$l\,\bar{l}$ pair $b\bar{b}$ production: a comparison of aMC@NLO vs POWHEG

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In collaboration with F. Maltoni (U. Louvain), A. Vicini (U. Milano) and M. Zaro (LPTHE)

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The Internet

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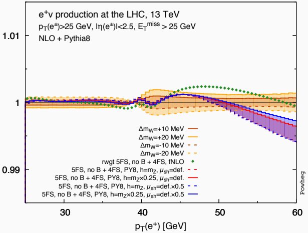
Overview

- *Detailed comparison* between `MG5_aMC@NLO` and the `POWHEG-BOX` performed in the context of the study of heavy-quark effects on the modeling of p_T^Z for the M_W measurement.
- See for instance M. Zaro's talk at the LHCTheory ERC Meeting (link), A. Vicini's talk at the LHC EW WG (link) and E. Bagnaschi's talk at QCD@LHC '17 (link).



- The $\bar{l}lb\bar{b}$ `MG5_aMC@NLO` generator is the one obtained out-of-the-box, besides a redefinition of the renormalization/factorization scales (`setscales.f`).
- A `POWHEG-BOX` generator has been developed for the purpose of this study, using `MadLoop5` to generate the virtual contribution.
- Another `POWHEG-BOX` completely independent implementation using the `HELAC-NLO` framework is also privately available. [Bagnaschi, Bevilacqua, Garzelli, Kardos]

The setup

- LHC pp @ $\sqrt{S} = 13$ TeV.
- PDF, reference set: NNPDF3.0 $n_f = 4$, $\alpha_S = 0.118$.
- μ_r and μ_f scale variation with a standard seven-combination prescription.
- MG5_aMC@NLO: two prescriptions for the extraction of the shower scale (H_T and $\hat{s}$).
- POWHEG-BOX: factor of 1/2 variation for the shower scale of the remnant events.

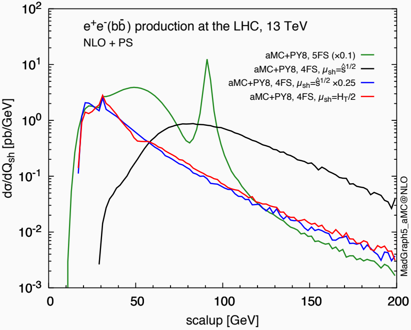
4FS $l\bar{l}b\bar{b}$

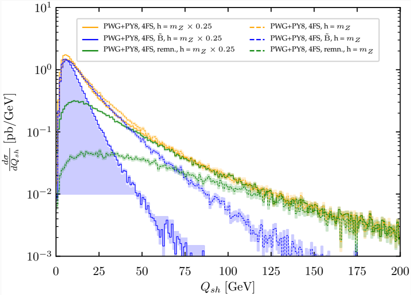
- $\mu_r = \frac{1}{4}\sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$
- $\mu_f = \frac{1}{4}\sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$
- Gen. cuts: $M(l\bar{l}) > 30$ GeV
- Analysis cuts:
  1. $p_\perp(l/\bar{l}) > 20$ GeV
  2. $\eta(l/\bar{l}) < 2.5$
  3. $|M(l\bar{l}) - M_Z| < 15$ GeV

Jet definition

- anti-k_T algorithm, $R = 0.4$ via FastJet.
- $p_\perp(j) > 30$ GeV.
- $|\eta(j)| < 2.5$.
- A jet is b-tagged if it contains at least one B-flavored hadron.
- We assume a 100% b-tagging efficiency and zero mis-tagging rate.

Shower scale (SCALUP) prescriptions



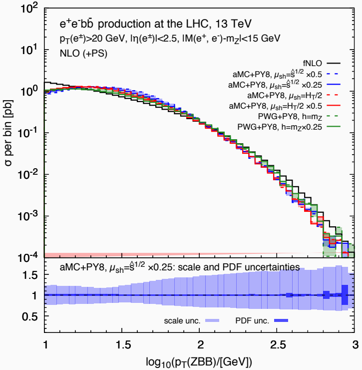


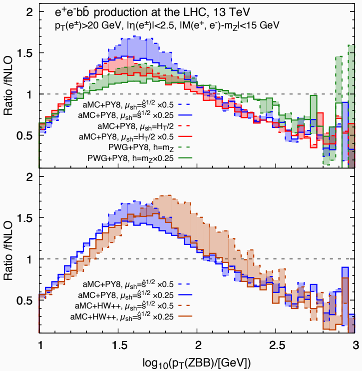
- Two different kinematic variables used to defined the shower scale distribution.
- For each one it is possible to apply "rescaling" factors.

- Two different event classes: $\tilde{B}$ and remnant.
- Shower scale for $\tilde{B}$ events is fixed by the POWHEG formalism.
- Shower scale for the remnant event can be modified from the default prescription (the p_T of the radiated parton). We apply a rescaling factor.

Results

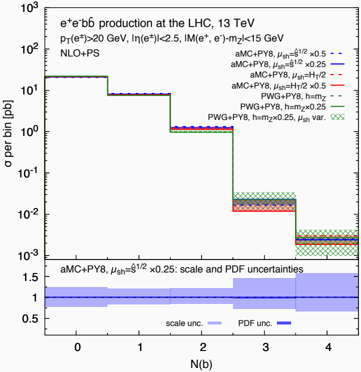
4FS: the transverse momentum of the $\bar{l}l b\bar{b}$ system

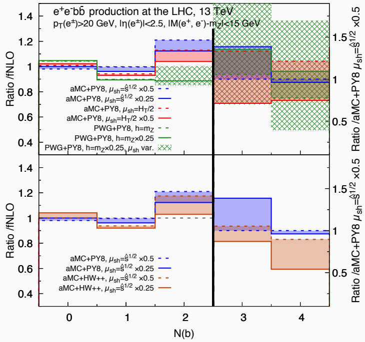




- LO system recoils against emitted parton; the p_T distribution is divergent at fixed order.
- Matching with PS cures the divergence.
- Maximum discrepancy between the frameworks in the intermediate region.
- Both MCs show a high-p_T tail below the fixed order.

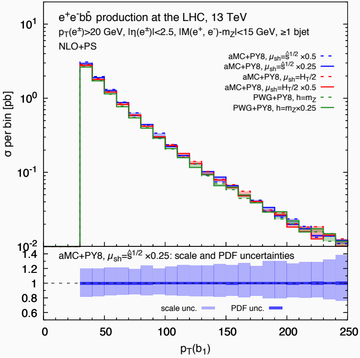
4FS: Number of b-tagged jets

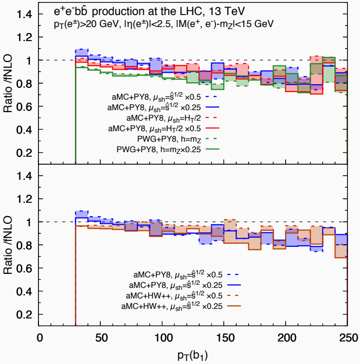




- B-jet cuts: $p_T(j) > 30$ GeV, $|\eta(j)| < 2.5$.
- Different behavior between the two MCs: in POWHEG suppression in the bjet=2 bin, in MG5_aMC@NLO enhancement.

4FS: p_T of the hardest b-jets





- 1st b-jet.
- Suppression of bjets rate in POWHEG w.r.t. to the NLO is manifest here.

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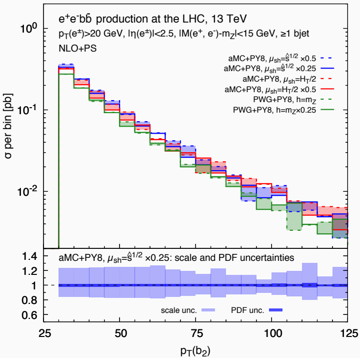
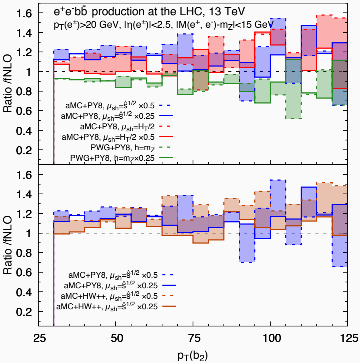
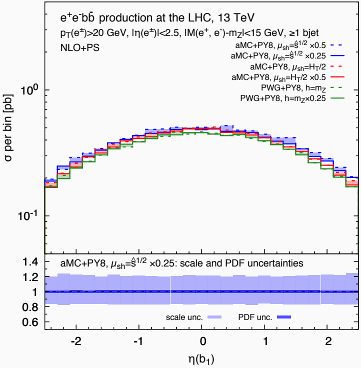
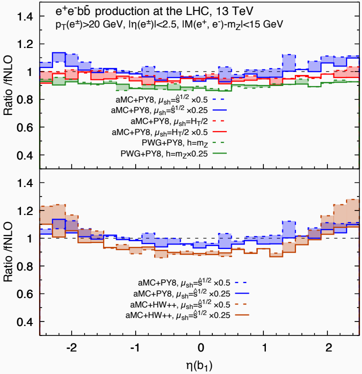




- 2nd b-jet.
- Suppression of bjets rate in POWHEG w.r.t. to the NLO is manifest here.

4FS: pseudorapidity of the hardest b-jets





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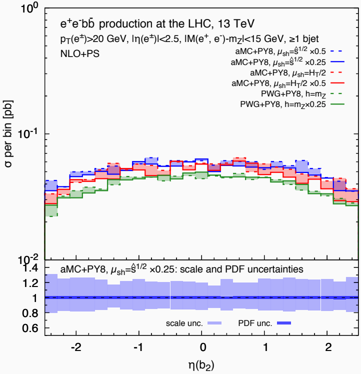

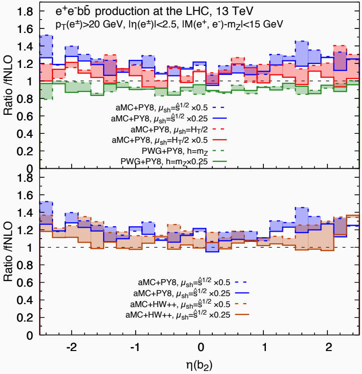

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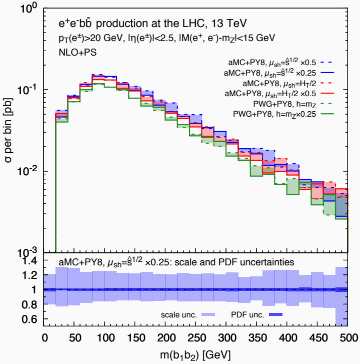
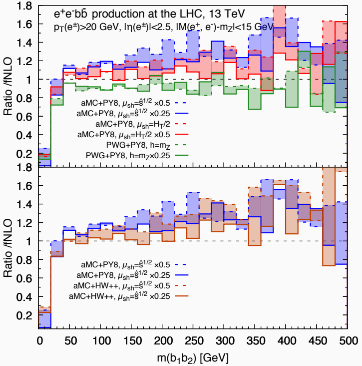
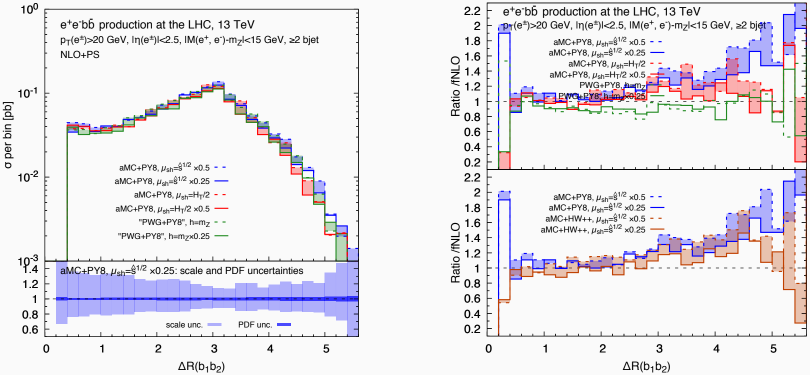
4FS: invariant mass of the b-jet pair





- POWHEG closer to NLO than aMC@NLO.
- Suppression of bjets rate in POWHEG w.r.t. to the NLO is manifest here.

4FS: separation of the hardest b-jets



- POWHEG closer to NLO than aMC@NLO.
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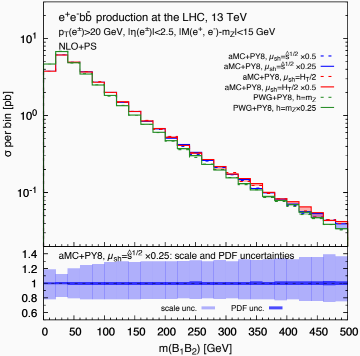
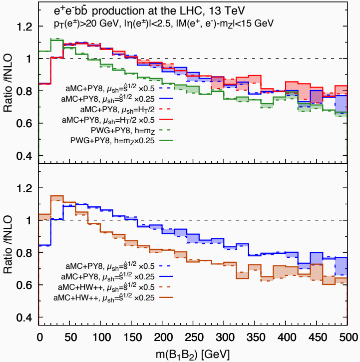
4FS: Invariant mass of the hardest b-hadrons





- no b-jet tagging.
- POWHEG peaks at lower masses than aMC@NLO+PY8, similarly to aMC@NLO+HW++.

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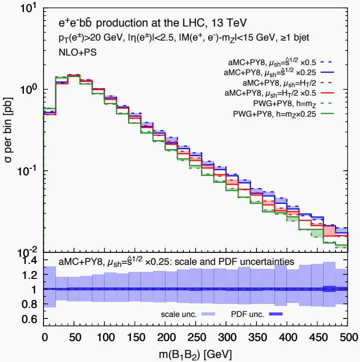
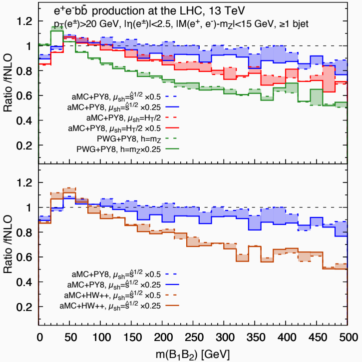
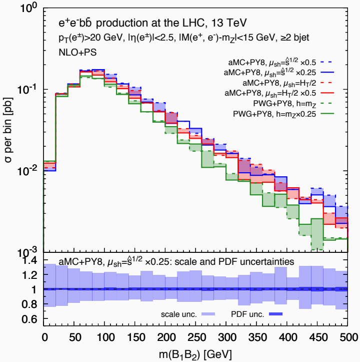
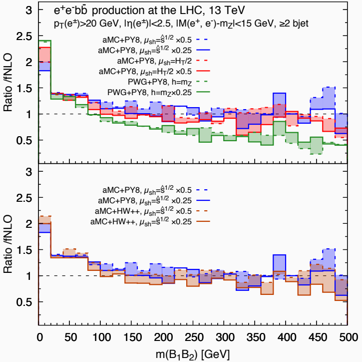




- 1 b-jet tagged.
- With one b-jet tagged, spread between the aMC@NLO predictions.

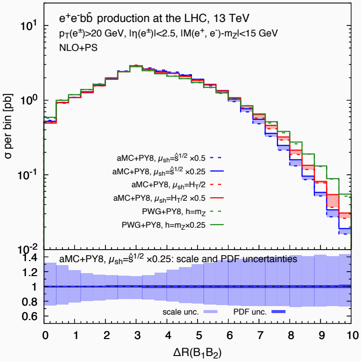
4FS: Invariant mass of the hardest b-hadrons

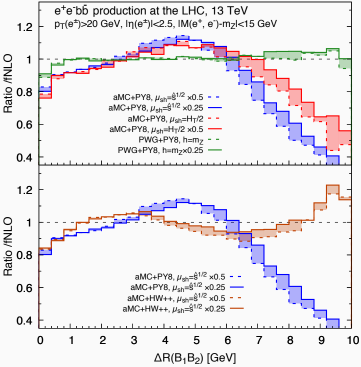




- 2 b-jet tagged.
- The difference becomes less prominent if we tag 2 b-jets.

4FS: separation of the hardest b-hadrons





- no b-jet tagging.
- POWHEG closer to NLO than aMC@NLO.
- Great difference in aMC@NLO between the two showers, unless 2 b-jets tagged.
- Suppression of bjets rate in POWHEG w.r.t. to the NLO is manifest here.

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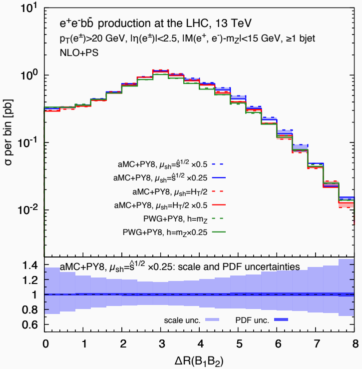

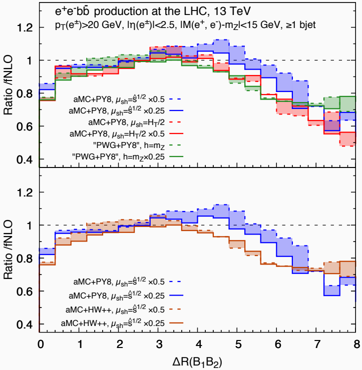

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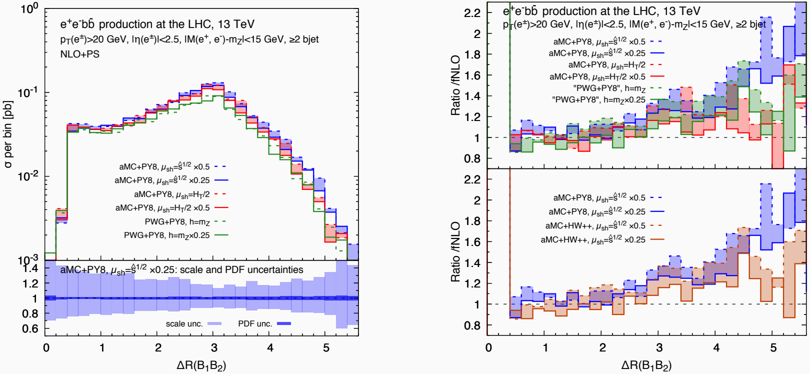

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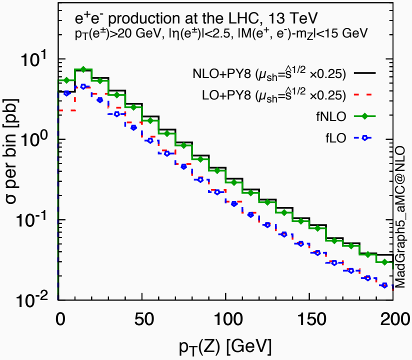
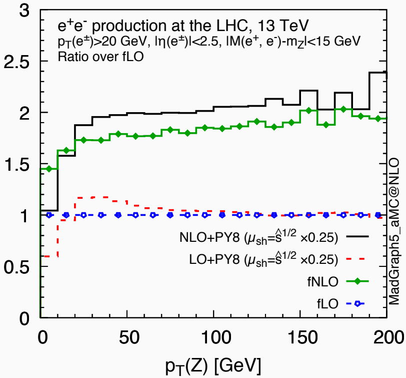
4FS: the transverse momentum of the $l\bar{l}$ system





- Large differential NLO k-factor.
- Sizable effects from PS.

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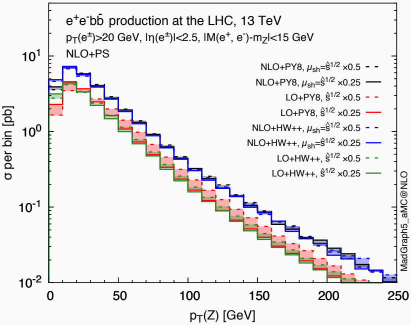

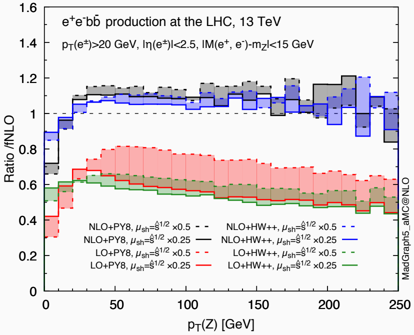

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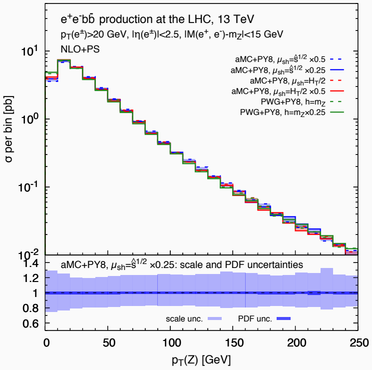
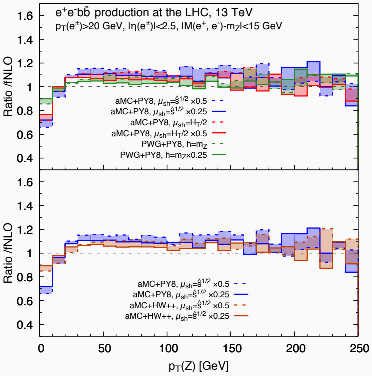
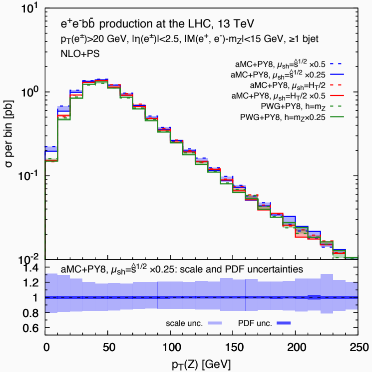
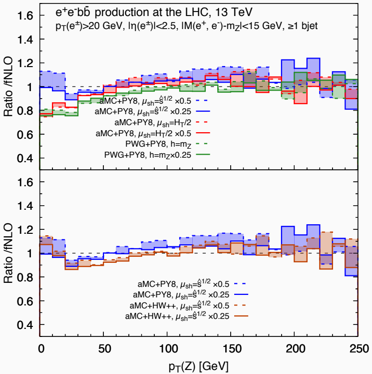




- PDF uncert. nearly constant, $\mathcal{O}(2\%)$; μ_r and μ_f scale dependence nearly constant, $\mathcal{O}(20\%)$.
- Matching uncertainty $\mathcal{O}(5\%)$ in both approaches.
- Larger differences between the two MCs and between PYTHIA8 and HERWIG++, especially in the first bins; non trivial dependence on p_T.

4FS: the transverse momentum of the $l\bar{l}$ system





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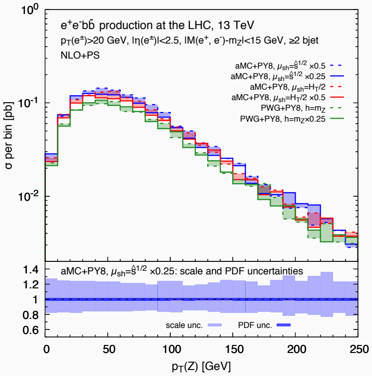

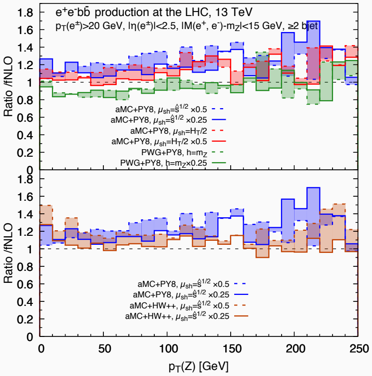

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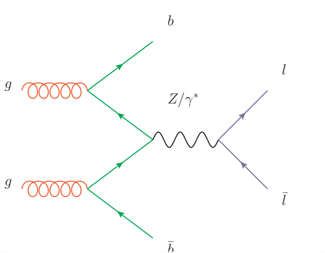
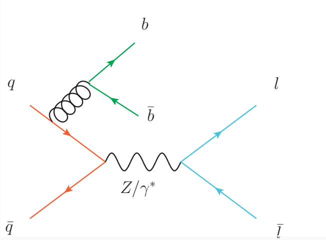
Conclusions

Summary and perspectives

Modeling the $l\bar{l}b\bar{b}$ process

- Multiscale process due to the presence of massive colored final states (the two bottom quarks).
- An accurate study of matching systematic shows sizable dependence on scheme/shower.
- Future: improved matching scheme needed to account for all the scales?





Backup slides

5FS scale choice

- Scale chosen to minimize the differences between the 5FS bottom-only contribution and the 4FS description.
- $\mu_r = \sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$
- $\mu_f = \sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$
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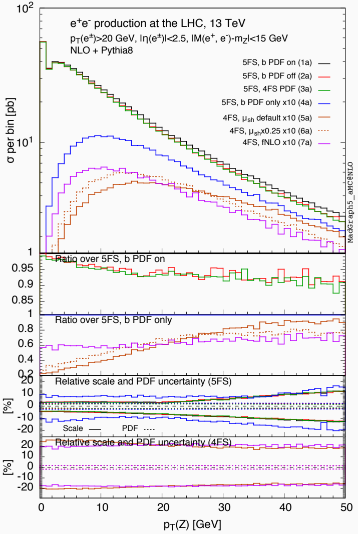

Setup-observables	σ w/ cuts
5FS $pp \to e^+e^-$	$800.9^{+3.2+2.0}_{-6.7-2.0}$
5FS $b\bar{b} \to e^+e^-$	$36.26^{+7.3+2.4}_{-11.8-2.4}$
4FS `MG5_aMC@NLO` $pp \to e^+e^- b\bar{b}$	$23.17^{+20.6+1.6}_{-17.1-1.6}$
4FS NLO $pp \to e^+e^- b\bar{b}$	$23.30^{+20.6+1.6}_{-17.1-1.6}$

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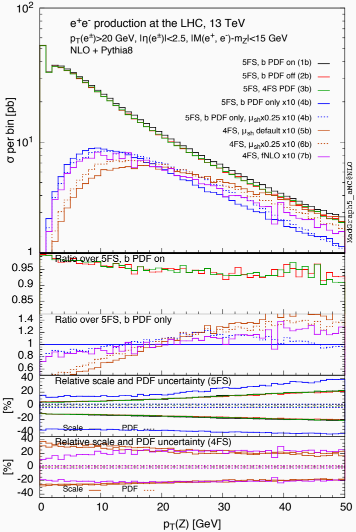
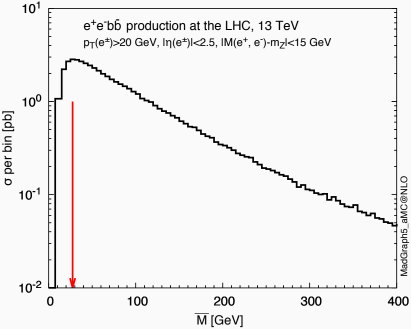
Setup-observables	σ w/ cuts
5FS $pp \to e^+e^-$	$754.3^{+10.4+2.1}_{-15.2-2.1}$
5FS $b\bar{b} \to e^+e^-$	$28.89^{+22.0+2.6}_{-37.1-2.6}$
4FS MG5_aMC@NLO $pp \to e^+e^- b\bar{b}$	$30.11^{+21.6+1.7}_{-20.6-1.7}$
4FS NLO $pp \to e^+e^- b\bar{b}$	$30.21^{+21.8+1.7}_{-20.7-1.7}$



Effective scale



- Peak at $\overline{M}$ of $\mathcal{O}(30~\mathrm{GeV})$.

- Following refs. [Maltoni et al '12] and [Lim et al 16], universal log factor associated with $g \to b\bar{b}$ splittings:

$$L = \log\left(\frac{M^2(e^+, e^-)}{m_b^2}\,\frac{(1-z_i)^2}{z_i}\right)$$

- $z_i \equiv \frac{M^2(e^+,e^-)}{s_i}$
- $s_i \equiv (q_+ + q_- + k_i)^2$
- We define the effective scale as

$$\overline{M} \equiv M(e^+, e^-)\frac{(1-z_i)}{\sqrt{z_i}}$$

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Neutral-current Drell-Yan

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- $\mu_r = \frac{1}{4}\sqrt{M(\bar{l}l)^2 + p_\perp(\bar{l}l)^2}$
- $\mu_f = \frac{1}{4}\sqrt{M(\bar{l}l)^2 + p_\perp(\bar{l}l)^2}$
- Gen. cuts: $M(\bar{l}l) > 30$ GeV
- Analysis cuts:
  1. $p_\perp(l/\bar{l}) > 20$ GeV
  2. $\eta(l/\bar{l}) < 2.5$
  3. $|M(\bar{l}l) - M_Z| < 15$ GeV

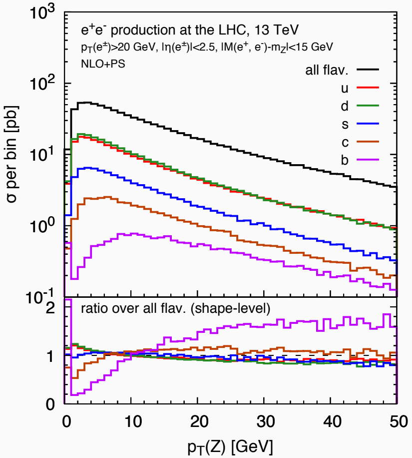
Charged-current Drell-Yan

- $\mu_r = \sqrt{M(\bar{l}l)^2 + p_\perp(\bar{l}l)^2}$
- $\mu_f = \sqrt{M(\bar{l}l)^2 + p_\perp(\bar{l}l)^2}$
- Analysis cuts:
  1. $p_\perp(l^\pm/missing) >$ 20 GeV
  2. $\eta(l^\pm) < 2.5$

5FS: the transverse momentum of the $l\bar{l}$ system

- Different initial state flavor contribute in a different way
- Bottom contribution peak shifted.
- Bottom: first bin kink due to PS when bottom quarks are involved.

initial state quark	cross section (pb)	%
u	374.44 ± 0.62	35.0
d	391.15 ± 0.63	36.5
c	91.44 ± 0.34	8.6
s	170.43 ± 0.45	15.9
b	43.13 ± 0.26	4.0
total	1070.58 ± 0.86	100.0



The reweighting function

The canonical way to include these effects is to re-tune the parton shower MCs on the Z data using this improved prediction. To estimate these effects without performing the tune, we adopt the following procedure:

1. Define:

$$\mathcal{R}(p_\perp^{l^+l^-}) \equiv \left(\frac{1}{\sigma_{fid}^{best}} \frac{d\sigma^{best}}{dp_\perp^{l^+l^-}}\bigg|_{tuneX} \right) \cdot \left(\frac{1}{\sigma_{fid}^{5FS}} \frac{d\sigma^{5FS}}{dp_\perp^{l^+l^-}}\bigg|_{tuneX} \right)^{-1}$$

2. Suppose that we have two PS tunes called `tune1` which describe the data:

$$\frac{1}{\sigma_{fid}^{exp}} \frac{d\sigma^{exp}}{dp_\perp^{l^+l^-}} = \frac{1}{\sigma_{fid}^{5FS}} \frac{d\sigma^{5FS}}{dp_\perp^{l^+l^-}}\bigg|_{\texttt{tune1}} = \frac{1}{\sigma_{fid}^{best}} \frac{d\sigma^{best}}{dp_\perp^{l^+l^-}}\bigg|_{\texttt{tune2}} = \mathcal{R}(p_\perp^{l^+l^-}) \frac{1}{\sigma_{fid}^{5FS}} \frac{d\sigma^{5FS}}{dp_\perp^{l^+l^-}}\bigg|_{\texttt{tune2}} .$$

3. From 1.+2. it follows that:

$$\frac{1}{\sigma_{fid}^{5FS}} \frac{d\sigma^{5FS}}{dp_\perp^{l^+l^-}}\bigg|_{\texttt{tune2}} = \frac{1}{\mathcal{R}(p_\perp^{l^+l^-})} \frac{1}{\sigma_{fid}^{5FS}} \frac{d\sigma^{5FS}}{dp_\perp^{l^+l^-}}\bigg|_{\texttt{tune1}} .$$

An improved prediction of $p_T^{l\bar{l}}$

- Goal: combine the two predictions in a consistent approach, avoiding double counting.

5FS

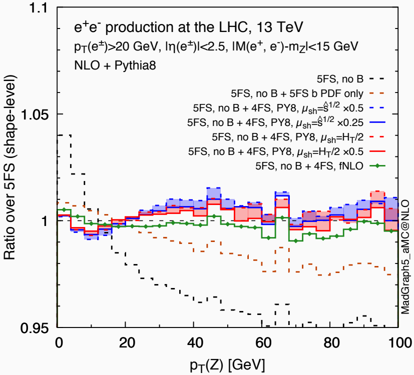
- B-hadrons from the PS in two cases:
  1. $b\bar{b}$ and bg channels: splitting in the backward evolution (no bottom content in the proton).
  2. For the other channel: $g \to b\bar{b}$ splitting.
- *We remove the bottom contribution by vetoing B-hadrons in final state.*

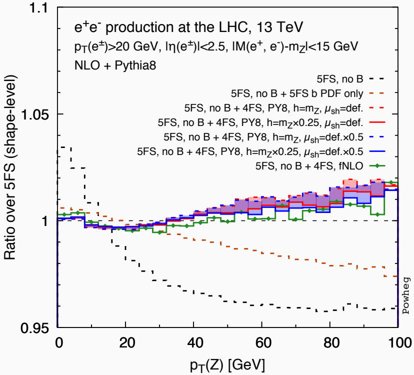
4FS

- By construction the process contains two massive bottom in the final state.
- Other bottoms will arise from PS splitting.
- Improved description which keeps into account the mass of the quark.

$$\frac{d\sigma^{\mathrm{best}}}{dp_\perp^{l^+l^-}} = \frac{d\sigma^{\mathrm{5FS-Bveto}}}{dp_\perp^{l^+l^-}} + \frac{d\sigma^{\mathrm{4FS}}}{dp_\perp^{l^+l^-}}$$

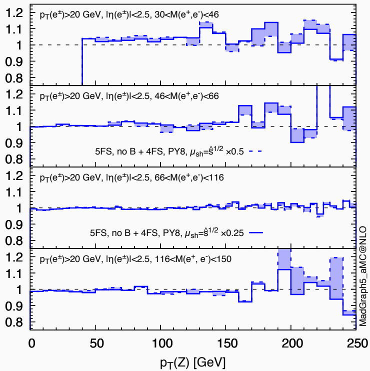
An improved prediction of p_T^{ll}

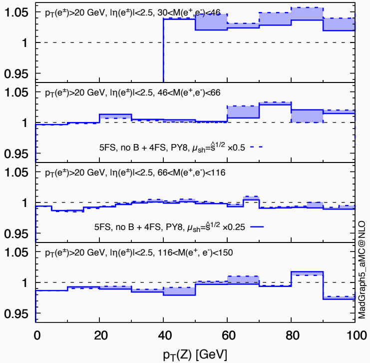




- 5FS b-contribution: non-trivial shape, the two contributions are of the same order of magnitude at large p_T, while at low p_t gluon splitting from light-quark induced processes dominates.
- Non-trivial shape distortion.
- Effects after merging of the order of $\mathcal{O}(\pm 1\%)$ for `MG5_aMC@NLO`, $\mathcal{O}(\pm 0.5\%)$.

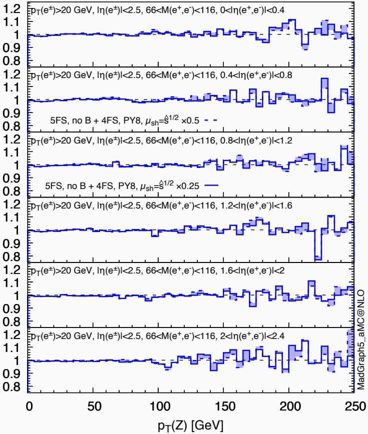
An improved prediction of p_T^{ll}

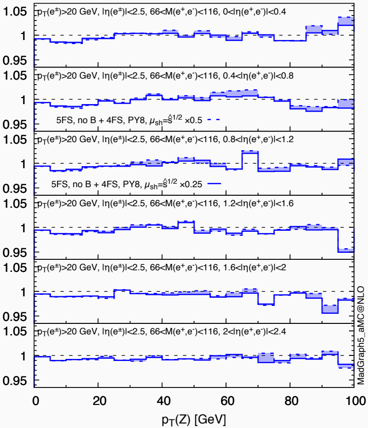




- Can we explain the difference in shape in observed spectrum vs the current MC samples? No.
- No sizable dependence on the invariant mass of the lepton pair.

An improved prediction of $p_T^{l\bar{l}}$





- Can we explain the difference in shape in observed spectrum vs the current MC samples? No.
- No sizable dependence on the pseudorapidity of the lepton pair.