Using particle correlations to probe the medium produced at RHIC

Helen Caines - Yale University

Oxford/RAL
November 2008
Relativistic Heavy-Ion Collider (RHIC)

Au+Au @ $\sqrt{s_{NN}} = 200$ GeV

$v = 0.99995 \cdot c$

1 km

AGS

TANDEMS

PHENIX

PHOBOS

STAR

BRAHMS
QGP expectation came from Lattice

\( \varepsilon/T^4 \sim \# \) degrees of freedom

confined: few d.o.f.

deconfined: many d.o.f.

\( T_c = (173 \pm 15) \text{ MeV} \)

\( \varepsilon_c \sim 0.7 \text{ GeV/fm}^3 \)
QGP expectation came from Lattice

$\frac{\varepsilon}{T^4} \sim \# \text{ degrees of freedom}$

$T_C \approx 173 \text{ MeV} \approx 2 \cdot 10^{12} \text{ K}$

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RHIC has created a new state of matter

The QGP is the:

- **hottest** ($T=200-400$ MeV ~ $2.5 \times 10^{12}$ K)
- **densest** ($\varepsilon = 30-60 \ \varepsilon_{\text{nuclear matter}}$)

matter ever studied in the lab. It flows as a

- **(nearly) perfect fluid**

with systematic patterns, consistent with

- **quark degree of freedom**

and a viscosity to entropy density ratio

- **lower**

than any other known fluid.
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Want to learn more about the properties
Elliptic flow – rapid thermalization

A Fourier expansion used to describe the angular distribution of the particles:

\[
\frac{dN}{d\varphi} \propto 1 + 2v_2 \cos[2(\varphi - \psi_R)] + \ldots
\]
Elliptic flow – rapid thermalization

A Fourier expansion used to describe the angular distribution of the particles

\[ \frac{dN}{d\varphi} \propto 1 + 2v_2 \cos[2(\varphi - \psi_R)] + \ldots \]

Driving spatial anisotropy vanishes \( \Rightarrow \) self quenching
Elliptic flow – rapid thermalization

A Fourier expansion used to describe the angular distribution of the particles

$$\frac{dN}{d\varphi} \propto 1 + 2v_2 \cos[2(\varphi - \psi_R)] + ...$$

Driving spatial anisotropy vanishes ⇒ self quenching

Sensitive to early interactions and pressure gradients
The flow is ~Perfect

Huge asymmetry found at RHIC

- massive effect in azimuthal distribution w.r.t reaction plane
- At higher $p_T$: Factor 3:1 peak to valley from 25% $v_2$
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Huge asymmetry found at RHIC
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“fine structure” $v_2(p_T)$
- ordering with mass of particle
- good agreement with ideal hydrodynamics (zero viscosity, $\lambda=0$)

⇒ “perfect liquid”
The constituents “flow”

\[ m_T = \sqrt{p_T^2 + m_0^2} \]
The constituents “flow”

- Scaling flow parameters by quark content $n_q$ (baryons=3, mesons=2) resolves meson-baryon separation of final state hadrons
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Constituents of liquid are partons
Viscous fluid

• supports a shear stress

• viscosity $\eta$:
  
  $\eta \approx$ momentum density $\times$ mean free path

  $\approx n\bar{p}\lambda = n\bar{p}\frac{1}{n\sigma} = \frac{\bar{p}}{\sigma}$

• small $\eta \Rightarrow$ large $\sigma \Rightarrow$ strong couplings
How perfect is “Perfect”?  

Viscous fluid

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  $\eta \approx \text{momentum density} \times \text{mean free path}$

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- small $\eta \Rightarrow$ large $\sigma \Rightarrow$ strong couplings

Hydrodynamic calculations for RHIC assumed zero viscosity

$\eta = 0 \Rightarrow$ “perfect fluid”

- But there is a (conjectured) quantum limit:

  $\eta \geq \frac{\hbar}{4\pi} \text{(Entropy Density)} = \frac{\hbar}{4\pi} s$

  N.B.: water (at normal conditions) $\eta/s \sim 380 \frac{\hbar}{4\pi}$
What is $\eta/s$ at RHIC?

**conjectured quantum limit**

- $\eta/s$ vs $4\pi \eta/s$
  - Drescher et al.: arXiv:0704.3553

**Observables that are sensitive to shear**

- **Elliptic Flow**

- **$p_T$ Fluctuations**

- **Heavy quark motion (drag, flow)**
Probing the medium - Jet production

Early production in parton-parton scatterings with large $Q^2$.

Direct interaction with partonic phases of the reaction

From p+p
- Obtain jet rate
- Obtain fragmentation functions
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In A+A look at
- attenuation or absorption of jets: “jet quenching”
- suppression of high $p_T$ hadrons
- modification of angular correlation
- changes of particle composition
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Differences due to medium
Jets – a calibrated probe?

Jet production in p+p understood in pQCD framework
Jets – a calibrated probe?

Jet production in p+p understood in pQCD framework
Particle production in p+p also well modeled.

Seems we have a reasonably calibrated probe
Charged hadron $\xi$ in p+p 200 GeV

Reasonable agreement between Pythia and data

M. Heinz
Hard Probes 2008
Charged hadron $\xi$ in p+p 200 GeV

Reasonable agreement between Pythia and data

Are these differences onset of beyond LL effects?
ξ for strange hadrons

- charged
- $K^0_{Short}$ (x5)
- $\Lambda$ (x5)

R<0.4

R<0.5

R<0.7

$10 < E_{reco} < 15$

$p_T < 0.5$

$15 < E_{reco} < 20$

$20 < E_{reco} < 50$

Clear differences between particles

M. Heinz Hard Probes 2008
Back to probing the medium

Compare Au+Au with p+p Collisions ⇒ \( R_{AA} \)

Nuclear Modification Factor:

\[
R_{AA}(p_T) = \frac{\text{Yield}(A + A)}{\text{Yield}(p + p) \times \langle N_{\text{coll}} \rangle}
\]

Average number of NN collision in an AA collision

No “Effect”:
- \( R < 1 \) at small momenta
- \( R = 1 \) at higher momenta where hard processes dominate

Suppression: \( R < 1 \)
High-\(p_T\) suppression

Observations at RHIC:

1. Photons are not suppressed
   - Good! \(\gamma\) don’t interact with medium
   - \(N_{\text{coll}}\) scaling works
High-\( p_T \) suppression

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2. **Hadrons are suppressed in central collisions**
   - Huge: factor 5
High-$p_T$ suppression

Observations at RHIC:

1. Photons are not suppressed
   - Good! $\gamma$ don’t interact with medium
   - $N_{\text{coll}}$ scaling works

2. Hadrons are suppressed in central collisions
   - Huge: factor 5

3. Hadrons are not suppressed in peripheral collisions
   - Good! medium not dense
Interpretation

**Gluon radiation:** Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium.
Interpretation

Gluon radiation: Multiple final-state gluon radiation off the produced hard parton induced by the traversed dense colored medium

- Mean parton energy loss $\propto$ medium properties:
  - $\Delta E_{\text{loss}} \sim \rho_{\text{gluon}}$ (gluon density)
  - Coherence among radiated gluons
    - $\Delta E_{\text{loss}} \sim \Delta L^2$ (medium length)
    - $\Rightarrow \sim \Delta L$ with expansion

- Characterization of medium
  - transport coefficient $\hat{q}$ is $\langle k_T^2 \rangle$ transferred per unit path length
    $$\hat{q} = \frac{\mu^2}{L} \approx \frac{\mu^2}{\lambda}$$
    $$\hat{q} = \hat{q}(\vec{r}, \tau)$$
  - gluon density $dN_g/dy$
## The model landscape (not exhaustive)

<table>
<thead>
<tr>
<th>Model</th>
<th>Implementation Details</th>
<th>Geometry/Collisional Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PQM (Parton Quench model)</strong></td>
<td>Implementation of BDMPS (calc. E loss via coherent gluon radiation - many soft scattering approx.)</td>
<td>Realistic geometry, static medium, q time average (depends on initial density, scheme evolution dependent), no initial state multiple scatterings, no modified PDFs</td>
</tr>
<tr>
<td><strong>GLV</strong></td>
<td>Implementation of GLV formalism (calc. E loss via gluon bremsstrahlung - few hard scatterings)</td>
<td>Realistic geometry, Bjorken expanding medium - calc. a priori (w/o E loss) average path length - use to calc. partonic E loss</td>
</tr>
<tr>
<td><strong>WHDG</strong></td>
<td>Implementation of GLV formalism (calc. E loss via gluon bremsstrahlung - few hard scatterings) + collisional energy loss</td>
<td>Realistic geometry - integral over all paths, expanding medium, no initial state multiple scatterings</td>
</tr>
<tr>
<td><strong>ZOWW</strong></td>
<td>Modified fragmentation model (radiative gluon E loss incorporated into effective medium modified FF)</td>
<td>Hard sphere geometry, expanding medium</td>
</tr>
</tbody>
</table>
### Constraining $\langle q \rangle$

<table>
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<tr>
<th>Model</th>
<th>Opacity Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>PQM</td>
<td>$\langle \bar{q} \rangle = 13.2 \ (2.1 - 3.2)$</td>
</tr>
<tr>
<td>GLV</td>
<td>$dN_g/dy = 1400 \ (270 - 150)$ ($\langle \bar{q} \rangle \sim 7$)</td>
</tr>
<tr>
<td>WHDG</td>
<td>$dN_g/dy = 1400 \ (200 - 375)$</td>
</tr>
<tr>
<td>ZOWW</td>
<td>$\varepsilon_0 = 1.9 \ (0.2 - 0.5)$ ($\langle \bar{q} \rangle \sim 1$)</td>
</tr>
</tbody>
</table>


$\langle \bar{q} \rangle$ only the natural unit in PQM

Neat other observables to dis-entangle all the possible effects
Jet correlations in heavy-ion collisions

- Full jet reconstruction very challenging background from bulk similar to signal for jet $p_T < \sim 30$ GeV

p+p collisions

Au+Au collisions
Jet correlations in heavy-ion collisions

- Full jet reconstruction very challenging background from bulk similar to signal for jet $p_T<\sim30\text{ GeV}$

Use di-hadron correlations

Back-to-back (away side) jet

Trigger (near side) jet

$p_{T\text{assoc}}$, $\Delta\phi$, $p_{T\text{trigger}}$, $\phi_{\text{trigger}}$
RHIC seminal di-hadron results

“The disappearance of the away-side jet”

d+Au results similar to p+p

→ final state interaction

→ d+Au can be used as the reference measurement instead of p+p

\[
\begin{align*}
4 < p_T^{\text{trig}} &< 6 \text{ GeV/c} \\
p_T^{\text{assoc}} &> 2 \text{ GeV/c}
\end{align*}
\]

\[ d+Au \text{ FTPC-Au 0-20\%} \]

\[ p+\text{p min. bias} \]

\[ Au+Au \text{ Central} \]

*Phys Rev Lett 90, 082302*
RHIC seminal di-hadron results

“The disappearance of the away-side jet”

d+Au results similar to p+p
→ final state interaction
→ d+Au can be used as the reference measurement instead of p+p

“High p_T Punch-through”

Away side correlation reappears for high p_T correlations
→ yield reduced compared to d+Au

\[
\frac{1}{N_{\text{trigger}}} \frac{dN}{d(\Delta \phi)}
\]

\begin{align*}
&\begin{array}{|c|c|}
\hline
4 < p_T^{\text{trig}} < 6 \text{ GeV/c} & p_T^{\text{assoc}} > 2 \text{ GeV/c} \\
\hline
\end{array}
\end{align*}

\[
\Delta \phi \text{ (radians)}
\]

\[
\begin{align*}
&\begin{array}{|c|c|}
\hline
8 < p_T^{\text{trig}} < 15 \text{ GeV/c} & p_T^{\text{assoc}} > 6 \text{ GeV/c} \\
\hline
\end{array}
\end{align*}
\]

\[
\begin{align*}
&\begin{array}{|c|c|c|}
\hline
\text{d+Au} & \text{Au+Au 20-40\%} & \text{Au+Au 0-5\%} \\
\hline
\end{array}
\end{align*}
\]

\[
\begin{align*}
&\begin{array}{|c|c|}
\hline
\text{STAR PRL 97 (2006) 162301} & \Delta \phi \\
\hline
\end{array}
\end{align*}
\]
Away-side di-hadron fragmentation

• Study medium-induced modification of fragmentation function due to energy loss
• Without full jet reconstruction, parton energy not measurable
• \( z \) not measured (\( z = \frac{p_{\text{hadron}}}{p_{\text{parton}}} \))
• \( z_T = \frac{p_{T,\text{assoc}}}{p_{T,\text{trig}}} \)

\[
D^{h_1 h_2}(z_T, p_T^{\text{trig}}) = p_T^{\text{trig}} \frac{d\sigma_{AA}^{h_1 h_2}}{dp_T^{\text{trig}}} \frac{dp_T}{d\sigma_{AA}^{h_1}} \frac{dp_T^{\text{trig}}}{d\sigma_{AA}^{h_2}}
\]

\[
I_{AA} = \frac{D_{AA}(z_T, p_T^{\text{trig}})}{D_{pp}(z_T, p_T^{\text{trig}})}
\]
Away-side di-hadron fragmentation

- Study medium-induced modification of fragmentation function due to energy loss
- Without full jet reconstruction, parton energy not measurable
  - \( z = \frac{p_{\text{hadron}}}{p_{\text{parton}}} \)
  - \( z_T = \frac{p_{T,\text{assoc}}}{p_{T,\text{trig}}} \)
- Inconsistent with Parton Quenching Model calculation
- Modified fragmentation model better

\[ D^{h_1 h_2}(z_T, p_T^{\text{trig}}) = p_T^{\text{trig}} \frac{d\sigma_{AA}^{h_1 h_2}}{dp_T^{\text{trig}}} \frac{dp_T}{d\sigma_{AA}^{h_1}} \]

\[ I_{AA} = \frac{D_{AA}(z_T, p_T^{\text{trig}})}{D_{pp}(z_T, p_T^{\text{trig}})} \]
Away-side di-hadron fragmentation


6 < $p_T^{trig}$ < 10 GeV

\[ 0.3 < z_T = p_T^{assoc}/p_T^{trig} < 1 \]

Denser medium in central Au+Au than central Cu+Cu
Similar medium for similar $N_{part}$

Vacuum fragmentation after parton $E_{loss}$ in the medium

O. Catu QM2008

Inconsistent with Parton Quenching Model calculation

Modified fragmentation model better
Two particles are better than one

Compare fits to $R_{AA}$ and $I_{AA}$

- Minima of data in same place
- Sharper for di-hadrons

$q_0\tau_0 \sim \hat{q} = 2.8 \pm 0.3 \text{ GeV}^2/\text{fm}$
Two particles are better than one

Compare fits to $R_{AA}$ and $I_{AA}$

- Minima of data in same place
- Sharper for di-hadrons

$q_0 \tau_0 \sim \hat{q} = 2.8 \pm 0.3 \text{ GeV}^2/\text{fm}$

Parton production points in transverse plane

- Surface bias effectively leads to saturation of $R_{AA}$ with density

minimize bias: di-hadron correlations full jets

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Path length dependencies

Non-central events have “elliptic” overlap geometries

Measurements w.r.t reaction plane angle:

Change path length
Keep everything else same

Isolate effects due to path length
Path length effect on di-hadron correlation

\[ \text{Au+Au } \sqrt{s_{NN}} = 200 \text{GeV, Cent=30-40\%, } 1 < p_{T,\text{asso}} < 2 \text{ GeV/c, } 2 < p_{T,\text{trig}} < 3 \text{ GeV/c} \]

- In-plane \( \phi_t - \Psi_{RP} = 0 \)

- Near side peak unchanged
- Shoulder peaks emerge as \( \phi_t - \Psi \) increases but are at fixed \( \Delta \phi \)
- Head peak (di-jet remnant) decreases as \( \phi_t - \Psi_{RP} \) increases

B. Cole QM2008
Centrality and path length effects

Au+Au 200 GeV

STAR Preliminary

Away-side RMS

0-5%

20-60%

\[ v_2 \text{ sys. error} \]

\[ v_2^{\{RP\}} \]

\[ v_2^{\{4\}} \]

\[ dAu \]

\[ RMS = \sqrt{\frac{\sum_{i}(\bar{\phi}_i - \bar{\phi})^2 y_i}{\sum_i y_i}} \]

A. Feng QM2008

\[ 3 < p_T^{\text{trig}} < 4 \text{ GeV/c}, 1.0 < p_T^{\text{asso}} < 1.5 \text{ GeV/c} \]

In-plane:

20-60% \sim d+Au

0-5% > d+Au

Out-of-plane:

20-60% \sim 0-5%

Au+Au > d+Au
Centrality and path length effects

Away-side RMS

\[ \text{Au+Au 200 GeV} \]

\[ \text{STAR Preliminary} \]

- 20-60%
- Top 5%

\[ v_2 \text{ sys. error} \]

\[ v_2^{\{\text{RP}\}} \]

\[ 3 < p_T^{\text{trig}} < 4 \text{ GeV/c}, \ 1.0 < p_T^{\text{asso}} < 1.5 \text{ GeV/c} \]

In-plane:
- 20-60% ~ d+Au
- 0-5% > d+Au

Out-of-plane:
- 20-60% ~ 0-5%
- \[ \text{Au+Au} > \text{d+Au} \]

Away-side features reveal path length effects

A. Feng QM2008
Deflected jets or conical emission?

Distinguish between models using 3-particle correlations.
Deflected jets or conical emission?

Distinguish between models using 3-particle correlations

Deflected jets

Conical Emission

Deflected jets

Conical Emission

Medium

near

away

Medium

near

away

STAR Preliminary
Deflected jets or conical emission?

Deflected jets

Conical Emission

STAR Preliminary

3 < p_{T\text{trigger}} < 4 GeV/c, 1 < p_{T\text{assoc}} < 2 GeV/c

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Deflected jets or conical emission?

Deflected jets:

Conical Emission:

\[ \frac{(\Delta \phi_1 - \Delta \phi_2)}{2} \]

\[ d+Au \]

\[ Au+Au \, 0-12\% \]

\[ \frac{(\Delta \phi_1 - \Delta \phi_2)}{2} \]

STAR Preliminary

3 < p_{\text{Trig}} < 4 \text{ GeV/c}, 1 < p_{\text{assoc}} < 2 \text{ GeV/c}
Au+Au data consistent with Conical emission

\[ \frac{(\Delta \phi_1 - \Delta \phi_2)}{2} \]

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STAR Preliminary

Au+Au 0-12%

Conical Emission

3 < p_{\text{Trig}} < 4 \text{ GeV/c}, 1 < p_{\text{assoc}} < 2 \text{ GeV/c}

Au+Au data consistent with Conical emission
Possible causes of conical emission

Mach Cone

Similar to jet creating sonic boom in air.

Energy radiated from parton deposited in collective hydrodynamic modes.

- Mach angle depends on $C_s$
  - $T$ dependent

\[
\frac{C_s}{v_{\text{parton}}} = \cos(\theta_M)
\]

- Angle independent of $p_T^{\text{assoc}}$
Possible causes of conical emission

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Čerenkov Gluon Radiation

Gluons radiated by superluminal parton.

\[
\frac{c_n}{v_{\text{parton}}} = \cos(\theta_c)
\]

\[
= \frac{c}{n(p)v_{\text{parton}}}
\]

\[
\approx \frac{1}{n(p)}
\]

Angle dependent on $p_{T\text{assoc}}$
Mach cone or Čerenkov gluons?

Angle predictions:

- **Mach-cone:**
  
  Angle independent of associated $p_T$

Čerenkov gluon radiation:

Angle decreases with associated $p_T$

![Diagram showing angle predictions and Čerenkov gluon radiation with data points and graphs.](image)
Mach cone or Čerenkov gluons?

Angle predictions:
- **Mach-cone:**
  Angle independent of associated $p_T$

Čerenkov gluon radiation:
Angle decreases with associated $p_T$

---

![Graph showing angle predictions](image-url)

**Au+Au 0-12%**

$\Delta \phi = (\Delta \phi_1 - \Delta \phi_2)/2$

**STAR Preliminary**

**PHENIX 1D analysis**

M. McCumber QM2008

J. Ulery QM2006

**Concise Summary:**
- Mach-cone: Angle independent of $p_T$
- Čerenkov gluons: Angle decreases with $p_T$

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Mach cone or Čerenkov gluons?

Angle predictions:

- Mach-cone: ✔
  Angle independent of associated $p_T$

Čerenkov gluon radiation:

Angle decreases with associated $p_T$

\[ (\Delta \phi_1 - \Delta \phi_2)/2 \]

\[ 0-20\% \text{ Au+Au} \]

\[ 2 < p_T^\ell < 3 \text{ GeV/c} \]

\[ 3 < p_T^\ell < 4 \text{ GeV/c} \]

\[ 4 < p_T^\ell < 5 \text{ GeV/c} \]

PHENIX 1D analysis

M. McCumber QM2008

J. Ulery QM2006

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1.36 ± 0.03
Parton interactions on near side

$\Delta(\phi)$ correlations

![Graph showing $\Delta(\phi)$ correlations for Au+Au central, d+Au central, and p+p interactions.](STAR)
Parton interactions on near side

\[ \Delta(\phi) \text{ correlations} \]

\[ \Delta(\eta) - \Delta(\phi) \text{ correlations} \]

Long range \( \Delta(\eta) \) correlation
– the “Ridge”
Parton interactions on near side

\[ \Delta(\phi) \text{ correlations} \]

\[ \Delta(\eta) - \Delta(\phi) \text{ correlations} \]

Long range \( \Delta(\eta) \) correlation – the “Ridge”

Persists out to very large \( \Delta(\eta) > 2 \)
Energy loss of trigger - “The ridge”

$3 < p_T^{(trig)} < 6$ GeV
$2 < p_T^{(assoc)} < p_T^{(trig)}$

- $d+Au$, 40-100%
- $Au+Au$, 0-5%
Energy loss of trigger - “The ridge”

**d+Au, 40-100%**

**Au+Au, 0-5%**

Ridge: Increases with $N_{\text{part}}$
Independent of colliding system

$3 < p_T(\text{trig}) < 6 \text{ GeV}$
$2 < p_T(\text{assoc}) < p_T(\text{trig})$
Energy loss of trigger - “The ridge”

Ridge: Increases with $N_{\text{part}}$
Independent of colliding system

Jet: Approx. flat with $N_{\text{part}}$
Independent of colliding system
Energy loss of trigger - “The ridge”

Ridge: Increases with $N_{\text{part}}$
Independent of colliding system

Jet: Approx. flat with $N_{\text{part}}$
Independent of colliding system

Parton interacts with medium (ridge), then vacuum fragments (jet)?
Spectra of ridge and shoulder particles

J. Putschke QM2006

\[ \text{slope}_{\text{ridge}} > \text{slope}_{\text{jet}} \approx \text{slope}_{\text{inclusive}} \]
Spectra of ridge and shoulder particles

Preliminary

slope_{ridge} > slope_{jet} 
\sim slope_{inclusive} 
\geq slope_{shoulder}
Un-triggered pair correlations

Method: measure pair densities $\rho(\eta_1 - \eta_2, \phi_1 - \phi_2)$ for all possible pairs in same and mixed events.
Define correlation measure as:

$$\frac{\rho_{\text{same}} - \rho_{\text{mixed}}}{\sqrt{\rho_{\text{mixed}}}} = \frac{\Delta \rho}{\sqrt{\rho_{\text{ref}}}} \propto \frac{\# \text{correlated pairs}}{\text{particle}}$$

Proton-Proton fit function

M. Daugherty QM2008

Minijet:
Same-side jet-like correlations with no trigger particle

longitudinal fragmentation 1D gaussian
HBT and $e+e-$ 2D exponential
Minijet Peak 2D gaussian
Away-side $-\cos(\phi)$

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Un-triggered pair correlations

Au-Au fit function

Use proton-proton fit function + \( \cos(2\phi_\Delta) \) quadrupole term ("flow").
This gives the simplest possible way to describe Au+Au data.
Un-triggered pair correlations

Au-Au fit function
Use proton-proton fit function + $\cos(2\varphi_\Delta)$ quadrupole term (“flow”). This gives the simplest possible way to describe Au+Au data.

Small residual indicates goodness of fit

Fit residual = data - model

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84-93%
75-84%
65-75%
55-65%
46-55%
28-38%
19-28%
9-19%
5-9%
0-5%
Evolution of mini-jet with centrality

Same-side peak

83-94%

55-65%

46-55%

0-5%

Little shape change from peripheral to 55% centrality

Large change within ~10% centrality

Smaller change from transition to most central

M. Daugherty QM2008
Evolution of mini-jet with centrality

Same-side peak

83-94%

55-65%

46-55%

0-5%

Little shape change from peripheral to 55% centrality

Large change within ~10% centrality

Smaller change from transition to most central

peak amplitude

200 GeV

62 GeV

peak $\eta$ width

binary scaling

references

M. Daugherty QM2008
Evolution of mini-jet with centrality

### Same-side peak

- **83-94%**
- **55-65%**
- **46-55%**
- **0-5%**

Binary scaling reference followed until sharp transition at $\rho \sim 2.5$

$\sim$30% of the hadrons in central Au+Au participate in the same-side correlation

**peak amplitude**

**peak $\eta$ width**

$\nu \equiv \frac{\langle N_{bin} \rangle}{\langle N_{part} / 2 \rangle}$

**binary scaling references**

M. Daugherty QM2008
Jets @ RHIC in Au-Au collisions

STAR preliminary

Clearly visible in central events on E-by-E basis

J. Putschke Hard Probes 2008
Jets @ RHIC in Au-Au collisions

Au+Au 0-20% $p_{t,\text{jet}}^{\text{rec}} \sim 47$ GeV

STAR preliminary

Clearly visible in central events on E-by-E basis

Au+Au 0-20% $p_{t,\text{jet}}^{\text{rec}} \sim 21$ GeV

STAR preliminary

Energies as low as 20 GeV resolvable

J. Putschke Hard Probes 2008
Jet-finding strategies in heavy-ion

Jet energy fraction outside cone

• Unmodified (p+p) jets:
  ~ 80% of energy within R~0.3

• Need to suppress heavy-ion background:
  small jet cones areas
  R~0.3-0.4
  remove underlying event
  \( p_{t,\text{track}}, E_{t,\text{tower}} > 1-2 \text{ GeV} \)

\[ R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \]

J. Putschke Hard Probes 2008
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Estimate background E-by-E by sampling Out-of-Cone area:

Out-of-Cone area:
used to estimate mean background energy and “mean background FF function”

Caveat: Precision depends on acceptance, event-by-event fluctuations and elliptic flow (small effect for central heavy-ion collisions) …
Jet spectrum in Au+Au collisions

**LOCone**
- $R_c=0.4$, $p_t^{\text{Seed}}>4.6$ GeV
- $p_t^{\text{cut}}>1$ GeV

**MB-Trig**: Good agreement with $N_{\text{bin}}$ scaled p+p collisions

**HT-Trig**: Large trigger bias how far up does it persist? (in p+p at least to 30 GeV)

Relative normalization systematic uncertainty: ~50%.

Further statistics of MB is needed to assess the bias in HT Trigger.

First reconstructed jets in central heavy ion collisions.

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black points: p+p mid-cone corrected to particle level (scaled by $N_{\text{bin}}$)

blue solid points: Au+Au minbias corrected for $p_t^{\text{cut}}$ and eff. using Pythia

red open points: Au+Au HT trigger not corrected for $p_t^{\text{cut}}$ and eff. using Pythia

S. Salur Hard Probes 2008
Modification of fragmentation function

- MLLA: good description of vacuum fragmentation (basis of PYTHIA)
- Introduce medium effects at parton splitting *Borghini and Wiedemann, hep-ph/0506218*

Jet quenching

Jet quenching $\Rightarrow$ fragmentation should be strongly modified at $p_{T_{\text{hadron}}} \sim 1-5 \text{ GeV}$

**Can we measure this at RHIC?**
RHIC “Summary”

We create a strongly coupled medium ⇒ sQGP

• not the asymptotically plasma of “free” quarks and gluons as expected - high $p_T$ partons interact very strongly with it
• It flows like a (nearly) perfect fluid with quark degrees of freedom and a viscosity to entropy density ratio lower than any other known fluid

We are past the discovery stage ⇒ towards the quantitative

• i.e. $\eta/s$, transport coefficients
• First full jet reconstruction in heavy-ion collisions - probing medium
• How medium varies as a function of collision energy/centrality/species
• New phenomena (e.g. ridge) challenge our understanding
• much remains to be done: EOS, initial conditions (ultimately needs EIC)

Next steps

• Ongoing upgrades to STAR and PHENIX
  ▸ Vertex detectors, increased coverage and PID, improved triggering capabilities ⇒ rare probes, heavy flavor, $\gamma$-jet, ...
• Electron Beam Ion Source (EBIS) to extend ranges of species (U+U)
• RHIC-II: increase luminosity by factor 5 using stochastic cooling
The Next Energy Frontier: LHC

A unique opportunity to investigate “QGP” at unparalleled high $\sqrt{s}$

Will this too create a strongly-coupled fluid?

![Graph showing $\varepsilon/T^4$ vs. T (MeV) for RHIC, SPS, LHC at 0, 2, 2+1, and 3 flavors.]

Targeted Studies: ATLAS

Targeted Studies: CMS

Dedicated Experiment: ALICE
Some possible explanations of the ridge

Recombination between thermal and shower partons at intermediate $p_T$


QCD bremsstrahlung radiation boosted by transverse flow

E. Shuryak, hep-ph:0706.3531

In medium radiation and longitudinal flow push


Broadening of quenched jets in turbulent color fields


Momentum Kick Model

C.Y. Wong  hep-ph:0712.3282

All qualitatively consistent with the features of the ridge
$p_T$ systematics of di-hadron correlations

Increase $p_T^{\text{Trigger}}$

Increase $p_T^{\text{Assoc}}$

PHENIX: arXiv:0801.4545
- Au+Au 0-20 %
- p+p
$p_T$ systematics of di-hadron correlations

Increase $p_T^{\text{Trigger}}$

Increase $p_T^{\text{Assoc}}$

Away-side peak reemerges
Shoulder emerges

PHENIX: arXiv:0801.4545
- Au+Au 0-20 %
- p+p

$Y_{\text{jet, ind}} = \frac{1}{N} \frac{dN^{a b}}{d\Delta \phi}$
**$p_T$ systematics of di-hadron correlations**

Increase $p_T$ Trigger

Increase $p_T$ Assoc

\[ Y_{\text{jet, ind}} = \frac{1}{N} \frac{dN}{d\Delta\phi} \]

PHENIX: arXiv:0801.4545

- Red: Au+Au 0-20 %
- Blue: p+p

Au+Au yield increases (why later ⇒ ridge)

Helen Caines - Yale - Nov 2008 - Oxford/RAL
p_T systematics of di-hadron correlations

Increase p_T Trigger

Increase p_T Assoc

Shoulder structure remains but gets smaller and smaller

PHENIX: arXiv:0801.4545

- Au+Au 0-20 %
- p+p

Helen Caines - Yale - Nov 2008 - Oxford/RAL

p_T = jet_ind Y \frac{d^2N_{ab}}{d\Delta \phi} (1/N)
High $p_T$ triggered away side RMS width

$Au+Au\sqrt{s_{NN}} = 200\, \text{GeV}$

Away side RMS width ($|\Delta\phi-\pi| < 1.0\, \text{rad}$)

Trigger $\pi^0 p_T = 7-9\, \text{GeV}$

PHENIX preliminary

- 0-20%
- 20-40%
- 40-60%
- 60-93%

RMS Width - centrality independent
High $p_T$ triggered away side RMS width

Au+Au $\sqrt{s_{NN}} = 200$ GeV
Away side RMS width ($|\Delta\phi-\pi| < 1.0$ rad)
Trigger $\pi^0$ $p_T = 7$-9 GeV

PHENIX preliminary
- $0$-$20\%$
- $20$-$40\%$
- $40$-$60\%$
- $60$-$93\%$

$p+p$ $\pi^0$-$h$:
- $p_T^{\text{trig}} = 6.5$-$8$ GeV/c
- $p_T^{\text{assoc}} = 1.4$-$5$ GeV/c
- RMS = $0.350 \pm 0.03$

PHENIX:
Phys Rev D 74 072002

RMS Width - centrality independent
Consistent with $p+p$ data

A. Adare QM2008
High $p_T$ triggered away side RMS width

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$p+p \pi^0$-h:

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RMS Width - centrality independent

Consistent with p+p data

Vacuum fragmentation?

PHENIX:

Phys Rev D 74 072002
Composition of ridge and shoulders

ridge ratio ~ inclusive ratio > jet ratio
Composition of ridge and shoulders

Ridge ratio ~ inclusive ratio > jet ratio

Shoulder ratio ~ inclusive ratio > jet ratio
Composition of ridge and shoulders

Ridge ratio ~ inclusive ratio > jet ratio

Shoulder ratio ~ inclusive ratio > jet ratio

Ridge and Shoulder similar properties

NOT vacuum fragmentation

Energy lost by jet partons seems to be re-distributed into the medium and freezes out in similar fashion
\[ C(\Delta \phi) \equiv \frac{Y_{\text{same}}(\Delta \phi)}{Y_{\text{mixed}}(\Delta \phi)} \times \int \frac{Y_{\text{mixed}}(\Delta \phi) d\phi}{Y_{\text{same}}(\Delta \phi) d\phi} \]

\[ C(\Delta \phi) \equiv b_0 \left[ 1 + 2v_{2}^{\text{assoc}} \langle v_{2}^{\text{trig}} \rangle \cos(2\Delta \phi) \right] + J(\Delta \phi) \]
\[
\frac{c_s}{v_{\text{parton}}} = \cos(\theta_M)
\]

\[
c_s^2 = \frac{\partial p}{\partial \varepsilon}; \quad v_{\text{parton}} \approx c
\]

- **Mach angle depends on speed of sound in medium**
  - \(T\) dependent
- **Angle independent of associated \(p_T\)**
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- Mach angle depends on speed of sound in medium
  - \(T\) dependent
- Angle independent of associated \(p_T\)
\[
\frac{c_s}{\nu_{\text{parton}}} = \cos(\theta_M)
\]

\[
c_s^2 = \frac{\partial p}{\partial \epsilon} ; \quad \nu_{\text{parton}} \approx c
\]

- Mach angle depends on speed of sound in medium
  - T dependent
- Angle independent of associated $p_T$.  

Mikherjee, Mustafa, Ray

\[ \frac{c_s}{v_{\text{parton}}} = \cos(\theta_M) \]

\[ c_s^2 = \frac{\partial p}{\partial \varepsilon}; \quad v_{\text{parton}} \approx c \]

- Mach angle depends on speed of sound in medium
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- Angle independent of associated \( p_T \).

Mikherjee, Mustafa, Ray

\[
\frac{c_n}{v_{\text{parton}}} = \cos(\theta_c) = \frac{c}{n(p)v_{\text{parton}}} \approx \frac{1}{n(p)}
\]
\[ \langle \xi \rangle \] for strange hadrons

- QCD predicts a \( \langle \xi \rangle \) p mass ordering

We observe an inversion of \( K^0_s \) and \( \Lambda \)

- Similar observation from BABAR for K and p
Observation of di-jets: punch through
Observation of di-jets: punch through

Select di-jets events:
Require T1 and T2 b-to-b

- **T1**: $p_T > 5\text{GeV}/c$
- **T2**: $p_T > 4\text{GeV}/c$
- **A1**: $p_T > 1.5\text{GeV}/c$
Observation of di-jets: punch through

Select di-jets events: Require T1 and T2 b-to-b

$T1: \ p_T > 5\text{GeV/c} \quad T2: \ p_T > 4\text{GeV/c}$

A1: $p_T > 1.5\text{GeV/c}$

What happens to away-side hump and near-side ridge if we trigger on di-jets?
Correlation between primary trigger (T1) and “away-jet-axis trigger” (T2).

- Require that the 2 highest $p_T$ particles are back-to-back in $\phi$.

$T_1: p_T > 5 \text{ GeV}/c$

$T_2: p_T > 4 \text{ GeV}/c$
• Hope to shift distribution of hard scattering towards center of medium. Near-side parton travels through more medium.

Create path lengths comparable in dense medium.

However not always from center could be tangential.
Di-jets are suppressed

Once selected:

• No Away-side suppression
  \( \text{Au+Au} \sim \text{d+Au} \)

• No Away-side shape modification
Di-jets are suppressed

Once selected:

- No Away-side suppression
  \( Au+Au \sim d+Au \)

- No Away-side shape modification

- No Ridge
Di-jets are suppressed

Once selected:

- No Away-side suppression
  \( \text{Au+Au} \sim \text{d+Au} \)

- No Away-side shape modification

- No Ridge

Di-Jets don't interact with medium. Tangential jets or punch through without interaction?