Using particle correlations to probe the medium produced at RHIC

Helen Caines - Yale University

JINR
May 2008
**Confinement - QCD**

Confinement: fundamental & crucial (but *not* understood!) feature of strong force - colored objects (quarks) have $\infty$ energy in normal vacuum

“white” proton
**Confinement - QCD**

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Confinement - QCD

**Confinement**: fundamental & crucial (but *not* understood!) feature of strong force - colored objects (quarks) have $\infty$ energy in normal vacuum

Strong **color** field
Force *grows* with separation !!!
Confinement: fundamental & crucial (but not understood!) feature of strong force - colored objects (quarks) have $\infty$ energy in normal vacuum

quark-antiquark pair
created from vacuum
Confinement: fundamental & crucial (but not understood!) feature of strong force - colored objects (quarks) have $\infty$ energy in normal vacuum

"white" proton (confined quarks)

"white" $\pi^0$ (confined quarks)
Confinement - QCD

**Confinement**: fundamental & crucial (but *not* understood!) feature of strong force - colored objects (quarks) have $\infty$ energy in normal vacuum

To understand the strong force and confinement: Create and study a system of deconfined colored quarks and gluons
QGP expectation came from Lattice calculations

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

deconfined: many d.o.f.

confined: few d.o.f.

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

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

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QGP expectation came from Lattice calculations

$\epsilon/T^4 \sim \#$ degrees of freedom

dehconfined: many d.o.f.

confined: few d.o.f.

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

$\epsilon_C \approx 0.7 \text{ GeV/fm}^3 (\sim 6\times \text{ normal nuclear densities})$
Relativistic Heavy-Ion Collider (RHIC)

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

$v = 0.99995 \cdot c$
Relativistic Heavy-Ion Collider (RHIC)

\[ v = 0.99995 \cdot c \]

\[ \text{Au+Au @ } \sqrt{s_{NN}} = 200 \text{ GeV} \]
The order of the phase transition

“A first-order QCD phase transition that occurred in the early universe would lead to a surprisingly rich cosmological scenario.”  Ed Witten, Phys. Rev. D (1984)
The order of the phase transition

“A first-order QCD phase transition that occurred in the early universe would lead to a surprisingly rich cosmological scenario.” Ed Witten, Phys. Rev. D (1984)

Apparently it did not! Thus we suspect a smooth cross over or a weak first order transition.
At RHIC we’ve 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.

Now want to learn more about properties
Using “jets” as probes

- Early production in parton-parton scatterings with large $Q^2$.
- Direct interaction with partonic phases of the reaction.
Using “jets” as probes

- Early production in parton-parton scatterings with large $Q^2$.
- Direct interaction with partonic phases of the reaction

Therefore use “jets” as probes at RHIC

- attenuation or absorption of jets: “jet quenching”
- suppression of high $p_T$ hadrons
- modification of angular correlation
- changes of particle composition
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
Jets in Au+Au collisions!

\[ p+p \rightarrow \text{dijet} \]

- Trigger: highest \( p_T \) track
- \( \Delta \phi \) distribution:

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

\[ p+p \text{ min. bias} \]
\[ 4 < p_T(\text{trig}) < 6 \text{ GeV/c} \]
\[ p_T(\text{assoc}) > 2 \text{ GeV/c} \]

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

*Phys Rev Lett 90, 082302*
Jets in Au+Au collisions!

$\Delta \phi \approx 0$: central Au+Au similar to p+p

$\Delta \phi \approx \pi$: strong suppression of back-to-back correlations in central Au+Au
Observation of “Punch through”

8<p_T^{trig}<15 GeV/c

If use high-p_T triggers:

- Away-side peak re-emerges
- Smaller in Au-Au than d-Au
- Virtually no background
Observation of “Punch through”

If use high-$p_T$ triggers:

- Away-side peak re-emerges
- Smaller in Au-Au than d-Au
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High energy jets “punch through” the medium.
High $p_T$ triggered away side RMS width

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

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

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

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

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

- $p_T^{\text{trig}} = 6.5-8 \text{ GeV/c}$
- $p_T^{\text{assoc}} = 1.4-5 \text{ GeV/c}$

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

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

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

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PHENIX preliminary

- $p+p \pi^0$-$h$:
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  - RMS = $0.350 \pm 0.03$

PHENIX:
Phys Rev D 74 072002

RMS Width - centrality independent

Consistent with $p+p$ data

Vacuum fragmentation?
Away-side di-hadron fragmentation functions

- Study medium-induced modification of fragmentation function due to energy loss
- Without full jet reconstruction, parton energy not measurable
  - $z$ not measured ($z=p_{\text{hadron}}/p_{\text{parton}}$)
  - $z_T=p_{T,\text{assoc}}/p_{T,\text{trig}}$
- Di-hadron fragmentation function - di-hadron jet-like correlated yield to single hadron yield ratio

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

\[
I_{AA} = \frac{D_{AA}(z_T, p_T^{\text{trig}})}{D_{pp}(z_T, p_T^{\text{trig}})}
\]
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$D^{h_1 h_2}(z_T, p_{T, \text{trig}}) = p_T^{\text{trig}} \frac{d\sigma_{AA}^{h_1 h_2}/dp_{T, \text{trig}}}{d\sigma_{AA}^{h_1}/dp_T} \frac{d\sigma_{AA}^{h_1}/dp_T}{d\sigma_{AA}^{h_1 h_2}/dp_{T, \text{trig}}}$

$I_{AA} = \frac{D_{AA}(z_T, p_T^{\text{trig}})}{D_{pp}(z_T, p_T^{\text{trig}})}$

- Inconsistent with Parton Quenching Model calculation
- Modified fragmentation model better


$6 < p_{T, \text{trig}} < 10 \text{ GeV}$
Away-side di-hadron fragmentation functions

- Inconsistent with *Parton Quenching* Model calculation
- **Modified fragmentation** model better

O. Catu QM2008


\( 6 < p_T^{\text{trig}} < 10 \text{ GeV} \)

\( \frac{dN}{dz} \) and \( \frac{1}{N_{\text{trig}}} \)

- 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
$p_T$ evolution of di-hadron correlations

- As $p_T$ decreases,
  - single-peak $\rightarrow$ double peak
  - Away-side yield increases
p_T evolution of di-hadron correlations

- As p_T decreases,
  - single-peak \rightarrow double peak
  - Away-side yield increases

- Head region yield begins to dominate over shoulder region
Head and Shoulder evolution

h-h correlations \[ 1 < p_{Ta} < 2.5 < p_{Tt} < 4 \text{GeV/c} \]

\[
J(\Delta\phi) = G(\Delta\phi) + G(\Delta\phi - \pi - D) + G(\Delta\phi - \pi + D)
\]

\[ \mu_n \equiv (\Delta\phi - \pi)^n, n = 2, 4 \ldots \]

\[ \text{rms} \equiv \sqrt{\mu_2} \]

\[ \text{kurtosis} \equiv \frac{\mu_4}{\mu_2^2} \]

Separation and width plateau for \( N_{\text{part}} \geq 100 \)
Head and Shoulder evolution

h-h correlations $1 < p_{Ta} < 2.5 < p_{Tt} < 4 \text{GeV/c}$

$$J(\Delta \phi) = G(\Delta \phi) + G(\Delta \phi - \pi - D) + G(\Delta \phi - \pi + D)$$


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PHENIX PRL 98, 232302 (2007)

Separation and width plateau for $N_{\text{part}} \geq 100$

Shoulder due to away side jet interacting with medium
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

Au+Au $\sqrt{s_{NN}}=200$GeV, Cent=30-40%, $1<p_{t,\text{assoc}}<2$ GeV/c, $2<p_{t,\text{trig}}<3$ 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 $\phi_t - \Psi_{\text{RP}}$ increases

B. Cole QM2008

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Centrality and path length effects

Au+Au 200 GeV  

\[ \text{RMS} = \sqrt{\frac{\sum (\bar{\phi}_i - \bar{\phi}_{RP})^2 y_i}{\sum y_i}} \]

\[ \phi = \phi - \phi_{RP} \text{ (deg)} \]

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

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

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

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Centrality and path length effects

\begin{align*}
\text{In-plane:} & \quad 20-60\% \sim d+Au \\
& \quad 0-5\% > d+Au \\
\text{Out-of-plane:} & \quad 20-60\% \sim 0-5\% \\
& \quad Au+Au > d+Au
\end{align*}

A. Feng QM2008

\begin{align*}
3 < p_T^{trig} < 4 \text{ GeV/c, } 1.0 < p_T^{asso} < 1.5 \text{ GeV/c}
\end{align*}
What causes shoulder peaks?

Deflected jets

Conical Emission

STAR Preliminary

B. Mohnaty QM2008
What causes shoulder peaks?

Two component approach:
- Correlated to trigger (jets..)
- Uncorrelated to trigger (except via anisotropic flow)

Bkg normalization 3-particle
ZYAM

B. Mohnaty QM2008
What causes shoulder peaks?

Deflected jets

Conical Emission

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What causes shoulder peaks?

Au+Au data consistent with Conical emission

Conical Emission

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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

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

- Angle independent of $p_T^{\text{assoc}}$
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
      \[
      \frac{C_s}{v_{parton}} = \cos(\theta_M)
      \]
  - Angle independent of $p_T^{assoc}$

Čerenkov Gluon Radiation
- Gluons radiated by superluminal parton.
  \[
  \frac{c}{v_{parton}} = \cos(\theta_c)
  \]
  \[
  = \frac{c}{n(p)v_{parton}}
  \]
  \[
  \approx \frac{1}{n(p)}
  \]
  - Angle dependent on $p_T^{assoc}$
Conical Emission Theories

- **Mach-cone:**
  - Can be produced in different theories:
    - **Hydrodynamics**
    - **Colored plasma**
    - **AdS/CFT**
- **Čerenkov Gluon Radiation:**
  - V. Koch et. al. (Phys. ReV. Lett. 96, 172302, 2006)
- **Parton Cascade:**

References are only a small subset of those existing. Apologies to those not included.
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](image)
Mach cone or Čerenkov gluons?

Angle predictions:

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

- **Čerenkov gluon radiation:**
  Angle decreases with associated $p_T$
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 and data points](image)
Parton interactions on near side

$\Delta(\phi)$ correlations

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

- $\text{Au+Au central}$
- $\text{d+Au central}$
- $\text{p+p}$

$\Delta\phi$ (radians)
Parton interactions on near side

$\Delta(\phi)$ correlations

$\Delta(\eta) - \Delta(\phi)$ 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 \( \Delta(\eta) > 2 \)
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
Path length dependence of the ridge

\[ d+Au, \, 40-100\% \]

\[ Au+Au, \, 0-5\% \]

\[ 3 < p_T^{(\text{trig})} < 6 \text{ GeV} \]

\[ 2 < p_T^{(\text{assoc})} < p_T^{(\text{trig})} \]

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Path length dependence of the ridge

Ridge: Increases with $N_{\text{part}}$
Independent of colliding system
Decreases with $\phi_t - \Psi$

C. Nattrass QM2008
Path length dependence of the ridge

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

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

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

Ridge: Increases with $N_{\text{part}}$
Independent of colliding system
Decreases with $\phi_t - \Psi$
Jet: Slight to no increases with $\phi_t - \Psi$
Au+Au ~ d+Au

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**STAR Preliminary**

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**STAR**

Preliminary

Au+Au 200 GeV
20-60%

**3 < $p_T^{\text{trig}}$ < 4 GeV/c, $p_T^{\text{asso}}$: 1.0-1.5 GeV/c**

Jet part, near-side

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Path length dependence of the ridge

Ridge: Increases with $N_{\text{part}}$
Independent of colliding system
Decreases with $\phi_t - \Psi$
Jet: Slight to no increases with $\phi_t - \Psi$
$Au+Au \sim d+Au$

Parton interacts with medium (ridge) and then vacuum fragments (jet)?

$3 < p_T^{\text{trig}} < 6 \text{ GeV}$
$2 < p_T^{\text{assoc}} < p_T^{\text{trig}}$

$\sqrt{s_{NN}}=200 \text{ GeV}, |\Delta\eta|<1.7$

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A. Feng QM2008
Spectra of ridge and shoulder particles

$\text{slope}_{\text{ridge}} > \text{slope}_{\text{jet}}$

$\sim \text{slope}_{\text{inclusive}}$

J. Putschke QM2006

Preliminary
Spectra of ridge and shoulder particles

\[ \text{slope} \text{ridge} > \text{slope} \text{jet} \approx \text{slope} \text{inclusive} \geq \text{slope} \text{shoulder} \]
Composition of ridge and shoulders

ridge ratio ~ inclusive ratio > jet ratio

C. Nattrass QM2008
Composition of ridge and shoulders

ridge ratio ~ inclusive ratio > jet ratio

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

Energy lost by jet partons seems to be re-distributed into the medium and freezes out in similar fashion

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
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

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Minijet:
Same-side jet-like correlations with no trigger particle
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.
Un-triggered pair correlations

**Au-Au fit function**

Use proton-proton fit function + \( \cos(2\varphi) \) quadrupole term ("flow").

This gives the *simplest possible* way to describe Au+Au data.

Small residual indicates goodness of fit

**Fit residual = data - model**
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%
  - STAR Preliminary

- 0-5%
  - Smaller change from transition to most central

M. Daugherty QM2008
Evolution of mini-jet with centrality

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- 0-5%

Peak amplitude

- 200 GeV
- 62 GeV

Path length $\nu$

- Binary scaling references
  - $\nu = \frac{\langle N_{\text{bin}} \rangle}{\langle N_{\text{part}}/2 \rangle}$

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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**

- **200 GeV**
- **62 GeV**

**peak $\eta$ width**

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

**path length $v$**

$V = \frac{\langle N_{bin} \rangle}{\langle N_{part} / 2 \rangle}$

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Di-jet triggered correlations

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: $p_T > 1.5\text{GeV}/c$
Di-jet triggered correlations

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

What happens to away-side hump and near-side ridge if we trigger on di-jets?
Change the surface-bias of near-side?

- Hope to shift distribution of hard scattering **towards center of medium**. Near-side parton travels through more medium.

![Diagram showing Trigger and Assoc](image-url)
Change the surface-bias of near-side?

- 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.
Change the surface-bias of near-side?

- 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-jet triggered correlations

Di-jets are suppressed

Once selected:

- No Away-side suppression \( \text{Au+Au} \sim \text{d+Au} \)
- No Away-side shape modification
Di-jet triggered correlations

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-jet triggered correlations

Di-jets are suppressed

Once selected:

- No Away-side suppression
  $Au+Au \sim d+Au$

- No Away-side shape modification

- No Ridge

Di-Jets don’t interact with medium. Tangential jets or punch through without interaction?
Towards true jet reconstruction

- Reduce leading trigger particle biases from di-hadron correlations

- First step to jet reconstruction in A+A

Use “cluster energy” as trigger:
- \( R_{\text{cone}} \) = 0.3
- \( p_{T,\text{seed}} \) > 5 GeV
- \( p_{T,\text{sec seed}} \) > 3 GeV
Towards true jet reconstruction

- Reduce leading trigger particle biases from di-hadron correlations

- First step to jet reconstruction in A+A

Multi-hadron trigger

Use “cluster energy” as trigger:
- $R_{\text{cone}} = 0.3$
- $p_{T,\text{seed}} > 5$ GeV
- $p_{T,\text{sec seed}} > 3$ GeV

- Single-hadron trig. ≈ multi-hadron trig.
- Single high $p_T$ triggered correlations probe jet-like correlations

B. Haag QM2008
Conclusions

Jets have been observed at RHIC

Making important steps towards constraining models that try to explain:

• How partons interact with and lose energy in the medium
• Where that energy goes
• How the medium changes with $\sqrt{s}$, centrality, and ion collided
Conclusions

Jets have been observed at RHIC

Making important steps towards constraining models that try to explain:

- How partons interact with and lose energy in the medium
- Where that energy goes
- How the medium changes with $\sqrt{s}$, centrality, and ion collided

RHIC on the threshold of new era of quantitative comparison between theory and experiment that will characterize the properties of the remarkable new matter discovered at here
BACKUPS
2 particle angular correlations

\[ C(\Delta\phi) \equiv \frac{Y_{\text{same}}(\Delta\phi)}{Y_{\text{mixed}}(\Delta\phi)} \times \frac{\int Y_{\text{mixed}}(\Delta\phi) d\phi}{\int Y_{\text{same}}(\Delta\phi) d\phi} \]

\[ C(\Delta\phi) \equiv b_0 \left[ 1 + 2 \langle v_2^{\text{assoc}} \rangle \langle v_2^{\text{trig}} \rangle \cos(2\Delta\phi) \right] + J(\Delta\phi) \]
Mach-Cone

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

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

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

Mach-Cone • Trigger

Mach-Cone • Away-side

Mach-Cone • PNJL Model

- Mikherjee, Mustafa, Ray

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Mach-Cone

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Mikherjee, Mustafa, Ray


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- Mikherjee, Mustafa, Ray

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Mach-Cone

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

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

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

- Mikherjee, Mustafa, Ray
Mach-Cone

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

\[
c_s^2 = \frac{\partial p}{\partial \varepsilon}; \quad v_{\text{parton}} \approx c
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- Mach angle depends on speed of sound in medium
  - T dependent
- Angle independent of associated $p_T$.

Mikherjee, Mustafa, Ray

Čerenkov Gluon Radiation

• Gluons radiated by superluminal partons.
• Angle is dependent on emitted momentum.

\[
\frac{c_n}{v_{\text{parton}}} = \cos(\theta_c) = \frac{c}{n(p)v_{\text{parton}}} \approx \frac{1}{n(p)}
\]

• Čerenkov angle vs emitted particle momentum
  - Koch, Majumder, Wang
  - PRL 96 172302 (2006)
Mach cone?

Naive calc. of time averaged velocity of sound in medium:

\[
\frac{c_s}{v_{\text{parton}}} = \cos(\hat{e}_M), \quad v_{\text{parton}} = c
\]

Cone angle \(\sim\) 1.36 radians

\(c_s = 0.2c\)!
Mach cone?

Naive calc. of time averaged velocity of sound in medium:

$$\frac{c_s}{v_{\text{parton}}} = \cos(\hat{e}_M), \quad v_{\text{parton}} = c$$

Cone angle $\sim 1.36$ radians

$c_s = 0.2c$!

- In cumulant approach: no conclusive evidence for conical emission so far

- Strength and shape of away side structures observed depends on assumed magnitude of flow coefficients
Ridge: 3-particle Correlation

Jet fragmentation and diffused gluons

In-medium radiated gluons diffused in $\eta$

In-medium radiated gluons still collimated
Ridge : 3-particle Correlation

Jet fragmentation and diffused gluons

In-medium radiated gluons diffused in $\eta$

In-medium radiated gluons still collimated

dAu : Jets

AuAu : 200 GeV

STAR Preliminary

$3 < p_T^{\text{Trig}} < 10 \quad 1 < p_T^{\text{Asso}} < 3 \quad |\Delta\phi| < 0.7$
Ridge : 3-particle Correlation

Jet fragmentation and diffused gluons

In-medium radiated gluons diffused in $\eta$

In-medium radiated gluons still collimated

Uniform overall excess of associated particles not due to correlated emission

$3<p_T^{\text{Trig}}<10 \quad 1<p_T^{\text{Asso}}<3 \quad |\Delta \phi|<0.7$

STAR Preliminary
Golden Probe of QCD Energy Loss - $\gamma$-Jet

$\gamma$ emerges “unscathed” from medium

- Full reconstruction of kinematics: real fragmentation function ($D(z)$)

QCD analog of Compton Scattering
Shower shape in Shower Maximum Detector gives $\gamma$-, $\pi^0$-enriched samples

The $\gamma$-rich sample has lower near-side yield than $\pi^0$. 
First measure of away-side $I_{AA}$ for $\gamma$-h

\begin{equation*}
E_{\text{jet}} = E_{\gamma} = E_{\text{trig}}
\end{equation*}

\begin{equation*}
I_{AA} = \frac{D_{AA}(z_T, E_T^{\text{trig}})}{D_{pp}(z_T, E_T^{\text{trig}})}
\end{equation*}

\begin{equation*}
D^{h_1h_2}(z_T, p_T^{\text{trig}}) = p_T^{\text{trig}} \frac{d\sigma_{AA}^{h_1h_2}/dp_T^{\text{trig}}}{d\sigma_{AA}/dp_T^{\text{trig}}}
\end{equation*}

Good agreement between theory and measurement for higher $p_{T\text{assoc}}$
First measure of away-side $I_{AA}$ for $\gamma$-h

Suppression similar level to inclusions in central collisions

$$E_{\text{jet}} = E_\gamma = E_{\text{trig}}$$

$$I_{AA} = \frac{D_{AA}(z_T, E_T^{\text{trig}})}{D_{pp}(z_T, E_T^{\text{trig}})}$$

Good agreement between theory and measurement for higher $p_{T,\text{assoc}}$

T. Renk and K. Eskola PRC75:054910, 2007
Data analysis: di-jet selection

- Correlation between primary trigger (T1) and “away-jet-axis trigger” (T2).

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

- Assume this defines the jet-axis, look in 2D-space about the second trigger.

T1T2 correlation

- T1: $p_T > 5$ GeV/c
- T2: $p_T > 4$ GeV/c