UNIVERSITÀ DEGLI STUDI
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Associated production e^+e^-bb and heavy quark impact on ptZ and MW

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Orsay, October 3rd 2017

preliminary results of a work in collaboration with: E.Bagnaschi, F.Maltoni, M.Zaro

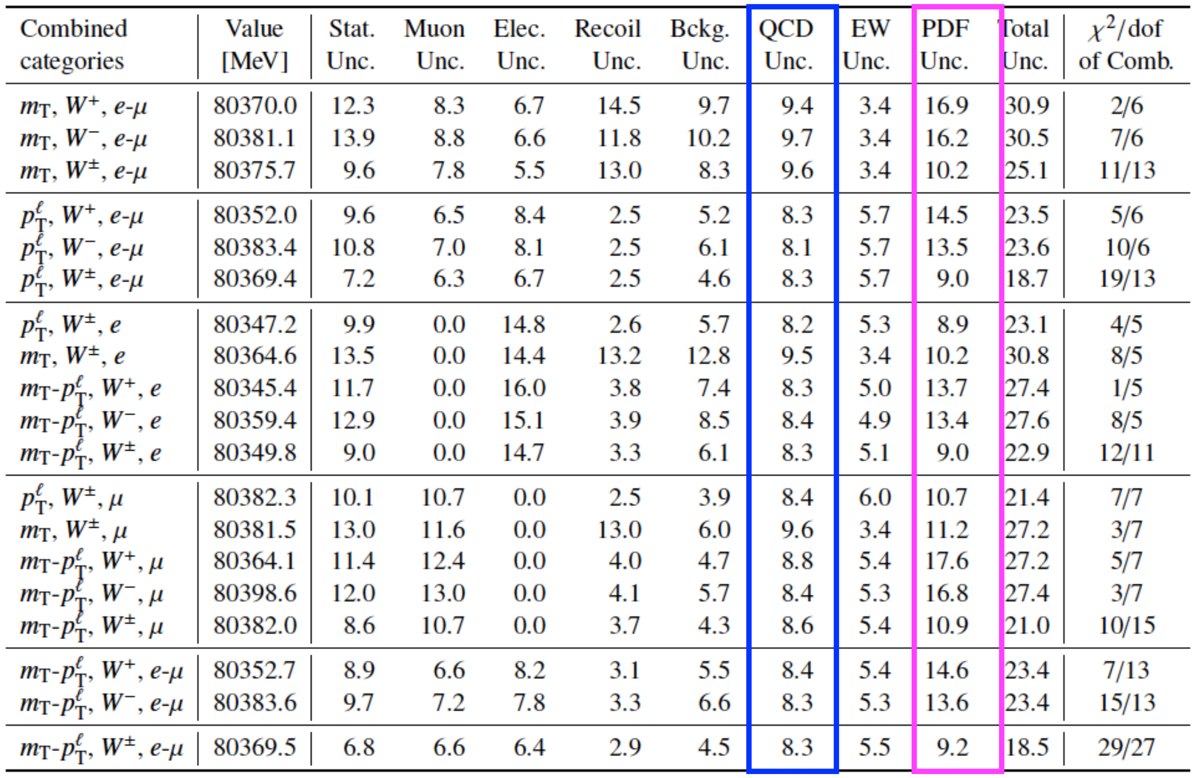
Outline of the talk

- Introduction and motivations
- QCD uncertainties
- Inclusive e^+e^- transverse momentum distribution
  - heavy quark contribution
  - 5FS vs 4FS
- Interplay between neutral- and charged-current Drell-Yan and the MW determination

MW determination: proton PDFs and heavy quark role

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

ATLAS arXiv:1701.07240



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
m_T-p_T^ℓ, $W^\pm$, 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^ℓ, $W^\pm$, 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	9.6	3.4	11.2	27.2	3/7
m_T-p_T^ℓ, 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^ℓ, 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^ℓ, $W^\pm$, 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^ℓ, W^+, e-μ	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^ℓ, W^-, e-μ	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^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

The MW measurement is mostly limited by
modelling systematics

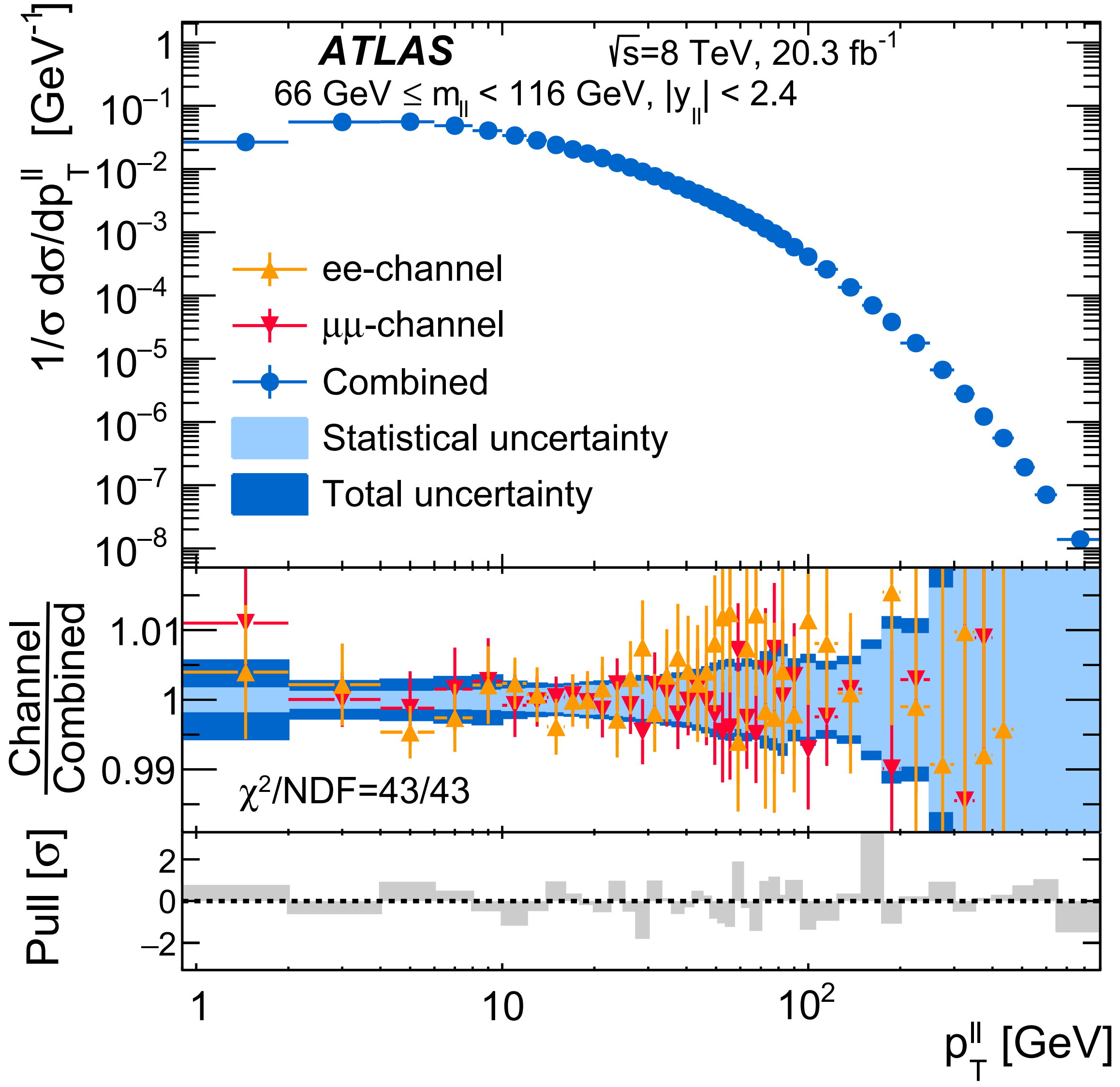
QCD and PDF effects are
two of the dominant systematic uncertainties

CC-DY and NC-DY differ by the initial state flavour structure, e.g. in the heavy quark contribution
CC-DY: u dbar, c sbar, … $\rightarrow W^+ \rightarrow l^+\nu$
NC-DY: u ubar, d dbar, c cbar, s sbar, b bbar,… $\rightarrow \gamma*/Z \rightarrow l^+l^-$

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 ?

Relevance of the ptZ distribution for the MW determination

ATLAS arXiv:1512.02192



inclusive lepton pair transverse momentum distribution

total error < 0.5% for 1 GeV < ptZ < ~50 GeV

extraordinary challenge to theory predictions
- → shape
- → absolute normalisation

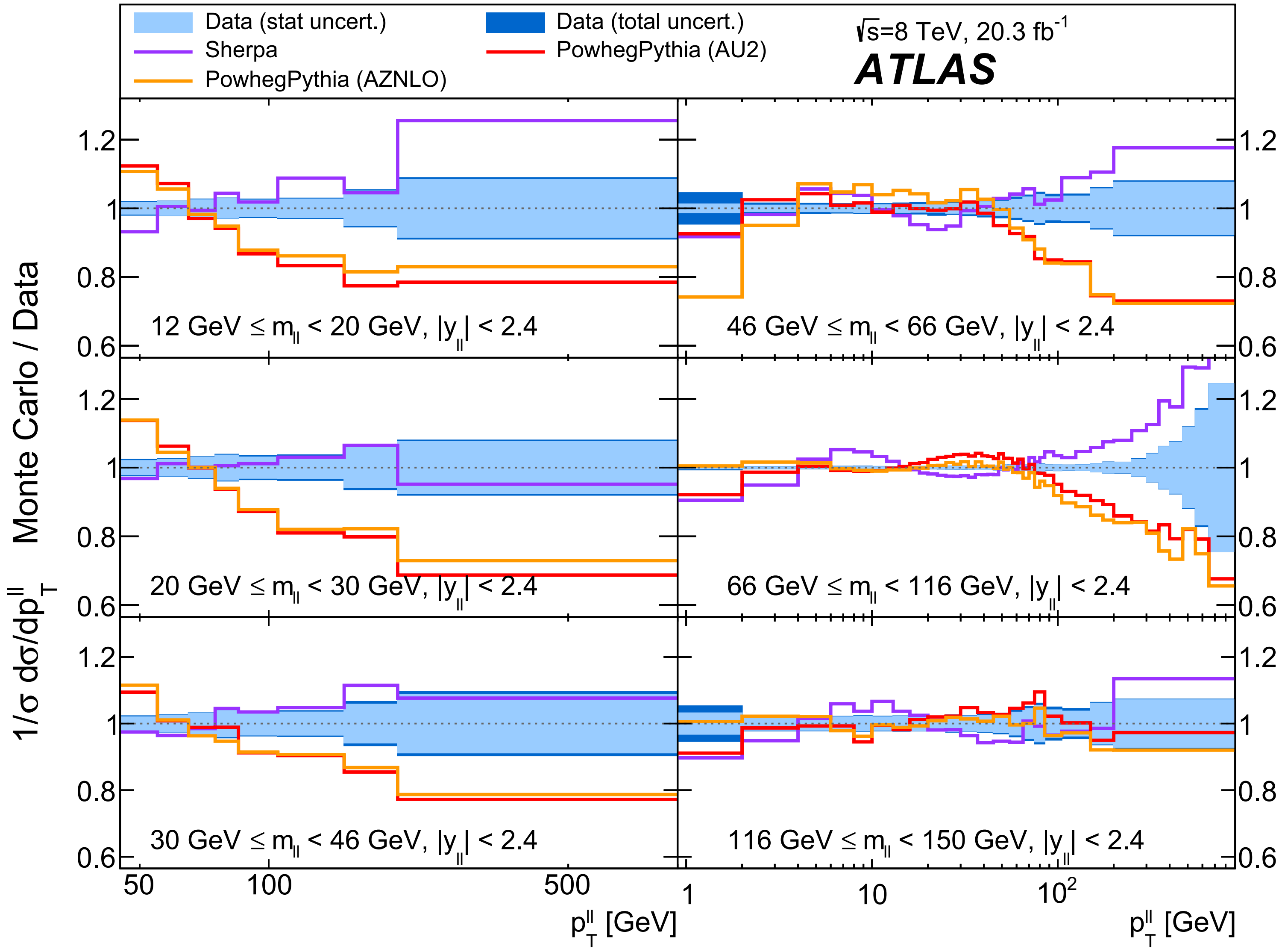
every contribution, also classified as "subleading", can become important at this level

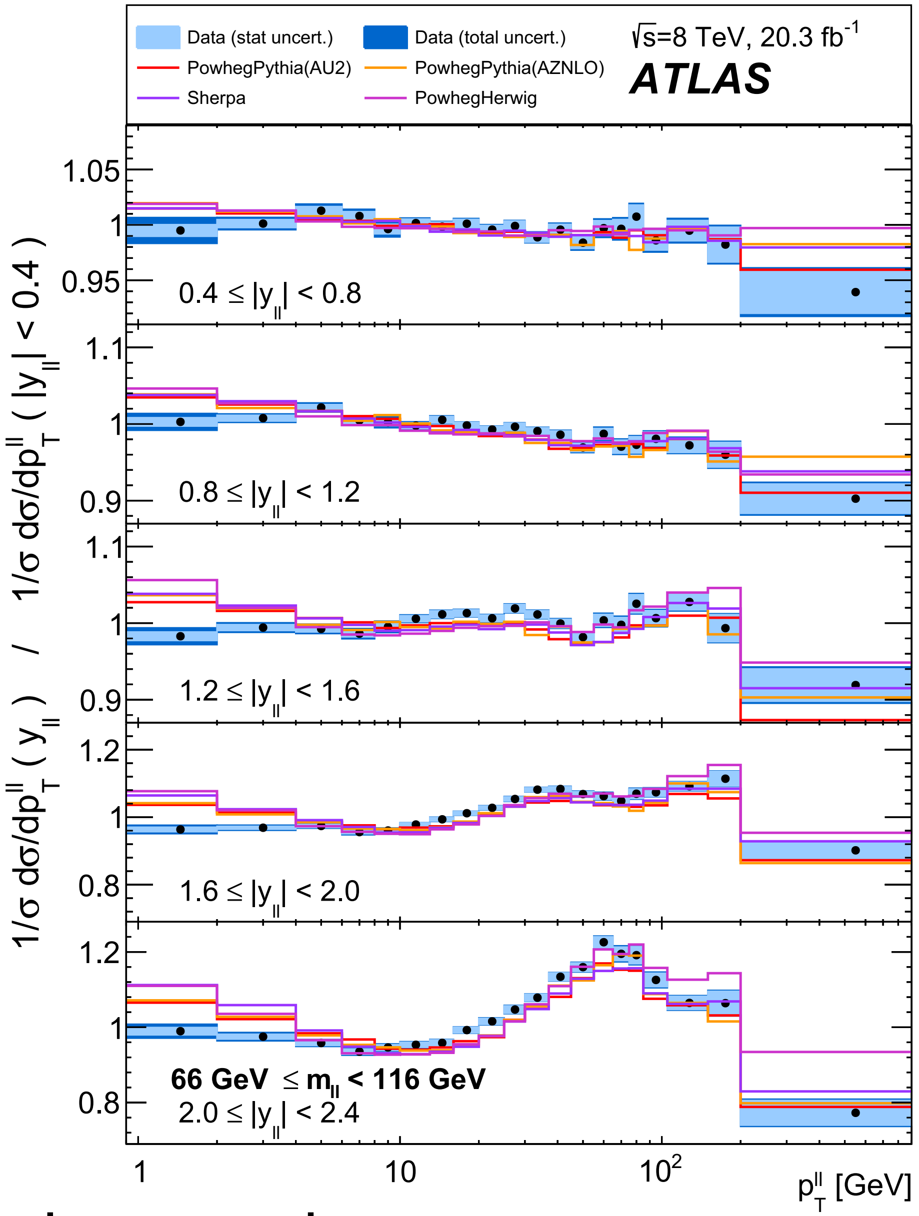
- the universality, the flavour and scale independence of the effects encoded in NP models are debated
- the bottom quark contribution to ptZ, almost absent in the ptW case, may introduce spurious unwanted contributions to MW

- an improved partonic description of the bottom quark contribution to ptZ may
  - → increase the overall precision of the theoretical predictions
  - → reduce the amount of information to be encoded in the NP models
  - → reduce the differences between bottom and the other quarks increasing the universality of the effects included in the NP param's

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

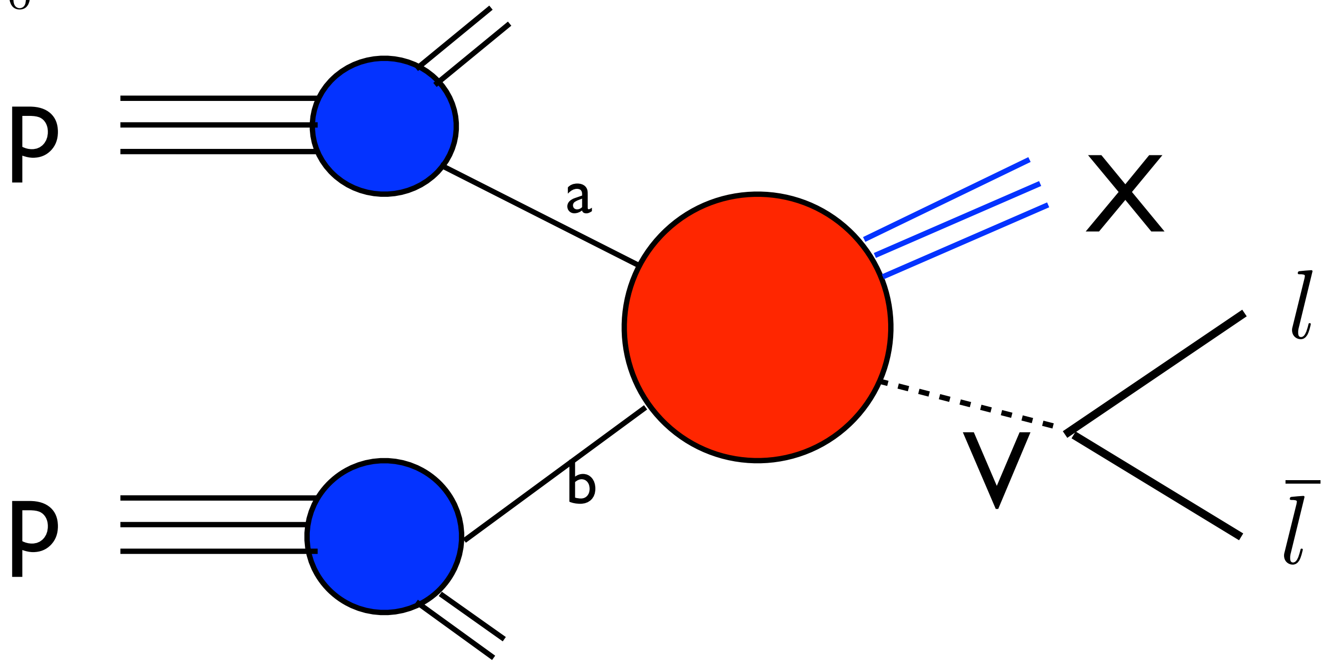
The tune is done at the Z resonance and for central rapidity of the lepton pair
Its extrapolation to different kinematical regions and the deviation from an accurate data description exhibits the limits of this modelling

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

QCD uncertainties

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 — 7-point scale variations
- factorization scale M_F
- PDF uncertainties — NNPDF3.0 (100 replicas)
- recipe of the matching between fixed- and all-orders terms — POWHEG vs aMC@NLO
- resummation scale (analytic resummation language)

  shower scale or (singular vs regular)-separation scale — factor 2 variation of "best" value

  (Monte Carlo event generators language)
- `scalup` Parton Shower phase-space variable
- Parton Shower model — Pythia 8.215 Monash *vs* Herwig++ 2.7.1

POWHEG vs aMC@NLO matching recipes

aMC@NLO

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

- the Parton Shower generates all the additional real partons, with improved NLO weight (soft event)

- the Sudakov form factor is the one implemented in the PS

- the PS populates a phase space limited by `scalup`,
  which is extracted according to the Shower Scale Q_{sh} probability distribution

- the hard matrix element corrections are applied, avoiding a double counting with the PS (hard event)

POWHEG vs aMC@NLO matching recipes

POWHEG

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

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

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

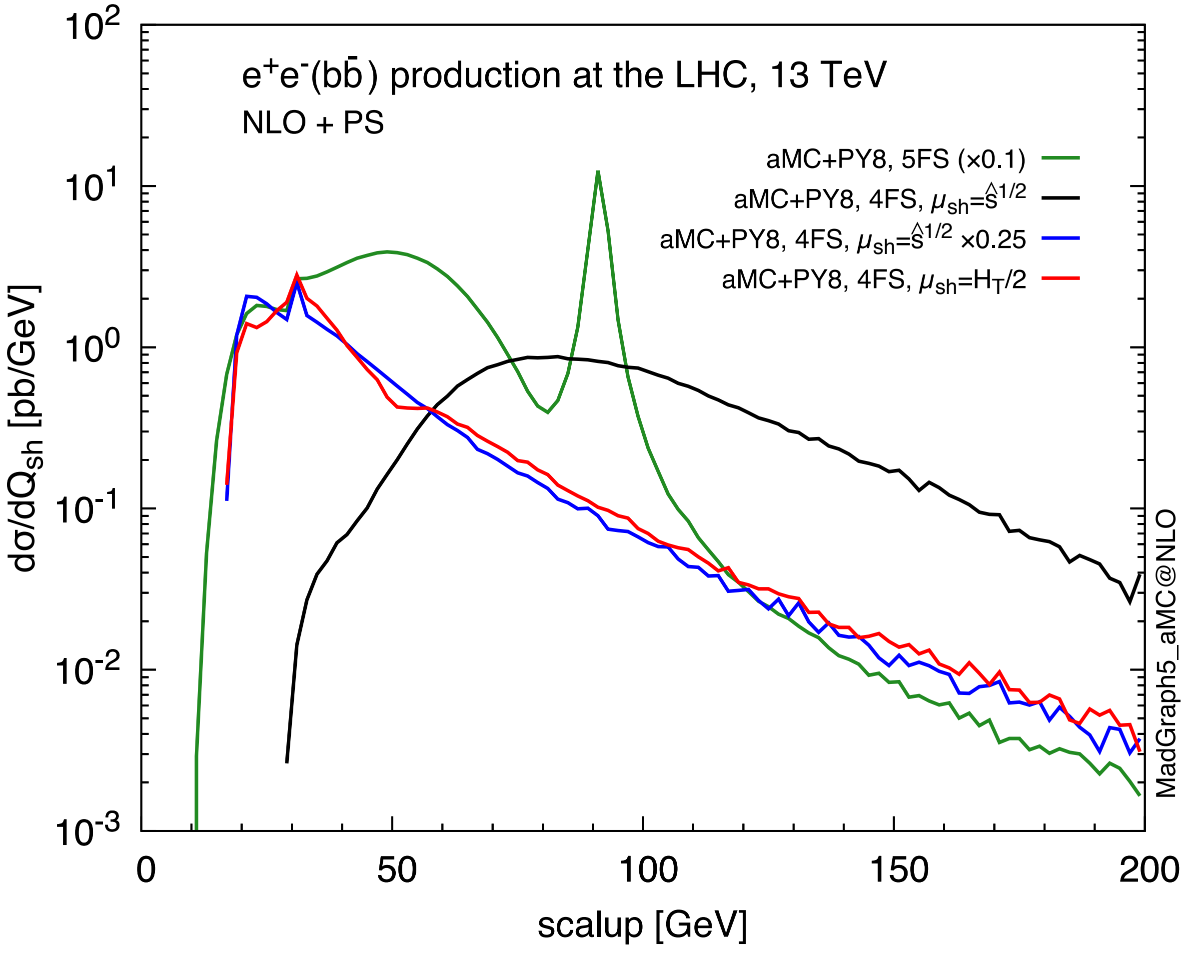
$$\Delta(\phi_n, p_\perp) \; = \; \exp\left(- \int d\phi_{rad} R^s(\phi_n, \phi_r ad)/B(\phi_n) \theta(k_\perp - p_\perp) \right)$$

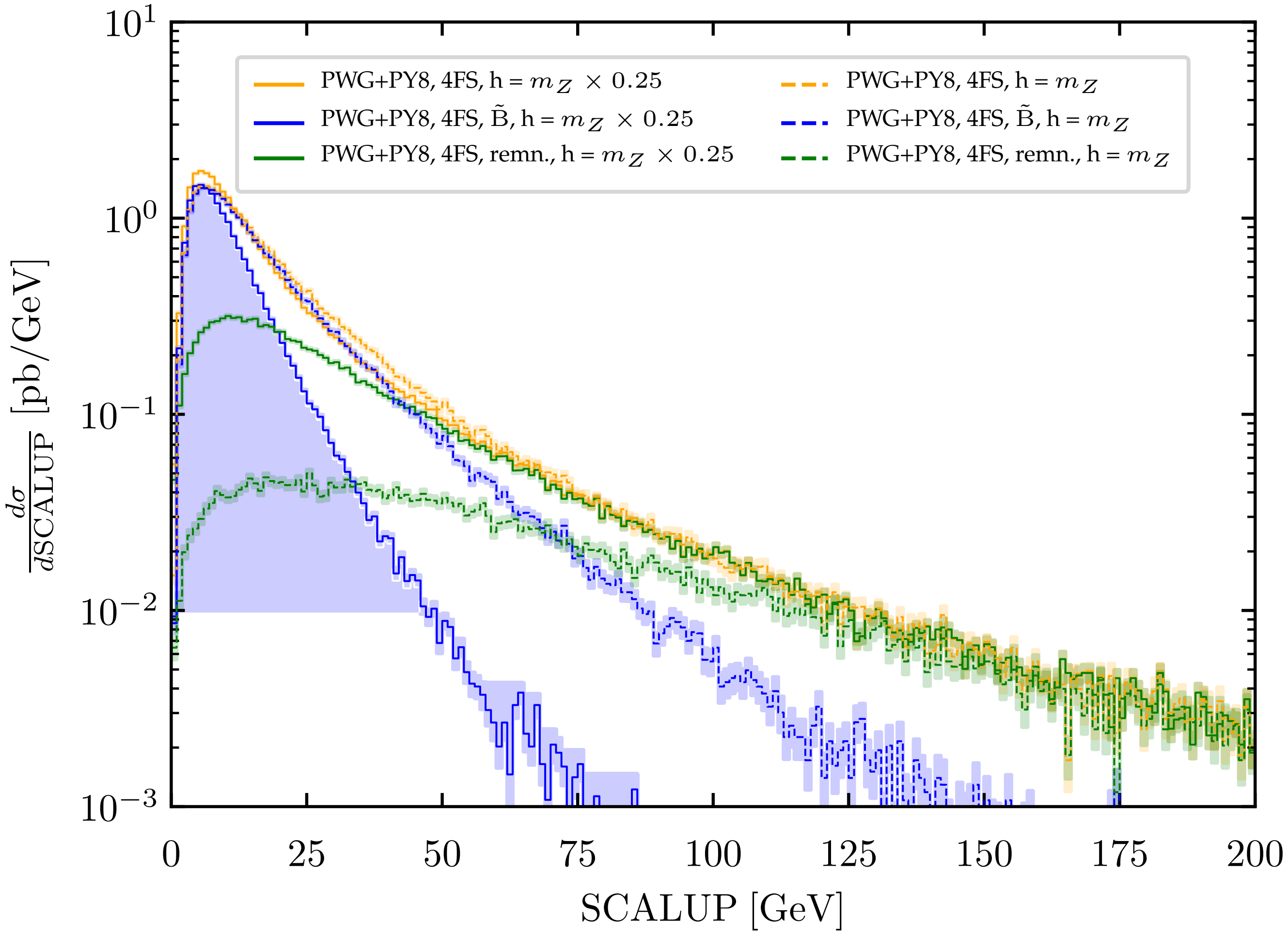
- the first emission is generated by POWHEG with its own Sudakov form factor Δ
  exact real matrix element

- 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 `scalup` the hardness of the first emission (singular events)
  an “arbitrary” function (regular events)

Interfacing the NLO 4FS e^+e^-bb event generator to the Parton Shower





- the Shower Scale in aMC@NLO is extracted according to a probability distribution
  expressed in terms of kinematical variables (shat, HT/2)
  dependent on the details of the PS for its exact shape

- the `scalup` distribution in POWHEG coincides with the final state pt distribution (singular part)
  and with a function of pt (regular part)
  the splitting between singular and regular is in turn controlled by the scale *h*

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 the e^+e^-bb process may enhance the differences:

one single scalup 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

These differences are mitigated when considering the ptZ distribution, inclusive over the bottom quark contributions

The fixed-order NLO-QCD results are our benchmarks

→ additional corrections and residual uncertainties are expressed in these units

Improving the ptZ description

Strategy to improve the ptZ description

we consider the two processes

$p\,p \rightarrow e^+e^- + X$ Drell-Yan (lepton-pair production inclusive over extra radiation) 5FS

$p\,p \rightarrow e^+e^-\, b\, \bar{b}$ (associated $Z/\gamma*$ production) 4FS

we develop a combination which exploits the advantages of the 5FS and 4FS descriptions

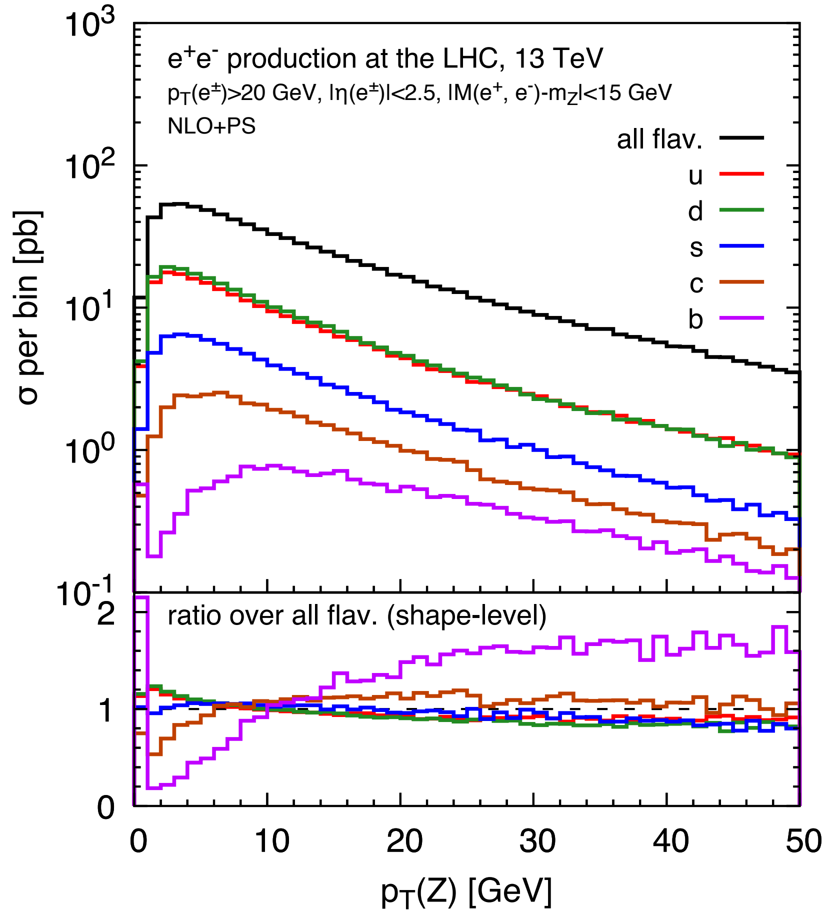
we evaluate the combination using tools with NLO-QCD + QCD-PS accuracy
(POWHEG and aMC@NLO) and discuss the associated QCD uncertainties

we develop a toy procedure to assess the impact on MW of the improvement in the ptZ description

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 ptZ ~ O(mb) ~ O(5 - 20 GeV)



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

- given the exp error below 0.5% in a large range the bottom contribution of O(4%)

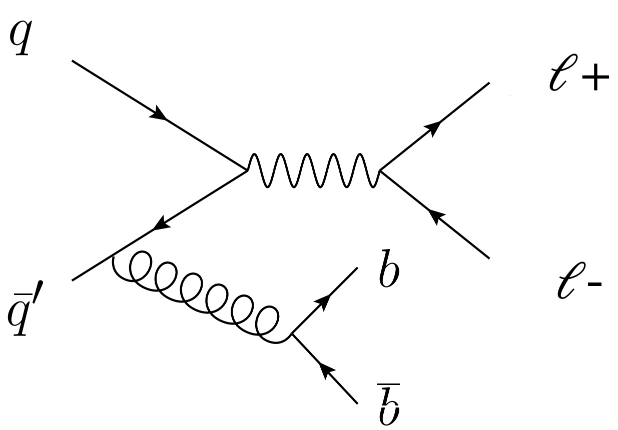
→ we need a prediction of the b contribution with a precision at the O(10%) level

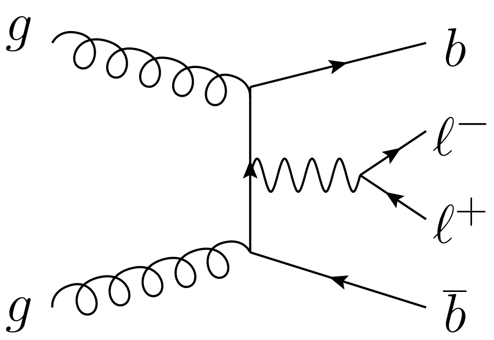
- the PDF evolution starts for the heavy quarks at Q ~ mq

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

→ POWHEG leaves to Pythia the description for 0 < ptZ < mb,
a 4FS NLOPS description in this region is more precise

Z b bbar associated production in the 4FS ($pp \to e^+e^-b\,\bar{b}$)

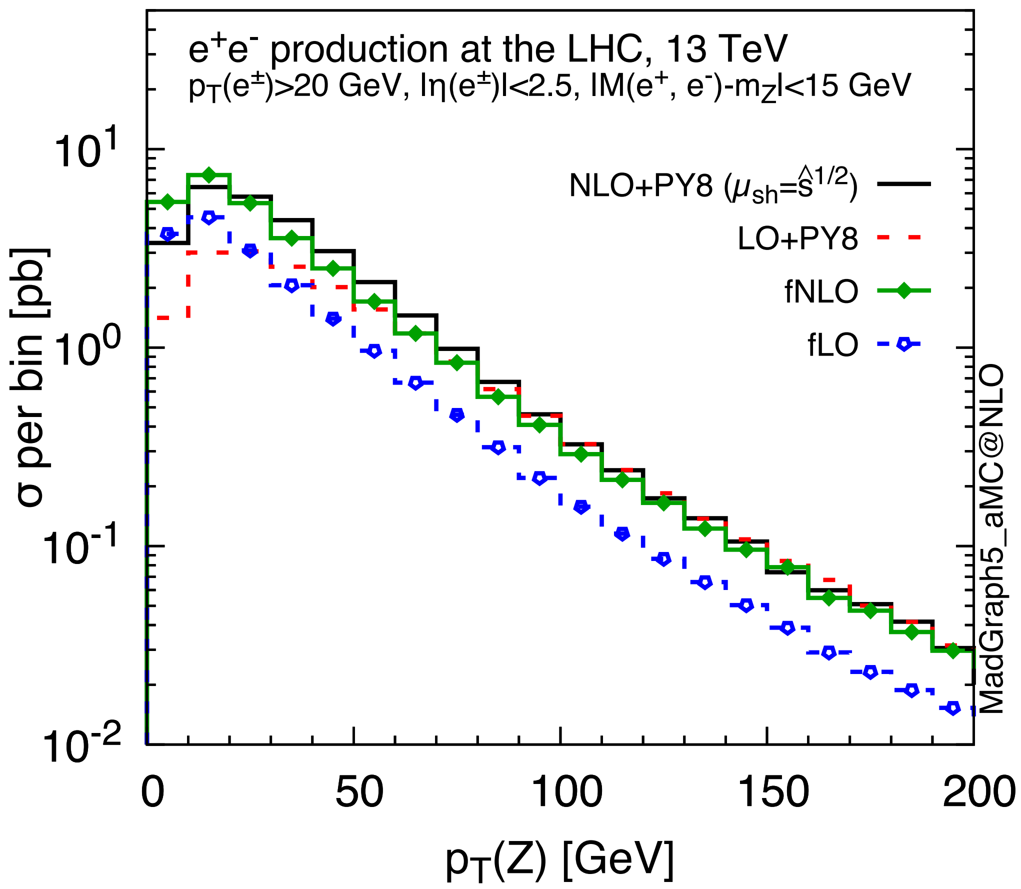


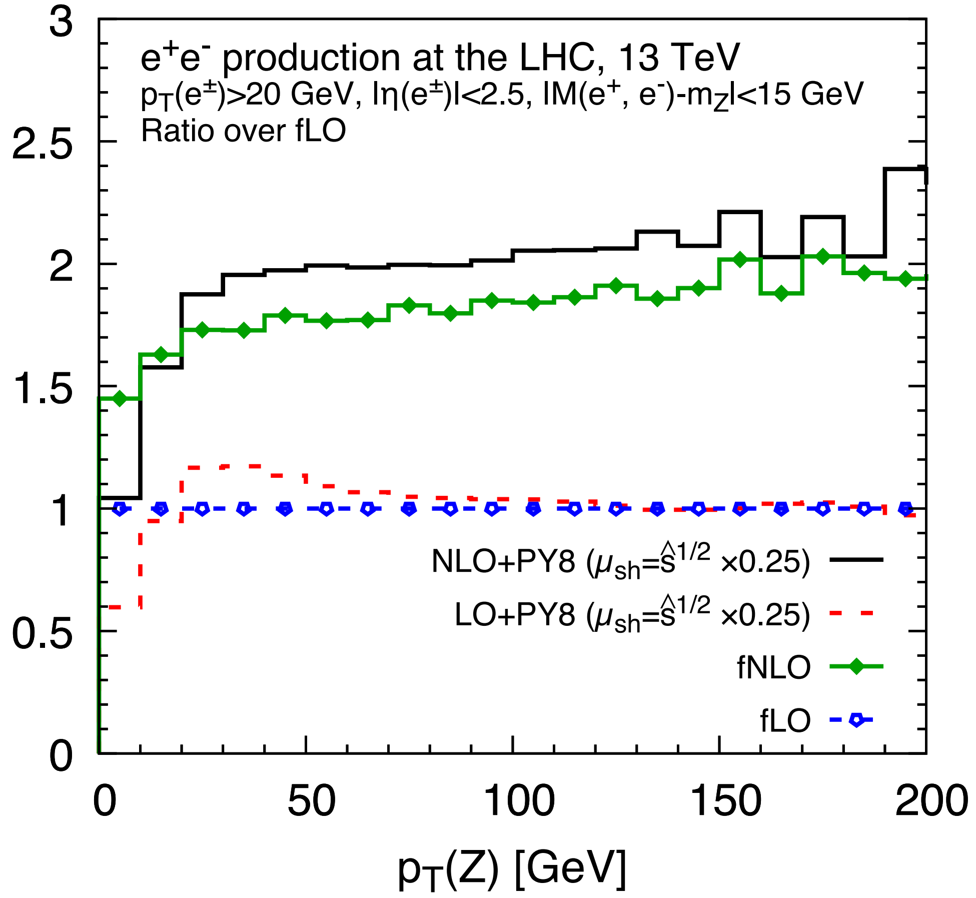


in the 4FS the bottom quark

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

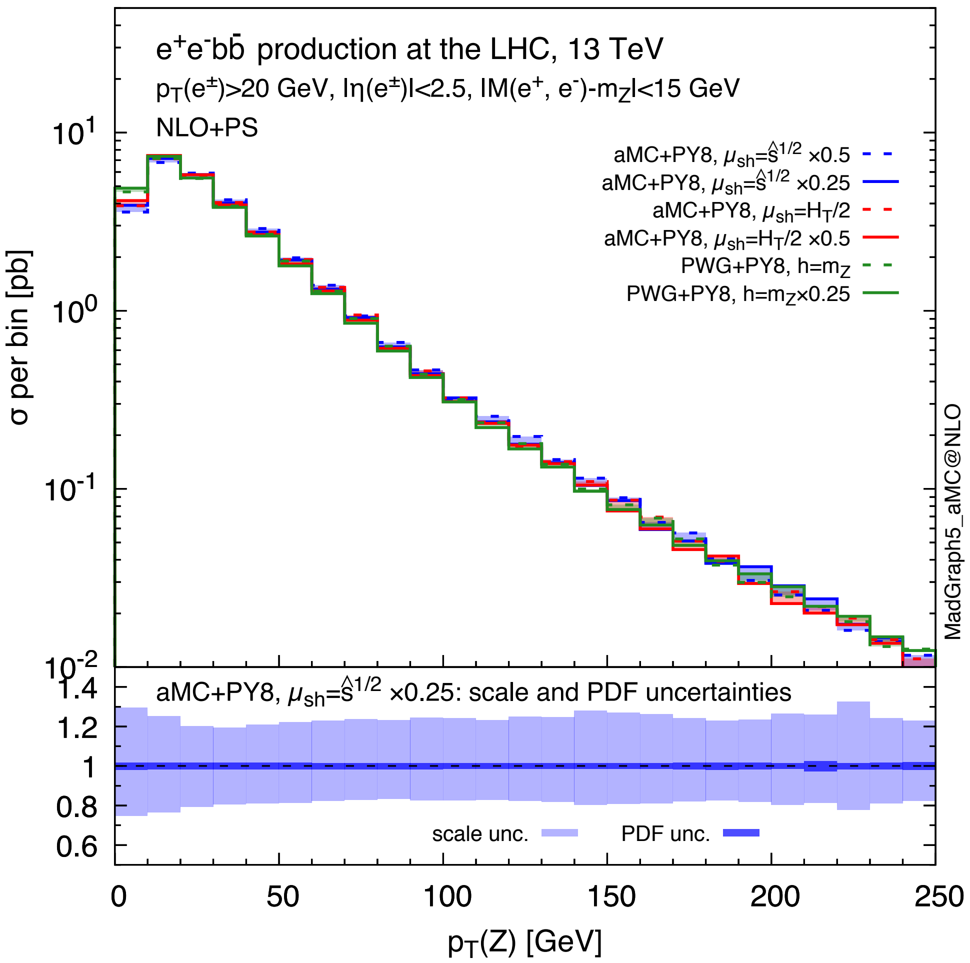
ptZ distribution (inclusive over b quarks)

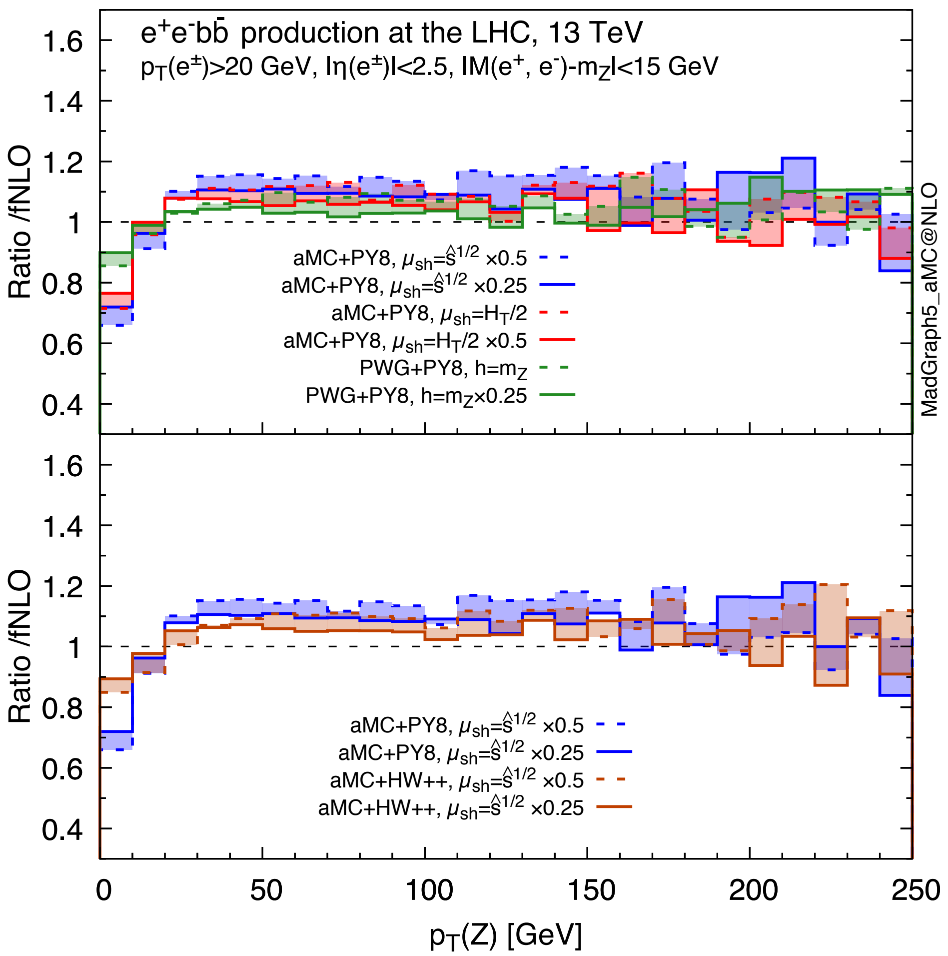




- regular when ptZ→0, but still sensitive to large log effects (aMC@NLO)
- the process has a large NLO K-factor
- large multiple gluon emission effects via QCD Parton Shower, for ptZ < 50 GeV

ptZ distribution in the 4FS (pp$\rightarrow e^+e^-$b bbar): QCD uncertainties



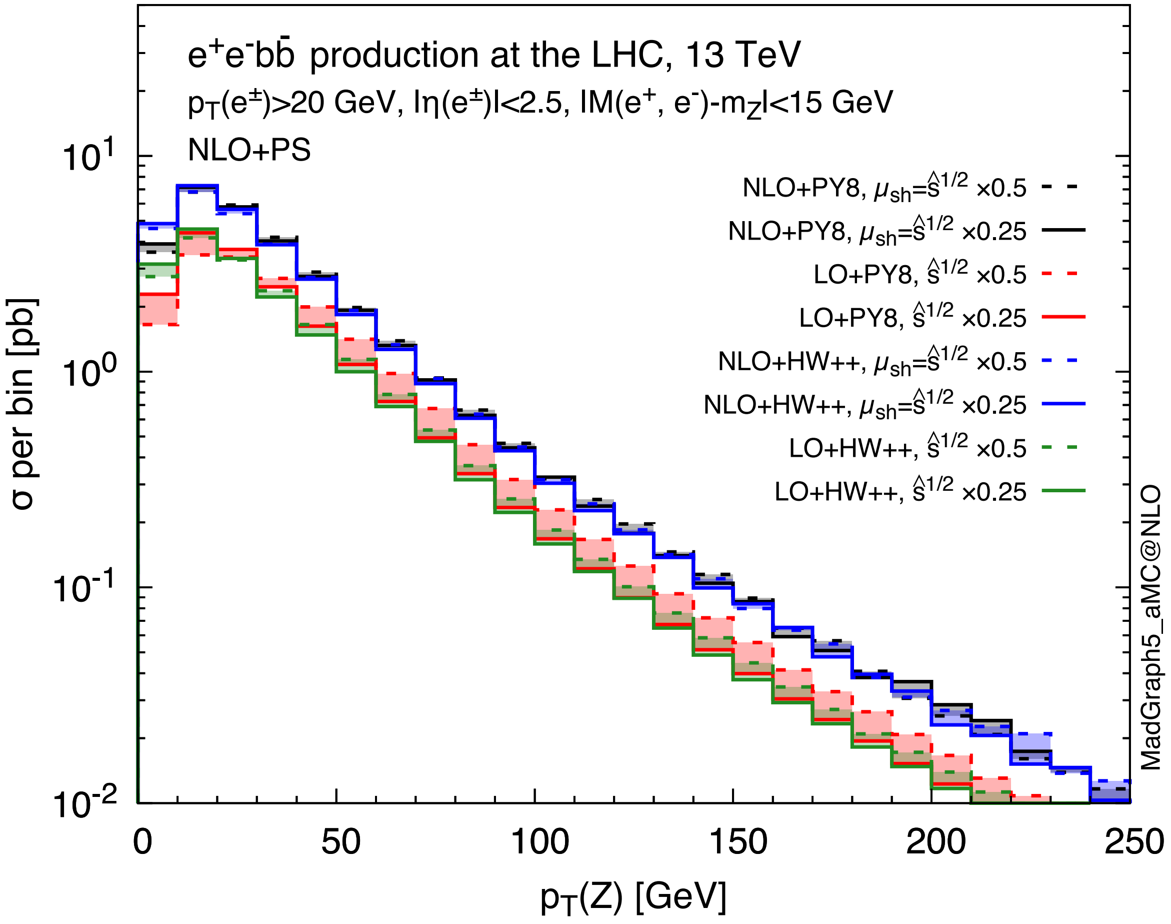


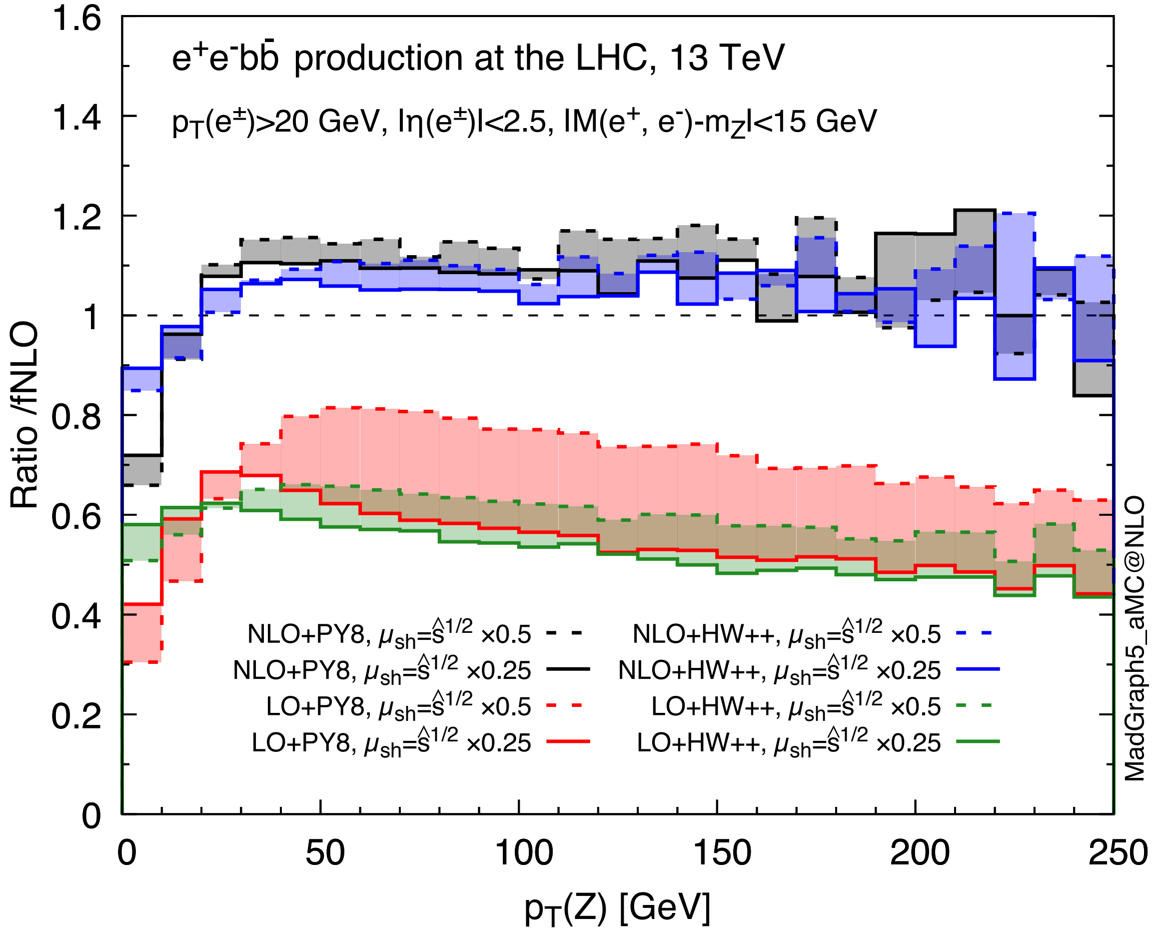
- both codes (POWHEG and aMC@NLO) have NLO-QCD + QCD-PS accuracy

- canonical PDF uncertainty and renormalization/factorization scale variations
- two different matching schemes: MC@NLO and POWHEG
- aMC@NLO: different options for the shower scale variable and for its range
- POWHEG: different values of the scale *h* of the damping factor in the Sudakov
  (and different settings of scalup in the remnant event contribution)
- different QCD Parton Shower models: PYTHIA8 and HERWIG++

- except in the first bin, matching+shower uncertainties at the 10% level, scale+PDF at the 20% level

ptZ distribution in the 4FS (pp→e^+e^-b bbar): 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→bb

- after the matching with NLO matrix elements,

  the dependence on the PS details is (should be) pushed one order higher

Improved prediction of the ptZ distribution: combining 5FS and 4FS

- the prediction of the ptZ distribution, inclusive over radiation, is split into two contributions with and without B hadrons in the final state

- we rely on the 5FS for the contributions without B hadrons (light quarks ~ massless partons)
  4FS for the contributions with B hadrons (exact massive kinematics +NLOPS acc.)
  and we combine the two results

- in the 5FS B hadrons are generated by the QCD PS with two mechanisms:
  i) presence of a bottom quark in the initial state (b bbar and bg initiated subprocesses)
  ii) gluon splitting into b bbar
  → the contribution without B hadrons is computed in the 5FS
  imposing a veto on the presence of B hadrons in the event analysis

- the contribution with B hadrons is computed in the 4FS
  by definition the process pp→e^+e^-b bbar contains bottom quarks in the final state
  additional b bbar pairs may be produced by gluon splitting

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

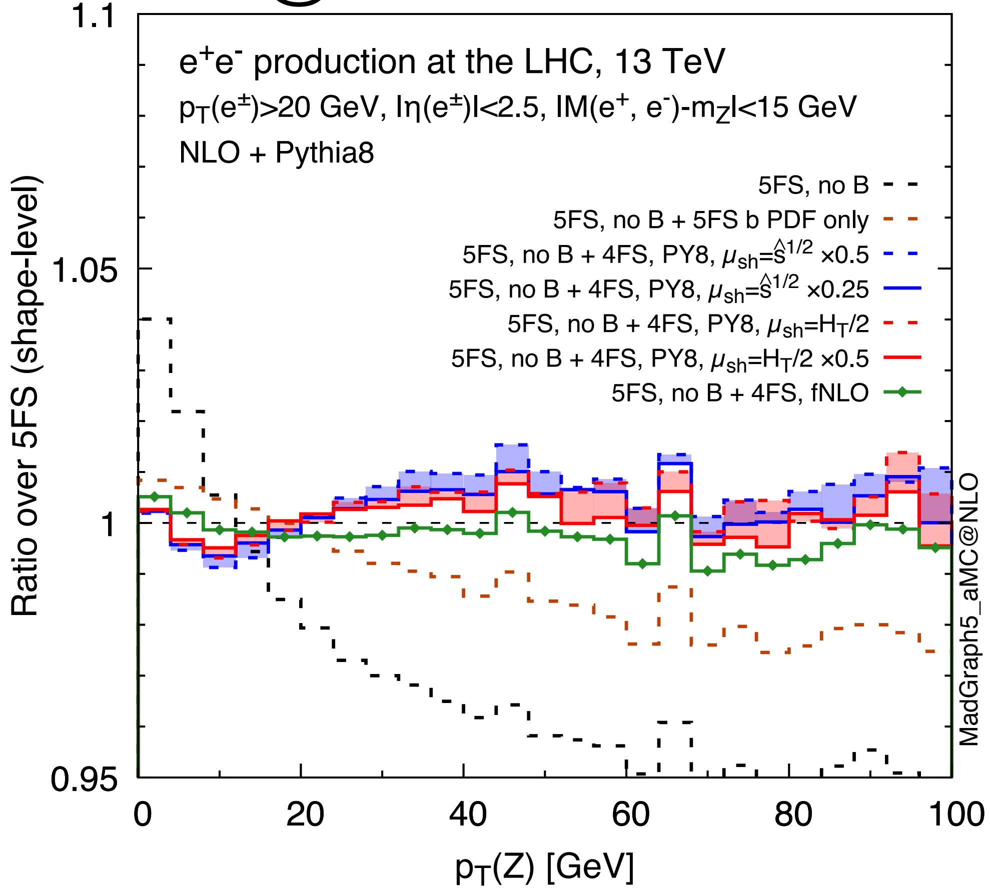
Improved prediction of the ptZ distribution

$$\mathcal{R}(p_\perp^{l^+l^-}) = \left(\frac{1}{\sigma_{fid}^{best}}\,\frac{d\sigma^{best}}{dp_\perp^{l^+l^-}}\right)\cdot\left(\frac{1}{\sigma_{fid}^{5FS}}\,\frac{d\sigma^{5FS}}{dp_\perp^{l^+l^-}}\right)^{-1}$$

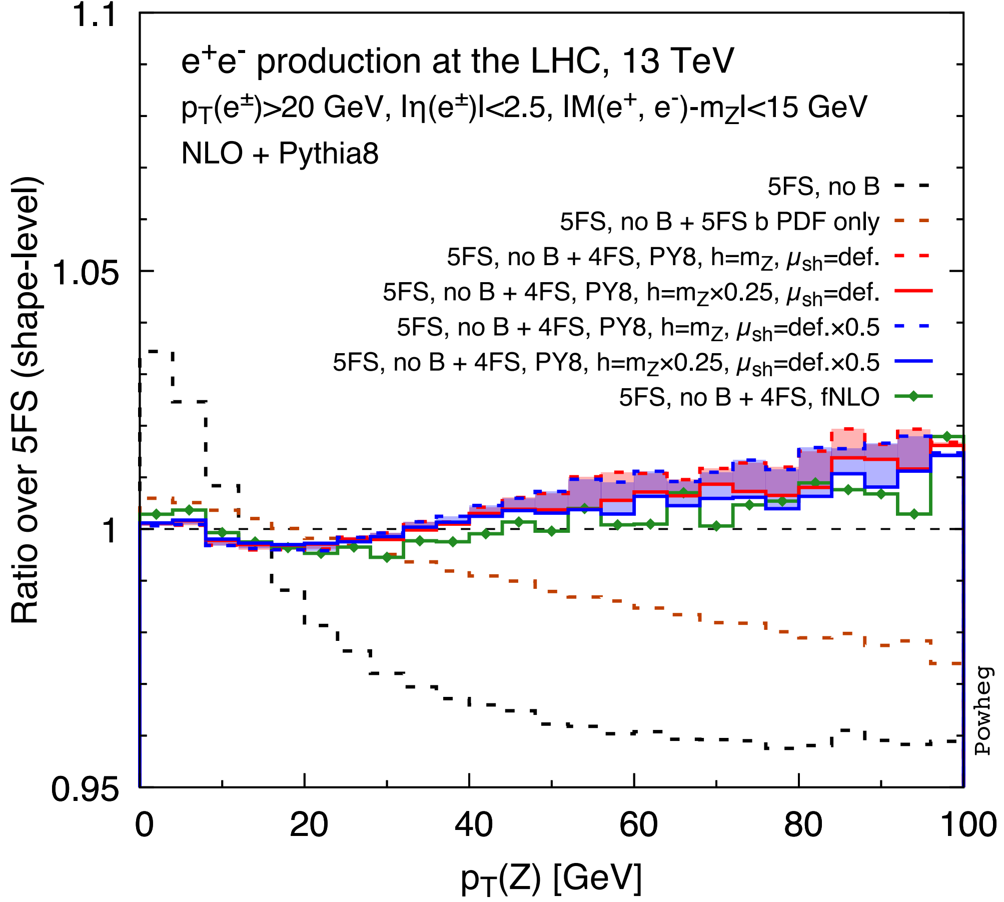
- $\mathscr{R}$ expresses the distortion of the improved ptZ, with respect to the full plain 5FS prediction

- for a given B-veto distribution the 4FS part is added in different approximations of Shower scale (aMC@NLO) or damping factor scale (POWHEG)
- $\mathscr{R}$ is computed for a given PS tune

aMC@NLO



POWHEG



- distortion with a non trivial shape for ptZ<50 GeV
- in aMC@NLO effects at the ±1% level, in POWHEG effects at the ±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`)

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

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

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

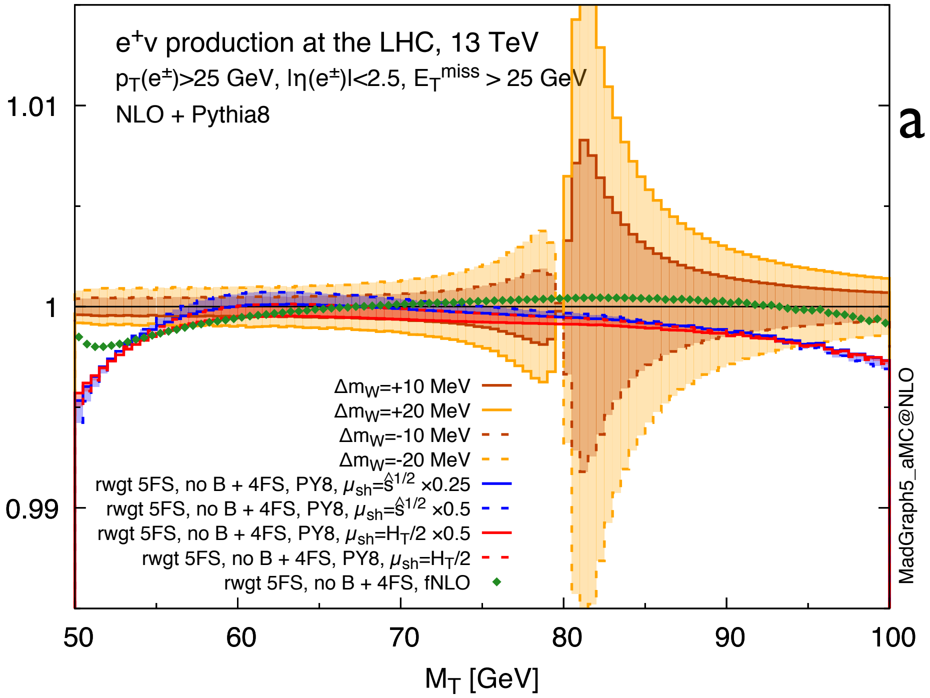
- we use $\mathcal{R}(p_\perp)$ to reweigh the CC-DY events according to their ptW value

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

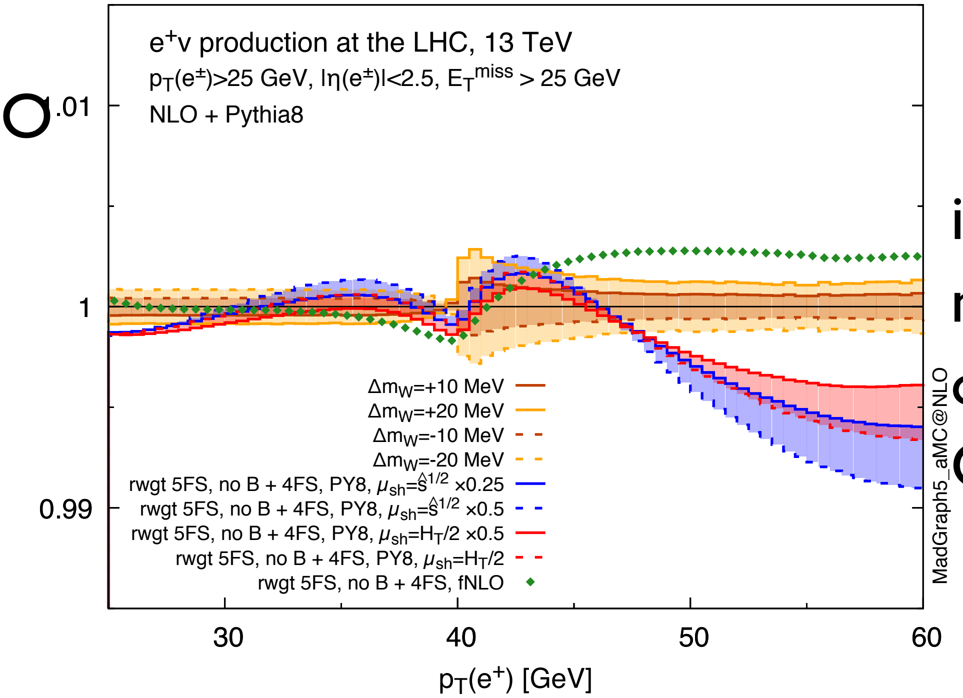
The CC-DY observables are evaluated in the plain 5FS

The change from `tune1` to `tune2` in the PS is mimicked by reweighing the events with $1/\mathscr{R}(p_\perp)$

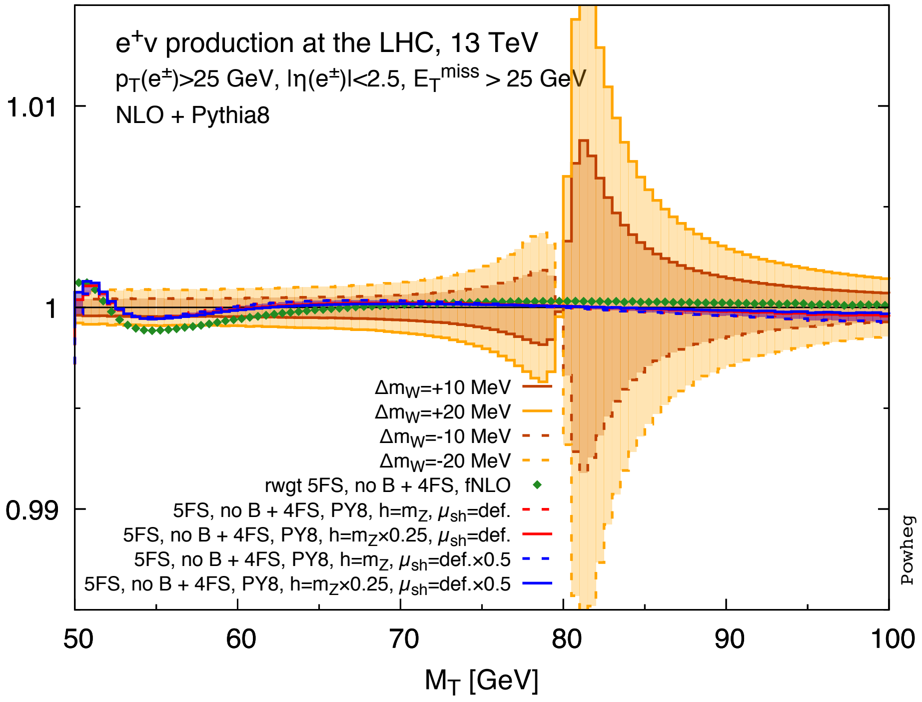
The impact on MW is estimated by template fit of the reweighed distributions (red/blue/green),
with templates evaluated in the plain 5FS (light brown)



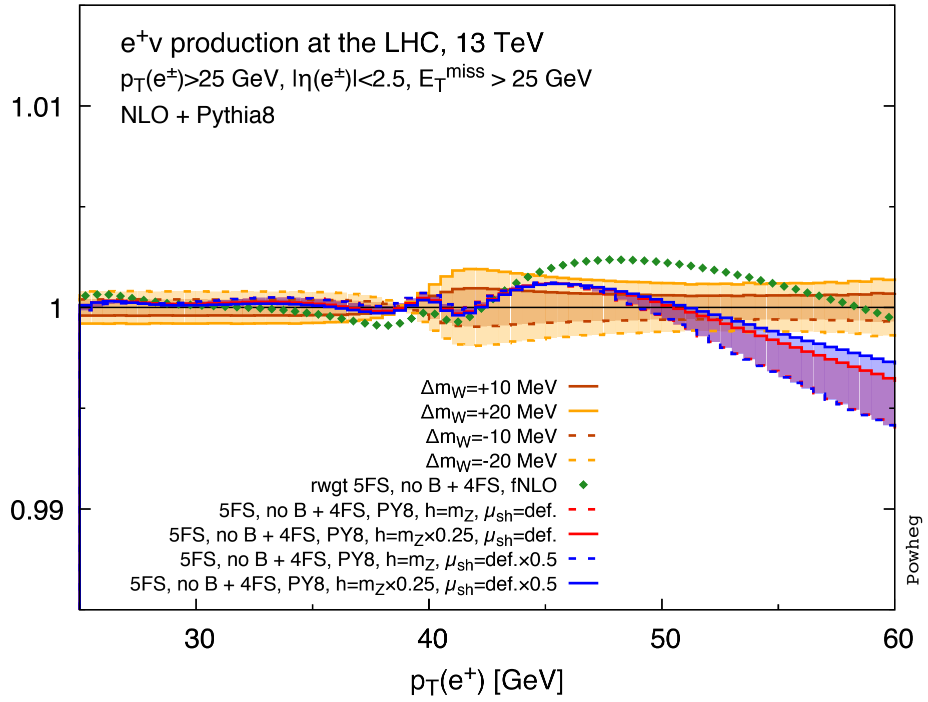
aMC@NLO



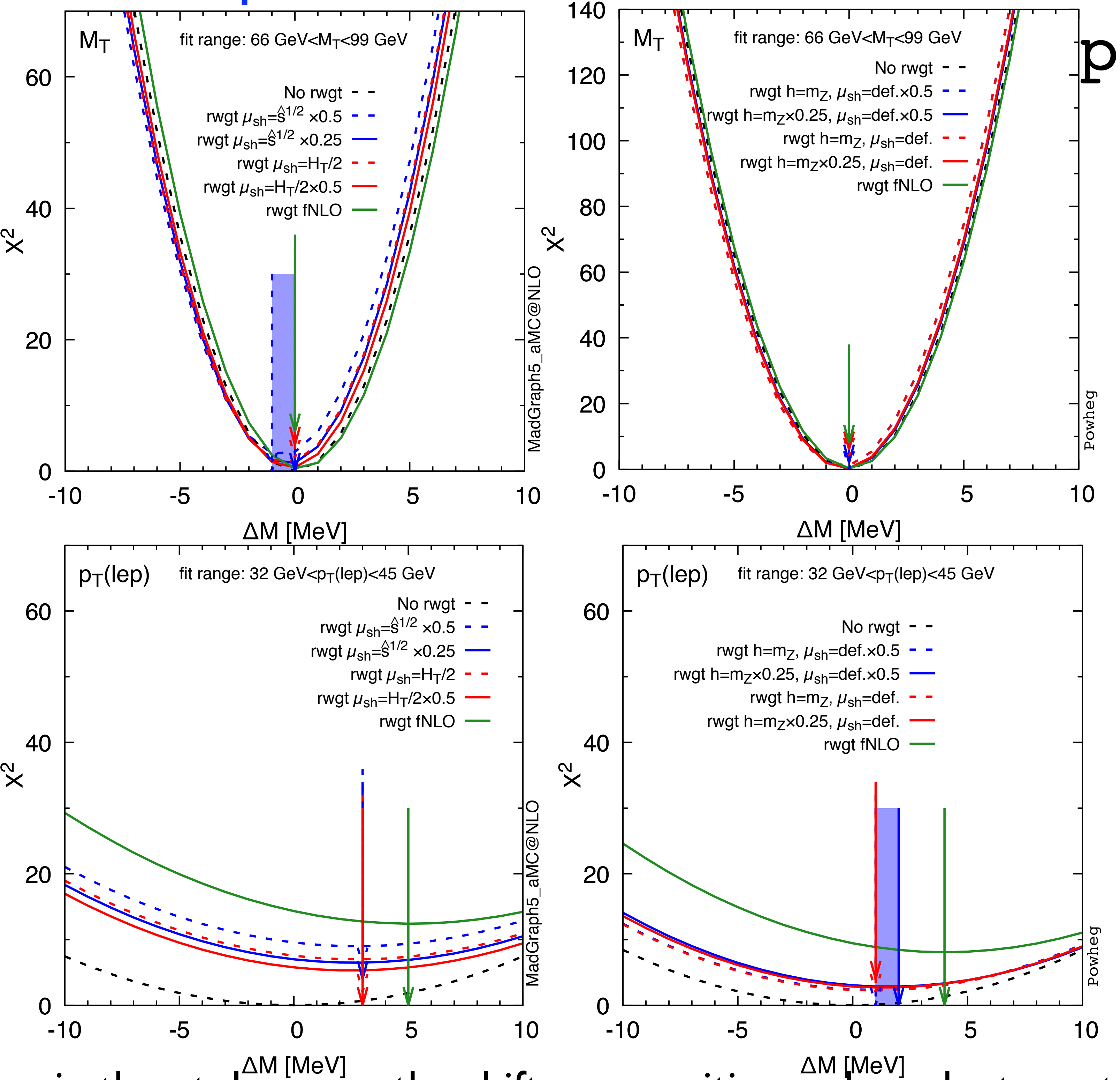
in the high-ptlep tail
non negligible effect
of the matching with
QCD_PS



POWHEG



Bottom quark effects on the MW determination

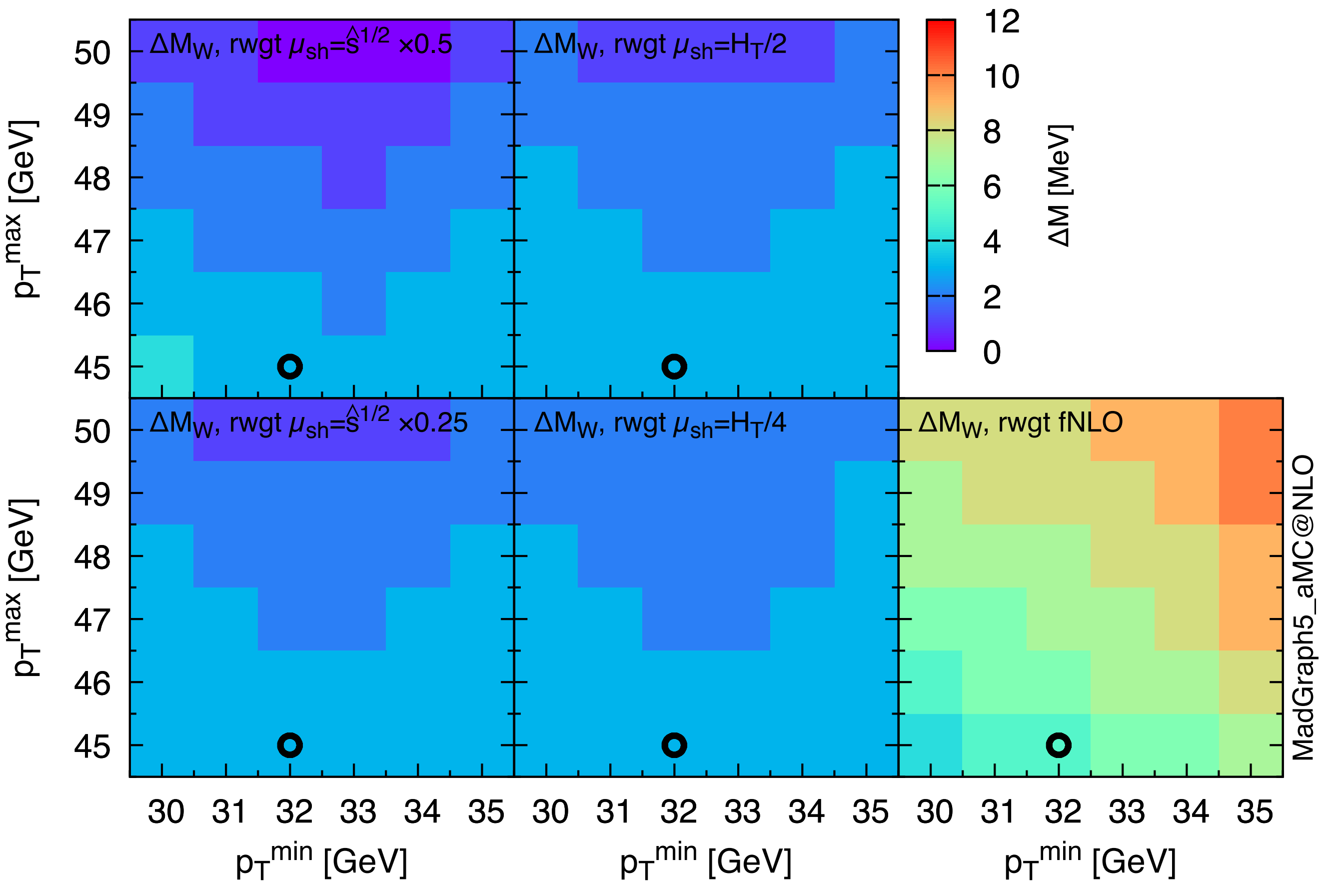


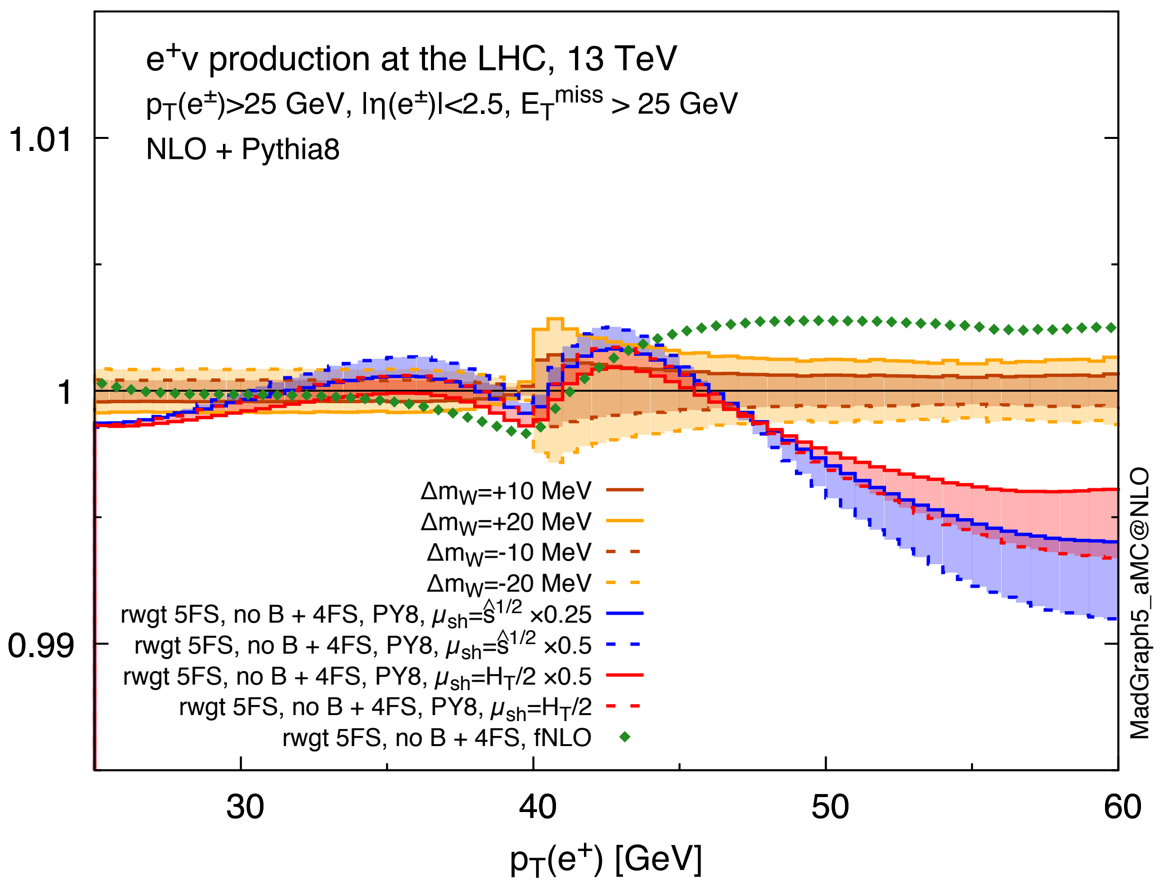
preliminary results

- 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
- fixed-order NLO results shown for
  technical interest (benchmarks)

- 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 MeV)
  further improvements expected in the statistical quality of the fits

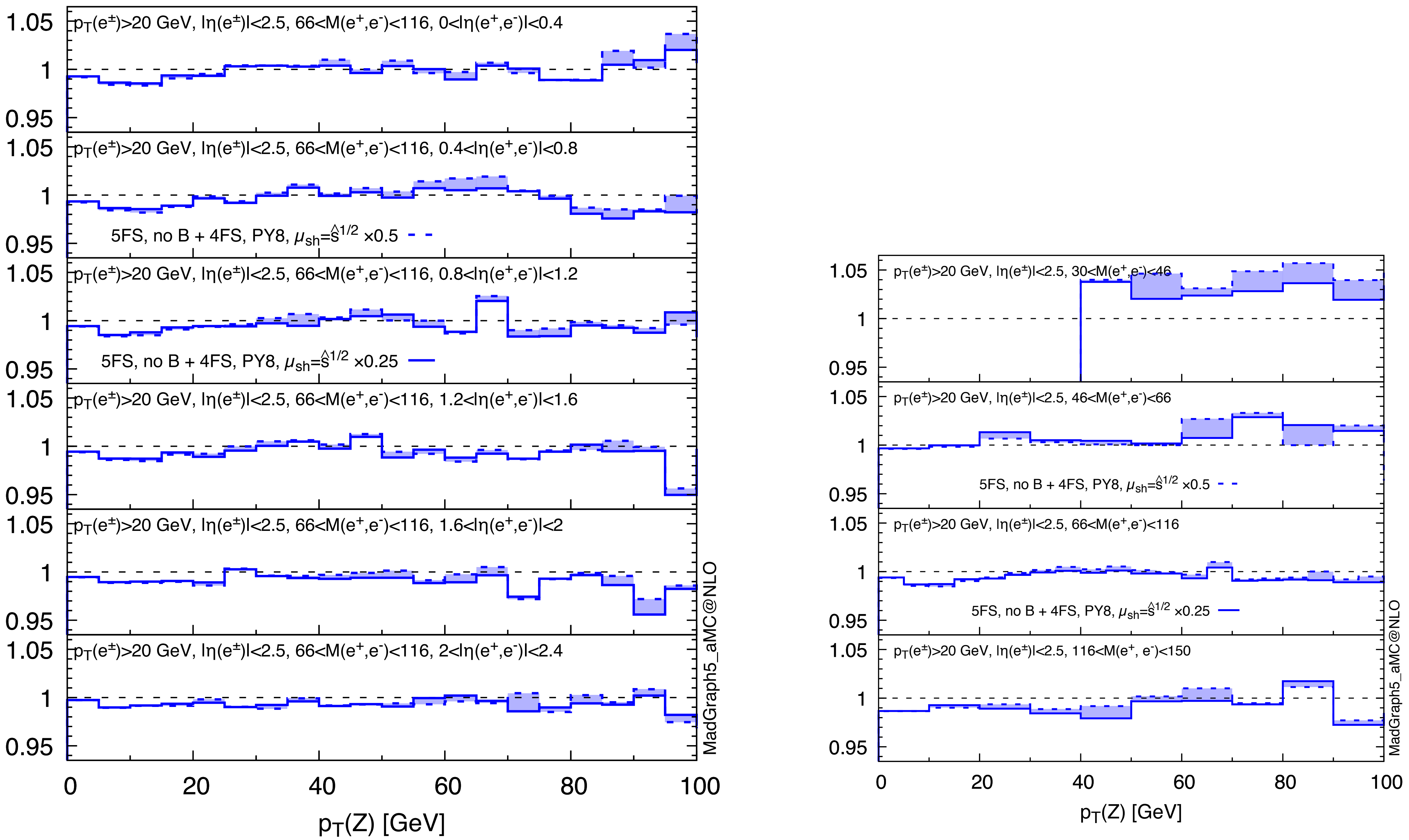
Dependence of the MW shifts on the fit window





- 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 ptlep ~ 45 GeV, pulling the χ^2 in opposite directions in the intervals [40,45] and [45,50] GeV
- above the jacobian peak, the fixed order NLO becomes flat above ptlep ~ 47 GeV stabilising the negative shift due to the interval [40,47]

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)

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 ptZ 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
  a realistic estimate is more cumbersome and will yield also an indicator of quality of the data description (e.g. a χ^2 value)
  → the present study offers only a qualitative statement about the MW sensitivity to b-quark effects
  (the shifts do not exceed the 3-5 MeV level in size and in general are smaller)

Open questions for discussion at the working meeting

Drell-Yan measurements and MW determination

- Several NC-DY and CC-DY observables contribute to the determination of MW

  is it a global fit in a technical sense? how are correlations treated between different quantities?

- The discussion about the ptW - ptZ interplay can possibly gain momentum starting from the

  PDF uncertainty discussion:

  how is the PDF uncertainty evaluated? how are PDF correlations included?

  is it done only for specific pairs of observables, or is it done at a global level?

- The bottom-quark treatment is a case study for the inclusion of subleading effects:

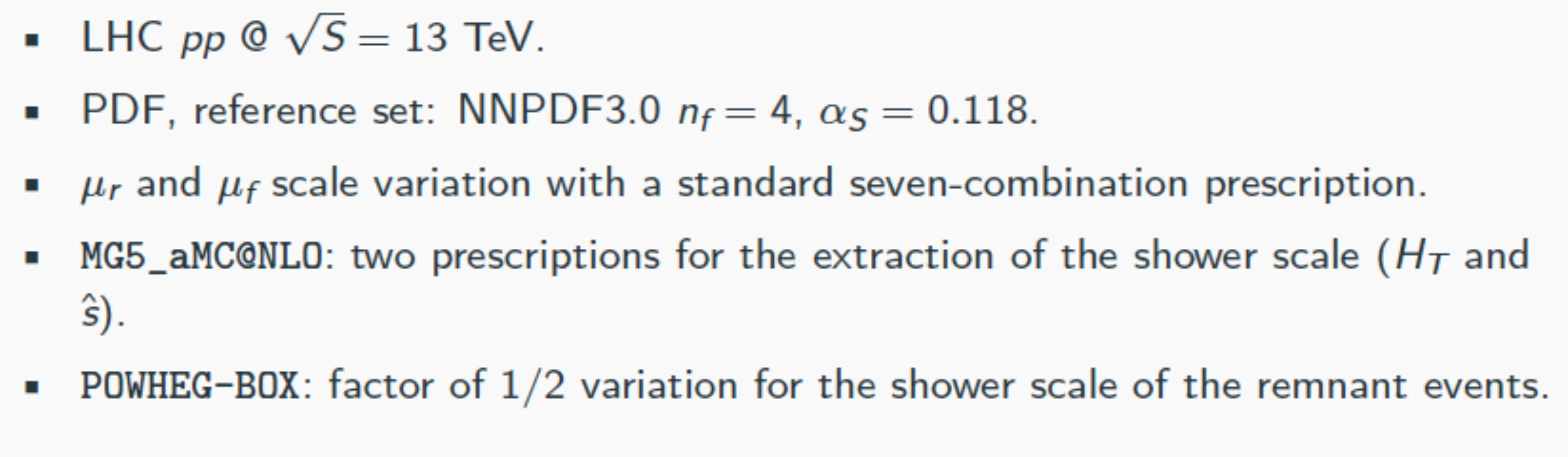
  given the availability of two descriptions, we can either

  1) choose the most precise and use it in the Parton Shower tuning

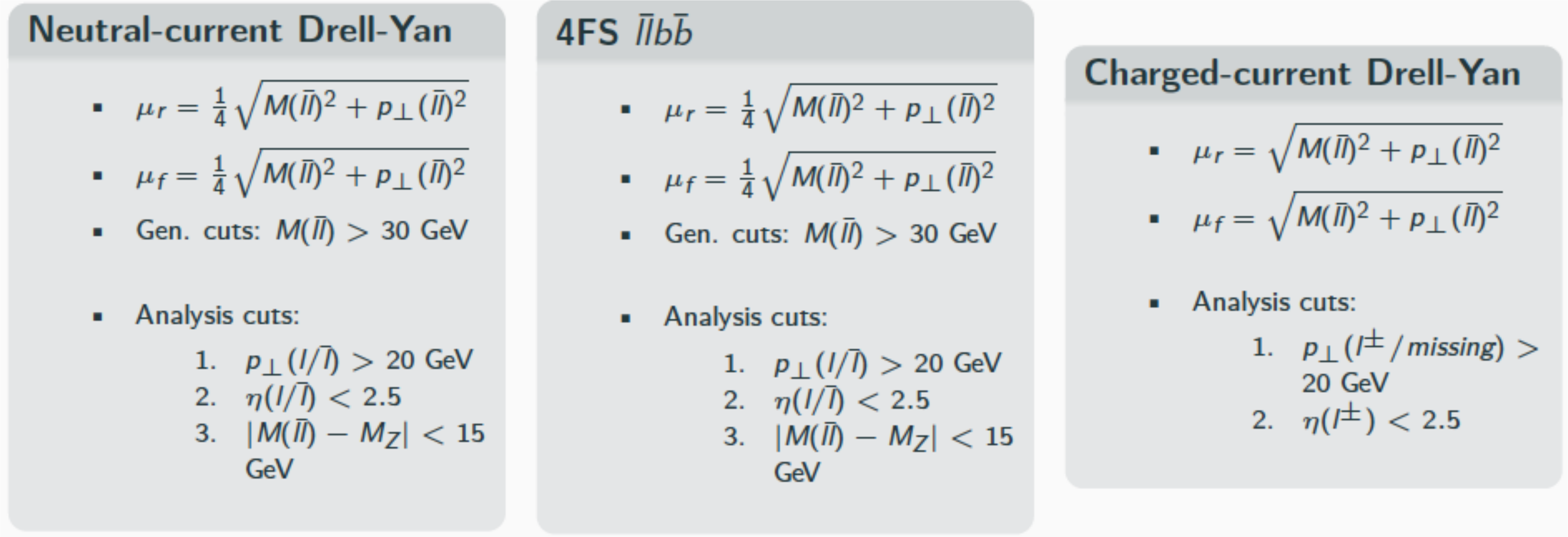
  2) introduce a nuisance parameter whose variation range covers the difference between the two

back-up slides

Setup of the simulations



- 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

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

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

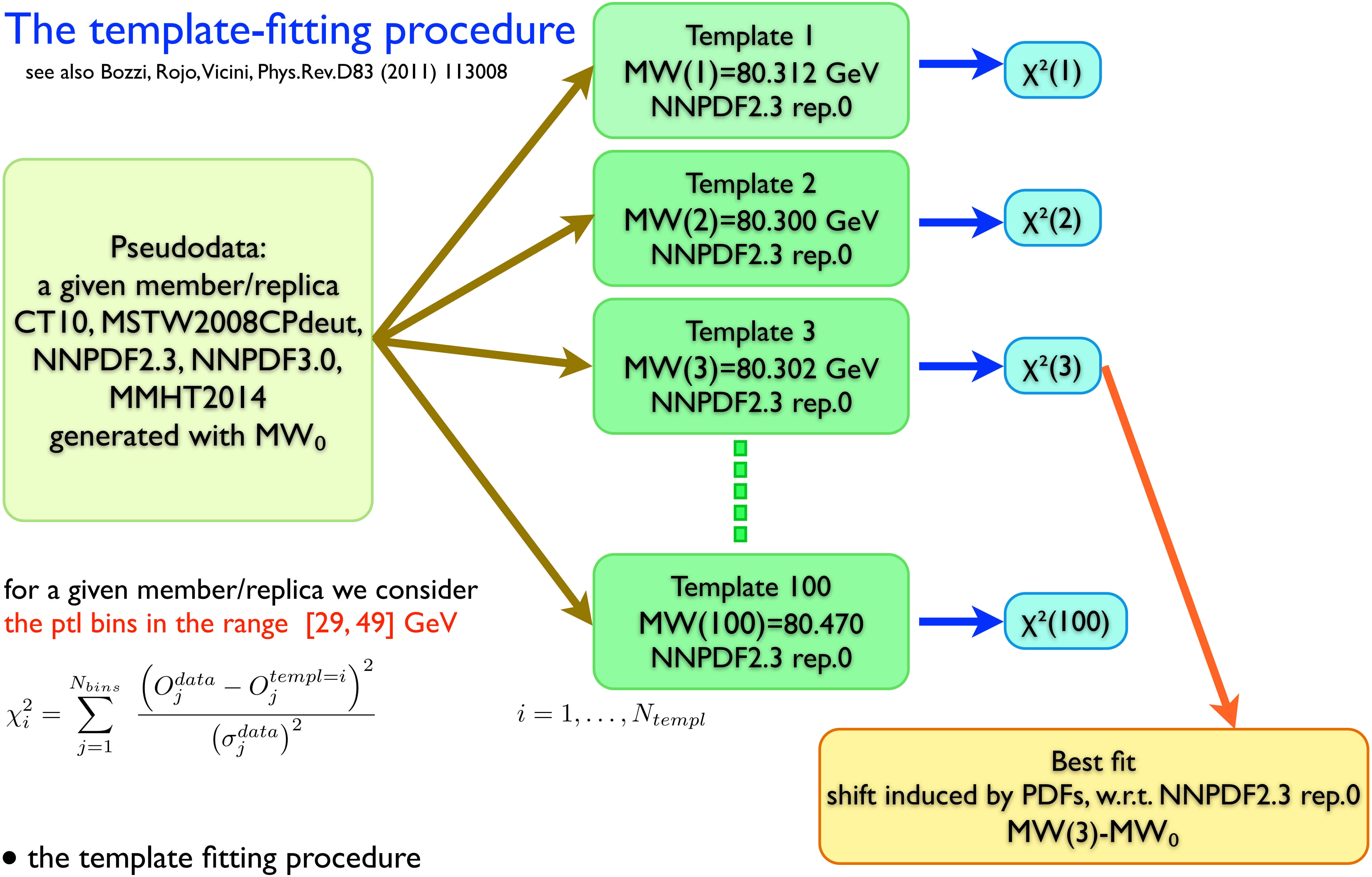
- $\mu_r = \frac{1}{4}\sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$
- $\mu_f = \frac{1}{4}\sqrt{M(l\bar{l})^2 + p_\perp(l\bar{l})^2}$
- Gen. cuts: $M(l\bar{l}) > 30$ GeV
- Analysis cuts:
  1. $p_\perp(l/\bar{l}) > 20$ GeV
  2. $\eta(l/\bar{l}) < 2.5$
  3. $|M(l\bar{l}) - M_Z| < 15$ GeV

Charged-current Drell-Yan

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

The template-fitting procedure

see also Bozzi, Rojo, Vicini, Phys.Rev.D83 (2011) 113008



Pseudodata:
a given member/replica
CT10, MSTW2008CPdeut,
NNPDF2.3, NNPDF3.0,
MMHT2014
generated with MW_0

Template 1
MW(1)=80.312 GeV
NNPDF2.3 rep.0

Template 2
MW(2)=80.300 GeV
NNPDF2.3 rep.0

Template 3
MW(3)=80.302 GeV
NNPDF2.3 rep.0

Template 100
MW(100)=80.470
NNPDF2.3 rep.0

$\chi^2(1)$

$\chi^2(2)$

$\chi^2(3)$

$\chi^2(100)$

Best fit
shift induced by PDFs, w.r.t. NNPDF2.3 rep.0
$MW(3)-MW_0$

for a given member/replica we consider
the ptl bins in the range [29, 49] GeV

$$\chi^2_i = \sum_{j=1}^{N_{bins}} \frac{\left(O_j^{data} - O_j^{templ=i}\right)^2}{\left(\sigma_j^{data}\right)^2} \qquad i = 1, \ldots, N_{templ}$$

- the template fitting procedure
measures the relative distance between NNPDF2.3 replica 0 and all the other sets/replicas
i.e.
it is an estimate of the difference that we would find if we would fit the real data with different PDFs

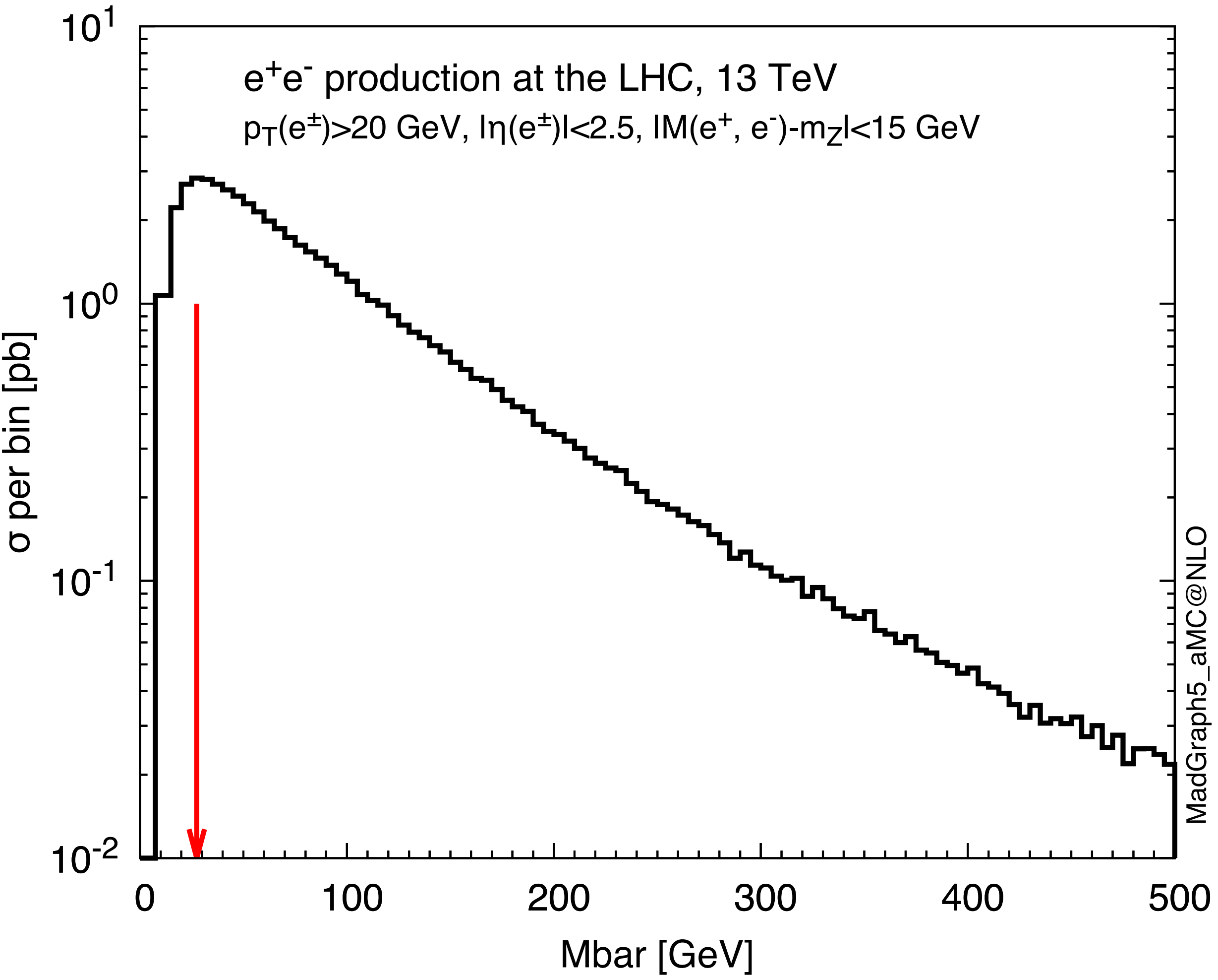
Estimate of the effective upper limit for additional radiation

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

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

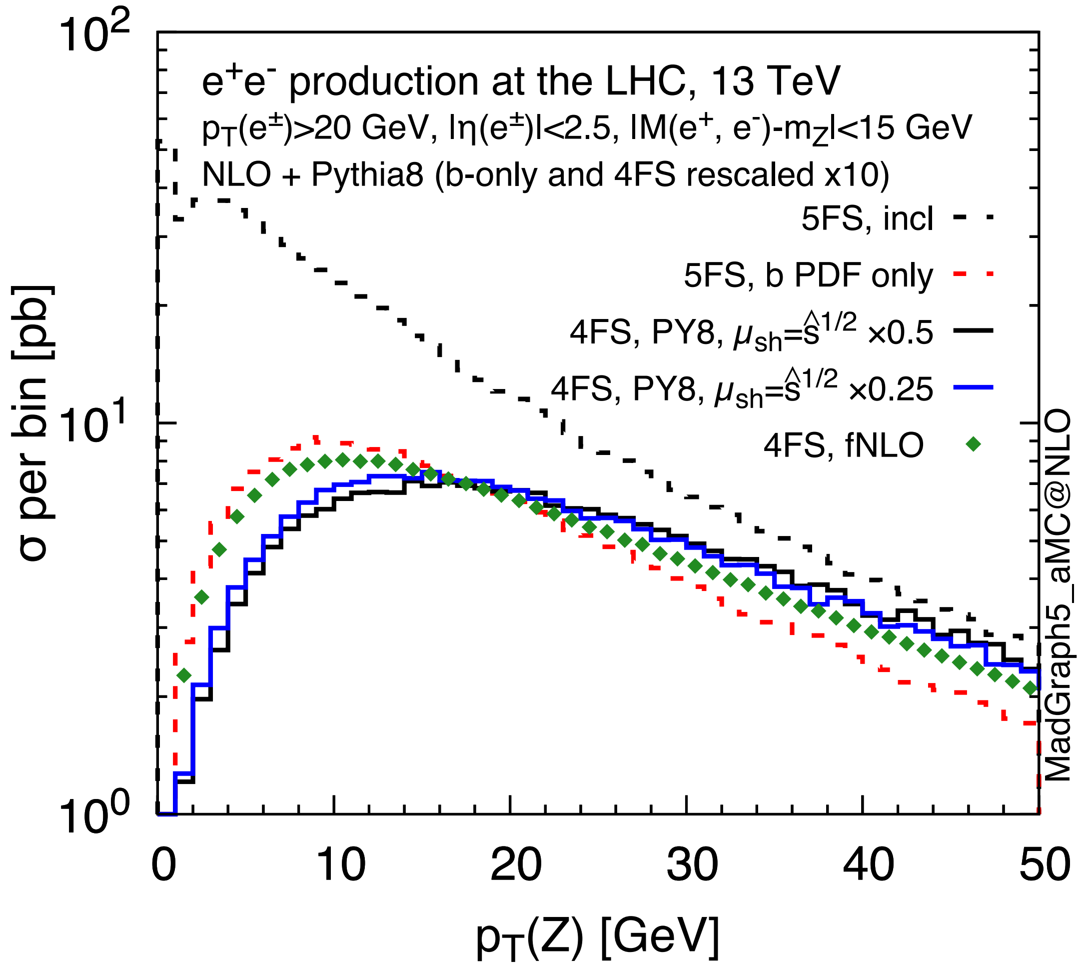
This leads to the introduction of an effective scale Mbar

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



the peak of dσ/dMbar
hints the value of a typical energy scale
of the 4FS process

Bottom contributions to ptZ in different schemes and approximations



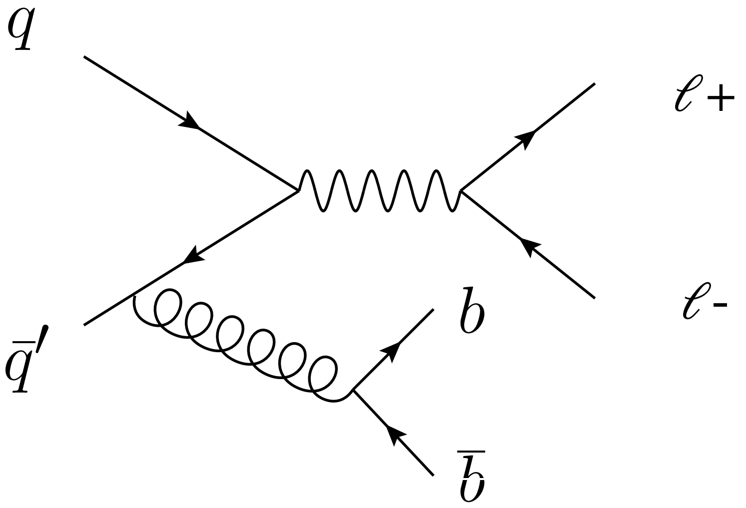
- 5FS: b-initiated subprocesses
  (technical benchmark)

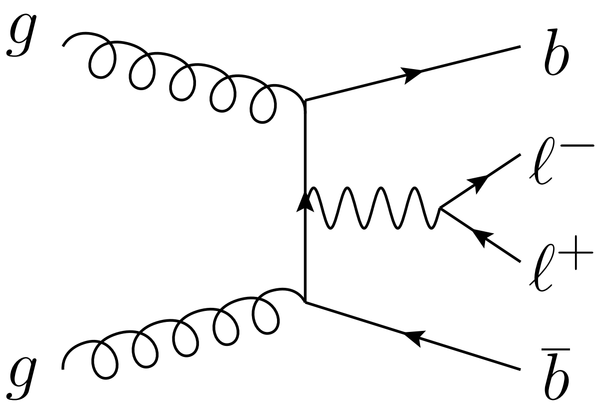
- 4FS: fixed-order NLO prediction
- 4FS: NLO-QCD + QCD-PS (Pythia 8)
  $Q_{sh} = \sqrt{\hat{s}}\ /2$
  $Q_{sh} = \sqrt{\hat{s}}\ /4$

- 4FS: sizeable impact of higher-order corrections via Parton Shower beyond NLO
  fixed-order NLO is not sufficient for a precise description of the shape of the distribution

Associated production e^+e^-bb

Associated production e^+e^-bb





- 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. Wackeroth, 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

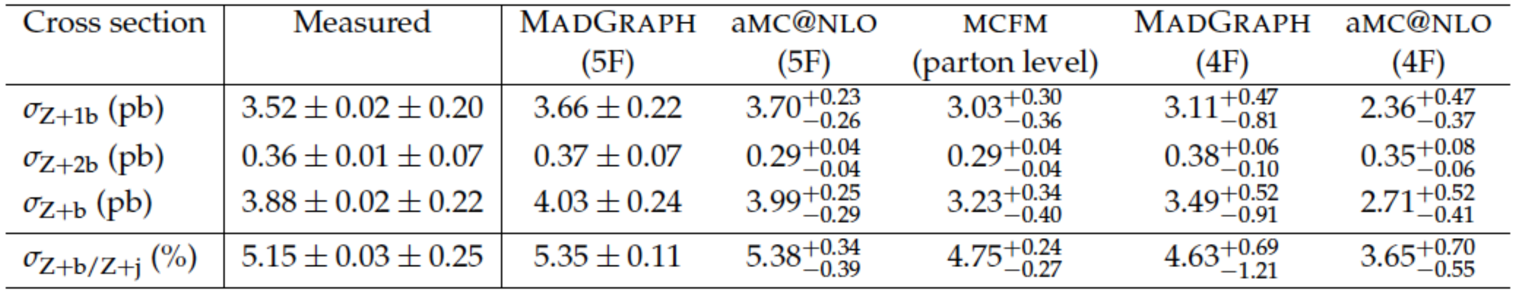
  F. Krauss, D. Napoletano, and S. Schumann, arXiv:1612.04640

- Several high precision measurements will benefit from a precise and reliable evaluation of
  the differential cross sections for this process
  the associated theoretical uncertainties

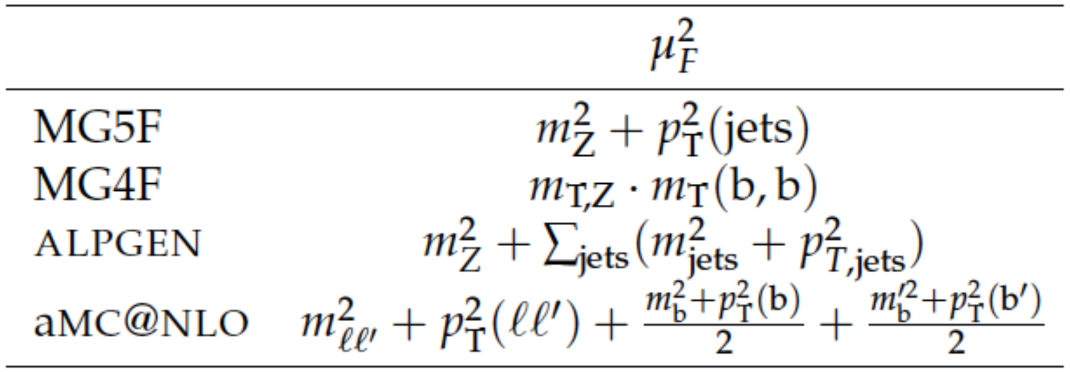
→ systematic reassessment of the theoretical uncertainties
difficult task because it is a multiscale process
→ multiple equivalent choices yield a spread of the predictions

Improvement of the (data *vs* theory) agreement

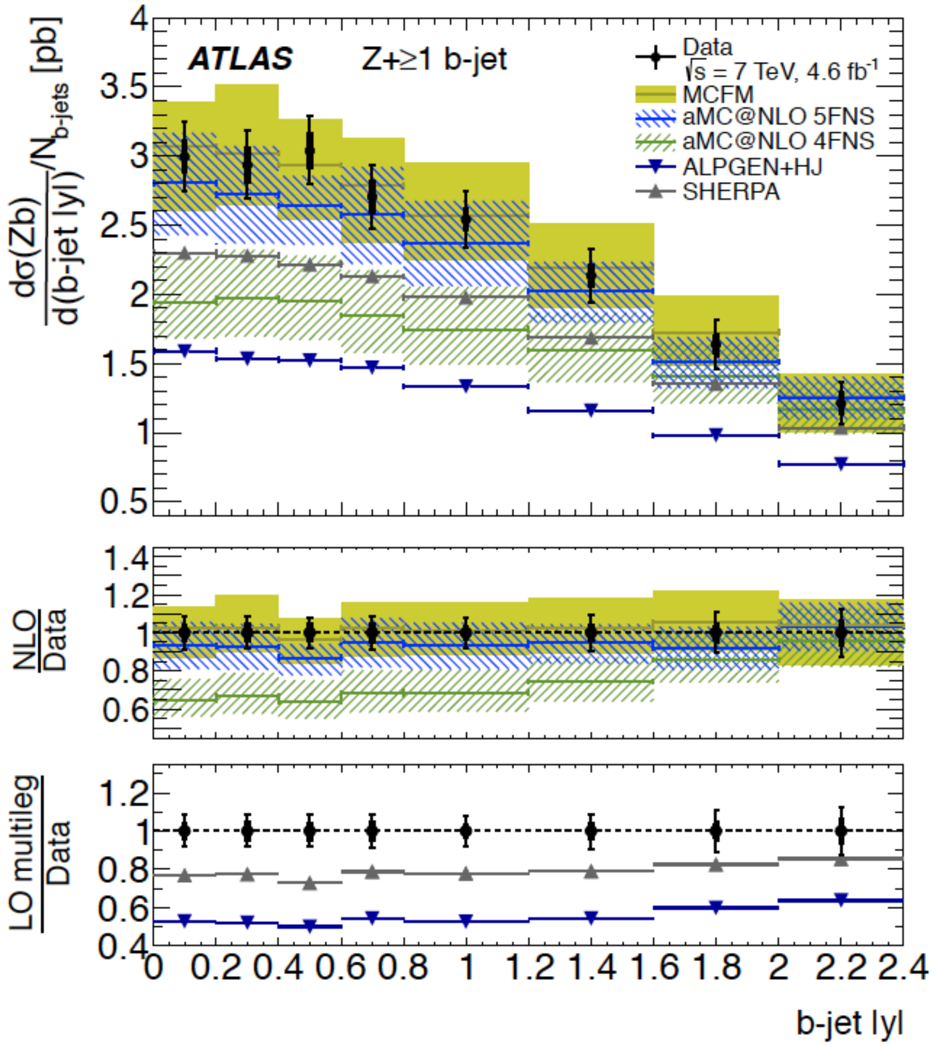
ATLAS, arXiv:1407.3643



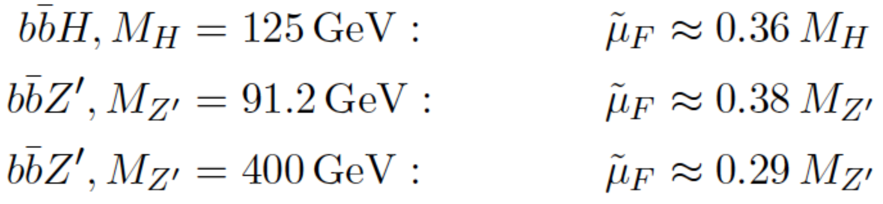
Cross section	Measured	MADGRAPH (5F)	aMC@NLO (5F)	MCFM (parton level)	MADGRAPH (4F)	aMC@NLO (4F)
σ_{Z+1b} (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.22	$3.70^{+0.23}_{-0.26}$	$3.03^{+0.30}_{-0.36}$	$3.11^{+0.47}_{-0.81}$	$2.36^{+0.47}_{-0.37}$
σ_{Z+2b} (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.07	$0.29^{+0.04}_{-0.04}$	$0.29^{+0.04}_{-0.04}$	$0.38^{+0.06}_{-0.10}$	$0.35^{+0.08}_{-0.06}$
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	$5.38^{+0.34}_{-0.39}$	$4.75^{+0.24}_{-0.27}$	$4.63^{+0.69}_{-1.21}$	$3.65^{+0.70}_{-0.55}$



	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



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

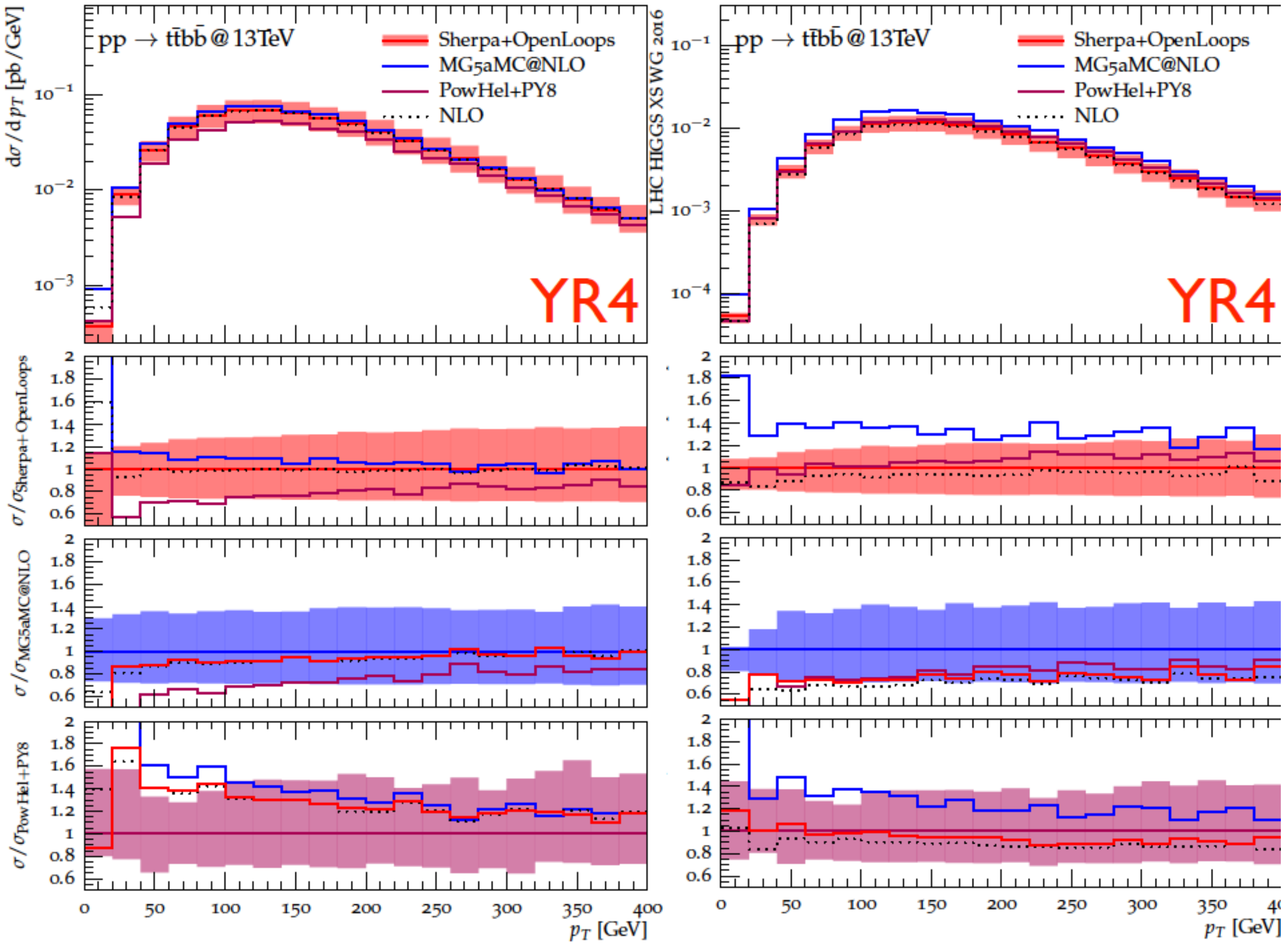
$b\bar{b}Z'$, $M_{Z'} = 91.2\,\text{GeV}$: $\tilde{\mu}_F \approx 0.38\, M_{Z'}$

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

extension also to differential distributions ?

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

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



HXSWG YR4 arXiv:1610.07922

ttbb is a crucial background to ttH

multiscale and high-multiplicity process

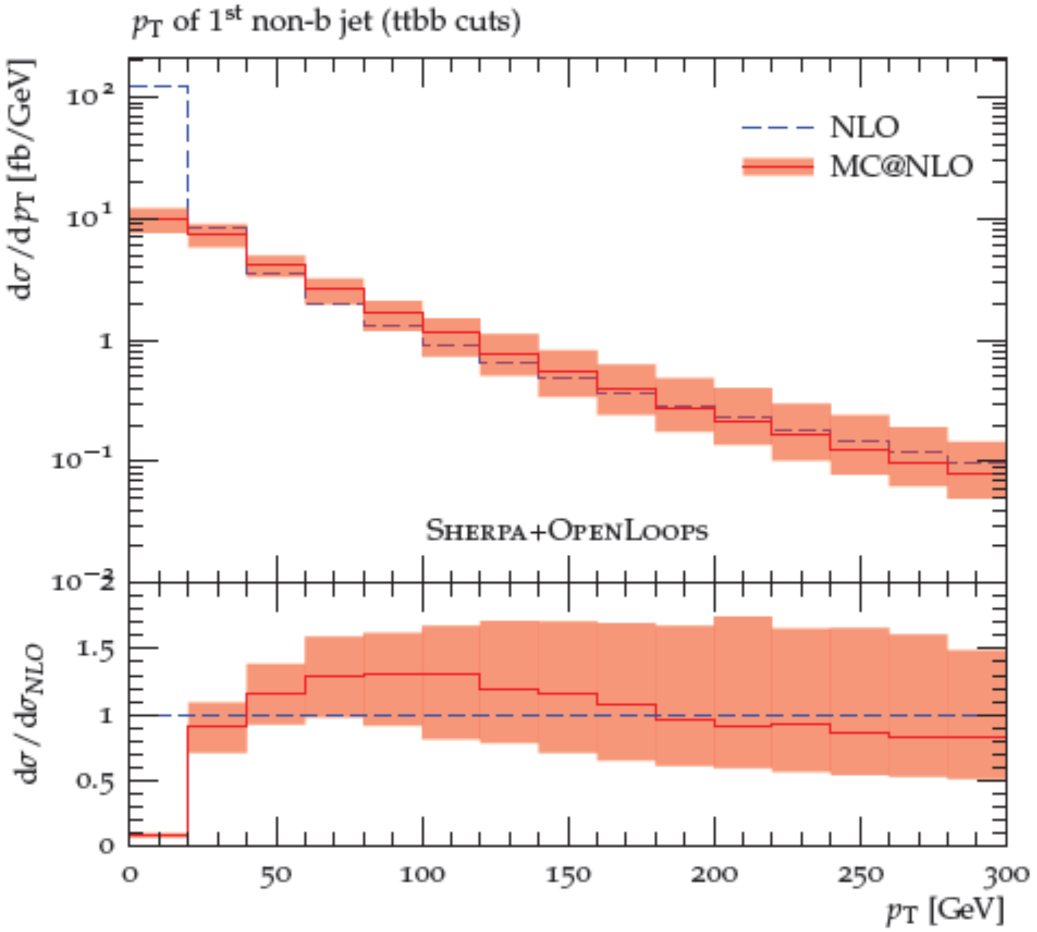
scale uncertainties of O(40%) at NLO

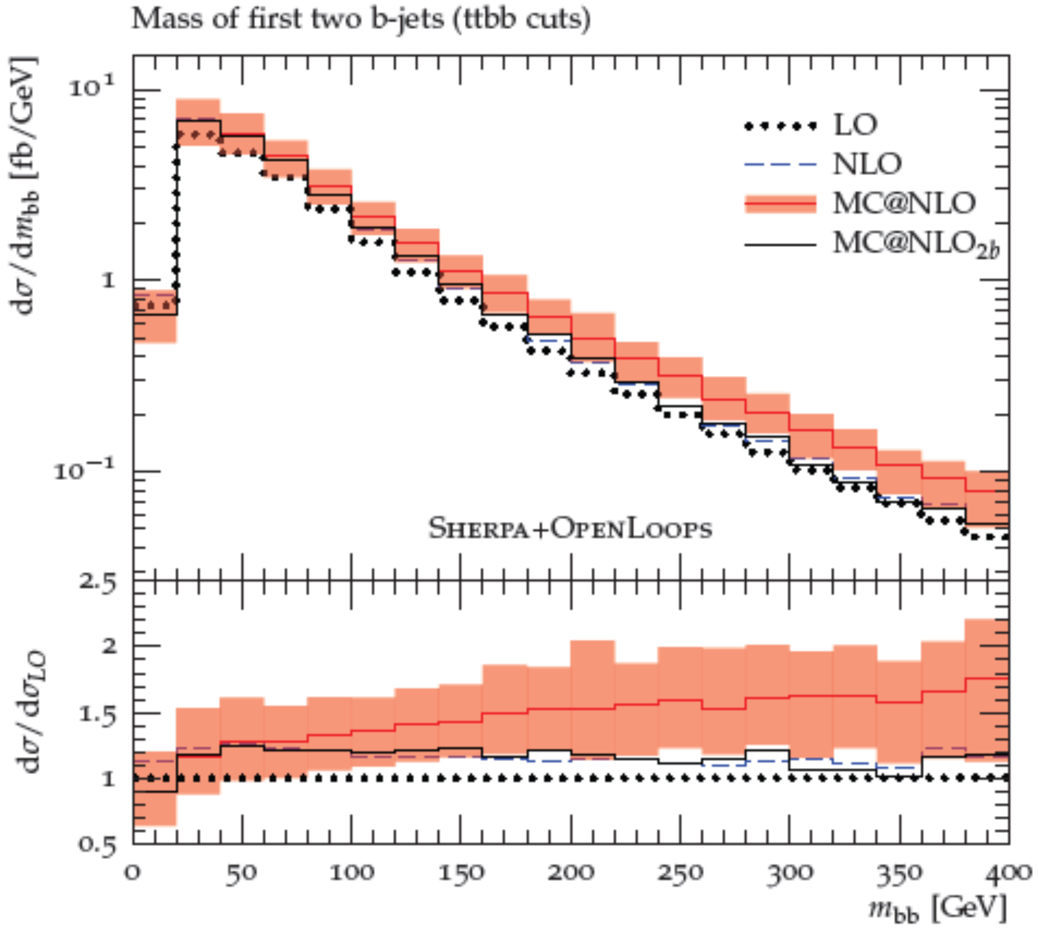
sizeable spread in predictions from different tools

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





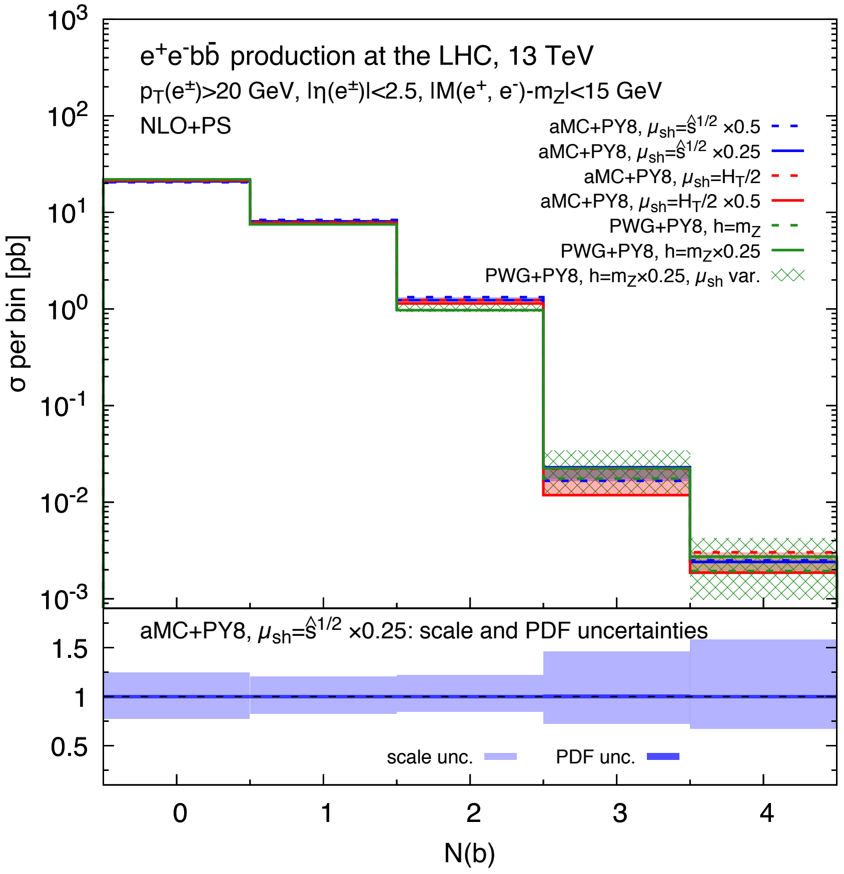
	ttb	ttbb	ttbb($m_{bb} > 100$)
σ_{LO}[fb]	$2644^{+71\%+14\%}_{-38\%-11\%}$	$463.3^{+66\%+15\%}_{-36\%-12\%}$	$123.4^{+63\%+17\%}_{-35\%-13\%}$
σ_{NLO}[fb]	$3296^{+34\%+5.6\%}_{-25\%-4.2\%}$	$560^{+29\%+5.4\%}_{-24\%-4.8\%}$	$141.8^{+26\%+6.5\%}_{-22\%-4.6\%}$
σ_{NLO}/σ_{LO}	1.25	1.21	1.15
σ_{MC}[fb]	$3313^{+32\%+3.9\%}_{-25\%-2.9\%}$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

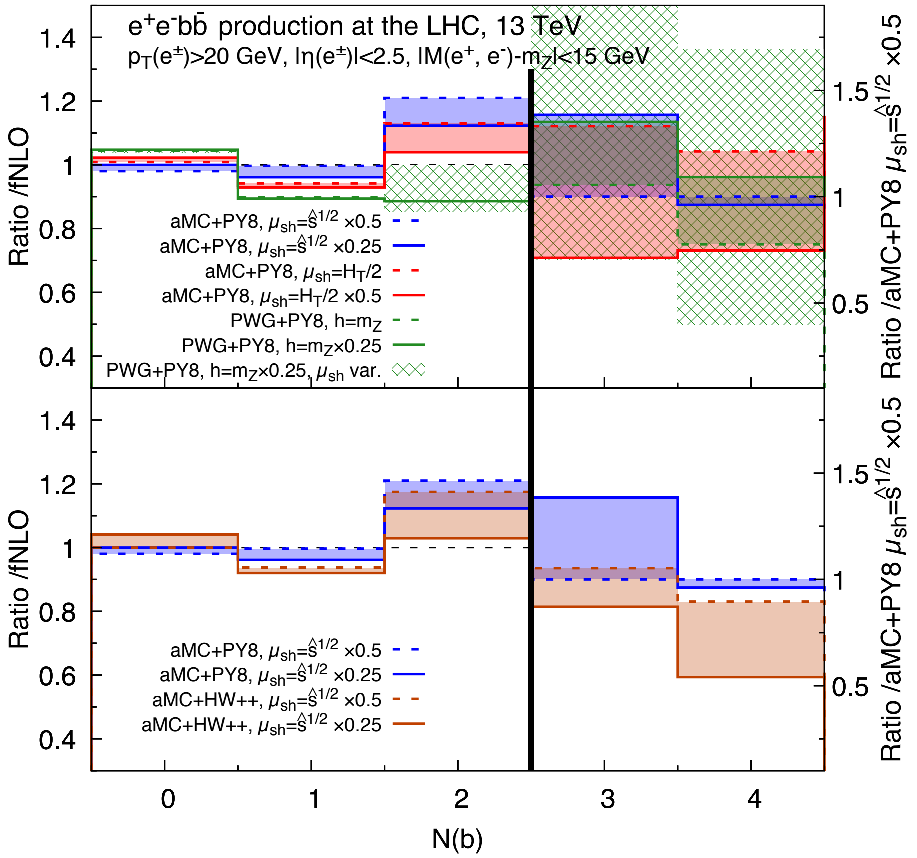
large additional contribution from g→bb splitting in the Parton Shower growing with the bb-pair invariant mass

in general PS effects at the few% level are expected

Exclusive signatures with tagged b-jets (B hadrons)

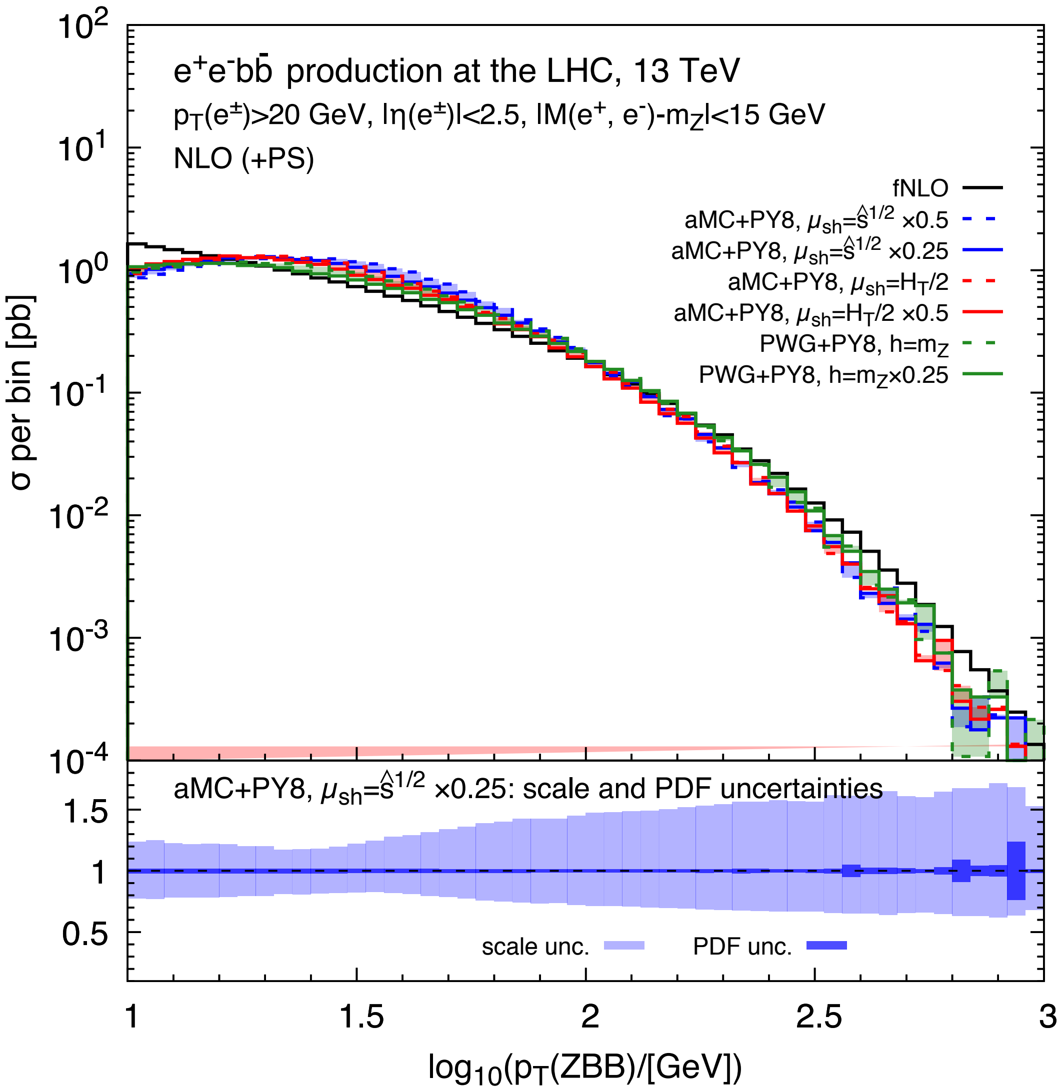
e^+e^-bb: b-jet multiplicities

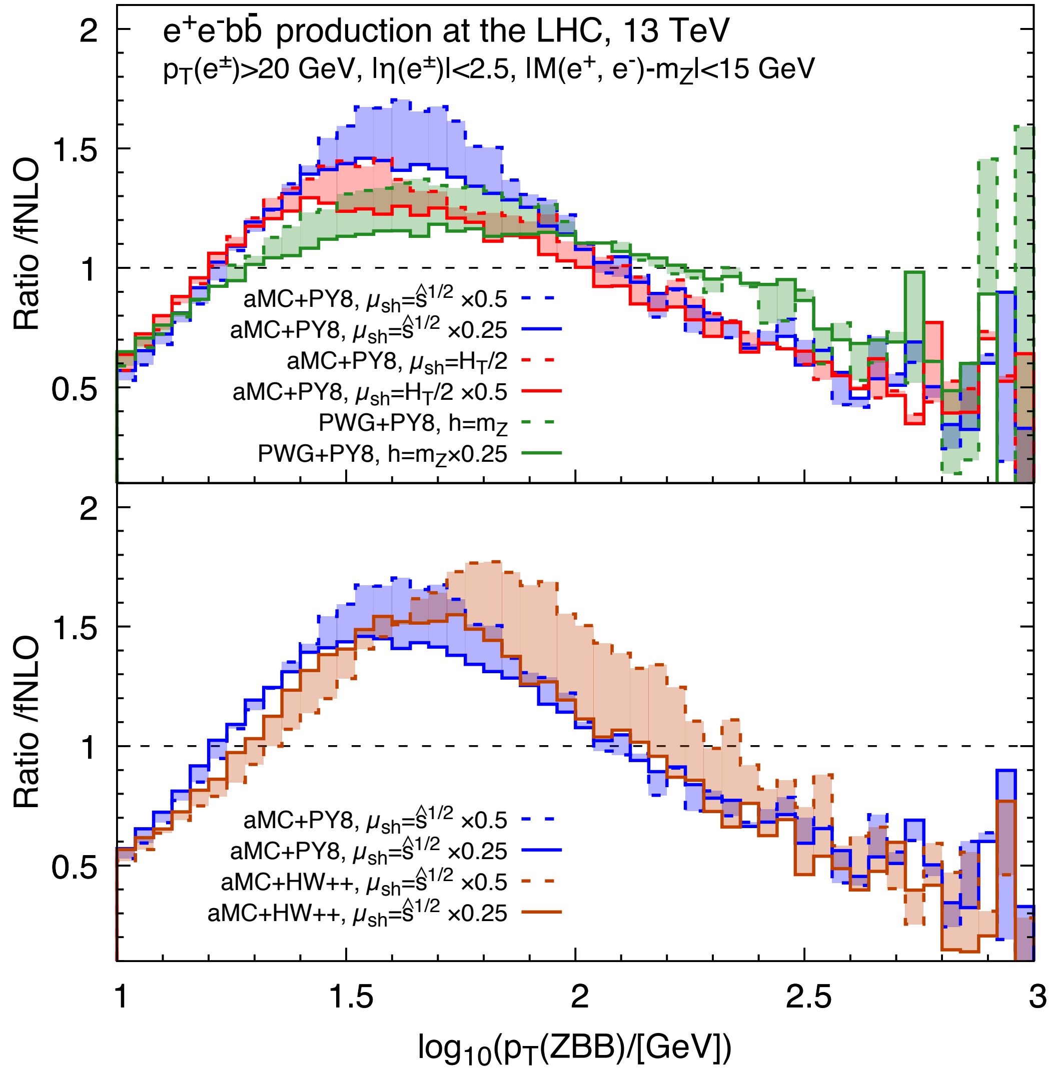




- a crucial quantity to understand the comparison between aMC@NLO and POWHEG at the exclusive level (classification w.r.t. the number of additional b-jets)
- the Parton Shower distorts the distribution of the final state bb pair (pushing in/out the acceptance)
  adds additional splittings g→bb, which may be successfully tagged as b-jets
- in POWHEG the PS reduces the number of tagged b-jets, sensitive to the *scalup* 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^-bb: pt distribution of the e^+e^-BB final state

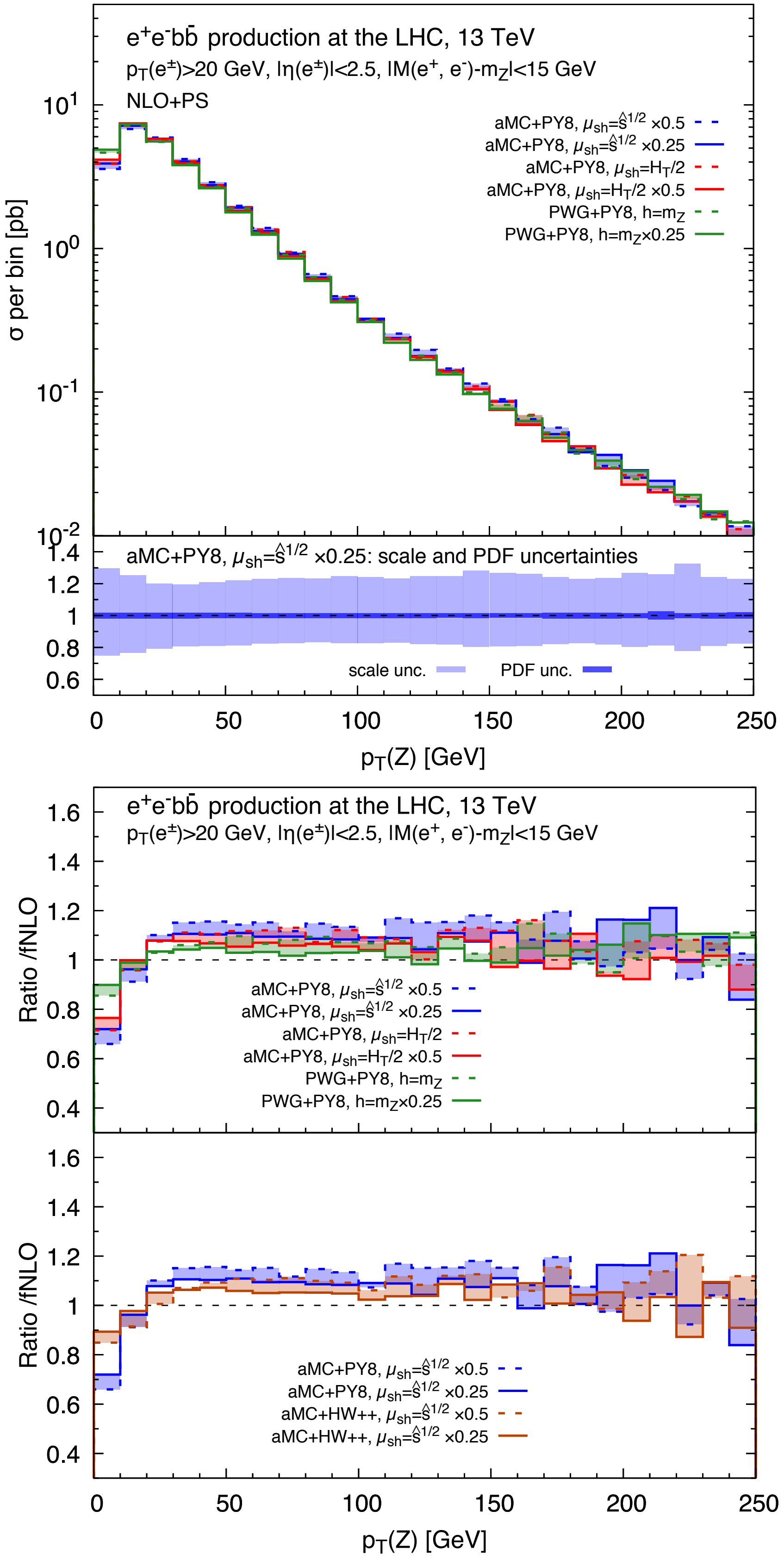




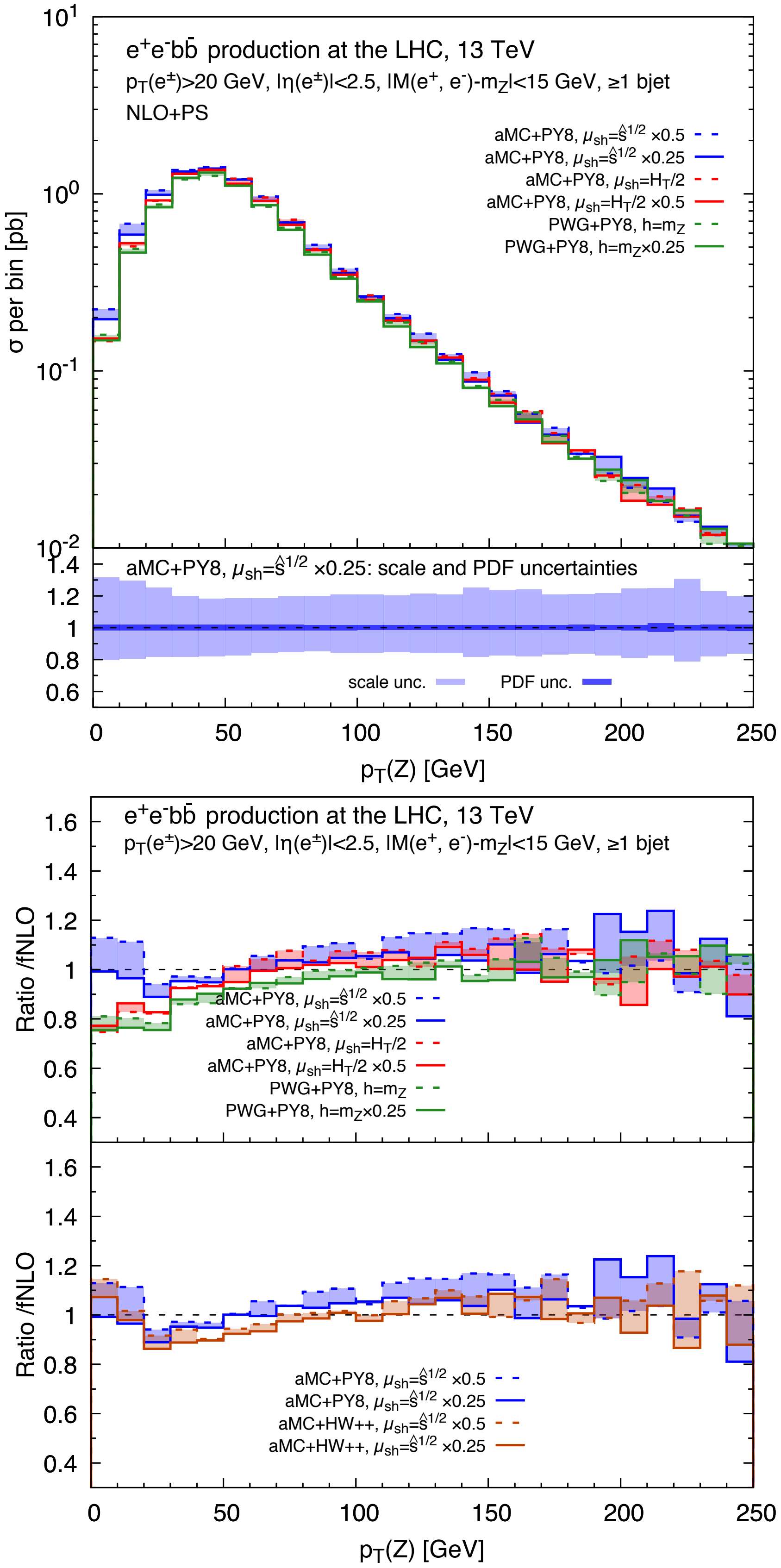
- a crucial quantity to understand the radiation patterns beyond NLO (defined in terms of b quarks)
- competition between initial and final state radiation
- the observed higher-order effects are common to all the codes, PS models, shower scale choices
- strong Sudakov suppression at low pt, strong enhancement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

e^+e^-bb: lepton-pair pt distribution in association with N b-jets

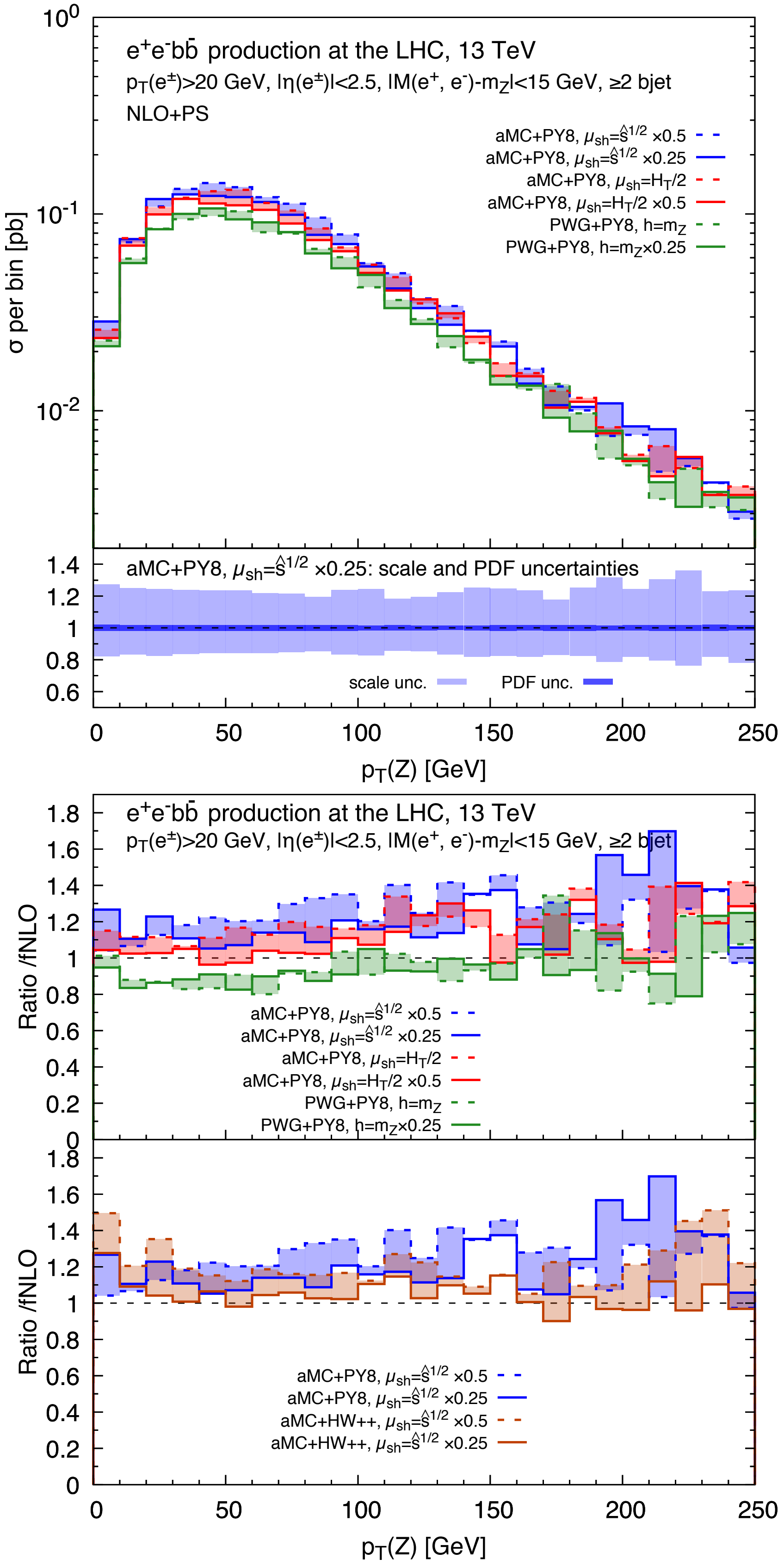
≥0 b-jets



≥1 b-jets



≥2 b-jets

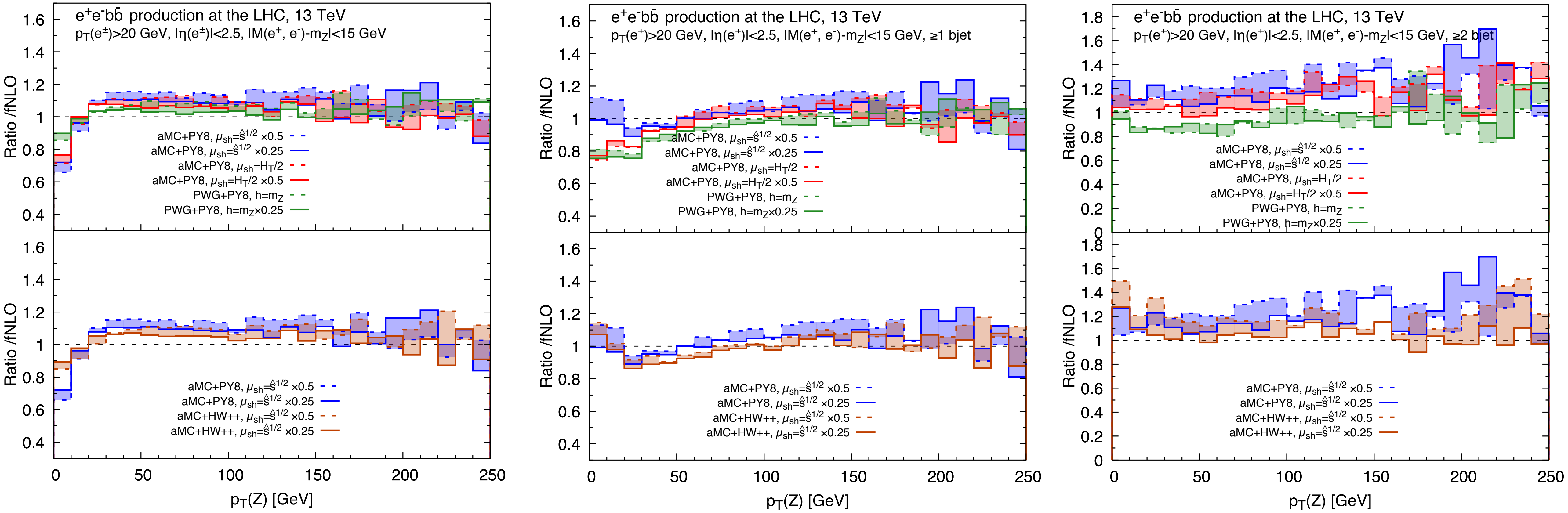


e^+e^-bb: lepton-pair pt distribution in association with N b-jets

- scale + PDF uncertainties at the ±20% level, with dominant scale uncertainties
- each shower-scale choice has an O(±10%) band, but the envelope of the bands spans a larger range

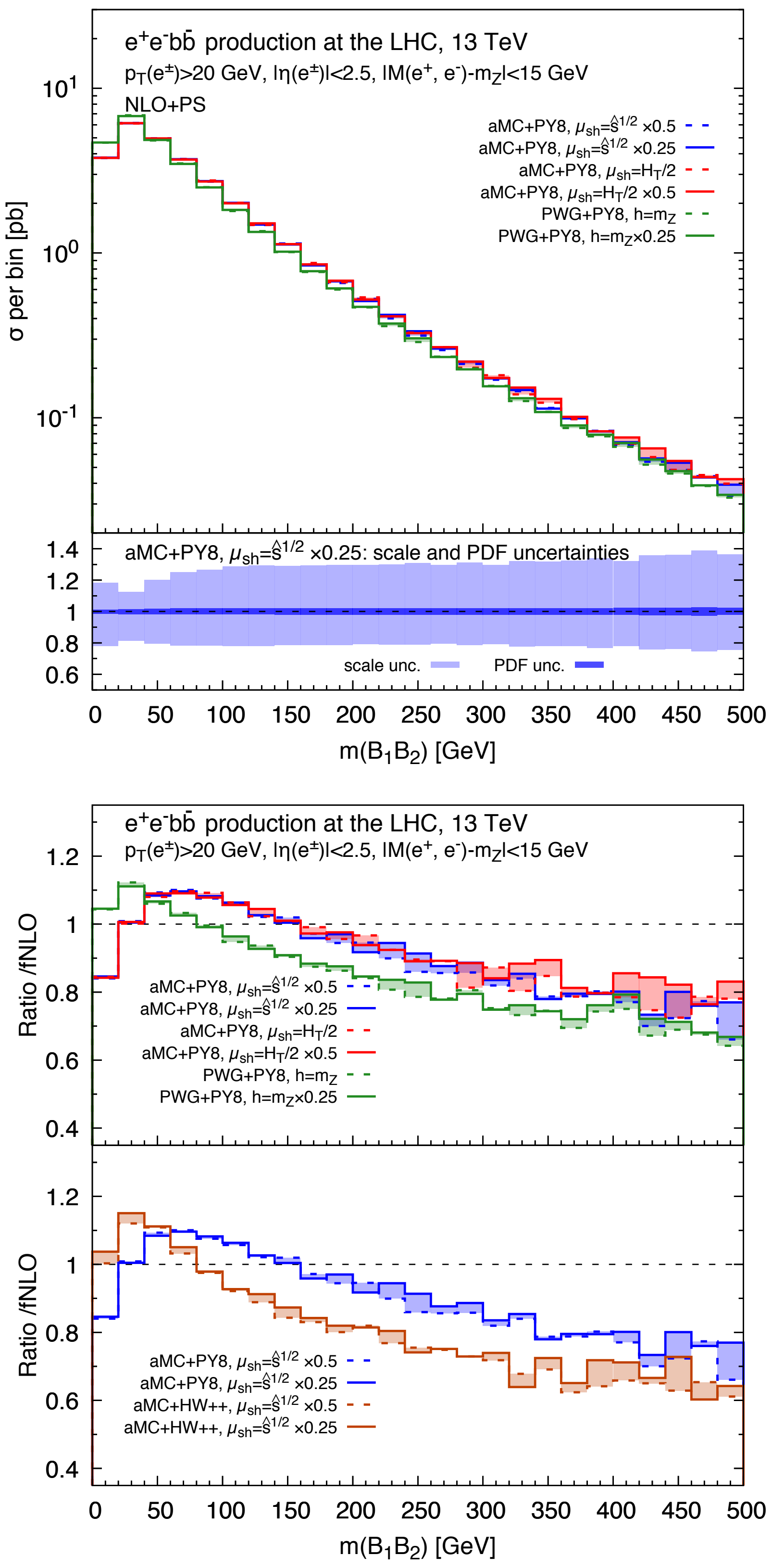
- with 2 tagged b-jets, the PS effects are flat over the whole ptZ range
- with 0 or 1 tagged b-jets, at low ptZ there are stronger differences
  between different matchings and different shower scale choices

- Pythia vs Herwig, with aMC@NLO and with the same shower scale are marginally compatible

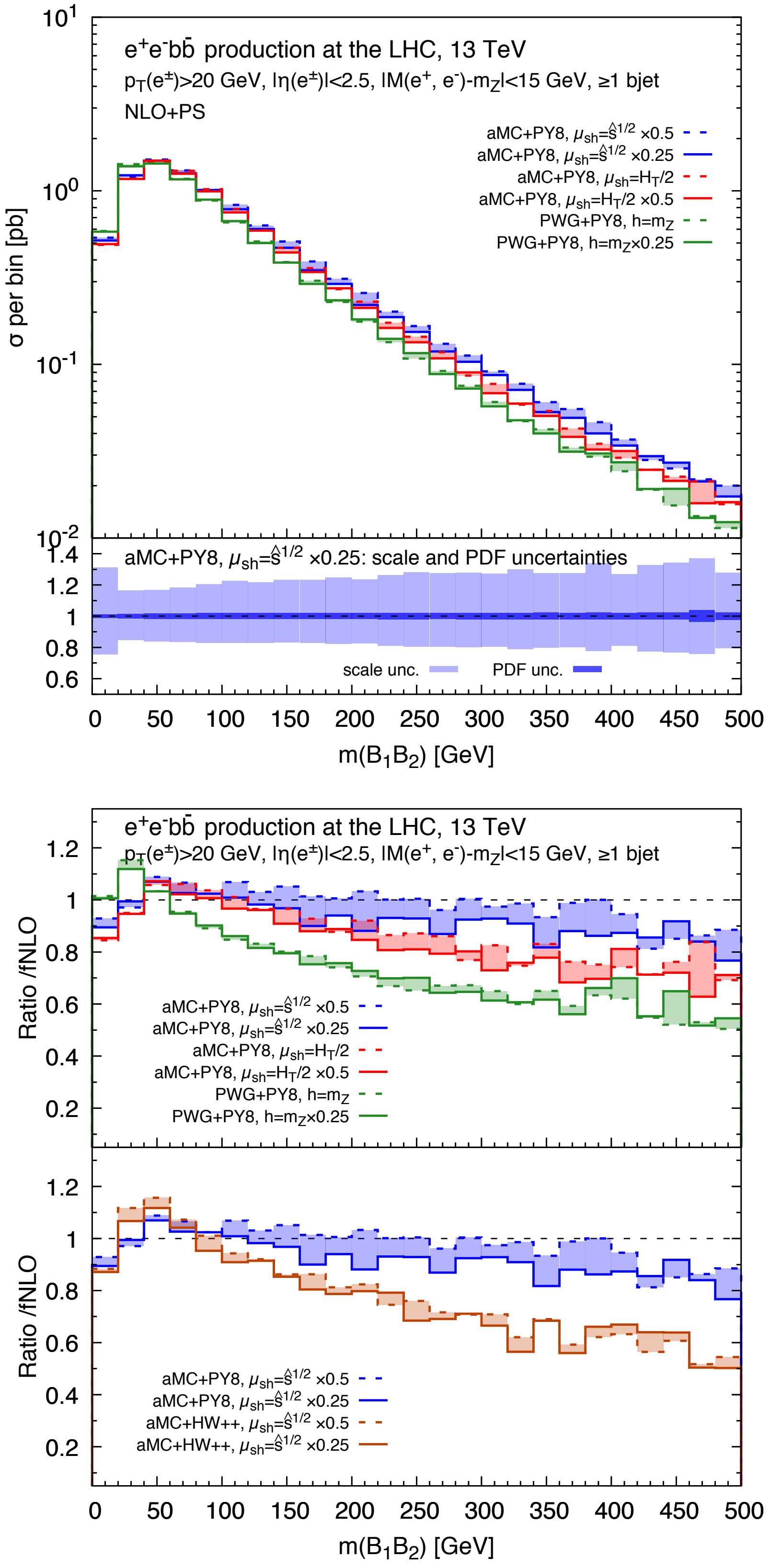


e^+e^-bb: B-pair invariant mass distribution in association with N b-jets

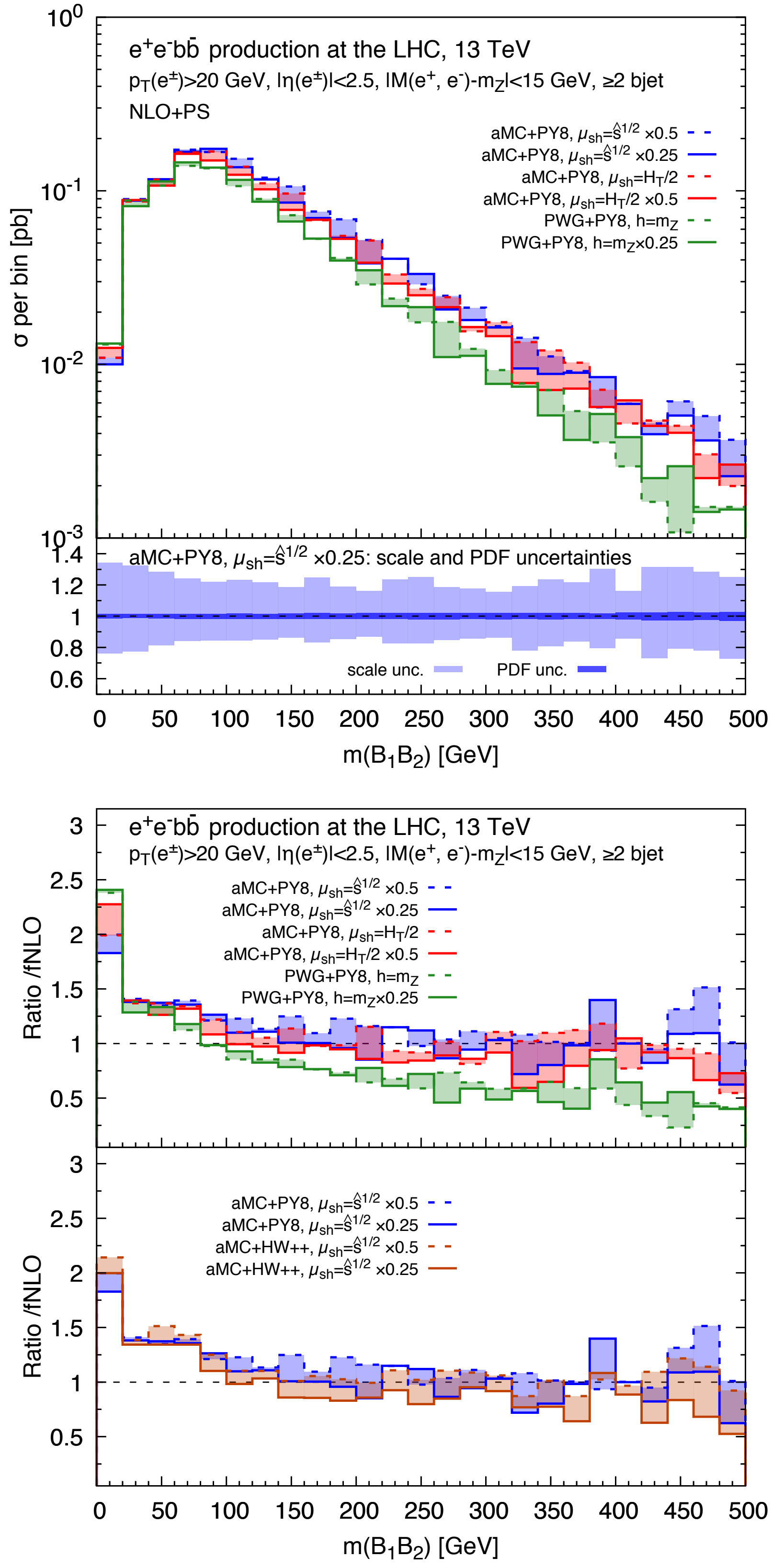
≥0 b-jets



≥1 b-jets



≥2 b-jets



e^+e^-bb: B-pair invariant mass distribution in association with N b-jets

- scale + PDF uncertainties at the (±15% - ±25%) level, with dominant scale uncertainties
- each shower-scale choice has an uncertainty band up to O(±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→bb splittings via the shower
- with 0 tagged b-jets, aMC@NLO has non 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