Understanding RHIC Collisions
Modified QCD fragmentation vs quark coalescence from a thermalized flowing medium

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Agenda

• Parton fragmentation in spectra and correlations
  – Spectrum hard components and pQCD
  – Minijet correlations and pQCD

• Paradigm challenges for spectrum analysis
  – Jet quenching and $R_{AA}$
  – Anomalous $p/\pi$ ratio
  – Radial flow

• Paradigm challenges for correlation analysis
  – $p_t$-integral elliptic flow
  – $p_t$-differential elliptic flow
Parton Fragmentation in Spectra

*pQCD-calculated fragment distributions* – FD

vs

*measured spectrum hard components* – $H_{xx}$

\[
y = \ln\left\{(E + p)/m_\pi\right\}
\]

\[
y_t = \ln\left\{(m_t + p_t)/m_\pi\right\}
\]
pQCD Folding Integral \( \rightarrow \) FDs

\[ \ln(2E_{\text{jet}}/m_\pi) = y_{\text{max}} \]

PRC 80, 044901 (2009)

\[ d^2n_h/dy_1dy_2 \approx \frac{\varepsilon_j(\Delta\eta)/2}{\sigma_{\text{NSD}}\Delta\eta_{4\pi}} \int_0^{\infty} dy_{\text{max}} D_{xx}(y,y_{\text{max}}) \frac{d\sigma_{\text{dijet}}}{dy_{\text{max}}} \]

\[ H_{pp} \]

\[ p-p \text{ data} \]

\[ \text{integrands} \]

\[ \text{measured FF ensembles} \]

\[ \text{hydro?} \]

\[ 2 \text{ GeV/c} \]

\[ \text{parton spectrum} \]

\[ \text{problem} \]

\[ \text{pp} \]

\[ \text{integrands} \]

\[ \text{hydro?} \]

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\textbf{pQCD Folding Integral \rightarrow FDs}

\begin{align*}
\ln(2E_{\text{jet}}/m_\pi) &= y_{\text{max}} \\
\text{PRC 80, 044901 (2009)}
\end{align*}

\[ \frac{d^2 n_h}{dy d\eta} \approx \frac{e_j(\Delta \eta)/2}{\sigma_{\text{NSD} \Delta \eta_{4\pi}}} \int_0^{\infty} dy_{\text{max}} D_{xx}(y, y_{\text{max}}) \frac{d\sigma_{\text{dijet}}}{dy_{\text{max}}} \]

\text{fragment distributions (FDs)} \leftrightarrow \text{spectrum hard components (H}_{xx})
Fragment Distributions – FDs

3 GeV parton spectrum cutoff

$\mathbf{F D_{ee-vac}}$ – reference for $H_{AA}$ evolution

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Hard Component Evolution – $H_{XX}$

$$r_{ee} = \frac{FD_{ee-med}}{FD_{ee-vac}}$$

$$r_{NN} = \frac{FD_{NN}}{FD_{ee-vac}}$$

sharp transition: centrality $\nu \sim 2.5$

$$\nu = \frac{2n_{bin}}{n_{part}}$$

$200$ GeV $p$-$p$

hydro??

$$\frac{2}{n_{part}} \int \frac{dn_{ch}}{dy_t} \left[ \frac{1}{1+y_t} \frac{d^2 n_{ch}}{d^2 y_t} - S_{NN}(y_t) \right] = S_{NN}(y_t) + \nu H_{AA}(y_t, b)$$

$pQCD$ describes $A$-$A$ spectrum hard-component evolution

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Parton Fragmentation in Correlations

Minijet phenomenology

Minijets and hadron production
2D Angular Autocorrelations

\[ \frac{\Delta \rho}{\sqrt{\rho_{\text{ref}}}} (\eta_\Delta, \Phi_\Delta) \]

\[ p_t \text{-integral} \]

\[ \begin{align*}
N-N & = \text{2D fits} \\
\text{minijets} & \leftrightarrow \text{sharp transition} \\
\text{peripheral} & \leftrightarrow \text{elliptic flow} \\
p-p & \\
\text{star preliminary} & \\
200 \text{ GeV Au-Au} & \\
\text{star preliminary} & \\
\text{b=0} & \\
\text{central} &
\end{align*} \]

IJMPE 17, 1219 (2008), arXiv:0704.1674

Jet Angular Correlations – 200 GeV Au-Au

\[ \rho_0(b) j^2(\eta_\Delta, \varphi_\Delta, b) = A_{2D} \exp\{-\varphi_\Delta^2/2\sigma_\varphi^2\} \exp\{-\eta_\Delta^2/2\sigma_\eta^2\} \]

same-side jet peak: all jet fragment pairs

\( \Delta \rho \)

\( \sqrt{\rho_{\text{ref}}} \)

angle-averaged pair ratio within angular acceptance

no “ridge” no “Mach cones”
Final-state Hadrons from Jets

$pQCD$-calculated jet number in $A-A$

Jet fragment yield

\[
\frac{d n_h}{d \eta} \equiv 2\pi H_{AA} = f(b) \times n_{ch,j}(b)
\]

Total single-particle density

\[
\nu H_{AA}(b) = \frac{2}{n_{part}} \rho_0(b) \sqrt{n_j(b) \times j^2(b)}
\]

Hard-component yield from jets

1/3 of all hadrons in 200 GeV central $Au-Au$ collisions are contained within resolved jets

ArXiv:1008.4759

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Paradigm Tests and Spectrum Structure

Jet quenching / $R_{AA}$

$p/\pi$ ratio

Radial flow

fragmentation vs recombination vs hydrodynamics
Jet quenching / \( R_{AA} \) 

\[ R_{AA} = \frac{1}{n_{bin}} \frac{\rho_{AA}}{\rho_{pp}} \]

\[ r_{AA} = \frac{H_{AA}}{H_{NN}} \]

\[ r_{xx} = \frac{H_{xx}}{FD_{ee-vac}} \]

\[ (2/n_{part}) \rho_{AA} = S_{NN}(y_t) + \nu H_{AA}(y_t, b) \]

\( R_{AA} \): parton fragments apparently suppressed

large fragmentation increase in central collisions

Opaque core??
B/M anomaly is a consequence of modified fragmentation
Radial Flow

\[ \langle \beta_t \rangle = 0.25 \]
\[ T = 0.14 \, \text{GeV} \]

\[ \langle \beta_t \rangle = 0.6 \]
\[ T = 0.10 \, \text{GeV} \]

jets

hydro?

blast-wave fits accommodate parton fragment distributions

“radial flow” is a jet manifestation

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JPhysG 37, 085004 (2010)
Paradigm Tests and Correlation Structure

Azimuth quadrupole correlations: “Elliptic Flow”

\[ p_t \text{ integral} \]

\[ p_t \text{ differential} \]
$v_2\{2D\}$  \hspace{1cm} $\eta_\Delta$-independent Structure

N-N $\sim$ p-p \hspace{1cm} quadrupole

84-93% \hspace{1cm} $A_Q=0.002$

200 GeV Au-Au

64-74% \hspace{1cm} $A_Q=0.026$

46-55% \hspace{1cm} $A_Q=0.117$

0-5% \hspace{1cm} $A_Q=0.008$

vanishing fitted SS 2D jet peak

remove fitted SS 2D jet peak

dipole $v$s quadrupole

two orthogonal components

separated without ambiguity
Systematics of $p_t$-integral $v_2\{2D\}(b)$

$\rho_0(b)v_2^2(b)$

$\frac{\Delta \rho[2]}{\sqrt{\rho_{\text{ref}}}}$ = 0.0045 $R \left( \sqrt{s_{\text{NN}}} \right) \varepsilon_{\text{opt}}^2(b) n_{\text{bin}}(b)$

compare with jets: $\rho_0(b)j_2^2(b)$

$\rho_0(b)$ single-particle density

nucleon MD  \hspace{1cm}  low-x glue

centrality and energy dependence factorize


STAR Preliminary
Published Minimum-bias $v_2(p_t)$

**B: viscous hydro**

\[ \langle \cos (2[\phi - \Psi_{RP}]) \rangle \]

PRC 66, 034904 (2002)
PRL 92, 052302 (2004)

what is source boost distribution $B(\Delta y_{t0})$?

\[ \frac{v_2(p_t)}{p_t} = \frac{(\ast)}{p_0(y_t, b)} \int d\Delta y_{t0} B(\Delta y_{t0}) \left\{ \frac{1}{p_t} \right\} \frac{1}{p_t} V_2(y_t, \Delta y_{t0}, b) \]

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PRC 78, 064908 (2008)

very simple systematics

narrow boost distribution... what centrality dependence?

\[ \frac{v_2(p_t)}{p_t} = \frac{(\ast)}{p_t} \int d\Delta y_{t0} B(\Delta y_{t0}) \left\{ \frac{1}{p_t} \right\} \frac{1}{p_t} V_2(y_t, \Delta y_{t0}, b) \]

universal species!
Systematics of differential $v_2 \{2D\}(p_t, b)$

quadrupole spectrum

\[ \frac{V_2(p_t)}{p'_t} \propto \frac{1}{n_2} \]

\[ T_2 = 0.09 \text{ GeV} \]

\[ \Delta y_{tv} = 0.58 \]

hadrons

Lévy

\[ V_2(p_t) \]

\[ \text{STAR Preliminary} \]

Q($y_t, b$) $\rightarrow$ Q$_0(y_t)$

200 GeV Au-Au

centrality dependence?

\[ Q(y_t, b) \rightarrow Q_0(y_t) \]

arXiv:1008.4793

cold spectrum, no jet contribution

hydro theory: PRC 78, 034915 (2008)

parametrized $v_2 \{2D\}(p_t)$

30-40%

20-30%

5-10%

0-5%

boost independent of centrality

no relation to jet sharp transition!

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Summary

- Hydro-motivated analysis suppresses fragmentation
- Most parton fragments appear below 2 GeV/c
- New fragmentation features are described by pQCD
- Jet correlations transform to absolute fragment yields
- 1/3 of hadrons in central Au-Au lie within resolved jets
- “Sharp transition” in spectrum and jet properties
- 2D quadrupole analysis leads to full $v_2$ factorization
- No apparent coupling between jets and quadrupole

**perturbative QCD describes RHIC collision evolution**

evidence for hydrodynamic flows is questionable