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High p_T identified particles in PHENIX: data *vs* theory

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Abstract. Two of the most interesting experimental results of heavy-ion reactions at RHIC collider energies are in the hard scattering sector where central Au+Au data show a very different behaviour compared to $p+p$ and peripheral Au+Au collisions. The so-called "high p_T π^0 suppression" and the "anomalous" baryon/meson ratio observed by PHENIX in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are reviewed and compared to various theoretical calculations based on different strongly interacting medium scenarios.

Keywords: Hard scattering, relativistic heavy-ions, high p_T, PHENIX, RHIC
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1. Introduction

Heavy-ion collisions at RHIC collider energies aim at the study of QCD matter at extreme energy densities where lattice calculations [1] predict a transition from hadronic matter to a deconfined, chirally symmetric plasma of quarks and gluons (QGP). The most interesting phenomena observed so far in Au+Au reactions at $\sqrt{s_{NN}} = 130$ and 200 GeV, are in the high transverse momentum ($p_T \gtrsim 2$ GeV/c) sector where the production of hadrons in central collisions shows subtantial differences compared to more elementary ($p+p$, e^+e^-) systems. One first observation [2,3] is that the high p_T yield of π^0 in central Au+Au is suppressed by as much as a factor 4–5 compared to $p+p$ and peripheral Au+Au scaled by the number of nucleon-nucleon (NN) collisions, N_{coll}. A second observation is that at intermediate p_T's ($1 < p_T < 4.5$ GeV/c) no suppression is seen for protons and anti-protons, yielding an "anomalous" baryon over meson $p/\pi \sim 1$ ratio [4,5] much larger than the ratio $p/\pi \sim 0.1 - 0.3$ observed in $p+p$ [6,7] and in e^+e^- jet fragmentation [8]. Both results point to strong medium effects at work in central Au+Au collisions, and have triggered extensive theoretical discussions based on perturbative [9–15] or "classical" [16] QCD. Most of the studies on the high p_T suppression are based on the prediction [18] that a deconfined and dense medium would induce multiple gluon radiation off the scattered partons, effectively leading to a depletion of the high-p_T hadronic fragmentation products ("jet quenching"). Alternative interpretations have been also put forward based on initial-state gluon saturation effects [16], or final-state hadronic reinteractions [17]. The different behaviour of baryons and mesons at moderately high p_T's has been interpreted, among others, in terms of "parton recombination" effects [19]. It is the purpose of this paper to present the $\sqrt{s_{NN}}$, p_T, centrality, and baryon-meson dependence of the high p_T production measured by PHENIX in Au+Au, and compare it to the different proposed physical explanations in order to shed some light on the properties of the underlying QCD medium of heavy-ion collisions at RHIC.

PHENIX [20] is specifically designed to measure penetrating probes by combining good mass and particle identification (PID) resolution in a broad momentum range, high rate capability, and small granularity. The results presented here concentrate on the Run-2 measurement of (i) neutral pions [3] reconstructed, via their $\gamma\gamma$ decay, in the electromagnetic calorimeter EMCal (covering $\Delta\eta = 0.7$, $\Delta\phi = \pi$), together with (ii) protons and anti-protons [5] identified using the central tracking system (a multi-layer drift chamber followed by a multi-wire proportional chamber with pixel-pad readout) plus the time-of-flight detector ($\Delta\eta = 0.7$ and $\Delta\phi = \pi/8$). The π^0 $(p,\bar{p})$ analysis uses $\sim 20\,(30)\times 10^6$ minimum bias events, triggered by a coincidence of the Beam-Beam Counters (BBC) and Zero-Degree Calorimeters (ZDC), with vertex position $|z| < 30$ cm. The average number of participant nucleons (N_{part}) and NN collisions (N_{coll}) in each Au+Au centrality bin are obtained from a Glauber calculation combined with the BBC and ZDC responses [3].

2. High p_T π^0 suppression: $\sqrt{s_{NN}}$ and p_T dependence

Details on hadron production mechanisms in AA can be obtained by investigating their scaling behavior with respect to $p+p$ collisions: soft processes ($p_T < 1$ GeV/c) are expected [21] to scale[1] with N_{part}, and hard process with N_{coll} [23]. In order to quantify the medium effects at high p_T, one uses the *nuclear modification factor* given by the ratio of the AA to the N_{coll} scaled $p+p$ invariant yields:

$$R_{AA}(p_T) \;=\; \frac{d^2N^{\pi^0}_{AA}/dydp_T}{\langle N_{coll}\rangle \;\times\; d^2N^{\pi^0}_{pp}/dydp_T}. \tag{1}$$

$R_{AA}(p_T)$ measures the deviation of AA from an incoherent superposition of NN collisions in terms of suppression (R_{AA} <1) or enhancement (R_{AA} >1). Figure 1 shows R_{AA} as a function of p_T for several π^0 measurements in high-energy AA collisions. The PHENIX R_{AA} values for central collisions at 200 GeV (circles) and 130 GeV (triangles) are noticeably below unity in constrast to the enhanced production (R_{AA} >1) observed at CERN-ISR [7] (stars) and CERN-SPS energies [24] (squares) and interpreted in terms of initial-state p_T broadening ("Cronin effect" [25]).

[1] They actually approximately do, see Fig. 2 (right plot, circles) and [22].

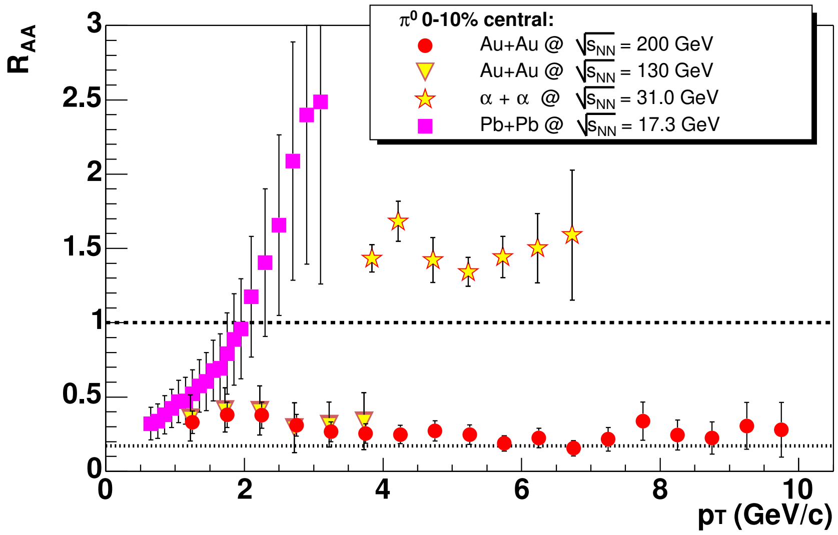

Fig. 1. Nuclear modification factor, $R_{AA}(p_T)$, for π^0 measured in central ion-ion reactions at CERN-SPS [24], CERN-ISR [7], and BNL-RHIC [2,3] energies.

The high p_T suppression in central collisions at RHIC is smallest at 2 GeV/c and increases to an approximately constant suppression factor of $1/R_{AA} \approx 4$–5 over $p_T = 4 - 10$ GeV/c, $\sim$30% above the expectation from N_{part} scaling (dotted line). The magnitude and p_T dependence[2] of R_{AA}, is alone inconsistent with "conventional" nuclear effects like leading-twist "shadowing" of the nuclear PDFs [26,27]. Different pQCD-based jet quenching calculations based on medium-induced radiative energy loss, can reproduce the *magnitude* of the π^0 suppression assuming the formation of a hot and dense partonic system characterized by different, but related, properties: i) large initial gluon densities $dN^g/dy \sim 1000$ [9], ii) large "transport coefficients" $\hat{q}_0 \sim 3.5$ GeV/fm^2 [12], iii) high opacities $L/\lambda \sim 3$–4 [14], or iv) effective parton energy losses of the order of $dE/dx \sim 14$ GeV/fm [15]. The predicted *p_T dependence* of the quenching, however, varies in the different models. All models that include the Landau-Pomeranchuck-Migdal (LPM) interference effect [28,29] predict a slow (logarithmic) increase of R_{AA}, not compatible with the data over the entire p_T range. Other approaches, such as constant energy loss per parton scattering, are also not supported as discussed in [10]. Analyses [9] which combine LPM jet quenching with shadowing and initial-state p_T broadening globaly reproduce the observed p_T dependence of the π^0 suppression. However, *semi-quantitative* estimates of final-state interactions in a dense hadronic medium [17] also seem to yield the same amount of quenching as models based on partonic energy loss.

[2]Corresponding to parton fractional momenta $x \approx 2p_T/\sqrt{s} \sim 0.02$–0.1 at midrapidity.

3. High p_T π^0 suppression at 200 GeV: centrality dependence

In each centrality bin, the value of the high p_T suppression can be quantified by the ratio of Au+Au over N_{coll}-scaled $p+p$ yields integrated, e.g., above 4 GeV/c. Fig. 2 (left) shows $R_{AA}(p_T > 4$ GeV/$c)$ as a function of: (i) centrality, (ii) N_{part}, and (iii) "Bjorken" energy density[3] ϵ_{Bj}. Within errors, high p_T production in 60–92% peripheral collisions is consistent with NN scaling ($R_{AA} \approx 1$). A departure from this scaling (at a 2-sigma level) is apparent for the 50–60% centrality corresponding to $b \approx 11$ fm, ~ 50 participants, or $\epsilon_{Bj} \approx 1.2$ GeV/fm^3. For more central reactions the suppression increases steadily up to a factor 4–5. Whether there is an abrupt or gradual suppression pattern cannot be ascertained with the present uncertainties of the data. However, *assuming* that there is a flat N_{coll} scaling in the most peripheral region, the departure from N_{coll} scaling for the 50–60% centrality is (perhaps coincidentally) in the ball-park of theoretical estimates for: (i) the minimal amount of nucleons needed to obtain parton "percolation" at RHIC energies ($N_{part} \sim 80$) [30], and (ii) the expected "critical" QCD energy density ($\epsilon_{crit} \approx 1$ GeV/fm^3) [1].

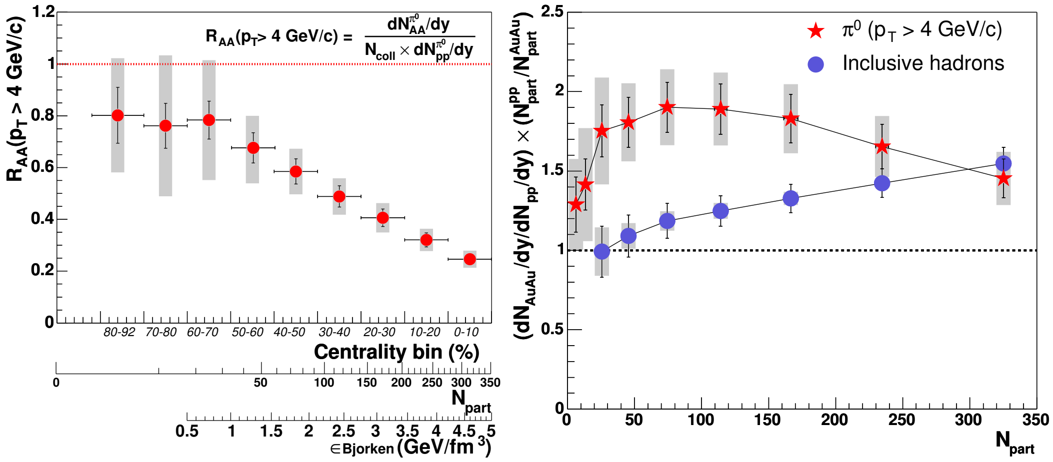

Fig. 2. *Left:* Evolution of the high p_T suppression, $R_{AA}(p_T > 4$ GeV/$c)$, as a function of (i) centrality bin, (ii) N_{part}, and (iii) "Bjorken" energy density. *Right:* In stars (circles), the ratio of $Au + Au$ over $p + p$ high p_T π^0 (inclusive hadron) yields normalized by N_{part}, as a function of N_{part}.

N_{part} (instead of N_{coll}) scaling at high p_T is expected in scenarios dominated either by gluon saturation [16] or by surface emission of the quenched jets [11]. Fig. 2 (right) shows the centrality dependence of the ratio of N_{part}-scaled Au+Au over $p+p$ yields for high p_T π^0 (stars), compared to the (clearly different) centrality

[3] For each centrality class, $\epsilon_{Bj} = 1/(\tau_0 \cdot A_{eff}) \times dE_T/dy$ ("Bjorken estimate", with $\tau_0 = 1$ fm/c), where dE_T/dy is the average transverse energy measured by PHENIX at $y = 0$ [22], and A_{eff} is the overlap area of the colliding ions given by a Glauber Monte Carlo.

dependence of the global charged hadron multiplicities[4] (circles). Although there is no true participant scaling for high p_T π^0 ($R_{AA}^{part} > 1$ for all centralities), their production per participant pair is, within errors, approximately constant over a wide range of intermediate centralities, in qualitative agreement with a gluon saturation model prediction [16].

4. High p_T suppression at 200 GeV: baryons *vs* mesons

Figure 3 (left) compares the N_{coll} scaled central to peripheral yield ratios for $(p+\bar{p})/2$ and π^0: $R_{cp} = (yield^{(0-10\%)}/N_{coll}^{0-10\%})/(yield^{(60-92\%)}/N_{coll}^{60-92\%})$. Since the 60–92% peripheral Au+Au spectra scale with N_{coll} when compared to the p+p yields [3, 5], R_{cp} carries basically the same information as R_{AA}. From 1.5 to 4.5 GeV/c the (anti)protons are not suppressed ($R_{cp} \sim 1$) at variance with the pions which are reduced by a factor of 2–3 in this p_T range. If both π^0 and $p, \bar{p}$ originate from the fragmentation of hard-scattered partons that lose energy in the medium, the nuclear modification factor R_{cp} should be independent of particle species contrary to the experimental result.

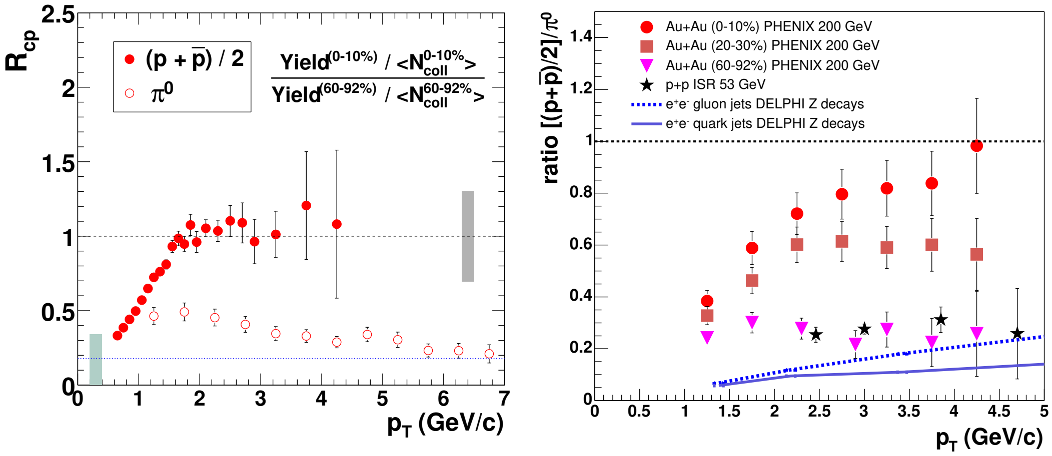

Fig. 3. *Left*: Ratio of central over peripheral N_{coll} scaled $(p+\bar{p})/2$ (dots) and π^0 (circles) yields in Au+Au, as a function of p_T. *Right*: Ratios of $(p+\bar{p})/2$ over π^0 versus p_T in: central (dots), mid-central (squares), and peripheral (triangles) Au+Au, and in $p+p$ (crosses), and e^+e^- (dashed and solid lines) collisions.

Figure 3 (right) shows the ratios of $(p+\bar{p})/2$ over π^0 as a function of p_T measured in central (0–10%, circles), mid-central (20–30%, squares), and peripheral (60–92%, triangles) Au+Au collisions, together with the corresponding ratios measured in

[4]The ratio of inclusive Au+Au over p+p multiplicities has been obtained normalizing PHENIX dN_{AuAu}/dy data [22] by the $dN_{p\bar{p}}/dy = 2.48 \pm 0.1$ measured by UA5 at $\sqrt{s_{NN}} = 200$ GeV [31].

$p+p$ collisions at CERN-ISR energies [6, 7] (crosses) and in gluon and quark jets from e^+e^- collisions [8] (dashed and solid lines resp.). Within errors, peripheral Au+Au results are compatible with the $p+p$ and e^+e^- ratios, but central Au+Au collisions have a p/π ratio ∼4–5 times larger. Such a result is at odds with standard perturbative production mechanisms, since in this case the particle ratios $\bar{p}/\pi$ and p/π should be described by a universal fragmentation function independent of the colliding system, which favors the production of the lightest particle. One explanation of this observation is based on the recombination (or coalescence), rather than fragmentation, of quarks [19]. In this picture the partons from a thermalized system recombine and with the addition of quark momenta, the soft production of baryons extends to much larger values of p_T than that for mesons. In this scenario, the effect is limited to $p_T < 5\,\mathrm{GeV}$, beyond which fragmentation becomes the dominant production mechanism for all species[5]. Alternative explanations based on medium-induced difference in the formation time of baryons and mesons, different "Cronin enhancement" for protons and pions, or "baryon junctions" are considered in [5].

5. Conclusions

PHENIX has measured π^0 and p, $\bar{p}$ at mid-rapidity up to p_T = 10 GeV/c and 4.5 GeV/c respectively, in different centrality bins of Au+Au collisions at $\sqrt{s_{_{NN}}}$ = 200 GeV, permiting a detailed comparative study of the properties of high p_T particle production in high-energy heavy-ion collisions as a function of $\sqrt{s}$, p_T, centrality, and particle composition. The spectral shape and invariant yields of *all* identified particles in *peripheral* reactions are consistent with those of $p+p$ reactions scaled by the number of inelastic NN collisions, in agreement with pQCD expectations. For π^0, a departure from "NN scaling" at a 2-sigma level is apparent for the 50-60% centrality class corresponding to ~ 50 participant nucleons, $b \approx 11$ fm, or $\epsilon_{Bj} \approx 1.2$ GeV/fm^3. For more central reactions the suppression increases steadily up to a factor 4-5. The existence or not of an abrupt or gradual suppression pattern cannot be ascertained within the present uncertainties. The magnitude of the deficit in central collisions can be reproduced by pQCD-based parton energy loss calculations in an opaque medium, but its p_T and centrality dependence puts strong constraints on the details of the energy loss and the properties of the medium. At variance with pions, a large $p, \bar{p}$ production, which increases from peripheral to central collisions, is observed in the range $1.5 < p_T < 4.5\,\mathrm{GeV}/c$. In this p_T range, the p and $\bar{p}$ yields show "NN scaling" independent of centrality, resulting in a much larger baryon over meson ratio than observed in $p+p$ and e^+e^-. This observation can be explained in terms of parton energy loss plus recombination effects in a thermalized medium. Stronger experimental constraints on the properties of the underlying QCD medium produced in AA reactions will be available with the data of the recent $d+Au$ run at RHIC, where final-state medium effects are absent.

[5]This indeed seems to be confirmed by the measured $h/\pi^0 \sim 1.6$ above $p_T \sim 5$ GeV/c in central and peripheral Au+Au [5] which is consistent with that measured in $p+p$ collisions and indicates that for higher p_T's the baryon yields approach the (suppresed) pion scaling

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