QCD Studies at the Tevatron

Craig Group
for the CDF and DØ Collaborations

Fermilab

Rencontres de Physique de La Vallee d’Aoste
February 26th, 2008
Outline

1 Introduction
   - The FNAL Tevatron
   - The CDF and DØ Experiments
   - QCD Jet Production

2 Recent QCD Results
   - Jet Cross Sections
   - Underlying Event Studies at CDF
   - Vector Boson + Jet Production

3 Summary and Conclusions
The Tevatron currently provides the highest energy proton-antiproton collisions in the world: $\sqrt{s} = 1.96$ TeV.
About 3 \( fb^{-1} \) of integrated luminosity recorded by CDF and DØ
(More than 30 \( \times \) the Run I integrated luminosity)
Expect 6 – 8 \( fb^{-1} \) by end of 2009!
The jet measurements discussed here rely on several components of the general-purpose CDF and DØ detectors:

- Luminosity measurement
- Silicon vertex detector
- Central tracking chamber
- Electromagnetic Calorimeters: Jets, e, and γ
- Hadronic Calorimeters: Jets
- Muon chambers
Many other Tevatron results to be presented this week:

- **On Wednesday:**
  - Electroweak results
  - Precision Top quark mass
  - Top properties
  - Single Top searches

- **On Wednesday:**
  - B states
  - CPV and $B_s$

- **On Thursday:**
  - Higgs searches
  - SUSY searches
  - Other exotic searches

- **On Friday:**
  - Project X
Model of hadronic collisions:

- **Perturbative** components:
  - 2→2 ‘hard’ scattering
  - Initial and final state radiation (parton shower)

- **Non-perturbative** contributions:
  - Underlying event
    - Beam-beam remnants
    - Multiple parton interactions
  - Hadronization effects

"Hard" Scattering Event

Simple model of hadronic collision
QCD color-confinement and detector effects make the picture more complicated

- Colored partons hadronize into color neutral hadrons.
- Particles from the components of proton-antiproton collision are indistinguishable.
- Jet clustering algorithms combine the particle energies from the event to form jets.
  ➔ Cone jet algorithms cluster jets based on their separation in rapidity-$\phi$ space.
Jet Cross Sections

Motivation:

- Theoretically simple → fundamental test of pQCD.
- Measurement over 8 orders of magnitude in cross section.
- Wide $P_T$ range → probes running of $\alpha_s$.
- Probe distance scale of order $10^{-19}\,m$.
- Sensitive to new physics → quark substructure.
- Probe large $x$ → constrain gluon PDFs.
Jet Cross Sections at the Tevatron

Benefit of including the forward region:

- High $x$ but low $Q^2$
- Less sensitive to BSM physics
  ➔ Constraints on PDFs
CDF and DØ: Jet Cross Section Distributions

Inclusive jet cross sections using the Midpoint clustering algorithm

CDF Run II Preliminary \( (L=1.13 \text{ fb}^{-1}) \)

- Data corrected to the hadron level
- Systematic uncertainty
- NLOJET++ + CTEQ 6.1M \( \mu_R = p_T/2, \mu_F = 1.3 \)

Midpoint: \( R = 0.7, f_{\text{merge}} = 0.75 \)

\[
\frac{d^2 \sigma}{dy p_T} (\text{GeV/c})
\]

\[
\begin{array}{c|c}
|y| < 0.1 & (x10^6) \\
0.1 < |y| < 0.7 & (x10^8) \\
0.7 < |y| < 1.1 & (x10^9) \\
1.1 < |y| < 1.6 & (x10^10) \\
1.6 < |y| < 2.1 & (x10^11) \\
\end{array}
\]

- CDF Run II
- \( |y| < 0.4 \) (x32)
- \( 0.4 < |y| < 0.8 \) (x16)
- \( 0.8 < |y| < 1.2 \) (x8)
- \( 1.2 < |y| < 1.6 \) (x4)
- \( 1.6 < |y| < 2.0 \) (x2)
- \( 2.0 < |y| < 2.4 \)

\[
\begin{array}{c|c}
L = 1.96 \text{ TeV} \\
R = 0.7 \text{ cone} \\
\end{array}
\]

\[
\begin{array}{c|c}
\text{CTEQ6.5M} & \mu_R = \mu_F = p_T \\
\end{array}
\]

- Compare to CTEQ6.1M PDFs
- Five rapidity regions \( (|y| < 2.1) \)
- Compare to CTEQ6.5M PDFs
- Six rapidity regions \( (|y| < 2.4) \)
CDF: Jet Cross Section Ratio to NLO pQCD

Reasonable agreement with NLO
Systematics are smaller at high y than PDF errors
Recently reduced JES systematic below 2 % over full $P_T$ range.

→ Stronger constraints on PDFs

CDF and DØ observe similar trends at high rapidity.
CDF: Dijet Mass Cross Section

- Used to set limits on:
  - excited quarks
  - massive gluons
  - $Z'$ and $W'$

- See S. Pronko’s talk on Friday:
  “Exotics Searches at the Tevatron”

Nice agreement with NLO PQCD predictions.
CDF: Exclusive Dijet Cross Section

First observation of exclusive dijet production at the Tevatron!
\( p + \bar{p} \rightarrow \bar{p}' + 2jets + \text{rapidity gap} \)

- Calibration channel for exclusive Higgs production at the LHC
- \( \Rightarrow \) Similar theoretical calculation
- Double Pomeron Exchange
- Use Di-jet mass fraction \( R_{jj} \equiv M_{jj}/M_X \)

CDF Run II Preliminary

- \( 3.6 < |\eta_{\text{gap}}| < 5.9 \)
- \( E_{T1}^\text{jet} > 10 \text{ GeV} \)
- \( E_{T2}^\text{jet} < 5 \text{ GeV} \)
- \( \eta^{\text{jet(2)}} < -0.5 \)

\( F_{\text{excl}} = 20.8 \pm 0.8 \% \) (stat. only)

ExHuME (Hadron Level)

- Default
- Derived from CDF Run II
- Preliminary \( \sigma_{jj}^{\text{excl}} (E_T^{\text{min}}) \)
- Systematic Uncertainty
DØ: Triple Differential $\gamma +$ Jet Cross Section

- $\frac{d^3 \sigma}{dp_T^\gamma d\eta^\gamma d\eta^\text{jet}}$
- $30 < dp_T^\gamma < 300$ GeV
- 4 $\gamma$ and jet $\eta$ regions
- NLO QCD (JetPhoX)
- scales = $p_T^\gamma$
- Significantly extends $x$ and $Q^2$ range of previous measurements
- Previous inclusive $\gamma$ measurements observed mediocre agreement

Test NLO predictions over a large $x$ and $Q^2$ range
Theoretical scale variations can not describe all four regions.

Data are outside CTEQ6.1 error bands.

Structure in central result similar to previous results from UA2, CDF, and DØ.

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La Thuile: QCD Studies at the Tevatron
Ratios:

- All photons are central
  - Systematics largely cancel in ratio
  - Total experimental uncertainty < 9%
- Shapes are reproduced by theory
- Quantitative disagreement

\[
\frac{\sigma_{\text{(Region 1)}}}{\sigma_{\text{(Region 3)}}} \text{ (Region 3)}
\]

\[p_T^\gamma (\text{GeV})
\]
Goal: Publish many distributions to help theorists tune MC models

Use leading jet and back-to-back topologies to study the UE event

The transverse regions (TransMAX and TransMIN) are sensitive to the UE observables. Defined as regions with MAX(MIN) densities on event by event basis

Leading jet, (Back-to-back), (Back-to-back exclusive di-jet) and other topologies are used to isolate various components of the collider event
**TransDIF = TransMAX - TransMIN**

- Taking the difference isolates the “hard” component of UE
- TransDIF better modeled by PYTHIA and HERWIG
Important background for searches:

- SUSY searches in MET+jets channel
- Vector Boson + b-jet also crucial to many searches:
  - Single Top quark
  - Higgs WH
  - Higgs ZH
Motivation:
- Test of pQCD
- Important background for SUSY searches

Method:
- Select $Z \rightarrow ee$ events
CDF: $Z + \text{jet cross section}$

**CDF Run II Preliminary**

- **CDF Data** $L = 1.7 \text{ fb}^{-1}$
- **Systematic uncertainties**
- **NLO MCFM CTEQ6.1M**

Corrected to hadron level

$\mu_0^2 = M_Z^2 + p_T^2(Z)$, $R_{\text{sep}} = 1.3$

$\mu = 2\mu_0$ ; $\mu = \mu_0/2$

PDF uncertainties

- **Data / Theory**

<table>
<thead>
<tr>
<th>Data / Theory</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 jet inclusive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\geq ee$ + jets</td>
<td>$Z \rightarrow ee + \geq 1$ jets inclusive</td>
<td>$Z \rightarrow ee + \geq 2$ jets inclusive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Ratio to LO**

<table>
<thead>
<tr>
<th>Ratio to LO</th>
<th>1</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq N_{\text{jets}}$</td>
<td>$\leq 1$</td>
<td>$\geq 1.2 \land</td>
<td>\eta</td>
<td>&lt; 2.8$</td>
<td>$p_T &gt; 30 \text{ GeV/c},</td>
</tr>
</tbody>
</table>

- NLO agrees well with data
- LO-NLO scale factor flat with jet multiplicity
**Motivation:**

- Probe heavy flavor content of the proton
- Important background for Single Top, ZH, and SUSY Higgs.

**Method:**

- Select $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events
- Use $b$-vertex mass to separate $b,c$, and light quark components.
CDF: $Z + b$-jet cross section

Analysis also produced other kinematic distributions to understand where each MC performs better.

<table>
<thead>
<tr>
<th></th>
<th>CDF Data</th>
<th>PYTHIA</th>
<th>ALPGEN</th>
<th>NLO +U.E+hadr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(Z + b\text{jet})$</td>
<td>$0.86 \pm 0.14 \pm 0.12$ pb</td>
<td>$-$</td>
<td>$-$</td>
<td>$0.53$ pb</td>
</tr>
<tr>
<td>$\sigma(Z + b\text{jet})/\sigma(Z)$</td>
<td>$0.336 \pm 0.053 \pm 0.041$%</td>
<td>$0.35$%</td>
<td>$0.21$%</td>
<td>$0.23$%</td>
</tr>
<tr>
<td>$\sigma(Z + b\text{jet})/\sigma(Z + \text{jet})$</td>
<td>$2.11 \pm 0.33 \pm 0.34$%</td>
<td>$2.18$%</td>
<td>$1.45$%</td>
<td>$1.71$%</td>
</tr>
</tbody>
</table>
DØ: W + c-jet cross section

- Test s-quark content of proton
- Important background for stop-quark and Higgs searches

![Diagram of W + c-jet interaction]

- ID W’s with e or μ
- c-quark tagged with μ
- c and W oppositely charged

Reasonable agreement with SM prediction of Alpgen
CDF: $W + b$-jet cross section

This is the dominant background for Single-Top and WH production!!

Phase space definition:
- $e$ or $\mu$ with:
  - $P_T > 20$ GeV/c
  - $|\eta| < 1.1$
- $\nu$ with $P_T > 25$ GeV/c
- 1 or 2 jets with:
  - $P_T > 20$ GeV/c
  - $|\eta| < 2.0$

$$\sigma_{W+b-\text{jets}} \times Br(W \rightarrow l\nu) = 2.74 \pm 0.27\text{(stat)} \pm 0.42\text{(syst)} \text{ pb}$$
Measurements from the Tevatron Run II are defining a new level of QCD precision measurements in hadron-hadron collisions.

- **The Tevatron has a rich program**: Jet cross sections, $W+$jets, $Z+$jets, $b$-jets, UE studies and much more..
- **Inclusive Jets**: CDF and DØ report nice agreement with NLO.
- **$W/Z + heavy flavor** cross sections have been measured
- **Even more**: $\gamma + heavy flavor$, diphoton cross section, fragmentation studies, jet and $b$-jet shapes ..

CDF and DØ are testing and constraining pQCD and also measuring cross sections of important background processes.
Jet Finding Algorithms

Clustering algorithms that ‘map’ the complex collider event onto “jets”.

Desired properties

- Same algorithm at parton, hadron, and detector level
- Infrared and collinear safe
- Fully specified and easy to use
- Independent of detector geometry/granularity

2 types of algorithms employed at CDF

- Cone algorithm: group particles based on separation in $Y - \phi$ space. (Midpoint algorithm)
- $K_T$ algorithm: group particles based on their relative transverse momenta
  (and separation in $Y - \phi$ space).

NOTE: Different algorithms produce different observables. Midpoint and $K_T$ are not expected to produce the same result.
The Midpoint Jet Clustering Algorithm

A basic cone algorithm was used in Run I (JetClu):

- Start with *seed* towers. (calorimeter towers with energy above given threshold)
- Cluster towers within the cone radius.
- Iterate to find stable cone.
- Sensitive to ‘soft’ radiation.

Midpoint algorithm replaced JetClu for Run II at CDF.

- Add extra *seeds* at the midpoint between all stable cones.
- Check for an additional stable cone at the midpoint between all stable cones.
- Less sensitive to ‘soft’ radiation.
The $K_T$ Algorithm

1) Construct for each particle and pair of particles:
   
   \[ d_{ij} \equiv \min(P^2_{T,i}, P^2_{T,j}) \times \frac{\Delta R^2}{D^2} \]  
   and \[ d_i \equiv P^2_{T,i} \]

2) Start with $\min(d_{ij}, d_i)$:
   - If a $d_i$ is the smallest, promote it to a jet.
   - If a $d_{ij}$ is the smallest, combine particles.

3) Iterate until all particles are in a jet.

**$K_T$ Algorithm** is theoretically preferred.
- Infrared and collinear safe to all orders in pQCD.

$K_T$ has been used successfully at e+e- and ep colliders. It is relatively new to the hadron-hadron collider environment.
CDF: $K_T$ Cross Section Distributions

CDF Run II Preliminary

\[ \int L = 0.98 \text{ fb}^{-1} \]

\[ d^2 \sigma / dy dy^{\text{JET}} dp_T^{\text{JET}} \text{ [nb/(GeV/c)]} \]

- Data
- Systematic uncertainties
- NLO: JETRAD CTEQ6.1M corrected to hadron level
- $\mu_R = \mu_F = \max p_T^{\text{JET}} / 2 = \mu_0$
- PDF uncertainties

$K_T D=0.7$

Integrals:
- $|y^{\text{JET}}|<0.1 \times 10^6$
- $0.1<|y^{\text{JET}}|<0.7 \times 10^3$
- $0.7<|y^{\text{JET}}|<1.1$
- $1.1<|y^{\text{JET}}|<1.6 \times 10^3$
- $1.6<|y^{\text{JET}}|<2.1 \times 10^6$
CDF: $K_T$ Ratio to NLO pQCD

CDF Run II Preliminary

$K_T$, $D = 0.7$

- Data ($L = 0.98$ fb$^{-1}$)
- Systematic uncertainties
- PDF uncertainties
- $\mu = 2 \times \mu_0 = \text{max} p_T^{\text{JET}}$
- MRST2004

PDF uncertainties

$|y^{\text{JET}}| < 0.1$

$0.1 < |y^{\text{JET}}| < 0.7$

$0.7 < |y^{\text{JET}}| < 1.1$

$1.1 < |y^{\text{JET}}| < 1.6$

$1.6 < |y^{\text{JET}}| < 2.1$
**b-tagging**

- **b-hadrons** decay in about 450 $\mu m$
- **Secondary vertices** reconstructed via the SVT
- **b-jets** are tagged via the secondary vertex
- **Tagging Efficiency:**
  - $\sim 50\%$ for 50 GeV jets
  - $\sim 25\%$ for 350 GeV jets

**Motivation:**
- **test of pQCD**
- Many backgrounds from b-jets:
  - Top quark physics
  - Low mass SM and SUSY
  - Higgs searches

**Graph:**
- N tagged jets (Data) vs. Mass secondary vertex [GeV/c$^2$]
- CDF RunII Preliminary

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**La Thuile : QCD Studies at the Tevatron**
Beyond Leading-Order

- Leading order MC not reliable for high $P_T$ multi-parton final states
  - MC@NLO : NLO rates for QCD
  - MCFM : NLO parton level MC
  - Alpgen : Leading order with many final state partons

- Need matching schemes to parton shower to avoid double counting
  - MLM Matching
  - CKKW
  - Mrenna-Richardson

- Alpgen + MLM matching provides exclusive N-jet rates.
Matching Example

Event matched, $N_{\text{jet}} = N_{\text{part}} = 3$, keep

NOT matched, $N_{\text{jet}} = N_{\text{part}} = 3$, but $N_{\text{match}} = 2$
   Throw away

Event matched, $N_{\text{jet}} > N_{\text{part}}$, keep for inclusive sample, but throw away for exclusive samples.