UNIVERSITÀ DEGLI STUDI DI MILANO

INFN Istituto Nazionale di Fisica Nucleare

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

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DESY, September 13th 2017

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

arXiv:1709.xxxxx

Outline of the talk

- Introduction and motivations

- Associated production e^+e^-bb : 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

Precision physics at LHC

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no new physics so far, need to look for small deviations from the SM

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example:
MW is extracted from charged-current Drell-Yan
all the calibrations are based on neutral-current DY
the uncertainty estimate requires the knowledge of correlations
→ non-trivial point for theoretical uncertainties

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Observables are quantities defined in terms of a counting procedure:

cross sections, asymmetries

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We measure them via a template fit procedure, i.e.
- we compute some kinematical distributions that depend on these parameters
- we keep these parameters as free variables and
  try to maximise the agreement in the comparison with the data
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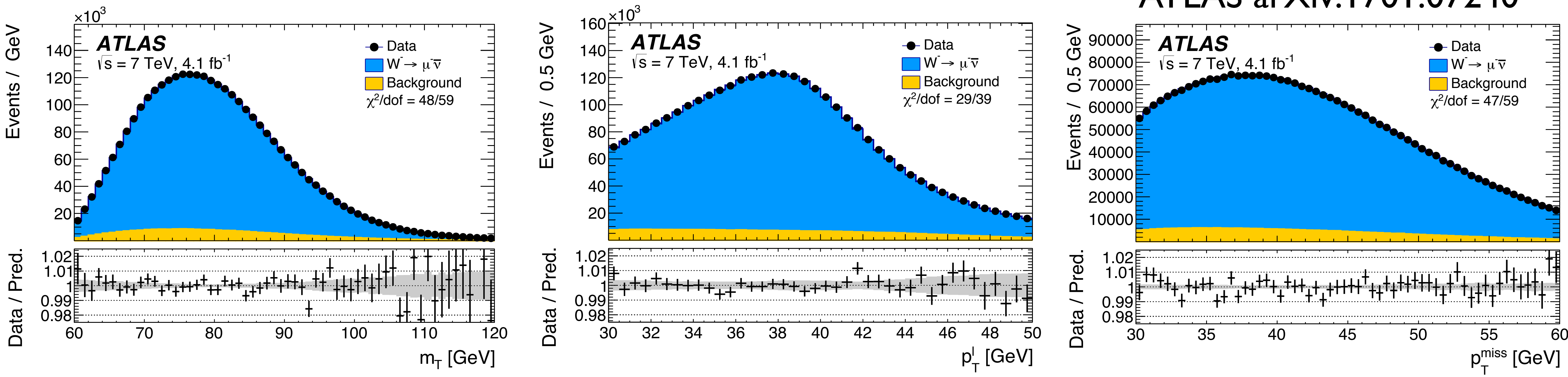
The uncertainties affecting the templates must be propagated as
theoretical systematic uncertainties in the error of the parameters

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

ATLAS arXiv:1701.07240



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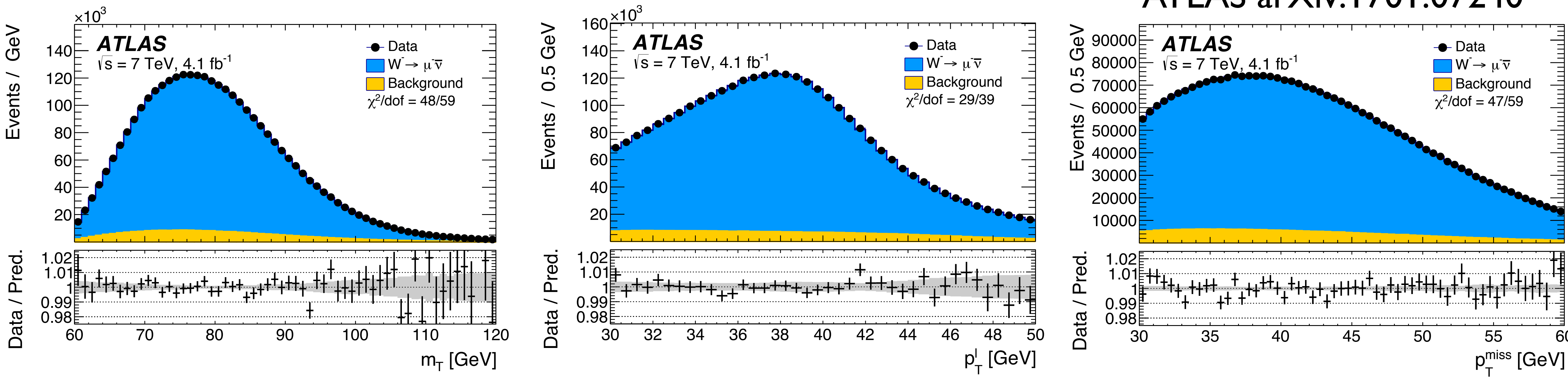
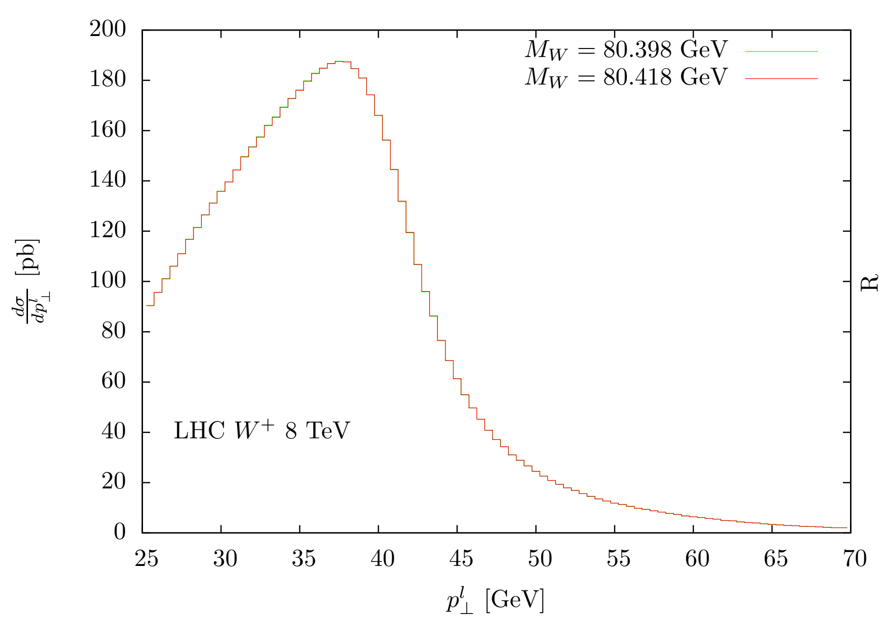
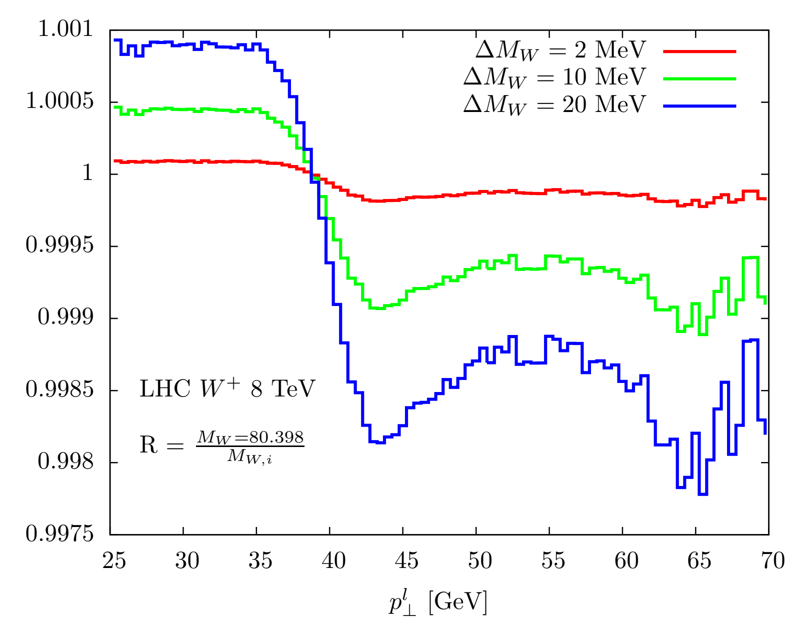


Challenging shape measurement:

a distortion at the few per mil level of the distributions yields a shift of O(10 MeV) of the MW value





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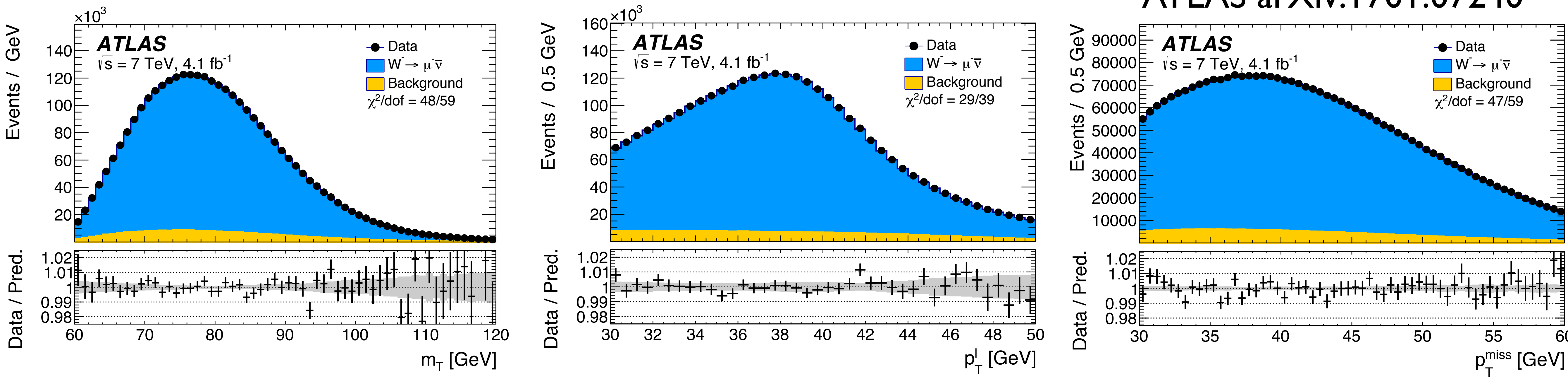

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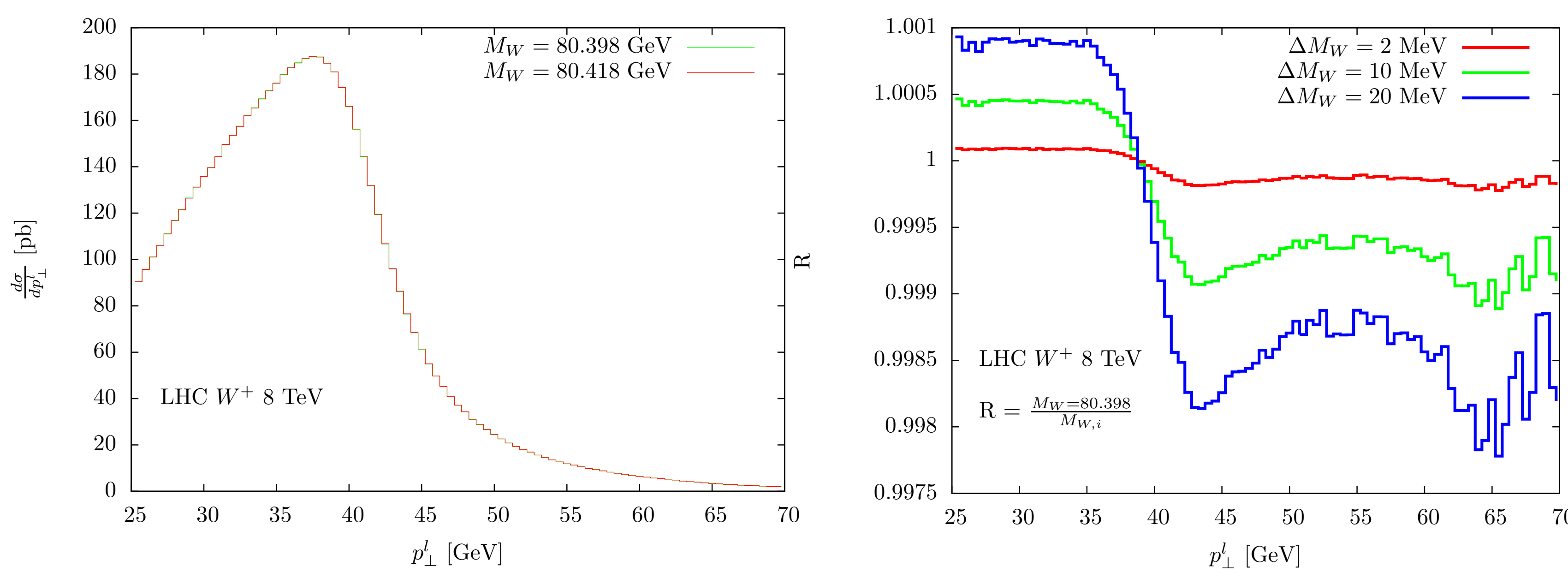

→Are all the relevant (i.e. that distort the shapes) radiative corrections under control?

→Is the interplay between NC-DY and CC-DY under control?

MW determination: proton PDFs and heavy quark role

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

The MW measurement is mostly limited by modelling systematics

QCD and PDF effects are two of the dominant systematic uncertainties

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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
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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 ?

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?

Associated production e^+e^-bb

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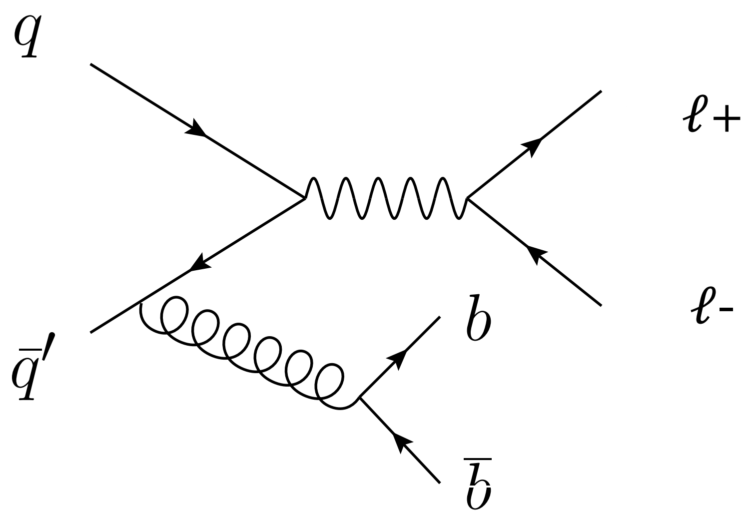
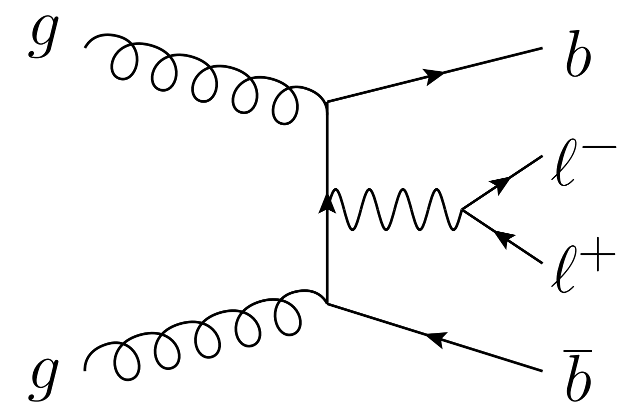




- NLO-QCD corrections to Z production in association with heavy quarks

  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

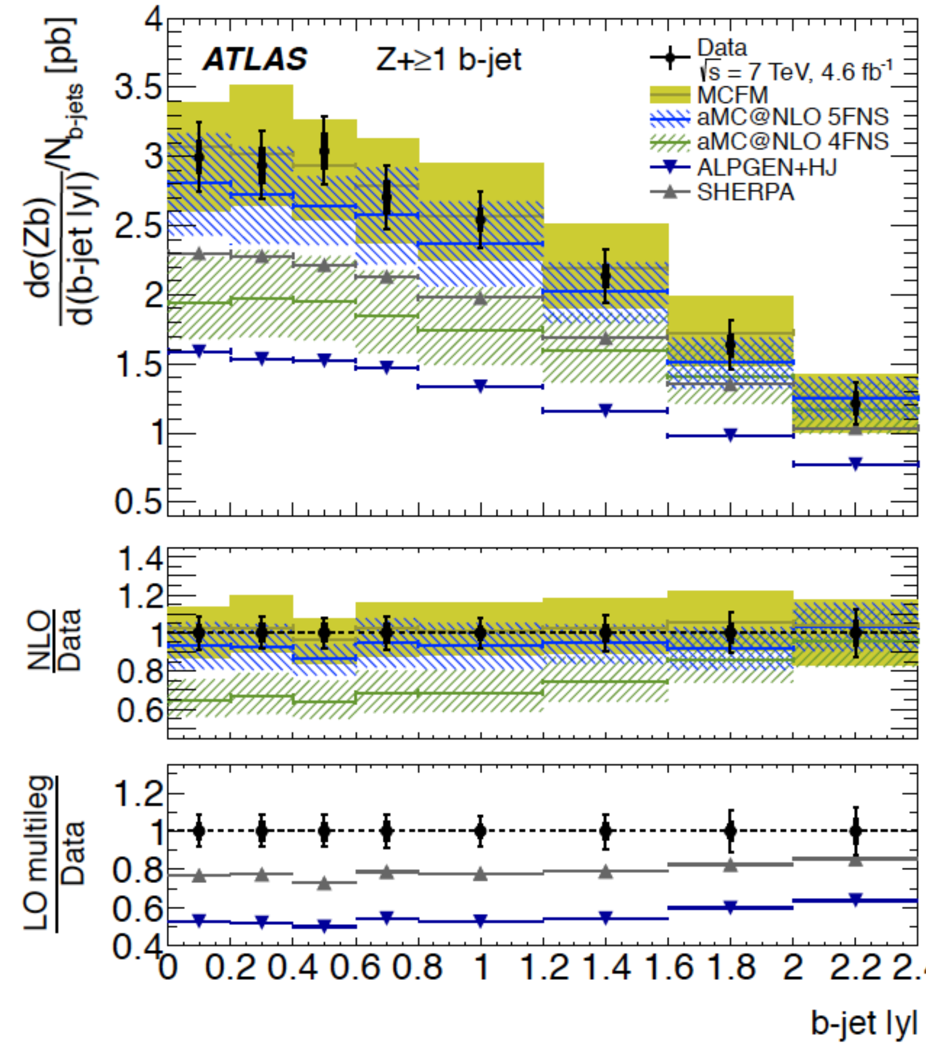
→ multiple equivalent choices yield a spread of the predictions

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



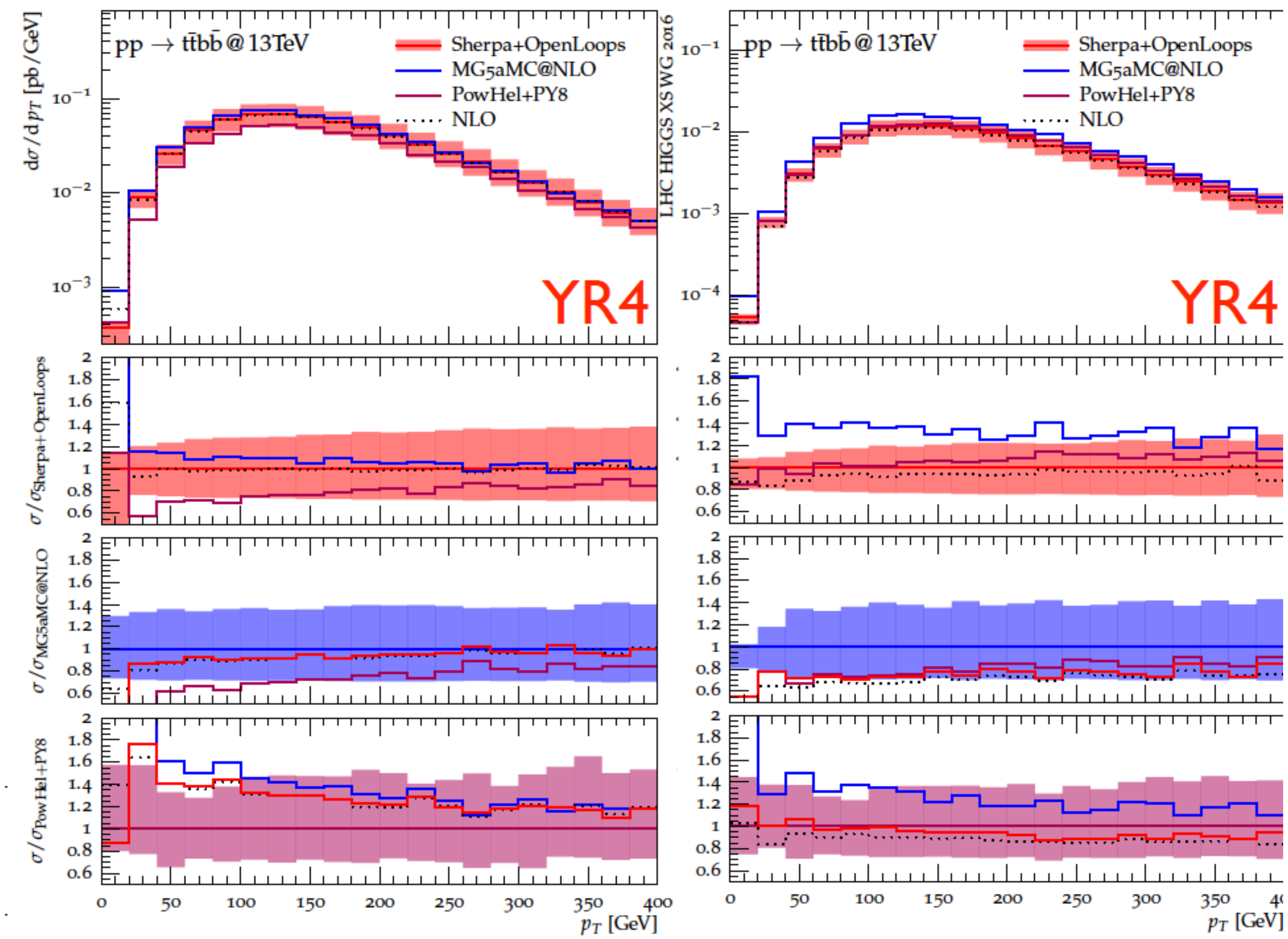
Lim, Maltoni, Ridolfi, Ubiali, arXiv:1605.09411
suggest that an appropriate factorisation scale choice,
based on analytical arguments on the initial state collinear logs,
has to be adopted to obtain accurate predictions in the 4FS for the total cross section

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

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

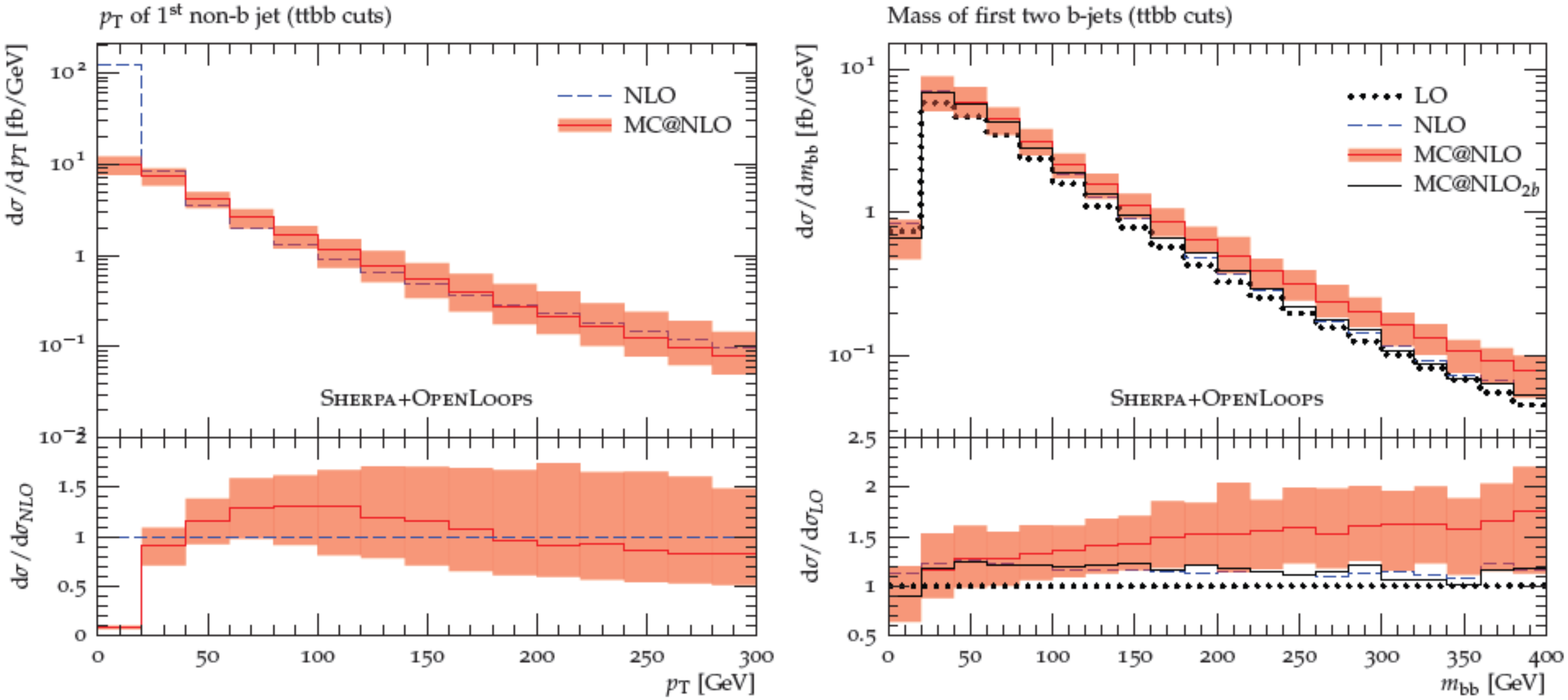
scale uncertainties of O(40%) at NLO

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



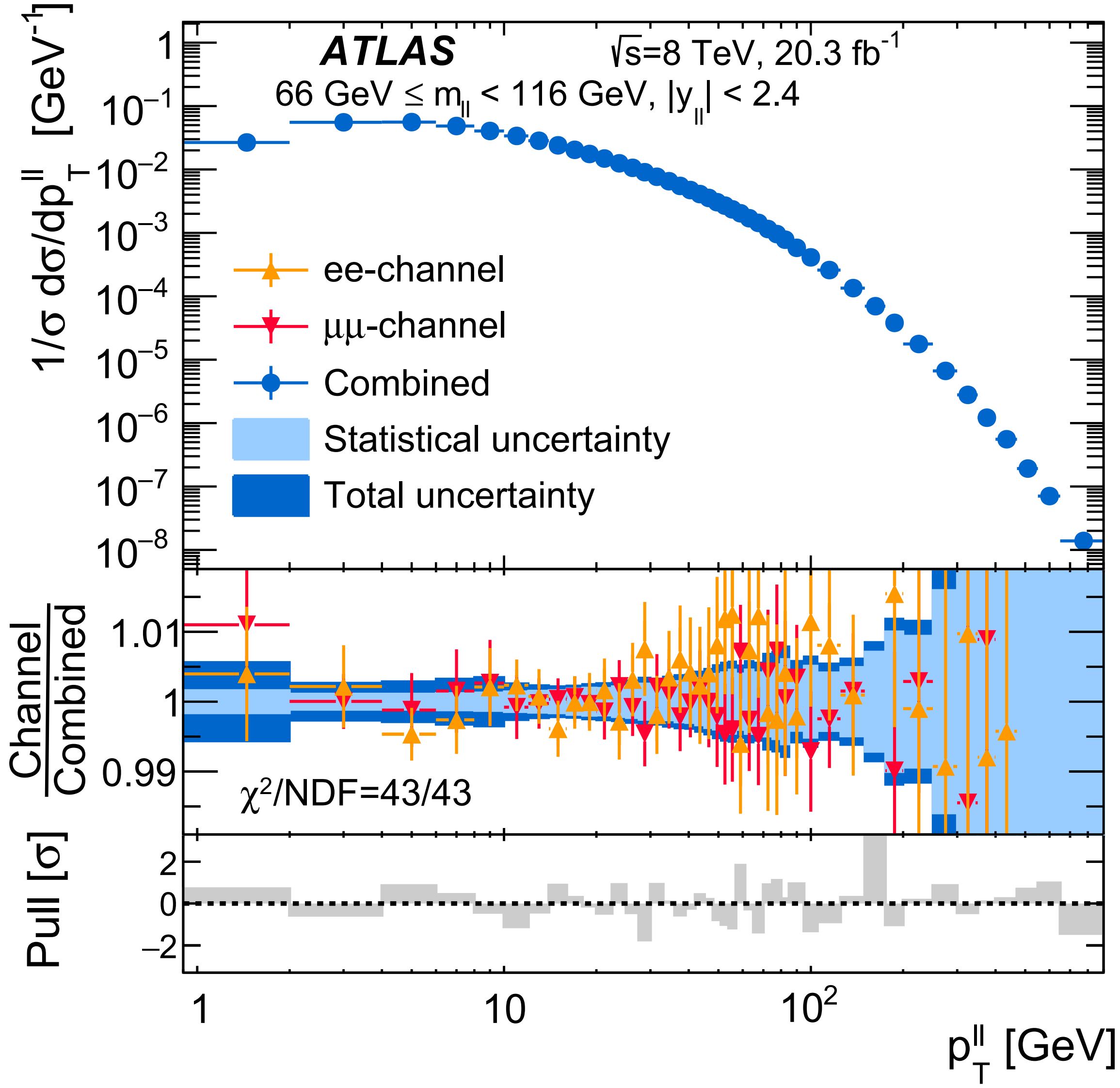
	ttb	ttbb	ttbb($m_{bb} > 100$)
σ_{LO}[fb]	$2644^{+71\%+14\%}_{-38\%-11\%}$	$463.3^{+66\%+15\%}_{-36\%-12\%}$	$123.4^{+63\%+17\%}_{-35\%-13\%}$
σ_{NLO}[fb]	$3296^{+34\%+5.6\%}_{-25\%-4.2\%}$	$560^{+29\%+5.4\%}_{-24\%-4.8\%}$	$141.8^{+26\%+6.5\%}_{-22\%-4.6\%}$
σ_{NLO}/σ_{LO}	1.25	1.21	1.15
σ_{MC}[fb]	$3313^{+32\%+3.9\%}_{-25\%-2.9\%}$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

Challenges offered by the inclusive ptZ distribution

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 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 ?

Challenges offered by the inclusive ptZ distribution

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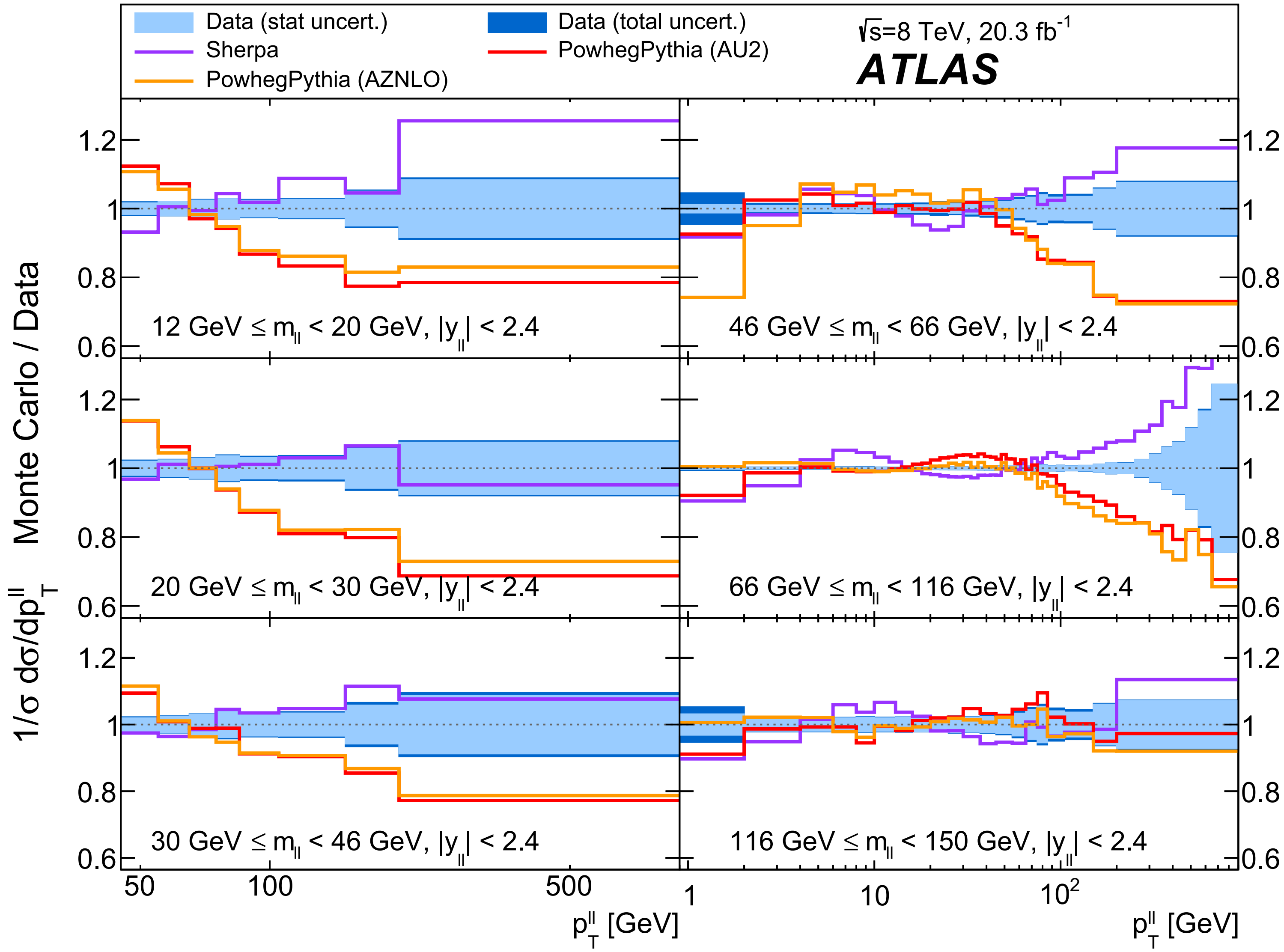
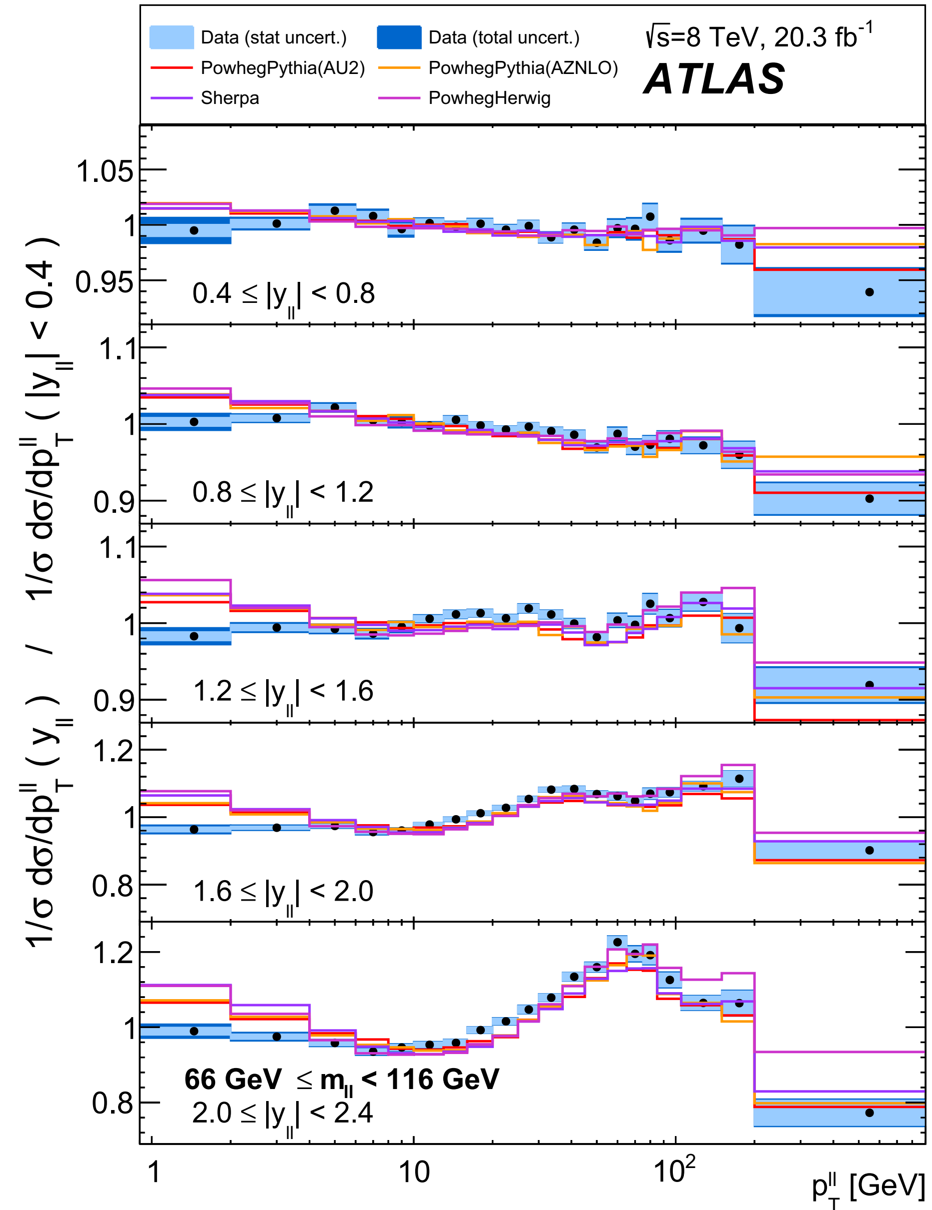




The inclusive lepton pair transverse momentum distribution is used to tune the parameters of the models implemented in the Parton Shower to describe low-pt physics

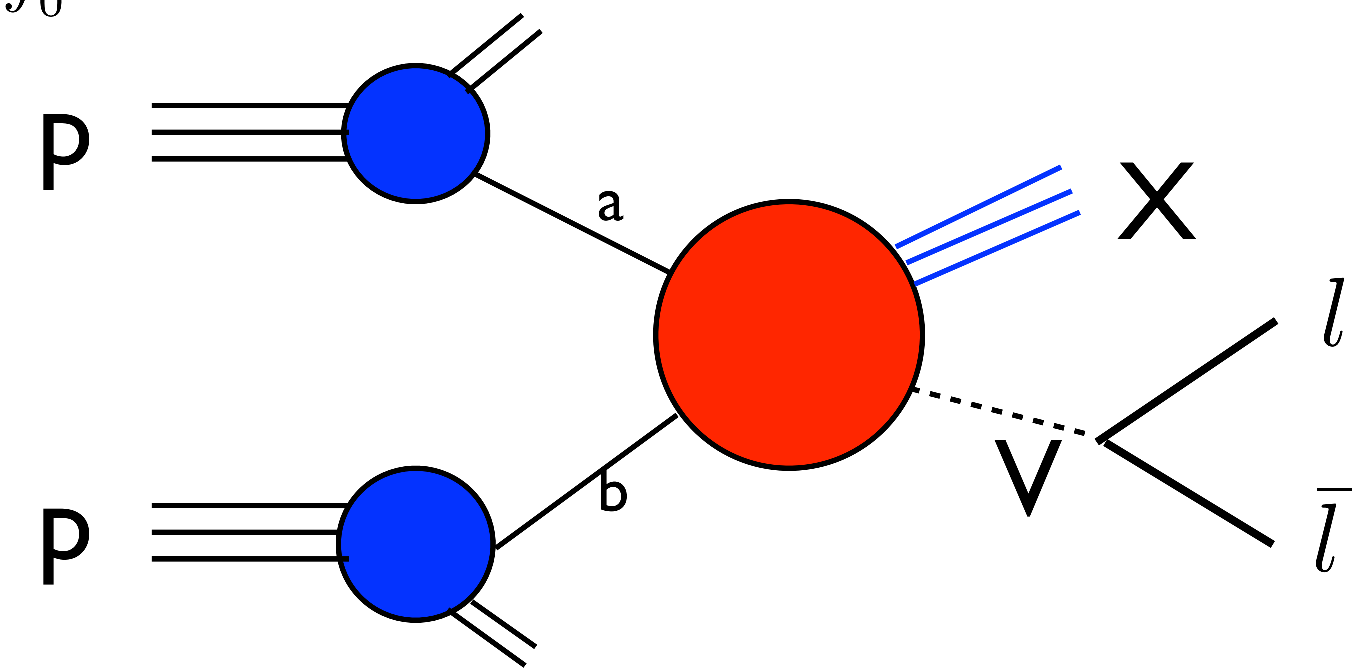
The tune is done at the Z resonance and for central rapidity of the lepton pair

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

$$\sigma(P_1,P_2;m_V)=\sum_{a,b}\int_0^1 dx_1 dx_2\, f_{h_1,a}(x_1,M_F) f_{h_2,b}(x_2,M_F)\,\hat\sigma_{ab}(x_1P_1,x_2P_2,\alpha_s(\mu),M_F)$$



- 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

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. $\eta(l^\pm) < 2.5$

POWHEG vs aMC@NLO matching recipes

aMC@NLO

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

- 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` the hardness of the first emission, 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

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

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

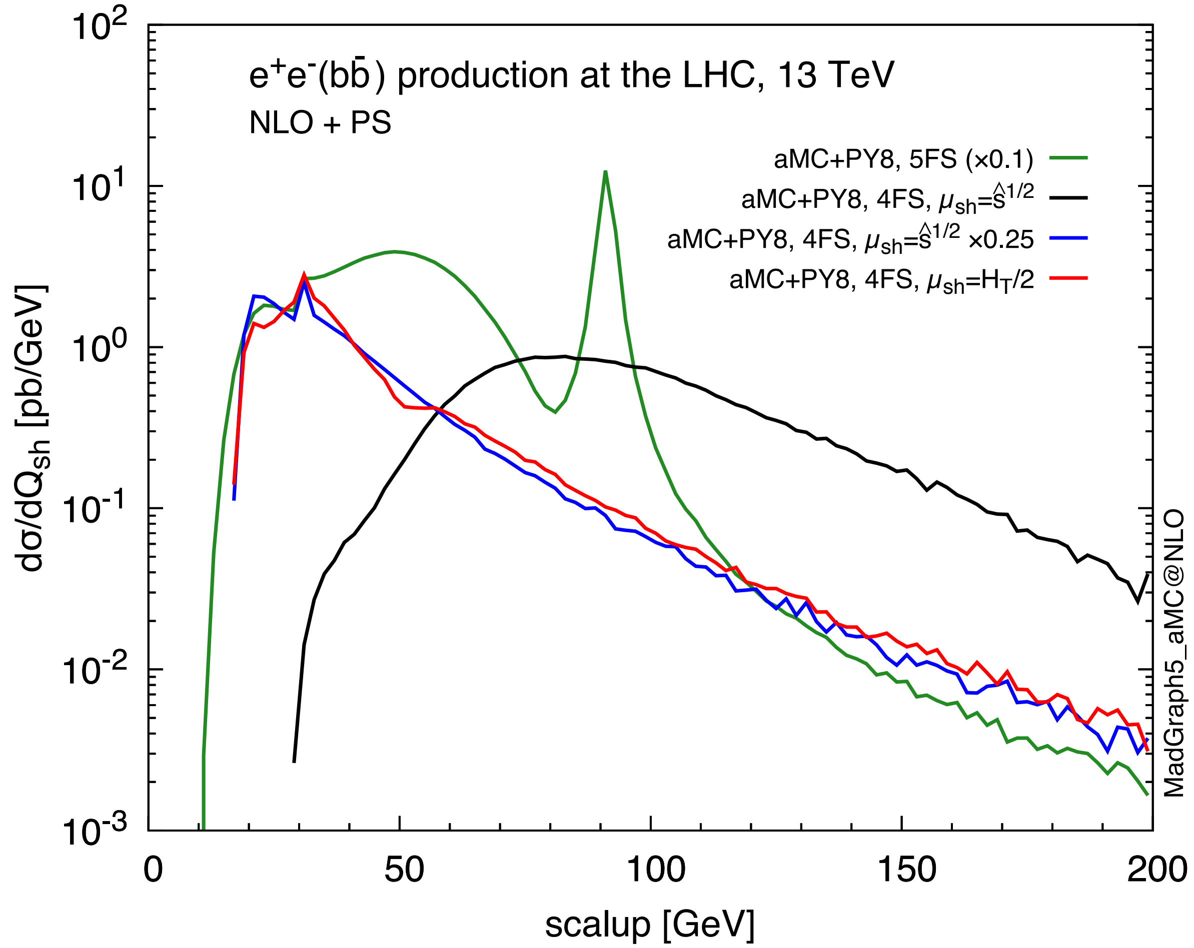
$$R = R^s + R^f \equiv f(h)R + (1 - f(h))\, R \qquad f(h) = \frac{h^2}{h^2 + k_\perp^2}$$

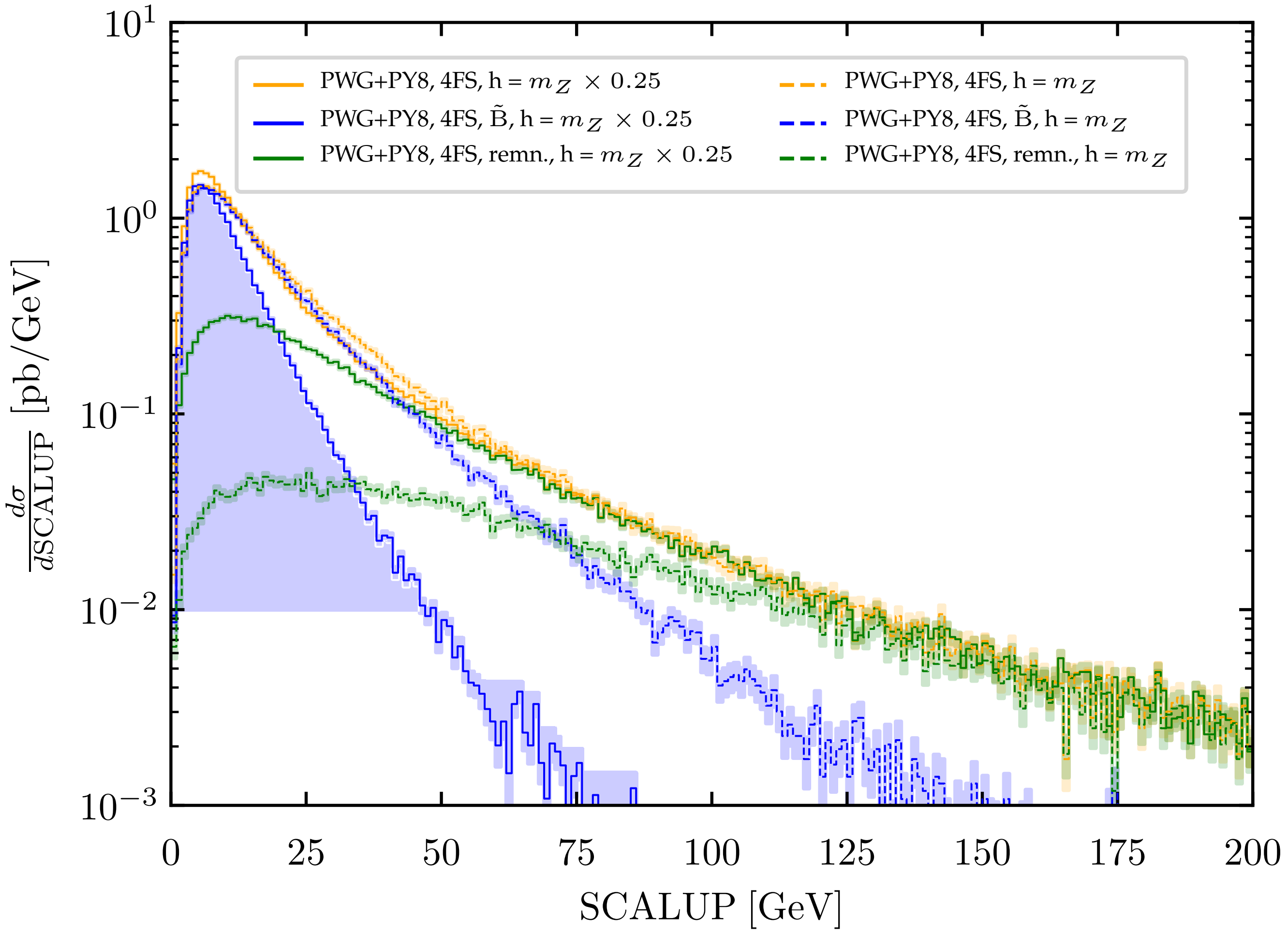
$$\Delta(\phi_n, p_\perp) = \exp\left(- \int d\phi_{rad} R^s(\phi_n, \phi_r ad)/B(\phi_n)\theta(k_\perp - p_\perp) \right)$$

- 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 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 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

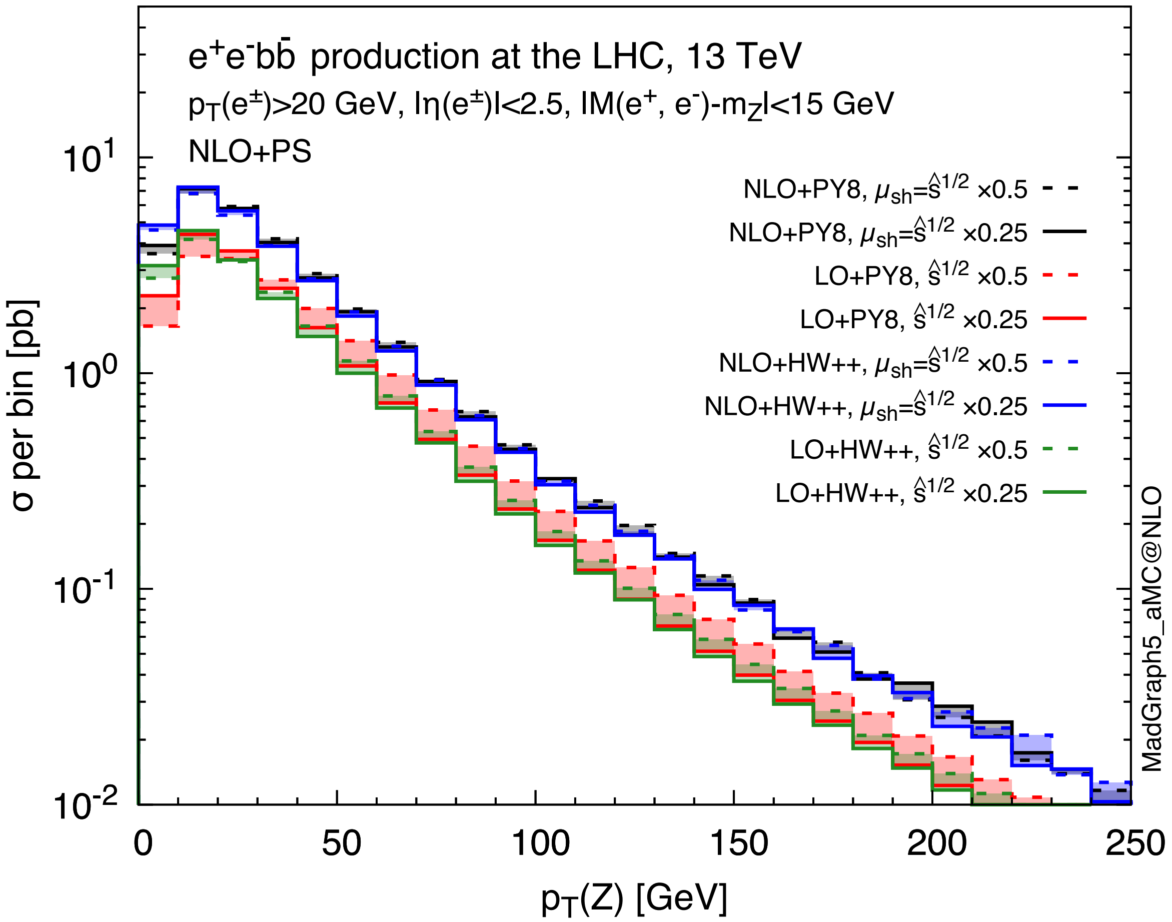
large logarithmically enhanced terms are not included to all orders

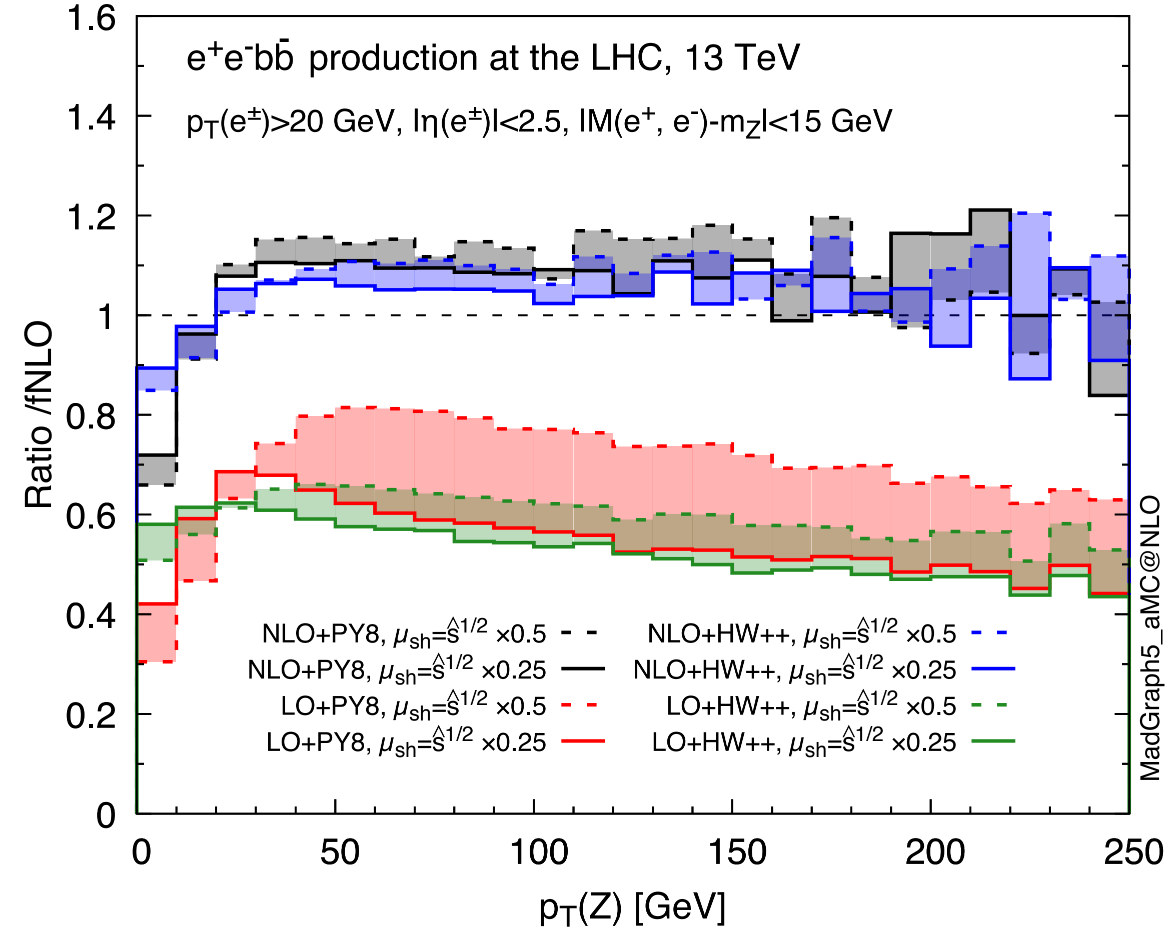
The fixed-order NLO-QCD results are our benchmarks

→ additional corrections and residual uncertainties are expressed in these units

Exclusive signatures with tagged b-jets (B hadrons)

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

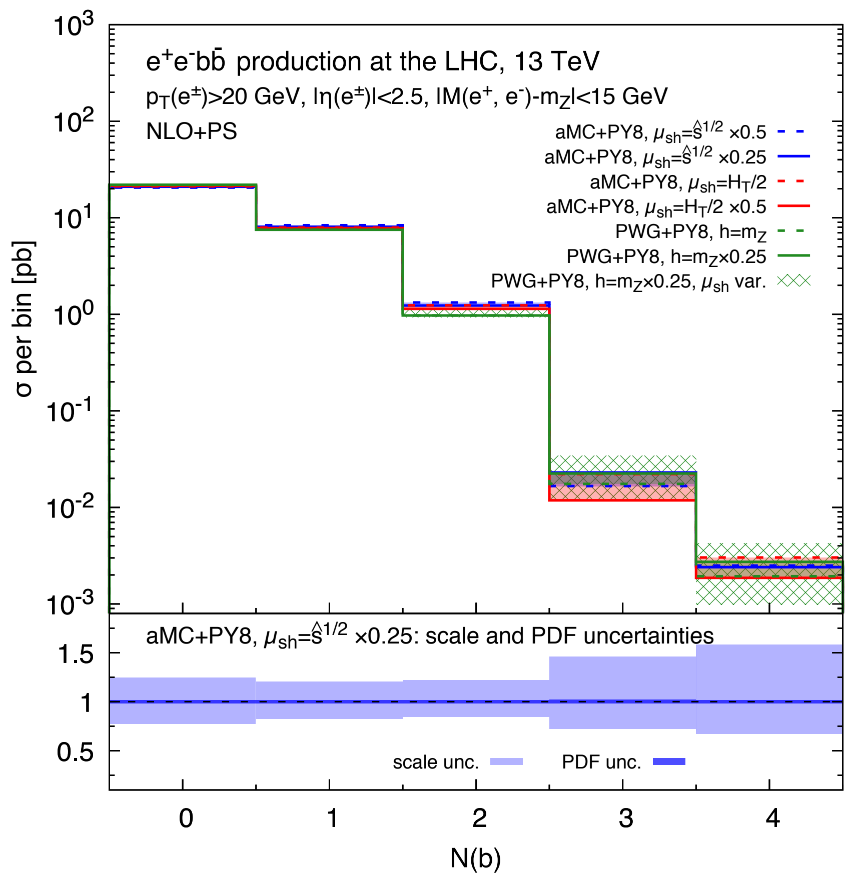
  a model that describes the intrinsic transverse momentum of the partons inside the proton

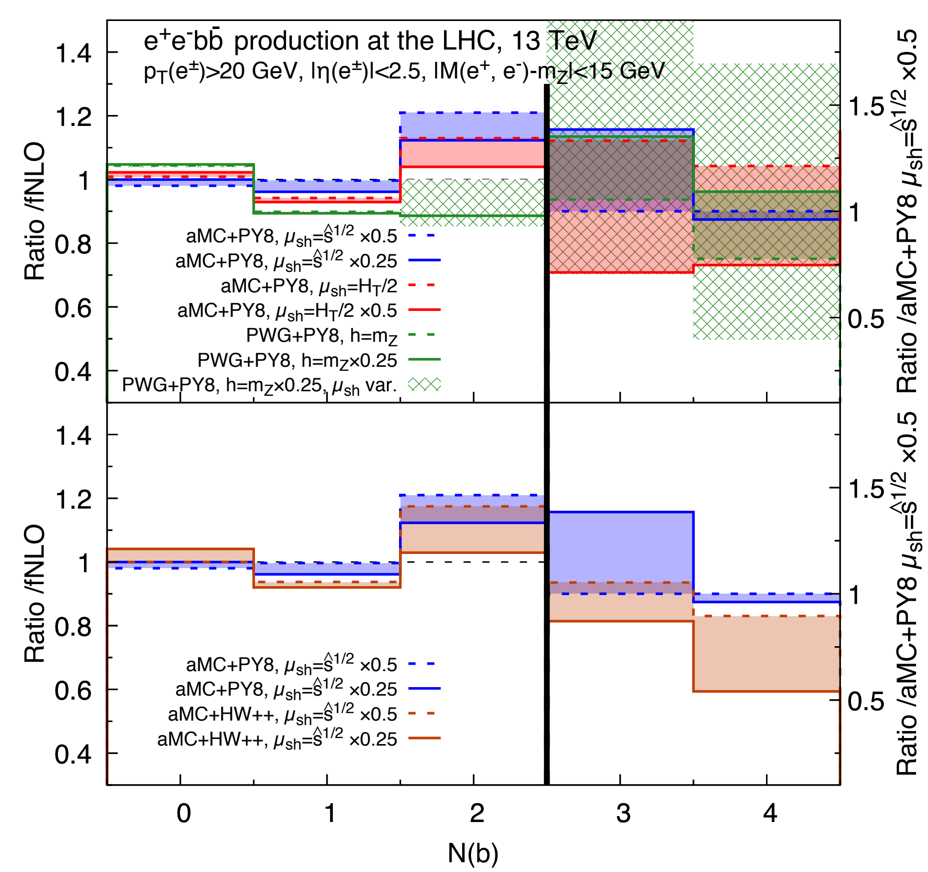
  a model in the backward evolution for the splitting $g \to bb$

- after the matching with NLO matrix elements,

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

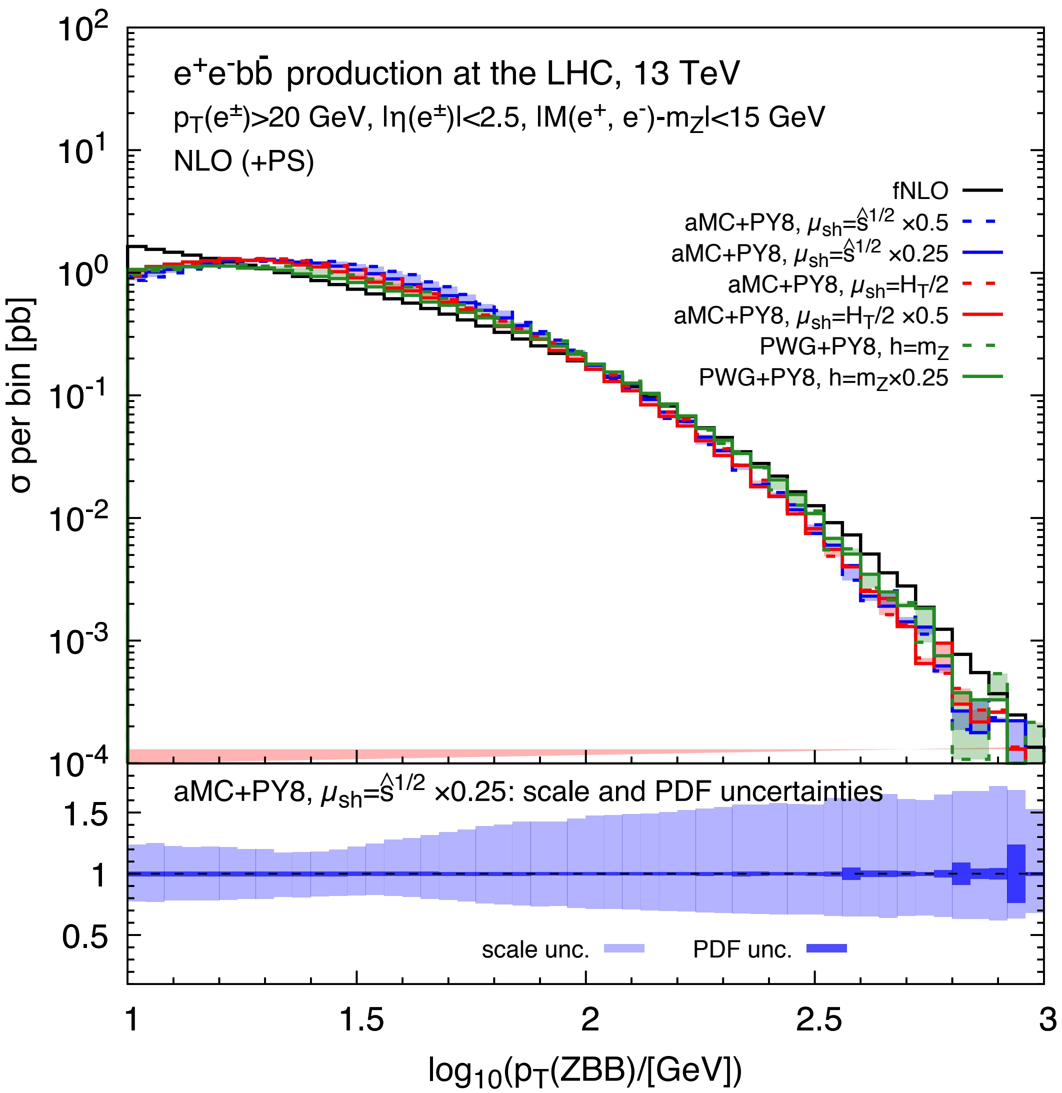
e^+e^-bb: b-jet multiplicities

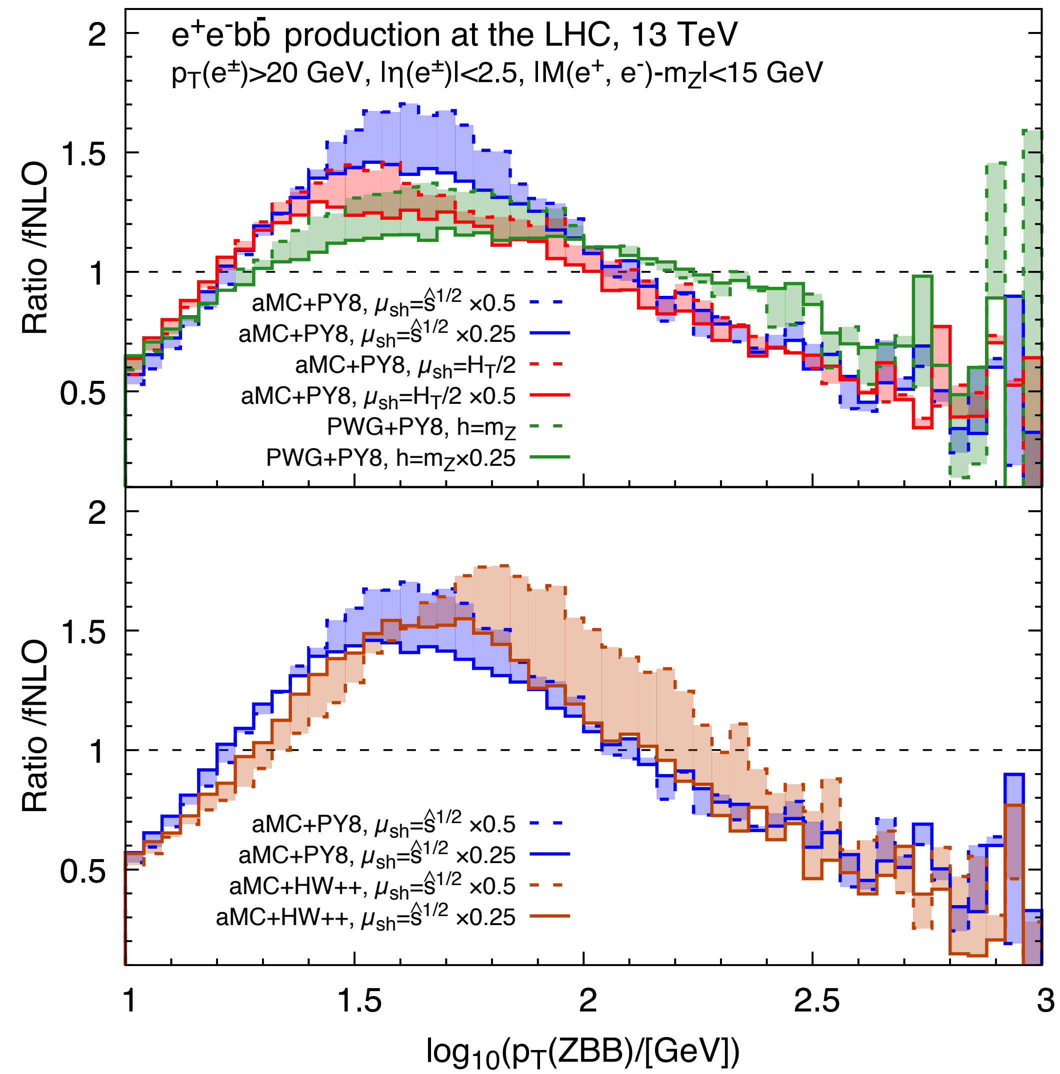




- a crucial quantity to understand the comparison between aMC@NLO and POWHEG at the exclusive level (classification w.r.t. the number of additional b-jets)
- the Parton Shower distorts the distribution of the final state bb pair (pushing in/out the acceptance)
  adds additional splittings $g \to bb$, 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

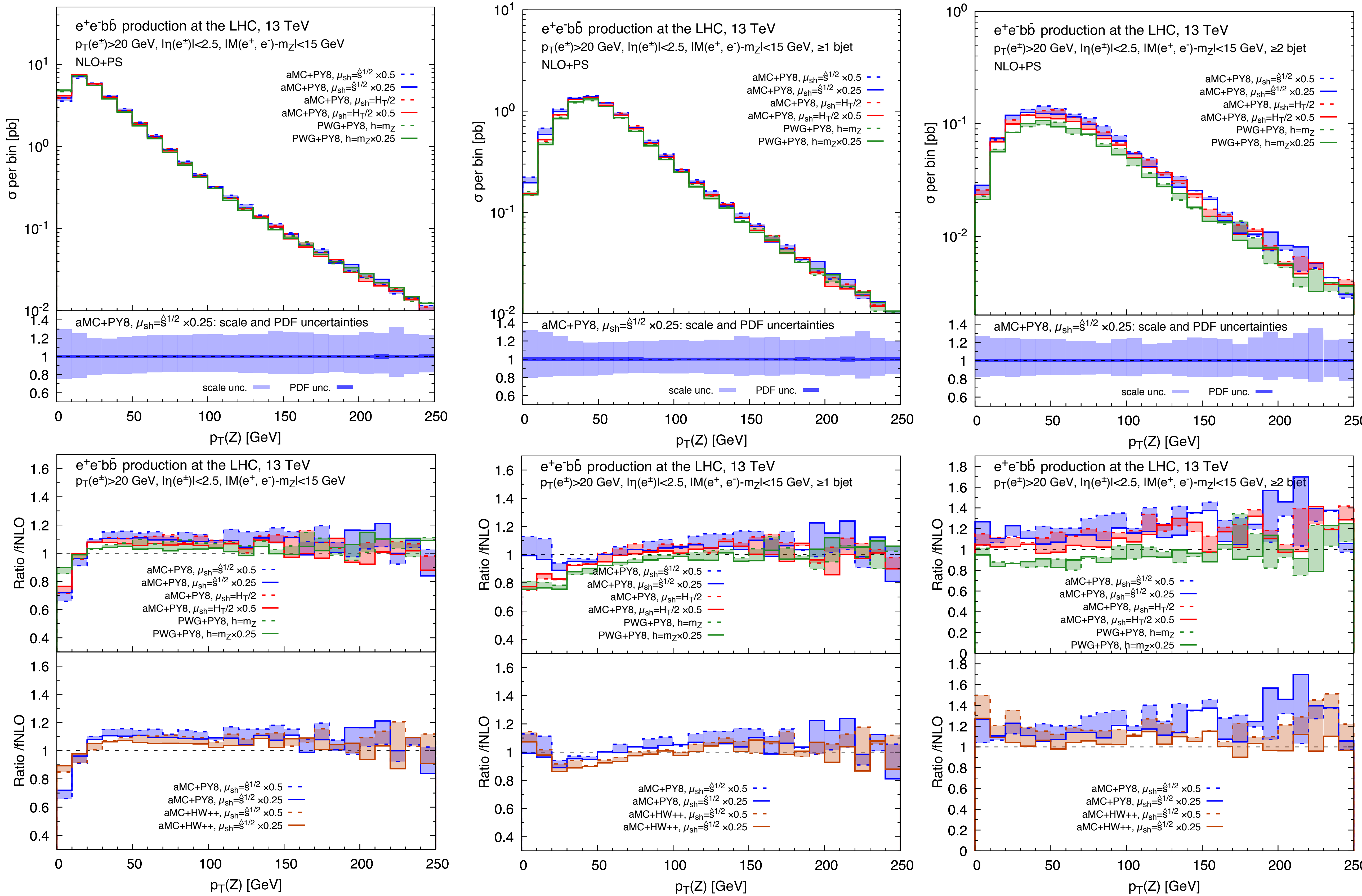




- a crucial quantity to understand the radiation patterns beyond NLO (defined in terms of b quarks)
- competition between initial and final state radiation
- the observed higher-order effects are common to all the codes, PS models, shower scale choices
- strong Sudakov suppression at low pt, strong enhancement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

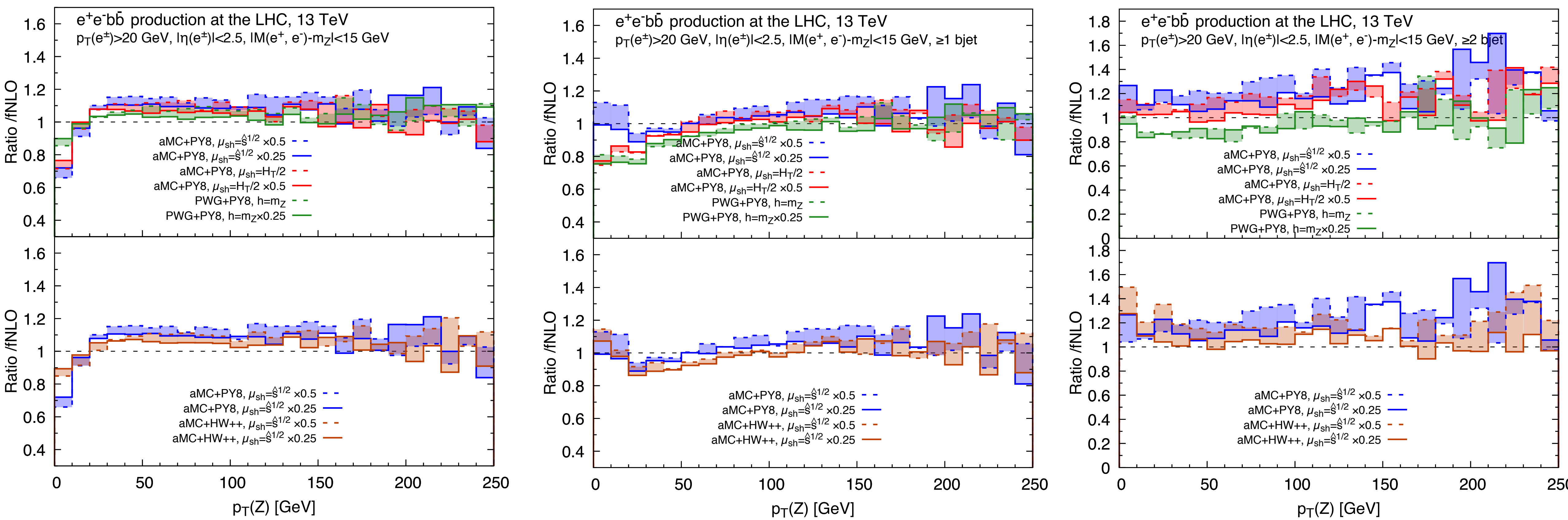


e^+e^-bb: lepton-pair pt distribution in association with N b-jets

- 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

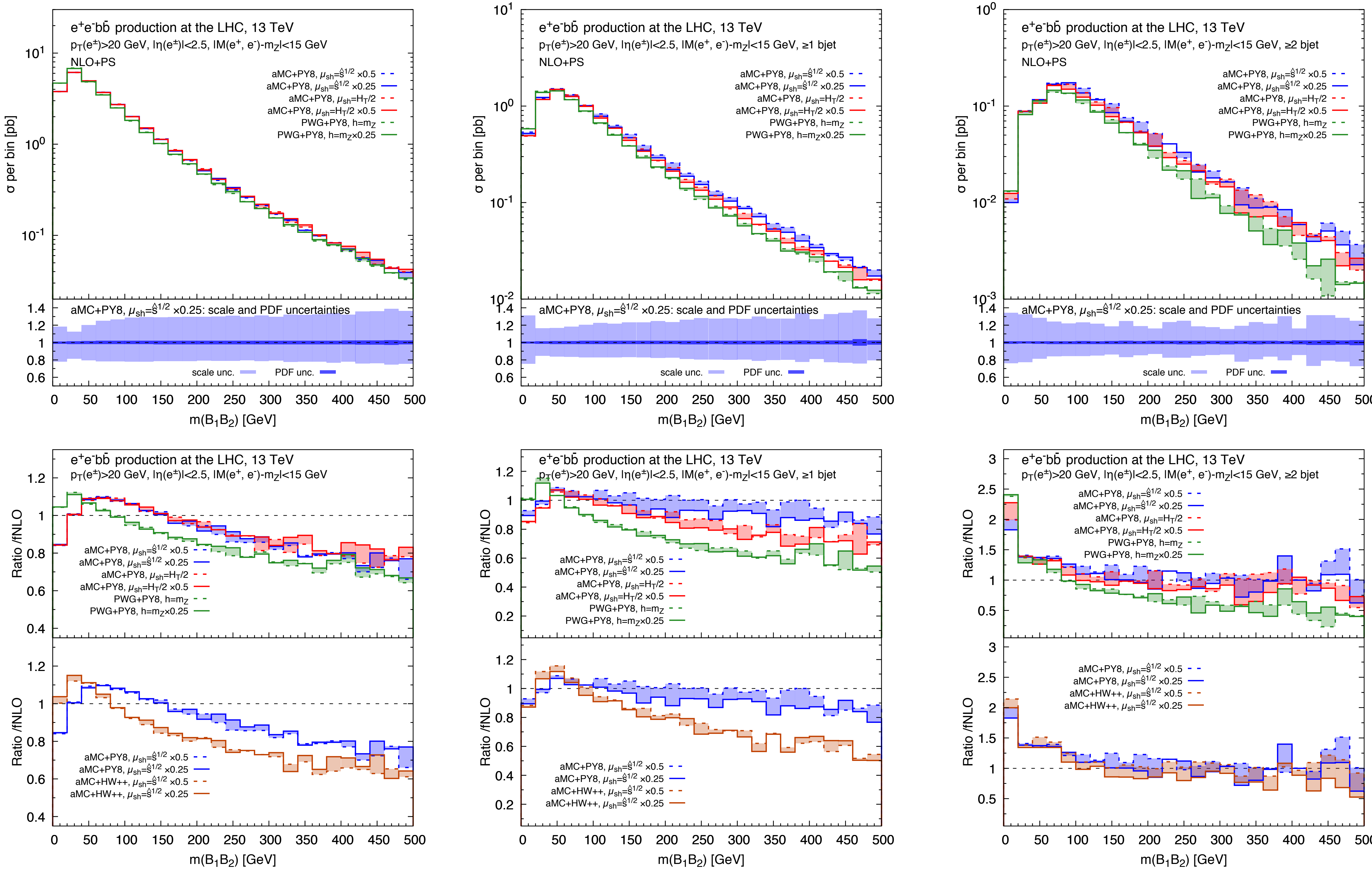
- with 2 tagged b-jets, the PS effects are flat over the whole ptZ range
- with 0 or 1 tagged b-jets, at low ptZ there are stronger differences
  between different matchings and different shower scale choices

- 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



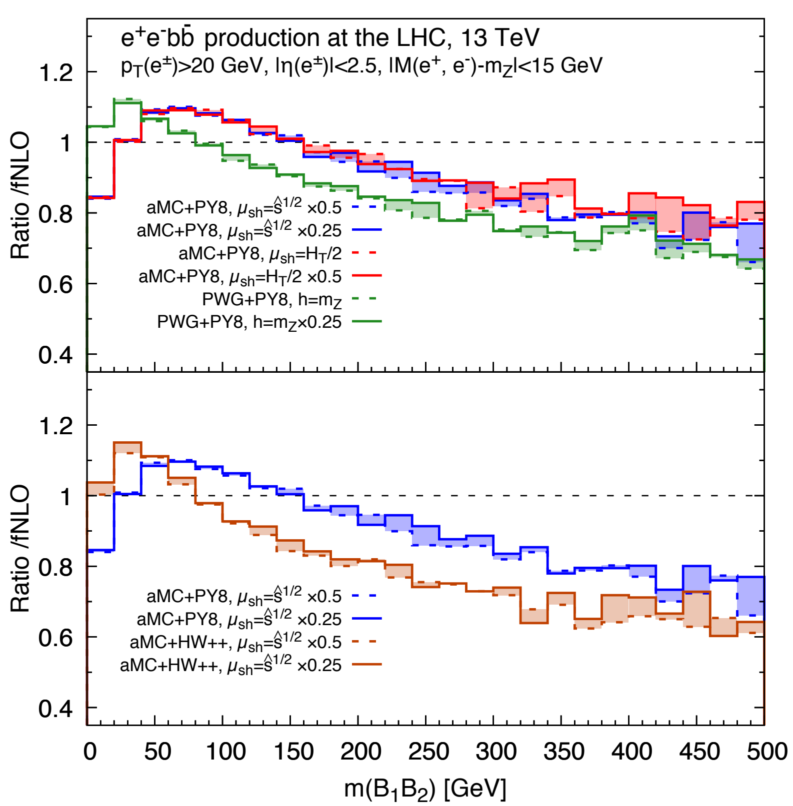
e^+e^-bb: B-pair invariant mass distribution in association with N b-jets

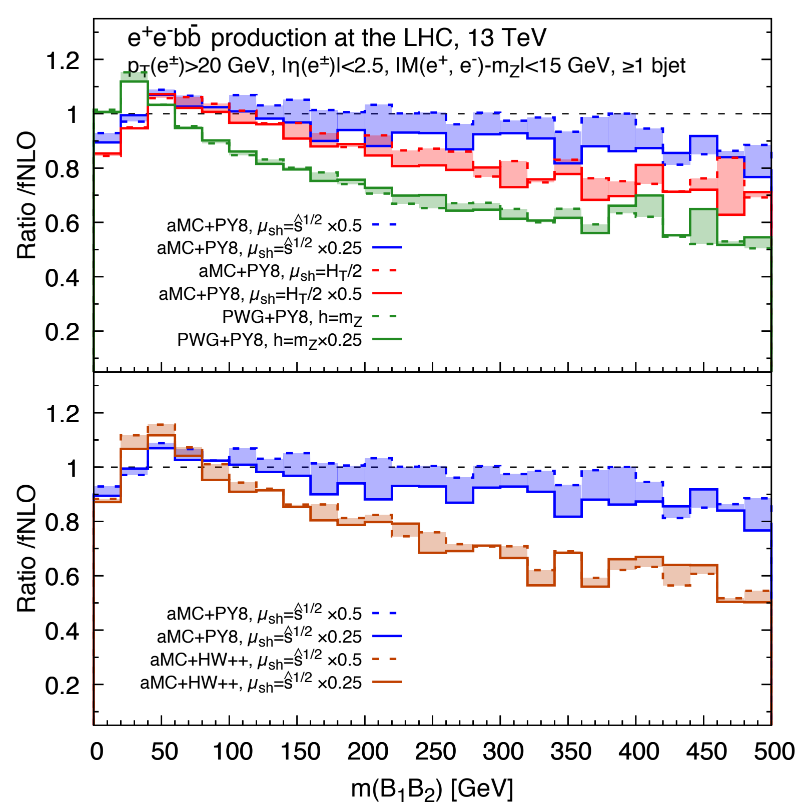
- scale + PDF uncertainties at the (±15% - ±25%) level, with dominant scale uncertainties
- each shower-scale choice has an uncertainty band up to O(±10%),

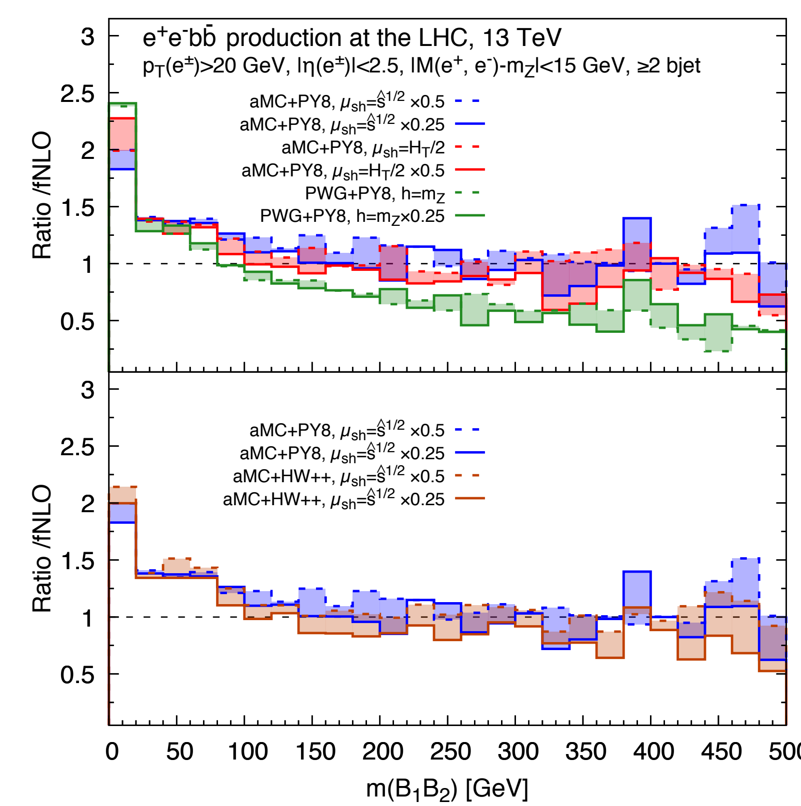
- POWHEG +Pythia is accidentally (?) similar to aMC@NLO+Herwig++
- very strong sensitivity to the QCD-PS model

- 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







Inclusive final state, integrated over the bottom quark contribution

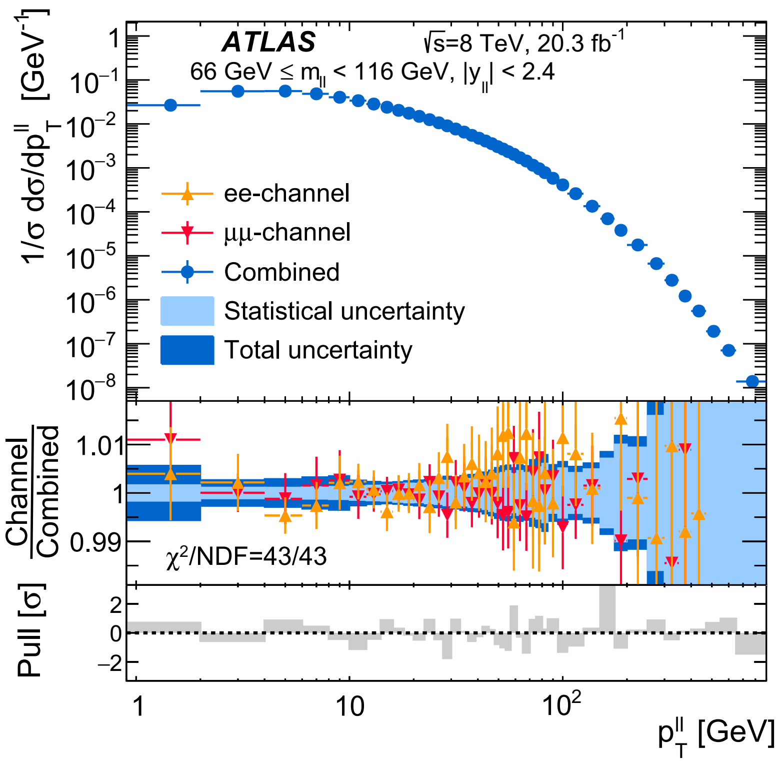
Relevance of the ptZ distribution for the MW determination

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 in QCD-PS, describing the low-pt part of the ptZ spectrum

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

→ an uncertainty from ptZ will propagate as a theoretical systematic error to other observables



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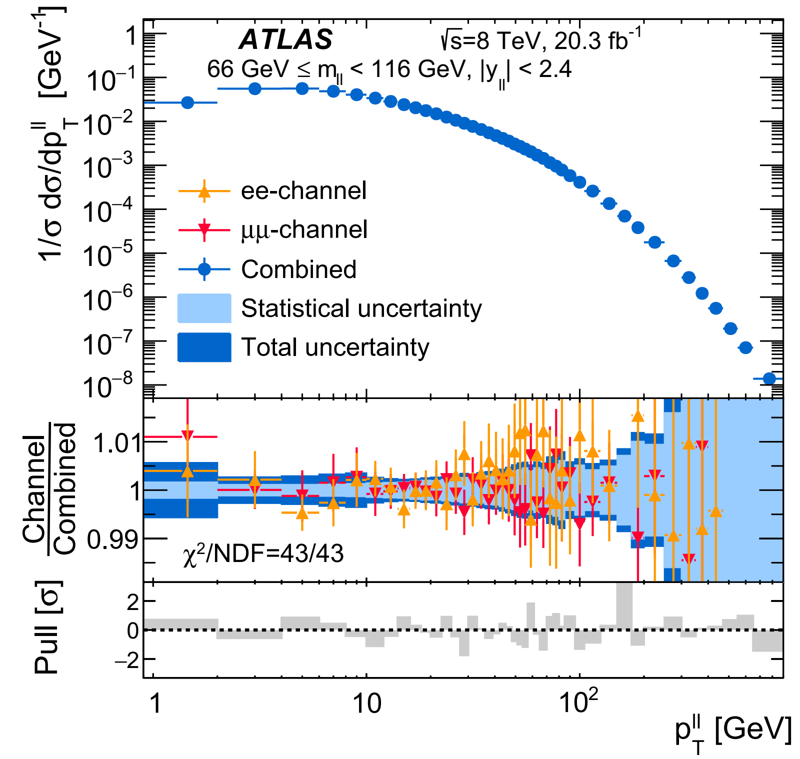

- the universality, the flavour and scale independence of the effects encoded in these NP models are a matter of debate
- the bottom quark contribution to ptZ, almost absent in the ptW case, may introduce spurious unwanted contributions in the ptW distribution, via the NP models

→ in turn affect the MW determination

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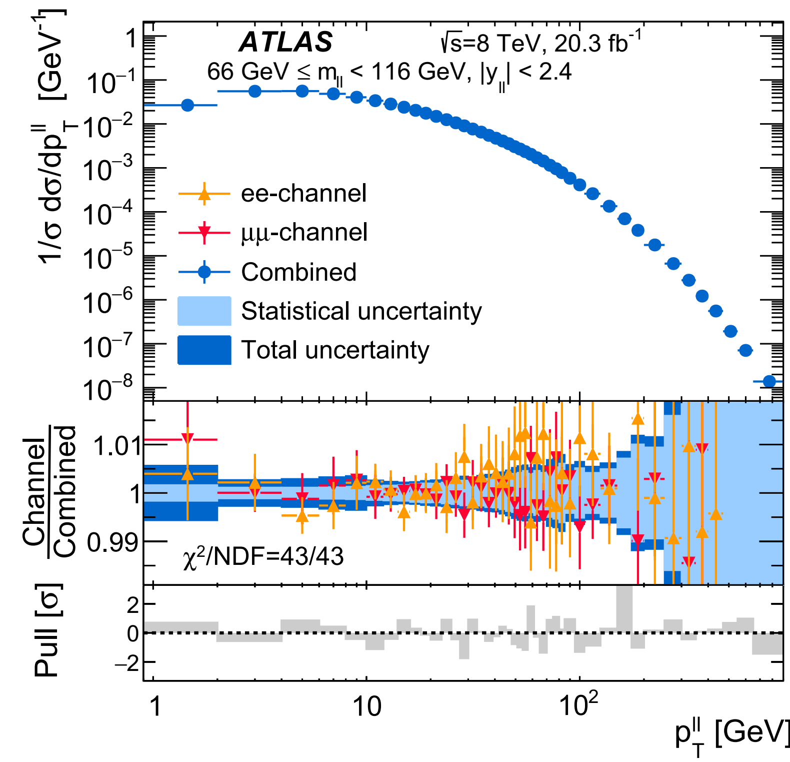

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- an improved partonic description of the bottom quark contribution to ptZ may

  → 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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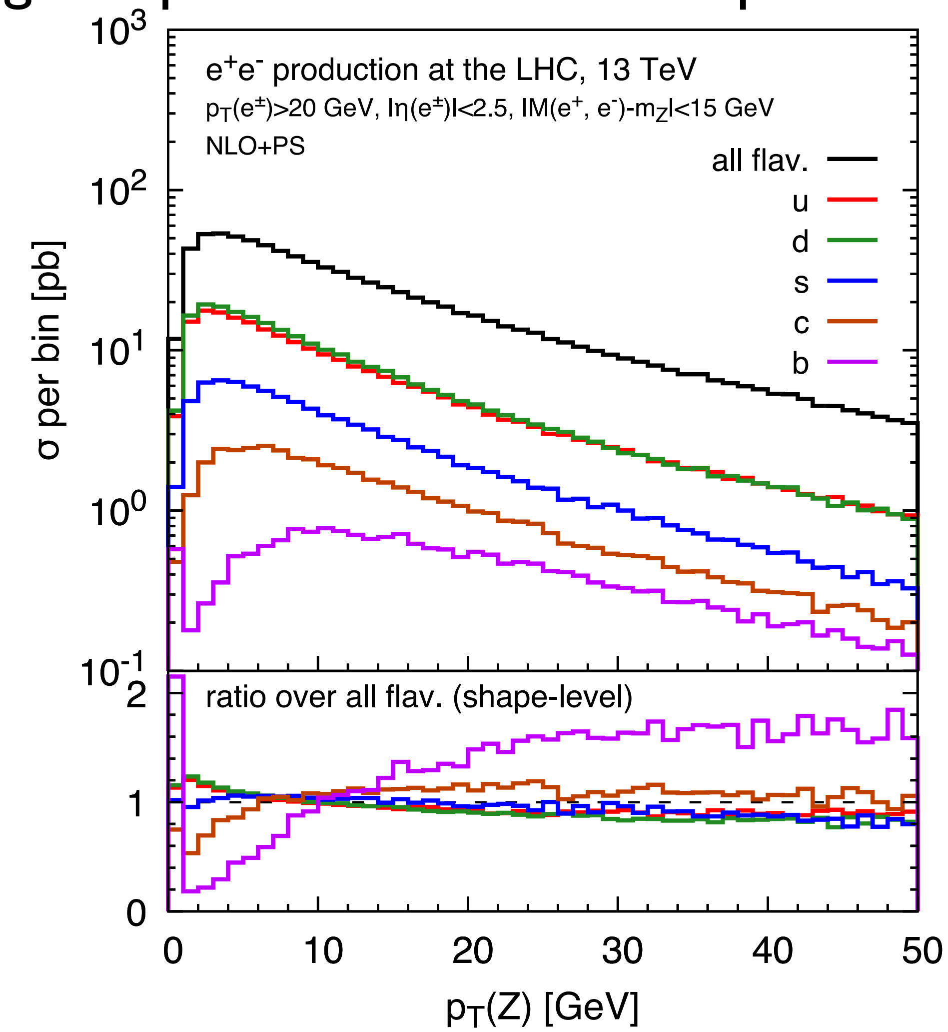

- the PDF evolution starts for the heavy quarks at Q ~ mq

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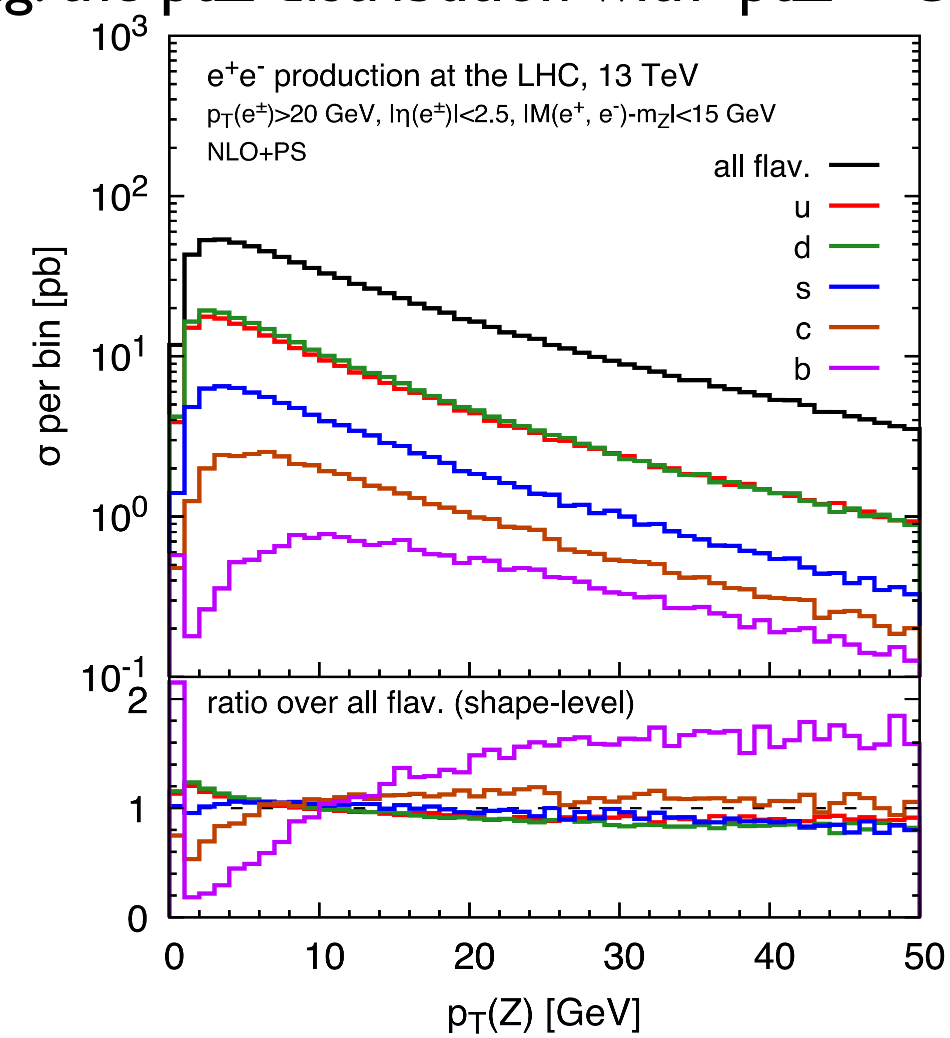


initial state quark	cross section (pb)	%
u	374.44 ± 0.62	35.0
d	391.15 ± 0.63	36.5
c	91.44 ± 0.34	8.6
s	170.43 ± 0.45	15.9
b	43.13 ± 0.26	4.0
total	1070.58 ± 0.86	100.0

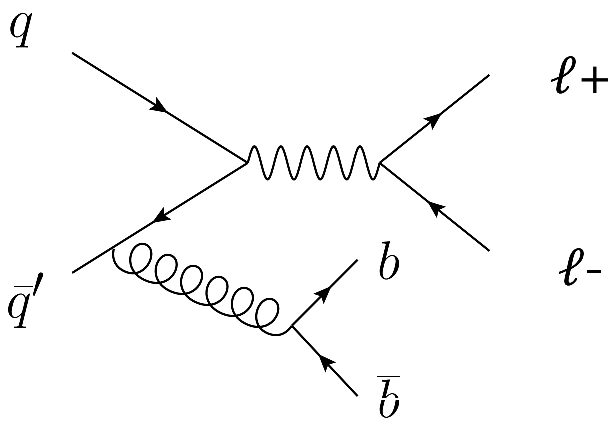
- given the exp error below 0.5% in a large range the bottom contribution of O(4%)

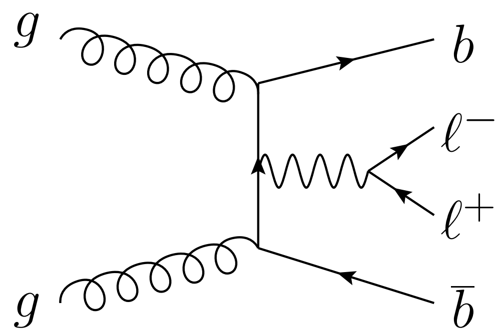
→ we need a prediction of the b contribution with a precision at the O(10%) level

- 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 ($pp \to e^+e^- b\,\bar{b}$)





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

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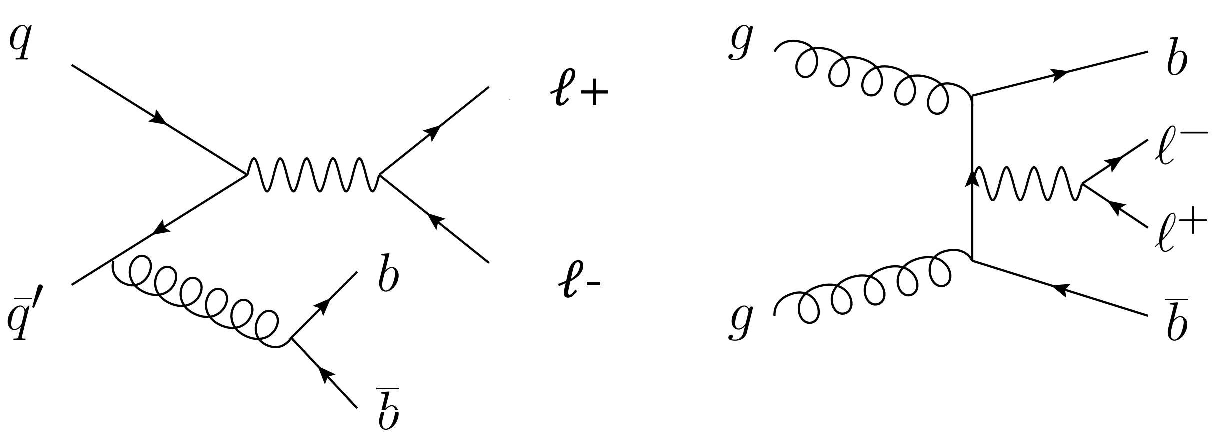

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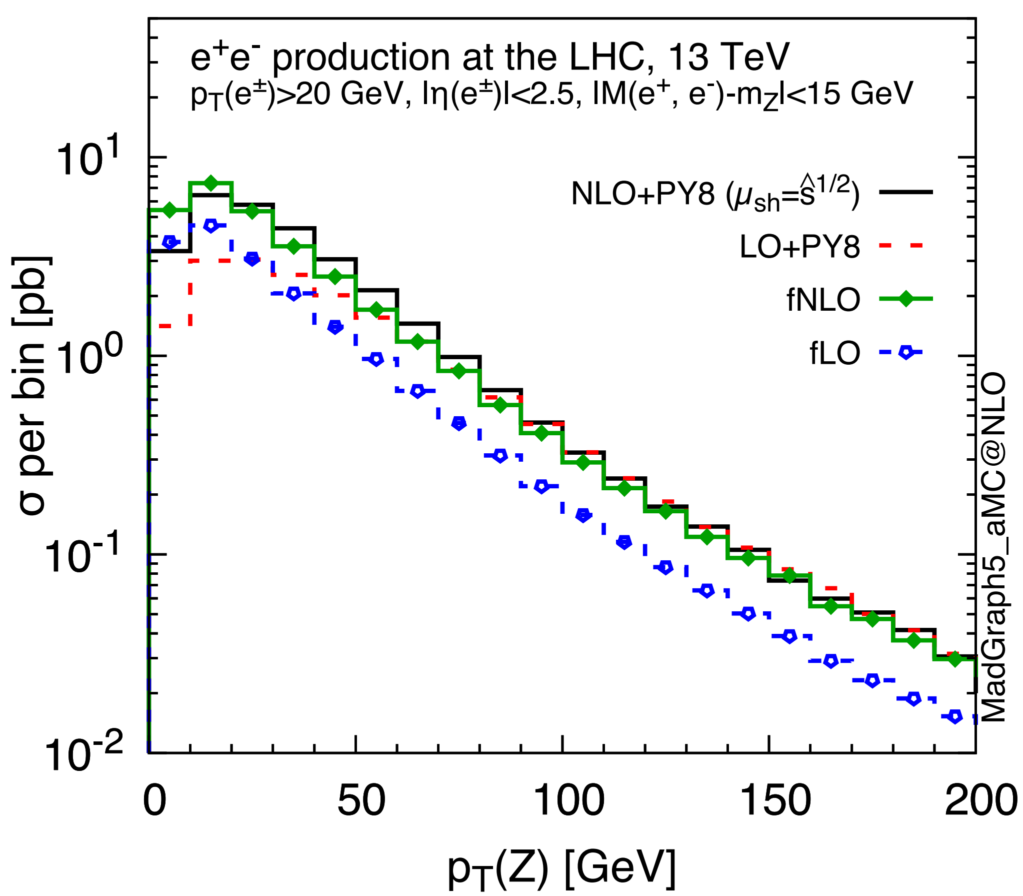
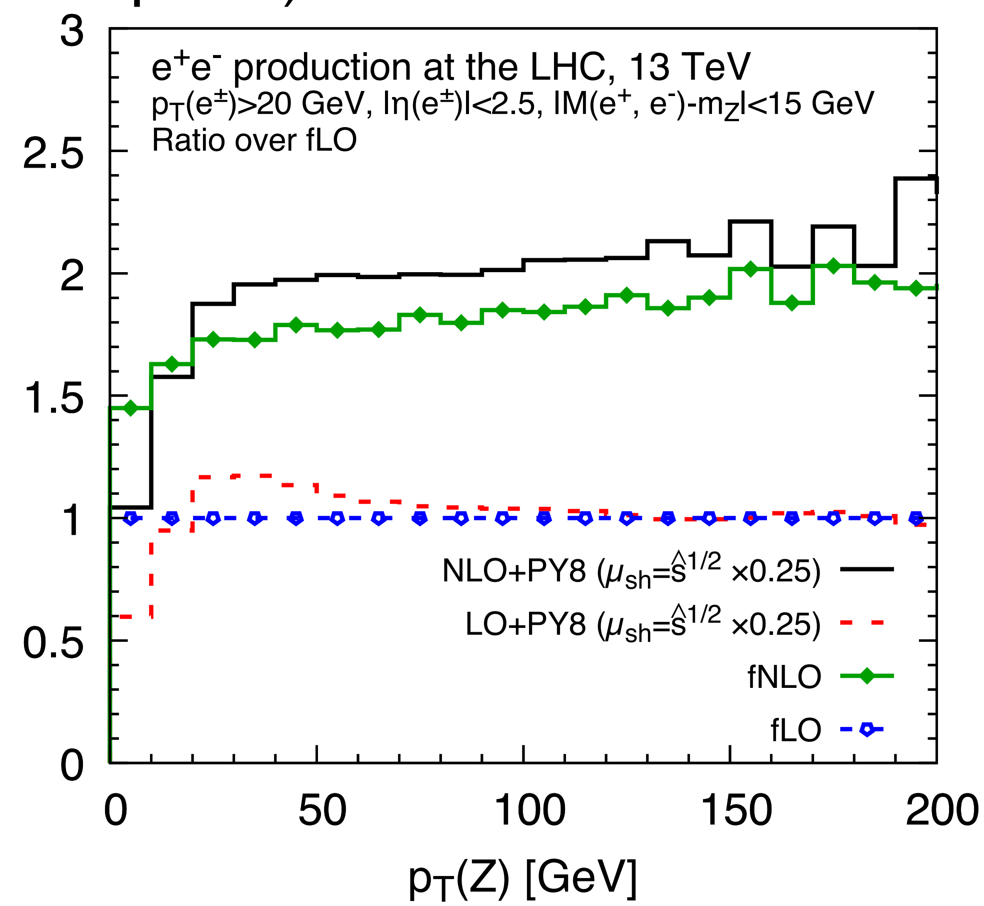
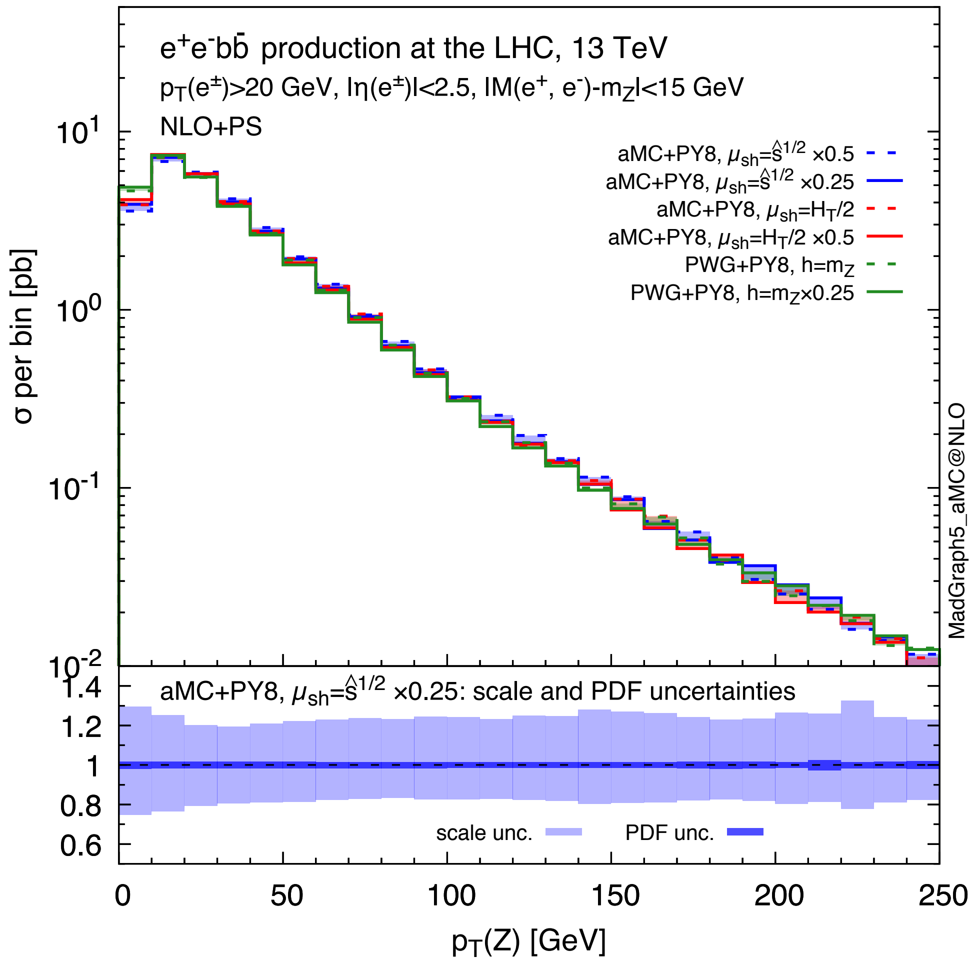
ptZ distribution (inclusive over b quarks)

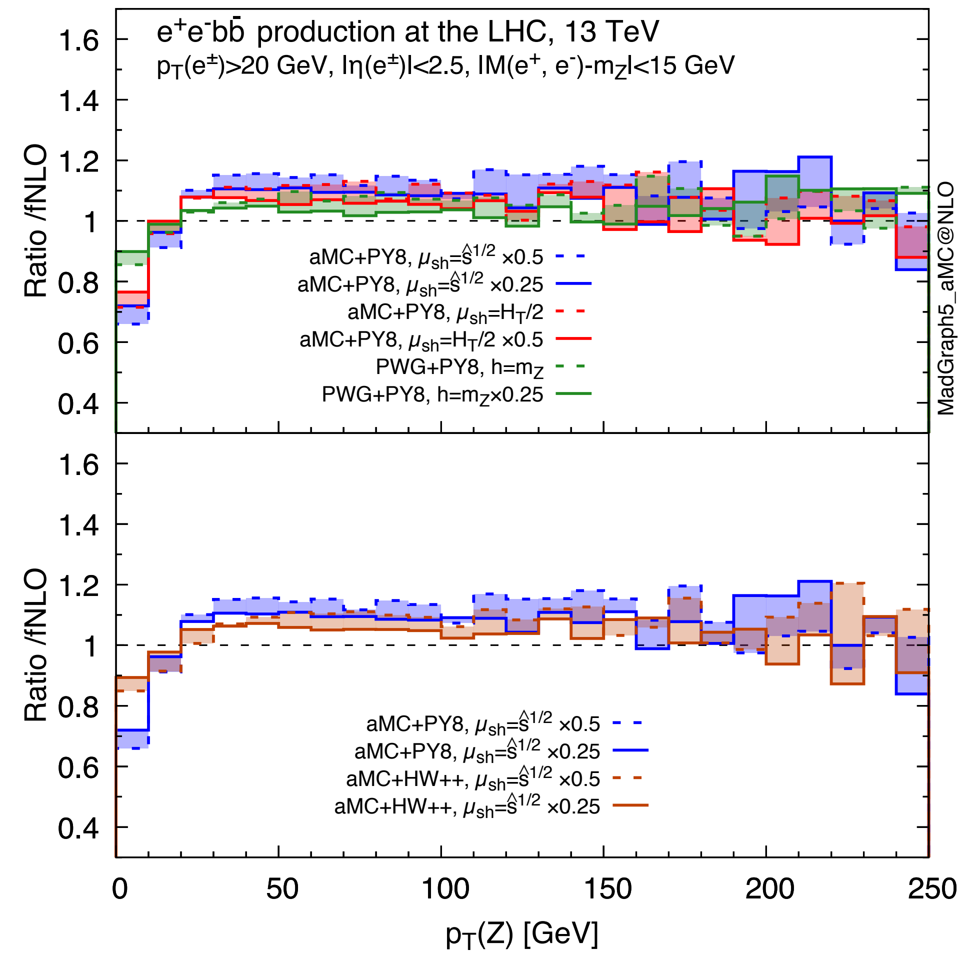




- regular when ptZ→0, but still sensitive to large log effects (aMC@NLO)
- the process has a large NLO K-factor
- large multiple gluon emission effects via QCD Parton Shower, for ptZ < 50 GeV

ptZ distribution in the 4FS (pp→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

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

- need to compare with analytical resummation in SCET, where a systematic handling of all large logarithmic corrections, at each ptZ value, is implemented

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  imposing a veto on the presence of B hadrons in the event analysis

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

- need to compare with analytical resummation in SCET, where a systematic handling of all large logarithmic corrections, at each ptZ value, is implemented

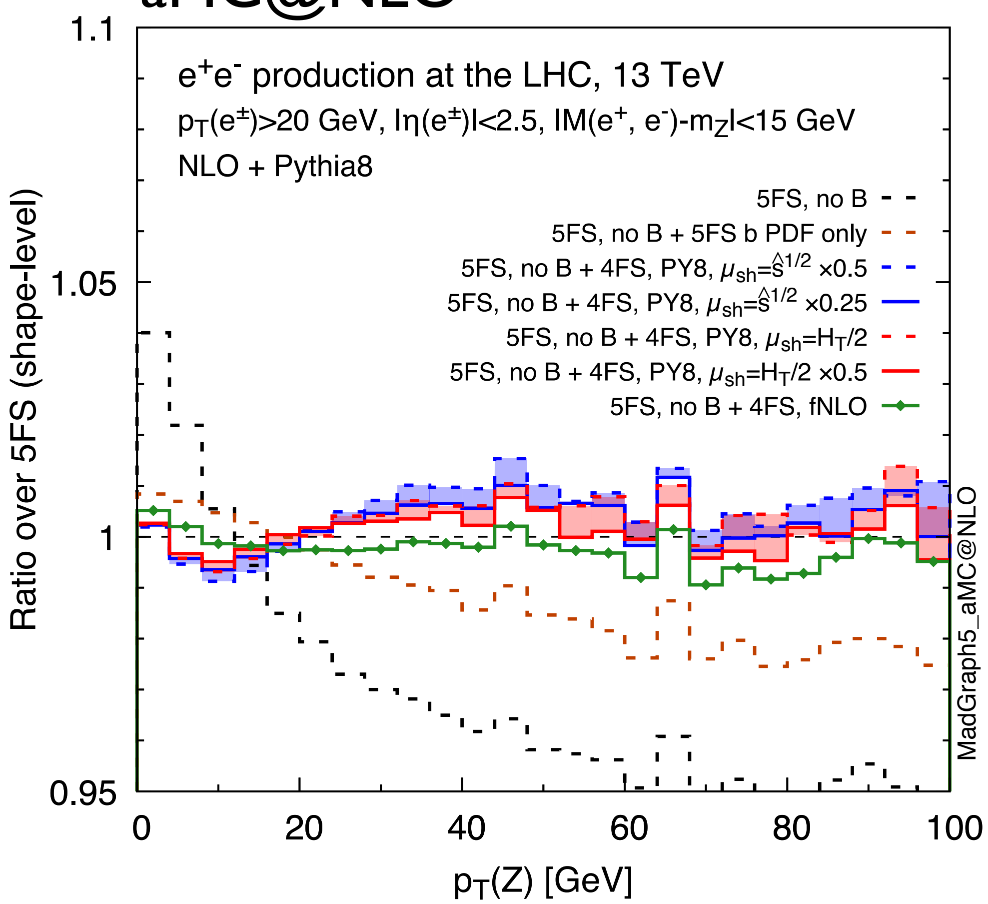
Improved prediction of the ptZ distribution

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

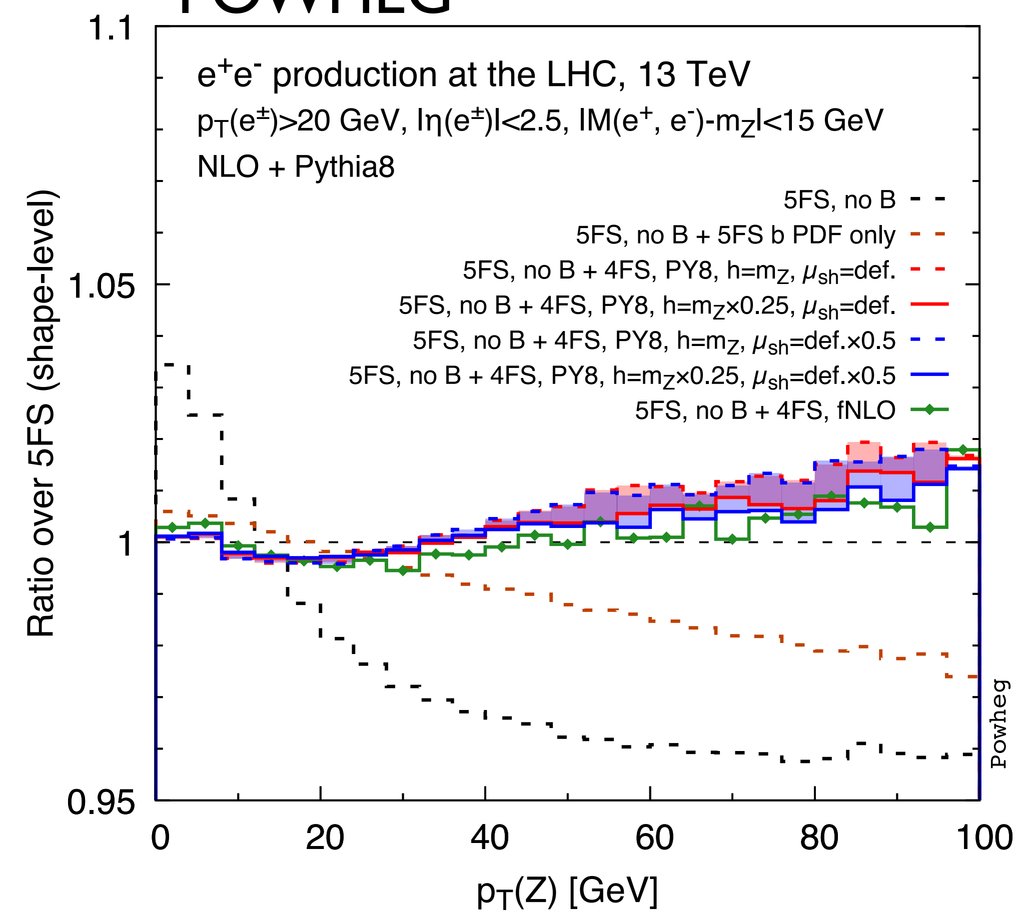
- $\mathcal{R}$ expresses the distortion of the improved ptZ, with respect to the full plain 5FS prediction

- 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

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`)

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

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

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

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

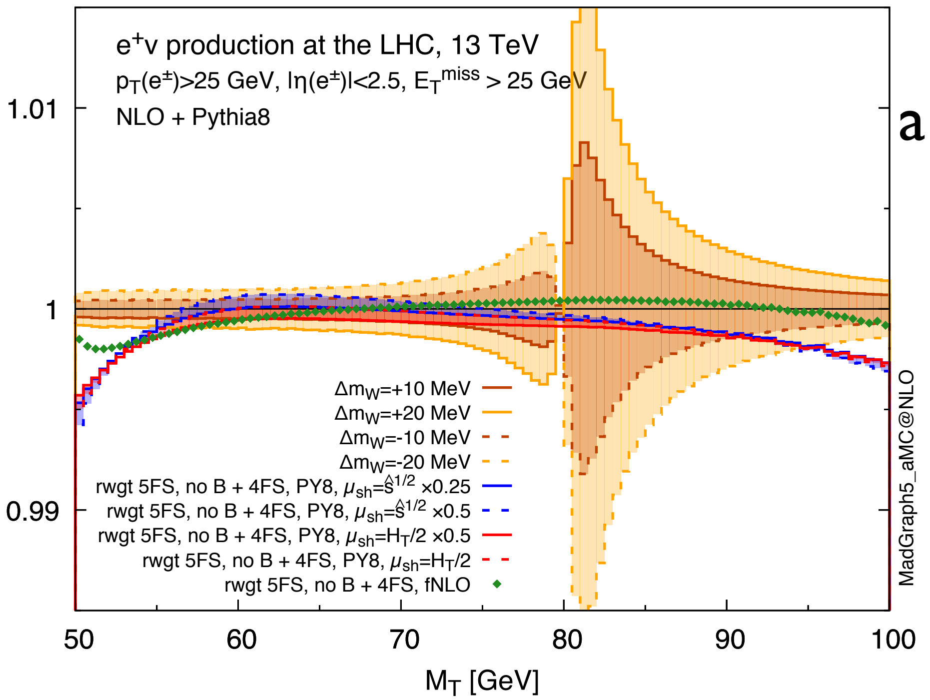
Impact on the CC-DY observables of b-quark effects

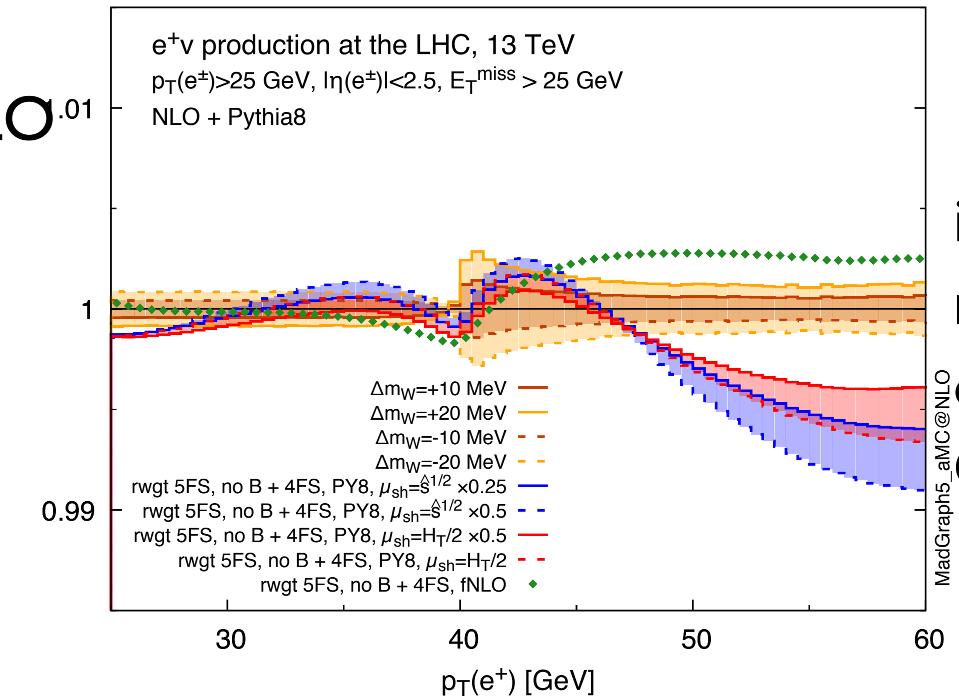
The CC-DY observables are evaluated in the plain 5FS

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

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)

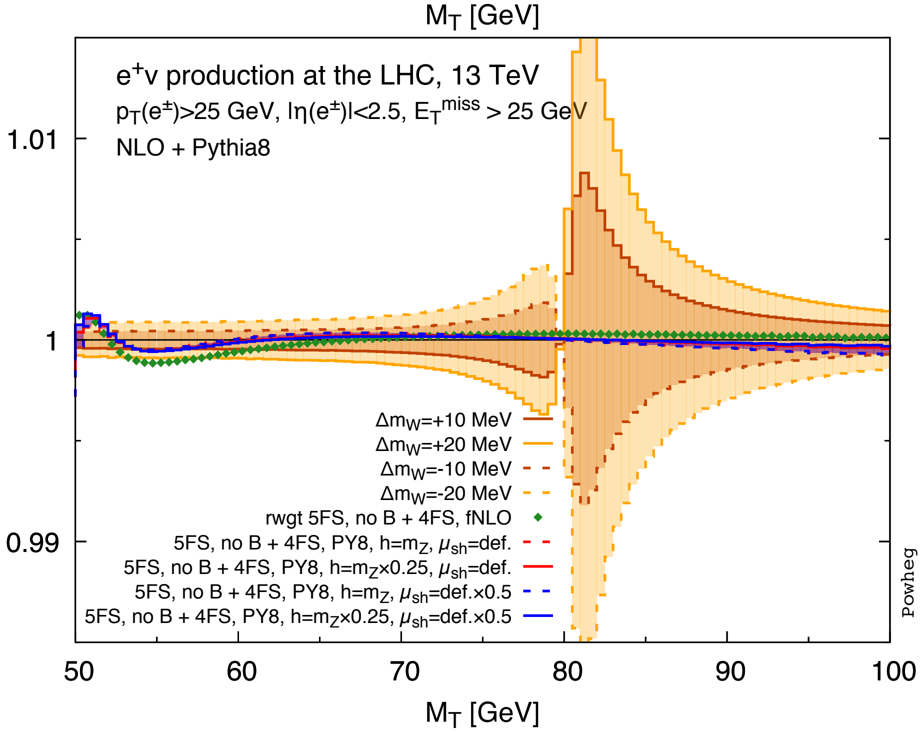
aMC@NLO

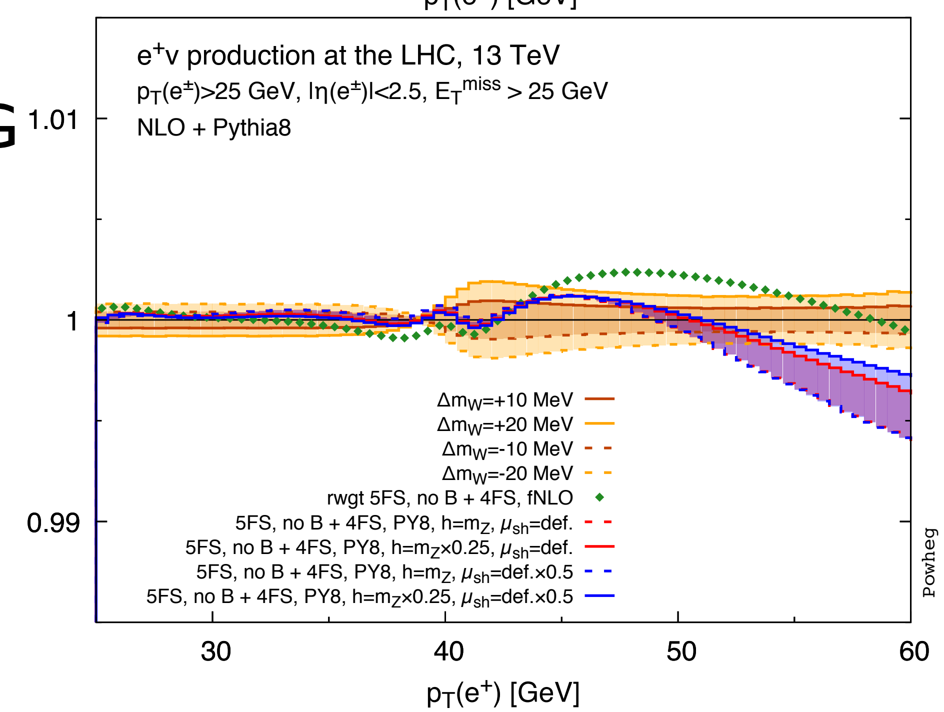




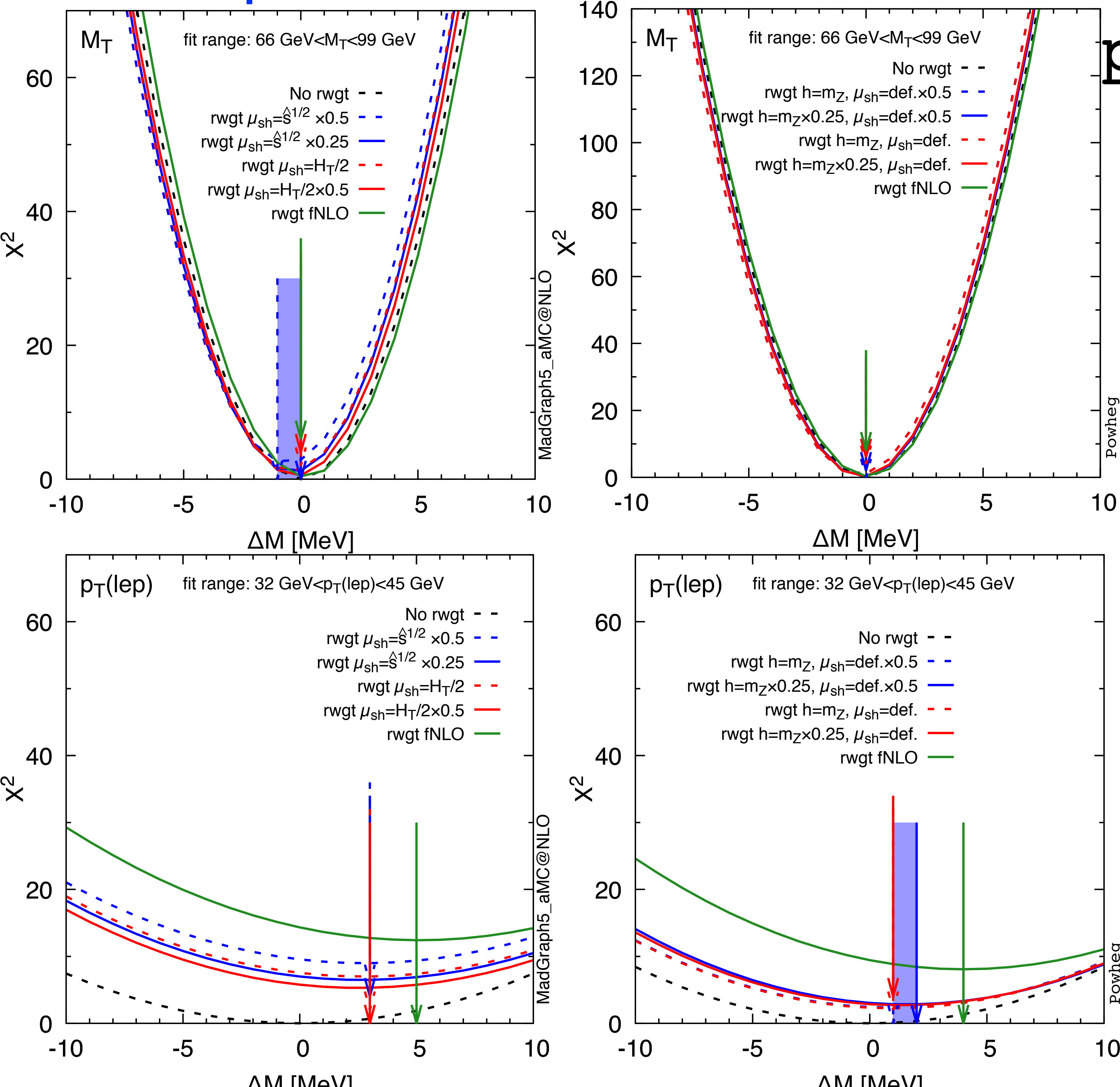
in the high-ptlep tail non negligible effect of the matching with QCD_PS

POWHEG





Bottom quark effects on the MW determination

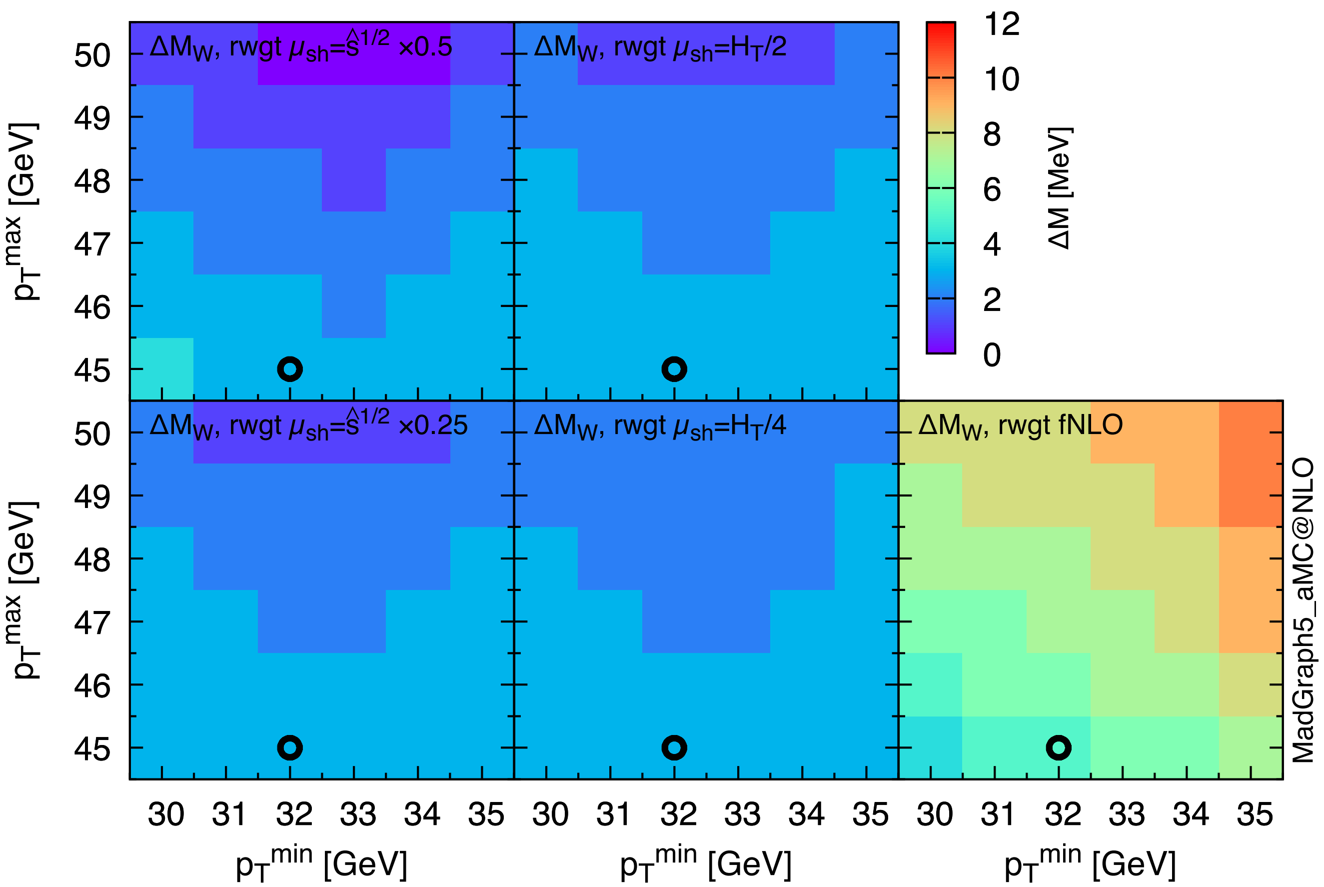


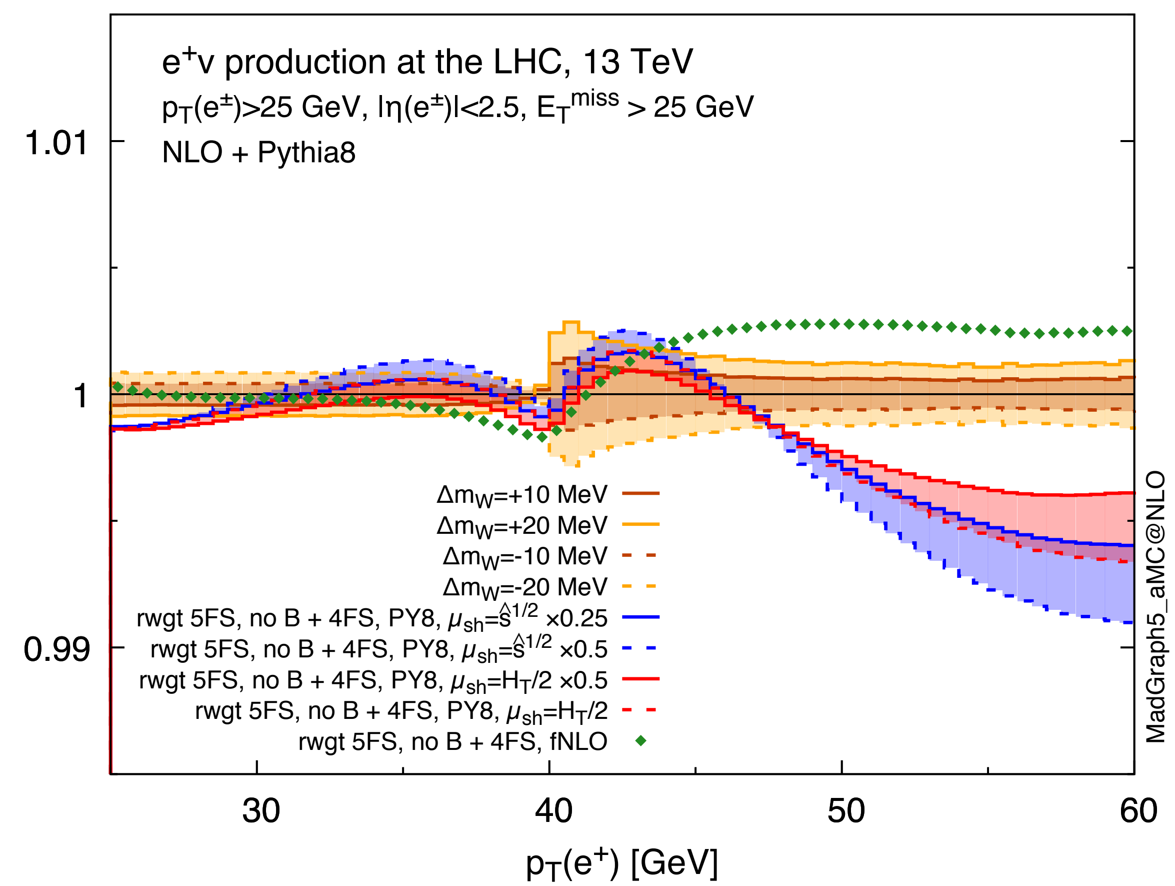
preliminary results

- 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 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

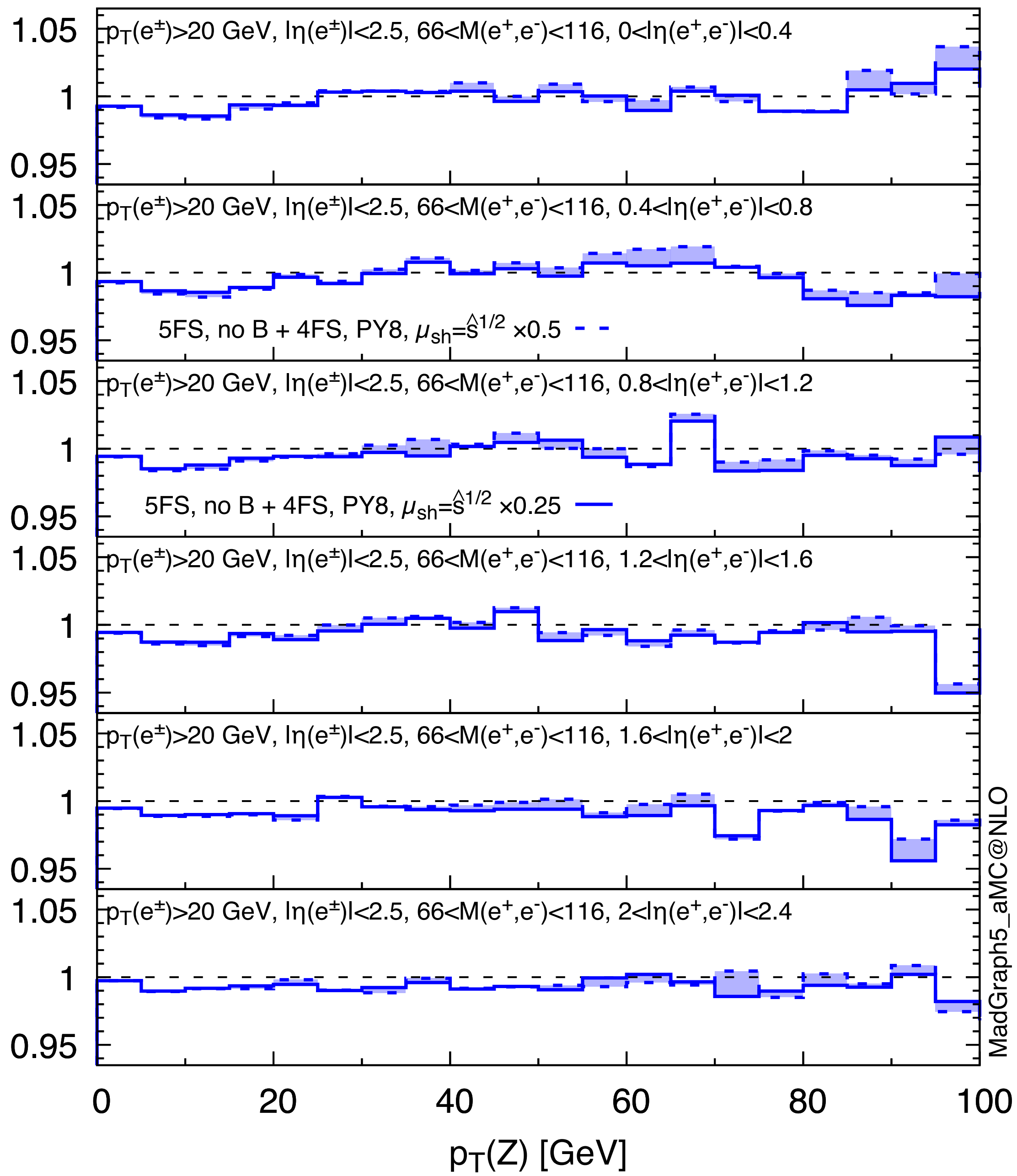
Dependence of the MW shifts on the fit window

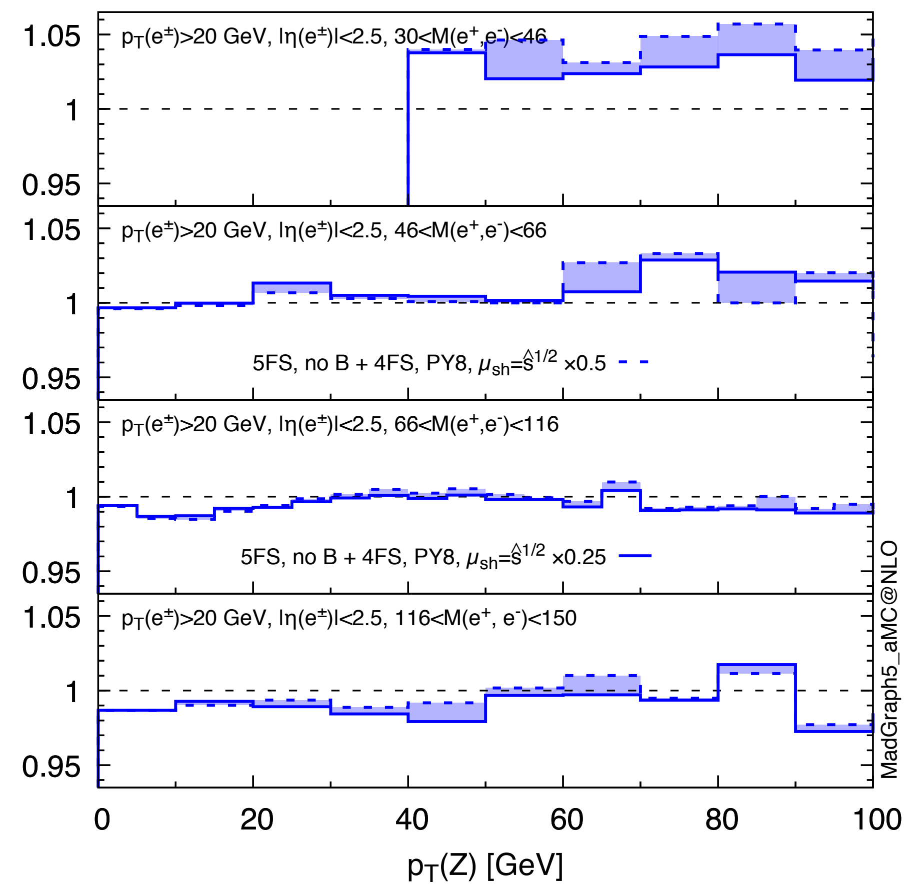




- the outcome of the template fit depends on the fit window, especially on the upper limit
- above the jacobian peak, the NLOPS distortion changes slope at ptlep ~ 45 GeV, pulling the χ^2 in opposite directions in the intervals [40,45] and [45,50] GeV
- above the jacobian peak, the fixed order NLO becomes 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

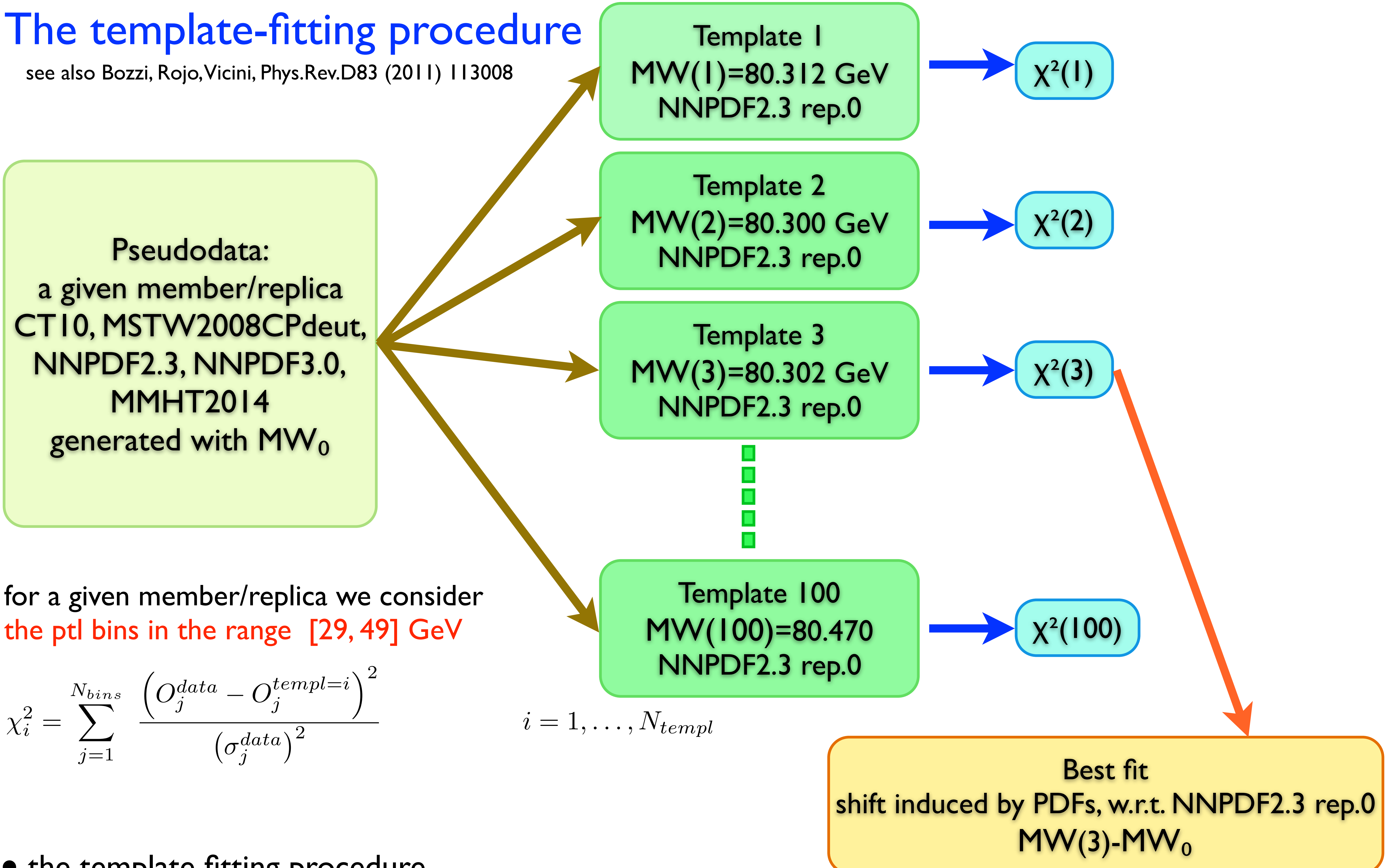
- a combination of 5FS and 4FS results has been attempted to improve the description of the bottom quark contributions to the ptZ distribution with respect to the plain 5FS approach, with a shape distortion at the O(1%) level

- 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)

- precision physics at the LHC requires a strong collaboration between theorists and experimentalists to make precise quantitative statements back-up slides

The template-fitting procedure

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



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

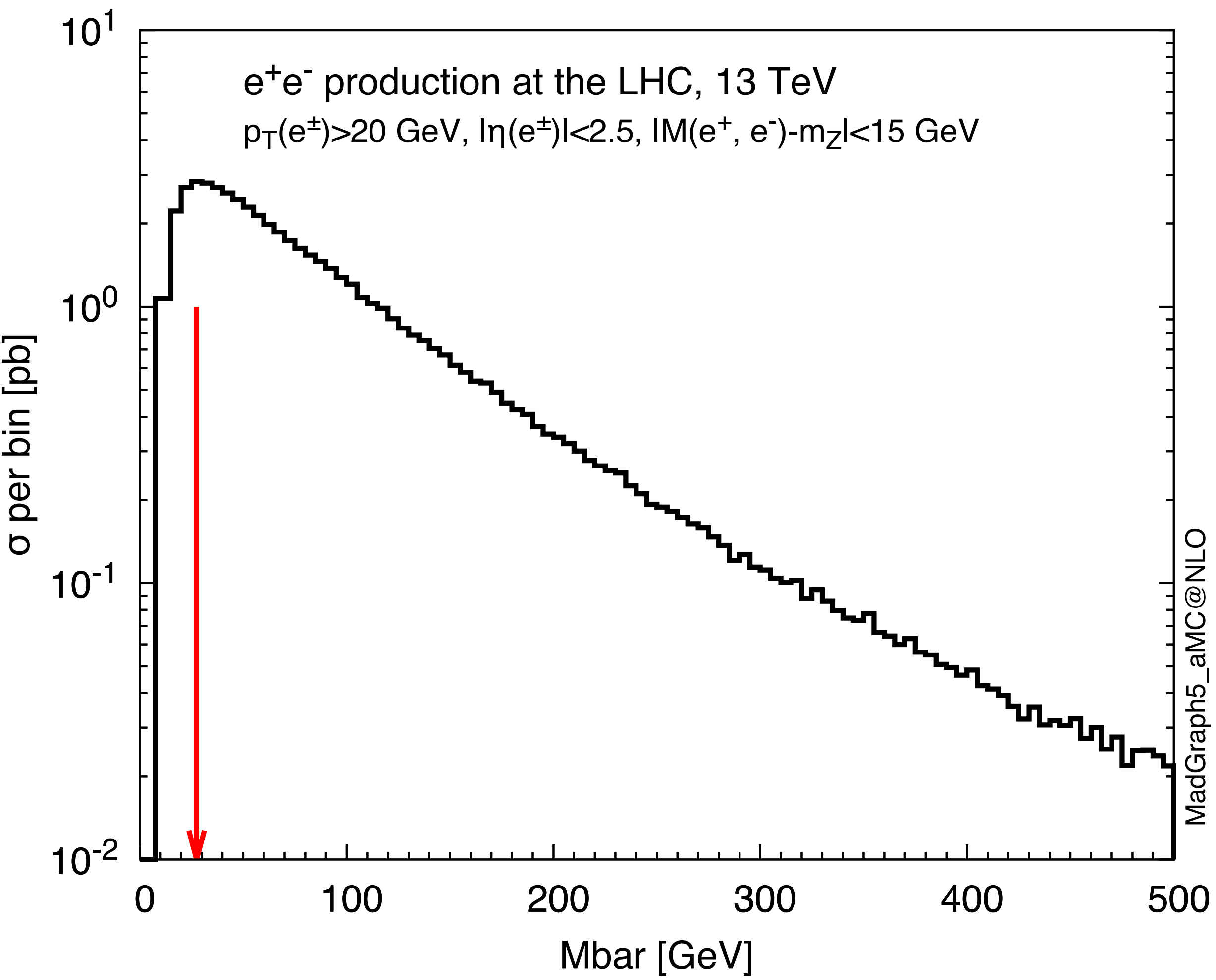
Estimate of the effective upper limit for additional radiation

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

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

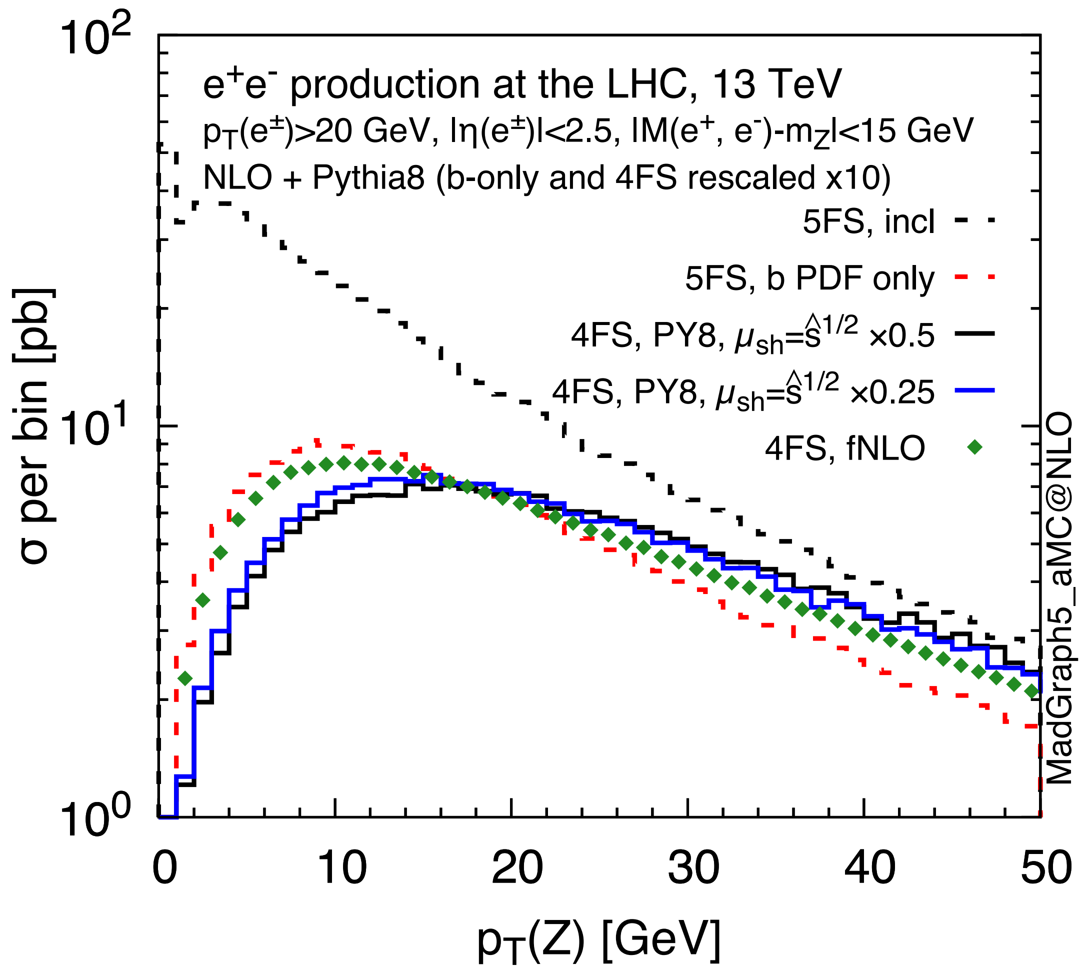
This leads to the introduction of an effective scale Mbar

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



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

e^+e^-bb: hardest b-jet pt distribution in association with N b-jets