$W + b$-jet Production at CDF: A Prerequisite to Higgs

Dr. Christopher Neu
Outline

• Motivation
• Measurement Definition
• Experimental apparatus
• Measurement strategy
• Results
Outline

• **Motivation**
• Measurement Definition
• Experimental apparatus
• Measurement strategy
• Results
With the LHC era on the horizon, the Fermilab Tevatron remains -- for the time being -- the highest energy accelerator in the world.

Run II has thus far been a great success and the vibrant Tevatron physics program continues.

Prominent pursuits remain, including: Deepening our understanding of the top quark, and furthering our pursuit of the Higgs boson.
Why Study $W+b$-jet Production?

- First, a definition:
  - $W+b$-jets refers to QCD production of $b$-jets in events with a $W$ boson.

Examples of $W+b$-jets production at tree level:

$O(\alpha_s^2)$

$O(\alpha_s^3)$

- Why is $W+b$-jets interesting?
  - Consider some primary Run II targets…
Signatures with $W’s$ and $b’s$

- **Rich top physics program at the Tevatron**
  - BR ($t \rightarrow Wb$) $\sim 100$
  - top pair production
    - $p \bar{p} \rightarrow t \bar{t} \rightarrow W^+ b W^- \bar{b}$
    - Production cross section = $\sim 7$ pb

- **Current hot topic: single top production**
  - $p \bar{p} \rightarrow W^* \rightarrow t \bar{b} \rightarrow W^+ b \bar{b}$: $\sim 0.3$ pb
  - $p \bar{p} \rightarrow t b q \rightarrow W^+ b \bar{b} q$: $\sim 0.6$ pb
  - Insight on $|V_{tb}|$

- **The Search for the Higgs**
  - Promising Tevatron production mode:
    - $p \bar{p} \rightarrow W^* \rightarrow W\pm H$: $\sim 0.1-0.2$ pb
  - Higgs decays to $b$ quarks if its mass is low:
    - $\text{BR}(H \rightarrow b \bar{b}) = \sim 70\%$ for $M_H = 120 \text{ GeV}/c^2$
Importance of $W+b$-jet Production

- Common trait of those prominent signatures:
  - $W$'s and $b$'s

- $W+b$-jet production casts a long shadow:
  - Largest background source
  - Rate for $W+b$-jets exceeds these others significantly
  - Theory prediction: 10 - 15 pb

- Good understanding of the $W+b$-jets process is essential for success
**W+b-jets: Theory**

- Several theory groups have tackled the $W+b$-jets calculation:
  - **Campbell, Ellis, Maltoni, Willenbrock at LO & NLO using MCFM** (hep-ph/0611348)
    - Several processes make up $W+b$-jets
    - Categorized according to outgoing partons
    - $W^{bb}$ and $W^{bq}$ categories ~80% of total NLO

<table>
<thead>
<tr>
<th>Inclusive Cross Section (pb)</th>
<th>LO</th>
<th>NLO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^{bb}$</td>
<td>4.96</td>
<td>6.28</td>
</tr>
<tr>
<td>$W^{bq}$</td>
<td>2.12</td>
<td>5.08</td>
</tr>
</tbody>
</table>

$p_T > 15 \text{ GeV}/c^2$, $|\eta| < 2.0$
for all outgoing $b, q$
in this calculation

- **Mangano, et al., at tree level** – original motivation for ALPGEN (hep-ph/0108069)
  - Qualitative agreement w/LO MCFM results
  - Wide use of ALPGEN at CDF for $W$+jets shapes ($W+b$-jets, $W+c$-jets, $W+\ell\phi$-jets)
Example: $W+b$-jets Prediction in $WH$ Search

- WH→lvbb analysis needs prediction for $W+b$-jet yield
- Predicted rates from MC distrusted for $W+b$-jets
- Predictions for these events use data to set the overall scale of $W$+jets production
- Ultimate prediction is fraught with systematic error
- Small $WH$ signal obscured by error on the background
- We must be able to do better.

### Predicted Event Yields

<table>
<thead>
<tr>
<th>Jet Multiplicity</th>
<th>1 jet</th>
<th>2 jets</th>
<th>3 jets</th>
<th>≥ 4 jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>\textit{WLF}</td>
<td>139.7 ± 27.3</td>
<td>53.9 ± 10.7</td>
<td>15.7 ± 3.1</td>
<td>4.2 ± 0.8</td>
</tr>
<tr>
<td>$Wbb$</td>
<td>306.9 ± 106.9</td>
<td>144.7 ± 49.4</td>
<td>29.9 ± 9.7</td>
<td>6.4 ± 2.5</td>
</tr>
<tr>
<td>$W\ell\ell$</td>
<td>63.1 ± 22.0</td>
<td>43.0 ± 14.7</td>
<td>8.7 ± 2.8</td>
<td>1.9 ± 0.8</td>
</tr>
<tr>
<td>$Wc$</td>
<td>185.7 ± 47.2</td>
<td>34.4 ± 9.0</td>
<td>3.4 ± 0.9</td>
<td>0.6 ± 0.2</td>
</tr>
<tr>
<td>$t\bar{t}(6.7\text{pb})$</td>
<td>6.9 ± 1.2</td>
<td>42.0 ± 6.6</td>
<td>84.9 ± 12.8</td>
<td>98.6 ± 14.3</td>
</tr>
<tr>
<td>Single Top</td>
<td>16.7 ± 1.8</td>
<td>23.5 ± 2.4</td>
<td>4.8 ± 0.5</td>
<td>0.8 ± 0.1</td>
</tr>
<tr>
<td>Diboson/$Z^0\to\tau\tau$</td>
<td>11.7 ± 2.2</td>
<td>14.2 ± 2.3</td>
<td>3.9 ± 0.9</td>
<td>1.0 ± 0.3</td>
</tr>
<tr>
<td>non-$W$ QCD</td>
<td>84.2 ± 14.1</td>
<td>38.9 ± 6.7</td>
<td>12.1 ± 2.3</td>
<td>5.5 ± 1.2</td>
</tr>
<tr>
<td>Total Background</td>
<td>814.9 ± 140.7</td>
<td>394.4 ± 66.6</td>
<td>163.4 ± 18.7</td>
<td>118.9 ± 14.9</td>
</tr>
</tbody>
</table>

| Observed Events | 856 | 421 | 177 | 139 |
| Expected Signal Events | \textit{Higgs Mass} 120 | 1.26 ± 0.12 |

**Question:**

Can we measure $W+b$-jets and **improve these predictions?**

Ultimately **improve the models?**
W+b-jets: Relevance for LHC

- Understanding W+b-jets at the Tevatron is important also for LHC
$W+b$-jets: Relevance for LHC

- Understanding $W+b$-jets at the Tevatron is important also for LHC
  - $WH$ observation in 300 fb only possible w/ precise background modeling – mostly $W+b$-jets
  - Not a discovery mode!
  - But this channel plays a vital role in understanding a Higgs discovered through other avenues
  - Lessons learned at the Tevatron can help build better models for ATLAS and CMS
Outline

- Motivation
- *Measurement Definition*
- Experimental apparatus
- Measurement strategy
- Results
$W+b$-jets Cross Section Definition

- Seek to improve our understanding of $W+b$-jet production
- Design the analysis to focus on the sample that is most relevant for Higgs and single top searches:
  - Leptonically decaying $W$
  - Exactly 1 or 2 total jets
- Seek a result that is insulated from theory dependence
  - MC events are used for shape and acceptance studies
    - Restrict phase space of considered events. Require:
      - MC $e$ or $\mu$ $w/p_T > 20$, $|\eta| < 1.1$
      - MC $\nu$ $w/p_T > 25$
      - Exactly 1 or 2 $E_T > 20$, $|\eta| < 2.0$ MC jets
    - Measure $b$ jet cross section rather than inclusive event cross section
      - Models have difficulty matching the definition of “event” when requiring precisely 1 or 2 jets
- Can calculate the $b$ jet cross section prediction under such conditions for one model:

\[
\text{ALPGEN: } \sigma_{b\text{-jets}} (W + b - \text{jets}) \times \text{BR}(W \rightarrow l \nu) = 0.78 \text{ pb}
\]
Outline

- Motivation
- Measurement Definition
- *Experimental apparatus*
- Measurement strategy
- Results
Tevatron Performance

- Tevatron integrated luminosity climbing higher and higher
- Integrated lum goal is to collect 5.5-6.5/fb through 2009
- Discussions underway about running through 2010 – quite valuable
- Stable, reliable beams provided by FNAL’s Accelerator Division allow us to get the most out of our experiments

\[ N_{\text{evts}} = \sigma_{\text{evt}} \cdot L_{\text{int}} \cdot A \cdot \varepsilon \]
The CDF Experiment

- **Collider Detector at Fermilab Experiment**
  - A collaborative effort
  - One of two collider physics experiments at the Tevatron

- **CDF detector:**
  - General-purpose
    - Can detect various decay products
    - Allows us to look for all sorts of phenomena
  - Handmade
    - Cannot buy these things at Radio Shack!

CDF Collaboration:
- 635 physicists
- 63 institutions
- 15 countries
The CDF Detector

Central Outer Tracker

SVX-II, ISL and L00

Solenoid

protons

antiprotons
The CDF Detector

Hadronic and electromagnetic calorimetry

SVX-II, ISL and L00

Central Outer Tracker

Solenoid

protons

antiprotons

x

y

z

x

y

z
The CDF Detector

Central Outer Tracker

SVX-II, ISL and L00

Hadronic and electromagnetic calorimetry

Central muon detectors

Solenoid

protons

antiprotons

x

y

z

x

y

z
The CDF Detector

Hadronic and electromagnetic calorimetry

Solenoid

Central muon detectors

\[ \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \]

\[ \eta = -\ln(\tan \frac{\theta}{2}) \]

protons

antiprotons

SVX-II, ISL and L00

Central Outer Tracker

- \( \phi \) = azimuthal angle
- \( \eta \) = pseudorapidity
- \( \Delta R \) = distance in space
Outline

- Motivation
- Measurement Definition
- Experimental apparatus
- Measurement strategy
- Results
Selecting $W+b$-jets Events

- Focus on leptonic $W$ decays, $W \rightarrow l\nu$, $l = e, \mu$

CDF end view
Transverse plane
Selecting $W+b$-jets Events

- Focus on leptonic $W$ decays, $W \rightarrow l \nu$, $l = e, \mu$

- Online event trigger:
  - 18 GeV $|\eta| < 1.1$ electron OR
  - 18 GeV $|\eta| < 0.6$ muon OR
  - 18 GeV $0.6 < |\eta| < 1.0$ muon
Selecting $W+b$-jets Events

- **Focus on leptonic $W$ decays**, $W \rightarrow l\nu, l=e,\mu$

- **Online event trigger:**
  - 18 GeV $|\eta| < 1.1$ electron OR
  - 18 GeV $|\eta| < 0.6$ muon OR
  - 18 GeV $0.6 < |\eta| < 1.0$ muon

- **$W$ selection:**
  - $p_T > 20$ GeV/c isolated central lepton
  - Large missing energy: MET > 25 GeV
Selecting $W+b$-jets Events

- **Focus on leptonic $W$ decays, $W \rightarrow l \nu, l = e, \mu$**

- **Online event trigger:**
  - $18 \text{ GeV } |\eta| < 1.1$ electron OR
  - $18 \text{ GeV } |\eta| < 0.6$ muon OR
  - $18 \text{ GeV } 0.6 < |\eta| < 1.0$ muon

- **$W$ selection:**
  - $p_T > 20 \text{ GeV}/c$ isolated central lepton
  - Large missing energy: MET $> 25$ GeV

- **Jet selection:**
  - Exactly 1 or 2 $E_T > 20 \text{ GeV}, |\eta| < 2.0$ jets
  - JetClu clustering with $R=0.4$ cone
Selecting $W+b$-jets Events

- **Focus on leptonic $W$ decays**, $W \rightarrow l\nu, \ |l|=e,\mu$

- **Online event trigger:**
  - $18 \text{ GeV} \ |\eta| < 1.1$ electron OR
  - $18 \text{ GeV} \ |\eta| < 0.6$ muon OR
  - $18 \text{ GeV} \ 0.6 < |\eta| < 1.0$ muon

- **$W$ selection:**
  - $p_T > 20 \text{ GeV}$ isolated central lepton
  - Large missing energy: MET $> 25 \text{ GeV}$

- **Jet selection:**
  - Exactly 1 or 2 $E_T > 20 \text{ GeV}, \ |\eta| < 2.0$ jets
  - JetClu clustering with R=0.4

- **Do not consider events from other processes:**
  - Veto events with $2$ high $p_T$ leptons to avoid ttbar
  - Guard against $Z \rightarrow ll$ production where one lepton is not fully reconstructed
  - Remove cosmic ray events, events with objects from different interactions
  - Veto fake $W$ events
Identification of $b$ Jets

- **What makes $b$-jets so special?**
  - Long lifetime of the $b$
  - Large mass of $B$ hadrons
  - High momentum decay products of $B$ hadrons

- **Some special relativity:**
  - $b$ quark lifetime: ~1.5 ps
  - Typical speed of $B$ hadron is close to the speed of light
  - Moving clocks run slower…
  - Distance traveled in lab frame before decaying: ~2-3 mm

- **Exploit this feature:**
  - Look within jets for displaced tracks
  - See if they intersect at a common point
  - Require the common point be significantly displaced from the primary interaction point

<table>
<thead>
<tr>
<th>Meaning</th>
<th>Typical</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_0$</td>
<td>150um</td>
<td>40um</td>
</tr>
<tr>
<td>$L_{2d}$</td>
<td>2-3mm</td>
<td>100um</td>
</tr>
</tbody>
</table>

Long-lifetime yields secondary decay vertex “$b$-tagging”
**b-tagging: b’s and Non-b’s**

Tagging of real b jet

- Displaced tracks
- Secondary vertex
- Primary vertex

\[ L_{2d} > 0 \]

Spurious tagging of light flavor jet: “mistag”

- Displaced tracks
- Prompt tracks
- Secondary vertex
- Primary vertex

\[ L_{2d} < 0 \]

**Tag efficiency for b jets**

![Graph showing tag efficiency for b jets]

**Tag efficiency for LF jets**

![Graph showing tag efficiency for LF jets]
**Yield of Tagged Jets**

**My cartoon:**

- **Jet 1**
- **Jet 2**

**The real thing:** event recorded 10/2005

- **Electron**
- **Jet 1** 3.9 GeV
- **Jet 2** 162.8 GeV
- **MET 37.1 GeV**

**Event has 2 tagged jets!**

**Yield in 1.9/fb of data:**

<table>
<thead>
<tr>
<th>Selected Events (before tagging)</th>
<th>175712</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Jets</td>
<td>199670</td>
</tr>
<tr>
<td>Tagged Jets</td>
<td>943</td>
</tr>
</tbody>
</table>
**W+b-jets: Measurement Strategy**

\[
\sigma_{b \text{ jets}} (W+b-jets) \times BR(W \rightarrow l \nu) = \frac{n^{\text{fit}}_{b\text{jets}} - n^{\text{notW+b}}_{b\text{jets}}}{L \cdot A_{W+b\text{ bjets}} \cdot \epsilon}
\]

Where do various pieces come from?

- Discriminate \(b/c/LF\) in tagged sample using **vertex mass**

- Determine contribution from **background** tagged \(b\) jets and subtract from overall yield

- Calculate **acceptance** for \(W+b\)-jet events

- Measure **tag efficiency** for \(b\) jets in \(W+b\)-jet production in MC and correct to match that of data
Extracting Species Content of Tagged Sample

- Tagged jets are not guaranteed to be just from $b$’s
  - $b$, $c$, or LF (u/d/s/g)

- Discriminate the species of tagged jets via **vertex mass**, $M_{\text{vert}}$:
  - Invariant mass of tracks participating in found Ultratight secondary vertex
  - Correlated to mass of decaying hadron: Qualitatively,
    
    $M_{B\text{-hadrons}} > M_{C\text{-hadrons}} > M_{LF\text{-hadrons}}$

    so

    $M_{b\text{ vert}} > M_{c\text{ vert}} > M_{LF\text{ vert}}$
Species Content of Tagged Sample: $b$ Shape

- Use MC events to build the shape for $b$:
  - Weighted contributions from main $b$ sources to selected sample
    - $W+b$-jets
    - ttbar
    - Single top
  - Shapes for each process are similar: not sensitive to assumed weight of each
  - Insensitive to even large changes in top, single top cross sections
Species Content of Tagged Sample: $c$ Shape

- **Shape for charm**: comes from significant $c$ sources
Species Content of Tagged Sample: LF Shape

- **Shape for LF** comes from tags of LF-matched jets in MC

- Several MC samples were studied, including:
  - W+jets MC
  - Dijet MC w/at least one pT>50 jet

- All shapes are reasonably consistent

- Chose to use the dijet MC shape for fitting and use high statistics alternative for setting a systematic
Data is comprised of three species

Use binned Poisson maximum likelihood fit to extract contribution from each source

Pseudoexperiment studies showed fit results were accurate and had relative fit error of ~5% on $f_b$.
Species Content of Tagged Sample: Fit Results

- Fit results in the CDF data!
- Fit claims ~71% of tagged jets are from $b$.
- Given the yield of 943 tagged jets that corresponds to

$$n_{b\text{jets}}^{\text{fit}} = 672.3 \pm 44.3\text{(stat)} \pm 60.4\text{(syst)}$$

Where does this systematic error come from?
Species Content of Tagged Sample: Systematics

- Seek calibration of shape for $b$
- Can construct a pure sample of Ultratight tagged $b$ jets in data:
  - Trigger: 8 GeV muon
  - Construct back-to-back dijet system:
    - Muon jet: UT-tagged, $M_{\text{vert}}>1.7$ GeV
    - Away jet: UT-tagged
  - Away jet $b$ purity $>99\%$ in Pythia

- Shape difference: $\delta f_b/f_b = 8\%$ effect
- $c$, LF shape syts have smaller effect on $f_b$
Vertex Mass Fit Consistency Check

- Check species fractions from fit in other variables
- Things look reasonable in these and other distributions
**W+b-jets: Measurement Strategy**

\[
\sigma_{b\,jets} (W+b-jets) \times BR(W \rightarrow l\nu) = \frac{n_{fit}^{b\,jets} - n_{notW+b}^{b\,jets}}{L \cdot A_{W+b\,bjets} \cdot \epsilon}
\]

Where do various pieces come from?

- Discminate \(b/c/LF\) in tagged sample using **vertex mass**
- Determine contribution from **background** tagged \(b\) jets and subtract from overall yield
- Calculate **acceptance** for \(W+b\)-jet events
- Measure **tag efficiency** for \(b\) jets in \(W+b\)-jet production in MC and correct to match that of data

\(n_{fit}^{b\,jets} = 672.3 \pm 44.3\) (stat) \(\pm 60.4\) (syst)

\(n_{notW+b}^{b\,jets}\)
Background Sources of $b$ Jets

• Various processes contribute to $b$-tags in $W+1,2$ jet sample

• Two categories treated here:
  - MC-driven (ttbar, single top, dibosons, others)
  - Data-driven (Fake $W$)

• MC-based backgrounds:
  - Use Pythia, MadEvent, ALPGEN
  - Apply event selection, get efficiency,
  - Use production cross section to estimate yield

• Top-based processes largest contributors

<table>
<thead>
<tr>
<th>Process</th>
<th>$n_{W+12j}^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{t}t$</td>
<td>73.1 ± 10.1*</td>
</tr>
<tr>
<td>s-channel</td>
<td>22.2 ± 9.6*</td>
</tr>
<tr>
<td>t-channel</td>
<td>33.4 ± 15.0*</td>
</tr>
<tr>
<td>$WZ$</td>
<td>9.1 ± 0.9</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>0.28 ± 0.03</td>
</tr>
<tr>
<td>$WW$</td>
<td>0.83 ± 0.12</td>
</tr>
<tr>
<td>$W + bb+Np, W \to \tau \nu$</td>
<td>7.3 ± 0.8</td>
</tr>
<tr>
<td>$Z + bb+Np, Z \to e^+e^-$</td>
<td>0.67 ± 0.08</td>
</tr>
<tr>
<td>$Z + bb+Np, Z \to \mu^+\mu^-$</td>
<td>4.1 ± 0.4</td>
</tr>
<tr>
<td>$Z + bb+ \geq Np, Z \to \tau^+\tau^-$</td>
<td>1.48 ± 0.20</td>
</tr>
</tbody>
</table>
Background Sources of $b$ Jets: $b$ Jets in Fake $W$ Events

- **What are fake $W$ events?**
  - Mostly QCD multijet production mimicking isolated lepton w/spurious missing energy from mismeasured jets
  - Tagged jets found elsewhere in the event
  - Characterized by:
    - small MET
    - large MET error
    - small $W$ transverse mass

- **Strategy here:**
  - Remove as much as possible from the start
  - Model what remains using data

- **Model for fake $W$: “antielectrons”**
  - Most fake electrons *just barely* satisfy electron identification
  - Construct a sample of objects that nearly satisfy electron ID - *marginal failures*
Background Sources of $b$ Jets: $b$ Jets in Fake $W$ Events

- With model in place can now determine how many tagged jets come from fake $W$

**Procedure:**

1. Use MET – discriminates between real and fake $W$ events
2. Relax MET cut (for lever arm)
3. Fit entire data MET dist to shapes from top, single top, $W$+jets, Fake-$W$
4. Return to MET>25 cut after fit and obtain Fake-$W$ fraction
5. Fit vertex mass of tagged jets to get $b$ fraction

From this fit, fake $W$ is responsible for $2.9\%$ of tagged jets in electron trigger data.

NB: Here antielectron shape used to model fake $W$’s in the muon trigger sample as well. Antimuons will be adopted in the future.
Step 5 fails – insufficient stats in antielectron sample with MET>25
Step through different MET cuts, examine behavior
As one tightens the MET cut \( f_b^{QCD} \) increases

Reasonable choice: \( f_b^{FakeW} = 0.8 \pm 0.2 \)
Summary: Background Sources of $b$ Jets

<table>
<thead>
<tr>
<th>Process</th>
<th>$n_{W+12j}^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>73.1 ± 10.1</td>
</tr>
<tr>
<td>s-channel</td>
<td>22.2 ± 9.6</td>
</tr>
<tr>
<td>t-channel</td>
<td>33.4 ± 15.0</td>
</tr>
<tr>
<td>$WZ$</td>
<td>9.1 ± 0.9</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>0.28 ± 0.03</td>
</tr>
<tr>
<td>$WW$</td>
<td>0.83 ± 0.12</td>
</tr>
<tr>
<td>$W + bb+ Np, W \rightarrow \tau\nu$</td>
<td>7.3 ± 0.8</td>
</tr>
<tr>
<td>$Z + bb+ Np, Z \rightarrow e^+e^-$</td>
<td>0.67 ± 0.08</td>
</tr>
<tr>
<td>$Z + bb+ Np, Z \rightarrow \mu^+\mu^-$</td>
<td>4.1 ± 0.4</td>
</tr>
<tr>
<td>$Z + bb+ \geq Np, Z \rightarrow \tau^+\tau^-$</td>
<td>1.48 ± 0.20</td>
</tr>
<tr>
<td>Non-$W$</td>
<td>24.5 ± 8.4</td>
</tr>
<tr>
<td>Total</td>
<td>176.8 ± 22.3</td>
</tr>
</tbody>
</table>

Predicted yields from all $b$-jet backgrounds in 1.9/fb.
Where do various pieces come from?

- Discriminate $b/c/LF$ in tagged sample using **vertex mass**
- Determine contribution from **background** tagged $b$ jets and subtract from overall yield
- Calculate **acceptance** for $W+b$-jet events
- Measure **tag efficiency** for $b$ jets in $W+b$-jet production in MC and correct to match that of data

$$\sigma_{b\text{ jets}} (W+b-\text{jets}) \times BR(W \rightarrow l\nu) = \frac{n_{\text{fit}}^{b\text{ jets}} - n^{\text{not}W+b}_{b\text{ jets}}}{L \cdot A_{W+b\text{ bjets}} \cdot \epsilon}$$

$$n_{b\text{ jets}}^{\text{fit}} = 672.3 \pm 44.3(\text{stat}) \pm 60.4(\text{syst})$$

$$n_{b\text{ jets}}^{\text{not}W+b} = 176.8 \pm 22.3(\text{syst})$$

$$A_{W+b\text{ bjets}} \epsilon$$
### Acceptance Definition

\[ A_{W+bjets} = \frac{\text{# reconstructed } b \text{ jets in events passing all selection}}{\text{# MC } b \text{ jets in event sample}} \]

- There are two effects the acceptance encodes:
  - **Smearing** provided by fragmentation effects, CDF detector, etc
    - MC events migrate in and out:
      - a true 25 GeV jet can be reconstructed at 18 GeV – fail jet requirement!
      - a true 15 GeV jet can be reconstructed at 22 GeV – pass!
  - **Reduction** in sample through selection cuts designed to isolate signal
    - MC events only migrate out:
      - eg, event vetos

- **Denominator of A:**
  - Number of \( b \)-jets in MC before detector simulation in events satisfying the phase space restrictions
  - Jets without the detector?
MC Jets

- Jets without the calorimeter!
  - **SpartyJet**: Software provides jet clustering on raw particles
  - Some knowledge of CDF geometry
  - Glimpse of “truth” jets

- Convention: exclude $W$ daughters but make jets out of everything else

- Natural mismatch wrt measured jet $E_T$-s
  - effect largest for $b$ jets

Measured $b$-jet energies are ~10% low on average wrt “truth”.
Agreement better for LF, $c$ jets.
Acceptance Results

• Denominator of the acceptance is defined wrt these MC jets
• Use ALPGEN MC to evaluate the acceptance
  – Recall the phase space restrictions are attempt to insulate result from theory dependence
• Folded into this acceptance term
  – Efficiency for being in the luminous region of CDF $|z_0| < 60$ cm
  – Trigger efficiency
  – Lepton identification efficiency
• Sources of systematic error on the acceptance
  – Jet Energy Corrections (3% effect on $A$)
  – Renormalization/factorization scale choice (3%)
  – Parton distribution functions (2%)

$$A_{W+b\text{ jets}} = 0.593 \pm 0.017(\text{syst})$$ integrated over all three trigger paths
Where do various pieces come from?

- Discriminate $b/c/LF$ in tagged sample using vertex mass
- Determine contribution from background tagged $b$ jets and subtract from overall yield
- Calculate acceptance for $W+b$-jet events
- Measure tag efficiency for $b$ jets in $W+b$-jet production in MC and correct to match that of data

\[
\sigma_{b\,jets} (W+b-\text{jets}) \times BR(W \rightarrow l \nu) = \frac{n_{fit}^{b\,jets} - n_{notW+b}^{b\,jets}}{L \cdot A_{W+b \,b\,jets} \cdot \epsilon}
\]

\[
n_{fit}^{b\,jets} = 672.3 \pm 44.3 \text{(stat)} \pm 60.4 \text{(syst)}
\]

\[
n_{notW+b}^{b\,jets} = 176.8 \pm 22.3 \text{(syst)}
\]

\[
A_{W+b \,b\,jets} = 0.593 \pm 0.017 \text{(syst)}
\]
Tag Efficiency

- Measure tag efficiency for signal $b$-jets in $W+b$-jet simulated samples
- Correct via known MC-to-data scale factor
  - Tracking simulation is generally more optimistic than reality

- Measuring the tag efficiency in the data
  - Dijet events, enhance HF content
  - Require probe jet to have a semileptonic hadron decay (muon inside the cone)
  - Muon’s relative momentum discriminates $b$/non-$b$
  - Fits for $b$ fraction in tagged, untagged samples allow one to extract efficiency

ALPGEN $W+b$-jet MC, after scaling: $\varepsilon = 0.16 \pm 0.01$ (syst)
**W+b-jets: Measurement Strategy**

\[
\sigma_{b\,jets}(W+b-jets)\times BR(W\rightarrow l\nu) = \frac{n_{fit}^{b\,jets} - n_{not\,W+b}^{b\,jets}}{L\cdot A_{W+b\,bjets}\cdot \epsilon}
\]

Where do various pieces come from?

- Discriminate \(b/c/LF\) in tagged sample using vertex mass
- Determine contribution from background tagged \(b\) jets and subtract from overall yield
- Calculate acceptance for \(W+b\)-jet events
- Measure tag efficiency for \(b\) jets in \(W+b\)-jet production in MC and correct to match that of data

\[
n_{fit}^{b\,jets} = 672.3 \pm 44.3(\text{stat}) \pm 60.4(\text{syst})
\]

\[
n_{not\,W+b}^{b\,jets} = 176.8 \pm 22.3(\text{syst})
\]

\[
A_{W+b\,bjets} = 0.593 \pm 0.017(\text{syst})
\]

\[
\epsilon = 0.16 \pm 0.01(\text{syst})
\]
Outline

- Motivation
- Measurement Definition
- Experimental apparatus
- Measurement strategy
- Results
**W+b-jets Cross Section Result**

**Pieces:**

\[ n_{bjets}^{fit} = 672.3 \pm 44.3 \text{(stat)} \pm 60.4 \text{(syst)} \]

\[ n_{bjets}^{notW+b} = 176.8 \pm 22.3 \text{(syst)} \]

\[ A_{W+b \, bjets} = 0.593 \pm 0.017 \text{(syst)} \]

\[ \varepsilon = 0.16 \pm 0.01 \text{(syst)} \]

**Insert pieces here:**

\[
\sigma_{bjets}(W+b-jets) \times BR(W \rightarrow l \nu) = \frac{n_{bjets}^{fit} - n_{bjets}^{notW+b}}{L \cdot A_{W+b \, bjets} \cdot \varepsilon}
\]

**And finally:**

\[
\sigma_{b-jets} (W+b-jets) \times BR(W \rightarrow l \nu) = 2.74 \pm 0.25 \text{(stat)} \pm 0.44 \text{(syst)} \text{ pb}
\]

What about the luminosity?

\[ L = 1905 \text{pb}^{-1} \]

averaged over three trigger paths

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.
Cross Check: $W \rightarrow ev$ and $W \rightarrow \mu\nu$ Exclusive Results, 1700/pb

$M_{vert}$ Fit - Data

CDF RunII Preliminary

- CEM data - 1.7/fb
- bottom contribution
- charm contribution
- LF contribution
- Summed contribution

$b$ fraction = 70.38 ± 6.724 %
$c$ fraction = 22.62 ± 7.758 %
LF fraction = 6.991 ± 4.584 %

$\sigma_{W+b jets} \cdot BR(W \rightarrow ev) = 2.5 \pm 0.5$ pb

$\sigma_{W+b jets} \cdot BR(W \rightarrow \mu\nu) = 3.0 \pm 0.6$ pb

Results for electron and muon triggers are consistent.
Discussion

- Measured $b$-jet cross section in $W+b$-jets: $2.74 \pm 0.25\text{(stat)} \pm 0.44\text{(syst)}$ pb
  - Mismatch not unexpected
  - ALPGEN (tree level only) should underestimate cross section, potentially by a large amount if NLO contributions are large
  - Comparison with MCFM at NLO is in the queue

- CDF sees a mismatch in $Z+b$-jets as well
  - Pythia seems to do a reasonable job at low ET
  - MCFM prediction similar to ALPGEN – surprising

\[ \text{x3.5 deficit in prediction} \]
What Is Next

- $\delta_{\text{syst}}(\sigma \times \text{BR})/(\sigma \times \text{BR}) = 16\%$
  - Recall predictions for $W+b$-jets had $\sim 40\%$ uncertainty
  - Prediction relies on a fudge factor, $K_{\text{HF}}$, that reconciles the HF content of $W+$jets in MC to that of a data control sample (eg., $W+1$ jet)
  - $K_{\text{HF}}$ is then used in the prediction for the sample used for the search (eg., $W+2$ jets)

This result probes the exact same issues. Minimally this result could contribute to a more precise value for $K_{\text{HF}}$.

More preferable would be to feed this result back to the MC developers for the purpose of improving the models.
Summary

• $W+b$-jet production is a formidable obstacle to measuring signatures containing $W$’s and $b$’s

• In an effort to understand the process at a deeper level, we at CDF have measured the $b$ jet cross section in events with a $W$ boson in 1.9 fb

• Find measured cross section to be $2.74 \pm 0.25\text{(stat)} \pm 0.44\text{(syst)}$ pb

• ALPGEN prediction for this process is x3.5 lower than measurement.

• Current work is focused on:
  – Getting more information out of this measurement
  – Using this result to improve the precision on the $W+b$-jet predictions that are necessary for single top and Higgs searches.

• Goal is to understand this process as best we can both from theory and experimental perspectives – we are on our way
Backup Slides
Fermilab Accelerator Complex

- Series of staged accelerators, culminates in main workhorse, the Tevatron
- Proton and antiproton beams
- Beam is actually discrete packets
  - 396ns between collisions
  - 7 MHz crossing rate
  - ~5E12 particles per packet
- Beams collide with energy 1.96 TeV
- LHC: protons only, 25ns, 40MHz, 1E11 protons per packet, 14TeV

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Highest Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cockroft Walton</td>
<td>750 keV</td>
</tr>
<tr>
<td>Linac</td>
<td>400 MeV</td>
</tr>
<tr>
<td>Booster</td>
<td>8 GeV</td>
</tr>
<tr>
<td>Main injector</td>
<td>150 GeV</td>
</tr>
<tr>
<td>TEVATRON</td>
<td>980 GeV</td>
</tr>
</tbody>
</table>

RunI: 1992-1995
RunIIa: 2001-2005
RunIIb: 2005-pres
# Jet Cross Section Definition

<table>
<thead>
<tr>
<th>Sample</th>
<th>DSID</th>
<th>$\sigma_{te} \times BR$ (pb)</th>
<th>$N_{re}$</th>
<th>$n_{\text{low-jets}}$</th>
<th>$\sigma_{b\rightarrow jets} \times BR$ (pb)</th>
<th>$\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wvbb0p</td>
<td>btop0w</td>
<td>2.98</td>
<td>1542539</td>
<td>2.915e+05</td>
<td>0.5631</td>
<td>0.722</td>
</tr>
<tr>
<td>Wvbb1p</td>
<td>btop1w</td>
<td>0.89</td>
<td>1545970</td>
<td>2.76e+05</td>
<td>0.1589</td>
<td>0.204</td>
</tr>
<tr>
<td>Wvbb2p</td>
<td>btop2w</td>
<td>0.29</td>
<td>1498550</td>
<td>1.196e+05</td>
<td>0.02314</td>
<td>0.030</td>
</tr>
<tr>
<td>Wvvec0p</td>
<td>ctop0w</td>
<td>5.00</td>
<td>2005399</td>
<td>49</td>
<td>0.0001222</td>
<td>0.000</td>
</tr>
<tr>
<td>Wvvec1p</td>
<td>ctop1w</td>
<td>1.79</td>
<td>1968365</td>
<td>68</td>
<td>6.184e-05</td>
<td>0.000</td>
</tr>
<tr>
<td>Wvvec2p</td>
<td>ctop2w</td>
<td>0.628</td>
<td>1885915</td>
<td>55</td>
<td>1.831e-05</td>
<td>0.000</td>
</tr>
<tr>
<td>Wvvec0p</td>
<td>stop0w</td>
<td>17.1</td>
<td>1943317</td>
<td>44</td>
<td>0.0003872</td>
<td>0.000</td>
</tr>
<tr>
<td>Wvvec1p</td>
<td>stop1w</td>
<td>3.39</td>
<td>1896728</td>
<td>72</td>
<td>0.0001287</td>
<td>0.000</td>
</tr>
<tr>
<td>Wvvec2p</td>
<td>stop2w</td>
<td>0.507</td>
<td>1837070</td>
<td>60</td>
<td>1.656e-05</td>
<td>0.000</td>
</tr>
<tr>
<td>Wvvec3p</td>
<td>stop3w</td>
<td>0.083</td>
<td>1745440</td>
<td>28</td>
<td>1.331e-06</td>
<td>0.000</td>
</tr>
<tr>
<td>Wvvec0p</td>
<td>ptop0w</td>
<td>1800</td>
<td>4868357</td>
<td>65</td>
<td>0.02403</td>
<td>0.031</td>
</tr>
<tr>
<td>Wvvec1p</td>
<td>ptop1w</td>
<td>225</td>
<td>4563248</td>
<td>168</td>
<td>0.008284</td>
<td>0.011</td>
</tr>
<tr>
<td>Wvvec2p</td>
<td>ptop2w</td>
<td>35.3</td>
<td>872814</td>
<td>43</td>
<td>0.001739</td>
<td>0.002</td>
</tr>
<tr>
<td>Wvvec3p</td>
<td>ptop3w</td>
<td>5.59</td>
<td>831222</td>
<td>33</td>
<td>0.0002219</td>
<td>0.000</td>
</tr>
<tr>
<td>Wvvec4p</td>
<td>ptop4w</td>
<td>1.03</td>
<td>775589</td>
<td>8</td>
<td>1.062e-05</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.780</td>
</tr>
</tbody>
</table>

### Table:

<table>
<thead>
<tr>
<th>Sample</th>
<th>DSID</th>
<th>$\sigma_{te} \times BR$ (pb)</th>
<th>$N_{re}$</th>
<th>$n_{\text{low-jets}}$</th>
<th>$\sigma_{b\rightarrow jets} \times BR$ (pb)</th>
<th>$\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wmvbb0p</td>
<td>btop5w</td>
<td>2.98</td>
<td>1524880</td>
<td>2.897e+05</td>
<td>0.5661</td>
<td>0.721</td>
</tr>
<tr>
<td>Wmvbb1p</td>
<td>btop6w</td>
<td>0.89</td>
<td>1508029</td>
<td>2.716e+05</td>
<td>0.1603</td>
<td>0.204</td>
</tr>
<tr>
<td>Wmvbb2p</td>
<td>btop7w</td>
<td>0.29</td>
<td>1506613</td>
<td>1.208e+05</td>
<td>0.02328</td>
<td>0.030</td>
</tr>
<tr>
<td>Wmvvec0p</td>
<td>ctop5w</td>
<td>5.00</td>
<td>1982424</td>
<td>49</td>
<td>0.0001236</td>
<td>0.000</td>
</tr>
<tr>
<td>Wmvvec1p</td>
<td>ctop6w</td>
<td>1.79</td>
<td>1961120</td>
<td>77</td>
<td>7.028e-05</td>
<td>0.000</td>
</tr>
<tr>
<td>Wmvvec2p</td>
<td>ctop7w</td>
<td>0.628</td>
<td>1949189</td>
<td>72</td>
<td>2.32e-05</td>
<td>0.000</td>
</tr>
<tr>
<td>Wmvvec3p</td>
<td>stop5w</td>
<td>17.1</td>
<td>1975397</td>
<td>56</td>
<td>0.0004848</td>
<td>0.001</td>
</tr>
<tr>
<td>Wmvvec1p</td>
<td>stop6w</td>
<td>3.39</td>
<td>1911713</td>
<td>78</td>
<td>0.0001383</td>
<td>0.000</td>
</tr>
<tr>
<td>Wmvvec2p</td>
<td>stop7w</td>
<td>0.507</td>
<td>1840847</td>
<td>73</td>
<td>2.011e-05</td>
<td>0.000</td>
</tr>
<tr>
<td>Wmvvec3p</td>
<td>stop8w</td>
<td>0.507</td>
<td>1754673</td>
<td>36</td>
<td>1.04e-05</td>
<td>0.000</td>
</tr>
<tr>
<td>Wmvvec1p</td>
<td>ptop5w</td>
<td>1800</td>
<td>4955756</td>
<td>72</td>
<td>0.02615</td>
<td>0.033</td>
</tr>
<tr>
<td>Wmvvec1p</td>
<td>ptop6w</td>
<td>225</td>
<td>4648605</td>
<td>135</td>
<td>0.006534</td>
<td>0.008</td>
</tr>
<tr>
<td>Wmvvec2p</td>
<td>ptop7w</td>
<td>35.3</td>
<td>872511</td>
<td>46</td>
<td>0.001861</td>
<td>0.002</td>
</tr>
<tr>
<td>Wmvvec3p</td>
<td>ptop8w</td>
<td>5.59</td>
<td>839645</td>
<td>26</td>
<td>0.0001731</td>
<td>0.000</td>
</tr>
<tr>
<td>Wmvvec4p</td>
<td>ptop9w</td>
<td>5.59</td>
<td>774744</td>
<td>12</td>
<td>7.989e-05</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.785</td>
</tr>
</tbody>
</table>
Veto of Events with Fake $W$ (aka NonW, aka QCD)

<table>
<thead>
<tr>
<th></th>
<th>1 Jet</th>
<th>2 Jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM</td>
<td>$M_T(W) &gt; 20$ GeV</td>
<td>$M_T(W) &gt; 20$ GeV</td>
</tr>
<tr>
<td></td>
<td>$S_{MET} \geq -0.05^* M_T(W) + 3.5$</td>
<td>$S_{MET} \geq -0.05^* M_T(W) + 3.5$</td>
</tr>
<tr>
<td></td>
<td>$S_{MET} \geq -7.6 + 3.2^* \Delta \phi(l,j1)$</td>
<td>$S_{MET} \geq 2.5-3.125^* \Delta \phi(MET,j2)$</td>
</tr>
<tr>
<td>CMUP</td>
<td>$M_T(W) &gt; 10$ GeV</td>
<td>$M_T(W) &gt; 10$ GeV</td>
</tr>
<tr>
<td></td>
<td>$MET \geq -145 + 60^* \Delta \phi(l,j1)$</td>
<td></td>
</tr>
<tr>
<td>CMX</td>
<td>$M_T(W) &gt; 10$ GeV</td>
<td>$M_T(W) &gt; 10$ GeV</td>
</tr>
</tbody>
</table>

• Seek to eliminate fake $W$ events – mostly QCD multijets – **hard to model**
• Effective non-$W$ removal developed by Karlsruhe group for 1.5+/fb single top analyses
• **Exploits features of fake $W$ events:**
  - Low transverse mass of spurious $W$
  - MET from spurious $W$ is less significant
  - Correlations between jets and leptons and MET
Secondary vertex $b$-tagging at CDF

- **SECVTX algorithm**: attempt to construct a secondary vertex among large impact parameter ($d_0$) tracks using a two-pass scheme
  - **Pass1**:
    - Starts with construction of 2-track "seed" vertex
    - **Attach** all remaining tracks that are consistent with seed.
    - Construct the multitrack vertex, iteratively **pruning** away the attached tracks if they spoil vertex fit.
    - Resulting candidate vertex required to have 3 or more tracks
  - **Pass2**: tighter track $d_0$ significance requirement
    - Attempt to **vertex** all these tracks to a common point.
    - **Remove** any track that spoils the vertex fit, re-vertexing after each removal.
    - Resulting candidate vertex required to have 2 or more tracks
  - **Apply vertex quality cuts**
    - removal of $K_{s,A}$ vertices
    - Removal of vertices in the material portion of CDF (beampipe, silicon ladders)
  - **If the vertex survives, the jet is “tagged” if $S_{L2D} > 7.5$**
    - sign of transverse displacement of secondary vertex wrt interaction point, $L_{xy'}$ determines positive tag or negative tag.
More on \( b \) and \( c \) Templates

**b Template**

- \( b \) Template
  - Entries: 59000
  - Mean: 1.24
  - RMS: 0.779
  - Underflow: 0
  - Overflow: 0
  - Integral: 0.994

**c Template**

- \( c \) Template
  - Entries: 59000
  - Mean: 1.13
  - RMS: 0.779
  - Underflow: 0
  - Overflow: 0
  - Integral: 0.994
Likelihood Maximization

\[ \mu_i = N^\text{total}_{jets} \left[ f^\text{fit}_b \cdot N^i_b + f^\text{fit}_c \cdot N^i_c + (1.0 - f^\text{fit}_b - f^\text{fit}_c) \cdot N^i_{LF} \right] \]

\[ P(n_i \mid \mu_i) = \frac{e^{-\mu_i} \mu_i^{n_i}}{n_i!} \]

\[ L = \prod_{i=1}^{N^\text{bins}} P(n_i \mid \mu_i) \]

\[ \ln L = \ln \left[ \prod_{i=1}^{N^\text{bins}} P(n_i \mid \mu_i) \right] \]

\[ \ln L = \sum_{i=1}^{N^\text{bins}} \left[ -\mu_i + n_i \ln \mu_i + \text{const} \right] \]

Vertex Mass Shapes
More on $b$ Calibration

![Histograms and Fit]

- **b fraction residual**
  - Entries: 5000
  - Mean: 0.001201
  - RMS: 0.04782
  - Underflow: 0
  - Overflow: 0
  - Integral: 5000

- **b Calib Sample $M_{vert}$ Fit**
  - $b$ fraction: $108.3 \pm 1.855\%$
  -charm contribution:
  - LF contribution:
  - Summed contribution:

- $c$ fraction: $-4.91 \pm 2.038\%$
- LF fraction: $-3.48 \pm 0.834\%$
Vertex Mass Fit Consistency Check
MET comparisons for W12j Contributors
Background Sources of $b$ Jets: Fake $W$ Events

CEM JET1 $N_{tag}=1$: \( QCD = 2.9\% \)

CMUP JET1 $N_{tag}=1$: \( QCD = 1.0\% \)

CMX JET1 $N_{tag}=1$: \( QCD = 1.2\% \)

CEM JET2 $N_{tag}=1$: \( QCD = 7.6\% \)

CMUP JET2 $N_{tag}=1$: \( QCD = 1.5\% \)

CMX JET2 $N_{tag}=1$: \( QCD = 2.2\% \)
## Acceptance Results

<table>
<thead>
<tr>
<th></th>
<th>$A_{jet}$</th>
<th>$A_{sel}$</th>
<th>$\epsilon_{UT}$</th>
<th>$w$</th>
<th>$(A \times \epsilon_{tag})_{CEM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wevbb0p</td>
<td>$0.7871 \pm 0.0008$</td>
<td>$0.4815 \pm 0.001$</td>
<td>$0.1556 \pm 0.001$</td>
<td>$0.7218$</td>
<td>$0.04256 \pm 0.0003$</td>
</tr>
<tr>
<td>Wevbb1p</td>
<td>$0.6798 \pm 0.0009$</td>
<td>$0.5629 \pm 0.001$</td>
<td>$0.1606 \pm 0.001$</td>
<td>$0.2037$</td>
<td>$0.01252 \pm 9e-05$</td>
</tr>
<tr>
<td>Wevbb2p</td>
<td>$0.6811 \pm 0.001$</td>
<td>$0.576 \pm 0.002$</td>
<td>$0.1592 \pm 0.002$</td>
<td>$0.02966$</td>
<td>$0.001853 \pm 2e-05$</td>
</tr>
<tr>
<td>Wevcc0p</td>
<td>$1.306 \pm 0.01$</td>
<td>$0.3438 \pm 0.06$</td>
<td>$0 \pm 0$</td>
<td>$0$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wevcc1p</td>
<td>$1.132 \pm 0.01$</td>
<td>$0.3636 \pm 0.05$</td>
<td>$0.03143 \pm 0.03$</td>
<td>$7.927e-05$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wevcc2p</td>
<td>$0.9455 \pm 0.03$</td>
<td>$0.4615 \pm 0.07$</td>
<td>$0.03667 \pm 0.04$</td>
<td>$2.348e-05$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wevc0p</td>
<td>$1.295 \pm 0.01$</td>
<td>$0.1754 \pm 0.05$</td>
<td>$0 \pm 0$</td>
<td>$0$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wevc1p</td>
<td>$1.069 \pm 0.01$</td>
<td>$0.3377 \pm 0.05$</td>
<td>$0 \pm 0$</td>
<td>$0$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wevc2p</td>
<td>$1.2 \pm 0.01$</td>
<td>$0.625 \pm 0.06$</td>
<td>$0.01956 \pm 0.02$</td>
<td>$2.123e-05$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wevc3p</td>
<td>$0.6786 \pm 0.09$</td>
<td>$0.6316 \pm 0.1$</td>
<td>$0 \pm 0$</td>
<td>$1.707e-06$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wev0p</td>
<td>$1.538 \pm 0.01$</td>
<td>$0.22 \pm 0.04$</td>
<td>$0 \pm 0$</td>
<td>$0.03081$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wev1p</td>
<td>$1.125 \pm 0.01$</td>
<td>$0.3069 \pm 0.03$</td>
<td>$0 \pm 0$</td>
<td>$0.01062$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wev2p</td>
<td>$0.7209 \pm 0.07$</td>
<td>$0.6452 \pm 0.09$</td>
<td>$0.044 \pm 0.05$</td>
<td>$0.002229$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wev3p</td>
<td>$0.7576 \pm 0.07$</td>
<td>$0.56 \pm 0.1$</td>
<td>$0 \pm 0$</td>
<td>$0.0002845$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wev4p</td>
<td>$1.125 \pm 0.01$</td>
<td>$0.4444 \pm 0.2$</td>
<td>$0 \pm 0$</td>
<td>$1.362e-05$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$0.0569 \pm 0.0003$</td>
</tr>
</tbody>
</table>

- $A_{jet}, A_{sel}$ behavior different for elec, muon triggers – from tight jet+lep counting
- Ultratight tag efficiency stable across samples, triggers
## Acceptance Results

<table>
<thead>
<tr>
<th></th>
<th>$A_{jet}$</th>
<th>$A_{sel}$</th>
<th>$\epsilon_{UT}$</th>
<th>$w$</th>
<th>$(A \times \epsilon_{tag})_{CMUP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wmvbb0p</td>
<td>0.8494 ± 0.0007</td>
<td>0.2559 ± 0.0009</td>
<td>0.1557 ± 0.001</td>
<td>0.7208</td>
<td>0.02439 ± 0.0002</td>
</tr>
<tr>
<td>Wmvbb1p</td>
<td>0.8867 ± 0.0006</td>
<td>0.2466 ± 0.0009</td>
<td>0.1579 ± 0.001</td>
<td>0.2041</td>
<td>0.007043 ± 7e-05</td>
</tr>
<tr>
<td>Wmvbb2p</td>
<td>0.9532 ± 0.0006</td>
<td>0.239 ± 0.001</td>
<td>0.1556 ± 0.002</td>
<td>0.02964</td>
<td>0.001051 ± 2e-05</td>
</tr>
<tr>
<td>Wmvcc0p</td>
<td>0.898 ± 0.04</td>
<td>0.1364 ± 0.05</td>
<td>0 ± 0</td>
<td>0.0001574</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Wmvcc1p</td>
<td>1.052 ± nan</td>
<td>0.2469 ± 0.05</td>
<td>0 ± 0</td>
<td>8.95e-05</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Wmvcc2p</td>
<td>0.9861 ± 0.01</td>
<td>0.09859 ± 0.04</td>
<td>0 ± 0</td>
<td>2.954e-05</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Wmvc0p</td>
<td>0.75 ± 0.06</td>
<td>0.2619 ± 0.07</td>
<td>0 ± 0</td>
<td>0.0006173</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Wmvc1p</td>
<td>1.231 ± nan</td>
<td>0.3438 ± 0.05</td>
<td>0 ± 0</td>
<td>0.0001761</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Wmvc2p</td>
<td>0.9726 ± 0.02</td>
<td>0.2676 ± 0.05</td>
<td>0 ± 0</td>
<td>2.56e-05</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Wmvc3p</td>
<td>1.139 ± nan</td>
<td>0.1707 ± 0.06</td>
<td>0 ± 0</td>
<td>1.325e-05</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Wmv0p</td>
<td>0.6528 ± 0.06</td>
<td>0.1915 ± 0.06</td>
<td>0 ± 0</td>
<td>0.0333</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Wmv1p</td>
<td>0.9926 ± 0.007</td>
<td>0.2985 ± 0.04</td>
<td>0 ± 0</td>
<td>0.008321</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Wmv2p</td>
<td>0.8261 ± 0.06</td>
<td>0.2105 ± 0.07</td>
<td>0 ± 0</td>
<td>0.00237</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Wmv3p</td>
<td>1 ± 0</td>
<td>0.1923 ± 0.08</td>
<td>0 ± 0</td>
<td>0.0002204</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Wmv4p</td>
<td>1.25 ± nan</td>
<td>0.3333 ± 0.1</td>
<td>0 ± 0</td>
<td>0.0001017</td>
<td>0 ± 0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>0.0325 ± 0.0002</strong></td>
</tr>
</tbody>
</table>
## Acceptance Results

<table>
<thead>
<tr>
<th></th>
<th>$A_{jet}$</th>
<th>$A_{sel}$</th>
<th>$\epsilon_{UT}$</th>
<th>$w$</th>
<th>$(A \times \epsilon_{tag})_{CMX}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wmvbb0p</td>
<td>$0.8494 \pm 0.0007$</td>
<td>$0.1345 \pm 0.0007$</td>
<td>$0.1543 \pm 0.002$</td>
<td>0.7208</td>
<td>$0.01271 \pm 0.00002$</td>
</tr>
<tr>
<td>Wmvbb1p</td>
<td>$0.8867 \pm 0.0006$</td>
<td>$0.1339 \pm 0.0007$</td>
<td>$0.1624 \pm 0.002$</td>
<td>0.2041</td>
<td>$0.003935 \pm 5e-05$</td>
</tr>
<tr>
<td>Wmvbb2p</td>
<td>$0.9532 \pm 0.0006$</td>
<td>$0.1311 \pm 0.001$</td>
<td>$0.1594 \pm 0.003$</td>
<td>0.02964</td>
<td>$0.0005902 \pm 1e-05$</td>
</tr>
<tr>
<td>Wmvcc0p</td>
<td>$0.898 \pm 0.04$</td>
<td>$0.1591 \pm 0.06$</td>
<td>$0 \pm 0$</td>
<td>0.0001574</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wmvcc1p</td>
<td>$1.052 \pm \text{nan}$</td>
<td>$0.08642 \pm 0.03$</td>
<td>$0 \pm 0$</td>
<td>8.95e-05</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wmvcc2p</td>
<td>$0.9861 \pm 0.01$</td>
<td>$0.2113 \pm 0.05$</td>
<td>$0 \pm 0$</td>
<td>2.954e-05</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wmvc0p</td>
<td>$0.75 \pm 0.06$</td>
<td>$0.2143 \pm 0.06$</td>
<td>$0 \pm 0$</td>
<td>0.0006173</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wmvc1p</td>
<td>$1.231 \pm \text{nan}$</td>
<td>$0.1042 \pm 0.03$</td>
<td>$0 \pm 0$</td>
<td>0.0001761</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wmvc2p</td>
<td>$0.9726 \pm 0.02$</td>
<td>$0.1549 \pm 0.04$</td>
<td>$0 \pm 0$</td>
<td>2.56e-05</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wmvc3p</td>
<td>$1.139 \pm \text{nan}$</td>
<td>$0.122 \pm 0.05$</td>
<td>$0 \pm 0$</td>
<td>1.325e-05</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wmv0p</td>
<td>$0.6528 \pm 0.06$</td>
<td>$0.06383 \pm 0.04$</td>
<td>$0 \pm 0$</td>
<td>0.0333</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wmv1p</td>
<td>$0.9926 \pm 0.007$</td>
<td>$0.1119 \pm 0.03$</td>
<td>$0 \pm 0$</td>
<td>0.008321</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wmv2p</td>
<td>$0.8261 \pm 0.06$</td>
<td>$0.1316 \pm 0.05$</td>
<td>$0 \pm 0$</td>
<td>0.00237</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wmv3p</td>
<td>$1 \pm 0$</td>
<td>$0.1923 \pm 0.08$</td>
<td>$0 \pm 0$</td>
<td>0.0002204</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Wmv4p</td>
<td>$1.25 \pm \text{nan}$</td>
<td>$0.1333 \pm 0.09$</td>
<td>$0 \pm 0$</td>
<td>0.0001017</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Total</td>
<td>$1.25 \pm \text{nan}$</td>
<td>$0.1333 \pm 0.09$</td>
<td>$0 \pm 0$</td>
<td>0.0172</td>
<td>$0.0172 \pm 0.00002$</td>
</tr>
</tbody>
</table>
### Acceptance Systematics

- **Choice of scale, \(Q^2\):**
  - Choice could affect jet \(E_T\) and \(\eta\) distributions, which impacts jet counting
  - ALPGEN scale chosen via:
    \[
    Q^2 = k \cdot (M_W^2 + \sum_p (m_p^2 + p_{T,p}^2))
    \]
    \[
    \delta(A \times \varepsilon)/(A \times \varepsilon) = 3\%
    \]

- **Choice of PDF:**
  - Evaluated in 700/\(pb\) analysis, small
  \[
  \delta(A \times \varepsilon)/(A \times \varepsilon) = 2\%
  \]

---

**Table:**

<table>
<thead>
<tr>
<th>Scale choice</th>
<th>((A \times \varepsilon)_{tag})</th>
<th>((A \times \varepsilon)_{CEM})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(k = 0.5)</td>
<td>Wzb (0.0467 \pm 0.0006)</td>
<td>Wzb (0.0615 \pm 0.0006)</td>
</tr>
<tr>
<td>Default (k = 1)</td>
<td>Wzb (0.0447 \pm 0.0003)</td>
<td>Wzb (0.0600 \pm 0.0003)</td>
</tr>
<tr>
<td>(k = 2.0)</td>
<td>Wzb (0.0456 \pm 0.0006)</td>
<td>Wzb (0.0611 \pm 0.0006)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scale choice</th>
<th>((A \times \varepsilon)_{tag})</th>
<th>((A \times \varepsilon)_{CMUP})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(k = 0.5)</td>
<td>Wmb (0.0257 \pm 0.0003)</td>
<td>Wmb (0.034 \pm 0.0003)</td>
</tr>
<tr>
<td>Default (k = 1)</td>
<td>Wmb (0.0257 \pm 0.0003)</td>
<td>Wmb (0.034 \pm 0.0003)</td>
</tr>
<tr>
<td>(k = 2.0)</td>
<td>Wmb (0.0266 \pm 0.0003)</td>
<td>Wmb (0.035 \pm 0.0003)</td>
</tr>
</tbody>
</table>

**Equation:**

\[
A_{W+b \text{ jets}} \cdot \varepsilon_{\text{tag}} = 0.057 \pm 0.005 \text{ (syst)} \text{ CEM} = 0.031 \pm 0.003 \text{ (syst)} \text{ CMUP} = 0.017 \pm 0.001 \text{ (syst)} \text{ CMX}
\]
Acceptance Systematics

- Sources of systematic error on $A_{W+b\,bjets} \cdot \epsilon_{\text{tag}}$
  - Tag efficiency
  - Jet Energy Corrections
  - $Q^2$ (event level and per-vertex level)
  - PDFs

- We know tag efficiency syst:
  - Comes from imprecise calibration of tag efficiency for data $b$ jets, familiar to most from “the scale factor”
  $\delta(A \times \epsilon)/(A \times \epsilon) = 6\%$

- Have quantified JES:
  - Look at $\pm 1\sigma$ variations on the L5 jet energy correction
  $\delta(A \times \epsilon)/(A \times \epsilon) = 3\%$

<table>
<thead>
<tr>
<th>$W_{\tau}b$ type</th>
<th>$(A \times \epsilon_{\text{tag}})_{i}$</th>
<th>$(A \times \epsilon_{\text{tag}})_{\text{CMU}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{\tau}bb0p$</td>
<td>0.0156 ± 0.0004</td>
<td>0.0616 ± 0.0004</td>
</tr>
<tr>
<td>$W_{\tau}bb1p$</td>
<td>0.0312 ± 0.0001</td>
<td>0.0600 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb2p$</td>
<td>0.0018 ± 3e-05</td>
<td>0.0600 ± 0.0003</td>
</tr>
<tr>
<td>Default $W_{\tau}bb0p$</td>
<td>0.0447 ± 0.0003</td>
<td>0.0600 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb1p$</td>
<td>0.0133 ± 0.0001</td>
<td>0.0581 ± 0.0004</td>
</tr>
<tr>
<td>$W_{\tau}bb2p$</td>
<td>0.0020 ± 3e-05</td>
<td>0.0581 ± 0.0004</td>
</tr>
<tr>
<td>$W_{\tau}bb0p$</td>
<td>0.0434 ± 0.0004</td>
<td>0.0581 ± 0.0004</td>
</tr>
<tr>
<td>$W_{\tau}bb1p$</td>
<td>0.0126 ± 0.0001</td>
<td>0.0581 ± 0.0004</td>
</tr>
<tr>
<td>$W_{\tau}bb2p$</td>
<td>0.0021 ± 3e-05</td>
<td>0.0581 ± 0.0004</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$W_{\tau}bb$ type</th>
<th>$(A \times \epsilon_{\text{tag}})_{i}$</th>
<th>$(A \times \epsilon_{\text{tag}})_{\text{CMUP}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{\tau}bb0p$</td>
<td>0.0271 ± 0.0003</td>
<td>0.035 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb1p$</td>
<td>0.0072 ± 7e-05</td>
<td>0.031 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb2p$</td>
<td>0.0011 ± 3e-05</td>
<td>0.031 ± 0.0003</td>
</tr>
<tr>
<td>Default $W_{\tau}bb0p$</td>
<td>0.0257 ± 0.0002</td>
<td>0.031 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb1p$</td>
<td>0.0076 ± 6e-05</td>
<td>0.031 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb2p$</td>
<td>0.0011 ± 2e-05</td>
<td>0.031 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb0p$</td>
<td>0.0241 ± 0.0003</td>
<td>0.031 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb1p$</td>
<td>0.0075 ± 7e-05</td>
<td>0.031 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb2p$</td>
<td>0.0012 ± 3e-05</td>
<td>0.031 ± 0.0003</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$W_{\tau}bb$ type</th>
<th>$(A \times \epsilon_{\text{tag}})_{i}$</th>
<th>$(A \times \epsilon_{\text{tag}})_{\text{CMX}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{\tau}bb0p$</td>
<td>0.0133 ± 0.0003</td>
<td>0.018 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb1p$</td>
<td>0.0038 ± 7e-05</td>
<td>0.018 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb2p$</td>
<td>0.0006 ± 2e-05</td>
<td>0.018 ± 0.0003</td>
</tr>
<tr>
<td>Default $W_{\tau}bb0p$</td>
<td>0.0133 ± 0.0002</td>
<td>0.018 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb1p$</td>
<td>0.0038 ± 6e-05</td>
<td>0.018 ± 0.0002</td>
</tr>
<tr>
<td>$W_{\tau}bb2p$</td>
<td>0.0006 ± 1e-05</td>
<td>0.018 ± 0.0002</td>
</tr>
<tr>
<td>$W_{\tau}bb0p$</td>
<td>0.0123 ± 0.0003</td>
<td>0.017 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb1p$</td>
<td>0.0038 ± 7e-05</td>
<td>0.017 ± 0.0003</td>
</tr>
<tr>
<td>$W_{\tau}bb2p$</td>
<td>0.0007 ± 2e-05</td>
<td>0.017 ± 0.0003</td>
</tr>
</tbody>
</table>
The Search for the Higgs Boson

- Electroweak symmetry is broken in SM
  - Imposition of mass to fundamental particles
- EWSB in the Standard Model: Higgs Mechanism
  - Additional consequence: existence of Higgs boson
  - Not yet observed – a missing piece of the puzzle
- Promising Tevatron production mode:
  \[ p p \rightarrow W^* \rightarrow W^\pm H : \sim 0.1-0.2 \text{ pb} \]
- Higgs decays to \( b \) quarks if its mass is low:
  \[ H \rightarrow b\bar{b} \]
## Systematics Summary

<table>
<thead>
<tr>
<th>Source</th>
<th>( \frac{\delta \sigma_{b\text{-jets}} \times BR}{\sigma_{b\text{-jets}} \times BR} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b shape modeling</td>
<td>8</td>
</tr>
<tr>
<td>c shape modeling</td>
<td>1</td>
</tr>
<tr>
<td>LF shape modeling</td>
<td>3</td>
</tr>
<tr>
<td>UT tag efficiency</td>
<td>6</td>
</tr>
<tr>
<td>Luminosity</td>
<td>6</td>
</tr>
<tr>
<td>Top Cross Sections</td>
<td>2</td>
</tr>
<tr>
<td>Fake ( W^\pm \not{E_T} ) fits</td>
<td>1</td>
</tr>
<tr>
<td>Tagged Fake ( W^\pm \not{E_T} ) fits</td>
<td>1</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>3</td>
</tr>
<tr>
<td>( Q^2 )</td>
<td>3</td>
</tr>
<tr>
<td>PDF</td>
<td>2</td>
</tr>
<tr>
<td>(</td>
<td>z_0</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Lepton ID efficiency</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>