WHERE FEYNMAN, FIELD AND FOX FAILED AND HOW WE FIXED IT AT RHIC

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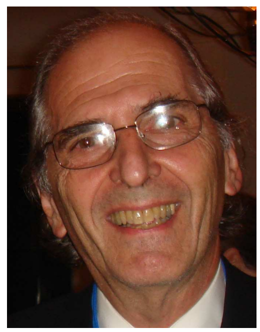


Hard-scattering of point-like constituents (or partons) in p-p collisions was discovered at the CERN-ISR in 1972 by measurements utilizing inclusive single or pairs of hadrons with large transverse momentum (p_T). It was generally assumed following a seminal paper by Feynman, Field and Fox (FFF) [1] (and much discussed in a talk that I gave at the 1979 Rencontres de Moriond) that "everything you wanted to know about hard-scattering and jets" could be measured by these methods. Recently, we found in PHENIX [2] that the p_{T_a} distribution of away side hadrons from a single particle trigger [with p_{T_t}] which is a leading fragment of the trigger jet, could not be used to measure the fragmentation function of the away jet as originally claimed by FFF. A new formula was derived which both exhibits scaling in the variable $x_E \sim p_{T_a}/p_{T_t}$ (a hot topic in 1979) and relates x_E, $\sim$ the ratio of the transverse momenta of the measured particles, to $\hat{x}_h = \hat{p}_{T_a}/\hat{p}_{T_t}$, the ratio of the transverse momenta of the away-side to trigger-side jets. Tests of the validity of the formula and applications to Au+Au central collisions at RHIC (where jets can not be reconstructed) are discussed.

1 Introduction

Following the discovery of hard-scattering in p-p collisions at the CERN-ISR [3] by the observation of an unexpectedly large yield of particles with large transverse momentum (p_T), which proved that the quarks of DIS were strongly interacting, the attention of experimenters turned to measuring the predicted di-jet structure of the hard-scattering events. The jet structure of high p_T scattering could be easily seen and measured using two-particle correlations, e.g. with a π^0 trigger with transverse momentum $p_{T_t} > 7$ GeV/c, and an associated charged particle detected with full and uniform acceptance over the entire azimuth, with pseudorapidity coverage $-0.7 \leq \eta \leq +0.7$ (Fig. 1a,b) [4]. In all cases strong correlation peaks on flat backgrounds are clearly visible for both the trigger-side and the away-side, indicating di-jet structure. Following

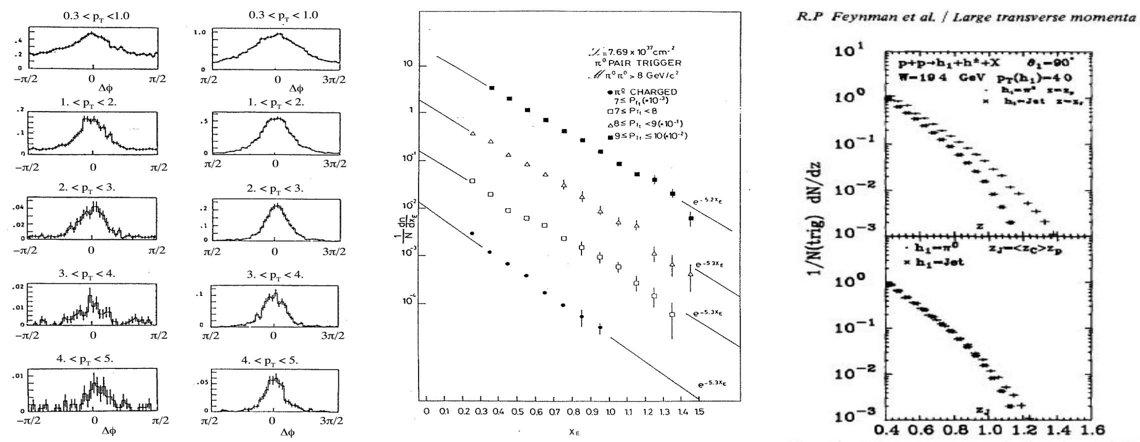
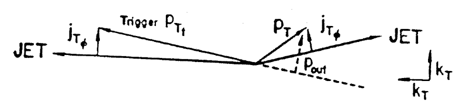


Figure 1: a) (left) trigger-side b) (left-center) away-side correlations of charged particles with indicated $p_T \equiv p_{T_a}$ for π^0 triggers with $p_{T_t} > 7$ GeV/c . c) (right-center) x_E distributions from this data d) right) [top] Comparison [1] of away side charged hadron distribution triggered by a π^0 or a jet, where $z_{\pi^0} = x_E$ and $z_j = p_{T_a}/\hat{p}_{T_a}$. [bottom] same distributions with π^0 plotted vs $z'_j = \langle z_t \rangle x_E$.

the methods of previous CERN-ISR experiments [3] and the best theoretical guidance [1], the away jet azimuthal angular distributions of Fig. 1b, which were thought to be unbiased, were analyzed in terms of the two variables: $p_{\rm out} = p_{T_a} \sin(\Delta\phi)$, the out-of-plane transverse momentum of a track, and x_E, where

$$x_E = \frac{-\vec{p}_{T_a} \cdot \vec{p}_{T_t}}{|p_{T_t}|^2} = \frac{-p_{T_a} \cos(\Delta\phi)}{p_{T_t}} \simeq \frac{z_a}{z_t}$$



$z_t \simeq p_{T_t}/\hat{p}_{T_t}$ is the fragmentation variable of the trigger jet with $\hat{p}_{T_t}$, and $z_a \simeq p_{T_a}/\hat{p}_{T_a}$ is the fragmentation variable of the away jet. Note that x_E would equal the fragmenation fraction z_a of the away jet, for $z_t \rightarrow 1$, if the trigger and away jets balanced transverse momentum, i.e. if $\hat{x}_h \equiv \hat{p}_{T_a}/\hat{p}_{T_t} = 1$. It was generally assumed, following the seminal article of Feynman, Field and Fox [1], that the p_{T_a} distribution of away side hadrons from a single particle trigger [with p_{T_t}], corrected for $\langle z_t \rangle$, would be the same as that from a jet-trigger (Fig. 1d) and follow the same fragmentation function as observed in e^+e^- or DIS [3]. The x_E distributions [4] for the data of Fig. 1b are shown in Fig. 1c and show the fragmentation behavior expected at the time, $e^{-6\, z_a} \sim e^{-6\, \langle z_t \rangle\, x_E} = e^{-5.3\, x_E}$.

2 Discoveries at RHIC

It was discovered at RHIC [5] that the high p_T π^0 from hard-scattering are suppressed by roughly a factor of 5 in central Au+Au collisions compared to the scaling for point-like processes. This is arguably *the* major discovery in Relativistic Heavy Ion Physics. The suppression is attributed to energy-loss of the outgoing hard-scattered color-charged partons due to interactions in the presumably deconfined and thus color-charged medium produced in Au+Au collisions at RHIC [6]. In Fig. 2-(left), a log-log plot of the π^0 invariant cross section in p-p collisions at $\sqrt{s} = 200$ GeV multiplied by the point-like scaling factor $\langle T_{AA} \rangle$ (the overlap integral of the nuclear thickness functions averaged over the centrality class) for Au+Au central collisions (0-10%) is compared to the measured semi-inclusive invariant yield of π^0. Both the Au+Au and p-p data show a pure power law, $p_T^{-8.10}$ for $p_T > 3$ GeV/c. The suppression is shown more dramatically in Fig. 2-(right) where the the data for π^0, η and direct-γ are presented as the ratio of the yield per central Au+Au collision (upper 10%-ile of observed multiplicity) to the point-like-scaled p-p cross section: $R_{AA}(p_T) = (d^2N^{\pi}_{AA}/N_{AA} dp_T dy)/(\langle T_{AA} \rangle d^2\sigma^{\pi}_{pp}/dp_T dy)$. The π^0 and η, which are fragments of hard-scattered partons, are both suppressed by a factor of 5 from $3 \leq p_T \leq 20$ GeV/c. This implies a strong medium effect in Au+Au central collisions because the direct-γ,

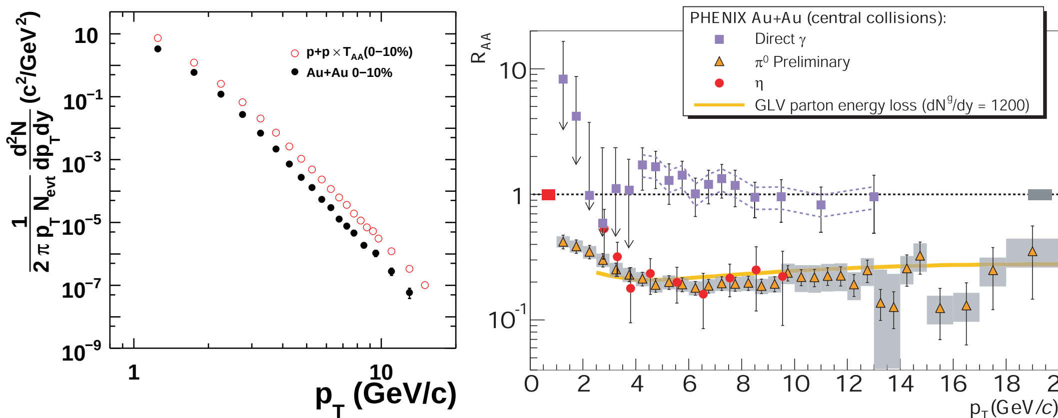


Figure 2: (left)log-log plot[7] of π^0 invariant cross section in p-p collisions at $\sqrt{s} = 200$ GeV multiplied by $\langle T_{AA}\rangle$ for Au+Au central collisions (0-10%) compared to the measured semi-inclusive invariant yield of π^0. (right) $R_{AA}(p_T)$ for π^0, η and direct-γ for Au+Au central (0-10%) collisions at $\sqrt{s_{NN}} = 200$ GeV[8].

which also participate directly in the 2-to-2 hard-scattering but do not interact with the medium, are not suppressed.

In order to measure whether the away-side parton from a high p_T π^0 trigger loses energy in the medium formed in Au+Au central collisions or has modified fragmentation, PHENIX[2] attempted to derive the the fragmentation function in p-p collisions from the measured x_E distributions (Fig. 3b) to use as a baseline for the Au+Au measurement. It didn't work. Finally,

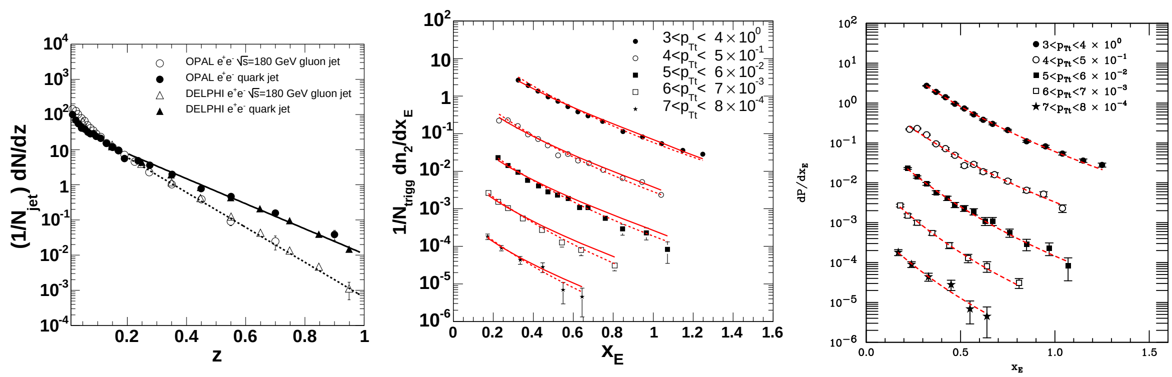


Figure 3: a) (left) LEP fragmentation functions. See Ref.[2] for details; b) (center) x_E distributions[2] together with calculations using fragmentation functions from LEP; c) (right) data from (b) with fits to Eq. 1 for $n = 8.10$.

it was found that starting with either the quark $\approx \exp(-8.2 \cdot z)$ or the gluon $\approx \exp(-11.4 \cdot z)$ fragmentation functions from LEP (Fig. 3a solid and dotted lines), which are quite different in shape, the results obtained for the x_E distributions (solid and dotted lines on Fig. 3b) do not differ significantly! Although nobody had noticed this for nearly 30 years, the reason turned out to be quite simple[2]. With no assumptions other than a power law for the jet $\hat{p}_{T_t}$ distribution ($d\sigma_q/\hat{p}_{T_t} d\hat{p}_{T_t} = A\hat{p}_{T_t}^{-n}$), an exponential fragmentation function ($D^{\pi}_q(z) = Be^{-bz}$), and constant $\hat{x}_h$, for fixed p_{T_t} as a function of p_{T_a}, it was possible[2] to derive the x_E distribution in the collinear limit, where $p_{T_a} = x_E p_{T_t}$:

$$\left.\frac{dP_\pi}{dx_E}\right|_{p_{T_t}} \approx N(n-1)\frac{1}{\hat{x}_h}\frac{1}{(1+\frac{x_E}{\hat{x}_h})^n} \qquad , \qquad (1)$$

and $N = \langle m\rangle$ is the multiplicity of the unbiased away-jet. The shape of the x_E distribution is given by the power n of the partonic and inclusive single particle transverse momentum spectra and does not depend on the exponential slope of the fragmentation function as shown by the excellent fits of Eq. 1 (Fig. 3c). Note that Eq. 1 provides a relationship between the ratio of

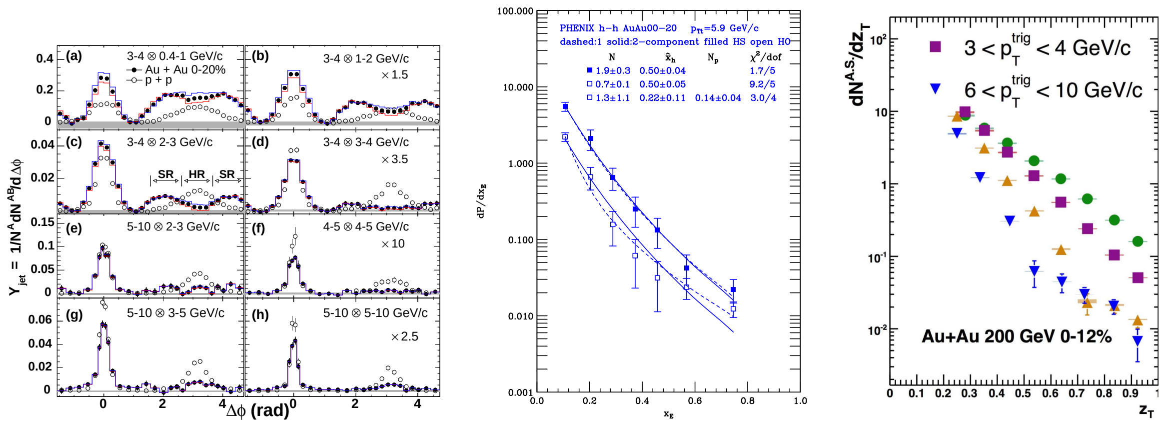


Figure 4: a) (left) Head Region and Shoulder Region definitions [9]; b) (center) $H + S$, HO data and fit for for AuAu 0-20%; c) (right) Away-side $x_E = z_T$ distributions for various p_{T_t} for AuAu 0-12% [10].

the transverse momenta of the away to the trigger particles, $x_E \approx p_{T_a}/p_{T_t}$, which is measured, to the ratio of the transverse momenta of the away to the trigger jets, $\hat{x}_h = \hat{p}_{T_a}/\hat{p}_{T_t}$, which can thus be deduced. In p-p collisions, the imbalance of the away-jet and the trigger jet indicated by fitted values of ($\hat{x}_h \sim 0.7 - 0.9$) in Fig. 3c is caused by k_T-smearing (the main topic of my 1979 Moriond talk). In A+A collisions, $\hat{x}_h$ is sensitive to the relative energy loss of the trigger and associated jets in the medium, which can be thus measured.

One of the many interesting new features in Au+Au collisions is that the away side azimuthal jet-like correlations (Fig. 4a) are much wider than in p-p collisions and show a two-lobed structure ("the shoulder") at lower p_{T_t} with a dip at 180°, reverting to the more conventional structure of a peak at 180° ("the head") for larger p_{T_t}. Eq. 1 provides excellent fits to both these regions in p-p and Au+Au collisions where fits to the Head region (HO) and the full width of the distribution, Head + Shoulder (HS) region, are shown (Fig. 4b). The fits give $\hat{x}_h = 0.5 \pm 0.05$ for Au+Au central collisions for both HO and HS, compared to $\approx 0.8 - 0.9$ in p-p, clear evidence for energy loss of the away-side parton in the medium produced in Au+Au central collisions. The fit in the Head region (HO) is greatly improved ($\Delta\chi^2 = 6/1$) if a second component with the same $\hat{x}_h$ as in p-p distributions is added (dashed curve), statistically indicating a parton that has apparently punched through the medium without losing energy, which is evident directly in the STAR measurement [10] (Fig. 4c) by the sharp change in slope at z_T (x_E) $= 0.5$ for $6 < p_{T_t} < 10$ GeV/c. Clearly, there are lots of new and interesting phenomena to be understood at RHIC.

Acknowledgments

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