

**Midrapidity Neutral-Pion Production in Proton-Proton Collisions at  $\sqrt{s} = 200$  GeV**

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The invariant differential cross section for inclusive neutral-pion production in  $p + p$  collisions at  $\sqrt{s} = 200$  GeV has been measured at midrapidity ( $|\eta| < 0.35$ ) over the range  $1 < p_T \lesssim 14$  GeV/ $c$  by the PHENIX experiment at the Relativistic Heavy Ion Collider. Predictions of next-to-leading order perturbative QCD calculations are consistent with these measurements. The precision of our result is sufficient to differentiate between prevailing gluon-to-pion fragmentation functions.

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Particle production at large transverse momenta,  $p_T$ , in hadronic reactions has provided an important testing ground for perturbative quantum chromodynamics (pQCD) [1]. Next-to-leading order (NLO) pQCD calcu-

lations describe Tevatron ( $\sqrt{s} = 1.8$  TeV) measurements of inclusive jet production [2] within 10% and direct photon production [3], in which the elementary quark-gluon scattering produces a photon directly, within 50%.

For high- $p_T$  pion production, the recent calculations have not been compared with the UA2 data [4] obtained at  $\sqrt{s} = 540$  GeV. However, at lower center of mass energies ( $\sqrt{s} \lesssim 63$  GeV), they underestimate the data by a factor of  $\sim 2.5$  [5]. Similar discrepancies were observed for direct photon measurements from fixed target experiments [6] and were attributed to effects of soft-gluon radiations beyond NLO [7], to effects of initial intrinsic transverse momentum,  $k_T$  [8], or to experimental problems in the difficult direct photon measurements [9,10]. The  $\pi^0$  calculations, as compared to the jet or direct photon calculations, also require the probability for the scattered quark or gluon to fragment into a pion.

Information on fragmentation to pions [11–15] has principally come from global analyses of inclusive hadron production in  $e^+e^-$  annihilation. These analyses constrain the quark-to-pion fragmentation functions well but, via the scale dependence, the gluon-to-pion fragmentation function to a lesser extent. For example, the latter function at a scale of 100 GeV<sup>2</sup> can vary by a factor of 2 to 10 when the fraction of the initial gluon momentum carried by the pion is above 0.5. The more direct measurements of gluon fragmentation functions from  $b$ -tagged, three jet event data from the Large Electron-Positron Collider [16] have played a limited role in the global analyses because NLO corrections are unavailable for the quantitative treatment, including scale and scheme dependencies, of these data. As has been explored for measurements of inclusive hadron production in  $p + \bar{p}$  collisions [17], results from inclusive pion production at high  $p_T$  can be included in the global NLO analyses and thus may provide meaningful constraints on the gluon-to-pion fragmentation. These results also provide a reference needed for quantifying the suppression of  $\pi^0$  production observed in Au-Au collisions at the Relativistic Heavy Ion Collider (RHIC) [18] and, to the extent of agreement with the calculations, the foundations for the planned polarized gluon density measurement with polarized protons in the RHIC [19].

In this Letter, we report the first results on inclusive neutral-pion production in  $p + p$  collisions at a center of mass energy ( $\sqrt{s}$ ) of 200 GeV as extracted from the data collected during the 2001–2002 run period (Run-2) of RHIC. The bunched proton beams in the collider were vertically polarized with spin orientations alternating in successive bunches. By balancing the integrated luminosity in the different spin states, the effects from polarization were canceled at the 0.1% level.

In Run-2, the PHENIX experiment [20] operated two central arm spectrometers, one muon arm spectrometer, and other detectors for triggering and vertex determination. This work used the beam-beam counters (BBC) [21] for determining the collision vertex and constructing the minimum bias (MB) trigger, and the electromagnetic calorimeters (EMCal) [22] for detecting the neutral pions and deriving high- $p_T$  triggers.

The unbiased differential cross section for  $\pi^0$  production is calculated from the MB triggered data sample as

$$E \frac{d^3\sigma}{dp^3} = \frac{1}{\hat{\mathcal{L}}} \frac{1}{2\pi p_T^*} \frac{C_{\text{reco}} C_{\text{conv}}}{f_{\pi^0}} \frac{N_{\pi^0}}{\Delta p_T \Delta y}, \quad (1)$$

where  $N_{\pi^0}$  is the number of  $\pi^0$ 's observed in a  $\Delta p_T$  wide bin at  $p_T^*$  defined as the  $p_T$  for which the cross section equals its average over the bin;  $\Delta y$  is the rapidity range;  $C_{\text{reco}}$  is a correction for the acceptance, reconstruction efficiency, and  $p_T$  smearing;  $C_{\text{conv}}$  is a correction for the conversion of decay photons;  $f_{\pi^0}$  is the fraction of the inclusive  $\pi^0$  yield for which the MB trigger condition was satisfied; and  $\hat{\mathcal{L}}$  is the integrated luminosity for the analyzed data sample. The high- $p_T$  triggered sample required an additional correction to account for the efficiency of this trigger for  $\pi^0$  detection.

The MB trigger imposed the requirement that the collision vertex was within 75 cm of the center of the interaction region. This vertex was reconstructed from the difference in the arrival times of particles at the BBCs which were located along the beam line at  $\pm 1.44$  m from the nominal interaction point and subtended the pseudorapidity range  $\pm(3.0\text{--}3.9)$  with full azimuthal coverage. In the analysis of the data, a more restrictive requirement of  $\pm 30$  cm was applied.

The EMCal consisted of two subsystems: a six sector, lead scintillator (PbSc) calorimeter and a two sector, lead glass (PbGl) calorimeter. Located at a radial distance of  $\sim 5$  m from the beam line, each of these sectors covered the pseudorapidity range of  $|\eta| < 0.35$  and an azimuthal angle interval of  $\Delta\phi \approx 22.5^\circ$ . Each of the towers in the calorimeter subtended  $\Delta\phi \times \Delta\eta \sim 0.01 \times 0.01$ , thus ensuring that the two photons from a decayed  $\pi^0$  were clearly resolved up to a  $p_T$  of 12 GeV/ $c$ . Shower profile analysis can extend this  $p_T$  range beyond 20 GeV/ $c$ . The energy calibration was corroborated by the position of the  $\pi^0$  invariant mass peak, the energy deposit from minimum ionizing charged particles traversing the EMCal (PbSc), and the correlation between the energy deposit in the EMCal and the measured momentum for electrons and positrons identified by the ring-imaging Čerenkov detector. These studies showed that the accuracy of the energy measurement was within 1.5%. At a  $p_T$  of  $\sim 11$  GeV/ $c$ , this uncertainty translates into a systematic error on the  $\pi^0$  yield of  $\sim 12\%$ . The effective energy resolution for the data set was deduced from the widths of the  $\pi^0$  mass peaks, which varied with  $p_T$  from 7% to 10% (PbSc) and from 12% to 13% (PbGl), and a comparison of the measured energy and momentum for identified electrons and positrons.

The number of recorded high- $p_T$   $\pi^0$ 's was enhanced by a high- $p_T$  trigger (denoted as  $2 \times 2$ ) in which threshold discrimination was applied independently to sums of the analog signals from nonoverlapping,  $2 \times 2$  groupings (called tiles) of adjacent EMCal towers. During this run, the thresholds corresponded to a deposited energy of 0.75 GeV. The efficiency of this trigger for  $\pi^0$

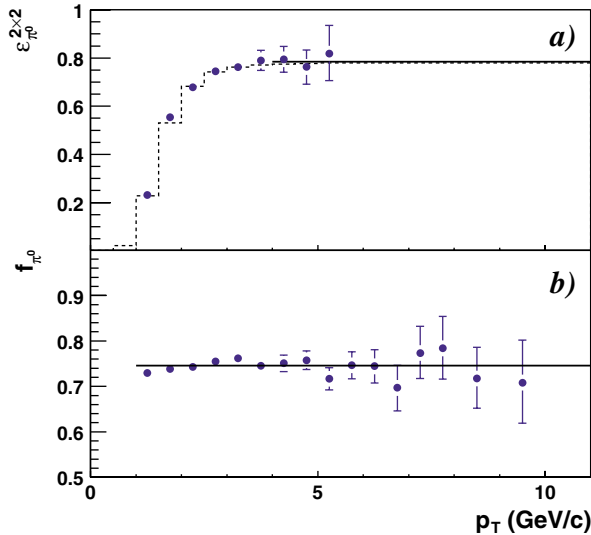


FIG. 1 (color online). (a) The efficiency of the  $2 \times 2$  high- $p_T$  trigger for  $\pi^0$  as a function of the  $p_T$  of the  $\pi^0$ . The dashed and solid lines show the results of a Monte Carlo simulation based on the  $2 \times 2$  trigger tile efficiencies and the limit derived from the fraction of active trigger tiles, respectively. (b) The fraction of the inclusive  $\pi^0$  yield which satisfied the MB trigger condition. The solid line shows a fit of these data to a constant.

detection,  $\varepsilon_{\pi^0}^{2 \times 2}(p_T)$ , was obtained from the MB data. As shown in Fig. 1(a), this efficiency reached a plateau at a  $p_T$  of  $\sim 3$  GeV/c. This dependence was reproduced by Monte Carlo calculations which included the tile threshold curves, the EMCal detector response, and the geometry of the active trigger tiles. The plateau level,  $0.78 \pm 0.03$  for both PbSc and PbGl, was consistent with the geometrical acceptance of the active trigger tiles.

Since only a fraction of inelastic  $p + p$  collisions produce particles which enter both BBCs, the MB trigger condition biased the recorded data sample, so only a fraction,  $f_{\pi^0}$ , of the inclusive  $\pi^0$  yield was detected. This fraction was determined from data collected by an additional, high- $p_T$  trigger which had not been operated in coincidence with the MB trigger. This trigger was formed by threshold discrimination of the sums of the analog signals from overlapping  $2 \times 2$  groupings of adjacent  $2 \times 2$  trigger tiles. As shown in Fig. 1(b), the fraction of these high- $p_T$  events with  $\pi^0$ 's for which the MB condition was also satisfied was  $0.75 \pm 0.02$ , independent of  $p_T$ .

In each event, the two photon invariant mass was calculated for each pairing of clusters. Clusters were paired if the energy asymmetry,  $|E_1 - E_2|/(E_1 + E_2)$ , was less than 0.8 (PbSc) or 0.7 (PbGl). For the PbGl, the pairings were further restricted to those clusters which were identified as electromagnetic via the shower profile and time of flight. The  $\pi^0$  yield was extracted by integrating the invariant mass spectrum over a region around the  $\pi^0$  mass. The background contribution in each  $p_T$  bin was estimated and then subtracted by fitting

the invariant mass distribution outside the peak region (PbSc) or using the mixed event technique (PbGl). For the PbSc and the PbGl, the background to signal ratio varied with increasing  $p_T$  from 1 to 0.1 and 1 to 0.03, respectively.

The raw yields were corrected for the  $p_T$  smearing arising from the EMCal energy resolution and the steeply falling spectrum, and for the losses due to disabled towers, incomplete azimuthal coverage, energy asymmetry cut, and photon identification cut (PbGl). The correction for these effects,  $C_{\text{reco}}$ , was calculated with Monte Carlo simulations which contained the configuration of the active EMCal towers. The energy and position of the decay photons were smeared with the measured test beam resolutions [22] augmented by a constant energy smearing of 5% (12%) for the PbSc (PbGl) to match the response of the EMCal.

The correction for the losses due to conversions of decay photons,  $C_{\text{conv}}$ , was determined to be 4% (PbSc) and 9% (PbGl) by using a GEANT3 [23] simulation of the PHENIX detector. The same simulation, using  $p + p$  events from the PYTHIA generator [24], showed that the contribution of  $\pi^0$ 's from secondary interactions was negligible and that the contribution from decays of other hadrons (e.g.,  $K^0$  and  $\eta$  mesons) was less than 6%. The  $\pi^0$  spectrum was not corrected for these decays.

The integrated luminosity,  $\hat{\mathcal{L}}$ , was determined from the number of MB events using an absolute calibration of the trigger cross section obtained via the van der Meer scan technique [25]. In a scan, the transverse profile of the beam overlap is measured by sweeping one beam across the other in steps while monitoring the MB trigger rate. This information, the bunch intensities of the two beams ( $\sim 10^{11}$ /bunch), and the revolution frequency (78 kHz) are then used to compute the instantaneous luminosity. The trigger cross section is the ratio of the MB trigger rate when the beams were overlapping maximally to the instantaneous luminosity. Based on three scans, this cross section was  $21.8 \pm 0.9$  (2.8) mb at the 68.5% (95%) confidence level with an absolute error of 0.7 mb. From the linear sum of the absolute error and half of the 95% confidence level, point-to-point systematic error, an error of 9.6% was assigned for the luminosity normalization.

During the run, the maximum and average instantaneous luminosities were  $1.5 \times 10^{30}$  and  $0.5 \times 10^{30}$  cm $^{-2}$  s $^{-1}$ , respectively. Contributions from multiple collisions per bunch crossing and beam-gas interactions were negligible. The MB trigger sample of  $16 \times 10^6$  events corresponded to  $0.7$  nb $^{-1}$ . As computed from the fraction of recorded MB events which also met the  $2 \times 2$  high- $p_T$  trigger condition ( $\sim 1/47$ ), the  $18 \times 10^6$  high- $p_T$  triggered events corresponded to an effective luminosity of  $39$  nb $^{-1}$ .

The invariant differential cross sections obtained from the MB and high- $p_T$  samples were consistent within the statistical errors over the  $p_T$  region of overlap ( $p_T \leq 5.5$  GeV/c). Moreover, the results determined

independently from the PbSc and the PbGl data samples were consistent within the total error as computed as the quadrature sum of the statistical and point-to-point systematic errors. The main sources of the latter were (i) the absolute energy scale, (ii) the extraction of the yield, (iii) the correction of the yield for reconstruction efficiency, and (iv) the correction of the yield for the geometric acceptance. The magnitude of these errors is tabulated for a low- and a high- $p_T$  bin in Table I.

From the MB and the high- $p_T$  trigger samples for  $p_T$  below and above 4 GeV/c, respectively, the cross section and the errors were obtained by averaging the PbSc and PbGl results using the total error for the weighting. Figures 2(a) and 2(b) show this combined result and its fractional statistical and systematic uncertainties ( $\Delta\sigma/\sigma$ ). The data are well parametrized by a power-law form  $A(1 + p_T/p_0)^{-n}$  with parameters of  $A = 393 \text{ mb GeV}^{-2} c^3$ ,  $p_0 = 1.212 \text{ GeV}/c$ , and  $n = 9.97$ .

In Fig. 2, our results are compared with NLO pQCD calculations [26–28]. In these calculations, the cross section is factorized into parton distribution functions (PDFs) for the protons, parton-to-pion fragmentation functions, and short-distance partonic hard-scattering cross sections which can be evaluated using perturbative QCD. Because of this factorization, the calculations depend on unphysical, factorization and renormalization scales which are of the order of the hard scale  $p_T$ . This dependence is reduced as higher order terms are included in the perturbation expansion and thus serves as a gauge for the uncertainty of calculations truncated at a given order.

The calculations in Fig. 2 were performed with equal renormalization and factorization scales of  $p_T/2$ ,  $p_T$ , and  $2p_T$ , the CTEQ6M [29] set of PDFs, and two sets of fragmentation functions. In general, these calculations are consistent with the data, even at low  $p_T$  ( $< 2 \text{ GeV}/c$ ) where the theory might be expected to be less applicable. The calculations vary slightly ( $\sim 15\%$ ) with the choice of PDFs, whereas they change markedly with the choice of fragmentation functions. As shown in Figs. 2(c) and 2(d), the calculation with the “Kniehl-Kramer-Pötter” (KKP) set of fragmentation functions [12] agrees with our data better than the calculation with the “Kretzer” set [13] does. These two sets differ mainly in that the gluon-to-

pion fragmentation function,  $D_g^\pi$ , is greater in the KKP set. This difference is exhibited primarily at low  $p_T$  because of the dominance of gluon-gluon and gluon-quark interactions for  $p_T$  below  $\sim 10 \text{ GeV}/c$  [26]. Our data are the first from a hadron experiment from which an unambiguous conclusion may be drawn about  $D_g^\pi$ .

In summary, the invariant differential cross section for inclusive neutral-pion production in  $p + p$  collisions at  $\sqrt{s} = 200 \text{ GeV}$  was measured at midrapidity ( $|\eta| < 0.35$ ) as a function of  $p_T$  up to  $\sim 14 \text{ GeV}/c$ . These results were compared with two NLO pQCD calculations which differed in the choice of fragmentation functions. Over the full range of  $p_T$ , the calculations were consistent with the results within the uncertainty of the calculations as judged from the scale dependence, although the results favored a larger gluon-to-pion fragmentation function.

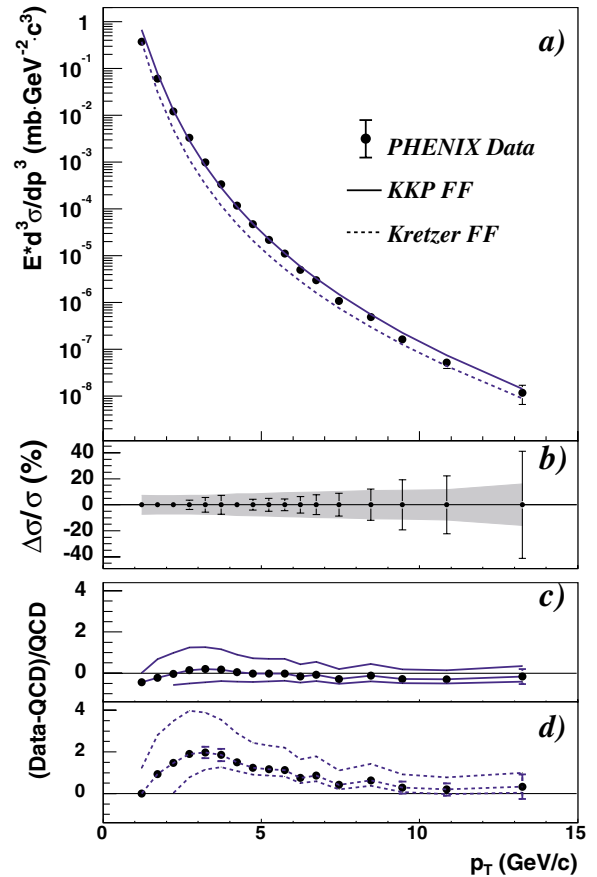


TABLE I. Summary of the sources of systematic errors on the  $\pi^0$  yields and the total systematic error for  $p_T$  of 1.2 and 10.9 GeV/c. The normalization error of 9.6% is not listed.

$p_T$ (in GeV/c)	% Error (PbSc)		% Error (PbGl)	
	1.2	10.9	1.2	10.9
Energy scale	3	11	6	12
Yield extraction	7	4	5	5
Yield correction	3	6	6	11
Acceptance stability	4.5	4.5	3	2
Total	9	14	10	17

FIG. 2 (color online). (a) The invariant differential cross section for inclusive  $\pi^0$  production (points) and the results from NLO pQCD calculations with equal renormalization and factorization scales of  $p_T$  using the “Kniehl-Kramer-Pötter” (solid line) and “Kretzer” (dashed line) sets of fragmentation functions. (b) The relative statistical (points) and point-to-point systematic (band) errors. (c),(d) The relative difference between the data and the theory using KKP (c) and Kretzer (d) fragmentation functions with scales of  $p_T/2$  (lower curve),  $p_T$ , and  $2p_T$  (upper curve). In all figures, the normalization error of 9.6% is not shown.

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