Jet physics at 2 TeV

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On behalf of CDF & D0 Collaborations
Tevatron

- proton-antiproton collisions
\[ \sqrt{s} = 1.96 \text{ TeV} \text{ (Run I } \rightarrow 1.8 \text{ TeV)} \]

- Main injector
  (150 GeV proton storage ring)

- antiproton recycler (commissioning)
  - Electron cooling this year
  - Operational on June'05
  - 40% increase in Luminosity

- 36 bunches (396 ns crossing time)

Long Term Luminosity Projection
(by end FY2009)

\[ \text{Base Goal } \rightarrow 4.4 \text{ fb}^{-1} \]
\[ \text{Design } \rightarrow 8.5 \text{ fb}^{-1} \]
Tevatron plans to deliver 300 pb-1 in FY04
CDF Detector

- Upgraded Muon Detectors
- New TOF Detector
- New Plug Calorimeters
- New Drift Chamber
- New Silicon Tracking
CDF Run II Data

CDF Efficiency > 80%

DAQ runs with 5% to 10% dead time
Rest coming from very careful operation of detector’s HV due to machine losses
(…to preserve silicon & trackers…)

CDF -> ~450 pb-1 on tape
The DØ Detector

- Upgraded muon coverage
- New Tracking System
- New Silicon Micro-vertex
- New Solenoid
- New Pre-showers
DØ Run II Data

DØ operating well and recording physics quality data with very high efficiency (~ 85%)

DØ -> ~390 pb⁻¹ on tape
Jet Physics at 2 TeV

- Jet Cross Sections**
  - Jet Algorithms
  - Data vs NLO pQCD
  - PDFs uncertainties
  - Soft contributions
- Underlying Event
- Dijet $\Delta \phi$ correlations
- Jet Shapes
- Boson +jet production
- B-jet production

**Big increase in x-section thanks to new $\sqrt{s}$
Jet algorithms & physics

- Final state partons are revealed through collimated flows of hadrons called jets

- Measurements are performed at hadron level & theory is parton level (hadron \(\rightarrow\) parton transition will depend on parton shower modeling)

- Precise jet search algorithms necessary to compare with theory and to define hard physics

- Natural choice is to use a cone-based algorithm in \(\eta-\phi\) space (invariant under longitudinal boost)
Run I -> Cone algorithm

1. Seeds with $E_T > 1$ GeV

2. Draw a cone around each seed and reconstruct the “proto-jet”

$$E_T^{\text{jet}} = \sum_k E_T^{k},$$

$$\eta^{\text{jet}} = \sum_k \frac{E_T^{k} \cdot \eta_k}{E_T^{\text{jet}}}, \quad \phi^{\text{jet}} = \sum_k \frac{E_T^{k} \cdot \phi_k}{E_T^{\text{jet}}}$$

3. Draw new cones around “proto-jets” and iterate until stability is achieved

4. Look for possible overlaps

pQCD NLO uses larger cone $R' = R_{\text{sep}} \times R$ to emulate experimental procedure

merged if common $E_T$ is more than 75% of smallest jet
Run I Results

Inclusive Jet cross section

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

CDF

1994-95
1992-93

NLO QCD prediction (EKS)

teq4m $\mu=E_t/2$ $R_{sep}=1.3$

$\sqrt{s}=1.8\text{TeV}$

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 $E_t/2$

Statistical errors only

Observed deviation in tail ....... was this a sign of new physics?
Important gluon-gluon and gluon-quark contributions at high-$E_T$... room for SM explanation...
Measurements in the forward region allow to constrain the gluon distribution.

Big uncertainty still remains for high-x gluons.

\[ \frac{d\sigma}{dE_T^{jet}} \]

\[ \sqrt{s} = 1.8 \text{TeV} \]

- NLO QCD
  (JETRAD, CTEQ4M)
Run II Inclusive Cross Section

- Using Run I cone algorithm & unfolding, $E_T^{\text{jet}}$ range increased by $\sim 150 \text{ GeV}$

- Comparison with pQCD NLO (over almost nine orders of magnitude)

Data dominated by jet energy scale
NLO error mainly from gluon at high $x$

No hadronization corrections applied to NLO prediction $\rightarrow$ relevant at low $E_T^{\text{jet}}$
Highest Mass Dijet Event

\[ E_T = 666 \text{ GeV} \]
\[ \eta = 0.43 \]

\[ E_T = 633 \text{ GeV} \]
\[ \eta = -0.19 \]

Dijet Mass = 1364 GeV
(probing distance \( \sim 10^{-19} \) m)
Notes on Run I Jet algorithm

Cone algorithm not infrared safe:

The jet multiplicity changed after emission of a soft parton

Cone algorithm not collinear safe:

Replacing a massless parton by the sum of two collinear particles the jet multiplicity changes

Fixed-order pQCD calculations will contain not fully cancelled infrared divergences:

- Inclusive jet cross section at NNLO
- Three jet production at NLO
- Jet Shapes at NLO
Fixed-order pQCD NLO calculations rely on exact cancellations of collinear and soft singularities between diagrams.

Infrared/collinear unsafe clustering leads to partial cancellations and introduces logarithmic dependence on soft emission.

Slicing method parameter $S_{\text{min}} = \min(M_{ij})$ (flat for well defined NLO calculation)
3-jet production vs NLO pQCD

Run I cone (R=0.7)

\[ E_T^{\text{jet}} > 20 \text{ GeV}, \ |\eta| < 2.0 \]

\[ \sum_{3 \text{ jets}} E_T^{\text{jet}} > 320 \text{ GeV} \]

Jet separation \( \Delta R > 1.0 \)

Dalitz variables in c.m.s of 3-jets

\[ X_i = \frac{2 \cdot E_i^{\text{jet}}}{M_{3 \text{ jets}}} \quad i = 3, 4, 5 \]

\[ X_3 > X_4 > X_5; X_3 + X_4 + X_5 \equiv 2 \]
Run II -> MidPoint algorithm

1. Define a list of seeds using CAL towers with $E_T > 1$ GeV

2. Draw a cone of radius $R$ around each seed and form “proto-jet”
   \[ E_{\text{jet}} = \sum_k E^K, \quad P_{i,\text{jet}} = \sum_k P_{i,K} \]
   (massive jets: $P_{T,\text{jet}}, Y_{\text{jet}}$)

3. Draw new cones around “proto-jets” and iterate until stable cones

4. Put seed in Midpoint ($\eta-\phi$) for each pair of proto-jets separated by less than $2R$ and iterate for stable jets

5. Merging/Splitting

Cross section calculable in pQCD

Arbitrary $R_{sep}$ parameter still present in pQCD calculation …
Agreement with theory within systematic uncertainties (dominated by jet-energy scale)

Inclusive jet $p_T$ cross section

NLO uncertainty due to gluon @ high x

Hadronization Corrections needed?
Dijet mass cross section

Look for narrow resonance in Dijet Mass spectrum

statistical errors only

DØ Run II preliminary

\(<d\sigma/dM_{jj}, \text{ pb/GeV}\>\)

\(\text{NLO (JETRAD) CTEQ6M} \quad R_{\text{sep}} = 1.3, \mu_R = \mu_F = 0.5 p_T^{\text{max}}\)

\(\text{cone } R = 0.7, |y_{\text{jet}}| < 0.5\)

\(M_{jj}, \text{ GeV/c}^2\)

Data/theory agree within large systematic errors (mainly jet-energy scale)
Measurements on large $|Y|$ range
Constrain gluon at high $x$
Good agreement with NLO pQCD

Measurements dominated by uncertainty on the jet energy scale
(to be highly improved soon)
Jet Production with $K_T$

- Inclusive $K_T$ algorithm
  \[ d_{ij} = \min(P_{T,i}^2, P_{T,j}^2) \frac{\Delta R^2}{D^2} \]
  \[ d_i = (P_{T,i})^2 \]
- Infrared/collinear safe (theoretically preferred)
- No merging / splitting
- Reasonable data-theory agreement
- NLO still needs to be corrected for Hadronization / Underlying Event
- High-Pt tail to be watched closely...
As $D$ increases data departs from pQCD NLO → more soft contributions
A typical Tevatron dijet event consists of:

- hard interaction
- initial/final gluon radiation
- secondary semi-hard interactions
- interaction between remnants

Underlying Event contribution must be removed from the jets before comparing to NLO QCD predictions.

Precise jet measurements require good modeling of the underlying event.

Interplay between pQCD and non-pQCD physics……
Underlying Event Studies (Run I)

<table>
<thead>
<tr>
<th>π</th>
<th>Away Region</th>
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<tbody>
<tr>
<td>Q</td>
<td>Transverse Region</td>
</tr>
<tr>
<td>Leading Jet</td>
<td>Toward Region</td>
</tr>
<tr>
<td>Toward Region</td>
<td>Transverse Region</td>
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<td></td>
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</tbody>
</table>

Jet #1 Direction

"Toward-Side" Jet

"Transverse" Jet

"Away-Side" Jet

$p_T^{\text{track}} > 0.5 \text{ GeV}, \ |\eta^{\text{track}}| < 1$

Transverse region sensitive to soft underlying event activity

Good description of the underlying event by PYTHIA after tuning the amount of initial state radiation, MI and selecting CTEQ5L PDFs (known as PYTHIA Tune A)
New Underlying Event Studies

Back-to-Back
\[ \frac{E_T(\text{jet#2})}{E_T(\text{jet#1})} > 0.8 \]
\[ \Delta\phi_{12} > 150^\circ \]

Suppresses contribution from additional hard radiation

Pythia Tune A describes the data

Herwig underestimates UE activity

Extended to 250 GeV jets
New Underlying Event Studies

- MAX (MIN) for the largest (smallest) charged particle density in transverse region

- MAX-MIN sensitive to remaining hard contribution

- MIN specially sensitive to the remnant-remnant contribution
Studies on $\Delta \phi$ between jets

LO in $\Delta \phi$  NLO in $\Delta \phi$

LO limited at hard (Mercedes Star) and soft limits for third emission

NLO closer to data...however soft gluon contributions are needed

Parton shower MC approximates the required re-summed calculation
ΔΦ distribution shows sensitivity to different modeling of parton cascades

HERWIG similar to PYTHIA Tune A (enhanced ISR) provides best description across the different regions in jet $p_T$

PYTHIA Tune A (enhanced ISR) provides best description across the different regions in jet $p_T$

ΔΦ & soft gluon radiation

ΔΦ shows sensitivity to

PYTHIA Tune A (enhanced ISR) provides best description across the different regions in jet $p_T$
Studies on Jet Fragmentation

- Jet shape dictated by multi-gluon emission form primary parton

- Test of parton shower models and their implementations

- Sensitive to quark/gluon final state mixture and run of strong coupling

- Sensitive to underlying event structure in the final state

$$\Psi(r) = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{P_T(0,r)}{P_T^{\text{jet}}(0,R)}$$
Jet Shapes Measurements

For central jets in the whole range of jet transverse momentum
• PYTHIA Tune A → describes data (enhanced ISR + MI tuning)
• PYTHIA default too narrow
• PYTHIA default (w/wo MI) similar
• HERWIG too narrow at low Pt

Jet shapes

CDF Run II Preliminary

\[ \psi(r/R) \]

- CDF DATA
- PYTHIA Tune A
- PYTHIA
- PYTHIA (no MI)
- HERWIG

\[ 37 < p_T^m < 45 \text{ GeV} \]
\[ 0.1 < |\eta^m| < 0.7 \]

MidPoint Algorithm (R=0.7)

- CDF DATA
- PYTHIA Tune A
- PYTHIA
- PYTHIA (no MI)
- HERWIG

\[ 0.1 < |\eta^m| < 0.7 \]
Jet shapes sensitive to the relative amount of quark- and gluon-jets in the final state and the running of strong coupling.
W+jet(s) Production

- Background to top and Higgs Physics
- Stringent test of pQCD predictions
- Test Ground for ME+PS techniques
  (Special matching → MLM, CKKW to avoid double counting on ME+PS interface)

W + 1 parton +PS

W + 2 partons
**W+ jet(s) Production**

ME+PS implementation tested using the $N^{th}$ jet spectrum in $W+N^{\text{jet}}$ events (more sensitive one)

**Dijet Mass in W+2jets**

- **CDF Run II Preliminary**
  - $W \rightarrow e\nu + \geq 2$ jets, 127 pb$^{-1}$
  - LO QCD $\mu_{RF} = M_{W}^{2}$
  - LO QCD $\mu_{RF} = \langle P_{T}^{2} \rangle$

- **Energy- scale**

- **CDF Data syst. ± Jet Energy Uncertainty**
  - JetClu $R=0.4$ ($E_{T}>15$ GeV, $|\eta_{j}|<2.4$)

**NLO now available for W+2jets**
$\gamma$+heavy flavour production

- Probes heavy-quark PDFs
- Background for SUSY (light stop)
- b/c-quark tag based on displaced vertices
- Secondary vertex mass discriminates flavour

MC templates for b/c & (uds) used to extract b/c fraction in data
\( \gamma \text{-heavy flavour production} \)

Good agreement with LO pQCD within still very large stat. errors

Validates quark flavour separation using secondary vertex mass
Same technique being used to measure b-jet inclusive and dijet production
Summary & Conclusions

• Very Rich Jet Physics Program at Tevatron

• High luminosity measurements will provide constraints to the gluon PDFs at high x and probe distances of $10^{-19}$ m

• Run II will explore different jet algorithms

• Studies of soft-gluon radiations are crucial for a proper comparison with pQCD and background estimations

• Studies of Boson + Jets physics and proper understanding of ME+PS matching important for Higgs

• B-jet Physics program just started... cross sections soon...