Neutral pion measurement at RHIC-PHENIX

Takao Sakaguchi for the PHENIX Collaboration

Center for Nuclear Study, Graduate School of Science, University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

Abstract. Transverse momentum spectra for identified π^0's in the range 1 GeV/c $< p_T <$ 4 GeV/c via $\pi^0 \rightarrow \gamma\gamma$ have been measured by the PHENIX experiment in Au-Au collisions at $\sqrt{s_{NN}} = 130$ GeV. The spectra from peripheral nuclear collisions are consistent with the simple scaling of p+p collisions with the mean number of nucleon-nucleon binary collisions. The spectra from central collisions and the ratio of central/peripheral spectra are significantly suppressed when compared to binary collision scaling.

PHYSICS OBJECTIVE

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory started operation in June 2000, that opened new frontiers in the study of hadronic matter under unprecedented conditions of temperature and energy density. The research is focused on the phase transition associated with quark deconfinement and chiral symmetry restoration expected to take place under these conditions. PHENIX is one of the four experiments at RHIC, that is designed to cover the entire time-scale of the interaction, from initial hard scattering to final state interactions by simultaneous measurement of a wide range of probes in the same detector.

The production yield of neutral pion in the high transverse momentum (p_T) range is of special interest. High p_T hadrons are produced primarily by hard-scattered partons which turns into jets of hadrons, and their rate of production in pp collisions can be calculated with perturbative QCD (pQCD), that are simply scaled to nuclear collisions by the relative number of binary nucleon-nucleon collisions. In the case of colliding nuclei, there are several nuclear effects that may modify the spectra of hadrons even in the ordinary nuclear medium, such as shadowing and k_T broadening. There are also predictions [1, 2] that if the medium becomes very dense, the scattered partons may lose considerable energy via gluon bremsstrahlung, and thus result in “jet quenching”. According to those predictions, the effect would cause a significant deficit in the spectrum at high p_T.

EXPERIMENTAL SETUP

The PHENIX detector consists of an axial-field magnet surrounded by two central arms (called East and West), each one covering 90° in azimuth and ± 0.38 units of pseudorapidity. Two spectrometers at forward angles ($10^\circ < \theta < 35^\circ$) around the beam axis are dedicated to track and identify muons. During the Year 2000 run, only a subset of the detectors of the central arm were read out and analyzed.

Trigger and basic event characterization were provided by two sets of beam-beam counters (BBC) covering 2π in azimuth and $\eta = \pm(3.0 - 3.9)$, and by two zero-degree calorimeters (ZDC) located ± 18.25 m from the collision point and covering $|\eta| > 6$ [3]. The interaction trigger is primarily generated by the coincidence between the two beam-beam counters that detect $92 \pm 2\%$ of the nuclear interaction cross section of $\sigma_{int} = 7.2$ barns. The coincidence between the two zero-degree calorimeters provides another trigger that are sensitive to unbound spectator neutrons from the nuclear interactions or from Coulomb dissociation. The correlation between the BBC and ZDC signals are used to determine the centrality of the collision. Using a Glauber model combined with a simulation of the BBC and ZDC responses, the numbers of participant nucleons (N_p) and binary collisions (N_{coll}) are estimated [3].

The central arm spectrometers consist of a multiplicity vertex detector (MVD), drift chambers (DC), two layers of pad chambers (PC), a gas-filled ring imaging Cherenkov detector (RICH), a time expansion chamber (TEC), and a high granularity electromagnetic calorimeter (EMC) consisting of eight sectors, each covering $|\eta| < 0.38$ and $\Delta\phi = 22°$. Six of eight calorimeter sectors are lead-scintillator sampling calorimeters (PbSc), while two of them consist of lead glass calorimeters (PbGl). The data presented here are obtained from two PbSc sectors in the West arm spectrometer, which have $8.2\%/\sqrt{E(\mathrm{GeV})} \oplus 1.9\%$ energy resolution and $5.7/\sqrt{E(\mathrm{GeV})} \oplus 1.6$ mm position resolution for electromagnetic showers in a low multiplicity environment. The energy calibration was first established using minimum ionizing particles, verified from the data using E/p matching for identified electrons in low multiplicity events and with the mass of the π^0. The energy gain is frequently maintained with a laser monitoring system, The systematic error on the overall energy scale is less than 1.5% [4].

EVENT SELECTION, DATA SET

Only events taken at full magnetic field and satisfying the primary interaction trigger, as explained above, are analyzed. Additional cuts are applied on the measured event vertex position ($|z| < 30$ cm) and on the consistency between the ZDC and BBC interaction time measurement. 1.17 million events passed these cuts and form the sample referred to as "minimum bias". Based upon the correlation of the measured BBC charge and ZDC energy, events are classified into several centralities as fractions of the total nuclear cross section. In this analysis "central" refers to the 0-10% most central collisions, while "peripheral" means the upper 60-80% range of σ_{int}. The number of events of central collisions is 128K, while that of peripheral collisions is 270K.

ANALYSIS

Neutral pions have been measured using their $\pi^0 \rightarrow \gamma\gamma$ decay mode. In this measurement, the invariant mass of the photon pairs are required to be within a narrow (2σ) window around the observed π^0 mass, that allows for less stringent photon identification cuts, which reduces the systematic errors on efficiency losses due to these cuts.

Each cluster found in the calorimeter is subject to a timing cut of 2.5nsec with respect to the expected time-of-flight of a photon coming from the event vertex (TOF cut). The cut rejects slow hadrons, especially anti-neutrons which are a major source of neutral clusters in the 1-2 GeV energy range. The shape of each cluster is compared to the known and parameterized shape of electromagnetic showers, and the χ^2 of the difference between the observed and predicted shower shape is calculated [4]. A $\chi^2 < 3$ cut is applied to the showers. Both cuts are optimized to keep the photon efficiency as high as possible. Therefore the accepted clusters have a significant contribution from other particles which are removed by the background subtraction method described below. The efficiency of both cuts depends on the event multiplicity, that was verified from the data by comparing π^0 peak contents at a given p_T extracted with different photon identification cuts, as well as by studying the effect of the cuts on well identified electrons.

The $\gamma\gamma$ invariant mass is calculated from all pairs of clusters in an event that passed the photon identification cuts. The combinatorial background is estimated using an event mixing method, which is subtracted from the invariant mass distribution after proper normalization.

The π^0 reconstruction efficiency as well as acceptance is calculated using Fast Monte Carlo with an input of measured/true energy ratios for different classes of centrality (hence, different degrees of overlap effects), PID efficiency, and clustering efficiency calculated from full PHENIX simulation.

The measured/true energy ratios for gammas are derived by simulated single electromagnetic showers merged both in real and simulated events. For different single shower energies and event centralities, the distributions of the ratios of the measured and true energies are stored (referred to as photon energy and event centrality-dependent $f(E_\gamma, cent)$ "smearing" functions). The simulated events have photons (also simulated) at certain energies inserted. This increases our statistics for higher energy photons, which is crucial for determining the amount of p_T smearing. The PID cuts are derived from simulation (using both CFD timing simulations and LED timing simulations). The cluster efficiency is the efficiency of finding the photon as a dominant contributor to a cluster, also determined from simulation. The systematic errors concerning PID efficiencies are estimated to be $15 \sim 20\%$ over the entire p_T range.

After evaluating the several inputs, Fast Monte Carlo generates neutral pions with the expected p_T distribution and allows to decay. For those cases, when both decay photons reach the calorimeter, their respective energies are randomized with the appropriate $f(E_\gamma, cent)$ smearing function, and the invariant mass is calculated using the randomized energies. The resulting simulated line-shapes are compared to line-shapes obtained from the data after mixed event subtraction. They agree very well, and the same cuts are applied to the data and the simulations to establish the efficiency. The process is two times iterative starting with a reasonable first guess of the final corrected spectrum. The systematic error on invariant mass cut in the simulation is estimated to be $<$20%, that on p_T shift and smearing is 10 $\sim$ 15%, respectively. These values vary depends on p_T's and centralities.

The full PHENIX simulations are also used to determine the background from particles striking the pole-tips and structural elements of detectors in front of the calorimeter. An additional source of background arises from those π^0's produced close to the collision vertex which are reconstructed in the calorimeter with the proper invariant mass. These particles increase the true π^0 yield, and thus also estimated using simulations (HIJING 1.35 [5]). The calculated contribution of non-vertex but properly reconstructed π^0 is $\sim$ 8% at $p_T = 1$ GeV/c and gradually decreases to $\sim$ 6% at $p_T > 2.5$ GeV/c, each of which has the systematic error of $\sim$50%. This yield has been subtracted from the measured π^0 yield. The overall systematic errors are estimated to be 25 $\sim$ 35%.

RESULTS AND DISCUSSION

The semi-inclusive transverse momentum distribution of π^0 in peripheral (upper 60-80% of σ_{int}) and 10% most central Au+Au collisions are shown in Figure 1. At high p_T the the spectra are limited by statistics. Error bars include both statistical and systematics errors.

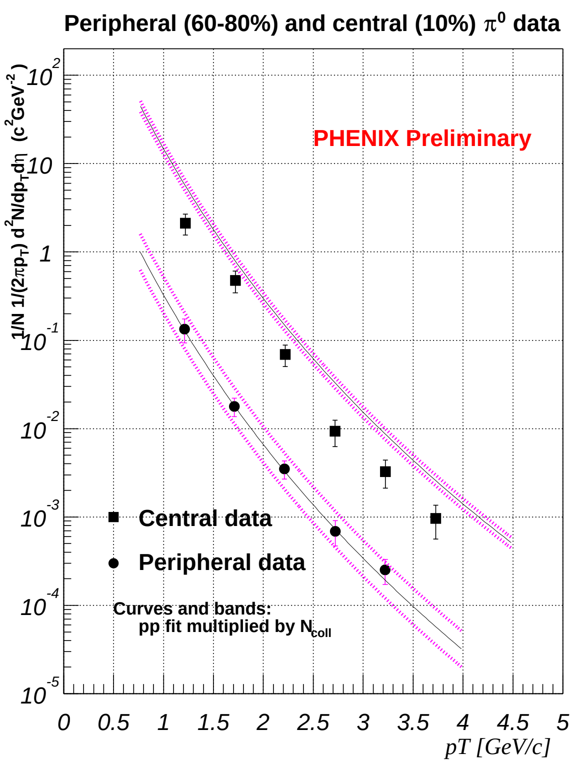

FIGURE 1. Semi-inclusive π^0 p_T distribution $(1/N_{int})(dN_{\pi^0}/2\pi p_T dp_T dy))$ in the upper 60-80% peripheral events (solid circles) and the 10% most central events (solid squares). The lines are a parameterization of pp charged hadron spectra, scaled by the mean number of collisions N_{coll}. The bands indicate the possible range due to the systematic error on N_{coll}.

Both spectra are compared to p_T spectra derived from nucleon-nucleon data. Since there is no measurement of π^0 production in pp at $\sqrt{s} = 130$ GeV, this reference spectrum is derived from UA1 [6] and CDF [7] charged hadron spectra. The available data are fitted with a function $d\sigma/2\pi p_T dp_T dy = A/(p_0 + p_T)^n$, and the fit parameters A, p_0, n are interpolated to RHIC energy. The result is divided by $\sigma_{pp} = 42$ mb for the yield and by 1.6 to obtain the pion content from the unidentified charged spectra. (The actual parameter values are $A = 275000/42/1.6$, $p_0 = 1.71$ and $n = 12.42$.) This parameterized curve is then multiplied by the estimated mean number of binary nucleon-nucleon collisions (19 ± 11 and 857 ± 128 in peripheral and central collision, respectively). The systematic error on the number of collisions is indicated by the two bands.

The scaled pp parameterization describes the results in peripheral collisions very well, while it significantly overpredicts the measured spectrum in central collisions, particularly at higher p_T. The observed deficit in the π^0 yield is even more pronounced considering the Cronin-type enhancement that is expected in 3-4GeV/c region (due to k_T broadening) above the scaled pp distribution.

The left side of Fig. 2 shows the ratio of per-collision yield of central events to pp data, which corresponds to the nuclear modification factor. It is expected that the ratio equal 1 if the central events can be simply scaled by binary collisions, and more than 1 if the Cronin effect is expected. The result shows the ratio less than 1, that is not explainable by these two scenarios.

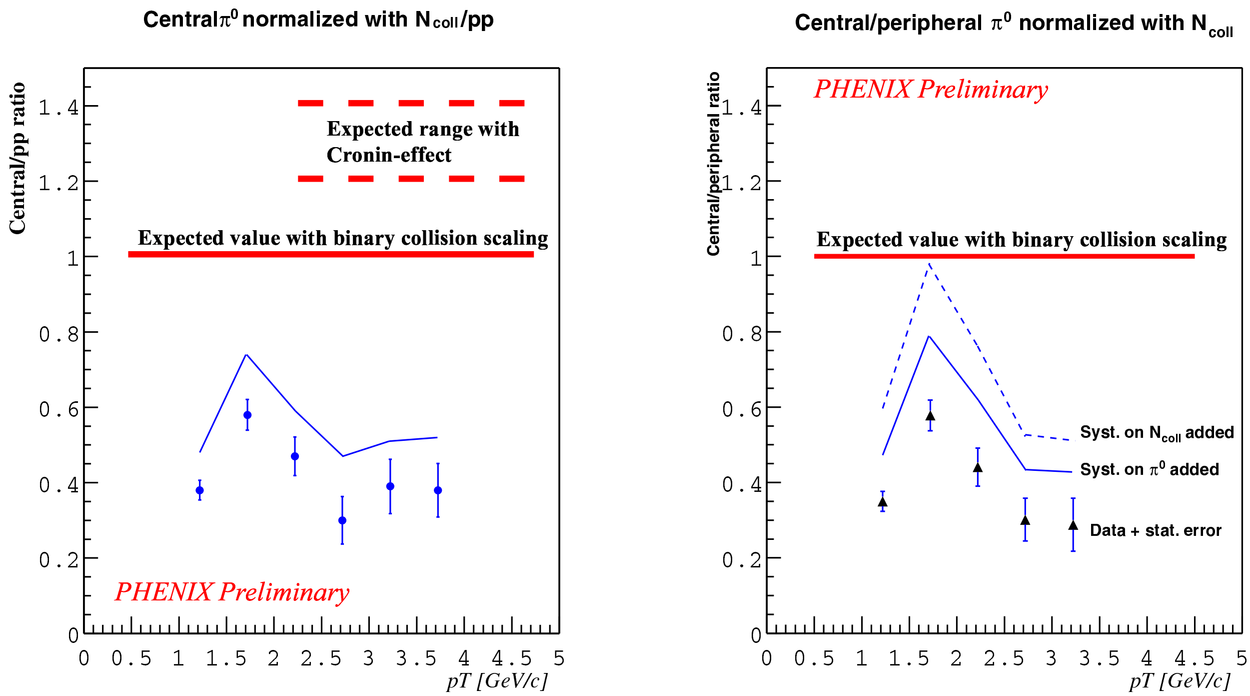

FIGURE 2. Left side: Ratio of the central π^0 spectra normalized by the mean number of collisions (857) to pp data. Error bars are statistical only. Solid line: systematic errors of the π^0 measurement added in quadrature. There is another systematic error of fitting to pp data. Right side: Ratio of the central and peripheral π^0 spectra, both normalized by the mean number of collisions (857 and 19, respectively). Error bars are statistical only. Solid line: systematic errors of the π^0 measurement added in quadrature. Dashed line: systematic errors on the number of binary collisions added in quadrature. Also shown: expected range of the ratio with the Cronin-effect.

The same deficit are seen in the right side of Figure 2 where both the central and the peripheral spectra are normalized by the respective number of binary collisions, and divided point-by-point. The central/peripheral ratios are shown as triangles, and the error bars are statistical only. The solid line gives the upper limit on the ratio considering that the systematic errors of the π^0 spectra are added in quadrature. The dashed line adds the systematic error on the number of collisions (N_{coll}) in quadrature to the solid line. The central/peripheral ratio, normalized by N_{coll}, is expected to be one in the case of simple scaling with N_{coll}. The measured ratio is much smaller, that can not be explained by simple scaling. The expected range of the central/peripheral ratio with a Cronin-effect included is also shown.

Figure 3 shows the results for both the peripheral and central collisions compared to three theoretical calculations [1] (curves). The solid lines are straightforward pQCD calculations for pp, with simple scaling to Au-Au collisions normalized by the mean number of binary collisions [1]. The dotted lines are calculations where effects of nuclear shadowing and k_T broadening are added. The result shows a change of slope, and a suppression of the soft part of the spectrum and enhancement of the hard scattering part (Cronin effect). The dashed lines includes the parton energy loss of $dE/dx = 0.25\ GeV/fm$ in addition to the shadowing and k_T broadening. The peripheral data are not inconsistent with either of three scenarios. However, the central data are well below the first and second (pQCD and shadowing/Cronin) curve, while they are not inconsistent with the third scenario that includes a parton energy loss.

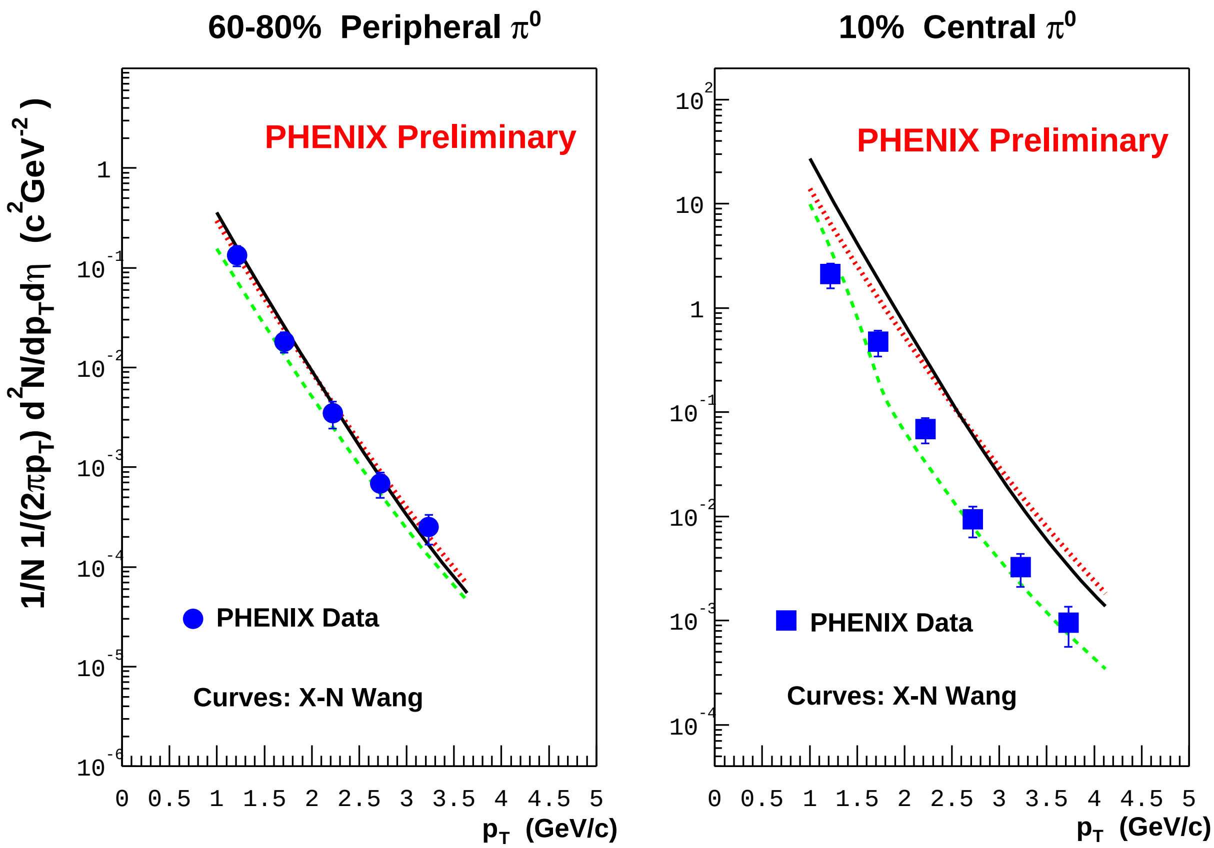

FIGURE 3. Comparison of PHENIX π^0 spectra to theoretical calculations under three scenarios and for two centralities. The points are the same as Figure 1. The curves are calculations of X-N. Wang [1]. Solid lines are a pQCD calculation for pp scaled by the mean number of binary collisions. The dotted lines add shadowing and k_T broadening. The dashed lines add a $dE/dx = 0.25$ GeV/fm parton energy loss.

CONCLUSION

Transverse momentum spectra for neutral pions in central and peripheral as well as their ratio at $\sqrt{s_{NN}} = 130$ GeV Au+Au collisions have been presented. The ratio of per-collision yield of central events to pp data shows the same tendency as the ratio of central/peripheral per-collision yield. The peripheral spectrum is consistent with the simple scaling of pp collisions with the mean number of binary nucleon-nucleon collisions. In the central spectra, a significant deficit with respect to this point-like scaling is observed at high transverse momenta. The consistency check between the data from lead scintillator and lead glass calorimeter is now in progress.

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