W/Z + jet production at Tevatron

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On behalf of the CDF and DØ Collaborations

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Motivation

- Test perturbative QCD at high $Q^2$
- Background for rare SM processes (top, diboson) and new Physics searches
- 30% - 40% uncertainty in some of the processes (boson + HF)
W/Z + Jets results from the Tevatron

Measurements with associated luminosity

<table>
<thead>
<tr>
<th>Final State</th>
<th>DO</th>
<th>UT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z → l⁺l⁻ + Jets</td>
<td>1.0 fb⁻¹</td>
<td>8.2 fb⁻¹</td>
</tr>
<tr>
<td>W + Jets</td>
<td>4.2 fb⁻¹</td>
<td>2.8 fb⁻¹</td>
</tr>
<tr>
<td>Z + b</td>
<td>4.2 fb⁻¹</td>
<td>7.9 fb⁻¹</td>
</tr>
<tr>
<td>W + b</td>
<td>-</td>
<td>1.9 fb⁻¹</td>
</tr>
<tr>
<td>W + c</td>
<td>1.0 fb⁻¹</td>
<td>4.3 fb⁻¹</td>
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New Results
Tevatron

- $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- Peak instantaneous luminosity $\sim 4 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
- $\sim 12$ fb$^{-1}$ of delivered luminosity
- End of Operations → September 30th 2011
DØ and CDF detectors

- Central Tracking systems
- Calorimeters
- Muon detectors
\[ Z/\gamma^* \rightarrow l^+l^- + \text{jets} \]

- Important background for \( ZH \rightarrow ll bb \), SUSY MET + jets
- Test pQCD NLO predictions

Measurements are unfolded back to Hadron level

\[ Z \rightarrow \mu^+\mu^- \text{ and } Z \rightarrow e^+e^- \text{ channels combined accounting for correlation between uncertainties} \]

Measurement in the \( Z \rightarrow e^+e^- \) channel published in PRL 100, 102001 (2008) with 1.7 fb\(^{-1}\)
Data driven backgrounds
- QCD multi-jet
- W + jet
MC backgrounds
- Z + γ
- Top
- Diboson
- Z → ττ + jets

Z/γ* → l⁺l⁻+ jets

Z Kinematic region
- 66 < M_Z < 116 GeV/c²
- E_T^l > 25 GeV/c, |η_l| < 1

5% to 15% systematic uncertainties
Jet Energy Scale is the dominant

Total backgrounds between 5%-10%
Main background is Z+γ
Z + jets

Theory prediction and measured cross sections corrected to Hadron level

Good Agreement between data and NLO pQCD predictions (BLACKHAT and MCFM)
Comparison with different PDF sets

- Dependence on PDF sets is visible only in a few distributions
- MSTW2008 better agrees than CTEQ6.6
- No significant difference between MSTW2008 and NNPDF2.1

Some observables like $H_T^{\text{jet}}$ are expected to have larger contribution at NNLO (Rubin, Salam, Sapeta arXiv:1006.2144)
Z + jets

$Z + \geq 2 \text{ jets } M_{jj}$

$Z + \geq 2 \text{ jets } M_{Z,jj}$

$M_{jj}$ and $M_{Z,ij}$ are sensitive to resonances production.

Main uncertainty comes from fixed order calculation.
$Z + \geq 3 \text{ jets}$

$Z + \geq 3 \text{ jets}$ inclusive $p_T^{\text{jet}}$

CDF Run II Preliminary

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

Many others jets and $Z$ variables measured
W → eν + jets

W Kinematic region

\begin{align*}
M_T^W &> 40 \text{ GeV/c}^2 \\
P_T^e &> 15 \text{ GeV}, |\eta^e| < 1.1 \\
\text{Missing } P_T &> 20 \text{ GeV/c}
\end{align*}

\[ \mathcal{L} = 4.2 \text{ fb}^{-1} \]

MIDPOINT R=0.5 jet

\begin{align*}
p_T &> 20 \text{ GeV/c}, |Y| < 3.2
\end{align*}

Measured differential cross sections as a function of n\textsuperscript{th} leading jet \( p_T \) up to \( W + \geq 4 \) jets final states

Unfolding to Hadron level

- ALPGEN+PYTHIA MC
- Matrix approach with GURU program

$W \rightarrow e\nu + \text{jets}$

$n^{\text{th}}$ leading jet $p_T$ for $W + \geq 1, 2, 3, 4$ jets

Measurements are normalized to $\sigma_W$ to reduce systematic uncertainties.

Data are compared to ROCKET+MCFM and BLACKHAT+SHERPA NLO pQCD predictions.

MSTW2008 PDF set.
$W \rightarrow e\nu + \text{jets}$

Good Agreement between data and NLO pQCD predictions

Large uncertainty coming from the functional form of $\mu$ scale

Theorists are investigating the discrepancy between calculations
$W \rightarrow ev + jets$

$W \rightarrow ev + 3$ jet final state compared to NLO pQCD predictions

$W + \geq 3$ jets measurement compared to NLO pQCD predictions

$W \rightarrow ev + 4$ jet final state compared to LO predictions

$W + \geq 4$ jets final state compared to LO predictions
W → ev + jets

Good Agreement between data and NLO pQCD predictions

σ /σ^−1 ratio reduces scale uncertainty
V + jets non pQCD Correction

- Parton to Hadron correction is a delicate point in V + jets measurements:
  - Larger corrections from UE for larger jet cone radius
  - Larger Hadronization correction for smaller cone radius
- In current analysis hadronization correction is evaluated independently with LO-based tools (PYTHIA and SHERPA)
- Theorists suggested an improvement would come from matching pQCD NLO results with NLO shower programs as MC@NLO and POWHEG (Berger, Bern, Dixon, Cordero, … arXiv 1004:1659)
- In W/Z + jets ratio non pQCD effects are expected to cancel out
W/Z + HF jets production

Challenging experimental measurements
- $b$ and $c$ identification
- Low statistics

Secondary vertex tag based on large $B$ lifetime

Soft Lepton tag (20% Branching ratio)

Challenging theory predictions
- Large variation wrt to scale choice
- PDF uncertainties at high momentum fraction $x$
**Z/γ* → l⁺l⁻+ b-jet**

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

**Jets:**
- Midpoint algorithm
- DR = 0.7
- $p_T \geq 20$ GeV/c
- $|Y| \leq 1.5$

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

\[ L = 7.9 \text{ fb}^{-1} \]
**Z + b-jet**

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

\[
\frac{\sigma_{Z+b-jet}}{\sigma_{Z}} = 2.84 \pm 0.29 \pm 0.29 \times 10^{-3}
\]

\[
\frac{\sigma_{Z+b-jet}}{\sigma_{Z+jet}} = 2.24 \pm 0.24 \pm 0.26 \times 10^{-2}
\]

Good Agreement with NLO MCFM
$\mathcal{L} = 4.2 \text{ fb}^{-1}$

Z + b-jets

\[
\frac{\sigma_{Z+b-\text{jet}}}{\sigma_{Z+\text{jet}}} = 0.0193 \pm 0.0022 \pm 0.0015
\]

PRD 83, 031105 (2011)
**W Kinematic region**

Combined e and μ channels

- $P_T > 20 \text{ GeV}, \mid \eta \mid < 1.1$
- $\text{MET} > 25 \text{ GeV}$

**W + b-jets**

- $\mathcal{L} = 1.9 \text{ fb}^{-1}$

**Vertex Mass Fit**

$\sigma_{W+b} \times \text{Br}(W \rightarrow l \nu)$

- $2.74 \pm 0.27 \pm 0.42 \text{ pb}$

- **ALPGEN** = $0.78 \text{ pb}$

- **NLO pQCD** = $1.22 \pm 0.14 \text{ pb}$

**b-quark composition extracted from fit to secondary vertex mass**

**Figure**

- Jets/0.1 GeV/c^2
- $M_{\text{vert}}$ (GeV/c^2)

**Measured Xs is higher than NLO prediction**

- JetCLU R=0.4 jet
- $E_T > 20 \text{ GeV}, \mid \eta \mid < 2.0$

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PRL 104, 131801 (2010)

Stefano Camarda – QCD@LHC 2011
JETCLU R = 0.4 jet
$E_T > 20$ GeV/c, $|\eta| < 2.0$

W + c (e channel)

Charm-jet identified by soft electron tagging (SLT$_e$) algorithm

$\sigma_{W+c} \times Br(W \rightarrow l \nu) = 21.1 \pm 7.1 (\text{stat}) \pm 4.6 (\text{syst})$ pb

NLO prediction (MCFM): $11.0^{+1.4}_{-3.0}$ pb

Data and NLO in reasonable agreement
W + c (μ channel)

JETCLU R=0.4 jet
p_T^c > 20 GeV/c, |η^c| < 1.5

$\mathcal{L} = 1.8 \text{ fb}^{-1}$

MIDPOINT R=0.5 jet
p_T^c > 20 GeV/c, |η^c| < 2.5

$\mathcal{L} = 1 \text{ fb}^{-1}$

Soft muon tagger

$\sigma_{W+c} \times Br(W \rightarrow l\nu)$

9.8$^{+2.8}_{-1.6}$ (stat)$^{+1.4}_{-0.6}$ (lum) pb

$NLO (MCFM) : 11.0^{+1.4}_{-3.0} \text{ pb}$

$\frac{\sigma_{W+c}}{\sigma_{W+jets}} = 0.074 \pm 0.019 ^{(stat)}_{-0.014 ^{(syst)}}$

LO (Alpgen + Pythia) 0.044$^{+0.012}_{-0.014} \text{ pb}$

Summary

- New precise measurements of Z+jets, Z+b, W+jets
- General good agreement with NLO predictions
- Prospects for Z + ≥1 jet nNLO and W/Z + ≥4 jets NLO comparison
- Ongoing work on Z+b, W+c and W+b updates

More details at:
- http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.htm
BACKUP
Angular distributions

\[ \frac{Z/\gamma^*}{\mu^+\mu^- + \text{jets}} \]

MIDPOINT $R=0.5$ jet

$P_T > 20$ GeV/c, $|Y| < 2.8$

Measurements are normalized to $\sigma_Z$ to reduce systematic uncertainties

Sherpa MC well describes shape but not normalization

W Kinematic region
\[ M_T^{W} > 30 / 40 \text{ GeV/c}^2 \] (\( \mu/e \))
\[ p_T^l > 20 \text{ GeV, } |\eta_1| < 1.1 \]

\[ \mathcal{L} = 2.8 \text{ fb}^{-1} \]

Separate measurements in
\[ W \rightarrow \mu\nu \text{ and } W \rightarrow e\nu \text{ channels} \]

Measured differential cross sections
in several kinematic variables

Alpgen+Pythia MC normalized
to data for each Njet bin in
control region \[ M_T > 20 \text{ GeV} \]
**Z + b-jets**

**e and μ channel combination**

*b-quark composition extracted from fit to secondary vertex mass*

\[
\frac{1}{N} \frac{d \sigma}{d E_T^{b\text{-jet}}} (Z+b\text{-jet}) = 3.32 \pm 0.53 \pm 0.42 \times 10^{-3}
\]

\[
\frac{\sigma_{Z+b-jet}}{\sigma_Z} = 2.8 \times 10^{-3} \left( Q^2 = M_Z^2 + P_{T,Z}^2 \right)
\]

\[
N_{b} = 273 \pm 43
\]

Measurement in agreement with NLO prediction (large uncertainties in both data and theory)

**JETCLU R = 0.7 jet**

**E_T > 20 GeV, |η| < 1.5**

**L = 2 fb^{-1}**

PRD 79, 052008 (2009)
W + 2 jets $M_{jj}$
W + 2 jets $M_{jj}$

CDF evaluated cross section
- $3.1 \pm 0.8$ pb (with $4.3 \text{ fb}^{-1}$)
- $3.0 \pm 0.7$ pb (with $7.3 \text{ fb}^{-1}$)

D0 Result
- $0.82 \pm 0.83$ pb

D0 favors the null hyptotesis
Two experiments are $\sim 2\sigma$ apart

Identified differences in D0 analysis:
- D0 jets corrected for out-of-cone: effective jet threshold lower
- Double QCD contamination from low purity electrons
- Fit procedure morphs $M_{jj}$ To correct for systematics

Ongoing task force at FNAL to understand CDF-D0 different results