Hard QCD Results with Jets @ CDF

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Introduction

• Mature QCD studies at the Tevatron benefit physics program at the LHC
  • Challenging measurements, sensitive to (N)NLO effects as well as non-perturbative physics

• Almost any new physics involves QCD
  • Parton Distribution Functions (PDFs) for background and signal processes
  • QCD often a dominant background to new physics
  • e.g. diphotons for Higgs discovery, jet substructure for boosted Higgs, etc.

• Better understanding of QCD means improved sensitivity to new physics
SM  Processes at the Tevatron

QCD jets

Inclusive
W production:
10-15% is W+jets

Dibosons,
t-quark, Higgs,
New Physics?

~10 orders of magnitude!
1. Jets
   - Incl. jets
   - Dijets
   - Jet substructure studies

2. VB+jets
   - W+jets
   - Z+jets

3. VB+HF
   - W+b
   - W+c
   - Z+b

4. Diffraction
   - see talk by Dino Goulianos yesterday
The Tevatron

p-pbar Collisions at $\sqrt{s}=1.96$ TeV
Run II ended September 30th, 2011

- Delivered 12 fb$^{-1}$
- Peak $4.3 \times 10^{32}$ cm$^{-2}$s$^{-1}$
- By comparison, Run I delivered 120 pb$^{-1}$
Which one is a jet at the Tevatron?
Inclusive Jet Cross Section

- Tests pQCD over 8 orders of magnitude
- Highest $p_T > 600$ GeV/c
- Measurements were done with 2 different clustering algorithms: Midpoint cone and $k_T$

PRD 78, 052006 (2008)
Jet production – Precision regime
PDF input

Exp. uncertainties are smaller than theoretical constrain PDF
Conclusions from Les Houches QCD 2011:
“Tevatron jet data vital to pin down high-\(x\) gluon, giving smaller low-\(x\) gluon and therefore larger \(\alpha_s\) in the global fit compared to a DIS-only fit.”
Jet production – Precision regime

$\alpha_s$ measurement

Historical note:

CDF Run I

Then  PRL 88:042001,2002

$\alpha_s(M_Z) = 0.1178 \pm 0.0001^{+0.0081}_{-0.0095} (\text{syst})$

Now: $\alpha_s(M_Z) = 0.1173^{+0.0041}_{-0.0049}$

PRD 80, 111107 (2009)

- Theory: NLO+2-loop threshold corrections
- Significantly improved precision
- Running tested to very high $Q^2$ values
suppression at LO of the background subprocesses ($J_z = 0$ selection rule)

“exclusive channel” → clean signal (no underlying event)
**MOTIVATION**: Mass of high-pT jets - important property, but only theor. studies:

- High mass:
  - QCD NLO predictions for jet mass
    - Ellis *et al.*, 0712.2447
    - Alemeida *et al.*, 0810.0934
  - Such jets form significant background to new physics signals
  - Examples: high $p_T$ tops, Higgs, neutralino ...

Use standard “$e$-scheme” for mass calculation

- 4-vector sum over towers in jet
- Each tower is a particle with $m = 0$
- Four vector sum gives $(E, p_x, p_y, p_z)$

Selection: $>1$ jet

- $p_T > 400$ GeV/c
- $0.1 < |\eta| < 0.7$
Jet Substructure

Jet Mass

• Compare differential jet cross section as a function of jet mass for different algorithms and cone sizes

• In leading-log approximation, a jet typically acquires a large mass due to a single hard gluon emission
Jet Substructure Studies: Angularity and Planar Flow

Jet substructure variables that are insensitive to soft radiation at high jet mass:

**Angularity:**

\[ \tau_a(R, p_T) = \frac{1}{m_J} \sum_{i \in \text{jet}} \omega_i \sin^a \theta_i [1 - \cos \theta_i]^{1-a} \]

- Emphasizes cone-edge radiation
- For large \( m_{\text{jet}} \), has analytic approximation

**Planar flow:**

- \( w_i \) - energy of particle \( i \)
- \( \lambda_1, \lambda_2 \) are eigenvalues

\[ I_{kl}^w = \frac{1}{m_{\text{jet}}} \sum_i \frac{p_{i,k} p_{i,l}}{w_i} \]

\[ Pf \equiv \frac{4\lambda_1\lambda_2}{(\lambda_1 + \lambda_2)^2} \]
MOTIVATION:

V + Jets Processes in many cases are in irreducible backgrounds in searches for new physics

- 30% - 40% uncertainty in some of the processes (boson + HF)

Need dedicated measurements on boson+jets
Measurements are unfolded back to Hadron level

- Combined $Z \rightarrow e^+ e^-$ and $Z \rightarrow \mu^+ \mu^-$ accounting for correlation between uncertainties
- Results updated with $\mathcal{L} = 8 \text{ fb}^{-1}$

Differential distributions in $Z + \geq 3$ jets final state
$Z/\gamma^* \rightarrow l^+l^- + \text{jets}$

Data driven backgrounds
- QCD multi-jet
- $W + \text{jet}$

MC backgrounds
- $Z + \gamma$
- Top
- Diboson
- $Z \rightarrow \tau\tau + \text{jets}$

Z Kinematic region
$66 < M_Z < 116 \text{ GeV/c}^2$
$E_T^l > 25 \text{ GeV/c}, |\eta^l| < 1$

Jet selection
MIDPOINT $R=0.7$ jet
$p_T > 30 \text{ GeV/c}, |Y| < 2.1$

5% to 15% syst. uncertainties
Jet Energy Scale is the dominant

● Total backgrounds between 5%-10%
● Main background is $Z+\gamma$
$Z/\gamma^* \rightarrow l^+l^- + \text{jets}$

Combined electron and muon channels

CDF Run II Preliminary

$\sigma_{\text{N jets}}$ [fb]

RATIO DATA/THORY

$\mu_0 = \frac{1}{2} p_T^l = \frac{1}{2} (\Sigma p_T^l + E_T^l)$

$\mu = 2\mu_0 ; \mu = \mu_0 / 2$

$\mu^2 = <p_T^l>$

$\mu^2 = M_Z^2 + M_1^2 (Z), R_{\text{sep}} = 1.3$

$\mu = 2\mu_0 ; \mu = \mu_0 / 2$

$\mu^2 = <p_T^l>$

$\mu^2 = M_Z^2 + M_1^2 (Z), R_{\text{sep}} = 1.3$

$\mu = 2\mu_0 ; \mu = \mu_0 / 2$

$\mu^2 = <p_T^l> = M_Z^2 + M_1^2 (Z), R_{\text{sep}} = 1.3$

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$\mu = 2\mu_0 ; \mu = \mu_0 / 2$

$\mu^2 = <p_T^l> = M_Z^2 + M_1^2 (Z), R_{\text{sep}} = 1.3$
Good agreement between data and NLO pQCD predictions (BLACKHAT and MCFM)
$Z/\gamma^* \rightarrow \ell^+\ell^- +\text{jets}$

CDF Run II Preliminary

$\frac{d^2\sigma}{dp_T^\ell p_T^{\ell}}$ [fb / (GeV/c)]

$Z/\gamma^*(\rightarrow \ell\ell) + \geq 3\text{ jets inclusive}$

$I = e, \mu$

$p_T^{\ell} \geq 30\text{ GeV/c, } |y^{\ell}| \leq 2.1$

Data / LO BLACKHAT

$p_T^{\ell} [\text{GeV/c}]$

$Z + \geq 3\text{ jets differential distributions compared to NLO pQCD prediction - BLACKHAT+SHERPA}$

$M_{jj}$ is sensitive to resonances production

Main uncertainty comes from fixed order calculation
Some observables like $HT(jet)$ are expected to have larger contribution from NNLO diagrams.

Comparison with different PDF sets
W/Z + HF jets production

Challenging experimental measurements
- b and c identification
- Low statistics

Soft Lepton tag (20% Branching ratio)

Challenging theory predictions
- Large variations wrt to scale choice
- PDF uncertainties at high momentum fraction x

Secondary vertex tag based on large B lifetime
Large background for many rare analysis

\[ \sigma_{(W+b\text{-jets})} \cdot \text{BR}(W \to l\nu) = 2.74 \pm 0.27 \text{ (stat)} \pm 0.42\text{(syst)} \text{ pb} \]

NLO : $1.22 \pm 0.14$ pb  Alpgen: $0.78$ pb

**W+charm Production**

- **Lepton**
  - MET > 25 GeV,
  - $m_T(W) > 20$ GeV/c²
  - $p_T > 15$ GeV/c, $|\eta| < 2.0$
  - $p_T > 25$ GeV/c, $|\eta| < 1$

- **Jet selection**
  - JETCLU R=0.4 jet

**Measurement of W+c production:**
- Sensitive to s-quark PDF; background to single-top and associated WH production

Select events with semi-leptonic $W + \text{one jet}$

Use soft lepton tagging (SLT) to identify heavy-flavour jet

**Exploit opposite charge correlation between W lepton and SLT lepton**

\[
\sigma_{Wc} \times BR(W \rightarrow \ell\nu) = \frac{N_{tot}^{OS-SS} - N_{bkg}^{OS-SS}}{Acc \cdot \int L \, dt}
\]

- $\text{SLT}_e = 13.4 \pm 2.3$ (stat) $\pm 2.4$ (syst) $\pm 1.1$ (lumi) pb
- $\text{SLT}_\mu = 14.2 \pm 6.5$ (stat) $\pm 3.4$ (syst) $\pm 1.2$ (lumi) pb

**Combination:** $13.3 \pm 3.3 - 2.9$ (stat+syst) pb

**NLO prediction:** $11.3 \pm 2.2$ pb
Z+b jets

Test of pQCD calculations and b-quark fragmentation, b-quark PDF
Z+b important background to single-top, ZH, new phenomena

- Measure cross section ratio with respect to Z inclusive and Z+jet
- Z decays leptonically in muons or electrons
- Improved muon identification efficiency obtaining a 30% gain in Z acceptance

Z Kinematic region
\[ 66 < M_Z < 116 \text{ GeV/c}^2 \]
\[ E_T^l > 25 \text{ GeV/c}, \quad |\eta^l| < 1 \]

Jet selection
MIDPOINT R=0.7 jet
\[ p_T > 20 \text{ GeV/c}, \quad |Y| < 1.5 \]

B identification:
Secondary Vertex Tagger
Extract b- jet composition from a fit to Secondary Vertex Mass
**Z+b jets**

- Main Systematic uncertainty due to vertex mass template modeling (9 %)
- Other systematics come from b-tag efficiency, JES, and backgrounds

\[
\frac{\sigma(Z+b)}{\sigma(Z)} = 0.284 \pm 0.029^{\text{stat}} \pm 0.029^{\text{syst}}\%
\]

\[
\frac{\sigma(Z+b)}{\sigma(Z+\text{jet})} = 2.24 \pm 0.24^{\text{stat}} \pm 0.27^{\text{syst}}\%
\]

Good agreement with NLO MCFM

NLO: (range from different scale choice)
\[
\frac{\sigma(Z+b)}{\sigma(Z)} = 0.23 - 0.28\%
\]
\[
\frac{\sigma(Z+b)}{\sigma(Z+\text{jet})} = 1.8 - 2.2\%
\]
Z+b jets – Differential distributions

Dominated by stat. uncertainty

General agreement with theory
Low Energy scan of the Tevatron

Dates: Sept 8\textsuperscript{th} – Sept 16\textsuperscript{th}

Total data taking time:
10 h at 300 GeV
39 h at 900 GeV

Main goals of the program:
1. Study of MB events: charged particle multiplicities, dN/d\eta, etc...
2. Study of UE events
3. Gap-X Gap events

Special trigger table; 3 x 3 bunches, no low-\beta
Asked for \sim 1 interaction/crossing, to maximize singles (no-PU) rate.

Data summary

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>0-bias</th>
<th>Minbias</th>
<th>Gap-X-Gap</th>
<th>Jets</th>
<th>$e,\mu,\nu$</th>
<th>Total # events</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>1.89 M</td>
<td>12.1 M</td>
<td>9.2 M</td>
<td>8.3 K</td>
<td>352</td>
<td>23.2 M</td>
</tr>
<tr>
<td>900</td>
<td>8.0 M</td>
<td>54.3 M</td>
<td>21.8 M</td>
<td>550 K</td>
<td>16 K</td>
<td>84.7 M</td>
</tr>
</tbody>
</table>
Much support from event generator community.

Example of PYTHIA tunes, based on Tevatron 1960 data:

Note big uncertainty at $\sqrt{s} = 300$, even at 900 GeV.

$|y| < 1$, $p_T > 0.5$ GeV

Factor 2 spread!
Conclusions

- Understanding of jet identification, JES, and systematics leads (in many cases) to experimental systematic uncertainties smaller than theoretical uncertainties.

- Next level of measurements:
  - Measurements of jet substructure variables
  - Validating phenomenological models for diffraction

- Comprehensive Tevatron V+jets/HF results provide detailed information for testing latest pQCD calculations and tuning event generators.

More to come from the QCD program at the Tevatron

http://www-cdf.fnal.gov/internal/physics/qcd/qcd.html