Università degli Studi di Milano

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SM physics at the LHC Run II

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Milano, February 11th 2015

acknowledgements: G. Degrassi for many discussions

Precision tests of the Standard Model

(MW, sin2theta_w, mtop, MH) measurements — likelihood of the EW fit of the SM

vector boson scattering and unitarity violations,
Higgs boson pair production — determination of the potential of the scalar sector (of the SM)

mtop measurement — stability of the EW vacuum

matrix element progresses for signals and backgrounds
development of Monte Carlo event generators
new input for the proton PDFs from LHC data

a very rich and interesting physics program in front of us
which requires a global coordinated effort to beat several important systematics

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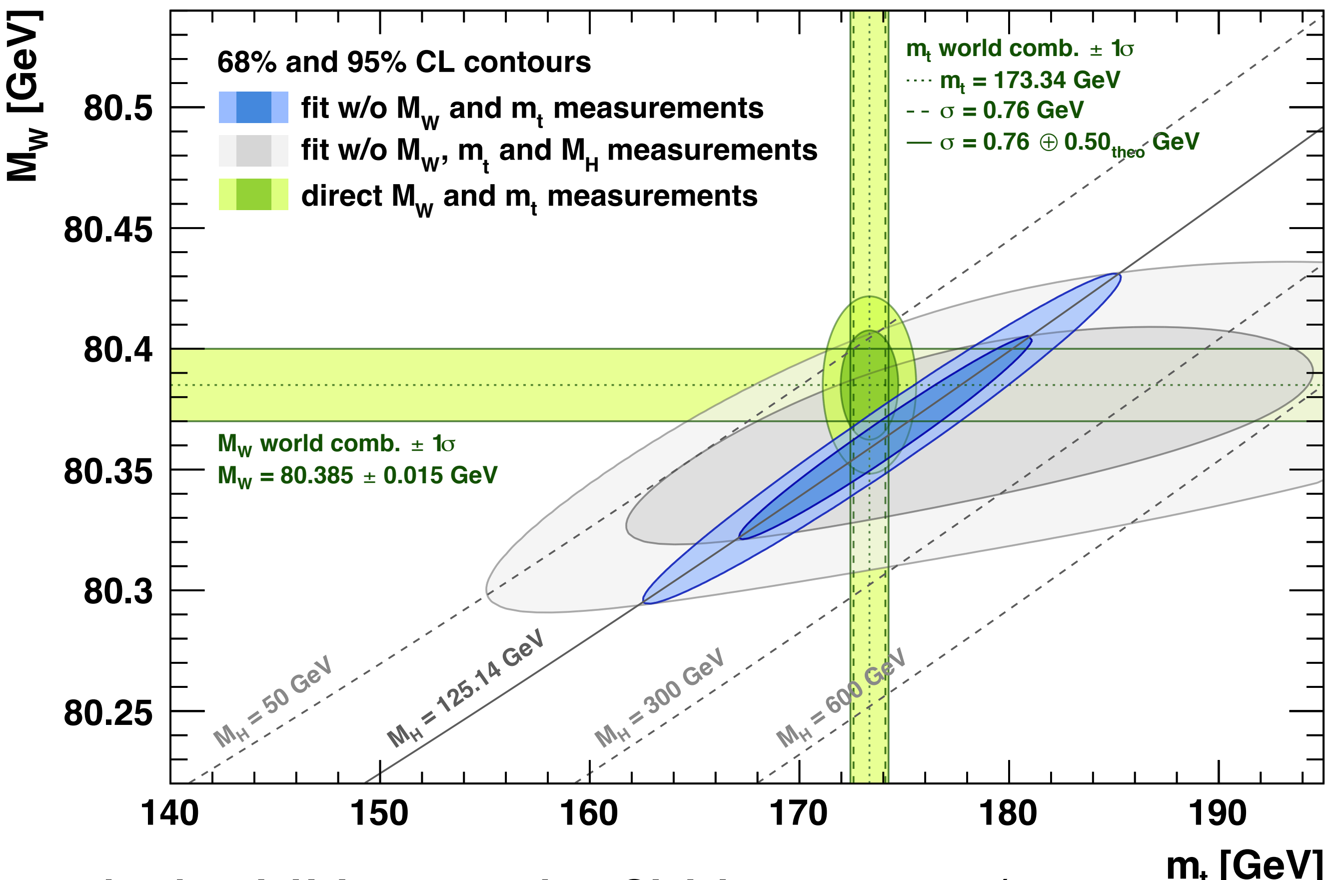
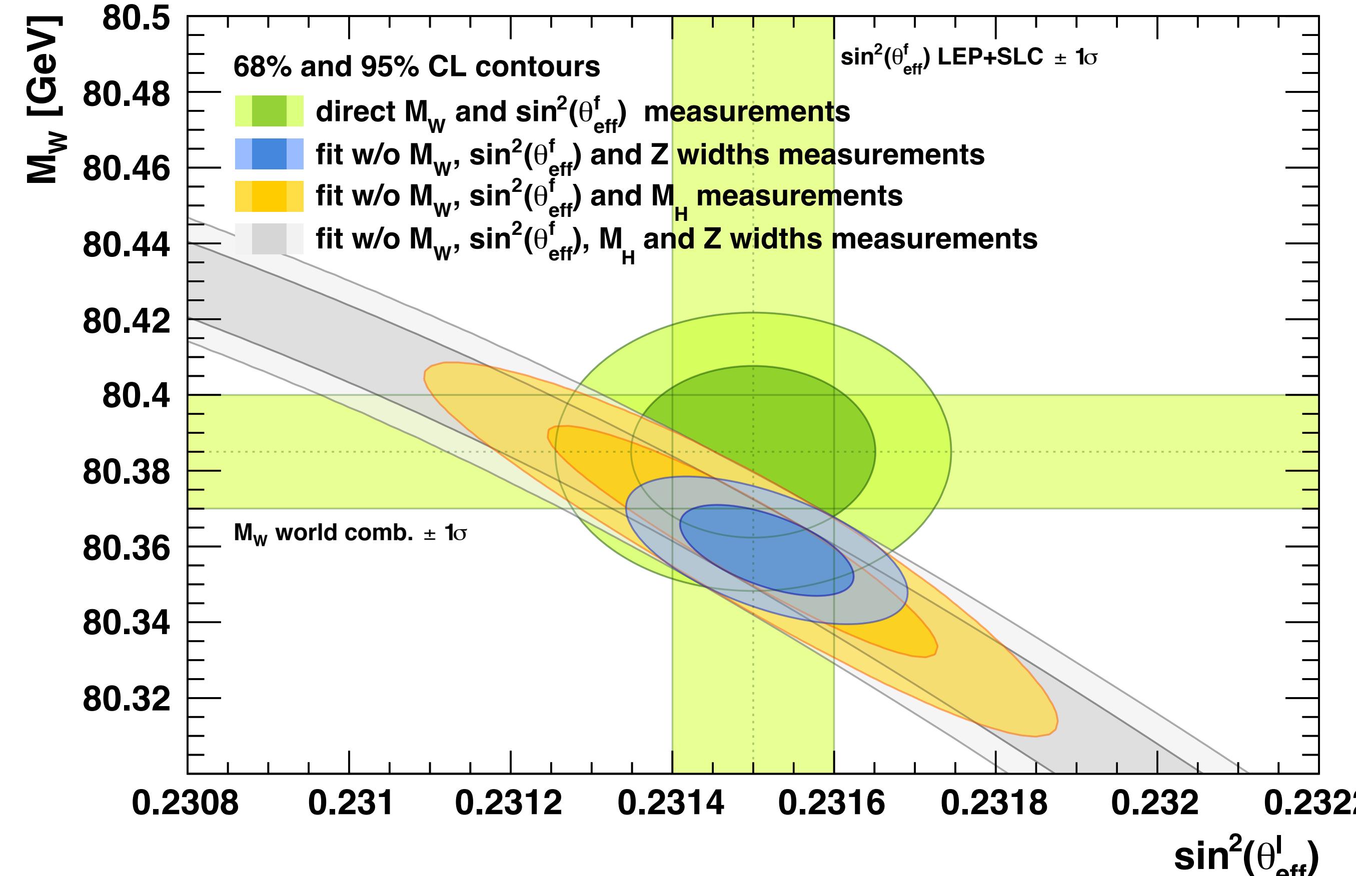
Precision tests of the Standard Model

GFitter, arXiv:1407.3792





with the MH input the SM lagrangian (gauge sector) is assigned,

the EW fit can determine the preferred MW (2-loop EW+h.o.) and mtop (free parameter)

and check the compatibility of the SM hypothesis with the experimental measurements

the result of the global EW fit of the SM

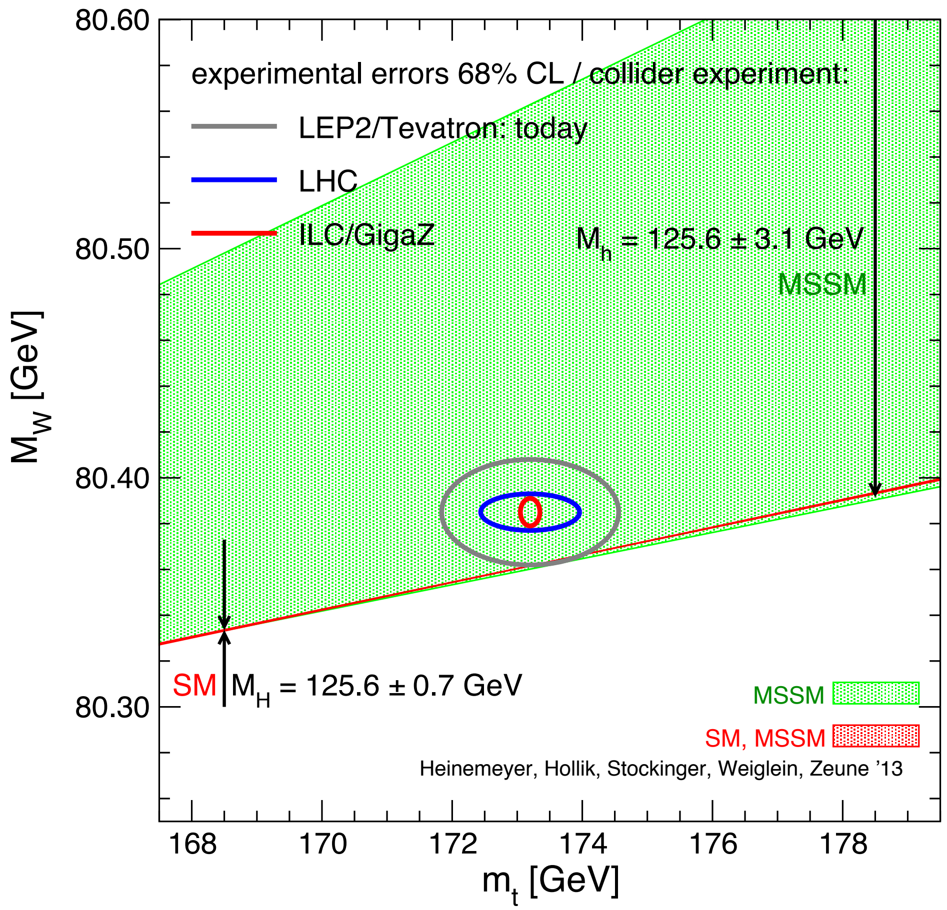
yields a result for MW with an error ΔMW=8 MeV smaller than the one of the direct measurement

mtop=173.81 ±0.85 GeV compatible with the world average top mass

is the 1.5 sigma discrepancy in the above plot, between the data and the theoretical prediction,

- just a fluctuation,
- a systematic effect of the MW measurement at hadron colliders
- a hint for BSM physics ?

Precision tests of the Standard Model



MW can be computed as a function of
(α, Gμ, MZ, MH; mtop,...)
in different models

$$m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\alpha}{G_\mu\sqrt{2}m_Z^2}(1+\Delta r)}\right)$$

$$m_W = m_W\left(\Delta r^{SM,MSSM}\right)$$

$$\Delta r^{SM,MSSM} = \Delta r^{SM,MSSM}\left(m_t, m_H, m^{SUSY}, \ldots\right)$$

relevance of a correct estimate of the central value and of the associated error
(in the plot only the central values of the two theoretical predictions are compared)

MW prediction in the SM

G.Degrassi, P.Gambino, P.Giardino, arXiv:1411.7040

recent re-evaluation of the MW prediction, with an MSbar calculation

MW = 80.357 ± 0.009 ± 0.003 GeV (parametric and missing higher orders)

includes the full 2-loop EW result, higher-order QCD corrections, resummation of reducible terms
central value obtained with the current top mass world average mt=173.xx ± ± GeV

MW grows with mtop: Δmt=+1 GeV $\rightarrow$ ΔMW = +6 MeV
with $\Delta\alpha_{had}$(MZ): $\Delta\alpha_{had}$(MZ)=+0.0003 $\rightarrow$ ΔMW = -6 MeV

a simultaneous variation of both parameters by +1σ may increase MW up to 80.370 GeV
-1σ may decrease MW down to 80.345 GeV

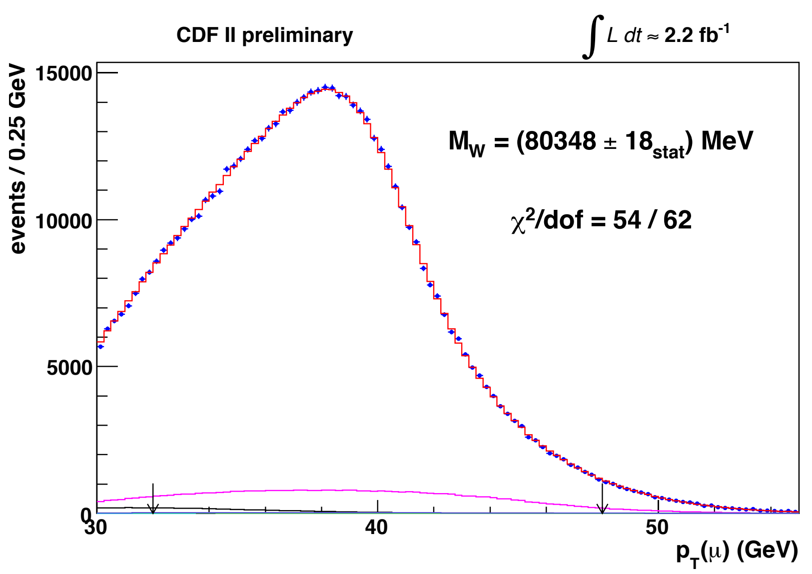
the comparison of this MSbar calculation with the corresponding one in the OS scheme
suggests that missing higher orders might have a residual effect of O(6 MeV)

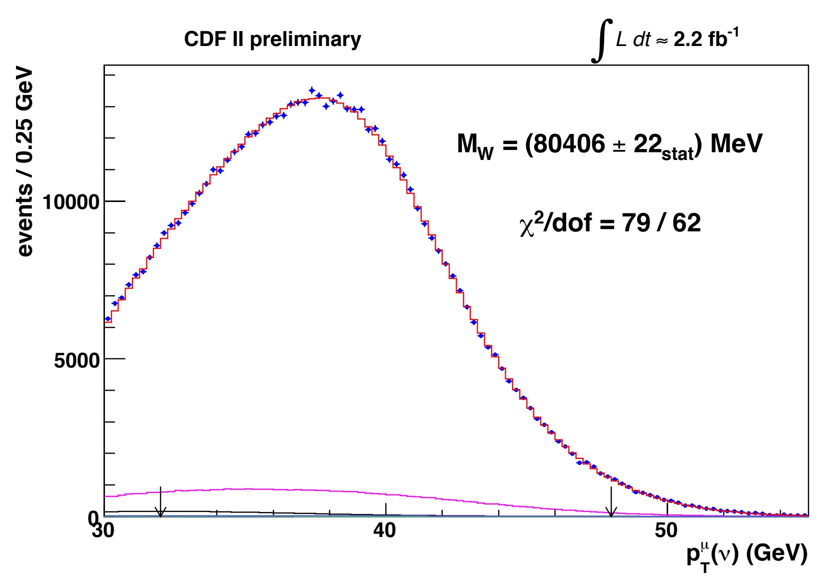
MW measurement from charged current Drell-Yan

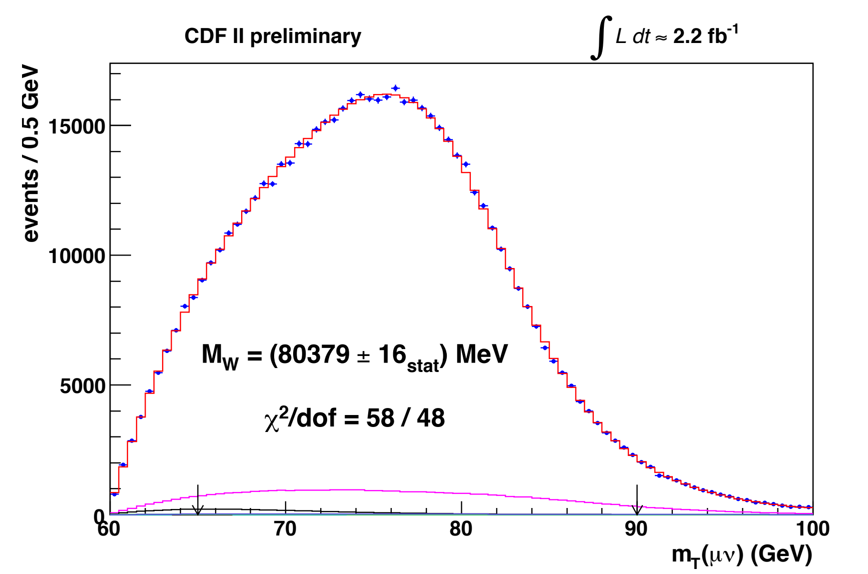
MW is measured from the study of charged-current Drell-Yan observables:

lepton-pair transverse mass, lepton transverse momentum, missing E_T

sensitive to MW because of a jacobian peak of the distributions







the MW measurement is challenging because of the missing neutrino:

the relevant observables can be defined only in the transverse plane and

the reconstruction of the missing momentum may suffer of the high pile-up of the events

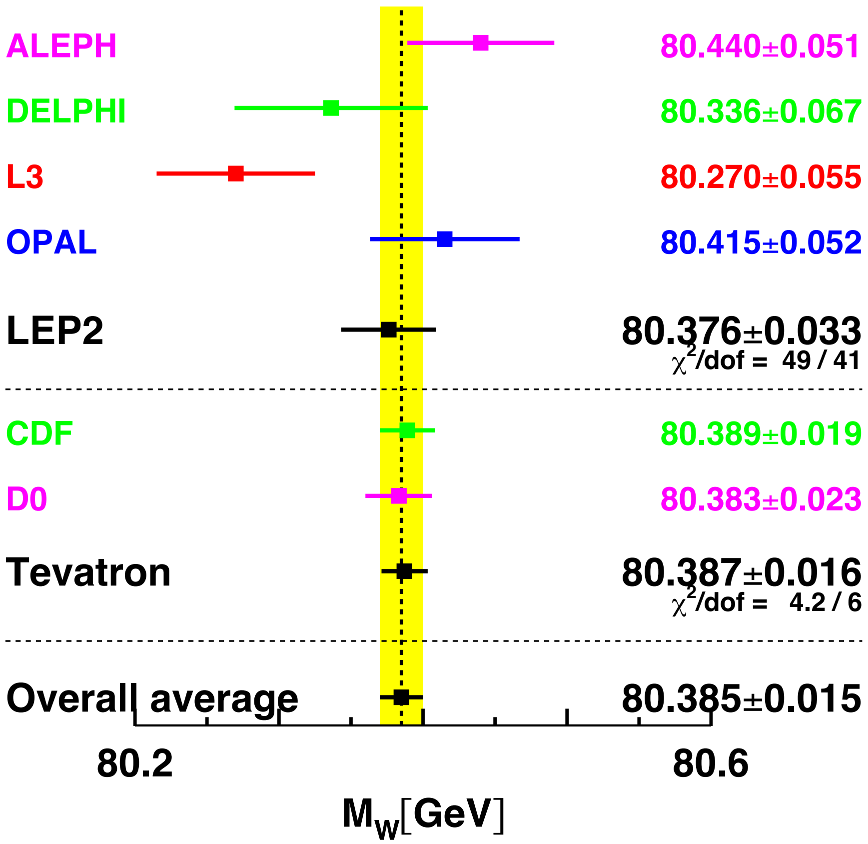
MW is extracted with a template-fit of the data

the theoretical input (model dependent) is crucial in the preparation of accurate templates

any theoretical uncertainty propagates to the MW extraction as a systematic uncertainty:

missing higher-order corrections, PDF uncertainties, non-perturbative effects

MW measurement



The current error of ±15 MeV is dominated by the Tevatron result

- are those error estimates realistic ?
- is a measurement at the 10 MeV level feasible at the LHC ?

The measurement will not be affected by statistical issues

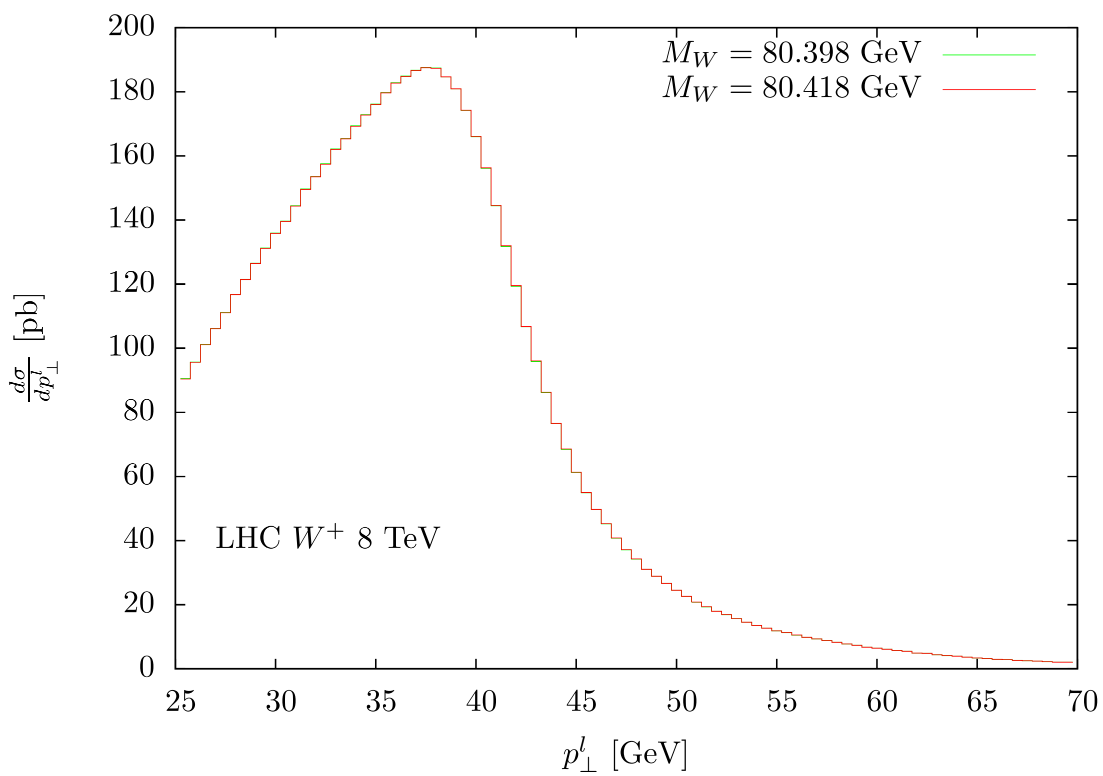
(also the NC-DY samples are sufficiently large to offer the possibility of an accurate study of W/Z ratios)

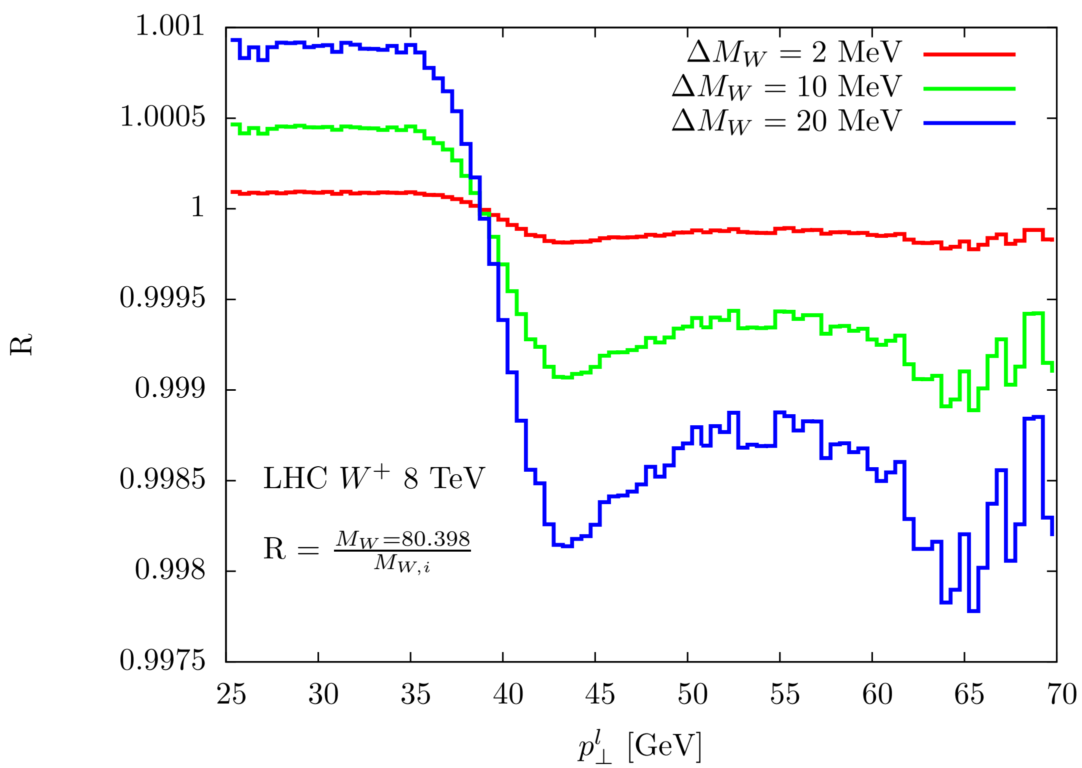
Critical points are the systematic error

of experimental (e.g. pile-up→recoil modeling) but also

of theoretical (templates accuracy) origin

Control of the shape at the (sub-)per mill level





MW measurement: errors as in CDF paper arXiv:1311.0894

m_T fit uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	0	0	0
Lepton tower removal	2	3	2
Recoil scale	5	5	5
Recoil resolution	7	7	7
Backgrounds	3	4	0
PDFs	10	10	10
W boson p_T	3	3	3
Photon radiation	4	4	4
Statistical	16	19	0
Total	23	26	15

p_T^ℓ fit uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	1	2	0
Lepton tower removal	0	0	0
Recoil scale	6	6	6
Recoil resolution	5	5	5
Backgrounds	5	3	0
PDFs	9	9	9
W boson p_T	9	9	9
Photon radiation	4	4	4
Statistical	18	21	0
Total	25	28	16

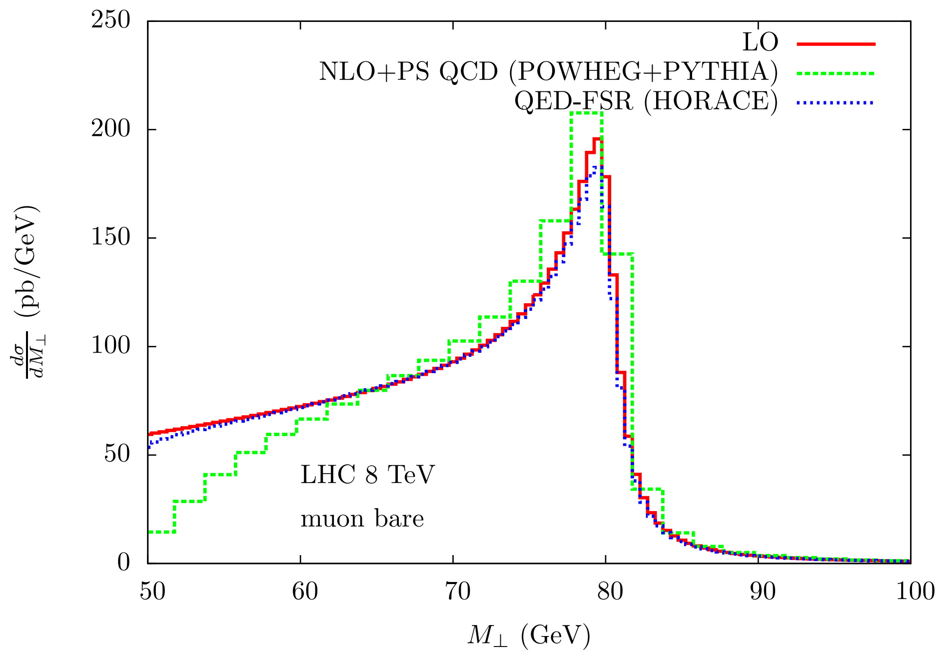
Are PDF uncertainties under control?

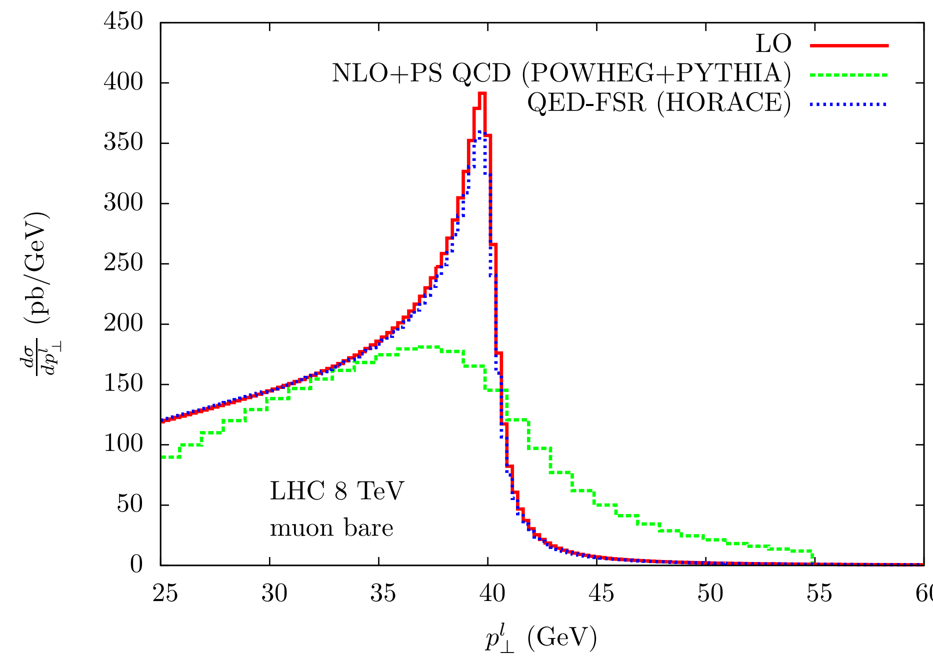
There is no pQCD uncertainty estimate

Which is the accurate treatment of NLO-EW effects?

Drell-Yan observables for MW and simulation codes

The basic description of the observables relevant for the MW measurement
(lepton-pair transverse mass, lepton transverse momentum, missing E_T distributions)
requires the simulation of multiple initial state QCD radiation and of QED final state radiation





The lepton-pair transverse mass is mildly sensitive to the details of QCD radiation, but receives large corrections at detector level

The lepton transverse momentum is very strongly sensitive to the details of QCD radiation, because of the log(ptV/MV) enhancement at low ptV values

The QED-FSR effects modify at the several per cent level the peak region,
yielding shifts of the extracted MW of O(150 MeV)

What is the needed perturbative accuracy of the templates, to meet the 10 MeV goal for the error?
which higher-order QCD, mixed QCD-EW, higher-order EW, non-perturbative effects must be included in the simulations?

Drell-Yan observables for MW and simulation codes

We need an accurate description of the ptV spectrum to predict the ptlep and the MT distributions

- perturbative elements (matching of QCD/EW matrix elements with resummation)

- non-perturbative elements (PDF uncertainties,
  intrinsic kt of the partons in the proton, part of the PS tune)

- different contribution of heavy- vs light- flavors in the PDF to the ptV spectrum

Matching QCD fixed order with resummation

- Analytic resummation of log(ptV/MV)   NNLO-QCD accuracy on the total xsec + NNLL resum.

    DYqT   (β-version of DYRes)   G. Bozzi, S.Catani, D. de Florian, G. Ferrera, M. Grazzini , arXiv:1007.2351

    ResBos   partial inclusion of NNLO   F.Landry, R.Brock, P.Nadolski, C.P.Yuan, hep-ph/0212159

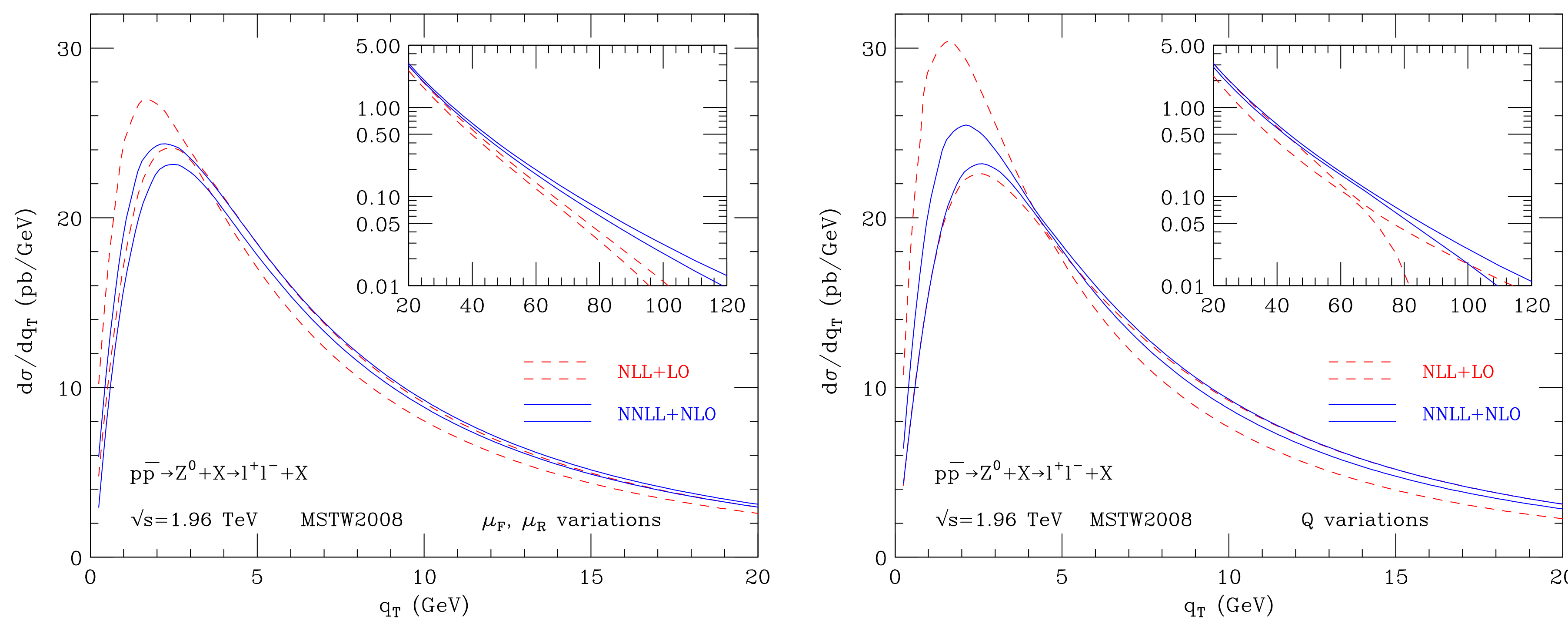
- Matching of NNLO-QCD matrix elements with QCD-PS

    DYNNLOPS   A.Karlberg, E.Re, G.Zanderighi, arXiv:1407.2940

    UN²LOPS+NNLO   S.Hoeche, Y.Li, S.Prestel, arXiv:1405.3607

- Matching NLO-(QCD+EW) matrix elements with (QCD+QED)-PS

    POWHEG   C.Bernaciak, D.Wackeroth, arXiv:1201.4804, L.Barzè et al., arXiv:1202.0465, arXiv:1302.4606



- The NNLL resummation affects the low-ptV part of the spectrum
- The high-ptV part of the spectrum has NLO accuracy
- The distribution depends on the resummation scale Q (matching between resummed and fixed order) the inclusion of higher orders reduces the dependence on Q

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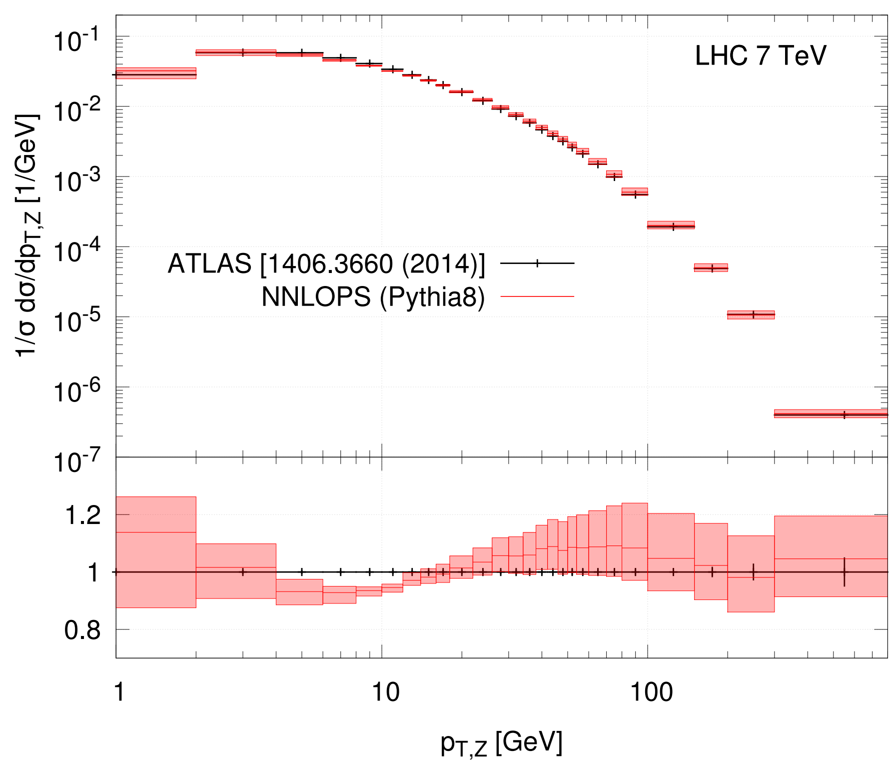

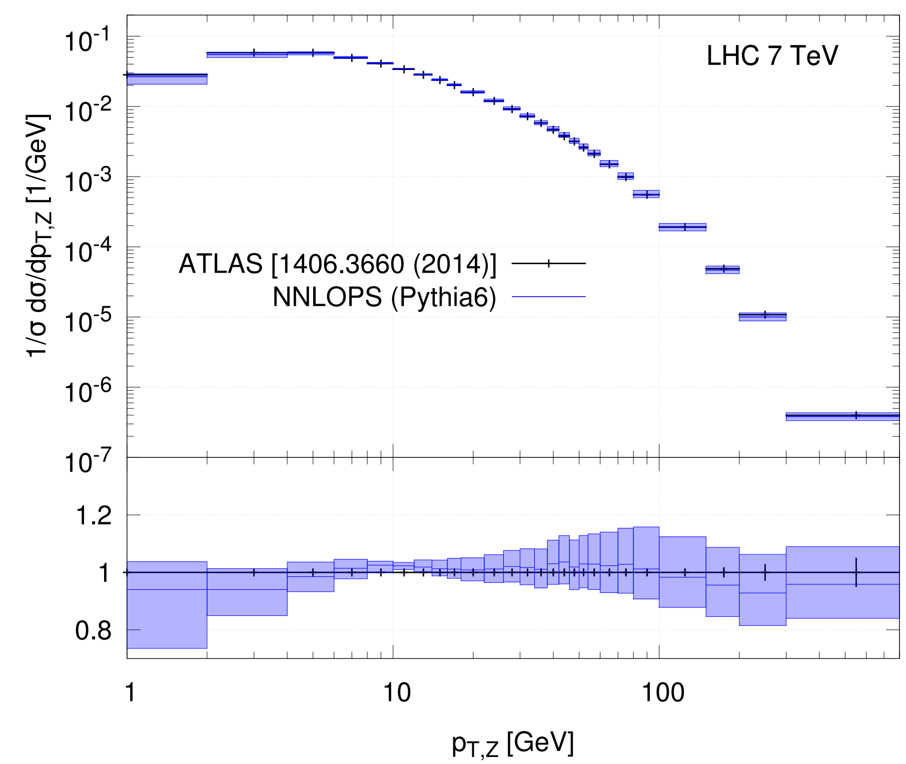

- Improvement of Wj (Zj) samples, done with the MiNLO approach and a modified Sudakov form factor
- The distribution has NLO accuracy through the whole ptV range
- The NNLO accuracy on the inclusive observables is based on the rescaling with DYNNLO results
- The uncertainty bands have been obtained varying with a combination of ren./fact. scale variations of the Wj/Zj MiNLO generator and of the DYNNLO simulation

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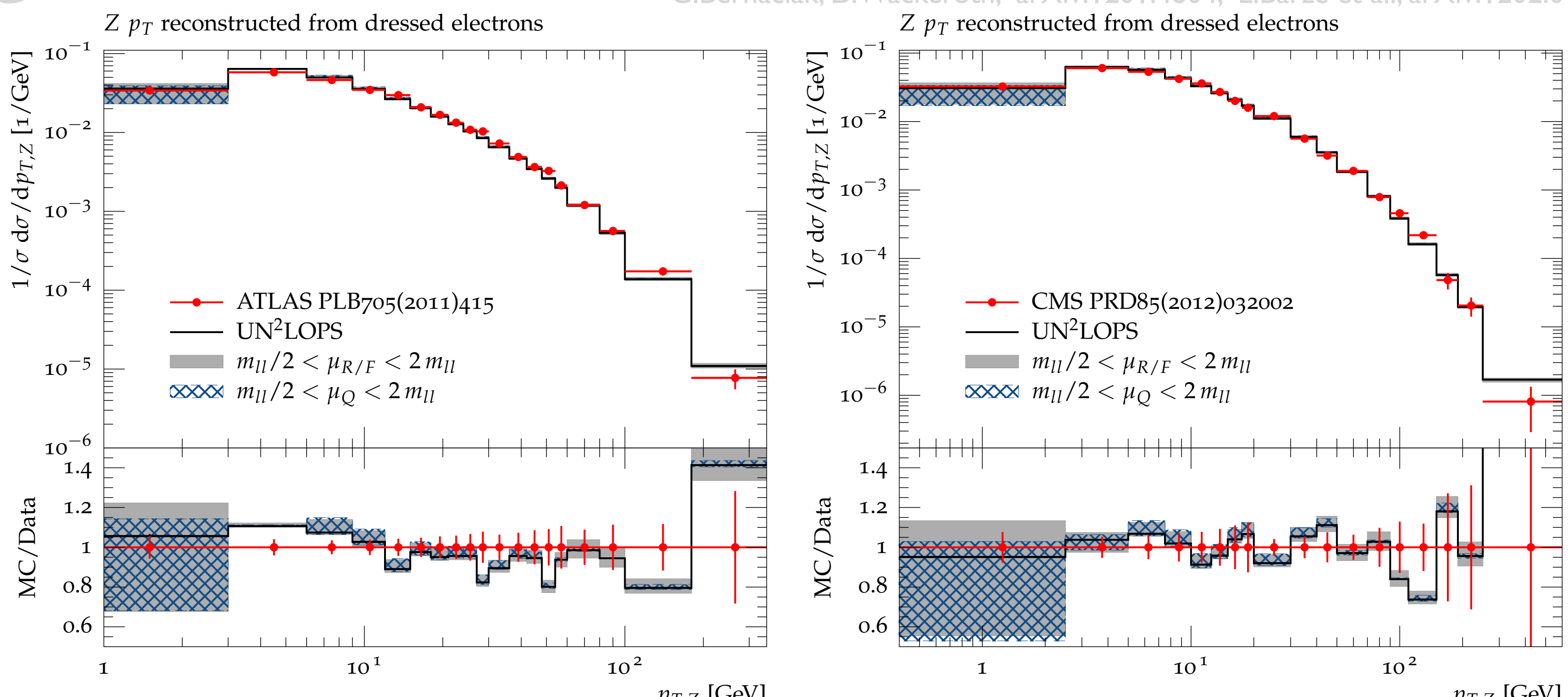

- The UNLOPS scheme merges 0-jet and 1-jet samples (it requires a merging scale), it preserves the accuracy on the total xsec with the definition of a 0-jet bin which is not showered
- The UN²LOPS scheme extends the approach at O(alphas²)

- Important differences in the definition of the uncertainty bands between DYNNLOPS and UN²LOPS comparison of the two approaches is in progress

Matching (QCD+EW) fixed order with (QCD+QED) Parton Shower

- Analytic resummation of log(ptV/MV)   NNLO-QCD accuracy on the total xsec + NNLL resum.
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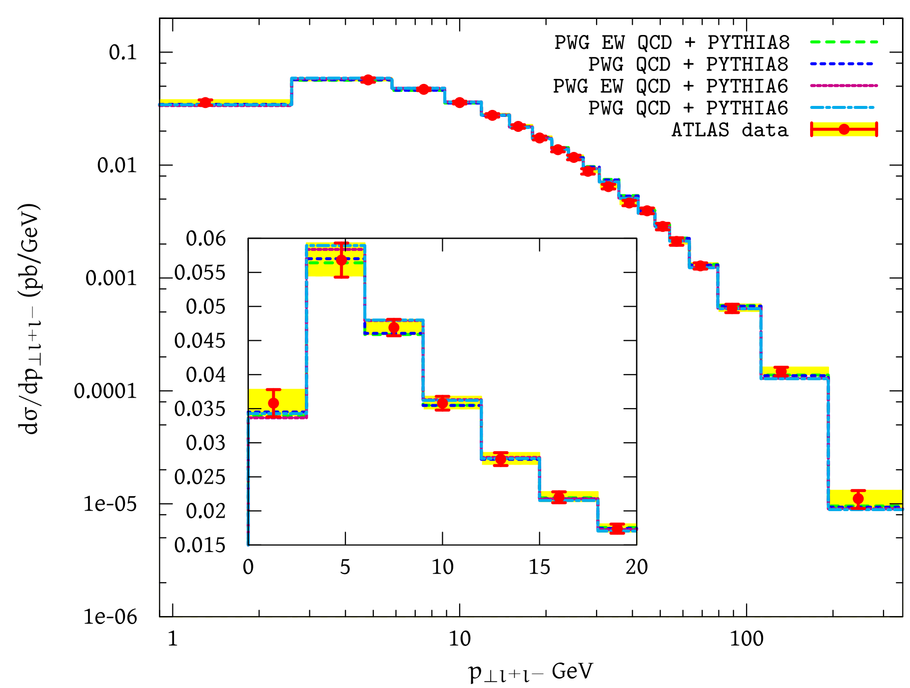
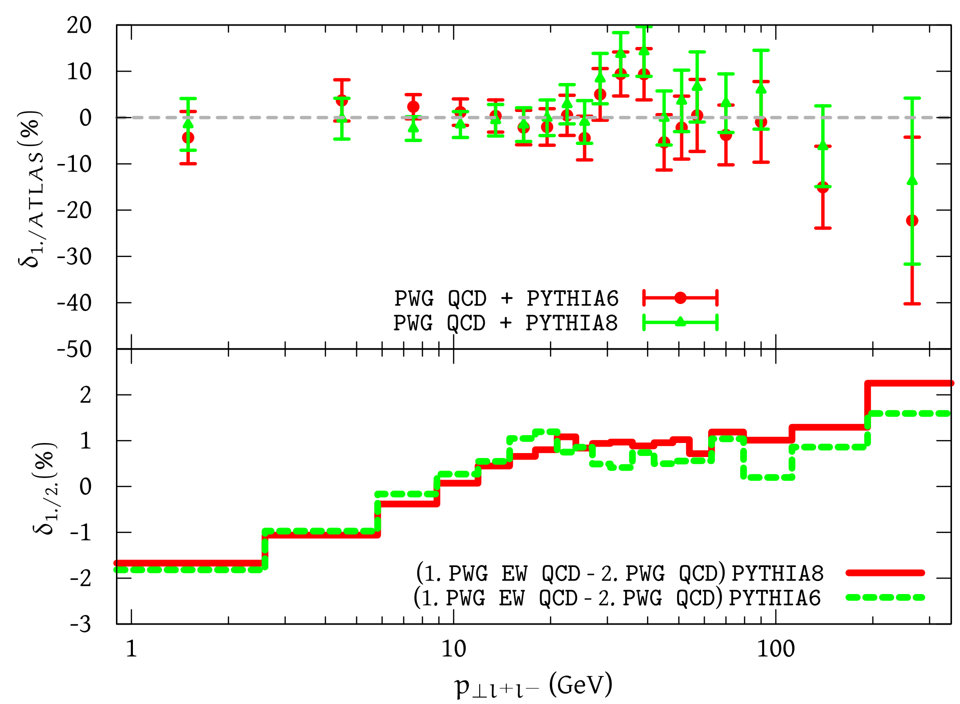




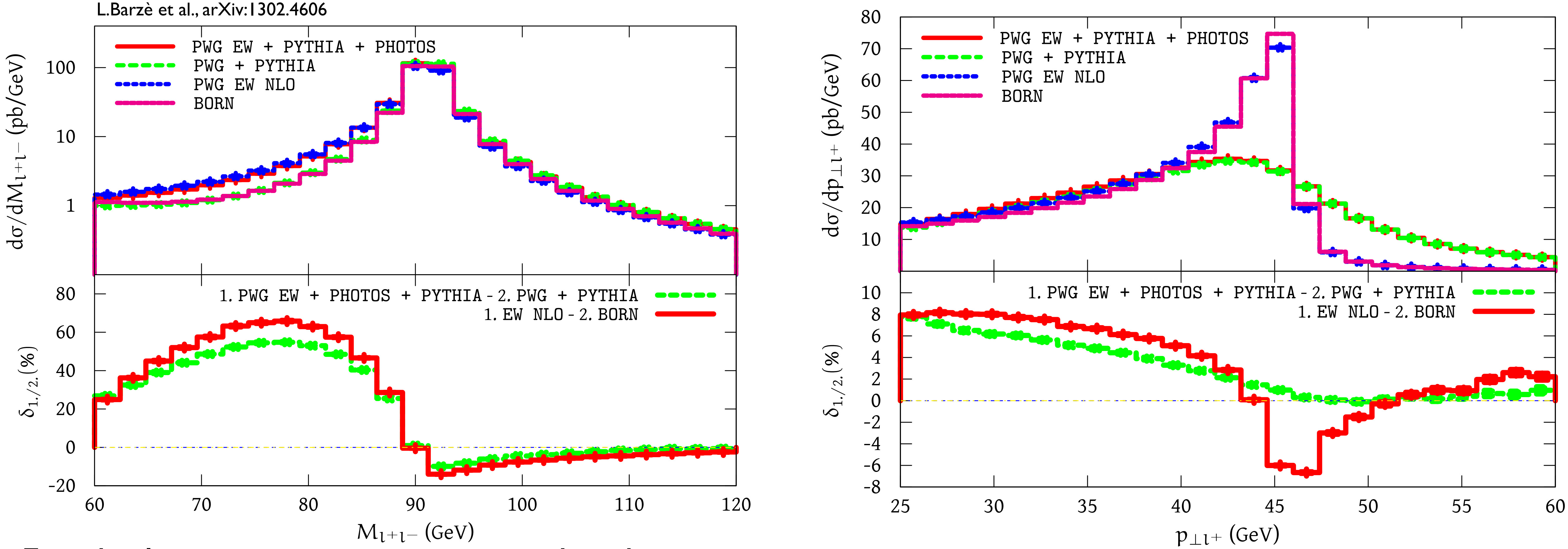
- The matching of NLO-(QCD+EW) matrix elements with (QCD+QED)-PS introduces a (small) additional suppression at low ptZ values

- CC-DY and NC-DY differ for the flavor (charge) of initial state quarks → different QED effects relevant in the PS tuning

Matching (QCD+EW) fixed order with (QCD+QED)-PS in POWHEG

Interplay of QCD and EW corrections: is a factorized Ansatz (differential K-factor) accurate ?
what is the role of the exact NLO-EW corrections ?

L.Barzè et al., arXiv:1302.4606



- For the lepton-pair invariant mass distributions
  the convolution of the EW kernel with QCD radiation preserves size and shape of EW corrections

- For the lepton transverse momentum distribution,
  the exact treatment of the radiation kinematics shows a large deformation of the EW effects by QCD showering (corrections of O(alpha alphas) and higher) S.Dittmaier, A.Huss, C. Schwinn, arXiv:1403.3216

- In the ptlep distribution, also the subleading EW terms can be enhanced by the large QCD logarithms (assessment of difference between pure QED-FSR and matched NLO-EW with QED PS in progress)

Drell-Yan observables for MW and simulation codes

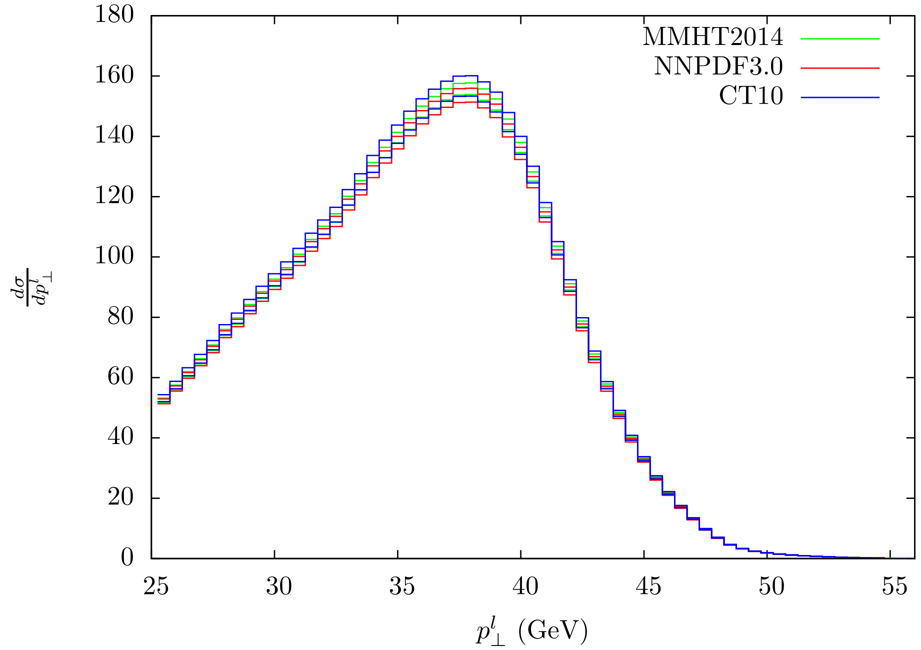
We need an accurate description of the ptV spectrum to predict the ptlep and the MT distributions

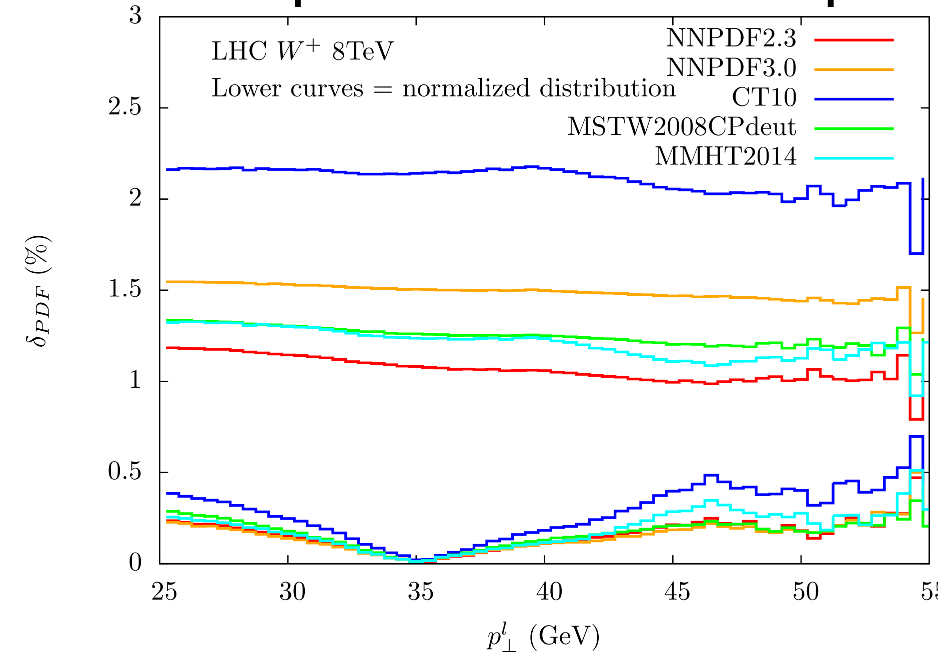
- perturbative elements (matching of QCD/EW matrix elements with resummation)
- non-perturbative elements (PDF uncertainties, intrinsic kt of the partons in the proton, part of the PS tune)
- different contribution of heavy- vs light- flavors in the PDF to the ptV spectrum

PDF uncertainty affecting MW extracted from the ptlep distribution

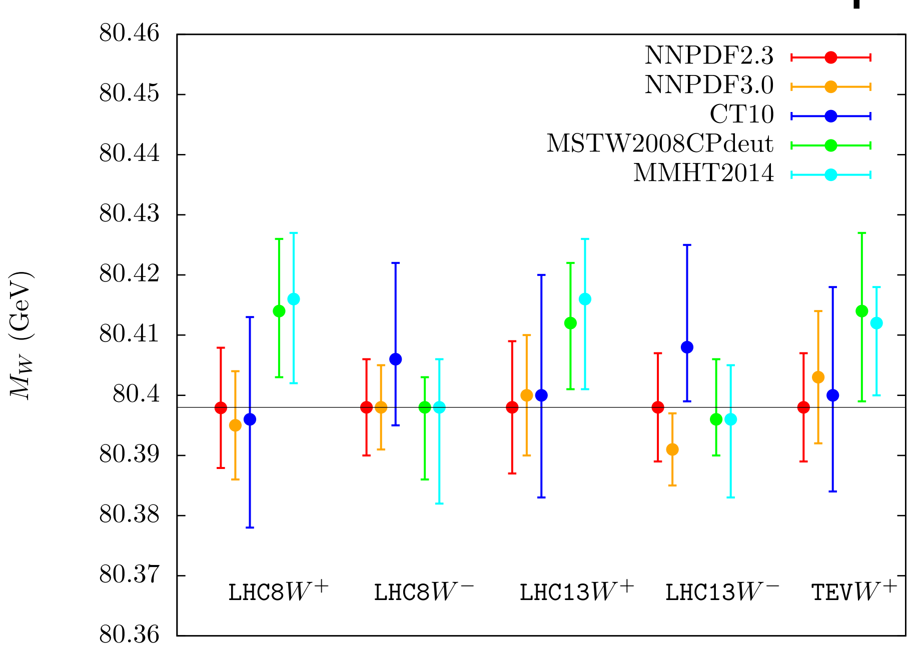
G.Bozzi, L.Citelli, AV, arXiv:1501.05587

Conservative estimate of the PDF uncertainty, obtained from the CC-DY channel alone,
using a template fit approach:
distributions obtained with POWHEG+PYTHIA, different PDF replicas are treated as pseudodata





Given a reference PDF set (NNPDF2.3 replica 0)
we estimate which would be the difference in the fit of the data
if we would use a different PDF replica in the preparation of the templates



	no $p_\perp^W$ cut		$p_\perp^W < 15$ GeV	
	δ_{PDF} (MeV)	Δ_{sets} (MeV)	δ_{PDF} (MeV)	Δ_{sets} (MeV)
Tevatron 1.96 TeV	27	16	21	15
LHC 8 TeV W^+	33	26	24	18
W^-	29	16	18	8
LHC 13 TeV W^+	34	22	20	14
W^-	34	24	18	12

the PDF4LHC recipe defines the half-width of the envelope δ_{PDF}
and the spread of the central values Δ_{sets}

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The dependence of the MW PDF uncertainty on the acceptance cuts provides interesting insights

normalized distributions			
cut on $p_\perp^W$	cut on $\lvert\eta_l\rvert$	CT10	NNPDF3.0
inclusive	$\lvert\eta_l\rvert < 2.5$	$80.400 + 0.032 - 0.027$	80.398 ± 0.014
$p_\perp^W < 20$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.027 - 0.020$	80.394 ± 0.012
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.017 - 0.018$	80.395 ± 0.009
$p_\perp^W < 10$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.392 + 0.015 - 0.012$	80.394 ± 0.007
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 1.0$	$80.400 + 0.032 - 0.021$	80.406 ± 0.017
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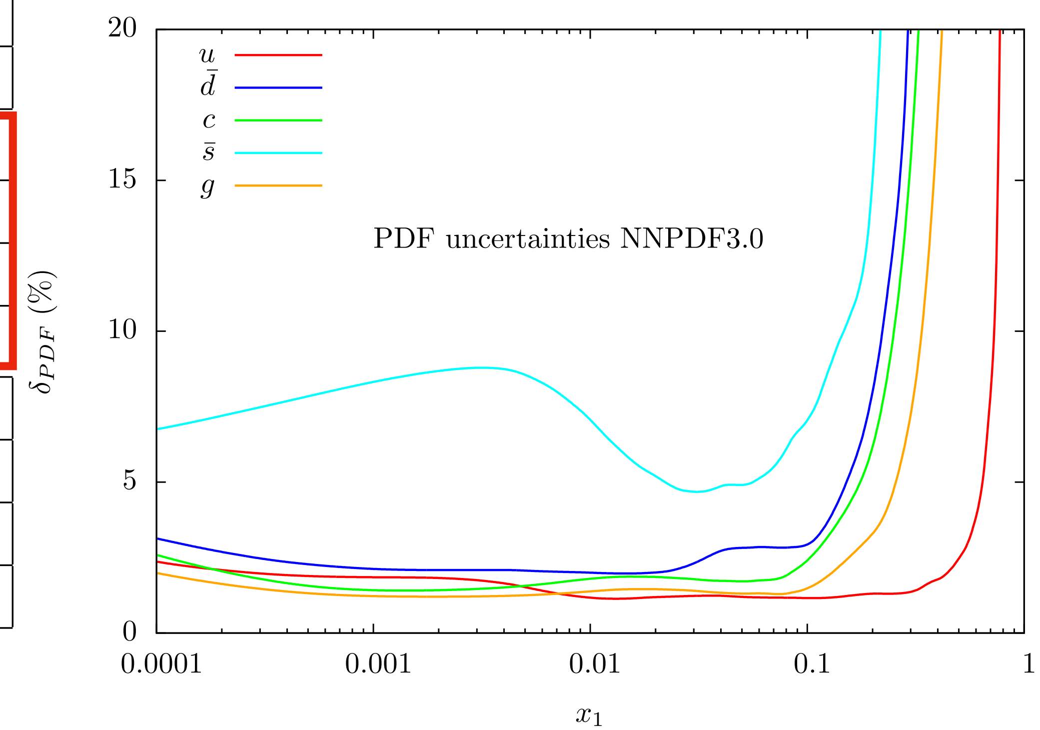
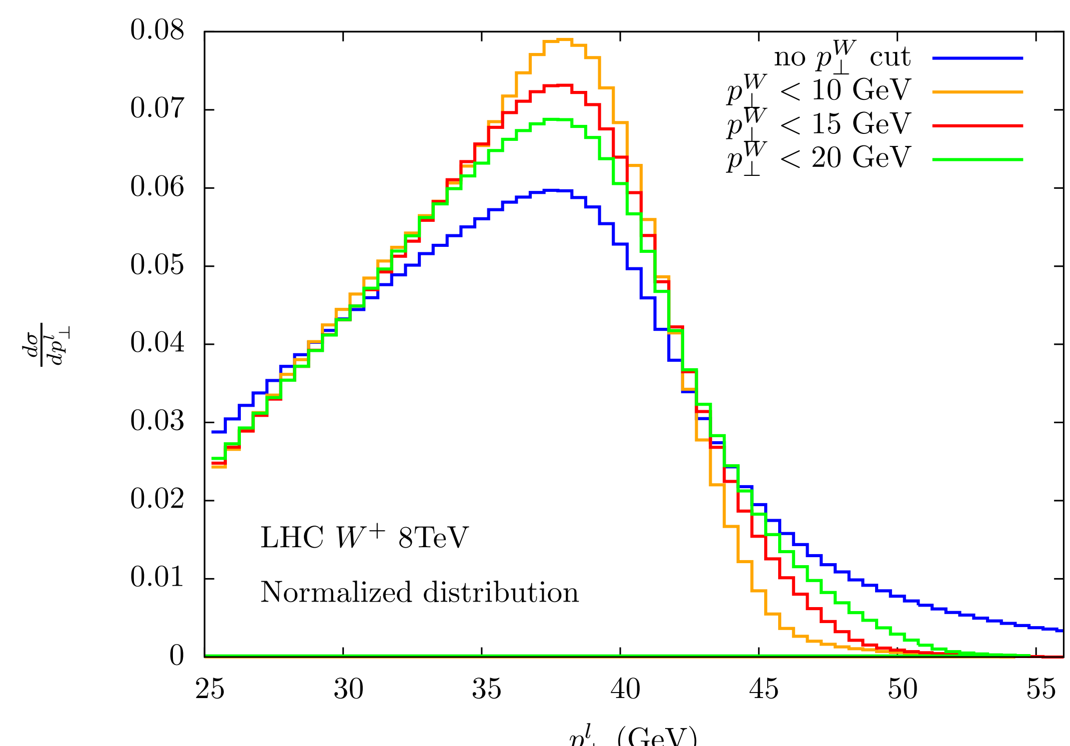
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 4.9$	$80.400 + 0.009 - 0.004$	80.401 ± 0.003
$p_\perp^W < 15$ GeV	$1.0 < \lvert\eta_l\rvert < 2.5$	$80.392 + 0.025 - 0.018$	80.388 ± 0.012



- the additional cut on PTW reduces the MW uncertainty
  - suppression of the large-x region
  - steeper shape of the ptlep distribution



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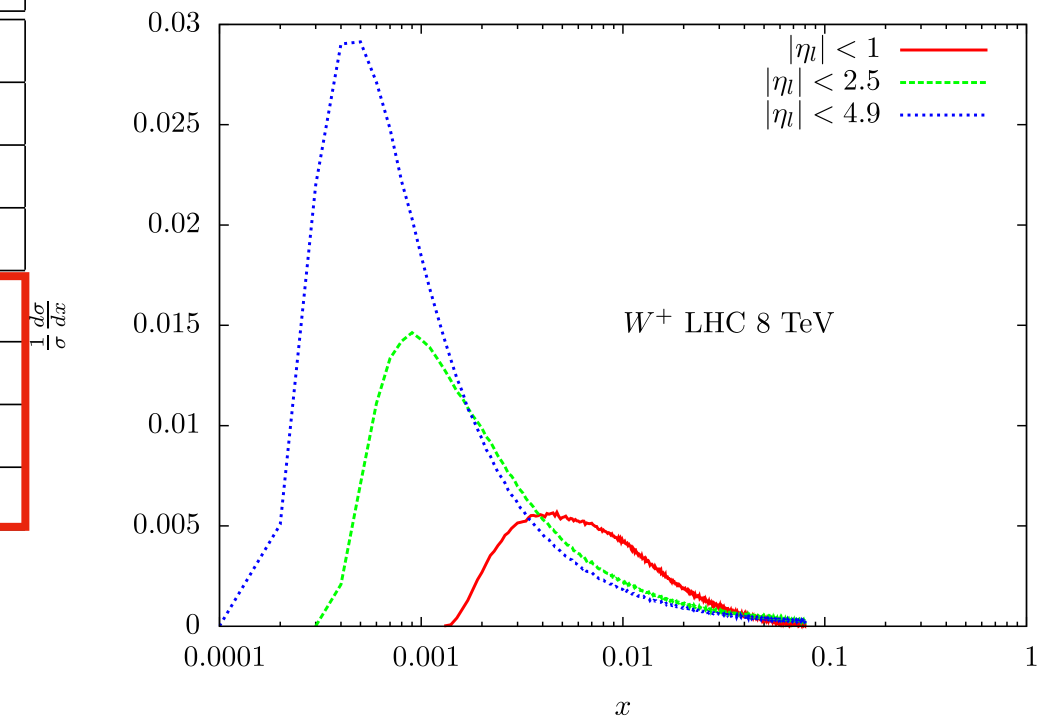

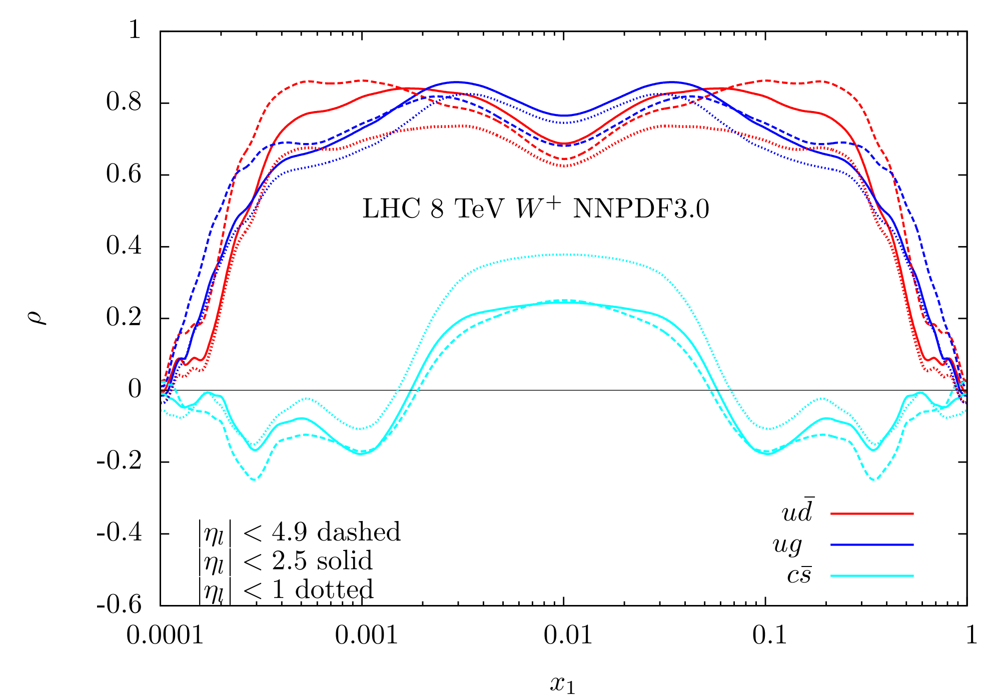

- cut on the lepton pseudorapidity
  - the normalized ptlep distribution, integrated over the whole lepton-pair rapidity range, does not depend on *x* and depends very weakly on the PDF replica
  - the central region is the most uncertain
  - PDF sum rules → non trivial compensations between different rapidity intervals among different flavors

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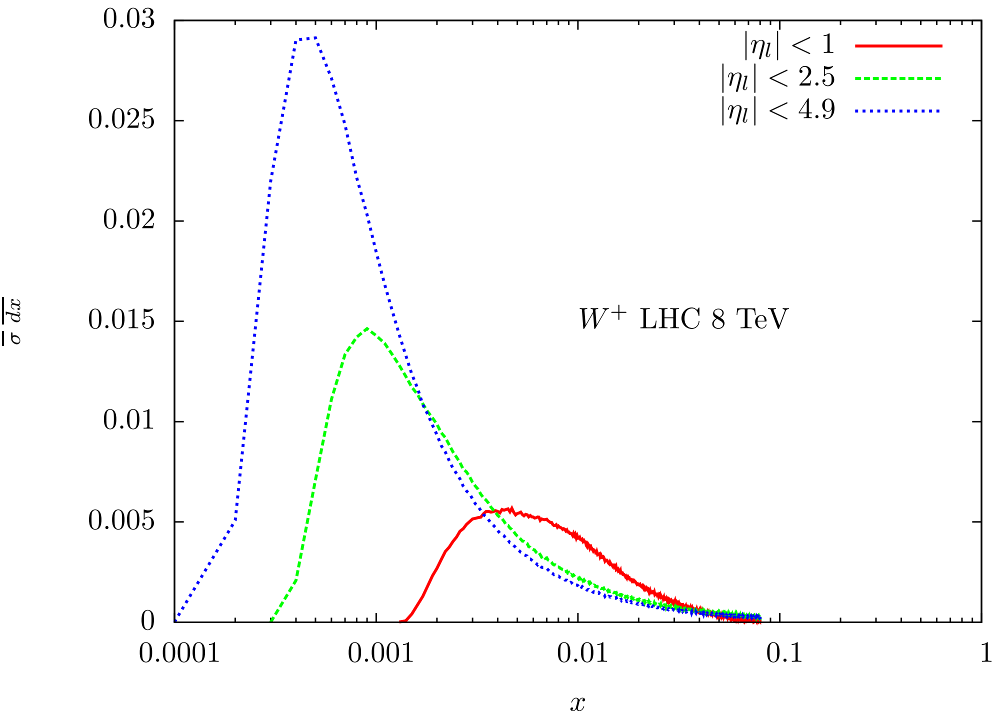
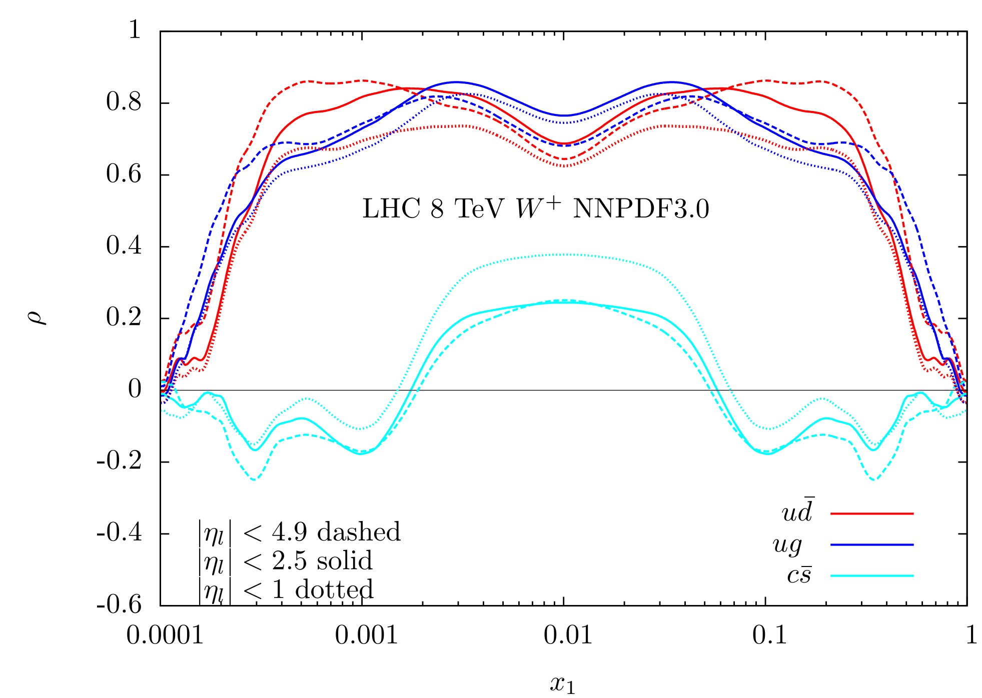
$p_\perp^W < 15$ GeV	$1.0 < \lvert\eta_l\rvert < 2.5$	$80.392 + 0.025 - 0.018$	80.388 ± 0.012





- cut on the lepton pseudorapidity
  - the normalized ptlep distribution, integrated over the whole lepton-pair rapidity range, does not depend on *x* and depends very weakly on the PDF replica
  - the central region is the most uncertain
  - PDF sum rules → non trivial compensations between different rapidity intervals among different flavors
- are PDFs a bottleneck for MW? can we improve?
  2 complementary answers: 1) more inputs to the PDF fit; 2) exploting ptZ info

Non-perturbative effects and the ptV spectrum

- the ptlep spectrum receives a very large contribution from the recoil of W,Z against QCD radiation
  it is crucial to get an accurate description of ptW

- In the ptV description (V=W,Z) we find
  - perturbative elements (factorization/renormalization/resummation scales, matching schemes)
  - non-perturbative elements (e.g. intrinsic kt of the partons in the proton, part e.g. of the PS tune)
  - PDFs (and their uncertainties)
  - different contribution of heavy- vs light- flavors in the PDF to the ptV spectrum

  All these elements are entangled.

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  All these elements are entangled.

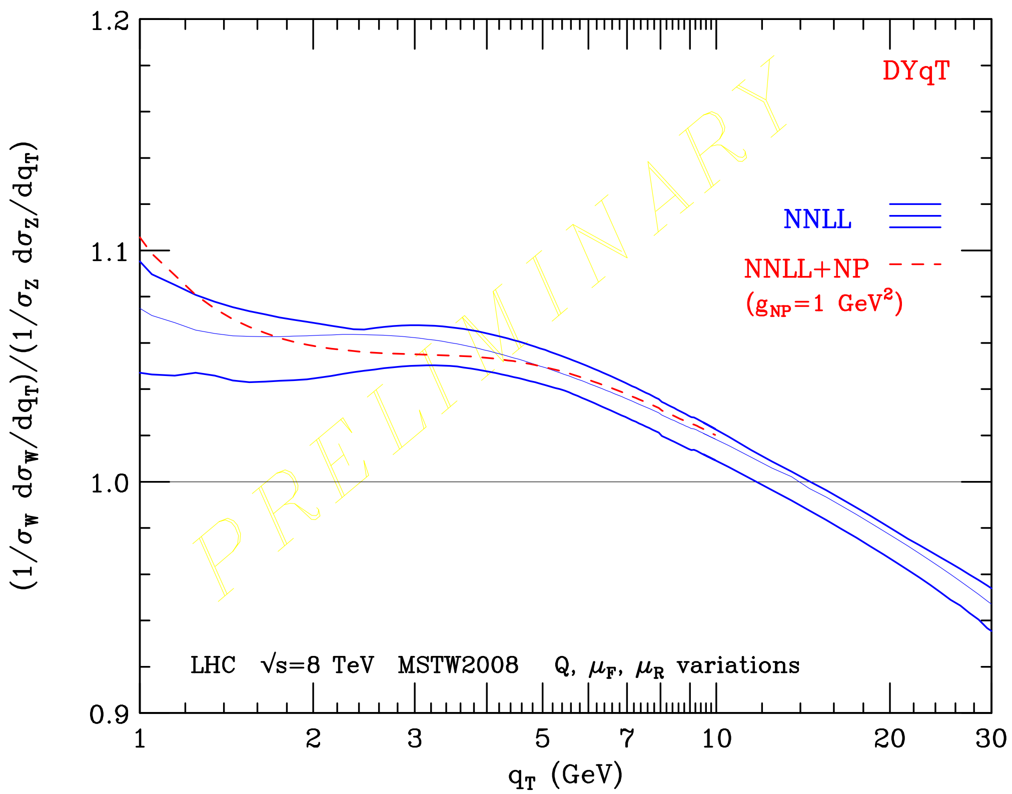
- The accurate ptZ measurement may constrain several parameters of the model-dependent part
  (e.g. the PS tune) of the simulations

  but
  - the interplay between the various effects above is not trivial (a global analysis would be needed)
  - the QCD scales can NOT be measured
    the fit of the model dependent part depends on the QCD scales
  - How accurate is the transfer of the ptZ description to the ptW simulation?
    Are the non-perturbative parameters universal? phase-space independent?
  - the use of the ptZ information to improve the description of the ptW spectrum
    is equivalent to say that one measures a W/Z relation

DY W/Z ratios

since W and Z observables share several common (QCD) features
⇒ convenient observables to extract MW are defines as ratio of W/Z quantities W.T.Giele, S.Keller, hep-ph/9704419

plot by G. Ferrera, talk at GGI workshop Joint ATLAS+CMS+TH meeting on M_W
http://www.ggi.fi.infn.it/talkfiles/slides/talk3553.pdf



ratio of shapes ptW/ptZ

NNLL perturbative uncertainty band very small:

2-5% for 1 < qT < 2 GeV, 1.5-2% for 2 < qT < 30 GeV.

Non perturbative effects within 1% for 1.5 < qT < 5 GeV and negligible for qT >5GeV.

A systematic study of the potential of W/Z ratios for an accurate MW determination is in progress

The amount of information, of experimental input, relevant for the MW central value determination is the same as in the case of W observables

The more symmetric treatment of W w.r.t. Z allows a discussion of systematic errors (e.g. pQCD) which would be otherwise “frozen” in the steps 1) extract from the Z and 2) input in the W simulation

Feasibility of a MW measurement at the 10 MeV level

It requires that several "minor" effects are under control

- impressive progress of MC generators, already available and with further developments, both for pure QCD and QCDxEW corrections

  ⇒ understanding the size of the impact on MW of several classes of available corrections is in progress (not trivial) L.Barzè, C.M.Carloni Calame, H.Martinez, G.Montagna, O.Nicrosini, F.Piccinini. AV, in progress

  MC working group of the CERN EW-WG

  ⇒ assessing the residual error due to missing higher order corrections is even less trivial

- a global improvement of PDFs will be made possible by the new LHC data

  the very accurate ptZ measurement should allow a detailed Parton Shower tune;

- for the ptlep distr. of CC-DY alone, non-perturbative uncertainties could be very hard to beat;

  ⇒ if W/Z ratios are less sensitive to all these effects, we could mitigate the bottleneck

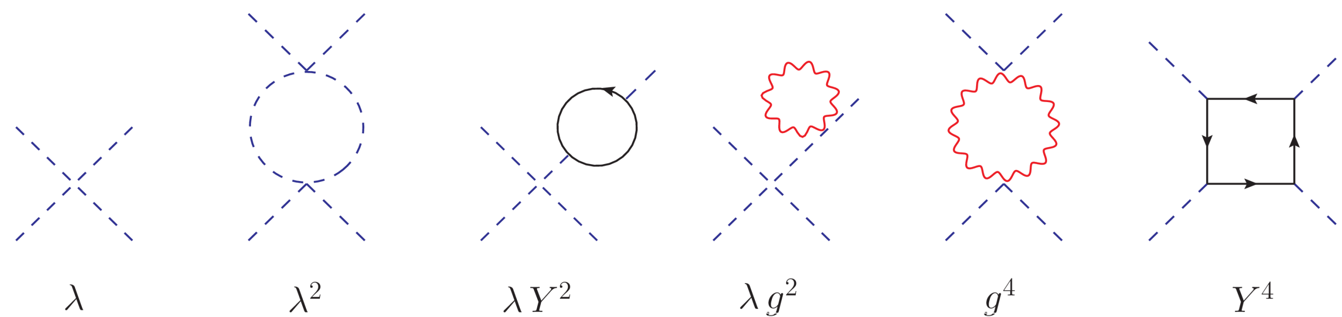
  are experimental ratios W/Z as accurate as the individual observables?

for the MT of CC-DY distribution, much milder pQCD and non-pert. QCD effects

more problematic experimental reconstruction (pile-up?)

mtop value and the stability of the EW vacuum

$$V^{class}(\phi) = -\frac{m^2}{2}\phi^2 + \lambda\phi^4 \qquad\qquad V^{eff}(\phi) = -\frac{m(\mu)^2}{2}\phi(\mu)^2 + \lambda(\mu)\phi(\mu)^4$$



$$\frac{d\lambda}{d\log\mu} = \frac{1}{16\pi^2}\left[+24\lambda^2 + \lambda\left(4N_c Y_t - 9g^2 - 3g'^2\right) - 2N_c Y_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g'^4 + \frac{3}{4}g^2 g'^2 + \dots\right]$$

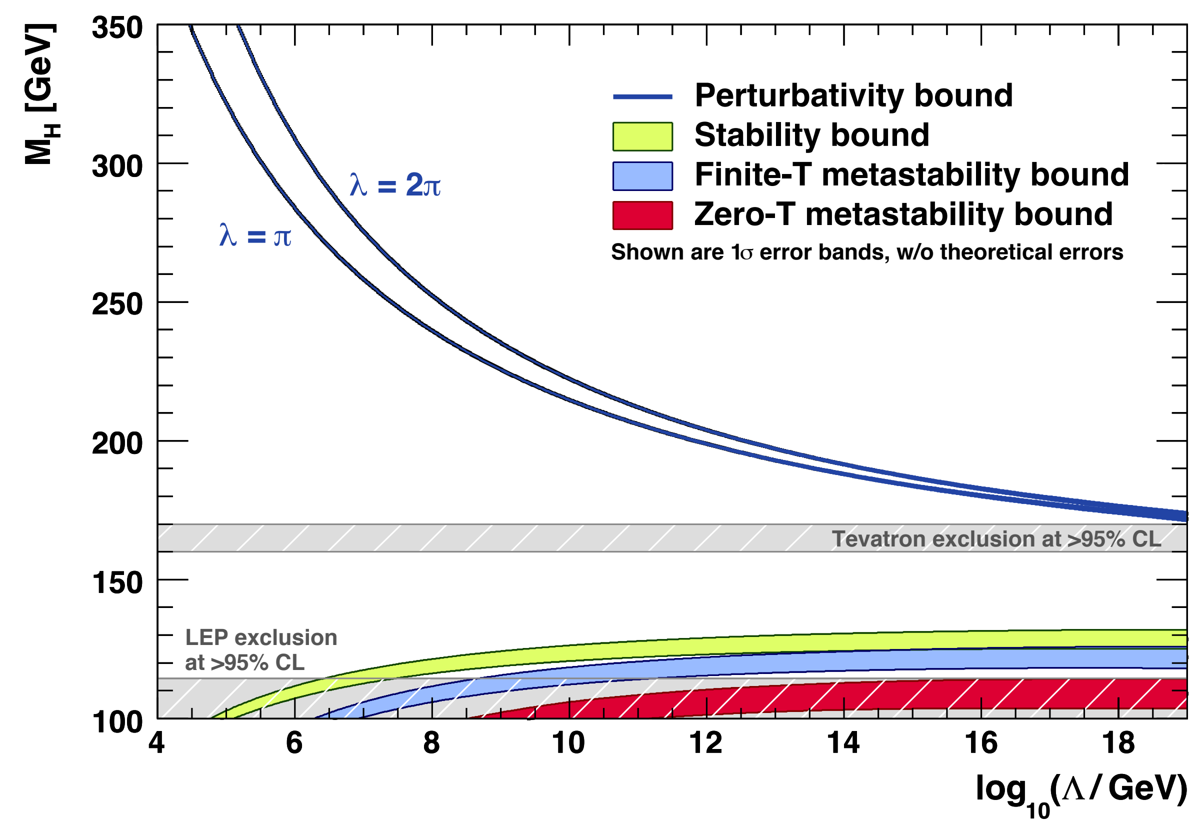
Avoiding a Landau pole

sets an upper bound on λ, i.e. on MH

The request that λ remains positive

(stability bound, potential bounded from below)

sets a lower bound on MH

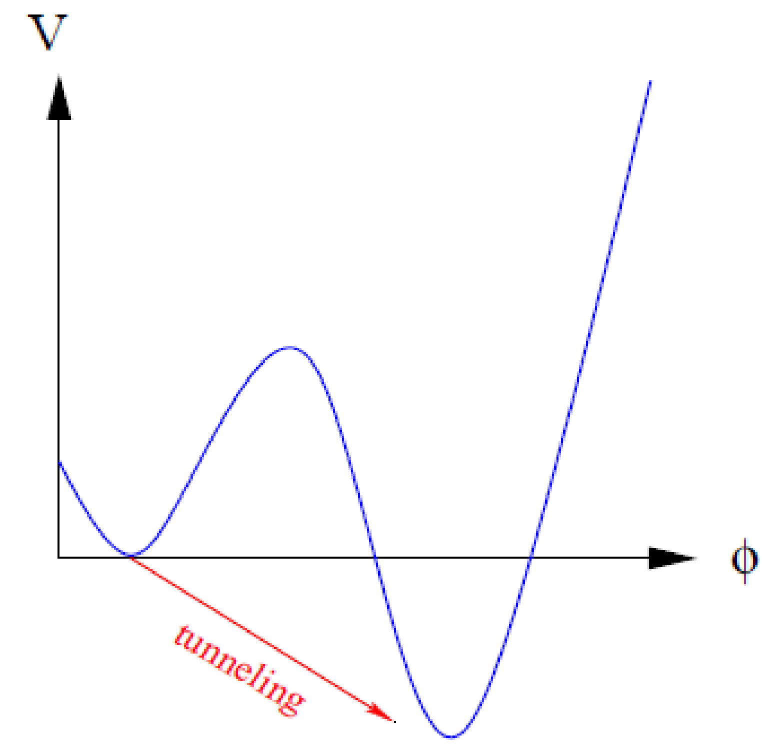


mtop value and the stability of the EW vacuum

Intermediate scenario:

the potential remains bounded from below,

but new local minima appear with a non-vanishing tunneling probability



two different alternatives:

- we could be living in a sufficiently long-lived (> age of the Universe) metastable vacuum
- new physics appear to restore the shape of the potential bounded from below

- first studies on the vacuum stability

Linde (76); Weinberg (76); Cabibbo, Maiani, Parisi, Petronzio (79); Hung (79); Lindner (86); Sher(89)

- two-loop effective potential

Ford, Jack, Jones 92,97; Martin (02)

- three-loop beta function

Mihaila, Salomon, Steinhauser (12), v. Ritbergen, Vermaseren, Larin (97); Czakon (05), Chetyrkin, Zoller (12, 13,); Bednyakov et al. (13)

- two-loop threshold corrections at the weak scale

Chetyrkin, Steinhauser (00); Melnikov, v. Ritbergen (00), Bezrukov, Kalmykov, Kniehl, Shaposhnikov (12), Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, (13)

Bezrukov et al. (12), Di Vita et al. (12) Di Vita, Degrassi, Elias-Miro, Espinosa, Giudice, Isisodri, Strumia, (12) Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, (13)

mtop value and the stability of the EW vacuum

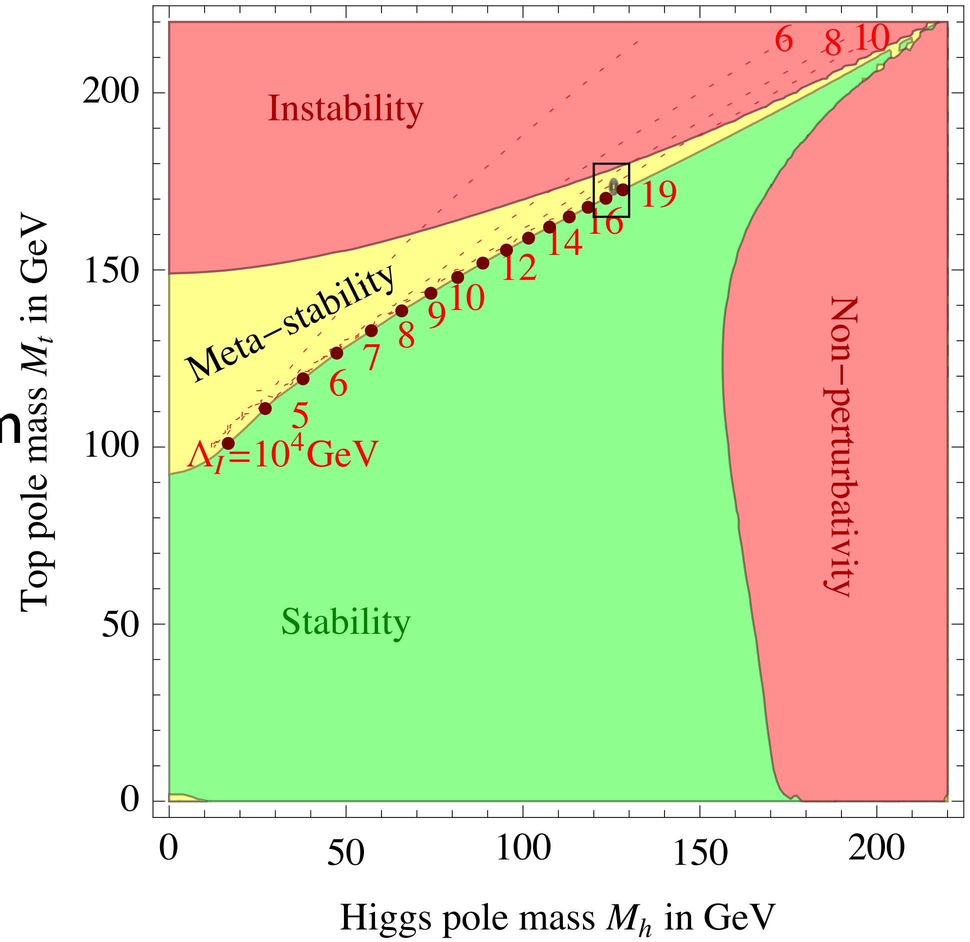
D.Buttazzo, G.Degrassi, P.Giardino, G.F.Giudice, F.Sala, A.Salvio, A.Strumia, arXiv:1307.3536

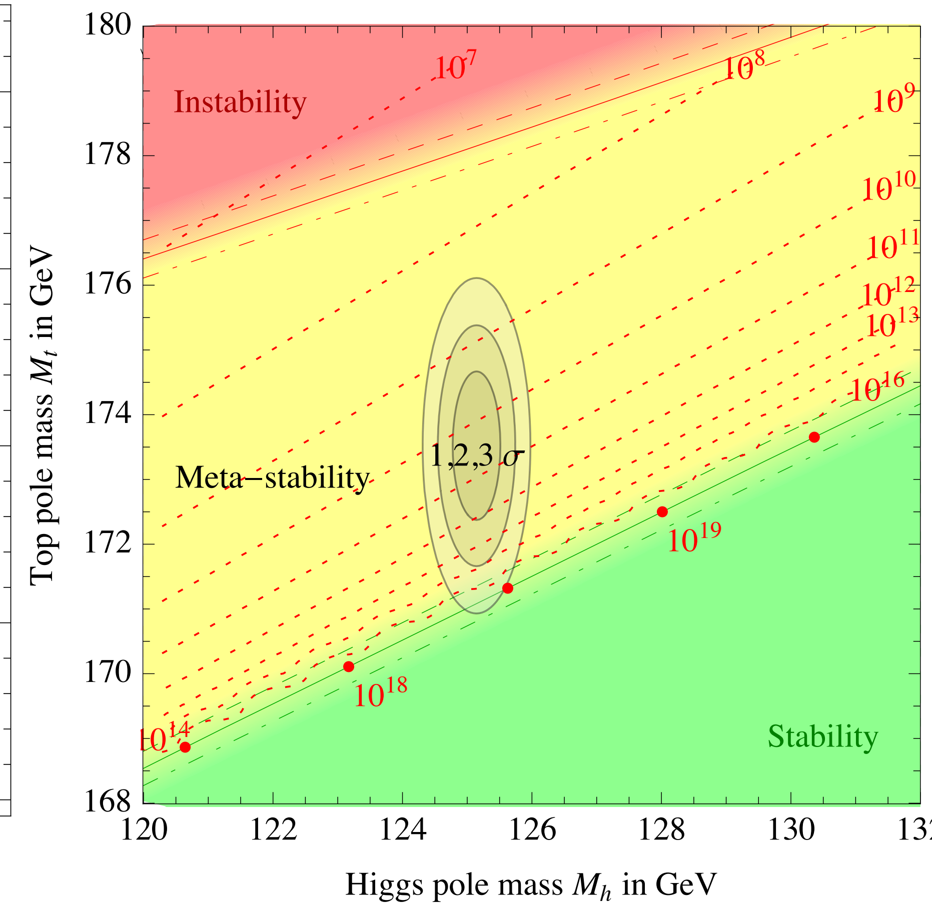
SM stability phase diagram

as a function of MH, mtop

we live in a metastable vacuum

close to the stability region





the stability bound is:

$$\frac{M_h}{\text{GeV}} > 129.6 + 1.3\left(\frac{M_t - 173.35\,\text{GeV}}{0.65\,\text{GeV}}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 0.3_{\text{pert.}} \pm 0.6_{\text{non-pert.}}$$

$$M_t < (171.36 \pm 0.15_{\text{pert.}} \pm 0.30_{\text{non-pert.}} \pm 0.25_{\alpha_s} \pm 0.17_{M_h})\,\text{GeV}$$

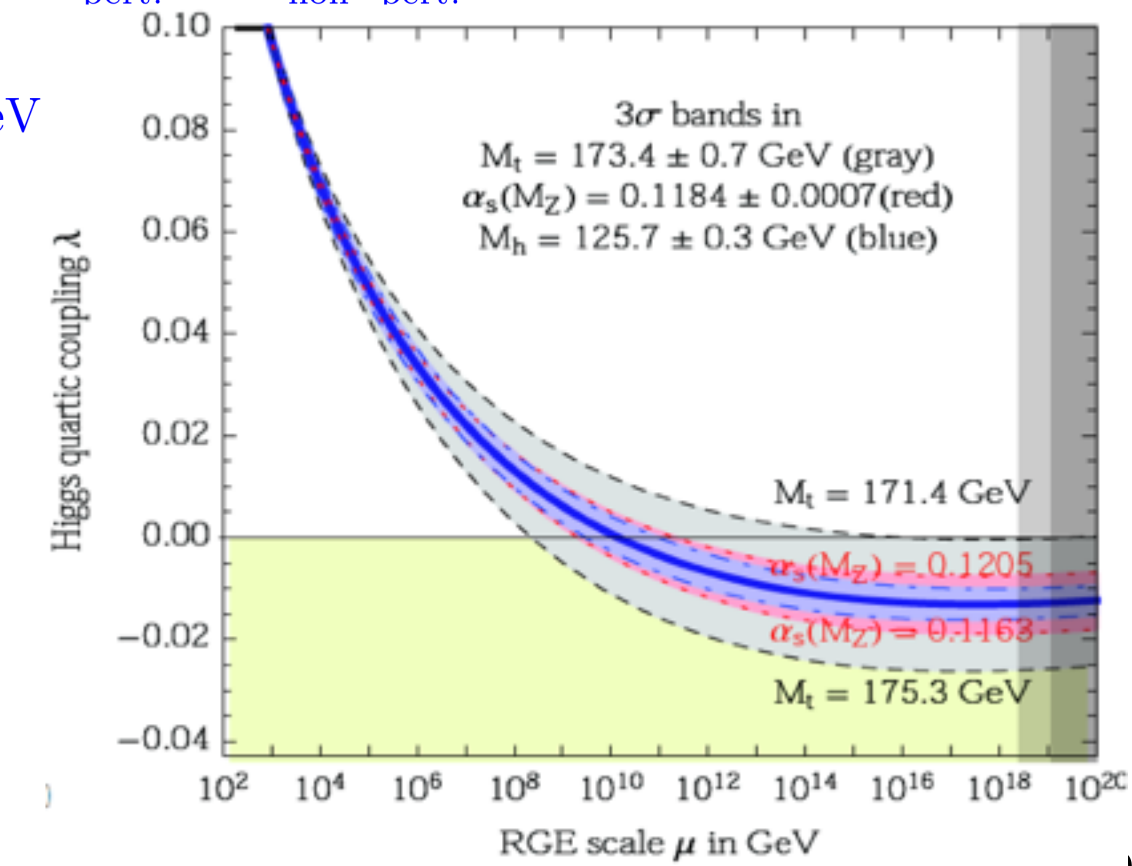
The stability bound (λ(M_Planck)>0)

depends on the precise value of mtop (and of alpha_s)

Here we assume the validity of the SM up to M_Planck

Different conclusions if we assume the existence of

new physics at some intermediate scale



mtop value, MW and the stability of the EW vacuum

- The stability arguments indicates a preference for a low mtop value   mtop ≲ 172 GeV
- With such values, the MW prediction in the SM decreases w.r.t. its central value,

  reaching a deviation of 2σ from the world average

  mtop=171.5 GeV   would predict a too light MH value in the SM
- Low values are disfavored by the SM global EW fit,

  which prefers as indirect mtop ~ 173.5 (177.0) GeV

- The determination of mtop from multiparticle final states suffers, at present,

  of some problems of conversion between:

  -the parameter present in the MC (with LO matrix elements and no control on the

  top mass renormalization) and fit to the data

  -the renormalized quantities (pole mass, MSbar mass) used in theoretical studies

cfr   S.Moch et al.,arXiv:1405.4781 S.Moch,arXiv:1408.6080

- The top MSbar mass, measured from the study of the total ttbar production xsec,

  leads to a value which, converted into a pole mass, is “low”

  mtop^MSbar = 162.3 ± 2.3 GeV   → mtop_pole = 171.2 ± 2.4 GeV S.Moch,arXiv:1408.6080

Conclusions

- The theoretical prediction of MW and the analysis of the EW vacuum stability
  may offer insights about possible BSM signals and about the consistency of the SM

- The measurements of MW at the O(10 MeV) level and of mtop at the O(0.5 GeV) level
  are very challenging

- in the MW case, a very long list of O(5 MeV) effects comes into the game
  we need to understand new observables that help us to reduce some important systematic effects
  plan a global improvement of PDFs
  develop a systematic assessment of (PDF+Parton Shower) systematics
  LHC has the potential to provide all the inputs needed to constrain the DY system and to allow
  EW precision tests