The Azimuth Quadrupole in Nuclear Collisions

INT Workshop on “The Ridge”
May, 2012

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Agenda

- Analysis methods
- $p_t$-integral 2D quadrupole data
- $p_t$-differential 2D quadrupole data
- Source boosts and quadrupole spectra
- Quadrupole factorization and universality
- Comparison with other $v_2$ methods
- Implications for “The Ridge”
Correlation Measures

\[ \rho_{\text{(2)}}(\vec{p}_1, \vec{p}_2) = \text{pair density in 6D two-particle momentum space} \]

\[ \rho_{\text{sibling}}(\vec{p}_1, \vec{p}_2) \]

\[ \rho_{\text{reference}}(\vec{p}_1, \vec{p}_2) \]

\[ \Delta \rho(\vec{p}_1, \vec{p}_2) = \rho_{\text{sib}}(\vec{p}_1, \vec{p}_2) - \rho_{\text{ref}}(\vec{p}_1, \vec{p}_2) \]

\[ \sqrt{\rho_{\text{ref}}} \approx \sqrt{\rho_{\text{(1)}}(\vec{p}_1)\rho_{\text{(1)}}(\vec{p}_2)} \text{ geometric mean} \]

per-particle measure

per-pair measure

2D angular correlations are featured

**Goal:** understand energy, centrality and \( p_t \) dependence of *nonjet* azimuth quadrupole
Projection to 2D Subspaces

from 6D pair space...
\[ \vec{p} \rightarrow (p_t, \eta, \phi) \]
\[ (p_{t1}, p_{t2}) \]
choose \( p_t \) range: 
integrate over all \( p_t \)
or select a subset

\[ \begin{array}{c}
\text{p}_{t2} \\
\text{p}_t \\
\text{p}_{t1} \\
\end{array} \]

marginal \( p_t \) cuts

project angle variables
\[ (\vec{p}_1, \vec{p}_2) \rightarrow (\eta_1, \phi_1, \eta_2, \phi_2) \rightarrow (\eta_\Delta, \phi_\Delta) \]

2D angular autocorrelation showing jet structure

structure appears on difference axes only

integrate over \((p_{t1}, p_{t2})\) and project \( \eta \) and \( \phi \) onto difference axes

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8-parameter 2D fit model

exclude sharp BEC-electron peak at (0,0)

$v_2\{2D\}$ derived from quadrupole term

SS 2D peak dominates “nonflow”

$Z = A$ (per-particle) or $B$ (per-pair)

\[
Z_0 + Z_{\text{soft}} G_{1D}(\eta_\Delta) + Z_{2D} G_{2D}(\eta_\Delta, \phi_\Delta) + Z_D \cos(\phi_\Delta - \pi)/2 + Z_Q 2\cos(2\phi_\Delta)
\]

\[B_Q = v_2^2\{2D\}\]
Momentum and Centrality Variables

\[ y_t = \ln \left( \frac{p_t + m_t}{m_\pi} \right) \]

Transverse rapidity

\[ \nu = \frac{2N_{\text{bin}}}{N_{\text{part}}} \]

Path length \( \nu \) tests binary-collision scaling
$p_t$-integral 2D Fit Results

200 GeV Au-Au data

similar for 62 GeV

83-93% ≈ N-N

22-32% data

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2D fit

residuals

83-93%

≈ N-N

22-32% data

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2D fit

residuals
Nonjet Quadrupole \{2D\} Systematics

*primary 2D quadrupole measurements*

\[ A_Q^{(2D)}(b) = \rho_0(b)\nu^2 \{2D\}(b) \]

\( \rho_0(b) \) single-particle 2D angular density

**curves: common shape defined next**

A new QCD phenomenon at RHIC?

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Quadrupole Factorization on \((b, \sqrt{s_{NN}})\)

\[
A_Q\{2D\}(b, \sqrt{s_{NN}}) = 0.0045 \frac{R(\sqrt{s_{NN}}) \varepsilon_{opt}^2(b)}{N_{bin}(b)}
\]

all \(p_t\)-integral Au-Au quadrupole data parametrized

Eur Phys J C 62, 175 (2009)

arXiv:0907.2686
200 GeV $p_t$-differential Data

40-50% central

similar for 62 GeV

$0.15-7$ GeV/c

per-pair measure

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$p_t$-differential Fit Results

SS 2D peak

40-50% central, 200 GeV

1.8 < $y_t$ < 2.2

3.4 < $y_t$ < 3.8

fit residuals

nonjet quadrupole insensitive to details of SS 2D peak model

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Fit Parameters – 200 GeV

**unexpected evolution of Gaussian widths with** $p_t$, centrality

$B_Q = v^2\{2D\}(y_t, b)$

**per-pair measures**

**SS peak widths**

nonjet quadrupole

SS 2D peak amplitude

peripheral

central

peripheral

central

central

peripheral
Source Boosts and Quadrupole Spectra

3D hadron densities:
\[ \rho(y_t, \varphi, b) = \rho_0(y_t, b) + \rho_2(y_t, \varphi, b) \]

- total 3D density
- SP spectrum
- azimuth dependence

represent \( \rho_2(y_t, \varphi, b) \) by blast-wave model

definition of \( v_2(y_t, b) \):
\[ v_2(y_t, b) = \frac{1}{2\pi} \int_0^{2\pi} d\varphi \frac{\rho_2(y_t, \varphi, b) \cos[2(\varphi - \Psi_R)]}{\rho_0(y_t, b)} \]

Cooper-Frye

\[ V_2(y_t, b) = \rho_0(y_t, b) v_2(y_t, b) \]

data:
\[ B_Q(y_t, b) = v_2(b) v_2(y_t, b), \quad \rho_0(y_t, b) \]

construct unit-normal quantity:
\[ Q(y_t, b) \equiv \frac{V_2(y_t, b)}{V_2(b)} \frac{1/p_t}{\left\langle 1/p_t \right\rangle} \]

\[ \approx \frac{\rho_2(y_t, b)}{\rho_2(b)} \]

Source Boosts and Quadrupole Spectra

\[ \Delta y_t(\varphi, b) = \Delta y_{t0}(b) + \Delta y_{t2}(b) \cos[2(\varphi - \Psi_R)] \]

monopole

quadrupole

\[ V_2(y_t, b) \approx \frac{\Delta y_{t2}(b)}{2T_2} \times p_t(\text{boost}) \rho_2(y_t, b; \Delta y_{t0}) \]

note

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Phys Rev C 78, 064908 (2008)
arXiv:0803.4002

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Source Boost [monopole] Distribution

minimum-bias PID data

STAR published

source boost independent of Au-Au centrality

no Hubble expansion

Δy_{t0} = 0.6

T_2 = 0.09 GeV

Δy_{t0} = 0.6

T_2 = 0.09 GeV

source boost

this analysis

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Universal Quadrupole Spectrum

Au-Au centrality dependence

boost is independent of centrality

minimum bias with PID

in the boost frame

200 GeV Au-Au
minimum-bias
quadrupole spectra

in the lab frame

boost is independent of centrality

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PRC 75, 054906 (2007); nucl-ex/0701010

PRC 78, 064908 (2008); arXiv:0803.4002
Quadrupole Factorization on \( (y_t, b, \sqrt{s_{NN}}) \)

From this analysis: \( \rho_2(y_t, b) \approx \rho_2(b) Q_0(y_t) \)

Conclusion:
\[
\frac{V_2(y_t, b, \sqrt{s_{NN}})}{p_t(\text{boost})} \approx 2.5 \left[ \rho_0(b, \sqrt{s_{NN}}) v_2(b, \sqrt{s_{NN}}) \right] Q_0(y_t)
\]

Blast-wave model implies:
\[
\frac{V_2(y_t, b)}{p_t} \approx \left\{ \frac{\Delta y_{12}(b)}{2T_2} \right\} \times \rho_2(y_t, b)
\]

\( y_t \)-differential result
\( y_t \)-integral result

\[
\rho_0(b, \sqrt{s_{NN}}) v_2^2(b, \sqrt{s_{NN}}) = 0.0045 R(\sqrt{s_{NN}}) \varepsilon_{\text{opt}}^2(b) N_{\text{bin}}(b)
\]

Universal quadrupole spectrum shape

Au-Au quadrupole collision energy, centrality and transverse-momentum trends factorized

Universal quadrupole hadron production
Comparisons with Other $v_2$ Methods

$$v_2^2 \approx v_2^2\{\text{EP}\} = v_2^2\{\text{SS}\} + v_2^2\{\text{2D}\}$$

$A_Q\{\text{method}\}(b)$

$p_t$-integral data

solid curves: $\{2D\}$ data

$p_t$-differential data

universal $\{2D\}$ parametrization

large contribution from SS 2D peak

Comparisons with Other $v_2$ Methods

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Comparisons with Other $v_2$ Methods

$A_Q\{\text{method}\}(b)$

$p_t$-integral data

solid curves: $\{2D\}$ data

$p_t$-differential data

universal $\{2D\}$ parametrization

large contribution from SS 2D peak
“Ridge” vs Nonjet (NJ) Quadrupole?

sharp transition (ST) in SS 2D peak properties

no comparable transition for NJ quadrupole

very different centrality evolution

$v^2_2\{2\} - v^2_2\{4\} \approx v^2_2\{SS\} \neq \sigma^2_v$ SS 2D (jet) peak, not flow fluctuations

SS 2D peak ("ridge") and NJ quadrupole have dramatically different centrality trends

disconnect: SS 2D peak and nonjet quadrupole
“Ridge” vs Higher Multipoles

isolate SS 2D peak

narrow Gaussian on $\phi_\Delta \rightarrow v_m$ predictions

$p_t$ cuts: $p_t = 2.5$ GeV/c

subtract nonjet quadrupole, AS dipole

SS 2D peak multipoles

the only source of “higher multipoles is the SS 2D peak

the SS 2D peak is consistent with a jet interpretation

disconnect: nonjet quadrupole and “higher harmonics”

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Summary

- **2D angular correlations:** three main components
- Quadrupole amplitude $A_Q^{2D}(y_t, b, \sqrt{s_{NN}})$ factorized
- Universal quadrupole spectrum shape $Q_0(y_t)$
- Nonjet (NJ) quadrupole source boost $\Delta y_{t0}(b)$ inferred
- Mean source boost $\approx$ independent of Au-Au centrality
- Boost distribution inconsistent with Hubble expansion
- “Ridge” and NJ quadrupole distinct (not hydro-related?)
- SS 2D peak (“ridge”) predicts all “higher harmonics”