Neutral Pion Distributions in PHENIX at RHIC

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

1. The PHENIX Experiment

1.1. Physics goals

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory started regular operations in June 2000, opening 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. It 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.

Here, the results on neutral pion production in the $1.0 < p_T < 4.0$ GeV/c transverse momentum range are presented. High p_T hadrons are produced primarily by initial hard scattering of partons, and their rate of production in *pp* collisions can be calculated in perturbative QCD, which simply scales to nuclear collisions by the relative number of binary nucleon-nucleon collisions. However, in the case of colliding nuclei, there are several nuclear effects that can modify the spectra of hadrons even in the ordinary nuclear medium, such as shadowing and p_T broadening. In addition, there are predictions [1,2] that if the medium becomes very dense, the scattered partons may lose considerable energy via gluon bremsstrahlung or "jet quenching". According to those predictions, this effect would cause a significant depletion of the spectra at high p_T.

*For the full PHENIX Collaboration authors list and acknowledgments, see "PHENIX Overview" presented by W. A. Zajc in this volume.

1.2. Experimental setup

The PHENIX detector consists of an axial-field magnet surrounded by two central arms (called East and West), each one subtending 90^0 in azimuth and ±0.38 units of pseudorapidity. Two spectrometers at forward angles ($10^o < \theta < 35^o$) around the beam axis serve to identify and track muons. During the Year 2000 data taking run, only a subset of the detectors of the central arm were read out and analyzed.

Trigger and basic event characterization was provided by two sets of beam-beam counters (BBC) covering 2π in azimuth and $\eta = \pm(3.0 - 3.9)$, as well as by two zero-degree calorimeters located ±18.25 m from the collision point and covering $|\eta| > 6$ [3]. The primary interaction trigger is generated by the coincidence between the beam-beam counters which detect $92 \pm 2\%$ of the nuclear interaction cross section of $\sigma_{int} = 7.2$ barns. Another trigger is generated by a coincidence between the two zero-degree calorimeters which 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. They are also used to establish the number of participant nucleons (N_p) and binary collisions (N_{coll}) using a Glauber-model calculation [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 the calorimeter sectors are lead-scintillator sampling calorimeters (PbSc), while two sectors 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 established using minimum ionizing particles, maintained with a laser monitoring system, and verified from the data using E/p matching for identified electrons in low multiplicity events, as well as with the mass of the π^0. The systematic error on the overall energy scale is less than 1.5% [4].

1.3. Event selection, data set

Only events taken at full magnetic field and satisfying the primary interaction trigger, as explained above, are analyzed. Additional cuts include the measured event vertex position ($|z| < 30$ cm), consistency between the ZDC and BBC interaction time measurement. Altogether, 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, centrality classes were established 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}. [2]

[2] At the Quark Matter conference we presented the upper 75-92% range of σ_{int} as "peripheral". This is now replaced by the upper 60-80% of σ_{int} where the sample is much cleaner and the results are less biased by the inefficiencies of the trigger in the most peripheral collisions. The centrality selection for the "central" spectra is the same (0-10% most central), but the points and the systematic errors have been revised.

2. 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 has to be within a narrow (2σ) window around the observed π^0 mass, thus allowing 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: it has to arrive within 2.5 ns with respect to the expected time-of-flight of a photon coming from the event vertex (TOF cut). This cut eliminates slow hadrons, in particular anti-neutrons which are a major source of neutral clusters in the 1-2 GeV energy range. In addition, the shape of each cluster is compared to the known and parametrized 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 then applied to the showers. Both cuts are designed to keep the photon efficiency as high as possible. Therefore the accepted clusters have a significant contribution for other particles which is removed by the backround subtraction method described below. Furthermore, the efficiency of both cuts depends on the event multiplicity. This 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 passing the photon identification cuts. The combinatorial background is estimated using an event mixing method, which after proper normalization, is subtracted from the invariant mass distribution.

The π^0 reconstruction efficiency is calculated by the following procedure. First, the effect of a second particle contributing to the same cluster is investigated (overlaps). Simulated single electromagnetic showers are merged both in real and simulated events. For different single shower energies and event centralities, the distributions of the ratios of the measured and original energies are stored (referred to as photon energy and event centrality-dependent $f(E_\gamma, cent)$ "smearing" functions). These functions are then used in a fast Monte Carlo simulation as follows. Neutral pions are generated with the expected p_T distribution and allowed 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.

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 (but not at) the collision vertex which reconstruct in the calorimeter with the proper invariant mass, increasing the true π^0 yield. This background is 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 $p_T > 2.5\ GeV/c$. This yield has been subtracted from the measured π^0 yield.

3. 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 is shown in Figure 1. At high p_t the peripheral spectrum is limited by statistics. Error bars include both statistical and systematics errors.

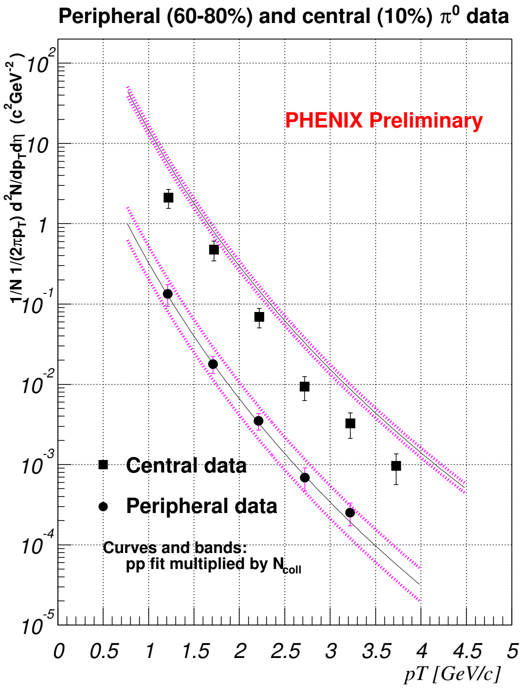

Figure 1. Semi-inclusive π^0 p_T distribution $(1/N_{int})(dN_{\pi^0}/2\pi p_T dp_T dy))$ in the upper 60-80% peripheral events (solid circles) and the 10% most central events (solid squares). The lines are a parametrization of pp charged hadron spectra, scaled by the mean number of collisions N_{coll}.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

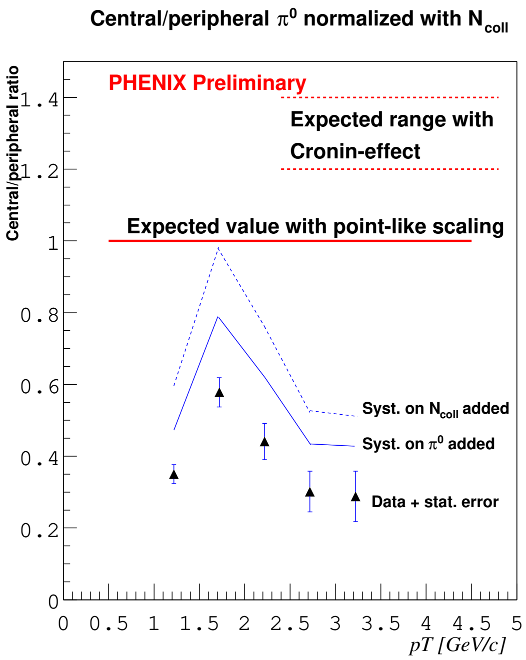

Figure 2. Ratio of the central and peripheral π^0 spectra, both normalized by the mean number of collisions (857 and 19, respectively). Error bars are statistical only. Solid line: systematic errors of the π^0 measurement added in quadrature. Dashed line: systematic errors on the number of binary collisions added in quadrature. Also shown: expected range of the ratio with the Cronin-effect.

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. First, the available data are fitted with a function $d\sigma/2\pi p_T dp_T dy = A/(p_0 + p_T)^n$, then 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 parametrized 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.

In peripheral collisions the scaled *pp* parametrization describes the results very well, but 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 surprising if one takes into account that at 3-4 GeV/c a Cronin-type enhancement due to p_t broadening above the scaled *pp* distribution would be expected.

The same deficit can be seen in Figure 2 without referring to parametrized *pp* results. Both the central and the peripheral spectra are normalized by the respective number of binary collisions, then divided point-by-point. The central/peripheral ratios are shown as triangles, and the error bars are statistical. The solid line gives the upper limit on the ratio if the systematic errors of the π^0 spectra are added in quadrature. The dashed line adds (in quadrature) the systematic error on the number of collisions (N_{coll}). The central/peripheral ratio, normalized by N_{coll}, is expected to be one in the case of simple scaling with N_{coll}. However, the measured ratio is much smaller. 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 a straightforward pQCD calculation for *pp*, with simple scaling to Au-Au collisions by the mean number of binary collisions [1]. The dotted lines are a calculation where effects of nuclear shadowing and p_T broadening are added, and result in a change of slope, suppressing the soft part of the spectrum and enhancing the hard scattering part (Cronin effect). The calculation plotted with dashed lines adds a constant $dE/dx = 0.25\ GeV/fm$ parton energy loss to the shadowing and p_T broadening. The peripheral data are consistent with all three scenarios. However, the central data are well below the first and second (pQCD and shadowing/Cronin) curve, but they are not inconsistent with the third scenario that includes a parton energy loss.

4. Conclusion

Transverse momentum spectra for neutral pions in central and peripheral $\sqrt{s} = 130$ GeV Au+Au collisions have been presented. 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.

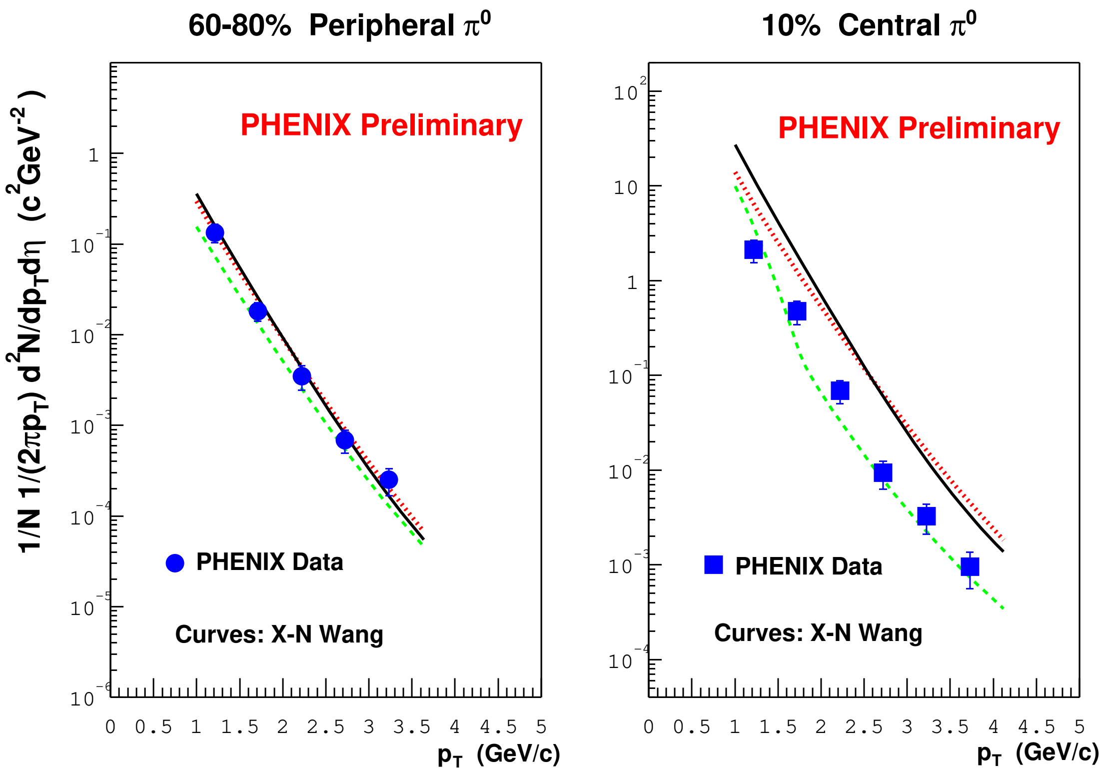

Figure 3. Comparison of PHENIX π^0 spectra to theoretical calculations under three scenarios and for two centralities. The points are the same as on Figure 1. The curves are calculations of X-N. Wang [1]. Solid lines are a pQCD calculation for pp scaled by the mean number of binary collisions. The dotted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

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