QCD Results from

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Outline

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Jet Cross Sections
Multi-jet Production
BFKL Results
Quark/Gluon Jet Structure
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Data Samples

<table>
<thead>
<tr>
<th>Collider Run</th>
<th>D0 Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992-93 @ 1800 GeV</td>
<td>13 pb⁻¹</td>
</tr>
<tr>
<td>1994-95 @ 1800 GeV</td>
<td>92 pb⁻¹</td>
</tr>
<tr>
<td>Dec 1995 @ 630 GeV</td>
<td>0.5 pb⁻¹</td>
</tr>
</tbody>
</table>

Caveat: This is not the entire D0 Run I QCD program - that is impossible in 20 minutes. For a complete list of results look under http://www-d0.fnal.gov/Run2Physics/qcd/
Jet Algorithms at Run 1

**Fixed Cone Algorithm:**

\[
E_T = \sum_i E_{Ti}
\]

\[
\eta_{jet} = \frac{\sum_i E_{iT}^i \eta^i}{\sum_i E_{iT}^i}
\]

\[
\phi_{jet} = \frac{\sum_i E_{iT}^i \phi^i}{\sum_i E_{iT}^i}
\]

Jet Seeds

Calorimeter \(E_T\)

\(\Delta R_{ij}^2 = (\Delta \eta_{ij})^2 + (\Delta \phi_{ij})^2\)

**\(K_T\) Jet Algorithm:**

\[\vec{p}_{ij} = \vec{p}_i + \vec{p}_j\]

\[E_{ij} = E_i + E_j\]

\(d_{i,j} = \min\left(\frac{E_T^2}{i,j}, \frac{E_T^2}{j}, \frac{\Delta R_{ij}^2}{D^2}\right)\)

Jet \(E_T\)

resolution parameter

\(y_{cut} \frac{E_T^2}{Jet}\)
Jet Selection and Corrections

- Acceptance cut on interaction vertex Z position
- Eliminate events with large missing transverse energy
- Apply jet quality cuts

Jet energy scale correction: “calorimeter” → “particle” jet

Unfold the effects of finite jet energy resolutions from very steeply falling inclusive jet cross sections

```
E_{true} = \frac{E_{meas} - E_O}{R_{jet} - R_{OOC}}
```

“True” Jet Energy; particle level

Measured Jet Energy

Offset (Ur noise, Mult. Int., pile-up, UE)

Calorimeter Jet Response

Measured in situ using $\gamma$ – Jet $P_T$ balance

Out of Cone Calorimeter Showering
Inclusive Jet Cross Section

$\bar{p}p \rightarrow jet + X$

- How well do we know proton structure (PDFs) ?
- Is NLO ($\alpha_s^3$) QCD "sufficient" ?
- Are quarks composite ?

\[
\frac{1}{\Delta E_T \Delta \eta} \int \int d\eta dE_T \frac{d^2\sigma}{dE_T d\eta} \quad \leftrightarrow \quad \frac{N_{jet}}{\Delta E_T \Delta \eta \varepsilon \int L dt}
\]

$\Delta E_T \rightarrow E_T$ bin size
$\Delta \eta \rightarrow \eta$ bin size
$N_{jet} \rightarrow \#$ of jets in the bin
$\varepsilon \rightarrow$ selection efficiency
$L \rightarrow$ inst. Luminosity
Inclusive Jet Cross Section

\( \sqrt{s} = 1800 \text{ GeV} \)

- DØ Data \(|\eta_{\text{jet}}| < 0.5\)
- JETRAD
- CTEQ3M, \( \mu = 0.5E_T^{\text{max}} \)
- Run 1B \( (\int L dt = 92 \text{ pb}^{-1}) \)

\[
\frac{1}{\Delta \eta \Delta E_T} \int \frac{d \sigma}{d E_T d \eta} d E_T d \eta \quad (\text{fb/GeV})
\]

Cross Section Uncertainty (%)

- Total Error
- Energy Scale (partially correlated)
- Overall Luminosity (fully correlated)
- Resolution (fully correlated)
- Relative Luminosity (partially correlated)
- Jet Selection (fully correlated)

Uncertainties

Statistical error bars & systematic error band
Theory Uncertainties

- NLO pQCD predictions ($\alpha_s^3$):

  - Renormalization Scale (~10%)
  - PDFs (~20% with $E_T$ dependence)
  - Clustering Alg. (~5% with $E_T$ dependence)

- DØ uses: \textbf{JETRAD}
  $\mu = 0.5E_T^{\text{Max}}$, $R_{\text{sep}} = 1.3$

- CDF uses: \textbf{EKS}
  $\mu = 0.5E_T^{\text{Jet}}$, $R_{\text{sep}} = 1.3$

$R_{\text{sep}}$ is the minimum separation of 2 partons to be considered distinct jets
Comparisons to NLO Theory

- No indication of an excess above 350 GeV.
- Good agreement quantitatively as indicated by $\chi^2$ test:

$$\chi^2 = \sum (D_i - T_i) C^{-1}_{ij} (D_j - T_j)$$

$D_i$ and $T_i$ data and theory, $C_{ij}$ covariance matrix.

| Model         | $|\eta| < 0.5$       | $0.1 < |\eta| < 0.7$ |
|---------------|---------------------|----------------------|
| CTEQ 3M       | 25.3 (0.39)         | 32.7 (0.11)          |
| CTEQ4M        | 20.1 (0.69)         | 26.8 (0.31)          |
| CTEQ4HJ       | 16.8 (0.86)         | 22.4 (0.56)          |
| MRS(A')       | 20.4 (0.67)         | 28.5 (0.24)          |
| MRST          | 25.3 (0.39)         | 29.6 (0.20)          |
Rapidity-Dependent Inclusive

- DØ's most complete cross section measurement
- Uncertainty in theory is larger than uncertainty in data!
- Discriminates between PDF
- MRST to improve gluon determination at large x

<table>
<thead>
<tr>
<th>PDF</th>
<th>$\chi^2$</th>
<th>$\chi^2$/dof</th>
<th>Prob</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTEQ3M</td>
<td>121.56</td>
<td>1.35</td>
<td>0.01</td>
</tr>
<tr>
<td>CTEQ4M</td>
<td>92.46</td>
<td>1.03</td>
<td>0.41</td>
</tr>
<tr>
<td>CTEQ4HJ</td>
<td>59.38</td>
<td>0.66</td>
<td>0.99</td>
</tr>
<tr>
<td>MRST</td>
<td>113.78</td>
<td>1.26</td>
<td>0.05</td>
</tr>
<tr>
<td>MRSTgD</td>
<td>155.52</td>
<td>1.73</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>MRSTgU</td>
<td>85.09</td>
<td>0.95</td>
<td>0.63</td>
</tr>
</tbody>
</table>

$\langle d^2\sigma/dE_T d\eta \rangle$ (fb/GeV)

$E_T$ (GeV)

PRL 86, 1707 (2001)

NLO Theory

- 0.0 ≤ $|\eta|$ < 0.5
- 0.5 ≤ $|\eta|$ < 1.0
- 1.0 ≤ $|\eta|$ < 1.5
- 1.5 ≤ $|\eta|$ < 2.0
- 2.0 ≤ $|\eta|$ < 3.0

Nikos Varelas

IPPP Workshop, Durham 2001
Comparison to NLO Theory

Closed: CTEQ4HJ  Open: CTEQ4M  Closed: MRST $g$  Open: MRST
Dijet Mass Spectrum

Experiments in excellent agreement.

Different rapidity ranges and very different analysis techniques.

Reasonable agreement with predictions.

PRL: 82 2457 (1999)
PRD 64, 032003 (2001)
Dijet Mass Cross Section Ratio

\[ \sigma (|\eta_{1,2}| < 0.5) / \sigma (0.5 < |\eta_{1,2}| < 1) \quad (\sqrt{s}=1800 \text{ GeV}) \]

PRL 82, 2457-2462, 1999

- DØ Data
- \( \Lambda^+ = 1.5 \text{ TeV} \)
- \( \Lambda^+ = 2.0 \text{ TeV} \)
- \( \Lambda^+ = 2.5 \text{ TeV} \)
- \( \Lambda^+ = 3.0 \text{ TeV} \)

NLO QCD in good agreement with data

\[ \Lambda > 2.4 - 2.7 \text{ TeV (95\% confidence level)} \]

Systematic Uncertainty \( \sim 8\% \)

Theory uncertainty \( \sim 6\% (\mu), 3\% (\text{PDF}) \)

\[ L_{qq} = \pm \frac{g^2}{2\Lambda_c^2} \bar{q}L\gamma^\mu q_L \bar{q}_L\gamma_\mu q_L \]
What Have We Learned?

- These results extend significantly the kinematic reach of previous studies and are consistent with pQCD calculations over the large dynamic range accessible ($|\eta| < 3$).

- Once incorporated into revised modern PDFs, these measurements will greatly improve our understanding of the structure of the proton at large $x$ and $Q^2$.

- Are gluon distributions at large $x$ enhanced?

  ➔ factor 20 more data in Run II will extend the reach to higher ET and should make the asymptotic behaviour clearer

Tevatron $x$-$Q^2$ reach overlaps and extends reach of DIS
Ratio of Cross Sections

- Express Inclusive Jet Cross Section as dimensionless quantity

$$\frac{E_T^3}{2\pi} \frac{d^2\sigma}{dE_T d\eta}$$

as a function of

$$x_T = \frac{2E_T}{\sqrt{s}}$$

- Various theoretical and experimental uncertainties tend to cancel in the ratio

![Graphs showing the ratio of cross sections for different jet energies and scales.](image_url)
Ratio of Cross Sections

DØ Data

Vary PDF

CTEQ4HJ $\mu = E_T/2$
CTEQ4M $\mu = E_T/2$
CTEQ3M $\mu = E_T/2$
MRST $\mu = E_T/2$

Vary $\mu$-scale

CTEQ3M $\mu = 2E_T$
CTEQ3M $\mu = E_T/2$
CTEQ3M $\mu = E_T$
CTEQ3M $\mu = E_T/4$

- Phys.Rev.Lett.86, 2523 (2001); hep-ex/0012046
- Data 10-15% below NLO QCD
- Uncertainty due to PDFs reduced in the ratio
- Better agreement with NLO QCD in shape than in normalization

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<th>PDF</th>
<th>$\chi^2$ (20 dof)</th>
<th>Prob(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTEQ3M</td>
<td>20.5</td>
<td>42.5</td>
</tr>
<tr>
<td>CTEQ4M</td>
<td>22.4</td>
<td>31.9</td>
</tr>
<tr>
<td>CTEQ4HJ</td>
<td>21.0</td>
<td>40.0</td>
</tr>
<tr>
<td>MRST</td>
<td>22.2</td>
<td>33.0</td>
</tr>
</tbody>
</table>
Jet Cross Section Using $K_T$

- hep-ex/0106032 (accepted by Phys Lett B)
- The first jet cross section measurement at a hadronic collider using $K_T$ algorithm
- Data: $-0.5 < \eta < 0.5$
  $D = 1.0$
- Predictions IR and UV safe
- Merging behavior well-defined for both exp. and theory
Jet Cross Section Using $K_T$

- In NLO QCD, $K_T$ cross section with $D=1.0$ equals Cone cross section with $R=0.7$

- Difference with NLO theory mostly at low $E_T$. 

\[ \chi^2=27\ (31\%) \text{ for } \text{MRST} \]

\[ \chi^2=31\ (15\%) \text{ for } \text{CTEQ4M} \]

\[ \chi^2=27\ (29\%) \text{ for } \text{CTEQ4HJ} \]
K_Τ – CONE Jet p_T: Data and MC

- **DØ Run 1 Data**
- **Herwig MC**
More on $K_T$ Jet Cross Section

- The measured $K_T$ and cone cross sections are consistent with each other if the energy difference between $K_T$ and cone jets is taken into account.

- $K_T$ and NLO cross section difference can be partially explained by:
  - Hadronic Showering effects (parton to particle)
  - Underlying Event uncertainties

\[
\chi^2 \text{ probability increases from } 29\% \text{ to } 44\%\]
Ratio of Multijet Cross Sections

\[ R_{32} = \frac{\sigma_{\geq 3 \text{Jets}}}{\sigma_{\geq 2 \text{Jets}}} \text{ vs } H_T = \sum_{\text{Jets}} E_T \]

- QCD multijet production
  - Background to interesting processes
  - Predict rates at future colliders
- Improve understanding of the limitations of pQCD
  - Prediction is sensitive to choice of renormalization scales
  - Probing the rate of soft gluon emission
- Investigate \( \mu_R \) scale sensitivity with Jetrad
  \[ \mu_R = \lambda H_T \text{ or } \mu_R = \lambda E_T^{\text{max}} \]
Several formulae for $\mu_R$ investigated

$\mu_R$ allowed to differ for jets in the same event - yet agreement not improved

Single-scales seem better than mixed-scales

$0.3*H_T$ is most robust

Need higher order terms for more predictive power

PRL 86, 1955 (2001)
BFKL

In hadron-hadron collisions:

- DGLAP (as in PYTHIA) gluon radiation strongly ordered
- BFKL many gluons all ~ same $p_T$

Look at jets widely separated in rapidity, or at low-$p_T$ multi-jet events -- many gluons of comparable $p_T$ can be present

BFKL provides a way to resum the contribution of these gluons
**BFKL: Decorrelation of Jets**

- **Old DØ data** (PRL 77, 595 (1996))
- **New calculation**
  Kwiecinski et al., hep-ph/0105039
- **The original BFKL formalism** failed to describe azimuthal decorrelation of dijet data
- **New calculation**: includes subleading effects and uses an **effective rapidity difference** $\hat{Y}$ (in place of usual $\Delta Y$)

  ➔ Much better description of tails of the azimuthal distribution

An attempt to find an observable which displays BFKL behavior

DØ measurement of 630/1800 GeV cross section ratio at large rapidity separations

- $E_T > 20$ GeV, $|\eta| < 3$
- use bins such that $x$ and $Q^2$ are the same in the two datasets but different $\Delta \eta \to A, B$
  (Mueller, Navelet)

\[ R = e^{(\alpha_{BFKL} - 1)(\Delta \eta_A - \Delta \eta_B)} \sqrt{|\Delta \eta_A/\Delta \eta_B|} \]

- What’s going on here?
  - data rise stronger than LLA BFKL (and HERWIG)
  - but is asymptotic BFKL expression applicable?
  - careful about effects of equal jet $E_T$ cuts, definition of momentum fraction $x$ of incoming partons, and $Q^2$ restrictions (Andersen, Del Duca, Frixione, Schmidt, Stirling, JHEP 0102, 007 (2001))
Low-\(E_T\) Multijet Events

- At high-\(E_T\), QCD does quite well
- But try looking at multijets at low-\(E_T\)...compare to Pythia
- This region may be sensitive to differences in BFKL and DGLAP descriptions
- Each jet's \(E_T\) > 20 GeV, \(|\eta| < 3\)
- For 2 jets or more, normalization is off, so correct to >40 GeV spectrum

- hep-ex/0106072
DØ Low-\(E_T\) Multijet Events

- Strong shape disagreement at low \(E_T\) for 3 and 4-jet samples
- Strong \(p_T\) ordering in DGLAP suppresses “spectator jets”
- BFKL can enhance radiation of “spectator jets” in initial state

(a) (b) (c)

---

\(E_T\) (GeV) (\(\geq 1\) jet)

\(E_T\) (GeV) (\(\geq 2\) jet)

\(E_T\) (GeV) (\(\geq 3\) jet)

\(E_T\) (GeV) (\(\geq 4\) jet)
Spectator jet in inclusive 3-jet event sample:

- find a pair of “best balanced” jets - angle $\phi_c$
  - distribution more back to back than in Pythia or Jetrad
- 3rd jet relative to these two - angles $\phi_{s1}$, $\phi_{s2}$ (for $|\pi-\phi_c| < 0.4$) - less correlation than in Pythia or Jetrad
Subjet Multiplicity in Quark & Gluon Jets

Motivation:
- Test of QCD: differences of q & g jets
- Separate q jets from q jets (top, Higgs, W+Jets events)

Method:
- Select quark enriched & gluon enriched jet samples
- Compare the subjet multiplicity of jets with same $E_T$ and $\eta$ at center of mass energies 630 and 1800 GeV and infer q and g jet differences

![Graph showing different final state gluon fraction]

Obtain gluon fractions for both energies from Herwig
(59% gluon jets at 1800 GeV; 33% at 630 GeV)
Subjet Multiplicity of Quark/Gluon Jets

- Rerun $k_T$ algorithm on all 4-vectors merged into jet:
  - Recombine energy clusters into subjets separated by $y_{\text{cut}}$ (a resolution parameter)

\[ d_{i,j} = \min\left(\frac{p_{T,i}^2}{\Delta R_{ij}^2}, \frac{p_{T,j}^2}{\Delta R_{ij}^2}\right) > y_{\text{cut}} \frac{p_{T,j}}{\Delta R_{ij}} \]

- Measure Subjet Multiplicity:

\[ R = \frac{\left\langle M_g \right\rangle^{-1}}{\left\langle M_q \right\rangle^{-1}} = 1.84 \pm 0.15 \text{ (stat)} \pm 0.22 \text{ (sys)} \]

**DO data:**

\[ R = 1.84 \pm 0.15 \text{ (stat)} \pm 0.22 \text{ (sys)} \]

**Herwig:**

\[ R = 1.91 \pm 0.16 \text{ (stat)} \]

D0 data:

\[ N_{\text{subjet}}(M) / N_{\text{tot jets}} \]

55 < $p_T$(jet) < 100 GeV

\[ |\eta(jet)| < 0.5 \]

- Gluon jets
- Quark jets

**D0 data:**

- $N_{\text{subjet}}$ vs $y_{\text{cut}}$

- $y_{\text{cut}} \rightarrow 1$, $N_{\text{subjet}} \rightarrow 1$,
- $y_{\text{cut}} \rightarrow 0$, $N_{\text{subjet}} \rightarrow \infty$

**hep-ex/0106040**

accepted by PRD
Subjet Multiplicity of Quark/Gluon Jets

- **Nice agreement with Herwig**
- **Analytic resummed calculation predicts slightly higher multiplicities**

Result is consistent with ALEPH measurement for $y_0 \sim 10^{-3}$
Looking Ahead: Tevatron Run 2

Started March 2001...

- Booster
- Tevatron
- Main Injector & Recycler
- CDF
- DØ
- p source
- 1.96 TeV
Tevatron timeline

1985  First proton-antiproton collisions
1988-89  First physics run, CDF
1992-96  Run 1: 120 pb\(^{-1}\), 1.8 TeV, CDF and DØ
          6 bunches, 3.5 \(\mu\)s between collisions;
          \(L \sim 10^{31}\) cm\(^{-2}\) s\(^{-1}\)
1995    Top Discovery (DØ, CDF)
1996-2001 Major detector upgrades
2001-04 Run 2a: 2 fb\(^{-1}\), 2 TeV
          36 bunches, 396 ns between collisions;
          \(L \sim 2 \times 10^{32}\) cm\(^{-2}\) s\(^{-1}\)
2004    Short shutdown to install new silicon
detectors (+ . . .)
2004-07 Run 2b: \(~ 15\) fb\(^{-1}\) (total)
          99 bunches, 132 ns between collisions;
          \(L \sim 5 \times 10^{32}\) cm\(^{-2}\) s\(^{-1}\)
2007?   LHC operation starts at CERN
Dramatic increase in high $p_T$ cross sections
Large gains in statistics

Dijet Mass Spectrum

JETRAD
CTEQ3M, $\mu = 0.5 E_T^{\max}$
$|\eta_{\text{jet}}| < 0.5$

Ratio of Cross Sections
$\sqrt{s} = 2.0 \text{ TeV}/\sqrt{s} = 1.8 \text{ TeV}$

Dijet Mass (GeV/c$^2$)

$\frac{d\sigma}{dE_M}$ (nb)

$\sqrt{s} = 2.0 \text{ TeV}$
$\sqrt{s} = 1.8 \text{ TeV}$
Jets in Run 2

**High ET jets:**

**Run 2a:**
~100 events ET > 490 GeV  
~1K events ET > 400 GeV

**Run 1:**
16 Events ET > 410 GeV

Great reach at high $x$ and $Q^2$, the place to look for new physics!

**Low ET jets:**

Improvements expected from better tracking measurements
Jet Algorithms in Run 2

- Fermilab Run 2 workshops
  http://theory.fnal.gov/people/ellis/QCDWB/QCDWB.html
- $K_T$ algorithms now in regular use
- **New Cone Algorithm**
  ➔ Theoretical desires
  - infrared and collinear safety
  - avoid ad hoc parameters (like $R_{sep}$)
  - level independence (parton/particle/detector)
  ➔ Cone algorithm improved by
  - clustering 4-vectors
  - modification of seed choices - midpoints
  - seedless algorithm? In development.

- **Experimental tuning**
  ➔ Reduce sensitivity to noise, pileup, negative energies
Jet Events

Using R=0.7 Cone Algorithm with Run 1 corrections

2-jet event
- $E_T^{jet1} \sim 230\text{GeV}$
- $E_T^{jet2} \sim 190\text{GeV}$

3-jet event
- $E_T^{jet1} \sim 310\text{GeV}$
- $E_T^{jet2} \sim 240\text{GeV}$
- $E_T^{jet3} \sim 110\text{GeV}$
- $E_T \sim 8\text{GeV}$
Jet Distributions

Using $R=0.7$ Cone Algorithm (energies partially corrected)

**Single Jet $P_T$**

**Dijet Invariant Mass**
Z → e⁺e⁻ Candidates

2 EM objects, E_T > 20 GeV, isolation and shower shape cuts

L~1.2pb⁻¹

invariant mass (GeV/c²)

(uncalibrated energy scale)
Closing Remarks

● Run 2 at Tevatron has started
  BIG Opportunity for QCD

● In most cases QCD predictions work well,
  especially at moderate to high scales

Issues: Low $p_T$ processes are problematic
  jets and photons
  underlying event (shall we be subtracting it from Jets?)
  event characteristics
  Should we correct jets for hadronization effects?

● Experimental results have recently reached or
  exceeded the accuracy of theoretical predictions
  need for NNLO calculations for jet production

● Any suggestions on studies of particular interest?