Jet Physics and the Underlying Event at the Tevatron

Outline of Talk

- The Jet Cross Section in Run 2 at the Tevatron: MidPoint Algorithm (CDF/D0) and K_T Algorithm (CDF).
- The b-Jet Inclusive Cross Section in Run 2 at the Tevatron (CDF/D0).
- The b-bbar Jet Cross Section and Correlations (CDF).
- Jet-Jet Correlations (D0).
- Understanding and Modeling the “Underlying Event” in Run 2 at CDF.
The TeVatron

The TeVatron delivered more than 350 pb\(^{-1}\) in 2004!

CDF has \(~900\) pb\(^{-1}\) on tape!

- \(\sqrt{s} = 1.96\) TeV (Run 1 = 1.8 TeV)
- 36 bunches: 396 ns crossing time
- Peak luminosity \(~10^{32}\) cm\(^{-2}\) s\(^{-1}\)
- 12-20 pb\(^{-1}\) per week!

Proton-antiproton collisions
“Theory Jets”

Experimental Jets: The study of “real” jets requires a “jet algorithm” and the different algorithms correspond to different observables and give different results!

Experimental Jets: The study of “real” jets requires a good understanding of the calorimeter response!

Experimental Jets: To compare with NLO parton level (and measure structure functions) requires a good understanding of the “underlying event”!

“Real Jets”

Experimental Jets: The study of “real” jets requires a good understanding of the calorimeter response!

Experimental Jets: To compare with NLO parton level (and measure structure functions) requires a good understanding of the “underlying event”!
Jet Corrections

Calorimeter Jets:
- We measure “jets” at the “hadron level” in the calorimeter.
- We certainly want to correct the “jets” for the detector resolution and efficiency.
- Also, we must correct the “jets” for “pile-up”.
- Must correct what we measure back to the true “particle level” jets!

Particle Level Jets:
- Do we want to make further model dependent corrections?
- Do we want to try and subtract the “underlying event” from the “particle level” jets.
- This cannot really be done, but if you trust the Monte-Carlo models modeling of the “underlying event” you can try and do it by using the Monte-Carlo models (use PYTHIA Tune A).

Parton Level Jets:
- Do we want to use our data to try and extrapolate back to the parton level?
- This also cannot really be done, but again if you trust the Monte-Carlo models you can try and do it by using the Monte-Carlo models.

The “underlying event” consists of hard initial & final-state radiation plus the “beam-beam remnants” and possible multiple parton interactions.
**MidPoint Cone Algorithm**
(R = 0.7, f_{merge} = 0.5)

**ε L = 380 pb^{-1}**

**Two rapidity bins**

**Highest P_T jet is 630 GeV/c**

**Compared with NLO QCD**
(JetRad, R_{sep} = 1.3?)
MidPoint Cone Algorithm 
\( R = 0.7, f_{\text{merge}} = 0.5 \)

\( \mathcal{L} = 143 \text{ pb}^{-1} \)

\( |y_{\text{jet}}| < 0.5 \)

Compared with NLO QCD 
(JetRad, \( R_{\text{sep}} = 1.3 \))

Update expected this Winter
CDF Inclusive Jet Cross Section

- MidPoint Cone Algorithm (R = 0.7, \( f_{\text{merge}} = 0.75 \))
- Data corrected to the parton level
- \( \mathcal{L} = 385 \, \text{pb}^{-1} \)
- \( 0.1 < |y_{\text{jet}}| < 0.7 \)
- Compared with NLO QCD (JetRad, \( R_{\text{sep}} = 1.3 \))
- Run 1 showed a possible excess at large jet $E_T$ (see below).
- This resulted in new PDF's with more gluons at large $x$.
- The Run 2 data are consistent with the new structure functions (CTEQ6.1M).

Run I CDF Inclusive Jet Data
(Statistical Errors Only)
JetClu $R_{\text{CONE}}=0.7$  $0.1<|\eta|<0.7$
$\mu_F=\mu_T=E_T/2$  $R_{\text{SEP}}=1.3$

NLO pQCD EKS CTEQ 6.1, $(\mu=\mu_T/2)$, $R_{\text{SEP}}=1.3$
Midpoint cone $R=0.7$, $f_{\text{reg}}=0.75$
Data corrected to parton level
$0.1<|Y|<0.7$  $\int L = 385 \text{ pb}^{-1}$

Systematic uncertainty.
Systematic uncertainty including hadronization and underlying event.
NLO pQCD PDF uncertainty.
Data/NLO pQCD

CDF Run II Preliminary
6% luminosity uncertainty not included

Rick Field - Florida/CDF
The $K_T$ Algorithm:

- Cluster together calorimeter towers by their $K_T$ proximity.
- Infrared and collinear safe at all orders of pQCD.
- No splitting and merging.
- No ad hoc $R_{sep}$ parameter necessary to compare with parton level.
- Every parton, particle, or tower is assigned to a “jet”.
- No biases from seed towers.
- Favored algorithm in $e^+e^-$ annihilations!

For each precluster, calculate

$$d_i = p_{T,j}^2$$

For each pair of preclusters, calculate

$$d_{ij} = \min(p_{T,j}^2, p_{T,j'}^2, (y_i - y_j)^2 + (\phi_i - \phi_j)^2) / D^2$$

Find the minimum of all $d_i$ and $d_{ij}$.

**Begin**

- For each precluster, calculate $d_i$.
- For each pair of preclusters, calculate $d_{ij}$.
- Find the minimum of all $d_i$ and $d_{ij}$.

**Merge i and j**

- Minumum is $d_{ij}$?
  - yes
  - no

**Move i to list of jets**

- Any Preclusters left?
  - yes
  - no

**End**

**Will the $K_T$ algorithm be effective in the collider environment where there is an “underlying event”?**

<table>
<thead>
<tr>
<th>Proton</th>
<th>Underlying Event</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outgoing Parton</td>
</tr>
<tr>
<td></td>
<td>PT(hard)</td>
</tr>
<tr>
<td></td>
<td>Final-State Radiation</td>
</tr>
<tr>
<td></td>
<td>AntiProton</td>
</tr>
<tr>
<td></td>
<td>Underlying Event</td>
</tr>
</tbody>
</table>

**CDF Run 2**

Only towers with $E_T > 0.5$ GeV are shown
Data at the “particle level”!

NLO parton level theory corrected to the “particle level”!

Correction factors applied to NLO theory!
Data at the “particle level”!

NLO parton level theory corrected to the “particle level”!

Correction factors applied to NLO theory!

ISMD 2005
August 11, 2005
The data are compared with PYTHIA (tune A)! Data/PYA ~ 1.4

Comparison with MC@NLO coming soon!

See the talk later this week by Mario Campanelli on “Heavy Flavor States at CDF”!
Jets containing heavy flavor often contain muons (e.g. $b \rightarrow c + W \rightarrow \mu + \nu$).
Searching for muons in jets enhances the heavy flavor content.
Data/PYTHIA flat ~ 1.3.
**The b-b bard DiJet Cross-Section**

- $E_T(b$-jet$\#1) > 30$ GeV, $E_T(b$-jet$\#2) > 20$ GeV, $|\eta(b$-jets$)| < 1.2$.  

**Preliminary CDF Results:**  

$$\sigma_{bb} = 34.5 \pm 1.8 \pm 10.5 \text{ nb}$$

**QCD Monte-Carlo Predictions:**

<table>
<thead>
<tr>
<th>Model</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYTHIA Tune A</td>
<td>$38.71 \pm 0.62 \text{ nb}$</td>
</tr>
<tr>
<td>CTEQ5L</td>
<td></td>
</tr>
<tr>
<td>HERWIG CTEQ5L</td>
<td>$21.53 \pm 0.66 \text{ nb}$</td>
</tr>
<tr>
<td>MC@NLO</td>
<td>$28.49 \pm 0.58 \text{ nb}$</td>
</tr>
</tbody>
</table>

**Large Systematic Uncertainty:**
- Jet Energy Scale ($\sim 20\%$).
- b-tagging Efficiency ($\sim 8\%$)

**Systematic Uncertainty**

- Large Systematic Uncertainty: $\sigma$-Jet Energy Scale ($\sim 20\%$).  
- b-tagging Efficiency ($\sim 8\%$)
The b-bbar DiJet Cross-Section

E_T(b-jet#1) > 30 GeV, E_T(b-jet#2) > 20 GeV, |η(b-jets)| < 1.2.

Preliminary CDF Results:

σ_{bb} = 34.5 ± 1.8 ± 10.5 nb

QCD Monte-Carlo Predictions:

<table>
<thead>
<tr>
<th>Model</th>
<th>Cross Section (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYTHIA Tune A</td>
<td>38.7 ± 0.6 nb</td>
</tr>
<tr>
<td>CTEQ5L</td>
<td></td>
</tr>
<tr>
<td>HERWIG CTEQ5L</td>
<td>21.5 ± 0.7 nb</td>
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<td>MC@NLO</td>
<td>28.5 ± 0.6 nb</td>
</tr>
<tr>
<td>MC@NLO + JIMMY</td>
<td>35.7 ± 2.0 nb</td>
</tr>
</tbody>
</table>

Adding multiple parton interactions (i.e. JIMMY) to enhance the “underlying event” increases the b-bbar jet cross section!

JIMMY: MPI
J. M. Butterworth
J. R. Forshaw
M. H. Seymour
The two b-jets are predominately “back-to-back” (i.e. “flavor creation”!)

Pythia Tune A agrees fairly well with the $\Delta\phi$ correlation!

Not an accident!
Jet#1-Jet#2 $\Delta \phi$ Distribution

- MidPoint Cone Algorithm ($R = 0.7$, $f_{merge} = 0.5$)
- $\mathcal{L} = 150$ pb$^{-1}$ (Phys. Rev. Lett. 94 221801 (2005))
- Data/NLO agreement good. Data/HERWIG agreement good.
- Data/PYTHIA agreement good provided PARP(67) = 1.0→4.0 (i.e. like Tune A).
The “Underlying Event” in Run 2 at CDF

The “underlying event” consists of hard initial & final-state radiation plus the “beam-beam remnants” and possible multiple parton interactions.

“Transverse” region is very sensitive to the “underlying event”!

→ Two Classes of Events: “Leading Jet” and “Back-to-Back”.
→ Two “Transverse” regions: “transMAX”, “transMIN”, “transDIF”.
→ Data corrected to the particle level: unlike our previous CDF Run 2 “underlying event” analysis which used JetClu to define “jets” and compared uncorrected data with the QCD Monte-Carlo models after detector simulation, this analysis uses the MidPoint jet algorithm and corrects the observables to the particle level. The corrected observables are then compared with the QCD Monte-Carlo models at the particle level.
→ For the 1st time we study the energy density in the “transverse” region.

New CDF Run 2 results ($\mathcal{L} = 385\ \text{pb}^{-1}$):

- Two Classes of Events: “Leading Jet” and “Back-to-Back”.
- Two “Transverse” regions: “transMAX”, “transMIN”, “transDIF”.
- Data corrected to the particle level: unlike our previous CDF Run 2 “underlying event” analysis which used JetClu to define “jets” and compared uncorrected data with the QCD Monte-Carlo models after detector simulation, this analysis uses the MidPoint jet algorithm and corrects the observables to the particle level. The corrected observables are then compared with the QCD Monte-Carlo models at the particle level.
- For the 1st time we study the energy density in the “transverse” region.
The “Transverse” Regions as defined by the Leading Jet

- Look at charged particle and calorimeter tower correlations in the azimuthal angle $\Delta \phi$ relative to the leading calorimeter jet (MidPoint, $R = 0.7$, $f_{\text{merge}} = 0.75$, $|\eta| < 2$).
- Define $|\Delta \phi| < 60^\circ$ as “Toward”, $60^\circ < -\Delta \phi < 120^\circ$ and $60^\circ < \Delta \phi < 120^\circ$ as “Transverse 1” and “Transverse 2”, and $|\Delta \phi| > 120^\circ$ as “Away”. Each of the two “transverse” regions have area $\Delta \eta \Delta \phi = 2 \times 60^\circ = 4 \pi/6$. The overall “transverse” region is the sum of the two transverse regions ($\Delta \eta \Delta \phi = 2 \times 120^\circ = 4 \pi/3$).
Look at the “transverse” region as defined by the leading jet (|\eta| < 2) or by the leading two jets (|\eta| < 2). “Back-to-Back” events are selected to have at least two jets with Jet#1 and Jet#2 nearly “back-to-back” (\Delta\phi_{12} > 150^\circ) with almost equal transverse momenta (P_T(jet#2)/P_T(jet#1) > 0.8) and P_T(jet#3) < 15 GeV/c.

Shows the \Delta\phi dependence of the charged particle density, dN_{chg}/d\eta d\phi, for charged particles in the range P_T > 0.5 GeV/c and |\eta| < 1 relative to jet#1 (rotated to 270^\circ) for 30 < E_T(jet#1) < 70 GeV for “Leading Jet” and “Back-to-Back” events.
Plot shows the “Transverse” charged particle density versus $P_T$(charged jet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).
“TransDIF” PTsum Density
PYTHIA Tune A vs HERWIG

“TransDIF” is very sensitive to the “hard scattering” component of the “underlying event”!

Use the leading jet to define the MAX and MIN “transverse” regions on an event-by-event basis with MAX (MIN) having the largest (smallest) charged PTsum density.

Shows the “transDIF” = MAX-MIN charge PTsum density, dPT_sum/dηdφ, for p_T > 0.5 GeV/c, |η| < 1 versus P_T(jet#1) for “Leading Jet” and “Back-to-Back” events.
Shows the charged PTsum density, \( \frac{dPT}{d\eta d\phi} \), in the “transMAX” and “transMIN” region \( (p_T > 0.5 \text{ GeV/c}, |\eta| < 1) \) versus \( P_T(\text{jet#1}) \) for “Leading Jet” and “Back-to-Back” events.

Compared the (corrected) data with PYTHIA Tune A (with MPI) and HERWIG (without MPI) at the particle level.
Shows the ETsum density, \(d\text{ET}_{\text{sum}}/d\eta d\phi\), in the “transMAX” and “transMIN” region (all particles \(|\eta| < 1\)) versus \(P_T(jet#1)\) for “Leading Jet” and “Back-to-Back” events.

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"TransMAX/MIN" ETsum Density

PYTHIA Tune A vs JIMMY

- Shows the ETsum density, $d\text{ET}_{\text{sum}}/d\eta d\phi$, in the "transMAX" and "transMIN" region (all particles $|\eta| < 1$) versus $P_T(\text{jet#1})$ for "Leading Jet" and "Back-to-Back" events.

- Compares the (corrected) data with PYTHIA Tune A (with MPI) and a tuned version of JIMMY (with MPI, $P_T\text{JIM} = 3.25$ GeV/c) at the particle level.

JIMMY was tuned to fit the energy density in the "transverse" region for "leading jet" events!
Shows the charged PTsum density, \( d\text{ET}_{\text{sum}}/d\eta d\phi \), in the “transMAX” and “transMIN” region \((p_T > 0.5 \text{ GeV}/c, |\eta| < 1)\) versus \( P_T(jet#1) \) for “Leading Jet” and “Back-to-Back” events.

Compares the (corrected) data with PYTHIA Tune A (with MPI) and a tuned version of JIMMY (with MPI, \( PT_{\text{JIM}} = 3.25 \text{ GeV}/c \)) at the particle level.
Shows the charged particle density, \(dN_{\text{ch}}/d\eta d\phi\), in the “transMAX” and “transMIN” region (\(p_T > 0.5\) GeV/c, \(|\eta| < 1\)) versus \(P_T(\text{jet#1})\) for “Leading Jet” and “Back-to-Back” events.

Compares the (corrected) data with PYTHIA Tune A (with MPI) and a tuned version of JIMMY (with MPI, \(PT_{\text{JIM}} = 3.25\) GeV/c) at the particle level.
“TransMAX/MIN” $<P_T>$
PYTHIA Tune A vs JIMMY

- Shows the charged particle $<P_T>$ in the “transMAX” and “transMIN” region ($p_T > 0.5$ GeV/c, $|\eta| < 1$) versus $P_T(jet\#1)$ for “Leading Jet” and “Back-to-Back” events.

- Compares the (corrected) data with PYTHIA Tune A (with MPI) and HERWIG and a tuned version of JIMMY (with MPI, $PT\text{JIM} = 3.25$ GeV/c) at the particle level.
The KT algorithm works fine at the Tevatron and theory/data (CTEQ61M) look flat!

The measured the inclusive b-jet section, b-bbar jet cross section and correlations, are behaving as expected from theory - nothing goofy!

We are making good progress in understanding and modeling the “underlying event”. We have PYTHIA Tune A and JIMMY tune A, however, we do not yet have a perfect fit to all the features of the “underlying event”. We are working on new improved Run 2 tunes!
The Future

Some CDF-QCD Group Analyses!

- Jet Cross Sections and Correlations: MidPoint and KT algorithms with $L = 1 \text{ fb}^{-1}$!
- DiJet Mass Distributions: $\Delta\phi$ distribution, compositness.
- Heavy Flavor Jets: b-jet and b-bbar jet cross sections and correlations.
- Z and W Bosons plus Jets: including b-jets.
- Jets Fragmentation: jet shapes, momentum distributions, two-particle correlations.
- Underlying Event Studies: distributions as well as averages for charged particles and energy for jet, jet+jet, $\gamma$+jet, Z+jet, and Drell-Yan.
- Pile-Up Studies: modeling of pile-up.
- Monte-Carlo Tuning: New Run 2 PYTHIA tune, tuned JIMMY, PYTHIA 6.3, Sherpa, etc..

Analyses using 1fb$^{-1}$ of data by Winter 2006!
The Past

Feynman, Field, & Fox (1978)

Predict large “jet” cross-section

CDF (2005)

Feynman quote from FFF:
“At the time of this writing, there is still no sharp quantitative test of QCD. An important test will come in connection with the phenomena of high P_T discussed here.”

CDF Run II Preliminary
$\sqrt{s}=1.96$ TeV  $L=385$ pb$^{-1}$

30 GeV/c!