Recent QCD Results from the Tevatron

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DØ Calorimeter

- Uranium-Liquid Argon Calorimeter stable, uniform response, radiation hard
- Compensating: $e/\pi \approx 1$
- Uniform hermetic coverage $|\eta| \leq 4.2$, recall $\eta \equiv -\ln[\tan(\theta/2)]$
- Longitudinal Segmentation
  - 4 EM Layers (2,2,7,10) $X_0$
  - 4–5 Hadronic Layers ($6\lambda$)
- Transverse Segmentation
  $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$ in EM
  $\Delta\eta \times \Delta\phi = 0.10 \times 0.10$ otherwise

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Cone Jet Definition

- $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$
- Run I
  - Add up towers around a “seed”
  - Iterate, using “jets” as seeds, until stable
  - Jet quantities: $E_\perp$, $\eta$, $\phi$
  - $E_\perp^{\text{jet}} = \sum_{R \leq 0.7} E_\perp^{\text{tower}}$
- Modifications for Run II
  - Use 4-vector scheme
  - $p_\perp$ instead of $E_\perp$
  - Add midpoints between jets as additional seeds
  - Infrared safe
- Correct to particles

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QCD Results from the Tevatron
Jet Energy Scale

- Measured jet energy is corrected to particle level
  \[ E_{\text{corr}} = \frac{E_{\text{uncorr}} - O}{RS} \]
- O energy due to previous events, multiple interactions, noise, etc. (minimum bias, etc.)
- R calorimeter response to hadrons (includes non-linearities, dead material, etc.)

Measured from \( E_\perp \) imbalance in \( \gamma + \) jet events

- S net fraction of particle-jet energy that remains inside jet cone after showering in calorimeter (jet transverse shapes)

- Large statistical uncertainties and substantial systematic uncertainties (increases with energy due to extrapolation)
- Current \( \gamma + \) jet statistics extends only to about 200 GeV
Dijets in Run II

- Cross section at $E_{CM} = 1.96$ TeV is 2-5 times greater as compared to 1.8 TeV
- Higher statistics allow:
  - Better determination of proton structure at large $x$
  - Testing pQCD at a new level (resummation, NNLO theory, NLO event generators, etc.)
  - Improved searches for new physics (quark compositeness, resonances, etc.)
Dijet Sample Selection

- Selection criteria:
  - \( N_{\text{jet}} \geq 2 \)
  - \( |\eta_{\text{jet}}| < 0.5 \)
  - \( \Delta R = 0.7 \) cone jets

- Data sample
  - \( \text{MET}/p_{\text{T}}^\text{jet} < 0.7 \)
  - Primary vertex:
    - \( |Z_{\text{vertex}}| < 50 \text{ cm} \)
    - \( N_{\text{tracks}} \geq 5 \)
  - Run selection based on hardware status, MET
  - Jet selection based on calorimeter characteristics to reduce fakes and noise (i.e. hot cells)

Integrated Luminosity: 34 pb\(^{-1}\)

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QCD Results from the Tevatron
Trigger Selection

- **Level 1**
  - Hardware trigger
  - Fast calorimeter readout
  - Multi-tower triggers
  - Coverage is $|\eta| < 2.4$

- **Level 2**
  - Software trigger with special hardware
  - Fast calorimeter readout
  - Simple jet clustering

- **Level 3**
  - Software trigger
  - Precision calorimeter readout
  - Simple cone algorithm with $\Delta R = 0.7$ (no splitting & merging)

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<table>
<thead>
<tr>
<th>L3 $p_\perp$ Threshold</th>
<th>Offline $M_{JJ}$ Cut</th>
</tr>
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<tbody>
<tr>
<td>25 GeV</td>
<td>150 GeV</td>
</tr>
<tr>
<td>45 GeV</td>
<td>180 GeV</td>
</tr>
<tr>
<td>65 GeV</td>
<td>300 GeV</td>
</tr>
<tr>
<td>95 GeV</td>
<td>390 GeV</td>
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</tbody>
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Unsmearing Correction

• Jet Energy Resolution
  – Use the data dijet sample
  – Asymmetry measurement
  \[ A = \frac{p_t^{jet1} - p_t^{jet2}}{p_t^{jet1} + p_t^{jet2}} \]
  – Correct for third jets and particle jet resolution

• Dijet Mass resolution unsmearing
  – Smear PYTHIA events in mass bins
  – Gaussian fit to \( \Delta M_{jj}/M_{jj} \) in each bin
  – Fit to
  \[ \frac{\sigma(M_{jj})}{M_{jj}} = \sqrt{\frac{N^2}{M_{jj}^2} + \frac{N^2}{M_{jj}} + C^2} \]
  – Determine unsmearing correction

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Dijet Mass Cross Section

\[ \left\langle \frac{d\sigma}{dM_{JJ}} \right\rangle = \frac{N_{\text{event}}}{L} \frac{1}{\Delta M_{JJ}} \frac{C_{\text{unsmear}}}{\varepsilon_{\text{eff}}} \]

- **Efficiencies**
  - Estimated from data
  - Vertex quality: \(~78\%\)
  - Jet quality: \(~94\%\)

- **10\% normalization uncertainty not shown** (luminosity)

- **NLO pQCD JETRAD compared to data**
  - All scales set equal
  - \(R_{\text{sep}} = 1.3\)

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Theory Comparison

- Main uncertainties: jet energy scale, $p_{\perp}$ resolution, jet quality cuts. (Dominated by jet energy scale.)
- 10% normalization uncertainty not shown.
Inclusive Jet Cross Section

\[
\left\langle \frac{d\sigma}{dp_T} \right\rangle = \frac{N_{\text{event}}}{L \cdot \Delta p_T} \times \frac{C_{\text{unsmear}}}{\varepsilon_{\text{eff}}}
\]

- Event and jet efficiencies are estimated from data
- 10% normalization uncertainty from luminosity is not shown
- The theory is NLO pQCD calculated with JETRAD

\[
\langle\frac{d\sigma}{dp_T}\rangle = [\text{pb} / (\text{GeV}/c)]
\]

\[
D\bar{O} \text{ Run II Data, } L_{\text{int}} = 34 \text{ pb}^{-1}
\]

\[
\text{NLO CTEQ6M, } R_{\text{sep}} = 1.3, \mu_R = \mu_F = \frac{E_T^{\text{max}}}{2}
\]

Cone Algorithm

\[
R_{\text{cone}} = 0.7
\]

\[
|\eta| < 0.5
\]
Inclusive Jet Cross Section

Systematic error band, dominated by energy scale
(10% luminosity normalization not included)

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QCD Results from the Tevatron
CDF Run II Preliminary

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QCD Results from the Tevatron

Collider Detector at Fermilab (CDF)
- New plug calorimeter \((1.1 < |\eta| < 3.6)\)
- New tracking system
- Upgraded trigger

Jet 1
\[ E_T = 583 \text{ GeV (raw)} \]
\[ \eta_{det} = 0.31 \]

Jet 2
\[ E_T = 546 \text{ GeV (raw)} \]
\[ \eta_{det} = -0.30 \]
Inclusive Jet Cross Section

- Repeat Run I analyses
  - Use CDF cone jet algorithm with $R = 0.7$ (JetClu)

- Event selection cuts
  - $|z_{\text{vertex}}| < 60$ cm
  - $\sum E_T < 1500$ GeV
  - $E_T^{\text{missing}} / \sqrt{\sum E_T} < 2$ to 7

\[
\frac{d\sigma}{dE_T} = \frac{N}{\varepsilon L \Delta E_T \Delta \eta}
\]

- Require fully efficient trigger
- Apply jet energy corrections (same as in Run I)

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QCD Results from the Tevatron
Luminosity uncertainty = 6%

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QCD Results from the Tevatron
Corrected: Log

8 orders of magnitude!

CTEQ 6.1: hep-ph/0303013

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QCD Results from the Tevatron
Corrected: Linear

CDF Run II Preliminary

JetClu cone \( R = 0.7 \), \( \sqrt{s} = 1.96 \, \text{TeV} \)

Good agreement (within uncertainties)

Inclusive jet \( E_T \) (GeV)

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QCD Results from the Tevatron
• Higher $\sigma$ in Run II due to higher $\sqrt{s}$

• 3 more bins at high dijet mass

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QCD Results from the Tevatron
Summary

• We have made significant progress on two important QCD measurements
  – Inclusive jet cross-section
  – Di-jet mass cross section

• Data/theory agreement excellent, although errors in this preliminary measurement are larger than our published results.

• Improved statistics for calibration will yield a measurement competitive with published results by summer, with superior results following.

• Analysis efforts ongoing, including a rich diffractive physics effort.
Our Jet Algorithm

- We use a four vector cone algorithm with a radius of 0.7 in \( \eta, \phi \) space
  - Identify seed tower in the calorimeter
  - Using the event’s vertex, assign a four vector to that seed
  - Add all other other four vectors inside \( R \) to generate the jet’s four vector
  - If the jet’s four vector does not line up with the seed’s repeat using the new jet four vector as the seed.

- Changes from Tevatron Run I
  - We use the midpoints between jets as seeds for new jets
  - We use four vectors instead of scalar quantities

The Jet Definition

\[
p^J = (E^J, \vec{p}^J) = \sum_{i \in J} (E^i, p_x^i, p_y^i, p_z^i)
\]

The Jet’s Properties

\[
p_T^J = \sqrt{(p_x^J)^2 + (p_y^J)^2}
\]

\[
y^J = \frac{1}{2} \ln \left( \frac{E^J + p_z^J}{E^J - p_z^J} \right) \quad \varphi^J = \arctan \left( \frac{p_y^J}{p_x^J} \right)
\]
Unsmearing

- The steeply falling cross section means that we get more jets migrating into a bin from its left than its right.
- To unsmear this, we guess an ansatz function for the true cross section and smear it with our jet resolution.
- We vary the ansatz’s parameters to get the best possible fit.
- Lastly, we multiply our data by the same amount that the ansatz is multiplied by to get the smeared ansatz that matches the data.

\[
F(M'_{jj}) = \int_0^{\sqrt{s}} dM'_{jj} f(M'_{jj}) G(M'_{jj} - M_{jj}, M'_{jj})
\]
Unsmearing the Cross Sections

- Because the cross section is steeply falling, imperfect jet resolution causes the cross section to shift to the right.