Jets and the Underlying Event in p+p Collisions at $\sqrt{s}=200$ GeV

Helen Caines - Yale University - for the STAR Collaboration

Workshop on high $p_T$ probes
RHIC/AGS Users Meeting
June 1-5 2009

Outline
- Jets and our data set
- $z$ and $\xi$ distributions
- The underlying event
- Summary and outlook
The p+p data set

- TPC tracks to identify charged particles contribution.
- Barrel EMCal for neutral energy contribution.

2006 Run

Sampled luminosity for Jet-Patch triggers:

~8.7 pb\(^{-1}\)
(~8 M events)

Jet-Patch Trigger:
BBB coincidence + EMCal Jet-Patch

Jet-Patch:

\[ E_T > 8 \text{ GeV in } \Delta\eta \times \Delta\phi = 1 \times 1 \]
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Jet-Patch:
$E_T > 8$ GeV in
$\Delta\eta \times \Delta\phi = 1 \times 1$

Jet-Patch - NEF FF bias - use non-triggered jet for studies.
Jet reconstruction - algorithms

Seedless Cone - SISCones

- $R_{cone} = \sqrt{(\Delta \phi^2 + \Delta \eta^2)}$
- all particles used.
- Splitting/Merging destroys cone shape.

Fastjet package - [Cacciari, Soyez, arXiv:0704.0292]
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Recombination

- \( k_T \) starts from lowest \( p_T \).
- merges weighted by \( 1/p_T \) i.e. high \( p_T \) is dis-favored.

Anti-\( k_T \)

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[Cacciari, Salam, Soyez, arXiv:0802.1189]
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$k_T$
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Anti-$k_T$
- starts from high $p_T$.
- merges weighted by $p_T$ i.e. low $p_T$ is dis-favored.

Compare results to explore systematics.

Fastjet package - [Cacciari, Soyez, arXiv:0704.0292]
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Jets – a calibrated probe

Jet cross-section in p+p is well described by NLO pQCD calculations over 7 orders of magnitude.

Excellent description when included in world data
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• Minimum bias particle production in p+p also well modeled.
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- Excellent description when included in world data
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What about fragmentation?

S. Albino et al. NPB 725 (2005) 181

STAR : PLB 637 (2006) 161
T. Kluge, K. Rabbertz, M. Wobish

STAR : PRL 97 (2006) 252001
Fragmentation functions (FF)

- No previous comparisons at RHIC energies available.

- Measurements at higher $\sqrt{s}$ agree well with theory.

Test energy scaling of fragmentation functions.

Sapeta & Wiedemann, hep-ph/0707.3494
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MLLA Theory

- FF are particle species dependent.

Need to study composition of jets and complete event.

Test energy scaling of fragmentation functions.
Jet reconstruction - the resolution parameter

% Energy within resolution parameter R

<table>
<thead>
<tr>
<th>p_T (GeV/c)</th>
<th>R = 0.4</th>
<th>R = 0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-30</td>
<td>77%</td>
<td>94%</td>
</tr>
<tr>
<td>30-40</td>
<td>83%</td>
<td>96%</td>
</tr>
<tr>
<td>40-50</td>
<td>89%</td>
<td>98%</td>
</tr>
</tbody>
</table>

- Larger energy → more focussed jet.
- CDF > 80% R=0.3. (Jet p_T ~ 50 GeV)

Compare FF using different radii.

<table>
<thead>
<tr>
<th>η_{jet}</th>
<th>&lt; 1 - R</th>
</tr>
</thead>
</table>

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Energy resolution - the jet energy scale

Calculated in two way:

- Simulation
  - MC input compared to reconstructed output.

- Offset due to missing energy:
  - Detector efficiencies.
  - Undetected particles (n, K^0_L).

- Resolution ~15-20% for \( p_{T\text{Jet}} > 15 \text{GeV/c} \).
Energy resolution - the jet energy scale

Calculated in two way:

- Simulation
  - MC input compared to reconstructed output.
- Real data

Offset due to missing energy:
- Detector efficiencies.
- Undetected particles ($n$, $K^0_L$).
- Resolution $\sim$15-20% for $p_{T,\text{Jet}}>15\text{GeV/c}$. 
ξ and z distributions for charged hadrons

Data not corrected to particle level.

“PYTHIA” = PYTHIA + GEANT

Reasonable agreement between data and PYTHIA+GEANT.
Charged hadrons $\xi$ for different R and jet $p_T$

$R=0.4$

$|\eta_{\text{jet}}|<1-R$

$p_T^{\text{track}} > 0.2$

Data not corrected to particle level.

“PYTHIA” + GEANT

$R=0.7$

Agreement similar between PYTHIA and data for both radii.
What about the Underlying Event?

• p-p events are complicated. More than just hard scattering.

• Underlying Event: soft or semi-hard multiple parton interactions, initial & final state radiation, beam-beam remnants

The Underlying Event is everything BUT the hard scattering
Measuring the Underlying Event

Define:

- $|\Delta \phi|$ – Angle relative to leading jet
- “Toward” $|\Delta \phi| < 60^\circ$
- “Away” $|\Delta \phi| > 120^\circ$
- “Transverse” $60^\circ < |\Delta \phi| < 120^\circ$
  - **TransMax** - Trans. region with highest $\Sigma p_T$ or $\Sigma N_{\text{track}}$
  - **TransMin** - Trans. region with least $\Sigma p_T$ or $\Sigma N_{\text{track}}$

Underlying Event is the data in the Transverse regions.
Sensitivities of the variables

leading: Most basic jet cut, one jet in our acceptance.

back-to-back: Sub-set of leading jet collection.
  Require $|\Delta \phi| > 150$, $p_{T_{Away}}/p_{T_{Lead}} > 0.7$
  Suppresses hard initial and final state radiation.

TransMin: Sensitive to beam-beam remnants and soft multiple parton interactions.

TransMax: Enhanced probability of containing hard initial and/or final state radiation component.
Sensitivities of the variables

**leading** : Most basic jet cut, one jet in our acceptance.

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**TransMin** : Sensitive to beam-beam remnants and soft multiple parton interactions.

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**Compare TransMin and TransMax data from leading and back-to-back jet samples →**

**Information about large angle initial/final state radiation.**
Charged track density

Back-to-Back, $R=0.7$, $|\eta_{\text{jet}}| < 1-R$, $p_{T\text{track}} > 0.2$ GeV/c

- Jet charged track density rises with jet $p_T$
- PYTHIA in good agreement with data

UE largely independent of jet $p_T$
CDF $\sqrt{s}=1.96$ TeV

- leading TransMax > back-to-back TransMax

Significant initial/final state radiation at large angles.
TransMin vs TransMax regions of UE

CDF \(\sqrt{s} = 1.96 \text{ TeV}\)
- leading TransMax > back-to-back TransMax
  - Significant initial/final state radiation at large angles.

STAR \(\sqrt{s} = 200 \text{ GeV}\)
- leading TransMax \(\sim\) back-to-back TransMax
  - Small initial/final state radiation at large angles.
TransMin vs TransMax regions of UE

CDF $\sqrt{s}=1.96$ TeV
- leading TransMax $>$ back-to-back TransMax
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STAR $\sqrt{s}=200$ GeV
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TransMin vs TransMax regions of UE

CDF $\sqrt{s}=1.96$ TeV
- leading TransMax $>$ back-to-back TransMax
  Significant initial/final state radiation at large angles.

STAR $\sqrt{s}=200$ GeV
- leading TransMax $\sim$ back-to-back TransMax
  Small initial/final state radiation at large angles.

- TransMax $>$ TransMin
  Poisson distribution with average $dN_{ch}/d\eta d\phi = 0.36$
  - UE $\sim$ independent of jet $p_{T}$.
Mean $p_T$ charged tracks

- Agreement between PYTHIA and data OK

, Back-to-Back, $R=0.7$, $|\eta_{jet}| < 1-R$, $p_{TTrack} > 0.2 \text{ GeV/c}$
Mean $p_T$ charged tracks

• Agreement between PYTHIA and data OK

, Back-to-Back, $R=0.7$, $|\eta_{\text{jet}}| < 1-R$, $p_{T\text{track}} > 0.2$ GeV/c

CDF higher than STAR merely due to lower $p_T$ cut?

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L.A. Cruz, “Using MAX/MIN transverse regions to study the underlying event in run 2 at the Tevatron” UMI-31-88071, 2005.
Max $p_T$ charged track

<table>
<thead>
<tr>
<th></th>
<th>UE</th>
<th>CDF</th>
<th>STAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Data&gt;</td>
<td></td>
<td>1.2</td>
<td>0.65</td>
</tr>
<tr>
<td>&lt;Pythia&gt;</td>
<td></td>
<td>1.0</td>
<td>0.6</td>
</tr>
</tbody>
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**“Transverse” Charged $p_T$max**

CDF Run 2 Preliminary

"Back-to-Back"

1.96 TeV

Charged Particles ($|\eta| < 1.0$, $P_T > 0.5$ GeV/c)

```
Max Charged Track $p_T$

Max Track $p_T$

<table>
<thead>
<tr>
<th>Toward</th>
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RHIC UE is a little softer

L.A. Cruz, “Using MAX/MIN transverse regions to study the underlying event in run 2 at the Tevatron” UMI-31-88071, 2005.
$p_T$ spectra in jet, UE, Min-Bias event

$15 < p_{T_{jet}} < 20$ GeV/c, $|\eta_{jet}| < 1-R$, $R=0.7$

Uncorrected Spectra

<table>
<thead>
<tr>
<th>Event Type</th>
<th>$\langle p_T \rangle$ (GeV/c)</th>
</tr>
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<tbody>
<tr>
<td>Jet</td>
<td>1.2</td>
</tr>
<tr>
<td>Max UE</td>
<td>0.5</td>
</tr>
<tr>
<td>Min UE</td>
<td>0.4</td>
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<td>Min-Bias</td>
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Minbias close to but **not** equal to UE
• $15 < p_{T_{\text{jet}}} < 20$ GeV/c, $|\eta_{\text{jet}}| < 1 - R$, $R = 0.7$

Uncorrected Spectra

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Minbias close to but not equal to UE

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Summary & outlook

- Different jet algorithms produce consistent results
- Charged hadron $\xi$ and $z$ distributions at $\sqrt{s}=200$ GeV similar to PYTHIA 6.4.
- Underlying Event largely decoupled from hard scattering.
- Large angle initial/final state radiation is small.
- Particle $p_T$ spectra are significantly softer out of the jet cone compared to in the jet.
- $p_T$ spectra of Underlying Event close to that of Min-Bias triggered events.

Outlook

- Compare more jet-variables ($k_T$, $j_T$, etc) to pQCD models.
- Use relativistic rise and newly installed ToF to identify $\pi$, $K$, $p$.
- Repeat measurements at $\sqrt{s}=500$ GeV.
- Measure PID FF in heavy ion collisions.
p_T spectra in jet, UE, Min-Bias event

15<p_Tjet<20 GeV/c, |η_jet|<1-R

Charged particles

All data raw

K^0_s

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