Standard Model and Higgs physics: Where do we need better predictions at the LHC?

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Trieste

Marco Zaro

LPTHE - Université Pierre et Marie Curie

Paris - France

Why precision physics at the LHC?

- The LHC measurements are a stress-test of the Standard Model and aim at finding some hint of new physics
- So far the SM performed extremely well!
- Since no easy discovery has (yet) shown up, if new physics exists, it is hiding extremely well
- New physics will probably manifest itself in tiny deviations from the SM predictions, either of SM parameters or of kinematical distributions

How do we do precision calculations?

- QCD master formula

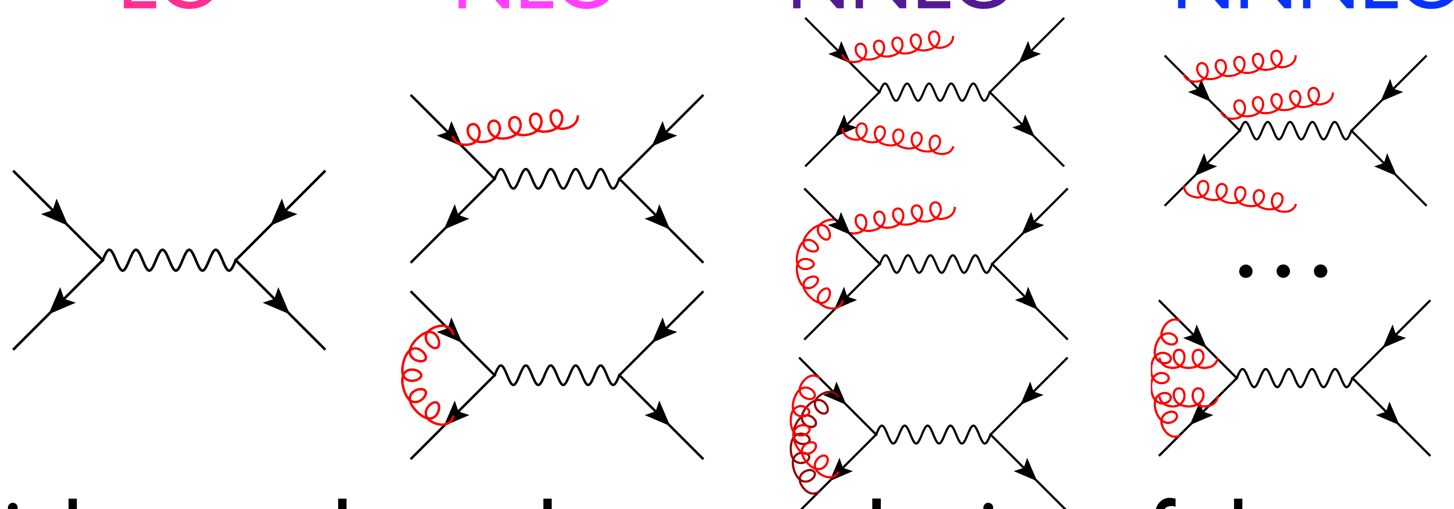
$$\sigma_{pp\to X}(s) = \sum_{ab} \int dx_1 dx_2 f_a(x_1) f_b(x_2) \hat{\sigma}_{ab\to X}(\hat{s} = x_1 x_2 s)$$

Parton distribution functions: must be fit to data, process independent

Partonic cross section: can be computed in perturbation theory, process dependent

$$\hat{\sigma}_{ab\to X} = \hat{\sigma}^{(0)}_{ab\to X} + \alpha_s \hat{\sigma}^{(1)}_{ab\to X} + \alpha_s^2 \hat{\sigma}^{(2)}_{ab\to X} + \alpha_s^3 \hat{\sigma}^{(3)}_{ab\to X} + \dots$$

LO NLO NNLO NNNLO

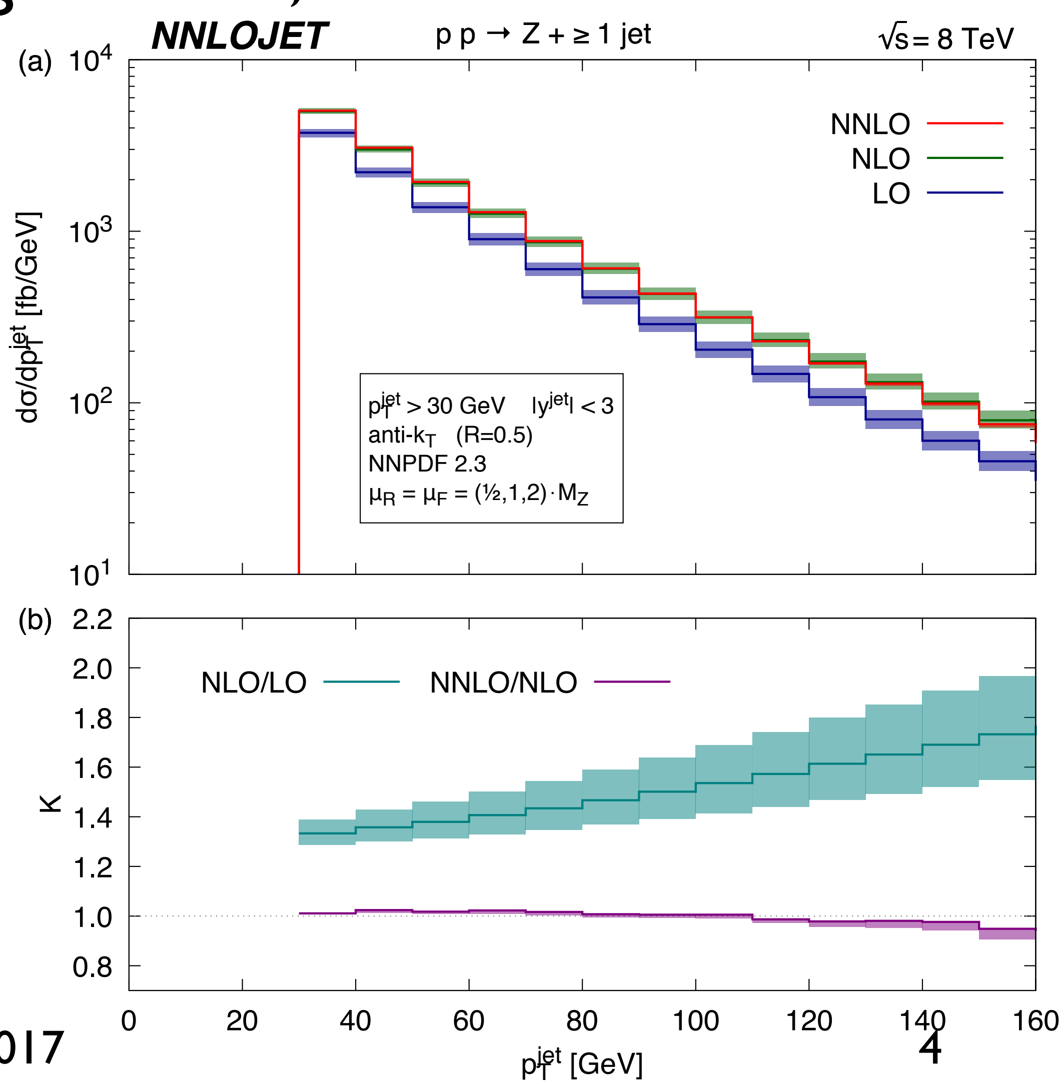


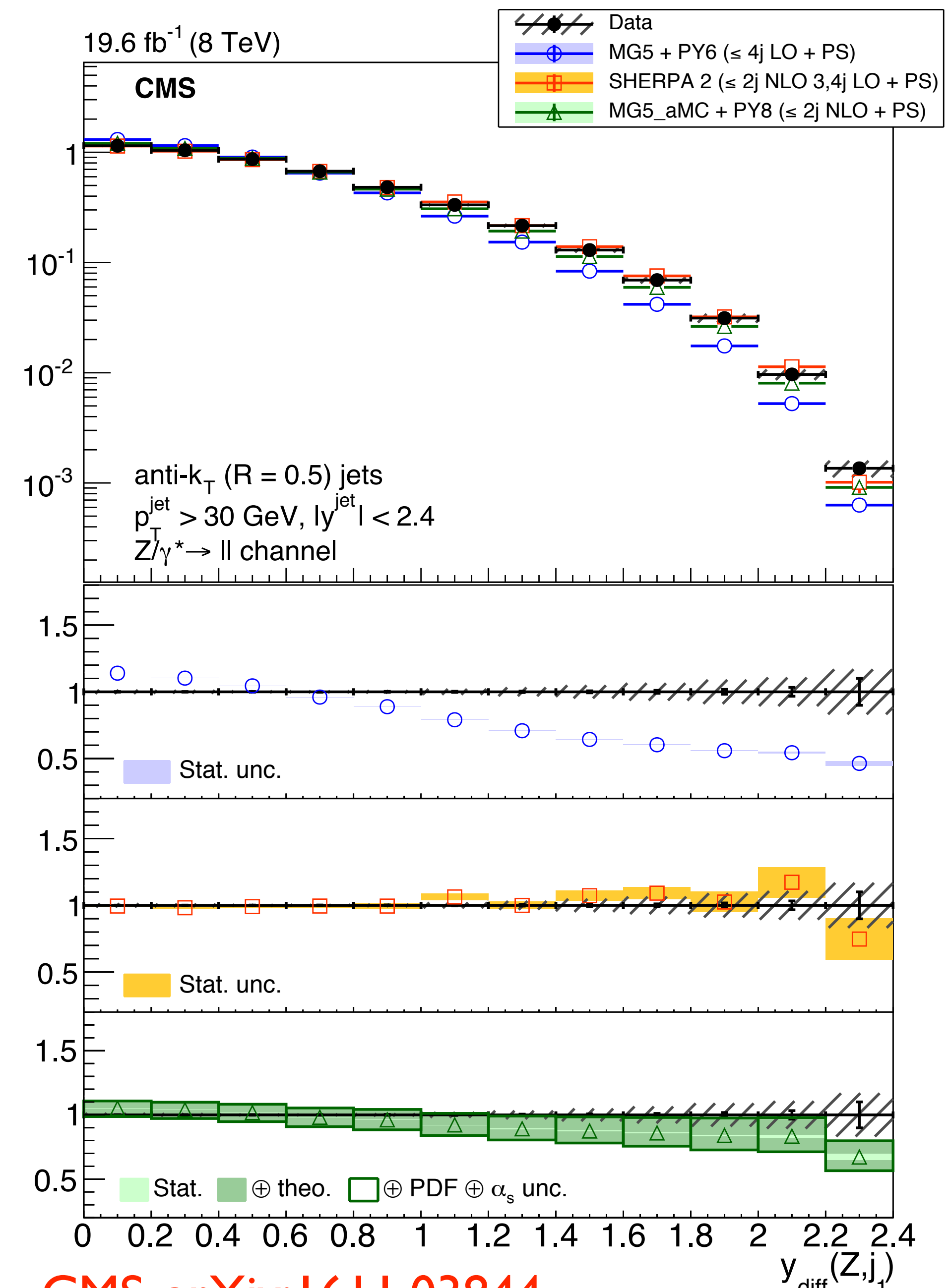
- Going higher orders, the complexity of the computation explodes

What do we gain?

- Higher order predictions reduce theoretical uncertainties
- Higher order predictions improve the theory-data agreement, and reduce the need of tuning

Gehrmann-de Ridder et al, arXiv:1507.02850





CMS, arXiv:1611.03844

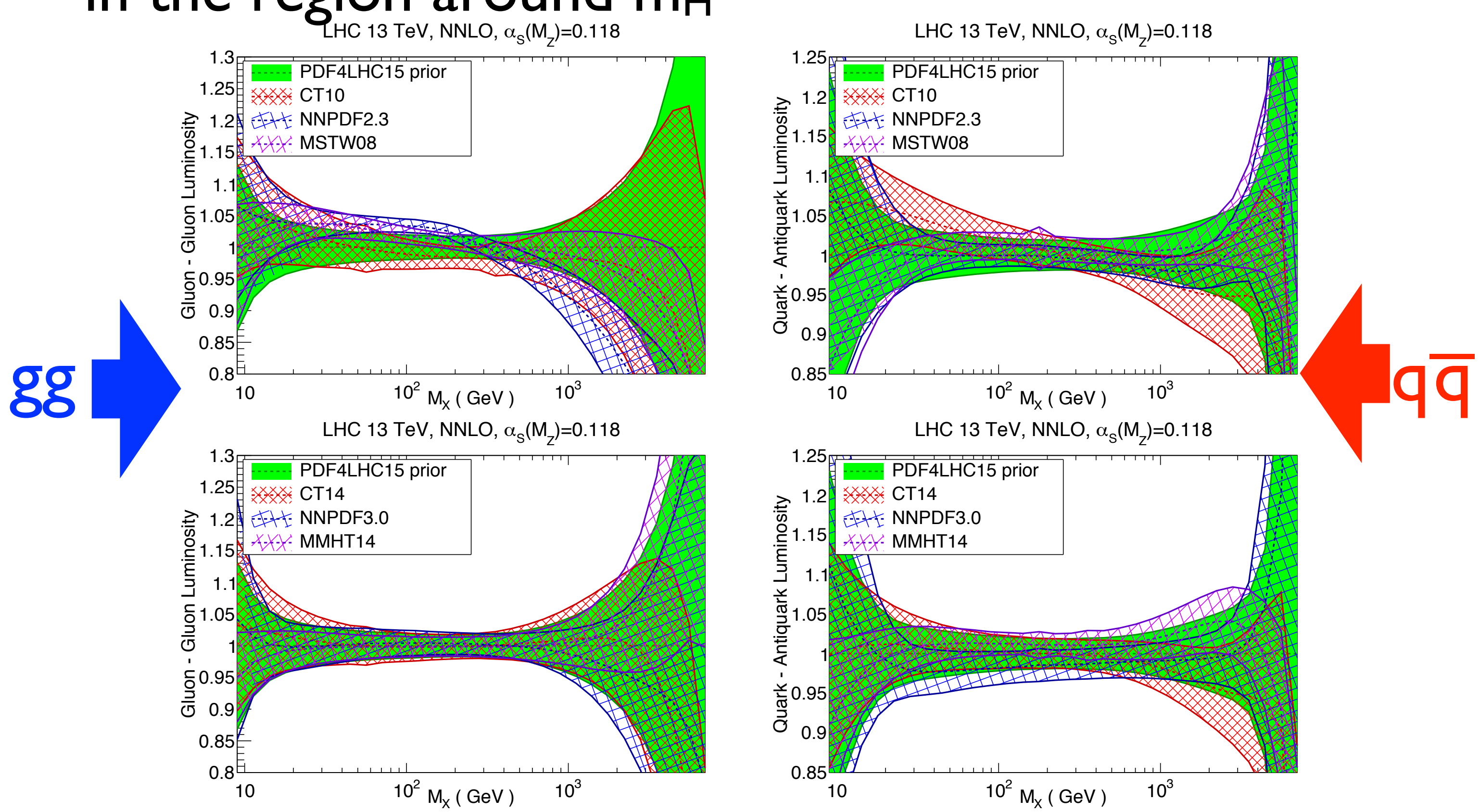
Where do we stand?

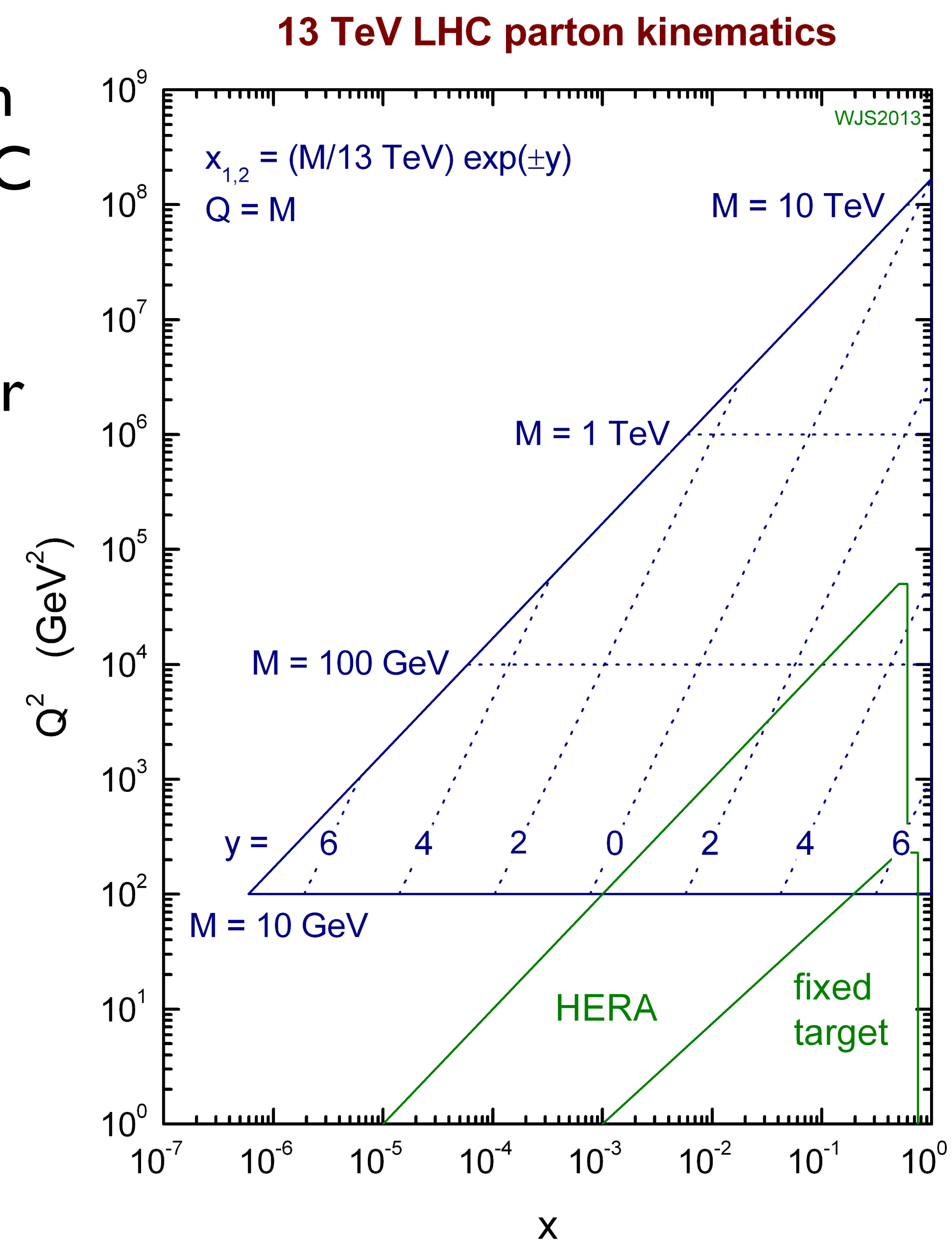
- Higgs cross section at N^3LO in QCD Anastasiou et al, arXiv:1503.06056
- NNLO available for all $2\to2$ processes, general subtraction techniques available see e.g Del Duca et al, arXiv:1501.07226, Caola et al, arXiv:1702.01352
- Bottleneck to go to higher multiplicities is the lack of 2-loop amplitudes
- NLO automated since a couple of years ago
- Since $\alpha \simeq \alpha_S^2$, NLO EW corrections cannot be neglected and have to be included. Automation in a very advanced stage

Progress on PDF fits (circa 2015)

see PDF4LHC15, arXiv:1510:03865 & chapter 2.1 in LHCHXSWG YR4 arXiv:1610.07922

- The quality and kinematics span of LHC data are crucial to improve PDF fits
- Global fits from the main PDF collaborations have been updated with improved methodology and including LHC data
- This has lead to excellent agreement in the parton luminosities coming from different PDF fits, in particular in the region around m_H

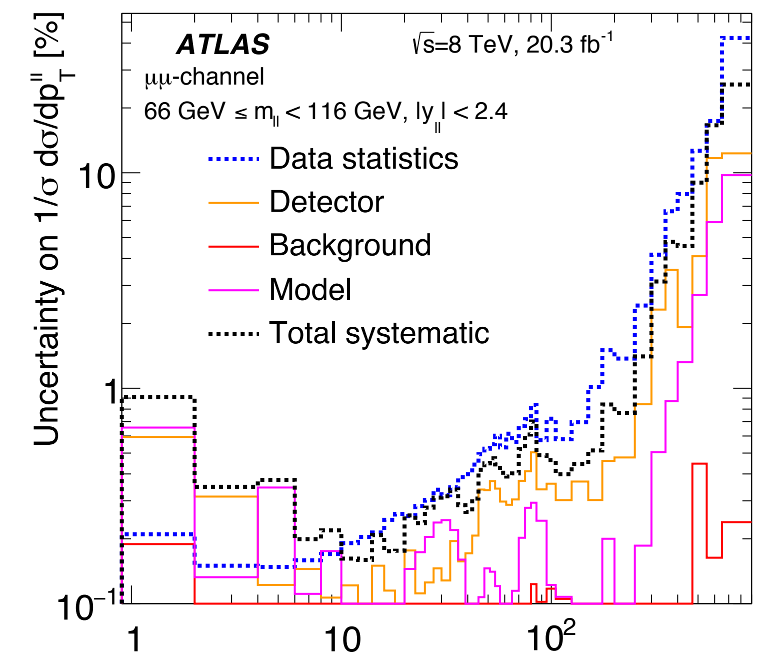




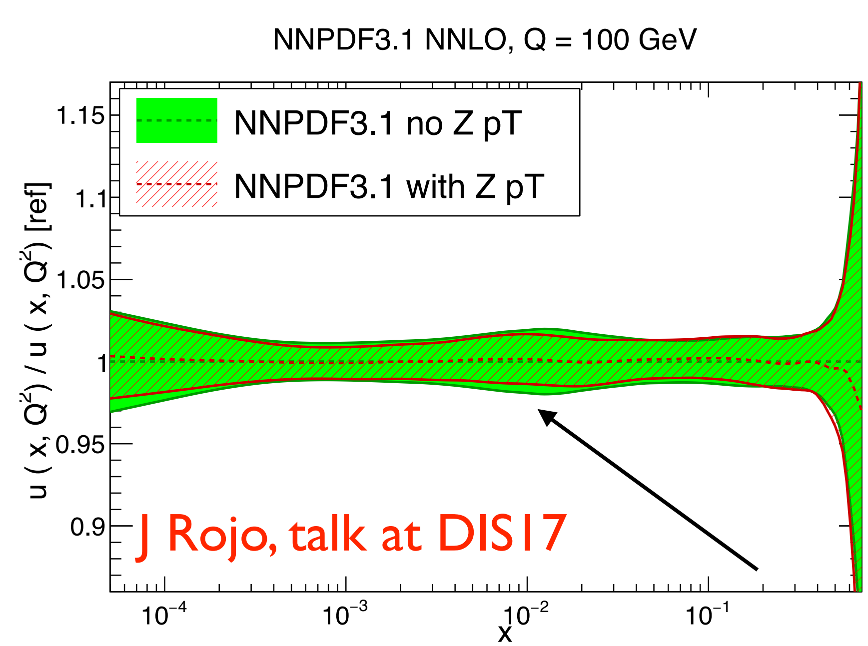
Progress in PDF fits (circa 2017)

see J. Rojo and M. Ubiali talks at DIS 2017

- New LHC datasets are being included in the PDF fits
  - One example is Z p_T: measurements at the LHC have already reached the 1% accuracy at Run I!
  - Excellent theoretical predictions exist (Z+jet at NNLO)
    Boughezal et al, 1512.01291, Gehrmann-de Ridder et al, arXiv:1605.04295
  - Inclusion of Z p_T data does not spoil the consistency of the fit. Small reduction of PDF uncertainties
- Great progresses have been made towards a precise determination of the *photon* PDF
  - A direct fit would give little sensitivity
  - LuxQED prediction uses DIS data to extract the photon PDF with very small errors

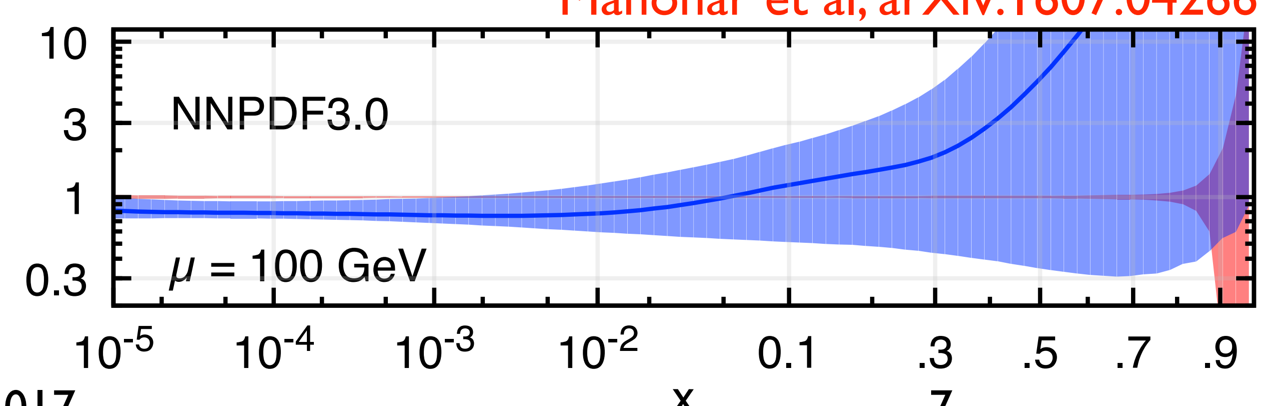


ATLAS arXiv:1512.02192



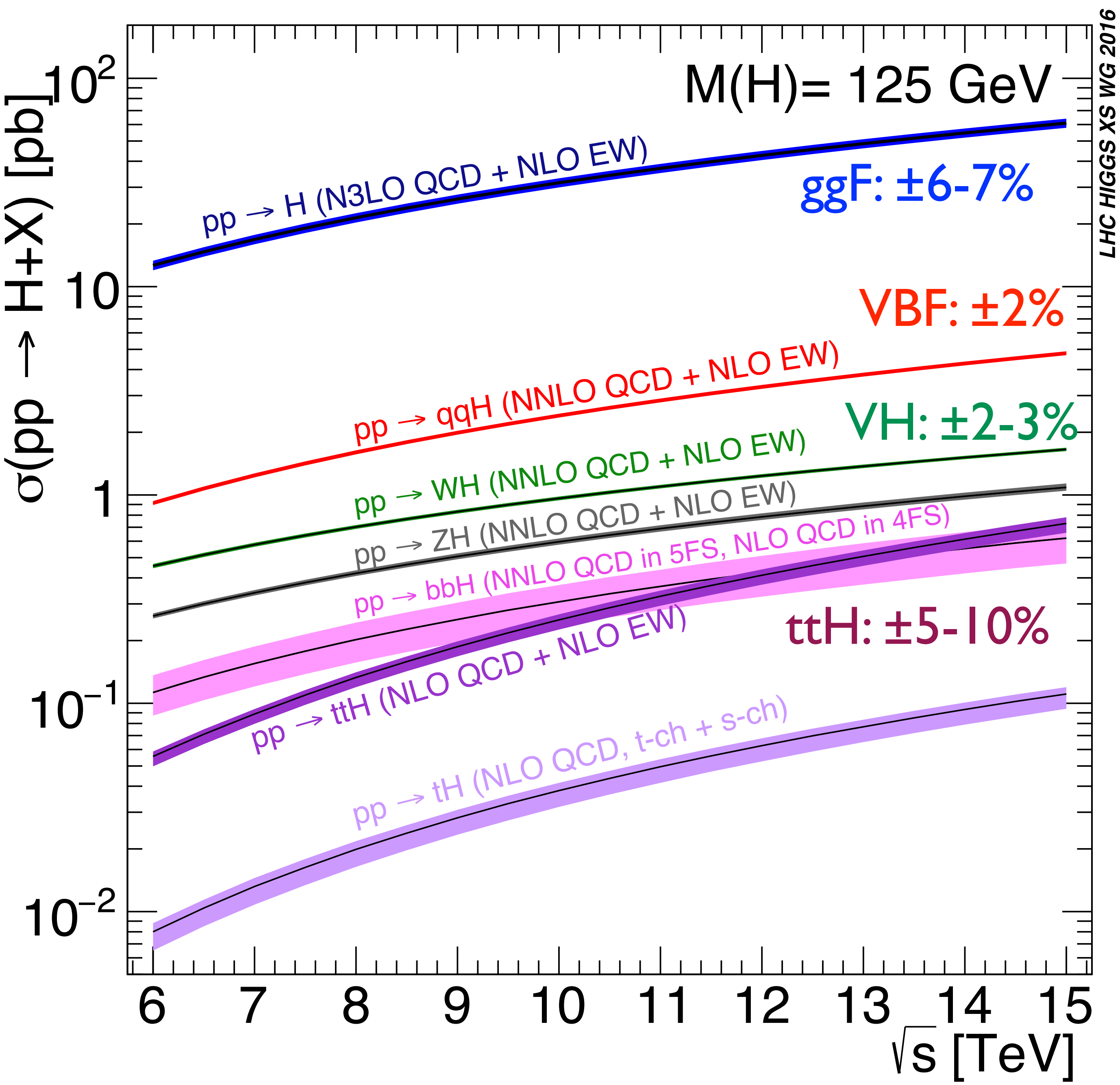
J Rojo, talk at DIS17

Manohar et al, arXiv:1607.04266



State of the art predictions for Higgs production

see LHC HXSWG YR4, arXiv:1610.07922



- Lot of efforts have been put into improving the theoretical predictions for Higgs production at the LHC
- Current predictions may be enough to survive until the end of the HL-LHC run II

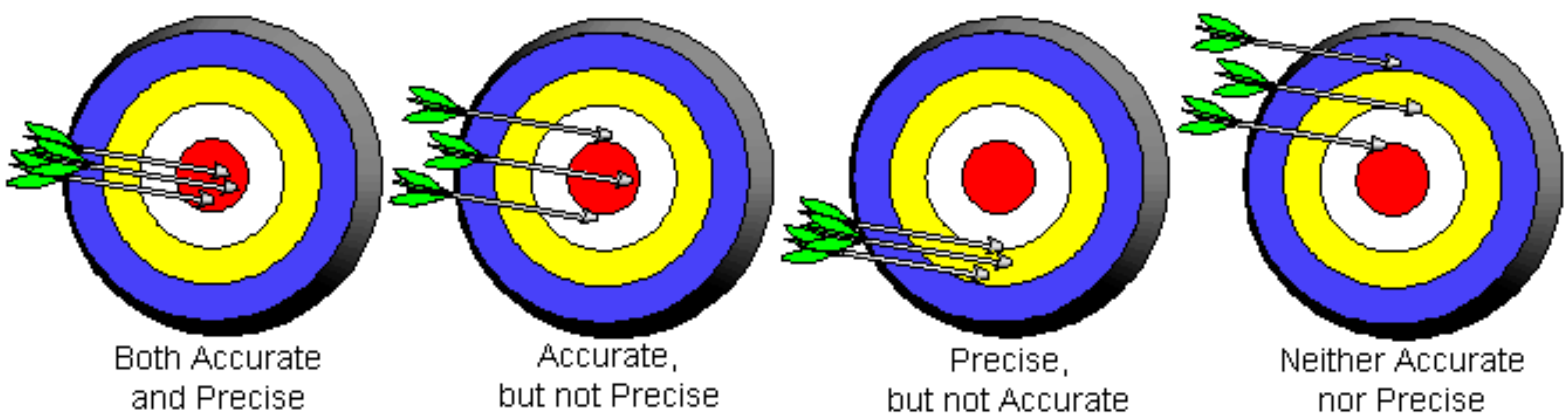
$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$gg \to H$	0.12	0.06	0.11	0.04
VBF	0.18	0.15	0.15	0.09
WH	0.41	0.41	0.18	0.18
$qqZH$	0.80	0.79	0.28	0.27
$ggZH$	3.71	3.62	1.47	1.38
ttH	0.32	0.30	0.16	0.10

Pre-N^{3}LO

ATL-PHYS-PUB-2014-016

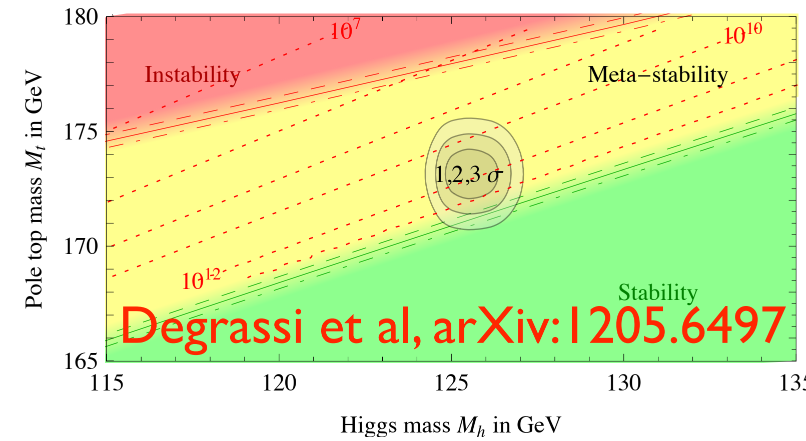
So, are we happy with that?

- In the many cases, the theoretical predictions we have now will make it possible to fully profit of the LHC data in the next O(few) years
- However, we must keep in mind the difference between accuracy and precision
- I will discuss one case where accuracy may be the main issue, and one where we still miss precision

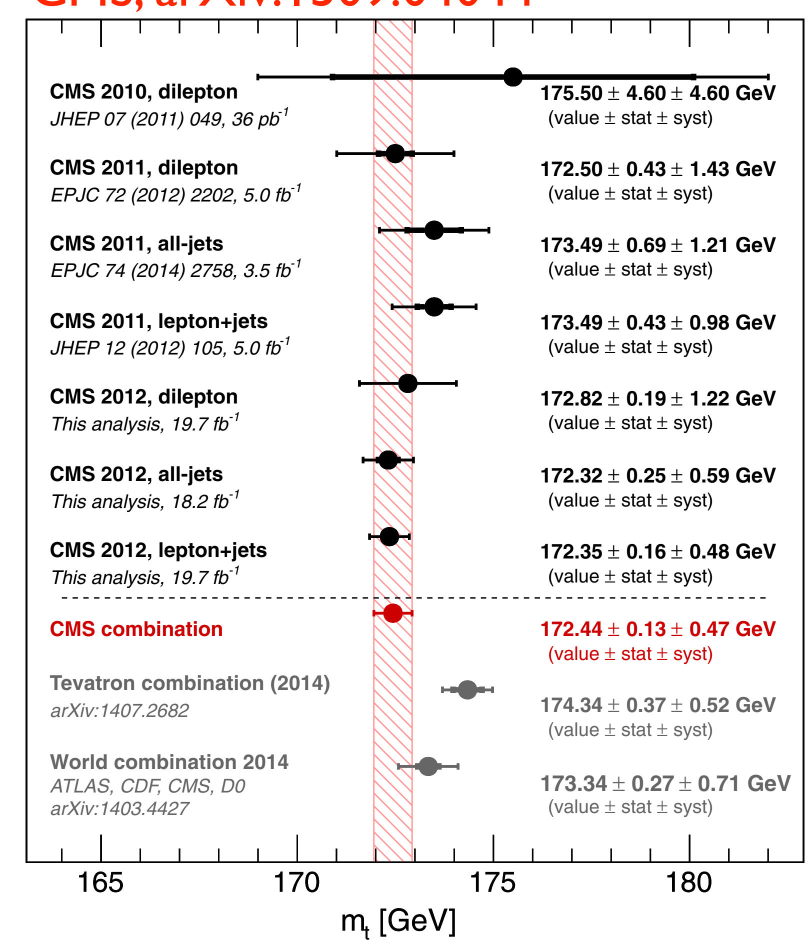


An accuracy case: the extraction of the top mass

- The destiny of the universe seem to be tied to the top mass
- The most recent Tevatron and LHC measurements have reached an astonishing ~0.5 GeV precision
- However, the signal (e.g. $pp \rightarrow l\nu jjb\bar{b}$) is mostly simulated using (NLO+PS) generators with intermediate stable tops. This may neglect effects such as spin correlations and off-shell effects



CMS, arXiv:1509.04044



The extraction of the top mass: higher orders and spin correlations

- Extracting the top mass from leptonic observables
  - Start with pseudo-data with m_t^{pd}=174.3 GeV
  - Use theoretical predictions with different accuracy

Frixione et al, arXiv:1407.2763

Theory	m_t [χ^2]
NLO+PS+MS	$174.48^{+0.73}_{-0.77}$ [5.0]
LO+PS+MS	$175.98^{+0.63}_{-0.69}$ [16.9]
NLO+PS	$175.43^{+0.74}_{-0.80}$ [29.2]
LO+PS	$187.90^{+0.6}_{-0.6}$ [428.3]
fNLO	$174.41^{+0.72}_{-0.73}$ [96.6]
fLO	$197.31^{+0.42}_{-0.35}$ [2496.1]

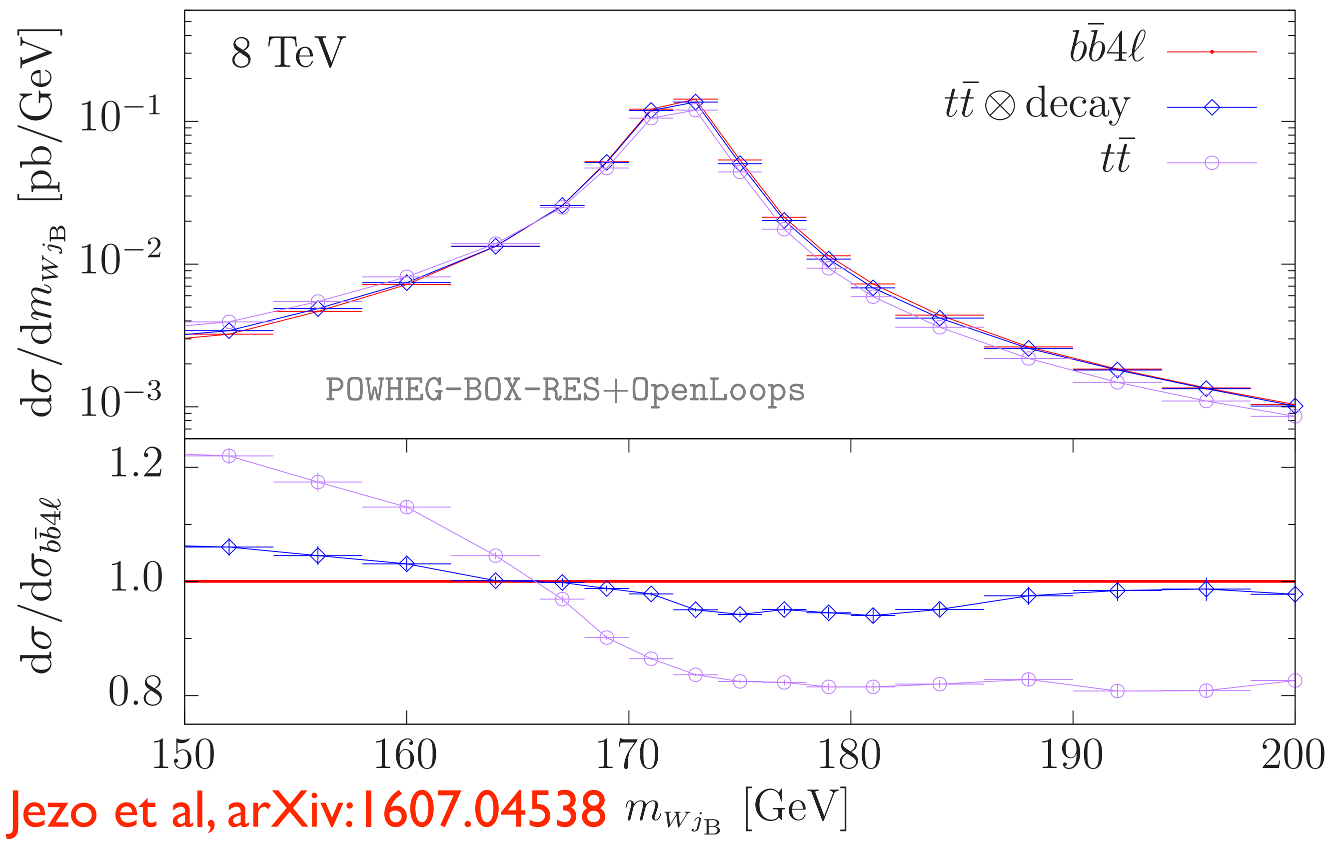
more details in Giancarlo Panizzo's talk

MS= tree-level spin correlations included with MadSpin
Artoisenet et al, arXiv:1212.3460

- Large differences appear in the extracted m_t, due to different theoretical inputs
- Better TH simulations improve central value *and reliability of uncertainties*

The extraction of the top mass: off shell effects

- Since very recently, NLO+PS generators are available which include off-shell effects for top quark productions
  Jezo et al, arXiv:1607.04538 (see also Frederix et al, arXiv:1603.01178 for single top)
- Simulations including different effects give a different top quark lineshape
- The details of the generator may reflect in the extracted value of m_t

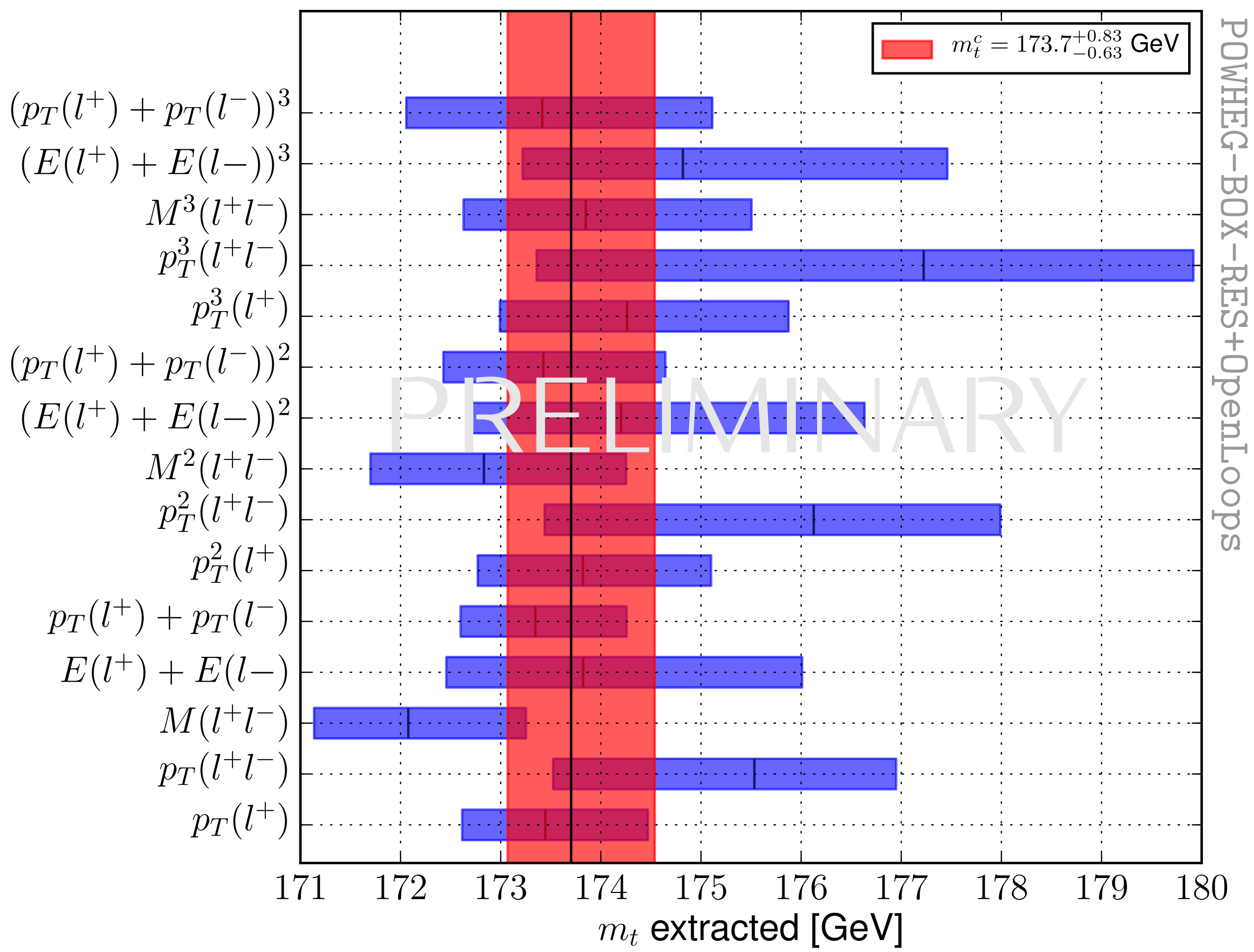


Jezo et al, arXiv:1607.04538

Leptonic observables

UZH

m_t using hvq as theoretical sample and $b\bar{b}4\ell$+PY8 with m_t=172.5 GeV as data



- Proposed in [Frixione et al. 2014]
- Pseudo data generated using `bb4l`
- Input mass m_t = 172.5 GeV
- Mass extracted using `hvq`
- Output mass $m_t = 173.7^{+0.83}_{-0.63}$ GeV
- Uncertainties from scale, pdf and shower variations

Slide from T. Jezo, DIS17
(Jezo et al, in preparation)

Still not precise: $t\bar{t}b\bar{b}$ as background for $t\bar{t}H$

- ttbb: among the most difficult processes for NLO MCs
  - Very large background for ttH, with sizeable residual theoretical uncertainties even at NLO
  - Mass effects are crucial to fill all the phase-space and to cover all kinematics configurations (boosted H→bb, b-jets outside acceptance, …)
  - Calculations with m_b=0 need unphysical cuts to have predictions also in the 1-b bin
  - g→bb splitting can affect rate in the M_{bb}~120 GeV region
    Cascioli et al, arXiv:1309.5912

$t\bar{t}b\bar{b}$ with massive b-quarks

Cascioli et al, arXiv:1309.5912

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

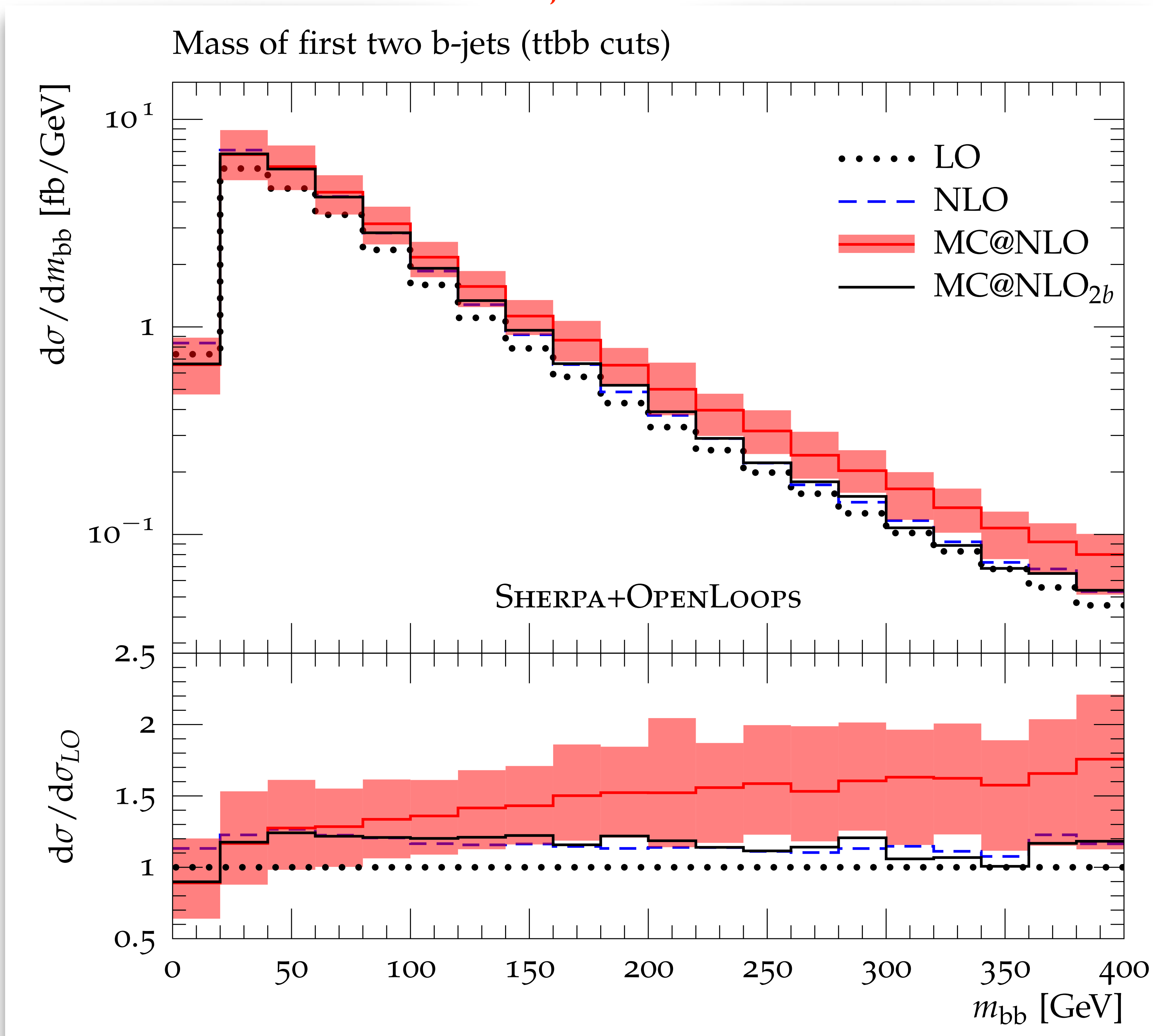
without g→bb splittings in the shower

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

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

$t\bar{t}b\bar{b}$ with massive b-quarks

Cascioli et al, arXiv:1309.5912



$b(m_{bb} > 100)$

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

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

15

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

28

6

03

without g→bb splittings in the shower

r the total

ects in the

ss section

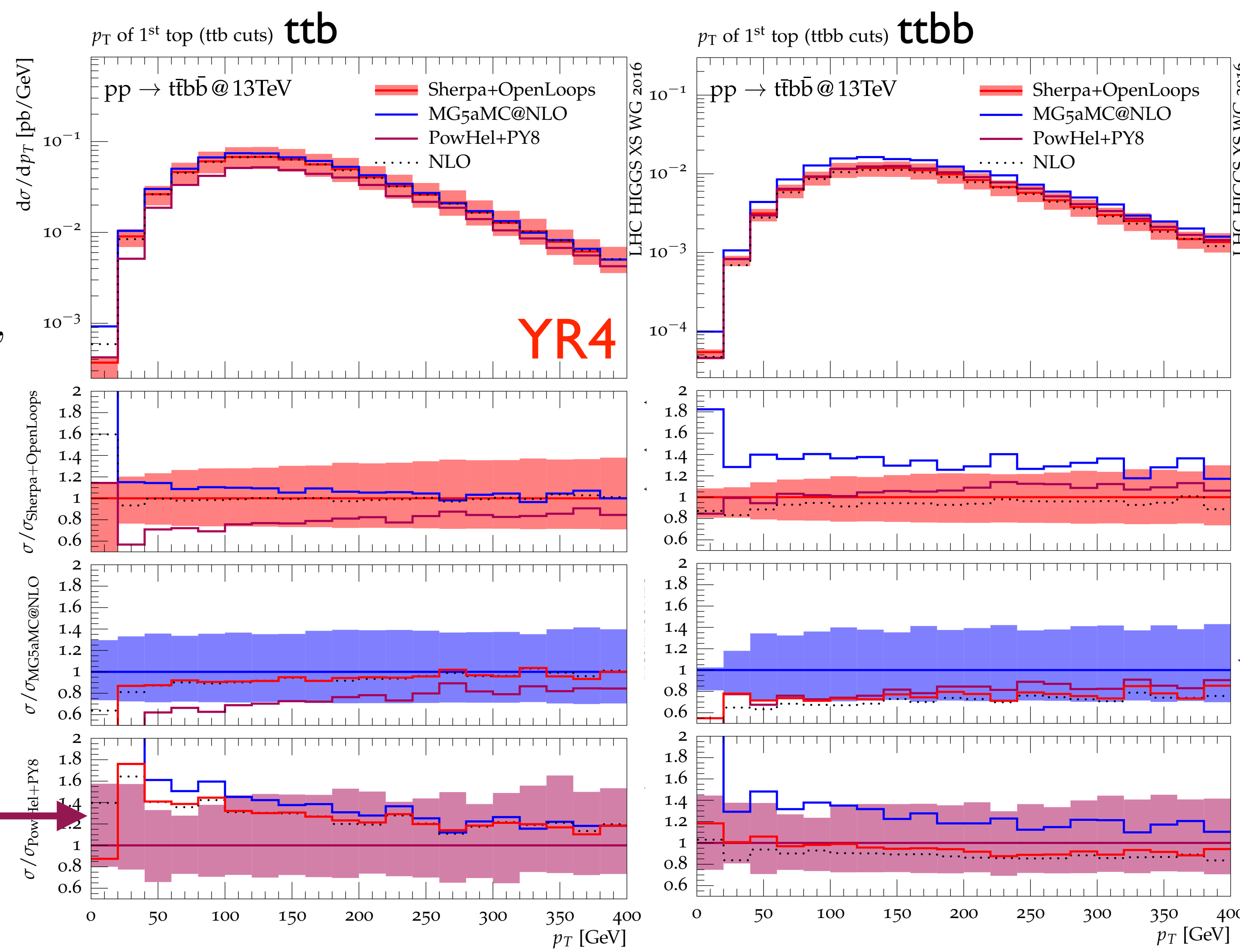
$t\bar{t}b\bar{b}$ tool comparison

YR4: arXiv:1610.07922

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

$$\mu_{F,0} = \frac{H_T}{2} = \frac{1}{2}\sum_{i=t,\bar{t},b,\bar{b},j} E_{T,i},$$

$$\mu_{R,0} = \left(\prod_{i=t,\bar{t},b,\bar{b}} E_{T,i}\right)^{1/4}$$



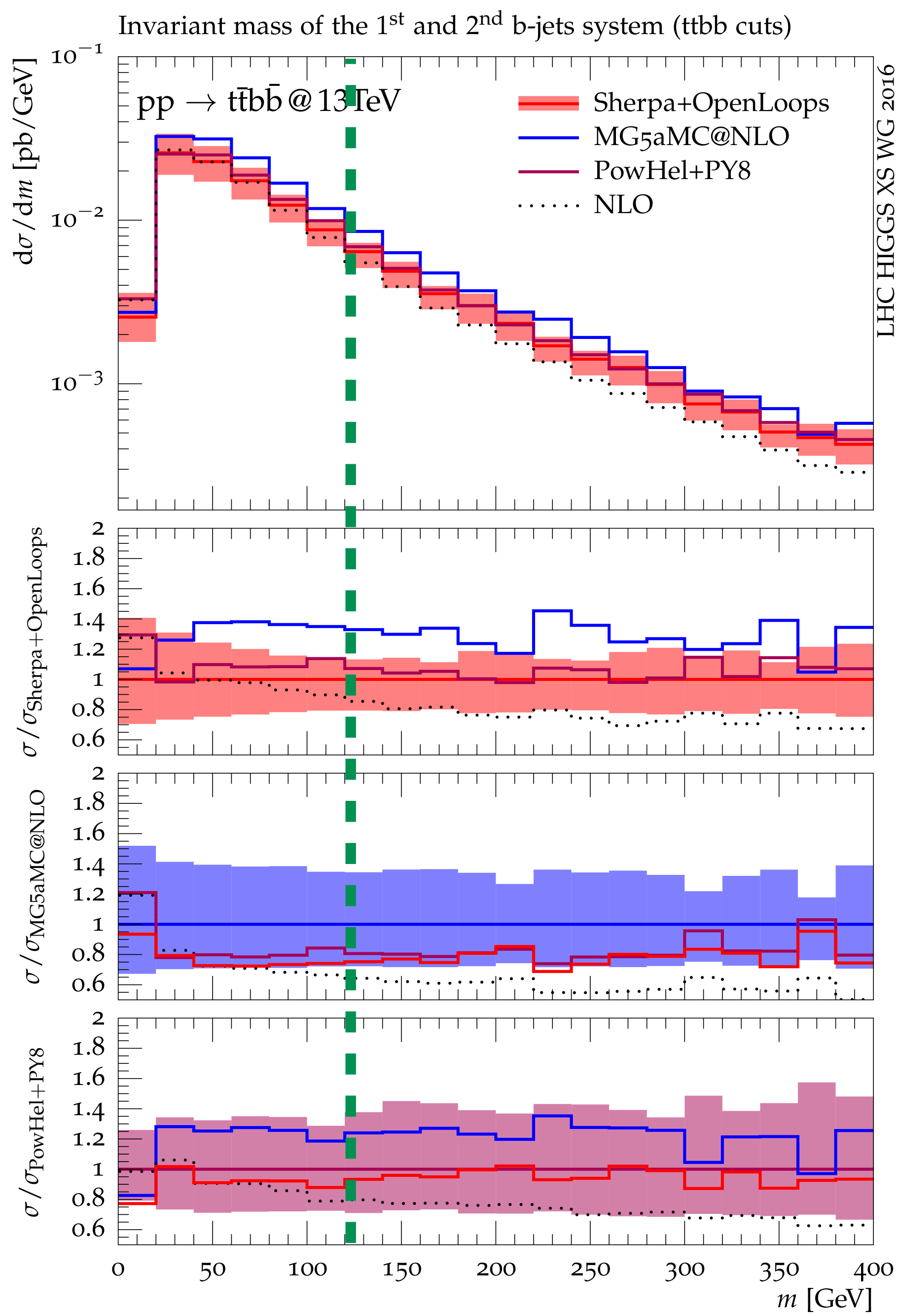
discrepancy due to shower scale and matching details in MG5_aMC

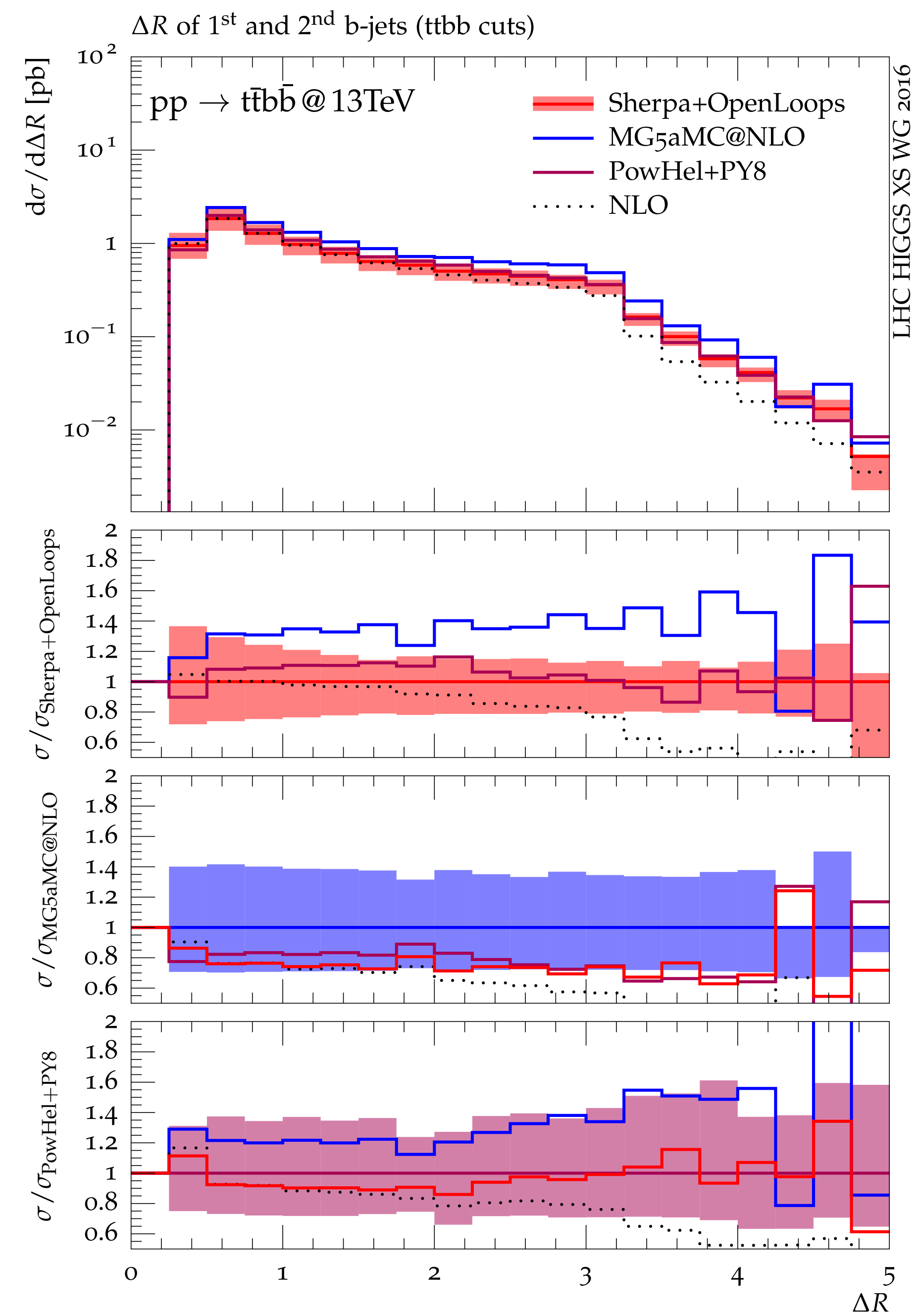
PowHel uses m_b=0 + M_{bb} cut

$t\bar{t}b\bar{b}$ tool comparison

YR4: arXiv:1610.07922

Large discrepancies appear also in the signal region





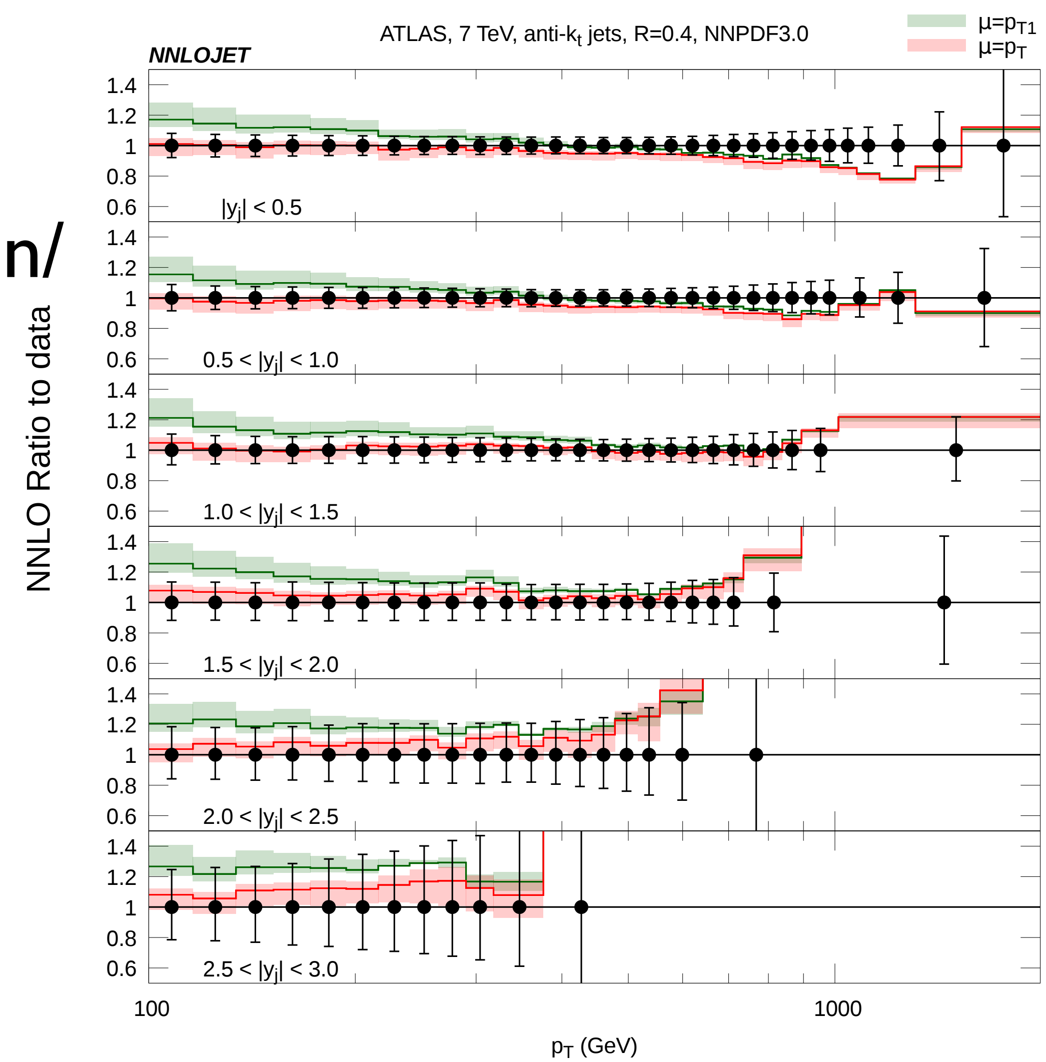
Conclusions

- Precision physics is of paramount importance at the LHC
- Great progresses have been achieved in the computation of higher-order corrections to cross sections and distributions, which make it possible to profit of the LHC data in the next years
- $t\bar{t}b\bar{b}$ (and in general processes with $b\bar{b}$ + a heavy object) are a notable exception. A better understanding of these processes is needed!
- At this level of precision, other effects besides perturbative corrections start to play an important role if we want to have accurate and precise measurements

Backup slides

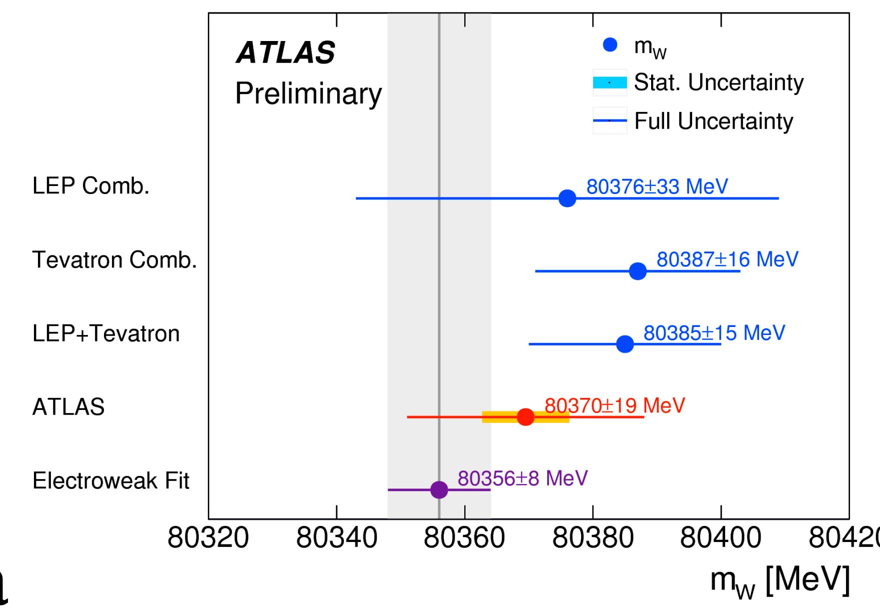
Jets at NNLO and impact on PDF fits

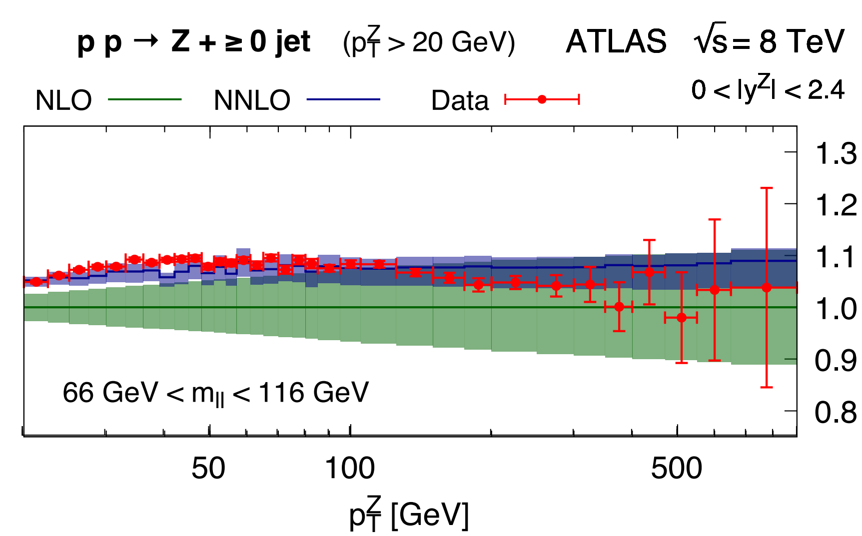
- NNLO predictions to inclusive-jet production have been computed
  Currie et al, arXiv:1611.01460, arXiv:1704.00923
- NNLO predictions show an unusually large dependence on the choice of renormalization/ factorization scale
- The jet-by-jet pT scale is to be preferred. However:
  - It is an 'unphysical' scale choice
  - It generates larger NNLO/NLO K-factors
- More studies are needed…



Bottom-mass effects on the Z-p_T spectrum

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

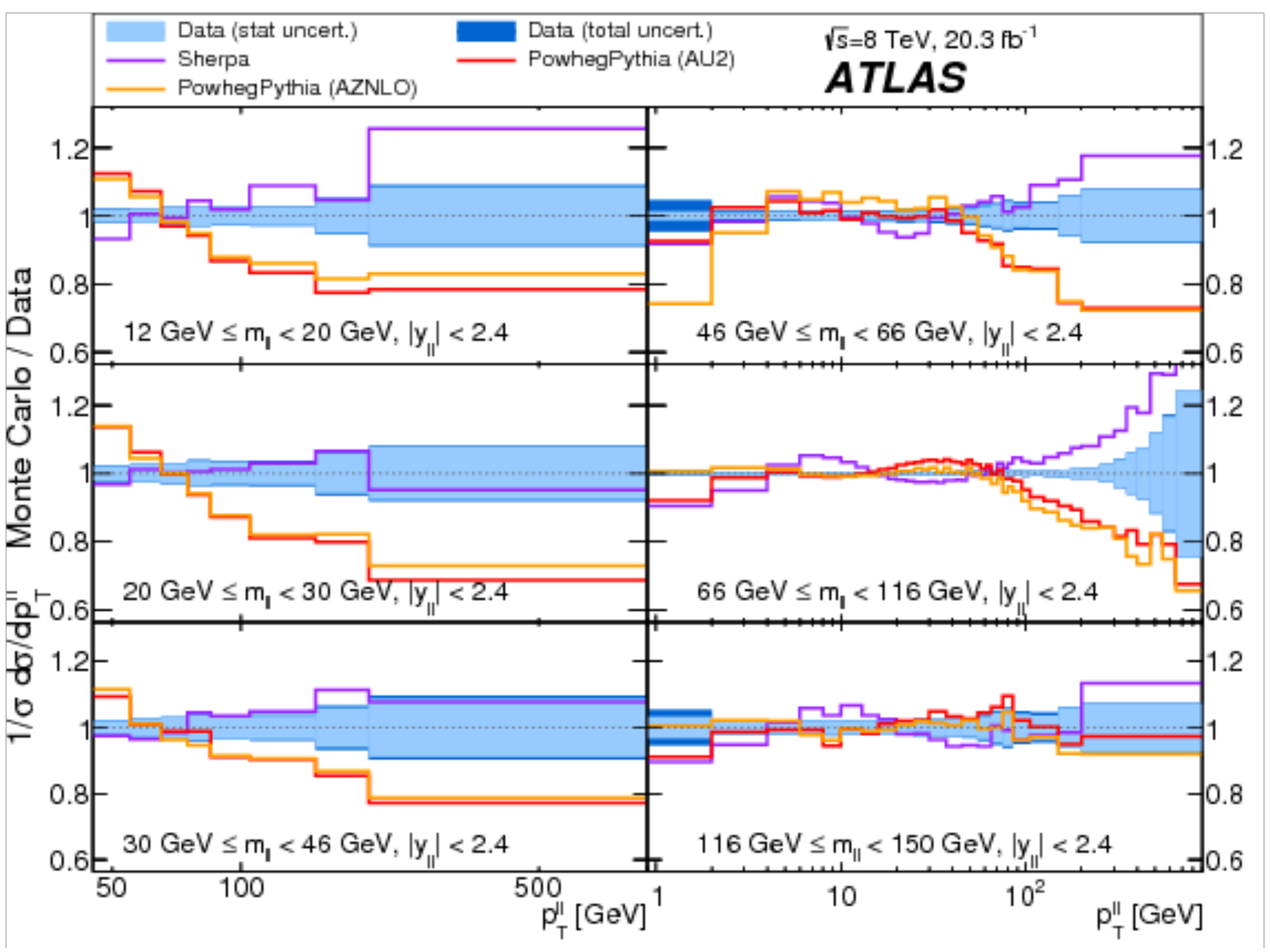


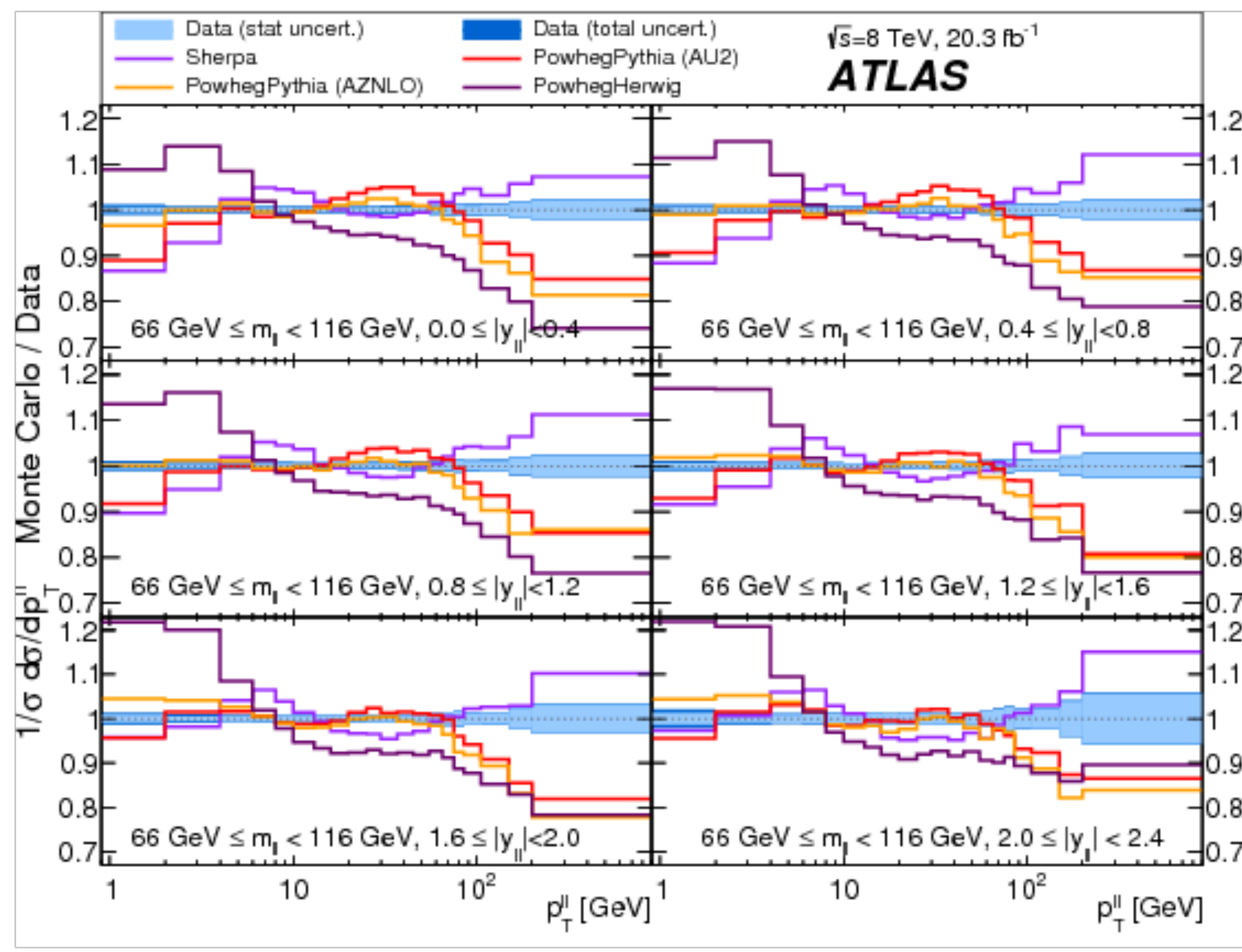


Gehrmann-de Ridder et al, arXiv:1605.04295

Still, there are some issues…

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

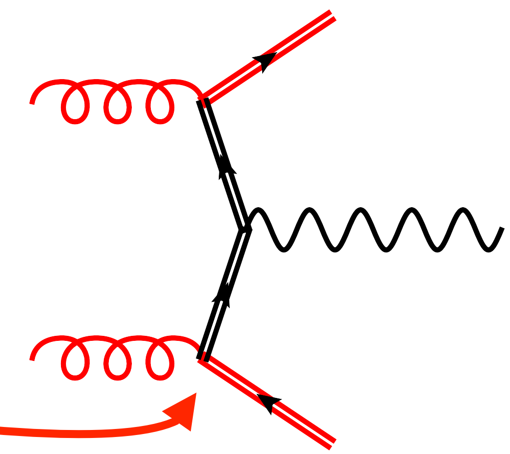


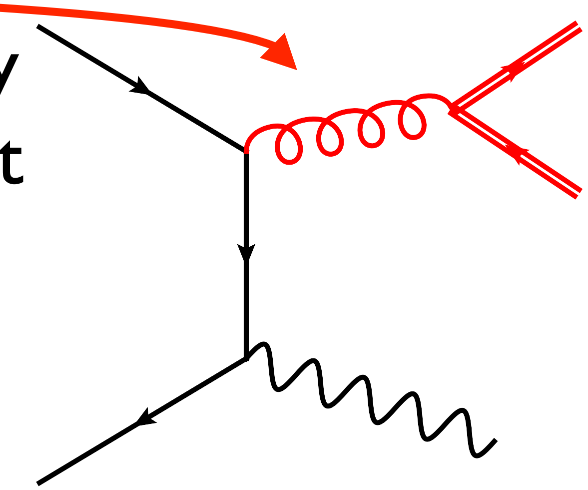


Include b-mass effects in inclusive-Z samples

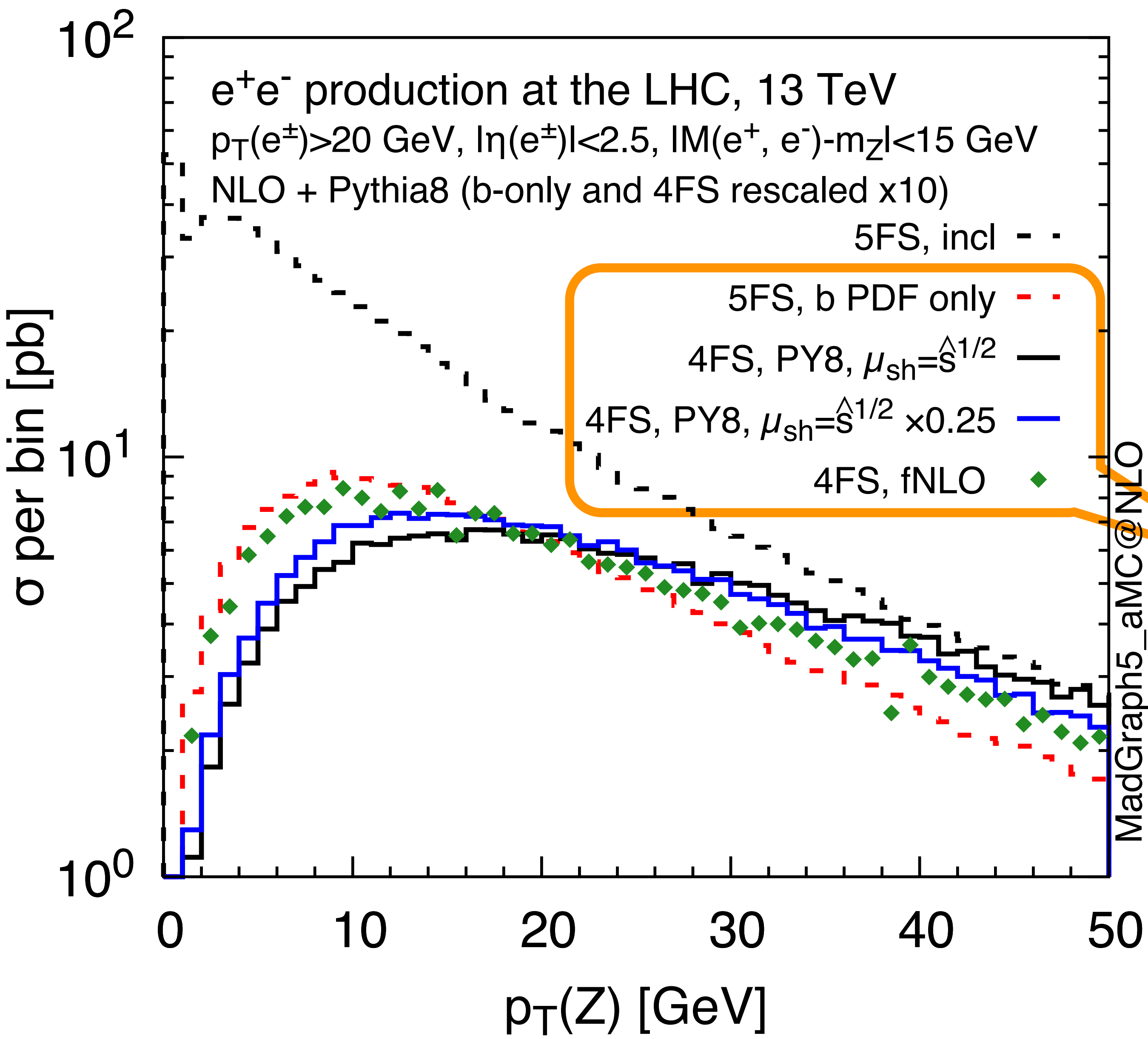
Bagnaschi, Maltoni, Vicini, MZ, in preparation

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





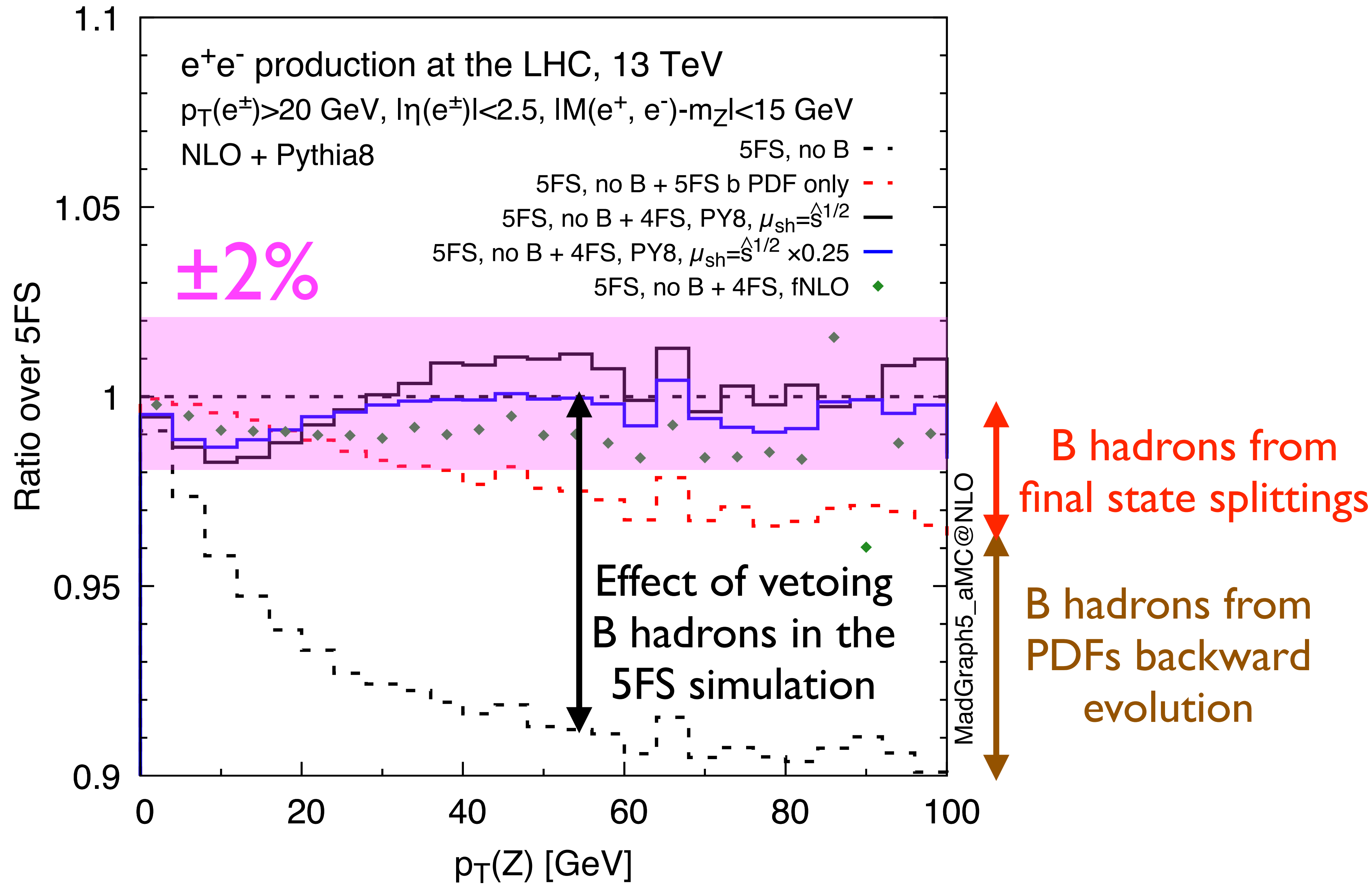
The b-initiated contribution to the Z p_T in various approximations



Flavour decomposition of the 5FS cross section

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

Bottom-mass effects on the Z-boson p_T



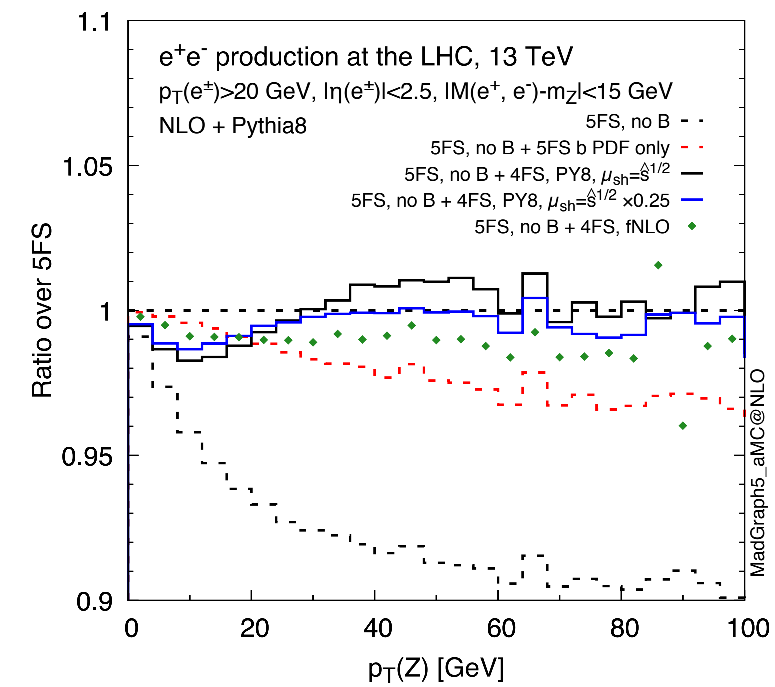
- Effects are rather small, but have impact on the small-p_T shape
- fNLO has a flat, slightly negative effect

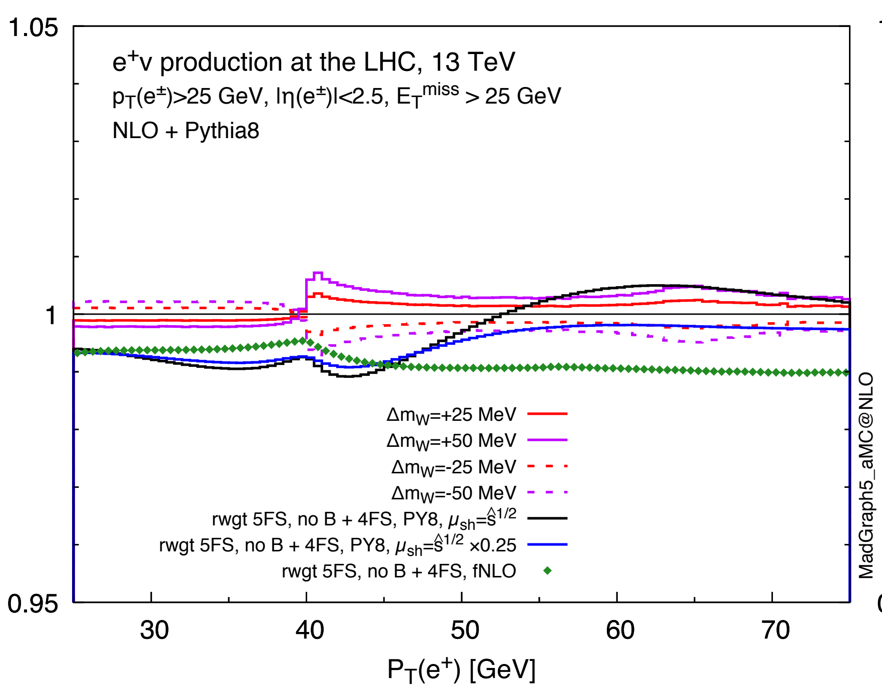
Estimate of the impact on the extraction of m_W

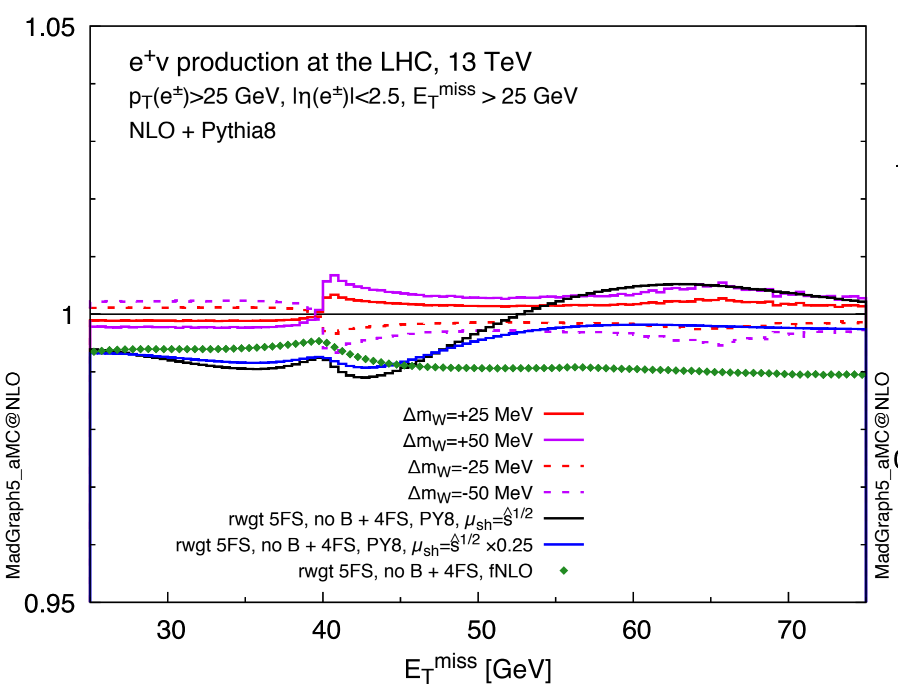
- Comparisons between Z-p_T predictions and data are used to extract non-perturbative parameters (NPPs), encoded e.g. in parton showers or hadronization models
- These NPPs are also used for other processes like charged-current Drell-Yan.
- The propagation of their uncertainties affects the extraction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

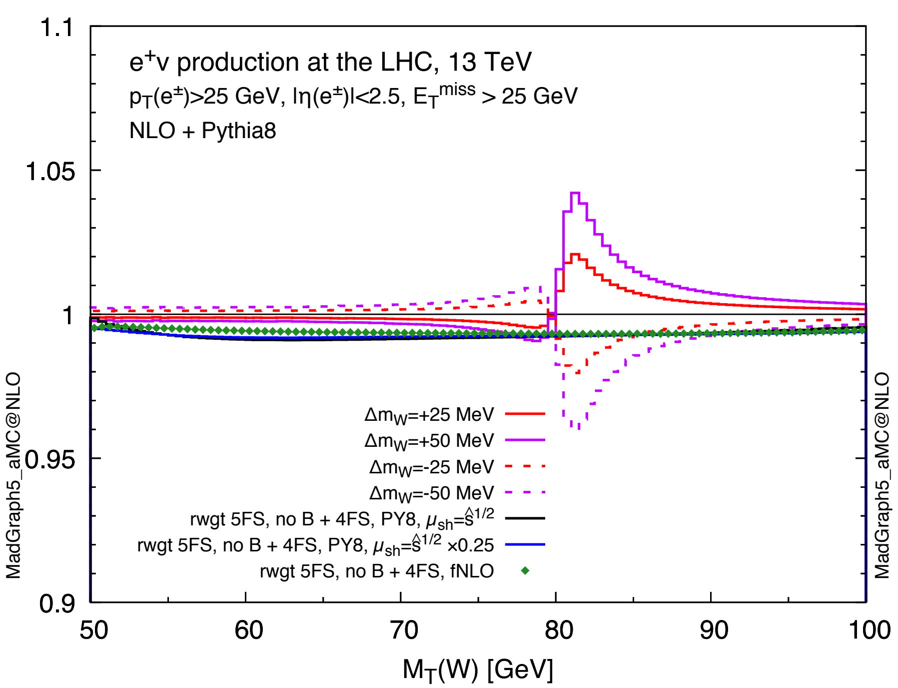
Strategy:

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



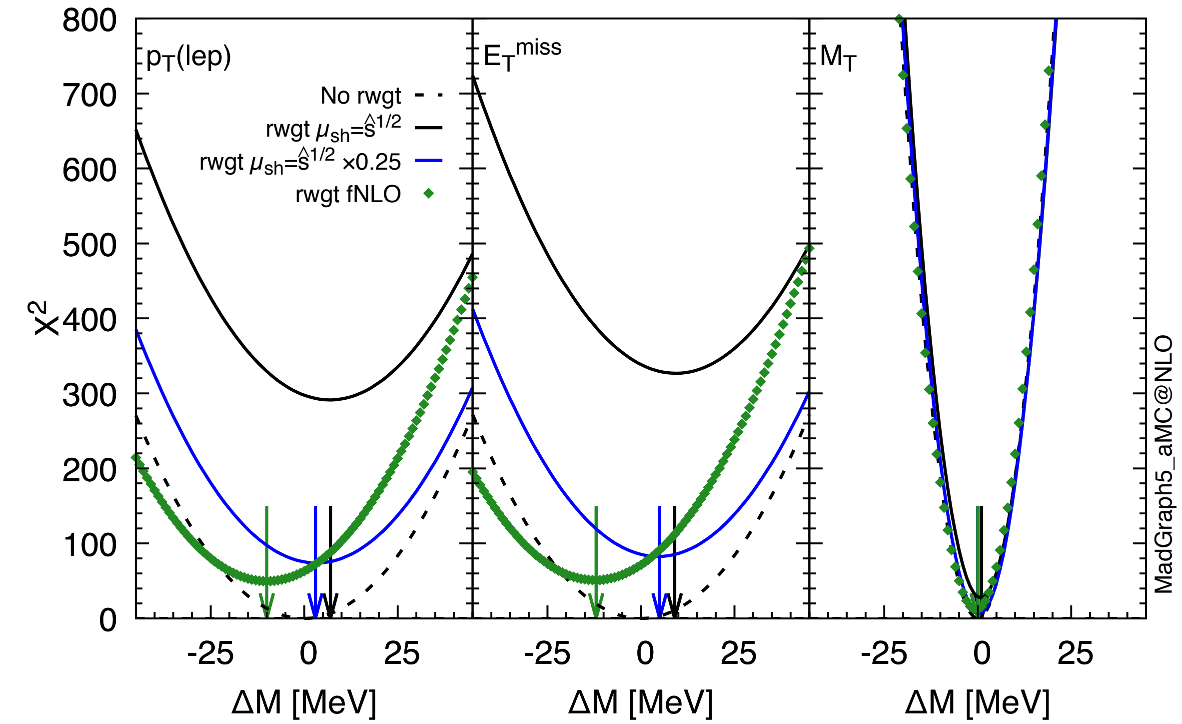






Results of the fit

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



ATLAS, arXiv:1701.7240

Combination	Weight
Electrons	0.427
Muons	0.573
m_T	0.144
p_T^ℓ	0.856