Jets as a probe of the Quark Gluon Plasma

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Outline

- Introduction to heavy ion collisions and the Quark Gluon Plasma
- The jet-like correlation
- The Ridge
- Comparison to theories
- Conclusion
Phase diagram of nuclear matter

![Diagram of nuclear phase transitions](image)

- QGP
- Critical point
- Hadron gas
- Vacuum
- Nuclear matter phases
- CFL

Parameters: $T$, GeV and $\mu_B$, GeV
Evolution of the Universe

The universe gets cooler!

Need temperatures around $1.5 \cdot 10^{12}$ K
~$10^5$ times hotter than the core of the sun
How to make a Quark Gluon Plasma

nucleus

Heat

Compress

nucleon boundary irrelevant
The phase transition in the laboratory
Relativistic Heavy Ion Collider

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Coverage:

\[ 0 < \phi < 2\pi \]

\[ -1 < \eta < 1 \]

Electromagnetic Calorimeter allows triggering
Some key features of a heavy ion collision*

- Particles exhibit collective flow relative to the reaction plane, behaving like a fluid of quarks and gluons
- For this measurement, that is a background
- The majority of particles produced are low $p_T$ light hadrons ($\pi, K, p$)
- The production of these particles is described reasonably well by statistical ("thermal") models
- These low $p_T$ particles are often called "the bulk"
  - At local equilibrium?
- A hard parton is a probe of "the bulk"

*I am glossing over details and disagreements within the field
A simple picture of a heavy ion collision
Jets as a probe of the quark gluon plasma
One jet “absorbed” by the medium
Studying jets through di-hadron correlations

Hard parton scattering ⇒ back-to-back jets
Good (calibrated?) probe of the medium
High multiplicity in A+A collisions
Individual jets difficult to reconstruct
Study jets via correlations of particles in space

both azimuth and pseudorapidity
Jets – azimuthal correlations

$p+p \rightarrow \text{dijet}$
Jets – azimuthal correlations

\[ p + p \rightarrow dijet \]
But at lower $p_T$...

Near-side shows modification

Excess yield in Au+Au relative to p+p

![Graph showing excess yield in Au+Au relative to p+p](STAR PRL 95 (2005) 152301)
Looking in two dimensions

- Trigger
- Associated
- $\Delta \phi$

$d+Au$ 0-10% STAR preliminary

- $p_{T_{\text{trigger}}} < 4 \text{ GeV}$
- $p_{T_{\text{assoc}}} > 2 \text{ GeV}$
In two dimensions in Au+Au

![Diagram showing two-dimensional analysis in Au+Au collisions with trigger and associated particles].

Au+Au 0-10% STAR preliminary

- $3 < p_{\text{trigger}} < 4$ GeV
- $p_{\text{assoc}} > 2$ GeV

Jet
Ridge

#entries

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A caveat...

Large background subtraction...

Signal/Background $\approx 0.05$ in central Au+Au

Depends on kinematic region

Signal/Background higher at higher $p_T$
The jet-like correlation

\[ 3 < p_{\text{trigger}} < 4 \text{ GeV} \]
\[ p_{\text{assoc}} > 2 \text{ GeV} \]
Baryon/meson ratios in jet-like correlation in Cu+Cu and Au+Au similar to p+p for both strange and non-strange particles
\(p_T^{\text{trigger}}\) dependence

Yield increases with \(p_T^{\text{trigger}}\)

No collision system dependence

PYTHIA – Monte Carlo \(p+p\) event generator tuned to data and incorporating many features of pQCD

1.5 GeV/c < \(p_T^{\text{associated}}\) < \(p_T^{\text{trigger}}\)
No collision system dependence
PYTHIA does not describe the data

Inverse slope parameter

<table>
<thead>
<tr>
<th>√s_{NN} = 62 GeV</th>
<th>√s_{NN} = 200 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu+Cu</td>
<td>359 ± 41</td>
</tr>
<tr>
<td>Au+Au</td>
<td>291 ± 28</td>
</tr>
<tr>
<td>d+Au</td>
<td></td>
</tr>
</tbody>
</table>

Statistical errors only
$N_{\text{part}}$ dependence

No collision system dependence at a given $N_{\text{part}}$

Jet-like yield increases with $N_{\text{part}}$

PYTHIA describes data at lower $N_{\text{part}}$
The *Ridge*
Extent of Ridge in $\Delta \eta$

Au+Au 0-30% central

Wenger QM08

PHOBOS preliminary
- Au+Au 0-10%
- PYTHIA v6.325

1/N_{trig} dN_{ch} / d\Delta \eta

1/N_{trig} dN_{ch} / d\Delta \phi
Jet-like correlation is like $p+p$, Ridge is like bulk

Spectra of particles associated with Ridge similar to inclusive
Spectra of particles associated with jet-like correlation harder
Ridge composition

Baryon/meson ratios in Ridge similar to bulk for both strange and non-strange particles

J. Bielcikova (STAR), v:0707.3100 [nucl-ex]
C. Nattrass (STAR), arXiv:0804.4683/nucl-ex

Christine Nattrass (UTK), University of Kentucky, 1 Oct. 2009
“Fragmentation functions”

Measure hadron triggered fragmentation functions:

\[ D_{h1,h2}(z_T) \]

\[ z_T = p_{\text{assoc}} / p_{\text{trigger}} \]

**Jet-like correlation**

+**Ridge**: \( D_{h1,h2}(z_T) \) different for d+Au, Au+Au

**Jet-like correlation only**: \( D_{h1,h2}(z_T) \) within errors for d+Au, Au+Au
Jet/Ridge w.r.t. reaction plane

Feng QM08

in-plane $\Psi_{S} = 0$

out-of-plane $\Psi_{S} = 90^\circ$

Jet yield decreases with $\phi_{S}$. Smaller ridge yield at larger $\phi_{S}$

Jet yield approx. independent of $\phi_{S}$ and comparable with d+Au

Jet yield independent of $\phi_{S}$, consistent with vacuum fragmentation after energy loss and lost energy deposited in ridge, if medium is “black” out-of-plane and more “gray” in-plane for surviving jets.
Ridge vs $N_{\text{part}}$

No system dependence at given $N_{\text{part}}$
Identified trigger: Near-side Yield vs $N_{\text{part}}$

Cu+Cu consistent with Au+Au at same $N_{\text{part}}$

If systematic errors in Au+Au are not correlated, there is no evidence of mass ordering

If systematic errors are correlated, Ridge is larger for larger mass

h are 50% p, 50% $\pi$
Key experimental results

Jet-like correlation is dominantly produced by fragmentation $\rightarrow$ Ridge production must not affect formation of jet-like correlation

Particle ratios in Ridge comparable to bulk

The Ridge is smaller in collisions at $\sqrt{s_{NN}} = 62$ GeV than 200 GeV

Ridge is larger in plane than out of plane

If there is a mass ordering, Ridge increases with increasing trigger mass

The Ridge is broad in $\Delta \eta$
Comparisons to theories
Radial flow + trigger bias

Radial flow means that most particles are moving out from the surface of the medium.

If hard partons are also surface biased, hadrons from fragmenting partons will also be surface biased.

This will lead to a correlation between hard partons and medium partons → the Ridge.

Several implementations of this mechanism:

- A boost in momentum mimicking radial flow added to PYTHIA (Voloshin, Pruneau, Gavin).
- Radial flow + trigger bias added to a Glasma initial state (Gavin, Moschelli, McLerrin).
- Correlated Emission Model adds this mechanism to Recombination (Hwa).
Radial flow + trigger bias

Jet-like correlation: not affected 😊

Particle ratios: from bulk → comparable to bulk 😊

Ridge in 62 vs 200 GeV: not clear 😐

Reaction plane dependence: described by data 😊

Mass ordering: If surface bias is from radial flow, ridge should be larger for lighter trigger particles because lighter particles have greater flow. The opposite trend is observed → if this is the mechanism, surface bias must come from jet quenching 😐

Ridge is broad in $\Delta \eta$: described by model 😊

→ Consistent with most observations but need more quantitative calculations
Momentum kick model

Hard partons moving through the medium collide with partons from the medium

These partons acquire a momentum kick in the direction of the hard parton, leading them to be correlated with the hard parton → the Ridge

Since the distribution of medium partons is broad in $\Delta \eta$, the Ridge is broad in $\Delta \eta$

Causal limit to how far in $\Delta \eta$ the correlation in $\Delta \eta$ can extend → unusual distribution in $\Delta \eta$, strongly $p_T$ dependent

Able to describe energy dependence
Momentum kick model

Jet-like correlation: not affected 😊
Particle ratios: from bulk → comparable to bulk 😊
Ridge in 62 vs 200 GeV: agrees with data 😊
Reaction plane dependence: naively greater for longer path length 😞
Mass ordering: unclear 😞
Ridge is broad in Δη: described by model 😊
→ Consistent with most observations but needs to be reconciled with reaction plane dependence
Gluon radiation

Hard partons moving through the medium emit gluon bremsstrahlung

Longitudinal flow:
Longitudinal flow sweeps these gluons in pseudorapidity → the Ridge

Plasma instabilities
Plasma instabilities form due to the rapidly fluctuating strong fields early in the formation of the collision
These fluctuating strong fields make the plasma unstable and deflect gluons radiated by hard partons
**Gluon radiation**

Jet-like correlation: not affected 😊

Particle ratios: from gluon fragmentation, likely comparable to ratios in p+p 😐

*Ridge* in 62 vs 200 GeV: not clear 😐

Reaction plane dependence: naively greater for longer path length 😐

Mass ordering: For longitudinal flow mechanism, also expect greater *Ridge* for lighter particles because flow is greater. 😐

*Ridge* is broad in Δη: not consistent with current calculations, may have causal problems 😐

→ Several aspects not likely consistent with data
Conclusions
Particle dependence consistent with vacuum fragmentation

No system dependence

PYTHIA quantitatively describes data except at lowest $p_T^{\text{trigger}}, p_T^{\text{assoc}}$

→ Jet-like correlation is dominantly produced by vacuum fragmentation

→ Can understand the effects of kinematic cuts on parton sample through jet-like correlation

→ Deviations from vacuum fragmentation either come from the Ridge or from a slight modification fragmentation in A+A
Several models on the market
Radial flow + trigger bias able to describe most aspects of the data
Momentum kick model consistent with data
Gluon bremsstrahlung models have several apparent inconsistencies with data → likely excluded
Radial flow + trigger bias mechanism dependent on validity of hydrodynamics, less speculative
But need more quantitative calculations!

The Ridge
Outlook

• More studies of energy dependence possible
  • RHIC beam energy scan
  • LHC
• Better studies of Ridge, jet-like correlation at RHIC
  • EMCal triggered data
  • Full jet reconstruction
Backups
PHOBOS

Coverage:

With tracking:
0\(<\phi\<0.2, \times2
0\(<\eta\<1.5

Without tracking:
0\(<\phi\<2\pi
-3\(<\eta\<3
PHENIX

Coverage:

\[ 0 < \phi < \pi/2, \; x^2 \]

\[-0.35 < \eta < 0.35 \]
Determination of yields and errors

Background:

\[ B(1+2 v_{\text{trig}} v_{\text{assoc}} \cos(2\Delta\Phi)) \]

Different fit methods for determination of \( B \)

1 point, 3 points

\( B \) as Free parameter (used as best guess)

\( v_{2} \) error

measurements in Cu+Cu in progress

Upper bound for \( v_{2} \) measured

\( v_{2} \approx 10-15\% \) depending on \( p_{T}, \) centrality

Estimate for lower bound, near 0

\( \Lambda, \bar{\Lambda}, K_{S}, \Xi^{+}, \Xi^{-}, \ldots \) \( v_{2} \): large statistical errors

Assume quark scaling of \( h v_{2} \) in Cu+Cu
Method: Yield extraction

Ridge previously observed to be independent in $\Delta \eta$ in Au+Au

To determine relative contributions, find yields for near-side, take $\Delta \Phi$ projections in

-0.75<$\Delta \eta$<0.75 \textit{Jet + Ridge}

0.75<$|\Delta \eta|$<1.75 \textit{Ridge}

Jet = (Jet+Ridge) – Ridge*.75/1.0

Ridge = yield from -1.75<$\Delta \eta$<1.75 – Jet yield

Flow contributions to Jet cancel

$v_2$ independent of $\eta$ for $|\eta|<1$

**Background – hydrodynamical flow**

Particles exhibit collective flow relative to the reaction plane

\[
E \frac{d^3N}{d^3p_T} = \frac{1}{2\pi \rho_T p_T d\eta} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \psi_{RP})) \right)
\]

If neither the trigger particle nor the associated particle comes from a jet, they will be correlated with the reaction plane.

This is a background in di-hadron correlation analyses:

\[ B(1 + 2v_2^{\text{trig}} v_2^{\text{assoc}} \cos(2\Delta\Phi)) \]

\( v_2 \) independent of \( \eta \) for \( |\eta| < 1 \)

Identified trigger: Near-side Yield vs $N_{\text{part}}$

Jet yield - No trigger type dependence

Data points at same $N_{\text{part}}$ offset for visibility
Jet yields: 10% error added to $V^0$ and $h$ triggers to account for track merging, 15% to $\Xi$ triggers

d+Au, Au+Au $\sqrt{s_{NN}}=200$ GeV from nucl-ex/0701047
Cu+Cu $\sqrt{s_{NN}}=200$ GeV from SQM2007
Identified associated particles

Associated baryons and mesons in Jet similar

\[ \frac{1}{N_{\text{trigger}}} \frac{1}{p_T} dN/dp_T \text{(jet near-side)} \]

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \ Au + Au \ 0-10\% \ Cu + Cu: 0-54\%
\[ \sqrt{s_{NN}} = 62 \text{ GeV} \ Au + Au \ 0-80\% \ Cu + Cu: 0-60\%
\]

Fits assuming \[ \frac{1}{p_T} dN/dp_T = A p_T \exp(-p_T/T) \]
Track merging

Intrinsic limits in two-track resolution $\rightarrow$ loss of tracks at small $\Delta \phi$, $\Delta \eta$
Crossing of tracks, true merging of tracks
Particle type dependent: affects reconstructed vertices ($K^0_s, \Lambda, \Xi$) more
Dependent on $p_T$: affects lower $p_T^{\text{trigger}}$, $p_T^{\text{assoc}}$ more
With Ridge/Jet separation method affects Jet only
Track merging correction

Calculate number of merged hits in a track pair from track geometry

If the fraction of merged hits is greater than 10%, throw out the pair

Do this for real and mixed event pairs

Bin by helicity of trigger and associated and reflect the points from unaffected helicity bins to recover dip

h_tr - helicity of trigger
h_as - helicity of associated
Extent of Ridge in $\Delta \eta$

Ridge yield approximately independent of $\Delta \eta$
Jet increases with $p_T^{\text{trigger}}$
Jet-like peak width in central Au+Au

Jet peak symmetric in $\Delta \eta$ and $\Delta \phi$ for $p_T^{\text{trigger}} > 4$ GeV and comparable to d+Au

Jet peak asymmetric in $\Delta \eta$ for $p_T^{\text{trigger}} < 4$ GeV and significantly broader than d+Au
Jet-like peak width in central Au+Au

Peak gets broader at higher $p_T^{\text{trigger}}$, lower $p_T^{\text{assoc}}$

Width in PHENIX kinematic range close to PHENIX acceptance
Ridge yield vs. pt,trig in Au+Au

Ridge yield persists to highest trigger pt ⇒ correlated with jet production

Putschke
WWND08
Applying this “2-component picture” to lower $p_{t,assoc}$ measurements:

- $z_{t,jet}(Au+Au) \sim z_{t,jet}(d+Au)$
- Subtracting $p+p$ jet energy from $Au+Au$
- Upper estimate of the energy deposit in the ridge \sim few GeV

“Direct” measure of energy loss?

Putschke
WWND08
3-particle correlations

Ridge appears uniform event-by-event within STAR detector

$\Delta \eta_1 = A1-T$
$\Delta \eta_2 = A2-T$

$3 < p_T^{\text{trigger}} < 10$  $1 < p_T^{\text{assoc}} < 3$  $|\Delta \phi| < 0.7$


Armesto et al, PRD 69, 054004

Radial flow + trigger bias

Christine Nattrass (UTK), University of Kentucky, 1 Oct. 2009
$Au+Au \sqrt{s_{NN}} = 200$ GeV Summary

**Ridge** persists to high $p_T^{\text{trigger}}$

**Ridge** is softer than Jet, comparable to inclusive

**Ridge** contains a few GeV of energy

Jet almost independent of reaction plane; Ridge dominantly in plane

Fragmentation function with Ridge subtracted similar in d+Au, Au+Au

Ridge uniform event-by-event

Christine Nattrass (UTK), University of Kentucky, 1 Oct. 2009
Identified trigger: Near-side Yield vs $N_{\text{part}}$

3.0 GeV/c $< p_T^{\text{trigger}}$ 6.0 GeV/c; 1.5 GeV/c $< p_T^{\text{associated}} < p_T^{\text{trigger}}$

Ridge yield - No trigger type dependence

Au+Au $\sqrt{s_{NN}}$=200 GeV from nucl-ex/0701047
Cu+Cu $\sqrt{s_{NN}}$=200 GeV from SQM2007

Data points at same $N_{\text{part}}$ offset for visibility