Fragmentation Functions in-Medium, Two Particle Correlations and Jets in PHENIX at RHIC

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Abstract. Latest results from the PHENIX experiment at RHIC on these topics will be presented. Results will be shown for Au+Au compared to p-p collisions as well as compared to results from fully reconstructed jets at LHC.

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The discovery, at RHIC, that π^0 produced at large transverse momentum, p_T, from hard-scattering of the constituent partons of the nucleons in nuclei are suppressed in central Au+Au collisions by roughly a factor of 5 compared to point-like scaling from p-p collisions is arguably *the* major discovery in Relativistic Heavy Ion Physics. For π^0 (Fig. 1a) [1] the hard-scattering in p-p collisions is indicated by the power law behavior p_T^{-n} with $n = 8.1 \pm 0.05$ for the invariant cross section, $Ed^3\sigma/dp^3$, for $p_T \geq 3$ GeV/c. The Au+Au data can be characterized either as shifted down in energy relative to the point-like scaled p-p data, or down in magnitude, i.e. suppressed. In Fig. 1b, the suppression of the many identified particles measured by PHENIX at RHIC is presented as the Nuclear Modification Factor, $R_{AA}(p_T)$, the ratio

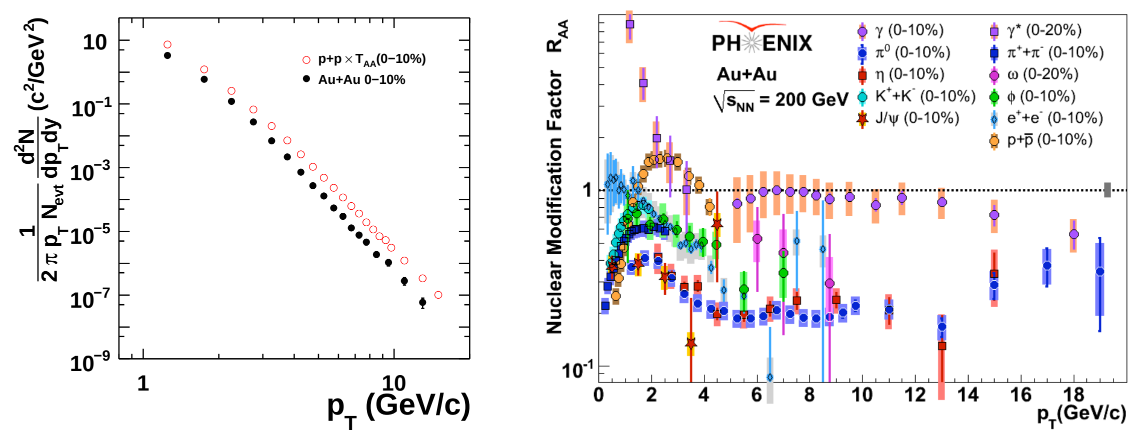


FIGURE 1. a) (left) Invariant yield of π^0 at $\sqrt{s_{NN}} = 200$ GeV as a function of transverse momentum p_T in p-p collisions multiplied by $\langle T_{AA}\rangle$ for Au+Au central (0–10%) collisions compared to the Au+Au measurement [1]. b) (right) $R_{AA}(p_T)$ for all identified particles so far measured by PHENIX in Au+Au central collisions at $\sqrt{s_{NN}} = 200$ GeV.

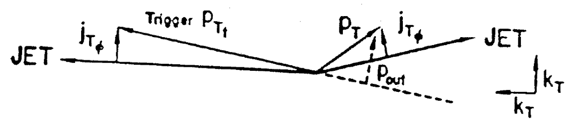
of the yield of per central Au+Au collision (upper 10%-ile of observed multiplicity) to the point-like-scaled p-p cross section:

$$R_{AA}(p_T) = [d^2N^{\pi}_{AA}/dp_T dy N_{AA}]/[\langle T_{AA}\rangle d^2\sigma^{\pi}_{pp}/dp_T dy] \quad , \qquad (1)$$

where $\langle T_{AA}\rangle$ is the overlap integral of the nuclear thickness functions. The striking differences of $R_{AA}(p_T)$ in central Au+Au collisions for the many particles measured by PHENIX (Fig. 1b) illustrates the importance of particle identification for understanding the physics of the medium produced at RHIC. Most notable are the equal suppression by a constant factor of 5 of π^0 and η for $4 \leq p_T \leq 15$ GeV/c, the equality of suppression of direct-single $e^{\pm}$ (from heavy quark (c, b) decay) and π^0 at $p_T \gtrsim 5$ GeV/c, the non-suppression of direct-γ from the QCD Compton effect [2], $g+q \rightarrow \gamma+q$, for $p_T \geq 4$ GeV/c and the exponential rise of R_{AA} of direct-γ for $p_T < 2$ GeV/c [3], which is totally and dramatically different from all other particles and attributed to thermal photon production by many authors (e.g. see citations in reference [3]). The fact that all hadrons are suppressed for $p_T \gtrsim 5$ GeV/c, but direct-γ are not suppressed, indicates that suppression is a medium effect on outgoing color-charged partons.

The key to measuring the fragmentation function of the jet of particles from an outgoing hard-scattered parton is to know the energy of the original parton which fragments, as pioneered at LEP [4]. Thus, a measurement of the direct-$\gamma - h$ correlation from $g+q \to \gamma + q$, where the h represents charged hadrons opposite in azimuth to the direct-γ, is (apart from the low rate) excellent for this purpose since both the energy and identity of the jet (8/1 u-quark, maybe 8/2 if the $\bar{q}+q \to \gamma + g$ channel is included) are known to high precision. Two particle correlations are analyzed in terms of the two variables [9]: $p_{\rm out} = p_T \sin(\Delta\phi)$, the out-of-plane transverse momentum of a track; and x_E, where:

$$x_E = \frac{-\vec{p}_T \cdot \vec{p}_{Tt}}{|p_{Tt}|^2} = \frac{-p_T \cos(\Delta\phi)}{p_{Tt}} \simeq \frac{z}{z_{\rm trig}} \qquad (2)$$



$z_{\rm trig} \simeq p_{Tt}/p_{T\rm jet}$ is the fragmentation variable of the trigger jet, and z is the fragmentation variable of the away jet. Note that x_E would equal the fragmenation fraction z of the away jet, for $z_{\rm trig} \to 1$, if the trigger and away jets balanced transverse momentum. The beauty of direct-γ for this purpose is that $z_{\rm trig} \equiv 1$.

Following the approach of Borghini and Wiedemann (Fig. 2a) [5] who predicted the medium modification of fragmentation functions in the hump-backed or $\xi = \ln(1/z)$ representation, PHENIX measured x_E distributions and converted to the $\xi = -\ln x_E$ representation as shown in Fig. 2b [6] which are in quite excellent agreement with the dominant u-quark fragmentation functions measured in e^+e^- collisions at $\sqrt{s}/2 = 7$ and 22 GeV, which cover a comparable range in jet energy. PHENIX preliminary measurements [7] of the $\xi = -\ln x_E$ distribution in central (0–

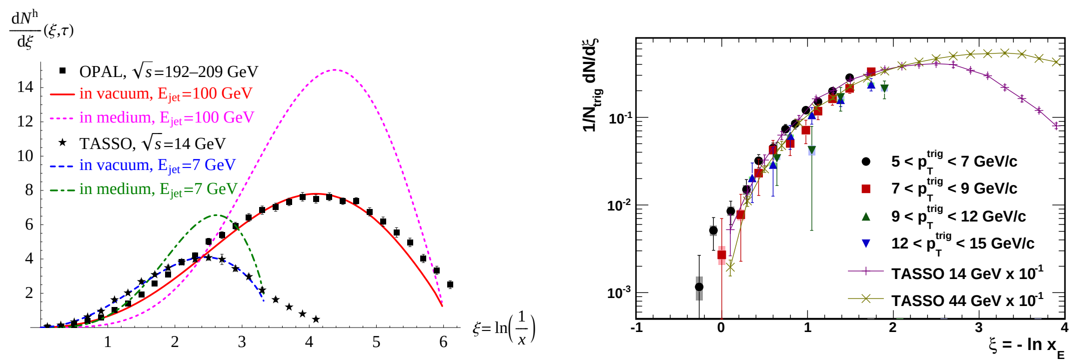


FIGURE 2. a) Predicted ξ distributions in vacuum and in medium for two jet energies [5], together with measurements from e^+e^- collisions. b) $\xi = -\ln x_E$ distributions for PHENIX isolated direct-γ data [6] for all p_{T_t} ranges combined, compared to e^+e^- collisions at $\sqrt{s} = 14$ and 44 GeV.

20%) Au+Au collisions, which suggest a modification consistent with Ref. [5] are shown in Fig. 3a. Final results with improved statistics should be available shortly. Fragmentation functions from full jet reconstruction in A+A collisions are not yet available although analysis has reached the stage of preliminary results for $R_{AA}(p_T)$ from jets in Cu+Cu

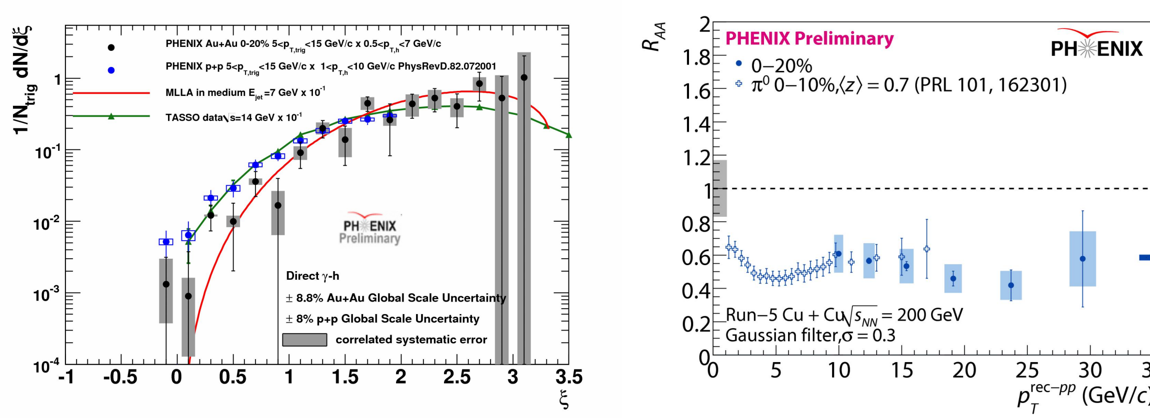


FIGURE 3. PHENIX Preliminary results: a) (left) $\xi = -\ln x_E$ distribution in Au+Au (0–20%) [7]; b) (right) $R_{AA}(p_T)$ for jets compared to π^0 in Cu+Cu (0–20%) central collisions [8]. See references [7, 8] for details.

collisions (Fig. 3b) [8]. These results agree well with the π^0 measurements but, importantly, go to much larger p_T, which is the main advantage, so far.

One of the important lessons learned about fragmentation functions at RHIC [9] is that the away-side x_E distribution of particles opposite to a trigger particle (e.g. a π^0), which is itself the fragment of a jet, does not measure the fragmentation function, but, instead, measures the ratio of $\hat{p}_{T_a}$ of the away-parton to $\hat{p}_{T_t}$ of the trigger-parton and depends only on the same power n as the invariant single particle spectrum:

$$\left.\frac{dP}{dx_E}\right|_{p_{T_t}} \approx N\,(n-1)\frac{1}{\hat{x}_h}\frac{1}{(1+\frac{x_E}{\hat{x}_h})^n} \quad . \tag{3}$$

This equation gives a simple relationship between the ratio, $x_E \approx p_{T_a}/p_{T_t} \equiv z_T$, of the transverse momenta of the away-side particle to the trigger particle, and the ratio of the transverse momenta of the away-jet to the trigger-jet, $\hat{x}_h = \hat{p}_{T_a}/\hat{p}_{T_t}$. PHENIX measurements [10] of the x_E distributions of π^0-h correlations in p-p and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV were fit to Eq. 3 (Fig. 4a,b) [11]. The results for the fitted parameters are shown on the figures.

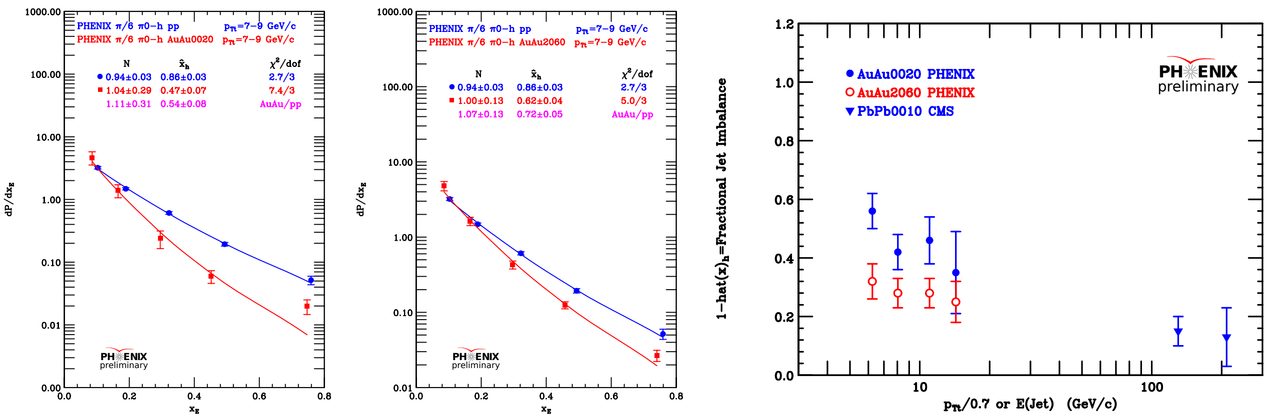


FIGURE 4. (left) x_E distributions [11] from p-p (blue circles) and AuAu (red squares) for $p_{T_t} = 7-9$ GeV/c, together with fits to Eq. 3 p-p (solid blue line), AuAu (solid red line) with parameters indicated: a) 00-20% centrality, b) 20–60% centrality. The ratios of the fitted parameters for AuAu/pp are also given. c) (right) Fractional jet imbalance [11], $1-\hat{x}_h^{AA}/\hat{x}_h^{pp}$, for RHIC and CMS data.

In general the values of $\hat{x}_h^{pp}$ do not equal 1 but range between $0.8 < \hat{x}_h^{pp} < 1.0$ due to k_T smearing and the range of x_E covered. In order to take account of the imbalance ($\hat{x}_h^{pp} < 1$) observed in the p-p data, the ratio $\hat{x}_h^{AA}/\hat{x}_h^{pp}$ is taken as the measure of the energy of the away jet relative to the trigger jet in A+A compared to p-p collisions. The fractional jet imbalance was also measured directly with reconstructed di-jets by the CMS collaboration at the LHC in Pb+Pb central collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV [12]; and with the large effect in p-p collisions corrected in the same way [11], the results compared to PHENIX are shown in Fig. 4c. The large difference in fractional jet imbalance between RHIC and LHC c.m. energies could be due to the difference in jet $\hat{p}_{T_t}$ between RHIC (~ 20 GeV/c) and LHC (~ 200 GeV/c), the difference in n for the different $\sqrt{s}$, or to a difference in the properties of the medium. Future measurements will need to sort out these issues by extending both the RHIC and LHC measurements to overlapping regions of p_T.

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