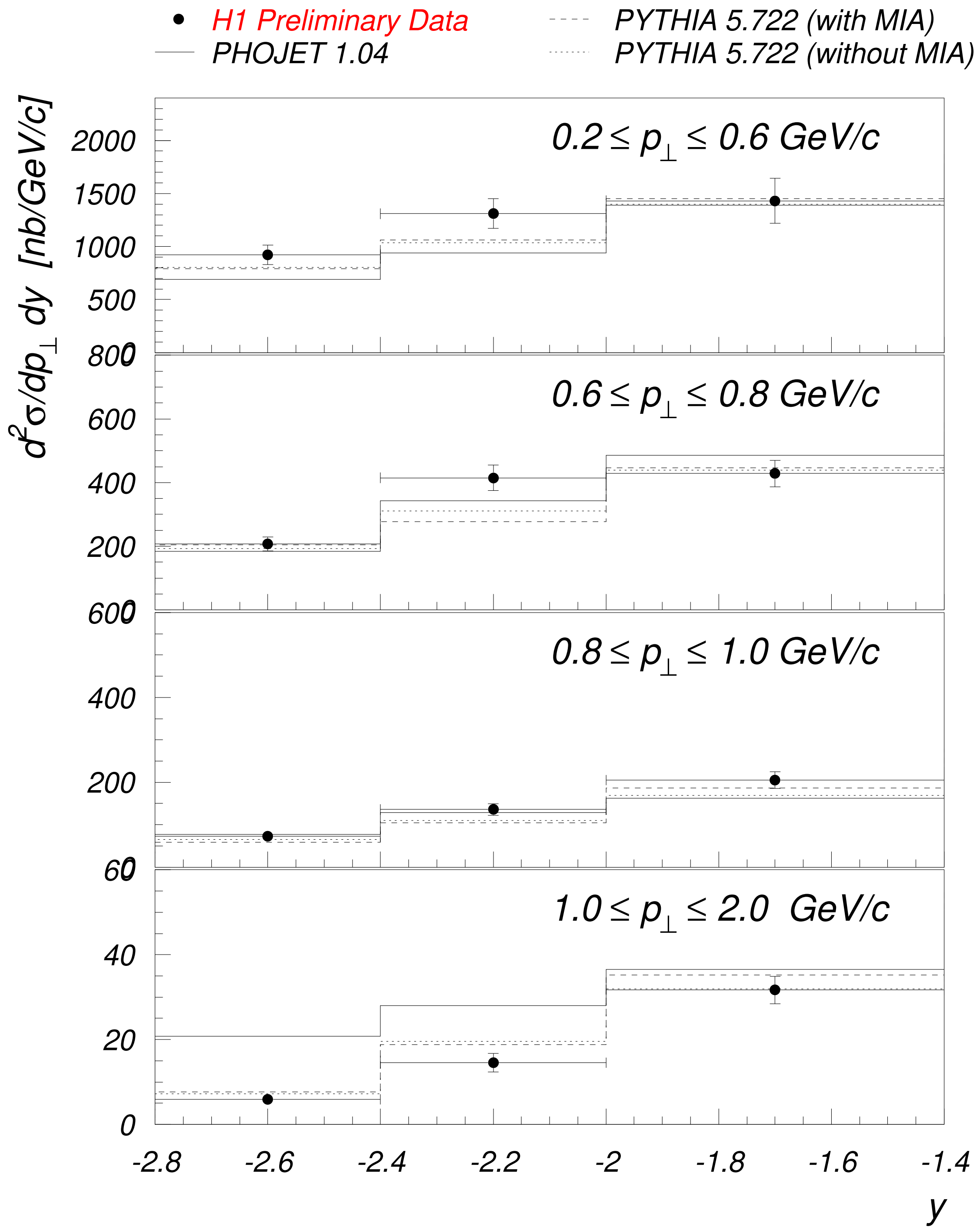

Figure 3: Measured π^0 cross section shown in dependence on the pion rapidity y, in comparison with different model predictions.

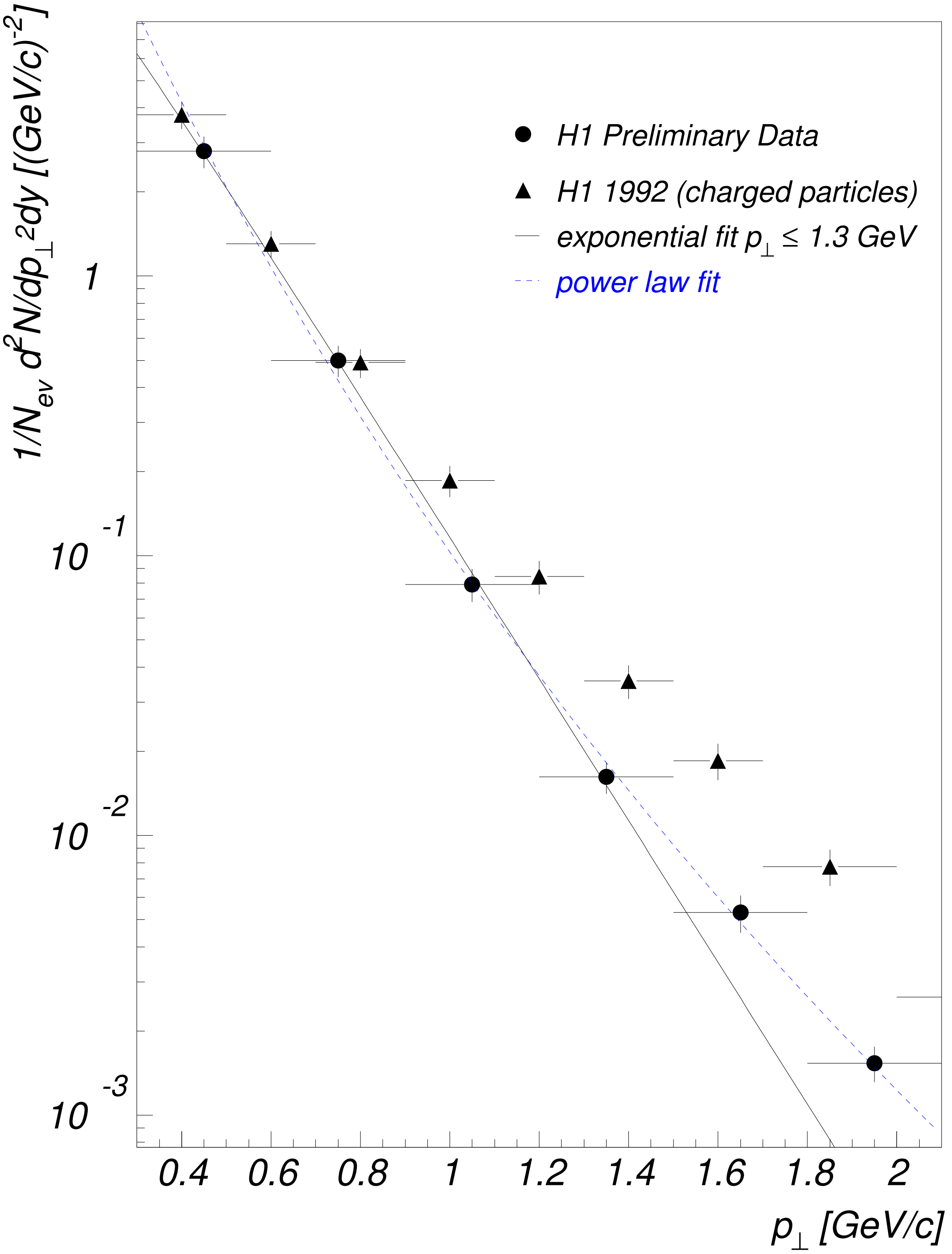

Figure 4: Invariant differential π^0 cross section in dependence on $p_\perp$, with an exponential fit in the $p_\perp$ range 0.3 GeV/c - 1.3 GeV/c, and a power law fit. The triangles indicate the H1 result on charged particles in the central rapidity region.