$l\,\bar{l}$ pair $b\bar{b}$ associated production and its impact on the W mass measurement

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03 May 2018
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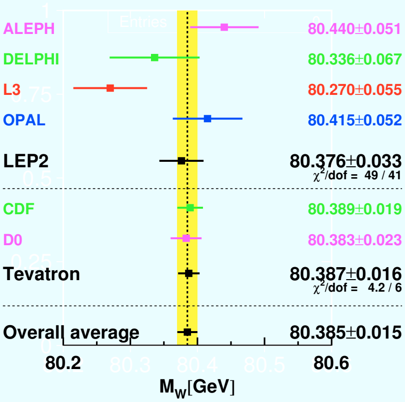
Talk structure

1. Introduction
2. The process
3. Results
   - B-jets
   - B-hadrons
4. Impact on the W mass measurement
5. Conclusions

Introduction

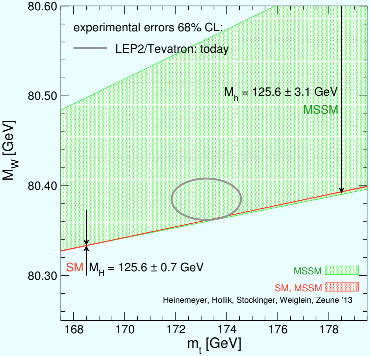
Introduction

- The M_W mass measurement is one of the important item of the SM precision program at the LHC.
- The value of M_W is important to understand the consistency of the SM and to constraint new physics.



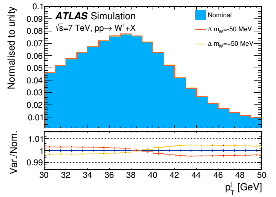
[PDG16]

Experiment	M_W
Tevatron+LEP II (PDG)	80.385 GeV $\pm$ 15 MeV
ATLAS (7 TeV)	80.370 GeV $\pm$ 19 MeV



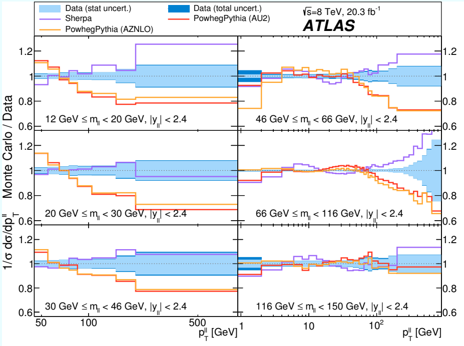
[Heinemeyer et al '13]

Introduction



- The measurement of the W mass is performed using a template-fit approach.
- it depends on the theory models encoded in the tools (Monte Carlo event generators) used to produce the templates.
- One element that therefore enters these predictions is the *non-perturbative tune* of the Parton Shower (PS).

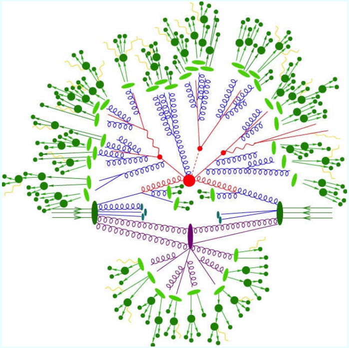
- To tune the PS, precisely measured observables are needed.
- A prime target is the transverse momentum distribution of the Z ($l\bar{l}$).



[ATLAS 1512.02192]

Introduction

- The PS non-perturbative tune adsorb in an effective way everything that has not been properly described by the theory prediction.



[SHERPA]

- One should strive to control as much as possible and leave in the tune only universal, non-perturbative effects.
- In the past few years, the question of how using a massless description for the bottom-quark induced contributions may/may not induce spurious *non-universal* terms to be included in the PS tune.
- Goal: build an improved description of the bottom-quark induced contribution to the Z transverse momentum.
- Another study of mass quark effects in Drell-Yan recently published, [Pietrulewicz et al '17].

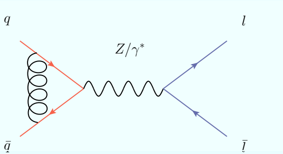
The process

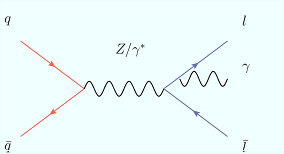
$\bar{l}l + X$ production

- Process studied since the '70 and now know to a quite high degree of accuracy.

QCD

- NNLO differential [Melnikov et al 06, Catani et al '09, Gavin et al '10 and '12]
- Resummation [Arnold et al '91, Balasz et al '95, Ellis et al '97, Qiu et al '00, Kulesza et al '01 and '02, Bozzi '10]
- NLO MC+PS [Frixione xx, Alioli '08, Alwall et al '14, SHERPA]
- NNLO MC+PS [Hoecher et al '14, Karlberg et al '14, Frederix et a]

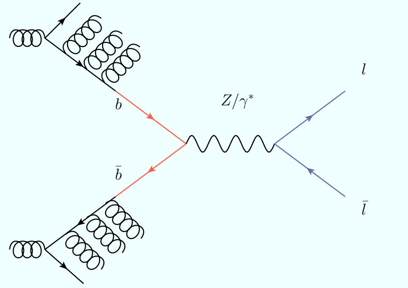


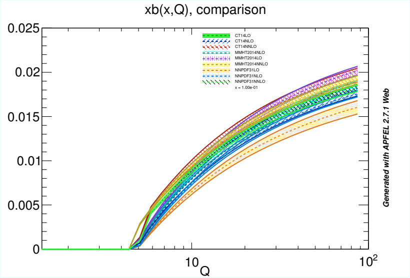


EW

- NLO EW [Baur et al '97-'04 , Brein et al '99, Dittmaier et al '01, Zykunov '01 and '05, Arbuzov et al '05 and '06, Carloni Calame et al '06 and '07, Brensing et al '07, Dittmaier et al '09]
- NLO QCD/EW + PS [Bernaciak et al, Barze et al '12 and '13, Mück et al '16]
- Mixed QCD-EW [Dittmaier et al '14 and '15]

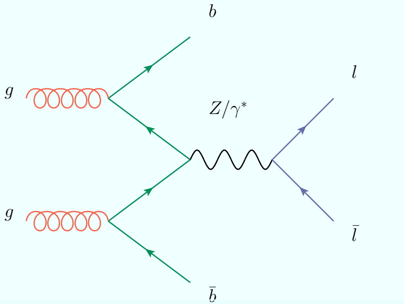
$l\bar{l} + X$ production: the 5FS





- Computation all in the 5FS, where the bottom is a massless initial state quark.
- DGLAP evolution of the bottom PDF resums large logs $\mathcal{O}(\log(m_Z/m_b))$.
- Neglects terms of order m_b/m_Z and less accurate description for kinematic distributions where the QCD radiation can be influenced by the natural mass scale of the bottom.

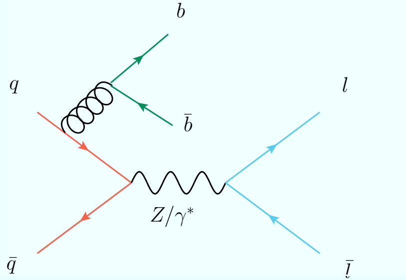
$l\bar{l}b\bar{b} + X$ production in the 4FS



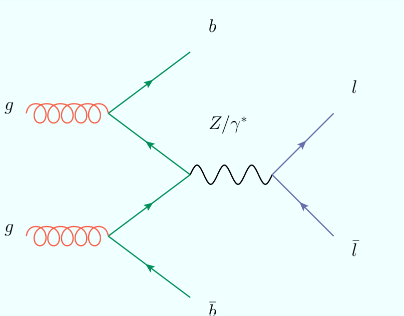
- In the 4FS the bottom quark is massive and no PDF is present in the proton.
- Collinear logs, which are resummed in the 5FS, are included only at FO in the 4FS.
- On the other hand, the terms of order m_b/m_Z are included.

QCD

- NLO-QCD: [J.M. Campbell and R.K. Ellis '06, Campbell et al. '03 and '06, Maltoni et al. '05, Febres Cordero et al. '08 and '09]



$\bar{l}l b\bar{b} + X$ production in the 4FS



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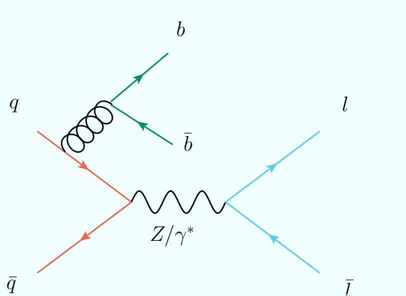
- Collinear logs, which are resummed in the 5FS, are included only at FO in the 4FS.
- On the other hand, the terms of order m_b/m_Z are included.

MC

- The process has been studied up to NLO-QCD+PS, using automated frameworks for the generation of the amplitudes. [Frederix et al '11, Krauss et al '16]



The frameworks

We use implementations of the 5FS and 4FS process in the MG5_aMC@NLO and POWHEG-BOX NLO+PS frameworks. To generate the matrix elements, MadGraph and MadLoop were used in both cases

MC@NLO

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}O}\right)_{\text{MC@NLO}} =$$
$$\sum_{n\geq 0} \int \left[B \otimes \Gamma + \hat{V}_{\text{fin}} \otimes \Gamma + \int \hat{R}^{s}_{\texttt{MC@NLO}} \otimes \Gamma \, \mathrm{d}\Phi^{\text{MC}}_{r} \right] \frac{\mathrm{d}\Phi_B \, \mathrm{d}\Phi^{\text{MC}}_{n}}{\mathrm{d}O} \mathcal{I}_n(t_1 \equiv Q^{s}_{\text{sh}})$$
$$+ \sum_{n\geq 1} \int \left[R \otimes \Gamma \frac{\mathrm{d}\Phi \, \mathrm{d}\Phi^{\text{MC}}_{n-1}}{\mathrm{d}O} - R^{s}_{\texttt{MC@NLO}} \otimes \Gamma \frac{\mathrm{d}\Phi^{\text{MC}} \, \mathrm{d}\Phi^{\text{MC}}_{n-1}}{\mathrm{d}O} \right] \mathcal{I}_{n-1}(t_1 \equiv Q^{h}_{\text{sh}})$$

- Matching systematic estimated by varying the shower scale prescription (Sudakov form factor only from the PS).

The frameworks

We use implementations of the 5FS and 4FS process in the `MG5_aMC@NLO` and `POWHEG-BOX` NLO+PS frameworks. To generate the matrix elements, `MadGraph` and `MadLoop` were used in both cases

POWHEG

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}O}\right)_{\texttt{POWHEG}} = \sum_{n\geq 1}\int \Big[\bar{B}^s\,\mathrm{d}\Phi_B \Big\{\Delta^s_{t_{\min}} + \Delta^s_t \frac{R^s_{\texttt{POWHEG}}}{B}\,\mathrm{d}\Phi_r\Big\} + R^f_{\texttt{POWHEG}} \otimes \Gamma\,\mathrm{d}\Phi + R_{\mathrm{reg}} \otimes \Gamma\,\mathrm{d}\Phi\Big] \frac{\mathrm{d}\Phi^{\mathrm{MC}}_{n-1}}{\mathrm{d}O}\mathcal{I}_{n-1}(t_1 \equiv p_\perp^{\mathrm{rad}})$$

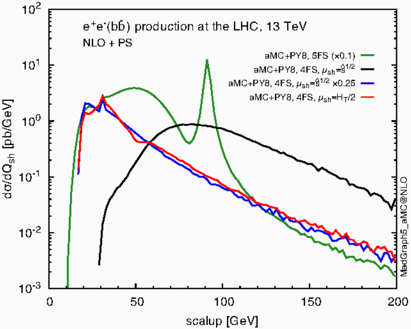
$$\overline{B}^s = B(\Phi_b) + \Big[V(\Phi_b) + \int \mathrm{d}\Phi_{R|B}\hat{R}^s_{\texttt{POWHEG}}(\Phi_{R|B})\Big]$$

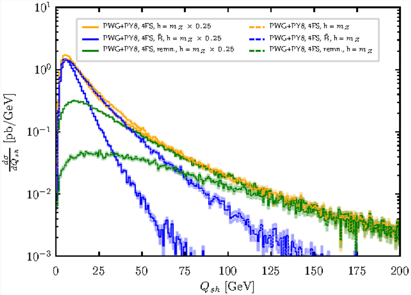
$$\Delta^s_t(\bar{\Phi}_B, p_T) = \exp\Big\{-\int d\Phi_{\mathrm{rad}} \frac{R^s_{\texttt{POWHEG}}(\bar{\Phi}_B, \Phi_{\mathrm{rad}})}{B(\Phi_1)}\theta(k_T - p_T)\Big\}$$

$$R^s_{\texttt{POWHEG}} = \frac{h^2}{h^2 + p_T^2} R \quad , \quad R^f_{\texttt{POWHEG}} = \frac{p_T^2}{h^2 + p_T^2} R$$

- Matching systematic estimated by varying the value of the damping factor and the shower scale prescription.

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.

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.

Neutral-current Drell-Yan

- $\mu_r = \frac{1}{4}\sqrt{M(\bar{l}l)^2 + p_\perp(\bar{l}l)^2}$
- $\mu_f = \frac{1}{4}\sqrt{M(\bar{l}l)^2 + p_\perp(\bar{l}l)^2}$
- 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

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

- $\mu_r = \frac{1}{4}\sqrt{M(\bar{l}l)^2 + p_\perp(\bar{l}l)^2}$
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Charged-current Drell-Yan

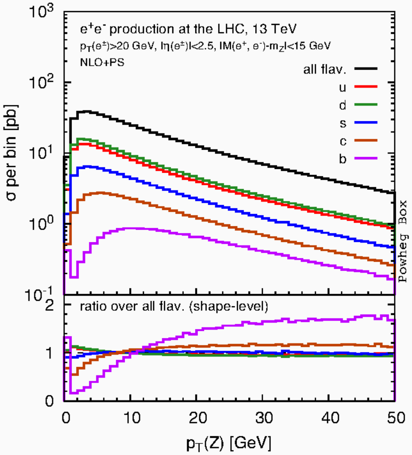
- $\mu_r = \sqrt{M(\bar{l}l)^2 + p_\perp(\bar{l}l)^2}$
- $\mu_f = \sqrt{M(\bar{l}l)^2 + p_\perp(\bar{l}l)^2}$
- Analysis cuts:
  1. $p_\perp(l^\pm/missing) > 25$ GeV
  2. $\eta(l^\pm) < 2.5$

Results

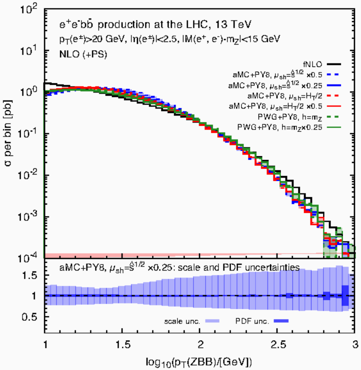
5FS: the transverse momentum of the $l\bar{l}$ system

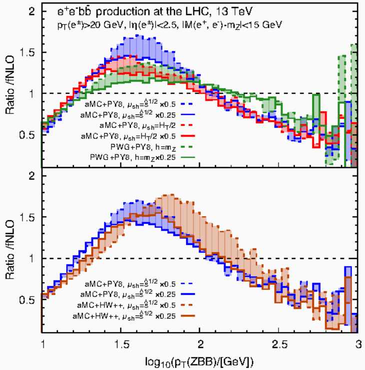
- Different initial state flavor contribute in a different way
- Bottom contribution peak shifted.
- Bottom: first bin kink due to PS when bottom quarks are involved.

initial state quark	cross section (pb)	%
u	245.54 ± 0.13	33.0
d	277.98 ± 0.14	37.4
c	63.86 ± 0.07	8.6
s	127.90 ± 0.09	17.2
b	28.31 ± 0.05	3.8
total	743.61 ± 0.22	100.0



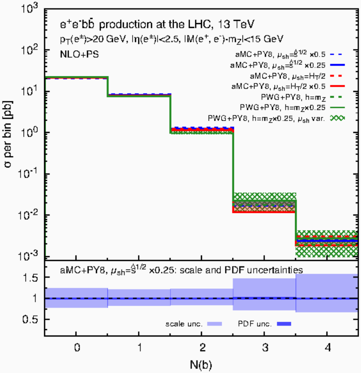
4FS: the transverse momentum of the $l\bar{l}b\bar{b}$ system

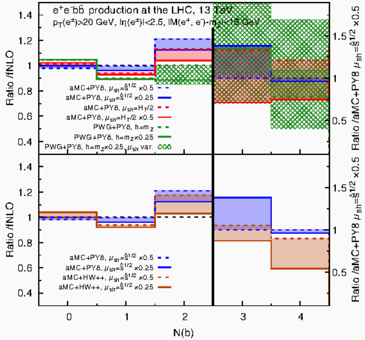




- LO system recoils against emitted parton; the p_T distribution is divergent at fixed order.
- Matching with PS cures the divergence.
- Maximum discrepancy between the frameworks in the intermediate region.
- Both MCs show a high-p_T tail below the fixed order.

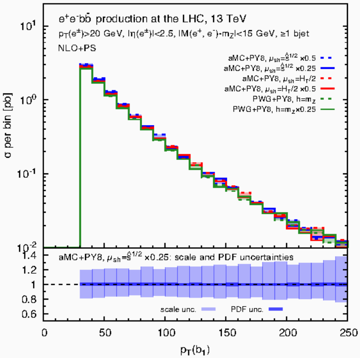
4FS: Number of b-tagged jets

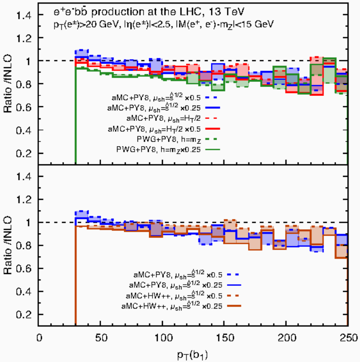




- B-jet definition: anti-K_T, $R = 0.4$, at least one b-hadron.
- B-jet cuts: $p_T(j) > 30$ GeV, $|\eta(j)| < 2.5$.
- Different behavior between the two MCs: in POWHEG suppression in the bjet=2 bin, in MG5_aMC@NLO enhancement.

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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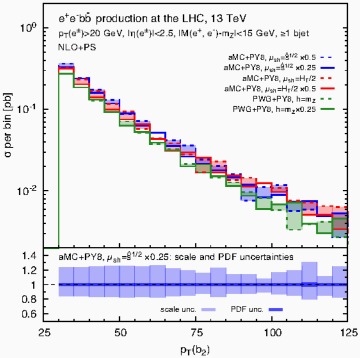
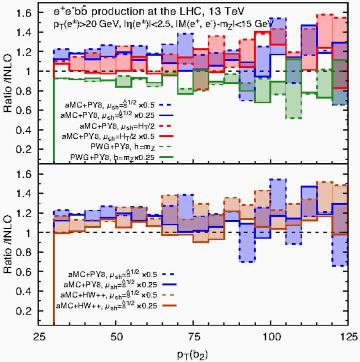
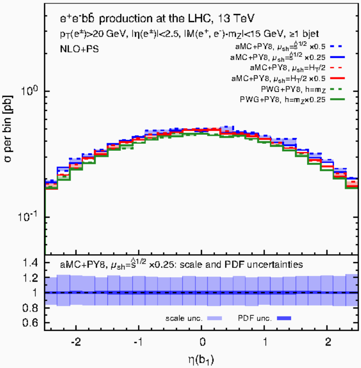
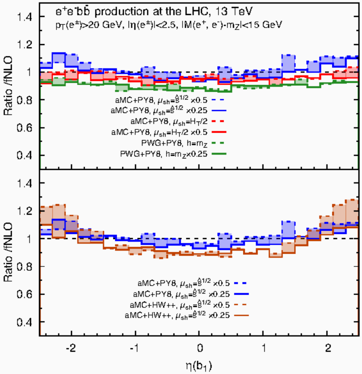




- 2nd b-jet.
- Suppression of bjets rate in POWHEG w.r.t. to the NLO is manifest here.

4FS: pseudorapidity of the hardest b-jets





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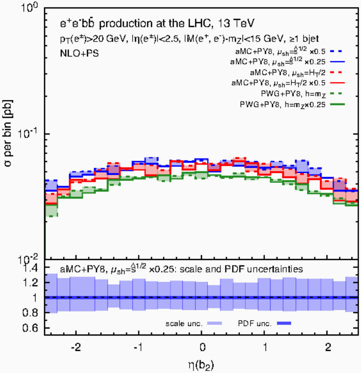

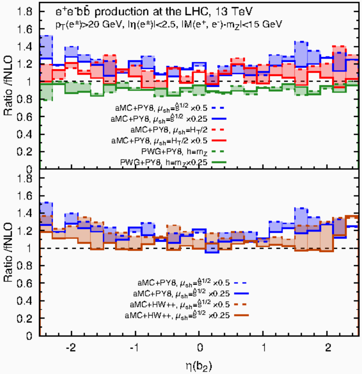

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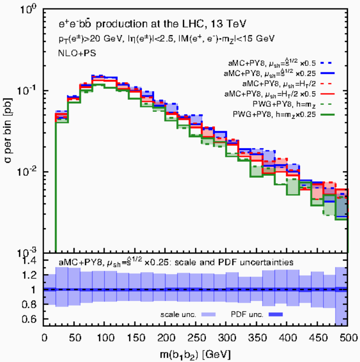

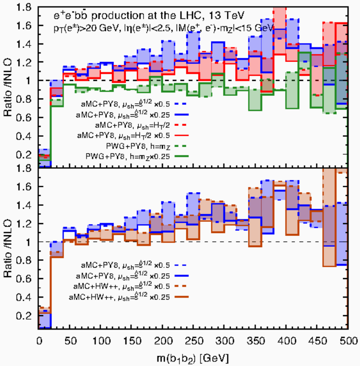

- POWHEG closer to NLO than aMC@NLO.
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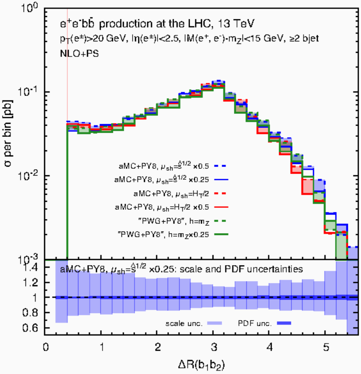
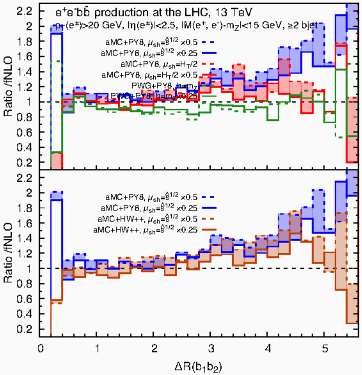
4FS: separation of the hardest b-jets





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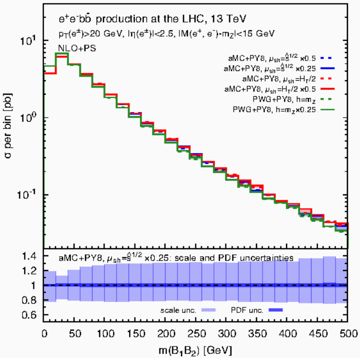
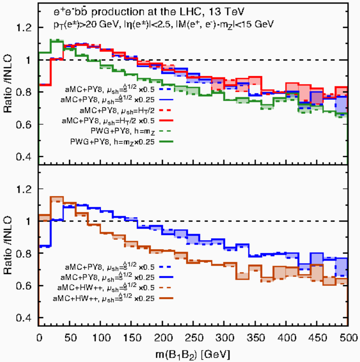
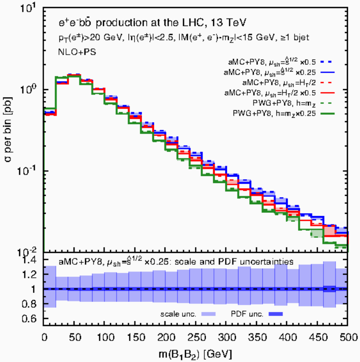
4FS: Invariant mass of the hardest b-hadrons

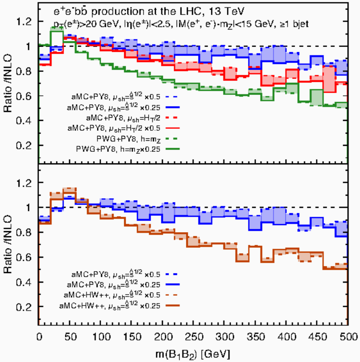




- no b-jet tagging.
- POWHEG peaks at lower masses than aMC@NLO+PY8, similarly to aMC@NLO+HW++.

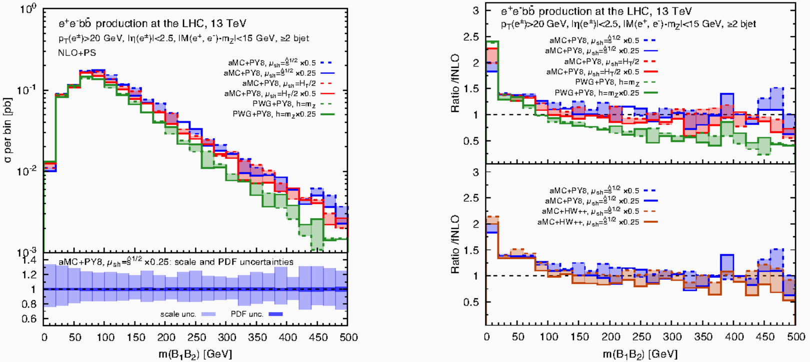
4FS: Invariant mass of the hardest b-hadrons





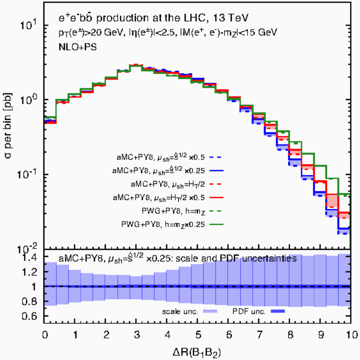
- 1 b-jet tagged.
- With one b-jet tagged, spread between the aMC@NLO predictions.

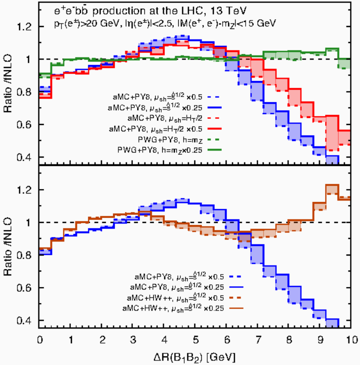
4FS: Invariant mass of the hardest b-hadrons



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

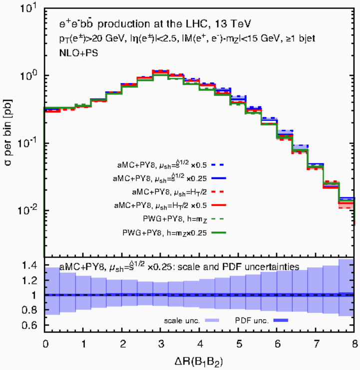
4FS: separation of the hardest b-hadrons

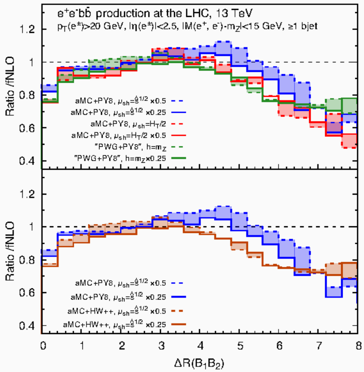




- no b-jet tagging.
- POWHEG closer to NLO than aMC@NLO.
- Great difference in aMC@NLO between the two showers, unless 2 b-jets tagged.
- Suppression of bjets rate in POWHEG w.r.t. to the NLO is manifest here.

4FS: separation of the hardest b-hadrons





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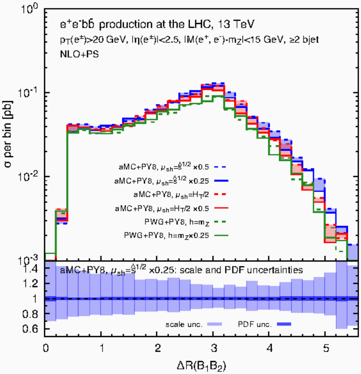
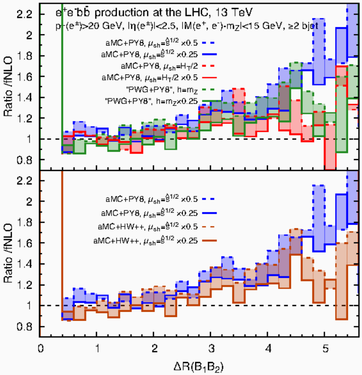
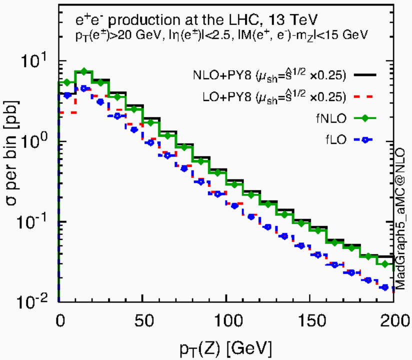
4FS: separation of the hardest b-hadrons

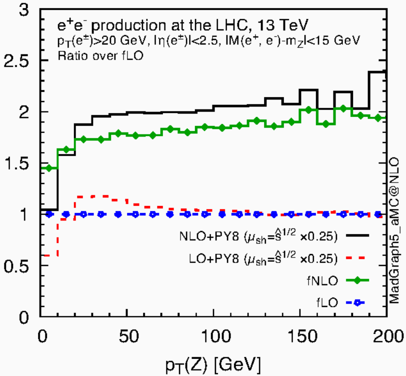




- 2 b-jet tagged.
- POWHEG closer to NLO than aMC@NLO.
- Great difference in aMC@NLO between the two showers, unless 2 b-jets tagged.
- Suppression of bjets rate in POWHEG w.r.t. to the NLO is manifest here.

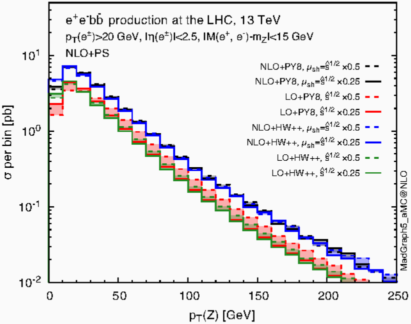
4FS: the transverse momentum of the $l\bar{l}$ system

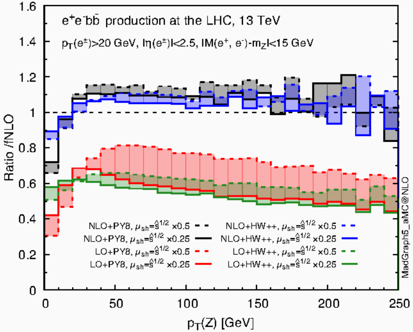




- Large differential NLO k-factor.
- Sizable effects from PS.

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





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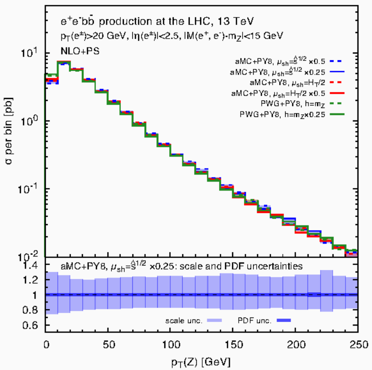
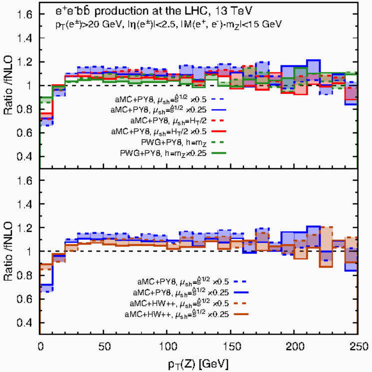
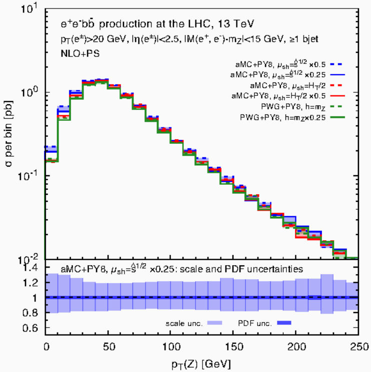
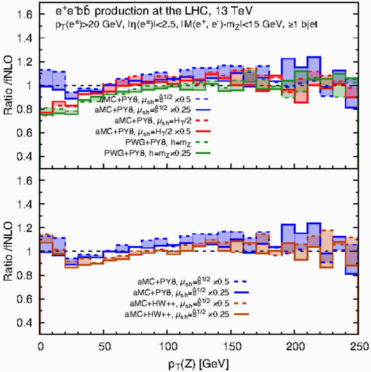




- PDF uncert. nearly constant, $\mathcal{O}(2\%)$; μ_r and μ_f scale dependence nearly constant, $\mathcal{O}(20\%)$.
- Matching uncertainty $\mathcal{O}(5\%)$ in both approaches.
- Larger differences between the two MCs and between PYTHIA8 and HERWIG++, especially in the first bins; non trivial dependence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

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





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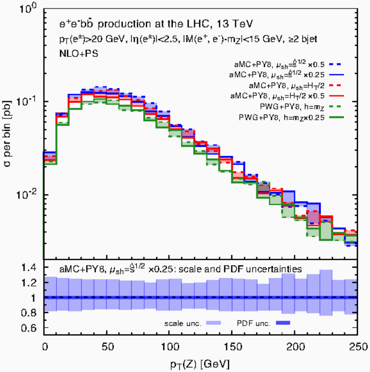

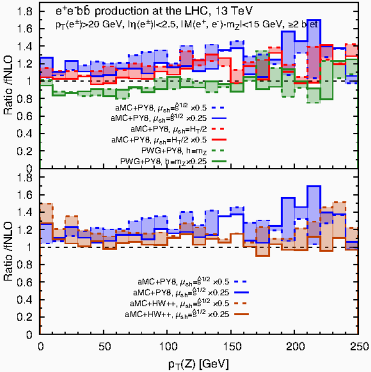

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An improved prediction of $p_T^{l\bar{l}}$

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

5FS

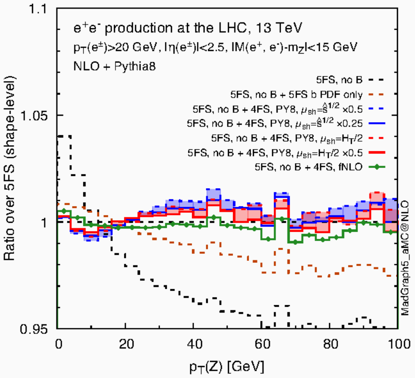
- B-hadrons from the PS in two cases:
    1. $b\bar{b}$ and bg channels: splitting in the backward evolution (no bottom content in the proton).
    2. For the other channel: $g \to b\bar{b}$ splitting.
- *We remove the bottom contribution by vetoing B-hadrons in final state.*

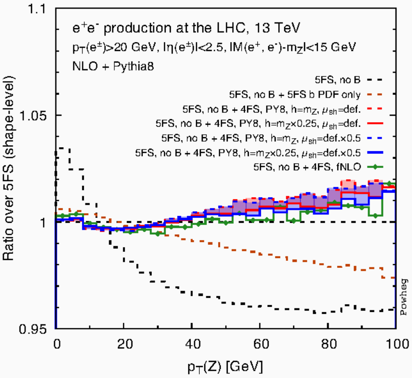
4FS

- 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.

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

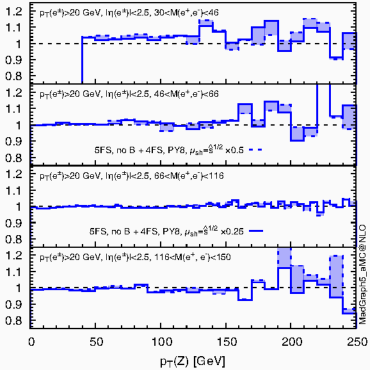
An improved prediction of $p_T^{l\bar{l}}$

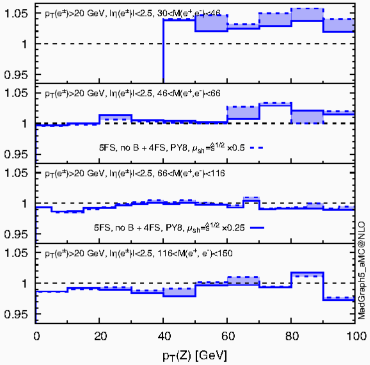




- 5FS b-contribution: non-trivial shape, the two contributions are of the same order of magnitude at large p_T, while at low p_t gluon splitting from light-quark induced processes dominates.
- Non-trivial shape distortion.
- Effects after merging of the order of $\mathcal{O}(\pm 1\%)$ for `MG5_aMC@NLO`,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

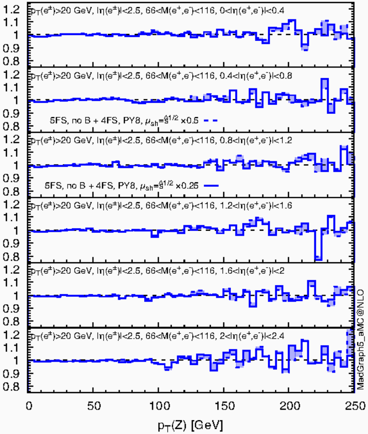
An improved prediction of $p_T^{l\bar{l}}$

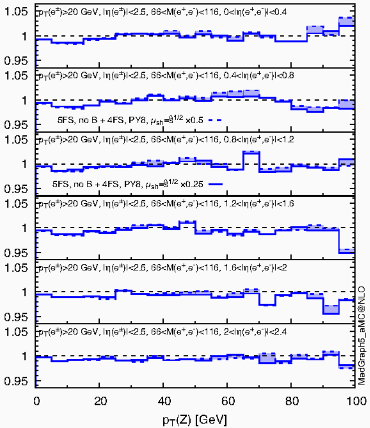




- Can we explain the difference in shape in observed spectrum vs the current MC samples? No.
- No sizable dependence on the invariant mass of the lepton pair.

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.

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:

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

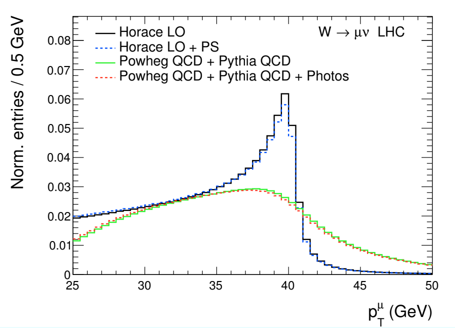
3. From 1.+2. it follows that:

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

Impact on the W mass measurement

Measuring the W mass at the LHC

Three observables sensitive to the W mass: p_T^l, M_T^W, $p_T(missing)$.



- High sensitivity to radiative corrections.
- Detector modeling under control.
- Peak around $m_W/2$.

[Carloni Calame et al '16]

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
$\langle\mu\rangle$ scale factor	0.2	1.0	0.2	1.0	0.2	1.0
$\Sigma\bar{E}_T$ correction	0.9	12.2	1.1	10.2	1.0	11.2
Residual corrections (statistics)	2.0	2.7	2.0	2.7	2.0	2.7
Residual corrections (interpolation)	1.4	3.1	1.4	3.1	1.4	3.1
Residual corrections ($Z \to W$ extrapolation)	0.2	5.8	0.2	4.3	0.2	5.1
Total	2.6	14.2	2.7	11.8	2.6	13.0

[ATLAS 1701.07240]

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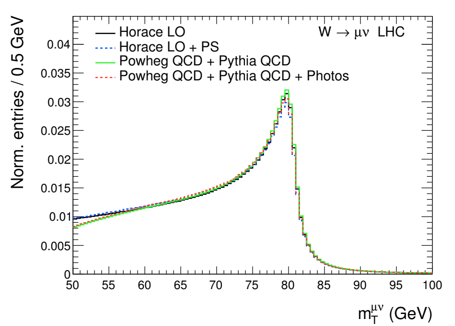
Three observables sensitive to the W mass: p_T^l, M_T^W, $p_T(missing)$.



- $M_T = \sqrt{2 p_T^l p_T^{miss}(1 - \cos\ \Delta\phi)}$
- Stability under radiative corrections.
- Suffer from pileup and detector effects since it relies on $\not{E}_T$.
- Peak around m_W.

[Carloni Calame et al '16]

W-boson charge	W^+		W^-		Combined	
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[ATLAS 1701.07240]

Current status of the theory uncertainty

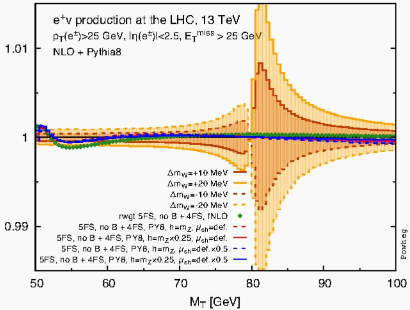
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T, W^+, e-μ	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
m_T, W^-, e-μ	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
m_T, $W^\pm$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
p_T^ℓ, W^+, e-μ	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
p_T^ℓ, W^-, e-μ	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
p_T^ℓ, $W^\pm$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
p_T^ℓ, $W^\pm$, e	80347.2	9.9	0.0	14.8	2.6	5.7	8.2	5.3	8.9	23.1	4/5
m_T, $W^\pm$, e	80364.6	13.5	0.0	14.4	13.2	12.8	9.5	3.4	10.2	30.8	8/5
m_T-p_T^ℓ, W^+, e	80345.4	11.7	0.0	16.0	3.8	7.4	8.3	5.0	13.7	27.4	1/5
m_T-p_T^ℓ, W^-, e	80359.4	12.9	0.0	15.1	3.9	8.5	8.4	4.9	13.4	27.6	8/5

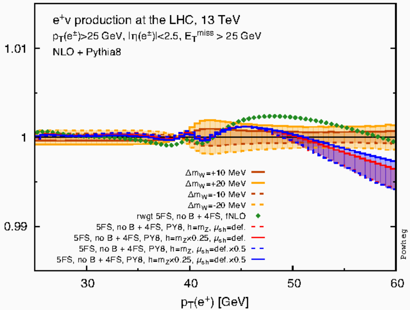
$$
\begin{aligned}
m_W &= 80369.5 \pm 6.8\ \text{MeV(stat.)} \pm 10.6\ \text{MeV(exp. syst.)} \pm 13.6\ \text{MeV(mod. syst.)} \\
&= 80369.5 \pm 18.5\ \text{MeV},
\end{aligned}
$$

[ATLAS 1701.07240]

- Estimation provided by ATLAS.
- We want to use our improved prediction to estimate the uncertainty from heavy flavors.

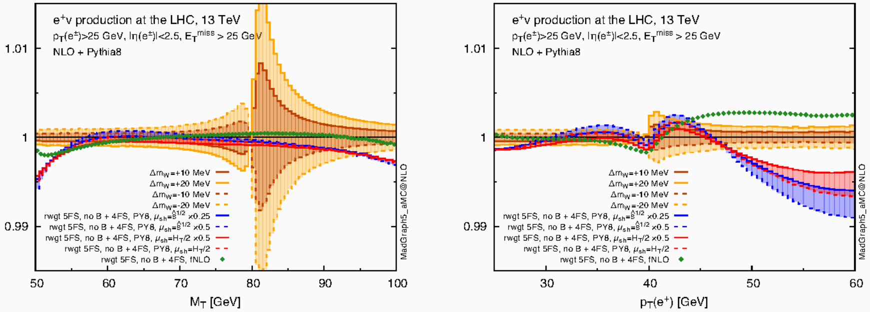
The templates





- Templates generation with both the POWHEG-BOX and MG5_aMC@NLO at NLO+PS in the 5FS.
- Different shape of the Jacobian peak for $p_T^{l^\pm}$ in the two Monte Carlos.
- Largest effects from the reweighting outside the canonical fit window.

The templates



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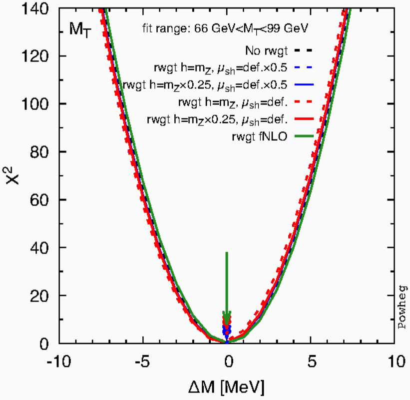
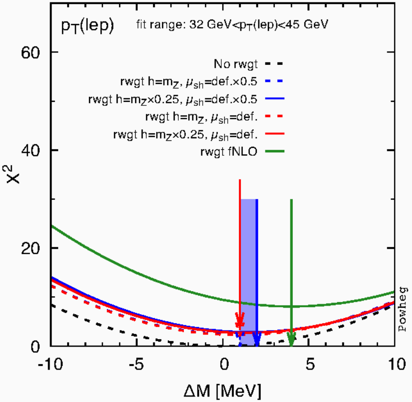
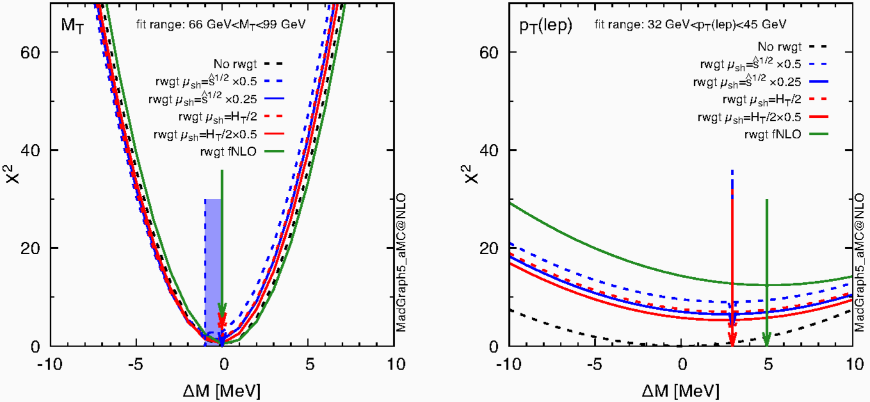
Shift on the W mass measurement





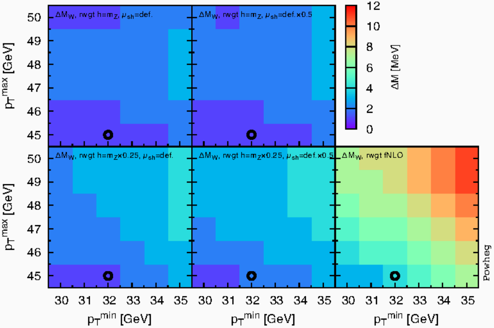
- Granularity of 1 MeV.
- Positive sign shift, at most reaching +5 MeV.
- Quite similar effect in POWHEG-BOX and in MG5_aMC@NLO.

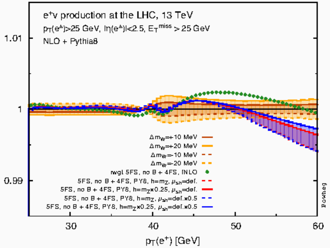
Shift on the W mass measurement



- Granularity of 1 MeV.
- Positive sign shift, at most reaching +5 MeV.
- Quite similar effect in `POWHEG-BOX` and in `MG5_aMC@NLO`.

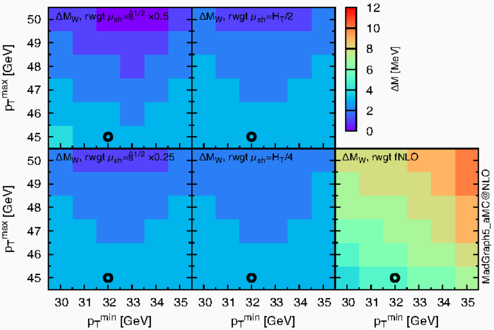
Dependence of the shift on the fit window

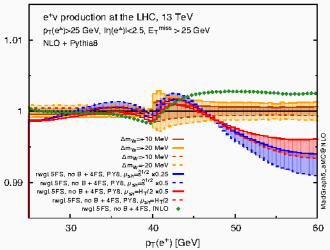




- Non-negligible dependence on the fit window due to the non-trivial shape of the reweighting function.

Dependence of the shift on the fit window





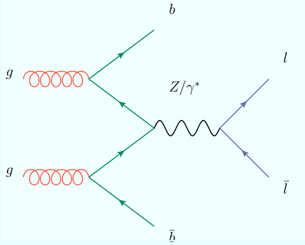
- Non-negligible dependence on the fit window due to the non-trivial shape of the reweighting function.

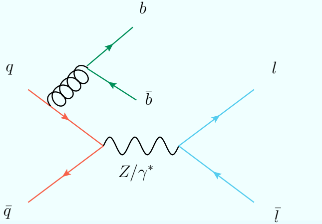
Conclusions

Summary and perspectives

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?

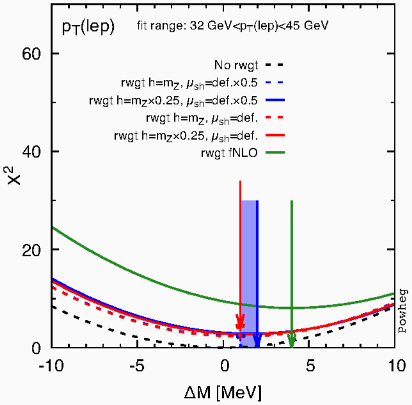




Summary and perspectives

W mass

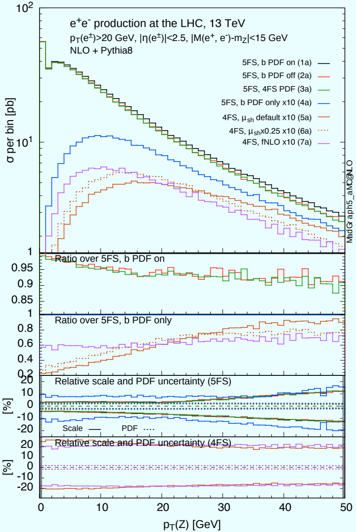
- We have estimated the impact of including an improved description of the bottom induced contribution on the $l\bar{l}$ spectrum with respect to the standard 5FS description.
- The impact of these effects are estimated to be at most of of $\mathcal{O}(5~\mathrm{MeV})$.
- Future: Study how the picture changes using the same approach to generate the reweighting function but one order higher in the 5FS description, using DY-NNLOPS.
- Future: Understand the differences in the p_T^l templates between the POWHEG-BOX and MG5_aMC@NLO.



Backup slides

5FS scale choice

- Scale chosen to minimize the differences between the 5FS bottom-only contribution and the 4FS description.
- $\mu_r = \sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$
- $\mu_f = \sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$
- $\mu_r = \frac{1}{4}\sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$
- $\mu_f = \frac{1}{4}\sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$

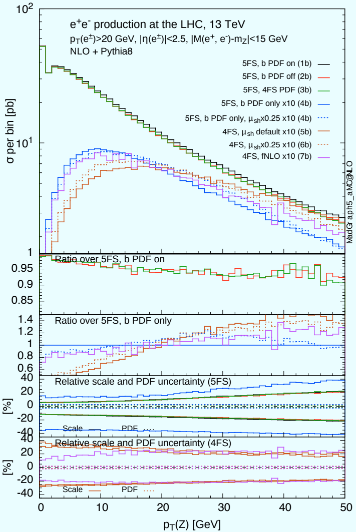


Setup-observables	σ w/ cuts
5FS $pp \to e^+e^-$	$800.9^{+3.2+2.0}_{-6.7-2.0}$
5FS $b\bar{b} \to e^+e^-$	$36.26^{+7.3+2.4}_{-11.8-2.4}$
4FS MG5_aMC@NLO $pp \to e^+e^- b\bar{b}$	$23.17^{+20.6+1.6}_{-17.1-1.6}$
4FS NLO $pp \to e^+e^- b\bar{b}$	$23.30^{+20.6+1.6}_{-17.1-1.6}$

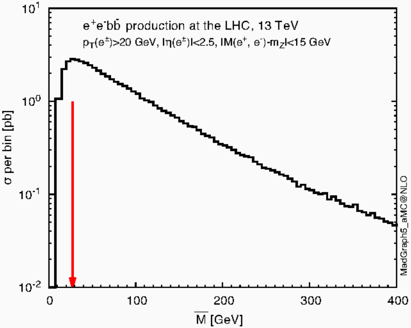
5FS scale choice

- Scale chosen to minimize the differences between the 5FS bottom-only contribution and the 4FS description.
- $\mu_r = \sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$
- $\mu_f = \sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$
- $\mu_r = \frac{1}{4}\sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$
- $\mu_f = \frac{1}{4}\sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$

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

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