The Jet
The Ridge
And what we know about them

Christine Nattrass
Yale University
Outline

- Introduction to RHIC
- Introduction to the Ridge
- Central Au+Au $\sqrt{s_{NN}} = 200$ GeV
- The Jet – energy, system, and particle type dependence
- The Ridge – energy, system, and particle type dependence
- Comparison to theories
- Conclusion
Phase diagram of nuclear matter

- Lattice says crossover at $\mu_B = 0$
- Some discussion on methods to extract $T_C$ (175 $\leq T_C/\text{MeV} \leq 191$)
- Lattice suggest the transition becomes 1st order at $\mu_B$ above the critical point (2nd order at the CP)
The phase transition in the laboratory

Collision
pre-equilibrium

QGP

Hadron Gas

Phase Transition/Cross-Over $T_c$
Chemical Freeze-Out (incl. collisions cease) $T_{ch}$
Thermal Freeze-Out (el. collisions cease) $T_{fo}$

Time
Relativistic Heavy Ion Collider
PHOBOS

- Coverage:
  With tracking:
  $0<\phi<0.2$, $x2$
  $0<\eta<1.5$
  Without tracking:
  $0<\phi<2\pi$
  $-3<\eta<3$
**PHENIX**

- Coverage:
  
  $0 < \phi < \pi/2$, $x^2$

  $-0.35 < \eta < 0.35$
STAR

- Coverage: $0<\phi<2\pi$
- $-1<\eta<1$
- Electromagnetic Calorimeter allows triggering
Why study jets in heavy ion collisions?

- 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
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Introduction to the Ridge
Motivation – Jet and Ridge

- Long-range pseudorapidity ($\Delta \eta$) correlations observed by STAR in Au+Au at intermediate $p_T$
- Near side jet peak sits on plateau (Ridge)
- Significant contribution to the near-side yield in central Au+Au
**Extent of Ridge in $\Delta \eta$**

- Ridge yield approximately independent of $\Delta \eta$
- Jet increases with $p_T^{\text{trigger}}$
**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}

- \textit{Jet} = \textit{(Jet+Ridge)} – \textit{Ridge}*.75/1.0

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

- Flow contributions to \textit{Jet} cancel
  - $v_2$ independent of $\eta$ for $|\eta|<1$

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
**Extent of Ridge in $\Delta \eta$**

**Au+Au 0-30% central**

![Graph showing the extent of the ridge in $\Delta \eta$ for Au+Au 0-30% central collisions.](graph1)

Wenger QM08

![Graph comparing PHOBOS preliminary and PYTHIA v6.325 models for $1/N_{\text{trig}} dN_{\text{ch}} / d\Delta \eta$.](graph2)
Track merging

- Intrinsic limits in two-track resolution → 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

\[ h_{tr} = -1 \]
\[ h_{as} = 1 \]
\[ h_{tr} = 1 \]
\[ h_{as} = -1 \]

genuine merging, most visible for low pt triggers

\[ h_{tr} - \text{helicity of trigger} \]
\[ h_{as} - \text{helicity of associated} \]

Bombara SQM07
Determination of yields and errors

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

- Different fit methods for determination of B
  - Zero Yield At Minimum (ZYAM)
    - 1 point, 3 points
    - B as Free parameter (used as best guess)
  - \( v_2 \) error
    - \( v_2 \) 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
        - \( \Lambda, \bar{\Lambda}, K^0, \Xi^+, \Xi^- \ldots \) \( v_2 \): large statistical errors
      - Assume quark scaling of \( h v_2 \) in Cu+Cu

3.0 GeV<\( p_T^{\text{trig}} <6.0 \) GeV, 1.5 GeV<\( p_T^{\text{assoc}} < p_T^{\text{trig}} \)
h-h, 0-20% Cu+Cu \( \sqrt{s_{\text{NN}}} = 200 \) GeV
Caveats and assumptions

• **Jet**: track merging
  - Correction CPU intensive, in progress
  - 5% in central Au+Au for $p_T^{\text{trigger}} \sim 3$ GeV/c, $p_T^{\text{assoc}} \sim 1.5$ GeV/c for h-h
  - Increases for lower $p_T^{\text{trigger}}, p_T^{\text{assoc}}$, identified particles

• **Ridge**: ZYAM

• **Jet** and **Ridge**: assumption that Ridge is independent of $\Delta \eta$
  - If not, may overestimate Jet
Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
Jet is like $p+p$, Ridge is like bulk

- Spectra of particles associated with Ridge similar to inclusive
- Spectra of particles associated with Jet harder
Measure hadron triggered fragmentation functions:
\[ D^{h_1,h_2}(z_T) \]
\[ z_T = \frac{p_T^{\text{assoc}}}{p_T^{\text{trigger}}} \]

- Jet+Ridge: \( D^{h_1,h_2}(z_T) \) different for d+Au, Au+Au
- Jet only: \( D^{h_1,h_2}(z_T) \) within errors for d+Au, Au+Au
Jet/Ridge w.r.t. reaction plane

Feng QM08

- Ridge 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 yield vs. $pt, trig$ in Au+Au

- Ridge yield persists to highest trigger $pt \Rightarrow$ 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 ~ few GeV

• “Direct” measure of energy loss?

STAR, Phys. Rev. Lett. 95 (2005) 15230
3-particle correlations

- Ridge appears uniform event-by-event within STAR detector

\[
\Delta \eta_1 = A1-T \quad \Delta \eta_2 = A2-T
\]

\[
3 < p_T^{\text{trigger}} < 10 \quad 1 < p_T^{\text{assoc}} < 3 \quad |\Delta \phi| < 0.7
\]
3-particle correlations

- **Ridge** appears uniform event-by-event within STAR detector

\[ \Delta \eta_1 = A1-T \]
\[ \Delta \eta_2 = A2-T \]

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

Radial flow + trigger bias

3-particle correlations

- **Ridge** appears uniform event-by-event within STAR detector

\[ \Delta \eta_1 = \text{A1-T} \]
\[ \Delta \eta_2 = \text{A2-T} \]

\[
\Delta \eta \leq |\Delta \phi| < 0.7
\]

\[ 3 < p_T^{\text{trigger}} < 10 \quad 1 < p_T^{\text{assoc}} < 3 \]

Long. flow picture
**Au+Au \( \sqrt{s_{NN}} = 200 \text{ GeV} \) 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

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Christine Nattrass (Yale), LLNL, April 14, 2009
The Jet

\[ 3 < p_{\text{trigger}} < 4 \text{ GeV} \]
\[ p_{\text{assoc.}} > 2 \text{ GeV} \]

Au+Au 0-10% STAR preliminary

Jet

#entries

\[ \Delta \phi \]
\[ \Delta \eta \]

32
Particle type dependence
Identified trigger: Near-side Yield vs $N_{\text{part}}$

Jet yield - No trigger type dependence

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

$\sqrt{s_{NN}}=200$ GeV, $|\Delta\eta|<0.7$

STAR preliminary

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
Identified associated particles

- Associated baryons and mesons in \textit{Jet} similar

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

Fits assuming \[ 1/p_T \, dN/dp_T = A \, p_T \, \exp(-p_T/T) \]
**Ridge composition**

- Baryon/meson ratios in *Jet* in Cu+Cu and Au+Au similar to p+p for both strange and non-strange particles

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J. Bielcikova (STAR), v:0707.3100 [nucl-ex]
C. Nattrass (STAR), arXiv:0804.4683/nucl-ex
Energy and System dependence
**$p_T^{\text{trigger}}$ dependence**

- Pythia 8.1 describes trends in data up to a scaling factor
  - Gets energy dependence right → this is a pQCD effect
  - Stronger deviations at low $p_T^{\text{trigger}}$, as expected
• What can Pythia tell us?
  – Higher $z_T$ (lower jet energy) in 62 GeV for same $p_T^{\text{trigger}}$

$p_{THatMin}$ = the parameter in Pythia for the minimum transverse momentum in the hard subprocess
Pythia comparisons

- What can Pythia tell us?
  - Higher $z_T$ (lower jet energy) in 62 GeV for same $p_T^{\text{trigger}}$

$p_{\text{THatMin}}$ = the parameter in Pythia for the minimum transverse momentum in the hard subprocess
\( p_T^{\text{associated}} \) dependence

- No system dependence
- Pythia 8.1 slightly harder than data
- Diverges slightly from Pythia 8.1 at lower \( p_T^{\text{associated}} \)

<table>
<thead>
<tr>
<th></th>
<th>( \sqrt{s_{NN}} = 62 \text{ GeV} )</th>
<th>( \sqrt{s_{NN}} = 200 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu+Cu</td>
<td>317 ± 26</td>
<td>445 ± 20</td>
</tr>
<tr>
<td>Au+Au</td>
<td>355 ± 21</td>
<td>478 ± 8</td>
</tr>
<tr>
<td>d+Au</td>
<td>469 ± 8</td>
<td>469 ± 8</td>
</tr>
<tr>
<td>Pythia</td>
<td>417 ± 9</td>
<td>491 ± 3</td>
</tr>
</tbody>
</table>

Inverse slope parameter

Statistical errors only

J. Bielcikova (STAR), arXiv:0806.2261/nucl-ex
C. Nattrass (STAR), arXiv:0804.4683/nucl-ex
\[ N_{part} \text{ dependence} \]

- No system dependence
- Some deviations from Pythia 8.1 with increase in \( N_{part} \)
  - Incomplete Ridge subtraction?
  - Jet modification at low \( p_T \)?

\[ \langle N_{part} \rangle \]

**Graph:**
- \( \text{Cu+Cu 62 GeV} \)
- \( \text{Au+Au 62 GeV} \)
- \( \text{d+Au 200 GeV} \)
- \( \text{Cu+Cu 200 GeV} \)
- \( \text{Au+Au 200 GeV} \)
- \( \text{Pythia 62 GeV}^{*2/3} \)
- \( \text{Pythia 200 GeV}^{*2/3} \)
Conclusions: Jet

- Pythia describes data well
  - Scaling factor needed but Pythia 8.1 is not as tuned as earlier versions
  - Energy dependence in Jet is pQCD effect
  - Trends for $p_T^{\text{trigger}}$, $p_T^{\text{assoc}}$ dependence right
- Particle ratios similar to p+p
  - Jet production mechanism dominated by fragmentation
    - Separation of Jet and Ridge works
    - Effects of triggers which don't come from jets small
    - Pythia can be used to estimate $z_T$ distributions, jet energy
The Ridge

Au+Au 0-10% STAR preliminary
3<p_{\text{trigger}}<4 \text{ GeV}
\p_{\text{assoc}} >2 \text{ GeV}

Ridge
Particle type dependence
Identified trigger: Near-side Yield vs $N_{part}$

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

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 $N_{part}$ offset for visibility

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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

Suarez, QM08
Energy and System dependence
- No system dependence at given $N_{\text{part}}$
Ridge vs $N_{part}$

- No system dependence at given $N_{part}$
- Ridge/Jet Ratio independent of collision energy
Conclusions: Ridge

- Extensive data on Ridge
  - Cu+Cu, Au+Au consistent at same \( N_{\text{part}} \)
  - Ridge/Jet ratio independent of energy
  - Persists to high \( p_T^{\text{trigger}} \)
  - Ridge looks like bulk
    - \( p_T^{\text{associated}} \) dependence, particle composition
- Jet agreement between different systems, with scaled Pythia
  - Simulations can be used to approximate \( z_T \) distribution for comparisons of data to models
  - More steeply falling jet spectrum in 62 GeV \( \rightarrow \) stronger bias towards unmodified/surface jets
    - Could explain smaller Ridge yield in 62 GeV
Comparisons to theories
**Models**

- **Radial flow+trigger bias**
  

  - Works for one set of kinematic cuts in central Au+Au at 200 GeV
  - Need more detailed comparisons (energy dependence)
  - Model needs some refinements (momentum conservation)

- **Plasma instability**

  Anisotropic plasma, P. Romatschke, PRC,75014901 (2007)

  - So far unable to make enough *Ridge* without Radial flow+trigger bias
Models

- **Longitudinal flow**
  - Problems due to $\Delta \eta$ width

- **Momentum kick**
  - Fits data well, including energy dependence

- **Recombination**
  Medium heating + recombination, Chiu & Hwa, PRC72, 034903
  - No quantitative comparisons
Conclusions

• Considerable evidence that Jet is dominantly produced by fragmentation
  – Can we use this information to learn more about the Ridge?

• Several models for the Ridge, few quantitative comparisons
  – Several depend on hydrodynamics
  – Need better calculations – more quantitative, more than central Au+Au

• Future:
  – More energy dependence (RHIC beam energy scan, LHC)
  – Jet reconstruction – more detailed studies of Ridge?
Backups
**Ω triggered correlations**

- Azimuthal correlations of comparable strengths seen with Λ (uds), Ξ (dss), and Ω (sss) triggers

- In Δη Λ-triggered correlations can be separated in jet and ridge
- Ξ-triggered Δφ correlations appear smeared in Δη direction (all ridge?)
Di-hadron triggered correlations

Di-jet measurements suggest that neither the widths in \( \Delta \eta \) and \( \Delta \phi \) (ridge/mach cone) are modified nor the yields are suppressed and comparable to d+Au

Caveat: Non-trivial bkg. subtraction

Surviving (di-jet) pairs at high \( p_t \) seem to favor conditions with small energy loss

\( \Rightarrow \) ridge correlated with energy loss (?)