Associate production of Z and b quarks and some applications

LHCTheory final meeting @ Louvain

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in collaboration with

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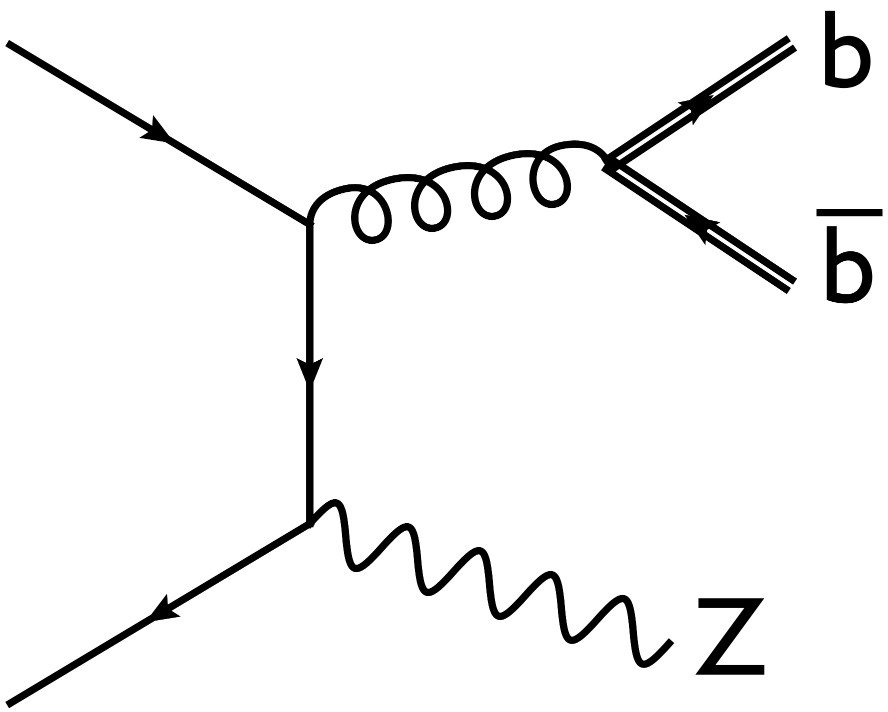
Why again $Zb\bar{b}$?



- NLO(+PS) predictions available since long time ago
  Frederix et al, arXiv:1106.6019, Campbell et al, 1107.3714, Krauss et al, 1612.04640
- Not a rare process: measurements possible already at 7 TeV
  CMS: arXiv:1310.1349, arXiv:1402.1521, ATLAS: arXiv:1407.3643

Motivation #1: Try to improve data/theory agreement

- 4FS description is expected to capture mass effects in a more reliable way than 5FS computations
- But the data/theory agreement is rather bad for the 4FS

Cross section	Measured	MADGRAPH (5F)	aMC@NLO (5F)	MCFM (parton level)	MADGRAPH (4F)	aMC@NLO (4F)
σ_{Z+1b} (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.22	$3.70^{+0.23}_{-0.26}$	$3.03^{+0.30}_{-0.36}$	$3.11^{+0.47}_{-0.81}$	$2.36^{+0.47}_{-0.37}$
σ_{Z+2b} (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.07	$0.29^{+0.04}_{-0.04}$	$0.29^{+0.04}_{-0.04}$	$0.38^{+0.06}_{-0.10}$	$0.35^{+0.08}_{-0.06}$
σ_{Z+b} (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.24	$3.99^{+0.25}_{-0.29}$	$3.23^{+0.34}_{-0.40}$	$3.49^{+0.52}_{-0.91}$	$2.71^{+0.52}_{-0.41}$
$\sigma_{Z+b/Z+j}$ (%)	$5.15 \pm 0.03 \pm 0.25$	5.35 ± 0.11	$5.38^{+0.34}_{-0.39}$	$4.75^{+0.24}_{-0.27}$	$4.63^{+0.69}_{-1.21}$	$3.65^{+0.70}_{-0.55}$

CMS, arXiv:1402.1521

- One issue was the scale used

	μ_F^2
MG5F	$m_Z^2 + p_T^2(\text{jets})$
MG4F	$m_{T,Z} \cdot m_T(b,b)$
ALPGEN	$m_Z^2 + \sum_{\text{jets}}(m_{\text{jets}}^2 + p_{T,\text{jets}}^2)$
aMC@NLO	$m_{\ell\ell'}^2 + p_T^2(\ell\ell') + \frac{m_b^2+p_T^2(b)}{2} + \frac{m_{b'}^2+p_T^2(b')}{2}$

- Recent studies show that lower values should be used

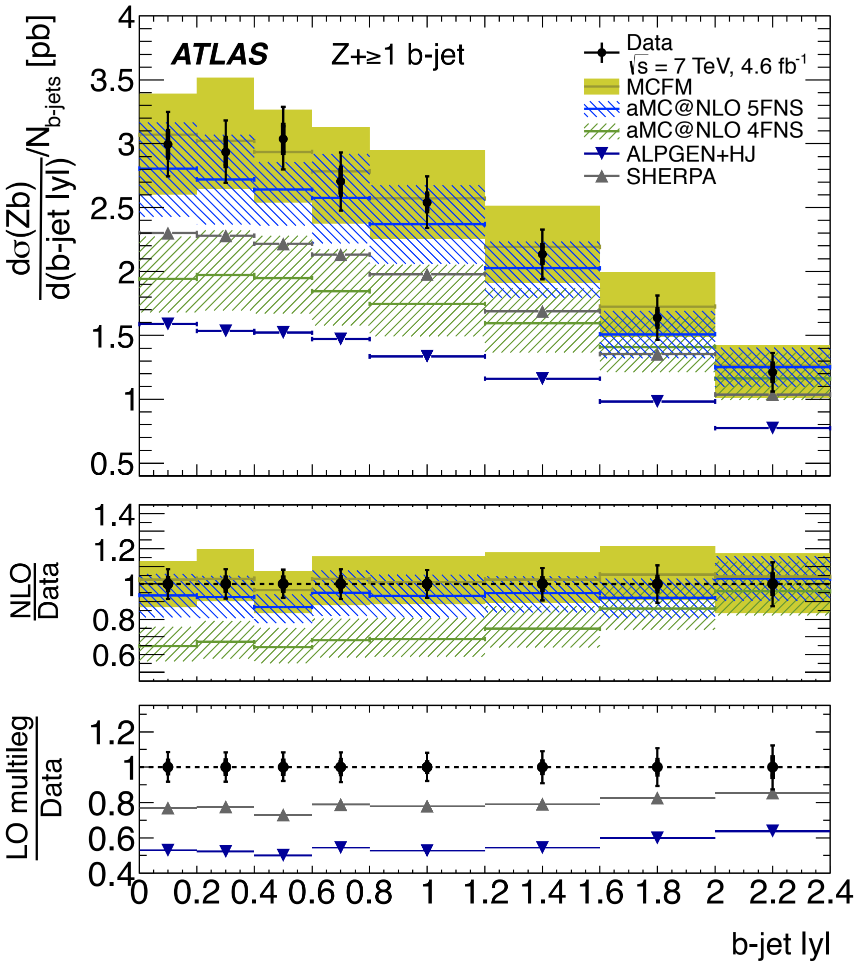
$b\bar{b}H, M_H = 125\,\text{GeV}: \quad \tilde{\mu}_F \approx 0.36\, M_H$

$b\bar{b}Z', M_{Z'} = 91.2\,\text{GeV}: \quad \tilde{\mu}_F \approx 0.38\, M_{Z'}$

$b\bar{b}Z', M_{Z'} = 400\,\text{GeV}: \quad \tilde{\mu}_F \approx 0.29\, M_{Z'}$

Lim, Maltoni, Ridolfi, Ubiali, arXiv:1605.09411

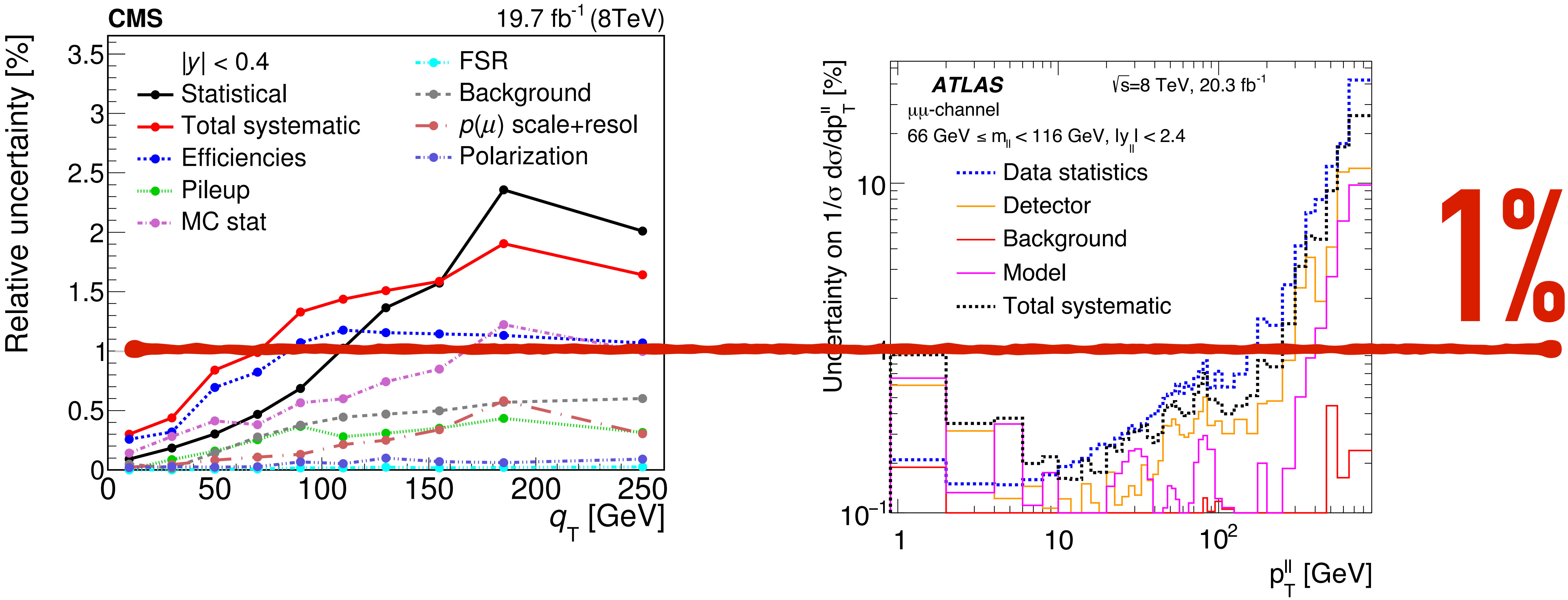
ATLAS: arXiv:1407.3643



Motivation #2: precision

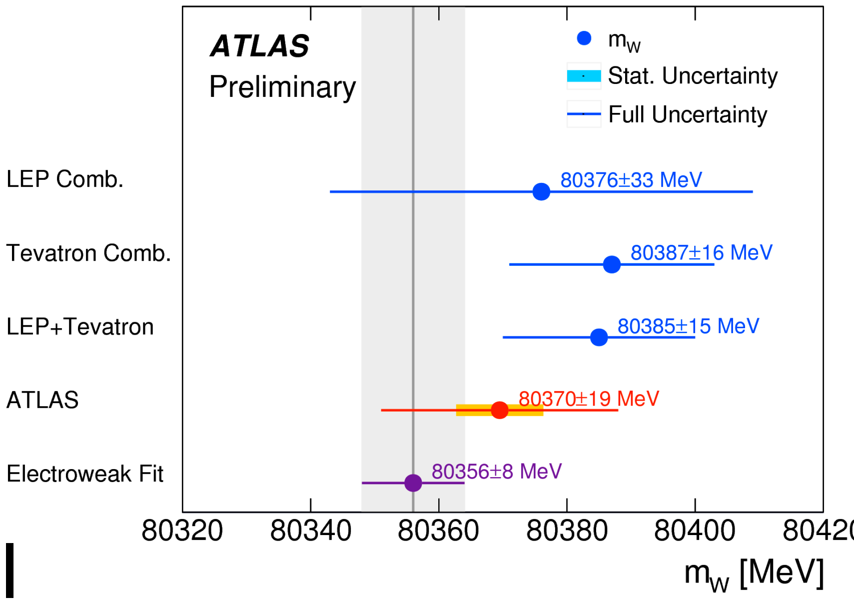
Z p_T: run 1 measurements have already reached 0.5–1% ! Gavin Salam at LHCP16

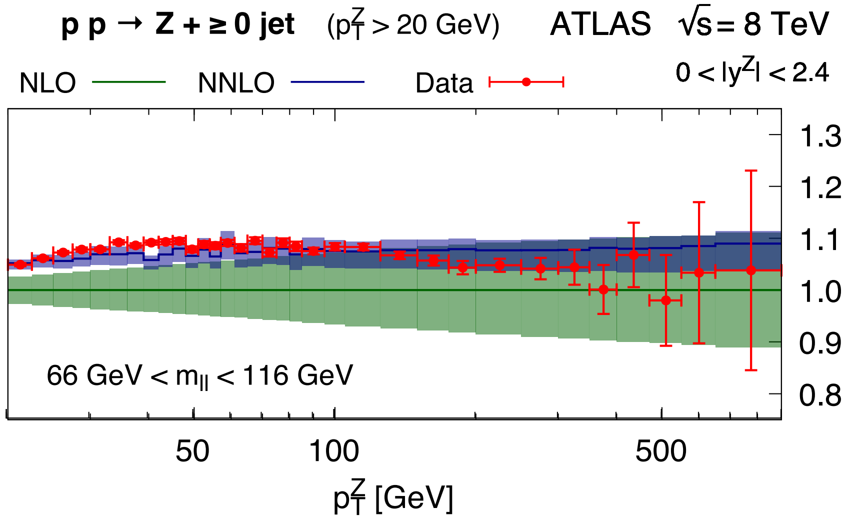
(normalised to fiducial Z cross section)



Motivation #2: precision

- An excellent measurement of Z-p$_T$ distribution at the LHC is crucial:
  - Fundamental ingredient of MC tunes
  - The modelling of the W boson p$_T$ strongly relies on the understanding of the Z p$_T$ → crucial for the extraction of the W mass
- Z-p$_T$ measurements at Run-I already hit the 1% wall
- Excellent predictions exist for Z+jet production (NNLO)
  Boughezal et al, 1512.01291, Gehrmann-de Ridder et al, arXiv:1605.04295
- Are the bottom-mass effects under control?

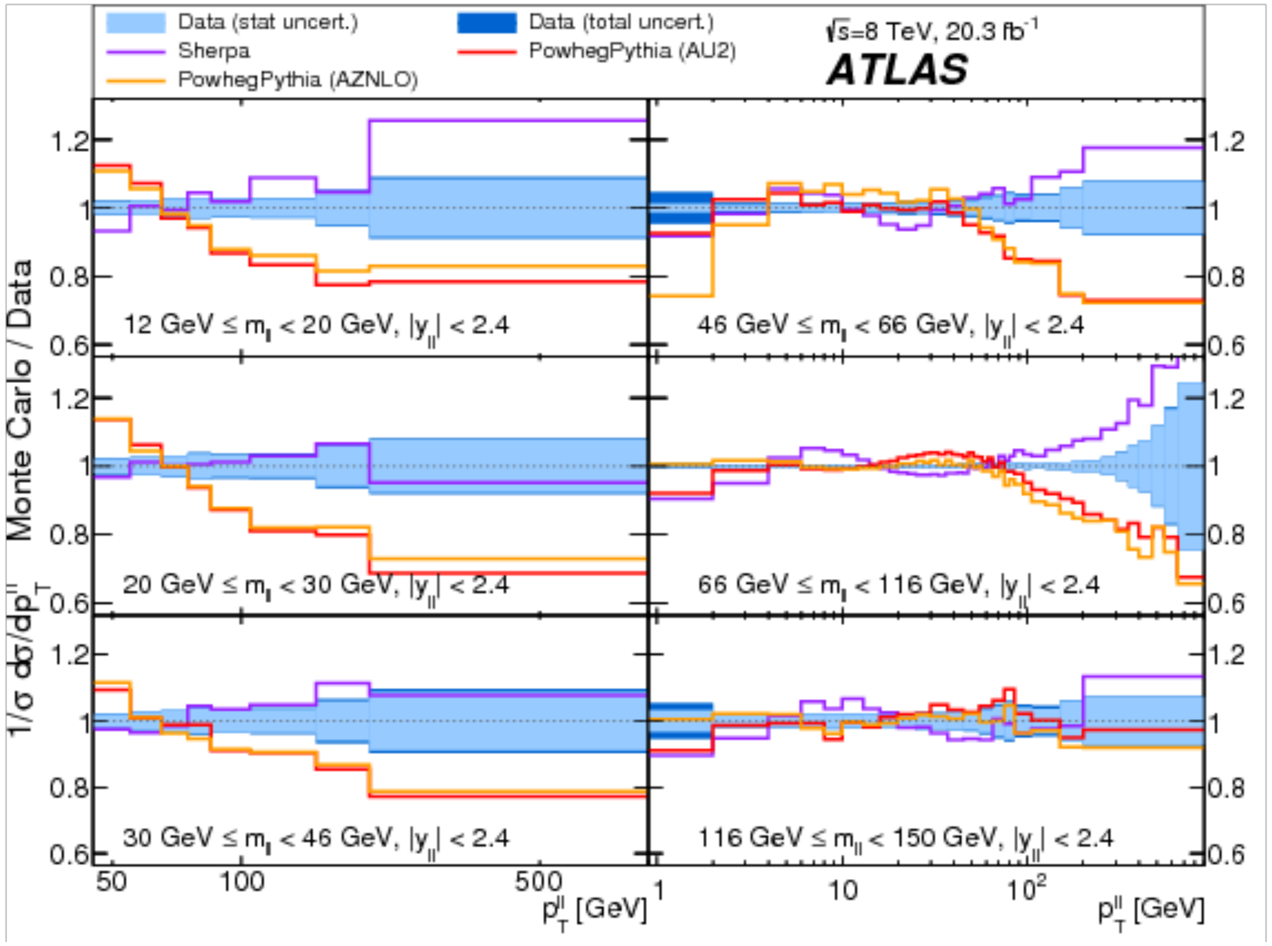


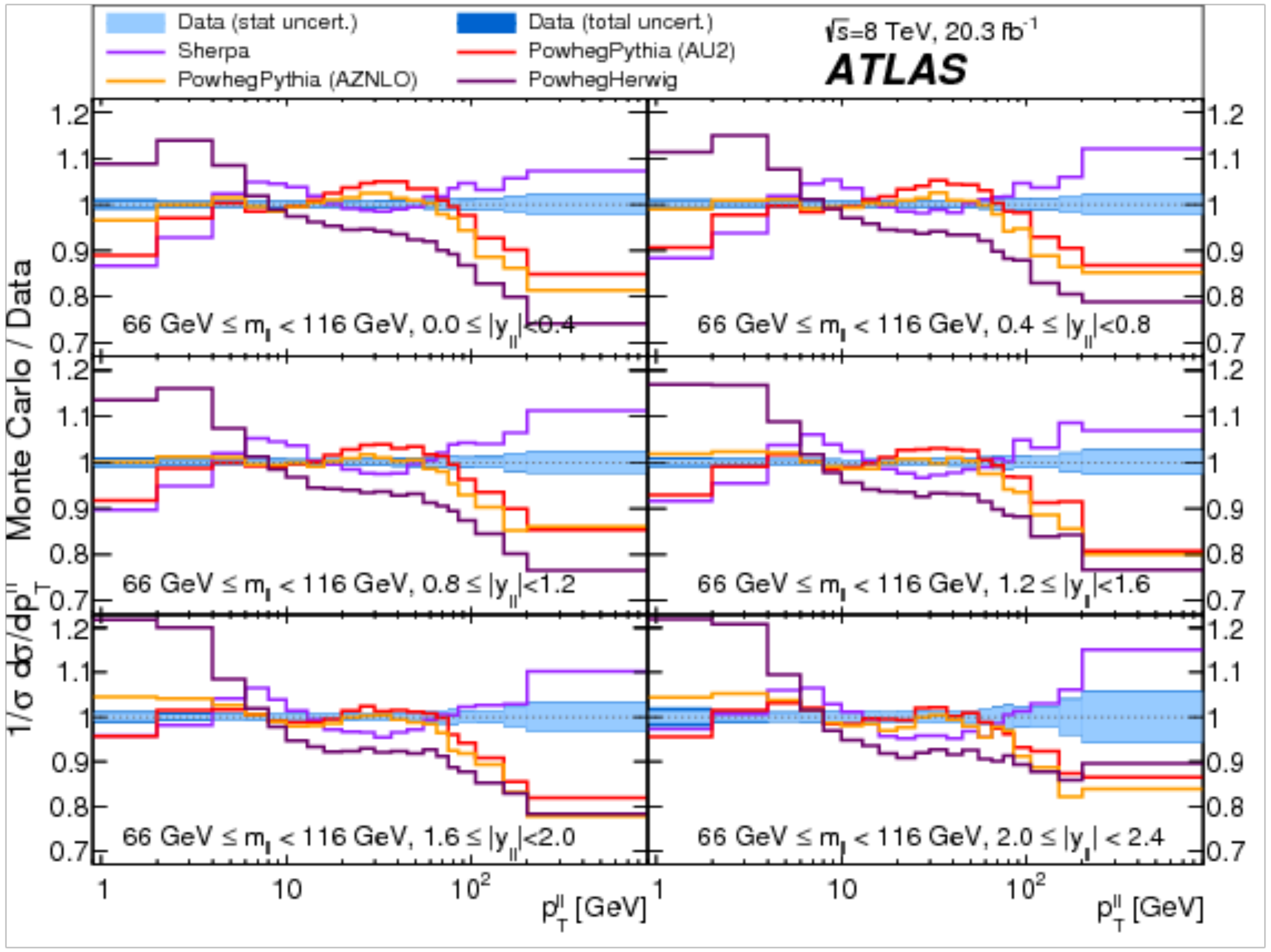


Gehrmann-de Ridder et al, arXiv:1605.04295

Still, there are some issues…

- No single tune / tool able to describe simultaneously various invariant-mass and rapidity bins

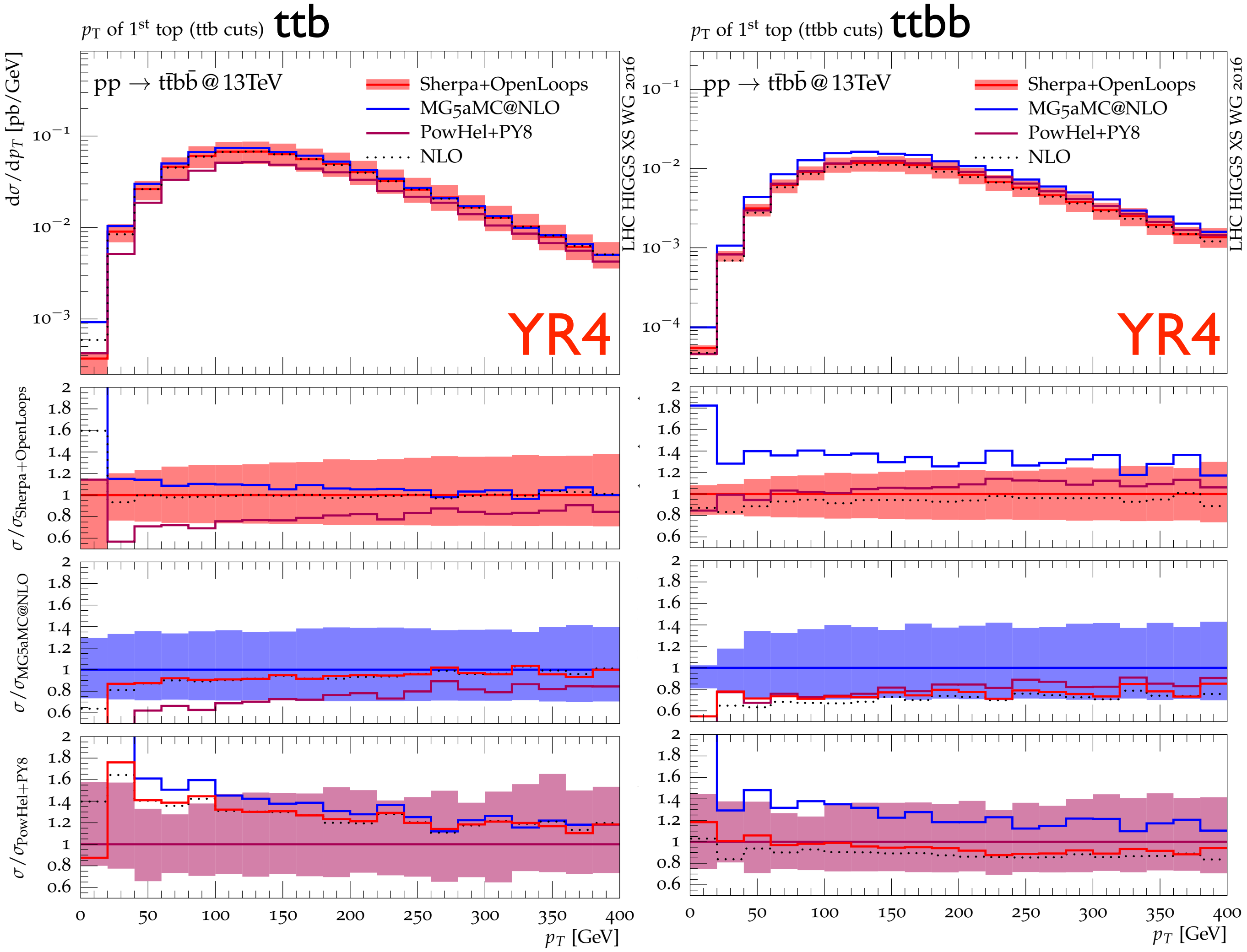




Motivation #3:
learning something for $t\bar{t}b\bar{b}$

- $t\bar{t}b\bar{b}$ is a crucial background for $t\bar{t}H$ production
- Multiscale and high-multiplicity process
- Theoretical uncertainties remain large at NLO, O(40%)
- Sizeable spread in predictions from different tools
- Differences mostly from g→$b\bar{b}$ splittings from the shower

$$\mu_{R,0} = \left(\prod_{i=t,\bar{t},b,\bar{b}} E_{T,i} \right)^{1/4}, \qquad \mu_{F,0} = \frac{H_T}{2} = \frac{1}{2} \sum_{i=t,\bar{t},b,\bar{b},j} E_{T,i},$$



Selection	Tool	σ_{NLO} [fb]	$\sigma_{\text{NLO+PS}}$ [fb]	$\sigma_{\text{NLO+PS}}/\sigma_{\text{NLO}}$
$n_b \geq 1$	SHERPA+OPENLOOPS	$12820^{+35\%}_{-28\%}$	$12939^{+30\%}_{-27\%}$	1.01
	MADGRAPH5_AMC@NLO		$13833^{+37\%}_{-29\%}$	1.08
	POWHEL		$10073^{+45\%}_{-29\%}$	0.79
$n_b \geq 2$	SHERPA+OPENLOOPS	$2268^{+30\%}_{-27\%}$	$2413^{+21\%}_{-24\%}$	1.06
	MADGRAPH5_AMC@NLO		$3192^{+38\%}_{-29\%}$	1.41
	POWHEL		$2570^{+35\%}_{-28\%}$	1.13

HXSWG YR4 De Florian et al. arXiv:1610.07922

Motivation #3: learning something for $t\bar{t}b\bar{b}$

Cascioli et al, arXiv:1309.5912

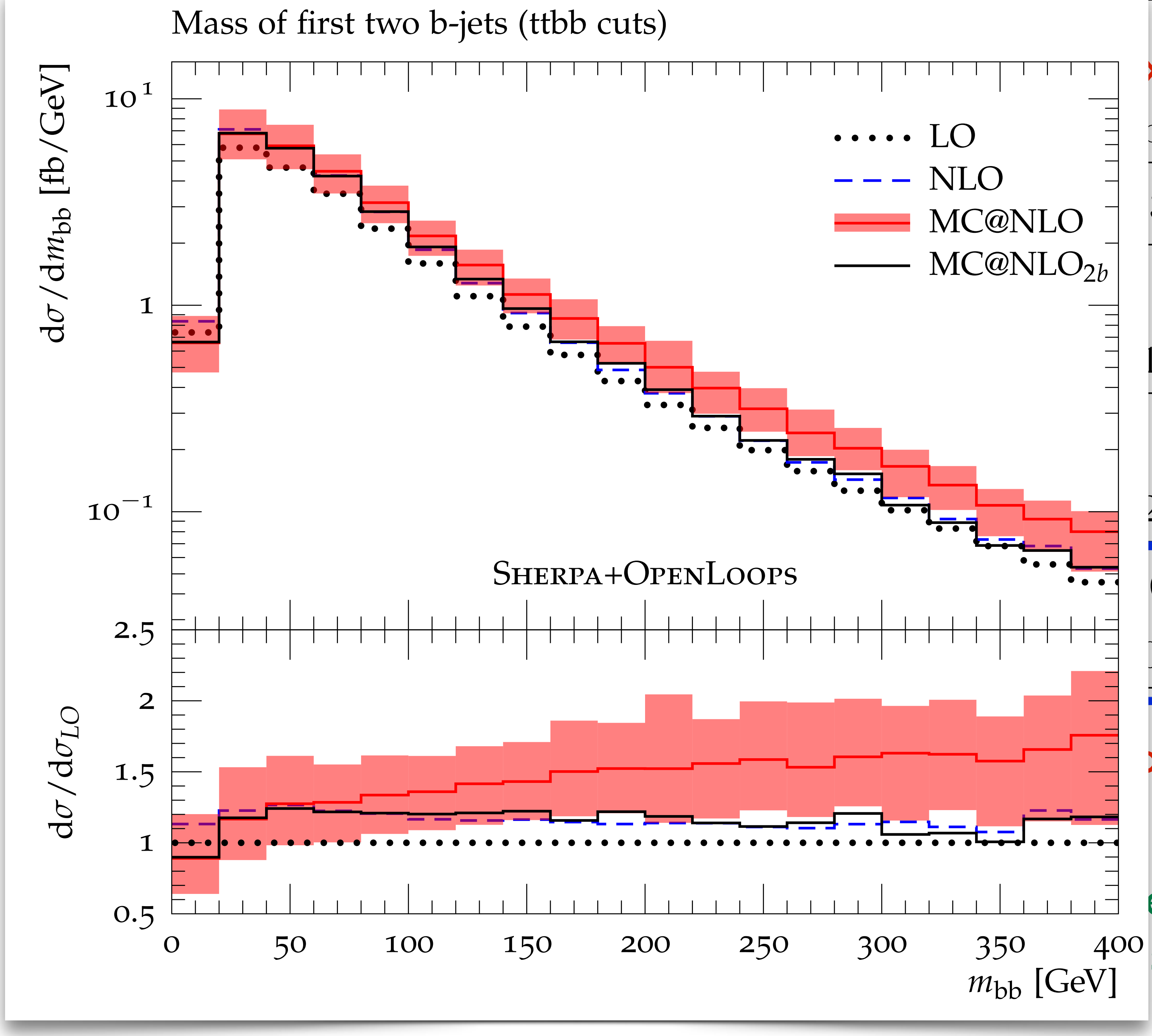
	ttb	ttbb	ttbb$(m_{\mathrm{bb}} > 100)$
$\sigma_{\mathrm{LO}}[\mathrm{fb}]$	$2644^{+71\%+14\%}_{-38\%-11\%}$	$463.3^{+66\%+15\%}_{-36\%-12\%}$	$123.4^{+63\%+17\%}_{-35\%-13\%}$
$\sigma_{\mathrm{NLO}}[\mathrm{fb}]$	$3296^{+34\%+5.6\%}_{-25\%-4.2\%}$	$560^{+29\%+5.4\%}_{-24\%-4.8\%}$	$141.8^{+26\%+6.5\%}_{-22\%-4.6\%}$
$\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$	1.25	1.21	1.15
$\sigma_{\mathrm{MC}}[\mathrm{fb}]$	$3313^{+32\%+3.9\%}_{-25\%-2.9\%}$	$600^{+24\%+2.0\%}_{-22\%-2.1\%}$	$181.0^{+20\%+8.1\%}_{-20\%-6.0\%}$
$\sigma_{\mathrm{MC}}/\sigma_{\mathrm{NLO}}$	1.01	1.07	1.28
$\sigma^{2\mathrm{b}}_{\mathrm{MC}}[\mathrm{fb}]$	3299	552	146
$\sigma^{2\mathrm{b}}_{\mathrm{MC}}/\sigma_{\mathrm{NLO}}$	1.00	0.99	1.03

without g→bb splittings in the shower

PS effects are 4x larger in the Higgs signal region than for the total cross section

Turning g→bb splittings off in the shower brings the effects in the Higgs signal region to similar values as for the total cross section

Motivation #3: learning something for $t\bar{t}b\bar{b}$



Xiv:1309.5912

$\mathrm{bb}(m_{bb} > 100)$

$3.4^{+63\%+17\%}_{-35\%-13\%}$

$1.8^{+26\%+6.5\%}_{-22\%-4.6\%}$

15

$1.0^{+20\%+8.1\%}_{-20\%-6.0\%}$

28

6

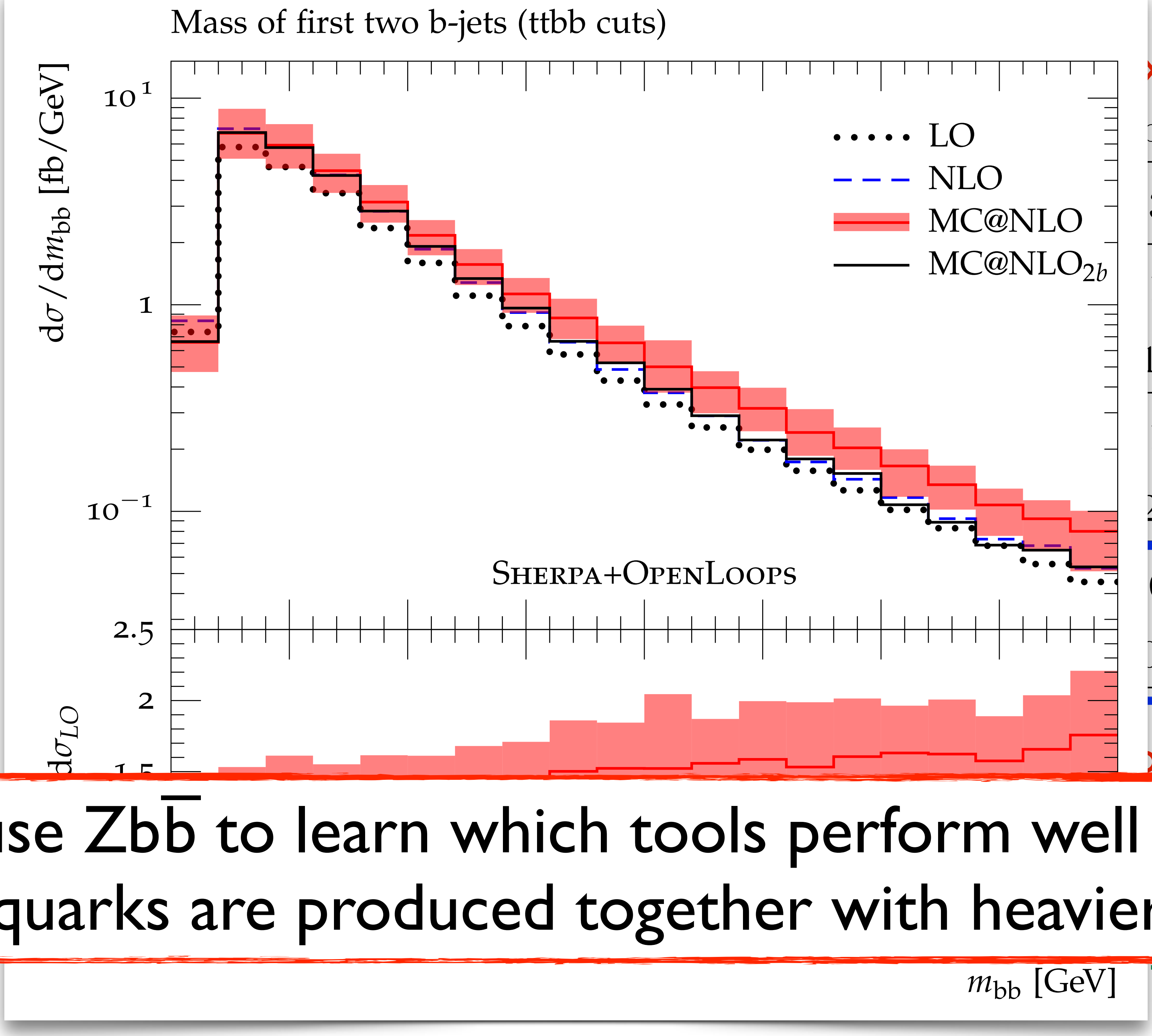
03

or the total

ects in the
ss section

without g→bb
splittings
in the shower

Motivation #3: learning something for $t\bar{t}b\bar{b}$



Xiv:1309.5912

b($m_{bb} > 100$)

$3.4^{+63\%+17\%}_{-35\%-13\%}$

$1.8^{+26\%+6.5\%}_{-22\%-4.6\%}$

15

$1.0^{+20\%+8.1\%}_{-20\%-6.0\%}$

28

6

03

or the total

ss section

without g→bb splittings in the shower

Can we use $Zb\bar{b}$ to learn which tools perform well (and why) when b quarks are produced together with heavier objects?

What we want to do

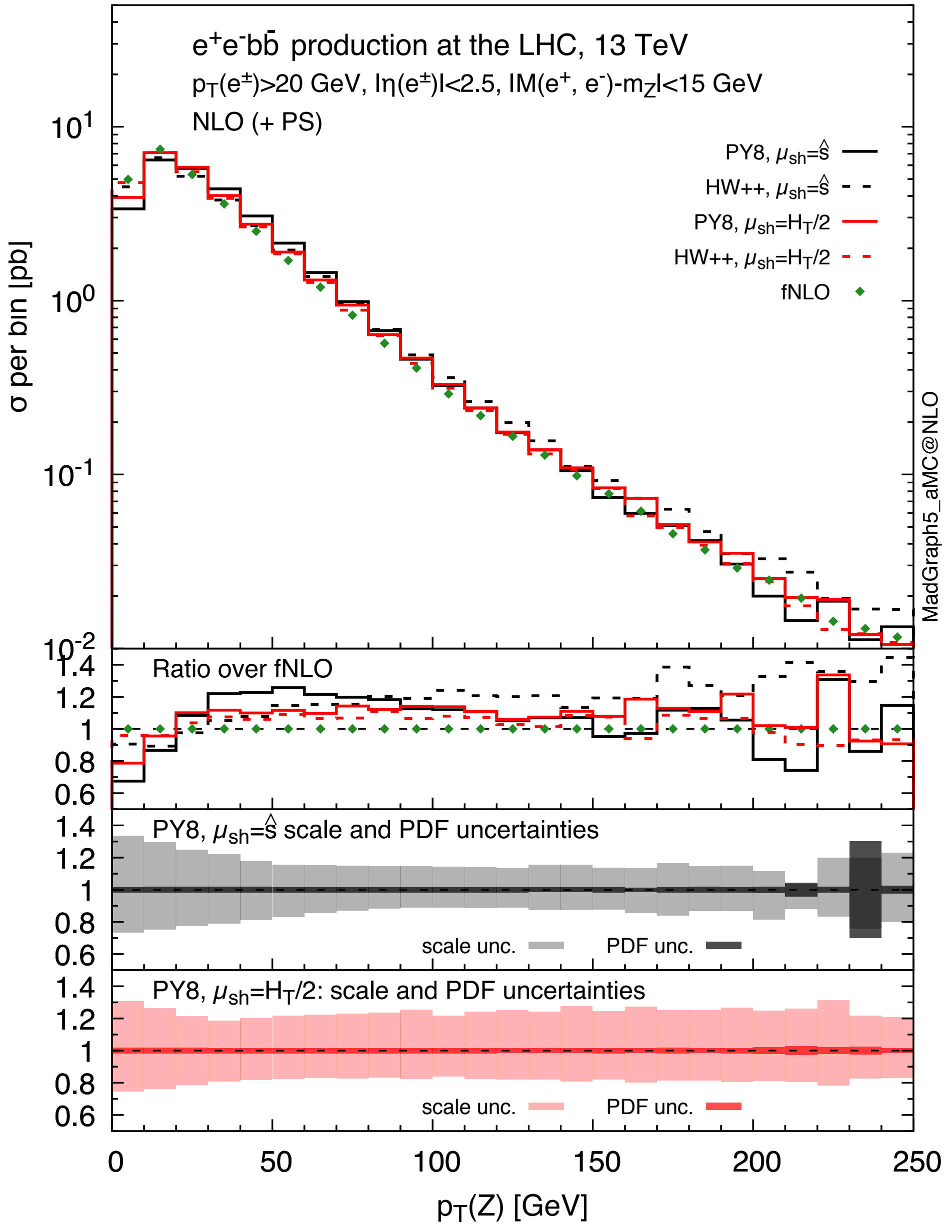
- Study $Zb\bar{b}$ and assess the impact of various sources of theoretical uncertainties (scale/PDF, matching *à la* Powheg or MC@NLO, parton shower, shower scale, …)
- Include b-mass effects in inclusive Z production samples
- Assess the impact of b-mass effects on the Z p_T distribution
- How do b-mass effects reflect on the extraction of the W mass?

Setup for the calculation

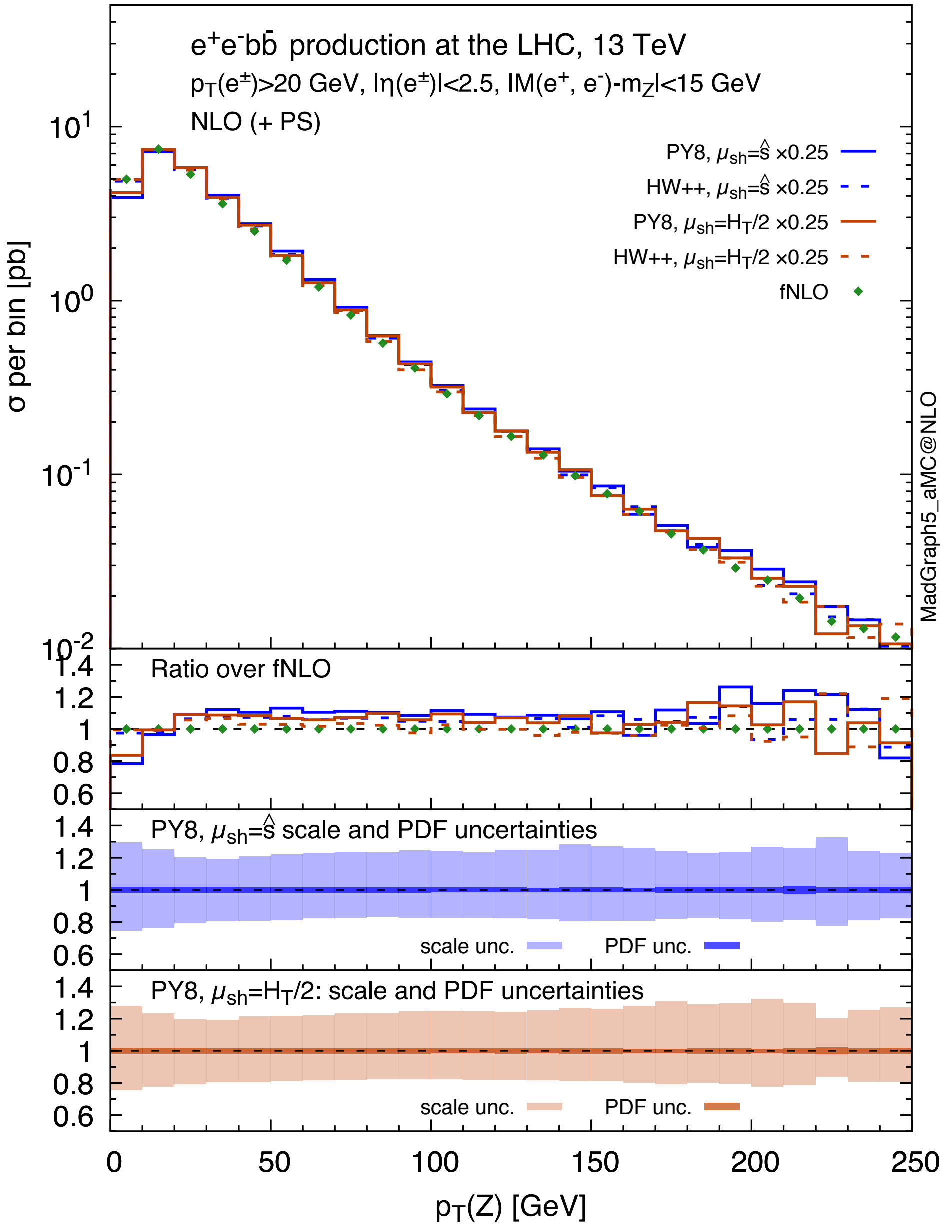
- Simulate the process p p → $e^+ e^- b \bar{b}$ at fixed NLO or including matching to PS
- Use Powheg and MG5_aMC (Powheg results not ready yet)
  - For MG5_aMC use both HW++ and PY8, with different shower scales ($\sim\sqrt{\hat{s}}$ as in versions ≤ 2.5.2, $\sim H_T/2$ as in versions > 2.5.2)
- For renormalisation and factorisation scale, use $\mu = m_T(e^+e^-)/4$
- Use 4FS PDFs (NNPDF 3.0)
- At generation, only impose $m(e^+e^-) > 30$ GeV; the analysis asks for two hard and central leptons ($p_T(e^\pm) > 20$ GeV, $|\eta(e^\pm)|<2.5$) and close to the Z mass ($|m(e^+e^-) - m_Z| < 15$ GeV)

Z$b\bar{b}$ results: $p_T(Z)$

Original μ_{sh} ($\sqrt{\hat{s}}$ and $H_T/2$)

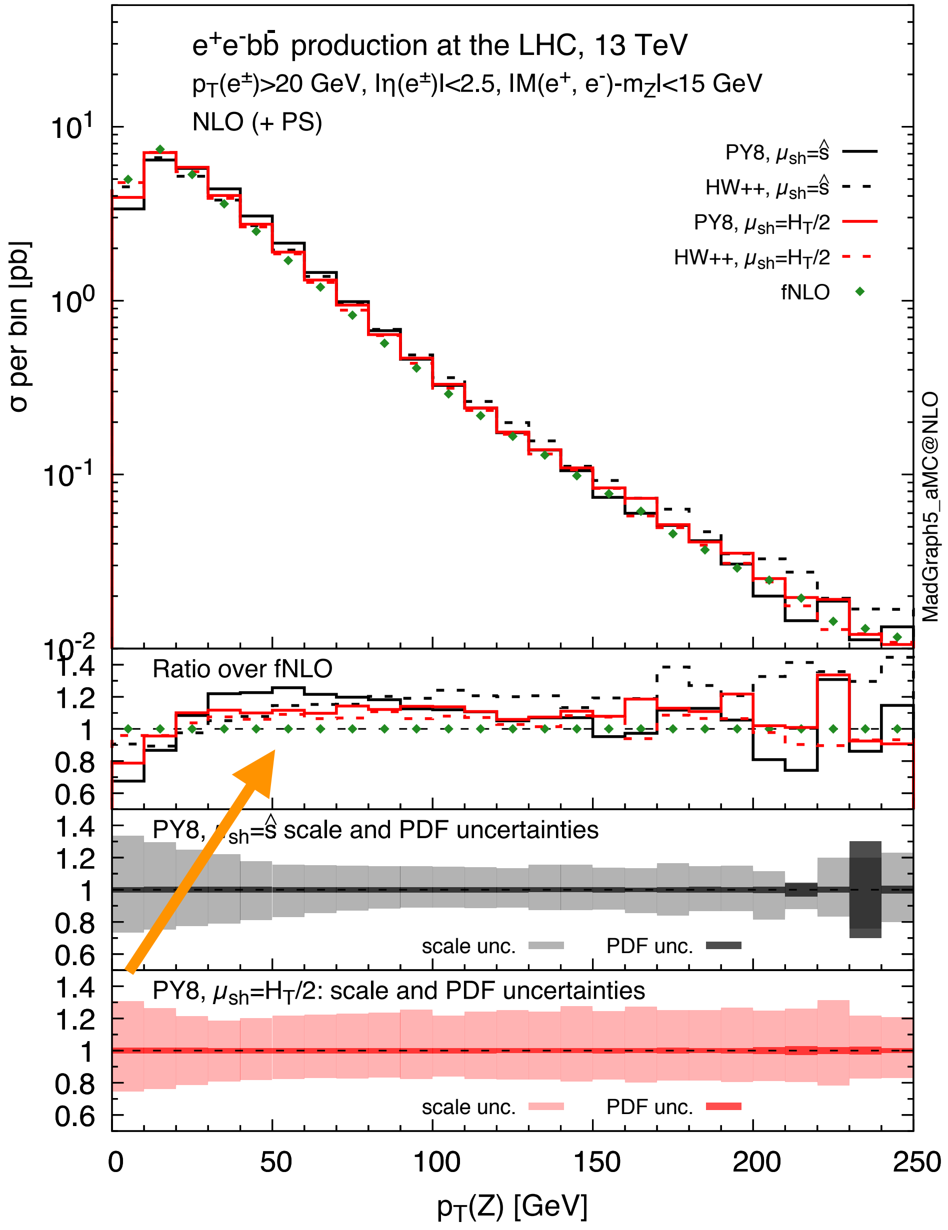


Reduced μ_{sh} ($\sqrt{\hat{s}}$ and $H_T/2$)

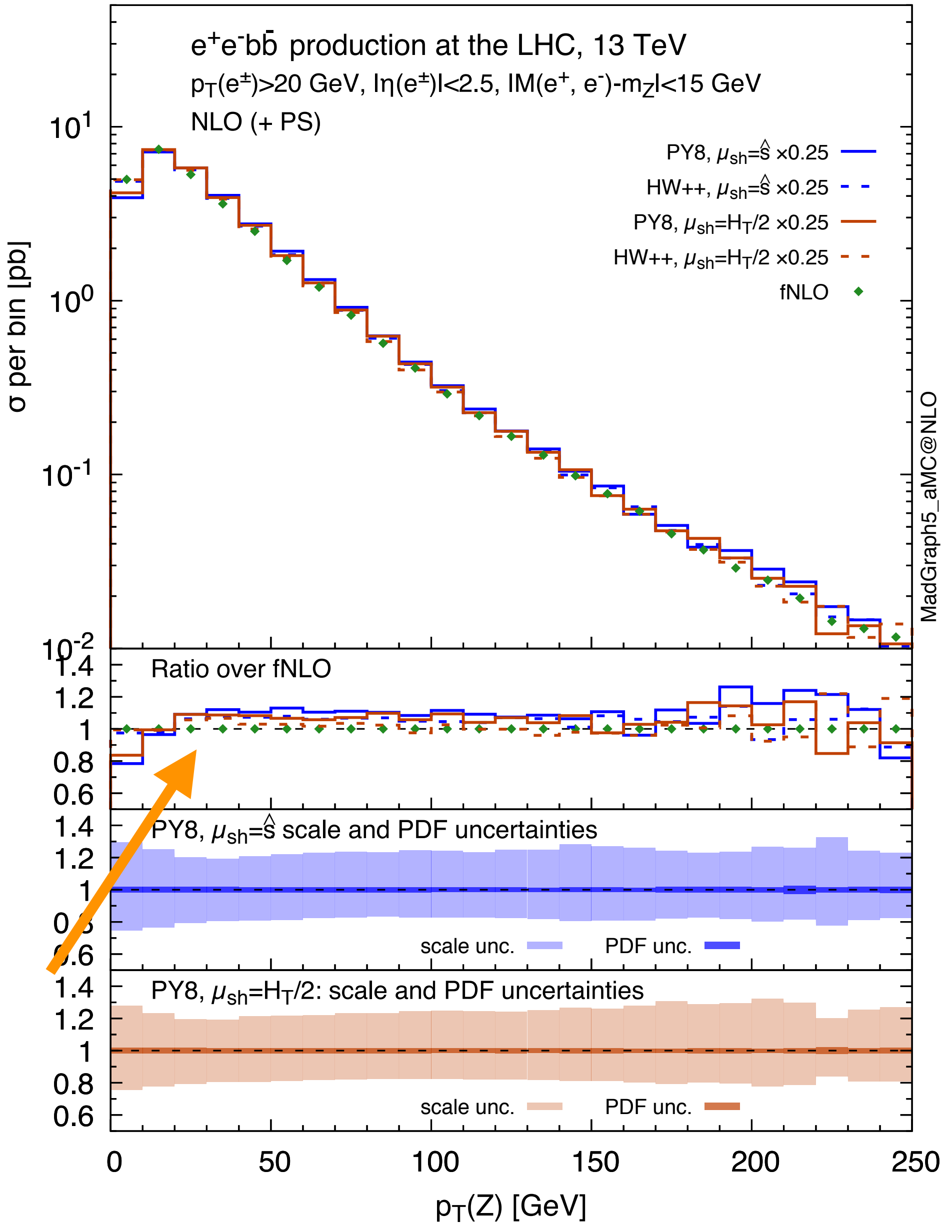


$Zb\bar{b}$ results: $p_T(Z)$

Original μ_{sh} ($\sqrt{\hat{s}}$ and $H_T/2$)



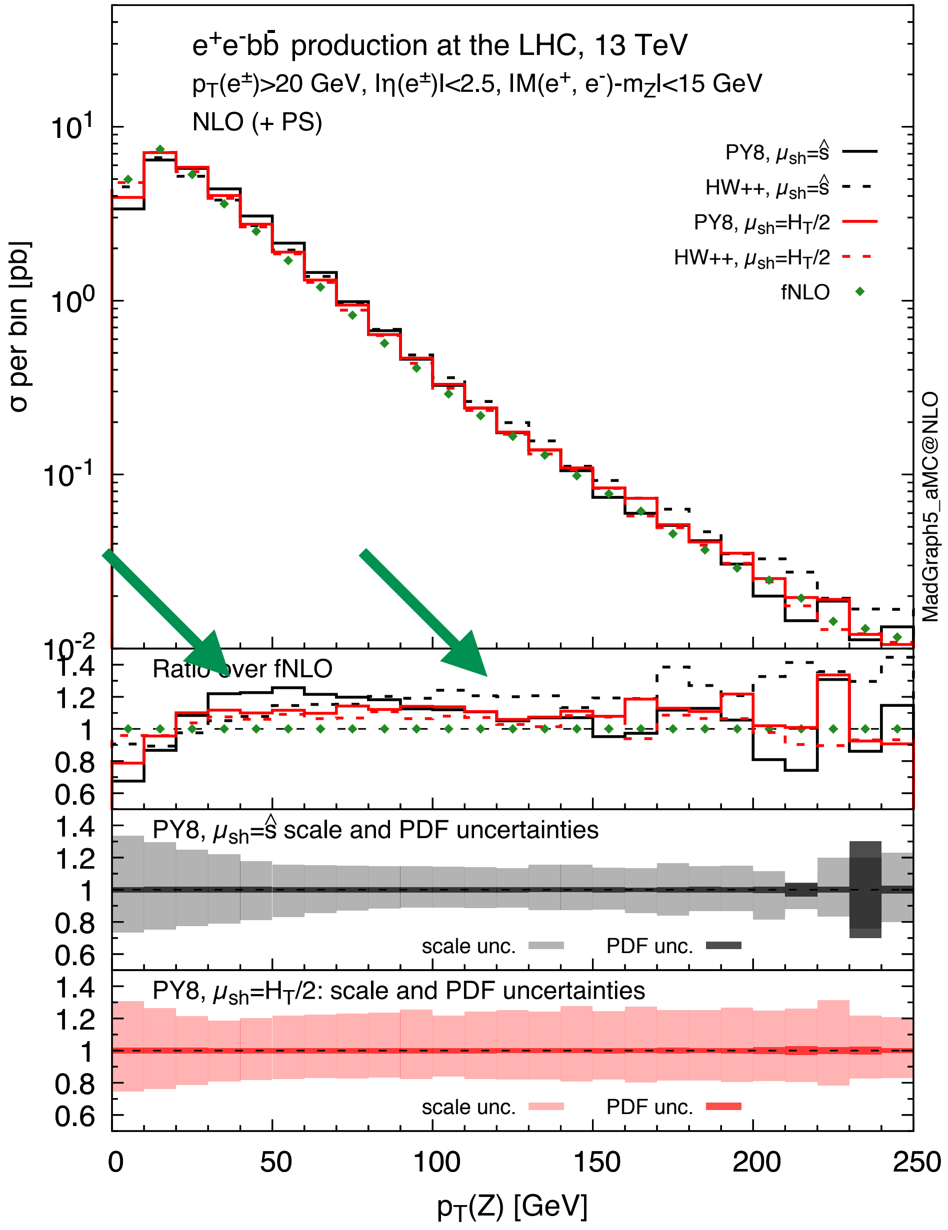
Reduced μ_{sh} ($\sqrt{\hat{s}}$ and $H_T/2$)



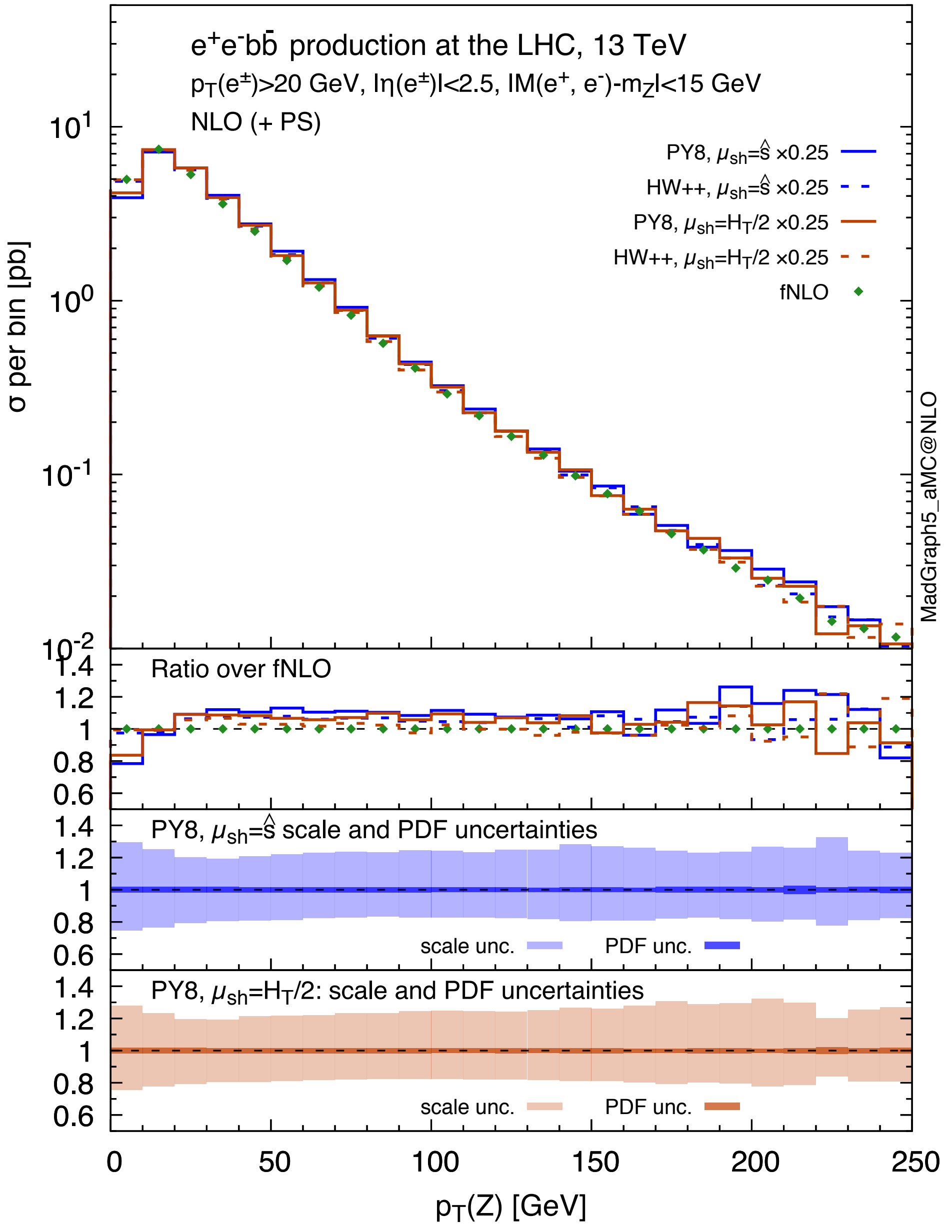
- In all cases, the NLOPS spectra are harder than fNLO. The shower adds radiation

$Zb\bar{b}$ results: $p_T(Z)$

Original μ_{sh} ($\sqrt{\hat{s}}$ and $H_T/2$)

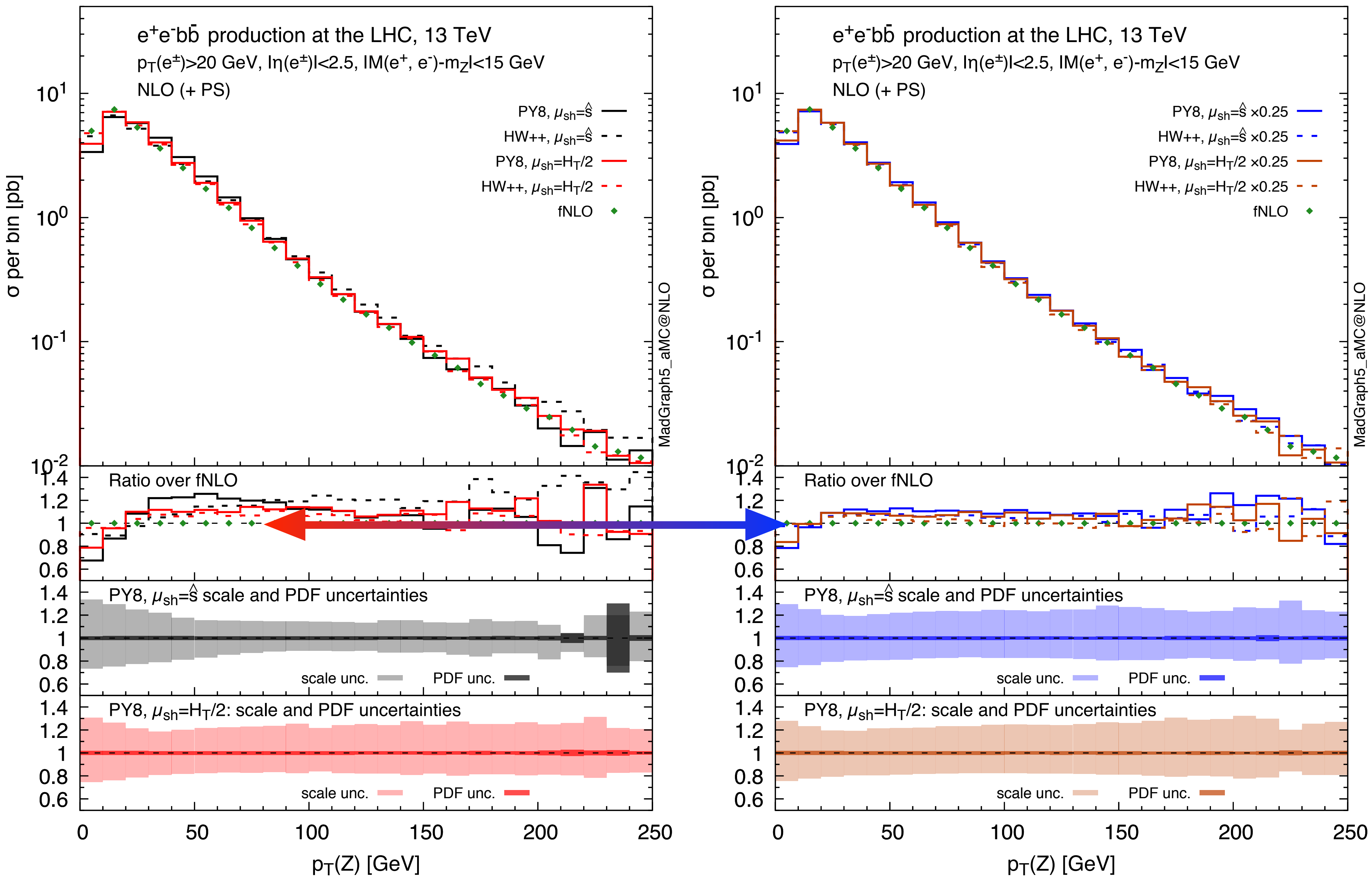


Reduced μ_{sh} ($\sqrt{\hat{s}}$ and $H_T/2$)



- In all cases, the NLOPS spectra are harder than fNLO. The shower adds radiation
- This effect is the largest for PY8 with $\mu_{sh}=\sqrt{\hat{s}}$ (up to 100 GeV) and HW++ with $\mu_{sh}=\sqrt{\hat{s}}$

$Zb\bar{b}$ results: $p_T(Z)$



Original μ_{sh} ($\sqrt{\hat{s}}$ and $H_T/2$)

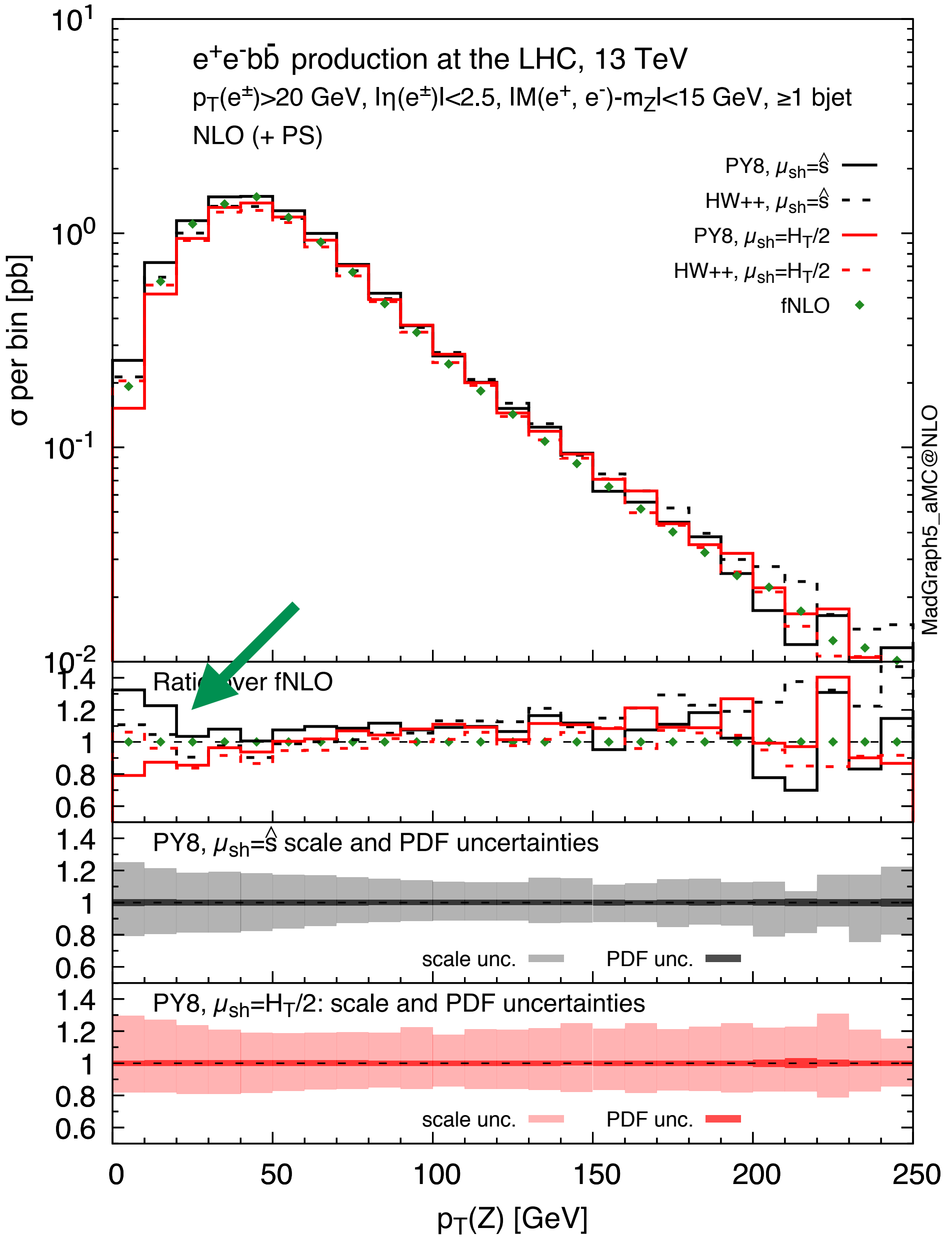
Reduced μ_{sh} ($\sqrt{\hat{s}}$ and $H_T/2$)

- In all cases, the NLOPS spectra are harder than fNLO. The shower adds radiation
- This effect is the largest for PY8 with $\mu_{sh}=\sqrt{\hat{s}}$ (up to 100 GeV) and HW++ with $\mu_{sh}=\sqrt{\hat{s}}$
- Predictions with lower values of μ_{sh} ($H_T/2$ or $\sqrt{\hat{s}}$ x0.25) are very similar
- Up to p_T=100 GeV, PY8 with $\mu_{sh}=\sqrt{\hat{s}}$ and with $\mu_{sh}=\sqrt{\hat{s}}$ x0.25 represent well the range of PS effects

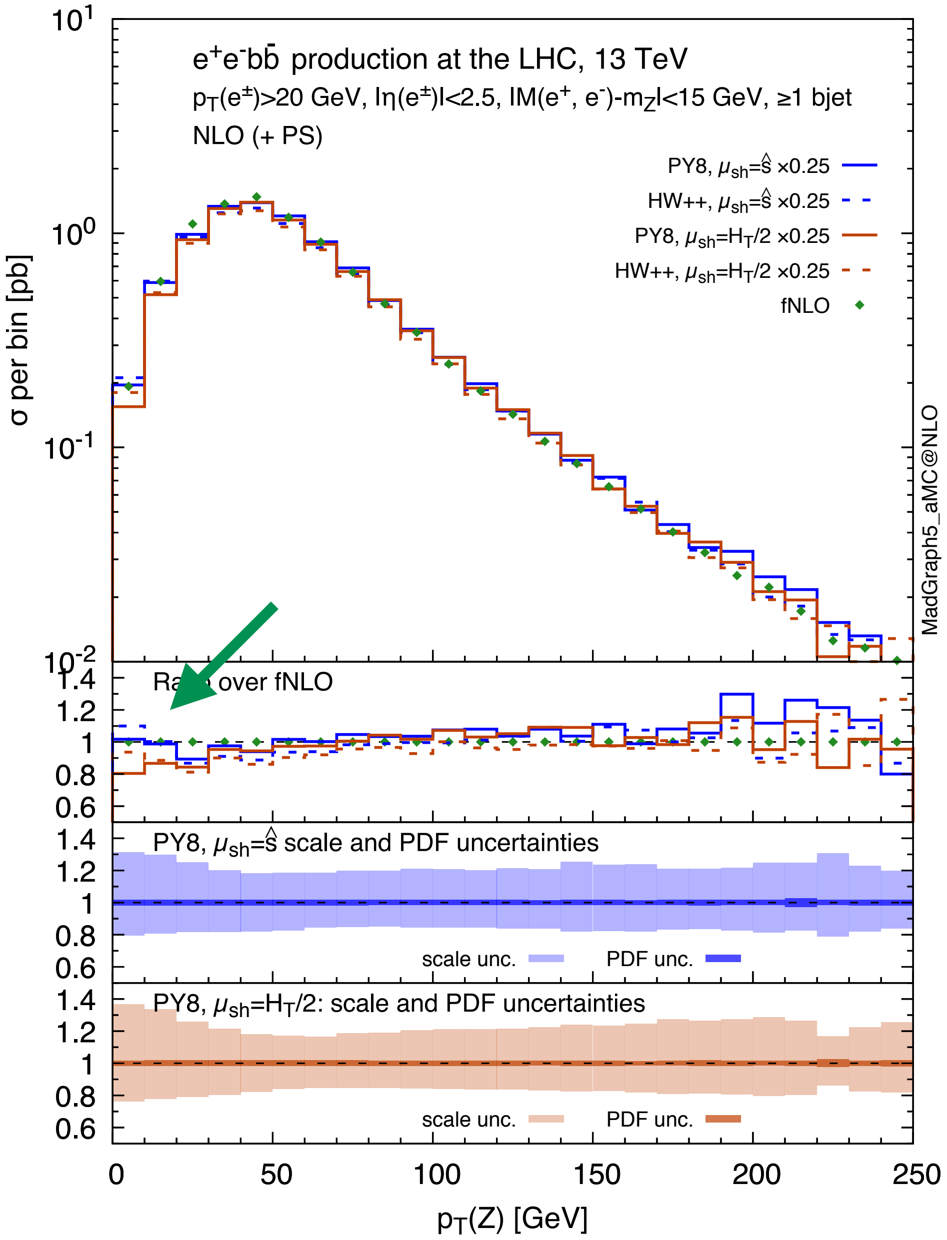
Z$b\bar{b}$ results: $p_T(Z)$ with ≥1 b jet

(anti-k_T, R=0.4, p_T>30 GeV, |η|<2.5)

Original μ_{sh} ($\sqrt{\hat{s}}$ and $H_T/2$)



Reduced μ_{sh} ($\sqrt{\hat{s}}$ and $H_T/2$)

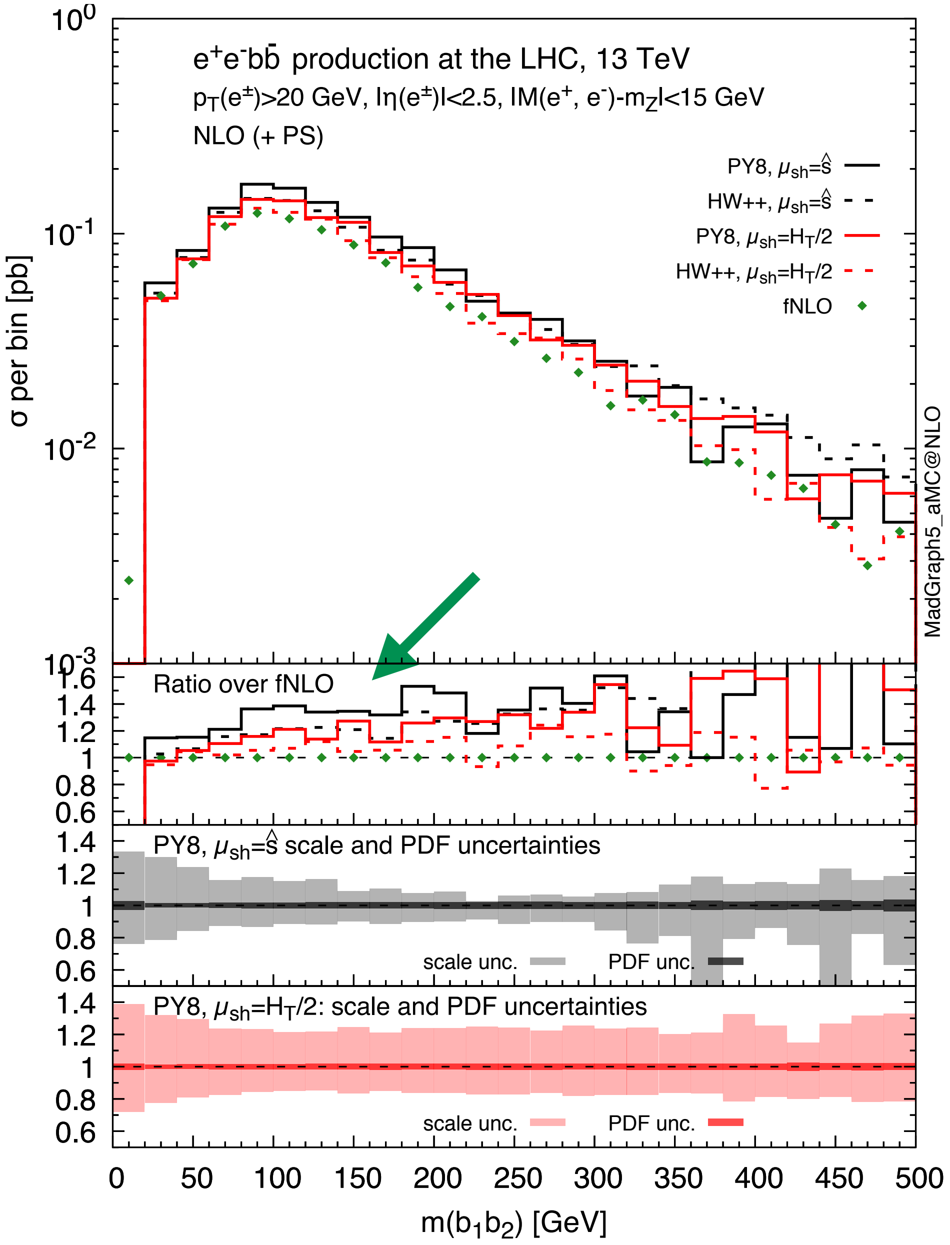


- Going more exclusive, differences between showers / shower scales grow as large as (or larger than) scale uncertainties
- Effects both on shape and rate

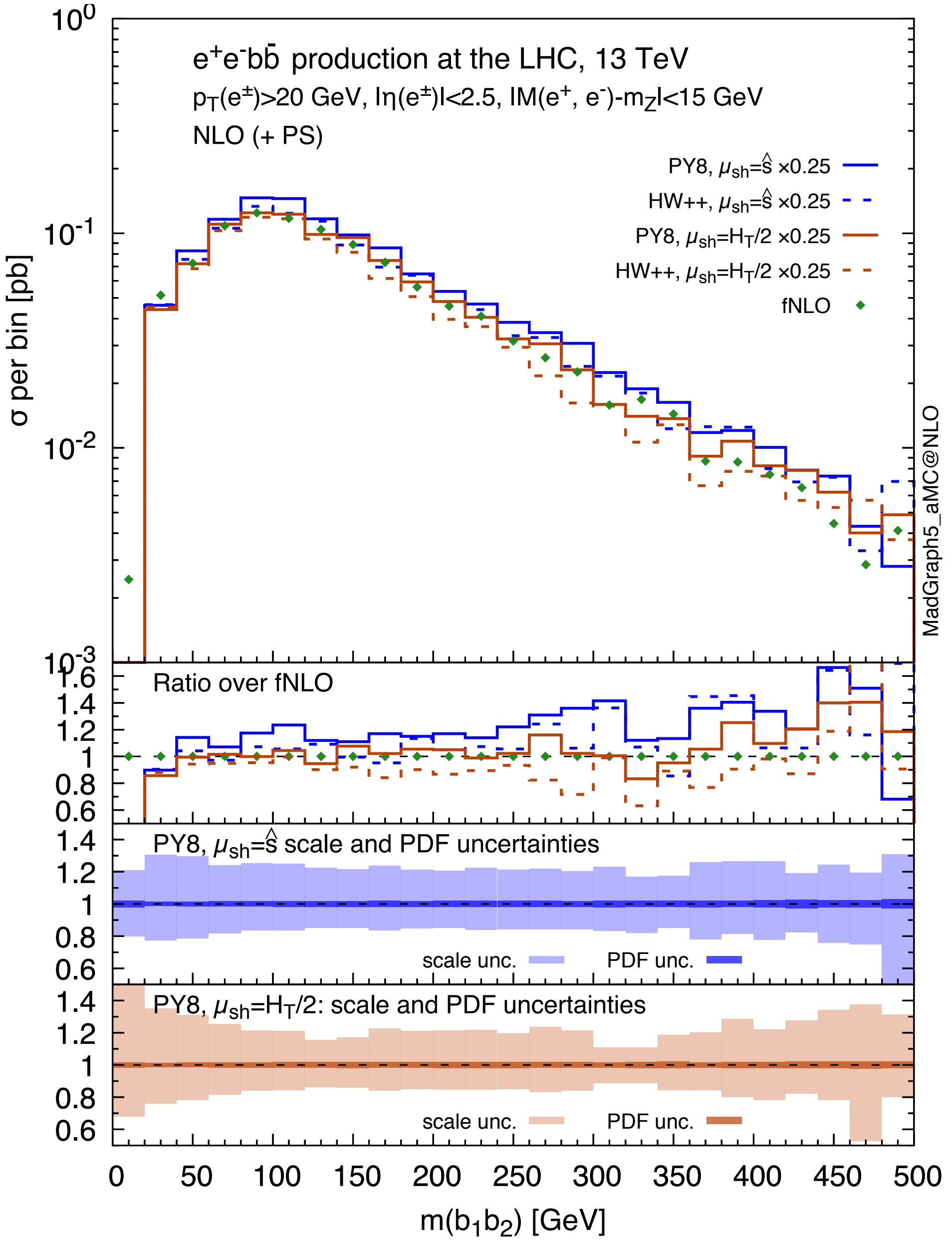
$Zb\bar{b}$ results: $m(b_1b_2)$

(anti-k_T, $R=0.4$, $p_T>30$ GeV, $|\eta|<2.5$)

Original μ_{sh} ($\sqrt{\hat{s}}$ and $H_T/2$)



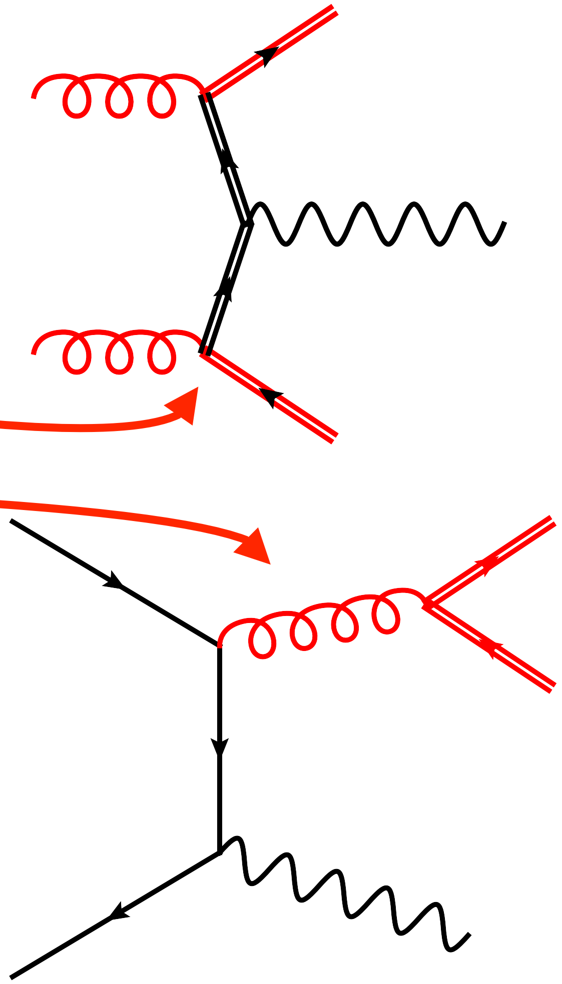
Reduced μ_{sh} ($\sqrt{\hat{s}}$ and $H_T/2$)



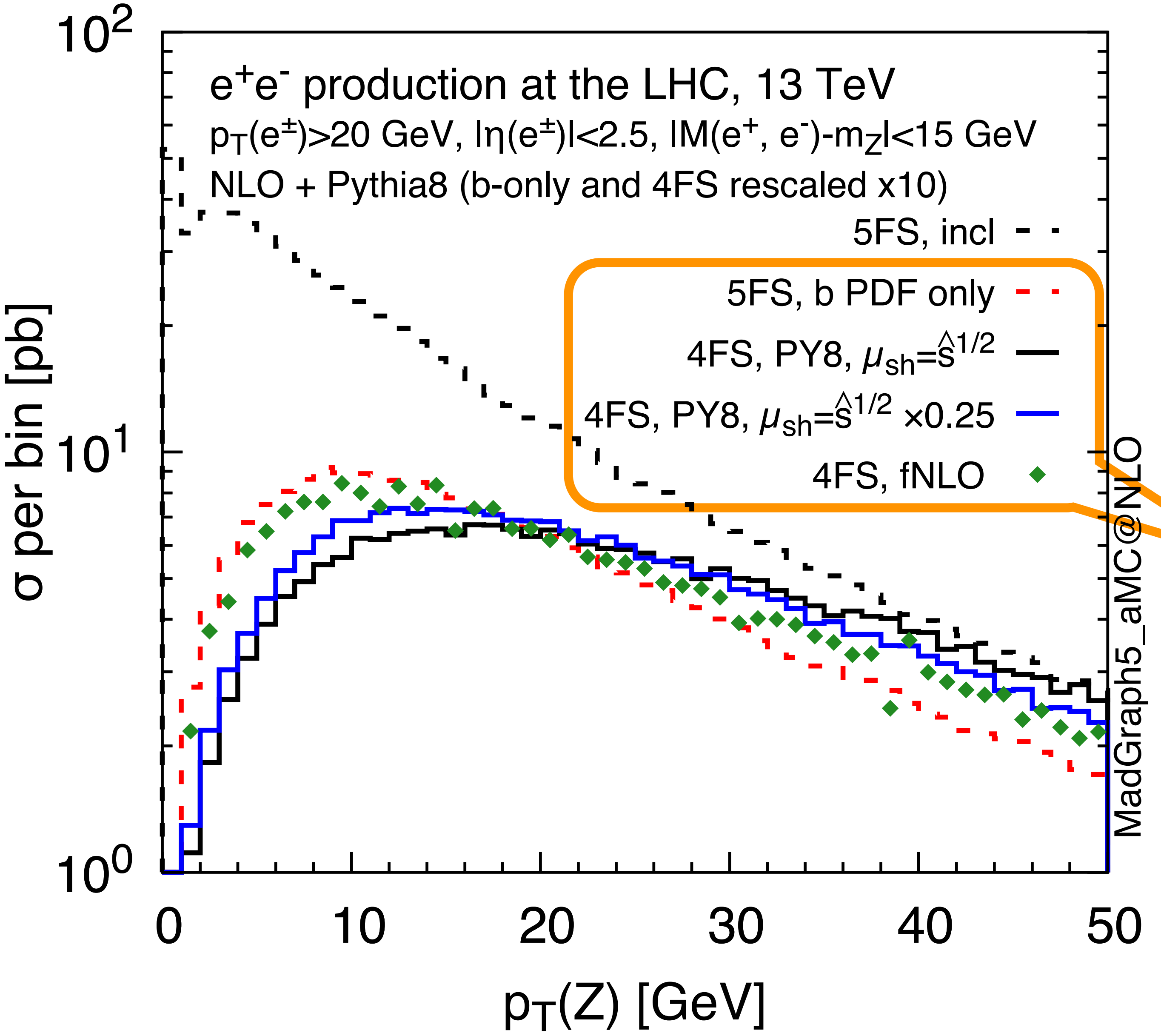
- As for $t\bar{t}b\bar{b}$, very sensitive observable w.r.t. the different showers
- Large shower scales bring +40% effect wrt fNLO at 150 GeV

Include b-mass effects in inclusive-Z samples

- Heavy quarks give distinctive contributions to Z-boson production
- In an inclusive (5F) Z-boson sample, two kind of contributions lead b quarks / B hadrons in the final state:
  - Backward evolution of the $b\bar{b}$-initiated process
  - Final-state g→$b\bar{b}$ splitting
- The description of both contributions can be improved by using the $Zb\bar{b}$ 4FS calculation, where they are described at the ME-level
- Combination: take the 5FS computation, shower the events and veto all events which have B hadrons in the final state. Then add the $Zb\bar{b}$ calculation in the 4FS
- A similar strategy has been proposed to generate an unified sample for $t\bar{t}$ (+jets) and $t\bar{t}b\bar{b}$ Moretti et al, arXiv:1510.08468



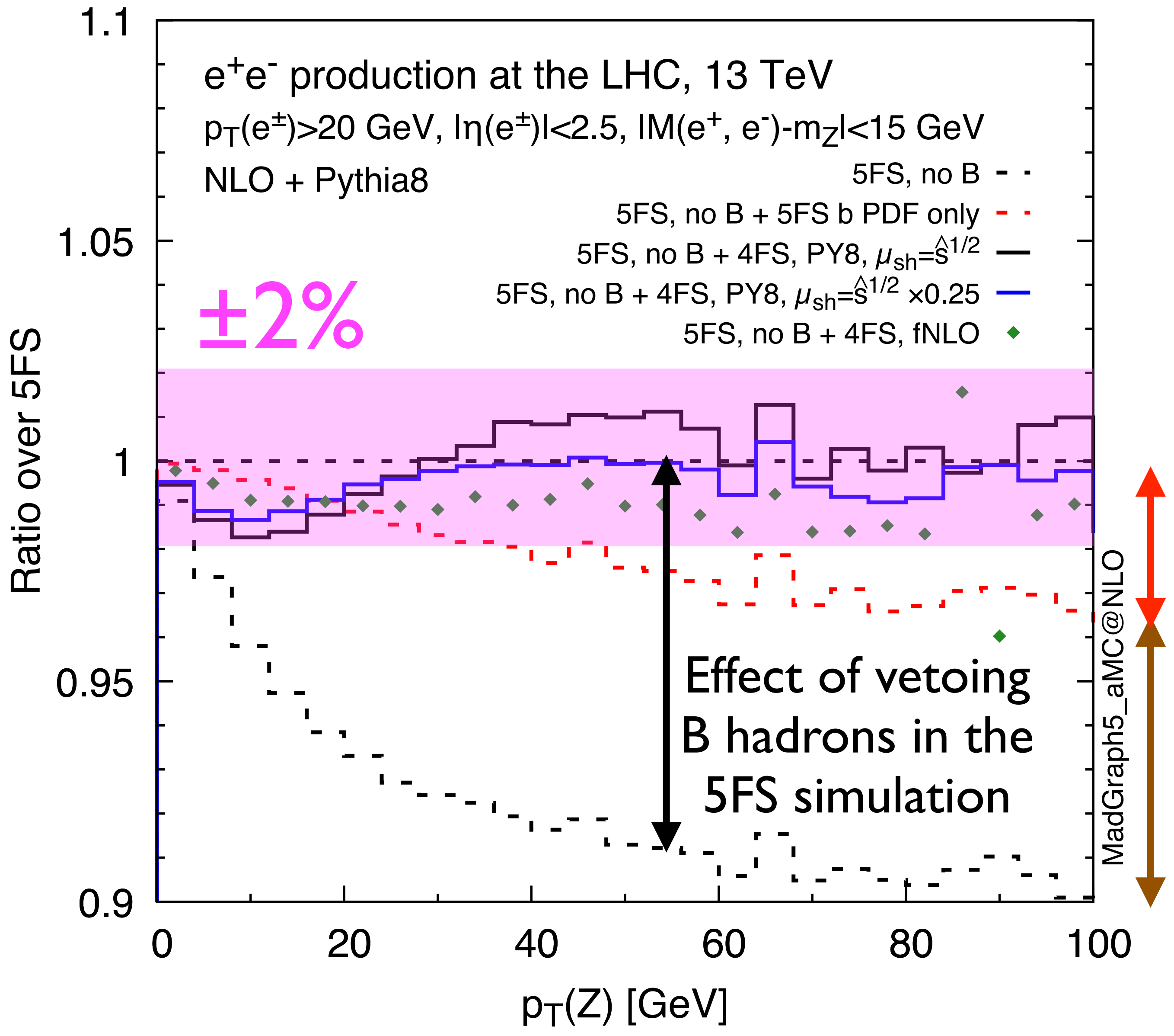
The b-initiated contribution to the Z p_T in various approximations



Flavour decomposition of the 5FS cross section

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

Bottom-mass effects on the Z-boson p_T



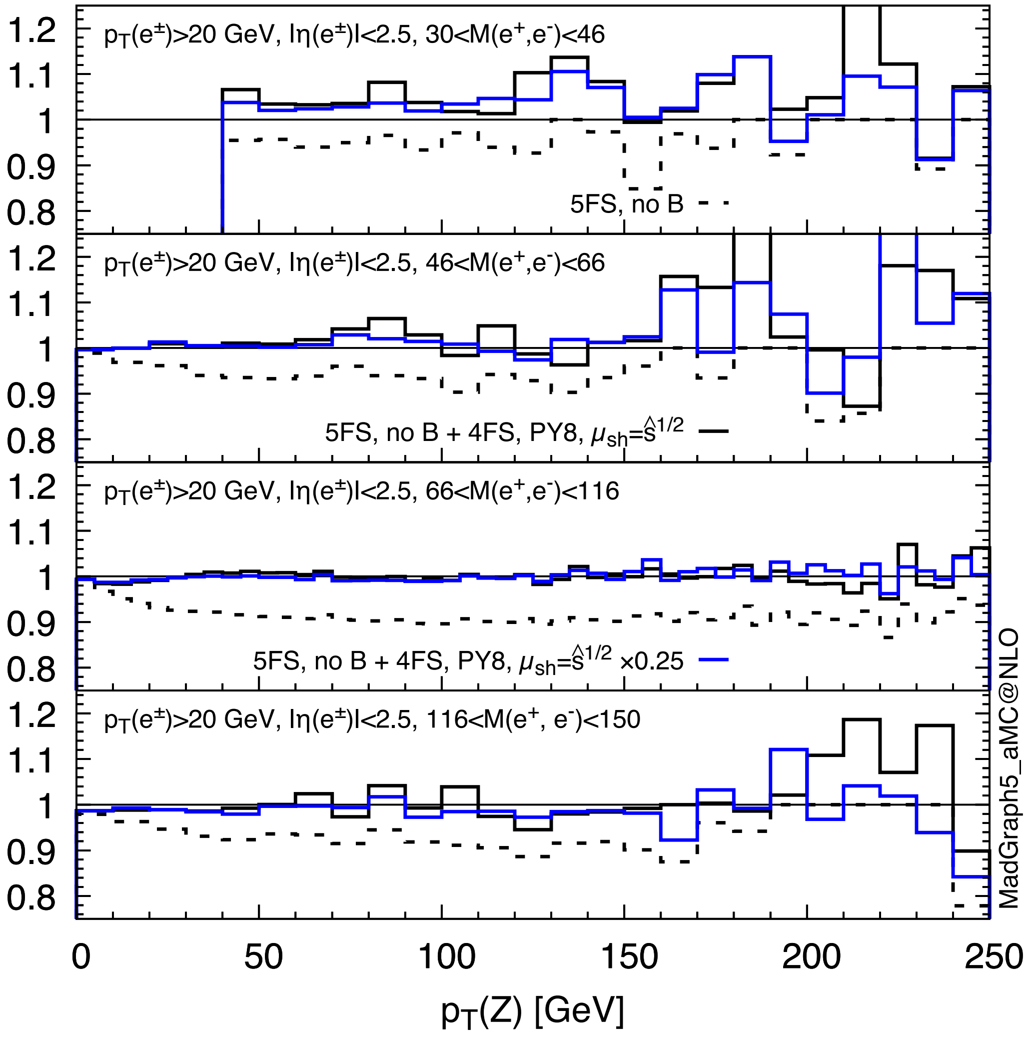
Effect of vetoing B hadrons in the 5FS simulation

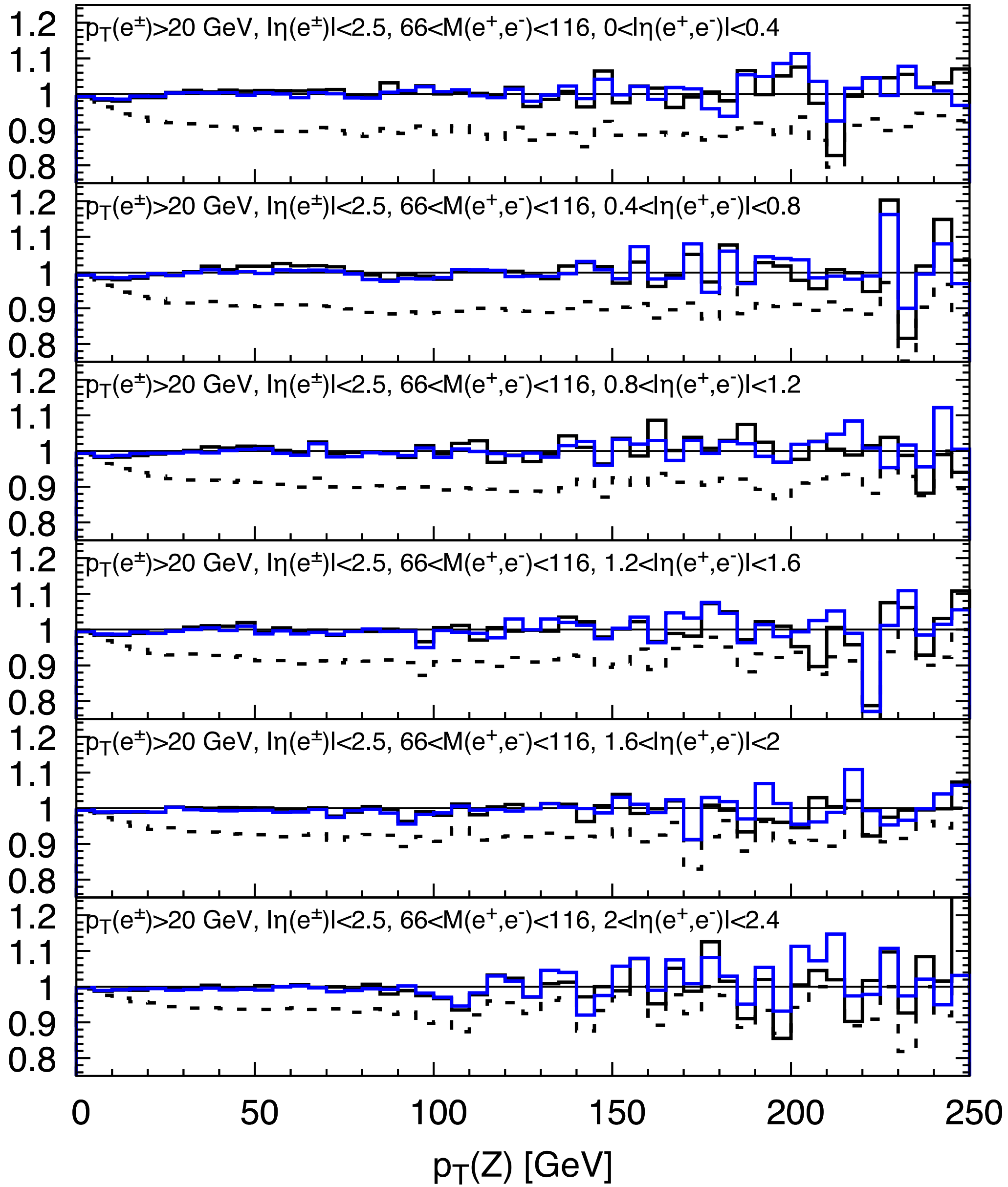
B hadrons from final state splittings

B hadrons from PDFs backward evolution

- Effects are rather small, but have impact on the small-p_T shape
- fNLO has a flat, slightly negative effect

Bottom-mass effects in the $m(e^+e^-)$ and $\eta(e^+e^-)$ bins





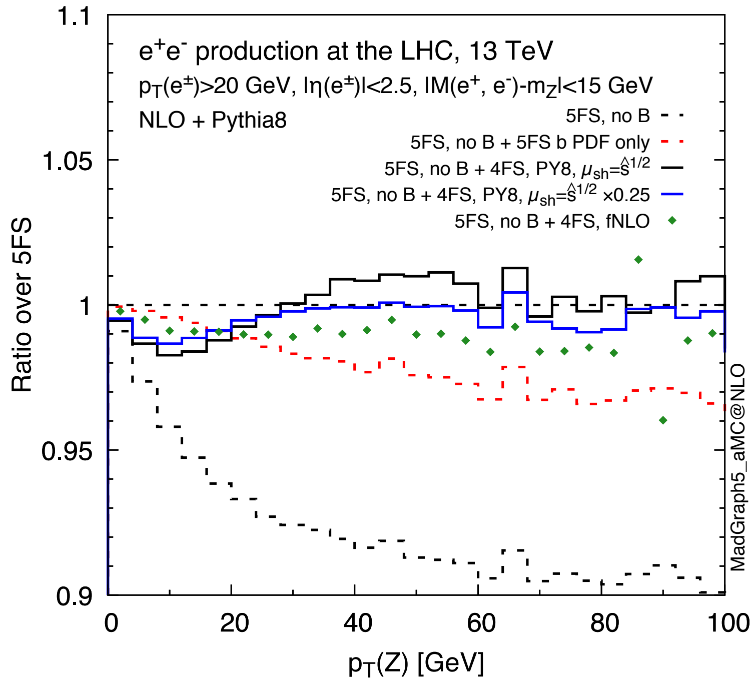
- b-mass effects remain very small in all bins

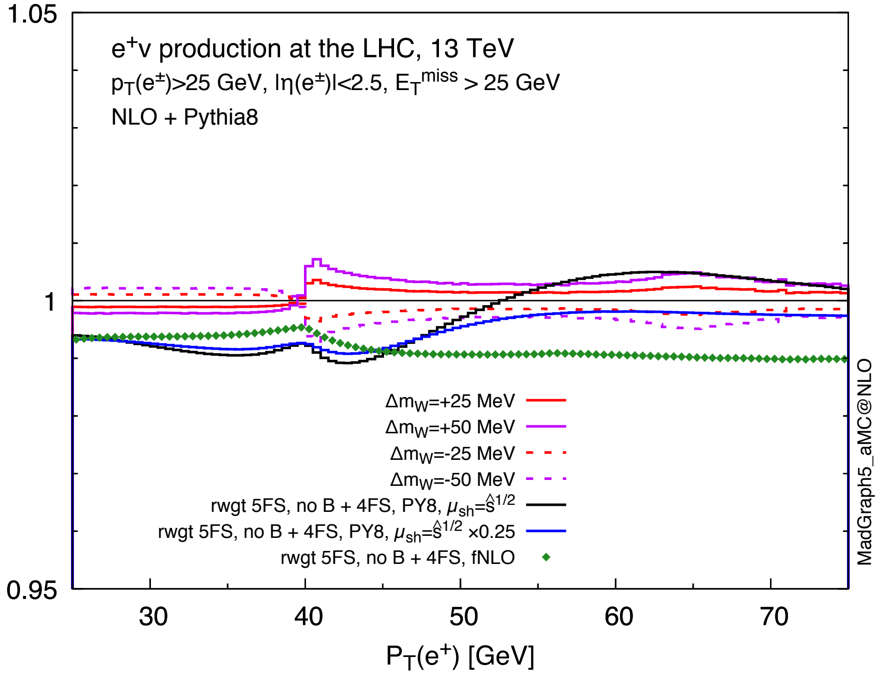
Estimate of the impact on the extraction of m_W

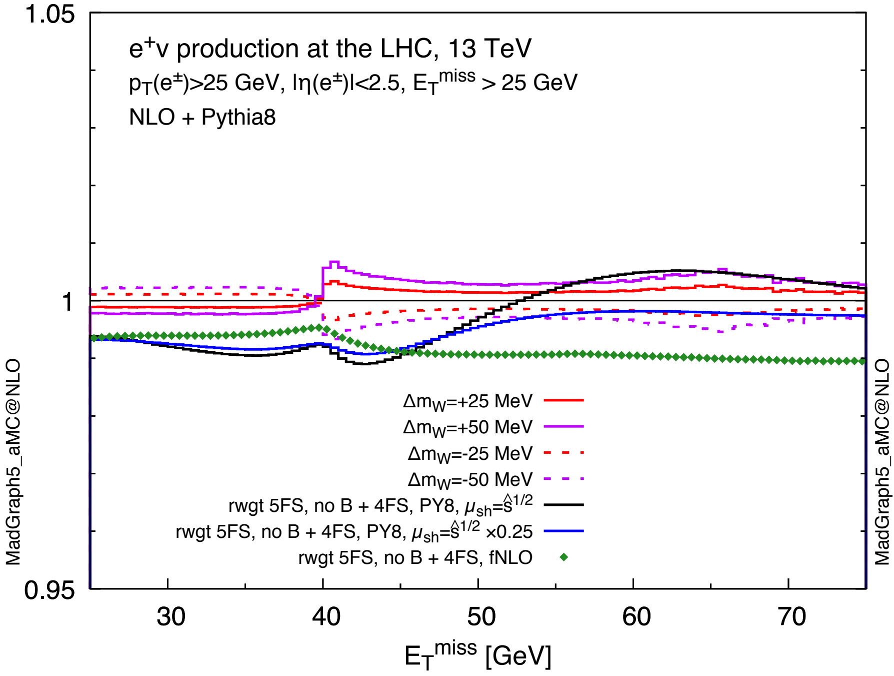
- Comparisons between Z-p_T predictions and data are used to extract non-perturbative parameters (NPPs), encoded e.g. in parton showers or hadronization models
- These NPPs are also used for other processes like charged-current Drell-Yan.
- The propagation of their uncertainties affects the extraction of quantities like m_W
- We assume that:
  - the fit of NPPs is equally good when the standard (5FS) and our 'imporved' predictions are used
  - the NPPs do not depend on the energy (at least they do not change between m_W and m_Z)
- Under these assumptions, changes on the Z p_T are reflected on the W p_T. What is the effect on the extraction of m_W?

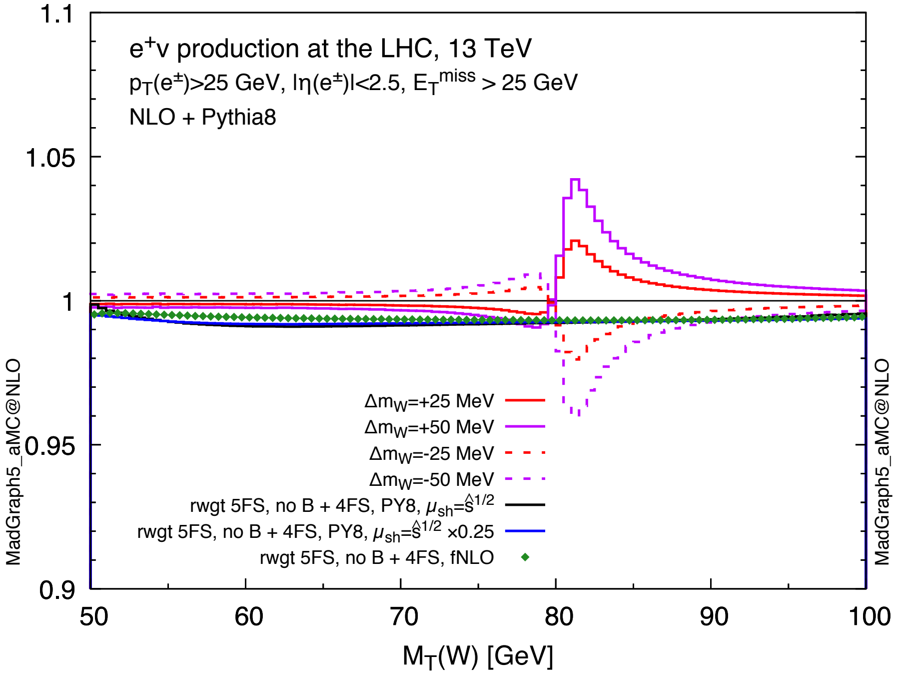
Strategy:

- Generate a sample of p p → $e^+ \nu_e$ events
- Reweight the $p_T(W)$ distribution using the improved $p_T(Z)$ predictions
- Fit m_W using the reweighted predictions by using $p_T(e^+)$, E_T^{miss} and $m_T(W)$
- Fits are done at the level of shapes only, in the range $\Delta m_W = \pm 50$MeV

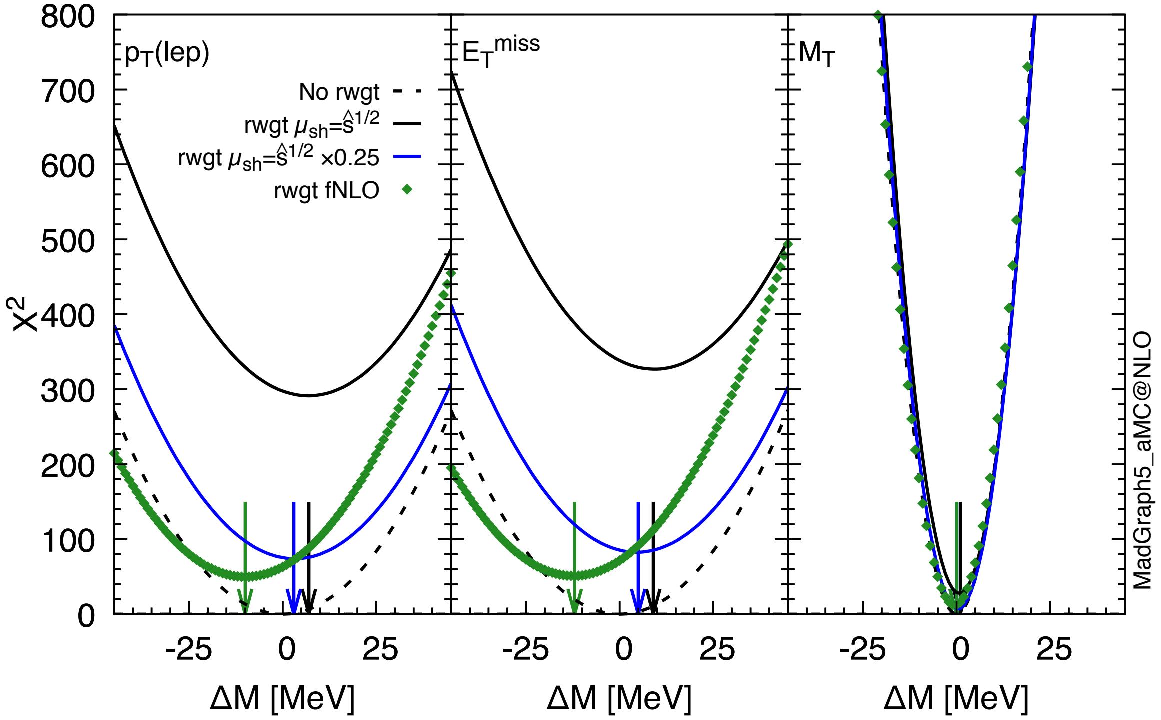








Results of the fit



- The transverse mass show the smallest sensitivity with no visible shift
- The preferred values of $p_T(e^+)$ / E_T^{miss} are shifted up to +7/10 MeV (NLO+PS with the highest shower scale)
- A 'reasonable' shower scale gives an effect of +4/5 MeV on $p_T(e^+)$ / E_T^{miss}
- The fNLO calculation, due to the lack of radiation, gives a shift which is even of the opposite sign; PS effects are important
- Take these numbers as indicative ones, as inputs to perform a real analysis (e.g. with true fits of NPPs using our 'improved' description)
- Some preliminary results with Powheg seem to confirm the trend

Conclusions

- Zbb remains a very interesting process to investigate at the LHC
- Sizeable spread in predictions from different tools and matching techniques, often larger than TH uncertainties
- We have shown a technique to improve the description of inclusive Z-boson production sample by including bottom quark mass effects
- Bottom mass effects on the Z p_T spectrum remain small
- Their inclusion leads to a shift on the W mass of the order of ~5 MeV. Further studies (possibly taking into account charm effects) are welcome!