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Bottom quark effects on the ptZ distribution and their impact on the MW determination

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Theory Institute "LHC and the Standard Model: Physics and Tools"

CERN, June 22nd 2017

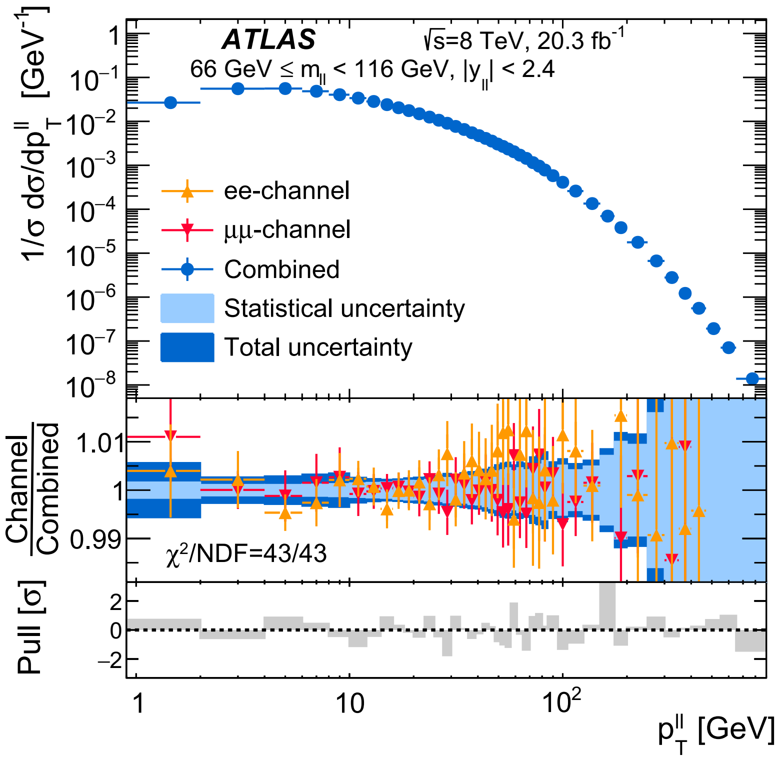
preliminary results of a work in collaboration with: E.Bagnaschi, F.Maltoni, M.Zaro

Relevance of the ptZ distribution for the MW determination

the very high precision ptZ measurement

- challenges the theoretical predictions at the sub percent level
- offers the possibility to tune the non-perturbative (NP) models describing the low-pt part of the ptZ spectrum

→ these models can be then used in the simulation of CC-DY



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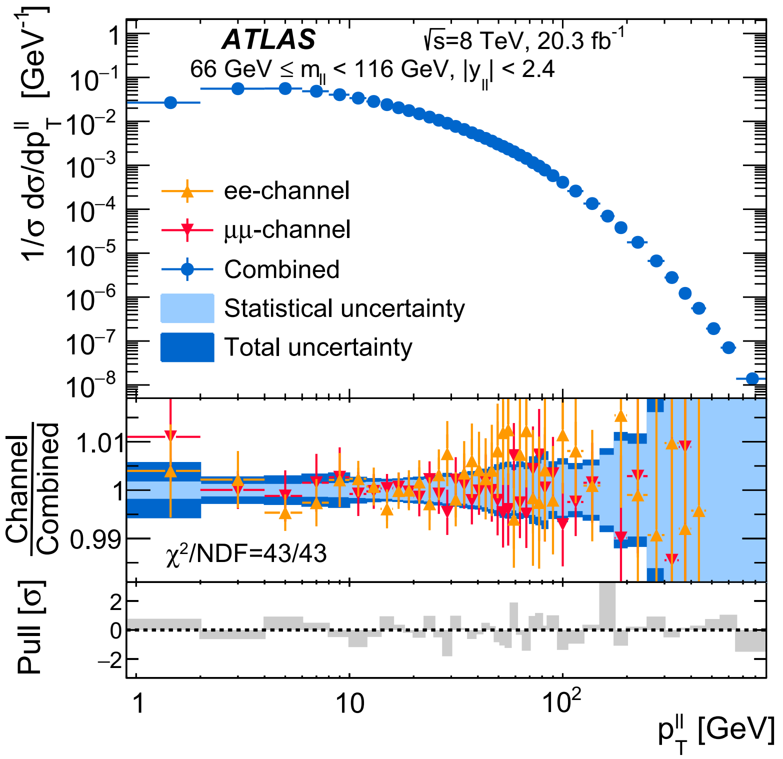

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  → in turn affect the MW determination

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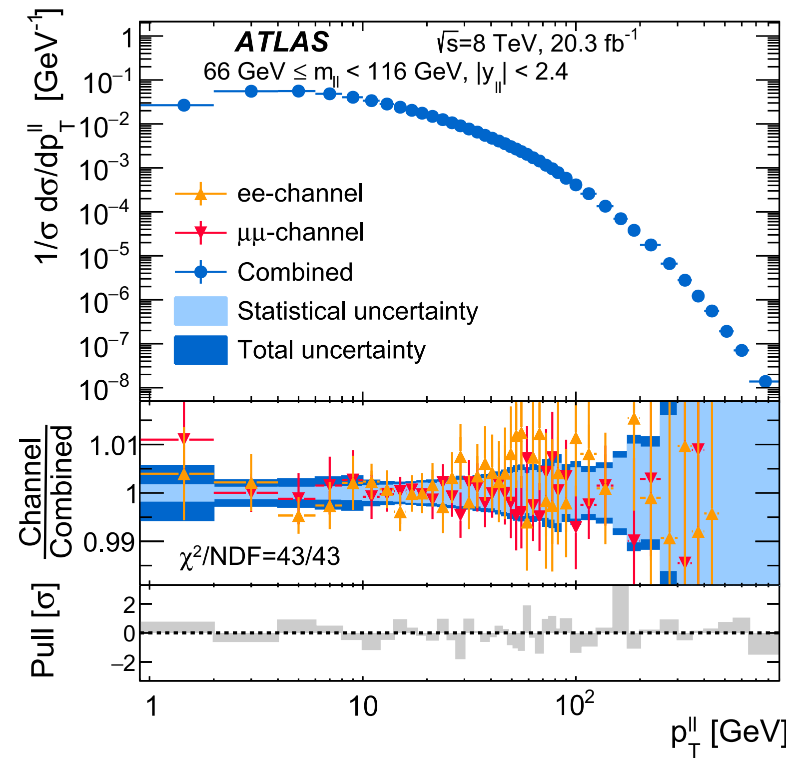

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- an improved partonic description of the bottom quark contribution to ptZ may
  → increase the overall precision of the theoretical predictions
  → reduce the amount of information to be encoded in the NP models
  → reduce the differences between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

Strategy to improve the ptZ description

we consider the processes

p p → e+e- + X   Drell-Yan (lepton-pair production inclusive over extra radiation) 5FS

p p → e+e- b bbar (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)

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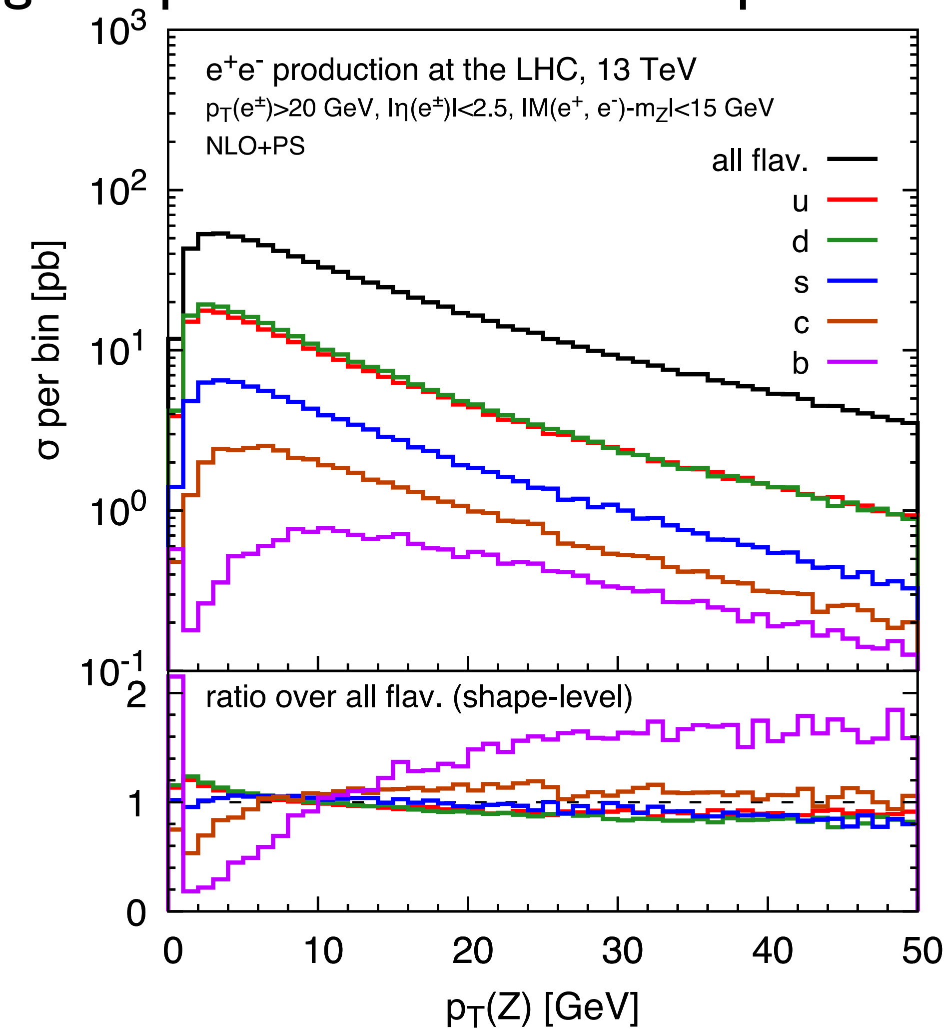

- the PDF evolution starts for the heavy quarks at Q ~ mq

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

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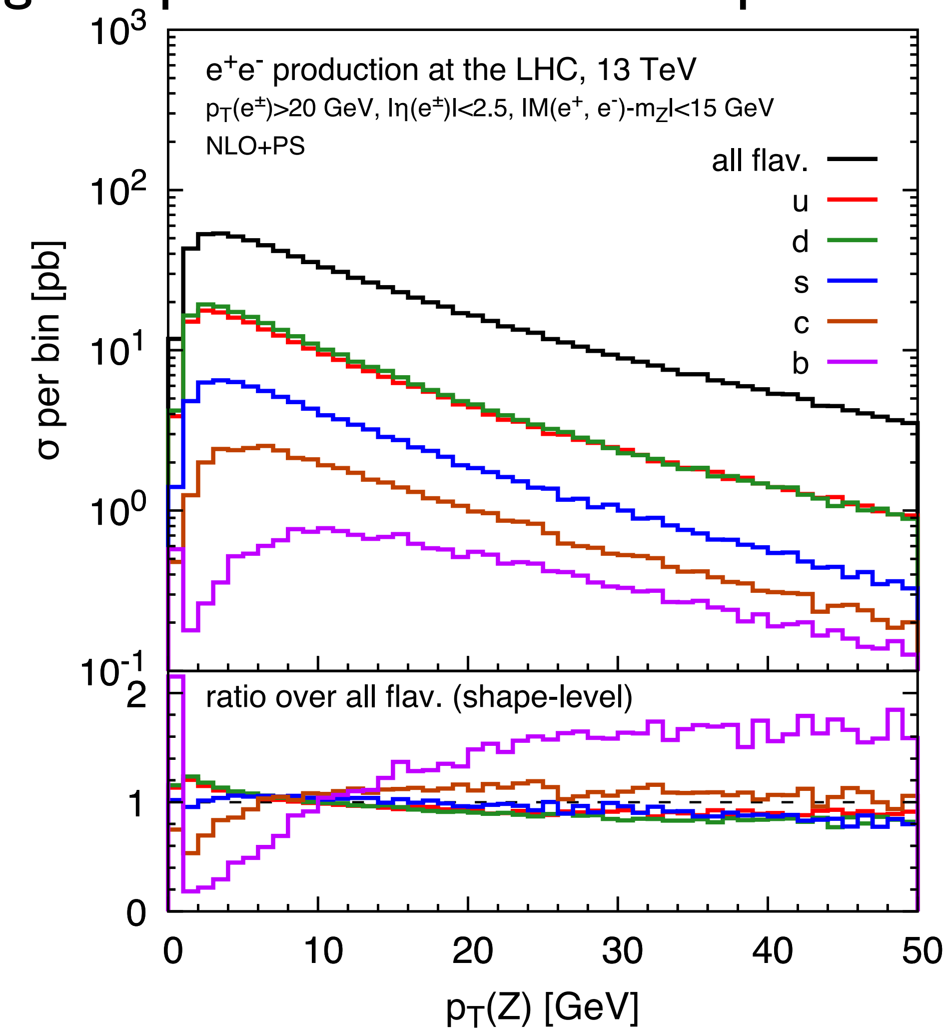


initial state quark	cross section (pb)	%
u	374.44 ± 0.62	35.0
d	391.15 ± 0.63	36.5
c	91.44 ± 0.34	8.6
s	170.43 ± 0.45	15.9
b	43.13 ± 0.26	4.0
total	1070.58 ± 0.86	100.0

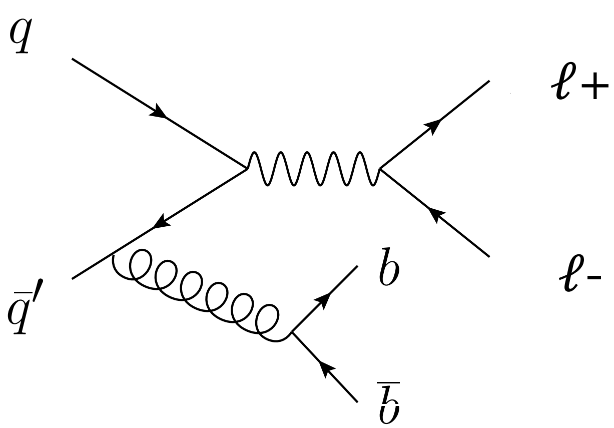
- given the exp error below 0.5% in a large range the bottom contribution of O(4%)

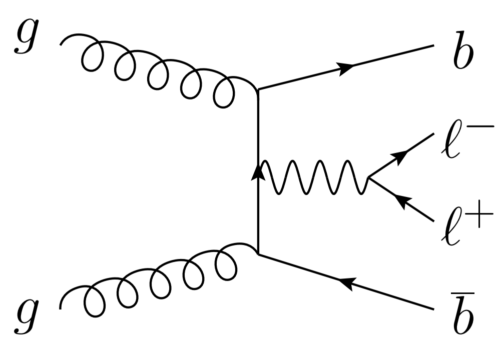
→ we need a prediction of the b contribution with a precision at the O(10%) level

- 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

Z b bbar associated production in the 4FS (pp→e$^+$e$^-$b bbar)

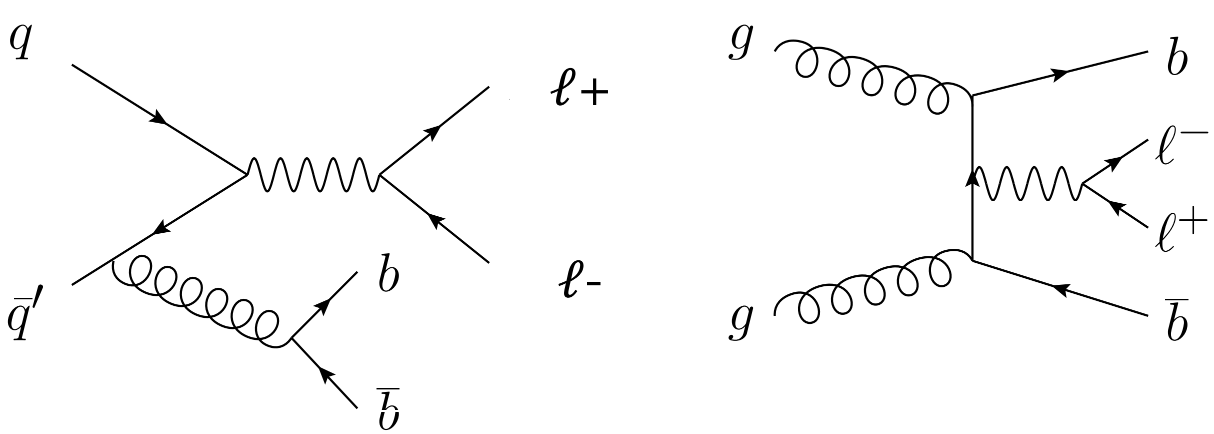




in the 4FS the bottom quark

- 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

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



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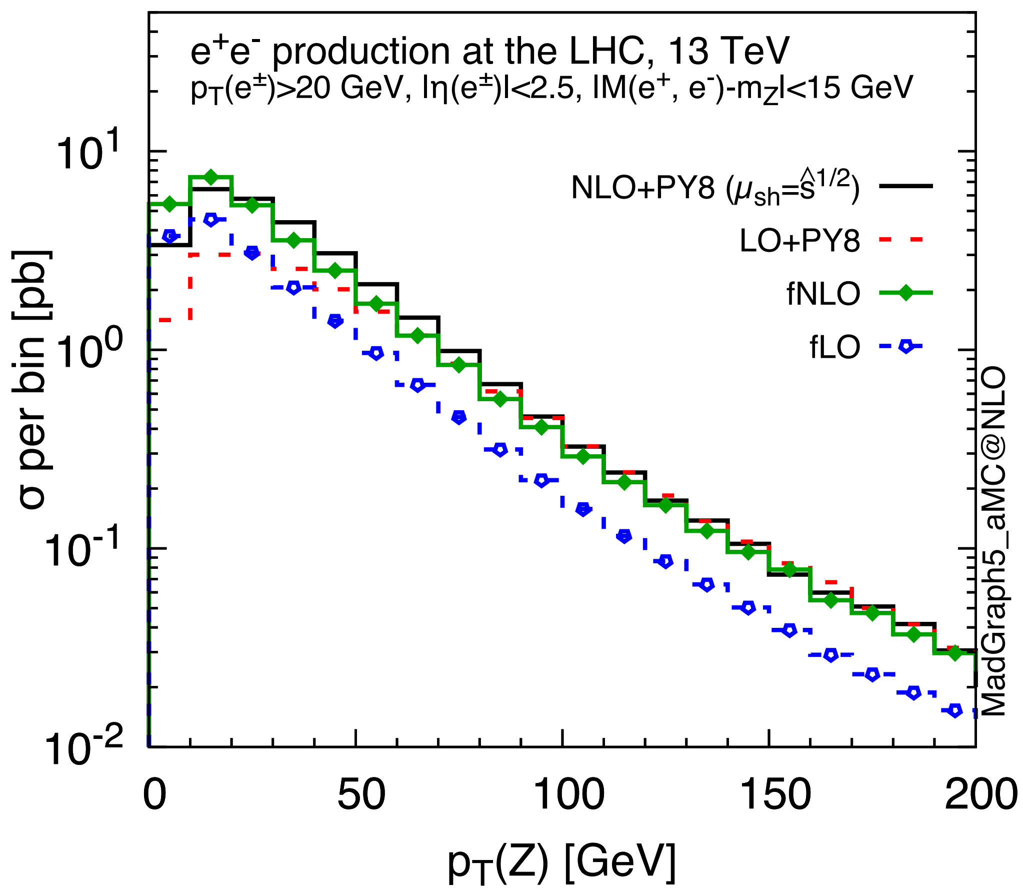
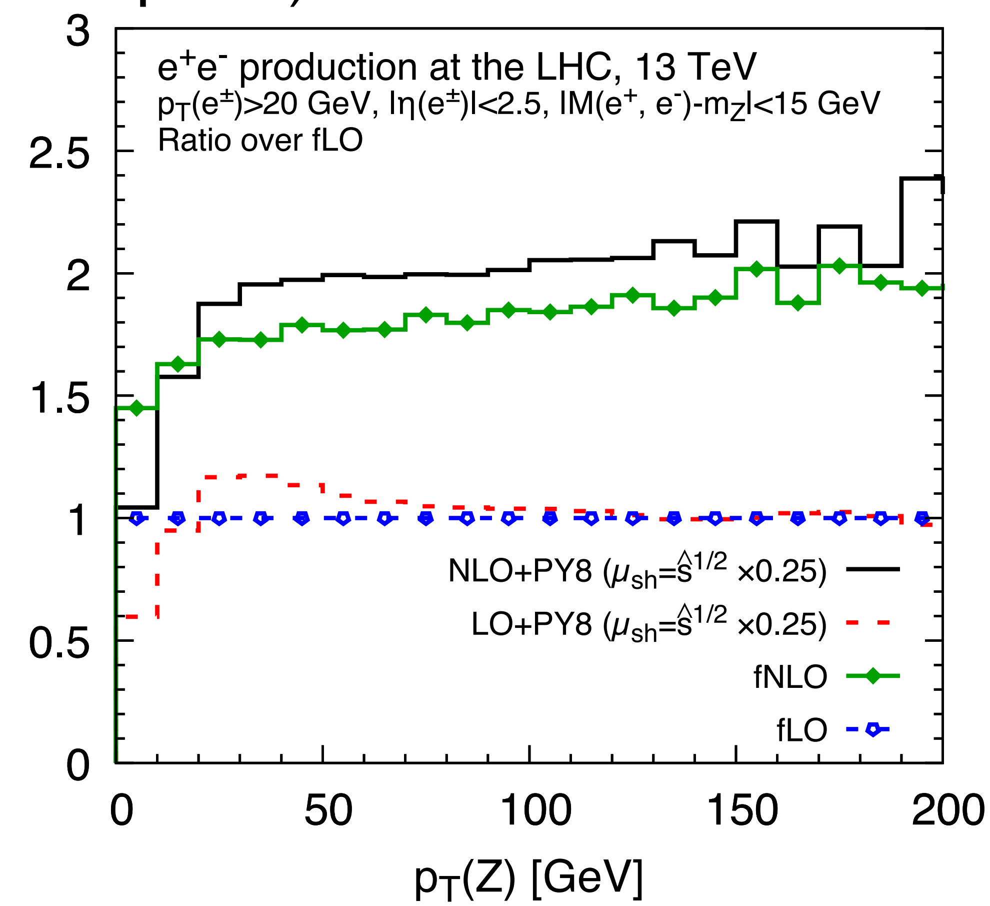
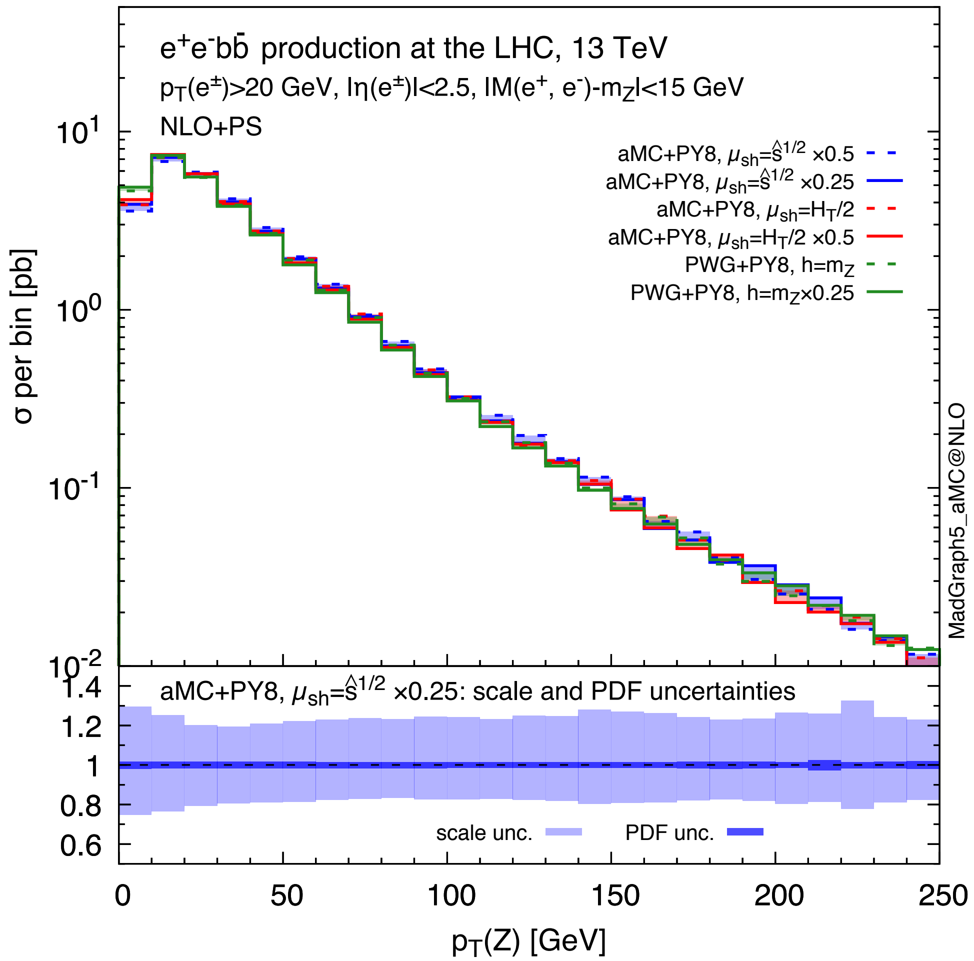
ptZ distribution (inclusive over b quarks)

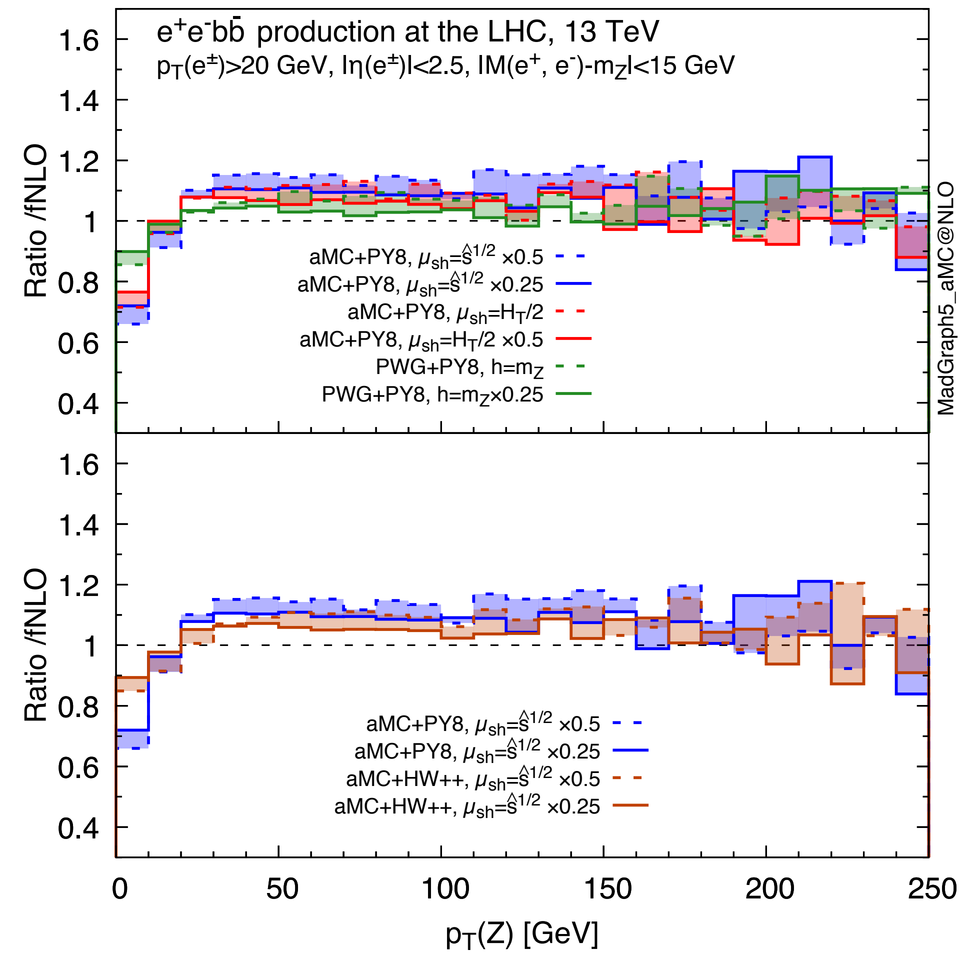




- regular when ptZ→0, but still sensitive to large log effects
- the process has a large NLO K-factor
- large multiple gluon emission effects via QCD Parton Shower, for ptZ < 50 GeV

ptZ distribution in the 4FS ($pp \to e^+e^- b\,\bar{b}$): 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

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

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- 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 $pp \to e^+e^- b\,\bar{b}$ contains bottom quarks in the final state
  additional b bbar pairs may be produced by gluon splitting

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

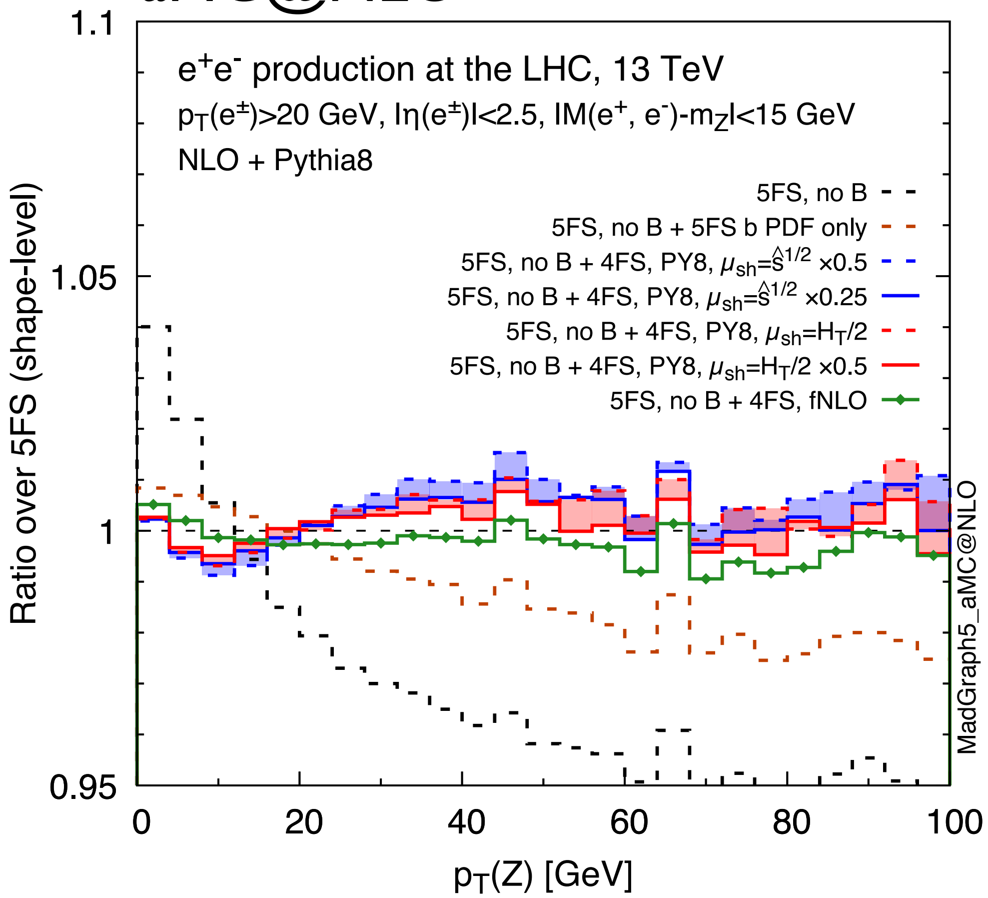
Improved prediction of the ptZ distribution

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

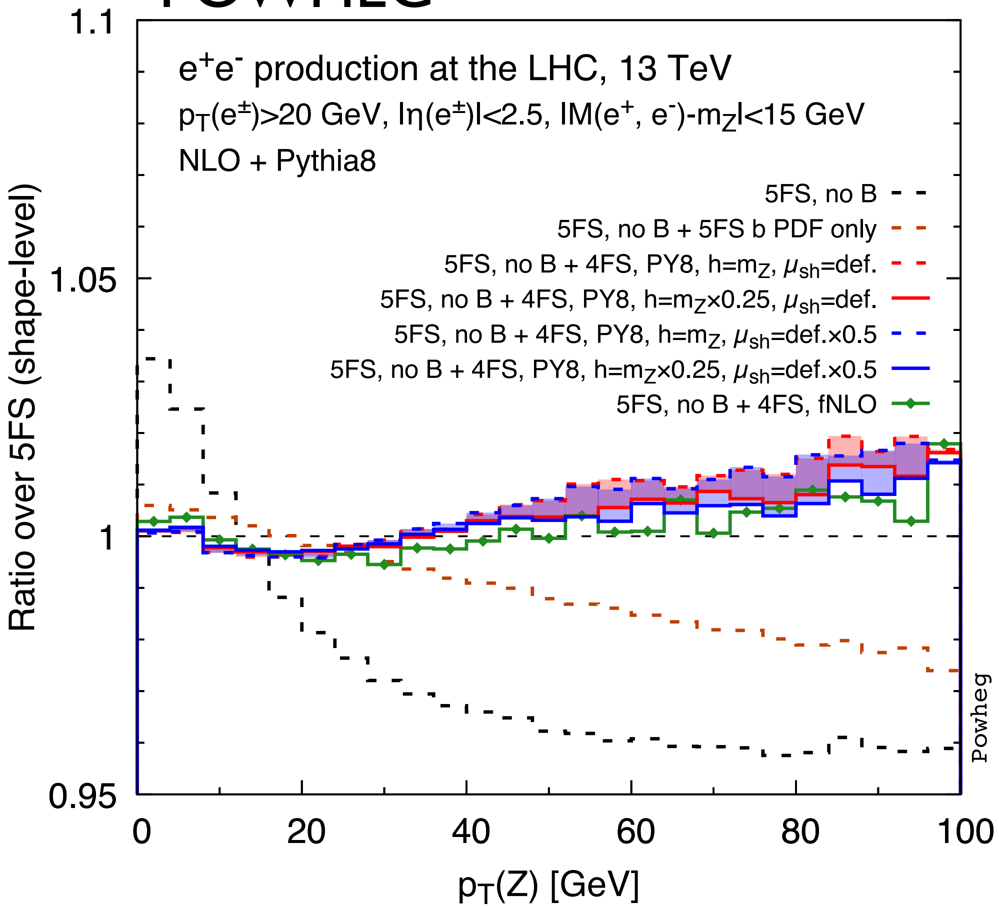
- $\mathcal{R}$ expresses the distortion of the improved ptZ, with respect to the full plain 5FS prediction

- 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

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

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`)

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

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

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

$$= \left(\frac{1}{\sigma_{fid}^{best}}\frac{d\sigma^{best}}{dp_\perp^{l^+l^-}}\bigg|_{tune1}\right)\cdot\left(\frac{1}{\sigma_{fid}^{best}}\frac{d\sigma^{best}}{dp_\perp^{l^+l^-}}\bigg|_{tune2}\right)^{-1}$$

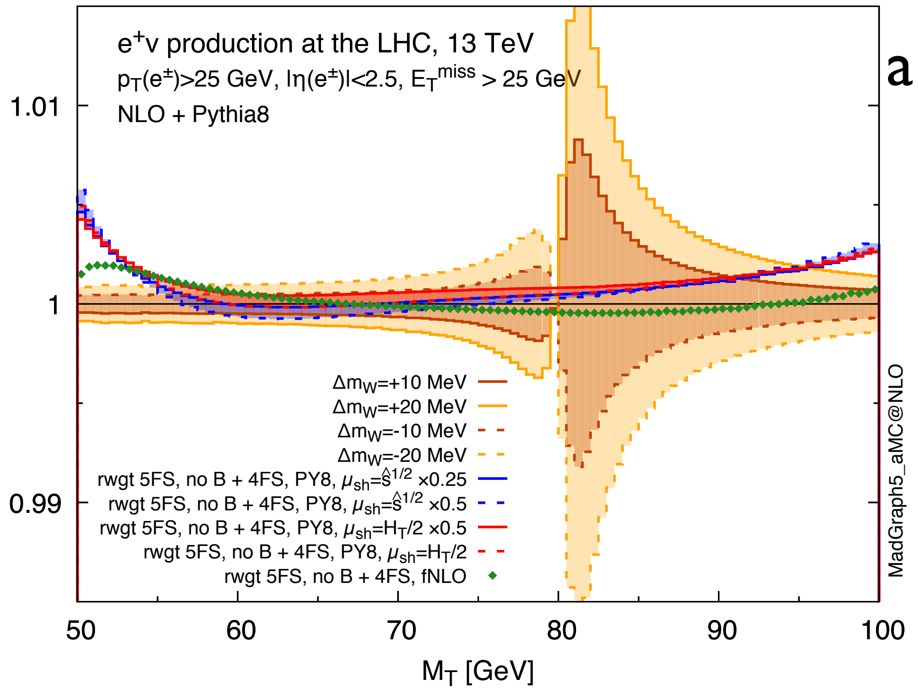
- we use $\mathcal{R}(p_\perp)$ to reweigh the CC-DY events according to their ptW value

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

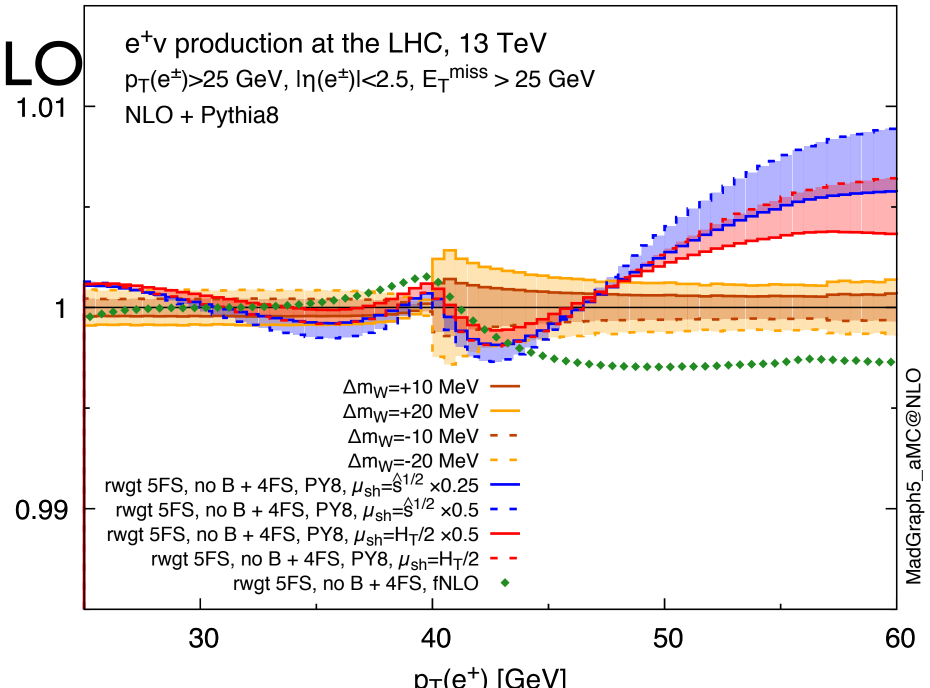
The CC-DY observables are evaluated in the plain 5FS

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

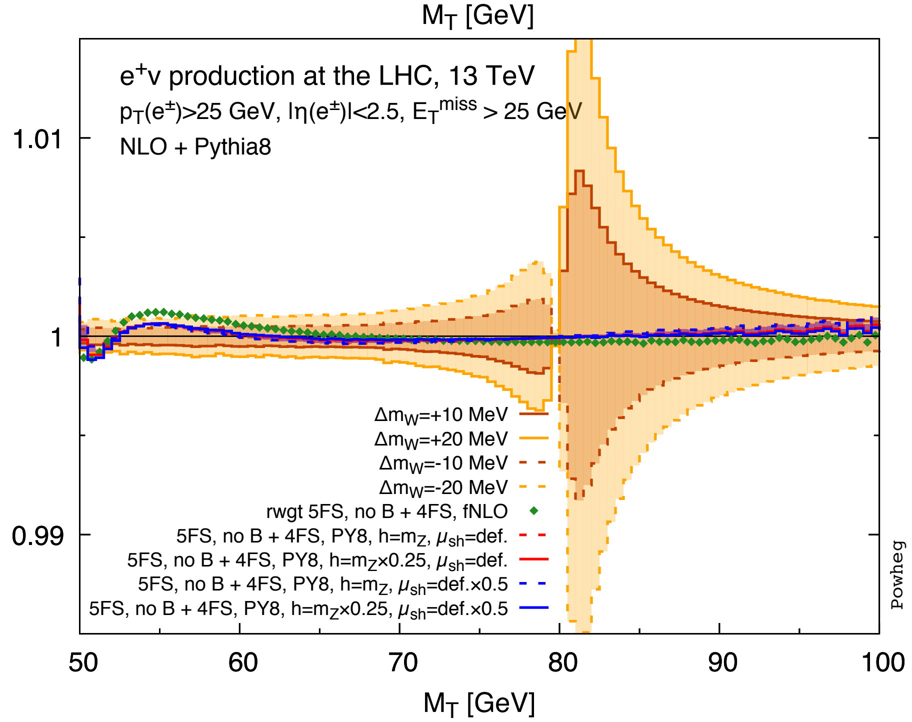
The impact on MW is estimated by template fit of the reweighed distributions (red/blue/green), with templates evaluated in the plain 5FS (light brown)



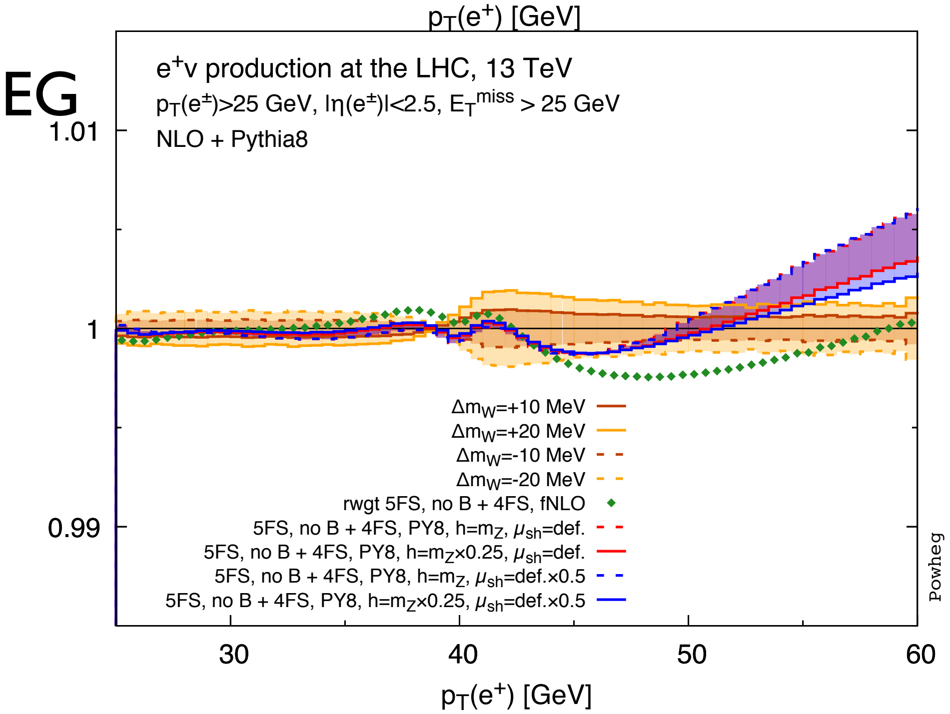
aMC@NLO



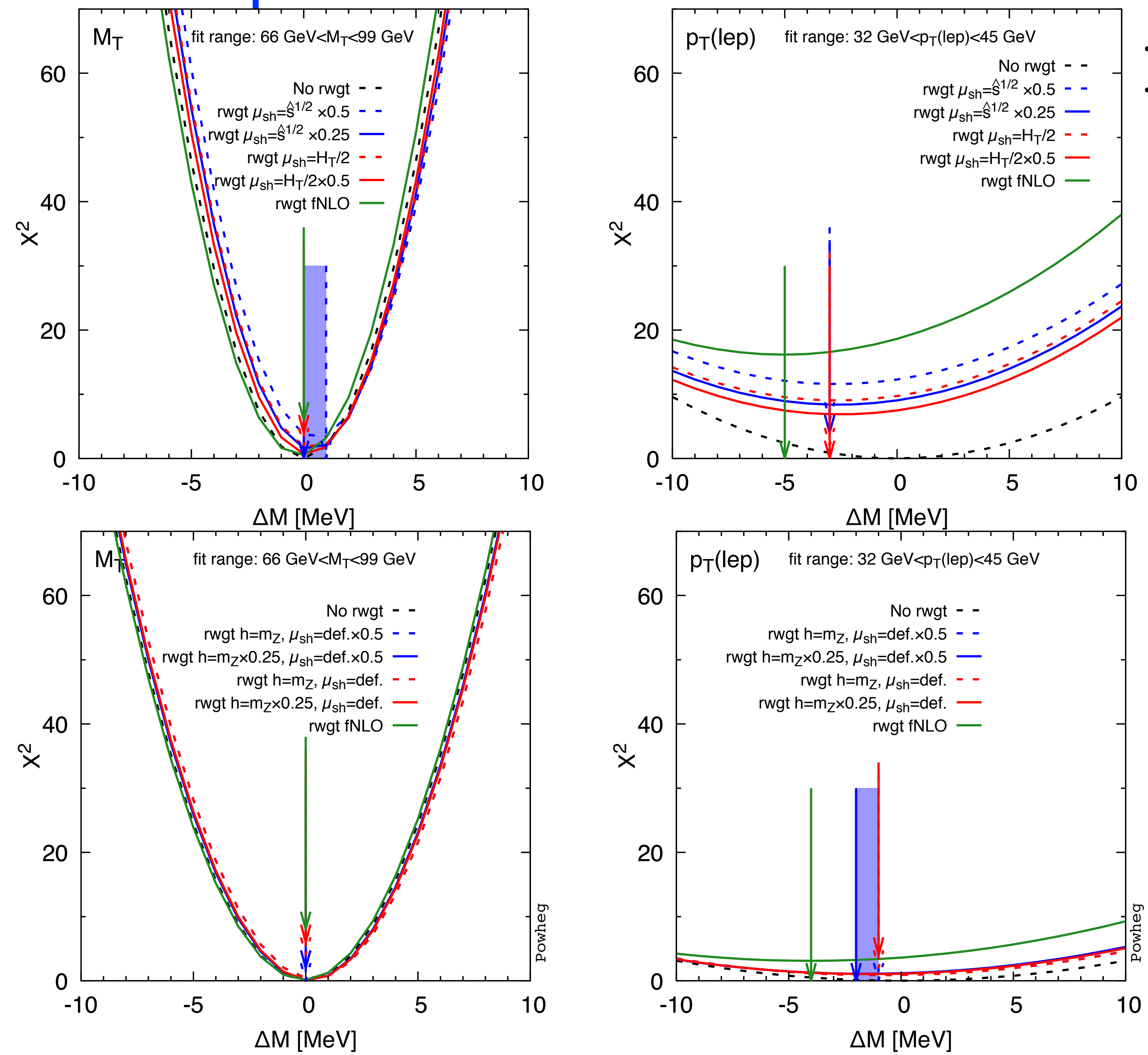
in the high-ptlep tail non negligible effect of the matching with QCD_PS



POWHEG



Bottom quark effects on the MW determination

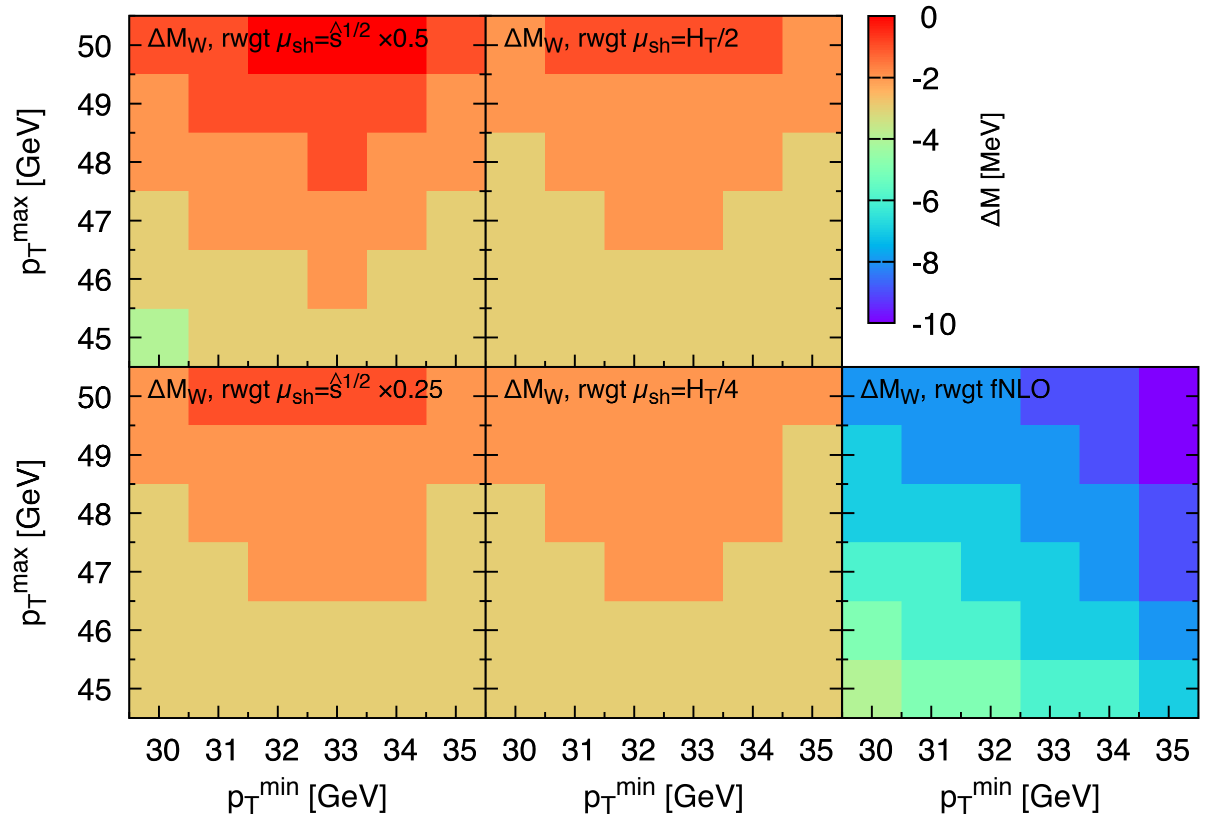


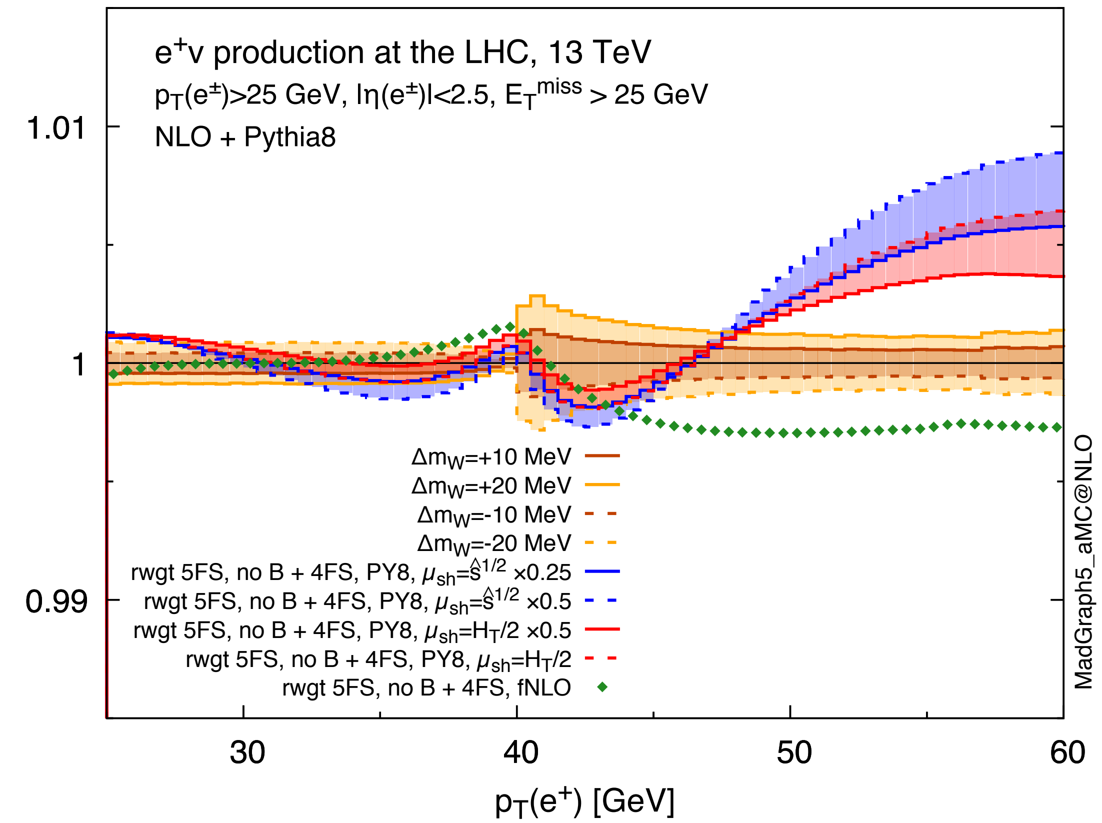
preliminary results

- 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

- in the pt_lep case, the shifts are negative 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]

Conclusions

- a combination of 5FS and 4FS results improves the description of the bottom quark contributions to the ptZ distribution with respect to the plain 5FS approach

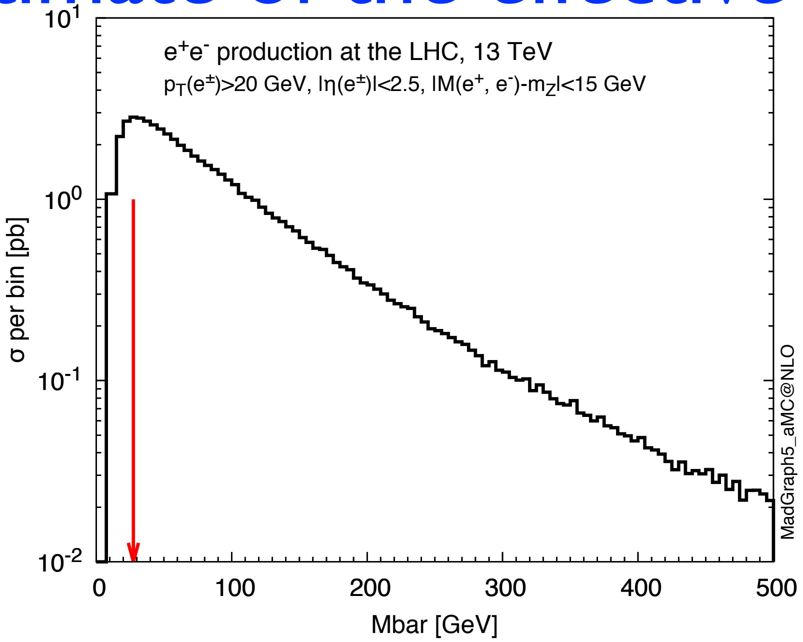
- a detailed discussion of the QCD effects and uncertainties is crucial:
  → matching NLO-QCD with QCD-PS has a sizeable impact on the distributions
  → matching and Parton Shower uncertainties are under control but not negligible

- assuming that the difference between plain 5FS and improved description can be reabsorbed in a new Parton Shower tune
  then it is possible to estimate the impact on CC-DY of this improved NC-DY description

- MW extracted from pt_lep distribution is sensitive to the bottom quark improvement with 4FS at NLOPS, the shifts do not exceed the 5 MeV level in size
  the uncertainty on the shifts can be estimated at the few MeV level

- a study of the bottom quark effects, as a function of lepton-pair invariant mass and rapidity is in progress back-up slides

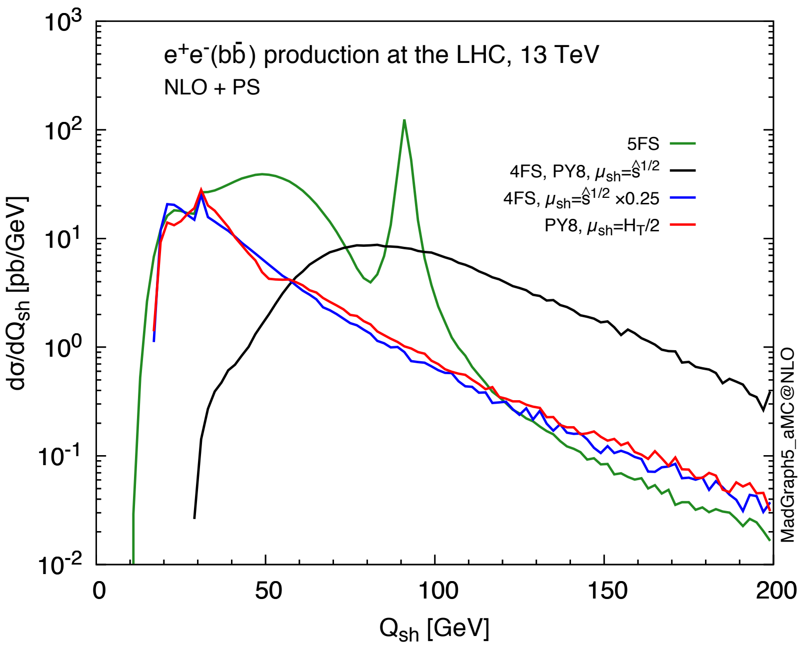
Estimate of the effective upper limit for additional radiation



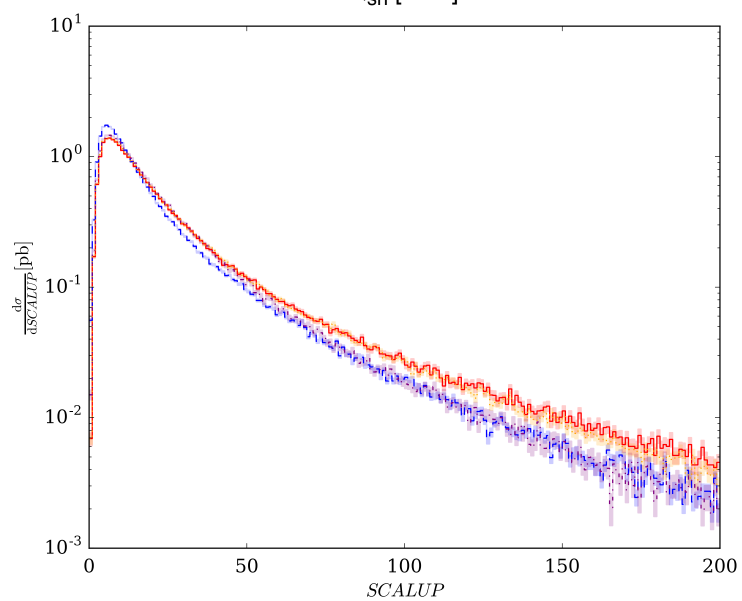
$$L = \log\left(\frac{M^2_{l^+l^-}}{m_b^2}\frac{(1-z_i)^2}{z_i}\right) \quad \text{with} \quad z_i = \frac{M^2_{l^+l^-}}{s_i}, \quad s_i = (q_+ + q_- + k_i)^2$$

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

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

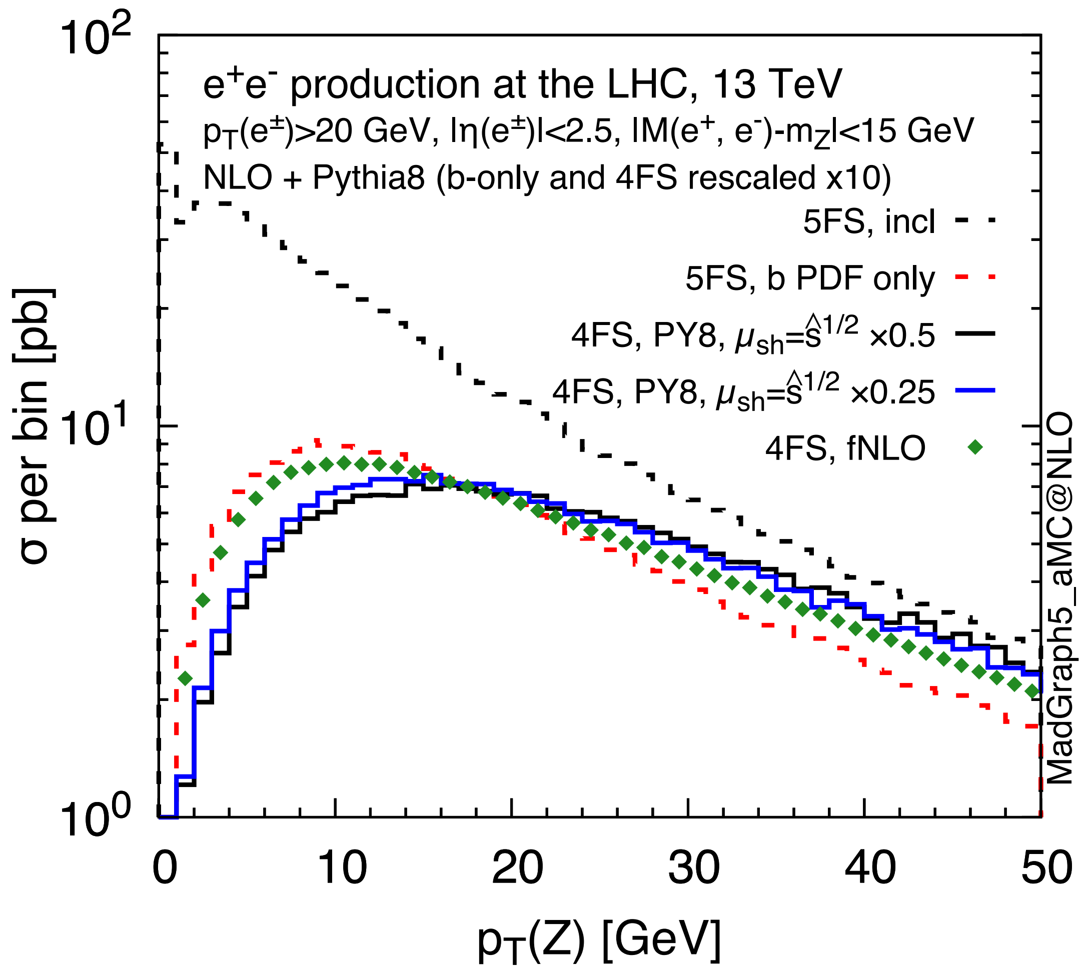


Q_{sh} is extracted in aMC@NLO according to a probability distribution
depends on the choice of one variable and on the details of PS



`scalup` in POWHEG is evaluated as
Btilde events: the pt of the first emission in the
remnant events: different criteria (pt of first emission,
minimum hardness of the emitting partons,)
it can be fixed to a constant value or extracted from a distrib.)

Bottom contributions to ptZ in different schemes and approximations



- 5FS: b-initiated subprocesses + QCD-PS (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

(partial) Bibliography on 4FS calculations

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

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- 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

- relations between 4FS and 5FS in the evaluation of the total cross section for the production of a boson (Higgs, Z) in association with bottom quarks

R. Harlander, M. Kr ̈amer and M. Schumacher, arXiv:1112.3478

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S. Forte, D. Napoletano, and M. Ubiali,arXiv:1508.01529, arXiv:1607.00389

apologies for any unintentional omission