Inclusive Jet Production at the Tevatron

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On behalf of the CDF Collaboration
Tevatron & CDF II

→ Proton - antiproton collider

→ $\sqrt{s} = 1.96$ TeV (Run I $\rightarrow 1.8$ TeV)

→ CDF detector was highly upgraded for Run II
  - New Silicon tracking, drift chamber and TOF
  - New Plug Calorimeters
  - Upgraded Muon system
  - New DAQ electronics & Trigger
Jets @ Tevatron

Jet production

- Stringent test of p-QCD
  - Over 9 order of magnitude
  - Sensitivity to distances $\sim 10^{-19}$ m
- Tail sensitive to new physics and PDFs

Highest dijet mass so far: Mass $\simeq 1.3$ TeV

- Higher $\sigma_{\text{jet}}$ with respect to RunI
- Increased $p_T$ range for jet production
Run I cross section

- Excess at high-$E_T$ → new physics?
- Important gluon-gluon and gluon-quark contributions at high-$E_T$
- Gluon pdf at high-$x$ not well known
Cross section vs $\eta$

Measurements in the forward region allow to constrain the gluon distribution.
Jet Measurement: Cone algorithms

Precise jet search algorithm necessary to compare with theory

- Run I cone-based algorithm is not infrared/collinear safe to all orders in p-QCD

- Run II ⇒ new cone-based algorithm: MidPoint
  1. Draw a cone of radius $R$ around each seed (CAL tower with $E > 1$GeV) and form “proto-jet”
  2. Draw new cones around “proto-jets” and iterate until stable cone
  3. Put seed in Midpoint ($\eta$-$\phi$) for each pair of proto-jets separated by less than $2R$ and iterate for stable jet
  4. Merging/Splitting
Jets cross sections using MidPoint ($\sim 1\text{fb}^{-1}$)

Results $0.1 < |Y^{\text{Jet}}| < 0.7$

Good agreement with NLO
NLO corrections

For comparison to NLO pQCD calculations corrections have to be applied for Underlying event and Hadronization effect (model dependent)

- Correction parton-hadron level based on PYTHIA Tune A MC
MC modeling

→ Jet Shape measurements
  - Test of parton shower models
  - Sensitive to the underlying event

\[
\Psi(r) = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} P_T(0,r)
\]


• PYTHIA Tune A provides a proper modeling of the underlying event contributions
MidPoint algorithm: merging/splitting

- Look for possible overlap

- Cone-based jet algorithms include an “experimental” prescription to resolve situations with overlapping cones

merged if common E is more than 75 % of smallest jet

This is emulated in pQCD theoretical calculations by an arbitrary increase of the cone size: $R \rightarrow R' = R \ast R_{\text{sep}}$

- Theory suggests to separate jets according to their relative transverse momentum
\textbf{K}_T \text{ algorithm}

\rightarrow \textbf{K}_T \text{ Algorithm preferred by theorists}

\begin{itemize}
  \item Separate jets according to their relative transverse momentum
  \end{itemize}

1. Compute for each pair (i, j) and for each particle (i) the quantities:
   \[ d_{ij} = \min (P_{T,i}^2, P_{T,j}^2) \frac{\Delta R^2}{D^2}, \quad d_i = (P_{T,i})^2 \]

2. Starting from smallest \{d_{ij}, d_i\}:
   \begin{itemize}
     \item If it is a \( d_i \) then it is called a jet and is removed from the list
     \item If it is a \( d_{ij} \) the particles are combined in “proto-jets” (E scheme)
   \end{itemize}

3. Iterate until all particles are in jets

\begin{itemize}
  \item Infrared/collinear safe to all order in p-QCD (relevant for NNLO)
  \item No merging/splitting parameter needed
\end{itemize}

Successfully used at LEP and HERA but its is relatively new in hadron colliders ⇒ more difficult environment (Underlying Event, Multiple pp interactions)
Jets cross sections using $K_T (\sim 1fb^{-1})$

Results $0.1 < |y^{\text{Jet}}| < 0.7$

Good agreement with NLO

Recent CDF publication with 385 pb$^{-1}$
$d_{ij} = \min(\rho^2_{T,i}, \rho^2_{T,j}) \frac{\Delta R^2}{D^2}$

**K_T Jets vs D**

- Parton-hadron corrections are important at low $P_T$ → they are under control
Jets cross sections using $K_T (~1 \text{fb}^{-1})$

**Results**

$|y^\text{Jet}| < 2.1$

Good agreement with NLO
Results with $K_T$: Data/NLO

Measurements in the forward region will allow to reduce the PDFs uncertainties
Inclusive jet cross section measured using ~1fb⁻¹ of CDF Run II data in five rapidity regions (up to \( |Y^{\text{Jet}}| < 2.1 \))

- Using the \( K_T \) algorithm and MidPoint algorithms
- Fully corrected to the hadron level
- Good agreement with theory (corrected for UE / Hadronization)

The \( K_T \) algorithm works fine in hadron colliders

We hope these measurements will be used to further constrain the PDFs (gluon at high \( x \))
Back Up
**MidPoint vs $K_T$-algorithm**

→ An example:

**Raw Jet $P_T$ [GeV/c]**
- JetClu $R=0.7$
- MidPoint $R=0.7$
- $K_T$ $D=1.0$
- $K_T$ $D=0.7$

**Event 1860695 Run 185777**

Only towers with $E_T > 0.5$ GeV are shown

Differences in the number of jets, the jet $E_T$ ...

**Different Cross section measurement**
Previous results with $K_T$-algorithm

- Successfully used at LEP and HERA

Photoproduction at HERA

- Relatively new in hadron colliders

Inclusive Jet Cross Section at Tevatron (RunI)

more difficult environment
(underlying Event, Multiple $p\bar{p}$ interactions)
Jet Energy scale

- Measured E/p using single particles
  - Charged pions, μ’s (J/Psi and W decays)
  - Z→ee mass is used to set absolute EM scale
- E/p used to tune the simulation
  ⇒ GFLASH parameterization of the showering in the calorimeter
- γ-jet balance used to check the jet energy scale

⇒ Systematic uncertainties
- Calorimeter simulation
  - Residual differences between data and simulation in the response of the calorimeter to single particles (E/p)
- Fragmentation
  - Spectra of the particles inside jets
- Stability
  - Calibration fluctuation with time
UE/Hadronization corrections
NLO calculations

$\rightarrow$ JETRAD CTEQ61 package

- $\mu_R = \mu_F = \text{Maximum Jet } P_T/2$

$\rightarrow$ NLO uncertainties

- uncertainties associated to the PDFs

Use the 40 sets corresponding to plus and minus deviations of the 20 eigenvectors
Run I Results

Inclusive Jet cross section

CDF Preliminary $0.1 < |\eta^{jet}| < 0.7$

NLO QCD prediction (EKS)
cteq4m $\mu = E_t/2$ $R_{sep} = 1.3$

$\sqrt{s} = 1.8$ TeV
Statistical Errors Only

Run I data compared to pQCD NLO

(DATA-THEORY)/THEORY

CDF Preliminary
Run 1B (87 pb$^{-1}$) with run 1A results overlayed
NLO QCD CTEQ3M scale Et/2

Statistical errors only

Observed deviation in tail ....... was this a sign of new physics?
Important **gluon-gluon** and **gluon-quark** contributions at high-$E_T$

Gluon pdf at high-$x$ not well known

...room for SM explanation....
Pythia – Tune A

- Smoothed out probability of Multi-Parton Interaction (MPI) vs impact
- Enhanced Initial State Radiation
- MPIs are more likely to produce gluons than quark-antiquark pairs and MPI gluons are more likely to have color connection to p-pbar remnants

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default</th>
<th>Tune</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PARP(67)</td>
<td>1.0</td>
<td>4.0</td>
<td>Scale factor that governs the amount of initial-state radiation.</td>
</tr>
<tr>
<td>MSTP(81)</td>
<td>1</td>
<td>1</td>
<td>Turns on multiple parton interactions (MPI).</td>
</tr>
<tr>
<td>MSTP(82)</td>
<td>1</td>
<td>4</td>
<td>Double Gaussian matter distribution.</td>
</tr>
<tr>
<td>PARP(82)</td>
<td>1.9</td>
<td>2.0</td>
<td>Cut-off for multiple parton interactions, $P_{T0}$.</td>
</tr>
<tr>
<td>PARP(83)</td>
<td>0.5</td>
<td>0.5</td>
<td>Warm Core: 50% of matter in radius 0.4.</td>
</tr>
<tr>
<td>PARP(84)</td>
<td>0.2</td>
<td>0.4</td>
<td>Warm Core: 50% of matter in radius 0.4.</td>
</tr>
<tr>
<td>PARP(85)</td>
<td>0.33</td>
<td>0.9</td>
<td>Probability that the MPI produces two gluons with color connections to the &quot;nearest neighbors&quot;.</td>
</tr>
<tr>
<td>PARP(86)</td>
<td>0.66</td>
<td>0.95</td>
<td>Probability that the MPI produces two gluons either as described by PARP(85) or as a closed gluon loop. The remaining fraction consists of quark-antiquark pairs.</td>
</tr>
<tr>
<td>PARP(89)</td>
<td>1,000.0</td>
<td>1,800.0</td>
<td>Determines the reference energy $E_0$.</td>
</tr>
<tr>
<td>PARP(90)</td>
<td>0.16</td>
<td>0.25</td>
<td>Determines the energy dependence of the cut-off $P_{T0}$ as follows $P_{T0}(E_{cm}) = P_{T0}(E_{cm}/E_0)^{-PARP(90)}$.</td>
</tr>
</tbody>
</table>