Measurements of the Associated Production of a Vector Boson with Jets at D0

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on behalf of the D0 Collaboration

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Outline

- Motivation
- The DØ Detector
- Measurement Strategy
- Results
  - $W + \text{jets}$
  - $\gamma + \text{jets}$
  - $W + b\text{ jets}$
  - $Z + b/c\text{ jets}$
  - $\gamma + b/c\text{ jets}$
- Conclusions
Motivation

- Test of pQCD calculations
  - Recent high jet multiplicity calculations available
  - 5FNS and 4FNS schemes
  - Novel techniques: NLO + Parton Shower merging
- Validation of simulation models
  - Novel techniques for matching Matrix Elements with Parton Shower
- Sensitive to heavy flavor content of the proton
- Backgrounds for variety of precision SM measurements and searches for new physics
  - Top quark properties
  - Study of Higgs Boson
  - SUSY searches (e.g. sbottom)
Results presented based on proton-antiproton collision data at $\sqrt{s}=1.96$ TeV with integrated luminosity of 6.1 – 9.7 fb$^{-1}$
<table>
<thead>
<tr>
<th>Process</th>
<th>Cross Section (fb)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma + \text{jet}$</td>
<td>8.7</td>
<td>arXiv:1308.2708</td>
</tr>
<tr>
<td>$W + \text{jets}$</td>
<td>6.2</td>
<td>arXiv:1302.6508</td>
</tr>
<tr>
<td>$Z + b\text{-jet}$</td>
<td>9.7</td>
<td>PRD 87, 092010 (2013)</td>
</tr>
<tr>
<td>$W + b\text{-jet}$</td>
<td>6.1</td>
<td>PLB 718, 1314 (2013)</td>
</tr>
<tr>
<td>$\gamma + b\text{-jet}$</td>
<td>8.7</td>
<td>PLB 714, 32 (2012)</td>
</tr>
<tr>
<td>$\gamma + c\text{-jet}$</td>
<td>8.7</td>
<td>PLB 719, 354 (2013)</td>
</tr>
<tr>
<td>$Z + c\text{-jet}$</td>
<td>9.7</td>
<td>Preliminary</td>
</tr>
</tbody>
</table>
Measurement of $d^3\sigma / dp_T^\gamma dy^\gamma dy^{jet}$ for

- Central photons: $|y^\gamma| < 1.0$
- Forward photons: $1.5 < |y^\gamma| < 2.5$
- 4 jet rapidity intervals
  - $|y^{jet}| \leq 0.8$
  - $0.8 < |y^{jet}| \leq 1.6$
  - $1.6 < |y^{jet}| \leq 2.4$
  - $2.4 < |y^{jet}| \leq 3.2$
- Configurations with same sign ($y^\gamma y^{jet} \geq 0$) and opposite sign ($y^\gamma y^{jet} < 0$) events

These regions probe different ranges of $x$ and $Q^2$
- varying contribution from gluon-initiated Compton process
- different levels of fragmentation contribution
NLO predictions describe data in almost all rapidity regions with some exceptions

- $p_T^\gamma < 40$ GeV for central photons

Typical uncertainties similar or smaller than PDF + scale uncertainties
**W + Jets Measurements**

arXiv:1302.6508

- Comprehensive study of $W+n$-jet production ($n=1-4$)
  - Measurements of 40 observables
  - Uncertainties smaller or similar compared to theoretical ones
  - Comparison with recent NLO calculations and MCs (PS, ME+PS)
  - Validation of new theoretical approaches and MC tuning

- Measurement of the $n$th-jet rapidity distribution
  - Tests the modeling of parton emission
  - All predictions largely agree in shape at central rapidities
W+Jets Measurements

arXiv:1302.6508

Dependence of mean no of jets in an event on total transverse energy of the hard interaction tested for the first time

- NLO describes $\langle N_{\text{jet}} \rangle$ spectrum over entire $H_T$ range
- Both PS and ME+PS underestimate amount of high $p_T$ jet emission
Heavy Flavor (HF) Jet Tagging

- Long lifetime (~1 ps) of b/c hadrons resulting in displaced secondary vertex.
- Large hadron masses 2-5 GeV
  - Tracks displaced from primary vertex with large impact parameters
- HF tagging exploits characteristics of the tracks to create a discriminant
  - Typically 50-60% efficient for 0.5-1.5% fake rate

![Graph showing MVA output vs. Misidentification Rate](attachment:image.png)

**DØ, Simulation**

- b jets
- light jets

**Background**

**Signal**

- MVA\(_{b}\), \( p_T > 30 \) GeV, \( h_j < 1.1 \)
- NN, \( p_T > 30 \) GeV, \( h_j < 1.1 \)
The tagged sample still has some fraction of misidentified jets.

To further separate jets of different flavors, use a discriminant:

- $M_{\text{SVT}}$ is invariant mass of tracks associated to secondary vertex.
- JLIP is jet lifetime impact parameter.

$$D_{\text{MJJL}} = \frac{M_{\text{svt}}/5 - \ln(\text{JLIP})/20}{2}$$

Fit background subtracted data distribution with the templates to extract the jet flavor fractions:

- For c-jet fraction, fitting with three templates return large uncertainties.
- Fit data with b- and c-jet templates after subtracting the residual contribution of light jets.
$\gamma + b$-jet(s)

\[
\frac{d\sigma}{dp_T^\gamma} = \frac{N_{\text{evt}} \times f_{\gamma} \times f_b}{A \times \varepsilon \times L \times \Delta p_T^\gamma}
\]

Forward photon

Central photon

DØ, L = 8.7 fb$^1$

- Data, $|y| < 1.0$
- Data, $1.5 < |y| < 2.5$
- NLO (Stavreva, Owens)
- $k_T$ fact. (Lipatov, Zotov)
- SHERPA, v1.3.1
- PYTHIA, v6.420

$|y| < 1.5$, $p_T^\gamma > 15$ GeV

(x0.3)
\( \gamma + b\text{-jet(s)} \)

Reasonable description within uncertainties at low \( p_T^\gamma < 70 \text{ GeV} \)

Disagreements (difference in slopes) at higher \( p_T^\gamma \)

- Need for higher order corrections at large \( p_T^\gamma \) dominated by annihilation process, and resummation of diagrams with additional gluon radiation.

Better description by SHERPA and \( k_T \)-factorization approach
W + b-jet(s)

- **W(\rightarrow l\nu) selection**
  - Isolated lepton $p_T > 20$ GeV
  - Muon: $|\eta_{\mu}| < 1.7$
  - Electron: $|\eta_{e}| < 1.1$
    - or $1.5 < |\eta_{e}| < 2.5$
  - Missing $E_T > 25$ GeV

- **Jet selection**
  - $\geq 1$ jet, $R=0.5$
  - $p_T > 20$ GeV, $|\eta| < 1.1$

\[
\sigma(W + b) \cdot B(W \rightarrow \ell\nu) = \frac{N_{W+b}}{\mathcal{L} \cdot \mathcal{A} \cdot \epsilon}
\]
\[
= 1.05 \pm 0.03 \text{ (stat.)} \pm 0.12 \text{ (syst.) pb}
\]
\[
= 1.34^{+0.41}_{-0.34} \text{ (MCFM NLO)}
\]

**Data – Bkg**

<table>
<thead>
<tr>
<th></th>
<th>$W\rightarrow\mu\nu$</th>
<th>$W\rightarrow\nu\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W+b frac.</td>
<td>0.30 \pm 0.04</td>
<td>0.27 \pm 0.03</td>
</tr>
</tbody>
</table>

Measurement consistent with NLO prediction within uncertainties

![Graph showing data and backgrounds](image-url)
\[ \frac{\sigma(Z + b \text{ jet})}{\sigma(Z + \text{ jet})} = \frac{N_{\text{fitted}} f_b}{N_{Z+j} \epsilon_{\text{btag}}^b} \times \frac{A_{\text{incl}}}{A_b} \]

- **Z(\rightarrow ee / \mu \mu) selection**
  - Missing \( E_T < 60 \text{ GeV} \)
- **Jet selection**
  - \( \geq 1 \text{ jet} \)
  - \( p_T > 20 \text{ GeV}, |\eta| < 2.5 \)
- **Measurement of ratio allows for precise comparison with theory**

<table>
<thead>
<tr>
<th></th>
<th>Z→μμ</th>
<th>Z→ee</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data – Bkg</strong></td>
<td>(3,921)</td>
<td>(3,576)</td>
</tr>
<tr>
<td><strong>Z+b %</strong></td>
<td>(21.5 \pm 1.6)</td>
<td>(19.8 \pm 1.9)</td>
</tr>
</tbody>
</table>

- **D0**
  - \(0.0196 \pm 0.0012 \text{ (stat.)} \pm 0.0013 \text{ (syst.)}\)
- **CDF**
  - \(0.0208 \pm 0.0018 \text{ (stat)} \pm 0.0027 \text{ (syst.)}\)

**MCFM [MSTW2008, M_Z^2+Σ(jet p_T)^2]**

\(0.0206^{+0.0022}_{-0.0013}\)
First measurement of the ratio differentially as a function of kinematic observables

σ \((Z+b \text{ jet}) / σ (Z + \text{ jets})\)

Reasonable description within uncertainties at low $p_T^\gamma < 70$ GeV

Systematic disagreement at higher $p_T^\gamma$

Need for HO corrections at large $p_T^\gamma$ dominated by annihilation process, and resummation of diagrams with additional gluon radiation.

Better description by SHERPA and $k_T$-factorization approach
Measurement of ratio allows more precise comparison with theory

Cancellation of many systematic uncertainties

$p_T^\gamma < 70$ GeV: Good agreement with NLO, PYTHIA and SHERPA, while $k_T$-factorization predicts smaller ratios

$p_T^\gamma > 70$ GeV: Data show systematically higher ratios

$k_T$-factorization tend to agree within uncertainties

BHPS model with small shift in normalization should provide better description

Predictions with larger $g \rightarrow cc$ rates ($\sim 1.7$) also provide better description
First measurement of the Z+c-jet production

\[ Z(\rightarrow ee / \mu \mu) \] selection

Jet selection

\[ \geq 1 \text{ jet, } p_T > 20 \text{ GeV, } |\eta| < 2.5 \]

\[
\frac{\sigma(Z + c \text{ jet})}{\sigma(Z + \text{ jet})} = \frac{N_{\text{fitted}} f_c}{N_{\text{pre}}^{Z+j} \epsilon_{\text{tag}}} \times \frac{A_{\text{incl}}}{A_c}
\]

D0

0.0829 ± 0.0052 (stat.) ± 0.0089 (syst.)

MCFM [MSTW2008, \( M_Z^2+\Sigma(\text{jet } p_T)^2 \)]

0.0368^{+0.0063}_{-0.0039}

MCFM [IC model, CTEQ6.6c]

0.0425^{+0.0048}_{-0.0029}

Measurements significantly in excess of predictions

<table>
<thead>
<tr>
<th>For 9.7 fb^{-1}</th>
<th>ee + \mu \mu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data-bkg</td>
<td>2125</td>
</tr>
<tr>
<td>Z+b jet</td>
<td>([51.4 \pm 2.8]) %</td>
</tr>
<tr>
<td>Z+c jet</td>
<td>([48.6 \pm 2.8]) %</td>
</tr>
</tbody>
</table>
Measurements significantly in excess of predictions

Predictions with enhanced $g \rightarrow cc$ rates provide better description
Cancellation of many syst. uncert. in the ratio

Allows for precise comparison with theory calculations

\[
\frac{\sigma(Z + c \text{ jet})}{\sigma(Z + b \text{ jet})} = \frac{f_c \epsilon^b_{\text{tag}}}{f_b \epsilon^c_{\text{tag}}} \times \frac{A_b}{A_c}
\]

Measurements significantly in excess of predictions
Conclusions

- Vector boson + heavy flavor jet production provides a good laboratory for precision tests of pQCD and probes the heavy flavor content of the proton
- Understanding of these processes key for the New Phenomena searches
- Many interesting results from the D0 experiment
  - Extend the previously probed phase space
  - Test various predictions from theory and simulation
  - Important feedback for the theory development & MC tuning
- Compressive study of $W+n$jet and photon+$n$jet production
- Many new measurements on vector boson plus heavy flavor jets
  - First measurement of $Z+c$-jet production
- More interesting measurements in the pipeline. Stay tuned.
Thank You!
Reconstruction
- Hadronic shower
- Iterative mid-point cone algorithm, $R = 0.5$

Jet Energy Scale
- Measured in $\gamma$+jet and Dijet events
- Correct energy to particle level
- Correct for detector response, out of cone showering, overlap with pile up energy

Correct parton-level theory for non-perturbative effects (hadronization and Underlying events) using parton shower Monte Carlo
Measurement of the probability of emission of 3\textsuperscript{rd} jet in the inclusive W+2jet events as a function of

- Dijet rapidity separation of two highest $p_T$ jets
- Dijet rapidity separation of two most rapidity-separated jets
- Dijet rapidity separation of two highest $p_T$ jets and the 3\textsuperscript{rd} jet is emitted into the rapidity interval defined by the two leading jets
FIG. 8: (color online) Comparison of the same-sign to opposite-sign cross section ratios for events with a central central jet and those with a forward photon and very forward jet.