



Associated production $e^+e^-b\bar{b}$ and heavy quark impact on $pT Z$ and MW

Alessandro Vicini
University of Milano, INFN Milano

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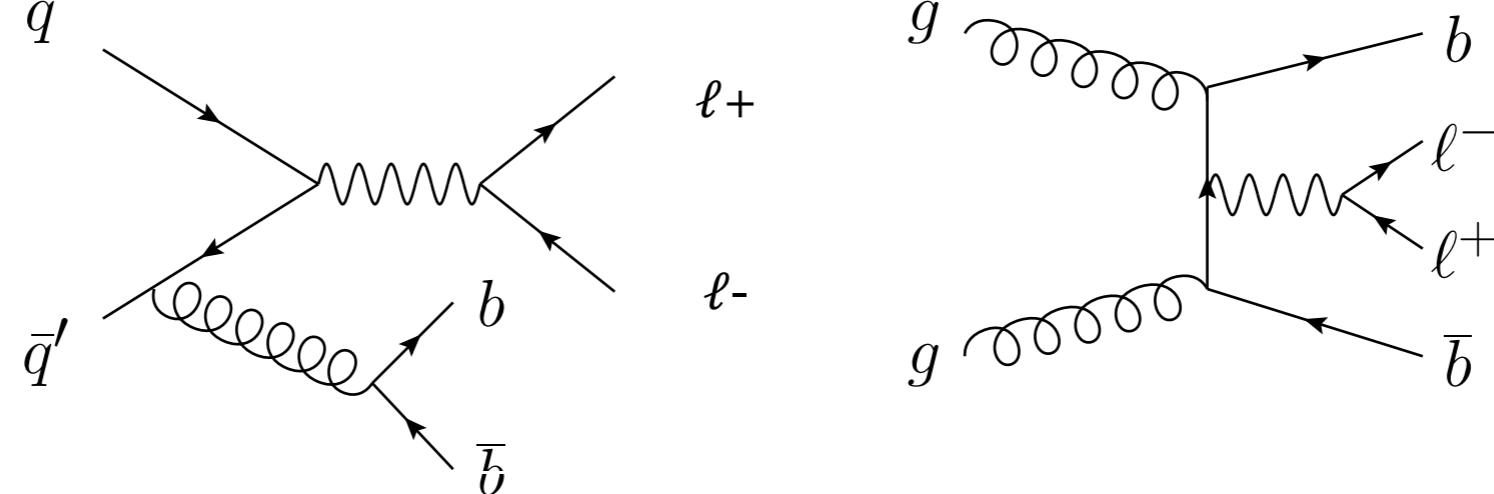
E.Bagnaschi, F.Maltoni, AV, M.Zaro, arXiv:1803.04336

Outline of the talk

- Introduction and motivations
 - Associated production $e^+e^- b \bar{b}$: exclusive final states with bottom quarks
 - QCD uncertainties
 - phenomenology
 - Inclusive e^+e^- transverse momentum distribution: very high-precision tests of the SM
 - heavy quark contribution
 - 5FS vs 4FS
 - Interplay between neutral- and charged-current Drell-Yan and the MW determination
- In this talk we don't discuss
the developments in the approaches matching 4FS and 5FS schemes

Associated production $e^+e^-b\bar{b}$

Associated production $e^+e^- b \bar{b}$



- NLO-QCD corrections to Z production in association with heavy quarks

J.M. Campbell and R.K. Ellis, hep-ph/0006304

J. M. Campbell, R. K. Ellis, F. Maltoni, and S. Willenbrock, hep-ph/0312024, hep-ph/0510362 ,

F. Maltoni, T. McElmurry, and S. Willenbrock, hep-ph/0505014

F. Febres Cordero, L. Reina, and D. Wackerlo, arXiv:0806.0808, arXiv:0906.1923

- Z production in association with heavy quarks with NLOPS-QCD accuracy

R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, R. Pittau, and P. Torrielli, arXiv:1106.6019

F. Krauss, D. Napoletano, and S. Schumann, arXiv:1612.04640

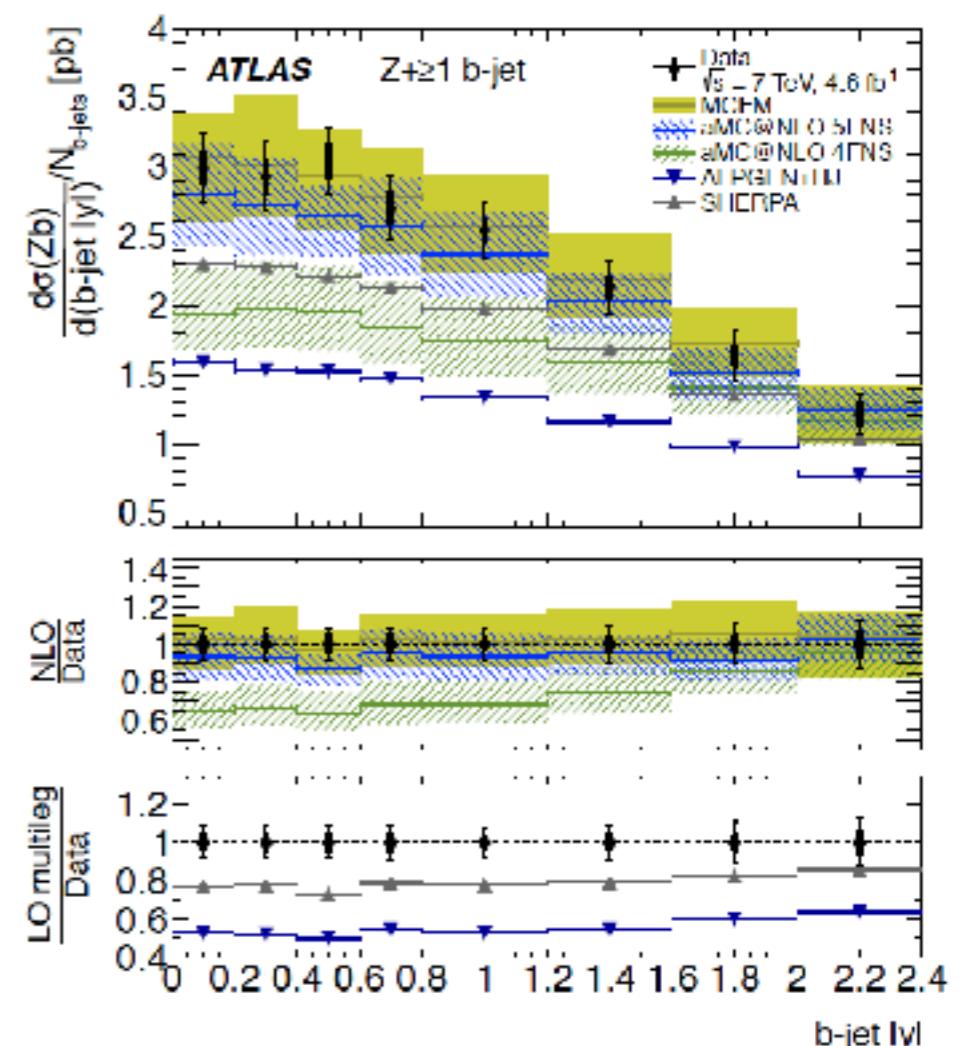
- new implementation in the POWHEG-BOX framework of the $e^+e^- b \bar{b}$ production process
- systematic reassessment of the theoretical uncertainties is desirable
difficult task because it is a **multiscale process** (M_Z , m_b , one typical p_T)
 - multiple equivalent choices yield a spread of the predictions

Improvement of the (data vs theory) agreement

ATLAS, arXiv:1407.3643,

Cross section	Measured	MADGRAPH (5I)	aMC@NLO (5I)	MCFM (parton level)	MADGRAPH (4I)	aMC@NLO (4I)
σ_{Z+1b} (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.22	$3.70^{+0.23}_{-0.26}$	$3.03^{+0.30}_{-0.36}$	$3.11^{+0.47}_{-0.61}$	$2.36^{+0.47}_{-0.37}$
σ_{Z+2b} (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.07	$0.29^{+0.01}_{-0.04}$	$0.29^{+0.01}_{-0.04}$	$0.38^{+0.06}_{-0.10}$	$0.35^{+0.06}_{-0.06}$
σ_{Z+b} (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.24	$3.99^{+0.25}_{-0.29}$	$3.23^{+0.31}_{-0.40}$	$3.49^{+0.52}_{-0.91}$	$2.71^{+0.52}_{-0.41}$
$\sigma_{Z+b}/\sigma_{Z+j}$ (%)	$5.15 \pm 0.03 \pm 0.25$	5.35 ± 0.11	$5.38^{+0.34}_{-0.39}$	$4.75^{+0.24}_{-0.27}$	$4.63^{+0.69}_{-1.21}$	$3.65^{+0.70}_{-0.55}$

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	$m_{\ell\ell'}^2 + p_T^2(\ell\ell') + \frac{m_b^2 + p_T^2(b)}{2} + \frac{m_{b'}^2 + p_T^2(b')}{2}$



Lim, Maltoni, Ridolfi, Ubiali, arXiv:1605.09411

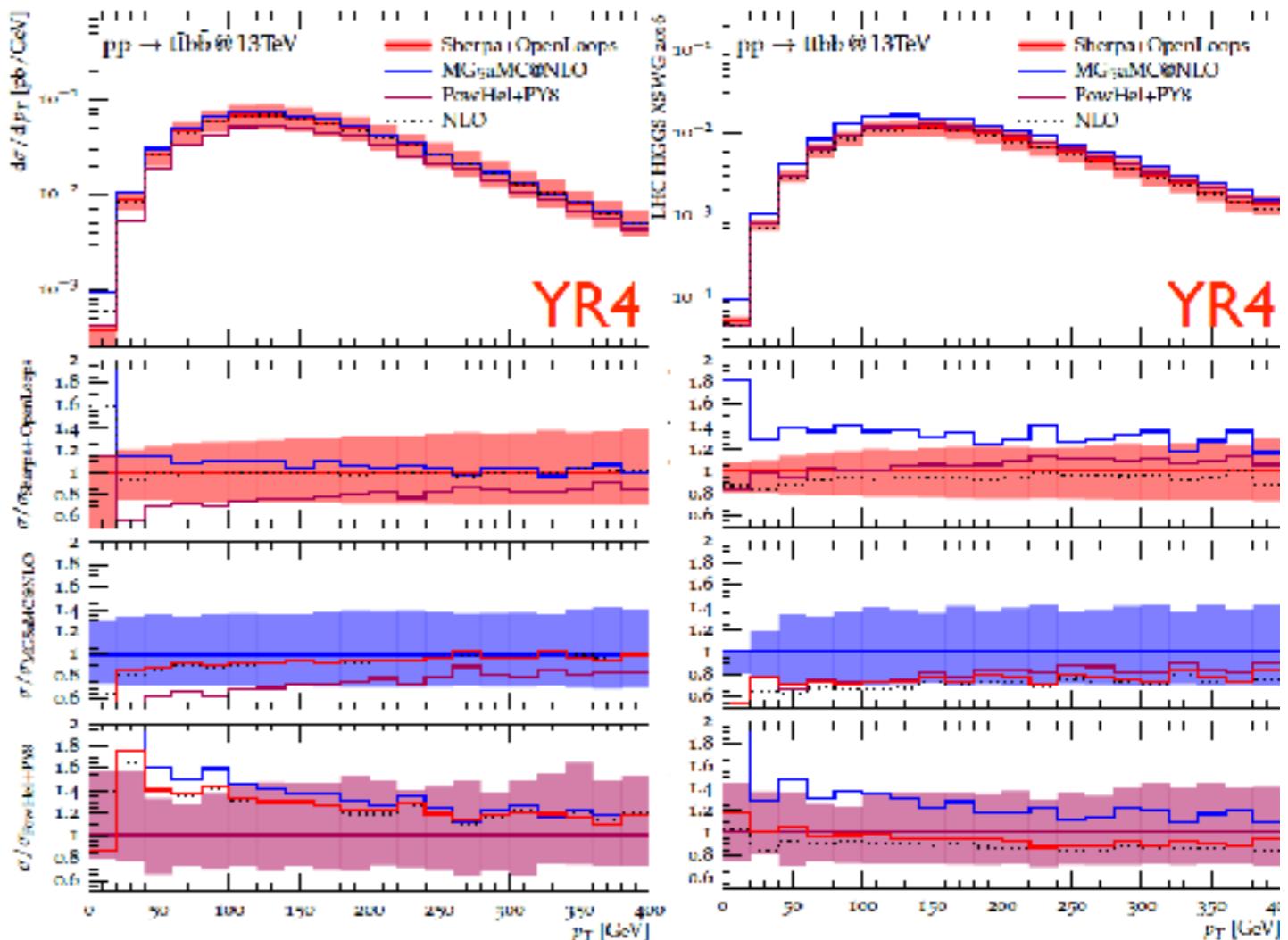
suggest that an appropriate factorisation scale choice, based on analytical arguments on the initial state collinear logs, has to be adopted to obtain accurate predictions in the 4FS for the total cross section

extension also to differential distributions ?

$$\begin{aligned} b\bar{b}H, M_H = 125 \text{ GeV} : & \quad \tilde{\mu}_F \approx 0.36 M_H \\ b\bar{b}Z', M_{Z'} = 91.2 \text{ GeV} : & \quad \tilde{\mu}_F \approx 0.38 M_{Z'} \\ b\bar{b}Z', M_{Z'} = 400 \text{ GeV} : & \quad \tilde{\mu}_F \approx 0.29 M_{Z'} \end{aligned}$$

Playground for other associated production processes: e.g. ttbb

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



HXSWG YR4 arXiv:1610.07922

ttbb is a crucial background to ttH

multiscale and high-multiplicity process

scale uncertainties of O(40%) at NLO

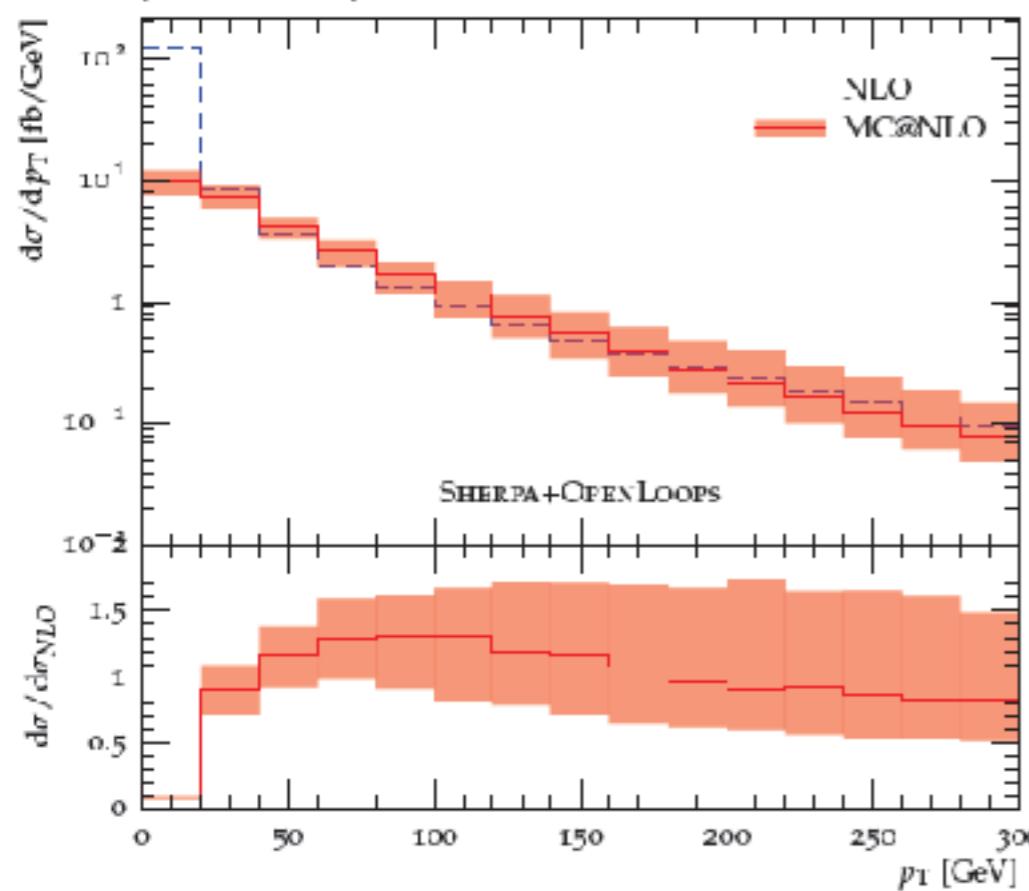
sizeable spread in predictions from different tools

can we learn from e^+e^-bb final state a lesson to choose the scales relevant to describe this class of processes ?

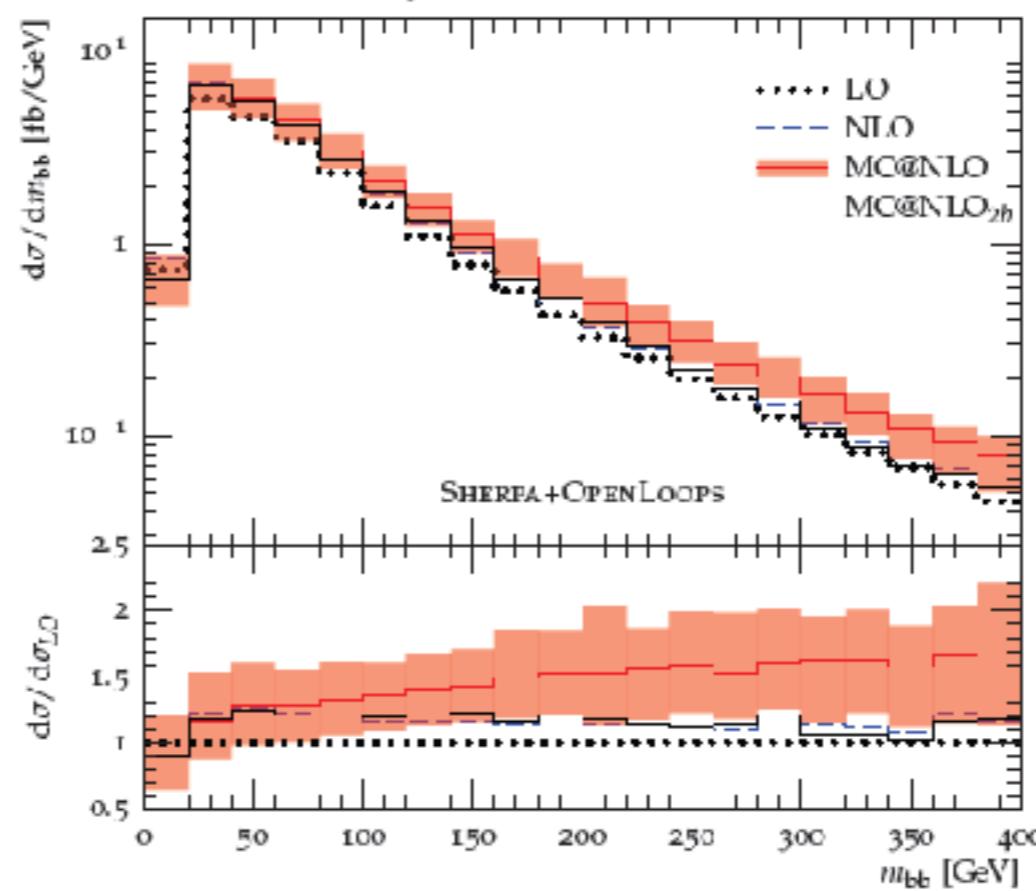
Playground for other associated production processes: e.g. ttbb

Cascioli et al., arXiv:1309.5912

p_T of 1st non-b jet (ttbb cuts)



Mass of first two b-jets (ttbb cuts)



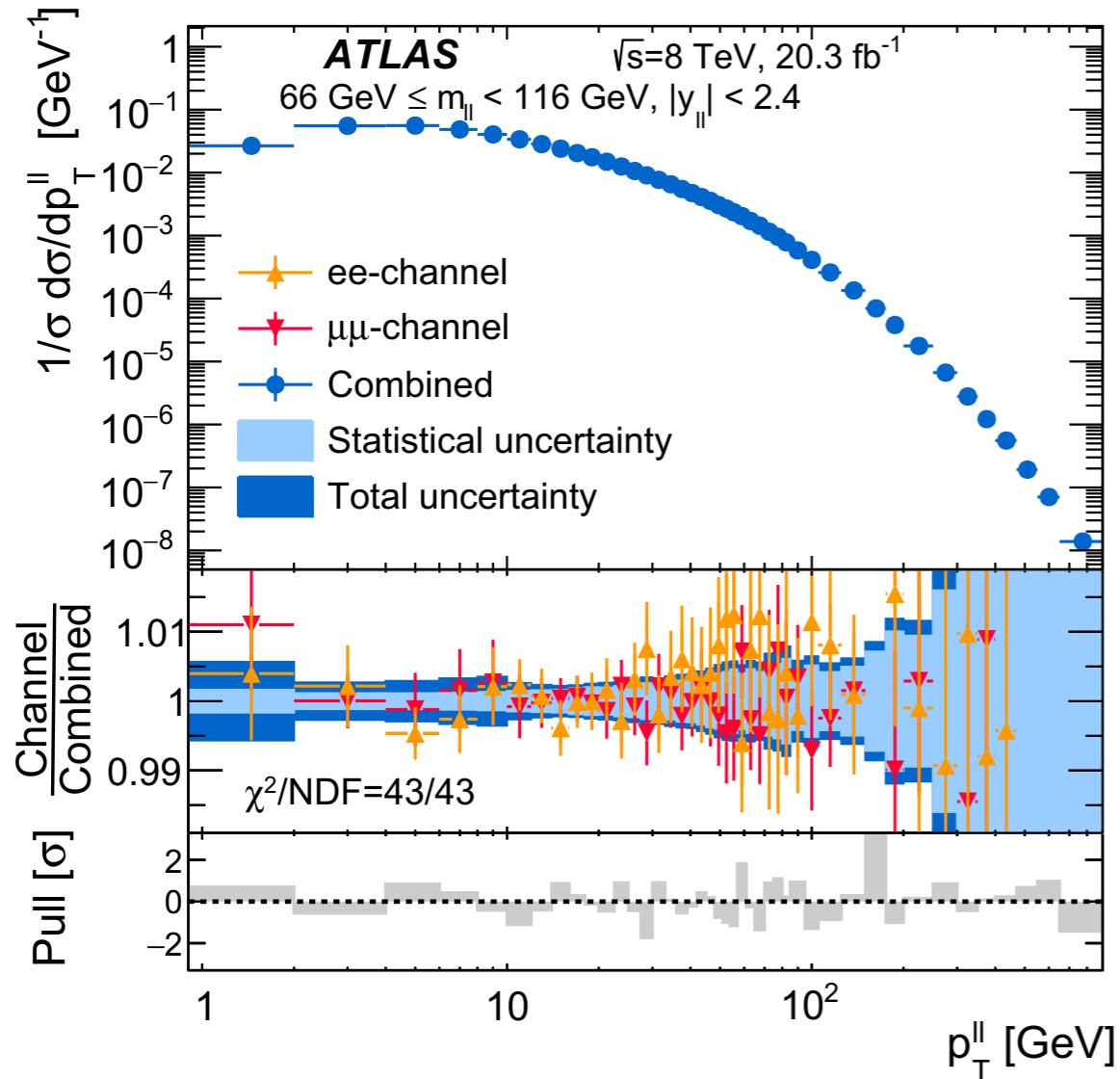
	ttb	ttbb	ttbb($m_{bb} > 100$)
σ_{LO} [fb]	$2644^{+71\% +14\%}_{-38\% -11\%}$	$463.3^{+66\% +15\%}_{-36\% -12\%}$	$123.4^{+63\% +17\%}_{-36\% -13\%}$
σ_{NLO} [fb]	$3296^{+34\% +5.6\%}_{-25\% -4.2\%}$	$560^{+29\% +5.4\%}_{-24\% -4.8\%}$	$141.8^{+26\% +6.5\%}_{-22\% -4.6\%}$
σ_{NLO}/σ_{LO}	1.25	1.21	1.15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

large additional contribution from $g \rightarrow bb$ splitting in the Parton Shower growing with the bb-pair invariant mass

in general PS effects at the few% level are expected

Challenges offered by the inclusive ptZ distribution

ATLAS arXiv:1512.02192



inclusive lepton pair transverse momentum distribution

total error $< 0.5\%$ for $1 \text{ GeV} < \text{ptZ} < \sim 50 \text{ GeV}$

extraordinary challenge to theory predictions

- shape
- absolute normalisation

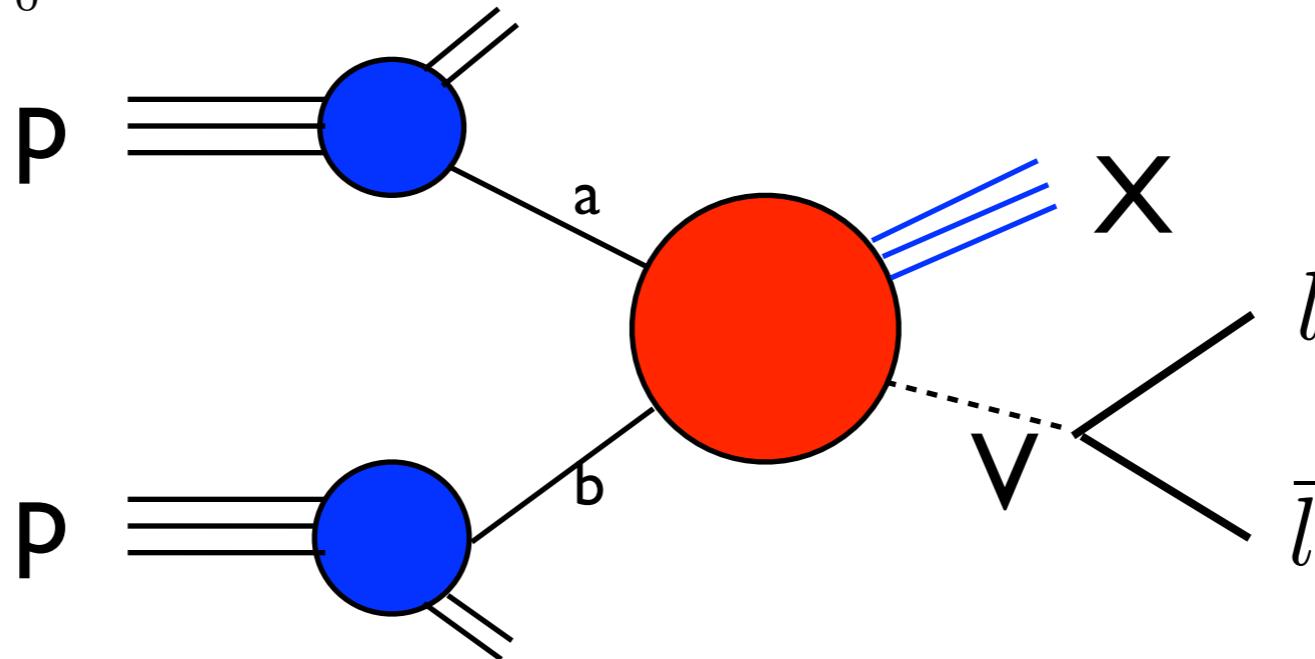
every contribution, also classified as “subleading”, can become important at this level:
e.g. treatment of bottom-quark related subprocesses

The inclusive lepton pair transverse momentum distribution plays a central role in the measurement of the W boson mass for it allows the **calibration of the detectors and of the Monte Carlo tools** as well

Can a more refined treatment of heavy quark effects
→ improve the description of ptZ ?
→ affect the MW value ?

QCD uncertainties

$$\sigma(P_1, P_2; m_V) = \sum_{a,b} \int_0^1 dx_1 dx_2 f_{h_1,a}(x_1, M_F) f_{h_2,b}(x_2, M_F) \hat{\sigma}_{ab}(x_1 P_1, x_2 P_2, \alpha_s(\mu), M_F)$$



- renormalization scale μ
 - factorization scale M_F
 - PDF uncertainties
 - recipe of the matching between fixed- and all-orders terms
 - resummation scale (analytic resummation language)
shower scale or (singular vs regular)-separation scale
(Monte Carlo event generators language)
 - Parton Shower model
- 7-point scale variations
- NNPDF3.0 (100 replicas)
- POWHEG vs aMC@NLO
- factor 2 variation of “best” value
- Pythia 8.215 Monash vs
Herwig++ 2.7.1

POWHEG vs aMC@NLO matching recipes

POWHEG

$$d\sigma = \bar{B}(\phi_n) d\phi_n \left\{ \Delta(\phi_n, p_\perp^{min}) + \Delta(\phi_n, p_\perp) \theta(p_\perp - p_\perp^{min}) \frac{R^s(\phi_{n+1})}{B(\phi_n)} d\phi_{rad} \right\} + R^f(\phi_{n+1}) d\phi_{n+1}$$

$$\bar{B}(\phi_n) = B(\phi_n) + V(\phi_n) + \int d\phi_{rad} R^s(\phi_n, \phi_{rad})$$

$$R = R^s + R^f \equiv f(h)R + (1 - f(h))R \quad f(h) = \frac{h^2}{h^2 + k_\perp^2}$$

$$\Delta(\phi_n, p_\perp) = \exp \left(- \int d\phi_{rad} R^s(\phi_n, \phi_{rad}) / B(\phi_n) \theta(k_\perp - p_\perp) \right)$$

- the first emission is generated by POWHEG with its own Sudakov form factor Δ
exact real matrix element
- the real matrix element is split into a singular and a regular part at a **separation scale h**
the regular part does not receive a Sudakov suppression
- the Parton Shower adds all the following emissions in a phase space limited by **Q_{sh}**
 Q_{sh} is chosen as the hardness of the first emission (singular events)
an “arbitrary” function (regular events)
- **Q_{sh}** is eventually written in the **scalup** entry of the LHE record

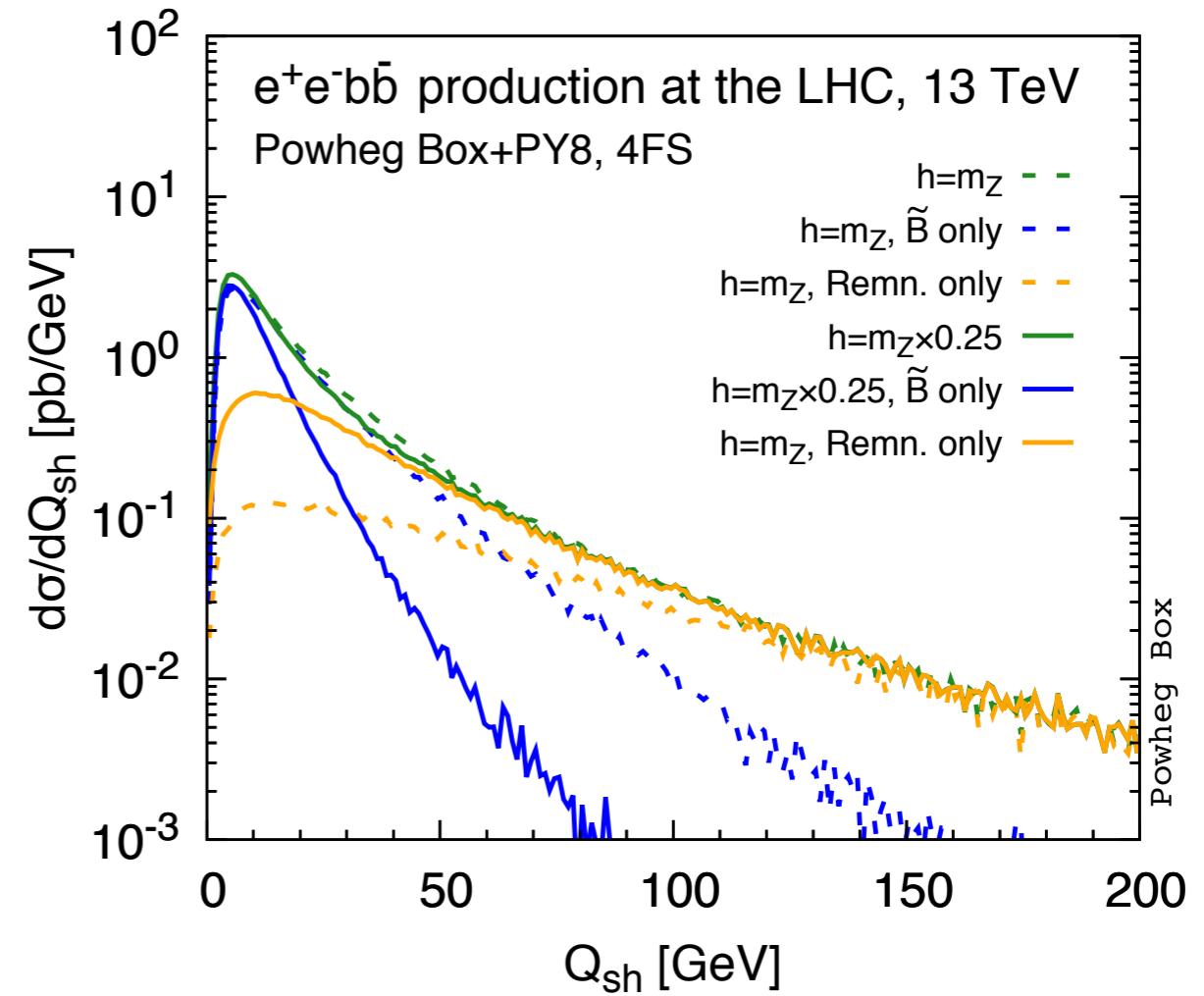
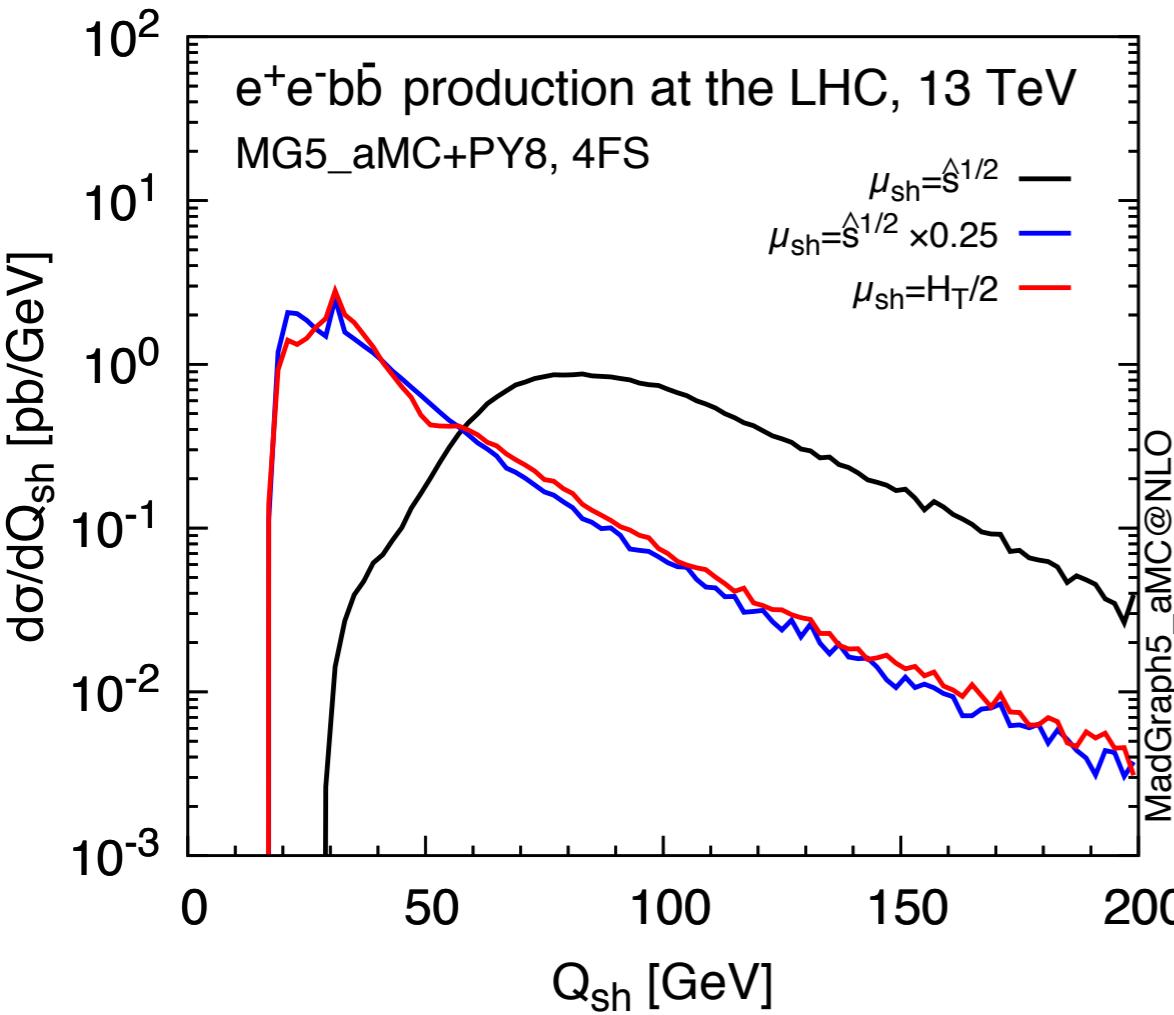
POWHEG vs aMC@NLO matching recipes

aMC@NLO

$$\left(\frac{d\sigma}{dO}\right)_{MC@NLO} = \sum_{n \geq 0} \int \left[B + \hat{V}_{fin} + \int R_{MC@NLO}^s d\Phi_r^{MC} \right] \frac{d\Phi_B d\Phi_n^{MC}}{dO} \mathcal{I}_n(t_1 = Q_{sh}) \\ + \sum_{n \geq 1} \int \left[R \frac{d\Phi d\Phi_{n-1}}{dO} - R_{MC@NLO}^s \frac{d\Phi^{MC} d\Phi_{n-1}^{MC}}{dO} \right] \mathcal{I}_{n-1}(t_1 = Q_{sh})$$

- Soft and Hard terms describe events with k and k+l final state partons
- the Parton Shower generates all the additional n partons using
 - the standard Sudakov form factor, approximated phase-space measure,
 - a limit to the radiation hardness set by a scale called Q_{sh}
- the scale Q_{sh} is extracted from a probability distribution whose functional form is fixed but depends parametrically on a second scale called μ_{sh}
- on a event-by-event basis μ_{sh} is computed from the event kinematics and eventually Q_{sh} is extracted
- PS populates a phase space limited by `scalup`, one of the LHE format entries, set equal to Q_{sh}
- the hard matrix element corrections are applied, avoiding a double counting with the PS (hard event)

Interfacing NLO event generators to Parton Shower: Q_{sh} distributions



- Q_{sh} distributions computed with aMC@NLO and POWHEG
- comparison of choices involving a high ($O(MZ)$) or a low ($O(MZ/4)$) scale
- POWHEG exhibits a softer Q_{sh} distributions compared to aMC@NLO
- The size of phase space available to the QCD-PS may enhance/reduce the PS model dependence
(Pythia 8.215 vs Herwig++ 2.7.1 comparison)

POWHEG vs aMC@NLO matching recipes

POWHEG and aMC@NLO

coincide in the fixed-order NLO-QCD predictions

differ by terms of higher-order in the α_s expansion

subleading w.r.t. to the counting of logarithmically enhancing factors

These differences can be reduced with tough higher-order calculations

have to be considered today as part of the theoretical uncertainty

The multiscale nature of e+e- b bbar production may enhance the differences:

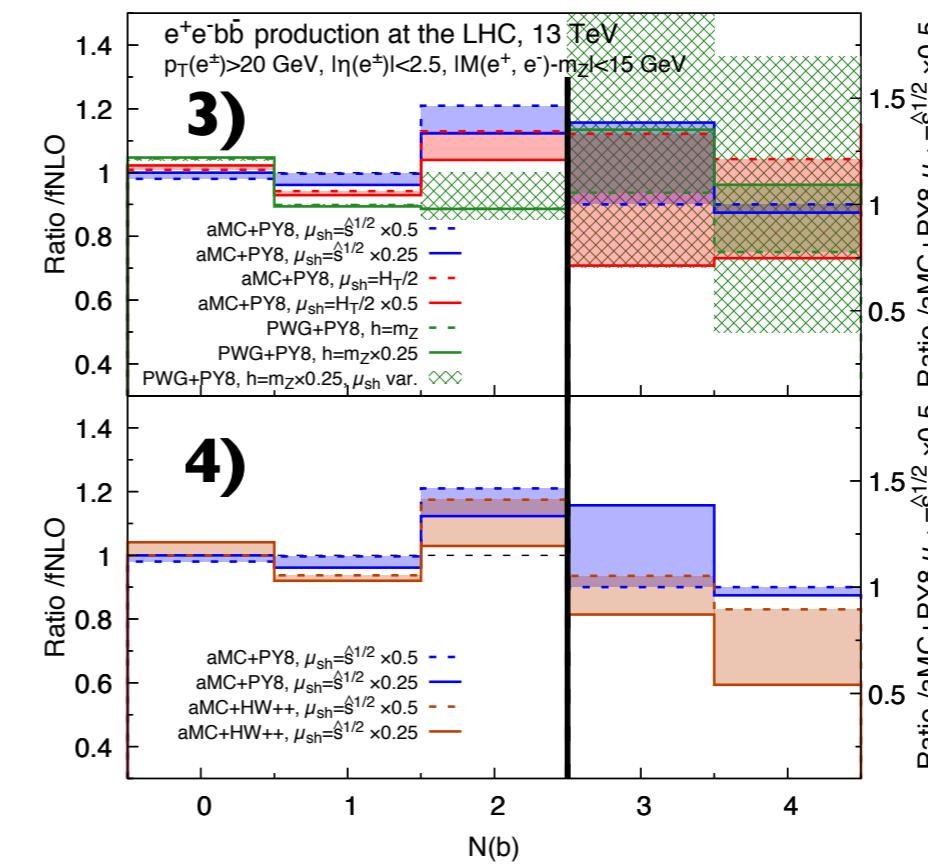
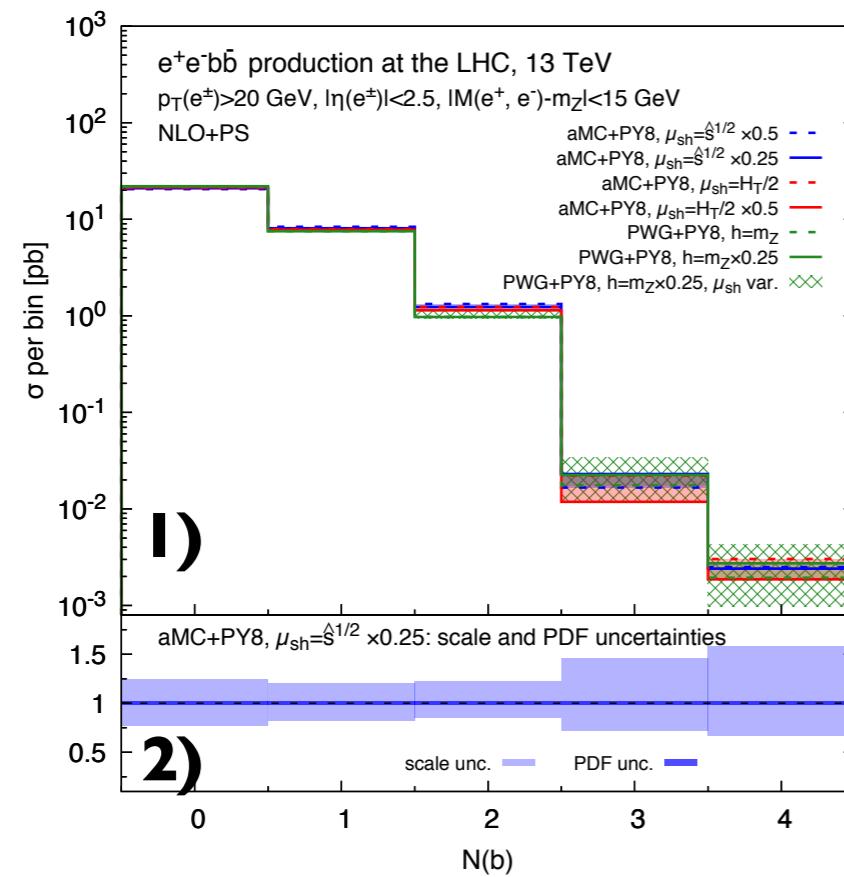
one single Q_{sh} choice might not be sufficient for an accurate description of
the radiation from all charged legs

possibly spurious terms are introduced

large logarithmically enhanced terms are not included to all orders

Exclusive signatures with tagged b-jets (B hadrons)

$e^+e^-b\bar{b}$: b-jet multiplicities



plots structure and color codes :

1) absolute predictions at NLOPS with Pythia 8.215:

aMCNLO with $\mu_{sh} = (\hat{s}/4, \hat{s}/2)$, aMCNLO with $\mu_{sh} = (H_T/4, H_T/2)$,

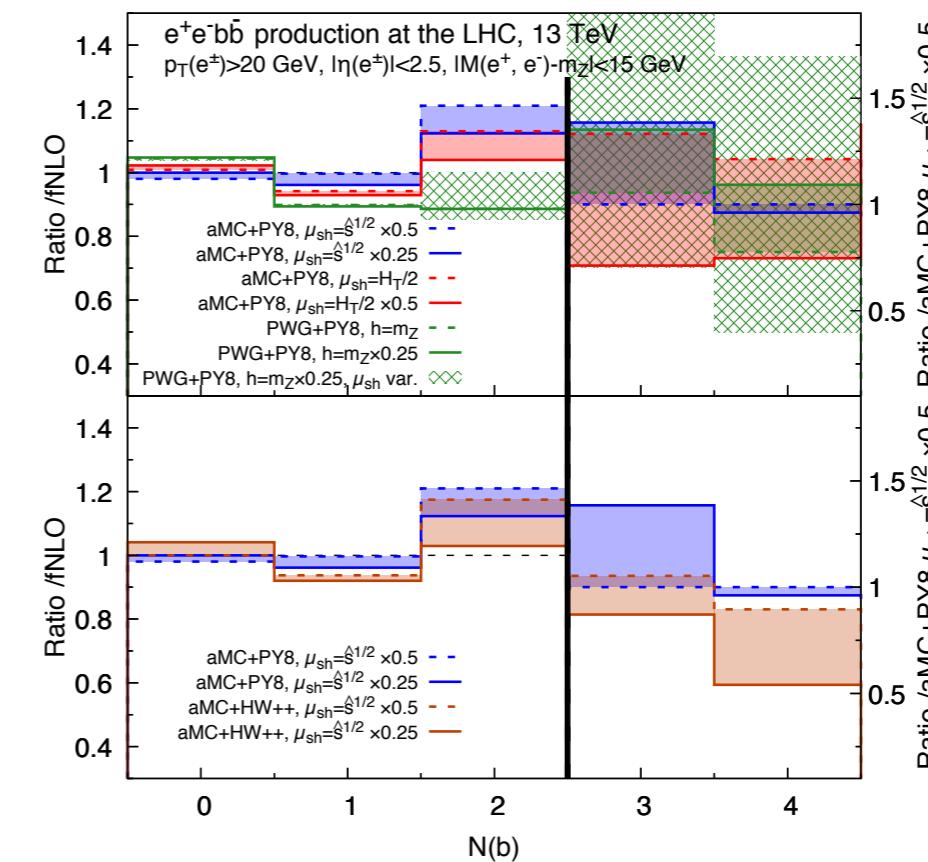
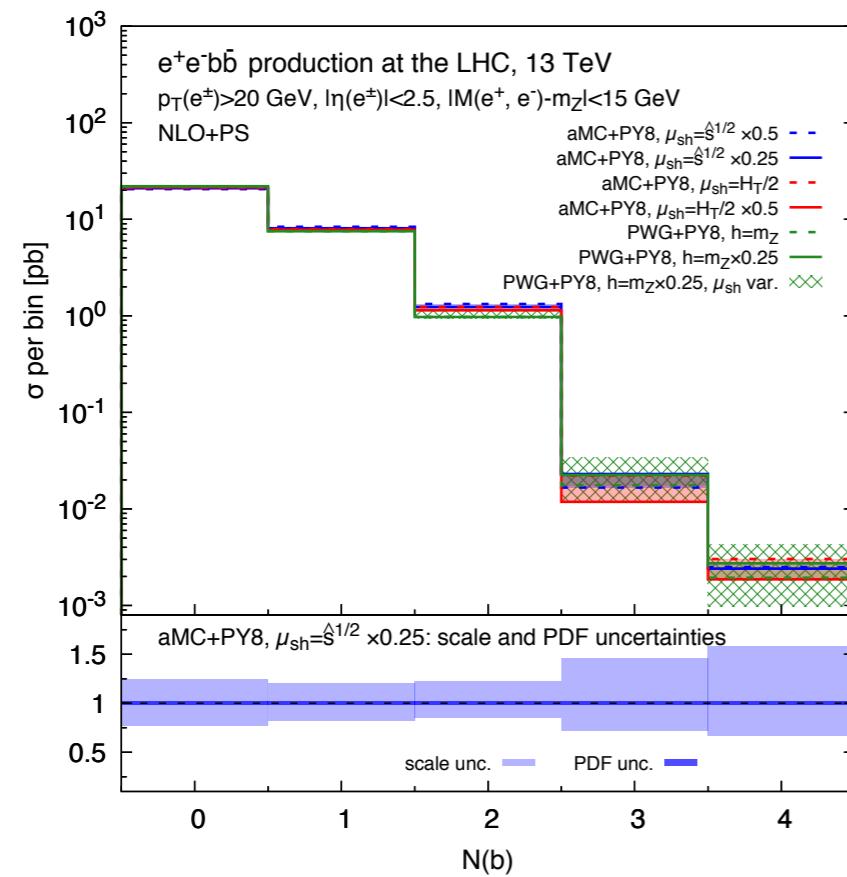
POWHEG with $h = (M_Z/4, M_Z)$ (shaded area uses a different Q_{sh} in remnant events)

2) renormalization/factorization scale variation (7 points) and PDF uncertainty bands

3) relative correction in comparison to fixed NLO predictions

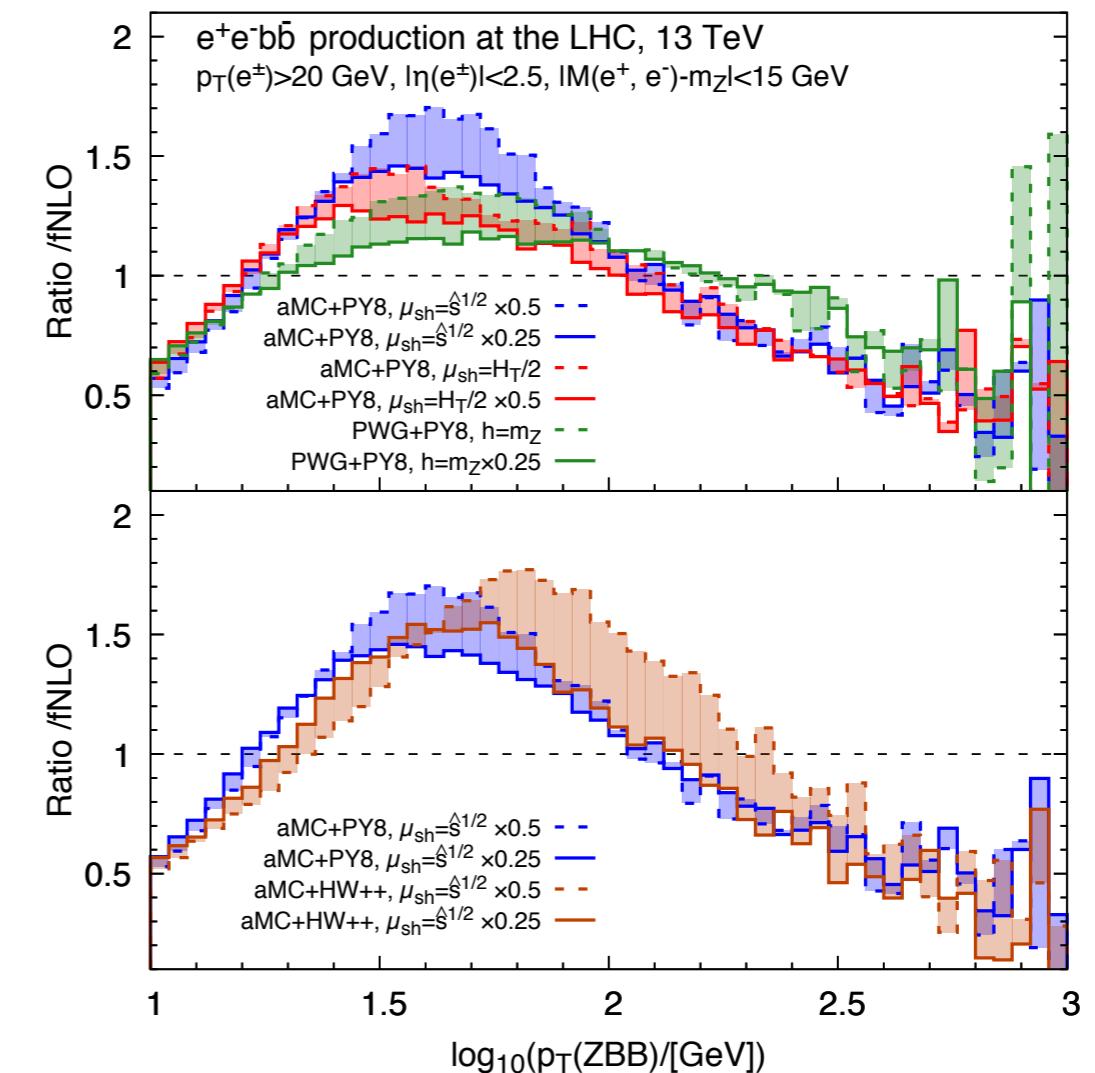
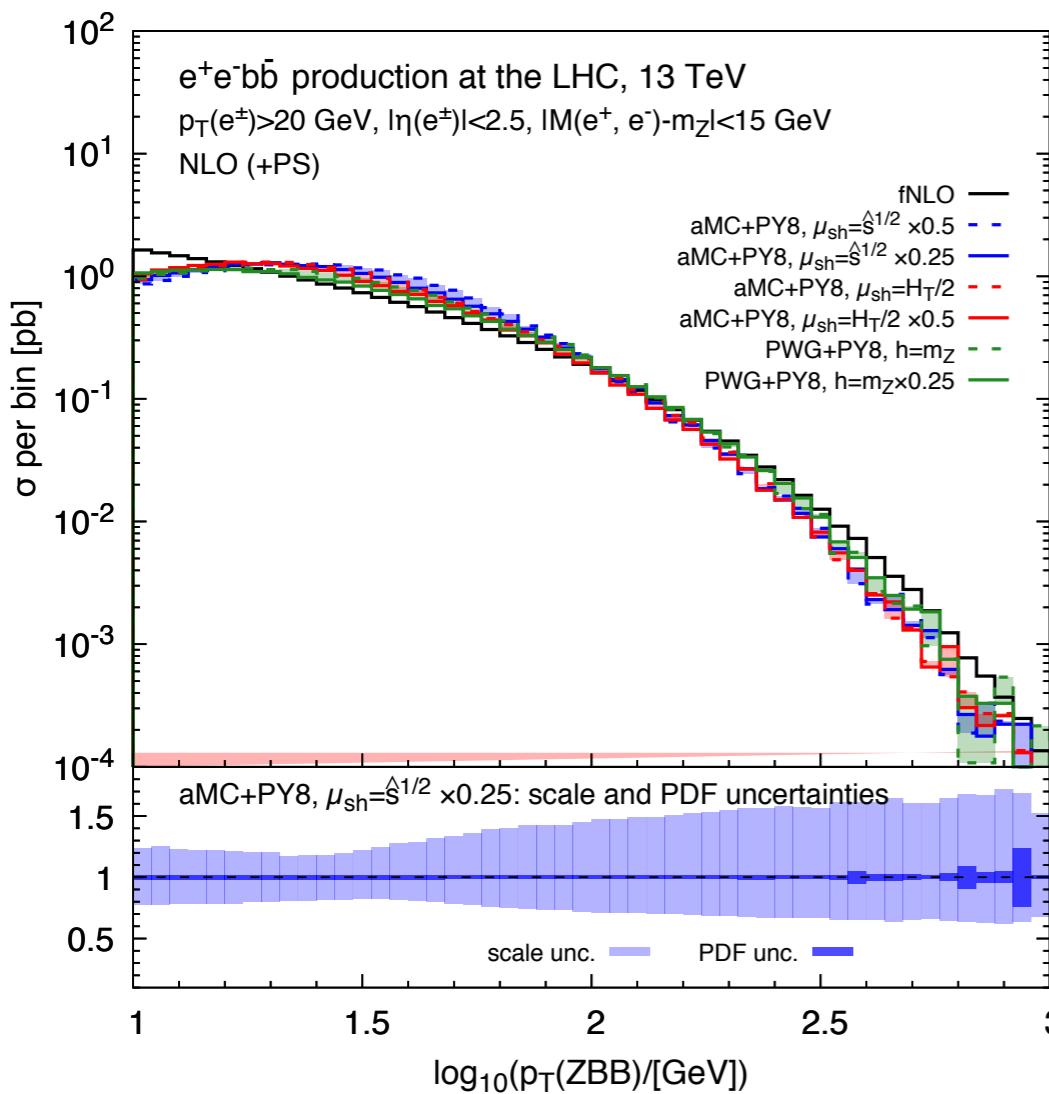
4) comparison of aMCNLO matched to Pythia 8.215 or to Herwig++ 2.7.1 w.r.t. fixed NLO

$e^+e^-b\bar{b}$: b-jet multiplicities



- a crucial quantity to understand the comparison between aMC@NLO and POWHEG at the exclusive level (classification w.r.t. the number of additional b-jets)
- the Parton Shower distorts the distribution of the final state $b\bar{b}$ pair (pushing in/out the acceptance) adds additional splittings $g \rightarrow b\bar{b}$, which may be successfully tagged as b-jets
- in POWHEG the PS reduces the number of tagged b-jets, sensitive to the Q_{sh} value
- in aMC@NLO there is a migration of events from the 1-b-jet to the 2-b-jets bin
- uncertainties from few to several % level
- higher multiplicities generated by the PS

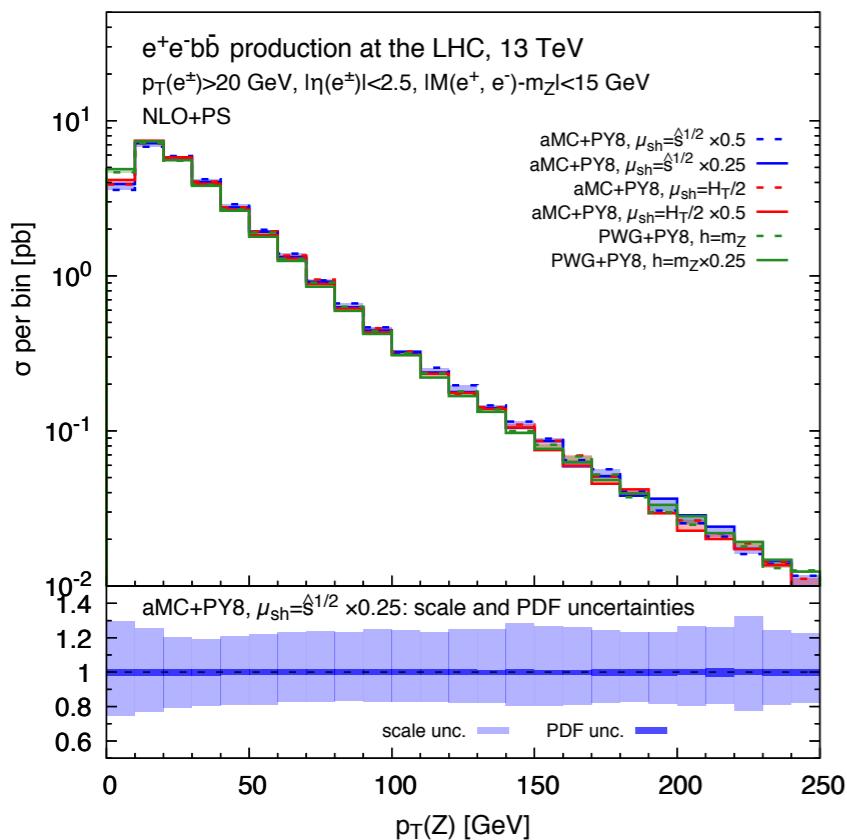
$e^+e^-b\bar{b}$: pt distribution of the e^+e^-BB final state



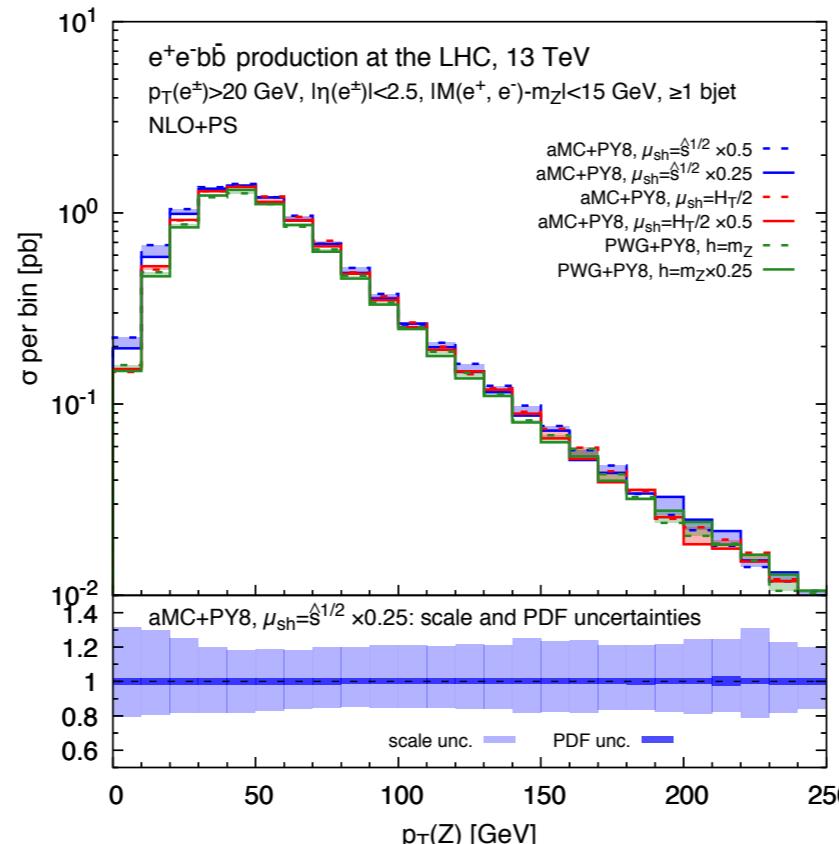
- a crucial quantity to understand the radiation patterns beyond NLO (defined in terms of b quarks)
- competition between initial and final state radiation
- the observed higher-order effects are common to all the codes, PS models, shower scale choices
- strong Sudakov suppression at low pt, strong enhancement at intermediate values
- strong shower-scale dependence at intermediate pt values

$e^+e^-b\bar{b}$: lepton-pair pt distribution in association with N b-jets

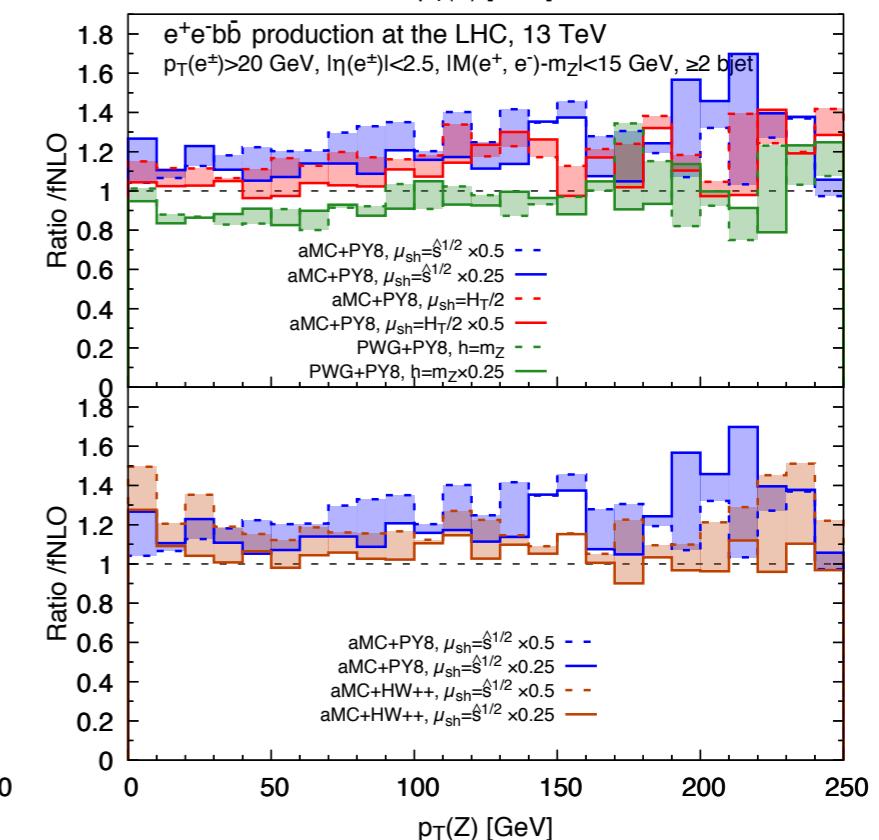
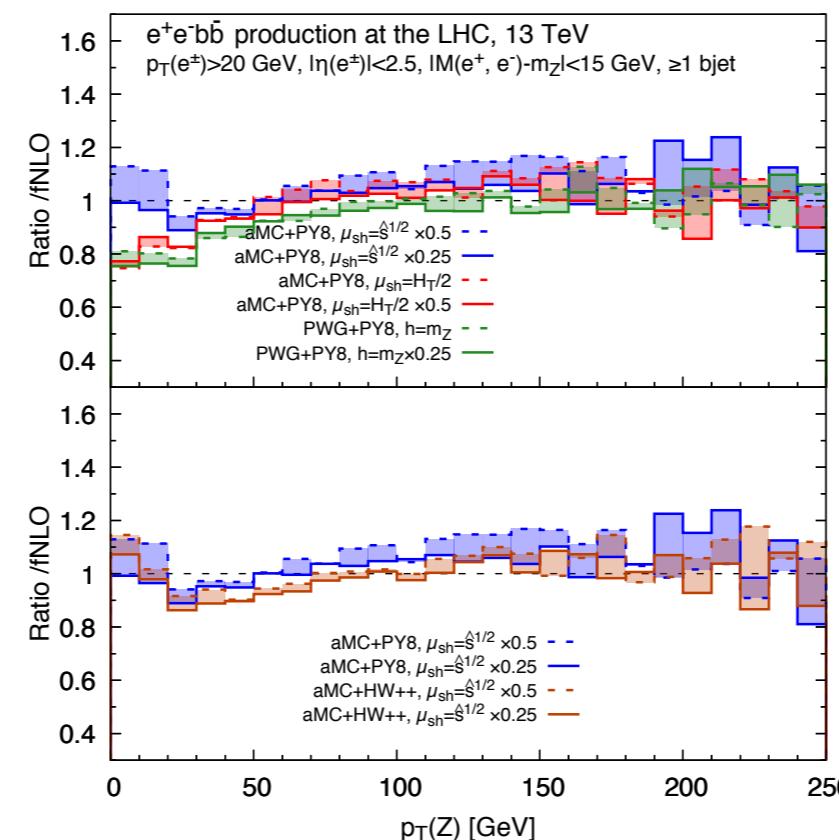
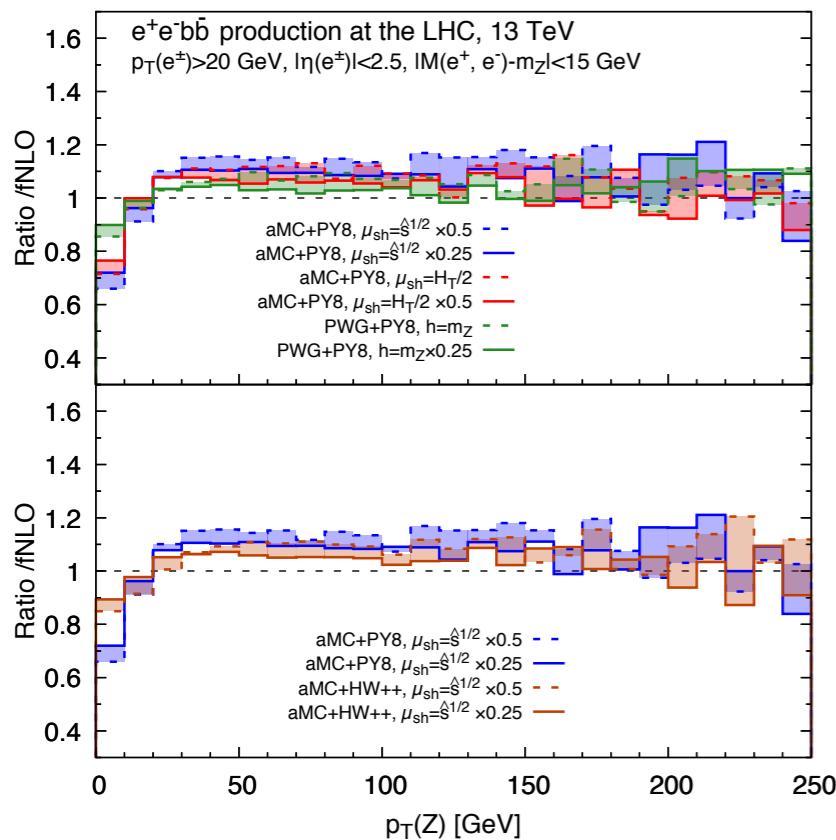
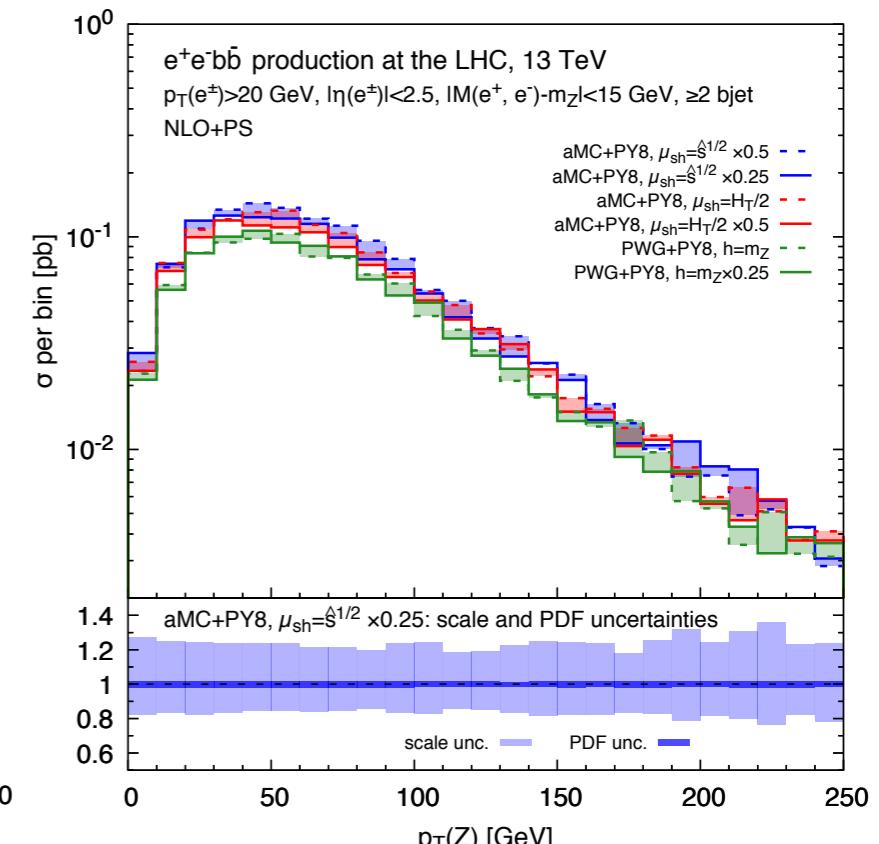
≥ 0 b-jets



≥ 1 b-jets

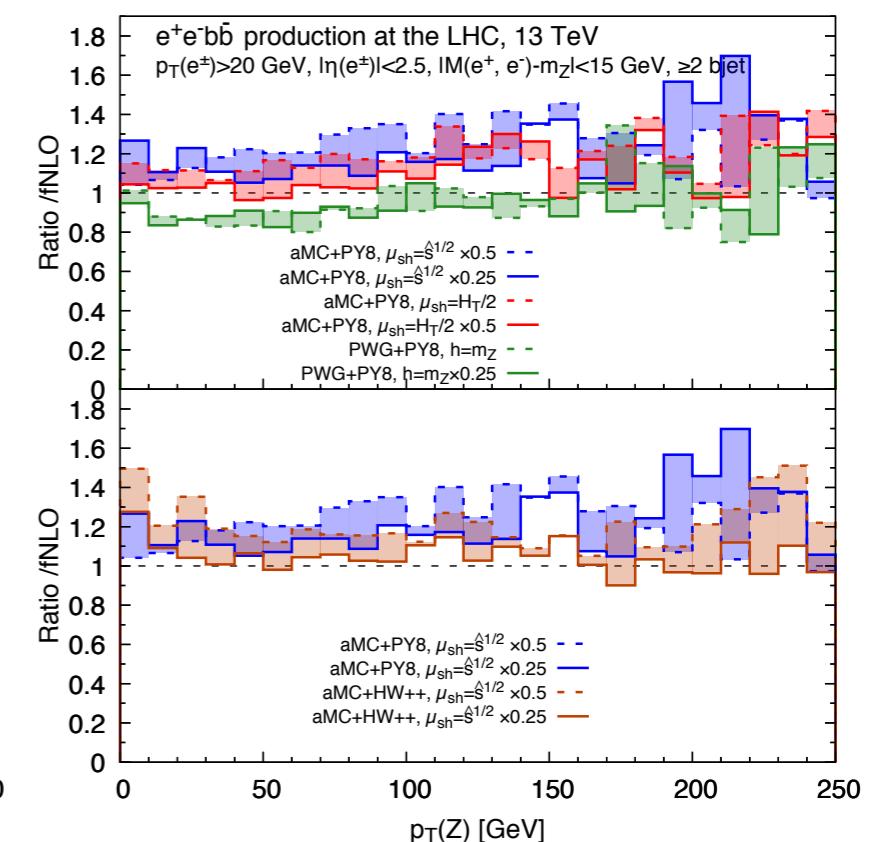
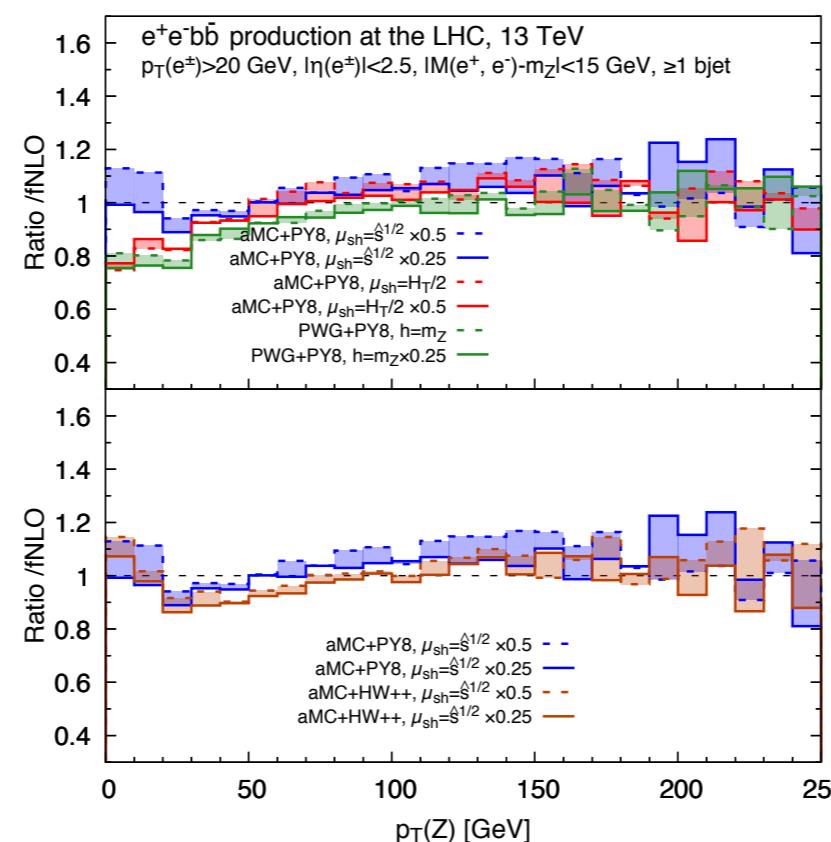
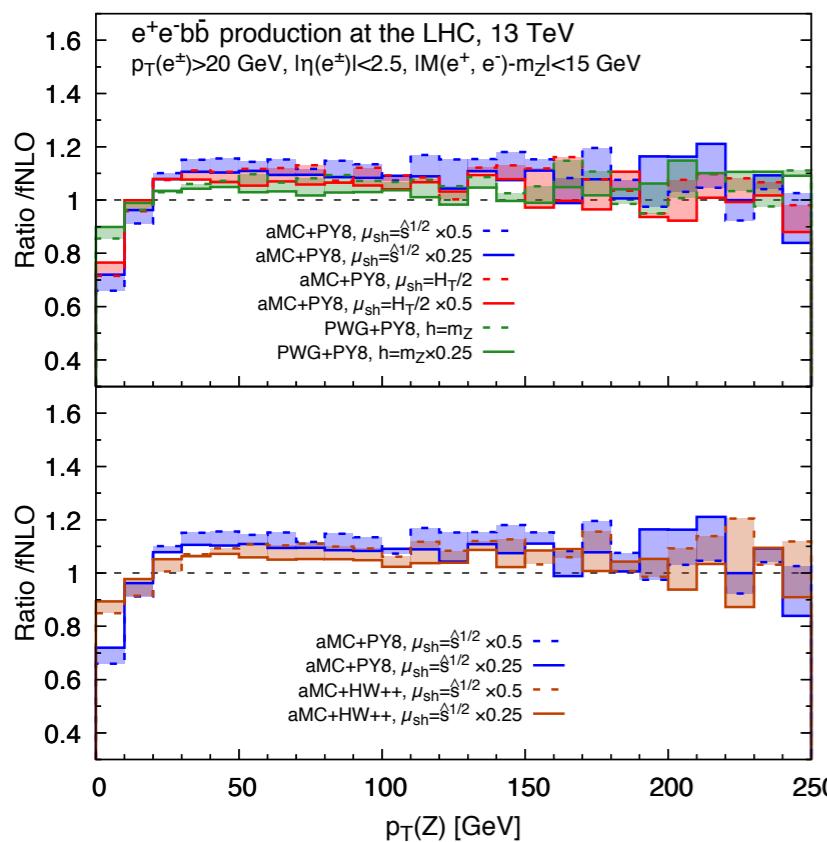


≥ 2 b-jets



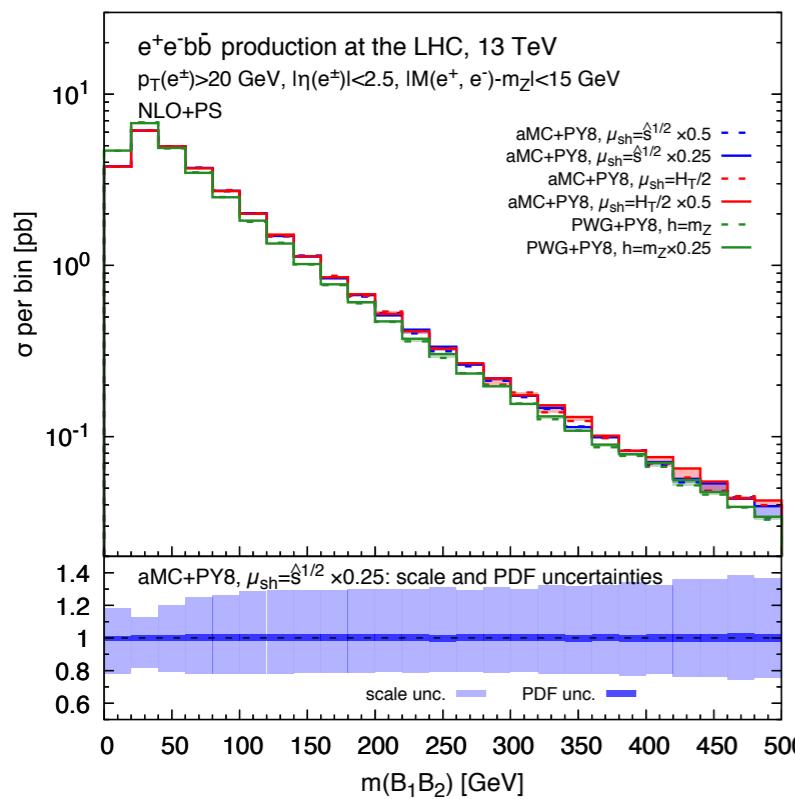
$e^+e^-b\bar{b}$: lepton-pair pt distribution in association with N b-jets

- scale + PDF uncertainties at the $\pm 20\%$ level, with dominant scale uncertainties
- each shower-scale choice has an $O(\pm 10\%)$ band, but the envelope of the bands spans a larger range
- with 2 tagged b-jets, the PS effects are flat over the whole $p_T Z$ range
- with 0 or 1 tagged b-jets, at low $p_T Z$ there are stronger differences between different matchings and different shower scale choices
- Pythia vs Herwig, with aMC@NLO and with the same shower scale are marginally compatible

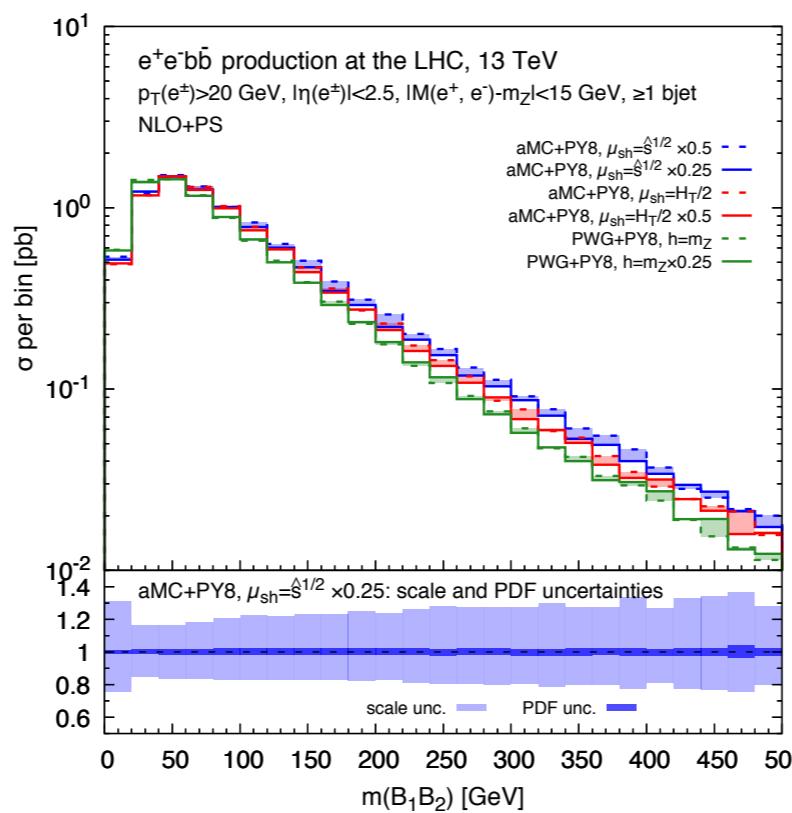


$e^+e^-b\bar{b}$: B-pair invariant mass distribution in association with N b-jets

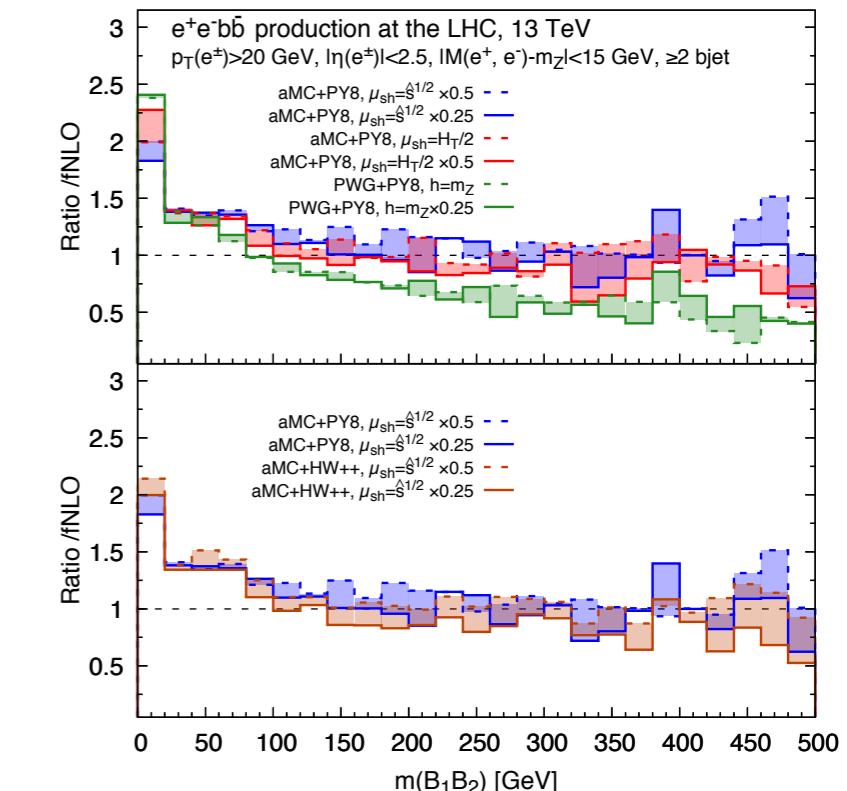
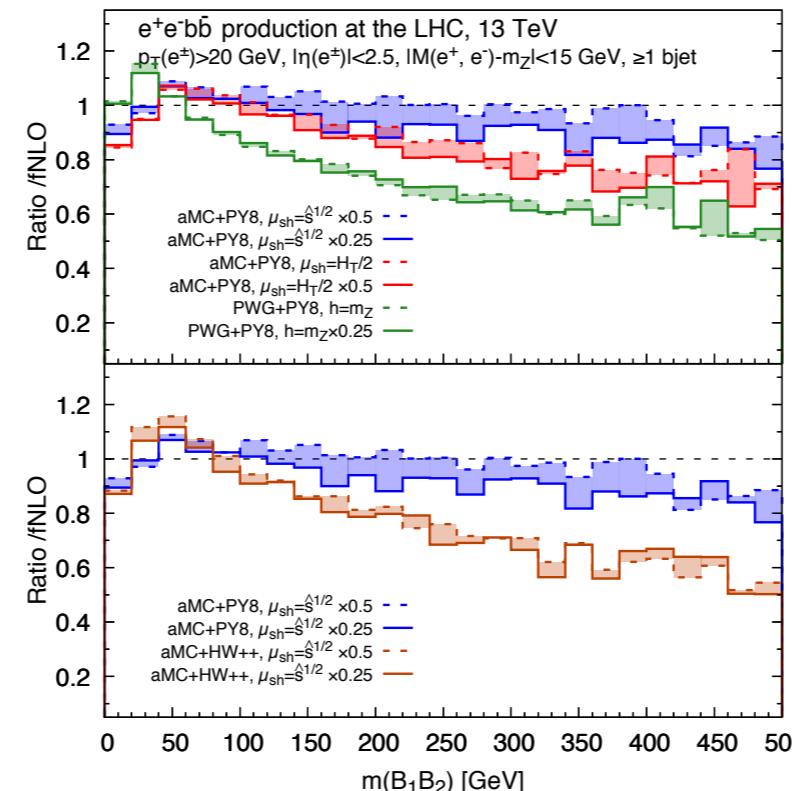
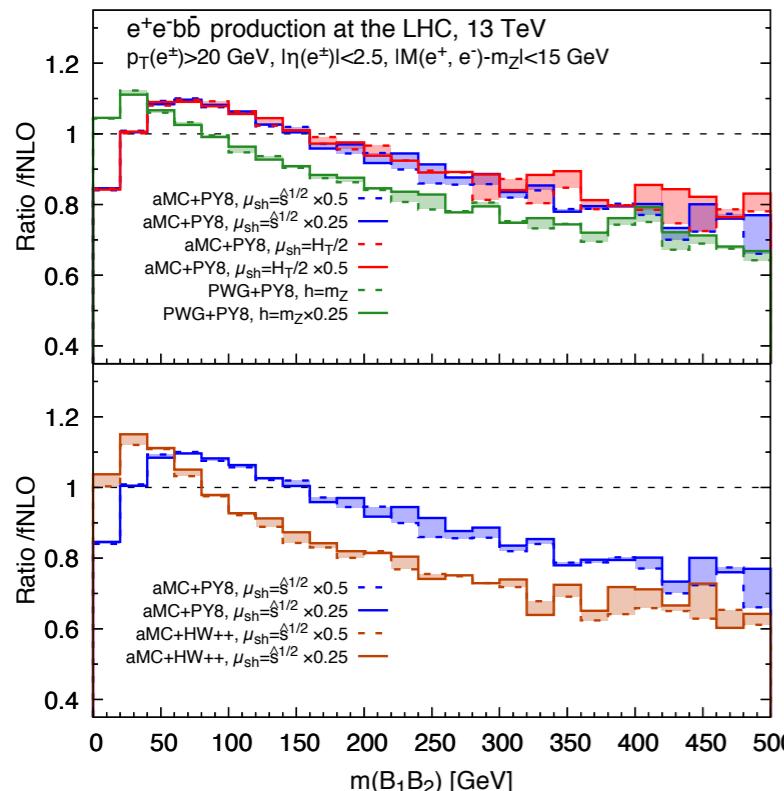
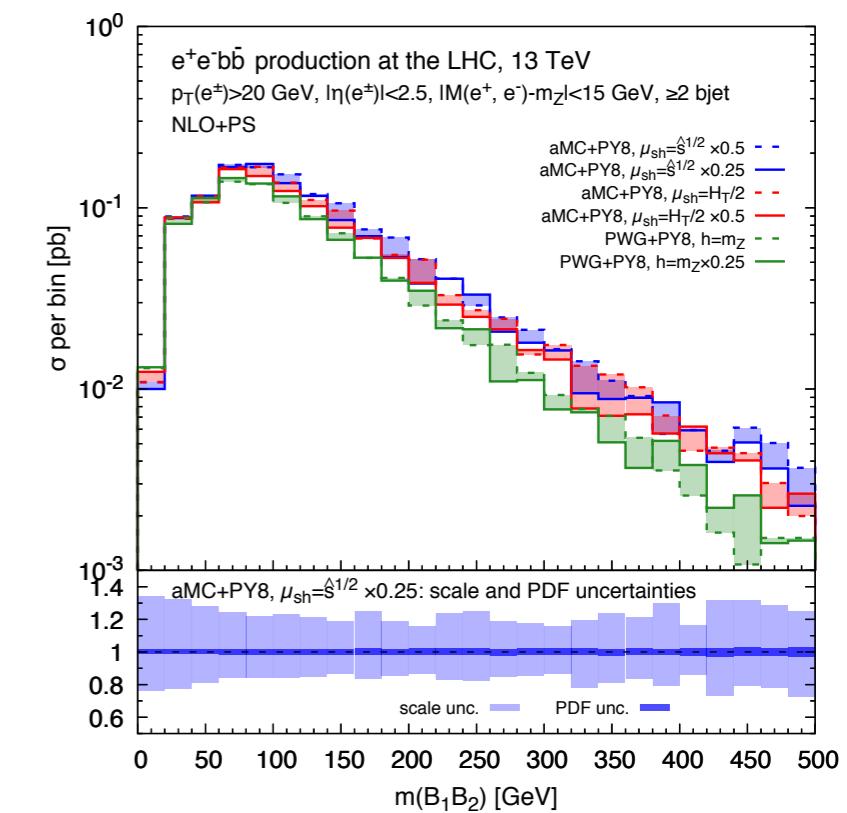
≥ 0 b-jets



≥ 1 b-jets

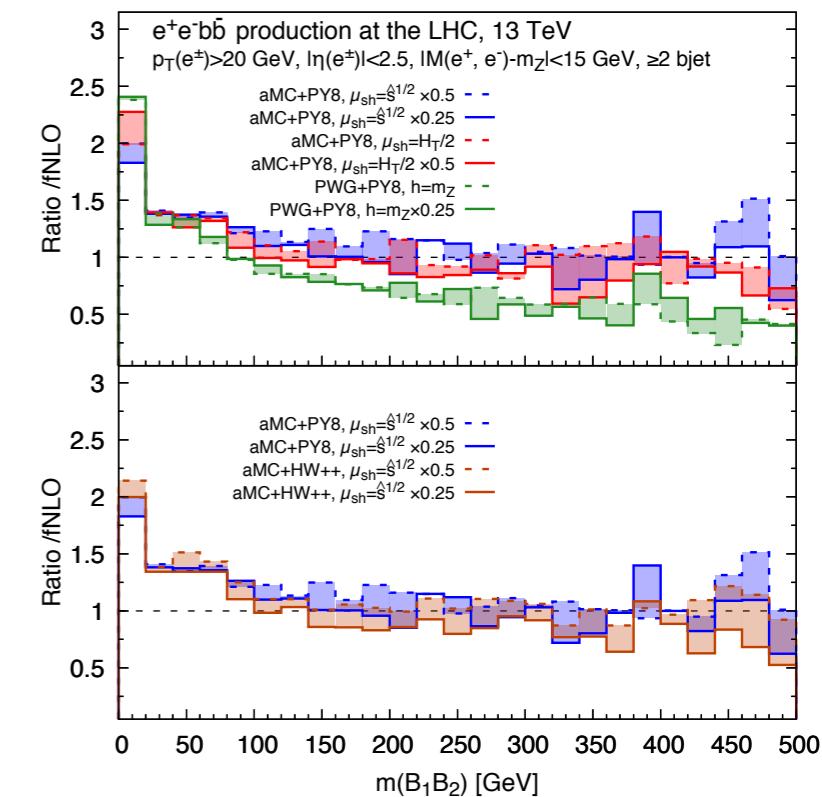
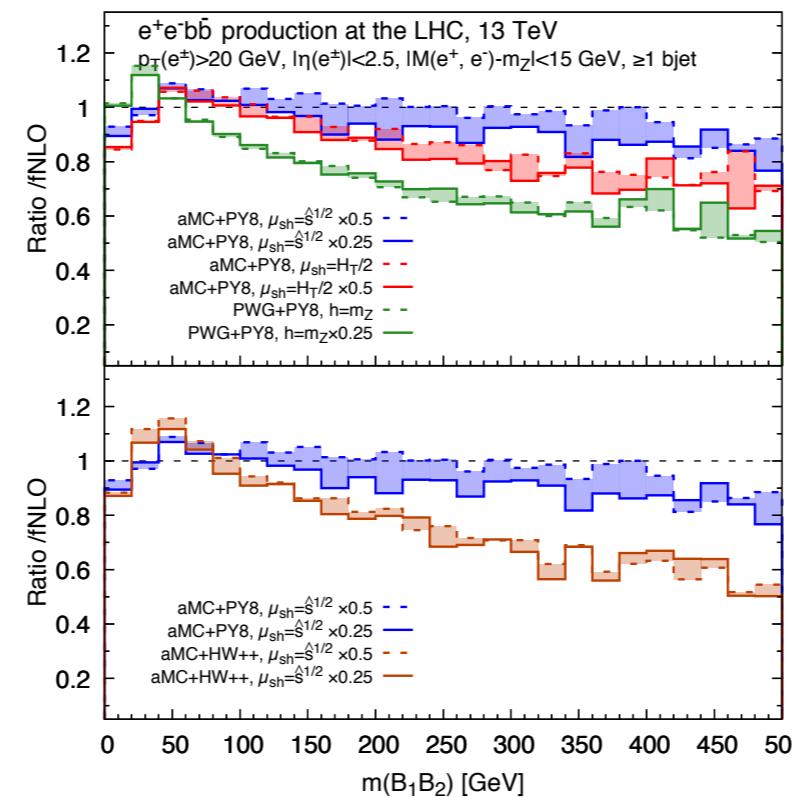
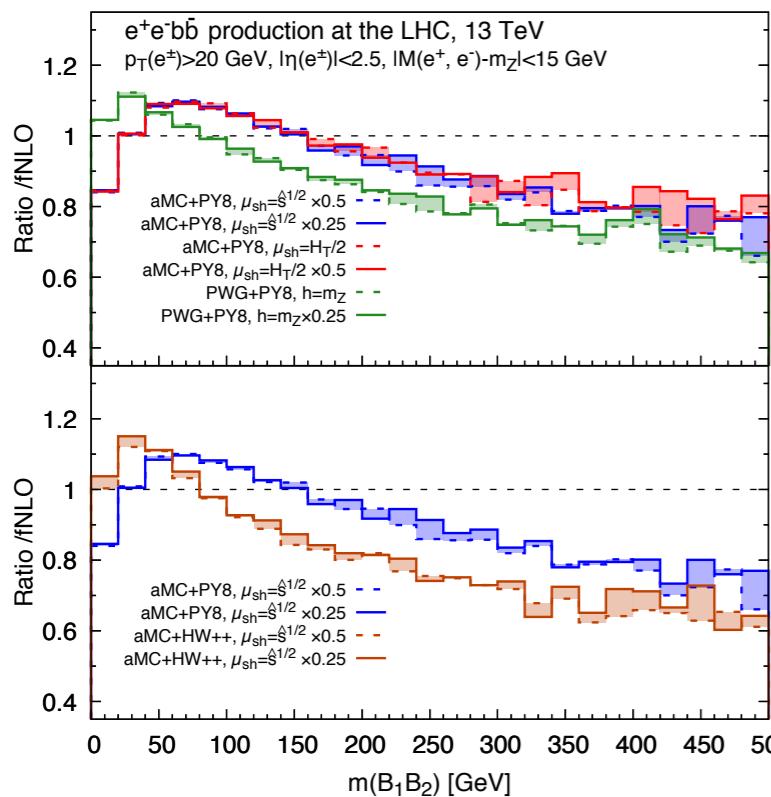


≥ 2 b-jets



$e^+e^-b\bar{b}$: B-pair invariant mass distribution in association with N b-jets

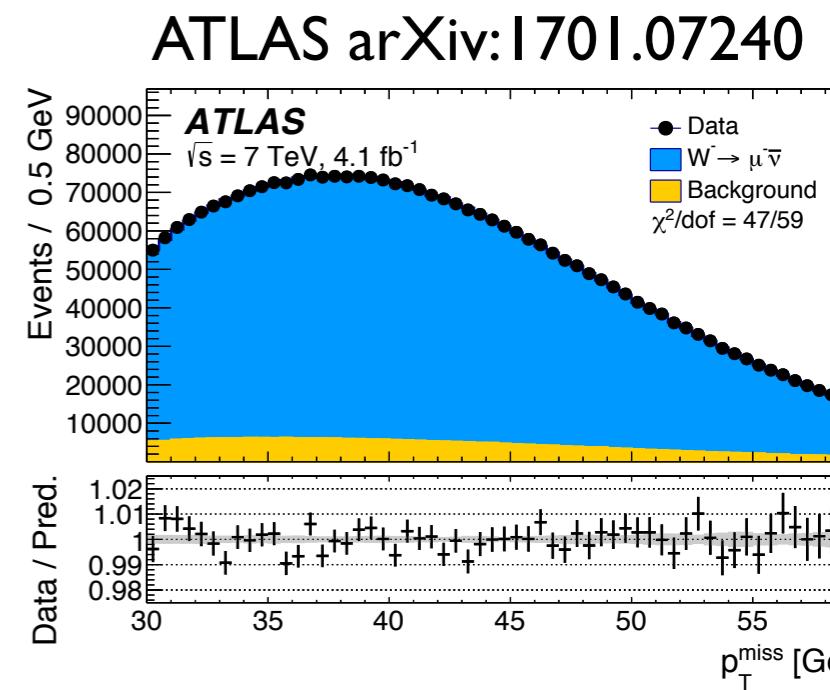
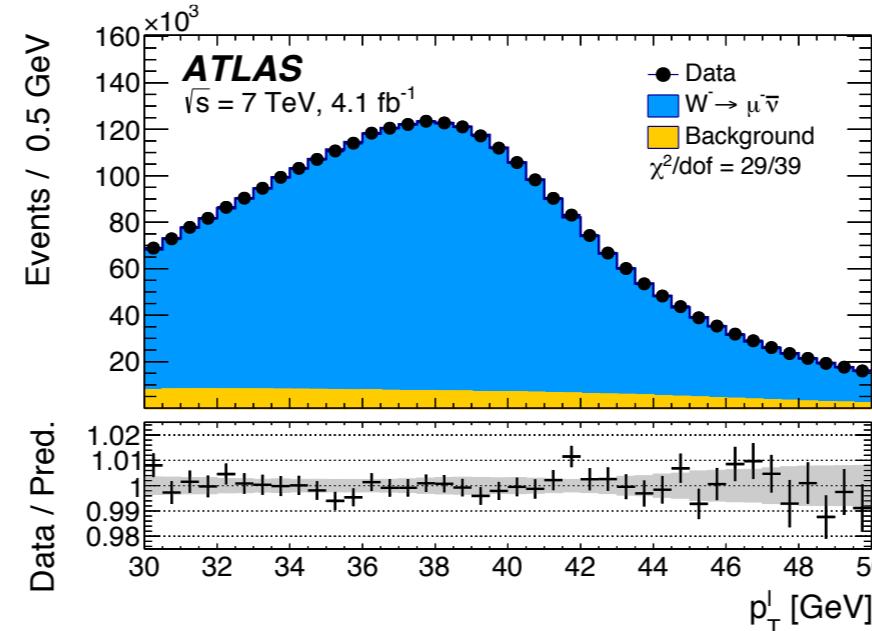
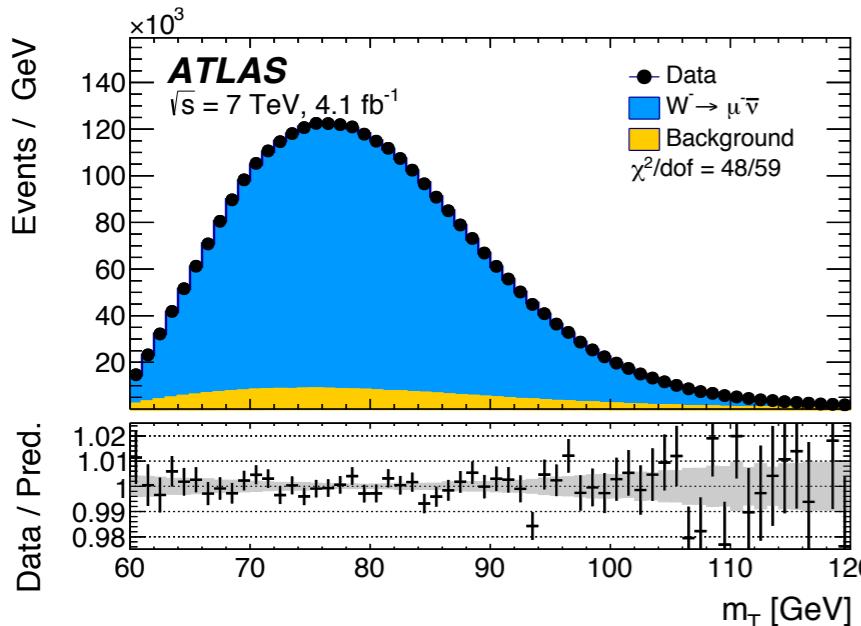
- scale + PDF uncertainties at the ($\pm 15\% - \pm 25\%$) level, with dominant scale uncertainties
- each shower-scale choice has an uncertainty band up to $O(\pm 10\%)$,
- POWHEG +Pythia is accidentally (?) similar to aMC@NLO+Herwig++
- very strong sensitivity to the QCD-PS model
- with 2 tagged b-jets, large correction at low mass, due to additional $g \rightarrow b\bar{b}$ splittings via the shower
- with 0 tagged b-jets, aMC@NLO hasn't got sensitivity to the shower scale variable
- with 1 tagged b-jets, the 3 predictions span a quite broad range of values
- all these effects are due to terms beyond NLO-QCD



The inclusive $p_T Z$ distribution and the MW determination

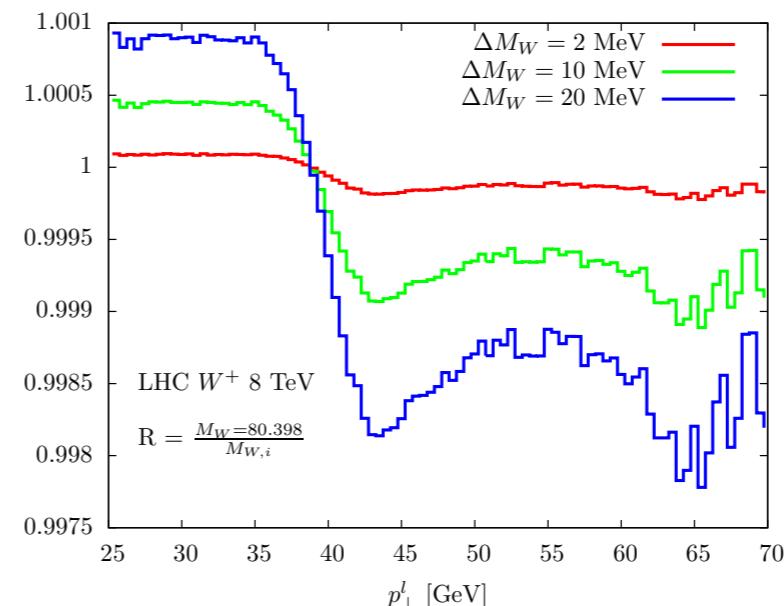
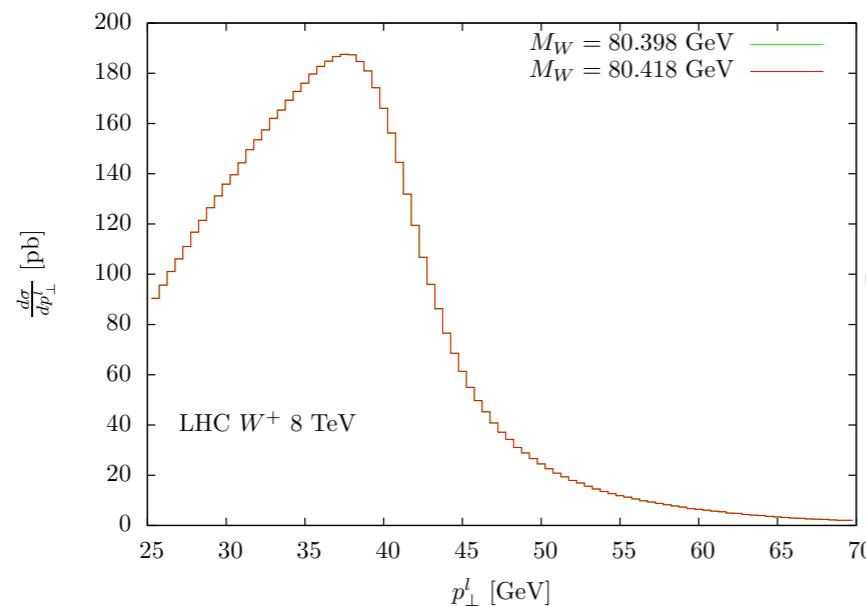
MW determination at hadron colliders: observables and techniques

MW extracted from the study of the **shape** of the MT, pt_lep, ET_miss distributions in CC-DY thanks to the **jacobian peak** that enhances the sensitivity to MW



Challenging shape measurement:

a distortion at the **few per mil** level of the distributions yields a shift of $O(10 \text{ MeV})$ of the MW value



- Are all the relevant (i.e. that distort the shapes) radiative corrections under control?
- Is the interplay between NC-DY and CC-DY under control?

MW determination: proton PDFs and heavy quark role

ATLAS arXiv:1701.07240

$$m_W = 80369.5 \pm 6.8 \text{ MeV(stat.)} \pm 10.6 \text{ MeV(exp. syst.)} \pm 13.6 \text{ MeV(mod. syst.)}$$

$$= 80369.5 \pm 18.5 \text{ MeV},$$

The MW measurement is mostly limited by modelling systematics

QCD and PDF effects are two of the dominant systematic uncertainties

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bkg Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
$m_T, W^+, e\mu$	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
$m_T, W^-, e\mu$	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
$m_T, W^\pm, e\mu$	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
$p_T^e, W^+, e\mu$	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
$p_T^e, W^-, e\mu$	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
$p_T^e, W^\pm, e\mu$	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
p_T^e, W^+, 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^+, 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^e, 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^e, W^-, e	80359.4	12.9	0.0	15.1	3.9	8.5	8.4	4.9	13.4	27.6	8/5
m_T, p_T^e, W^\pm, e	80349.8	9.0	0.0	14.7	3.3	6.1	8.3	5.1	9.0	22.9	12/11
p_T^e, W^\pm, μ	80382.3	10.1	10.7	0.0	2.5	3.9	8.4	6.0	10.7	21.4	7/7
m_T, W^\pm, μ	80381.5	13.0	11.6	0.0	13.0	6.0	9.5	3.4	11.2	27.2	3/7
m_T, p_T^e, W^+, μ	80364.1	11.4	12.4	0.0	4.0	4.7	8.8	5.4	17.6	27.2	5/7
m_T, p_T^e, W^-, μ	80398.6	12.0	13.0	0.0	4.1	5.7	8.4	5.3	16.8	27.4	3/7
m_T, p_T^e, W^\pm, μ	80382.0	8.6	10.7	0.0	3.7	4.3	8.6	5.4	10.9	21.0	10/15
$m_T, p_T^e, W^\pm, e\mu$	80352.7	8.9	6.6	8.2	3.1	5.5	8.4	5.4	14.6	23.4	7/13
$m_T, p_T^e, W^\pm, e\mu$	80383.6	9.7	7.2	7.8	3.3	6.6	8.3	5.3	13.6	23.4	15/13
$m_T, p_T^e, W^\pm, e\mu$	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

CC-DY and NC-DY differ by the initial state flavour structure, e.g. in the heavy quark contribution

CC-DY: $u \bar{d}, c \bar{s}, \dots \rightarrow W^+ \rightarrow l^+ \nu$

NC-DY: $u \bar{u}, d \bar{d}, c \bar{c}, s \bar{s}, b \bar{b}, \dots \rightarrow \gamma^*/Z \rightarrow l^+ l^-$

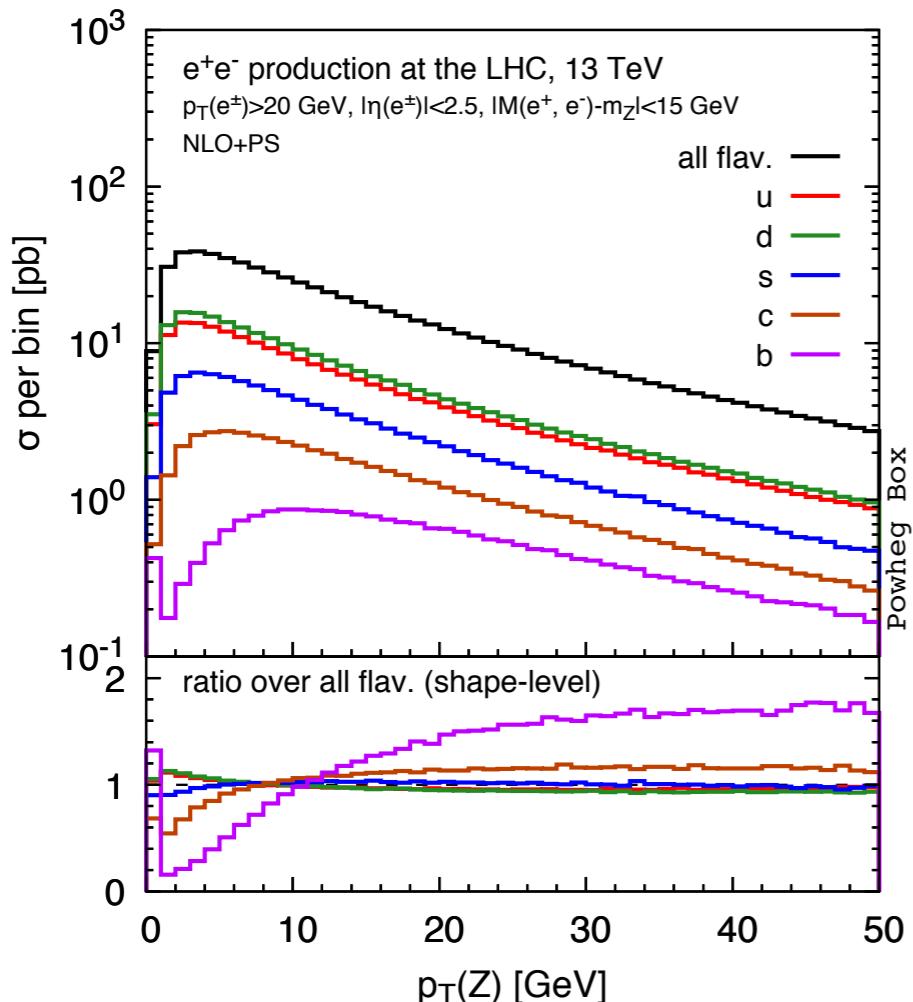
The calibration of Monte Carlo tools based on NC-DY embeds a bottom-quark contribution.
Are these bottom effects universal / relevant for CC-DY / accurately described ?

Does an improved perturbative description of the bottom quark contributions

- modify the NC-DY observables?
- have an impact on the Monte Carlo Parton Shower calibration ?
- modify the MW determination?

Bottom quark contributions to the ptZ distribution in the 5FS

- in the 5FS the bottom quark is treated as a massless parton
- the bottom density in the proton resums via DGLAP eqs large collinear logs
- the masslessness of the bottom may affect some kinematical distributions where the quark mass acts as a natural regulator of the transverse d.o.f.
e.g. the ptZ distribution with $\text{ptZ} \sim \mathcal{O}(\text{mb}) \sim \mathcal{O}(5 - 20 \text{ GeV})$



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

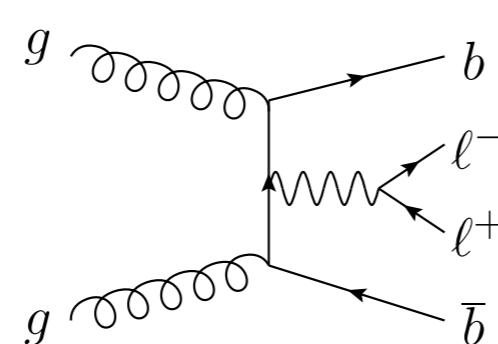
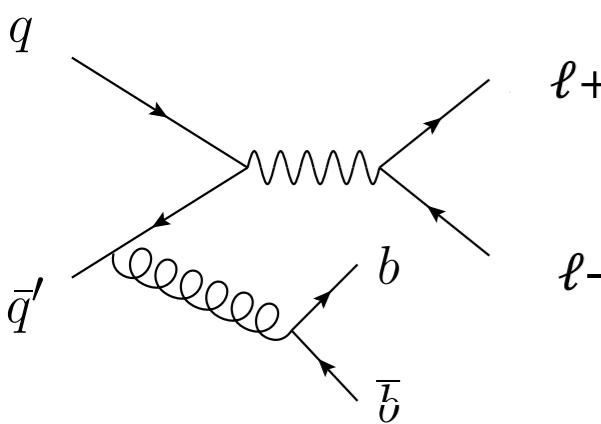
- given the exp error below 0.5% in a large range
the bottom contribution of $\mathcal{O}(4\%)$
→ we need a prediction of the *b* contribution
with a precision at the $\mathcal{O}(10\%)$ level

- the PDF evolution starts for the heavy quarks
at $Q \sim m_q$

- in the 5FS the bottom contrib. to the ptZ spectrum
is harder than the one of light quarks

→ in the 5FS the bottom effects for $\text{ptZ} < \text{mb}$
are handled by the Parton Shower

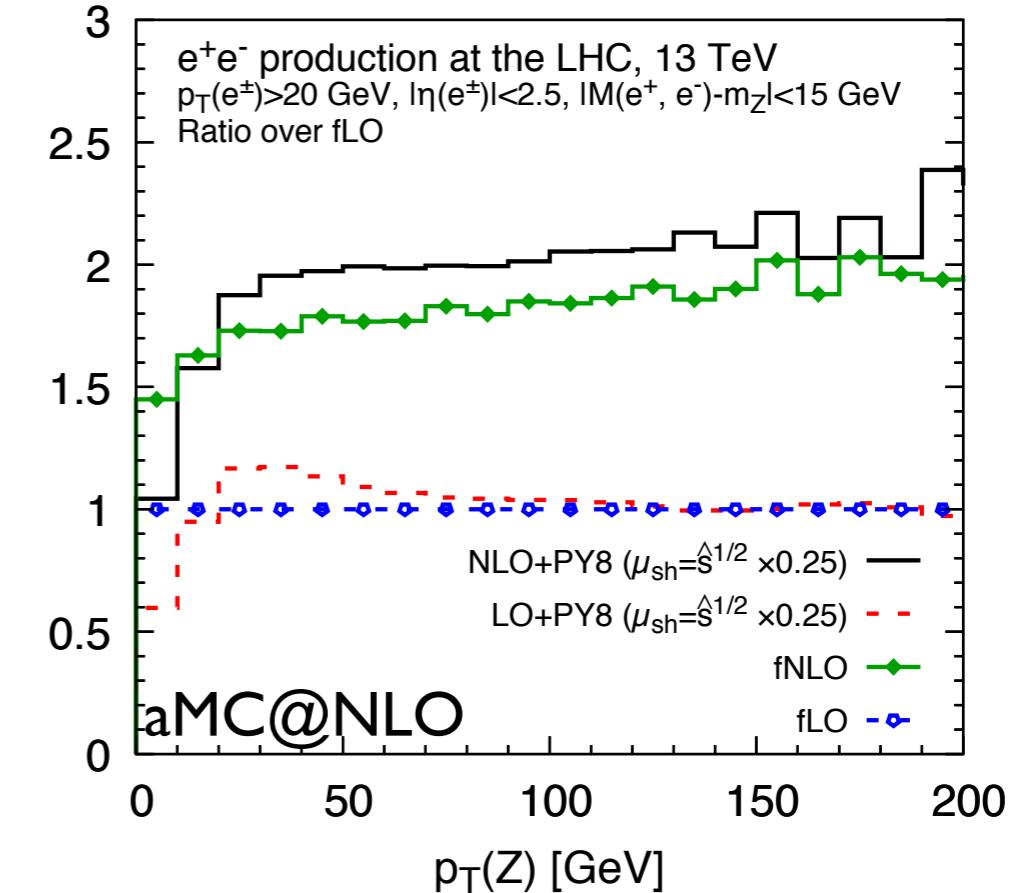
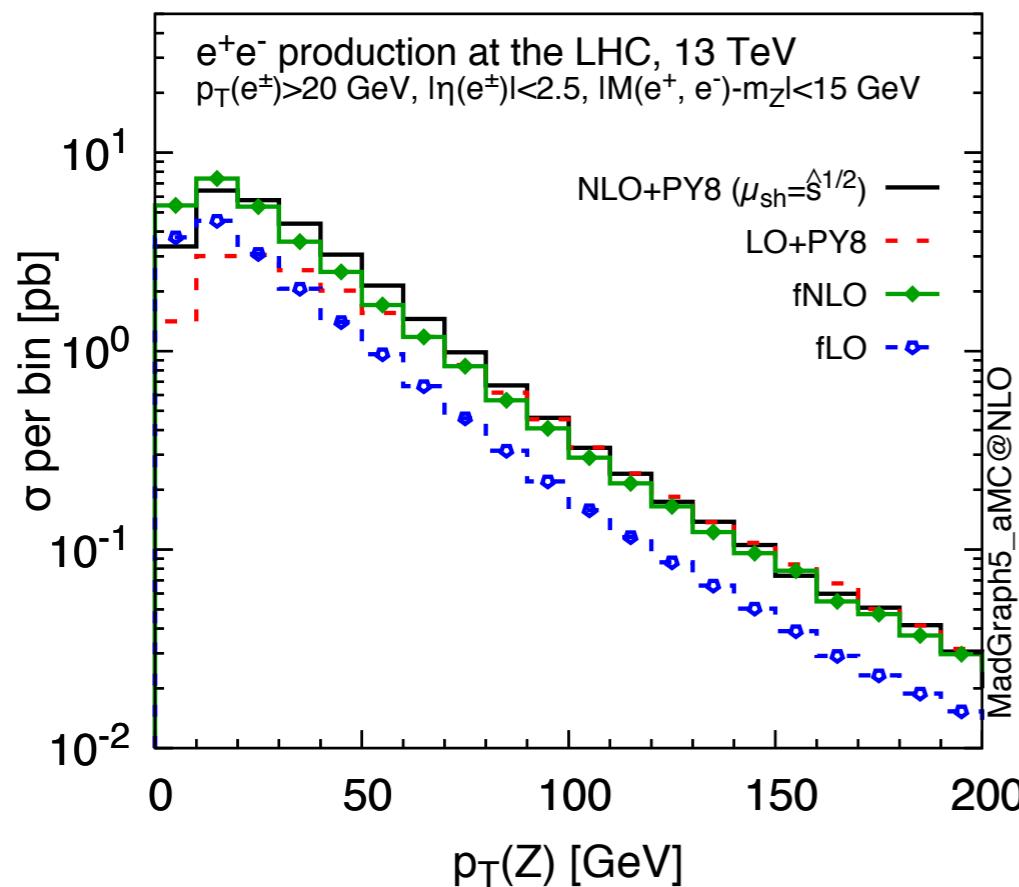
$e^+e^-b\bar{b}$: ptZ distribution in the 4FS



in the 4FS the bottom quark

- is absent in the proton
- it can be produced in the final state as a massive particle
→ improved description of the kinematical distributions
- the collinear logs are included only at fixed order

ptZ distribution ($e^+e^-b\bar{b}$ final state integrated over b quarks)



- regular when $ptZ \rightarrow 0$, but still sensitive to large log effects
- the process has a large NLO K-factor
- large multiple gluon emission effects via QCD Parton Shower, for $ptZ < 50$ GeV

ptZ distribution with b-quark mass effects: combining 4FS and 5FS

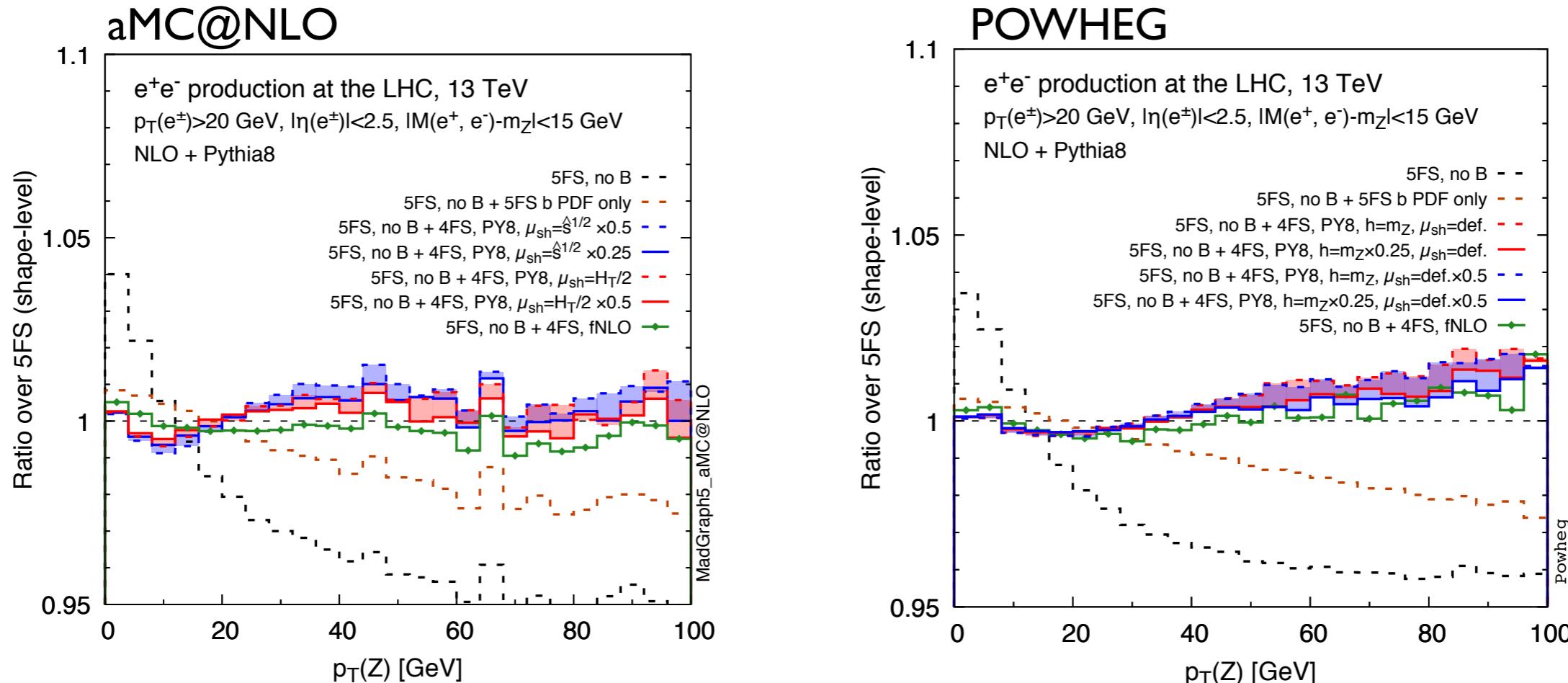
- the prediction of the ptZ distribution, inclusive over radiation, is split into two contributions **with** and **without** B hadrons in the final state
 - the contribution **with** B hadrons is computed in the 4FS
(exact massive kinematics +NLOPS accuracy)
by definition the process $p\bar{p} \rightarrow e^+ e^- b \bar{b}$ contains bottom quarks in the final state
additional b bbar pairs may be produced by gluon splitting
 - the contribution **without** B hadrons is computed in the 5FS (massless b, NLOPS accuracy)
imposing a veto on the presence of B hadrons in the event analysis
in the 5FS B hadrons are generated by the QCD PS with two mechanisms:
 - presence of a bottom quark in the initial state (b bbar and bg initiated subprocesses)
 - gluon splitting into b bbar
 - our description including bottom mass effects combines the two samples

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

Improved prediction of the ptZ distribution

$$\mathcal{R}(p_{\perp}^{\ell^+\ell^-}) = \left(\frac{1}{\sigma_{\text{fid}}^{\text{mass}}} \frac{d\sigma^{\text{mass}}}{dp_{\perp}^{\ell^+\ell^-}} \Big|_{\text{tunex}} \right) \cdot \left(\frac{1}{\sigma_{\text{fid}}^{\text{5FS}}} \frac{d\sigma^{\text{5FS}}}{dp_{\perp}^{\ell^+\ell^-}} \Big|_{\text{tunex}} \right)^{-1}$$

- \mathcal{R} expresses the distortion of the improved ptZ, with respect to the full plain 5FS prediction
- for a given B-veto distribution the 4FS part is added in different approximations of Shower scale (aMC@NLO) or damping factor scale (POWHEG)
- \mathcal{R} is computed for a given PS tune



- distortion with a non trivial shape for $p_T Z < 50$ GeV
- in aMC@NLO effects at the $\pm 1\%$ level, in POWHEG effects at the $\pm 0.5\%$ level

Impact on CC-DY of the improvements in the ptZ description

Impact on CC-DY of the improvements in the ptZ description

Assumptions:

- it is possible in the 5FS to tune the QCD-PS to perfectly reproduce the experimental data (tune1)
- it is possible also in the improved approximation to tune the QCD-PS to perfectly reproduce the experimental data (tune2)

$$\frac{1}{\sigma_{\text{fid}}^{\text{exp}}} \frac{d\sigma^{\text{exp}}}{dp_{\perp}^{\ell^+\ell^-}} = \frac{1}{\sigma_{\text{fid}}^{\text{5FS}}} \frac{d\sigma^{\text{5FS}}}{dp_{\perp}^{\ell^+\ell^-}} \Big|_{\text{tune1}} = \frac{1}{\sigma_{\text{fid}}^{\text{mass}}} \frac{d\sigma^{\text{mass}}}{dp_{\perp}^{\ell^+\ell^-}} \Big|_{\text{tune2}} = \mathcal{R}(p_{\perp}^{\ell^+\ell^-}) \frac{1}{\sigma_{\text{fid}}^{\text{5FS}}} \frac{d\sigma^{\text{5FS}}}{dp_{\perp}^{\ell^+\ell^-}} \Big|_{\text{tune2}}$$

- $\mathcal{R}(p_{\perp})$ expresses the difference of the predictions obtained in the best partonic approximation convoluted respectively with tune1 and tune2

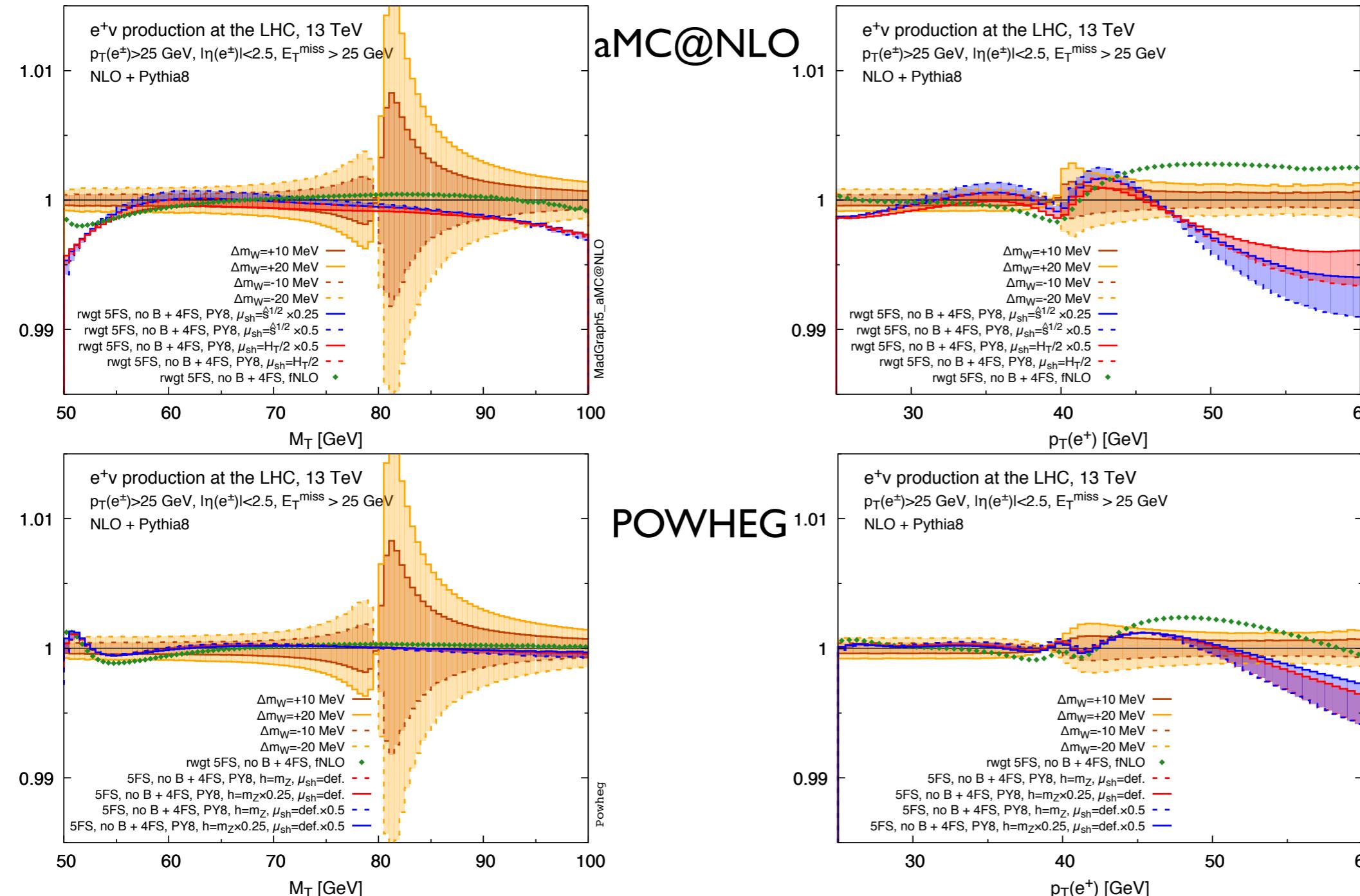
$$\frac{1}{\sigma_{\text{fid}}^{\text{5FS}}} \frac{d\sigma^{\text{5FS}}}{dp_{\perp}^{\ell^+\ell^-}} \Big|_{\text{tune2}} = \frac{1}{\mathcal{R}(p_{\perp}^{\ell^+\ell^-})} \frac{1}{\sigma_{\text{fid}}^{\text{5FS}}} \frac{d\sigma^{\text{5FS}}}{dp_{\perp}^{\ell^+\ell^-}} \Big|_{\text{tune1}}$$

- we use $\mathcal{R}(p_{\perp})$ to reweigh the CC-DY events according to their ptW value

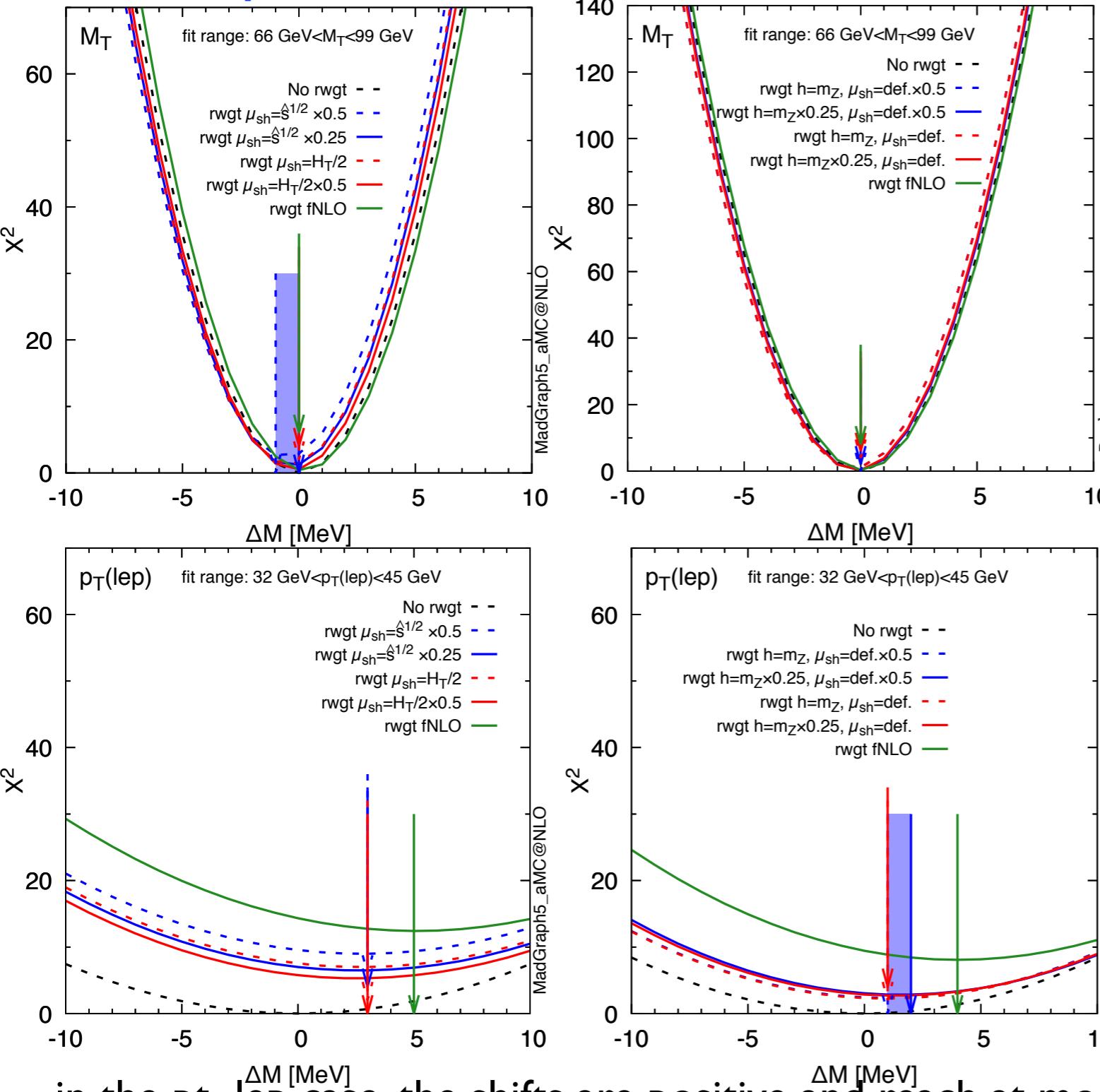
Impact on the CC-DY observables of b-quark effects

The CC-DY events are: i) evaluated in the plain 5FS with tune1
ii) reweighted by $1/\mathcal{R}(p_\perp)$ (tune1 \rightarrow tune2)

The impact on MW is estimated by template fit of the reweighted distributions (red/blue/green),
with templates evaluated in the plain 5FS (light brown)



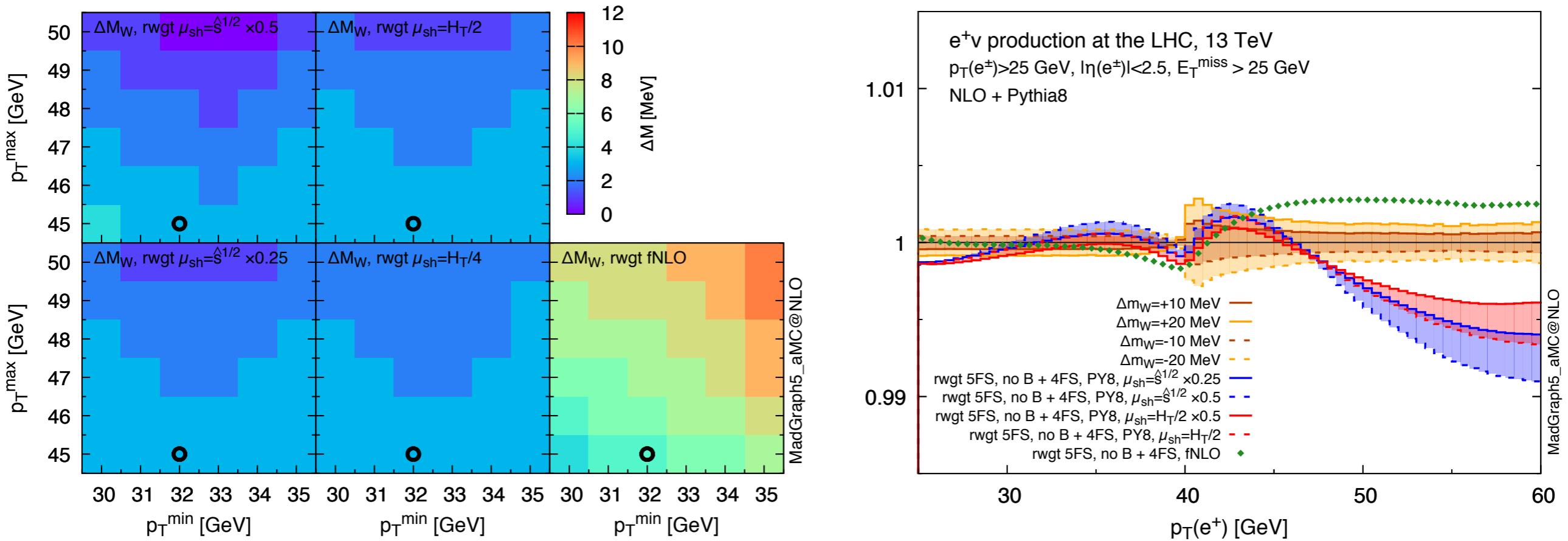
Bottom quark effects on the MW determination



- without reweighing the preferred value coincides with the input one MW_0 (sanity check)
- fit windows: pt_lep [32,45] GeV, MT [60,100] GeV

- in the pt_lep case, the shifts are positive and reach at most +5 MeV (fixed order NLO)
- matching NLO-QCD with QCD-PS reduces the size of the shift
- details of matching and of QCD-PS implementation yield an uncertainty of $O(1 \text{ MeV})$
- further improvements expected in the statistical quality of the fits

Dependence of the MW shifts on the fit window



- the outcome of the template fit depends on the fit window, especially on the upper limit
- above the jacobian peak, the NLOPS distortion changes slope at $p_{\text{tlep}} \sim 45 \text{ GeV}$, pulling the χ^2 in opposite directions in the intervals $[40,45]$ and $[45,50] \text{ GeV}$
- above the jacobian peak, the fixed order NLO becomes flat above $p_{\text{tlep}} \sim 47 \text{ GeV}$ stabilising the negative shift due to the interval $[40,47]$

Conclusions

- gauge boson production in association with heavy quarks has a non-trivial phenomenology for both exclusive and inclusive signatures
- a detailed discussion of the QCD effects and uncertainties is crucial:
 - matching NLO-QCD with QCD-PS has a sizeable impact on the distributions
 - matching and Parton Shower uncertainties are often under control but not negligible
- a combination of 5FS and 4FS results has been attempted to improve the description of the bottom quark contributions to the $p_T Z$ distribution with respect to the plain 5FS approach, with a shape distortion at the $O(1\%)$ level
- the information transfer from NC-DY to CC-DY has been estimated assuming that two perfect Parton Shower tunes are possible
 - qualitative statement about the MW sensitivity to b-quark effects, small ($\Delta MW < 5$ MeV) but visible
- precision physics at the LHC requires a strong collaboration between theorists and experimentalists to make precise quantitative statements

back-up slides

Setup of the simulations

- LHC $pp @ \sqrt{S} = 13 \text{ TeV}$.
- 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

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

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

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

Charged-current Drell-Yan

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

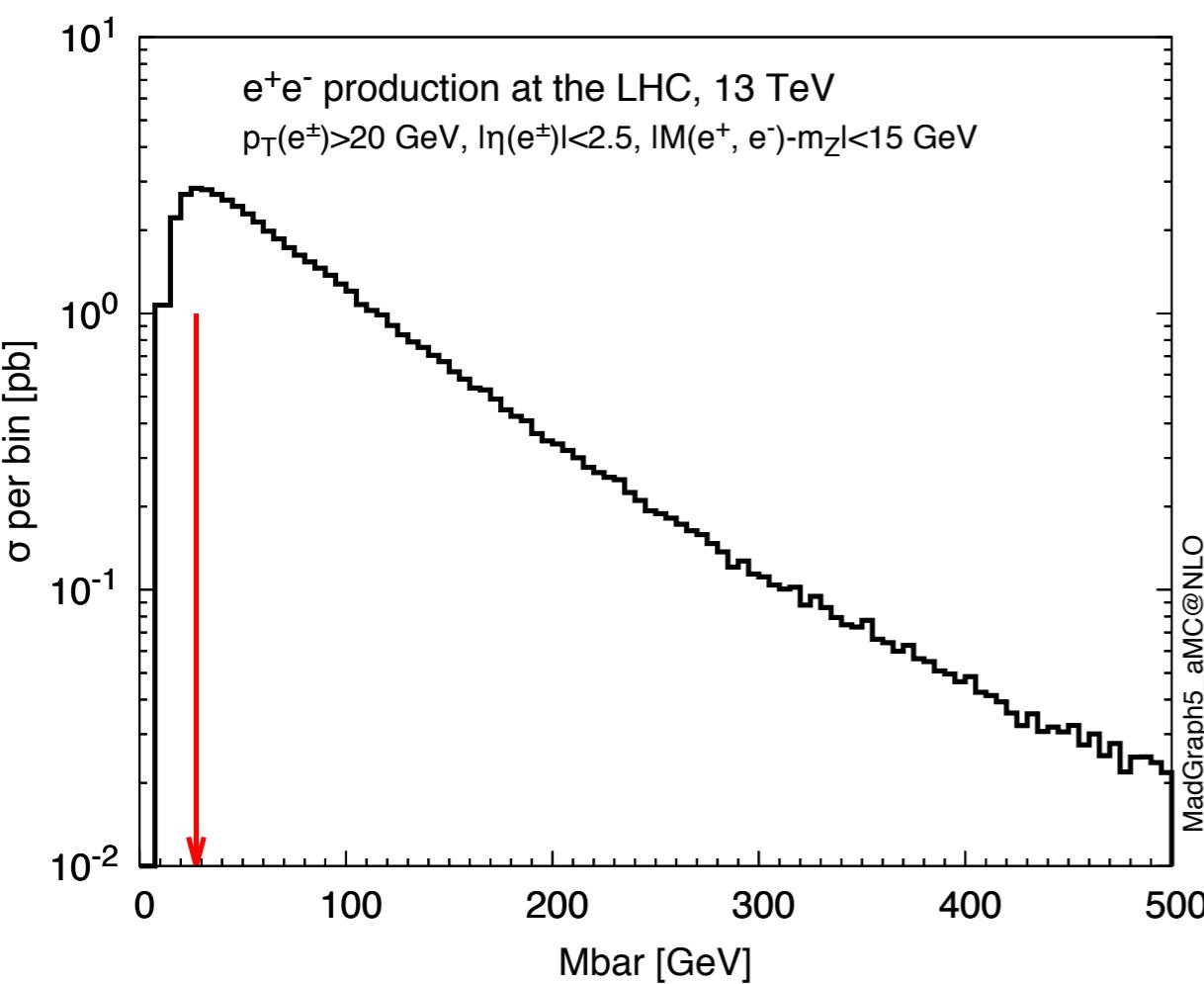
Estimate of the effective upper limit for additional radiation

Following Lim, Maltoni, Ridolfi, Ubiali, arXiv:1605.09411
we consider the factorisation of L from the partonic cross section
which is then reabsorbed in the proton PDFs

$$L = \log \left(\frac{M_{l^+l^-}^2}{m_b^2} \frac{(1 - z_i)^2}{z_i} \right) \quad \text{with} \quad z_i = \frac{M_{l^+l^-}^2}{s_i}, \quad s_i = (q_+ + q_- + k_i)^2$$

This leads to the introduction of an effective scale **Mbar**

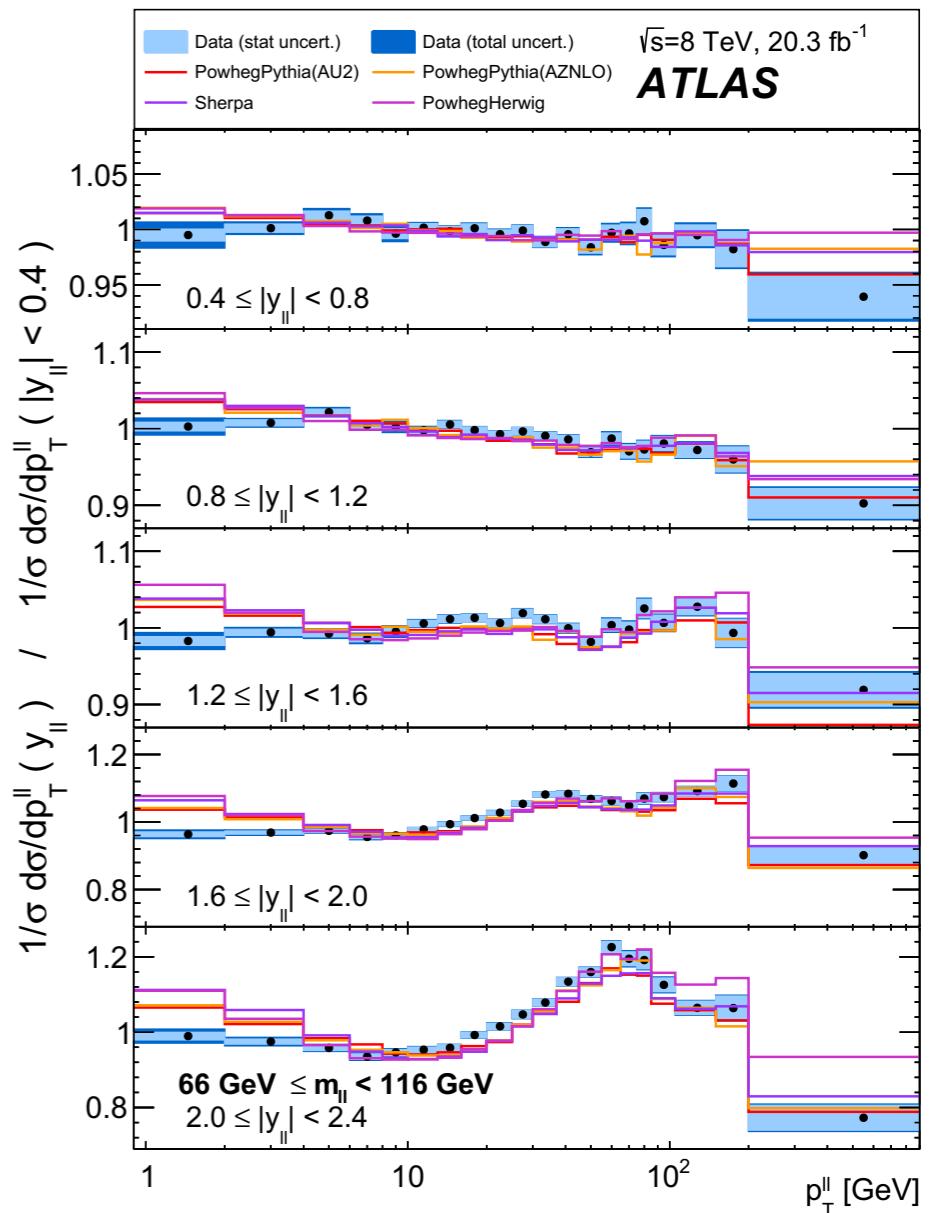
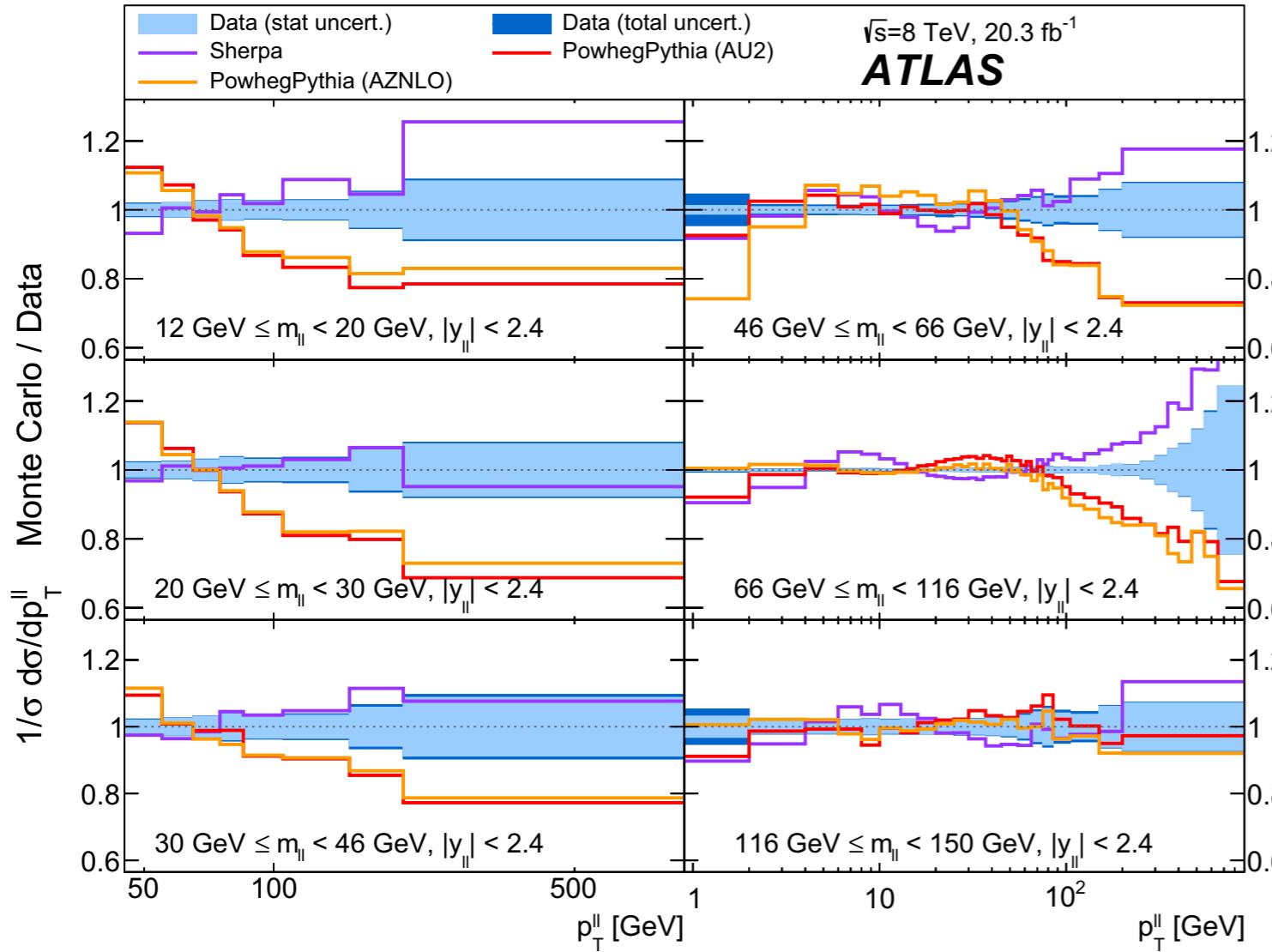
$$\overline{M} \equiv M_{l^+l^-} \frac{(1 - z_i)}{\sqrt{z_i}}.$$



the peak of $d\sigma/d\text{Mbar}$
hints the value of a typical energy scale
of the 4FS process

Challenges offered by the inclusive ptZ distribution

ATLAS arXiv:1512.02192

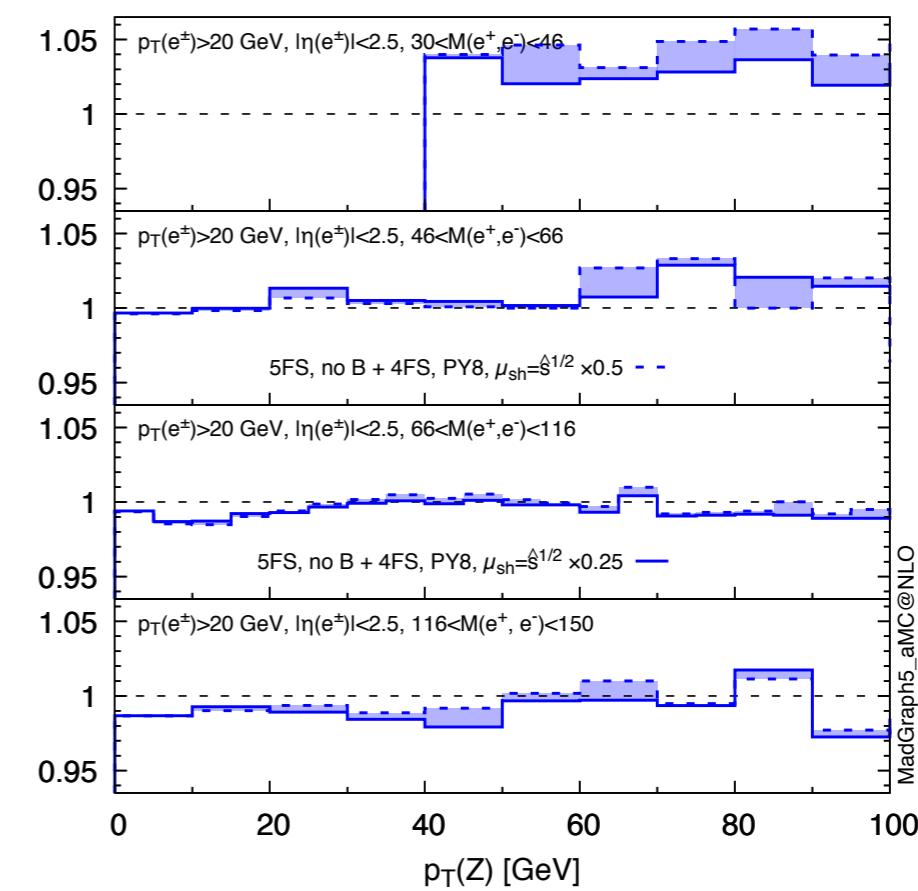
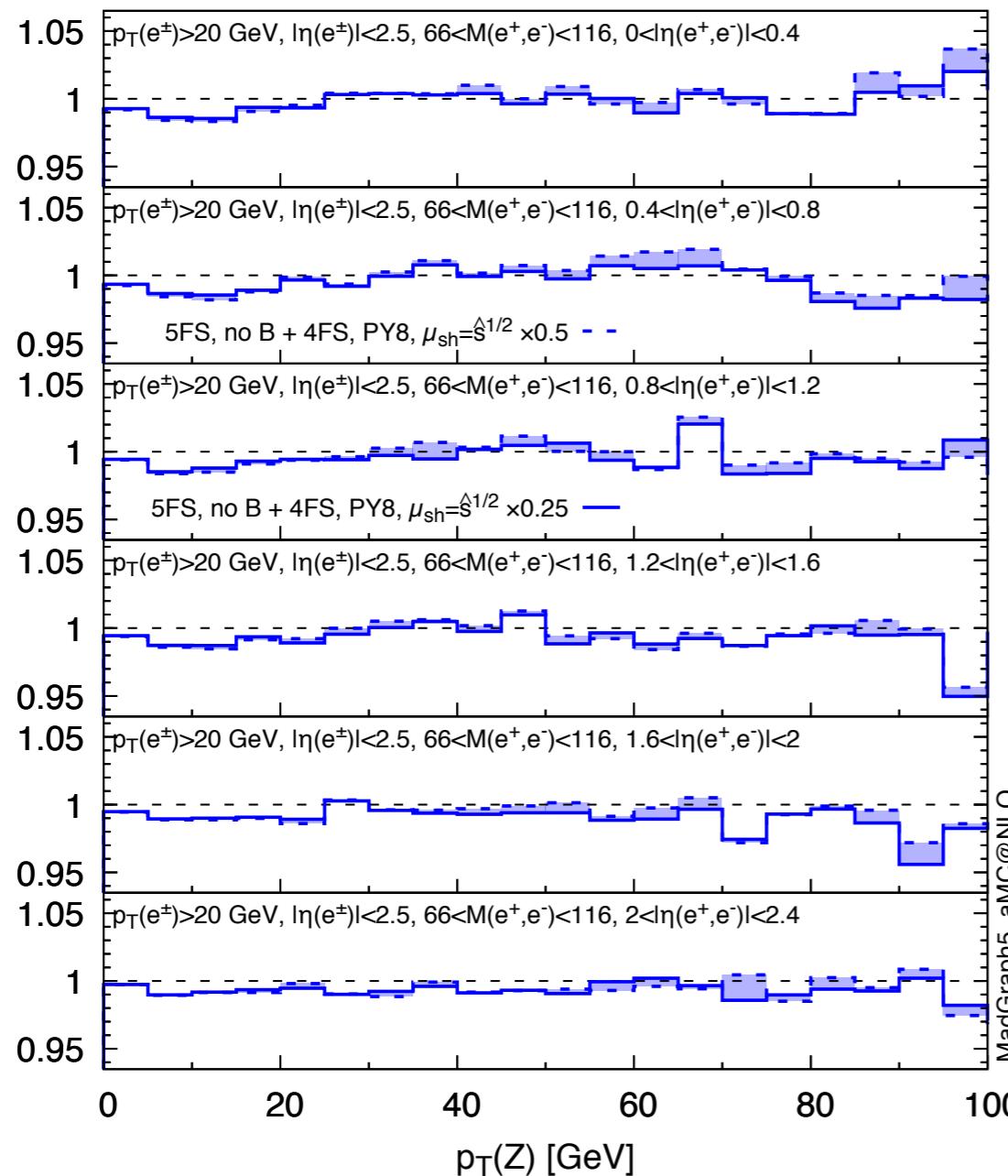


The inclusive lepton pair transverse momentum distribution is used to tune the parameters of the models implemented in the Parton Shower to describe low-pt physics

The tune is done at the Z resonance and for central rapidity of the lepton pair
 Its extrapolation to different kinematical regions and the deviation from an accurate data description exhibits the limits of this modelling

Can a more accurate perturbative description e.g. of heavy quark effects reduce the discrepancy?

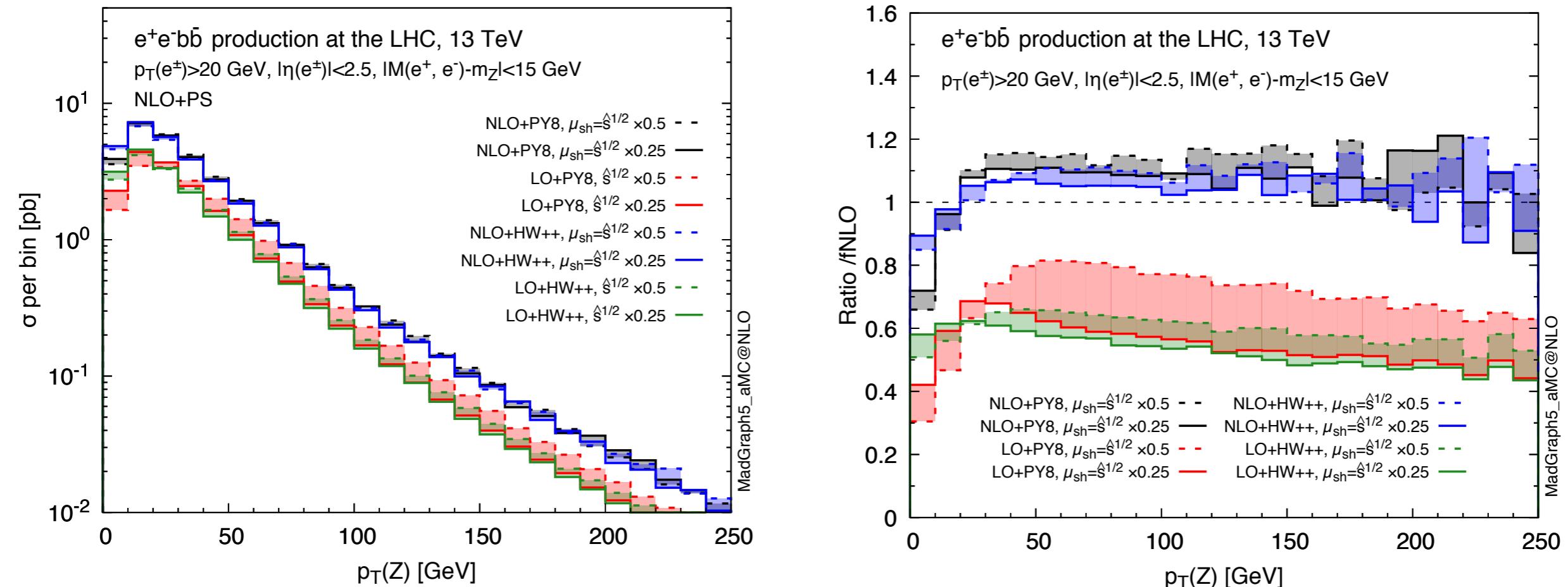
Bottom effects as a function of the e^+e^- invariant mass and rapidity



lepton-pair transverse momentum distribution as a function of the e^+e^- invariant mass and rapidity

the effects do not appear sufficient to explain the extrapolation problems
observed with POWHEG + Pythia(AZNLO)

$e^+e^-b\bar{b}$: ptZ distribution in the 4FS, Parton Shower models



- a Parton Shower model requires (among others) the choice of:
 - the analytical expression of the emission amplitudes
 - the radiation ordering variable
 - the argument of the strong coupling constant and its evolution
 - a model that describes the intrinsic transverse momentum of the partons inside the proton
 - a model in the backward evolution for the splitting $g \rightarrow b\bar{b}$
- after the matching with NLO matrix elements,
 - the dependence on the PS details is (should be) pushed one order higher