Systematics of parton fragmentation in $e^+e^-$ and nuclear collisions

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(Received ?)

Parametrizations of fragmentation functions (FFs) from $e^+e^-$ and p-\bar{p} collisions are combined with a parton spectrum model in a pQCD folding integral to produce minimum-bias fragment distributions. A model of in-medium FF modification is included. Calculated fragment distributions are compared with hard components from p-p and Au-Au $p_t$ spectra. Data are well described by pQCD over a large kinematic region for a range of Au-Au centralities.

PACS numbers: 12.38.Qk, 13.87.Fh, 25.75.Ag, 25.75.Bh, 25.75.Ld, 25.75.Nq
Keywords: fragmentation, jet quenching, pQCD, heavy ion collisions, two-component model

I. INTRODUCTION

RHIC collisions are conventionally described in terms of hydrodynamic (hydro) evolution of a thermalized bulk medium and energy loss of energetic partons (hard probes) in that medium. Hydro should dominate $p_t$ spectra below 2 GeV/c, parton fragmentation above 5 GeV/c, and “quark coalescence” in the intermediate $p_t$ interval.

However, recent analysis of spectrum and correlation structure has revealed 

minijet

structures in RHIC collisions. 

Two-component analysis of p-p and Au-Au spectra reveals a corresponding hard component (minimum-bias fragment distribution), suggesting that jet phenomena extend down to 0.1 GeV/c. Minijets appear to dominate the transverse dynamics of nuclear collisions at energies above $\sqrt{s_{NN}} \sim 15$ GeV and provide unbiased access to fragment distribution structure down to a small cutoff energy for scattered partons (3 GeV) and to the smallest detectable fragment momenta ($\sim 0.1$ GeV/c).

Minijets can be studied in the form of $p_t$-spectrum hard components isolated via the two-component spectrum model. Measured hard components are compared with pQCD fragment distributions (FDs). Parton spectrum parameters and modifications to fragmentation functions (FFs) in more-central Au-Au collisions are inferred. The goal is a comprehensive pQCD description of all nuclear collisions.

II. TWO-COMPONENT MODEL

The two-component (soft+hard) spectrum model was first obtained from a Taylor-series expansion of p-p $p_t$ spectra on uncorrected event multiplicity $n_{ch}$ for ten multiplicity classes. The soft component was interpreted as longitudinal nucleon fragmentation, the hard component as transverse scattered-parton fragmentation.

The two-component model for p-p collisions with soft and hard multiplicities $n_s + n_h = n_{ch}$ is

$$\frac{1}{n_s(n_{ch})} \frac{1}{y_t} \frac{dn_{ch}(\hat{n}_{ch})}{dy_t} = S_0(y_t) + \frac{n_h(\hat{n}_{ch})}{n_s(\hat{n}_{ch})} H_0(y_t)$$  

Coefficient $n_h/n_s$ scales as $\alpha \cdot n_{ch}$, $S_0(y_t)$ is a Lévy distribution on $m_t = H_0(y_t)$, $H_0(y_t)$ is a Gaussian plus QCD power-law tail on transverse rapidity $y_t = \ln((m_t + p_t)/m_0)$. To compare with A-A spectra we define $S_{pp}(1/y_t) \frac{dn_{s}/dy_t}$ with reference model $n_s S_0$ and similarly for $H_{pp} \leftrightarrow n_h H_0$.

The corresponding two-component model for per-participant-pair A-A spectra is

$$\frac{2}{n_{part}} \frac{1}{y_t} \frac{dn_{ch}}{dy_t} = S_{NN}(y_t) + \nu H_{AA}(y_t; \nu)$$

where $S_{NN} (\sim S_{pp})$ is the soft component and $H_{AA}$ is the A-A hard component (with reference $H_{NN} \sim H_{pp}$). Ratio $r_{AA} = H_{AA}/H_{NN}$ is an alternative to nuclear modification factor $R_{AA}$. Centrality measure $\nu \equiv 2n_{binary}/n_{participant}$ estimates the mean nucleon path length. We are interested in the evolution of hard component $H_{AA}$ or ratio $r_{AA}$ with A-A centrality.
III. FRAGMENTATION FUNCTIONS

$e^+e^-$ (e-e) fragmentation functions (FFs) have been parametrized accurately over the full kinematic region relevant to nuclear collisions [12]. Light-quark and gluon fragmentation functions $D_{xx}(x,Q^2)$ are described above energy scale $Q = 2E_{jet} \sim 10$ GeV by a two-parameter beta distribution $\beta(u;p,q)$ on normalized rapidity $u$ [12]. Fragment rapidity for unidentified hadrons is $y = \ln[(E + p)/m]$, and parton rapidity $y_{max} = \ln(Q/m_\pi)$. Parameters $(p,q)$ vary slowly and linearly with energy above $Q = 10$ GeV and can be extrapolated down to $Q \sim 4$ GeV.

Fig. 1 (first panel) shows measured FFs for three energy scales from HERA/LEP [13, 14]. The curves are $\beta(p,q)$ parametrizations which describe data over the entire fragment momentum range. Fig. 1 (second panel) shows the FF ensemble vs energy scale $Q$ as a surface plot [12].

Figure 1 (third panel) shows FF data from p-p collisions for three energies with $Q = 2E_{jet}$ GeV [15]. The spectrum integrates to $2\Delta y \approx 3$ GeV inferred from a p-p $p_t$ spectrum hard component [11]. The bold dotted curve is an ab-initio pQCD calculation [16].

The pQCD fragmentation (solid curve) with cutoff $\sim 3$ GeV inferred from a p-p $p_t$ spectrum hard component [11]. The bold dotted curve is an ab-initio pQCD calculation [16]. The spectrum integrates to $2.5 \pm 0.6$ mb, consistent with pQCD theory [17].

The pQCD folding (convolution) integral used to obtain fragment distributions is

$$\frac{d^2 n_h}{dy\,d\eta} \approx \epsilon(\delta\eta,\Delta\eta) \int_{y_{max}}^{\infty} dy_{max} D(y, y_{max}) \frac{d\sigma_{dijet}}{dy_{max}}$$

where $D(y, y_{max})$ is the FF ensemble from some collision system (e-e, p-p, A-A, in-medium or in-vacuum), and $d\sigma_{dijet}/dy_{max}$ is the parton spectrum [11]. Hadron spectrum hard component

IV. pQCD FRAGMENT DISTRIBUTIONS

The parton $p_t$ spectrum from minimum-bias scattering into an $\eta$ acceptance near projectile mid-rapidity can be parametrized as

$$\frac{1}{p_t} \frac{d\sigma_{dijet}}{dp_t} A_{n_{QCD}} \frac{d\sigma_{dijet}}{dy_{max}}$$

$$= f_{cut}(y_{max}) A_{n_{QCD}} \exp\{-2(n_{QCD} - 2)y_{max}\},$$

with $y_{max} \equiv \ln(2p_t/m_\pi)$. The cutoff factor

$$f_{cut}(y_{max}) = (\tanh[(y_{max} - y_{cut})/\xi_{cut}] + 1)/2$$

represents the minimum parton momentum which can lead to detectable charged hadrons as neutral pairs. Parton spectrum and cutoff parameters are determined by comparing FDs with p-p and Au-Au spectrum hard components.

Fig. 2 (first panel) shows the parton spectrum (solid curve) with cutoff $\sim 3$ GeV inferred from a p-p $p_t$ spectrum hard component [11]. The bold dotted curve is an ab-initio pQCD calculation [16]. The spectrum integrates to $2.5 \pm 0.6$ mb, consistent with pQCD theory [17].

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d\frac{\sigma_{\text{NN}}}{dy} \text{d}z \frac{dy}{dy_{\text{max}}}$ represents the fragment yield from scattered parton pairs into $\eta$ acceptance $\delta\eta$. Efficiency factor $\epsilon \sim 0.5$ includes the probability that the second jet also falls within $\delta\eta$. $\Delta\eta \sim 5$ is the effective $4\pi$ $\eta$ interval for scattered partons. $\sigma_{\text{NSD}} \sim 36 \text{ mb}$ for $\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$ is the cross section for NSD p-p collisions.

Fig. 2 (second panel) shows integrand $D_{ee}(y, y_{\text{max}}) \frac{dy_{\text{cut}}}{dy_{\text{max}}}$ of Eq. (6) with unmodified FFs from e-e collisions and lower bound at $y_{\text{min}} \sim 0.35$ ($p_t \sim 0.05 \text{ GeV/c}$) (dotted line). Fig. 2 (third panel) shows the corresponding FD (solid curve), the “correct” FD describing inclusive hadrons from partons produced by free parton scattering from p-p collisions. The dash-dotted curve is the hard-component model inferred from p-p spectrum data [3]. The FD from e-e FFs lies well above the measured p-p hard component for hadron $p < 2 \text{ GeV/c}$ ($y < 3.3$), and the mode is shifted down to $\sim 0.5 \text{ GeV/c}$. The “correct” e-e FD strongly disagrees with the hard component of the p-p $p_t$ spectrum. Nevertheless, the e-e FD is the proper reference for nuclear collisions [11].

Fig. 2 (fourth panel) shows FD $H_{N,N-\text{vac}}$ as the solid curve, with measured FFs from p-p collisions. The mode of the FD is $\sim 1 \text{ GeV/c}$. The solid points are hard-component data from p-p collisions and the dash-dotted curve is p-p model function $H_{pp}$ [3]. The comparison determines parton spectrum parameters $y_{\text{cut}} = 3.75$ ($E_{\text{cut}} \sim 3 \text{ GeV}$), $A_{\text{max}}$, and exponent $n_{QCD} = 7.5$ and establishes a quantitative relationship among parton spectrum, measured FFs and measured spectrum hard components over all $p_t$, not just a restricted interval above 2 GeV/c.

V. PARTON “ENERGY LOSS” MODEL

Fragmentation in A-A collisions requires a model of parton “energy loss” or medium modification. We adopt a minimal model of FF modification (Borghini-Wiedemann or BW) [18]. Figure 3 (first panel) illustrates the BW model (cf. Fig. 1 of [18], $\xi_p = \ln(p_{jet}/p) = \ln(2p_{jet}/m_\pi) - \ln(2p/m_\pi) \sim y_{\text{max}} - y$). In-vacuum e-e FFs for $Q = 14$ and 200 GeV from the beta parametrization are shown as dashed and solid curves [12]. We can simulate BW accurately by changing parameter $q$ in $\beta(u;p,q)$ by $\Delta q \sim 1$ (dash-dotted and dotted curves) [11]. Small reductions at larger fragment momenta (smaller $\xi_p$) are compensated by much larger increases at smaller momenta. The largest changes (central Au-Au) correspond to an inferred 25% leading-parton fractional “energy loss.” Fig. 3 (second panel) shows the modified e-e FF ensemble with FF modes shifted to smaller fragment rapidities $y$.

Figure 3 (third panel) shows $H_{ee-\text{med}}$ (solid curve), the FD obtained by inserting in-medium e-e FFs from the second panel into Eq. (6). The dotted curve is the $H_{ee-\text{vac}}$ reference from in-vacuum e-e FFs. The mode of $H_{ee-\text{med}}$ is $\sim 0.3 \text{ GeV/c}$. Fig. 3 (fourth panel) shows results for p-p FFs. Major differences between p-p and e-e FDs appear below $p_t \sim 2 \text{ GeV/c}$ ($y_t \sim 3.3$). Conventional comparisons with theory (e.g., data
energy loss" [18] (dash-dotted and dotted curves), Second: $\epsilon ^{+} - \epsilon ^{-}$ FF ensemble modified according to [18]. Third: Medium-modified FD from $\epsilon ^{+} - \epsilon ^{-}$ FFs (solid curve) compared to in-vacuum $\epsilon ^{+} - \epsilon ^{-}$ FD (dotted curve) Fourth: Medium-modified FD from p-p FFs (solid curve) compared to in-vacuum N-N FD (dotted curve).

FIG. 3: First: $\epsilon ^{+} - \epsilon ^{-}$ FFs for two energies unmodified (solid and dashed curves) and modified to emulate parton “energy loss” [18] (dash-dotted and dotted curves). Second: $\epsilon ^{+} - \epsilon ^{-}$ FF ensemble modified according to [18]. Third: Medium-modified FD from $\epsilon ^{+} - \epsilon ^{-}$ FFs (solid curve) compared to in-vacuum $\epsilon ^{+} - \epsilon ^{-}$ FD (dotted curve) Fourth: Medium-modified FD from p-p FFs (solid curve) compared to in-vacuum N-N FD (dotted curve).

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vs NLO FDs) typically do not extend below 2 GeV/c [19]. The large difference between the two collision systems below 2 GeV/c reveals that the small-$p_t$ region, conventionally assigned to hydro phenomena, may be essential for effective study of fragmentation evolution in A-A collisions.

VI. FRAGMENTATION EVOLUTION

Measured FFs are combined with a parametrized pQCD parton spectrum to produce calculated $FD_{xx}$ for comparison with measured spectrum hard components $H_{xx}$. Figure 4 (first panel) shows spectrum hard components $H_{AA}$ (solid curves) for five centralities from 200 GeV Au-Au collisions [9]. The hard components scale proportional to $n_{\text{binary}}$, as expected for parton scattering and fragmentation (jets). The points are from 200 GeV NSD p-p collisions [8]. The dashed curve is $H_{NN-vac}$, and the upper dotted curve is $H_{ee-med}$ with $\Delta y = 1.15$, which corresponds to the most-central Au-Au curve (0-12%). The parton spectrum cutoff for $H_{ee-med}$ has been reduced from 3 GeV ($y_{\text{max}} = 3.75$) to 2.7 GeV ($y_{\text{max}} = 3.65$) to match the central Au-Au hard component near $y_t = 3$.

Jet-related spectrum structure can also be studied with ratios. The conventional spectrum ratio at RHIC is $R_{AA}$. Because it includes the spectrum soft component $R_{AA}$ strongly suppresses fragment contributions at smaller $y_t$. Hard-component evolution with centrality is better resolved by ratio $r_{AA} = H_{AA}/H_{NN}$. However, studies in Ref. [11] reveal that the proper refer-

ence for all systems is the in-vacuum FD from e-e FFs, not p-p FFs. We therefore define ratios $r_{xx} = FD_{xx-vac}/FD_{ee-vac}$ with $xx = ee$, NN, AA and $y_{yy} = \text{med}$ or vac to be compared with equivalent spectrum hard components $H_{xx-vac}$.

Figure 4 (second panel) shows ratios redefined in terms of the ee-vac reference: $H_{pp} (p-p$ data – points), $H_{AA}$ (peripheral Au-Au data – solid curve [9]) and calculated $H_{ee-med}$ (dash-dotted curve) and $H_{NN-vac}$ (dashed curve) all divided by reference $H_{ee-vac}$. Strong suppression of p-p and peripheral Au-Au data apparent at smaller $y_t$ results from the cutoff of p-p FFs.

Figure 4 (third panel) shows measured $H_{AA}/H_{ee-vac}$ for more-central Au-Au collisions (solid curves) above a transition point on centrality at $\nu \sim 2.5$, with partial restoration of the suppressed region at smaller $y_t$ and strong suppression at larger $y_t$. The latter has been a major observation at RHIC (high-$p_t$ suppression, "jet quenching" [20]). Newly apparent is the accompanying large increase in fragment yield below 2 GeV/c, still strongly correlated with the parent parton [7]. Changes in fragmentation depend strongly on centrality near the transition point. It is remarkable that the trend at 10 GeV/c corresponds closely to the trend at 0.5 GeV/c. $H_{pp}$, $H_{AA}$ and ratios based on the e-e in-vacuum reference are well described by pQCD FDs from 0.3 to 10 GeV/c [11].
VII. CONCLUSIONS

Hard components of $p_t$ spectra can be identified with minimum-bias parton fragmentation in nuclear collisions. Minimum-bias fragment distributions (FDs) can be calculated by folding a power-law parton energy spectrum with parametrized fragmentation functions (FFs) derived from $e^+e^-$ and $p\bar{p}$ collisions. Alterations to FFs due to parton “energy loss” or “medium modification” in Au-Au collisions are modeled by adjusting FF parametrizations consistent with rescaling QCD splitting functions. The reference for all nuclear collisions is the FD derived from in-vacuum $e^+e^-$ FFs. Relative to that reference the hard component for $p\bar{p}$ and peripheral Au-Au collisions is found to be strongly suppressed for smaller fragment momenta. At a specific point on centrality the Au-Au hard component transitions to enhancement at smaller momenta and suppression at larger momenta, consistent with FDs derived from medium-modified $e^+e^-$ FFs.

I thank the organizers of ISMD 2009 for a delightful and informative conference. This work was supported in part by the Office of Science of the US DOE under grant DE-FG03-97ER41020.

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