UNIVERSITÀ DEGLI STUDI
DI MILANO

INFN
Istituto Nazionale
di Fisica Nucleare

Precision physics session: wrap-up

Alessandro Vicini
University of Milano, INFN Milano

Precision theory for precise measurements at the LHC and future colliders
ICISE, September 28th 2016

Precision physics session

(from a test of the EW sector to a fully entangled QCDxEW test of the SM)

- **Precision tests of the Standard Model**
  - → high-precision predictions of EW observables with higher-order radiative corrections
    - global EW fit (*Erler, Pfeiffer*)
    - improvement on parametric uncertainties (*Nomura, Mackenzie*)
  - → high-precision measurements of EW observables
    - lepton-flavour violation experiments (*Mihara*)
    - at hadron colliders (*Croft, Azzurri*)
    - progress in the evaluation of higher-order radiative corrections (*Di Vita*)
      - in the development of simulation codes (*Piccinini*)
  - → towards an estimate of the uncertainties affecting EW measurements, with special focus on MW

- **Test of the gauge and scalar sectors of the SM**
  - → automation of EW calculations for many particle processes (*Le Duc, Shao*) allows to study high-energy regimes with QCD and EW interactions in the same simulation tool
  - → EFT formulation of BSM effects (*Marzocca*)
  - → Experimental results with diboson final states (*Li*)

Predictivity of the Standard Model

- The Standard Model is a renormalizable gauge theory based on $SU(3) \times SU(2)_L \times U(1)_Y$
- The gauge sector of the SM lagrangian is assigned specifying (g,g',v,λ) in terms of 4 measurable inputs
- More observables can be computed and expressed in terms of the input parameters, including the available radiative corrections, to all orders in perturbation theory
- The validity of the SM can be tested comparing these predictions with the corresponding experimental results
- A convenient choice for the inputs is $(g,g',v,\lambda) \leftrightarrow (\alpha, G_\mu, MZ, MH)$
- MW and $\sin^2\theta_{eff}$ are important predictions of the SM,

  because of their indirect sensitivity to new physics via virtual effects
- Stability of the EW vacuum → new constraints between the SM parameters (mtop, MH, …)

- What are the limiting factors to improve the precision of SM predictions?
  Missing higher orders? Parametric uncertainties?

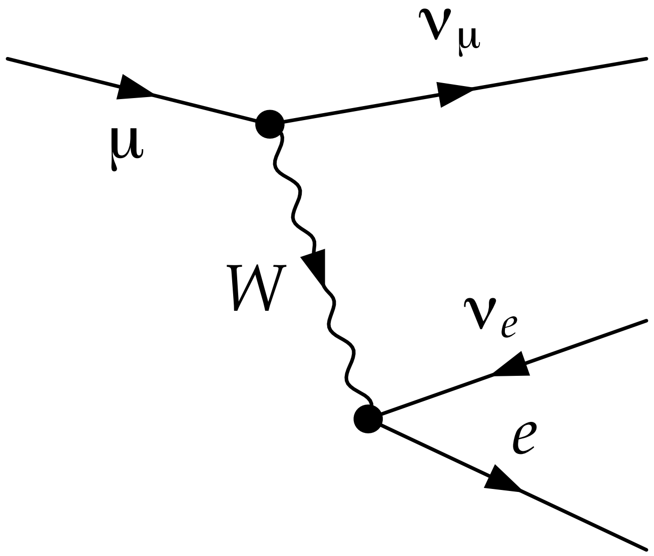
- How do we measure EW precision observables?
  What is the theoretical contribution to the systematic error?

The W boson mass: theoretical prediction

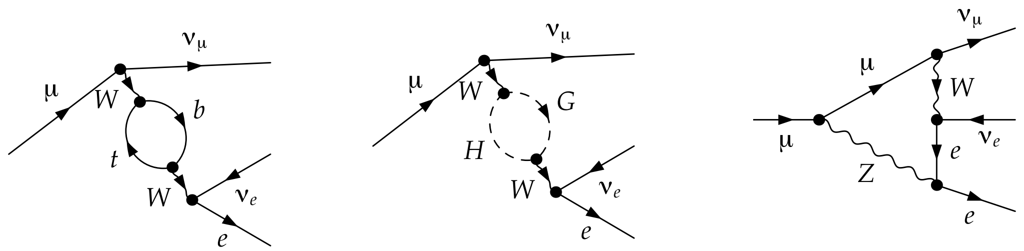
$$\mathcal{L}_{SM} = \mathcal{L}_{SM}(\alpha,\, G_\mu,\, m_Z; m_H; m_f; CKM)$$

$$\rightarrow \text{we can compute } m_W$$

$$\frac{G_\mu}{\sqrt{2}} = \frac{g^2}{8 m_W^2}\,(1+\Delta r)$$



+



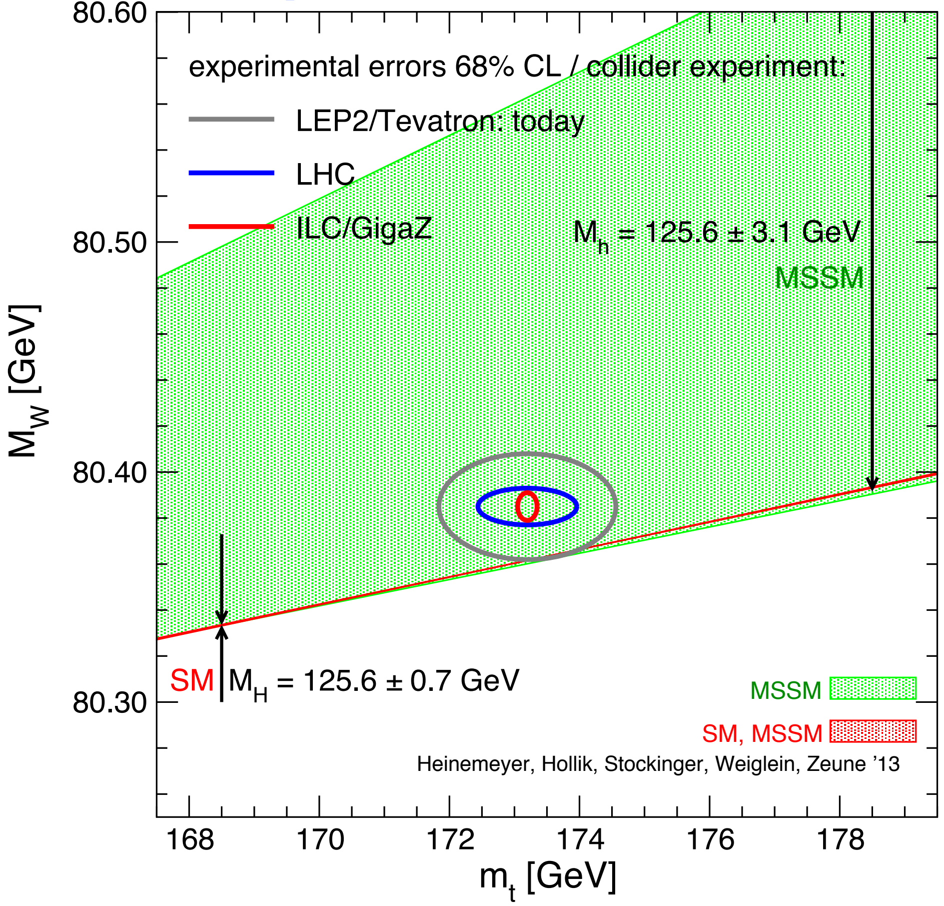
+ ....

$$\Delta r = \Delta r(m_t, m_H, \ldots)$$

⇨

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

Possible interpretation of the MW measurement



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

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

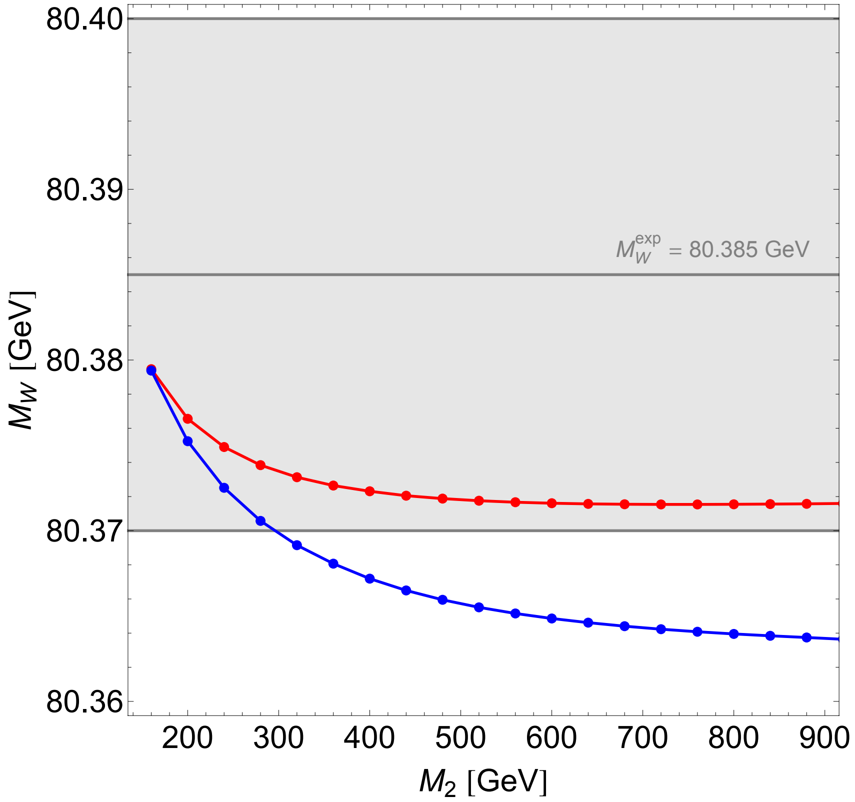
$$m_W = m_W\left(\Delta r^{SM,MSSM}\right)$$

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

relevance of a correct estimate of the MW central value and associated error

O. Stål, G. Weiglein, L. Zune, arXiv:1506.07465

different dependence on the neutralino mass M_2
of the MW prediction in the MSSM and NMSSM



MW prediction in the SM

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

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 2014 top mass world average mt=173.34 $\pm 0.76_{\text{exp}} \pm 0.3_{\text{th}}$ GeV

$\Delta\alpha_{\text{had}}(MZ) = 0.02750 \pm 0.00033$

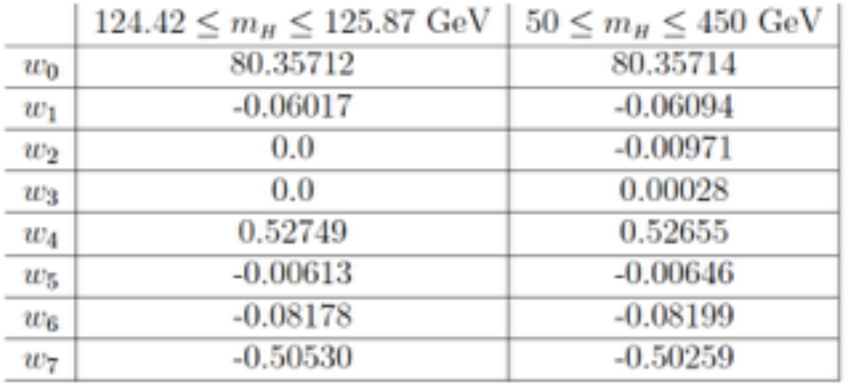
MW varies with mtop: Δmt=+1 GeV → ΔMW = +6 MeV

with $\Delta\alpha_{\text{had}}(MZ)$: $\Delta\alpha_{\text{had}}(MZ)=+0.0003$ → ΔMW = -6 MeV

a simultaneous variation of both parameters by 1σ may increase MW up to 80.370 GeV
or 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)

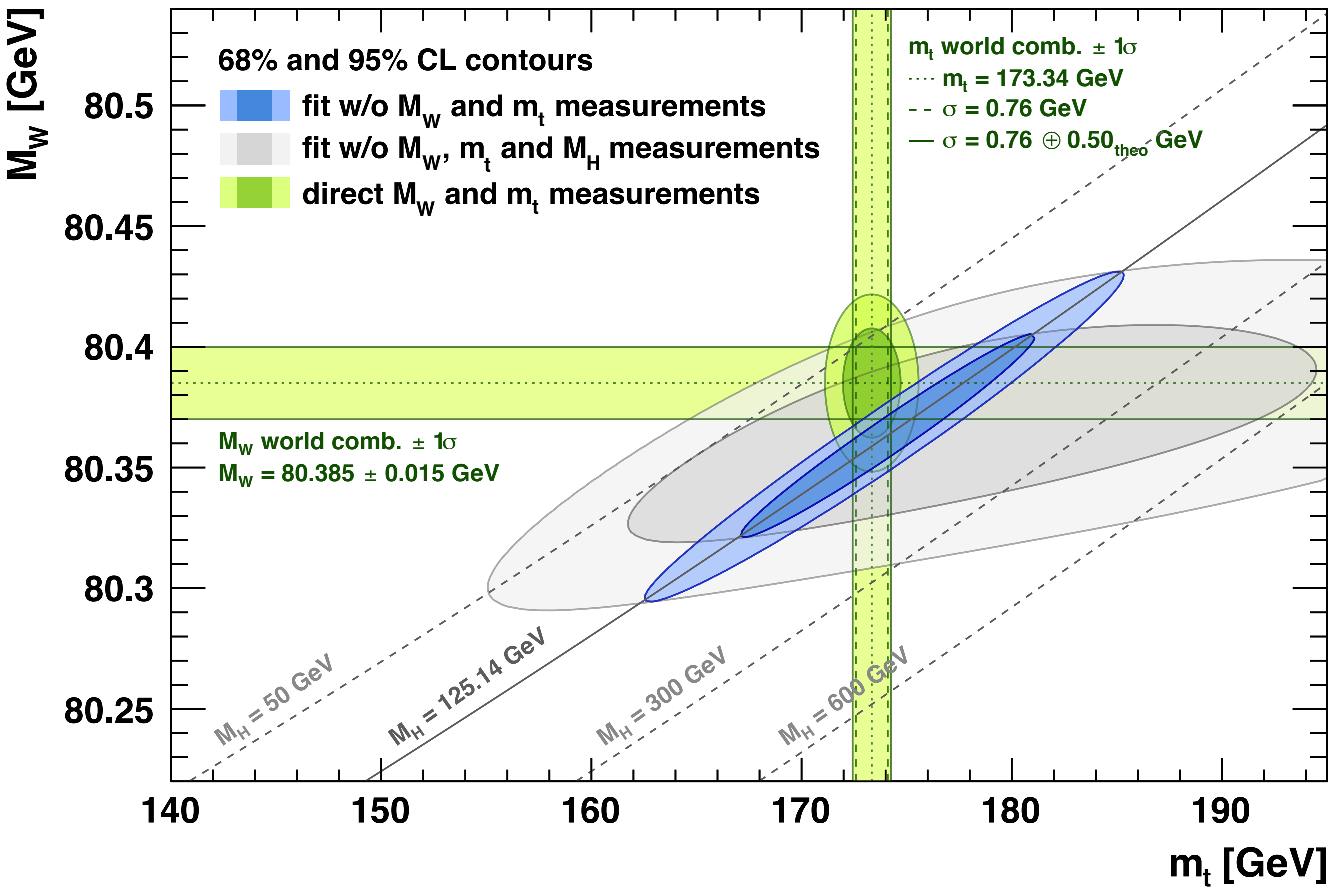
$$m_W = w_0 + w_1 dH + w_2 dH^2 + w_3 dh + w_4 dt + w_5 dH dt + w_6 da_s + w_7 da^{(5)}$$

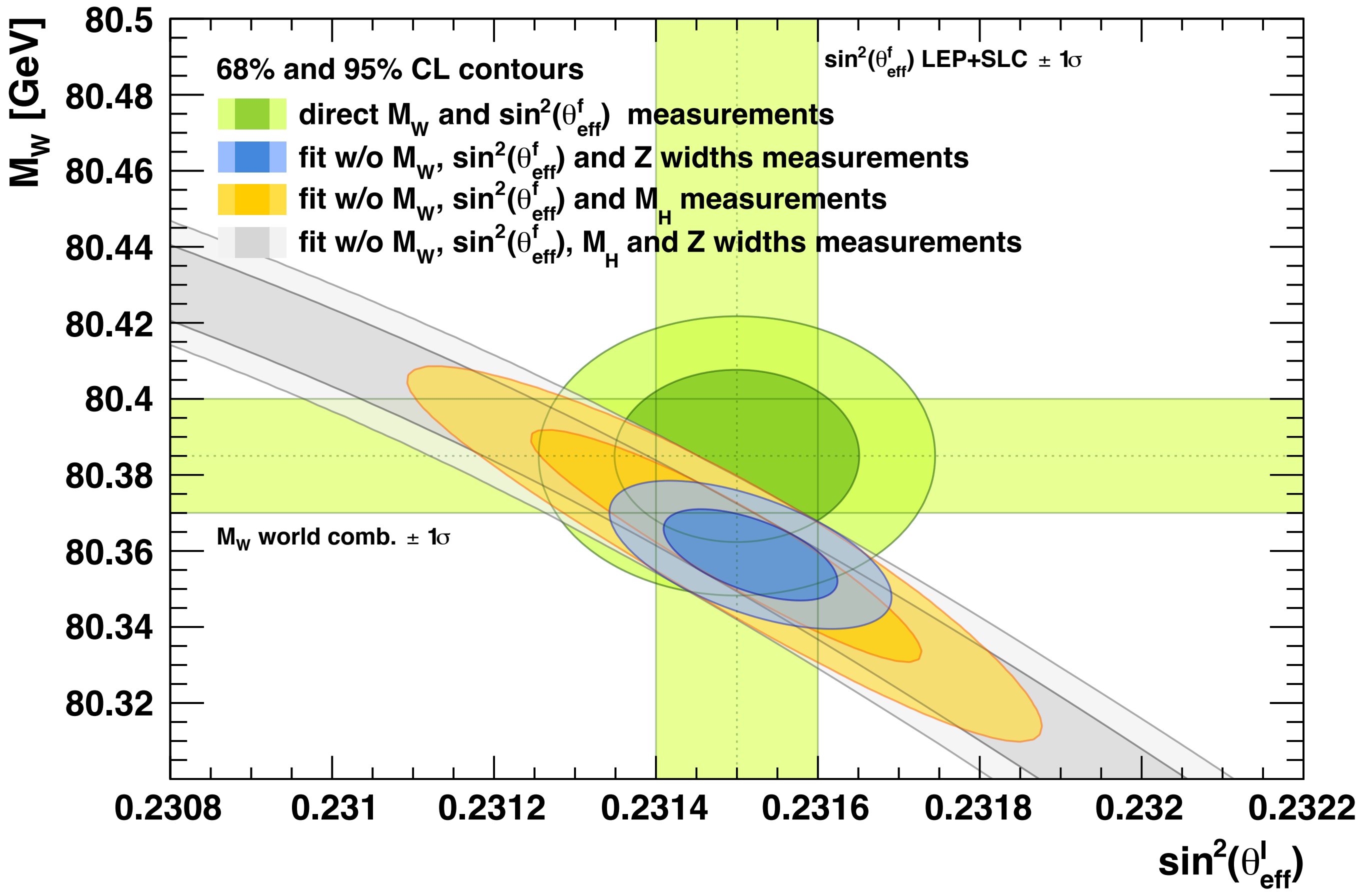


	$124.42 \le m_H \le 125.87$ GeV	$50 \le m_H \le 450$ GeV
w_0	80.35712	80.35714
w_1	-0.06017	-0.06094
w_2	0.0	-0.00971
w_3	0.0	0.00028
w_4	0.52749	0.52655
w_5	-0.00613	-0.00646
w_6	-0.08178	-0.08199
w_7	-0.50530	-0.50259

Global EW fit 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)

or MW and $\sin^2\theta_{eff}$

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

the result of the global EW fit of the SM

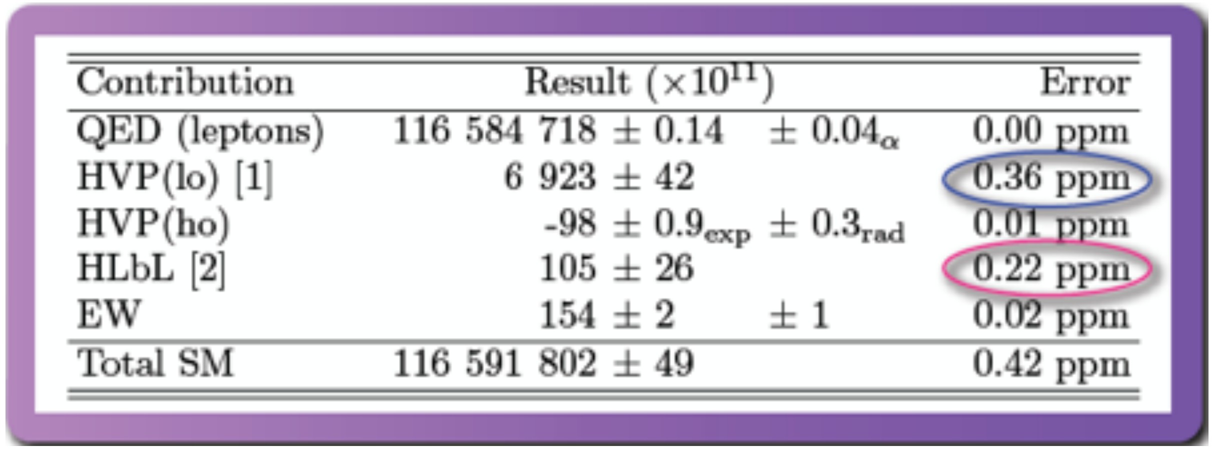
yields a result for MW with an error ΔMW=8 MeV smaller than the one of the direct measurement

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

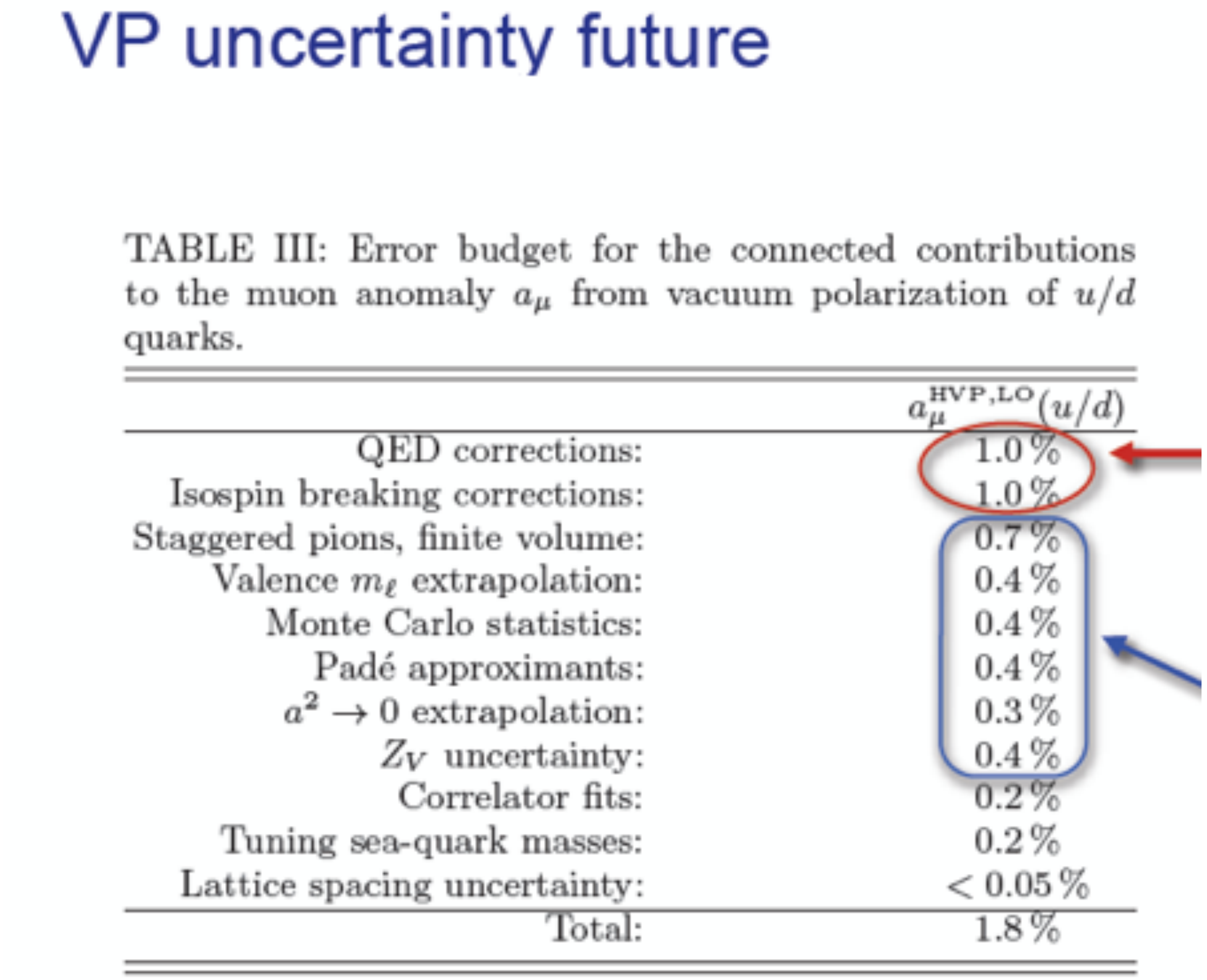
ΔMW=8 MeV is smaller than the estimate from the analysis of MW alone (Degrassi, Gambino, Giardino)

Determination of $\Delta\alpha_{had}$(MZ)

Mackenzie



Contribution	Result ($\times 10^{11}$)		Error
QED (leptons)	116 584 718 ± 0.14	$\pm\, 0.04_\alpha$	0.00 ppm
HVP(lo) [1]	6 923 ± 42		0.36 ppm
HVP(ho)	$-98 \pm 0.9_{\rm exp}$	$\pm\, 0.3_{\rm rad}$	0.01 ppm
HLbL [2]	105 ± 26		0.22 ppm
EW	154 ± 2	± 1	0.02 ppm
Total SM	116 591 802 ± 49		0.42 ppm

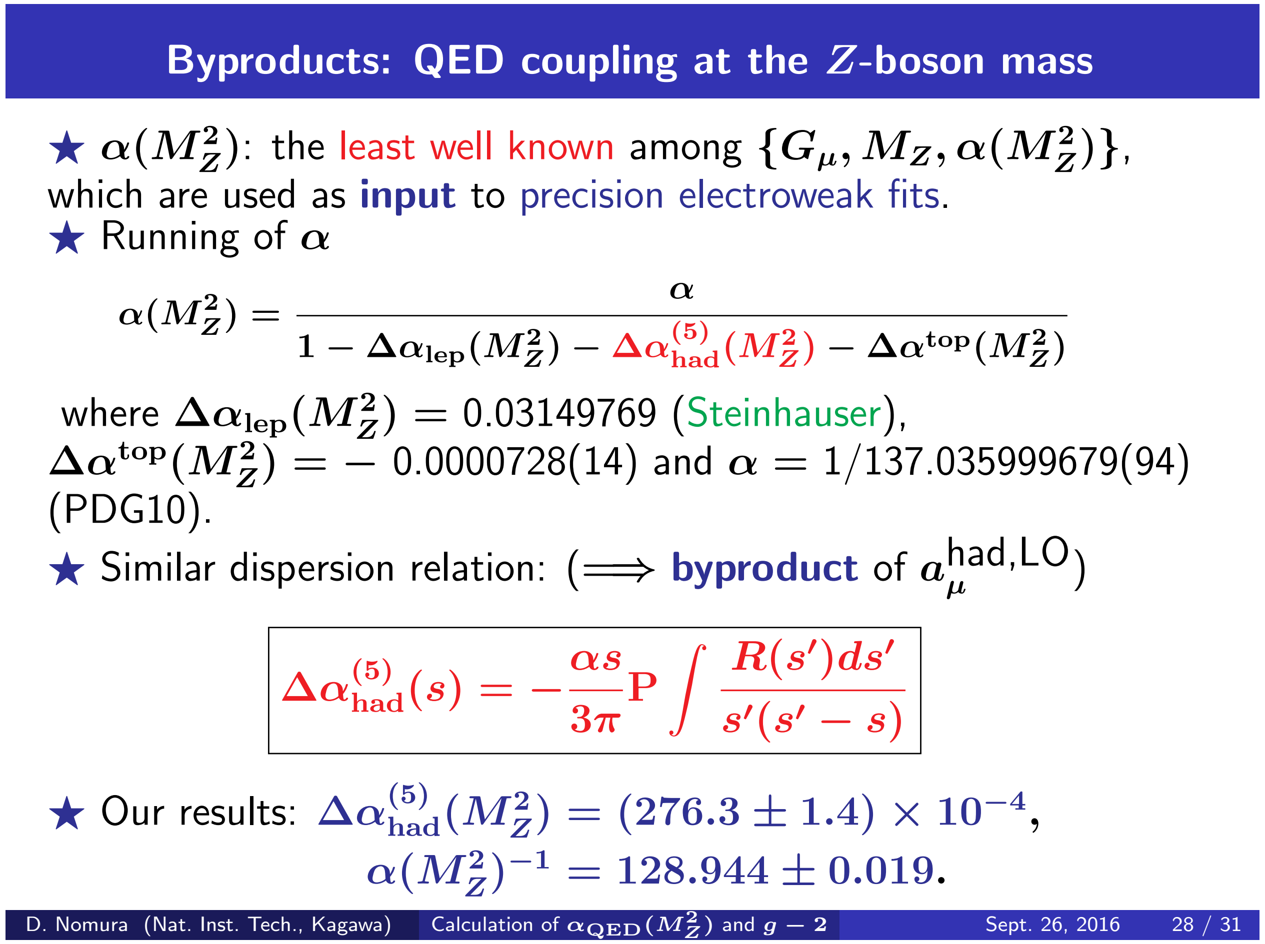


VP uncertainty future

TABLE III: Error budget for the connected contributions to the muon anomaly a_μ from vacuum polarization of u/d quarks.

	$a_\mu^{\rm HVP,LO}(u/d)$
QED corrections:	1.0 %
Isospin breaking corrections:	1.0 %
Staggered pions, finite volume:	0.7 %
Valence m_ℓ extrapolation:	0.4 %
Monte Carlo statistics:	0.4 %
Padé approximants:	0.4 %
$a^2 \to 0$ extrapolation:	0.3 %
Z_V uncertainty:	0.4 %
Correlator fits:	0.2 %
Tuning sea-quark masses:	0.2 %
Lattice spacing uncertainty:	< 0.05 %
Total:	1.8 %

Nomura



Byproducts: QED coupling at the Z-boson mass

★ $\alpha(M_Z^2)$: the least well known among $\{G_\mu, M_Z, \alpha(M_Z^2)\}$, which are used as **input** to precision electroweak fits.

★ Running of α

$$\alpha(M_Z^2) = \frac{\alpha}{1 - \Delta\alpha_{\rm lep}(M_Z^2) - \Delta\alpha_{\rm had}^{(5)}(M_Z^2) - \Delta\alpha^{\rm top}(M_Z^2)}$$

where $\Delta\alpha_{\rm lep}(M_Z^2) = 0.03149769$ (Steinhauser), $\Delta\alpha^{\rm top}(M_Z^2) = -0.0000728(14)$ and $\alpha = 1/137.035999679(94)$ (PDG10).

★ Similar dispersion relation: ($\Longrightarrow$ **byproduct** of $a_\mu^{\rm had,LO}$)

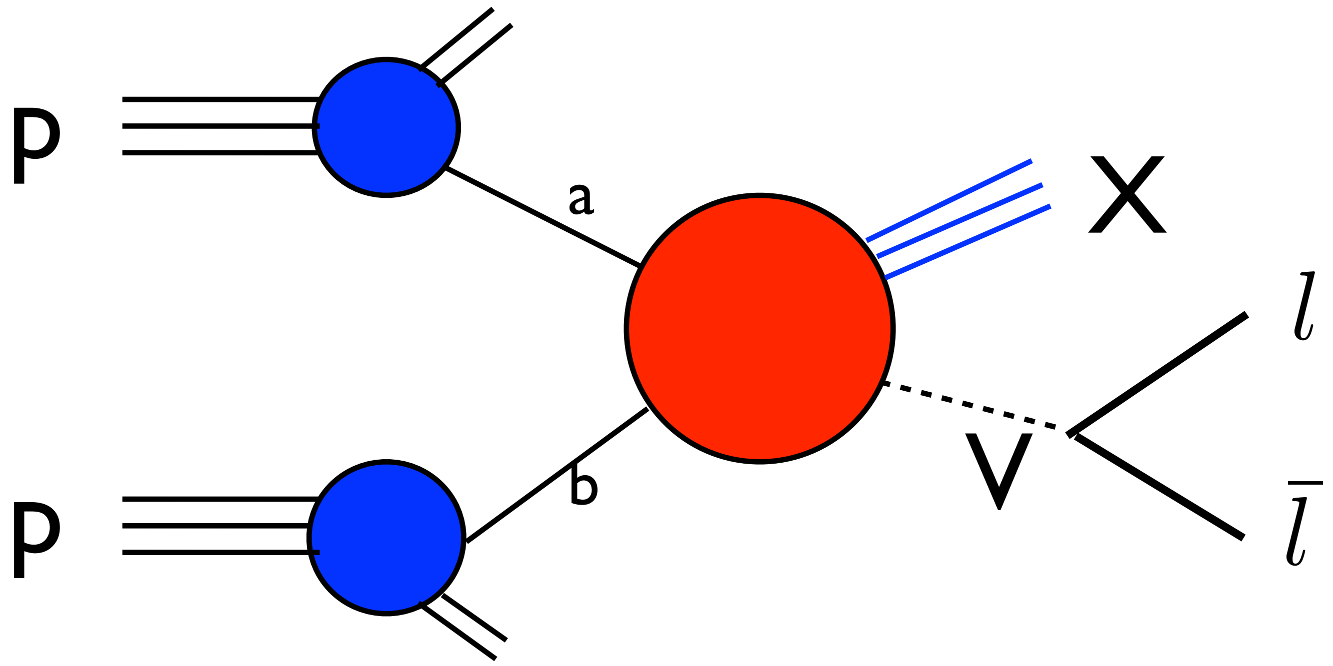
$$\boxed{\Delta\alpha_{\rm had}^{(5)}(s) = -\frac{\alpha s}{3\pi} {\rm P} \int \frac{R(s')ds'}{s'(s'-s)}}$$

★ Our results: $\Delta\alpha_{\rm had}^{(5)}(M_Z^2) = (276.3 \pm 1.4) \times 10^{-4}$,
$\alpha(M_Z^2)^{-1} = 128.944 \pm 0.019$.

D. Nomura (Nat. Inst. Tech., Kagawa) Calculation of $\alpha_{\rm QED}(M_Z^2)$ and $g-2$ Sept. 26, 2016 28 / 31

Hard scattering in hadronic collisions

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



The prediction of the hadron level cross section requires

- best description of the partonic cross section including fixed- and all-orders radiative corr. QCD, EW, mixed QCDxEW (SM, MSSM,…,EFT,…)
- accurate and consistent description of the QCD environment including PDFs, intrinsic partonic kt,…

- we are aiming at measuring the hard-scattering parameters (EW masses, EW and Higgs couplings,…) in a hadronic environment
  → we need to separate long from short distance physics (factorization, resummation scales)
  → define (pseudo-)observables stable w.r.t. the description of the environment (need to include multiple parton emissions)
  → define for these observables an uncertainty associated to the environment

- the measurement of pseudo-observables is in general model (theory+environment) dependent (theoretical systematic error)

The Drell-Yan process and EW measurements

Observables quantities accessible via counting experiments
cross sections and asymmetries

Pseudo-Observables quantities that are functions of the cross section and symmetries
require a model to be properly defined

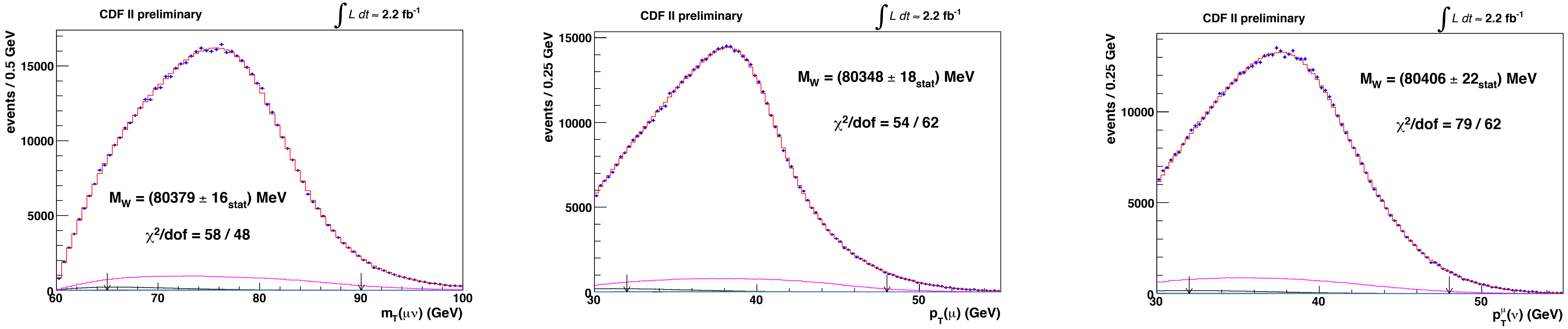
- the Z boson mass at LEP as the pole of the Breit-Wigner resonance factor
- the W mass at hadron collider as the fitting parameter of a template fit procedure
  the templates are computed in a model (typically the SM)

Template fit

- several histograms describing a differential distribution are computed with the highest available theoretical accuracy and degree of realism in the detector simulation letting the fit parameter (e.g. MW) vary in a range
- the histogram that best describes the data selects the preferred, i.e. measured, MW value

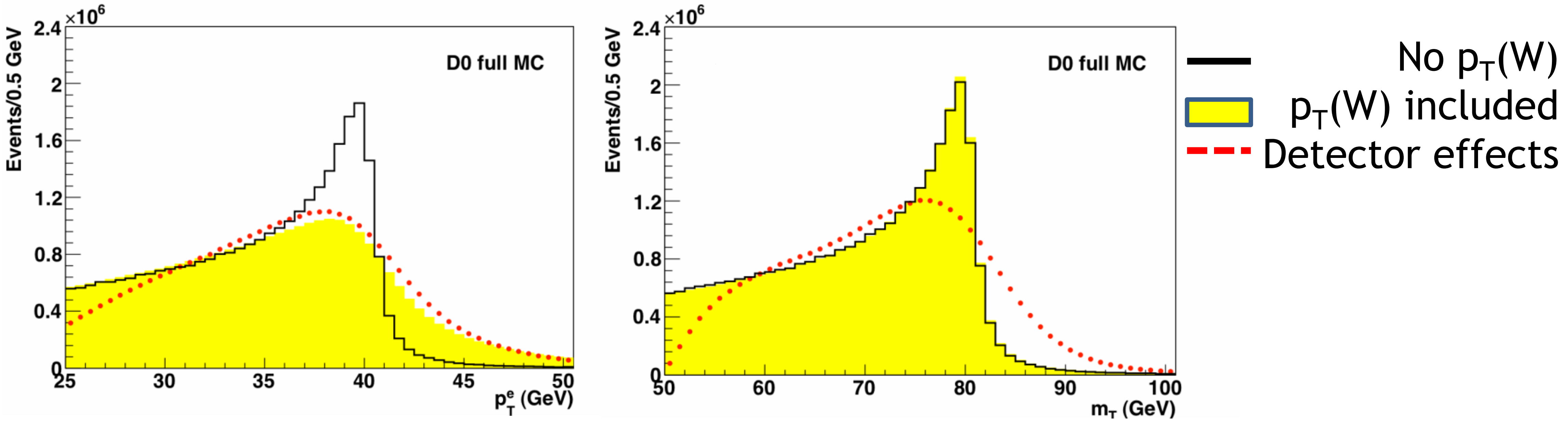
- the result of the fit depends on the hypotheses used to compute the templates
  these hypotheses should be treated as theoretical systematic errors
- more accurate calculations, properly implemented in Monte Carlo event generators are needed to reduce this systematic error

MW determination at hadron colliders: observables and techniques



- MW extracted from the study of the shape of the lepton-pair transverse mass, lepton transverse momentum, missing transverse momentum distributions thanks to the jacobian peak that enhances the sensitivity to MW

- Transverse mass: important detector smearing effects, moderate impact from the ptW modelling
  Lepton pt: moderate detector effects, extremely sensitive to the ptW modelling

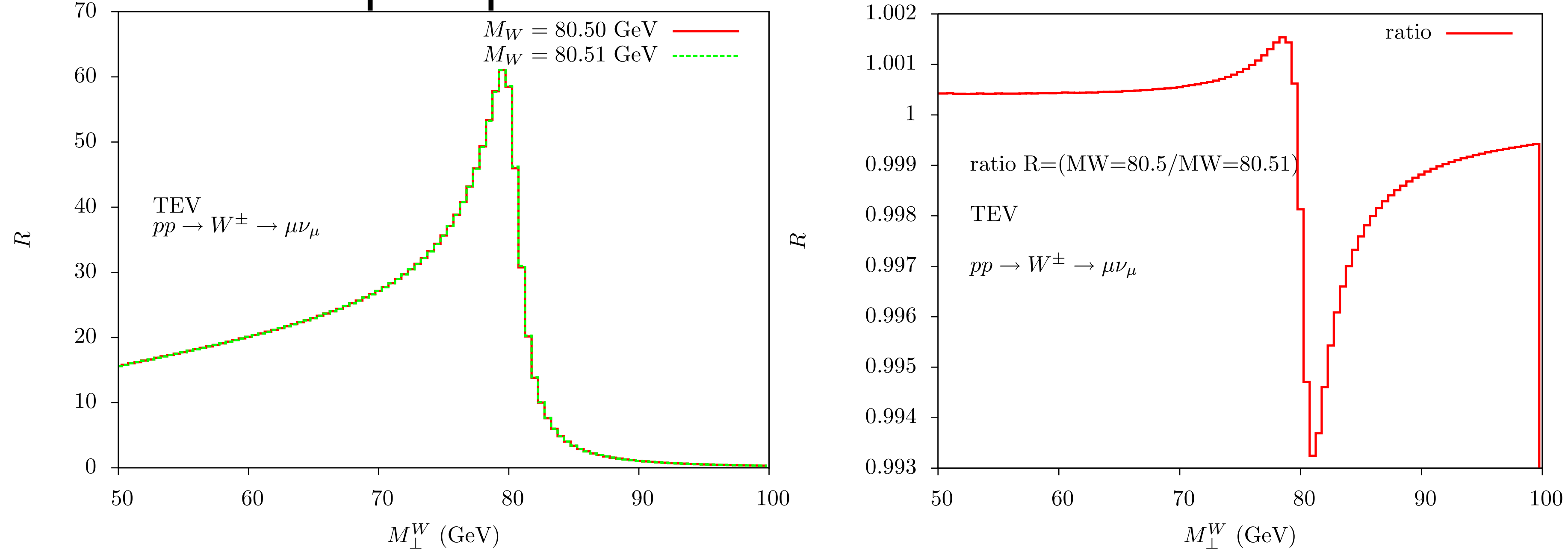


the ptW modelling strongly depends on the all-order treatment of the QCD corrections

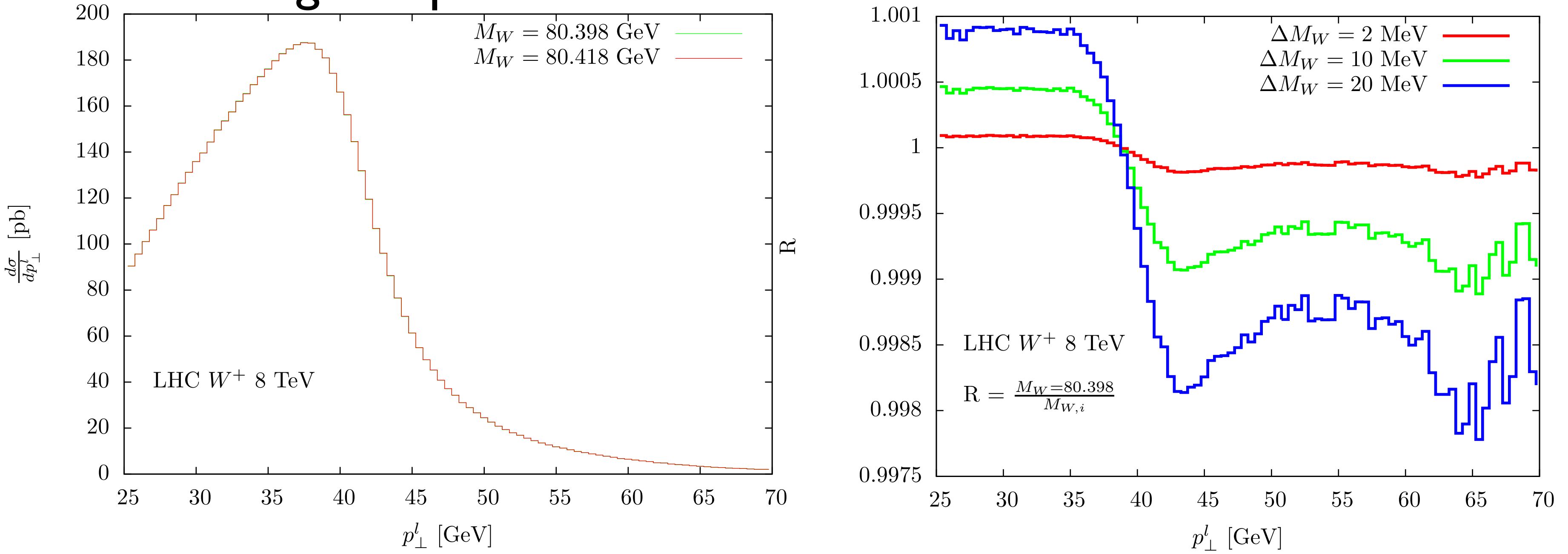
MW determination at hadron colliders: observables and techniques

- 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

lepton-pair transverse mass distribution

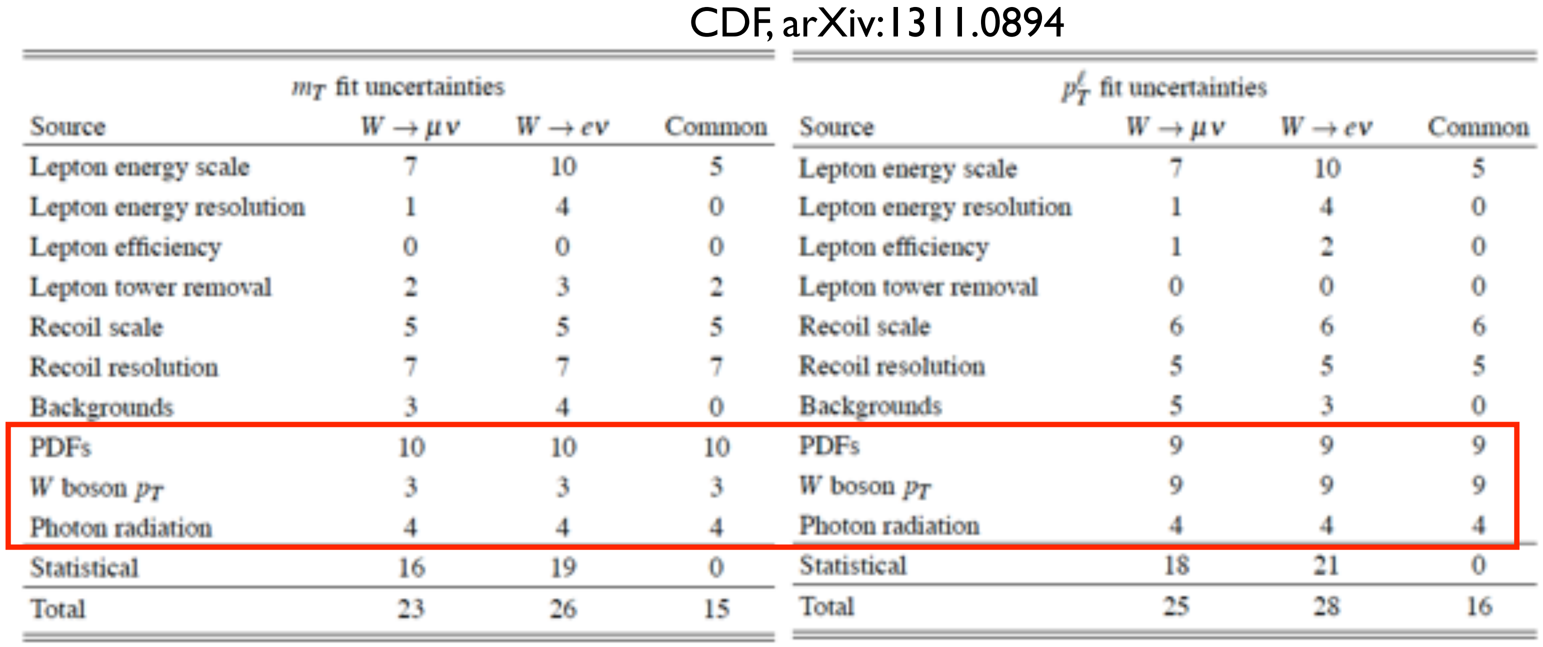


charged-lepton transverse momentum distribution



- Which corrections shall we need to keep under control?

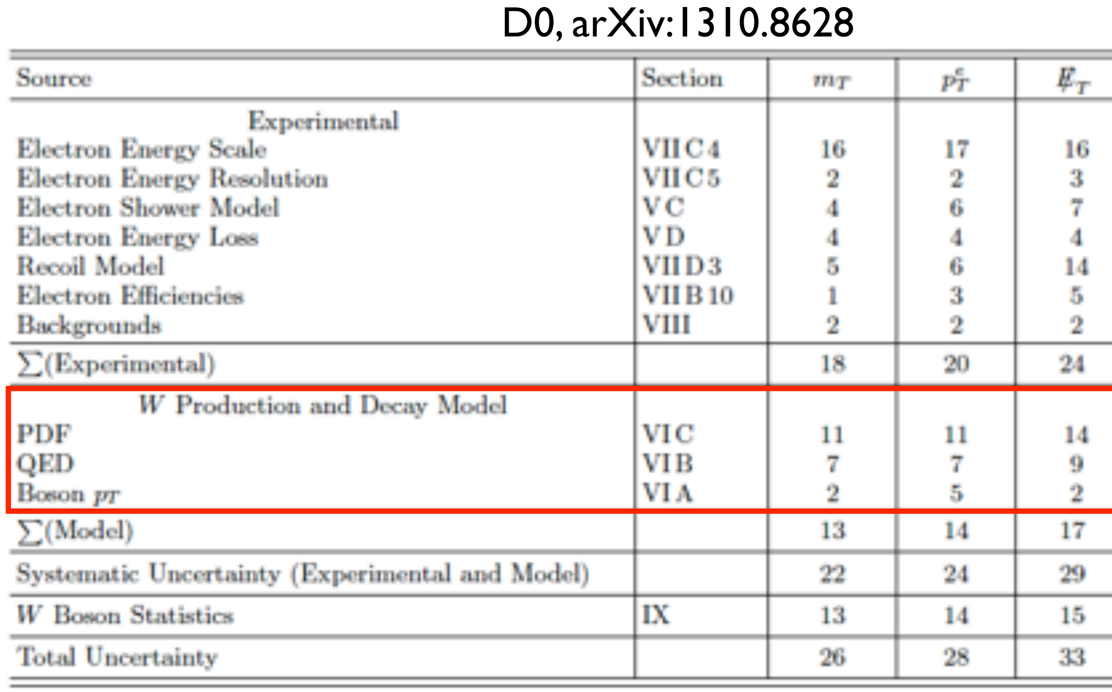
Breakdown of uncertainties on MW estimated by CFD and D0



CDF, 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



D0, arXiv:1310.8628

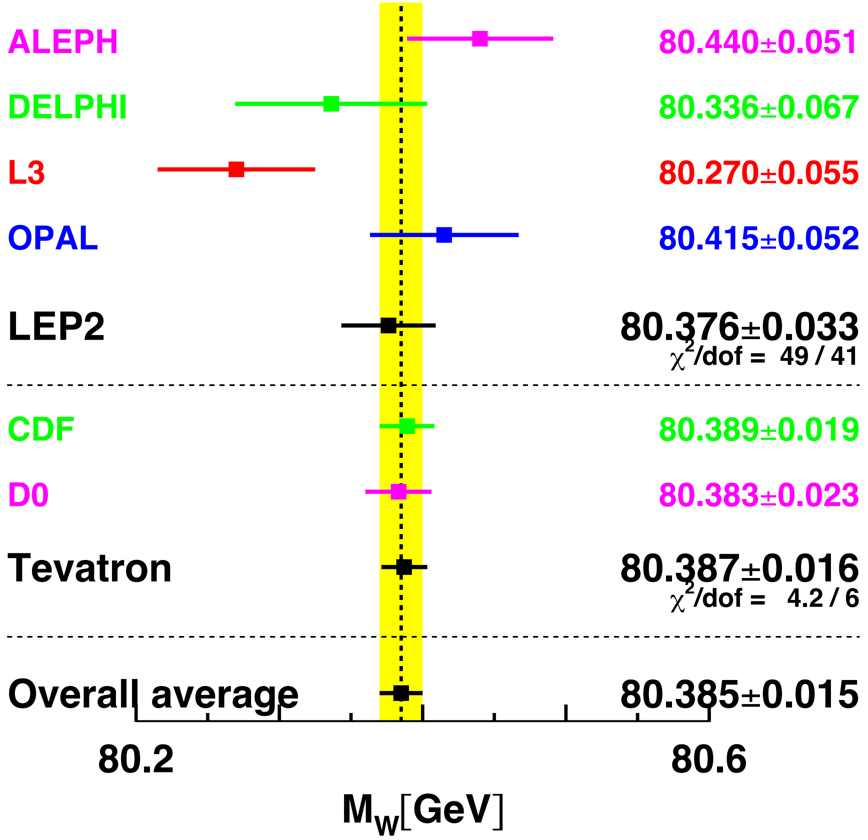
Source	Section	m_T	p_T^e	$\not{E}_T$
Experimental				
Electron Energy Scale	VII C 4	16	17	16
Electron Energy Resolution	VII C 5	2	2	3
Electron Shower Model	V C	4	6	7
Electron Energy Loss	V D	4	4	4
Recoil Model	VII D 3	5	6	14
Electron Efficiencies	VII B 10	1	3	5
Backgrounds	VIII	2	2	2
$\sum$(Experimental)		18	20	24
W Production and Decay Model				
PDF	VI C	11	11	14
QED	VI B	7	7	9
Boson p_T	VI A	2	5	2
$\sum$(Model)		13	14	17
Systematic Uncertainty (Experimental and Model)		22	24	29
W Boson Statistics	IX	13	14	15
Total Uncertainty		26	28	33

3 items of theoretical systematic uncertainty
are framed in red in the CDF and D0 tables

are weak effects relevant? do we need only QED?

perturbative QCD uncertainties are not quoted!

what is the correct procedure to evaluate
perturbative and non-perturbative QCD uncertainties?



Roadmap towards an estimate of the uncertainties on EW param’s

- Improve the calculation of exact matrix elements with higher order

  see talk by Di Vita

- Embed available matrix elements into Monte Carlo event generators

  see talk by Piccinini

- Estimate the size of available and missing higher orders

  see arXiv:1606.02330 for a systematic comparison of different available codes

- Consider in a global effort all the uncertainties of the description of the QCD environment

  still in progress

- Combine QCD-environment and perturbative uncertainties

Available codes compared in arXiv:1606.02330

- codes included in the study

DYNNLO, FEWZ,	NNLO-QCD
POWHEG,	(NLO+PS)-QCD
DYNNLOPS, SHERPA NNLO+PS,	(NNLO+PS)-QCD
RADY, SANC,	NLO-EW and NLO-QCD
PHOTOS,	QED-FSR
HORACE, WINHAC, WZGRAD,	NLO-EW,(NLO+PS)-EW
POWHEG BMNNP, POWHEG BMNNPV, POWHEG BW	(NLO+PS)-(QCD+EW)

- authors involved

S. Alioli[a1] , A.B. Arbuzov[a2 ,a3] , D.Yu. Bardin[a2] , L. Barz`e[a4] , C. Bernaciak[a5] , S.G. Bondarenko[a2,a3], C. Carloni Calame[a6], M. Chiesa[a4,a6], S. Dittmaier[a7], G. Ferrera[a8] , D. de Florian[a9 ,a10] , M. Grazzini[a11] , S. Ho¨che[a12] , A. Huss[a13] , S. Jadach[a14] , L.V. Kalinovskaya[a2] , A. Karlberg[a15] , F. Krauss[a16] , Y. Li[a17] , H. Martinez[a4,a6] , G. Montagna[a4,a6] , A. Mu¨ck[a18] , P. Nason[a19] , O. Nicrosini[a6] , F. Petriello[a20 ,a21] , F. Piccinini[a6] , W. Placzek[a22] , S. Prestel[a12] , E. Re[a23] , A.A. Sapronov[a2] , M. Sch¨onherr[a13] , C. Schwinn[a7] , A. Vicini[a8] , D. Wackeroth[a5 ,a24] , Z. Was[a14], G. Zanderighi[a1]

- repository with the codes (or links) and instructions to run them to reproduce the benchmarks

https://twiki.cern.ch/twiki/bin/view/Main/DrellYanComparison

Comments on the assessment of the theoretical uncertainty

- several higher-order effects which are available to DY observables
  have been classified in arXiv:1606.02330
  they are not an uncertainty,
  they should be either added in the simulations or quoted in the theoretical systematic error
  e.g. at $O(\alpha^2)$ additional lepton-pair production

- all the missing higher orders which are not available can only be guessed
  the estimate is observable dependent
  - for observables stable under the inclusion of radiative effects (rapidity, invariant/transverse mass)
    the QCD uncertainty can be studied e.g. with canonical scale variations
    the propagation to mixed QCDxEW corrections should be safely stable

  - for observables sensitive to radiative effects it is necessary to use matched calculations
    → the QCD uncertainty should account also for the matching uncertainty
    → careful extrapolation from purely EW estimates to QCDxEW estimates
    e.g lepton-pair production effect on the lepton ptl distribution in presence of QCD

Impact of EW corrections on the MW determination

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, in preparation

	Templates accuracy: LO	M_W shifts (MeV)			
		$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$	
	Pseudodata accuracy	M_T	p_T^ℓ	M_T	p_T^ℓ
1	HORACE only FSR-LL at $\mathcal{O}(\alpha)$	-94±1	-104±1	-204±1	-230±2
2	HORACE FSR-LL	-89±1	-97±1	-179±1	-195±1
3	HORACE NLO-EW with QED shower	-90±1	-94±1	-177±1	-190±2
4	HORACE FSR-LL + Pairs	-94±1	-102±1	-182±2	-199±1
5	PHOTOS FSR-LL	-92±1	-100±2	-182±1	-199±2

estimate of shifts based on a template fit approach

1 · the first final state photon dominates the correction on MW

2 · multiple photon radiation has still a sizeable O(-10%) effect

3 · subleading QED and weak effects are negligible, O(1-2 MeV)

4 · additional pair production is not negligible, with a shift ranging from 3 to 5 MeV

5 · the agreement between PHOTOS and HORACE QED-PS is acceptable, given the subleading differences of the two implementations

Comments on the assessment of the theoretical uncertainty

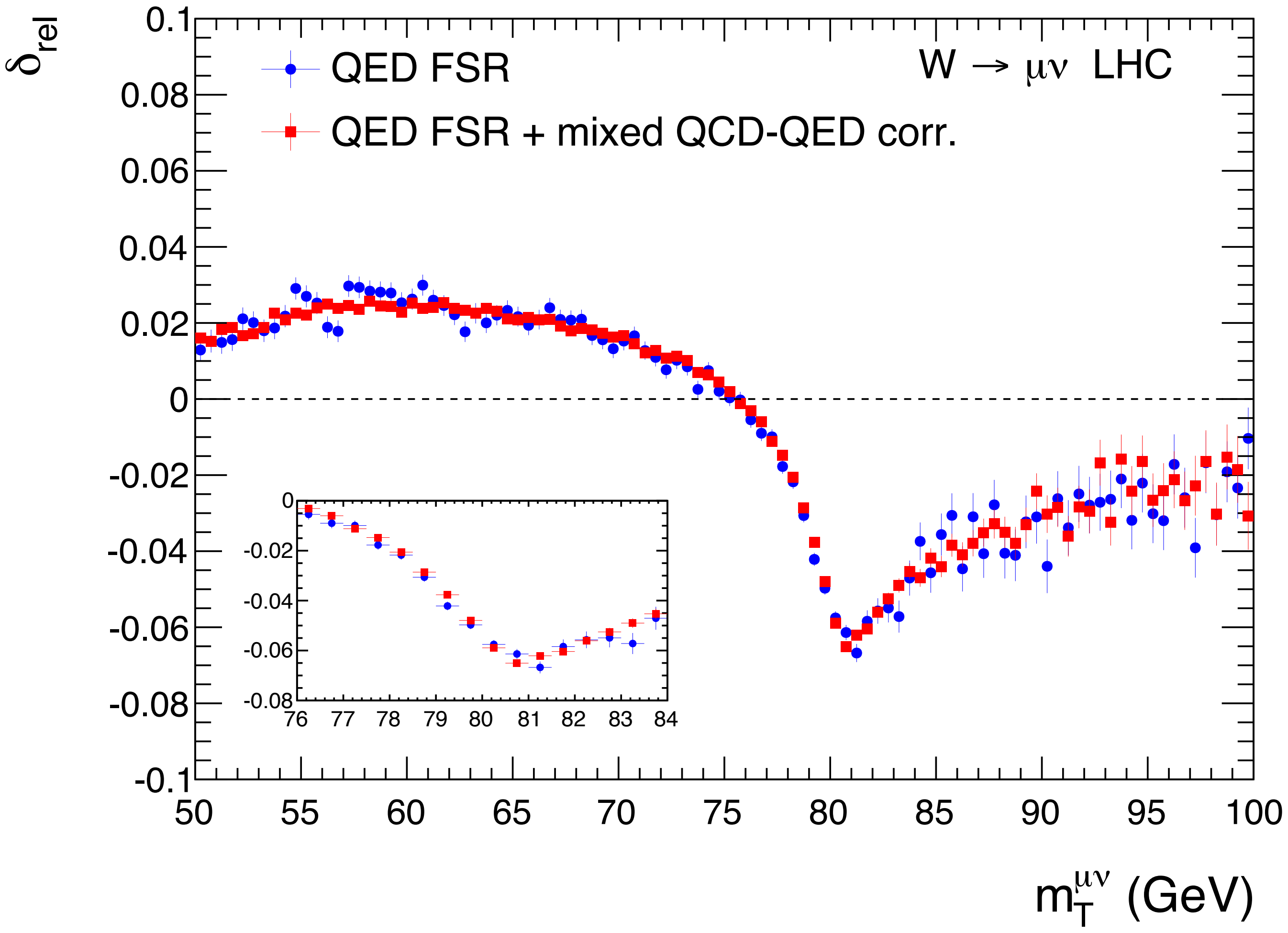
- several higher-order effects which are available to DY observables
  have been classified in arXiv:1606.02330
  they are not an uncertainty,
  they should be either added in the simulations or quoted in the theoretical systematic error
    e.g. at $O(\alpha^2)$ additional lepton-pair production

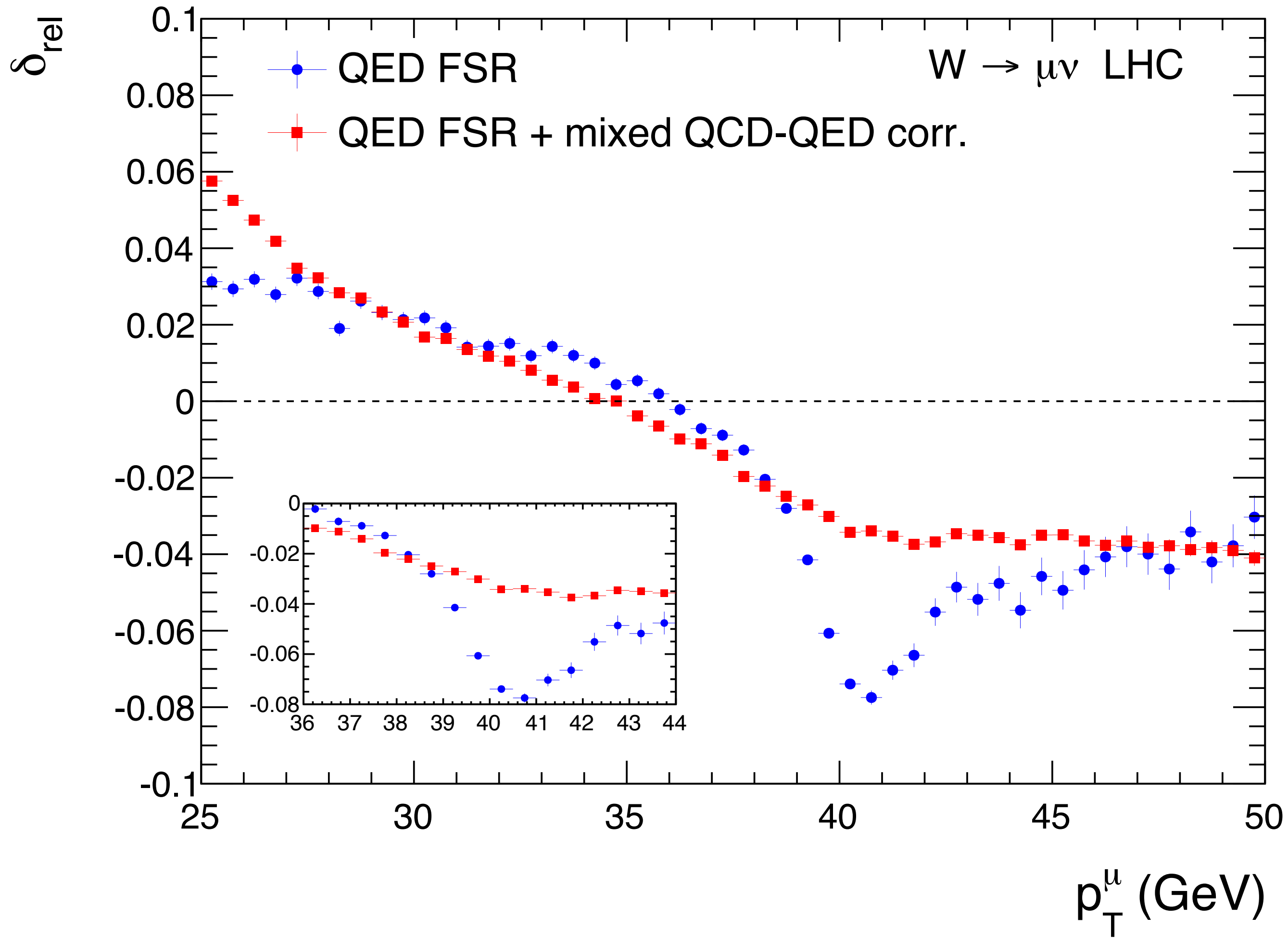
- all the missing higher orders which are not available can only be guessed
  the estimate is observable dependent
    - for observables stable under the inclusion of radiative effects (rapidity, invariant/transverse mass)
      the QCD uncertainty can be studied e.g. with canonical scale variations
      the propagation to mixed QCDxEW corrections should be safely stable

    - for observables sensitive to radiative effects it is necessary to use matched calculations
      → the QCD uncertainty should account also for the matching uncertainty
      → careful extrapolation from purely EW estimates to QCDxEW estimates
        e.g lepton-pair production effect on the lepton ptl distribution in presence of QCD

Combination of QCD and EW corrections: POWHEG results

Do QCD corrections preserve the QED effects ?





the difference between red and blue is due to mixed QCDxQED terms

(these effects are already taken into account in the Tevatron and LHC analyses)

One remark on POWHEG

- POWHEG NLO-(QCD+EW)
  - it has NLO-(QCD+EW) accuracy on the total cross section
  - it describes with exact matrix elements the hardest parton (gluon, quark, photon) emission
  - it includes to all orders QCD and QED effects via Parton Shower

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \left\{ \Delta^{f_b}(\mathbf{\Phi}_n, p_T^{min}) + \sum_{\alpha_r\in\{\alpha_r|f_b\}} \frac{\left[d\Phi_{rad}\,\theta(k_T-p_T^{min})\,\Delta^{f_b}(\mathbf{\Phi}_n,k_T)\,R(\mathbf{\Phi}_{n+1})\right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r}=\mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \right\}$$

the virtual QCD and EW corrections (and the integral over radiation of the real corrections)

are included in the Bbar function, factored in front of the curly bracket

contribute to the correct NLO normalisation of the distributions independently of the number of additional partons

have a minor role when we consider the shape of the distributions

this structure differs with respect to fixed-order calculations (additive formulation)

where virtual corrections modify

the contribution only of the lowest multiplicity cross section (no additional partons)

and in turn the shape of the distributions

Comments on the QCD uncertainties

- The MW determination requires not only the fit of CC-DY observables
  but also, for calibration purposes, several ancillary measurements of NC-DY quantities like e.g.
  - lepton-pair invariant mass ($M_{\ell\ell}$) and rapidity distribution, …
  - transverse momentum (ptZ)

  These additional observables form a more constrained system,
  with more information and possibly with reduced uncertainties

- A QCD uncertainty on MW is present
  because our templates are computed at finite order in perturbation theory.

  It has to be estimated including all the CC and NC observables involved in the fit

- The QCD scales (renormalisation, factorisation, resummation) have no physical meaning
  (the exact result is independent of them) and can not be measured.

  A convenient choice of the QCD scales may optimise the χ^2 of the global fit
  can not remove the QCD uncertainty

Comments on the QCD uncertainties

- The QCD uncertainty is due to a list of partially entangled factors:
  - pQCD scales (renormalization, factorisation, resummation)
  - matching uncertainty (POWHEG vs MC@NLO vs SHERPA; DYNNLOPS vs UN2LOPS)
  - size of non-perturbative transverse momentum contributions, Parton Shower tune
  - collinear PDF uncertainty (entering also in the Parton Shower tune)
  - initial state heavy quarks treatment

- A variation of each of these parameters in the CC-DY observables alone
  may lead to an overestimate of the uncertainty on MW
  → the inclusion of the NC DY "ancillary" calibration observables
  is needed to perform a consistent estimate of the uncertainty (?)

we are fitting all these observables in the same model:
some choices have to be consistent
(e.g. if we used a given PDF replica in NC-DY, we should use the same in CC-DY simulation)
other choices are less constrained (e.g. pQCD scales in CC-DY and NC-DY)
the correlation (if any) of the observables reduces the uncertainty on the MW determination
(ratios W/Z, Giele, Keller, hep-ph/9704419)

→ the inclusion of more DY observables (CC and NC)
may help to further constrain the system:
e.g. the role of a MW measurement from ptl at LHCb to reduce the PDF uncertainty

Questions

- Should we clearly state that the MW measurement is a global fit of several observables, (MT(W), ptlep(W), ptlep(Z),pt(Z),Y_Z, …) with MW as fit parameter and a global χ^2?

- How sensitive is the result for MW e.g. to a "mismodeling" of the data (e.g. ptZ)?

- Can a proper treatment of correlations (cfr. formulation of QCD uncertainties) between the different DY observables reduce the sensitivity of MW to the "mismodeling" ?

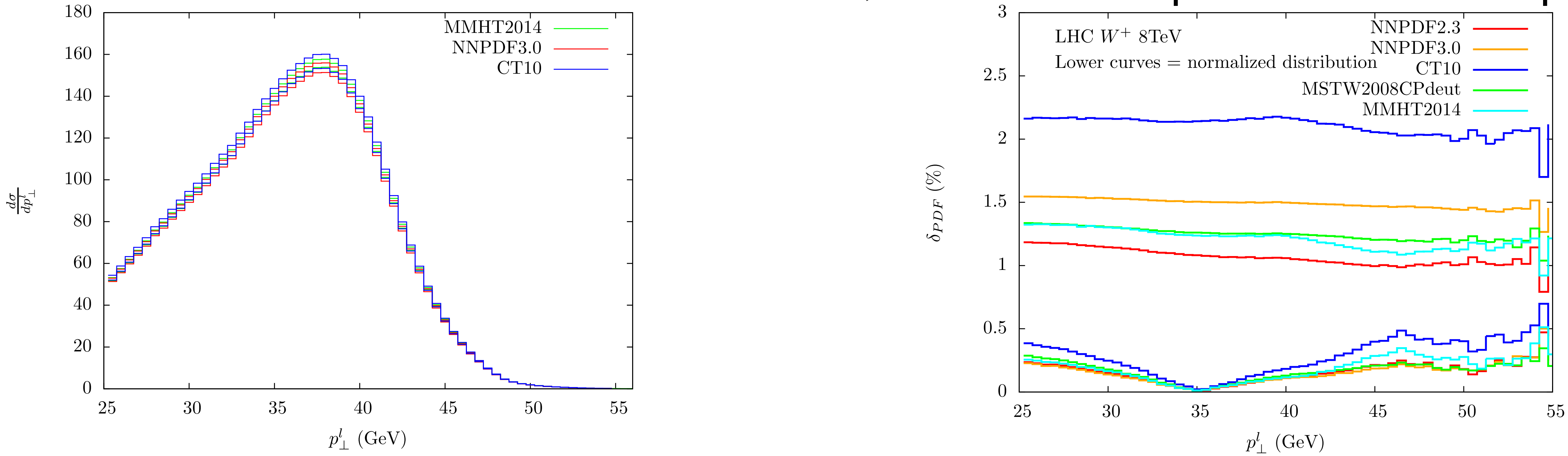
  (the presence of the "mismodeling" would be signalled by a bad χ^2)

  Can we reduce the MW dependence on QCD contributions at low pt?

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 6.4, different PDF replicas are treated as pseudodata



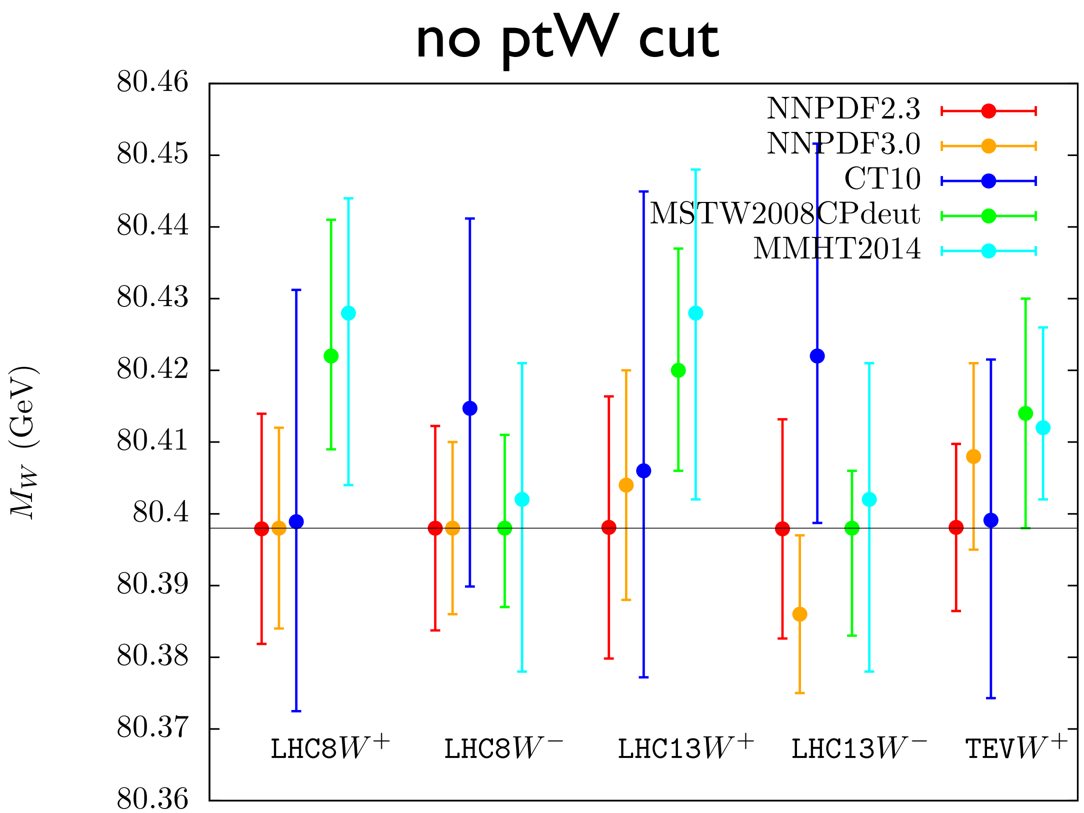
- The PDF uncertainty over the relevant ptl range is almost flat, of O(2%)
  the normalized distributions have an uncertainty below the O(0.5%) level,
  still sufficient to yield large MW shifts

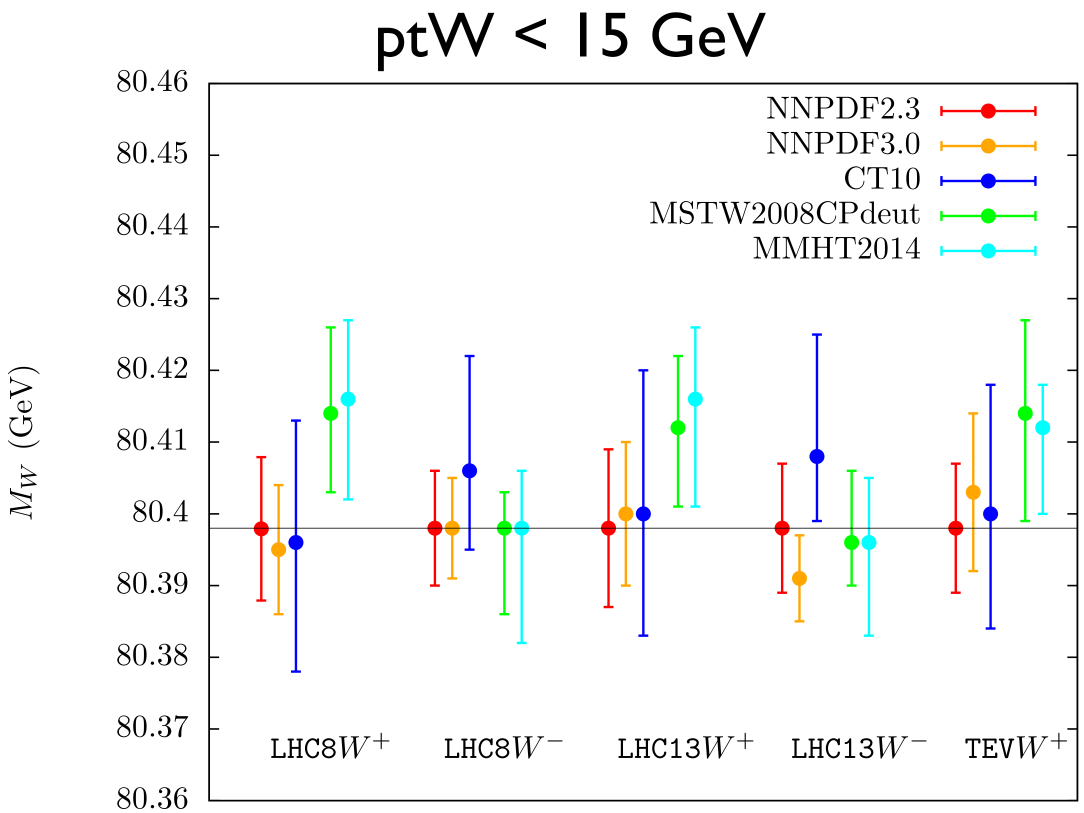
- Given a reference PDF set (NNPDF2.3 replica 0)
  we estimate which would be the difference in the fit of the data
  if we would use a different PDF replica in the preparation of the templates

We combine the resulting MW values according to the prescriptions of the different groups

PDF uncertainty affecting MW extracted from the ptlep distribution

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


no ptW cut


ptW < 15 GeV

	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}

- Modern individual PDF sets provide not-pessimistic estimates , ΔMW ~ O(10 MeV), but the global envelope still shows large discrepancies of the central values

- The Tevatron analyses did not adopt the PDF4LHC approach

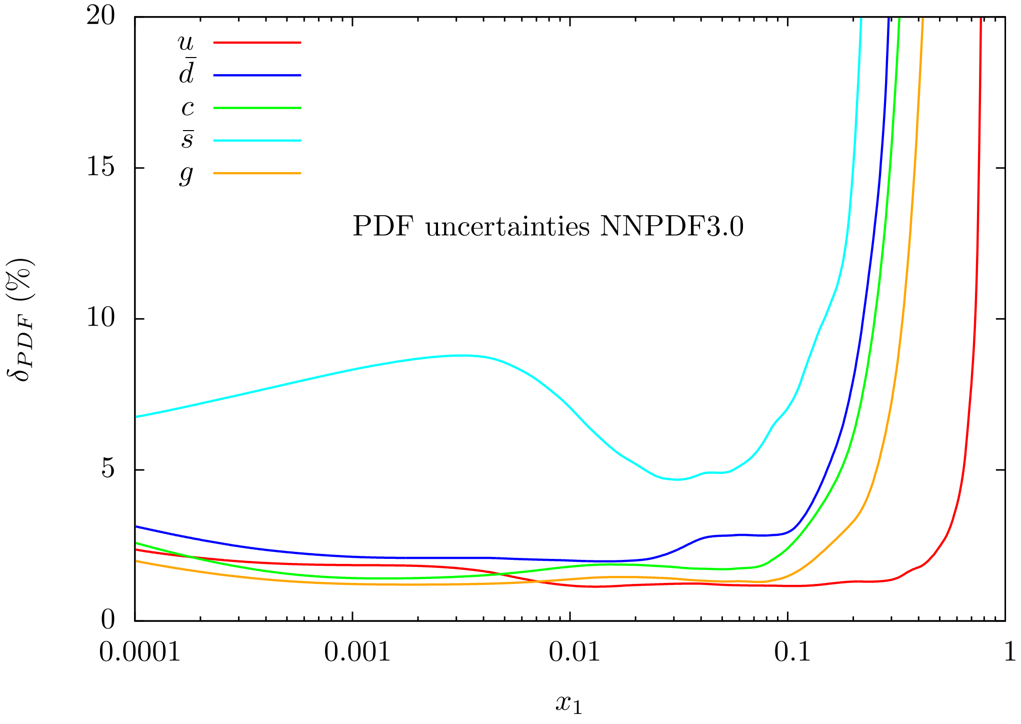
- Conservative analysis (only CC-DY values have been included)

PDF uncertainty affecting MW and acceptance cuts

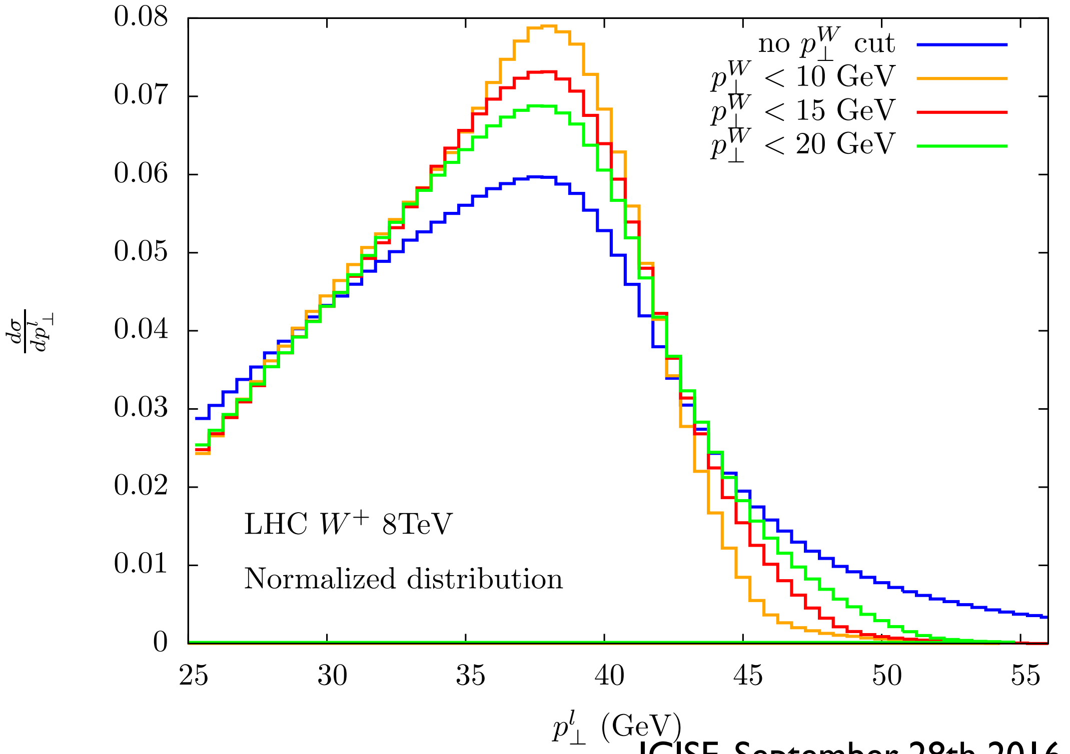
G.Bozzi, L.Citelli, AV, arXiv:1501.05587

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

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



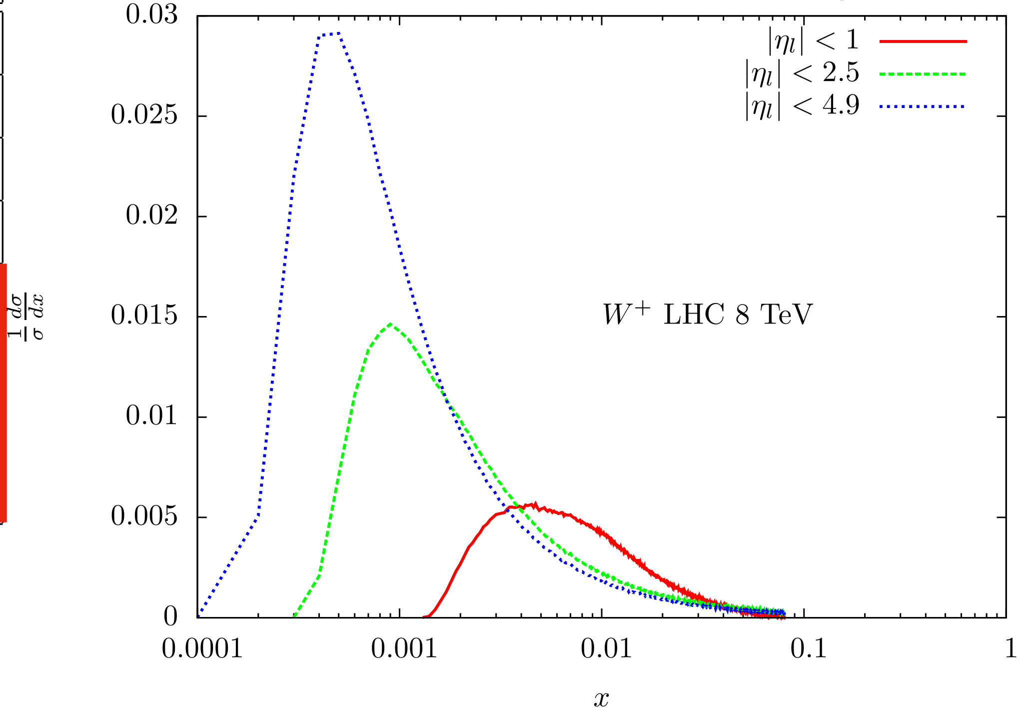
PDF uncertainty affecting MW and acceptance cuts

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

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

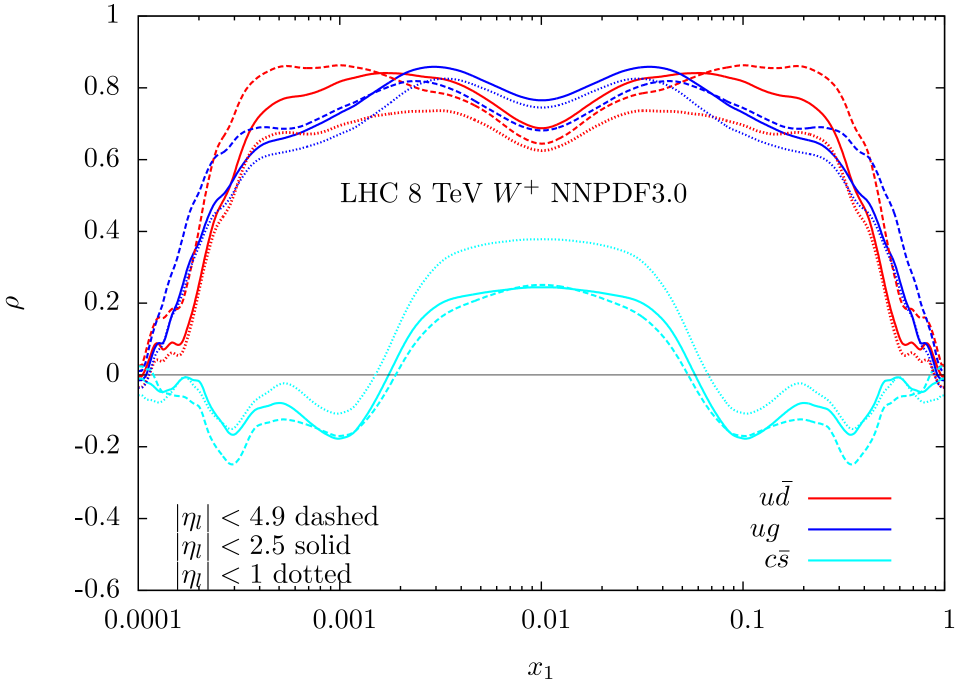
normalized distributions			
cut on $p_\perp^W$	cut on $\lvert\eta_l\rvert$	CT10	NNPDF3.0
inclusive	$\lvert\eta_l\rvert < 2.5$	$80.400 + 0.032 - 0.027$	80.398 ± 0.014
$p_\perp^W < 20$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.027 - 0.020$	80.394 ± 0.012
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.017 - 0.018$	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
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.017 - 0.018$	80.395 ± 0.009
$p_\perp^W < 15$ 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

normalized cross section differential in partonic x



- 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 rapidity region is the most uncertain
  - PDF sum rules →
    non trivial compensations between different rapidity intervals among different flavors

correlation of parton-parton luminosities with the ptl bin 40.5 GeV



Summary

- Estimating the theoretical uncertainties plays a crucial role in the comparison between theoretical predictions and experimental data for precision EW observables

- A clear definition of the procedure to estimate the QCD uncertainty on the MW determination (i.e. in a global fit of several observables) can provide guidelines to extract EW parameters from hadron collider observables

Back-up slides

Report on precision calculations for DY   Alioli et al, arXiv:1606.02330

- modern MC event generators are complex tools,
  their results out-of-the-box should be checked before starting any analysis
  → first goal of the report: provide a set of benchmark results computed by the authors of the codes

- the relevance of different available higher-order corrections can be appreciated only in a systematic classification framework, with a common unit that allows a sensible comparison
  → second goal of the report: higher-order corrections expressed as percentage corrections
  using (N)NLO results as unit

- combination of (fixed- and all-orders) QCD and EW corrections
  → third goal of the report: discussion of some available analytical and MC results

- the residual theoretical uncertainty is a complex topic, observable dependent;
  the report does not make an assessment of the uncertainty
  but provides some examples useful to spot the dominant sources of ambiguity

Master Integrals for the evaluation of DY processes at $O(\alpha\alpha_s)$

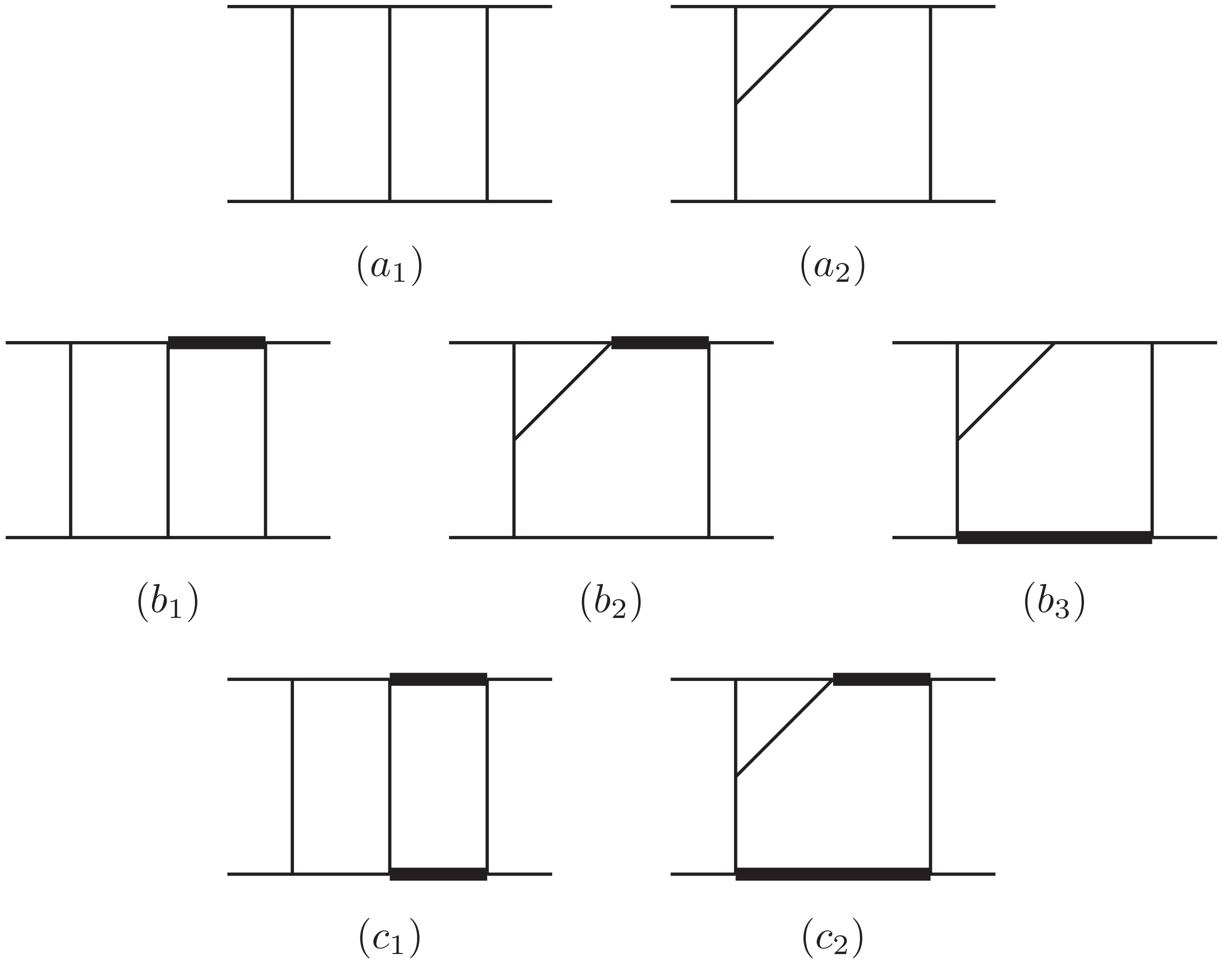
R. Bonciani, S. Di Vita, P. Mastrolia, U. Schubert, arXiv:1604.08581

thin lines   massless
thick lines   massive
topologies **b** and **c** were not known

2 masses topologies evaluated with the same mass

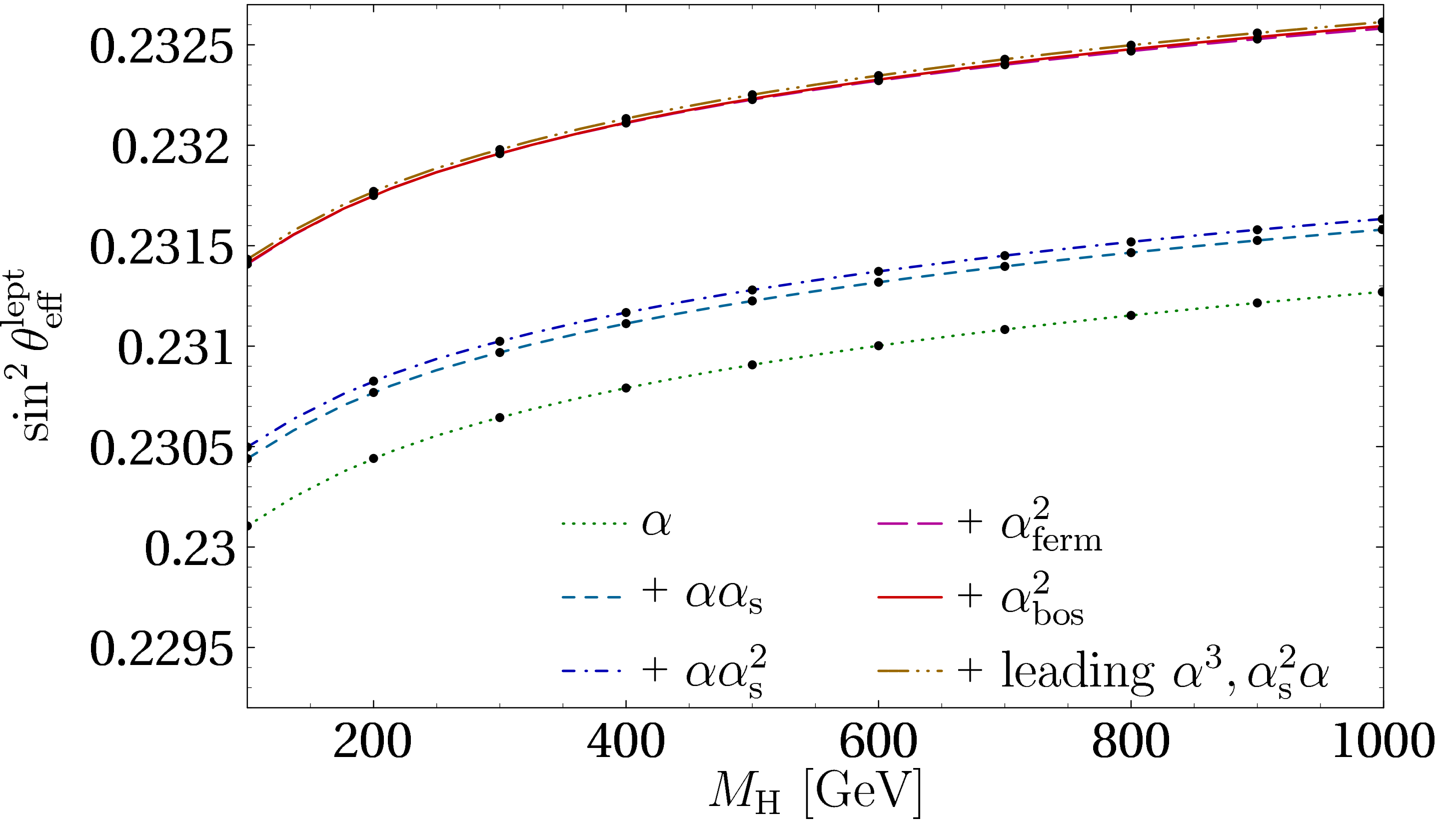
SM results, where both W and Z appear,
can be evaluated with an expansion in ΔM=MZ-MW

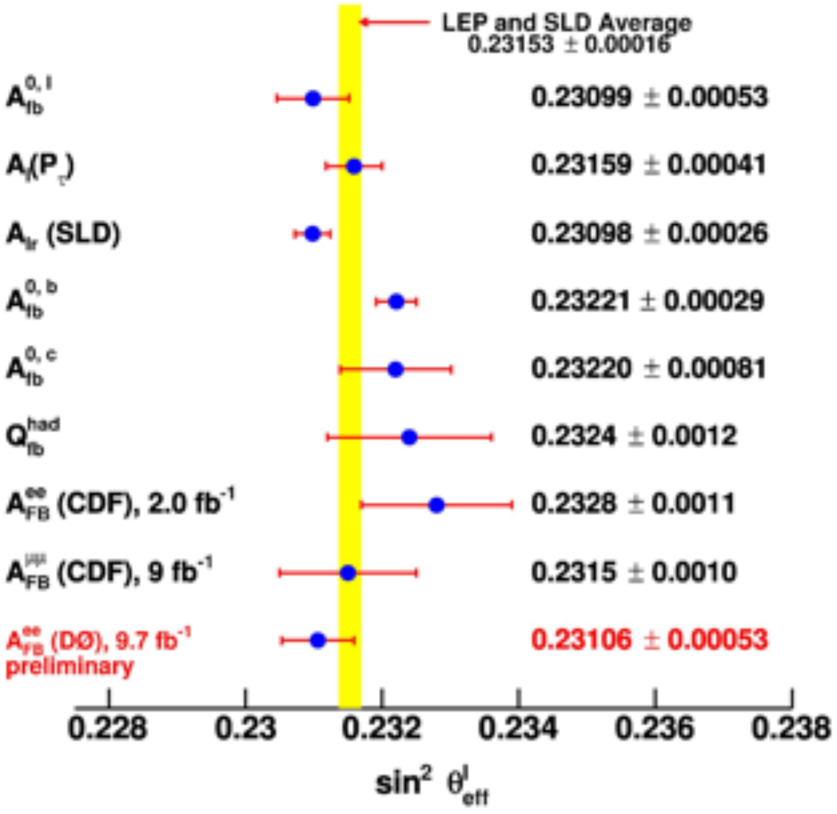
49 MI identified (8 massless, 24 1-mass, 17 2-masses)
solution of differential equations expressed in terms of
iterated integrals (mixed Chen-Goncharov representation)



The weak mixing angle: prediction, parametric unc. and BSM tests

M.Awramik, M. Czakon, A. Freytas, arXiv:hep-ph/0608099





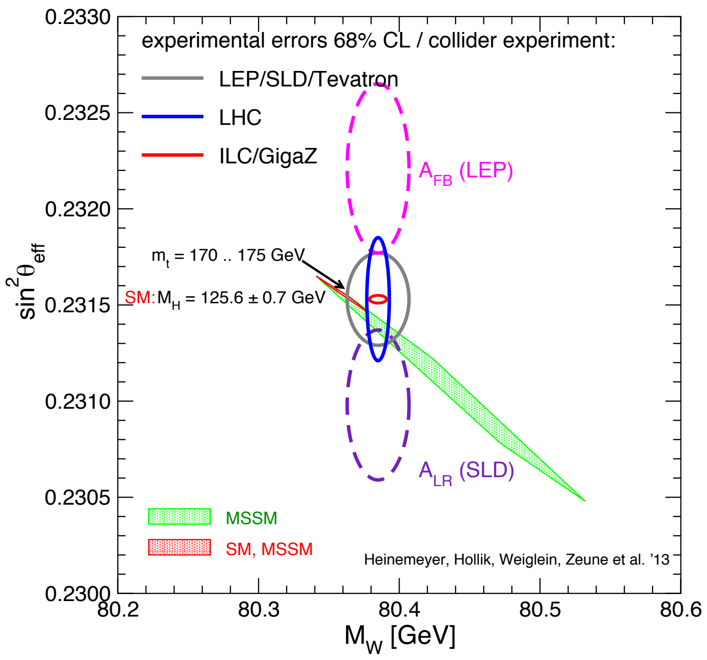
$\sin^2\theta_{\mathrm{eff}}$ varies with mtop: Δmt=+1 GeV → Δ $\sin^2\theta_{\mathrm{eff}}$ = + 3.1 10^{-5}

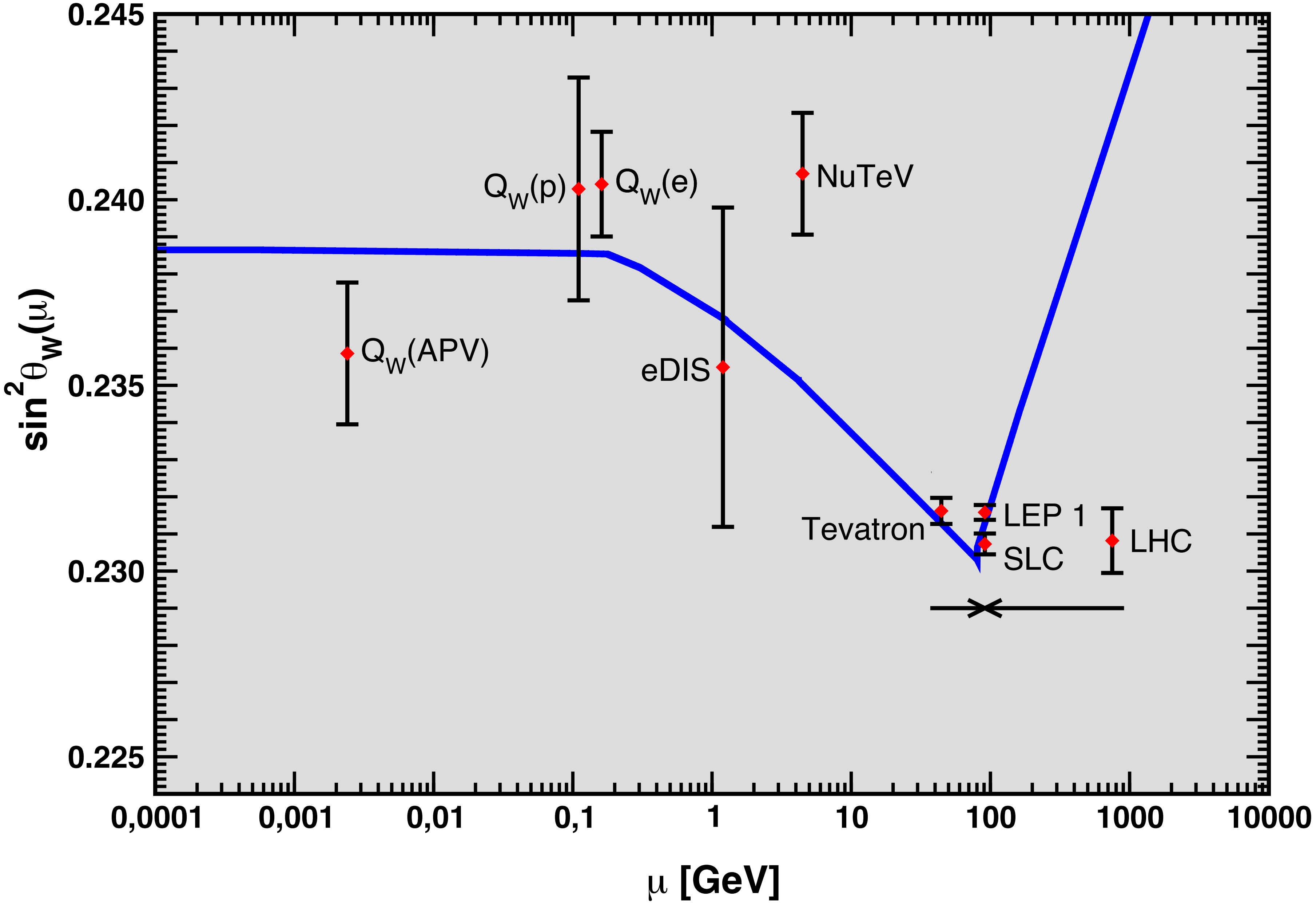
with $\Delta\alpha_{\mathrm{had}}$(MZ): $\Delta\alpha_{\mathrm{had}}$(MZ)=+0.0003 → Δ $\sin^2\theta_{\mathrm{eff}}$ = +10.4 10^{-5}

$$\sin^2\theta_{\mathrm{eff}}^f = s_0 + d_1 L_H + d_2 L_H^2 + d_3 L_H^4 + d_4(\Delta_H^2 - 1) + d_5\Delta_\alpha \\ + d_6\Delta_t + d_7\Delta_t^2 + d_8\Delta_t(\Delta_H - 1) + d_9\Delta_{\alpha_s} + d_{10}\Delta_Z$$

$$L_H = \log\left(\frac{M_H}{100\ \mathrm{GeV}}\right), \quad \Delta_H = \frac{M_H}{100\ \mathrm{GeV}}, \quad \Delta_\alpha = \frac{\Delta\alpha}{0.05907} - 1,$$

$$\Delta_t = \left(\frac{m_t}{178.0\ \mathrm{GeV}}\right)^2 - 1, \quad \Delta_{\alpha_s} = \frac{\alpha_s(M_Z)}{0.117} - 1, \quad \Delta_Z = \frac{M_Z}{91.1876\ \mathrm{GeV}} - 1.$$




0.245
0.240
0.235
0.230
0.225
$\sin^2\theta_W(\mu)$
0,0001
0,001
0,01
0,1
1
10
100
1000
10000
μ [GeV]
Q_W(p)
Q_W(e)
NuTeV
Q_W(APV)
eDIS
Tevatron
LEP 1
SLC
LHC

(Erler)

A_{FB} in neutral current Drell-Yan and the measurement of $\sin^2\theta_W$

$$A_{FB}(M_{l^+l^-}) = \frac{F(M_{l^+l^-}) - B(M_{l^+l^-})}{F(M_{l^+l^-}) + B(M_{l^+l^-})}$$

$$F(M_{l^+l^-}) = \int_0^1 \frac{d\sigma}{d\cos\theta^*} d\cos\theta^* \qquad B(M_{l^+l^-}) = \int_{-1}^0 \frac{d\sigma}{d\cos\theta^*} d\cos\theta^*$$

$$\cos\theta^* = f \frac{2}{M(l^+l^-)\sqrt{M^2(l^+l^-) + p_t^2(l^+l^-)}} [p^+(l^-)p^-(l+) - p^-(l^-)p^+(l^+)]$$

$$p^\pm = \frac{1}{\sqrt{2}}(E \pm p_z) \qquad f = \frac{|p_z(l^+l^-)|}{p_z(l^+l^-)}$$

- At $Y_Z = 0,\ A_{FB}$ is exactly zero: LHC is a symmetric collider (pp) and the asymmetry of q-qbar and qbar-q initiated processes cancels

- At large Y_Z , the different weight of q-qbar and qbar-q initiated processes leaves a residual asymmetry: the larger Y_Z , the more pronounced A_{FB}

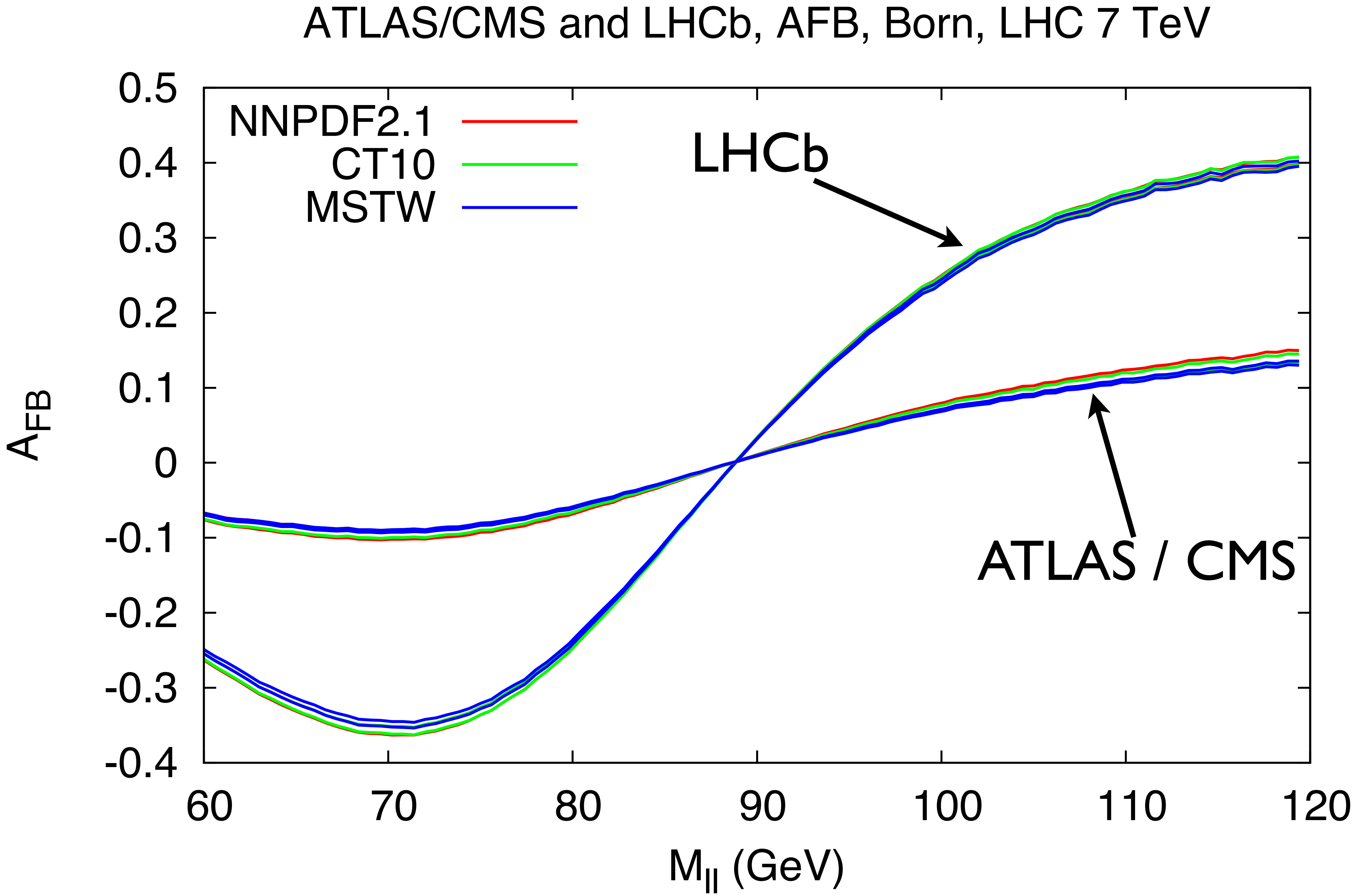
- The asymmetry is due to the difference between valence and sea components of the quark densities

→ the asymmetry is larger in the LHCb acceptance region

A_{FB} at ATLAS/CMS and at LHCb

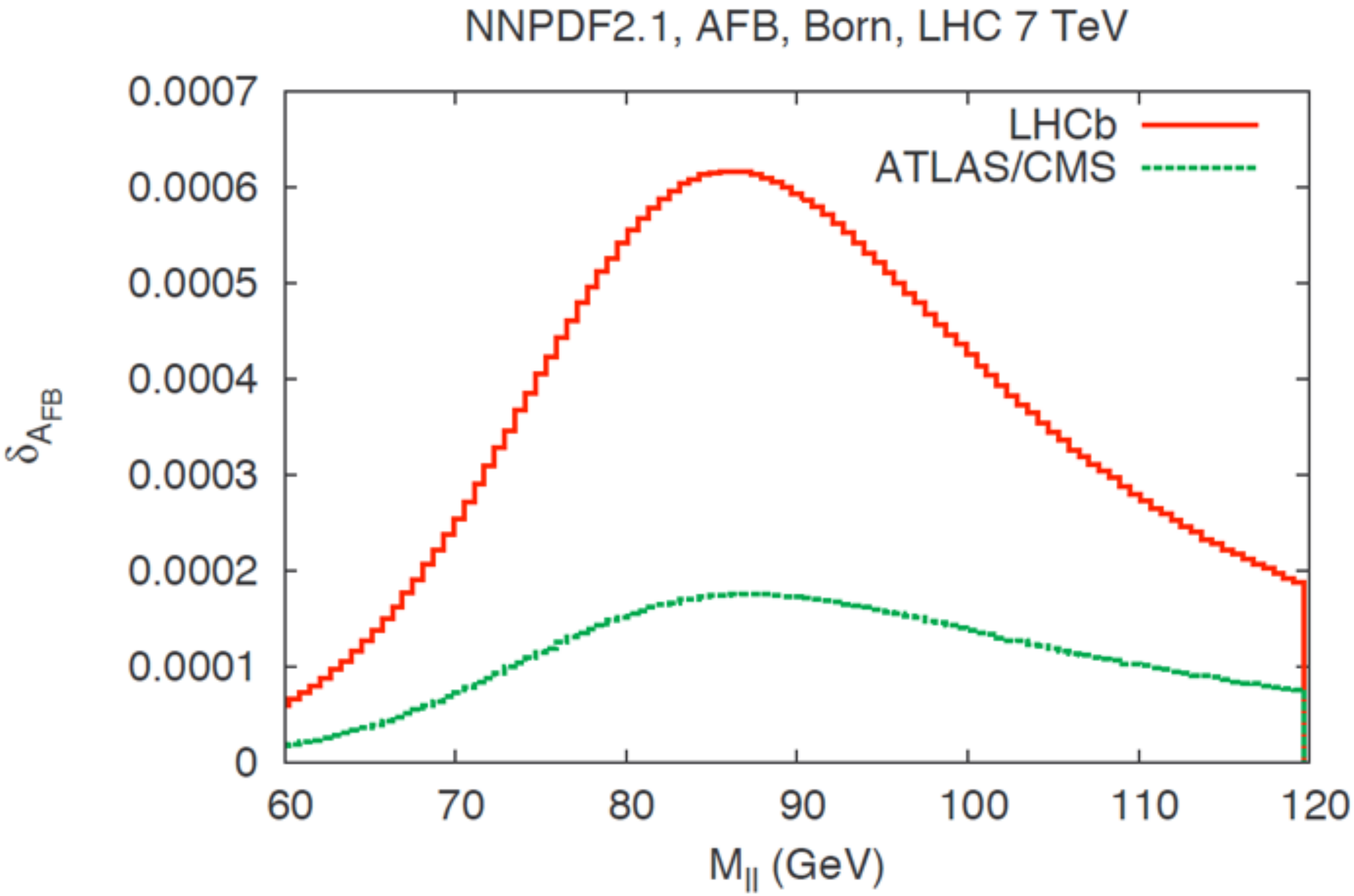
acceptance cuts: $p_\perp^l > 25\,\mathrm{GeV}$

ATLAS / CMS $|\eta_l| < 2.5$
LHCb $2.0 < \eta_l < 4.5$



stronger asymmetry at LHCb
the asymmetry vanishes for $M_{ll} \simeq 88.5\,\mathrm{GeV}$
region of maximal sensitivity to $\sin^2\theta_W$ around MZ, i.e. where A_{FB} is still small

Sensitivity of A_{FB} to a variation of $\sin^2\theta_W$



$$\delta A_{FB} = A_{FB}(\sin^2\theta_W + \delta\sin^2\theta_W) - A_{FB}(\sin^2\theta_W - \delta\sin^2\theta_W)$$

$$\delta\sin^2\theta_W = 0.0001$$

best PDG value $\sin^2\theta_{eff}^{lep} = 0.23146 \pm 0.00012$

can we measure A_{FB} with an accuracy of few parts in 10^{-4} , to extract $\sin^2\theta_W$?

Available simulation tools (partial list)

- analytic resummation of log(ptV/MV) with NNLL accuracy: ResBos arXiv:hep-ph/9704258
  with NNLO-QCD + NNLL accuracy DYRes arXiv:1507.06937

- event generator with NLO-QCD + QCD-PS: POWHEG arXiv:0805.4802
  MC@NLO arXiv:hep-ph/0204244

- event generator with NNLO-QCD + QCD-PS accuracy: DYNNLOPS arXiv:1407.2940
  SHERPA@NNLO with UN^{2}LOPS
  arXiv:1405.3607

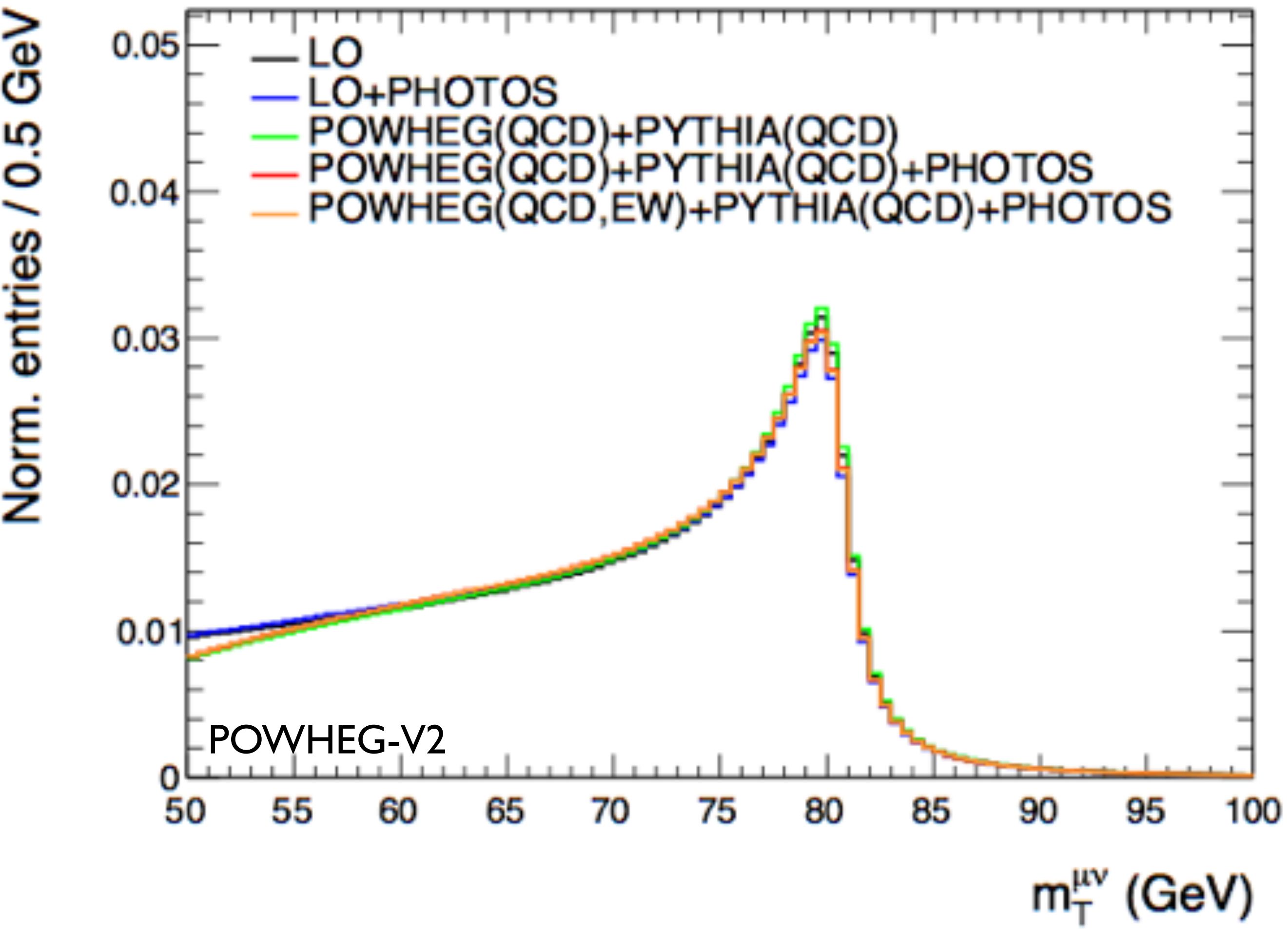
- QED FSR multiple photon description: Photos Comput.Phys.Commun. 79 (1994) 291-308
  HORACE 1.0 hep-ph/0303102, hep-ph/0502218
  PYTHIA QED arXiv:0710.3820

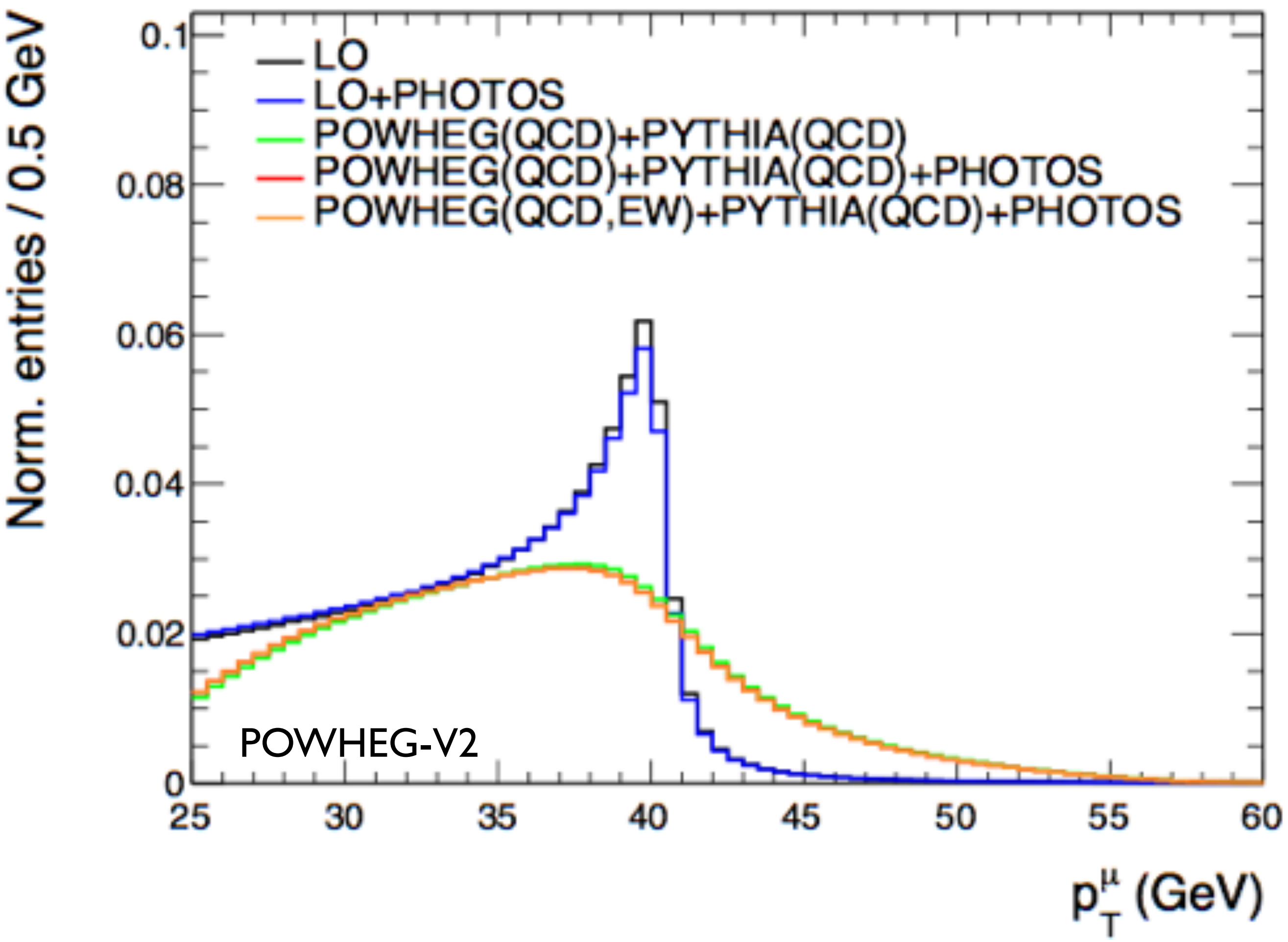
- NLO-EW corrections : WZGRAD hep-ph/9807417, hep-ph/0108274
  RADY hep-ph/0109062, arXiv:0911.2322
  SANC arXiv:hep-ph/0506110 , arXiv:0711.0625

- event generator with NLO-EW + QED-PS: HORACE 3.1 hep-ph/0609170, arXiv:0710.1722

- event generator with NLO-(QCD+EW) + (QCD+QED)-PS: POWHEG arXiv:1201.4804,
  arXiv:1202.0465, arXiv:1302.4606

Combination of QCD and EW corrections: POWHEG results





- LO vs LO+PHOTOS shows the bulk of FSR-QED effect, the LO shape is preserved

- POWHEG(QCD)+PYTHIA(QCD) shows the huge impact of QCD corrections on the lepton pt
  mild W MT

- POWHEG(QCD)+PYTHIA(QCD)+PHOTOS shows the impact of i) QED-FSR
  ii) mixed QCDxQED terms
  on top of the pure QCD description

- POWHEG(QCD,EW)+PYTHIA(QCD)+PHOTOS adds subdominant QED/EW terms
  absent in PHOTOS

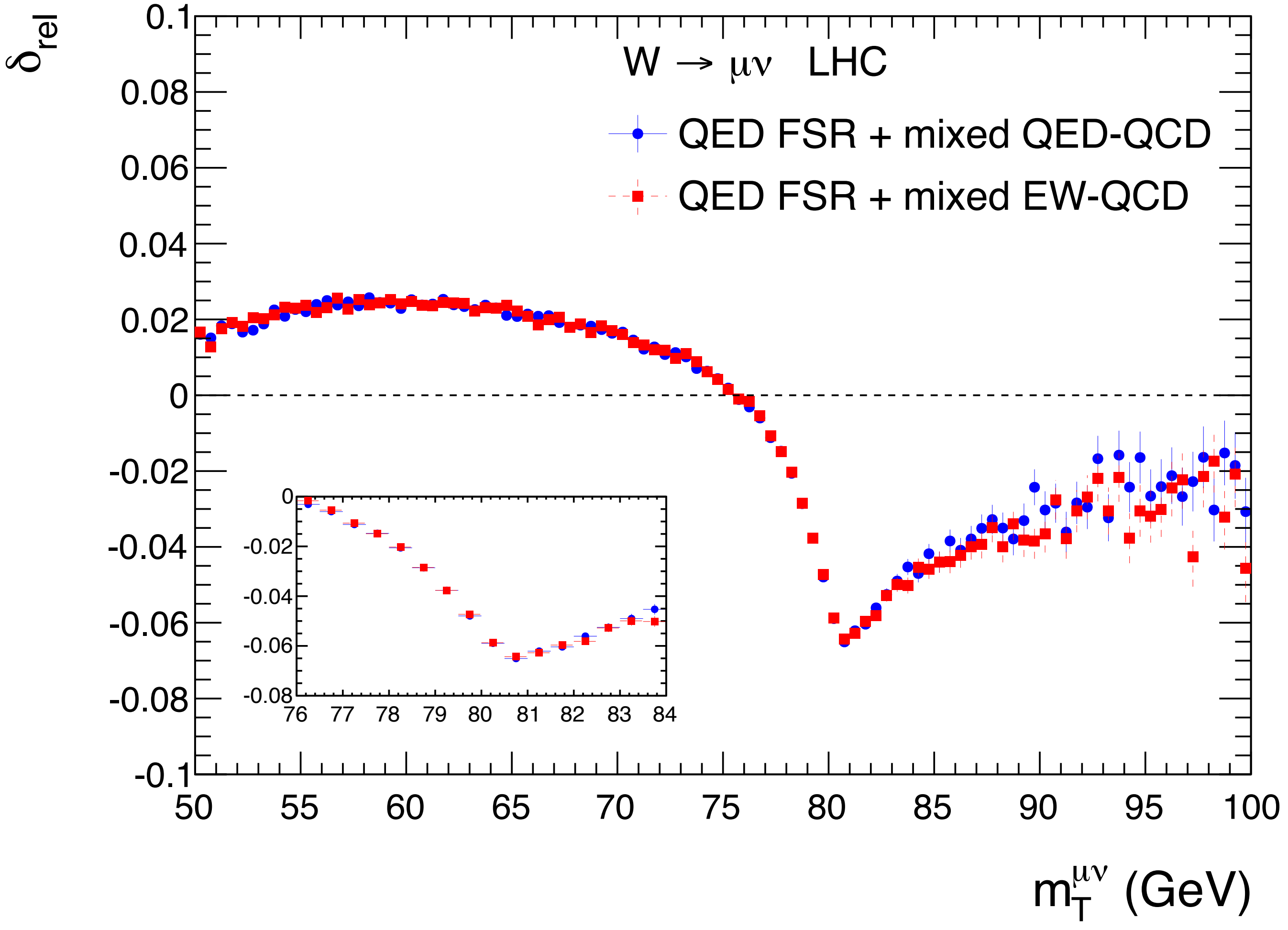
Combination of QCD and EW corrections: POWHEG results

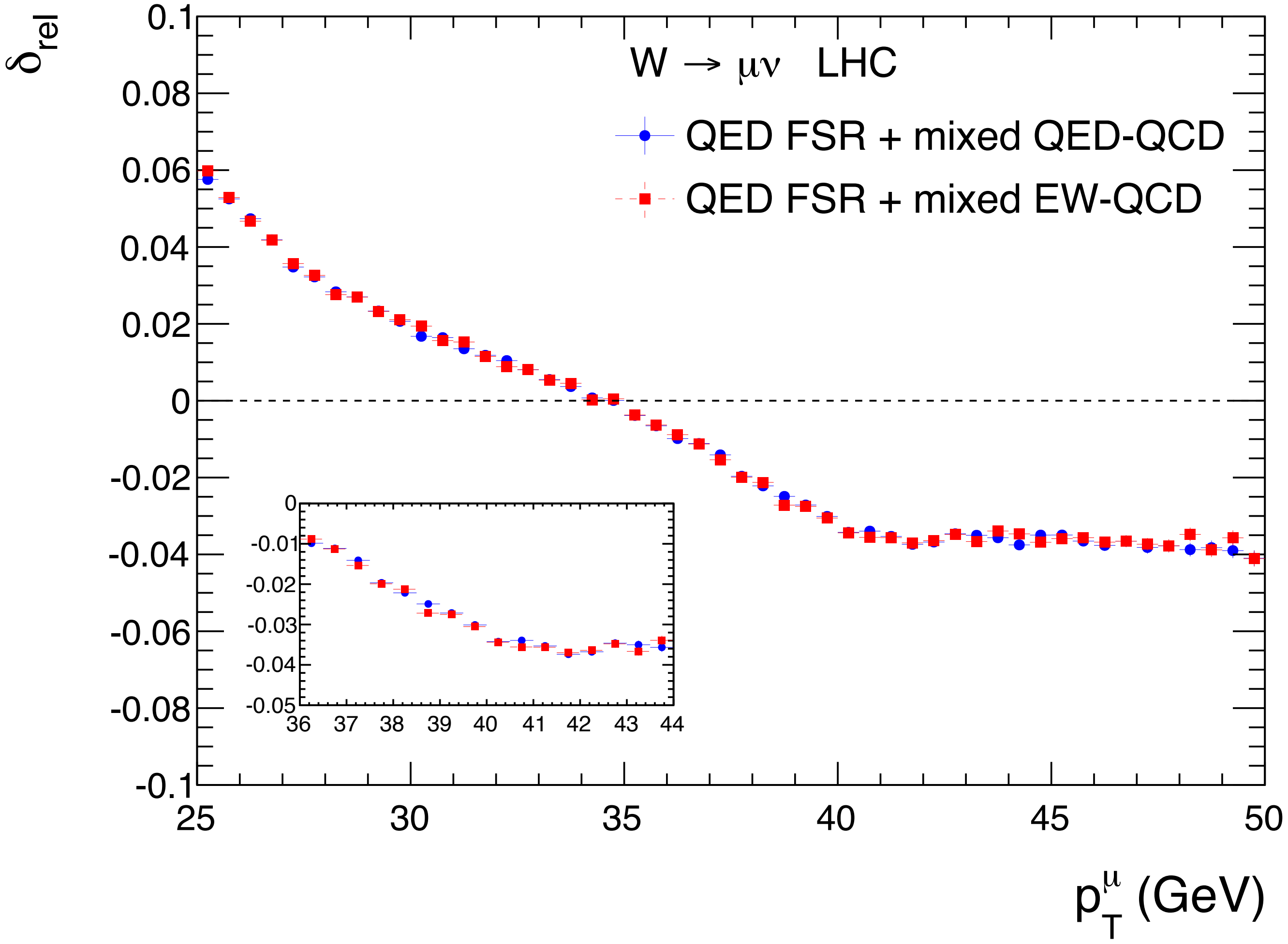
What is the impact of the full set of NLO-EW corrections?

POWHEG(QCD,EW) +PYTHIA(QCD) + PHOTOS

vs

POWHEG(QCD) + PYTHIA(QCD) + PHOTOS





Crucial role played by the algorithm that matches fixed-order results and Parton Shower in presence of two competing interactions

Is the impact of EW corrections preserved in a QCD environment ?

	Templates accuracy: LO	M_W shifts (MeV)			
		$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$	
	Pseudodata accuracy	M_T	p_T^ℓ	M_T	p_T^ℓ
1	HORACE only FSR-LL at $\mathcal{O}(\alpha)$	-94±1	-104±1	-204±1	-230±2
2	HORACE FSR-LL	-89±1	-97±1	-179±1	-195±1
3	HORACE NLO-EW with QED shower	-90±1	-94±1	-177±1	-190±2
4	HORACE FSR-LL + Pairs	-94±1	-102±1	-182±2	-199±1
5	PHOTOS FSR-LL	-92±1	-100±2	-182±1	-199±2

	Templates: NLO-QCD+QCD_{PS}		M_W shifts (MeV)			
			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+$(\text{QCD+QED})_{\text{PS}}$	PYTHIA	-95.2 ± 0.6	-400 ± 3	-38.0 ± 0.6	-149 ± 2
2	NLO-QCD+$(\text{QCD+QED})_{\text{PS}}$	PHOTOS	-88.0 ± 0.6	-368 ± 2	-38.4 ± 0.6	-150 ± 3
3	NLO-(QCD+EW)+$(\text{QCD+QED})_{\text{PS}}$	PYTHIA	-101.8 ± 0.4	-423 ± 2	-45.0 ± 0.6	-179 ± 2
4	NLO-(QCD+EW)+$(\text{QCD+QED})_{\text{PS}}$	PHOTOS	-94.2 ± 0.6	-392 ± 2	-45.2 ± 0.6	-181 ± 2
5	NLO-(QCD+EW)+$(\text{QCD+QED})_{\text{PS}}$(two-rad)	PYTHIA	-89.0 ± 0.6	-371 ± 3	-38.8 ± 0.6	-157 ± 3
6	NLO-(QCD+EW)+$(\text{QCD+QED})_{\text{PS}}$(two-rad)	PHOTOS	-88.6 ± 0.6	-370 ± 3	-39.2 ± 0.6	-159 ± 2

Lepton-pair transverse mass: yes!

Lepton transverse momentum: no, the shift are sizeably amplified

(these effects are already taken into account in the Tevatron and LHC analyses)

Effect of the NLO-EW matching on subleading QED contributions

PHOTOS and PYTHIA-QED Parton Showers share Leading-Logarithmic accuracy
differ at subleading level in the collinear region

The matching with the exact O(α) matrix elements shifts the differences one order higher

	Templates: NLO-QCD+QCD$_{\rm PS}$		M_W shifts (MeV)			
			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+(QCD+QED)$_{\rm PS}$	PYTHIA	-95.2 ± 0.6	-400 ± 3	-38.0 ± 0.6	-149 ± 2
2	NLO-QCD+(QCD+QED)$_{\rm PS}$	PHOTOS	-88.0 ± 0.6	-368 ± 2	-38.4 ± 0.6	-150 ± 3
3	NLO-(QCD+EW)+(QCD+QED)$_{\rm PS}$	PYTHIA	-101.8 ± 0.4	-423 ± 2	-45.0 ± 0.6	-179 ± 2
4	NLO-(QCD+EW)+(QCD+QED)$_{\rm PS}$	PHOTOS	-94.2 ± 0.6	-392 ± 2	-45.2 ± 0.6	-181 ± 2
5	NLO-(QCD+EW)+(QCD+QED)$_{\rm PS}$(two-rad)	PYTHIA	-89.0 ± 0.6	-371 ± 3	-38.8 ± 0.6	-157 ± 3
6	NLO-(QCD+EW)+(QCD+QED)$_{\rm PS}$(two-rad)	PHOTOS	-88.6 ± 0.6	-370 ± 3	-39.2 ± 0.6	-159 ± 2

The results of lines 3 and 4 have been obtained with the old public version of POWHEG which has been superseeded by the improved (two-rad) version (lines 5 and 6),
with a separate handling of QCD and QED radiation

Effect of the NLO-EW weak contributions

After the matching at NLO-(QCD+EW)
the impact on MW of weak contribution, of QED ISR and interferences is tiny

This conclusion is specific for MW, because we study the shape of the distributions

The predictions for other observables significantly differ with and without the NLO-EW matching
e.g. large invariant mass/transverse momentum regions where EW Sudakov logs are important

	Templates: NLO-QCD+QCD$_{\mathrm{PS}}$		M_W shifts (MeV)			
			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+(QCD+QED)$_{\mathrm{PS}}$	Pythia	-95.2 ± 0.6	-400 ± 3	-38.0 ± 0.6	-149 ± 2
2	NLO-QCD+(QCD+QED)$_{\mathrm{PS}}$	Photos	-88.0 ± 0.6	-368 ± 2	-38.4 ± 0.6	-150 ± 3
3	NLO-(QCD+EW)+(QCD+QED)$_{\mathrm{PS}}$	Pythia	-101.8 ± 0.4	-423 ± 2	-45.0 ± 0.6	-179 ± 2
4	NLO-(QCD+EW)+(QCD+QED)$_{\mathrm{PS}}$	Photos	-94.2 ± 0.6	-392 ± 2	-45.2 ± 0.6	-181 ± 2
5	NLO-(QCD+EW)+(QCD+QED)$_{\mathrm{PS}}$(two-rad)	Pythia	-89.0 ± 0.6	-371 ± 3	-38.8 ± 0.6	-157 ± 3
6	NLO-(QCD+EW)+(QCD+QED)$_{\mathrm{PS}}$(two-rad)	Photos	-88.6 ± 0.6	-370 ± 3	-39.2 ± 0.6	-159 ± 2

Estimate of EW uncertainties via input scheme variation

- a full NNLO-EW calculation is not available (only leading QED O(α^2) contributions available)

	Templates accuracy: LO		M_W shifts (MeV)	
			$W^+ \to \mu^+\nu$	
	Pseudodata accuracy	Input scheme	M_T	p_T^ℓ
1	HORACE NLO-EW	α_0	-101±1	-117±2
2		$G_\mu - I$	-112±1	-130±1
3		$G_\mu - II$	-101±1	-117±1
4	HORACE NLO-EW+QED-PS	α_0	-70±1	-81±1
5		$G_\mu - I$	-72±2	-83±1
6		$G_\mu - II$	-72±1	-82±2

- different input schemes introduce different subsets of higher order corrections, beyond the formal accuracy of the calculation
  → the comparison probes the size of NNLO-EW corrections related to the LO couplings

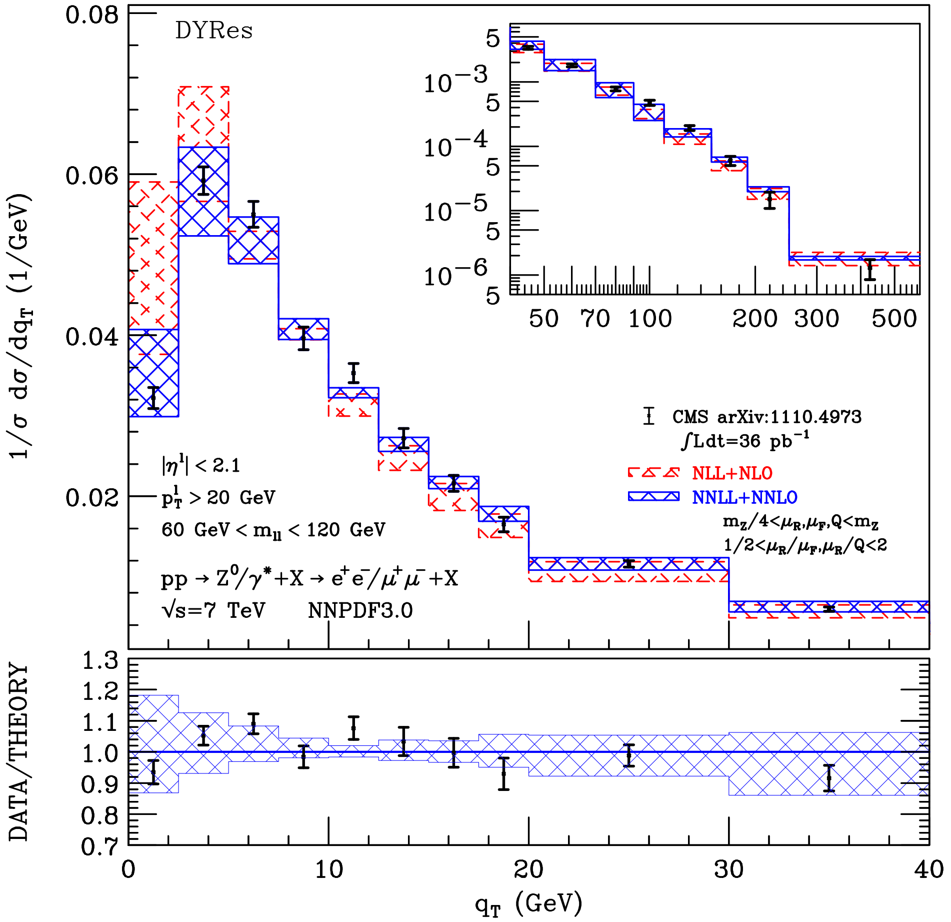
- at fixed order NLO-EW α_0 and G_μ schemes differ by O(10 MeV):
  the virtual corrections affect only the 0-photons contribution to the distributions
  change of shape

- in the matched HORACE formulation the difference is reduced at the O(1 MeV) level (negligible) because the virtual corrections act in a prefactor common to all the events (with different photon multiplicities) and do not affect the shape of the distributions

- how do these uncertainties behave when convoluted with QCD radiation?

DYRes (NNLO-QCD + NNLL) with leptonic decays

S. Catani, D. de Florian, G. Ferrera, M. Grazzini, arXiv:1507.06937

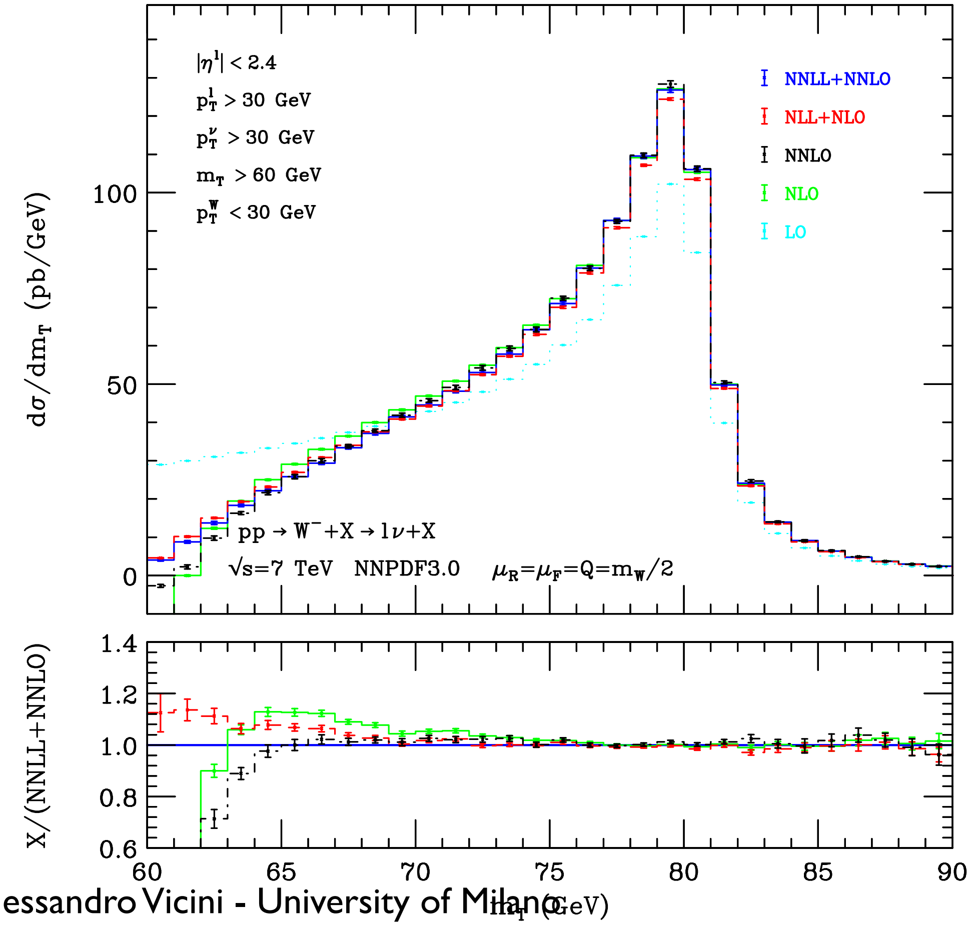


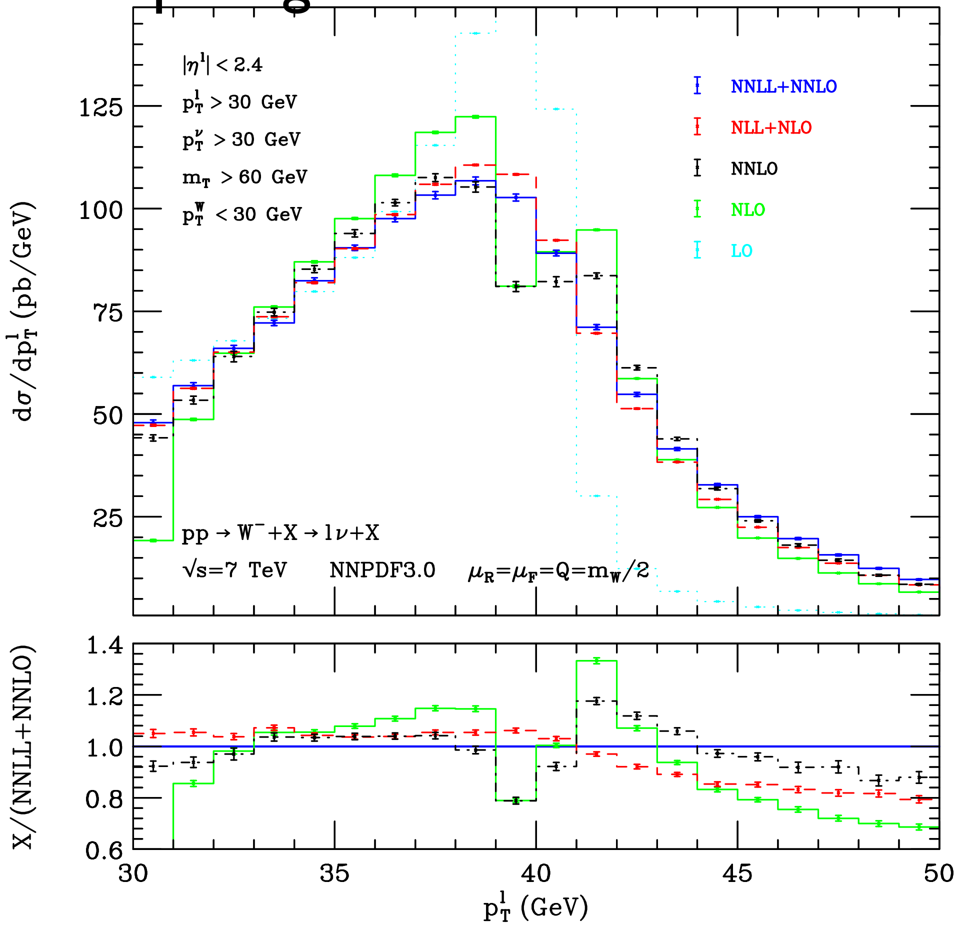
- NNLO accuracy on the total xsec matched with NNLL accuracy in the description of the low ptZ region

- good description of ptZ data in pure pQCD within the theory uncertainty bands no urgent need of a non-perturbative component

- remarkable stability of the MT distribution at the jacob. peak when including higher order corrections

- the lepton pt distribution is distorted at few % level when comparing NLL+NLO w.r.t. NNLL+NNLO



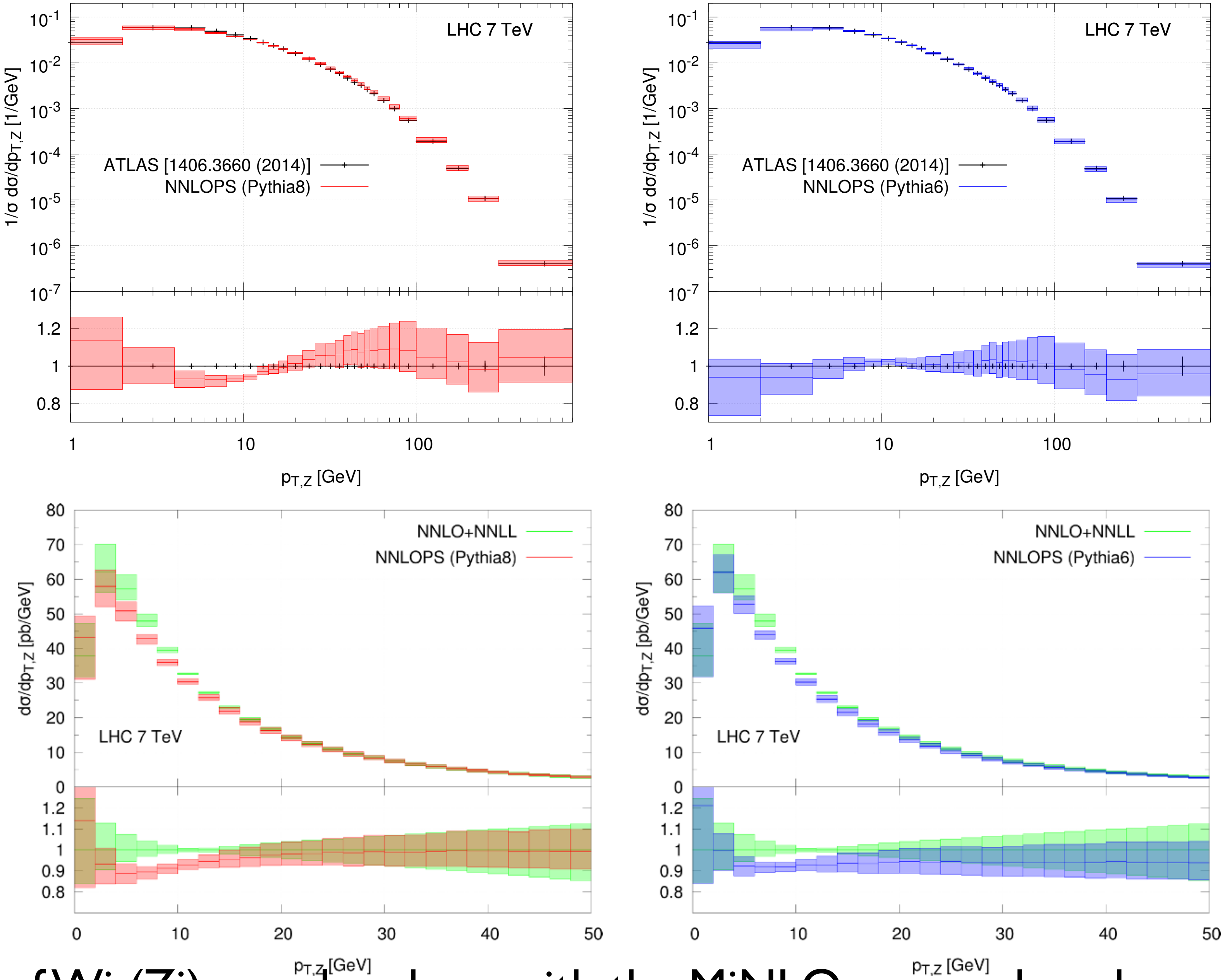


DYNNLOPS

- 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



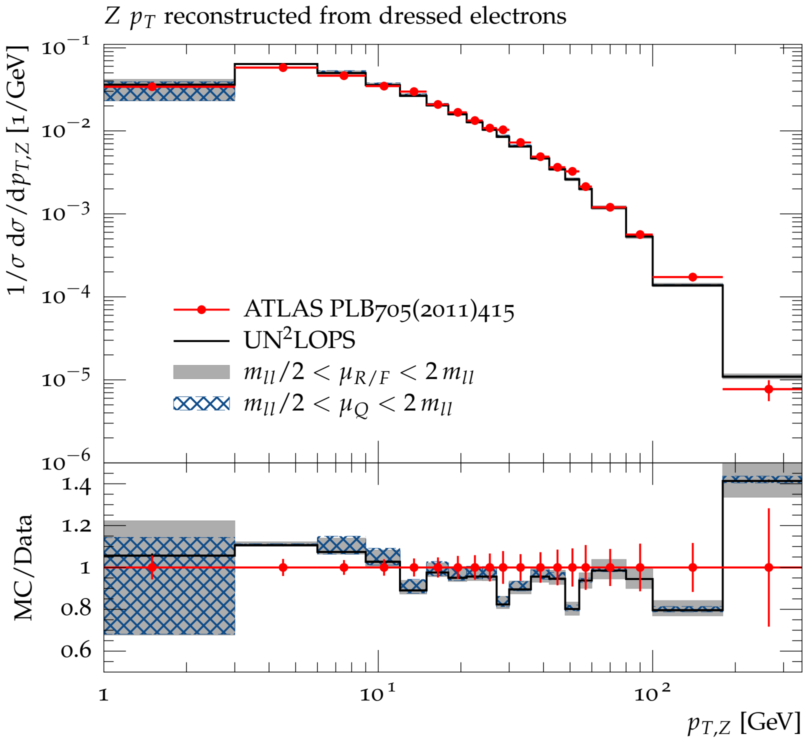
- Improvement of Wj (Zj) samples, done with the MiNLO approach and a modified Sudakov form factor
- The distribution has NLO accuracy through the whole ptV range
- The NNLO accuracy on the inclusive observables is based on the rescaling with DYNNLO results
- The uncertainty bands have been obtained varying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

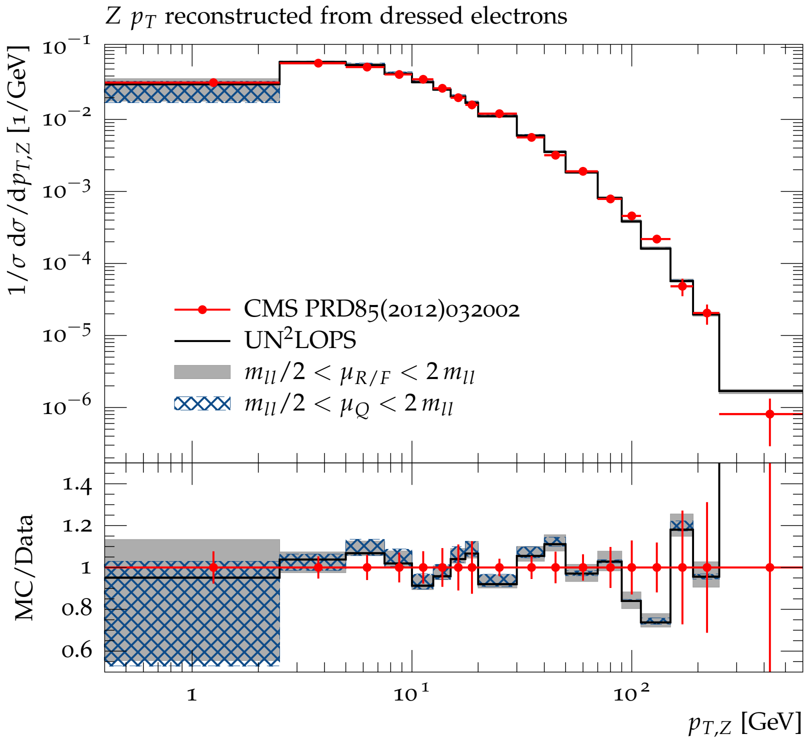
UN^2LOPS + NNLO

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

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

  UN^2LOPS+NNLO S.Hoeche, Y.Li, S.Prestel, arXiv:1405.3607

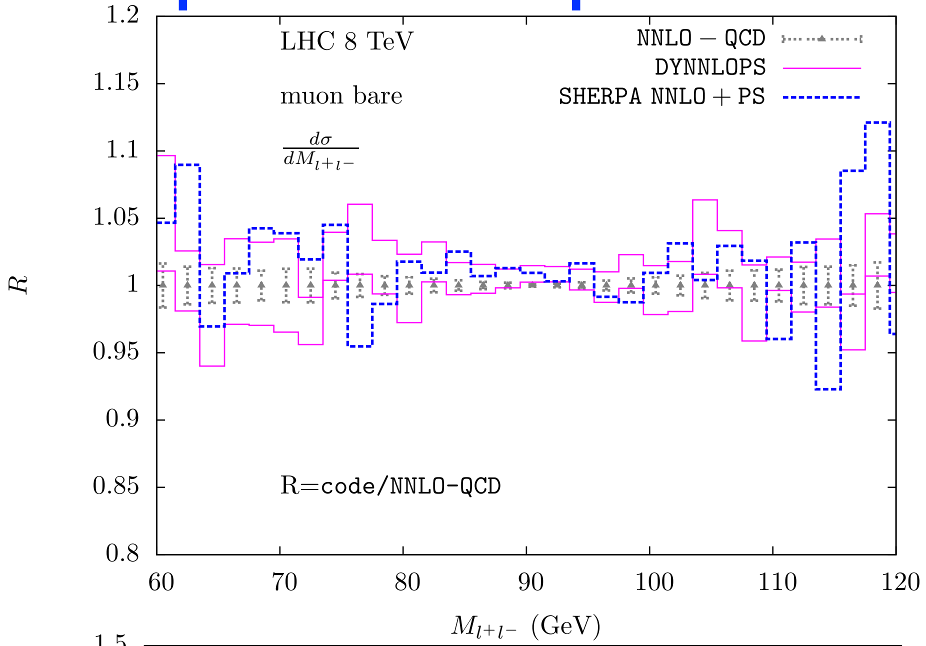


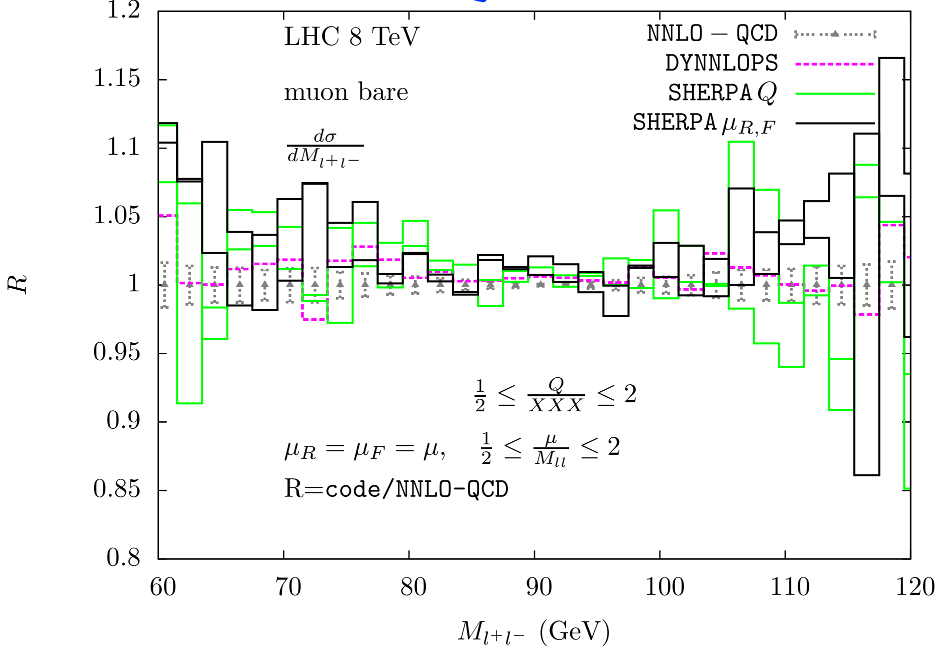


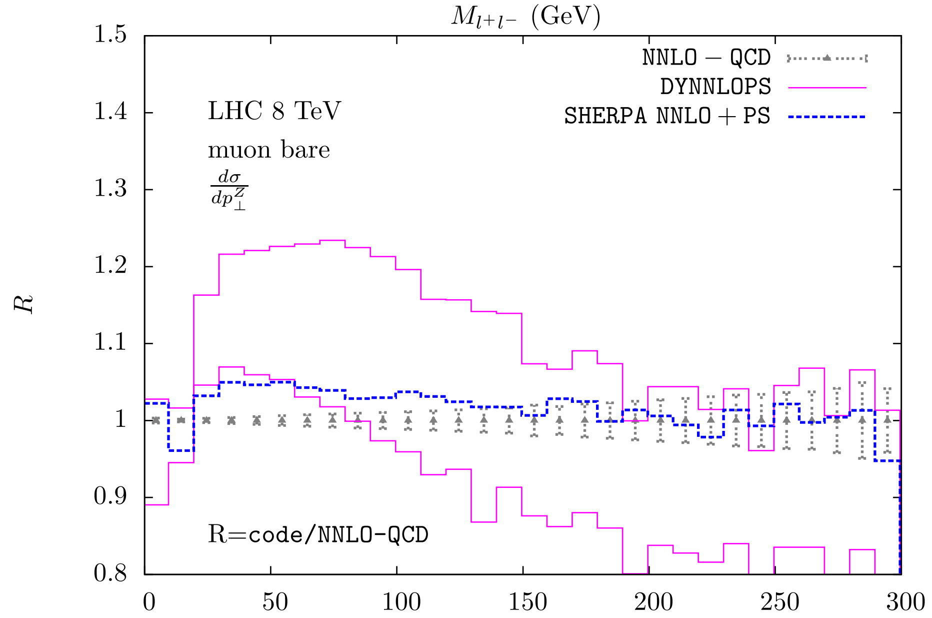
- The UNLOPS scheme merges 0-jet and 1-jet samples (it requires a merging scale), it preserves the accuracy on the total xsec with the definition of a 0-jet bin which is not showered
- The UN^2LOPS scheme extends the approach at O(alphas^2)

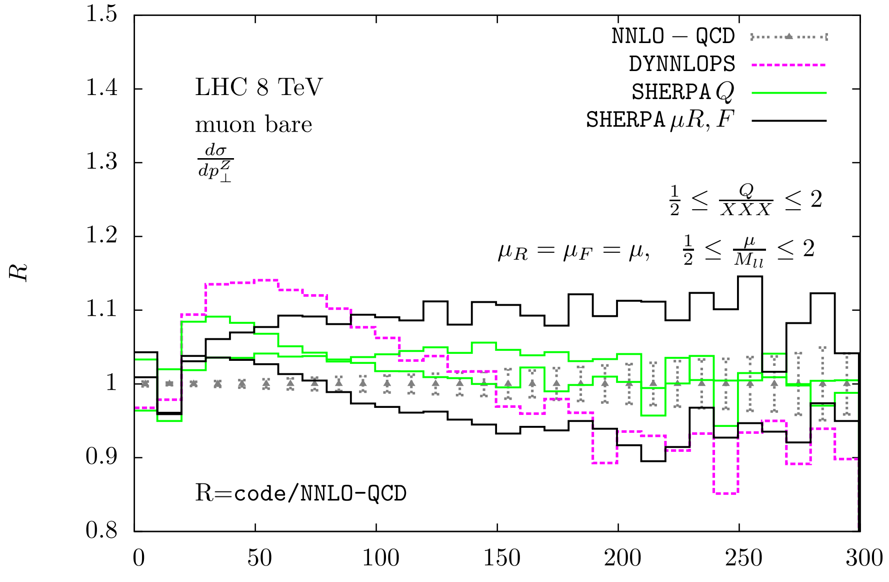
- Important differences in the definition of the uncertainty bands between DYNNLOPS and UN^2LOPS

Comparison of ptZ distributions, NNLO+PS QCD arXiv:1606.02330









Comparison of two different NNLO+PS matching schemes (DYNNLOPS and SHERPA UN²LOPS)

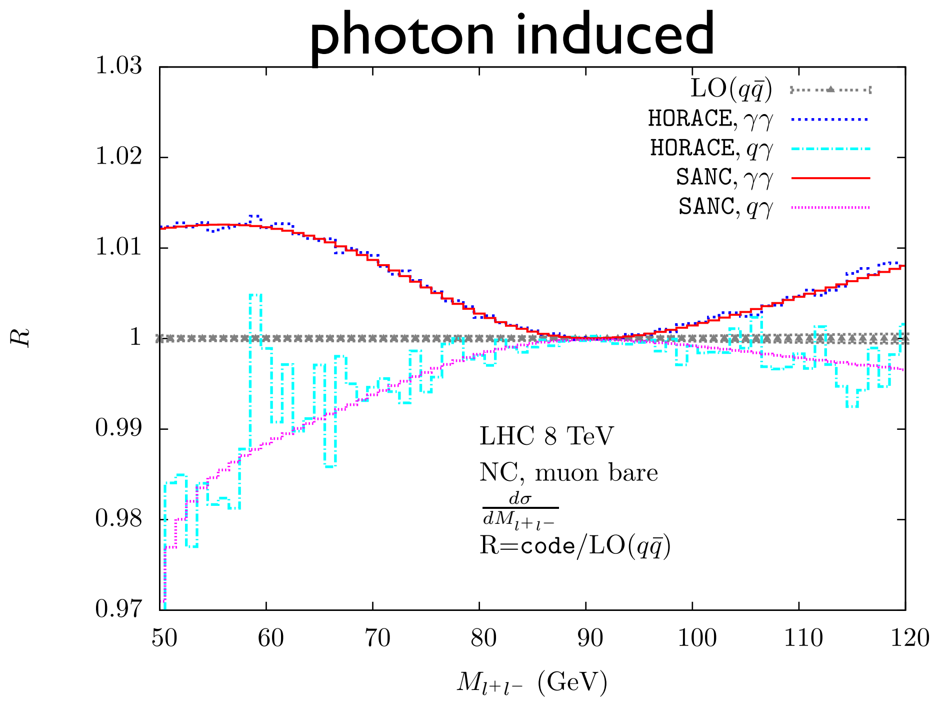
The impact of higher-order corrections is expressed in units NNLO-QCD.

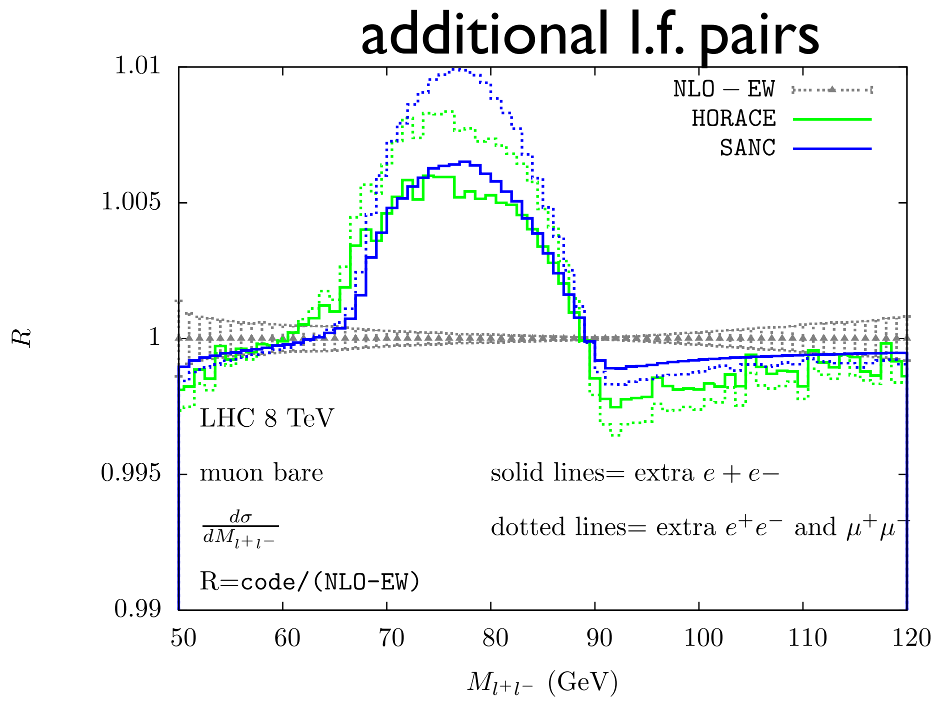
Different definitions of the uncertainty bands (DYNNLOPS uses 21 scale combinations,
SHERPA separate muR, muF and Q variations)

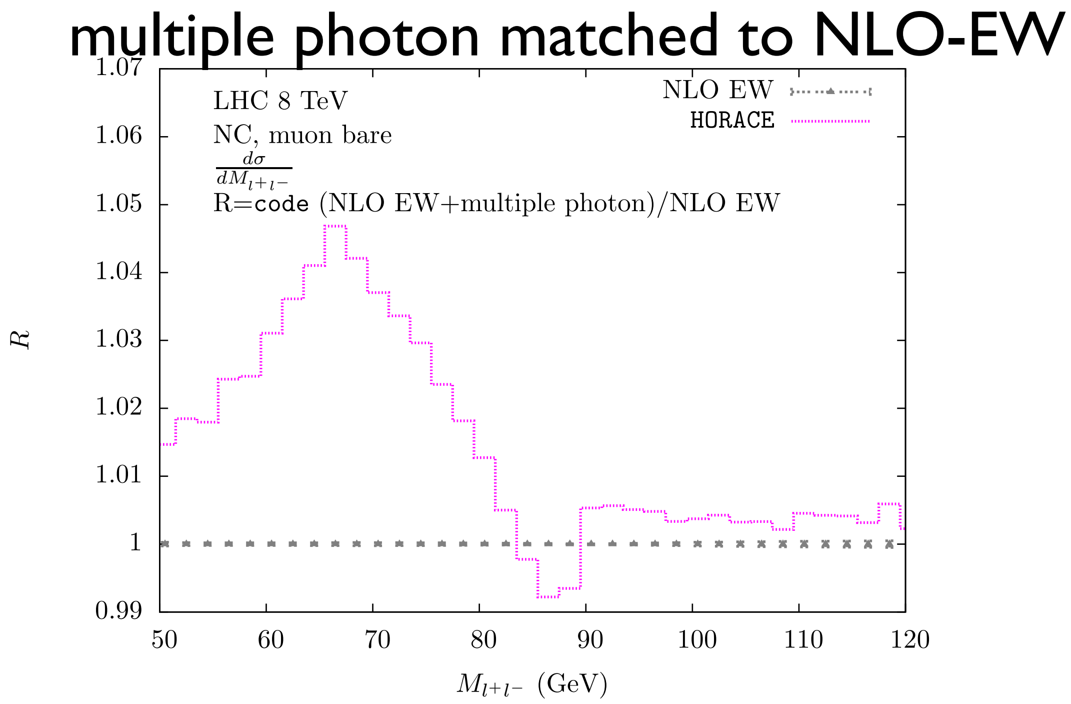
The two matchings differ only by several percent (improvement w.r.t. NLO+PS) for ptV,
but the uncertainty bands are not yet negligible.

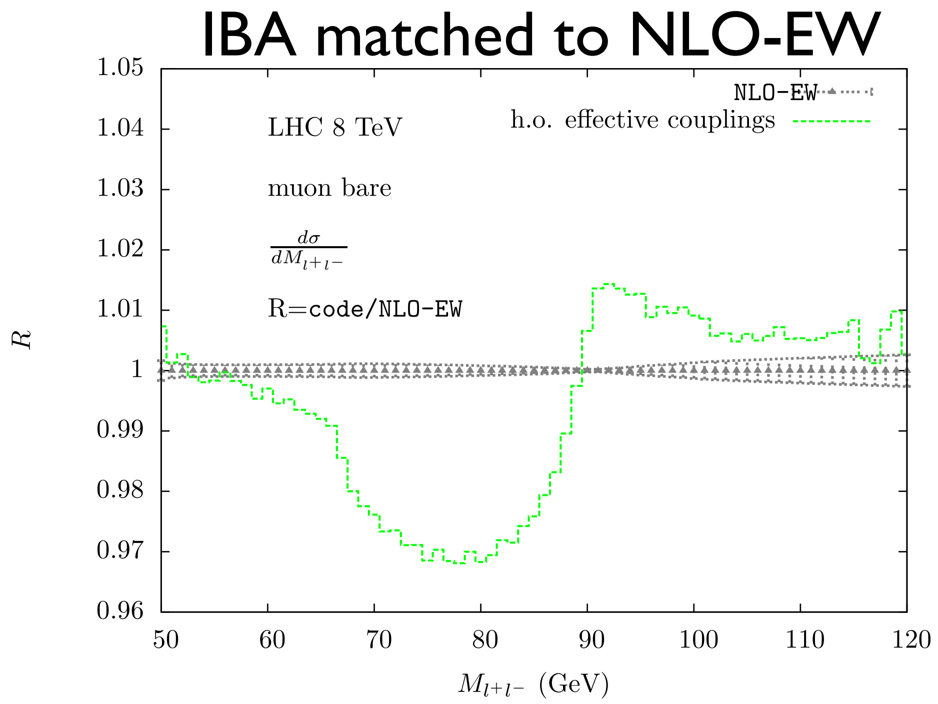
We need a systematic study of the matching uncertainties on ptZ,
analogous to the one for the Higgs ptH of Bagnaschi, Harlander, Mantler, AV, Wiesemann, arXiv:1510.08850

Benchmark results: lepton-pair invariant mass, EW higher orders


photon induced


additional l.f. pairs


multiple photon matched to NLO-EW

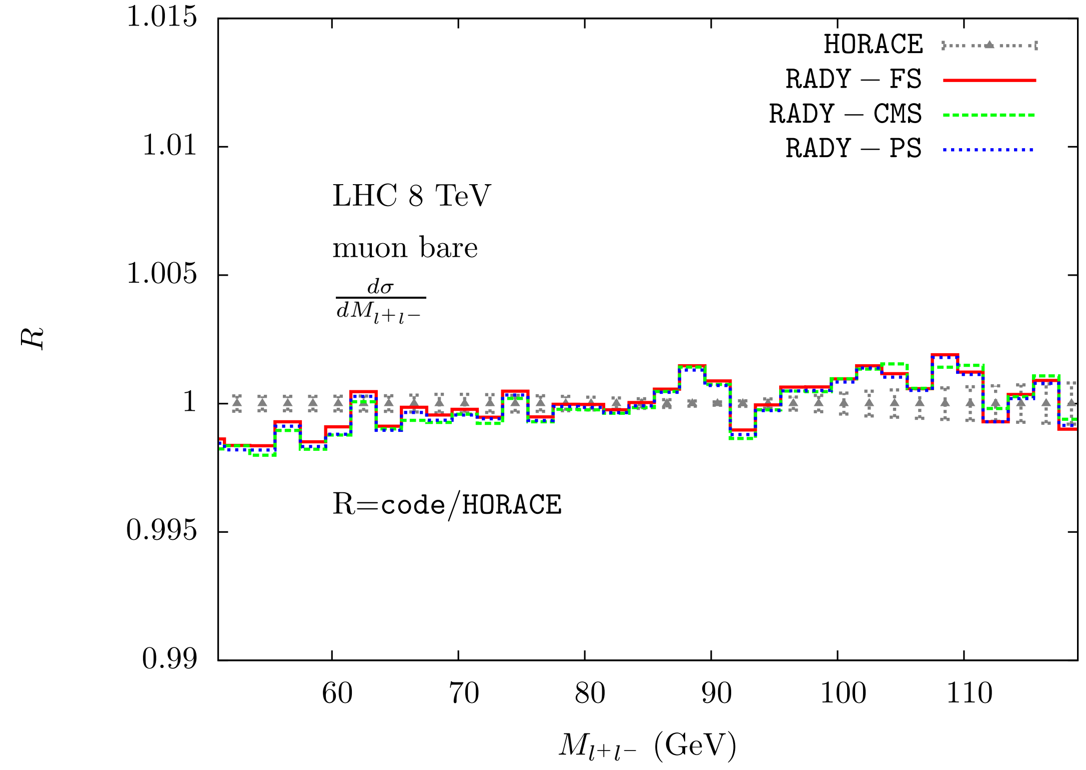

IBA matched to NLO-EW

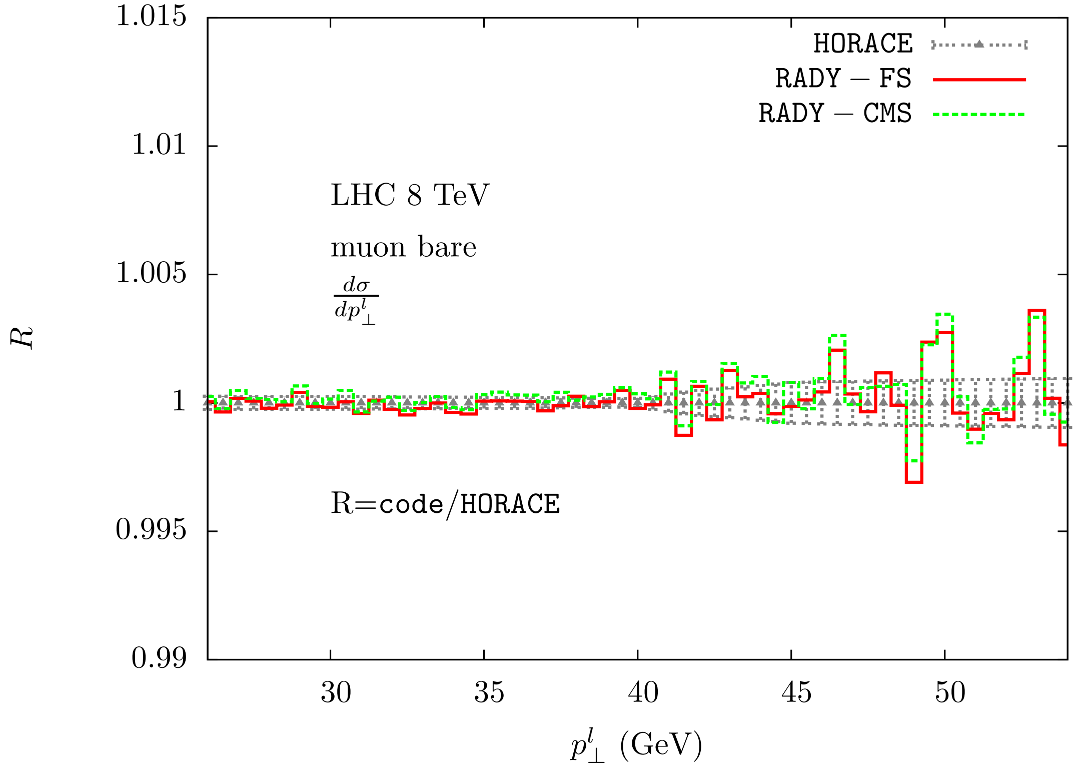
The impact of the O(α^2) and higher corrections is expressed in units NLO-EW.

The effects are of O(1%), with the exception of the left tail of the Z resonance where the large (+85%) FSR corrections enhances in turn all the O(α^2) terms

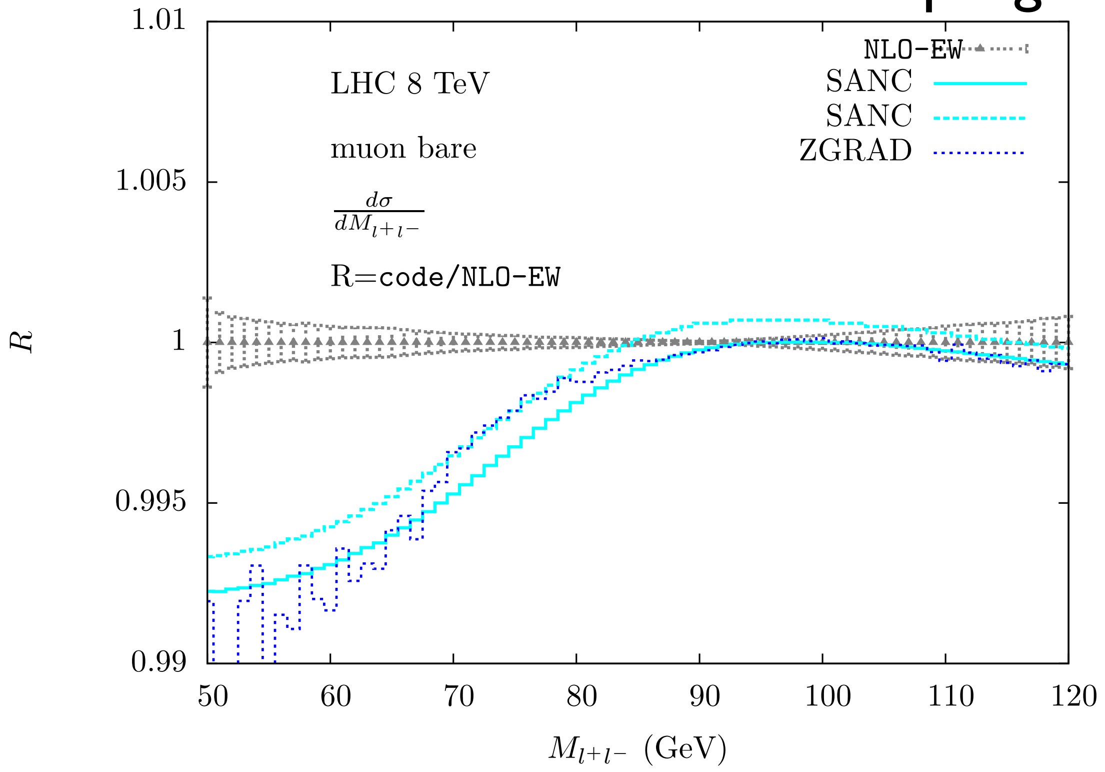
Benchmark results: differential distributions, EW inputs

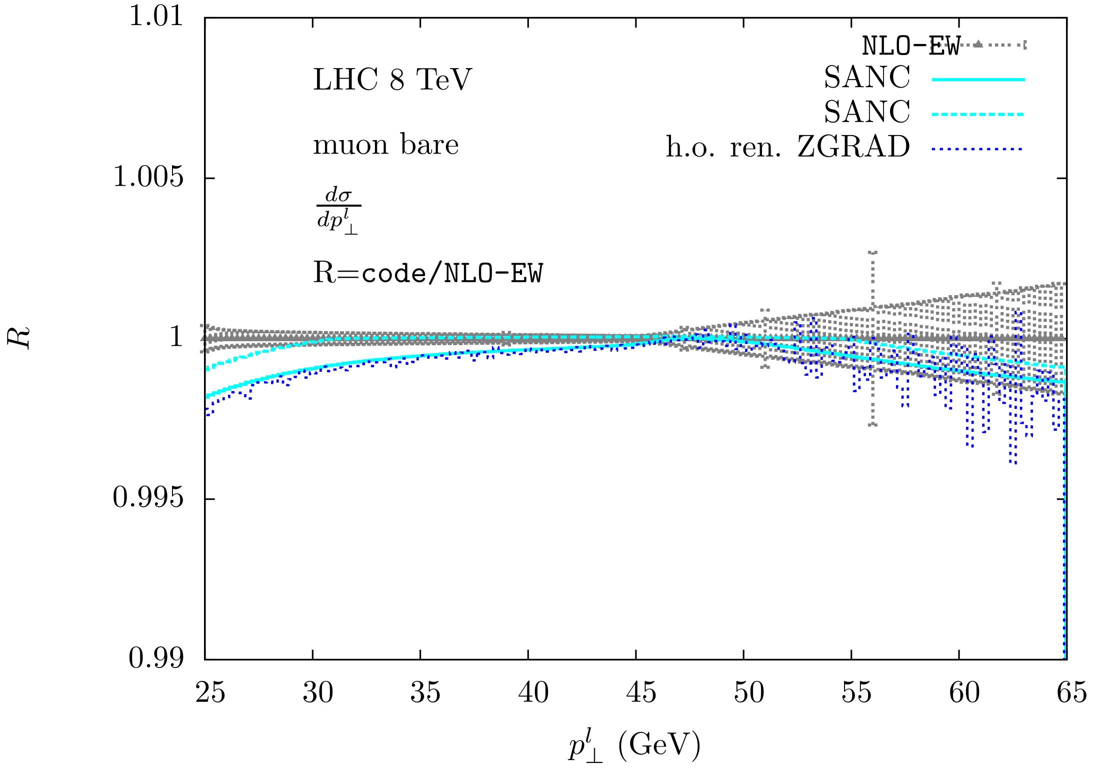
different definitions of the renormalized Z mass





inclusion of universal higher orders via redefinition of the LO couplings

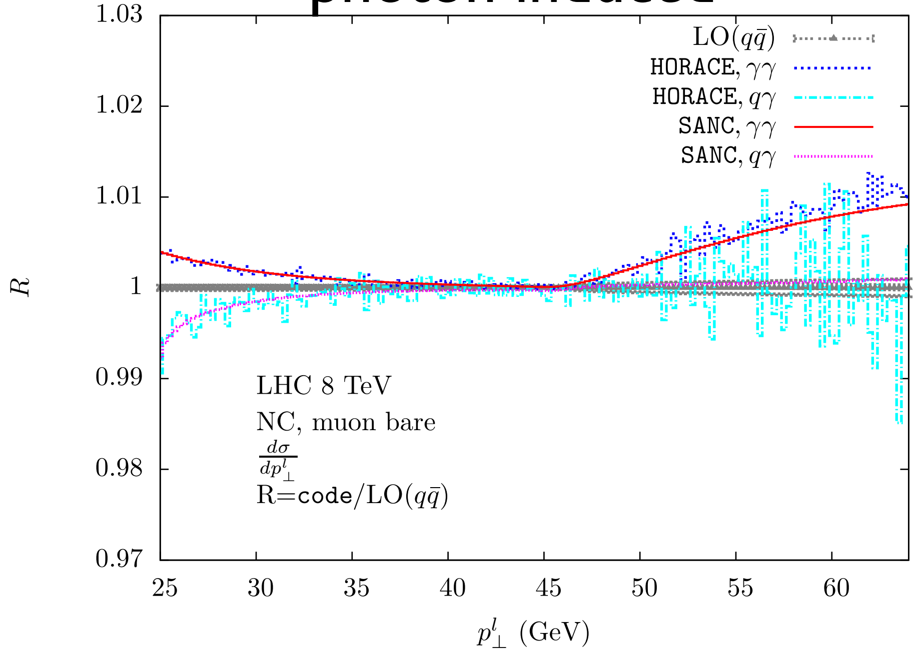




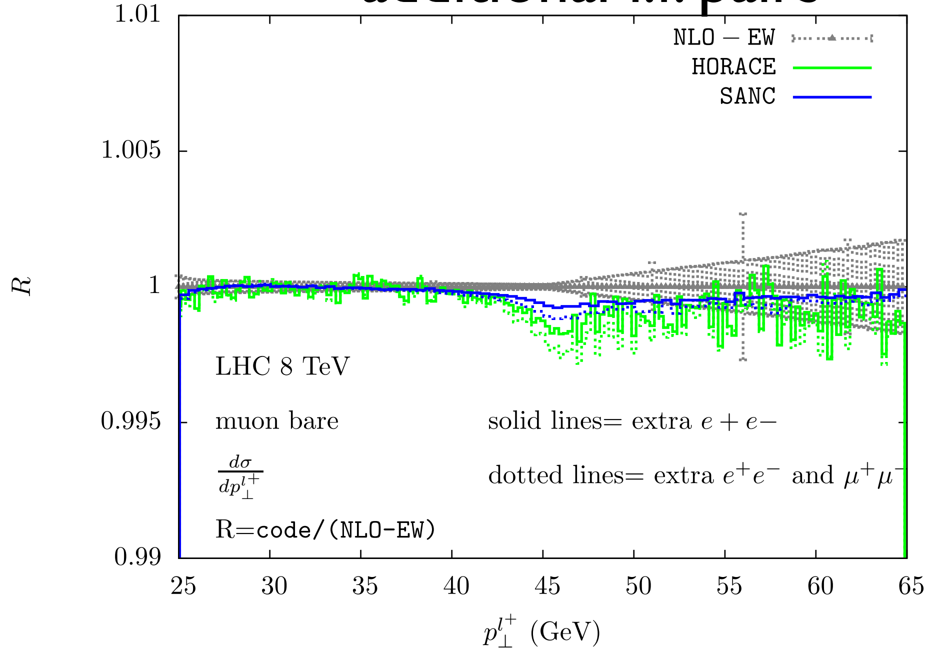
The impact of the O(α²) and higher corrections is expressed in units NLO-EW.

Benchmark results: lepton pt, EW higher orders

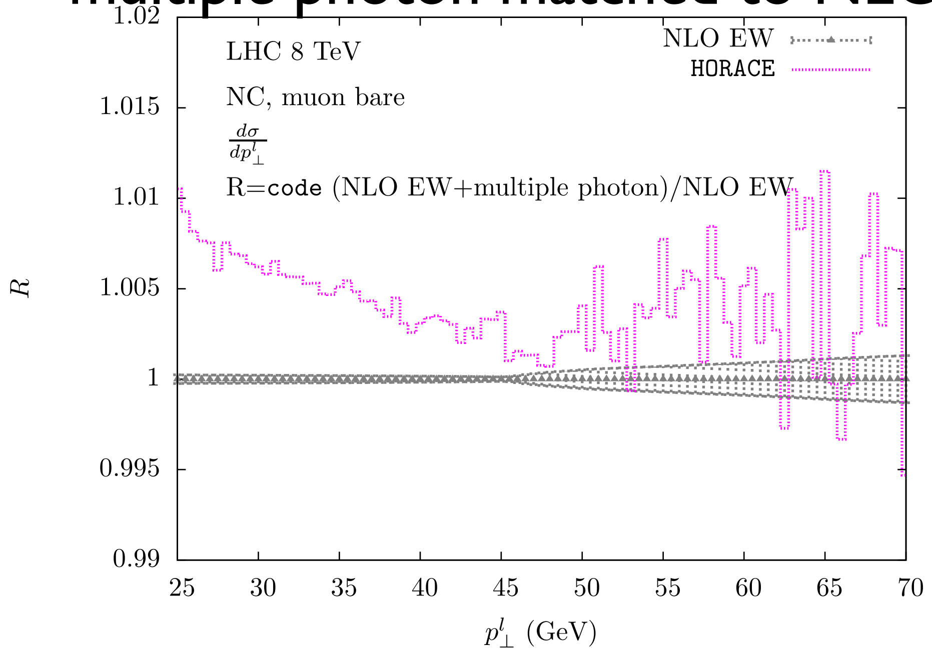
photon induced



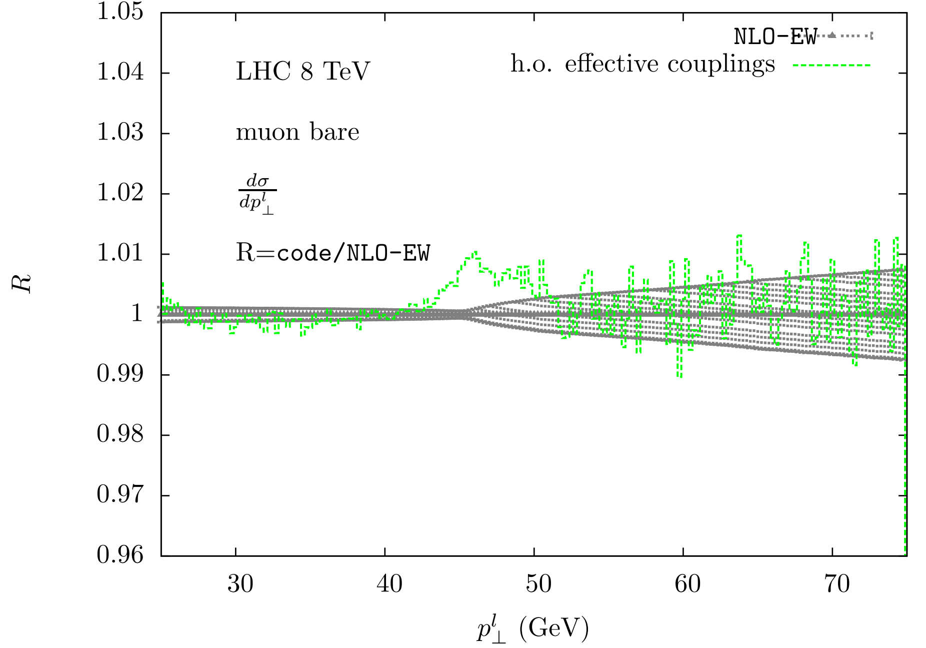
additional l.f. pairs



multiple photon matched to NLO-EW



IBA matched to NLO-EW



The impact of the O(α^2) and higher corrections is expressed in units NLO-EW.

The effects are at the subpercent level

Searching for BSM physics: Effective Field Theory approach

- Instead of testing the likelihood of the SM against the data
  we can enlarge the content of the Lagrangian adding new sets of operators
  classified according to their dimensionality, respecting the basic symmetries of the theory

$$\mathcal{L}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

- the additional EFT parameters may describe possible deviations of the data from the SM predictions

- alternatively, in the absence of tensions with the SM, we can set limits on the new ETF couplings

$$\sigma = \sigma^{\rm SM} + \sum_i \left(\frac{c_i^{(6)}}{\Lambda^2}\sigma_i^{(6\times {\rm SM})} + {\rm h.c.} \right) + \sum_{ij} \frac{c_i^{(6)} c_j^{(6)*}}{\Lambda^4}\sigma_{ij}^{(6\times 6)} + \sum_j \left(\frac{c_j^{(8)}}{\Lambda^4}\sigma_j^{(8\times {\rm SM})} + {\rm h.c.} \right) + \dots$$

- after LEP and Tevatron studies, we are looking after effects in the % realm, in multi boson production
- the tension comparing the data with the SM depends on the precision of the theoretical predictions

  → deviations are searched/expected at large energy scales
  → both QCD and EW radiative corrections play an important role
  → many particles final states
  → important role of automation tools to reach at least NLO-QCD and NLO-EW accuracy

PHENOMENOLOGY STUDY: TTBAR+H/V

Frixione, Hirschi, HSS, Pagani, Zaro ’14,’15

- **EWC** on differential distributions (and for fiducial xs)
  - Both NLO EW and photon PDF become important when boost final states

    NNPDF2.3QED here
  - **EWC** for ttW is more significant (~-8% at 13 TeV) than ttH and ttZ
    - No LO EW to cancel NLO EW (color flow) and HBR opens gg initial states