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HIGHT P_T MEASUREMENT AT RHIC

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We present recent high transverse momentum measurements in Au+Au and p+p collisions at the Relativistic Heavy Ion Collider (RHIC). We define and show the nuclear modification factor for neutral pions and charged hadrons and discuss the particle species dependence. By means of the nuclear modification factor, we observe a suppression factor at high p_T of 5-6 for neutral pions and 3-4 for charged hadrons in central Au+Au collisions relative to the binary-scaled yields in p+p (or peripheral) collisions. Finally we present strong evidence for the observation of jets in Au+Au collisions and the disappearance of the away-side jet in central Au+Au collisions.

1. Introduction

The Relativistic Heavy Ion Collider (RHIC) is located at Brookhaven National Laboratory (BNL) on Long Island, New York. It is a versatile collider, with two independent rings, that can collide almost any two nuclear species at $\sqrt{s_{NN}} = Z/A \ (500GeV)$. The motivation to collide heavy ions at ultra-relativistic energies is to create hot and dense conditions suitable for reaching deconfinement, a state of matter called the Quark Gluon Plasma (QGP). In Run-I, RHIC provided Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV. In Run-II, RHIC delivered both Au+Au and p+p collisions at $\sqrt{s_{NN}} = 200$ GeV. At these energies, hard scattering is expected to contribute significantly to particle production. It is known that hard scattering and the fragmentation of the scattered partons dominates the production of hadrons above $p_T \sim 2$ GeV/c [1] in p+p collisions. In the physics of heavy ion collisions (Au+Au in this case), the measurement of particle yields in p+p collisions provides a baseline for the measurement in Au+Au collisions. In Au+Au collisions, hard scatterings are of particular interest because they occur early in the collision, leaving the hard-scattered partons sensitive to the properties of the collision medium. Further interactions of these partons in the dense medium might cause the high transverse momentum tail of the hadron spectrum, where the hadrons are likely to be the leading particles of jets, to be suppressed [2]. Due to the high multiplicity environment, jets cannot be directly observed in a heavy ion collision. We can however study the contribution of jet fragmentation to hadron yields at high p_T via correlation measurements and use this knowledge to interpret the measured hadron p_T spectra.

In the following sections, we present the production cross section as a function of p_T for neutral pions in p+p collisions. We define the nuclear modification factor and, with this quantity, compare the particle spectra at high p_T measured in Au+Au collisions to those measured in p+p collisions with the objective of measuring the effect of the dense medium on the hard-scattered partons. With the measurement of charged hadrons, identified protons, and neutral pions, we also investigate the particle species dependence of the nuclear modification factor. Finally, we use two-particle correlations to verify that the hadrons at high p_T are due to the fragmentation of hard-scattered partons. We present evidence for the disappearance of the away-side jet in central Au+Au collisions.

2. High p_T Particle Spectra

Shown in Fig. 1 is the neutral pion production cross section as a function of p_T, measured by the PHENIX experiment, in p+p collisions [4]. The measured p+p spectrum is compared to a fit to UA1 data [5] over the range $p_T < 6$ GeV/c, extrapolated to higher p_T. Although the PHENIX measurement agrees with the UA1 data, it disagrees with this extrapolation at very high p_T. This new measurement provides an important reference spectrum for comparison with the Au+Au data, and having the measurement within the same experiment reduces the systematics in the comparison between the Au+Au and p+p spectra.

In Au+Au collisions, the dynamics depends on the impact parameter or "centrality" of the collision. Events are binned into centrality selections, where the most central collisions have the smallest impact parameter and the most peripheral have the largest. Centrality is expressed as a percentage of the total inelastic cross section. The spectra are not shown here, but the comparison to p+p collisions is shown and discussed in the following sections.

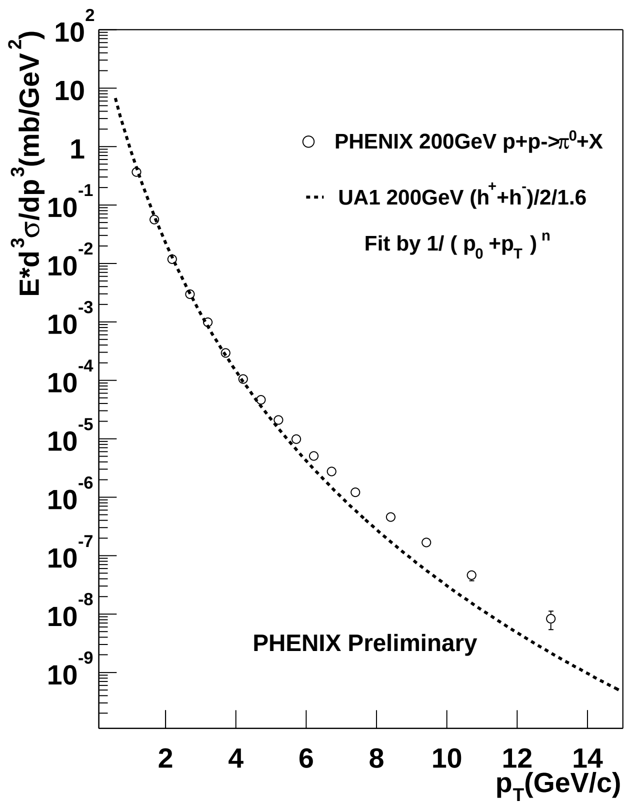

Figure 1. Neutral pion production cross section vs. p_T in p+p collisions at $\sqrt{s_{NN}}$ = 200 GeV.

3. R_{AA} for Neutral Pions

In order to compare high p_T particle yields measured in a particular centrality selection in Au+Au collisions to the spectrum measured in p+p collisions, we now define R_{AA}. The nuclear modification factor R_{AA} quantifies the effect of the A+A system compared to p+p collisions on particle yields for point-like processes. It is the ratio of the particle yield in a A+A collision to the yield in a p+p collision scaled by the mean number of binary (nucleon+nucleon) collisions N_{coll} in the A+A event sample. Because hard processes are generally believed to scale with N_{coll} ("binary-scaling"), this ratio is expected to be one at high p_T in the absence of any nuclear effects.

$$R_{AA}(p_T) = \frac{(\mathrm{Yield_{A+A}})}{\langle N_{coll}\rangle(\mathrm{Yield_{p+p}})} = \frac{d^2N^{A+A}/dp_Td\eta}{\langle N_{coll}\rangle(d^2\sigma^{p+p}/dp_Td\eta)/\sigma^{p+p}_{inelastic}}. \quad (1)$$

Shown in Fig. 2 is R_{AA} as a function of p_T for central Pb+Pb collisions at $\sqrt{s_{NN}} = 17$ GeV from WA98 [8] and central Au+Au collisions at $\sqrt{s_{NN}} =$ 130 GeV from PHENIX Run I [9]. In this comparison, the suppression relative to binary-scaling at 130 GeV is striking. It is quite different from the enhancement observed at 17 GeV. This enhancement is consistent with the previously observed "Cronin effect" [10] which has been attributed to p_T broadening due to initial state scatterings [11,12]. Figure 3 shows R_{AA} for central and peripheral Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The central

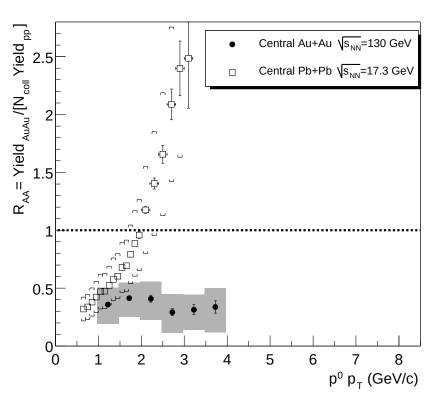

Figure 2. R_{AA} (π^0) for central Pb+Pb collisions at $\sqrt{s_{NN}} = 17$ GeV and central Au+Au collisions at $\sqrt{s_{NN}} =$ 130 GeV. The error bars are the statistical $\oplus$ p_T-dependent systematic errors. The brackets/boxes are the errors on the normalization of this ratio.

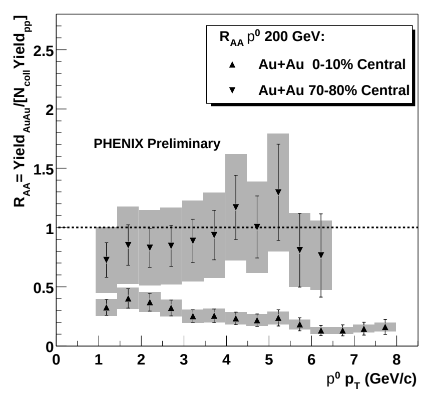

Figure 3. R_{AA} (π^0) for central and peripheral Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV. The error bars are the statistical $\oplus$ p_T-dependent systematic errors. The shaded boxes are the errors on the normalization of the ratio.

data again show a suppression as seen at 130 GeV. With a measurement that extends to much larger p_T, the suppression is shown to persist up to $p_T \sim 8$ GeV/c and is as much as a factor of 5-6 at the largest p_T. The measurement of the p+p reference spectrum with the same detector greatly reduces the systematic error in R_{AA} for central events. The R_{AA}

for peripheral events is consistent with binary-scaling (p+p yields scaled by the number of binary collisions in the peripheral event sample). The error in this ratio is dominated by the uncertainty in $\langle N_{coll} \rangle$ for peripheral collisions. The 10% most central events have a suppression factor reaching 5-6, while the 70-80% centrality selection is consistent with binary-scaled p+p collisions. The deviance from binary-scaling as the Au+Au collisions become more central indicates possible strong medium effects.

We now address the evolution of the nuclear modification factor from the most peripheral to the most central collisions, in terms of the mean number of participating nucleons N_{part} in a centrality selection. For the 10% most central collisions, $\langle N_{part} \rangle = 327$, and for the 70-80% central collisions, $\langle N_{part} \rangle = 14$. Figure 4 shows R_{AA} vs. N_{part} for neutral pions with $4 < p_T < 6$ GeV/c. The suppression increases gradually from peripheral to

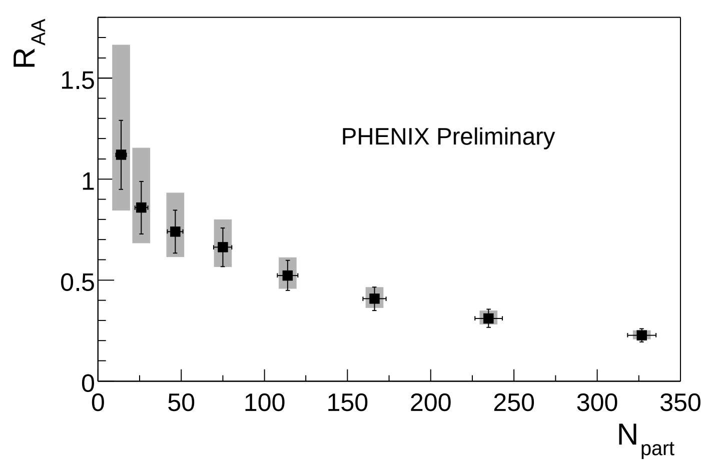

Figure 4. $R_A A$ vs. N_{part} for neutral pions.

central events.

4. Comparison of Central Collisions with Respect to Peripheral Collisions

An alternate measure of the nuclear modification is the central-to-peripheral ratio scaled by the number of binary collisions,

$$\text{Binary}-\text{Scaled Central/Peripheral} = \frac{(\text{Yield}_{\text{central}})/\langle \text{N}_{\text{coll}}^{\text{central}} \rangle}{(\text{Yield}_{\text{peripheral}})/\langle \text{N}_{\text{coll}}^{\text{peripheral}} \rangle}. \quad (2)$$

Since the π^0 spectrum in peripheral Au+Au collisions is consistent with the binary-scaled p+p π^0 spectrum (Fig. 3), this ratio is similar to R_{AA}. An advantage of this ratio is that many of the systematic uncertainties in the measurement cancel, particularly for charged hadrons. A disadvantage is that it is sensitive to the centrality dependence of the Cronin effect, which is not known. Figure 5 shows this ratio as a function of p_T for neutral pions, charged hadrons, and charged pions. The suppression is observed in all three measurements. In the charged hadrons, the suppression factor reaches 3-4 at high p_T. The difference in this ratio between the identified pions and charged hadrons is due to the particle composition. In particular, PHENIX has measured $p/\pi^0 \sim 1$ in central collisions for $p_T = 2-4$ GeV/c while $p/\pi^0 \sim 0.4$ in peripheral collisions [16]. The error in the normalization, denoted by a shaded area for the charged hadrons and outlines for the neutral pions, is dominated by the uncertainty in $\langle N_{coll} \rangle$ for peripheral collisions.

5. Particle Species Dependence

The difference in the suppression factors for inclusive hadrons and identified pions seems to indicate that the protons are not suppressed in central Au+Au collisions. Shown in Fig. 6 is the central-to-peripheral ratio for (anti)protons compared to the same ratio for pions. Remarkably, unlike the suppressed pions, the (anti)proton yields are consistent with binary-scaling for intermediate p_T ($1.5 < p_T < 4$ GeV/c). Naively, one might conclude that the protons in this region of p_T are produced from hard processes. However, unlike the pions which are produced in hard collisions, the protons appear not to be suppressed. Therefore, production mechanisms other than hard processes may be contributing to the proton yields at these p_T in central Au+Au collisions. Competing with production from hard processes is the "flow," or collective expansion of the A+A system. Although flow is commonly believed to primarily affect the yields at low p_T, where particle production is dominated by soft processes, the boundary

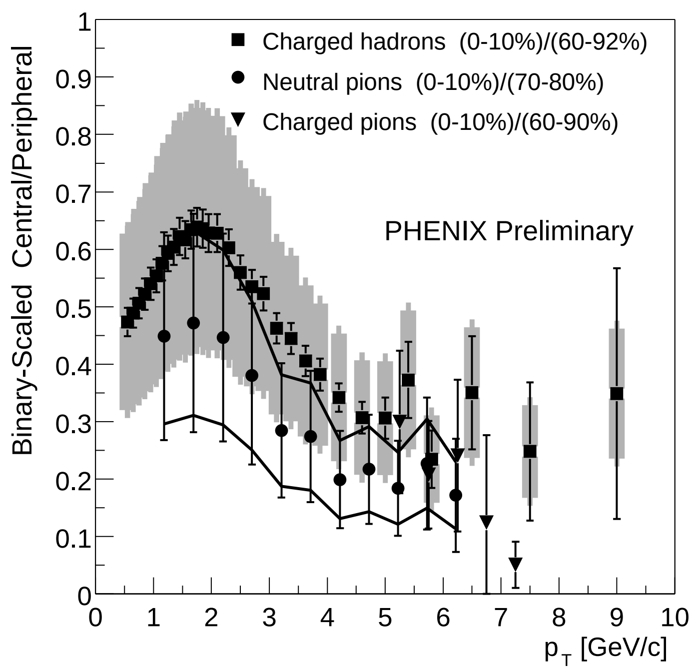

Figure 5. Binary-scaled central-to-peripheral ratio vs. p_T for charged hadrons, neutral pions, and charged pions measured in Au+Au collisions. The error bars are statistical $\oplus$ p_T-dependent systematic errors. The error in the overall normalization is shown as outlines for neutral pions and a shaded area for charged hadrons. For charged pions, the error is dominated by statistics.

between soft and hard is at larger p_T for protons than for pions. Another possible mechanism that has been proposed to explain the different behavior of protons and pions in this intermediate p_T region is the recombination (rather than fragmentation) of quarks [21].

6. High p_T Hadron Production due to Jet Fragmentation

Since jets cannot be directly observed in Au+Au collisions, a correlation analysis is required to detect their presence. There are several sources of correlations, as well as a combinatorial background, that need to be disentangled from the jet correlations. Correlations due to flow and resonance decays contribute to the signal. Flow, dijets, and the combinatorial background contribute to correlations at all relative pseudo-rapidities (η), while

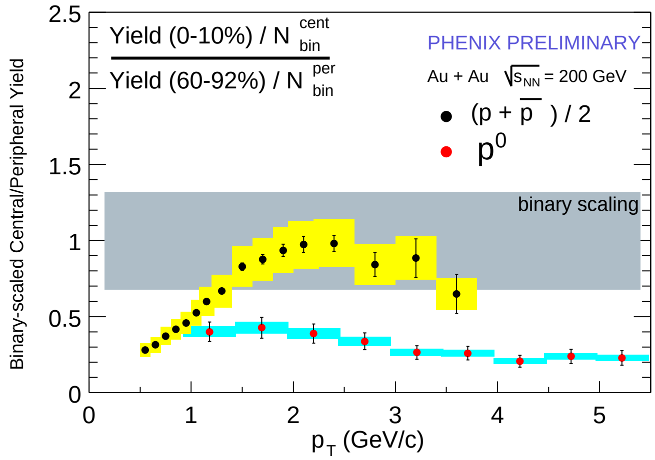

Figure 6. Binary-scaled central-to-peripheral ratio vs. p_T for (anti)protons. The error bars are statistical $\oplus$ p_T-dependent systematic errors. The error in the normalization is shown as shaded bands around the points. The error on N_{coll} is shown as a percent error around 1, which is the expected value for binary-scaling.

jets and resonance decays have correlations that are restricted to small relative pseudo-rapidities. The STAR experiment has measured correlations due to jets by subtracting the large $\Delta\eta$ correlations from the small $\Delta\eta$ correlations. A high p_T charged particle, $4 < p_T^{trig} < 6$ GeV/c, as the trigger is correlated with all other charged particles in the event with 2 GeV/c$< p_t < p_T^{trig}$. Figure 7 shows the distribution of the 2-particle correlations in $\Delta\phi$. The lower panel is the remaining distribution due to jets and resonance decays alone. Since resonance decays would have correlations mainly for opposite-sign pairs, the same-sign is dominated by jet correlations. This is strong evidence that hadrons measured with $p_T > 4$ GeV/c are produced from jet fragmentations.

7. Disappearance of Away-Side Jet

Assuming that triggered high p_T Au+Au events are simply a superposition of triggered high p_T p+p events plus an elliptic flow term, a deviation due to the dense medium can be measured. This deviation is quantified by,

$$I_{AA}(\Delta\phi_1, \Delta\phi_2) = \frac{\int_{\Delta\phi_1}^{\Delta\phi_2} d(\Delta\phi)[C_2^{AuAu} - B(1 + 2v_2^t v_2^a cos(2\Delta\phi))]}{\int_{\Delta\phi_1}^{\Delta\phi_2} d(\Delta\phi) C_2^{pp}} \quad (3)$$

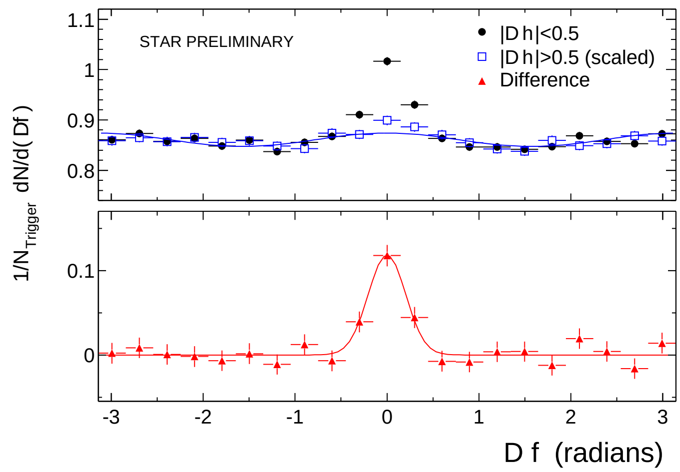

Figure 7. Azimuthal distributions of charged hadrons for central Au+Au collisions. The top panel shows the small and large relative $\Delta\eta$ distributions separately, and the bottom panel shows the difference.

The "near-side" correlations are those at small $|\Delta\phi|$, and the "away-side" are at large $|\Delta\phi|$. The elliptic flow is measured using a reaction plane method [?]. Figure 8 shows this ratio as a function of centrality, or N_{part} for the near-side and away-side peaks. The ratio I_{AA} for the away-side

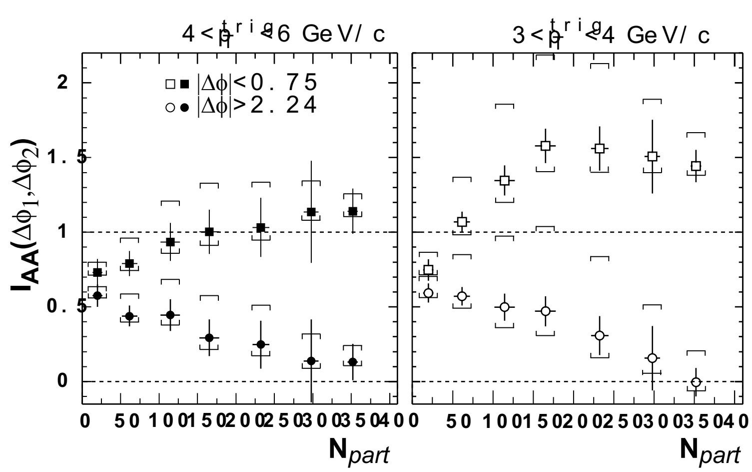

Figure 8. I_{AA} vs. N_{part} for small $|\Delta\phi|$ ("near-side") and large $|\Delta\phi|$ ("away-side").

peak is decreasing with increasing centrality, indicating a suppression of the away-side jet as the collisions become more central.

8. Conclusions

We have presented the production cross section as a function of p_T for neutral pions in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV. With the nuclear modification factor, we have shown that the high p_T yields in central Au+Au collisions are suppressed relative to the binary-scaled p+p yields up to $p_T \sim 8$ GeV/c. The suppression increases gradually with increasing centrality, or N_{part}. The neutral pions are suppressed by a factor of 5-6 and the charged hadrons by 3-4 for $p_T > 4$ GeV/c in the most central collisions. The difference in suppression is due to the proton content of the charged hadrons; the protons, unlike the pions, are not suppressed relative to binary-scaling. We have also shown that high p_T hadrons ($p_T > 4$ GeV/c) are produced by jet fragmentations. Finally, we have shown evidence that the away-side jet disappears in the most central collisions, which is another indication of dense medium effects.

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