Experimental Studies of W/Z + Jets and W/Z + Heavy Flavor Jets at the Tevatron

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on behalf of the CDF and DØ Collaborations

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Outline:
• Importance of W/Z + jets
• Recent Tevatron progress
• Summary and future
**Importance of W/Z + Jet Physics**

**Why study W/Z + jet production?**

- Important tests of Quantum Chromodynamics (QCD)
- Recent LO and NLO simulations need experimental verification
- Signature shared with top production, Higgs, other searches at Tevatron, LHC

<table>
<thead>
<tr>
<th>Result (1/fb)</th>
<th>DØ</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>W+jets</td>
<td>--</td>
<td>0.320</td>
</tr>
<tr>
<td>Z+jets</td>
<td>0.950</td>
<td>1.700</td>
</tr>
<tr>
<td>W+b-jets</td>
<td>0.382</td>
<td>1.900</td>
</tr>
<tr>
<td>Z+b-jets</td>
<td>0.152</td>
<td>2.000</td>
</tr>
<tr>
<td>W+c-jets</td>
<td>1.000</td>
<td>1.800</td>
</tr>
<tr>
<td>Z+c-jets</td>
<td>--</td>
<td>--</td>
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</tbody>
</table>

NB: New DØ results coming this summer!
The CDF and DØ Experiments

Common features:

- Charged particle tracking in magnetic field
- Electromagnetic and hadronic calorimetry
- Muon detection
- Luminosity monitoring
- Three level event trigger

\[ \phi = \text{azimuthal angle} \]
\[ \eta = -\ln(\tan \frac{\theta}{2}) \]
\[ \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \]
$W + \geq 1$ jet

**CDF Run II Preliminary**

- Data 320 pb$^{-1}$
- Combined
- $W$+jets signal (tt, WZ, WW...)
- Fake $W$ bkgd
- Real $W$ bkgd

$S/B \sim 10/1$

**$W + \geq 2$ jets**

- Data 320 pb$^{-1}$
- Combined
- $W$+jets signal
- Fake $W$ bkgd
- Real $W$ bkgd

$S/B \sim 1.2/1$

**$W + \geq 3$ jets**

- Data 320 pb$^{-1}$
- Combined
- $W$+jets signal
- Fake $W$ bkgd
- Real $W$ bkgd

**$W + \geq 4$ jets**

- Data 320 pb$^{-1}$
- Combined
- $W$+jets signal
- Fake $W$ bkgd
- Real $W$ bkgd

$S/B \sim 1.2/1$

**$W$ selection:** seek $W \rightarrow e \nu$

- $e$: $E_T > 20$ GeV, $|\eta| < 1.1$
- $\nu$: missing transverse energy $\text{MET} > 30$ GeV
- $M_T(W) > 20$ GeV/c$^2$

**Jet definition:** Cone algorithm, $R = 0.4$

- Corrected $E_T > 20$ GeV, $|\eta| < 2.0$
Total cross section for jet multiplicity, $n$:

$$\sigma_n = \sigma(W \rightarrow e\nu + \geq n\text{- jet}; E_T^n > 25)$$

NLO prediction more accurate than LO! ...and relative rates from bin-to-bin consistent with data.
**W + Inclusive Jets**

PRD 77, 011108(R)

Can examine differential cross sections for nth jet within each multiplicity bin....

Total cross section for jet multiplicity, $n$:

$$\sigma_n = \sigma(W \rightarrow e\nu + \geq n - \text{jet}; E_T^n > 25)$$

NLO prediction more accurate than LO!

...and relative rates from bin-to-bin consistent with data.
**W + Inclusive Jets**

![Graph showing data points and uncertainties for W+jets events](chart.png)

**“MCFM”:**
MCFM (NLO) + no shower

**“MLM”:**
ALPGEN (LO) + Herwig (shower) + MLM matching

**“SMPR”:**
MadGraph (LO) + Pythia (shower) + CKKW matching

- **LO calculation procedure:** Generate $p\bar{p}\rightarrow W+N$ partons at tree level, ignore loop corrections, employ parton shower.

- **Ambiguities arise:**
  - Possibility for double counting if $N_{parton} \neq N_{jet}$
  - SMPR and MLM refer to algorithms for avoiding/removing overlaps

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**At LO, MadGraph+Pythia+CKKW provides better performance.**
**W + Inclusive Jets**

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- Ambiguities arise:
  - Possibility for double counting if $N_{\text{partons}}$ at tree level, ignore loop corrections, employ parton shower.
  - SMPR and MLM refer to algorithms for avoiding/removing overlaps.

**But why?** Is it the matrix element? Shower? Matching? Work is ongoing.
Z/γ* + Inclusive Jets

- Validity of NLO predictions borne out in Z/γ*+jets?

- Z/γ* selection: seek Z/γ*→e⁺e⁻
  - Two E_T > 25 GeV electrons
  - 66 < M_{ee} < 116 GeV/c²

- Jet definition:
  - Corrected p_T > 30, |y| < 2.1
  - Cone algorithm, R=0.7

\[
y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right)
\]

- Major backgrounds: S/B ~ 7/1
  - QCD multijets
  - W + jets
  - ttbar, diboson
  - Z+γ, Z→ττ

Can’t see the NLO prediction points - close overlap with data!

NLO prediction once again more accurate than LO!
Z/γ* + Inclusive Jets

- Differential cross section:
  - NLO was good in W+jets, true here too?

  **NLO prediction reliable – as in W+jets**

- Analysis would benefit from increased statistics to further populate the Z+≥2-jets sample

- NLO for Z+≥3-jets would be valuable as well.

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- CDF Data L = 1.7 fb⁻¹
- Systematic uncertainties
- NLO MCFM CTEQ6.1M
  - Corrected to hadron level
  - $\mu_0^2 = M_Z^2 + p_T^2(Z)$, $R_{sep}=1.3$
  - $\mu = 2\mu_0$; $\mu = \mu_0/2$
- PDF uncertainties

**Z/γ*(→ee⁺) + ≥1 jet inclusive**

- Data / Theory

**Z/γ*(→ee⁺) + ≥2 jets inclusive**

- Data / Theory
**DØ Z/γ* (→ee)+jets analysis: 950/ pb**

- **Purpose here:** compare **Pythia** ($p\bar{p} \rightarrow W + 1\text{p}^+$ internal PS) and **Sherpa** ($p\bar{p} \rightarrow W + N\text{p} + \text{internal PS + CKKW matching}$) event generators
  - Test of different prediction techniques
  - Some confidence in CKKW from CDF W+jets LO studies…true here as well?
Sherpa + CKKW represents data better than Pythia

- $p_T$ of jet 1,2,3
- $Z$ $p_T$ Jet multiplicity
- $\Delta \eta$(jet, jet), $\Delta \phi$(jet, jet)

Not unexpected given the nature of Pythia’s calculation.
Summary so far...

- **W/Z+1,2 jet NLO predictions** from MCFM look reliable
- NLO predictions **not yet in hand** for $W/Z+\geq3$ jet
- Technique of calculating/generating $pp\rightarrow W+N+$ parton shower + matching scheme (ala ALPGEN, MadGraph, Sherpa) **superior** to Pythia+PS alone
- Differences among available tools still need to be understood

- **W/Z + heavy flavor ($b,c$) jets also important**
  - background to top, Higgs, others
  - $W+c$ production has unique features
**W + Single c Production**

- **Importance of $W^\pm$ +single c:**
  - Insight on PDF for s at rather large $Q^2$
  - Insight on $|V_{cs}|$
  - Part of $W+$jets bkgd to top, Higgs searches

- **Event selection similar to $W+$jets:**
  - Here use $W \rightarrow e/\mu\nu$ for $W$ selection

- **Exploit $W^\pm$ +single c feature:**
  - charm hadron semileptonic daughter and $W$ have opposite charge

\[
\sigma_{Wc} \times \text{BR}(W \rightarrow \ell \nu) = \frac{N_{\text{OS-SS}}^{\text{Tot}} - N_{\text{OS-SS}}^{\text{Bkg}}}{A \cdot \mathcal{L}}
\]

- **Major opposite-sign (OS) backgrounds:**
  - Drell Yan $\mu^+\mu^-$
  - Fake $W$
  - $Wq$
  - Insensitive to $W+$bb, $W+$cc, (OS/SS random)
**W + Single c Production**

- **Result:** for $p_T^c > 20$, $|\eta^c| < 1.5$
  
  $\sigma_{xBR} = 9.8 \pm 2.8$ (stat) $^{+1.4}_{-1.6}$ (syst) $\pm 0.6$ (lum) pb

- **Prediction:** NLO from MCFM
  
  $\sigma_{xBR} = 11.0 \ ^{+1.4}_{-3.0}$ pb

Good agreement!

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W + Single c Production

- Similar analysis completed at DØ: 1/fb
- Measures the ratio
  \[
  \frac{\sigma(W + \text{single}-c)}{\sigma(W + \text{jets})}
  \]
  which allows for cancellation of many systematic errors
- Result:
  \[
  \frac{\sigma(W + \text{single}-c)}{\sigma(W + \text{jets})} = 0.071 \pm 0.017
  \]
  which can be compared to the LO prediction: 0.040 \pm 0.003 (PDF)

LO prediction reasonably good.

Statistics limited measurement
Systematics dominated by JES.
Vertex Tagging: $b$’s and Non-$b$’s

**Tagging of real $b$ jet:**
- Long lifetime + large boost = secondary vertex
- $L_{2d} > 0$

**Spurious tagging of light flavor jet:**
- "mistag"
- $L_{2d} < 0$

**Tag efficiency for $b$ jets**

<table>
<thead>
<tr>
<th>Jet $E_T$ (GeV)</th>
<th>Fractional $\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Loose SecVtx</td>
</tr>
<tr>
<td></td>
<td>Tight SecVtx</td>
</tr>
<tr>
<td></td>
<td>Ultra-light SecVtx</td>
</tr>
</tbody>
</table>

**Tag efficiency for $u/d/s$ jets**

<table>
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<th>Jet $E_T$ (GeV)</th>
<th>Fractional $\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Loose SecVtx</td>
</tr>
<tr>
<td></td>
<td>Tight SecVtx</td>
</tr>
<tr>
<td></td>
<td>Ultra-light SecVtx</td>
</tr>
</tbody>
</table>
**Goals:**
- Measure $W+b$-jet production cross section
- Use measurement to improve background estimate for Higgs search

- $W$ and jets selection here similar to $W+$ inclusive jets analysis
  - key difference: 1 or 2 jets only

- Here we need to identify jets that are likely $b$’s (via high purity tagging) and determine how many are really $b$’s via vertex mass:
  - invariant mass of charged particle tracks in secondary vertex

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**Vertex Mass Shapes**

From simulation

- $b$
- $c$
- $\text{LF} = u/d/s/g$

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Generally,

$$M_{B\text{-hadrons}} \geq M_{C\text{-hadrons}} \geq M_{\text{LF-hadrons}}$$

so

$$M_{b\text{ vert}} \geq M_{c\text{ vert}} \geq M_{\text{LF vert}}$$
**W + b-Jets**

- **Largest backgrounds:** S/B ~ 3/1
  - ttbar (40% of total bkgd)
  - single top (30%)
  - Fake W (15%)
  - WZ (5%)
  - Total contribution: ~180 tagged b jets

- **Result:** measure $\sigma_{b\text{-jets}}(W+b\text{-jets}) \times BR(W\rightarrow l\nu)$

|$\sigma \times BR = 2.74 \pm 0.27 \text{ (stat)} \pm 0.42 \text{ (syst) pb}$

- **Prediction:**

|$\sigma \times BR = 0.78 \text{ pb}$

(default ALPGEN)

**New result** - x3.5 mismatch

NB: This cross section is for b jets from W+b-jet production in events with a high $p_T$ central lepton, high $p_T$ neutrino and 1 or 2 total jets.

Publication in preparation.

- ~1000 tagged jets among which ~700 are consistent with coming from a b quark

**Vertex Mass Fit**

CDF Run II Preliminary - 1.9/fb

- Data
- bottom contribution
- charm contribution
- LF contribution
- Summed contribution

$b = 71.3 \pm 4.7\text{(stat)} \pm 6.4\text{(syst)} \%$

$c = 15.9 \pm 5.5\text{(stat)} \%$

$LF = 12.6 \pm 3.5\text{(stat)} \%$

KS Prob = 84.8 %

High purity $b$-tagging at work!
**W + b-Jets**

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  \]

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  \]
  (default ALPGEN)

**Other predictions? Work is ongoing.**

~1000 tagged jets among which ~700 are consistent with coming from a $b$ quark

NB: This cross section is for $b$ jets from $W+b$-jet production in events with a high $p_T$ central lepton, high $p_T$ neutrino and 1 or 2 total jets.

**Publication in preparation.**
Z + b-Jets

- Similar CDF analysis for Z+b-jets: 2/fb
- Utilize $Z \rightarrow ee$ and $\mu\mu$
- Similar jet definition
  - Corrected $E_T > 20$ GeV, $|\eta| < 1.5$
  - Cone algorithm with $R=0.7$
  - Secondary vertex tags

- Differential cross sections with comparisons to LO, NLO predictions
- Dividing by $\sigma(Z)$ puts LO, NLO on equal footing
- Pythia does a good job at low jet $E_T$
• ALPGEN (LO) and MCFM (NLO) undershoot data in several bins

• Pythia on target in some regimes – despite LO predictions being low in other analyses (eg, Z+jets).

Publication in preparation.
## W/Z + b-Jets: Summary

<table>
<thead>
<tr>
<th></th>
<th>CDF Data</th>
<th>Pythia</th>
<th>ALPGEN</th>
<th>Herwig</th>
<th>NLO</th>
<th>NLO (corr’d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma(Z+b \text{ jet}) ) (pb)</td>
<td>0.9 ± 0.1 ± 0.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.51</td>
<td>0.53</td>
</tr>
<tr>
<td>( \sigma(Z+b \text{ jet})/\sigma(Z) ) (%)</td>
<td>0.34 ± 0.05 ± 0.04</td>
<td>0.35</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.23</td>
</tr>
<tr>
<td>( \sigma(Z+b \text{ jet})/\sigma(Z+\text{jet}) ) (%)</td>
<td>2.11 ± 0.33 ± 0.34</td>
<td>2.18</td>
<td>1.45</td>
<td>1.24</td>
<td>1.88</td>
<td>1.77</td>
</tr>
<tr>
<td>( \sigma(W+b \text{ jet}) ) (pb)</td>
<td>2.7 ± 0.3 ± 0.4</td>
<td>-</td>
<td>0.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- More studies for \( W+b \)-jets are forthcoming

- Need to understand NLO predictions
  - In \( Z+b \)-jets it is strange that the NLO prediction undershoots data
  - Borne out in \( W+b \)-jets?
Conclusions

- *W/Z + jets* physics plays an **important role** in current collider physics programs

- Current NLO predictions for *W/Z +* look to be **accurate**, higher multiplicities desirable

- *W/Z+b-jets* studies have indicated deficiencies in both LO and NLO predictions; **more study and more data** is needed

- *W+single c* studies indicate **reasonable agreement** with NLO, LO predictions
$W + \text{Inclusive Jets}$

**MCFM:**
- MCFM (NLO)

**MLM:**
- ALPGEN (LO) + Herwig (shower) + MLM matching

**SMPR:**
- MadGraph (LO) + Pythia (shower) + CKKW matching
**W + Inclusive Jets: Definition of Terms**

- **MCFM**: Monte Carlo for Femtobarn Processes
  - NLO predictions for cross sections and kinematics
- **MLM**: Michelangelo Mangano, author of ALPGEN
- **ALPGEN, MadGraph**: matrix element generators
  - Generate fixed order processes (eg., W+0,1,2,3 partons for W+jets)
  - Shower the N-parton final state to get N-jets (eg. Pythia or Herwig)
  - Gather all the fixed order samples (eg., W+N-p for W+jets)
  - Remove double-counting via **matching algorithm**
- **MLM matching**:
  - Allow event iff $N_{\text{jets}} = N_{\text{partons}}$ (exclusive) or $N_{\text{jets}} \geq N_{\text{partons}}$ (inclusive)
- **CKKW matching**:
  - Assign each event weights from $\alpha_s$ nodes, legs
  - Veto event if event weight is below some cut
  - Use shower to add legs only up to some cutoff
- **SMPR**: variant of CKKW, named after S Mrenna and P Richardson

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**MCFM :**
MCFM (NLO)

**MLM :**
ALPGEN (LO) + Herwig (shower) + MLM matching

**SMPR :**
MadGraph (LO) + Pythia (shower) + CKKW matching
Identifying $b$ Jets

- **$B$ hadron lifetime**: $\sim 1.5$ ps
  - Large boost ($v \sim 0.95c$) means the $B$ lifetime is long in the lab frame
  - $B$ travels macroscopic distance before decaying which we can detect

- **Exploit the long lifetime** -
  - Reconstruct charged particle tracks
  - See if they intersect at a common point
  - Require the common point be significantly displaced from the primary $p$-$p$ collision point

<table>
<thead>
<tr>
<th></th>
<th>Meaning</th>
<th>Typical</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_0$</td>
<td>Track impact parameter</td>
<td>150um</td>
<td>40um</td>
</tr>
<tr>
<td>$L_{2d}$</td>
<td>Vertex displacement</td>
<td>2-3mm</td>
<td>100um</td>
</tr>
</tbody>
</table>
$W + b$-Jets

**Data - MC Comparison**

CDF Run II Preliminary - 1.9/ft

- Data
- Summed contribution, uncertainty from $M_{\text{vert}}$ fit
- bottom contribution
- charm contribution
- LF contribution

Jet $E_T$ (GeV)

Jet $\eta$
$W + \text{ Single } c \text{ Production}$

Signed $\mu$ track impact parameter significance.

$\mu p_T \text{ relative to jet axis}$