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RECENT RESULTS ON HIGH p_{T} PARTICLE PRODUCTION FROM THE PHENIX EXPERIMENT*

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Particles with large transverse momentum (p_{T}) produced during the initial phase of a nuclear collision can be used to probe the dense excited matter created during the collision process. The p_{T} spectra of neutral pions and charged hadrons in Au+Au and d + Au collisions GeV are compared to $p+p$ spectra at the same $\sqrt{s_{NN}}$. In central Au+Au collisions a factor of 4–5 suppression of high p_{T} neutral pion and charged hadron yields is observed compared to expectations from scaled p+p results. No suppression of high p_{T} particles is observed in d + Au collisions, suggesting that the observed suppression in central Au+Au collisions is due to the produced dense matter.

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1. Introduction

A primary objective of the heavy-ion program at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory is the study of QCD matter at extremely high energy densities where lattice calculations predict a transition from hadronic matter to a deconfined plasma of quarks and gluons. While the bulk of the particles produced in relativistic nucleus-nucleus collisions are produced in the late hadronization phase of the collision, high transverse momentum ($p_{\mathrm{T}} > 2$ GeV/c) hadrons arise from the fragmentation of partons (quarks and gluons) produced in parton–parton scatterings with large momentum transfer (hard processes) during the initial phase of the collision. While the scattered partons in proton–proton interactions propagate through the normal QCD vacuum before fragmenting into the observed colorless hadrons, in nucleus–nucleus collisions, the

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partons produced in hard scatterings in the early phase of the collision must propagate through the surrounding dense excited matter (see Fig. 1). As they traverse the dense matter, the partons will interact with it and radiate, losing energy before finally fragmenting into the observed hadron, or jet of hadrons. The magnitude of this "jet quenching" in terms of parton energy loss, or corresponding suppression of the high p_{T} particle yields can thus provide a means to probe the created matter [1, 2].

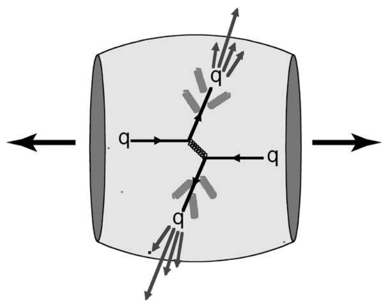

Fig. 1. In a heavy ion collision, a parton produced in an initial hard scattering within the overlap volume must traverse the surrounding dense excited matter and may lose energy as it propagates, leading to the phenomena of parton energy loss or "jet quenching".

2. The PHENIX experiment

Neutral pions and charged particles were measured with the two central spectrometer arms of the PHENIX experiment shown in Fig. 2 [3]. Each arm covers the pseudorapidity region $|\eta| < 0.35$ with $\Delta\phi = \pi/2$ in azimuth. Neutral pions were measured with the PHENIX electromagnetic calorimeters (EMCal) via reconstruction of the $\pi^0 \to \gamma\gamma$ decay. The EMCal consists of two different detector technologies with half of one arm consisting of lead-glass cherenkov modules (PbGl) and the rest of the EMCal consisting of lead-scintillator sampling calorimeter modules (PbSc). The EMCal is located at a radial distance of about 5 m from the interaction region and has a fine lateral segmentation to provide a $\Delta\eta \times \Delta\phi \approx 0.01 \times 0.01$ cell size.

The PHENIX charged particle spectrometer consists of the central magnet with axially symmetric field with integral $B\,dl = 0.78$ Tm. Charged particle tracks are reconstructed in a drift chamber, largely outside the central field, followed by 2(east arm) or 3(west arm) layers of multiwire proportional chambers with pad readout used primarily for pattern recognition in the track reconstruction. The charged particle tracks can be further identified by association with a hit in the RICH (Ring Imaging CHerenkov) detector (electron or high momentum pion) or by time of flight measurement (π, K, p) in the TOF or EMCal.

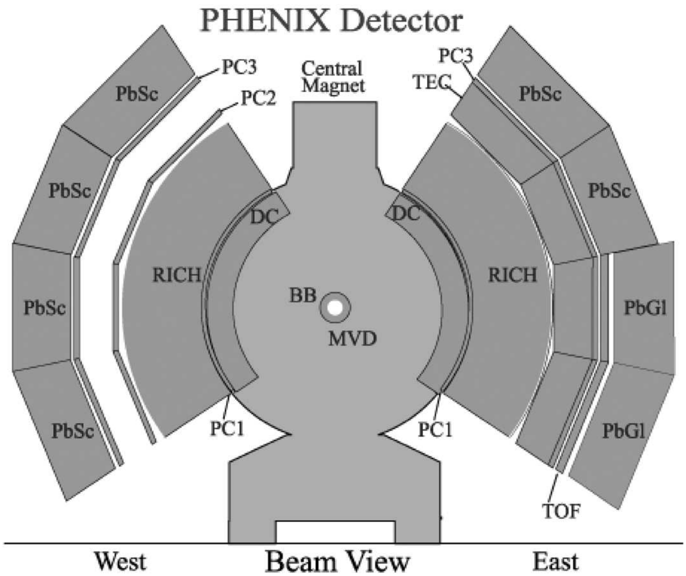

Fig. 2. The PHENIX experiment at RHIC (beam view).

The data presented here were taken during RHIC runs with Au+Au at $\sqrt{s_{NN}} = 130$ GeV in 2000, and with Au+Au and $p+p$ at $\sqrt{s_{NN}} = 200$ GeV in 2001–2002, and with $d+$ Au at $\sqrt{s_{NN}} = 200$ GeV in 2002–2003.

3. First results from RHIC

One of the earliest and most exciting results from RHIC was obtained from the first year of RHIC operation. Despite very modest integrated luminosity and consequent limits on the extent of the p_T measurements, the yield of hadrons at moderately large transverse momenta was observed to be significantly suppressed, in qualitative agreement with expectations that it was a consequence of parton energy loss, or jet quenching. The suppression effect is seen in Fig. 3 where the charged hadron and neutral pion spectra are shown for peripheral and central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV [4].

Hard processes with small cross section are expected to occur as an incoherent process and therefore should scale with the number of binary nucleon–nucleon collisions in $A+A$ collisions. The expected charged hadron and neutral pion yield in $p+p$ collisions at $\sqrt{s_{NN}} = 130$ GeV was obtained by interpolation between results at $\sqrt{s_{NN}} = 63$ GeV and $\sqrt{s_{NN}} = 200$ GeV and scaled by the number of binary nucleon–nucleon collisions for the peripheral and central Au+Au selections [4]. The scaled results are shown by the solid

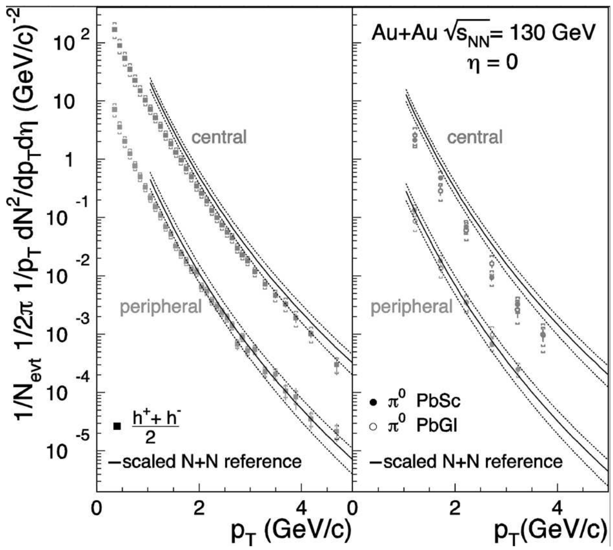

Fig. 3. Charged hadron (left) and neutral pion (right) p_{T} spectra for central and peripheral Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV. The data are compared to expectations from interpolated and scaled $p + p$ collision measurements (solid curves, dashed curves indicate uncertainties in the scaled results).

curves in Fig. 3. It is observed that while the peripheral Au+Au results are consistent with the scaled $p + p$ results, the central Au+Au yields are significantly below the scaled expectations.

4. The nuclear suppression

The nuclear medium effects on high p_{T} production can be quantified by the nuclear modification factor, R_{AB}, defined for collisions of $A + B$ as the ratio of invariant yield in $A + B$ to that of $p + p$, scaled by the number of binary collisions.

$$R_{AB}(p_{\mathrm{T}}) = \frac{(1/N_{AB}^{\mathrm{evt}})\, d^2N_{AB}/d\eta dp_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle/\sigma_{pp}^{\mathrm{inel}}\, d^2\sigma_{pp}/d\eta dp_{\mathrm{T}}} = \frac{(1/N_{AB}^{\mathrm{evt}})\, d^2N_{AB}/d\eta dp_{\mathrm{T}}}{\langle T_{AB}\rangle d^2\sigma_{pp}/d\eta dp_{\mathrm{T}}},$$

where $\langle N_{\mathrm{coll}}\rangle$ is the average number of inelastic nucleon–nucleon collisions per event, and $\langle T_{AB}\rangle = \langle N_{\mathrm{coll}}\rangle/\sigma_{pp}^{\mathrm{inel}}$ is the average of the nuclear overlap function, which is a determined purely from the nuclear geometry. Thus $\langle T_{AB}\rangle$ represents the parton luminosity and $\langle T_{AB}\rangle d^2\sigma_{pp}/d\eta dp_{\mathrm{T}}$ gives the expected yield for the experimentally selected nuclear geometry.

For heavy ion collisions R_{AB} is expected to be below unity at low p_{T} where the bulk of the particle production is due to soft processes which scale like the overlap volume, or number of participant nucleons $\langle N_{\mathrm{Part}}\rangle$, rather than as $\langle N_{\mathrm{coll}}\rangle$. At high p_T however, R_{AB} should be unity in the absence of nuclear medium effects.

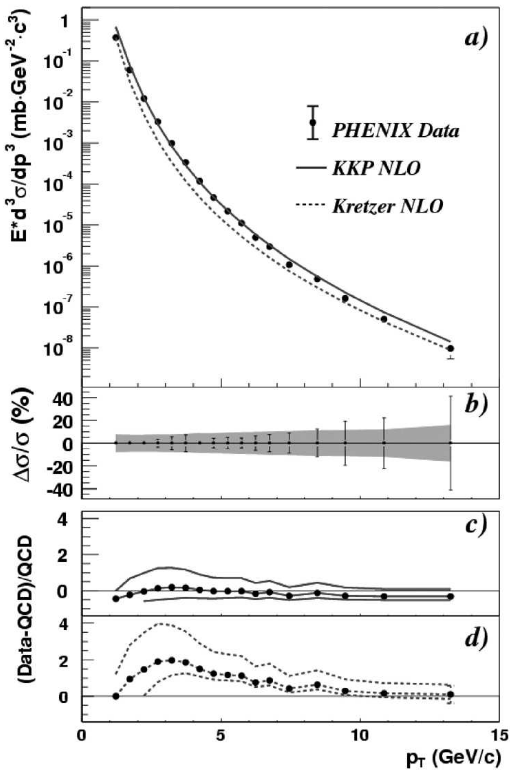

Fig. 4. The neutral pion p_T spectrum for $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The data are compared to NLO pQCD calculations for two different sets of parton fragmentation functions.

During Run 2, RHIC provided Au+Au collisions as well as $p+p$ collisions at full energy of $\sqrt{s_{NN}} = 200$ GeV. The invariant yield of neutral pions in $p+p$ collisions measured by PHENIX [5] is shown in Fig. 4. The spectrum is described well by NLO pQCD calculations and is seen to discriminate between two different parton fragmentation functions, which differ primarily in their gluon fragmentation [5]. The measured $p+p$ spectrum is used to compute R_{AB} and thus provides the reference measurement to study the nuclear modifications.

The nuclear modification factor $R_{AA}(p_T)$ for π^0 in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is shown in Fig. 5 [7]. The high p_T suppression observed at $\sqrt{s_{NN}} = 130$ GeV is seen to be of similar magnitude at the

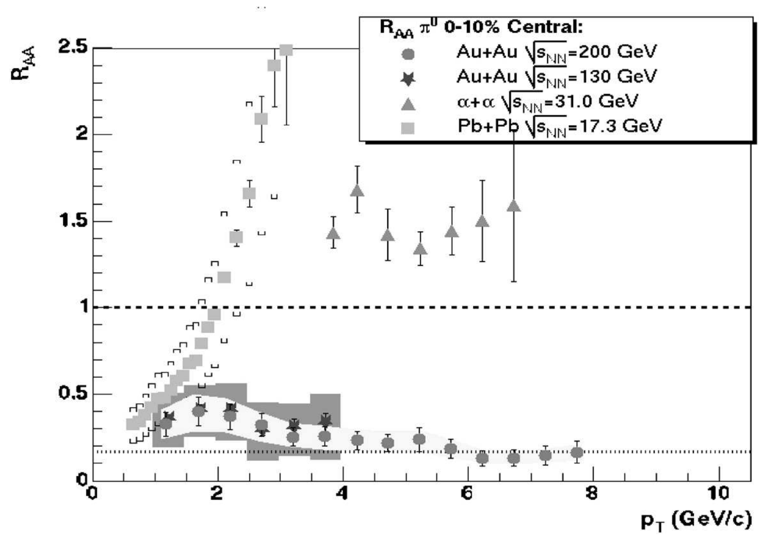

Fig. 5. The nuclear modification factor $R_{AA}(p_{\rm T})$ for π^0's in central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV (stars) and at $\sqrt{s_{NN}} = 200$ GeV (filled circles) as a function of $p_{\rm T}$. Results for central Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV [6] and $\alpha + \alpha$ collisions at $\sqrt{s_{NN}} = 31$ GeV are also shown.

higher $\sqrt{s_{NN}}$ with a factor of ~ 5 suppression. The suppression extends up to $p_{\rm T} = 8$ GeV/c. The high $p_{\rm T}$ suppression observed at RHIC energies is dramatically different from the behaviour observed at the lower energies of the SPS or ISR, also shown in Fig. 5. At lower incident energies the high $p_{\rm T}$ yield is instead enhanced by an effect attributed to soft initial scatterings of the partons as they traverse the nucleus, prior to the hard collision, which provide a transverse momentum broadening.

The centrality dependence of the high $p_{\rm T}$ suppression is shown in Fig. 6 where the nuclear modification factor has been calculated for the region of the spectrum above 4 GeV/c [7]. The suppression is observed to increase smoothly as a function of the centrality of the collision. This behaviour is qualitatively in agreement with the expected suppression of the high $p_{\rm T}$ yield due to energy loss through gluon Bremsstrahlung [1, 2] by the hard scattered parton as it traverses the produced dense excited matter, reducing the parton momentum and depleting the yield of high p_T hadrons [8–10]. The jet quenching explanation is a final state effect attributed to the spatially extended medium created in $A + A$ collisions.

On the other hand, initial state effects such as nuclear modifications to the parton momentum distributions, and soft scatterings experienced by the incoming parton prior to its hard scattering, could also contribute. In fact,

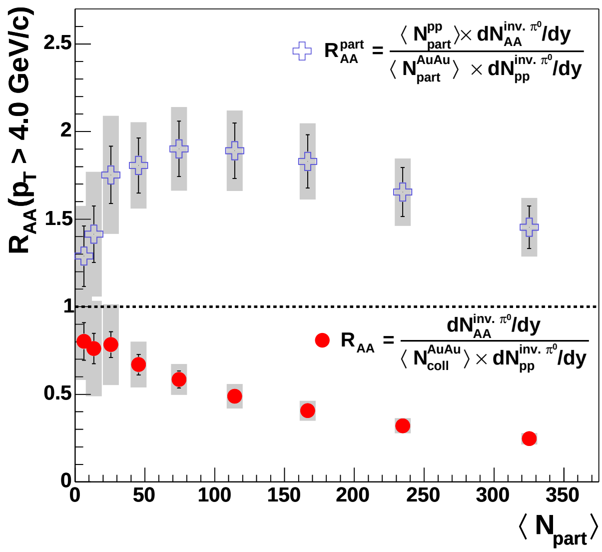

Fig. 6. The centrality dependence of the nuclear modification factor R_{AA} for π^0's with $p_T > 4$ GeV/c in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (filled circles) as a function of the number of participant nucleons N_{Part}. The nuclear modification factor assuming N_{Part} rather than N_{Coll} scaling is shown also (open crosses).

interpretations of the Au+Au results based on initial state gluon saturation effects [11] also predict a considerable suppression of the hadron production at high p_T. This gluon saturation model predicts that the high p_T yield scales proportional to the number of participant nucleons, similar to observation (see Fig. 6), rather than proportional to the number of collisions.

5. The d+Au control experiment

In order to distinguish between an initial state explanation and a final state explanation for the observed suppression, $d+$Au collisions at $\sqrt{s_{NN}} =$ 200 GeV were studied at RHIC during Run 3. While initial state nuclear effects will be present in the $d+$Au system (although to a lesser extent than in the Au+Au system), there will be no large hot dense medium produced. Thus if the hadron suppression is due to parton energy loss in the produced matter, the suppression should not be observed in $d+$Au collisions. The measured charged and neutral pion invariant yields are shown in Fig. 7 [12] and compared to the results for $p+p$ collisions [13].

For closer comparison, the nuclear modification factor R_{dA} is plotted in Fig. 8 for charged hadrons and neutral pions, and compared to the results for central Au+Au collisions. It is seen that there is no suppression of high

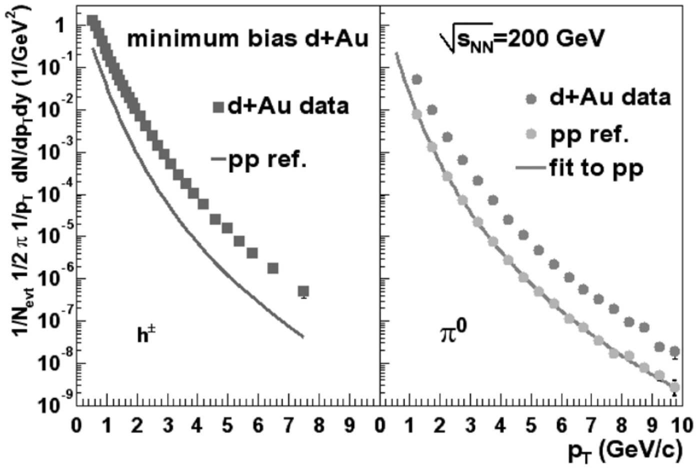

Fig. 7. The p_{T} spectra of charged particles (left) and and π^0's (right) from minimum bias d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The π^0 spectrum measured by PHENIX for $p+p$ collisions is shown by the curve on the right for comparison. The $p+p$ π^0 result is scaled by 1.6 and shown on the left for comparison with the charged hadron result. The $d+$Au results should be divided by $\langle N_{\mathrm{Coll}}\rangle \approx 8.5$ for comparison with the $p+p$ results.

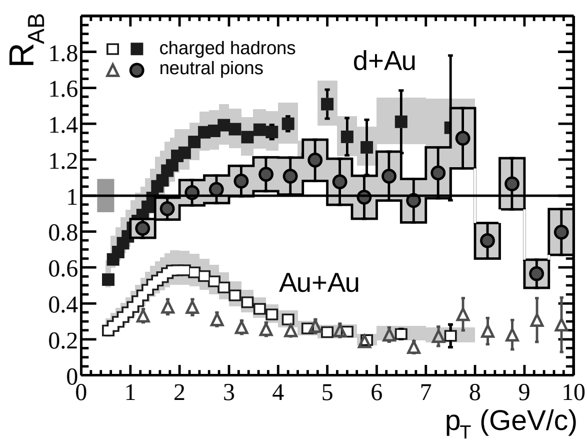

Fig. 8. Comparison of the p_{T} dependence of the nuclear suppression factor R_{AB} for charged hadrons and π^0's in minimum bias $d+$Au collisions and central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

p_{T} particles in d+Au collisions, but rather the yield is slightly enhanced for $p_{\mathrm{T}} > 2$ GeV/c, similar to observations at lower incident energies for $p + A$ collisions [13]. The results strongly indicate that the suppression in central Au+Au collisions is not an initial state effect, but instead is most likely a final state effect due to the produced dense medium.

6. Summary and conclusion

The suppression of high p_{T} hadron production observed in central Au+Au collisions is perhaps the most dramatic and interesting result from RHIC. Suppression of the high p_{T} hadron yield had been predicted as a consequence of parton energy loss in the dense matter produced in central heavy-ion collisions, and suggested as a possible signature of quark gluon plasma formation. The lack of suppression observed in d + Au collisions strongly suggests that the suppression observed in central Au+Au collisions may be attributed to the dense excited matter produced in these collisions.

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