NLO for heavy flavor W+jets

- Stating the problem: goals and past experience
- Differences between matched Alpgen and LO MCFM
- Loosening MCFM parton level cuts to study sensitivity of the k-factors: try to match MCFM and Alpgen
- HF fraction from MCFM
- Studying massive b-quarks effect: prescription
- Wbj at NLO in MCFM: how to handle it?
- We have data: make the measurement!
The problem

- We know the NLO cross section changes wrt LO values for Wbb and Wcc, and also for Wjj.

- Since we usually normalize all W+jets to data, the problem is not so much the absolute $\sigma(Wbb)$ or $\sigma(Wjj)$, but the fraction of Wbb (and Wcc) in W+jets: the HF ratio.

- Our Alpgen samples have LO cs values and massive b's, and they are matched (generated with no parton cut on b pT).

- MCFM gives NLO with massless b's and requires a b pT cut.

- In the past, Alpgen was not matched and we could use MCFM with the same Alpgen parton cuts (away from $m_b$) and got a NLO value for both Wbb and Wjj, and ensured the HF fraction was that NLO ratio.

- But now Alpgen is matched, so what NLO $\sigma$ should we use, i.e. what is the effect of not using parton cuts in Alpgen? And what is the effect of massive b's?

- We need to know a $\sigma_{NLO}(Wbb)/\sigma_{NLO}(Wjj)$ that is applicable to our Alpgen v2.06 samples, and study its limitations.
Matched Alpgen issues (T. Nunnemann)

- Alpgen $\sigma$ (Wbb) much larger (x2) with ickkw=1 than 0 → fixed in v2.1
  - ickkw=1 implements the CKKW prescription for the running of $\alpha_s$'s in the extra gluon emission processes
- Good agreement in LO MCFM and Alpgen ickkw=0 distributions
- But ickkw=1 is required for matching!
Matched Alpgen issues

- Compare Alpgen v2.06 in DØ production and MCFM (NLO)
- "k-factors" are large and depend on kinematics!

Black: MCFM
Red: Alpgen

- MCFM (NLO) (closest to the truth) vs. Alpgen (as in production, except b-cut)
Parton cuts dependence

- LO MCFM and LO Alpgen are hard to compare!
  - Default matching settings did not agree with MCFM
- So let's take a look at the old MCFM NLO numbers and see if we can relax the parton level cuts and get something meaningful
- In Alpgen 1.3.3-1 (with no matching), we used:
  - $p_T(jet) > 8 \text{ GeV}$, $|\eta(jet)| < 3.0$ and $\Delta R(jet,jet) > 0.4$
  - And then used MCFM with same parton cuts to get NLO
- In Alpgen 2.06 there are no parton cuts, but we use the following cuts for the MLM clustering criteria:
  - $p_T(jet) > 8 \text{ GeV}$, $\Delta R(jet,jet) > 0.4$
- What cuts should we use in MCFM to compare to MLM?
- Tables of results can be seen here
Pretty large dependence of the Wbb k-factor with jet pT
We should be making a b jet pT dependent correction
Although Wbb matched Alpgen with constant scale factor (+acceptance cuts) seems to agree well with data
Jet $p_T$ with other cuts and smaller $p_T$

- I'm not sure I understand the difference between this plot and the previous one, based on the different cuts.

- Mass effect turn on at $p_T \sim 5\text{GeV}$: MCFM always requires $p_T(b) > 4.620$ & $m(bb) > 9.240$, to simulate the effect of mass.
Allowing for more jet merging (smaller $\Delta R(jet,jet)$ cut) decreases by 20% the Wjj k-factor down to k-factor=1

Wbb k-factor is unaffected
Summary of cuts dependence

To summarize what we have seen:

- No lepton $\eta$ cut dependence: 10 is fine
- No jet $\eta$ cut dependence: 3 is fine
- Relaxing the jet $p_T$ from 8 to 4 GeV gives:
  - $W_{bb}$ $1.642 \rightarrow 1.880$ (+14%); $W_{jj}$ $1.220 \rightarrow 1.197$ (-2%)
  - Huge jet $p_T$ dependence for higher jet $p_T$s
- $W_{jj}$ $k$-factor changes with $\Delta R(jet, jet)$, $W_{bb}$ is stable.
  - Going from 0.4 to 0.05: $W_{jj}$ $k$-factor $1.2 \rightarrow 1.0$ (-17%)
  - Going from 0.4 to 1: $W_{jj}$ $k$-factor $1.2 \rightarrow 1.4$ (+17%)
- We cannot simply apply our old factors
- We could take the numbers from our loosest operating point: what errors?
What we really want

- We really only need $\sigma_{\text{NLO}}(\text{Wbb})$ and $\sigma_{\text{NLO}}(\text{Wjj})$ for a given point.
- In other terms, you can calculate how much you need to boost your Wbb contribution over Wjj in Alpgen to account for NLO: HF factor=$\frac{\text{Wbb k-factor}}{\text{Wjj k-factor}}$.

<table>
<thead>
<tr>
<th>Jet pT</th>
<th>Wbb k-factor</th>
<th>Wjj k-factor</th>
<th>HF factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1.880</td>
<td>1.197</td>
<td>1.571</td>
</tr>
<tr>
<td>6</td>
<td>1.742</td>
<td>1.233</td>
<td>1.413</td>
</tr>
<tr>
<td>8</td>
<td>1.642</td>
<td>1.220</td>
<td>1.346</td>
</tr>
<tr>
<td>10</td>
<td>1.580</td>
<td>1.232</td>
<td>1.282</td>
</tr>
</tbody>
</table>

- Ideally, we'd like: NLO massive/LO massive (Alpgen).
- CDF has measured Wbb and finds a factor $1.5\pm0.4$ to multiply matched Alpgen to agree with data.

A note on Wcc: even though Wcc is not calculated explicitly in MCFM, it has the same production mechanisms as Wbb. And since Wcc is a really small fraction of Wjj (few%), we can treat Wcc/Wjj the same way as Wbb/Wjj before tagging (with some caveats).
Adding b mass to LO distribution decreases $\sigma(Wbb)$

The same effect can be expected for NLO (hep-ph/0606102)
Wbb/Wjj ratio with less jet merging

- NLO massive should lay somewhere between red and green
- Flipping back and forth from previous page, we can see the $\Delta R(\text{jet, jet})$ cut effect: Wjj k-factor is bigger at 1 than at 0.4
NLO Wbb/Wjj with massive b's

Plot kindly provided by D. Wackeroth et al. (hep-ph/0606102)

massive NLO = NLO massless * LO(massive)/LO(massless)
Wbj NLO production

Most recent MCFM calculation (Willenbrock et al. hep-ph/0611348)

<table>
<thead>
<tr>
<th>Collider</th>
<th>(LO) NLO</th>
<th>Cross sections (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$W_{bj}$</td>
<td>$W_{b\bar{b}}$</td>
</tr>
<tr>
<td>TeV $W^+ (= W^-)$</td>
<td>(1.06) 2.54</td>
<td>(2.48) 3.14</td>
</tr>
<tr>
<td>TeV $W^+ (= W^-)$</td>
<td>(261) 290</td>
<td>W jj</td>
</tr>
</tbody>
</table>

- Wbj has large k-factor!
- Wbj is produced in Wbbj in Alpgen

Wbj behaves similarly to Wbb: also comparable in size!

Dashed: LO  
Full: NLO
Conclusions and open questions

- MCFM can be used to obtain NLO cross sections
- Interpretation of results to apply to matched Alpgen is difficult, since LO MCFM and LO Alpgen are difficult to “match”
- Need to take massive b effects into account: prescription ready
- Loosening MCFM parton cuts changes significantly the result
- Wbb k-factor has strong dependence on b jet $p_T$: we should parametrize the HF fraction as a function of jet $p_T$
- Wbj has large k-factor, but behaves like Wbb. Study it separately? Covered by Wbb k-factor?

Possible solutions:

1- If Alpgen/MCFM agree at LO, use NLO MCFM with mass effects taken into account
2- Use the data to measure HF fraction (Wcc? shape dependence?)
3- Use the data to measure Wbb (Wcc? shape dependence?)

*What errors are associated to each possibility?*
Extra slides
Check list: things to do

- Latest MLM version effect of ickkw=1,0
- How to match Alpgen and LO MCFM with massive b: compare MCFM and Alpgen to check agreement
- Shape dependence of k-factors
- How to determine the errors on a k-factor from MCFM? Comparing to what?
- How to determine the errors on a k-factor measured in data? What effects should we look at?
- Study Wc k-factors if/when available in MCFM
- Study Wbj process in Alpgen and make sure its large k-factor is covered
- ...

Arán García-Bellido
Some basics

- k-factor = \( \sigma_{\text{NLO}} / \sigma_{\text{LO}} \)
- HF ratio = \( \sigma(\text{Wbb}) / \sigma(\text{Wjj}) \)
- I'm running MCFM v5.1 with native PDFs and ewscheme=+1
  - \( \alpha_s(M_Z) \) and \( \sin^2 \theta_W \) are calculated from other fixed EW parameters, like Alpgen 2 does
  - Factorization and renormalization scales: \( \mu^2 = M_W^2 + p_T(W)^2 \)
- The k-factors are calculated with CTEQ6M (NLO PDF) for \( \sigma_{\text{NLO}} \) and with CTEQ6L1 (LO PDF) for \( \sigma_{\text{LO}} \), as was done before.
  - Both are massless b's caculations
  - No big difference if I use CTEQ6L1 (LO PDF) for \( \sigma_{\text{NLO}} \)
- MCFM can give you:
  - Wbb LO (with massive b's)
  - Wbb NLO (with massless b's), but no NLO with massive b's
  - Wjj NLO and Wjj LO, but no Wcc (Wcc is included in Wjj)
Comparison with p14 numbers

- Derived by Thomas Nunnemann [here]
- He used MCFM v3.4.5 and CTEQ5L (for LO) and CTEQ5M (for NLO)
- My numbers use v5.1 and CTEQ6M (for NLO) and CTEQ6L1 for LO

p14 Higgs Alpgen parton cuts:

- $p_T(\text{parton}) > 8$ GeV
- $|\eta(\text{parton})| < 3.0$
- $\Delta R(\text{parton,parton}) > 0.4$

<table>
<thead>
<tr>
<th></th>
<th>Thomas</th>
<th>Aran</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma$ LO [pb]</td>
<td>90.168±0.126</td>
<td>112.774±0.177</td>
</tr>
<tr>
<td>$\Sigma$ NLO [pb]</td>
<td>135.180±0.844</td>
<td>137.584±0.142</td>
</tr>
<tr>
<td>$K$-factor</td>
<td>1.499±0.005</td>
<td>1.220±0.014</td>
</tr>
<tr>
<td></td>
<td>2.179±0.004</td>
<td>1.642±0.012</td>
</tr>
</tbody>
</table>
With Alpgen 2.06, massive b-quarks

- $\sigma$ given for one $W$ charge and one $l$ flavor only

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpgen, icckw=0, no b-cut</td>
<td>2.15 pb</td>
<td></td>
</tr>
<tr>
<td>Alpgen, icckw=1, no b-cut</td>
<td>4.07 pb</td>
<td>p17 production: 3.98 pb</td>
</tr>
<tr>
<td>Alpgen, icckw=0, w. b-cut</td>
<td>0.81 pb</td>
<td></td>
</tr>
<tr>
<td>Alpgen, icckw=1, w. b-cut</td>
<td>1.23 pb</td>
<td></td>
</tr>
<tr>
<td>MCFM, LO, massive $b$, w. b-cut</td>
<td>0.78 pb</td>
<td></td>
</tr>
<tr>
<td>MCFM, LO, massless $b$, w. b-cut</td>
<td>0.92 pb</td>
<td></td>
</tr>
<tr>
<td>MCFM, NLO, massless $b$, w. b-cut</td>
<td>1.52 pb</td>
<td>$\rightarrow$ K-factor: 1.65</td>
</tr>
</tbody>
</table>