QCD at the Tevatron: The Production of Jets & Photons plus Jets

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for the
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Outline

• Introduction to
  – QCD physics
  – The Tevatron and Detectors
  – Jet measurement issues

• Results
  – Jets
  – Photons plus jets
QCD Scattering Processes

- Jets of particles originate from hard collisions between quarks and gluons
- Quark and gluon density described by Parton Distribution Functions (PDFs)
- Proton remnants form underlying event

\[ x_T = \frac{2p_T}{\sqrt{s}} \]

- Inclusive jets: Tevatron Run II 
  \(|y| < 0.4\)
  \(qq \rightarrow \text{jets}\)

- \(gg \rightarrow \text{jets}\)

\(p_T (\text{GeV})\)

fractional contributions
Why Look at Jet Physics?

Measurements of large $p_T$ processes with jet final states:

- Are the dominant process at hadron colliders
- Allow precision tests of pQCD
- Constrain PDFs, fragmentation, and $\alpha_s$
  - Crucial to understand as background to other processes
- Are sensitive to new physics including quark substructure and heavy particles
The Tevatron

- $\sqrt{s} = 1.96$ TeV
- Peak Luminosity: $3.5 \times 10^{32}$ cm$^{-2}$s$^{-1}$
- Over 6 fb$^{-1}$ delivered
- Experiments typically collect data with 80-90% efficiency

Since 3/2001: 6 fb$^{-1}$

3.5 x $10^{32}$
The Detectors

CDF

- Common features
  - Magnetic trackers with silicon vertexing
  - Electromagnetic and hadronic calorimeters
  - Muon systems

- Distinctive features
  - CDF has better track momentum resolution and displaced track triggers at Level 1
  - DØ has finer calorimeter segmentation and a muon system extending farther forward.

DØ calorimeter and pseudorapidity segmentation
Defining Jets

- Run II cone algorithm:
  - Start with seed
  - Add particles with energy in a cone around seed:
    - $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < R_{\text{cone}}$
  - Merge jets if overlap
    - Some differences in DØ and CDF merging, etc.

- Other methods (such as the $k_T$ algorithm) can also be used but not are not used in any of the analysis described today
Jets, Particles, and Partons

- We do not see partons or particles
- Calorimeter ADC counts are corrected to the particle level using the Jet Energy Scale (JES)
- Calibrate using $Z$+jets, $\gamma$+jets, dijets
- JES can include
  - Energy Offset (energy not from the hard scattering process)
  - Detector Response
  - Out-of-Cone showering
  - Resolution
- Energy scale uncertainties typically are the largest systematic errors in jet measurements.
- Correction to parton level requires fragmentation model
Many measured distributions are steeply falling

- Due to finite resolution of the detector, higher bins are preferentially populated
- Unsmearing (unfolding) corrects for this effect
- Different unsmearing methods are used
Analyses to Discuss

• Production of Jets
  – Inclusive Jet Production Cross Section
  – Dijet Mass Production Cross Section
  – Dijet Angles

• Production of Photons Plus Jets
  – Inclusive Photon Production Cross Section
  – Photon plus Jets Production Cross Section
  – Production of Photons plus Heavy Flavors
  – Double Parton Scattering
Inclusive Jet Production

- Large amount of data
- Measurement over large rapidity region up to high $p_T$
• Data and theory agree
• Data favors the lower edge of CTEQ6.1 at high $p_T$

CDF Data/Theory

Midpoint: $R=0.7$, $f_{\text{merge}}=0.75$
Uncertainty & Correlations

- Leading sources of uncertainty are from JES
  - The DØ uncertainties are improved by up to a factor of two in the central region since 2006
- Uncertainties that are 100% correlated can only change measurement normalization
  - Only 5 highest out of 23 correlated uncertainties are shown.
- CDF/DØ are consistent & well-described by NLO pQCD
- Experimental uncertainties are less than PDF uncertainties
  - CTEQ6.5 reduced PDF uncertainties by about a factor of 2 compared to CTEQ6.1
Dijet Mass Cross Section

**Equations and Details:**

- \( E_{\text{jet}} = \Sigma E_i \), \( p_{\text{jet}} = \Sigma p_i \)
- \( M_{jj}^2 = (E_{j1} + E_{j2})^2 - (p_{j1} + p_{j2})^2 \)
- Additional sensitivity to heavy particle resonances

**Graph:**

- CDF Run II Data (1.13 fb\(^{-1}\))
- Systematic uncertainties
- NLO pQCD, CTEQ6.1M corrected to hadron level
- \( \mu = \mu_0 = p_T^{\text{mean jet1,2}}/2 \)

**Graph Details:**

- D0 Preliminary
- \( R_{\text{cone}} = 0.7 \)
- \( L = 0.7 \text{ fb}^{-1} \)
- \( \sqrt{s} = 1.96 \text{ TeV} \)
• Data agrees with MSTW2008 within pdf and scale uncertainties
• Central region is compatible with CTEQ6.6 but not forward regions
CDF Dijet Data/Theory

- Data in good agreement with NLO prediction (CTEQ6.1M)

arXiv:0812.4036 [hep-ex], submitted to PRD
CDF Dijet Resonance Search

- Select jets with $|\eta|<1.0$
- Use midpoint cone algorithm with $R=0.7$
- Select $M_{jj} > 180$ GeV
  - $M_{jj}$ up to 1.3 TeV!
- Fit spectrum with parameterized model shape
  - Described by NLO pQCD
  - No indications for resonances
  - Set limits using Bayesian approach
### Limits from CDF Dijet Mass

<table>
<thead>
<tr>
<th>Exclusion (GeV)</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>280–840</td>
<td>$W'$ (SM couplings)</td>
</tr>
<tr>
<td>320–740</td>
<td>$Z'$ (SM coupling)</td>
</tr>
<tr>
<td>260–870</td>
<td>Excited quark</td>
</tr>
<tr>
<td></td>
<td>(SM couplings)</td>
</tr>
<tr>
<td>260–1100</td>
<td>Color-octet techni-rho</td>
</tr>
<tr>
<td>260–1250</td>
<td>Axigluon &amp; flavor-universal color</td>
</tr>
<tr>
<td>290–630</td>
<td>$E_6$ diquark</td>
</tr>
</tbody>
</table>

Most Stringent limits except for $W'$ and $Z'$

No exclusion for RS Graviton
Search for new physics using $\chi_{\text{dijet}} = \exp(|y_1-y_2|)$

- At LO, related to parton CM scattering angle, $\theta^*$:
  $$\chi_{\text{dijet}} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$
- Enhanced at low $\chi_{\text{dijet}}$ for many new physics models
  - Quark compositeness
  - Large extra dimensions
  - TeV$^{-1}$ extra dimensions

- Examine normalized distribution
  $$(1/\sigma)(d\sigma/d\chi_{\text{dijet}})$$
  to reduce experimental and theoretical uncertainties
- Correct distributions to particle level
- Analyze data in ranges of dijet invariant mass
- Measures angular distributions of a scattering process above 1 TeV
- Good agreement w/QCD, set limits on new physics models
Limits from DØ Dijet Angles

Quark Compositeness:
$\Lambda = 2.58 \text{ TeV}$

A.D.D. LEDs:
$M_S = 1.56 \text{ TeV}$

TeV$^{-1}$ Extra Dims.:
$M_C = 1.42 \text{ TeV}$

Bayesian limits shown
CDF Angle Distribution

- Analysis done in four bins of $M_{jj}$
  - 550-650 GeV
  - 650-750 GeV
  - 750-850 GeV
  - 850-950 GeV
- Analysis uses $\chi = \exp(|\eta_1 - \eta_2|)$
- Fit fractions of $Q^2 = p_T^2$ and $Q^2 = \hat{\sigma}$

![Graphs showing data and MC fits for CDF angle distribution.](image-url)
Limits from CDF Angles

- Study effect of substructure on $\chi$ as a function of scale $\Lambda$ in MC
- Compare ratio of $R(\Lambda)/R(\infty)$ where $R(\Lambda) = (1<\chi<10)/(15<\chi<25)$ in MC and data
  - $R(\infty)$ means no substructure
- Set limit using Cousins-Feldman method
  - $\Lambda > 2.4$ TeV @ 95% CL
Photon Production & Detection

- Direct photons come unaltered from the hard scattering
  - Allows probe of hard scattering dynamics with fewer soft QCD effects
  - Probes gluon PDFs
- Background from neutral mesons and EM object in jets.
  - Use isolated photons
  - Purity of sample must be determined
CDF Photon Purity

- CDF has new measurement of the inclusive isolated photon production cross section using 2.5 fb\(^{-1}\)!
- Use MC to create templates for photon and background isolation.
  - Done in bins of \(p_T\)
- Fit data to combination to determine photon signal fraction
  - Use other methods to determine systematic uncertainty

![CDF Run II Preliminary](image-url)

**CDF Data, L=2.5 fb\(^{-1}\)**

- **Fit result:** \(f S + (1-f) B\)
- **S:** Photon MC
- **B:** Dijet MC
  (no systematics included)

**Signal Fraction (iso<2 GeV)**

- \(f = 0.911 \pm 0.009\)
- \(70<p_T<80\) GeV/c

![CDF Data, L=2.5 fb\(^{-1}\)](image-url)

**Signal Fraction**

- \(E_T > 30\) GeV, \(E_T^{iso} < 2\) GeV
- **Systematic Uncertainty**
  - Z data templates
  - Dijet corrected templates
  - 2-bin method
  - CES/CPR method

Mike Strauss

APS Annual Meeting

May 3, 2009
- Data/theory agree except at low $p_T$
  - Low $p_T$ has historically been an area of disagreement.
  - Measurement to $p_T = 400$ GeV
Photon plus Jet Production

- Investigate source(s) for data/theory disagreement
  - measure differential distributions
  - tag photon and jet
  - reconstruct full event kinematics
- measure in 4 regions of $y_\gamma$, $y_{\text{jet}}$
  - photon: central ($|\eta|<1$)
  - jet: central / forward
  - same side / opposite side
- Dominant production at low $p_T^{\gamma}$ (< 120 GeV) is through Compton scattering: $qg \rightarrow q+g$
  - Probe PDF's in the range $0.007<x<0.8$ and $p_T^{\gamma}=900<Q^2<1.6 \times 10^5$ GeV$^2$

DØ Photon Purity

Neural net is used to determine photon purity

DØ, $I_{\text{int}} = 1 \text{ fb}^{-1}$

- Data
- $\gamma + \text{jet}, \text{Simulation}$
- dijet, Simulation

$1/N dN/dQ_N$

SS

central

DØ, $I_{\text{int}} = 1 \text{ fb}^{-1}$

1.5 < |$y_{\gamma}$| < 2.5, $y_{\gamma}, y_{\text{jet}} > 0$

Fit: $1 - \exp (a + bp_{\gamma}^T)$

- Systematic uncertainty
- Total uncertainty

$|y_{\gamma}| < 1.0$

$|y_{\text{jet}}| < 0.8, y_{\gamma}, y_{\text{jet}} > 0$

$1.5 < |y_{\text{jet}}| < 2.5, y_{\gamma}, y_{\text{jet}} > 0$

OS

forward

$|y_{\gamma}| < 0.8, y_{\gamma}, y_{\text{jet}} < 0$

$p_{\gamma}^T > 15 \text{ GeV}$
All shapes cannot be easily accommodated by any single theory.
DØ Ratio of Regions

- Most errors cancel in ratios between regions (3-9% across most $p_T^\gamma$ range)
- Data & Theory agree qualitatively
- A quantitative difference is observed in the central/forward ratios
- Need improved and consistent theoretical description for $\gamma$+ jet
DØ Photon plus HF (b/c) Jets

- Measure triple differential cross section:
  \[ d^3\sigma/(dp_T \ dy_\gamma \ dy_{\text{jet}}) \]
  - Jet and γ in central region
  - \( y_\gamma y_{\text{jet}} > 0 \)
  - \( y_\gamma y_{\text{jet}} < 0 \)

- Use MC template to determine particle fractions

arXiv:0901.0739 [hep-ex], submitted to PLB
$d^3\sigma / (dp_T^\gamma dp_T^{y_{\text{jet}}})$ (pb/GeV)

DØ, $L_{\text{int}} = 1.0$ fb$^{-1}$

- $y_{\gamma y_{\text{jet}}} > 0$
- $y_{\gamma y_{\text{jet}}} < 0$

- NLO QCD
- CTEQ 6.6M
- $\mu_{R,F,t} = p_T^\gamma$

$\gamma + c + X$

$\gamma + b + X$

$|y| < 1.0$

$|y_{\text{jet}}| < 0.8$

$p_T^{\text{jet}} > 15$ GeV

$x(3.0)$

$x(1.0)$

$x(0.3)$

$x(0.1)$

$p_T^\gamma$ (GeV)
Theory describes data for b jets but not for c jets.

- Disagreement increases with higher $p_T^\gamma$.
- Maybe too little intrinsic charm in proton, or not enough charm in gluon splitting from annihilation process.
• Study reactions in which two partons in a single proton interact
  – May impact PDFs
  – Help understand multiple interactions and high luminosity

\[ \sigma_{DP} = \sigma_{\gamma j} \frac{\sigma_{jj}}{\sigma_{\text{eff}}} \]

Main background

signal
Double Parton Signal Variables

Calculated for the pair that gives the minimum value of $S$.

$$S_{\phi} = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{\Delta \phi(y, i)}{\delta \phi(y, i)}\right)^2 + \left(\frac{\Delta \phi(j, k)}{\delta \phi(j, k)}\right)^2}$$

$$S_{p_T} = \frac{1}{\sqrt{2}} \sqrt{\left|\frac{\Delta p_T(y, i)}{\delta p_T(y, i)}\right|^2 + \left|\frac{\Delta p_T(j, k)}{\delta p_T(j, k)}\right|^2}$$

$$\Delta S = \Delta \phi\left(p_T^{\gamma,jet_i}, p_T^{jet_j,jet_k}\right)$$
The measurement is done in 3 bins depending on the $p_T$ of the 2nd jet:
- 15-20 GeV
- 20-25 GeV
- 25-30 GeV

Lower $p_T$ should have higher fraction of DP events
The measured DP fraction drops from $0.47\pm0.04$ at $15<p_{T2}<20$ GeV to $0.23\pm0.03$ at $25<p_{T2}<30$ GeV.

Effective cross section is approximately the same and averages to $\sigma_{\text{eff}} = 15.1\pm1.9$ mb.

Good agreement with previous measurements by CDF.
Conclusions

• The Tevatron is operating at $\sqrt{s} = 1.96$ TeV with very high luminosity
• QCD measurements using Jets and Photons are probing higher energy scales than ever before
• Current PDFs model most processes quite well
• Still some improvement needed in PDFs at very highest $x$
• No evidence from QCD measurements of any physics beyond the standard model
• QCD will continue to be a rich field of study and extremely important in the LHC era