W/Z production with 2b at NLO

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Eugene, September 09

• Motivations: main background to
  → WH/ZH associated production;
  → single-top production;
  → H/A + b¯b and other signals of new physics;
  → t¯t production;
  → several non-standard model signatures.

• New studies:
  → Wb¯b/Zb¯b at NLO, b massive (F. Febres Cordero, L. R., D. Wackeroth)
  → W + 1 b-jet, 4FNS and 5FNS merged at NLO (J. Campbell, K. Ellis,
    F. Febres Cordero, F. Maltoni, L. R., D. Wackeroth, S. Willenbrock)

• Outlook
$Wb\bar{b}/Zb\bar{b}$ production at NLO, some history . . .

- $V \rightarrow 4$ partons (1-loop massless amplitudes) (Bern, Dixon, Kosower (97))
- $p\bar{p}, pp \rightarrow Vb\bar{b}$ (at NLO, 4FNS, $m_b = 0$) (Campbell, Ellis (99))
- $p\bar{p}, pp \rightarrow Vb + j$ (at NLO, 5FNS) (Campbell, Ellis, Maltoni, Willenbrock (05,07))
- $p\bar{p}, pp \rightarrow Wb\bar{b}$ (at NLO, 4FNS, $m_b \neq 0$) (Febres Cordero, L.R., Wackeroth (06,09))
- $p\bar{p}, pp \rightarrow Zb\bar{b}$ (at NLO, 4FNS, $m_b \neq 0$) (Febres Cordero, L.R., Wackeroth (08,09))
- $p\bar{p}, pp \rightarrow W + 1$ $b$-jet (at NLO, 5FNS+4FNS with $m_b \neq 0$) (Campbell, Ellis, Febres Cordero, Maltoni, L.R., Wackeroth, Willenbrock (08))
$Wb\bar{b}/Zb\bar{b}$ production with full $m_b$ effects

**LO Feynman diagrams:**

Subprocesses at LO:

$\to Wb\bar{b}: \quad q\bar{q}' \to Wb\bar{b}$

$\to Zb\bar{b}: \quad q\bar{q} \to Zb\bar{b}$ and

$gg \to Zb\bar{b}$
Including $O(\alpha_s)$ corrections

\[
\hat{\sigma}_{ij}^{NLO}(x_1, x_2, \mu) = \alpha_s^2(\mu) \left\{ f_{ij}^{LO}(x_1, x_2) + \frac{\alpha_s(\mu)}{4\pi} f_{ij}^{NLO}(x_1, x_2, \mu) \right\}
\]

\[\equiv \hat{\sigma}_{ij}^{LO}(x_1, x_2, \mu) + \delta \hat{\sigma}_{ij}^{NLO}(x_1, x_2, \mu),\]

\[\delta \hat{\sigma}_{ij}^{NLO} = \hat{\sigma}_{ij}^{\text{virt}} + \hat{\sigma}_{ij}^{\text{real}}.\]

- **Virtual Corrections:** consist of one-loop diagrams interfered with corresponding LO amplitude
  - $Wb\bar{b}$: one subprocess, $qq' \to Wb\bar{b}$
  - $Zb\bar{b}$: two subprocesses, $q\bar{q} \to Zb\bar{b}$ and $gg \to Zb\bar{b}$

- **Real Corrections:** consist of tree level diagrams with one extra parton
  - $Wb\bar{b} + k$: two subprocess, $qq' \to Wbb + g$ and $q(\bar{q})g \to Wb\bar{b} + q'(\bar{q}')$
  - $Zb\bar{b} + k$: three subprocesses, $q\bar{q} \to Zb\bar{b} + g$, $gg \to Zb\bar{b} + g$ and $q(\bar{q})g \to Zb\bar{b} + q(\bar{q})$
$W/Z + 2 b$-jets

Febres Cordero, L.R., Wackeroth (06-09)

- We use the $k_T$ jet algorithm with $R = 0.7$ and study two cases:
  - Inclusive Cross Section: events with two $(b + \bar{b})$ or three $(b + \bar{b} + j)$ jets resolved contribute to the cross section.
  - Exclusive Cross Section: only events with two $(b + \bar{b})$ jets resolved contribute to the cross section.

Same convention used by MCFM (used to obtain the results for $m_b = 0$).

- $b$-jet kinematical cuts:
  - Transverse momentum of the $b$-jets: $p_t > p_t,_{min} (15-25 \text{ GeV})$ for both $b$ and $\bar{b}$ jets.
  - Pseudorapidity: $|\eta| < \eta_{max} (2-2.5)$ for both $b$ and $\bar{b}$ jets.

- PDF: for LO results we use 1-loop evolution of $\alpha_s$ and CTEQ6L1, while for NLO results 2-loop evolution of $\alpha_s$ and CTEQ6M.
Tevatron: summary of LO and NLO total cross sections
massive and massless calculation, setting $\mu_r = \mu_f = M_V + 2m_b$ ($V = W, Z$).

<table>
<thead>
<tr>
<th>Cross Section, $Wb\bar{b}$</th>
<th>$m_b \neq 0$ (pb) [ratio]</th>
<th>$m_b = 0$ (pb) [ratio]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma^{LO}$</td>
<td>2.20[-]</td>
<td>2.38[-]</td>
</tr>
<tr>
<td>$\sigma^{NLO}$ inclusive</td>
<td>3.20[1.45]</td>
<td>3.45[1.45]</td>
</tr>
<tr>
<td>$\sigma^{NLO}$ exclusive</td>
<td>2.64[1.2]</td>
<td>2.84[1.2]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cross Section, $Zb\bar{b}$</th>
<th>$m_b \neq 0$ (pb) [ratio]</th>
<th>$m_b = 0$ (pb) [ratio]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma^{LO}$</td>
<td>2.21[-]</td>
<td>2.37[-]</td>
</tr>
<tr>
<td>$\sigma^{NLO}$ inclusive</td>
<td>3.34[1.51]</td>
<td>3.64[1.54]</td>
</tr>
<tr>
<td>$\sigma^{NLO}$ exclusive</td>
<td>2.75[1.24]</td>
<td>3.01[1.27]</td>
</tr>
</tbody>
</table>
Tevatron: scale dependence and theoretical uncertainty at NLO

\[ \sigma_{\text{total}} \text{(pb)} \]

- LO scale uncertainty \( \sim 40\% \).
- Inclusive NLO scale uncertainty \( \sim 20\% \).
- Exclusive NLO scale uncertainty \( \sim 10\% \).
$Wb\bar{b}$, scale dependence: LO vs NLO and massless vs massive

(PRD 78 (2008) 074014)
$Z\bar{b}b$, scale dependence: LO vs NLO and massless vs massive

(orrected graph with legend)

(PrD 78 (2008) 074014)
$Zb\bar{b}$: $m_{bb}$ distributions, massive vs massless

$$
\begin{align*}
\mu_r &= \mu_f = M_Z + 2m_b \\
\text{Inclusive case} & \quad \sigma_{\text{total}} = 2.21 \text{ GeV} \\
& \quad \sigma_{\text{total}} = 2.37 \text{ GeV} \\
& \quad \sigma_{\text{total}} = 3.34 \text{ pb} \\
& \quad \sigma_{\text{total}} = 3.64 \text{ pb}
\end{align*}
$$

(From PRD 78 (2008) 074014)
**Wb̅b/Zb̅b, m_{b̅b} distributions:** testing rescaling LO $\rightarrow$ NLO

Clear effect in the low $m_{b̅b}$ invariant mass region.

*Wb̅b*: PRD 74 (2006) 034007

*Zb̅b*: PRD 78 (2008) 074014
LHC: scale dependence and theoretical uncertainty at NLO

\[ p_t > 15 \text{ GeV} \quad |\eta| < 2.5 \]

\[ p_t > 25 \text{ GeV} \quad |\eta| < 2.5 \]

\[ \sigma \text{[gb]} \]

\[ \frac{\sigma}{\mu_0} \]

\[ \frac{\sigma}{\mu_0} \]

\[ \mu_0 = M_W + 2m_b \]

\[ W^+bb \]

\[ Wbb \]

\[ W^+bb \]

\[ Wbb \]

\[ \mu/\mu_0 > 1 \]

\[ \mu_0 \]

\[ \mu/\mu_0 > 1 \]

\[ \mu_0 \]

\[ (PRD 80:034015, 2009) \]

\[ \rightarrow \text{NLO corrections very large, particularly for inclusive production;} \]

\[ \rightarrow \text{large NLO scale-dependence (LO: 30\%, NLO}_{\text{inc}}: 50\%, \text{NLO}_{\text{exc}}: 20\%),} \]

\[ \text{induced by the opening of the } qg(\bar{q}g) \rightarrow Wb\bar{b} + q'(\bar{q}') \text{ channel;} \]

\[ \rightarrow \text{theoretical uncertainty not only given by scale-dependence!} \]
NLO corrections still large, particularly for inclusive production;

more moderate NLO scale-dependence (LO: 50%, NLO$_{\text{inc}}$: 30%, NLO$_{\text{exc}}$: 5%): $qg(\bar{q}g) \rightarrow Zb\bar{b} + q(\bar{q})$ channel not as dominant.
<table>
<thead>
<tr>
<th></th>
<th>$W^+bb$</th>
<th></th>
<th>$Zbb$</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$m_b \neq 0$</td>
<td>$m_b = 0$</td>
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</tr>
<tr>
<td>$p_T^b &gt; 15$ GeV</td>
<td>$p_T^b &gt; 25$ GeV</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>$\sqrt{s} = 10$ TeV</td>
<td>$\sqrt{s} = 14$ TeV</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{LO}$ (pb)</td>
<td>$14.4^{+2.6}_{-2.1}$</td>
<td>$15.5^{+2.7}_{-2.2}$</td>
<td>$6.49^{+1.3}_{-1.0}$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{NLO,inc}$ (pb)</td>
<td>$33.6^{+7.8}_{-5.6}$</td>
<td>$36.4^{+8.1}_{-6.2}$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{NLO,exc}$ (pb)</td>
<td>$18.6^{+1.7}_{-1.6}$</td>
<td>$20.3^{+1.7}_{-1.8}$</td>
</tr>
<tr>
<td>$\sigma_{LO}$ (pb)</td>
<td>$19.8^{+3.1}_{-2.5}$</td>
<td>$21.3^{+3.2}_{-2.7}$</td>
<td>$9.02^{+1.6}_{-1.3}$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{NLO,inc}$ (pb)</td>
<td>$51.9^{+12}_{-8.7}$</td>
<td>$56.3^{+13}_{-9.6}$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{NLO,exc}$ (pb)</td>
<td>$27.8^{+3.1}_{-2.5}$</td>
<td>$30.4^{+3.5}_{-2.8}$</td>
</tr>
</tbody>
</table>
LHC: some interesting NLO distributions ...
→ NLO distributions cannot be rescaled from LO ones via a K-factor;
→ large corrections in particular for $Wb\bar{b}$ and in the inclusive case.
\( d\sigma / dp_t \) vs. \( p_t \) for \( W^+ b\bar{b} \) and \( Z b\bar{b} \) production.

- **W^+ b\bar{b}**:
  - \( p_t > 15 \text{ GeV} \)
  - \(|\eta| > 2.5\)
  - \( R = 0.7 \)
  - \( E_{\text{CM}} = 14 \text{ TeV} \)

- **Z b\bar{b}**:
  - \( p_t > 15 \text{ GeV} \)
  - \( |\eta| > 2.5\)
  - \( R = 0.7 \)
  - \( E_{\text{CM}} = 14 \text{ TeV} \)
Comparison with massless $b$-quark results . . .

![Graph comparison with massless b-quark results](image-url)
Consistently combine 4FNS ($m_b \neq 0$) and 5FNS ($m_b = 0$) at NLO in QCD:

1. $q\bar{q}' \rightarrow Wb\bar{b}$ at tree level and one loop ($m_b \neq 0$)
2. $q\bar{q}' \rightarrow Wb\bar{b}g$ at tree level ($m_b \neq 0$)
3. $bq \rightarrow Wbq'$ at tree level and one loop ($m_b = 0$)
4. $bq \rightarrow Wbq'g$ and $bg \rightarrow Wbq'\bar{q}$ at tree level ($m_b = 0$)
5. $gq \rightarrow Wb\bar{b}q'$ at tree level ($m_b \neq 0$) → avoiding double counting:

Indeed: a fully consistent NLO 5FNS calculation (S-ACOT scheme).
• improved scale dependence: NLO corrections to $gq \rightarrow Wb\bar{b}q'$ partially included;
• need to keep $m_b \neq 0$ for final state $b$ quarks (one $b$ quark has low $p_T$)

![Graph showing distribution of mb](image)

• four signatures studied: exclusive/inclusive, with single and double-$b$ jets, using $p_T^j > 15$ GeV, $|\eta^j| < 2 - 2.5$, cone algorithm with $\Delta R = 0.7$:
  $\rightarrow$ $Wb$, $W(b\bar{b})$ (exclusive)
  $\rightarrow$ $Wb$ and $Wb + j$, $W(b\bar{b})$ and $W(b\bar{b}) + j$ (inclusive)
which can be combined to obtain different backgrounds, ...
• both contributions play important complementary roles (Tevatron/LHC, inclusive/exclusive);
- **NLO results** at a glance:

<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>$Wb$</td>
<td>$W(b\bar{b})$</td>
</tr>
<tr>
<td>TeV $W^+ (= W^-)$</td>
<td>8.02+0.62[-0.05]=8.64</td>
<td>3.73-0.02[-0.02]=3.71</td>
<td></td>
</tr>
<tr>
<td>LHC $W^+$</td>
<td>40.0+48.4[22.6]=88.4</td>
<td>22.7+11.7[11.7]=34.4</td>
<td></td>
</tr>
<tr>
<td>LHC $W^-$</td>
<td>29.8+29.4[12.6]=59.2</td>
<td>17.2+6.5[6.5]=23.7</td>
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</tr>
</tbody>
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<tr>
<td></td>
<td></td>
<td>$Wb + X$</td>
<td>$W(b\bar{b}) + X$</td>
</tr>
<tr>
<td>TeV $W^+ (= W^-)$</td>
<td>11.77+2.40[0.77]=14.17</td>
<td>4.17+0.39[0.39]=4.56</td>
<td></td>
</tr>
<tr>
<td>LHC $W^+$</td>
<td>53.6+136.1[68.9]=189.7</td>
<td>25.1+35.9[35.9]=61.0</td>
<td></td>
</tr>
<tr>
<td>LHC $W^-$</td>
<td>39.3+88.2[44.6]=127.5</td>
<td>18.9+23.6[23.6]=42.5</td>
<td></td>
</tr>
</tbody>
</table>

→ first number: Processes 1 + 2 (pure 4FNS)
→ second number: Processes 3 + · · · + 5 (pure 5FNS plus $qg \to Wb\bar{b} + q'$)
→ number in square brackets: Process 5 alone ($qg \to Wb\bar{b} + q'$)
Ongoing and future activity on $W/ZQ\bar{Q}$ production . . .

- Provide input to experimental studies:
  - DØ, CDF: $W + b$ study (see Febres Cordero’s and Thomson’s talks), Higgs and single-top working groups;
  - CMS Higgs working group: provide parton level distributions with specific cuts and interface with NLO parton shower Monte Carlo (POWHEG):
    - study $Z + 2b$ as background to $H \rightarrow ZZ$ inclusive production;
    - study $Z + 2b$ and $Z + 1b$ to measure $b$-PDF.
  - ATLAS study of $WH$ with $H \rightarrow b\bar{b}$ in boosted regime (Butterworth, Piacquadio, et al.).

- $Z + 1b$-jet using both 4FNS with $m_b \neq 0$ and 5FNS NLO calculations:
  - $bg \rightarrow Zb$ at tree level and one loop (with $m_b = 0$);
  - $bg \rightarrow Zb + g$, $bq \rightarrow Zb + q$ (with $m_b = 0$);
  - $q\bar{q}, gg \rightarrow Zb\bar{b}$ at tree level and one loop (with $m_b \neq 0$);
  - $q\bar{q}, gg \rightarrow Zb\bar{b} + g$ and $gq(g\bar{q}) \rightarrow Zb\bar{b} + q(\bar{q})$ (with $m_b \neq 0$).

quite different pattern: one loop corrections to $q\bar{q}, gg \rightarrow b\bar{b}Z$ are now a piece of the NNLO 5FNS calculation, comparable to two-loop corrections to (and double parton emission from) $bg \rightarrow Zb$ (?).
• Possible to use $Z + 1b$ to measure $b$-PDF? → reduce the PDF error in $H + 1b$ production?

• Resum large final state collinear logs from $g \rightarrow b\bar{b}$ splitting in $Wg \rightarrow Wb\bar{b}$ (and $Zg \rightarrow Zb\bar{b}$) (with S. Dawson).

• Need too investigate NLO corrections to $qg(\bar{q}g) \rightarrow Wb\bar{b} + q'(\bar{q}')$? (now within reach)

↓

more in D. Wackeroth’s talk tomorrow