Using particle correlations to probe the medium produced at RHIC

Helen Caines - Yale University

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

\[ \text{Au+Au @ } \sqrt{s_{NN}} = 200 \text{ GeV} \]

\[ v = 0.99995 \cdot c \]
QGP expectation came from Lattice

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

deconfined: many d.o.f.

confined: few d.o.f.

\[ T_c = (173 \pm 15) \text{ MeV} \]
\[ \varepsilon_c \sim 0.7 \text{ GeV/fm}^3 \]
QGP expectation came from Lattice

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- **Deconfined:**
  - Many d.o.f.

- **Confined:**
  - Few d.o.f.

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

$\varepsilon_C \approx 0.7 \text{ GeV/fm}^3$ (~6x normal nuclear densities)

$T_C = (173 \pm 15) \text{ MeV}$

$\varepsilon_C \sim 0.7 \text{ GeV/fm}^3$

**LHC**

**RHIC**

**SPS**

**3 flavour**

**2 flavour**

"2+1-flavour"
RHIC has created a new state of matter

The QGP is the:

- **hottest** \((T=200-400 \text{ MeV} \sim 2.5 \times 10^{12} \text{ K})\)
- **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

![Diagram of reaction plane and initial spatial anisotropy leading to final momentum anisotropy with 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

Initial spatial anisotropy \rightarrow Interactions \rightarrow Final momentum anisotropy

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

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

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

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

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

Driving spatial anisotropy vanishes \(\Rightarrow\) self quenching

Sensitive to \textbf{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\% $v_2$
The flow is \( \sim \) 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\% \( v_2 \)

“fine structure” \( v_2(p_T) \)
- ordering with mass of particle
- good agreement with ideal hydrodynamics (zero viscosity, \( \lambda=0 \))

\[ 2v_2 \]

\( \Rightarrow \) “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
The constituents “flow”

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Constituents of liquid are partons
Viscous fluid

- supports a shear stress
- viscosity $\eta$
  
  $\eta \approx \text{momentum density} \times \text{mean free path}$
  
  $\approx n\bar{p}\lambda = n\bar{p}\frac{1}{n\sigma} = \frac{\bar{p}}{\sigma}$

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

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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?

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
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

Are these differences onset of beyond LL effects?
$\xi$ for strange hadrons

- $\xi_{charged}$
- $K^0_{short} \times 5$
- $\Lambda \times 5$

10 $< E_{reco} <$ 15
$P_T <$ 0.5
15 $< E_{reco} <$ 20
20 $< E_{reco} <$ 50

R $< 0.4$
R $< 0.5$
R $< 0.7$

Clear differences between particles

M. Heinz Hard Probes 2008
Back to probing the medium

Compare Au+Au with p+p Collisions $\Rightarrow R_{AA}$

Nuclear Modification Factor:

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

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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   - Huge: factor 5
High-$p_T$ suppression

Observations at RHIC:

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

$$\hat{q} = \frac{\langle k_T^2 \rangle}{L} \approx \frac{\mu^2}{\lambda}$$

$\hat{q} = \hat{q} (\vec{r}, \tau)$

- gluon density $dN_g/dy$

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The model landscape (not exhaustive)

**PQM (Parton Quench model)**
- Implementation of BDMPS (calc. E loss via coherent gluon radiation - many soft scattering approx.)
- Realistic geometry
- Static medium, q time average (i.e. depends on initial density, scheme evolution dependent )
- No initial state multiple scatterings
- No modified PDFs

**WHDG**
- Implementation of GLV formalism (calc. E loss via gluon brehmsstrahlung -few hard scatterings) + collisional energy loss.
- Realistic geometry - integral over all paths
- Expanding medium
- No initial state multiple scatterings

**GLV**
- Implementation of GLV formalism (calc. E loss via gluon brehmsstrahlung -few hard scatterings.)
- Realistic geometry
- Bjorken expanding medium - Calc. a priori (w/o E loss) average path length - use to calc. partonic E loss

**ZOWW**
- Modified fragmentation model (radiative gluon E loss incorporated into effective medium modified FF)
- Hard sphere geometry
- Expanding medium
Constraining $\langle \bar{q} \rangle$

<table>
<thead>
<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>


**PHENIX:** http://arxiv.org/abs/0801.1665

\[ \langle \bar{q} \rangle \text{ only the natural unit in PQM} \]

Need 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 $p_T<\sim30$ 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 $p_T<\sim 30$ GeV

Use di-hadron correlations

Back-to-back (away side) jet

$\Delta \phi$

$p_T^{assoc}$

$p_T^{trigger}$

$\phi_{trigger}$

Trigger (near side) jet

$p+\bar{p}$ collisions

Au+Au collisions
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

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

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

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

\[\text{Phys Rev Lett 90, 082302}\]
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
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 ($z = p_{\text{hadron}} / p_{\text{parton}}$)
- $z_T = p_{T,\text{assoc}} / p_{T,\text{trig}}$

$$D_{h_1 h_2}^{h_1 h_2}(z_T, p_T^{\text{trig}}) = p_T^{\text{trig}} \frac{d\sigma_{AA}}{dp_T^{\text{trig}}} \frac{d\sigma_{h_1 h_2}}{dp_T}$$

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

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- Without full jet reconstruction, parton energy not measurable
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Inconsistent with Parton Quenching Model calculation
Modified fragmentation model better
Away-side di-hadron fragmentation


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

[Graph showing data points and curves for different reactions]

Inconsistent with Parton Quenching Model calculation

Modified fragmentation model better

O. Catu QM2008

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

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

$\chi^2(I_{AA})$

$\chi^2(R_{AA})$

$\chi^2(I_{AA})$

$\chi^2(R_{AA})$

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

• 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

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

- 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
Centrality and path length effects

**Au+Au 200 GeV**

**STAR Preliminary**

- **20-60%**
- **Top 5%**
- \( v_2 \) sys. error
- \( v_2 \{\text{RP}\} \)

**Away-side RMS**

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Au+Au 200 GeV</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-60%</td>
<td>~ d+Au</td>
<td></td>
</tr>
<tr>
<td>0-5%</td>
<td>&gt; d+Au</td>
<td></td>
</tr>
<tr>
<td>20-60%</td>
<td>~ 0-5%</td>
<td></td>
</tr>
</tbody>
</table>

**In-plane:** 20-60% ~ d+Au

**Out-of-plane:** 20-60% ~ 0-5%

**Au+Au > d+Au**

A. Feng QM2008

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

**RMS**

\[
\text{RMS} = \sqrt{\frac{\sum (\bar{\phi}_i - \delta)^2 y_i}{\sum y_i}}
\]
Centrality and path length effects

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

Out-of-plane:
- 20-60% ~ 0-5%

Au+Au > d+Au

Away-side features reveal path length effects
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 or conical emission?

Deflected jets

Conical Emission

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3 < p^{Trig} < 4 GeV/c, 1 < p^{Assoc} < 2 GeV/c

Au+Au 0-12%
Deflected jets or conical emission?

Deflected jets

Conical Emission

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\[ \Delta \phi = \frac{\phi_1 - \phi_2}{2} \]

\[ \Delta \phi = \frac{\phi_1 - \phi_2}{2} \]
Deflected jets or conical emission?

Au+Au data consistent with Conical emission

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

STAR Preliminary

3 < p_{T\text{trig}} < 4 \text{ GeV/c}, 1 < p_{T\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

\[
\frac{C_s}{\nu_{\text{parton}}} = \cos\left(\theta_M\right)
\]

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

Mach Cone

Similar to jet creating sonic boom in air.

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• Mach angle depends on $C_s$
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$$\frac{C_s}{v_{parton}} = \cos(\theta_M)$$

• Angle independent of $p_T^{assoc}$

Čerenkov Gluon Radiation

Gluons radiated by superluminal parton.

$$\frac{c_n}{v_{parton}} = \cos(\theta_c)$$

$$= \frac{c}{n(p)v_{parton}}$$

$$\approx \frac{1}{n(p)}$$

Angle dependent on $p_T^{assoc}$
Mach cone or Čerenkov gluons?

Angle predictions:

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

Čerenkov gluon radiation:

Angle decreases with associated $p_T$

![Graph showing Au+Au 0-12%](image)

![Graph showing cone angle](image)

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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 $p_T$

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

Au+Au 0-12%

\[
\begin{aligned}
&0.5 & 1 & 1.5 & 2 \\
&0.2 & 0.4 & 0.6 & 0.8 & 1
\end{aligned}
\]

\[
\begin{aligned}
&-2 & -1.5 & -1 & -0.5 & 0 & 0.5 & 1 & 1.5 & 2 \\
&0.2 & 0.4 & 0.6 & 0.8 & 1 & 1.5 & 2
\end{aligned}
\]

\[
\text{Cone angle (radians)}
\]

\[
\begin{aligned}
&0.5 & 1 & 1.5 & 2 & 2.5 \\
&0.1 & 0.2 & 0.3 & 0.4 & 0.5
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\[
\begin{aligned}
1.36 \pm 0.03
\end{aligned}
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Mach cone or Čerenkov gluons?

Angle predictions:

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  Angle independent of associated $p_T$

Čerenkov gluon radiation:
Angle decreases with associated $p_T$

![Graph showing angle predictions]

- **Au+Au 0-12%**

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

![Graph showing cone angle (radians)]

- **STAR Preliminary**
- **PHENIX 1D analysis**

- **M. McCumber QM2008**
- **J. Ulery QM2006**

$1.36 \pm 0.03$
Parton interactions on near side

$\Delta(\phi)$ correlations

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

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

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

$\Delta(\phi)$ correlations

$\Delta(\eta)$ – $\Delta(\phi)$ correlations

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

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

- d+Au, 40-100%
- Au+Au, 0-5%

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

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

\[ \text{slope}_{\text{ridge}} > \text{slope}_{\text{jet}} \sim \text{slope}_{\text{inclusive}} \]

J. Putschke QM2006
Spectra of ridge and shoulder particles

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

Method: measure pair densities $\rho(\eta_1-\eta_2,\varphi_1-\varphi_2)$ for all possible pairs in same and mixed events.
Define correlation measure as:

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

Proton-Proton fit function

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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(\varphi)
Un-triggered pair correlations

Au-Au fit function

Use proton-proton fit function + \( \cos(2\phi) \) quadrupole term ("flow"). This gives the simplest possible way to describe Au+Au data.

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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.

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%

Little shape change from peripheral to 55% centrality

55-65%

Large change within ~10% centrality

46-55%

Smaller change from transition to most central

0-5%

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Evolution of mini-jet with centrality

Same-side peak

- 83-94%
  - Little shape change from peripheral to 55% centrality

- 55-65%
  - Large change within ~10% centrality

- 46-55%
  - Smaller change from transition to most central

- 0-5%

**peak amplitude**

- 200 GeV
- 62 GeV

**peak \( \eta \) width**

\[
V = \frac{\langle N_{\text{bin}} \rangle}{\langle N_{\text{part}} / 2 \rangle}
\]

M. Daugherty QM2008
Evolution of mini-jet with centrality

Same-side peak

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**

**peak amplitude**

**peak $\eta$ width**

Transverse particle density $\tilde{\rho} = \frac{3}{2} \frac{dN_{ch}}{d\eta} / S$

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

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

STAR preliminary

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

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Jets @ RHIC in Au-Au collisions

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

STAR preliminary

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

Energies as low as 20 GeV resolvable

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Jet-finding strategies in heavy-ion

- 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 GeV

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

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
  - $p_{t,track}, E_{t,tower} > 1-2$ GeV

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) …

J. Putschke Hard Probes 2008
Jet spectrum in Au+Au collisions

**STAR preliminary; stat. errors only**

HT not trigger bias corrected!

**LO Cone**

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

**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.

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

Helen Caines - Yale - Nov 2008 - Oxford/RAL
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*

\[
\xi = \ln\left(\frac{E_{\text{Jet}}}{p_{\text{hadron}}}\right)
\]

Jet quenching

Jet quenching ⇒ 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 with different flavors (0, 2, 2+1, 3) for RHIC and LHC.]

Targeted Studies: ATLAS

Targeted Studies: CMS

Dedicated Experiment: ALICE