UNIVERSITÀ DEGLI STUDI DI MILANO

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EW measurements at LHC
theory issues

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Outline: brief sketch of open issues in EW precision measurements

- motivations: precision tests of the Standard Model (or of the SMEFT ?)

- measurement: comparison of "a" model against the data
  which model? which Pseudo-Observables? which simulation code? EW input scheme?

- validation of tools: 1) precision (i.e. theoretical uncertainty) 2) accuracy (i.e. data description)

- QCD modelling and QCDxEW entanglement
  estimate of the associated theoretical uncertainties
  PDF uncertainties

- several single and double differential distributions must be investigated to exploit their potential
  → to learn how to describe the (mostly QCD) environment where the DY processes take place
  → while preserving the sensitivity to the EW parameters
  → to discuss how to set the stage for a comprehensive global EW fit of LHC observables

Motivations

from the Fermi theory to the current measurements of MW and $\sin^2\theta$

From the Fermi theory of weak interactions to the discovery of W and Z

Fermi theory of β decay

muon decay $\mu^- \to \nu_\mu e^- \bar{\nu}_e$ $\frac{1}{\tau_\mu} \to \Gamma_\mu \to G_\mu$

QED corrections to Γ_μ necessary for precise determination of G_μ
computable in the Fermi theory (Kinoshita, Sirlin, 1959)

The independence of the QED corrections of the underlying model (Fermi theory vs SM) allows

- to define G_μ and to measure its value with high precision

$$G_\mu = 1.1663787(6)\ 10^{-5}\ \ \mathrm{GeV}^{-2}$$

- to establish a relation between G_μ and the SM parameters

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

The properties of physics at the EW scale
with sensitivity to the full SM and possibly to BSM via virtual corrections (Δr)
are related to a very well measured low-energy constant

From the Fermi theory of weak interactions to the discovery of W and Z

The SM predicts the existence of a new neutral current, different than the electromagnetic one
(Glashow 1961, Weinberg 1967, Salam 1968)

The observation of weak neutral current immediately allowed the estimate of the value of the weak mixing angle in the correct range
GARGAMELLE, Phys.Lett. 46B (1973) 138-140

From the basic relation among the EW parameters it was immediately possible to estimate the order of magnitude of the mass of the weak bosons, in the 80 GeV range
(Antonelli, Maiani, 1981)

The discovery at the CERN SPPS of the W and Z bosons and the first determination of their masses allowed the planning of a new phase of precision studies accomplished with the construction of two e^+e^- colliders (SLC and LEP) running at the Z resonance

The precise determination of MZ and of the couplings of the Z boson to fermions
and in particular the value of the effective weak mixing angle
allowed to establish a framework for a test of the SM at the level of its quantum corrections

There is evidence of EW corrections beyond QED with 26 σ significance!
Full 1-loop and leading 2-loop radiative corrections are needed to describe the data
(indirect evidence of bosonic quantum effects)

The renormalisation of the SM and a framework for precision tests

- The Standard Model is a renormalizable gauge theory based on SU(3) x SU(2)$_L$ x 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, at any order in perturbation theory
- The validity of the SM can be tested comparing these predictions with the corresponding experimental results

- The input choice (g,g',v,λ) ↔ (α, G_μ, MZ, MH) minimises the parametric uncertainty of the predictions

$$\begin{aligned} \alpha(0) &= 1/137.035999139(31) \\ G_\mu &= 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2} \\ m_Z &= 91.1876(21)\ \mathrm{GeV}/c^2 \\ m_H &= 125.09(24)\ \mathrm{GeV}/c^2 \end{aligned}$$

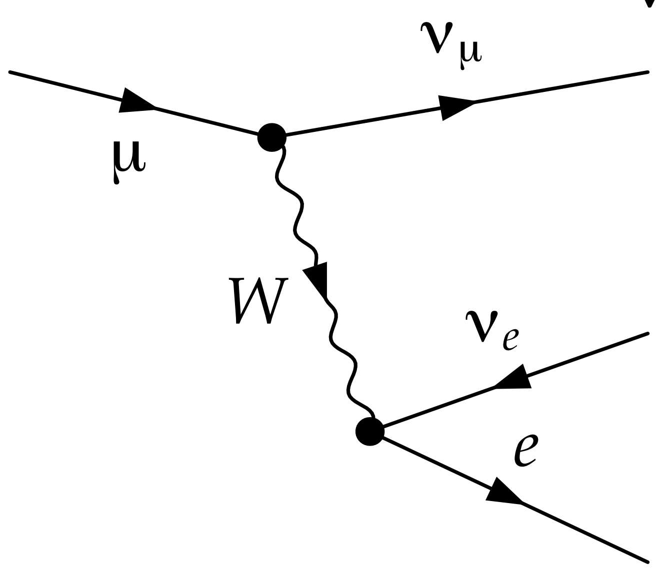
- with these inputs, MW and the weak mixing angle are predictions of the SM, to be tested against the experimental data

The W boson mass: theoretical prediction

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

$\rightarrow$ we can compute m_W

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



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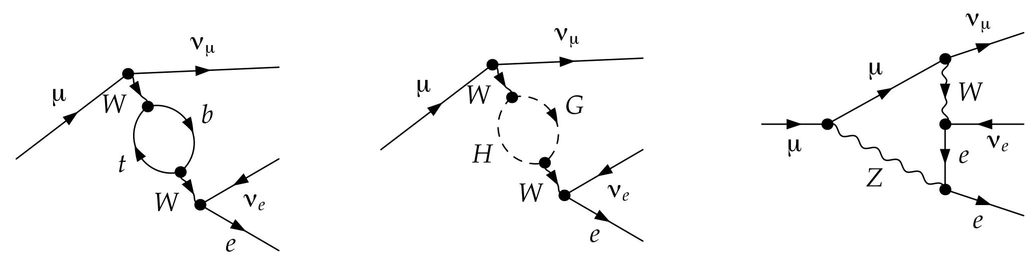

+ ....

$$\Delta r = \Delta r(\alpha, G_\mu, m_Z, m_H; m_f; CKM)$$

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

The W boson mass: theoretical prediction

Sirlin, 1980, 1984; Marciano, Sirlin, 1980, 1981;
van der Bij, Veltman, 1984; Barbieri, Ciafaloni, Strumia 1993;
Djouadi, Verzegnassi 1987; Consoli, Hollik, Jegerlehner, 1989;
Chetyrkin, Kühn, Steinhauser, 1995;
Barbieri, Beccaria, Ciafaloni, Curci, Viceré, 1992, 1993; Fleischer, Tarasov, Jegerlehner, 1993;
Degrassi, Gambino, AV, 1996; Degrassi, Gambino, Sirlin, 1997;
Freitas, Hollik, Walter, Weiglein, 2000, 2003;
Awramik, Czakon, 2002; Awramik, Czakon, Onishchenko, Veretin, 2003; Onishchenko, Veretin, 2003

The best available prediction includes
the full 2-loop EW result, higher-order QCD corrections, resummation of reducible terms

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

$$dt = [(M_t/173.34\,\mathrm{GeV})^2 - 1]$$

$$da^{(5)} = [\Delta\alpha^{(5)}_{\mathrm{had}}(m_Z^2)/0.02750 - 1]$$

$$dH = \ln\left(\frac{m_H}{125.15\,\mathrm{GeV}}\right)$$

$$dh = [(m_H/125.15\ \mathrm{GeV})^2 - 1].$$

$$da_s = \left(\frac{\alpha_s(m_Z)}{0.1184} - 1\right)$$

	$124.42 \le m_H \le 125.87$ 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

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

The weak mixing angle(s): theoretical prediction(s)

- the prediction of the weak mixing angle can be computed in different renormalisation schemes differing for the systematic inclusion of large higher-order corrections

- on-shell definition: $$\sin^2\theta_{OS} = 1 - \frac{m_W^2}{m_Z^2}$$ definition valid to all orders

- MSbar definition:

$$\frac{G_\mu}{\sqrt{2}} = \frac{g^2}{8m_W^2} \longrightarrow \hat{s}^2\hat{c}^2 = \frac{\pi\alpha}{\sqrt{2}G_\mu m_Z^2(1-\Delta\hat{r})} \qquad \hat{s}^2 \equiv \sin^2\hat{\theta}$$

weak dependence on top-quark corrections

Awramik, Czakon, Freitas, hep-ph/0608099

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weak dependence on top-quark corrections

- the effective leptonic weak mixing angle enters in the definition of the effective Z-f-fbar vertex at the Z resonance

$$\mathcal{M}^{eff}_{Zl^+l^-} \; = \; \bar{u}_l \gamma_\alpha \left[\mathcal{G}_v^f(m_Z^2) - \mathcal{G}_a^f(m_Z^2)\gamma_5\right] v_l \varepsilon_Z^\alpha \qquad 4|Q_f|\sin^2\theta^f_{eff} \; = \; 1 - \frac{g_V^f}{g_A^f}$$

and can be computed in the SM (or in other models) in different renormalisation schemes

$$\sin^2\theta^{lep}_{eff} \; = \; \kappa(m_Z^2)\sin^2\theta_{OS} \; = \; \hat{\kappa}(m_Z^2)\sin^2\hat{\theta}$$

- the parameterization of the full two-loop EW calculation is

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

f	e,μ,τ	$\nu_{e,\mu,\tau}$	u,c	d,s
s_0	0.2312527	0.2308772	0.2311395	0.2310286
d_1 $[10^{-4}]$	4.729	4.713	4.726	4.720
d_2 $[10^{-5}]$	2.07	2.05	2.07	2.06
d_3 $[10^{-6}]$	3.85	3.85	3.85	3.85
d_4 $[10^{-6}]$	-1.85	-1.85	-1.85	-1.85
d_5 $[10^{-2}]$	2.07	2.06	2.07	2.07
d_6 $[10^{-3}]$	-2.851	-2.850	-2.853	-2.848
d_7 $[10^{-4}]$	1.82	1.82	1.83	1.81
d_8 $[10^{-6}]$	-9.74	-9.71	-9.73	-9.73
d_9 $[10^{-4}]$	3.98	3.96	3.98	3.97
d_{10} $[10^{-1}]$	-6.55	-6.54	-6.55	-6.55

Awramik, Czakon, Freitas, hep-ph/0608099

Results from LEP and SLC: $\sin^2\theta_{eff}$(leptonic)

- the forward-backward asymmetry in e^+e^- collisions: "forward" is defined w.r.t. the incoming e^-
- Born-level relation

$$A_{FB}(m_Z^2) = \frac{3}{4}\frac{2g_v^e g_a^e \times 2g_v^f g_a^f}{[(g_v^e)^2+(g_a^e)^2][(g_v^f)^2+(g_a^f)^2]} \equiv \frac{3}{4}\mathcal{A}^e\mathcal{A}^f$$

- radiative corrections in the SM at the Z resonance, "Z-pole approximation" :

  neglecting non-resonant box contributions and bosonic corrections to photon-exchange diagrams

  ⇒ factorisation of the Z amplitude as the product of initial- and final-state EW form factors

  ⇒ the structure of AFB remains 3/4 $\mathcal{A}$^e $\mathcal{A}$^f , tree-level couplings replaced by form factors

  ⇒ definition of an effective coupling at $\sqrt{s}$=MZ, with the real part of the form factors

$$4|Q_f|\sin^2\theta^f_{eff} = 1 - \frac{g_V^f}{g_A^f}$$

- "model independent" parameterisation of the Z boson couplings to fermions at the Z resonance used for the fit to the experimental data

  → sensitivity to Higgs and to BSM physics
  entering via the gauge boson vacuum polarization (oblique corrections)

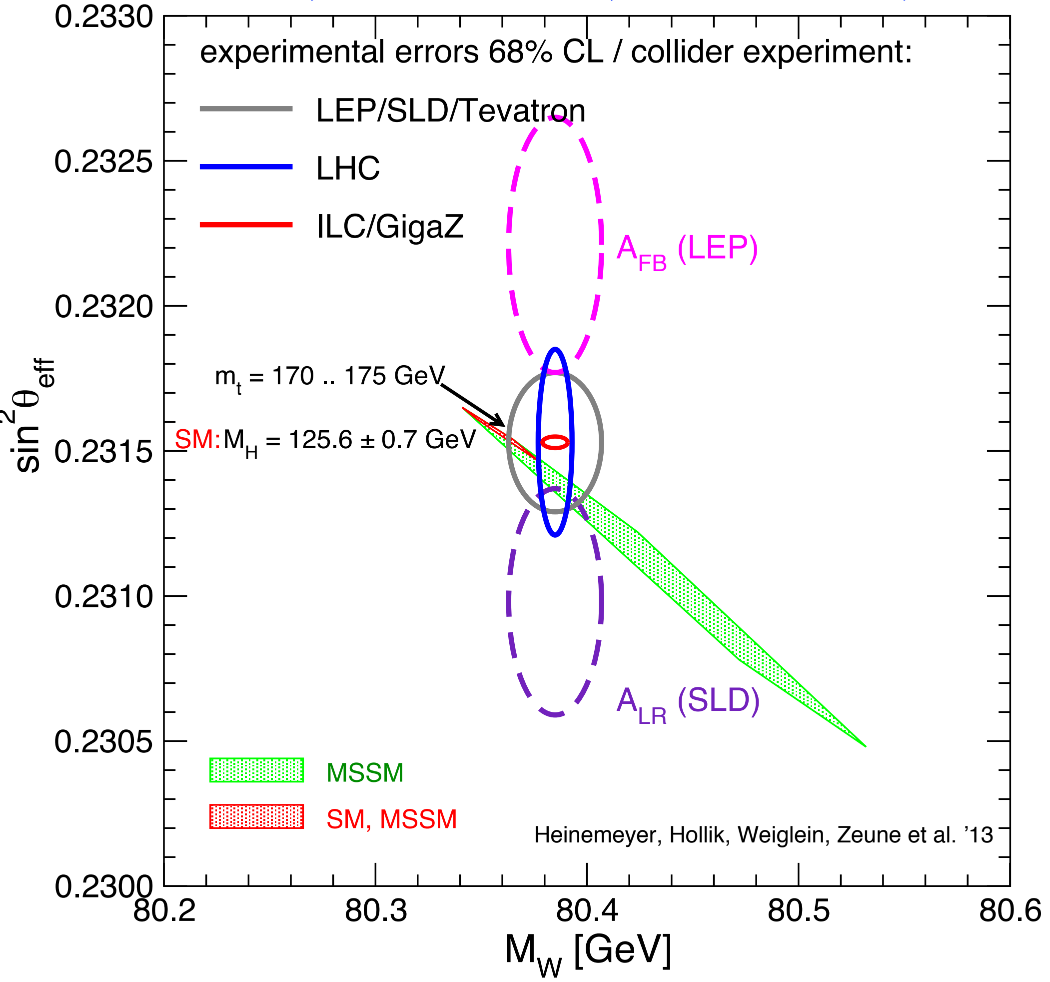
- the left-right polarization asymmetry at the Z resonance allowed at SLD

  crucial complementary tests of the effective angle

$$A_{LR}(m_Z^2) = \mathcal{A}^e$$

Relevance of new high-precision measurement of EW parameters

Baak et al., arXiv:1310.6708, Snowmass 2013, EW WG



The precision measurement of MW and $\sin^2\theta_{eff}$
with an error of 5 MeV and 0.00021
(formidable challenges!)
would offer a very stringent
test of the SM likelihood

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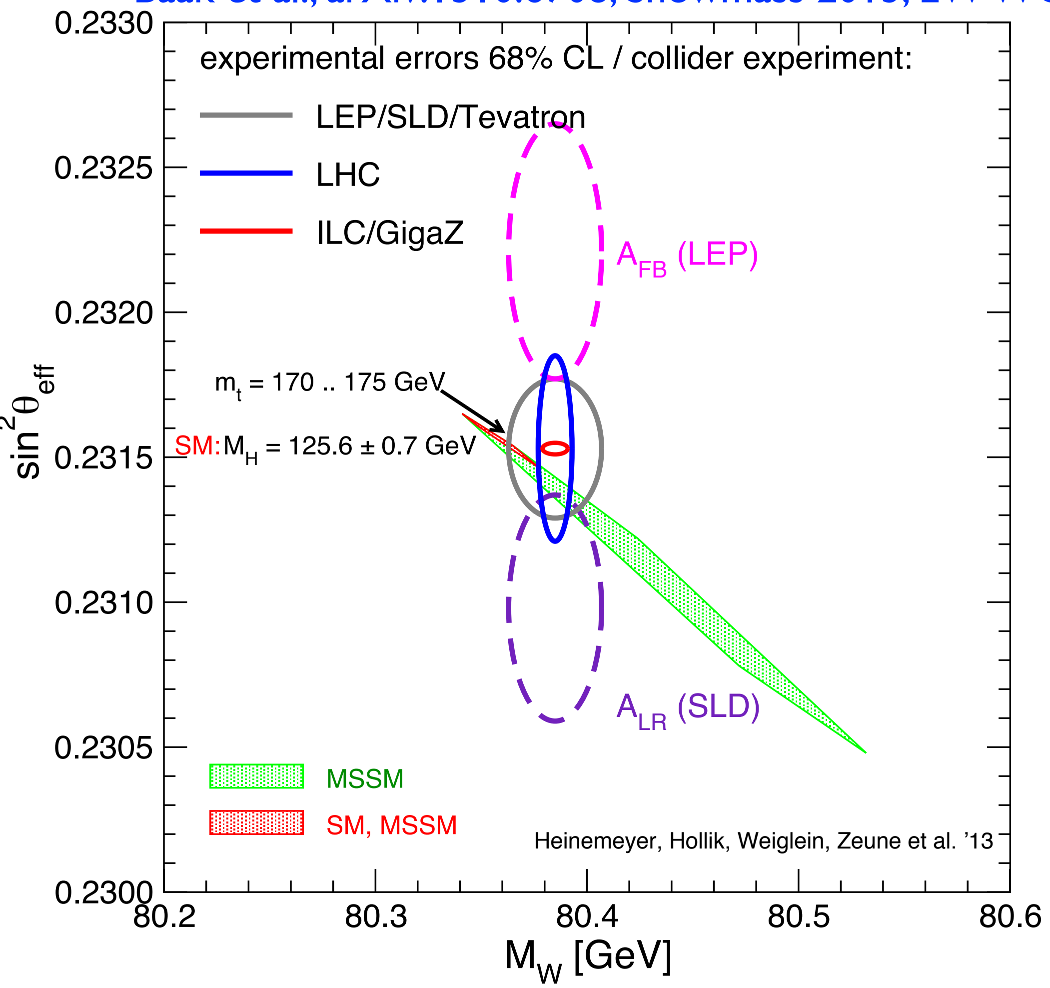

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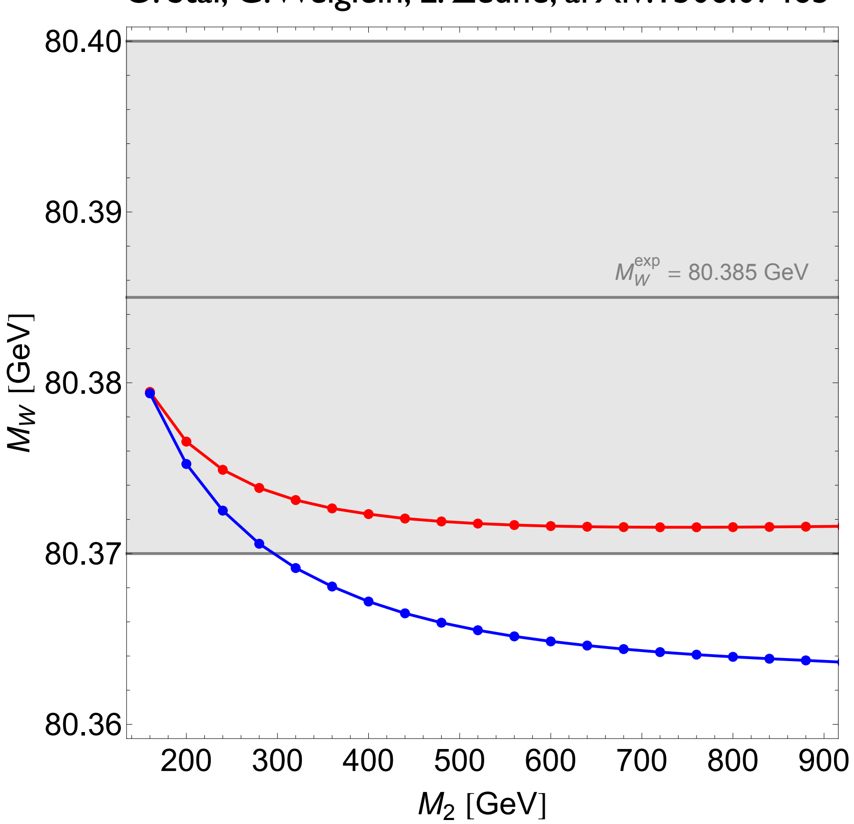
O. Stål, G. Weiglein, L. Zeune, arXiv:1506.07465

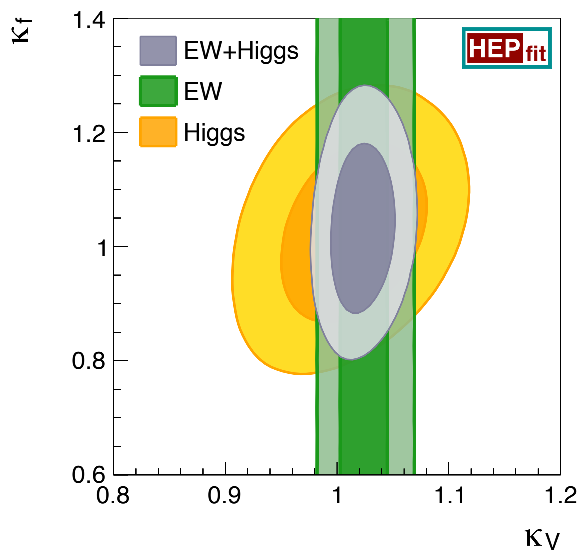


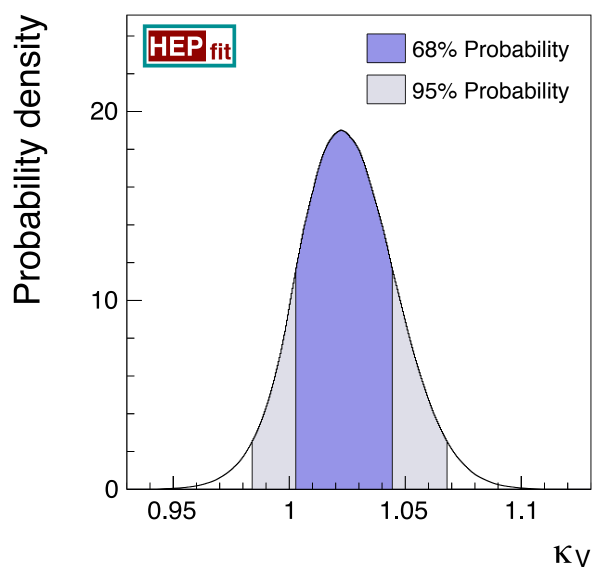
In the case a BSM particle had been discovered
a very precise MW value would offer
a strongly discriminating tool about the mass spectra
in BSM models

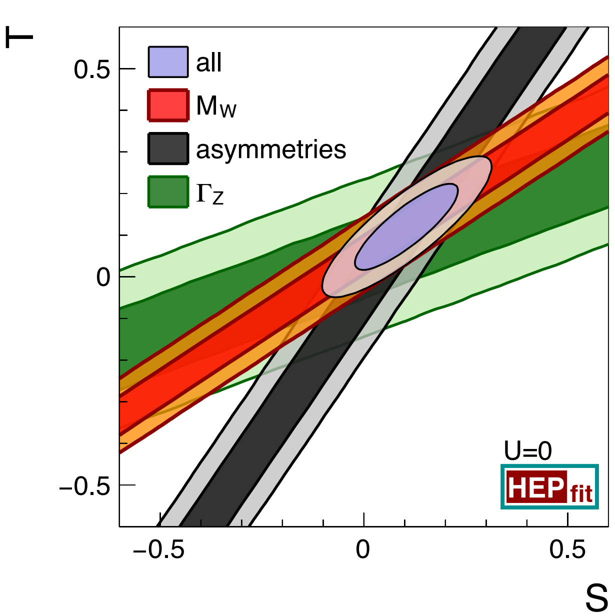
different dependence on the neutralino mass M_2
of the MW prediction in the MSSM and NMSSM

Relevance of new high-precision measurement of EW parameters

de Blas et al, arXiv:1608.01509







$$\mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \xrightarrow[\text{Effects suppressed by}]{} \left(\frac{q}{\Lambda}\right)^{d-4} \quad q = v, E < \Lambda$$

Λ: Cut-off of the EFT

$$\mathcal{O}_{\phi WB} = \phi^\dagger \sigma_a \phi B^{\mu\nu} W^a_{\mu\nu} \quad \text{EWSB} \to \begin{cases} v^2 B^{\mu\nu} W^3_{\mu\nu} & \text{gauge boson masses} \\ vh B^{\mu\nu} W^3_{\mu\nu} & h \to ZZ, \gamma\gamma \end{cases}$$

$$M_W^2 = M_Z^2 c^2 \left[1 - \frac{c^2}{c^2 - s^2}\left(\frac{1}{2}C_{\phi D} + 2\frac{s}{c}C_{\phi WB} + \frac{s^2}{c^2}\Delta_{G_\mu}\right)\frac{v^2}{\Lambda^2}\right]$$

A precise measurement of MW and of $\sin^2\theta_{\rm eff}$ constrains several dim-6 operators contributing to Higgs and gauge interaction vertices.

Today still one of the strongest constraints

High-precision measurements

MW and $\sin^2\theta$ determination at hadron colliders

Vocabulary

Observables quantities accessible via counting experiments

cross sections and asymmetries

Pseudo-Observables quantities that are functions of the cross section and asymmetries

require a model to be properly defined

- the Z boson mass at LEP as the pole of the Breit-Wigner resonance factor
- $\sin^2\theta_{eff}$ at the Z resonance at LEP from the ratio of $\mathcal{G}v/\mathcal{G}a$ form factors
- the W mass at hadron collider as the fitting parameter of a template fit procedure with templates computed in a model (typically the SM)

Template fit
- several histograms describing a differential distribution, computed in a given model, 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
  1) on the chosen model
  2) on the hypotheses used to compute the templates ($\rightarrow$ theoretical systematic errors)
- accurate calculations, properly implemented in Monte Carlo event generators are needed to reduce this systematic error

Model dependency
- new physics might affect the kinematical distributions via virtual corrections (whose impact depends on the specific formulation of the event generator)

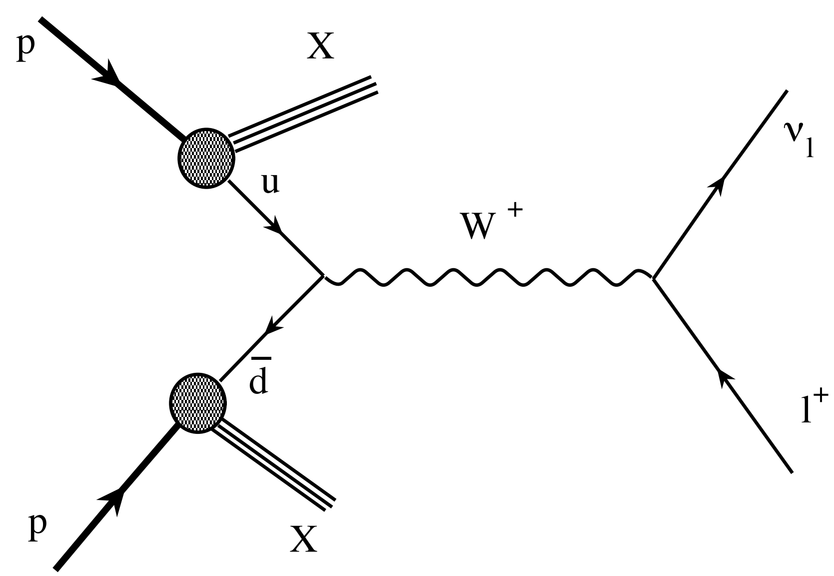
how different is the result for MW with MSSM templates vs SM templates ?

The Drell-Yan process

- production of a pair of leptons with high transverse (missing) momentum
  in hadron-hadron collisions (either collider or fixed target experiments)

- along the beam axis large soft (i.e. non-perturbative) hadronic activity

→ the large lepton momenta in the plane transverse to the beam axis guarantee
a clean signature
the perturbative regime of QCD



- important probe of QCD dynamics:
  1) the lepton pair recoils in the transverse plane against initial state QCD radiation
  2) the lepton-pair rapidity is directly connected to the proton PDFs

these d.o.f. are two of the mostly relevant (limiting) factors for precision EW measurements

MW determination at hadron colliders

In charged-current DY, it is NOT possible to reconstruct the lepton-pair invariant mass
Full reconstruction is possible (but not easy) only in the transverse plane

MW extracted from the study of the shape of the MT, pt_lep, ET_miss distributions in CC-DY thanks to the jacobian peak that enhances the sensitivity to MW

$$\frac{d}{dp_\perp^2} \to \frac{2}{s}\frac{1}{\sqrt{1-4p_\perp^2/s}}\frac{d}{d\cos\theta}$$

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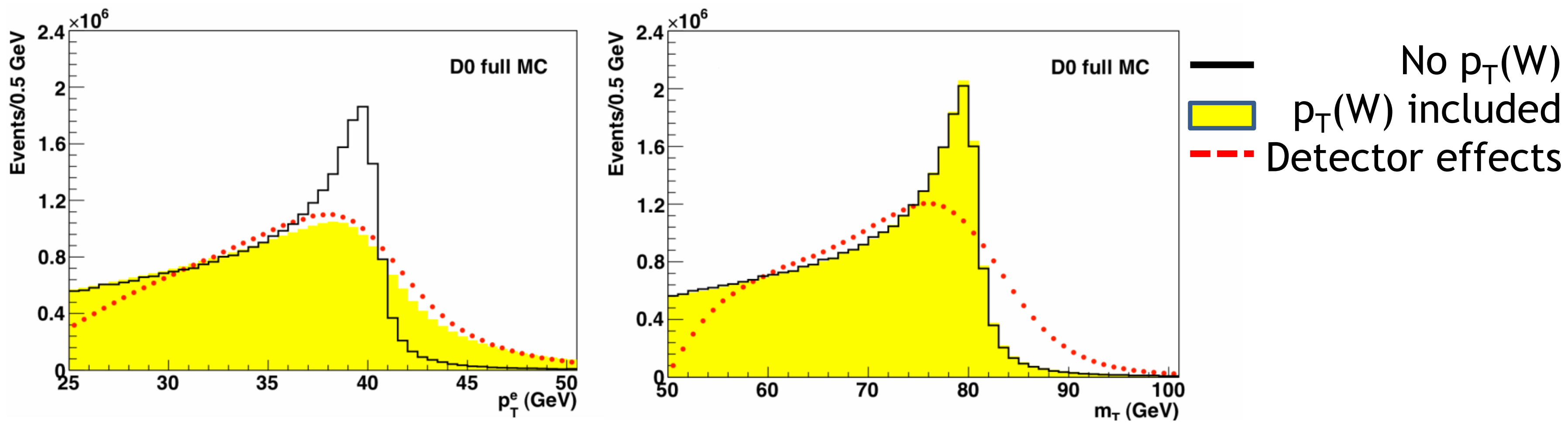
problems are due to
- the smearing of the distributions due to difficult neutrino reconstruction
- strong sensitivity to the modelling of initial state QCD effects



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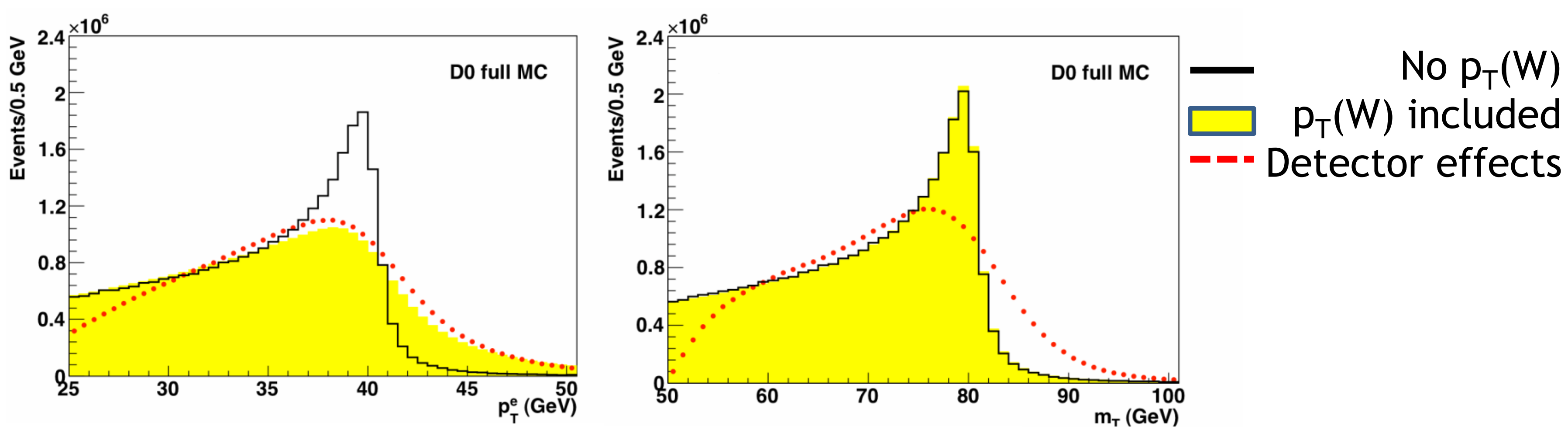
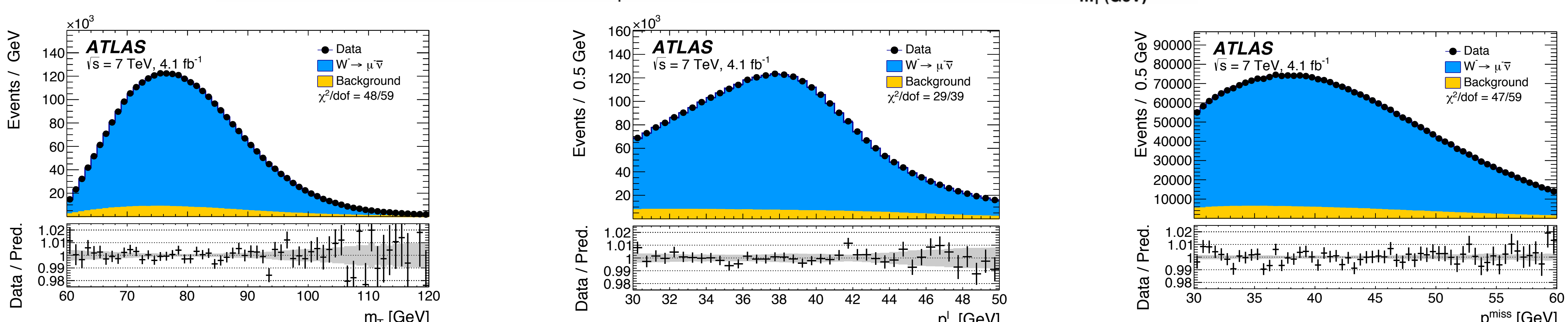




$$m_W = 80369.5 \pm 6.8\ \text{MeV(stat.)} \pm 10.6\ \text{MeV(exp. syst.)} \pm \boxed{13.6\ \text{MeV(mod. syst.)}}$$
$$= 80369.5 \pm 18.5\ \text{MeV},$$

ATLAS error dominated by modelling systematics

Weak mixing angle determination at hadron colliders (I)

invariant mass Forward-Backward asymmetry in neutral-current DY

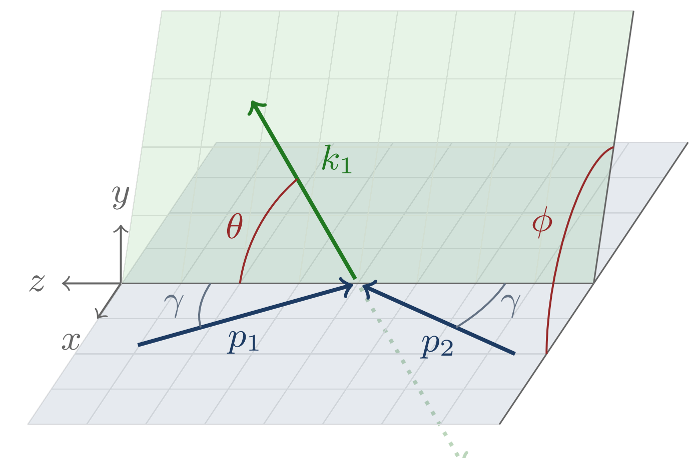
$$A_{FB}(M_{l^+l^-}) = \frac{F(M_{l^+l^-}) - B(M_{l^+l^-})}{F(M_{l^+l^-}) + B(M_{l^+l^-})}$$

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

scattering angle defined in the Collins-Soper frame → “Forward” (“Backward”)

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

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



we would like to appreciate parity violation like at LEP,
observing an asymmetry with respect to the direction of the incoming particle
- → it is not possible because we have both q-qbar and qbar-q annihilation processes
- → at the LHC the symmetry of the collider (p-p) removes one possible preferred direction

but…

Weak mixing angle determination at hadron colliders (I)

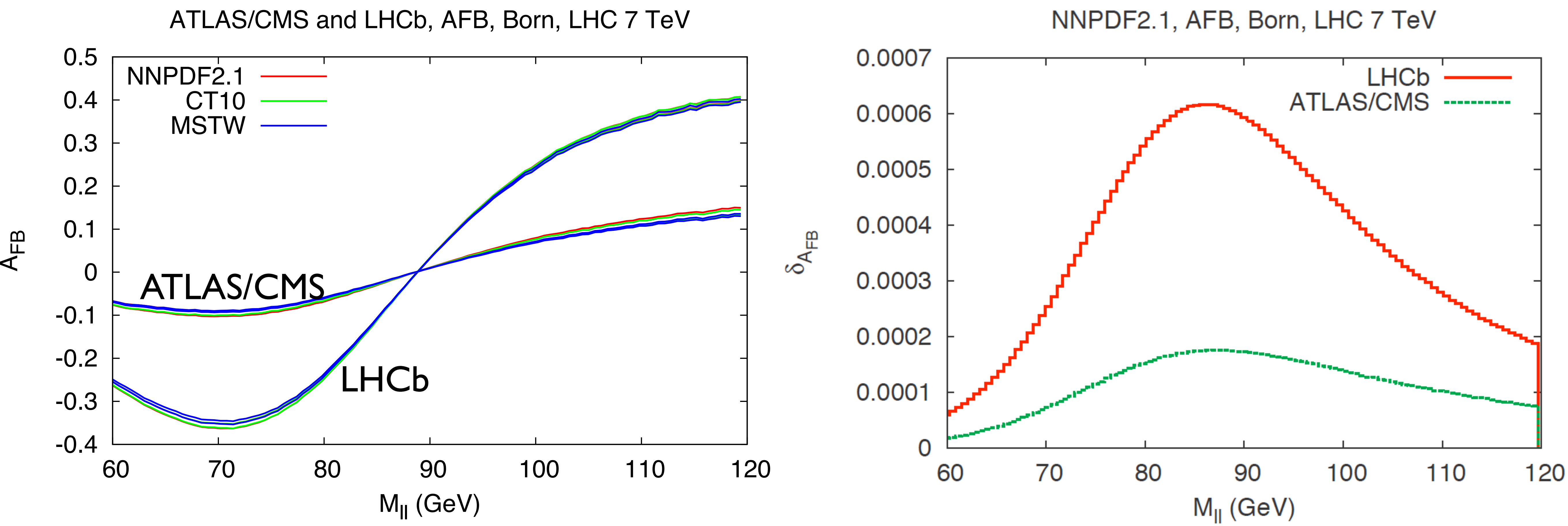
…but

at a given lepton-pair rapidity Y

q-qbar and qbar-q have different weight because of the PDFs ⇒ do not cancel each other

the parton luminosity unbalance is due to the different *x* dependence of the valence and sea quarks

AFB is more pronounced at large Y, e.g. at LHCb



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

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

close to MZ : small AFB but good sensitivity to the weak mixing angle

away from MZ : large AFB, no sensitivity to the weak mixing angle, possible effects from new Z'…

AFB probes a PDF weighted combination of up, down and leptonic effective angles

away from MZ: "model independent" parameterisation of AFB is not possible, we compute it in the SM

Weak mixing angle determination at hadron colliders (II)

The Drell-Yan process, including QCD corrections only, can be described as the production of a vector boss and its subsequent decay

The leptons kinematics can be described in terms of angular coefficients A_i, which carry the information about the initial state QCD dynamics (pt, invariant mass, rapidity of the lepton pair)

$$\frac{d\sigma}{d^4q\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{unpol}}{d^4q}\left\{1+\cos^2\theta + \right.$$

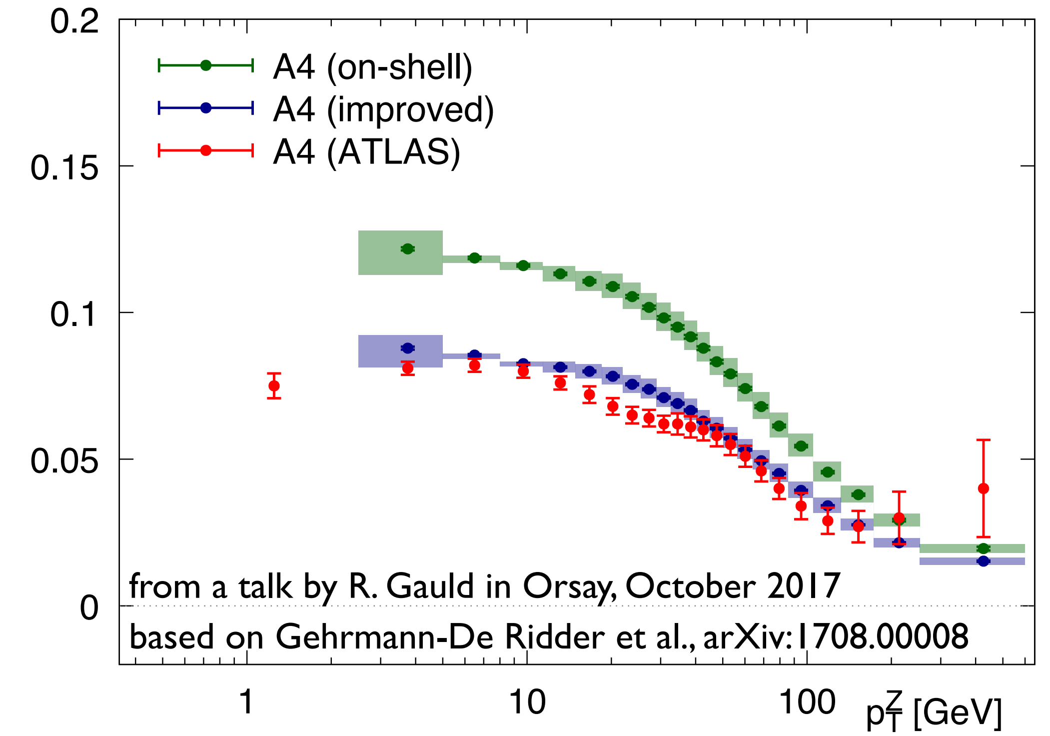
normalised by dσ(unpol)

even under parity $$A_0(1-\cos^2\theta) + A_1\sin(2\theta)\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos(2\phi) +$$

odd under parity $$A_3\sin\theta\cos\phi + A_4\cos\theta +$$

start at O(α_s^2) $$\left. A_5\sin^2\theta\sin(2\phi) + A_6\sin(2\theta)\sin\phi + A_7\sin\theta\sin\phi\right\}$$

The coefficients A3 and A4 describe the contribution of the cross section odd under parity
and in turn are sensitive to the weak mixing angle.



Pseudo-observables and EW input schemes

To fit a pseudo-observable, the templates are computed in a given model (e.g. SM)

Every quantity (observable and pseudo-observable) predicted e.g. in the SM
is expressed in terms of the lagrangian input parameters

The lagrangian inputs are the only parameters which can be varied in the template fitting procedure

example: when using (α, G_μ, MZ, MH) as inputs (the LEP scheme),
then MW is a prediction and can NOT be used as fitting parameter
at most, we can assess the SM likelihood for a given (α, G_μ, MZ, MH) set

The G_μ scheme is commonly used at hadron colliders and treats (G_μ, MW, MZ, MH) as inputs
in this scheme we can fit MW
relation between $\sin^2\theta_{eff}$ and MW known at 2-loop EW level (available in POWHEG)
$\sin^2\theta_{eff}$ is a derived quantity, which can be computed given the measured MW value

CC and NC DY should be studied in a common framework, with the same input scheme
pro: consistent reduction of common systematic uncertainties
caveat: only the chosen inputs can be varied, i.e. measured

SM lagrangian parameters and EW input schemes

$(g, g', v; \lambda)$ + 9 yukawa couplings + 4 CKM param's $\lambda \to m_H = v\,\sqrt{\lambda/2}$

The gauge sector is parameterised by 3 independent couplings (g, g', v) .
Any other observable can/must be computed in terms of these 3 couplings.

Different possibilities to express (g, g', v) in terms of measured quantities.

$(g, g', v) \to (\alpha_0, G_\mu, m_Z)$ LEP scheme: minimal parametric uncertainty in the predictions
Z and γ diagrams have their "natural" coupling
MW and $\sin^2\theta_W$ are predictions, can not be fitted

$\to (G_\mu, m_W, m_Z)$ Gmu scheme: MW is a free parameter which can be fitted

independent of light-quark masses
it reabsorbs large logarithmic corrections

α and $\sin^2\theta_W$ are predictions, can not be fitted

$\to (\alpha_0, m_W, m_Z)$ α_0 scheme: dependent on the light-quark masses
receives large logarithmic corrections

Simulating the DY processes

Tools for Drell-Yan simulations: inclusive lepton-pair production

i.e. how we compute the templates

Codes including fixed-order results

FEWZ	NNLO QCD (W)
	NNLO QCD + NLO EW (Z)
DYNNLO	NNLO QCD
MCFM	NLO QCD
WZGRAD	NLO EW
SANC	NLO QCD + NLO EW
RADY	NLO QCD + NLO EW

Codes including the matching of fixed- and all-order results

DYRes	NNLO+NNLL QCD
ResBos	(N)NLO+NNLL QCD
RadISH	NNLO+N3LL
MC@NLO	NLO+PS QCD
POWHEG	NLO+PS QCD
DYNNLOPS	NNLO+PS QCD
Sherpa	NNLO+PS QCD
HORACE	NLO-EW +QED-PS
POWHEG	NLO-(QCD+EW) + (QCD+QED)-PS

Technical comparison and systematic classification of higher orders in Alioli et al., arXiv:1606.02330
repository of all the codes involved in https://twiki.cern.ch/twiki/bin/view/LHCPhysics/EWWG1

Exact $O(\alpha\alpha_s)$ results are not available,

bulk of these contributions included in approximated way in simulation codes

Coupling expansion and logarithmic enhancements (I)

$$\alpha_s(m_Z) \simeq 0.118, \qquad \alpha_{em}(m_Z) \simeq 0.0078 \qquad \frac{\alpha_s(m_Z)}{\alpha_{em}(m_Z)} \simeq 15.1 \qquad \frac{\alpha_s^2(m_Z)}{\alpha_{em}(m_Z)} \simeq 1.8$$

Coupling strength → first classification (NNLO-QCD ~ NLO-EW) is appropriate for those observables that do not receive any logarithmically enhanced correction

$$\begin{aligned}\sigma_{tot} \;=\; \sigma_0 \;&+\; \alpha_s\sigma_{\alpha_s} \;+\; \alpha_s^2\sigma_{\alpha_s^2} \;+\; \ldots && \text{QCD}\\ &+\; \alpha\sigma_{\alpha} \;+\; \alpha^2\sigma_{\alpha^2} \;+\; \ldots && \text{EW}\\ &+\; \alpha\alpha_s\,\sigma_{\alpha\alpha_s} \;+\; \alpha\alpha_s^2\,\sigma_{\alpha\alpha_s^2} \;+\; \ldots && \text{mixed QCDxEW}\end{aligned}$$

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At differential level, in specific phase-space corners, a plain coupling constant expansion is inadequate
→ fixed-order EW corrections can become as large as (or even bigger than) QCD corrections because of log-enhanced factors
→ log-enhanced corrections have to be resummed to all orders, if possible, analytically or via Parton Shower, rearranging the structure of the perturbative expansion

In presence of resummed expressions, the QCDxEW interplay entangles classes of corrections to all orders in α_s and α

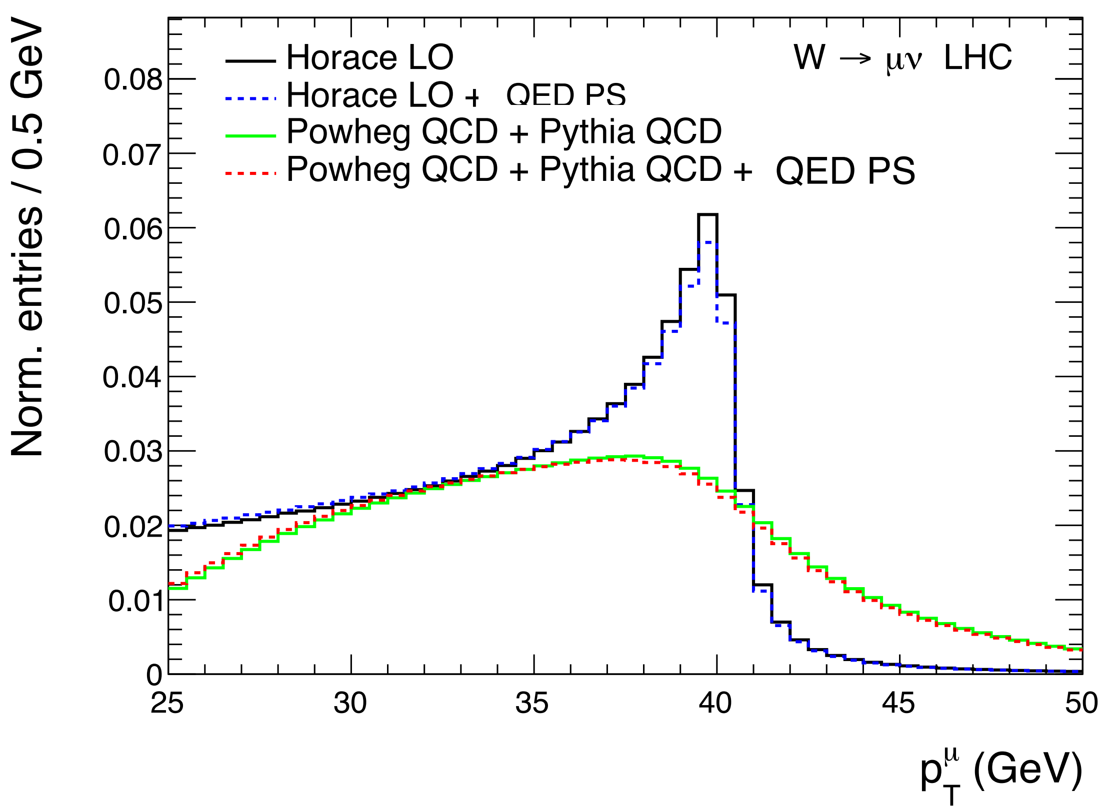
The perturbative convergence depends on the presence of all allowed partonic channel that may contribute to a given final state.

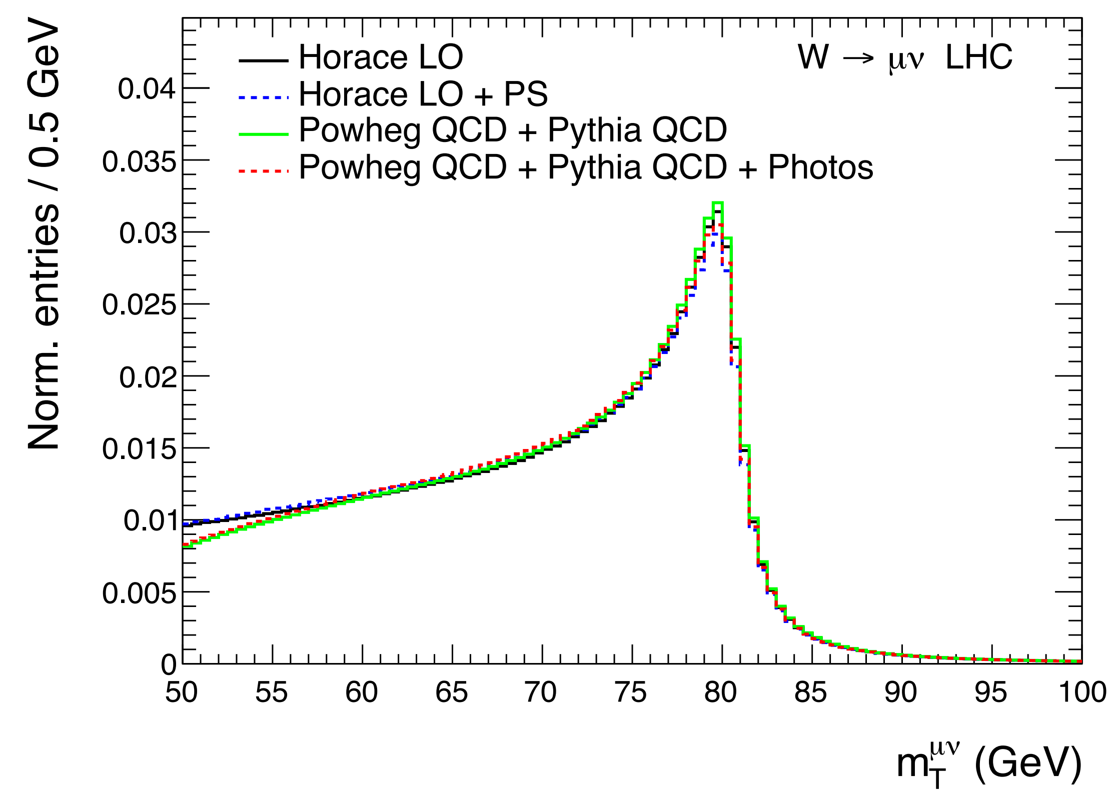
Coupling expansion and logarithmic enhancements (2): QCD

- QCD ISR is responsible for large logarithmic corrections ~ $L_{QCD} \stackrel{\text{def}}{=} \log(\, ptV \,/\, mV\,)$ for a final state V which need to be resummed to all orders, e.g. via QCD Parton Shower

two examples in DY: single lepton pt needs resummation, fixed-order QCD prediction meaningless
lepton-pair transverse mass is very mildly affected when integrating over QCD

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, arXiv:1612.02841

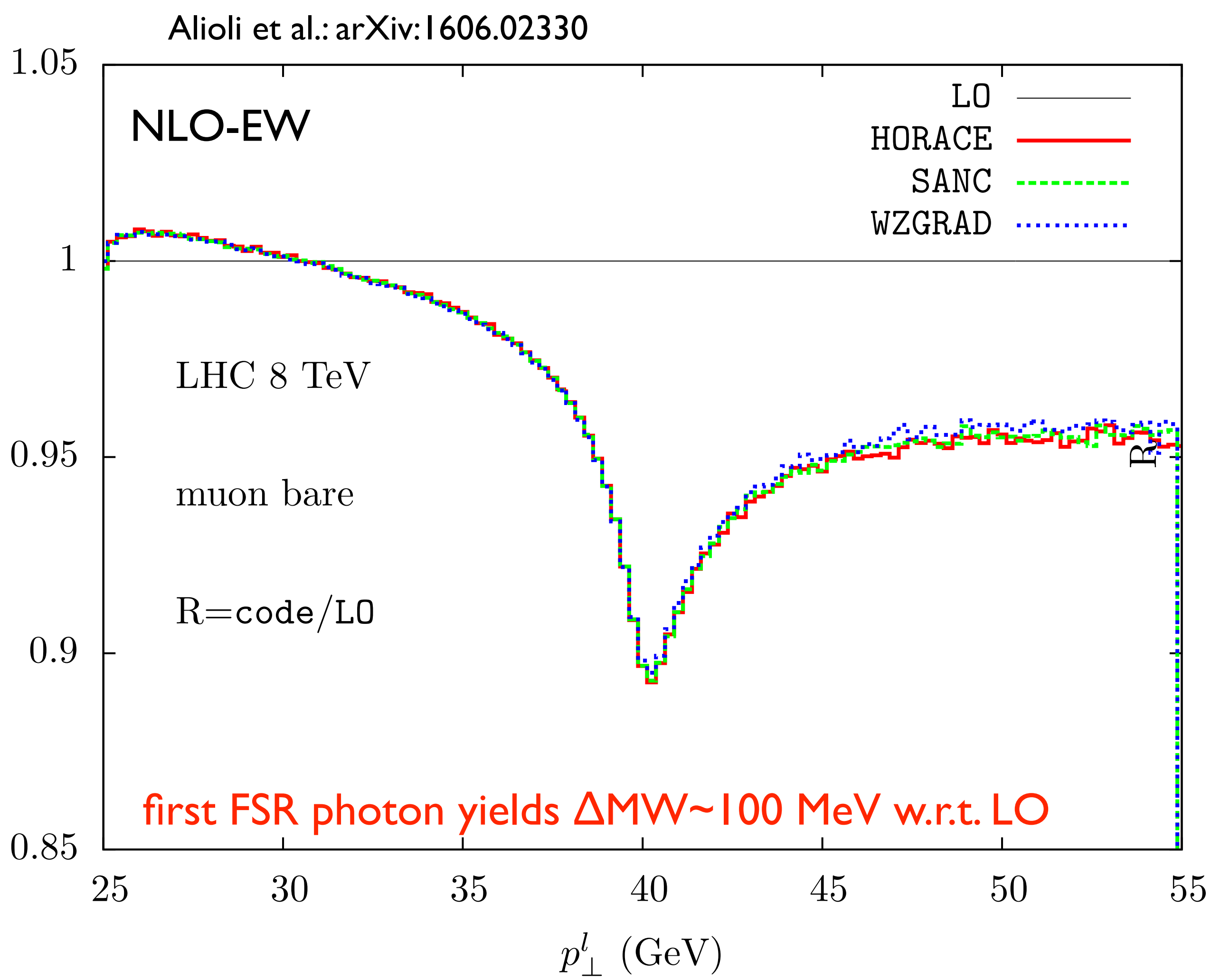


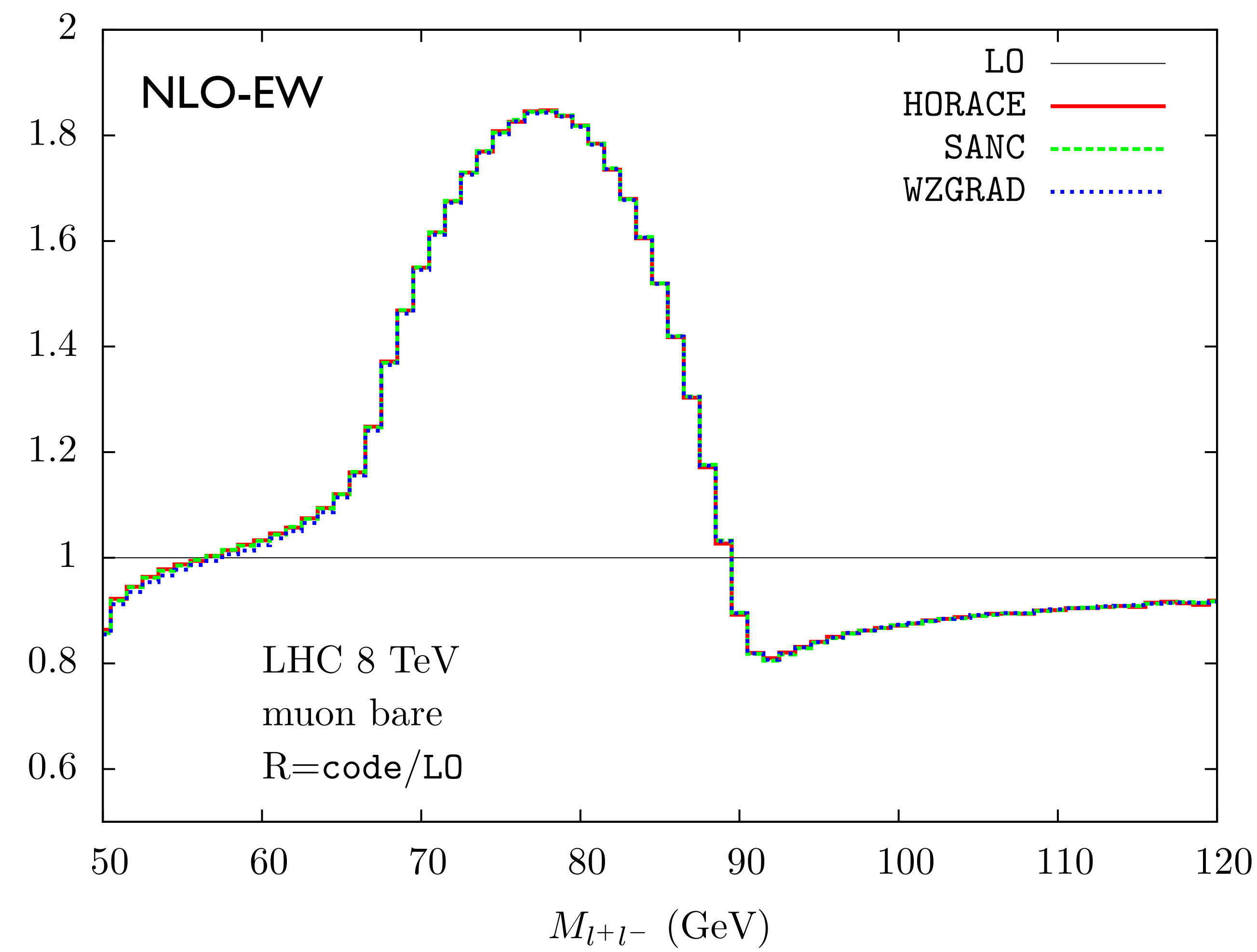


single lepton pt: sensible lowest order approximation offered by LO+PS

Coupling expansion and logarithmic enhancements (2): EW

- QED FSR is responsible for the energy/momentum loss of final state particles, e.g. leptons, yielding large collinear logarithmic corrections ~ $L_{QED} \stackrel{\text{def}}{=} \log(\hat{s}/m_f^2)$ which strongly affect the value of reconstructed observables





Which are the most relevant radiative corrections and uncertainties for precision EW measurements?

- QCD modelling both perturbative and non-perturbative QCD contributions

  transverse d.o.f. → gauge bosons PT spectra → non-pert contributions at low PTZ

  longitudinal d.o.f. → rapidity distributions → PDF uncertainties

- EW and mixed QCDxEW effects

  important QED/EW corrections modulated by the underlying QCD dynamics

  flavour sensitivity

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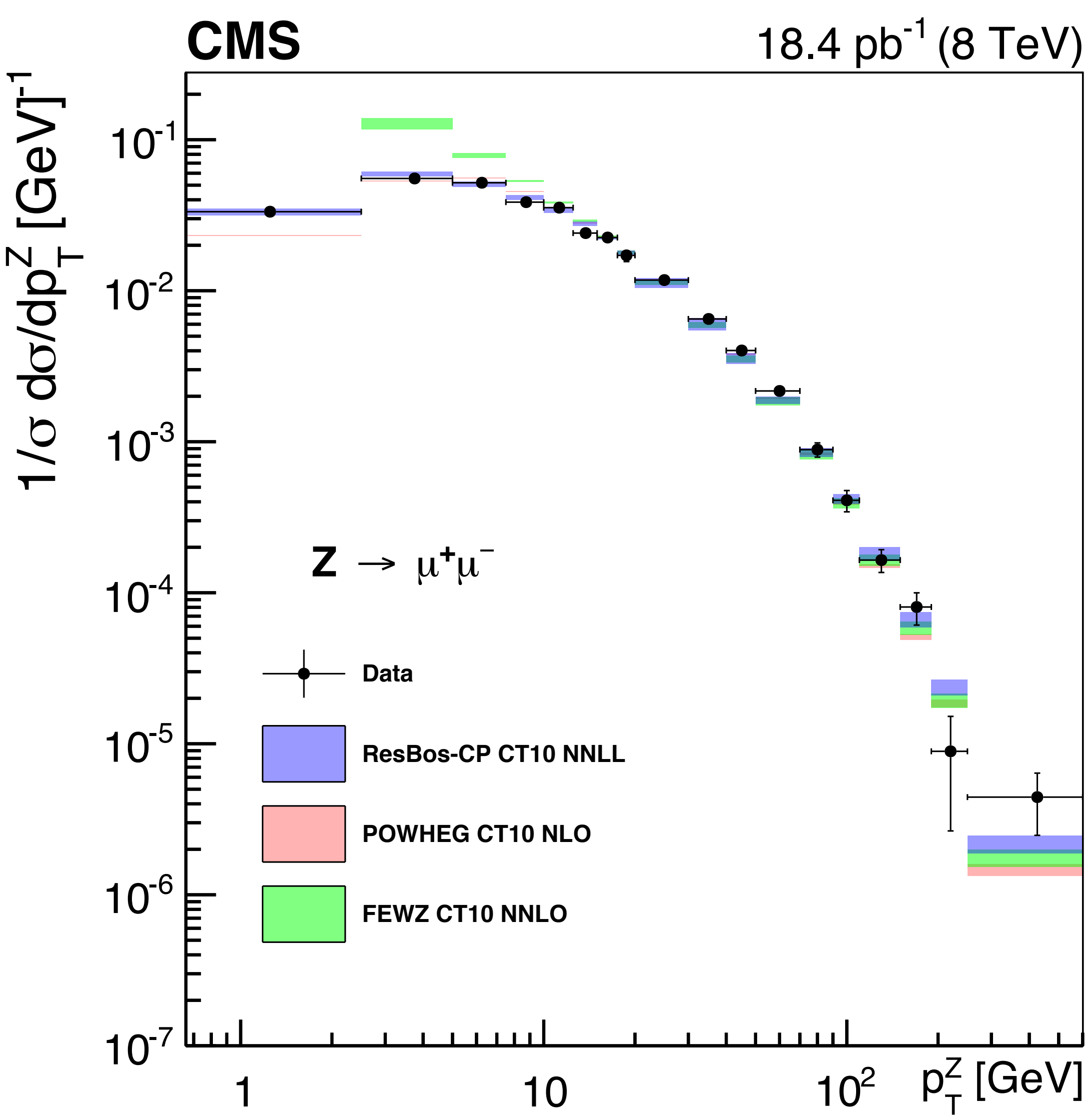
  flavour sensitivity

The simultaneous analysis of CC-DY and NC-DY forces us to discuss
similarities and differences of the two processes w.r.t. radiative corrections and to QCD modelling

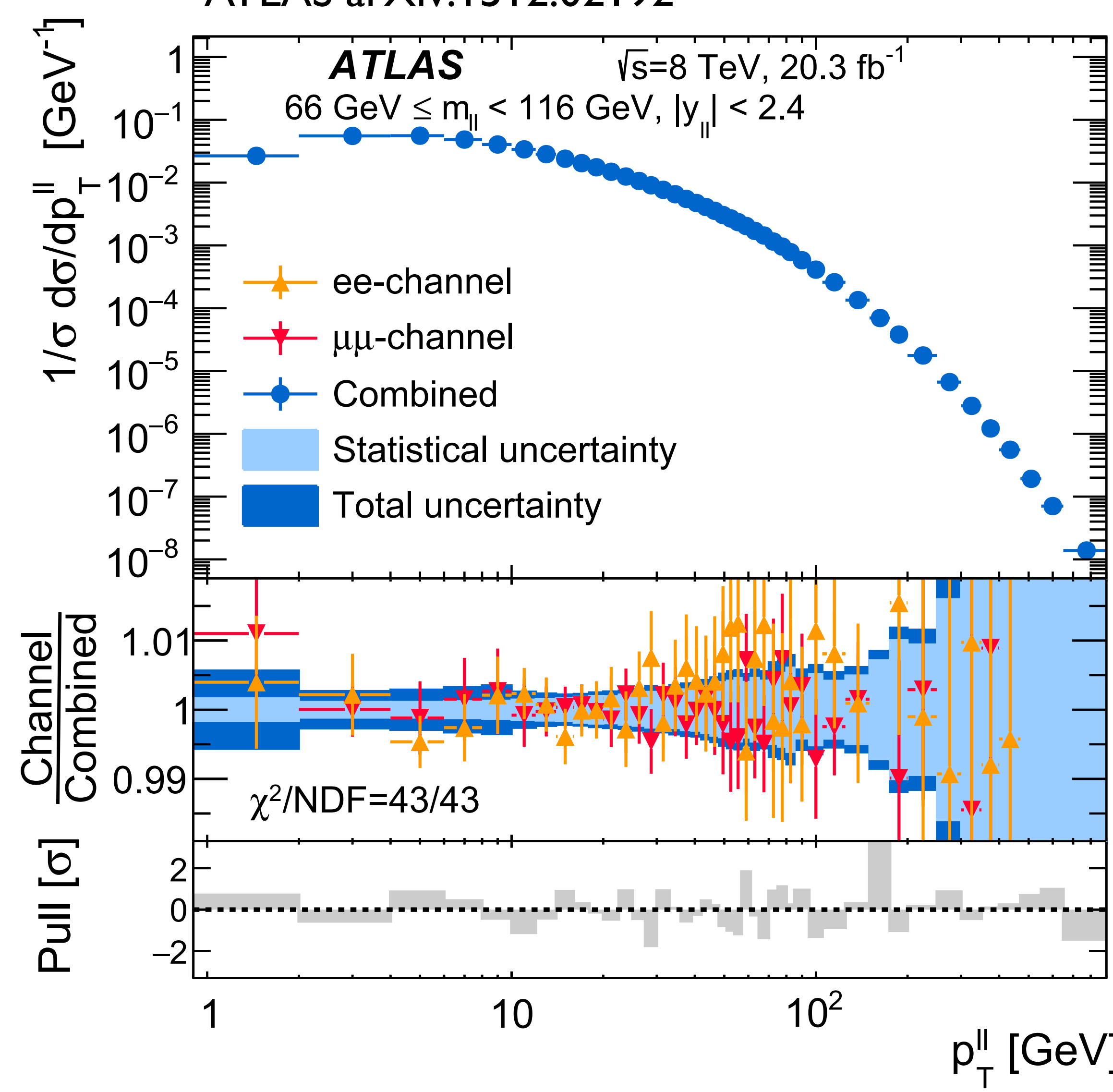
QCD modelling

Lepton-pair transverse momentum distribution

- A crucial role in precision EW measurements (MW in particular) is played by the ptZ distribution
  - ▹ MW is extracted from the fit to the pt_lep, MT and ET_miss distributions
  - ▹ the pt_lep and pt_ν determination strongly depends on a precise control of the ptW distribution
  - ▹ a precise ptW measurement is not yet available → we rely on ptZ and extrapolate from it
  - ▹ ptZ is used to calibrate 1) detectors 2) Monte Carlo tools (Parton Shower at low-ptZ)



ATLAS arXiv:1512.02192

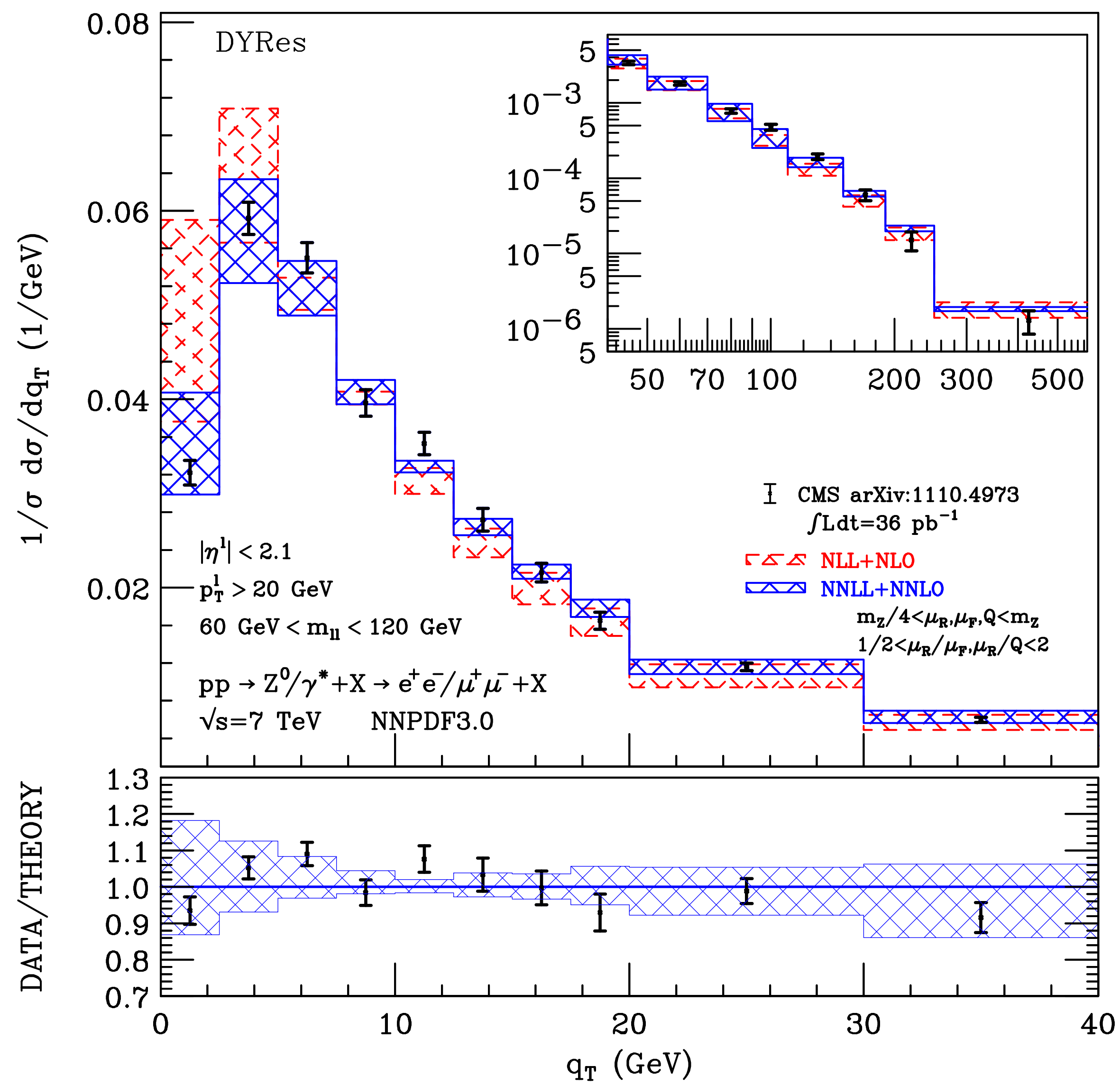


Lepton-pair transverse momentum distribution

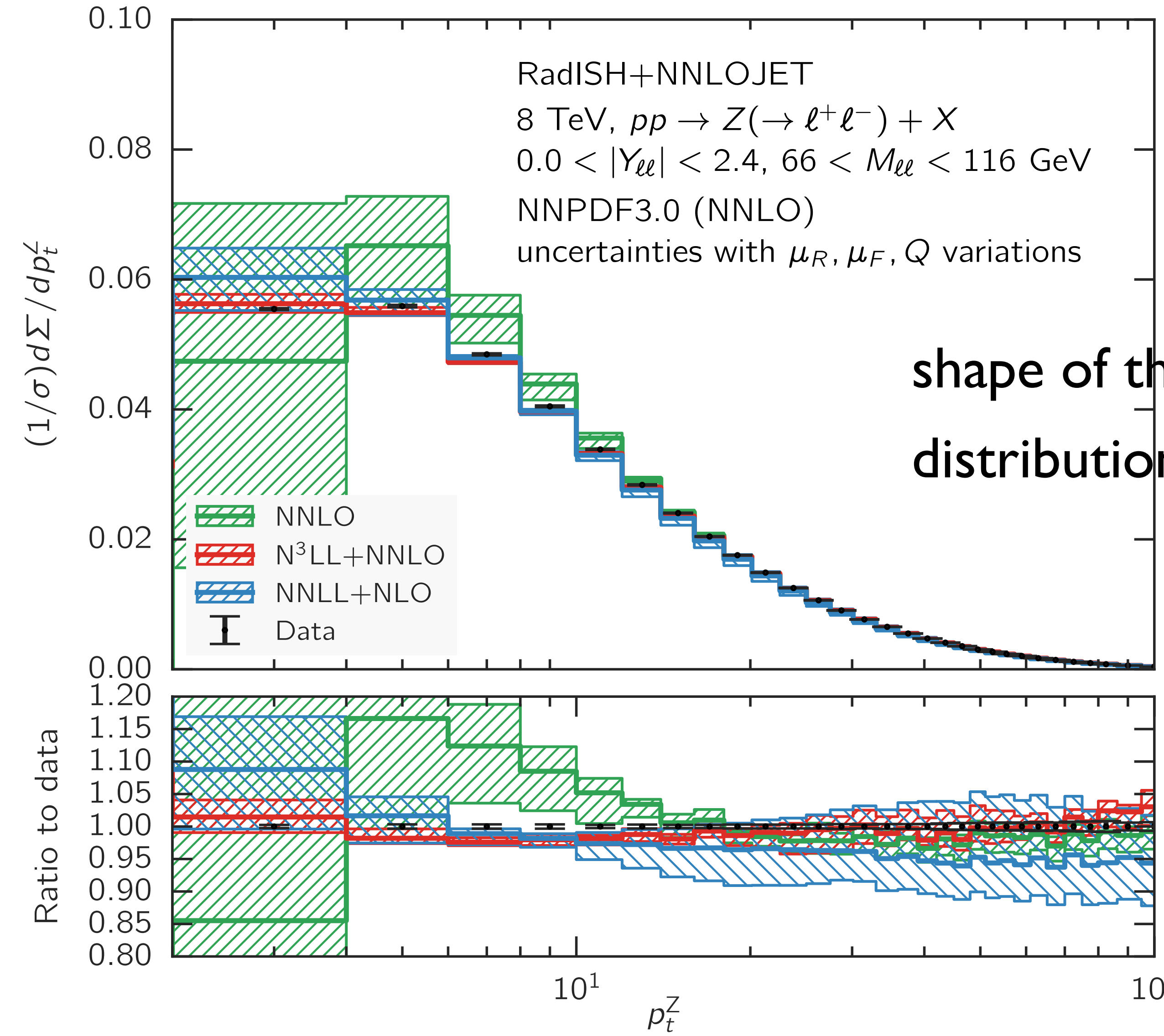
· The precision of the theoretical prediction for ptZ, in dedicated calculations/tools, depends on:

- ▹ logarithmic accuracy (N3LL) in the log(ptZ/MZ) resummation → relevant at small ptZ
- ▹ fixed-order accuracy (NNLO) in the ptZ spectrum → relevant at large ptZ
- ▹ matching prescription → relevant at intermediate ptZ

Catani, De Florian, Ferrera, Grazzini, arXiv: 1507.06937



Bizon et al, arXiv:1805.05916



shape of the distributions

good stability of the RadISH predictions under changes of the matching scheme

Lepton-pair transverse momentum distribution

Matched shower Monte Carlo event generators (cfr. DYNNLOPS, or SHERPA+UN2LOPS)

- ▹ are fully exclusive, general purpose tools; crucial in the experimental analyses
- ▹ accuracy: NNLO-QCD on the inclusive observables, NLO-QCD at large ptZ, (N)LL at small ptZ
- ▹ require a tuning of the Parton Shower parameters (non perturbative effects at low ptZ)
- ▹ are affected by non-negligible matching uncertainties (recipe, matching param's dependence)
- ▹ depend on several algorithmic details (e.g. Parton-Shower phase space)

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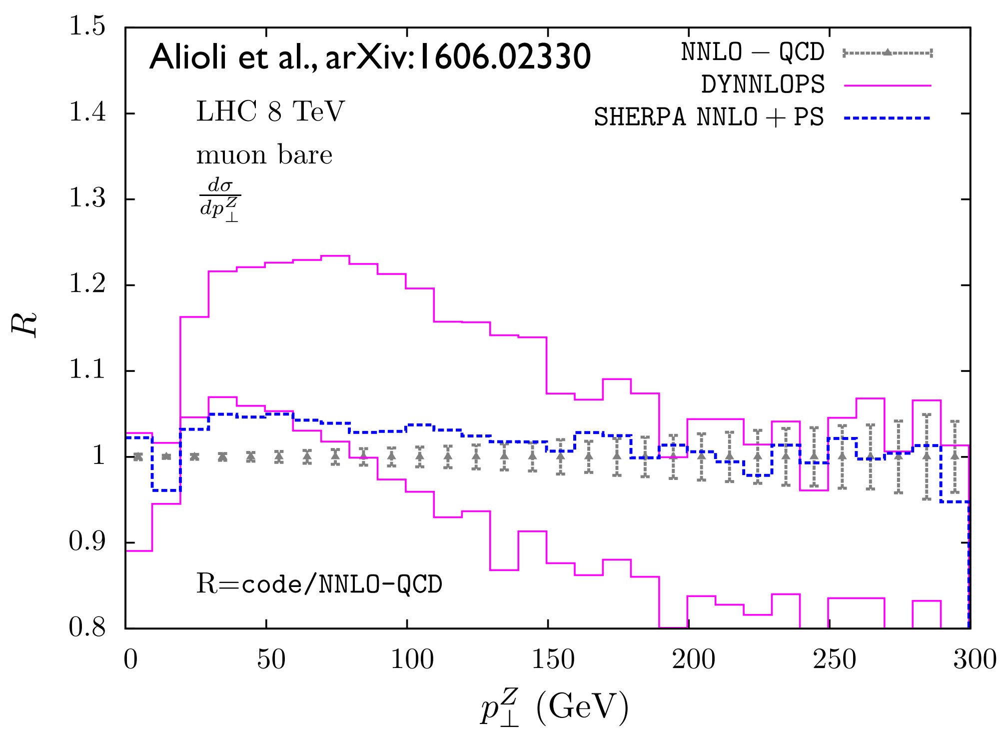
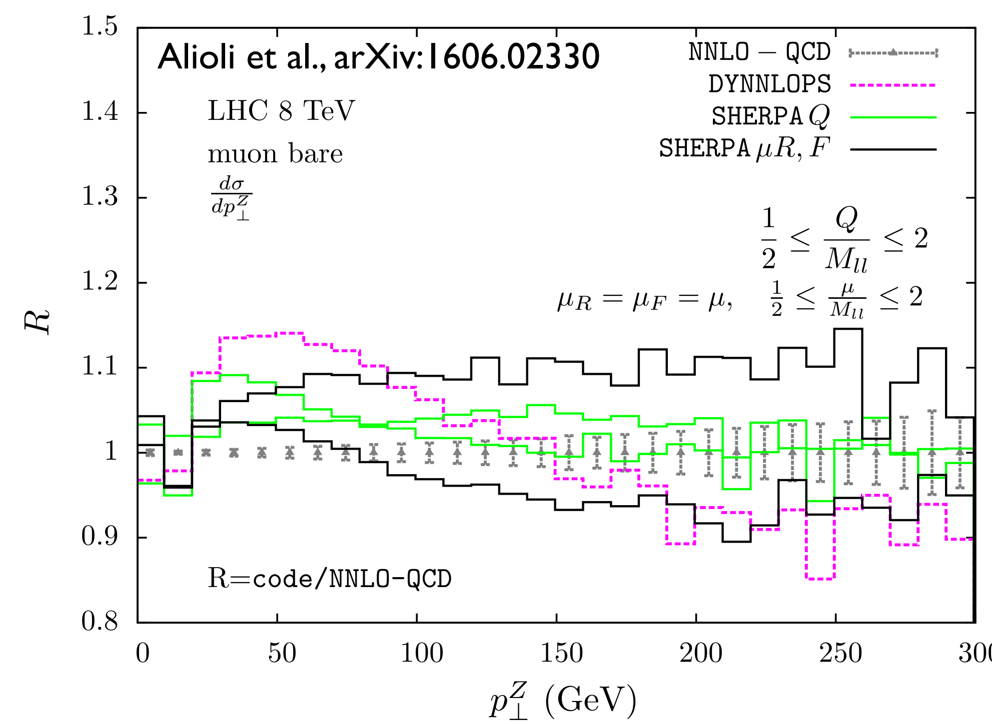
Comparison of the DYNNLOPS and SHERPA+UN2LOPS scale uncertainty bands





comparison of absolute distributions

Lepton-pair transverse momentum distribution

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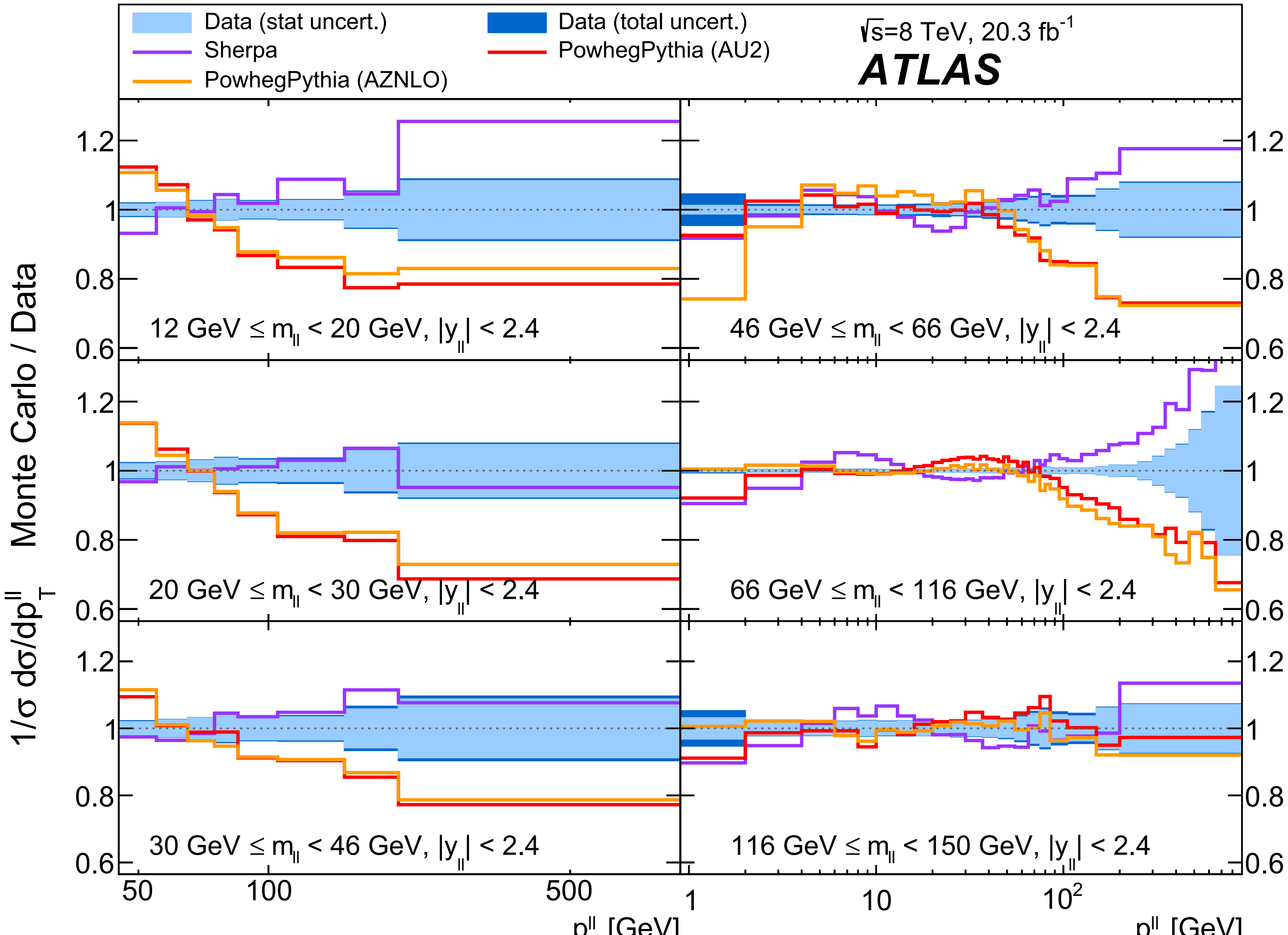

tuning of the Parton Shower
in the combination POWHEG + Pythia 8
at the Z resonance

extrapolation to different
invariant mass windows

Lepton-pair transverse momentum distribution: Z to W extrapolation

The parameters (intrinsic kt, α_s in the PS, hadronization) derived from the calibration on ptZ are used in the CC-DY studies to determine MW.

- are these param's 1) universal ? (i.e. flavour independent)
  2) scale independent (MW ≠ MZ !) ?
- the flavour structure of CC-DY and NC-DY is different

  CC-DY: u dbar, c sbar, … $\rightarrow W^+ \rightarrow l^+\nu$

  NC-DY: u ubar, d dbar, c cbar, s sbar, b bbar,… $\rightarrow \gamma*/Z \rightarrow l^+l^-$

  how do the different flavour structures affect (Z to W)?

  e.g. is the effect of scale variations different (different DGLAP evolution) ?

  role of heavy quarks?

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e.g. is the effect of scale variations different (different DGLAP evolution) ?

role of heavy quarks?

For a realistic estimate of the QCD theoretical uncertainties, we need:

▹ an improved description of all the elements of difference between CC-DY and NC-DY

▹ a good control over the correlation between Z and W w.r.t. the different sources of uncertainty

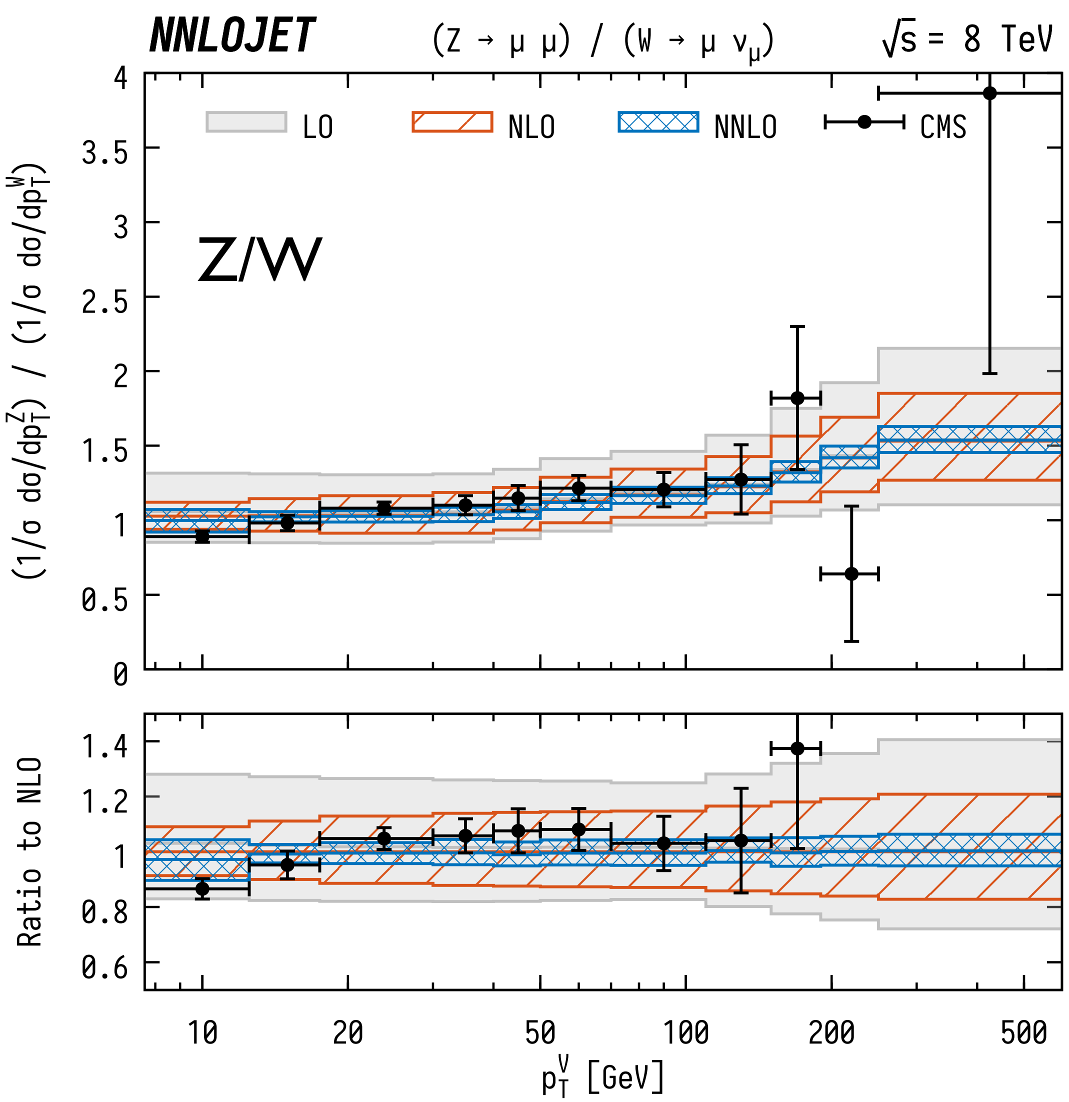
any uncertainty estimate (PDFs, scale variations, etc.) based on CC-DY alone leads to an overestimate of the uncertainty

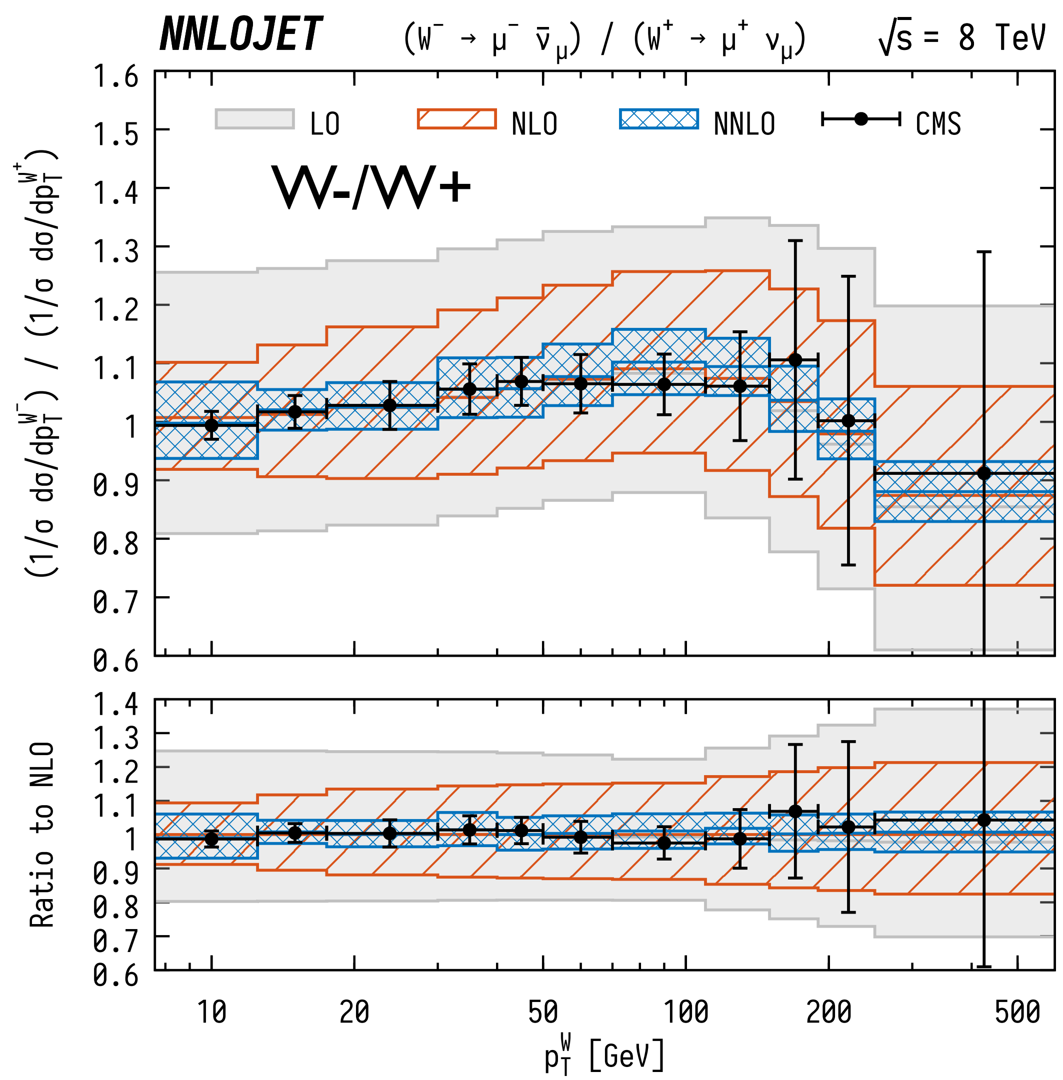
The MW measurement studies the MZ-MW interdependence; it's not an absolute measurement of MW

Lepton-pair transverse momentum distribution: Z to W extrapolation

cfr. Bizon, Chen, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Torrielli, arXiv:1805.05916

plots from A. Huss's talk https://indico.cern.ch/event/656250/contributions/2876486/attachments/1635166/2608517/ahuss.pdf





ratio of shapes of PTV distributions

conservative combination of QCD scales (31 out of 49=7x7)

evident reduction of scale dependence

in the Z/W case a residual shape difference can be guessed

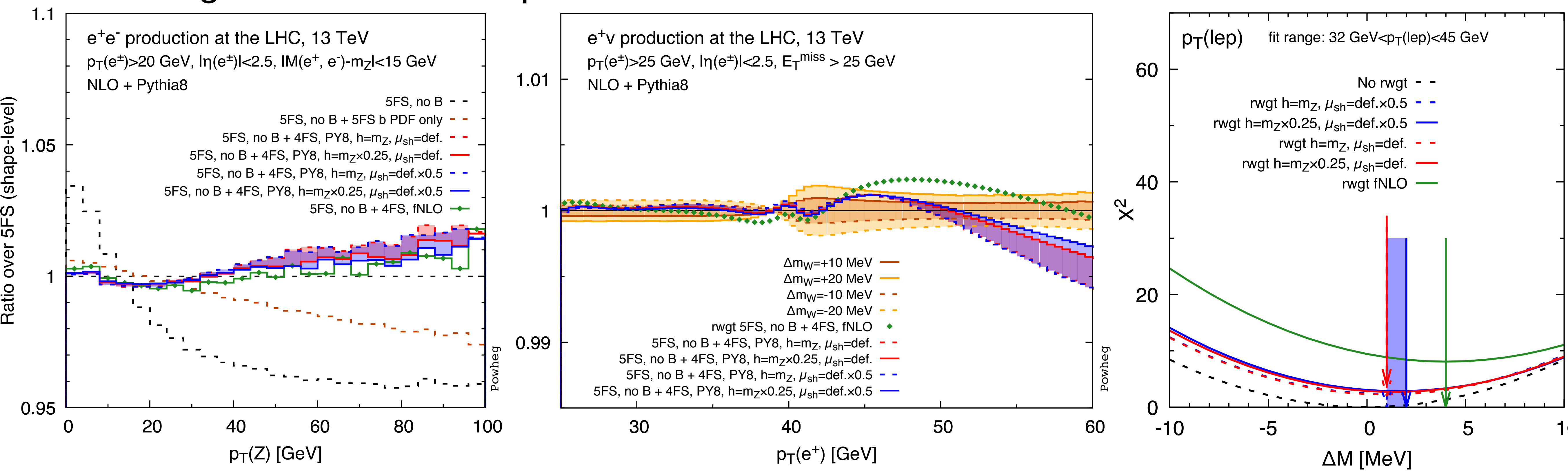
Improving the description of the bottom contributions to ptZ

Bagnaschi, Maltoni, AV, Zaro, arXiv:1803.04336

the standard MW analysis is based on massless 5FS description of Drell-Yan processes

→ which would be the impact of a description of the bottom as a massive quark? 1) on ptZ; 2) on MW

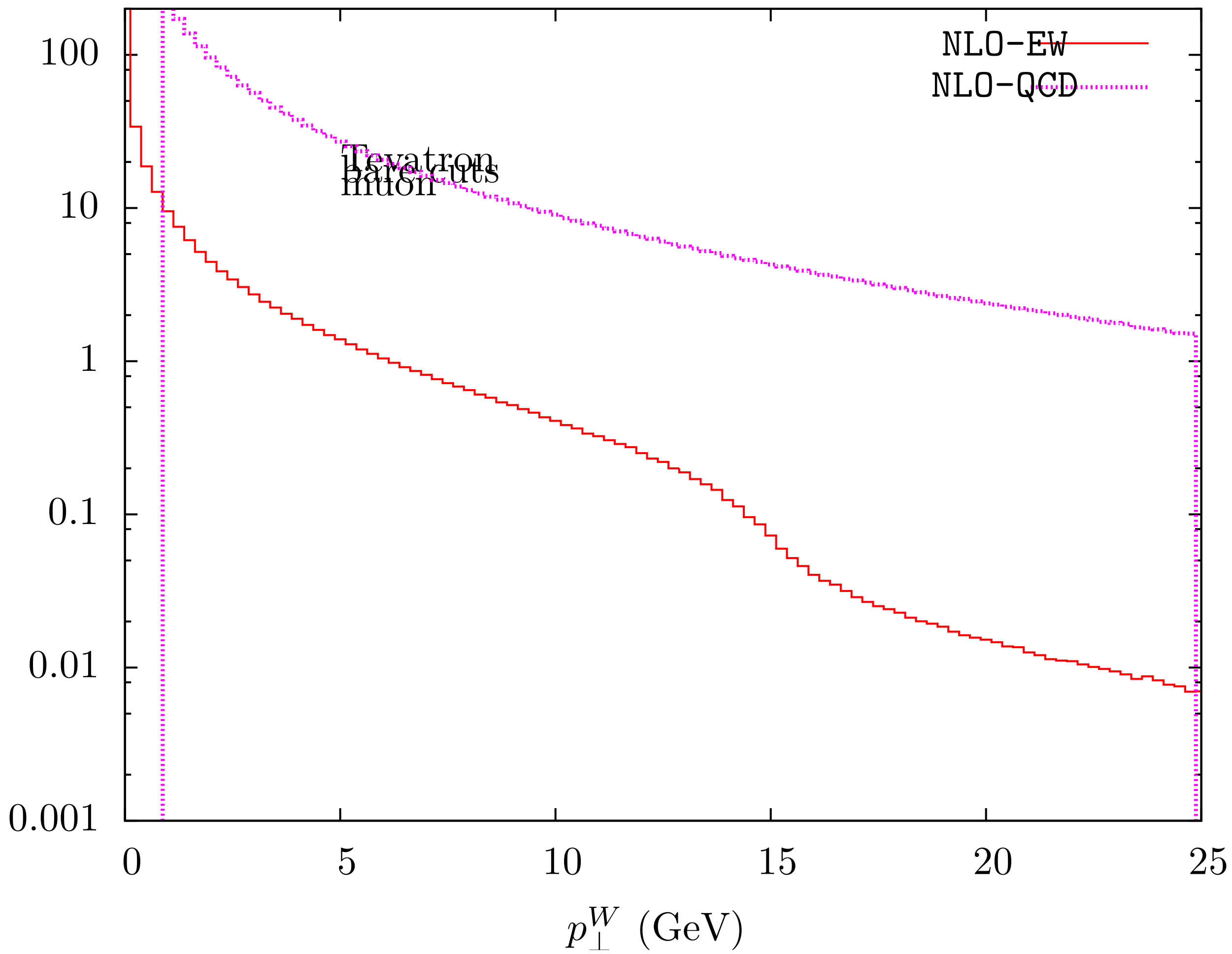
- ▹ a combination of 4FS and 5FS results improves the ptZ description, in the region ptZ ~ 0-25 GeV
- ▹ the tuning of the Parton Shower would be affected by this improved NC-DY description
  - → the CC-DY simulation would be in turn modified
- ▹ the change in the CC-DY templates would lead to a different value of MW extracted from the data

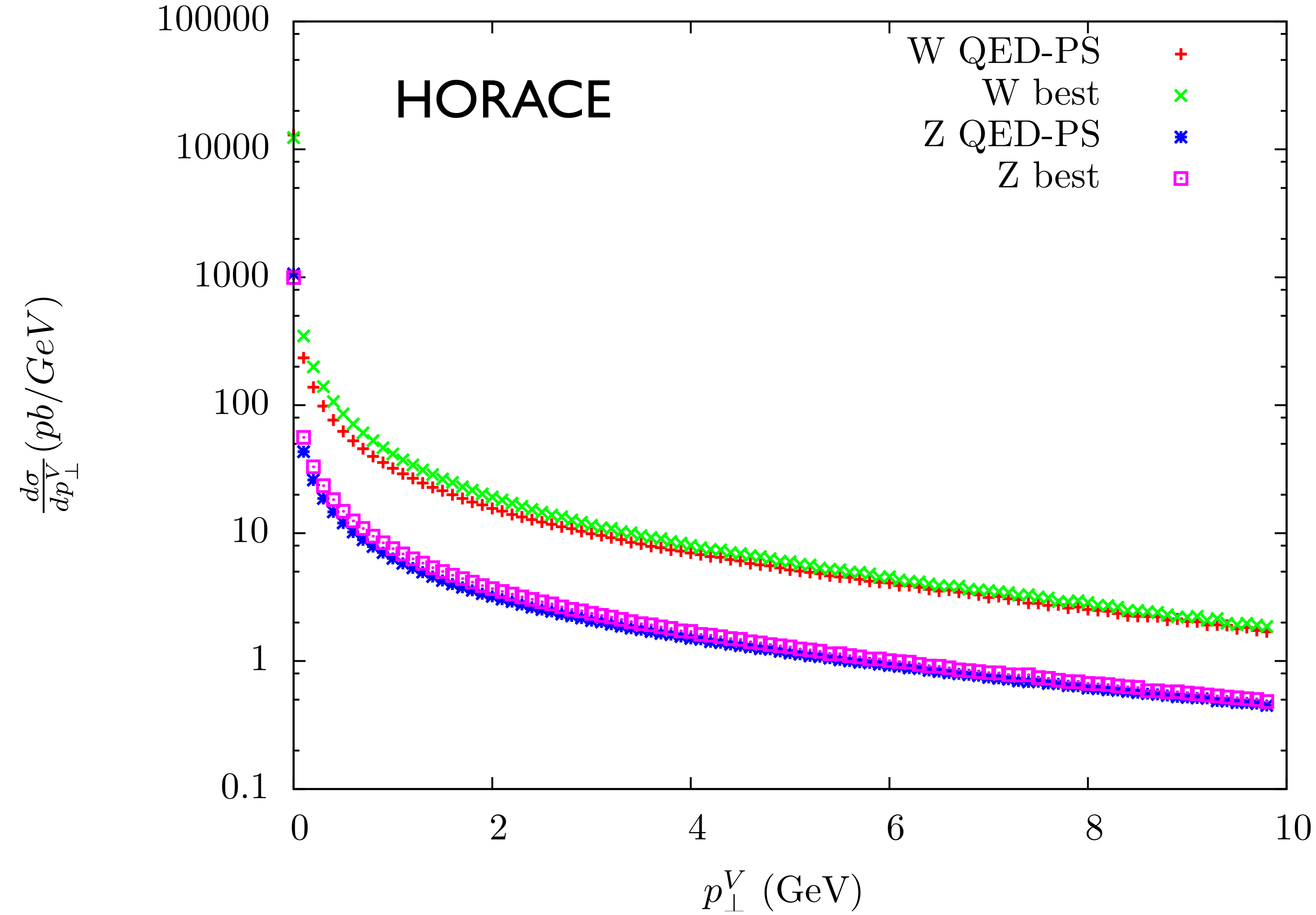


if the elements of difference between Z and W are explicitly computed,
then the effects encoded in the PS tunes become "more universal"

analogous approach studies the flavour dependence in the TMD framework, Bozzi et al., arXiv:1807.02101

QED induced W(Z) transverse momentum





QED contribution to the PTV spectra is O(1%) of the QCD component

Differences between W and Z because of flavour structure

Bulk of the contribution due to QED-FSR,
but
matching with full NLO-EW adds more contributions,
again different between W and Z

$\langle p_\perp^V \rangle =$

Z	FSR-PS	0.409	GeV
Z	best	0.463	GeV
W	FSR-PS	0.174	GeV
W	best	0.207	GeV

Estimate of the "non-final state" component different in the 2 cases
$\Delta\langle p_\perp V\rangle$ = 54 (Z) - 33 (W) = 21 MeV

PDF uncertainties

PDF uncertainties and Drell-Yan processes

The experimental PDF uncertainty is represented in terms of replicas

and can be propagated to any observable, e.g. to the templates used to fit the EW parameters

→ it represents a theoretical systematic uncertainty of the EW measurements

Different observables are correlated w.r.t. a PDF replica variation

→ this correlation must be taken into account in the template fit procedure

Drell-Yan processes (NC and CC) share a similar kinematical regime,

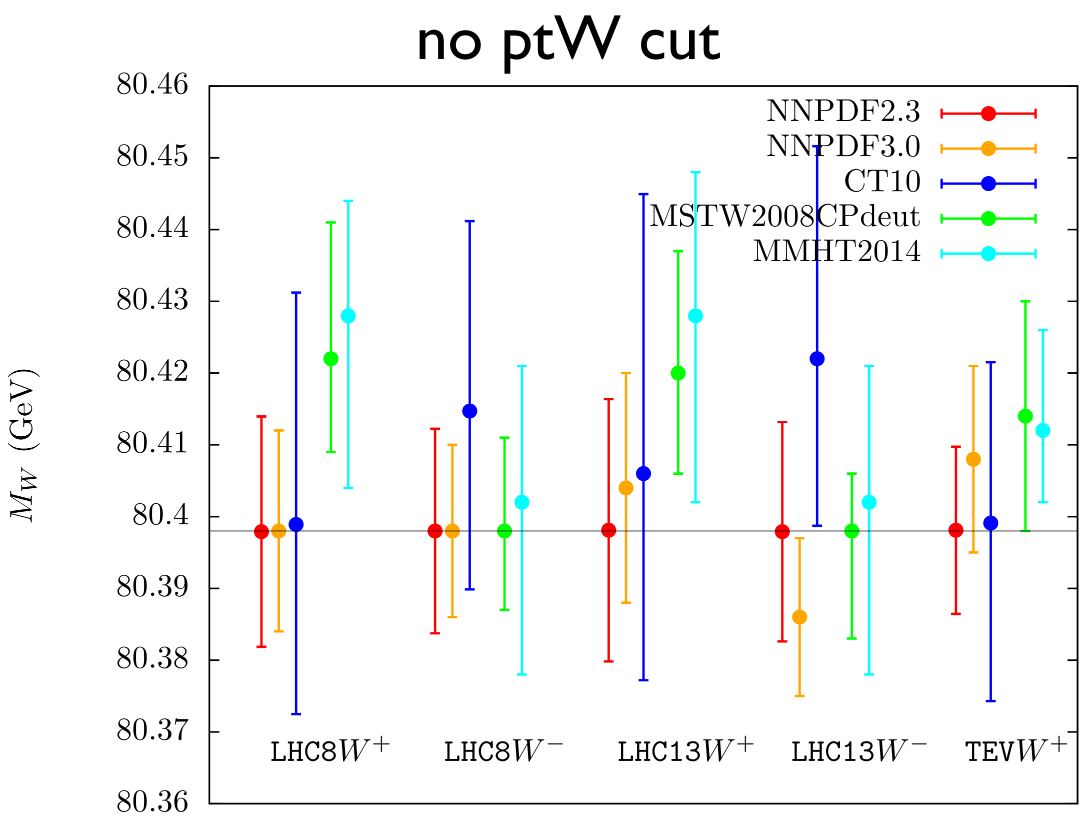
but also differ because of the different initial state flavour structure

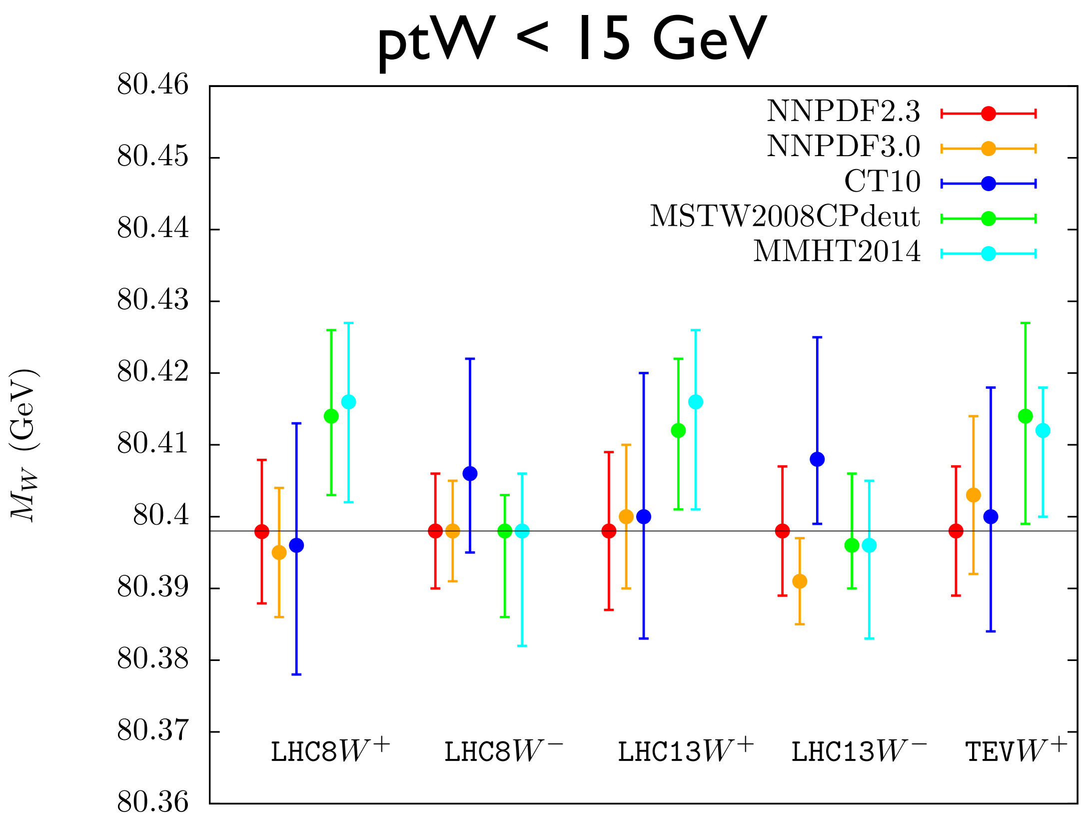
→ we can expect a strong interplay (but not a perfect cancellation) of PDF uncertainties in a simultaneous fit of CC and NC observables

The role of a PDF4LHC prescription, often considered as too conservative, should be rediscussed to understand if it is legitimate to say that high-precision data may select (prefer) one PDF set

PDF uncertainty affecting MW extracted from the ptlep distribution

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





	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 in 2015 was showing large discrepancies of the central values

- The Tevatron analyses did not adopt the PDF4LHC approach

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

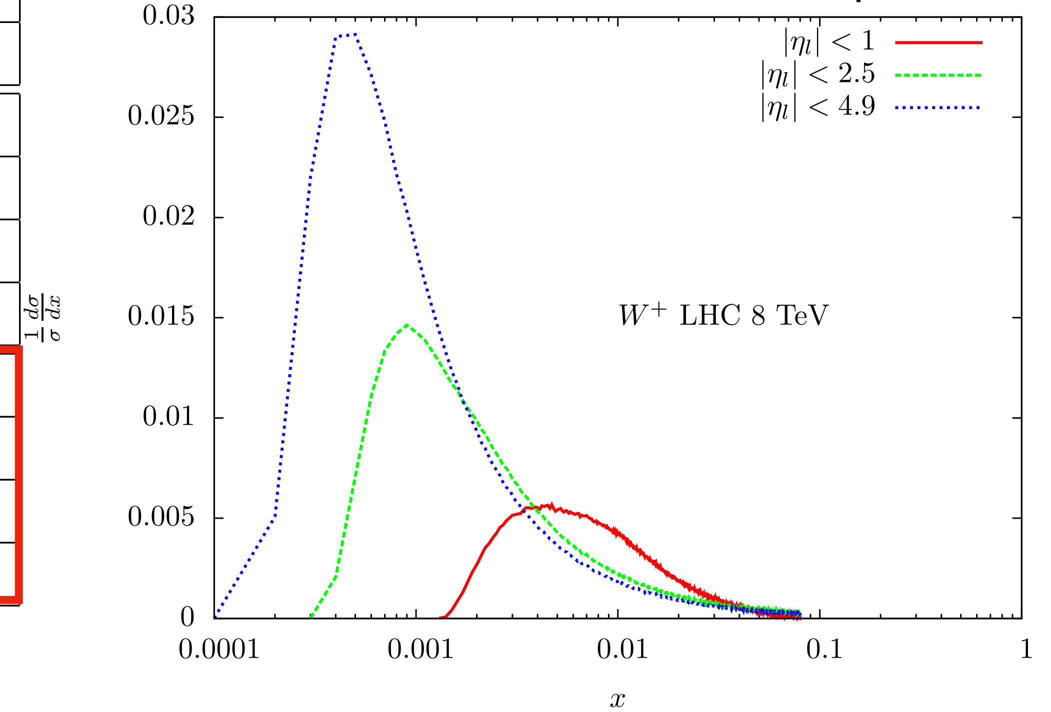
PDF uncertainty and acceptance cuts; anticorrelations

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

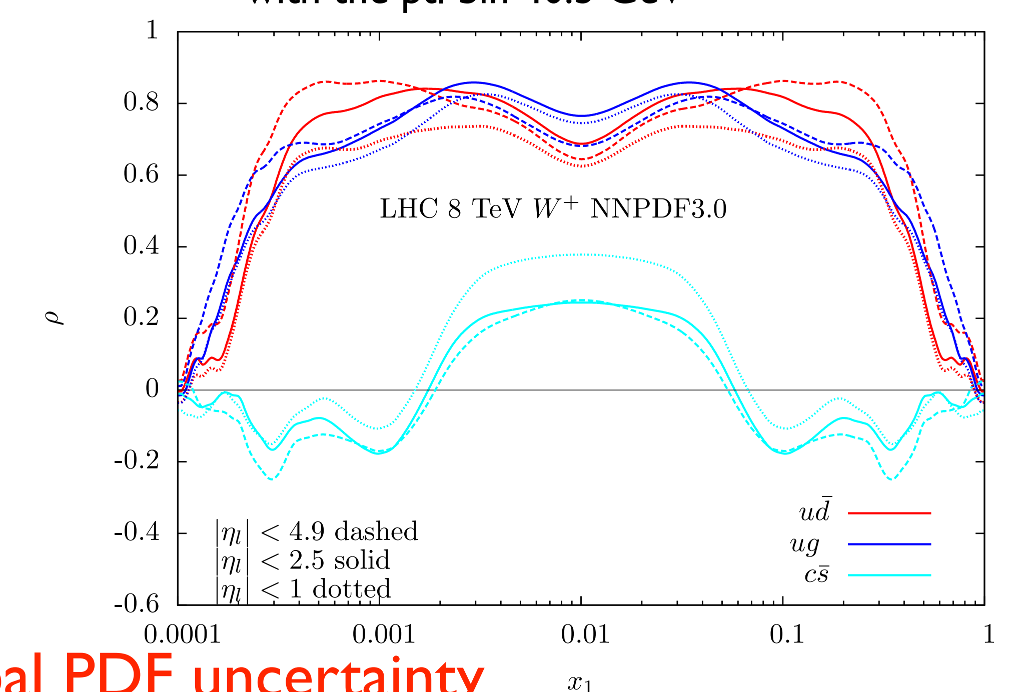
The dependence of the MW PDF uncertainty on the acceptance cuts provides interesting insights

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

normalized cross section differential in partonic x



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



- 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

- PDF sum rules → non trivial compensations between different rapidity intervals among different flavors

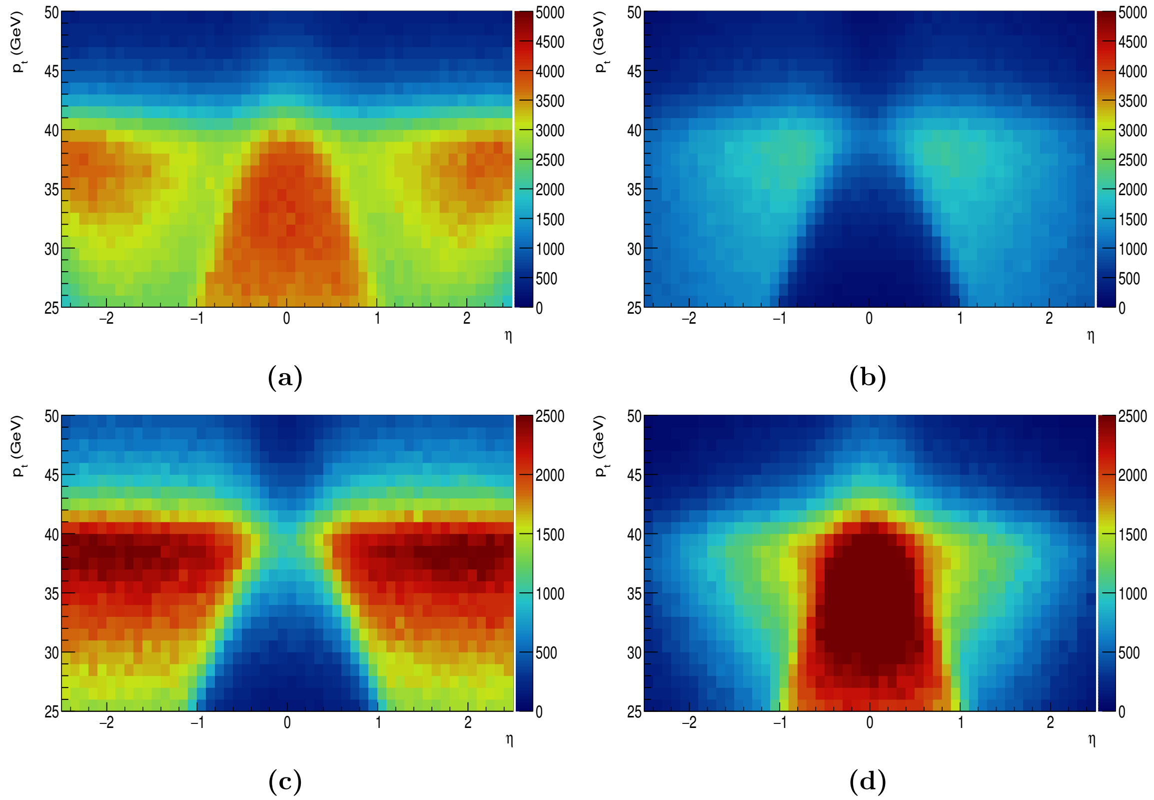
- MW measurement at LHCb could significantly reduce the global PDF uncertainty
- W+ and W- determinations are anti correlated w.r.t. PDFs their combination benefits of a reduction of the PDF error

PDF uncertainty and "W kinematics": *in situ* reduction

E. Manca, O. Cerri, N. Foppiani, L. Rolandi, arXiv:1707.09344

The strong kinematic correlations between
the helicities of intermediate W+ / W- boson and (pt_lep, eta_lep) 2D distribution
allows to make a strongly motivated guess
about the kinematics of the intermediate boson

In turn, the intermediate boson couples
in well distinct ways to partons, depending on its helicity



The 2D lepton-(pt,eta) distribution is thus an interesting tool to probe PDFs
it offers the possibility of an "in situ" reduction of the PDF uncertainty
by selecting those PDF replicas most compatible with new DY data

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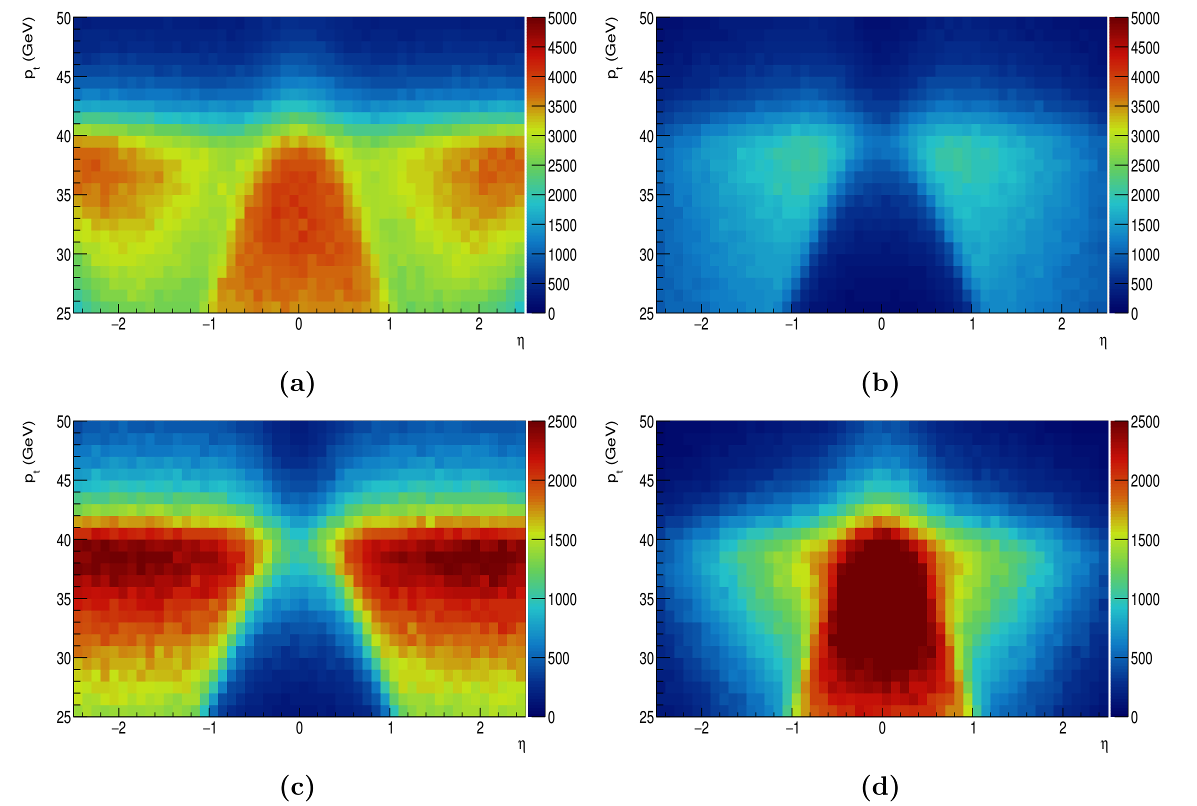

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The estimate of the reduction of the PDF uncertainty induced by new data

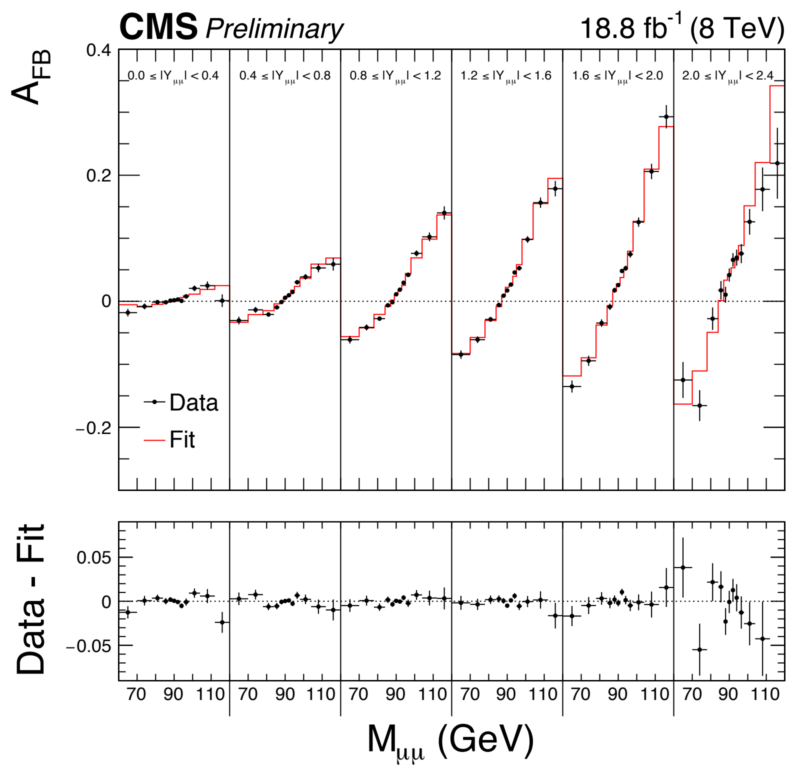
can not replace a full global PDF fit

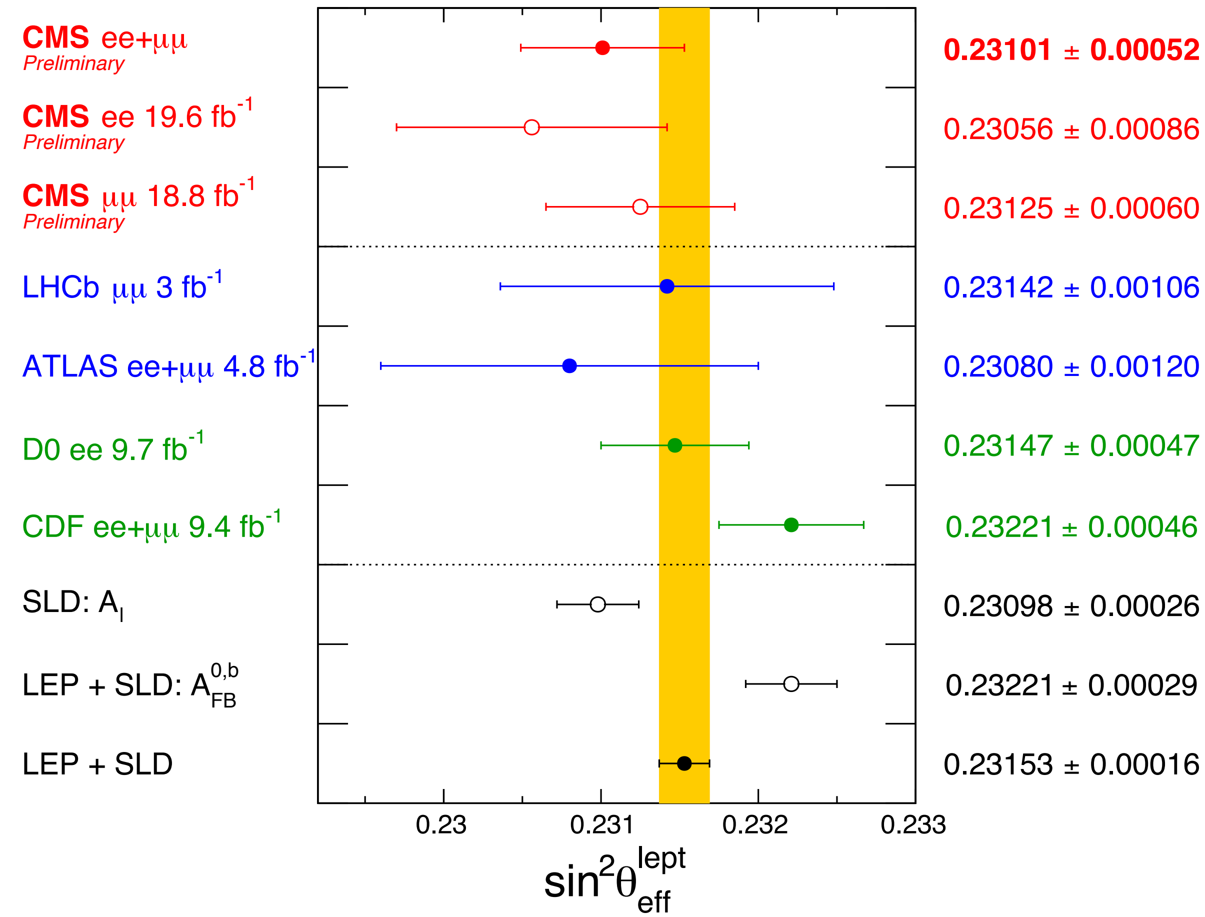
→ quantitative problem: a single very precise data point may lead to overestimate the unc.reduction

→ qualitative problem: the proton is a universal function, not a DY function

The $\sin^2\theta_{eff}$(leptonic) at the LHC: *in situ* reduction of PDF uncertainty

CMS PAS SMP-16-007





different PDF dependence of the 72 (M_{ll}-Y) bins →

the bins close to MZ, dominated by $|M_Z|^2$ sensitive to $\sin^2\theta_{eff}$(leptonic)

the bins far from MZ, dominated by $(\mathcal{M}_\gamma \mathcal{M}_Z^\dagger)$ used to "choose" the best PDF replicas that yield a better agreement with the data

reduction of the PDF uncertainty via Bayesian reweighing of the PDF MC replicas

CMS PAS SMP-16-007

Channel	without constraining PDFs	with constraining PDFs
Muon	0.23125 ± 0.00054	0.23125 ± 0.00032
Electron	0.23054 ± 0.00064	0.23056 ± 0.00045
Combined	0.23102 ± 0.00057	0.23101 ± 0.00030

the inclusion of bins far from MZ implies that the template fit is done in the SM and $\sin^2\theta_W$ (or MW), the fit parameter, should be one of the lagrangian inputs

EW and mixed QCDxEW effects

Overall status of EW and QCDxEW corrections

EW corrections affect the final state lepton distributions

leading effects are mostly due to QED-FSR

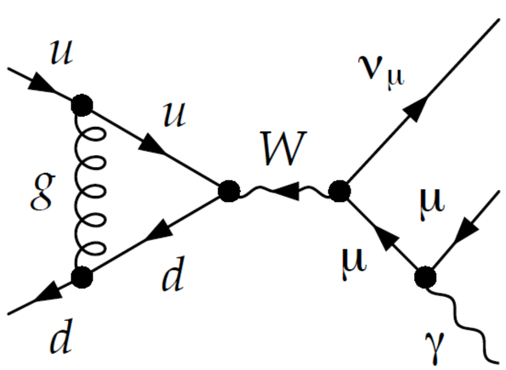
after the matching with a full NLO-EW all first order subleading effects included

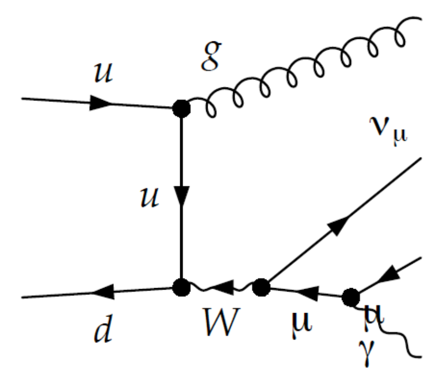
residual subleading second order effects are tiny

QCDxEW the QCD modelling modulates the EW effects

the bulk of the effects is included in the simulations (with some caveats)

a sound estimate of the associated uncertainties is not available (NNLO QCDxEW frontier)





Impact of EW corrections on the MW determination

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, arXiv:1612.02841

	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

Combination of QCD and EW corrections in DY simulation tools

· Fixed-order tools:

additive combination of exact $O(\alpha_s)$, $O(\alpha_s^2)$ and $O(\alpha)$ corrections (e.g. FEWZ)

$$\sigma = \sigma_0 \, (1 + \delta\alpha_s + \delta\alpha_s^2 + \delta\alpha + \ldots)$$

possibility to arrange terms in factorized combinations

$$\sigma = \sigma_0 \, (1 + \delta\alpha_s + \ldots)\,(1 + \delta\alpha)$$

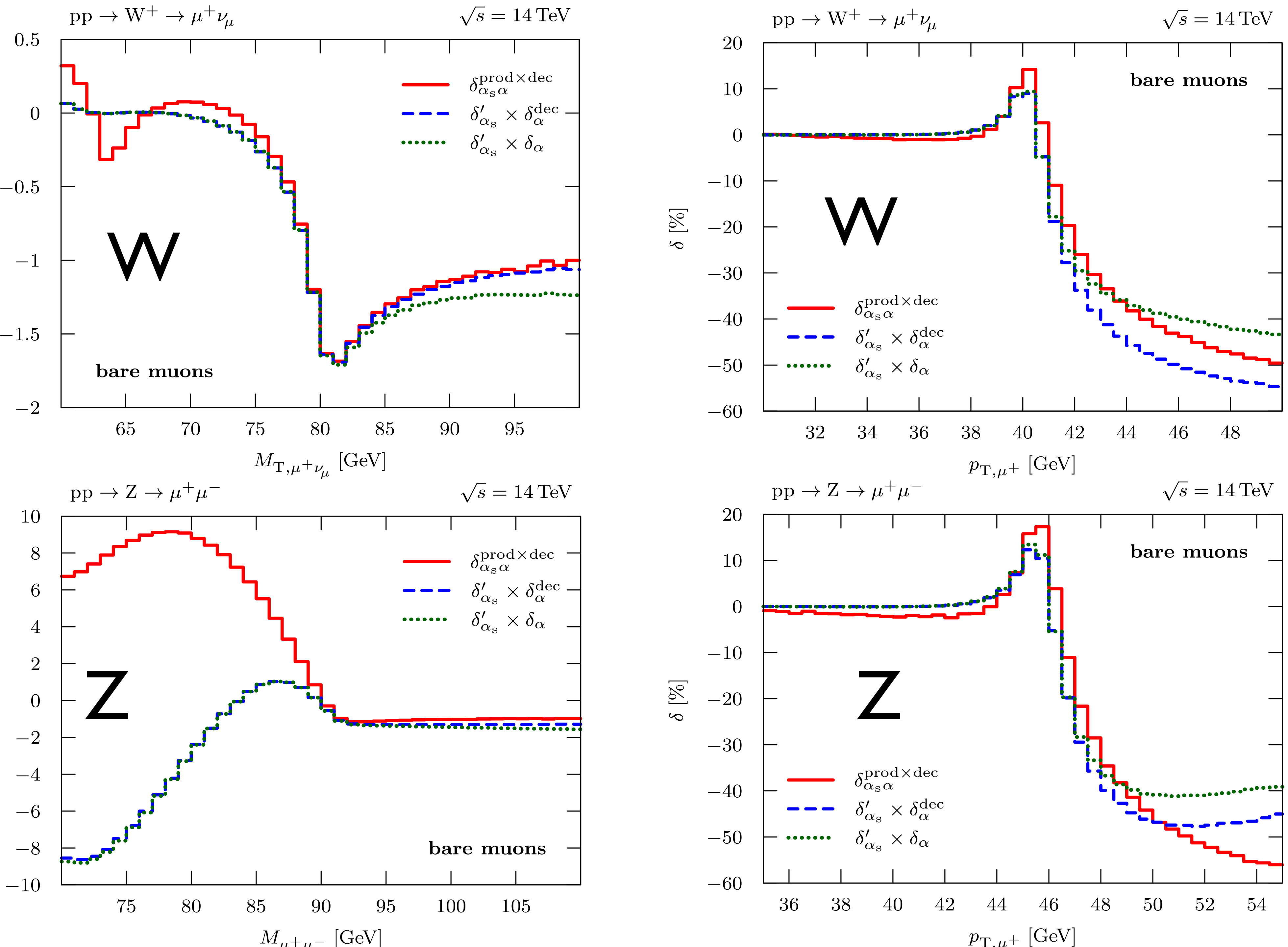
→ estimate of size $O(\alpha\alpha_s)$ terms

WARNING: kinematics plays a very important role

multiplying integrated corrections factors ≠ convoluting fully differential corrections

O(αα$_s$) corrections in pole approximation

S. Dittmaier, A. Huss, C. Schwinn, Nucl.Phys.B885 (2014) 318, Nucl.Phys.B904 (2016) 216



full result pole approximation

QED-FSR

NLO-EW

the difference between red and the others tests the naive factorization

the difference between green and blue tests the impact of weak corr. and the pole approximation

the naive factorization works nicely for the W transverse mass, at the resonance

fails in the lepton pt case, where the kinematical interplay of photons and gluons is crucial

fails in the Z invariant mass, where the large FSR correction is modulated by ISR QCD radiation and requires exact kinematics

POWHEG-V2 two-rad (resonance aware) simulation of DY

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, arXiv:1612.02841

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

The NLO-(QCD+EW) accuracy on the total cross section is always guaranteed by the Bbar function

Bbar includes also the virtual corrections

The curly bracket describes the real radiation generation

The presence of a resonance (W/Z) allows to treat separately higher-order emissions

from the resonance (preserving its correct virtuality) → QED

from the initial state → QCD+QED-ISR

(two distinct parameters `scalup` are computed)

preserving the logarithmic accuracy of both QCD and QED emissions

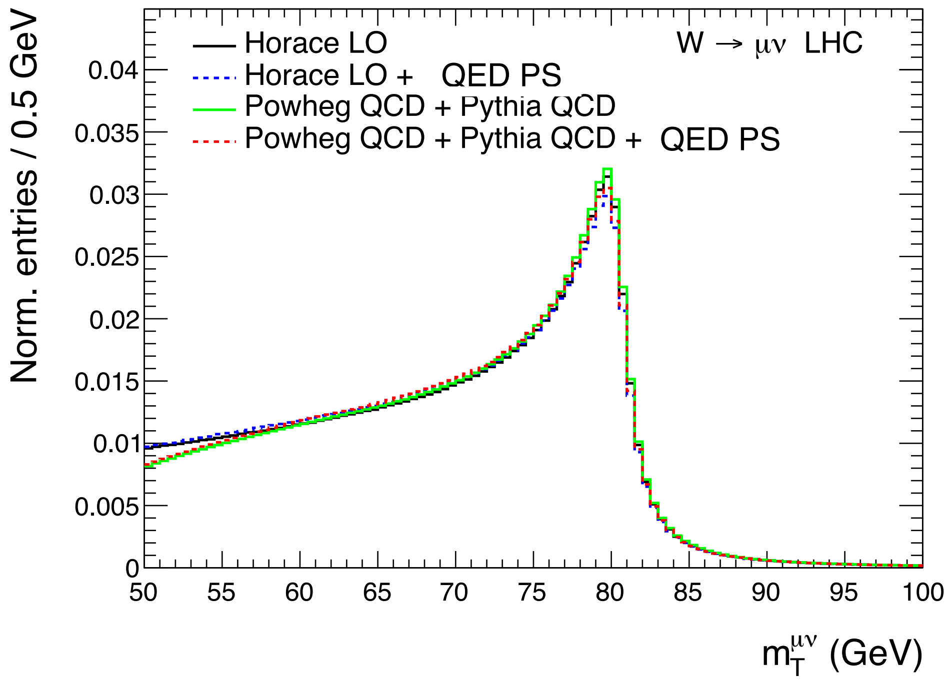
The MSSM implementation of DY simulation would have the MSSM virtual corrections in Bbar replacing the SM ones;

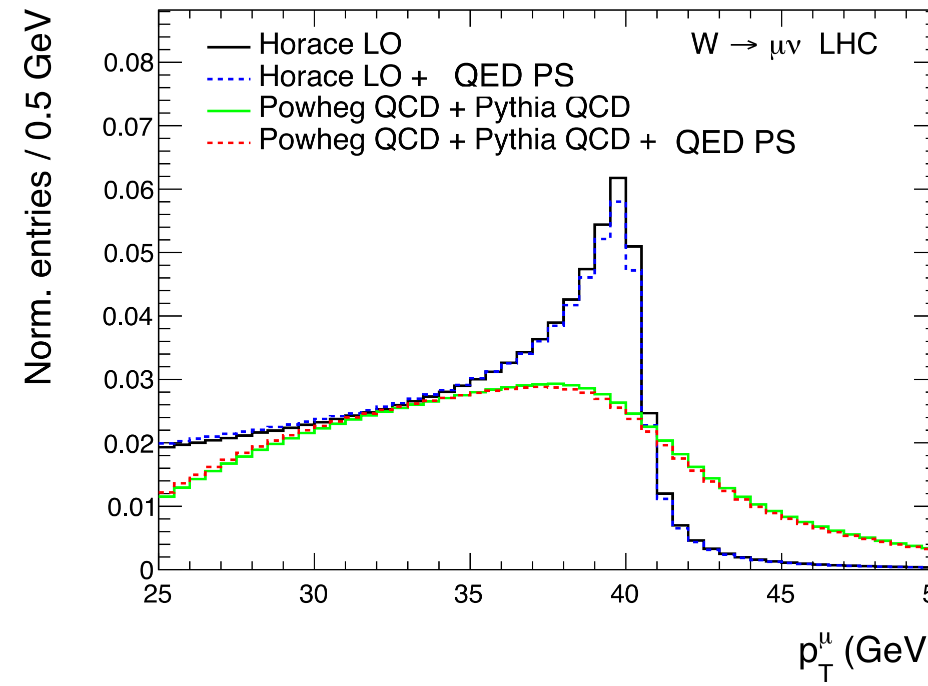
The factorised structure of the formula minimises the impact of these virtual effects on the shape of the kinematical distributions

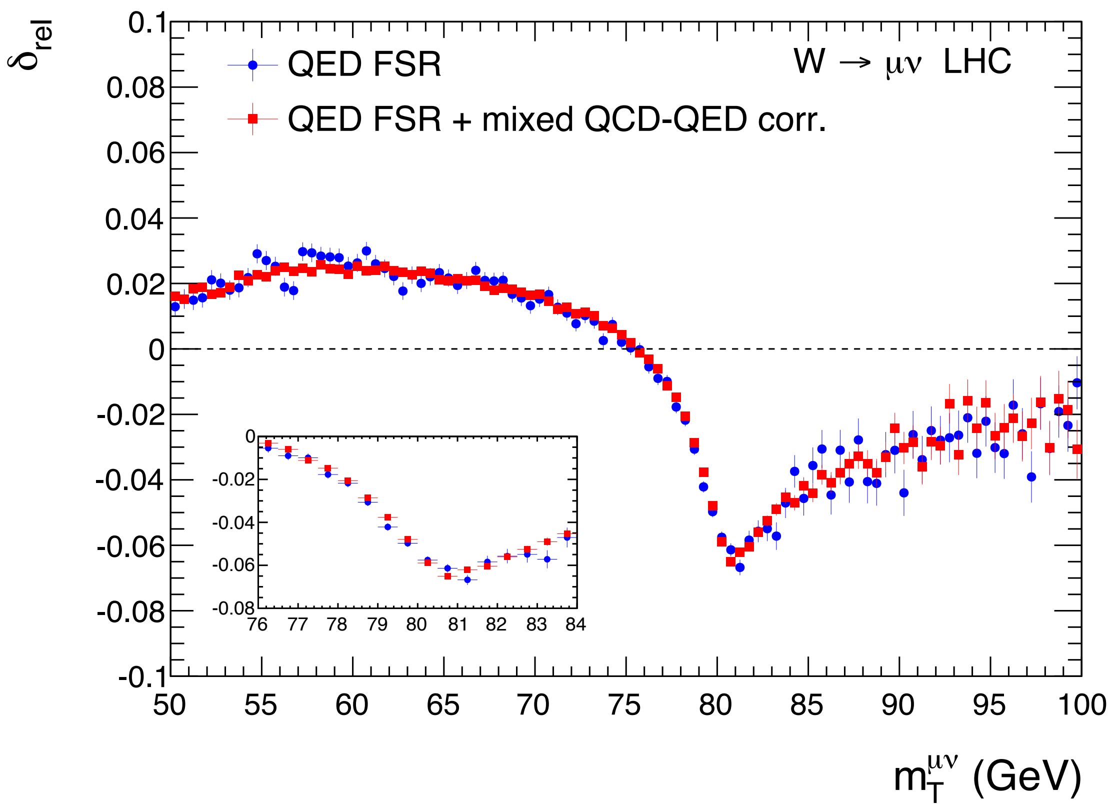
Combination of QCD and QED corrections: POWHEG results

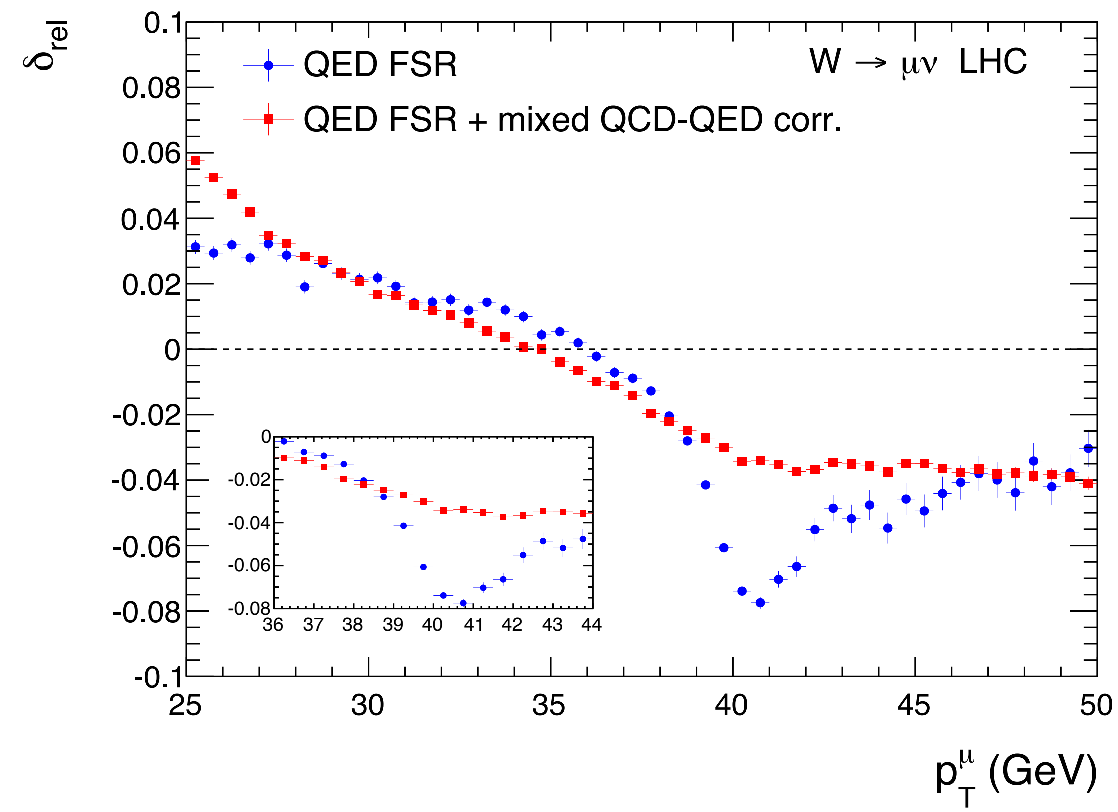
Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, arXiv:1612.02841

Does the convolution with QCD corrections preserve the QED effects ?









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

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

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, arXiv:1612.02841

Template fit applied to classify the impact of sets of radiative corrections

	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
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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

	$pp \to W^+$, $\sqrt{s} = 14$ TeV Templates accuracy: NLO-QCD+QCD$_{\text{PS}}$		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)$_{\text{PS}}$	PYTHIA	-95.2±0.6	-400±3	-38.0±0.6	-149±2
2	NLO-QCD+(QCD+QED)$_{\text{PS}}$	PHOTOS	-88.0±0.6	-368±2	-38.4±0.6	-150±3
3	NLO-(QCD+EW)+(QCD+QED)$_{\text{PS}}$`two-rad`	PYTHIA	-89.0±0.6	-371±3	-38.8±0.6	-157±3
4	NLO-(QCD+EW)+(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 shifts are sizeably amplified

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

The lepton transverse momentum has a 85% weight in the final ATLAS MW combination and a sound estimate of the uncertainty on the QCDxEW effects is crucial

Better control over higher-order subleading terms after matching

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, arXiv:1612.02841

$pp \to W^+$, $\sqrt{s} = 14$ TeV			M_W shifts (MeV)			
Templates accuracy: NLO-QCD+QCD$_{\text{PS}}$			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+(QCD+QED)$_{\text{PS}}$	Pythia	-95.2±0.6	-400±3	-38.0±0.6	-149±2
2	NLO-QCD+(QCD+QED)$_{\text{PS}}$	Photos	-88.0±0.6	-368±2	-38.4±0.6	-150±3
3	NLO-(QCD+EW)+(QCD+QED)$_{\text{PS}}$`two-rad`	Pythia	-89.0±0.6	-371±3	-38.8±0.6	-157±3
4	NLO-(QCD+EW)+(QCD+QED)$_{\text{PS}}$`two-rad`	Photos	-88.6±0.6	-370±3	-39.2±0.6	-159±2

PHOTOS and PYTHIA-QED differ at the level of O(α) subleading terms

→ large impact when used on top of a pure QCD code to describe also the first photon emission

After the matching with the O(α) matrix elements,
the role of the QED-PS starts from the second photon emission
and the difference are of O(α²) subleading, yielding vanishing MW shifts

Conclusions

SM precision tests are the basic fundamental step to understand the likelihood of the SM itself
to set constraints on SM extensions like the EFT

The precision measurement of EW parameters like MW and the weak mixing angle offers
sensitivity to BSM physics active via the oblique corrections

LHC can be an EW precision machine (!!!), provided that

- ▹ the modelling of the QCD environment is understood
  in terms of all the correlations between the processes (NC and CC) included in the analysis
  PDFs, heavy quarks, low-pt non-perturbative effects
  scale uncertainties in the simultaneous fit of several processes
- ▹ the exact $O(\alpha\alpha_s)$, consistently matched, will be included in Monte Carlo event generators

so that

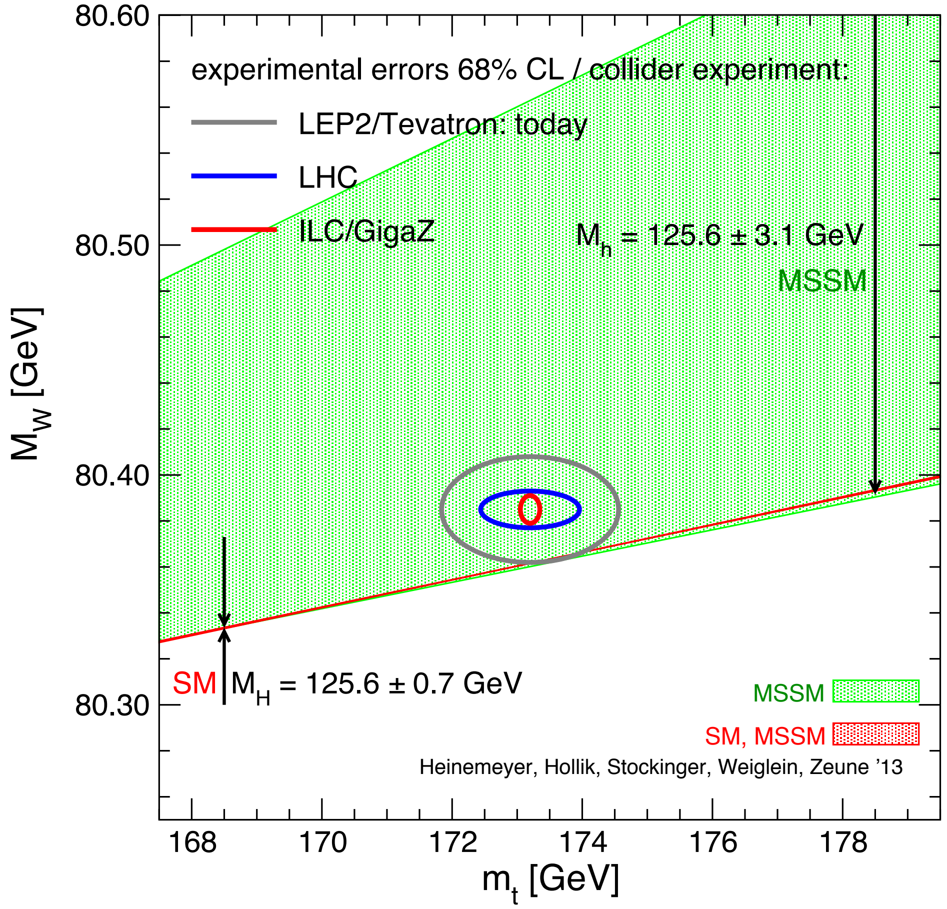
- ▹ a realistic estimate of the theoretical uncertainties will become possible.
- ▹ the full amount of available information will be extracted from the wealth of precision data

The combination of (LEP, Tevatron, LHC) EW measurements urgently requires

- ▹ an agreement on the definition and meaning of the measured parameters

backup slides

Possible interpretation of the MW measurement



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

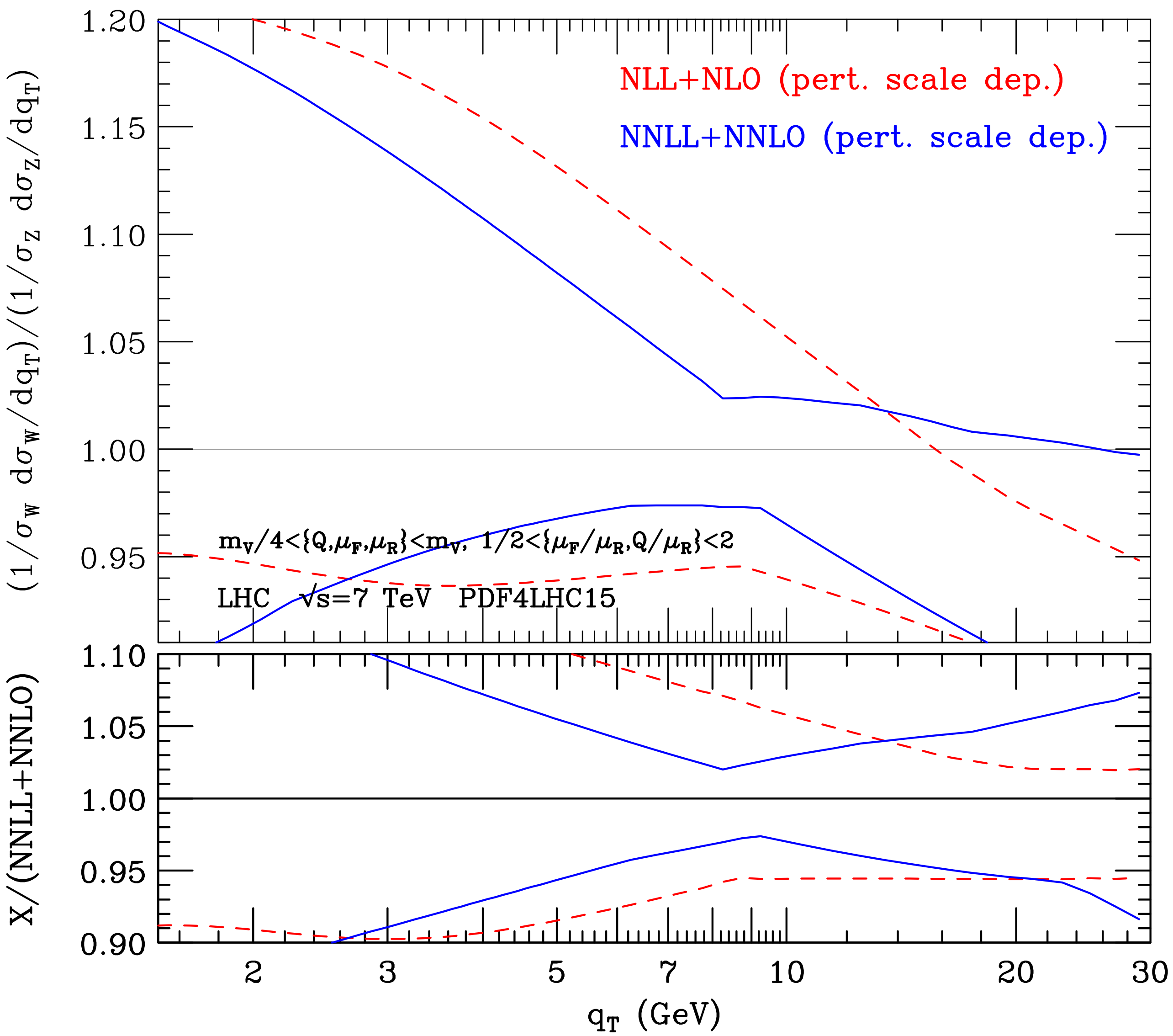
$$m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\alpha}{G_\mu\sqrt{2}m_Z^2}(1+\Delta r)}\right)$$

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

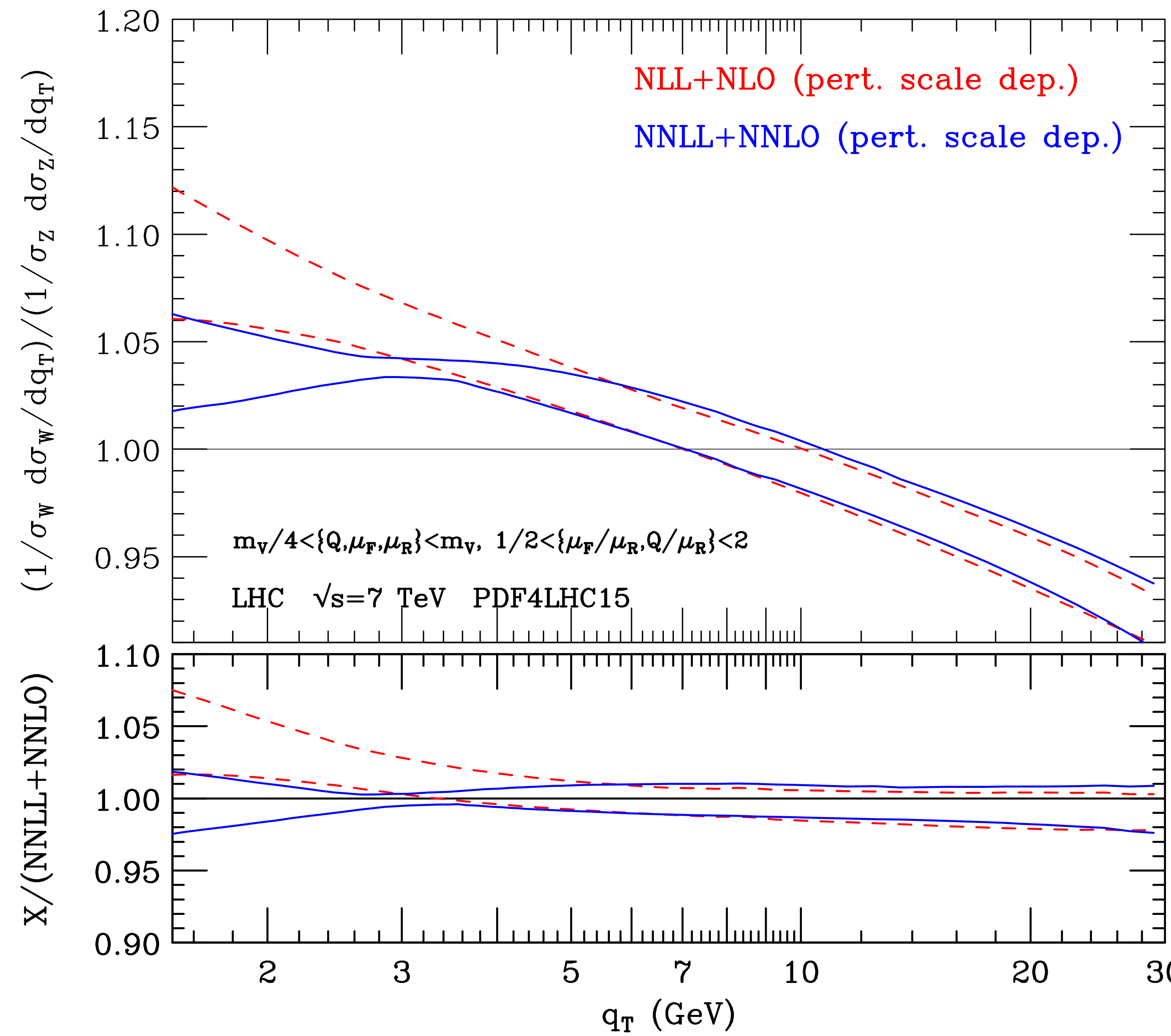
$$\Delta r^{SM,MSSM} = \Delta r^{SM,MSSM}\left(m_t, m_H, m^{SUSY}, \ldots\right)$$

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

W/Z ratio q_T spectrum: perturbative scale uncertainty



DYqT resummed predictions for the ratio of W/Z normalized q_T spectra. Uncorrelated perturbative scale variation band.



DYqT resummed predictions for the ratio of W/Z normalized q_T spectra. Correlated perturbative scale variation band.

Impact of a LHCb MW measurement in combination with the ATLAS/CMS results

G.Bozzi, L.Citelli, M.Vesterinen, AV, arXiv:1508.06954

- using the standard acceptance cuts for ATLAS/CMS (called **G**) and for LHCb (called **L**) and both W charges we study the MW determination from the lepton pt distribution assuming that a LHCb measurement becomes available

  - PDF uncertainty on MW according to PDF4LHC (NNPDF3.0, MMHT2014)

$$\delta_{\rm PDF} = \begin{pmatrix} \mathbf{G}^+ & 24.8 \\ \mathbf{G}^- & 13.2 \\ \mathbf{L}^+ & 27.0 \\ \mathbf{L}^- & 49.3 \end{pmatrix}$$

  - correlation matrix ρ w.r.t. PDF variation of the replicas of the NNPDF3.0 set

    → non negligible anticorrelation
    consequence of the sum rules satisfied by the PDFs
    it appears because we probe different rapidity regions

$$\rho = \begin{pmatrix} & \mathbf{G}^+ & \mathbf{G}^- & \mathbf{L}^+ & \mathbf{L}^- \\ \mathbf{G}^+ & 1 & & & \\ \mathbf{G}^- & -0.22 & 1 & & \\ \mathbf{L}^+ & -0.63 & 0.11 & 1 & \\ \mathbf{L}^- & -0.02 & -0.30 & 0.21 & 1 \end{pmatrix}.$$

  - the linear combination that minimizes the final uncertainty on MW is given by the coefficients α

$$m_W = \sum_{i=1}^{4} \alpha_i m_{W\ i} \qquad \alpha = \begin{pmatrix} \mathbf{G}+ & 0.30 \\ \mathbf{G}- & 0.45 \\ \mathbf{L}+ & 0.21 \\ \mathbf{L}- & 0.04 \end{pmatrix}$$

- the exercise is robust under conservative assumptions for the LHCb main systematic uncertainties and guarantees a reduction by 30% of the PDF uncertainty estimated for ATLAS/CMS alone

- potential serious bottleneck for a measurement based on ptl: ptW modeling in the LHCb acceptance

More on the structure of QCDxEW corrections in POWHEG

- EW corrections may become large in the photon soft/collinear limit or in the EW Sudakov regime

POWHEG NLO-(QCD+EW)

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

the difference between QCDxQED and QCDxEW approximations starts at O(αα$_s$)

POWHEG NLO-QCD x (QCD+QED)-PS

$$\alpha_s \alpha \left(c_2 L_{\rm QCD}^2 + c_1 L_{\rm QCD} + c_0 \right) \left(c_{11} L_{\rm QED} l_{\rm QED} + c_{10} L_{\rm QED} + c_{01} l_{\rm QED} \right)$$

POWHEG NLO-(QCD+EW) x (QCD+QED)-PS

$$\alpha_s \alpha \left(c_2 L_{\rm QCD}^2 + c_1 L_{\rm QCD} + c_0 \right) \left(c_{11} L_{\rm QED} l_{\rm QED} + c_{10} L_{\rm QED} + c_{01} l_{\rm QED} + c_{00} \right)$$

the difference $\alpha_s \alpha\, c_{00} \left(c_2 L_{\rm QCD}^2 + c_1 L_{\rm QCD} + c_0 \right)$ important when c_{00} is large

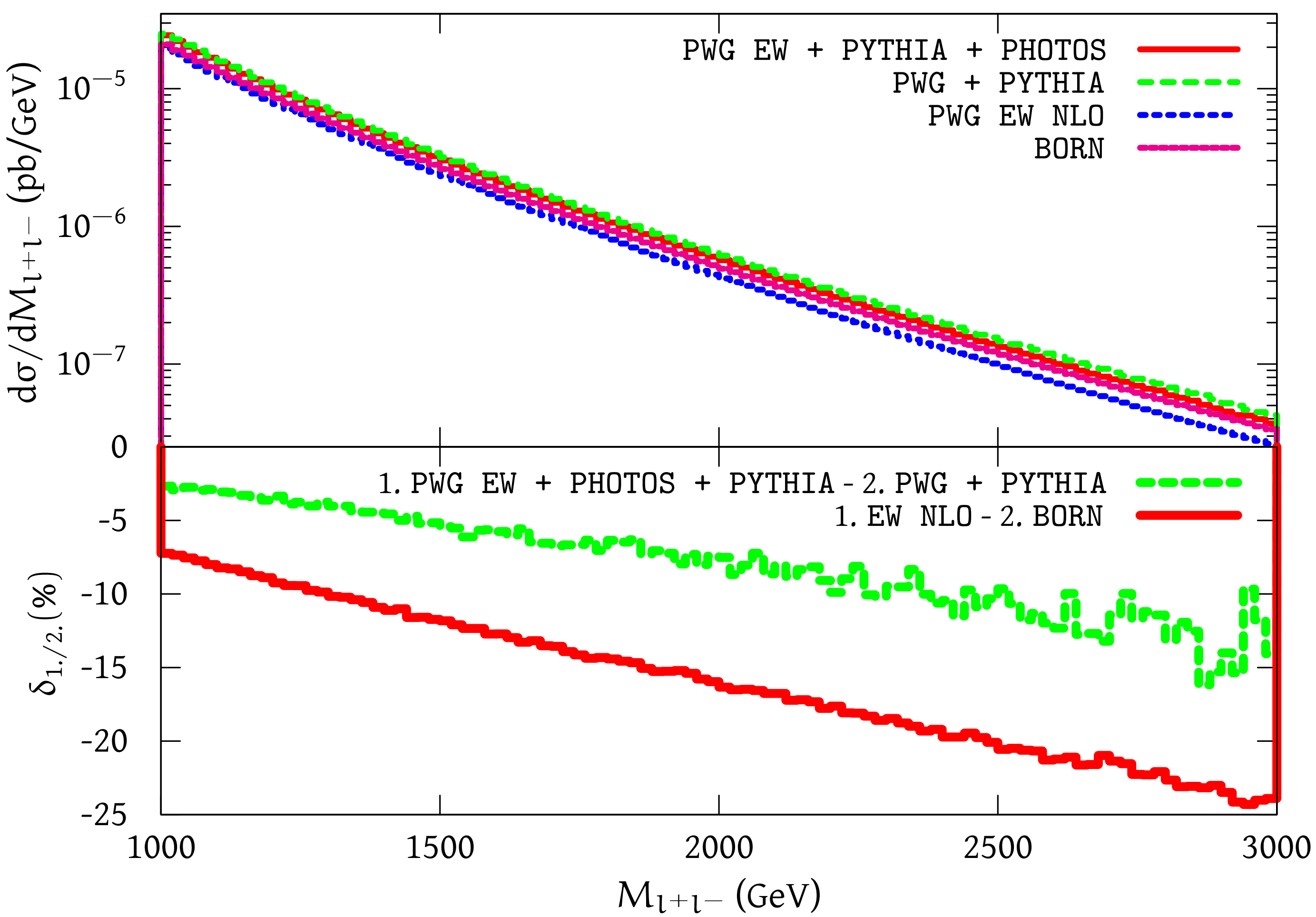
c_{00} does not contain QED logs, but Sudakov EW logs $\quad c_{00} \propto -\frac{\alpha}{4\pi \sin^2\theta_W} \log^2 \frac{s}{m_W^2}$

More on the structure of QCDxEW corrections in POWHEG

- EW corrections may become large in the photon soft/collinear limit or in the EW Sudakov regime

POWHEG NLO-(QCD+EW)

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



the difference between red and green
due to O(αα$_s$)
arising from the product of Bbar x { … }

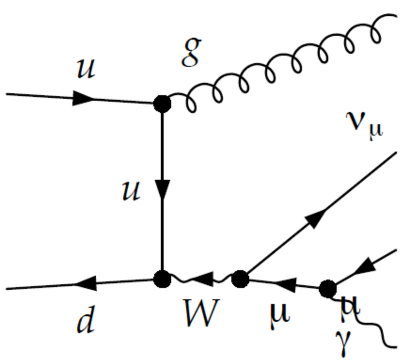
relevant when setting limits on Z' masses

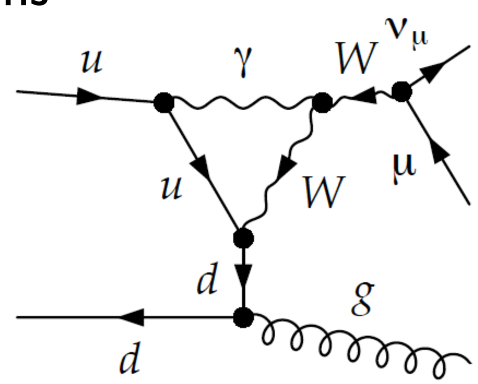
terms beyond the formal accuracy of the code
missing e.g. in FEWZ
→need of exact O(ααs)
to provide a more robust prediction

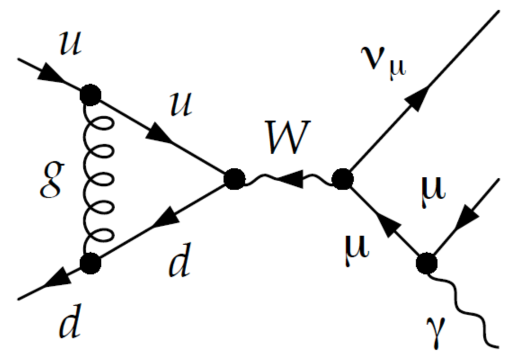
Exact mixed QCDxEW corrections the Drell-Yan cross section

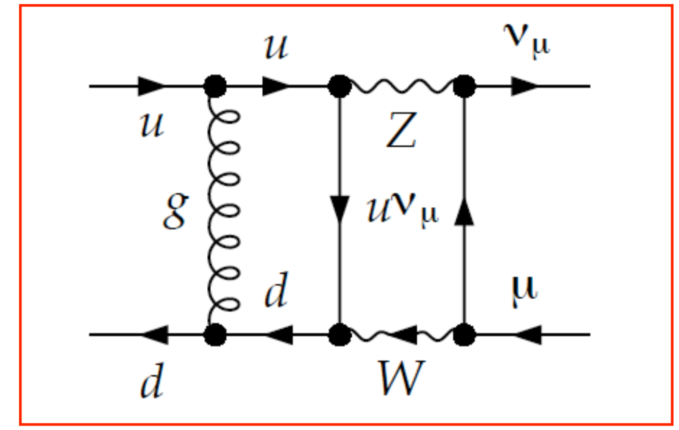
- The first mixed QCDxEW corrections of $O(\alpha\alpha_s)$ include different contributions:
  - emission of two real additional partons (one photon + one gluon/quark)
  - emission of one real additional parton (one photon with QCD virtual corrections, one gluon/quark with EW virtual corrections)
  - two-loop virtual corrections

$$\begin{aligned}\sigma_{tot} &= \sigma_0 + \alpha_s\sigma_{\alpha_s} + \alpha_s^2\sigma_{\alpha_s^2} + \dots \\ &\quad + \alpha\sigma_\alpha + \alpha^2\sigma_{\alpha^2} + \dots \\ &\quad + \boxed{\alpha\alpha_s\,\sigma_{\alpha\alpha_s}} + \alpha\alpha_s^2\,\sigma_{\alpha\alpha_s^2} + \dots\end{aligned}$$





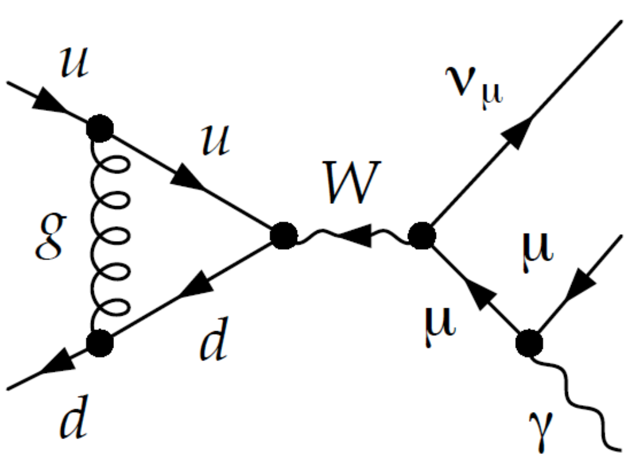


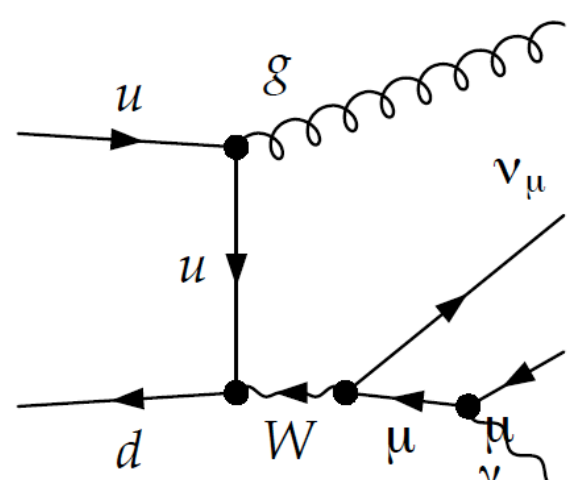


→ exact complete calculation is not yet available, neither for DY nor for single gauge boson production

- The bulk of the mixed QCDxEW corrections, relevant for a precision MW measurement,
  - is factorized in QCD and EW contributions:

(leading-log part of final state QED radiation) X (leading-log part of initial state QCD radiation || NLO-QCD contribution to the K-factor)

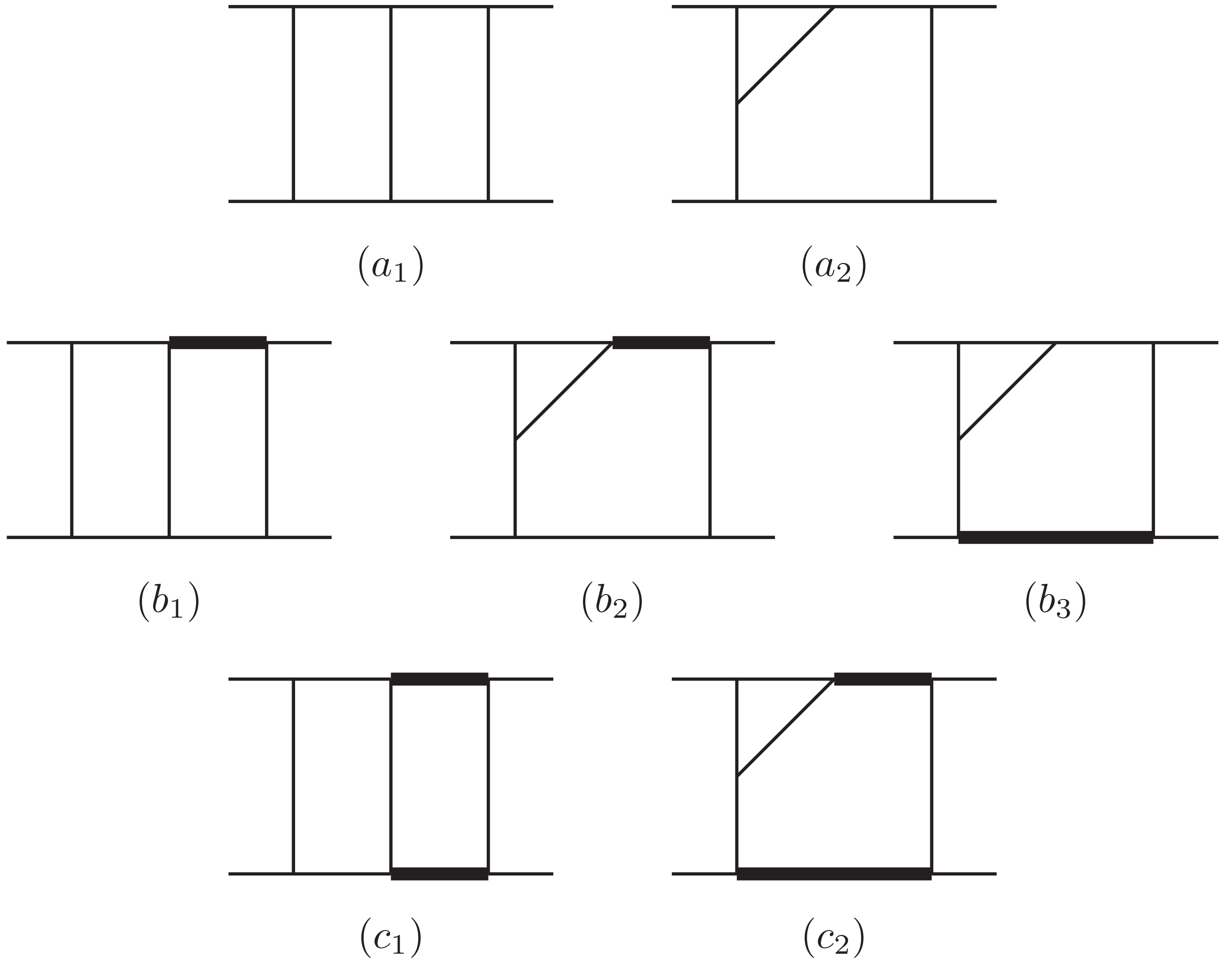




- is included in all Monte Carlo simulation tools

Analytic progress: Master Integrals for 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

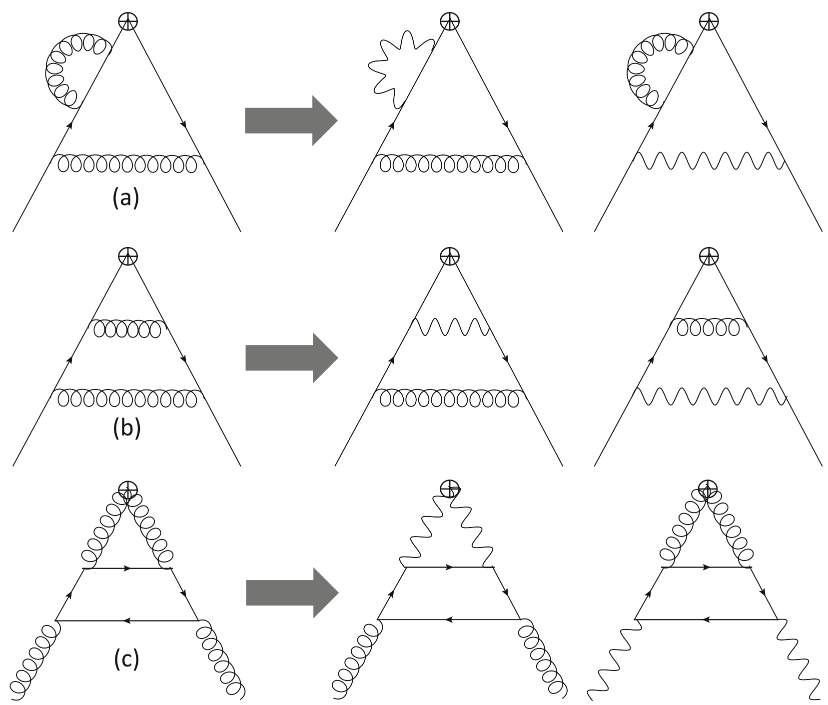
SM results, where both W and Z appear,
can be evaluated with an expansion in ΔM=MZ-MW

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)

Splitting functions at O(αα$_s$)

D. de Florian, G.F.R. Sborlini, G. Rodrigo, Eur.Phys.J. C76 (2016) no.5, 282 , arXiv:1606.02887

starting from the expressions by Curci-Furmanski-Petronzio



needed for a complete subtraction in partonic calculations of initial state collinear singularities at O(αα$_s$)

not sufficient for a consistent PDF evolution at the same order

$$P_{q\gamma}^{(1,1)} = \frac{C_F\, C_A\, e_q^2}{2} \Big\{ 4 - 9x - (1-4x)\ln(x) - (1-2x) \times \ln^2(x) + 4\ln(1-x) + p_{qg}(x) \Big[2\ln^2\left(\frac{1-x}{x}\right) - 4\ln\left(\frac{1-x}{x}\right) - \frac{2\pi^2}{3} + 10 \Big] \Big\}, \quad (26)$$

$$P_{g\gamma}^{(1,1)} = C_F\, C_A \left(\sum_{j=1}^{n_F} e_{q_j}^2 \right) \Big\{ -16 + 8x + \frac{20}{3}x^2 + \frac{4}{3x} - (6+10x)\ln(x) - 2(1+x)\ln^2(x) \Big\}, \quad (27)$$

$$P_{\gamma\gamma}^{(1,1)} = -C_F\, C_A \left(\sum_{j=1}^{n_F} e_{q_j}^2 \right) \delta(1-x), \quad (28)$$

$$P_{qg}^{(1,1)} = \frac{T_R\, e_q^2}{2} \Big\{ 4 - 9x - (1-4x)\ln(x) - (1-2x) \times \ln^2(x) + 4\ln(1-x) + p_{qg}(x) \Big[2\ln^2\left(\frac{1-x}{x}\right) - 4\ln\left(\frac{1-x}{x}\right) - \frac{2\pi^2}{3} + 10 \Big] \Big\},$$

$$P_{\gamma g}^{(1,1)} = T_R \left(\sum_{j=1}^{n_F} e_{q_j}^2 \right) \Big\{ -16 + 8x + \frac{20}{3}x^2 + \frac{4}{3x} - (6+10x)\ln(x) - 2(1+x)\ln^2(x) \Big\},$$

$$P_{gg}^{(1,1)} = -T_R \left(\sum_{j=1}^{n_F} e_{q_j}^2 \right) \delta(1-x),$$

$$P_{qq}^{S(1,1)} = P_{q\bar{q}}^{S(1,1)} = 0, \quad (32)$$

$$P_{qq}^{V(1,1)} = -2\, C_F\, e_q^2 \Big[\left(2\ln(1-x) + \frac{3}{2} \right) \ln(x)\, p_{qq}(x) + \frac{3+7x}{2}\ln(x) + \frac{1+x}{2}\ln^2(x) + 5(1-x) + \left(\frac{\pi^2}{2} - \frac{3}{8} - 6\zeta_3 \right) \delta(1-x) \Big], \quad (33)$$

$$P_{q\bar{q}}^{V(1,1)} = 2\, C_F\, e_q^2 \left[4(1-x) + 2(1+x)\ln(x) + 2 p_{qq}(-x) S_2(x) \right], \quad (34)$$

$$P_{gq}^{(1,1)} = C_F\, e_q^2 \Big[-(3\ln(1-x) + \ln^2(1-x))\, p_{gq}(x) + \left(2 + \frac{7}{2}x \right) \ln(x) - \left(1 - \frac{x}{2} \right) \ln^2(x) - 2x\ln(1-x) - \frac{7}{2}x - \frac{5}{2} \Big], \quad (35)$$

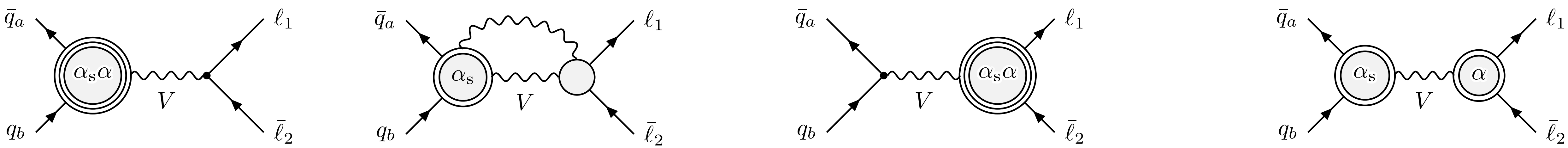
$$P_{\gamma q}^{(1,1)} = P_{gq}^{(1,1)}, \quad (36)$$

O(αα$_s$) corrections in pole approximation

S. Dittmaier, A. Huss, C. Schwinn, Nucl.Phys.B885 (2014) 318, Nucl.Phys.B904 (2016) 216

- The pole approximation provides a good description of the W (Z) region, as it has already been checked for the pure NLO-EW corrections

- At O(αα$_s$) there are 4 groups of contributions



- The last group yields the dominant correction to the process, due to factorizable corrections QCD-initial x QED-final

$$\sigma_{\mathrm{NNLO_{s\otimes ew}}} = \sigma_{\mathrm{NLO_s}} + \alpha\,\sigma_\alpha + \alpha\alpha_s\,\sigma_{\alpha\alpha_s}^{\mathrm{prod\times dec}} \qquad \delta_{\alpha\alpha_s}^{\mathrm{prod\times dec}} = \frac{\alpha\alpha_s\,\sigma_{\alpha\alpha_s}^{\mathrm{prod\times dec}}}{\sigma_{\mathrm{LO}}}$$

full result
pole approximation

$$\sigma_{\mathrm{NNLO_{s\otimes ew}}}^{\mathrm{naive\,fact}} = \sigma_{\mathrm{NLO_s}}(1+\delta_\alpha)$$

naive factorization

$$\frac{\sigma_{\mathrm{NNLO_{s\otimes ew}}} - \sigma_{\mathrm{NNLO_{s\otimes ew}}}^{\mathrm{naive\,fact}}}{\sigma_{\mathrm{LO}}} = \delta_{\alpha\alpha_s}^{\mathrm{prod\times dec}} - \delta_\alpha\delta'_{\alpha_s}$$

test of the validity of the naive factorization

the δ are the inclusive correction factor

- We need to compare these results with the O(αα$_s$) terms available in Monte Carlo (POWHEG)

The W boson mass: theoretical prediction

re-evaluation of the MW prediction G.Degrassi, P.Gambino, P.Giardino, arXiv:1411.7040

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

parametric uncertainties

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

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

estimate of missing higher-order contributions

two calculations performed directly in the OS renormalization scheme or

in the MSbar scheme with the eventual translation to OS values

MSbar scheme → systematic inclusion of higher-order corrections in the couplings

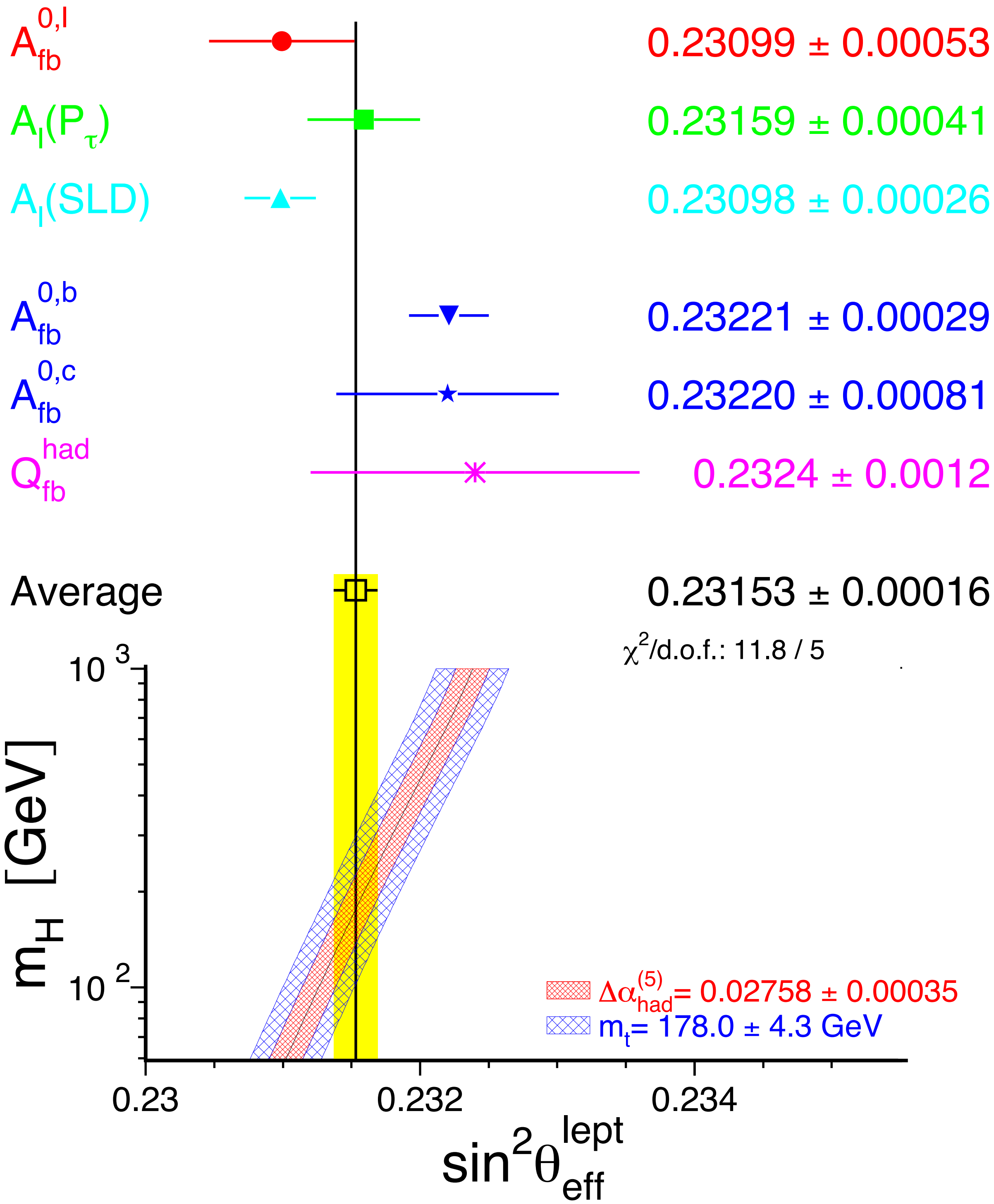
the comparison of the two numerical results

suggests that missing higher orders might have a residual effect of O(6 MeV)

Global electroweak fit (Gfitter, arXiv:1407.3792)

MW = 80.358 ± 0.008 GeV indirect determination more precise than direct measurement

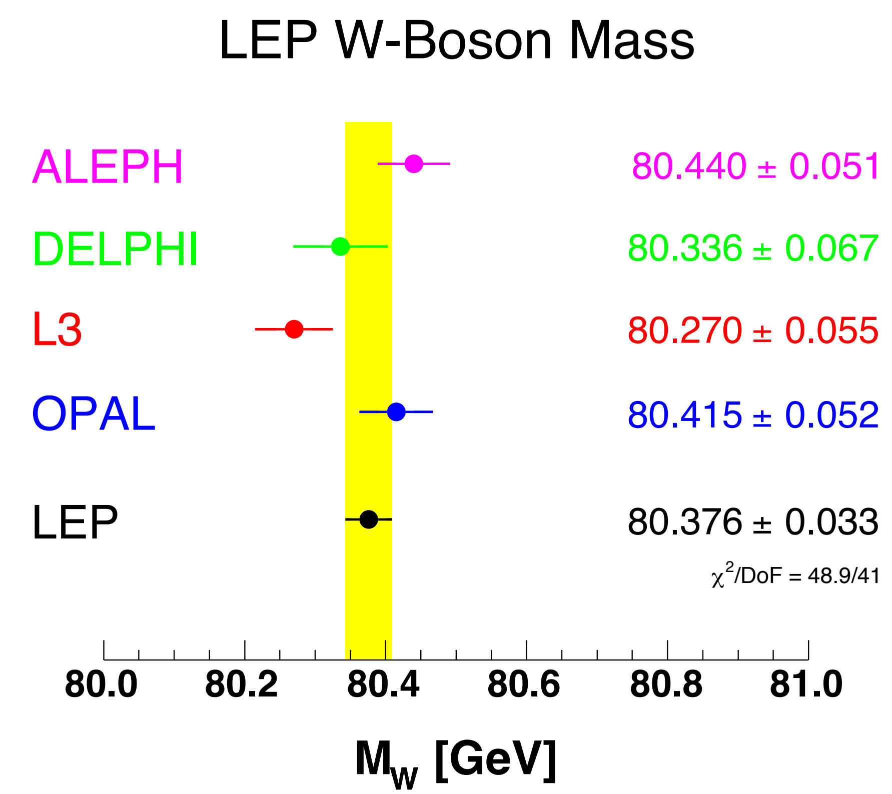
Results from LEP and SLC: $\sin^2\theta_{eff}$(leptonic)



- good sensitivity to the Higgs mass value
- tension between SLD and LEP results
- tension between leptonic and b-quark asymmetries

an independent measurement at hadron colliders can help to test the likelihood of the SM

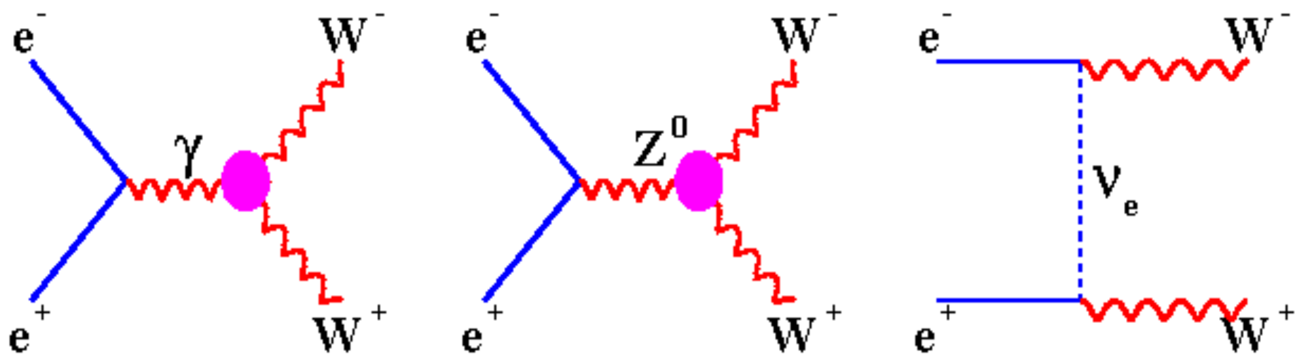
Results from LEP2 for MW

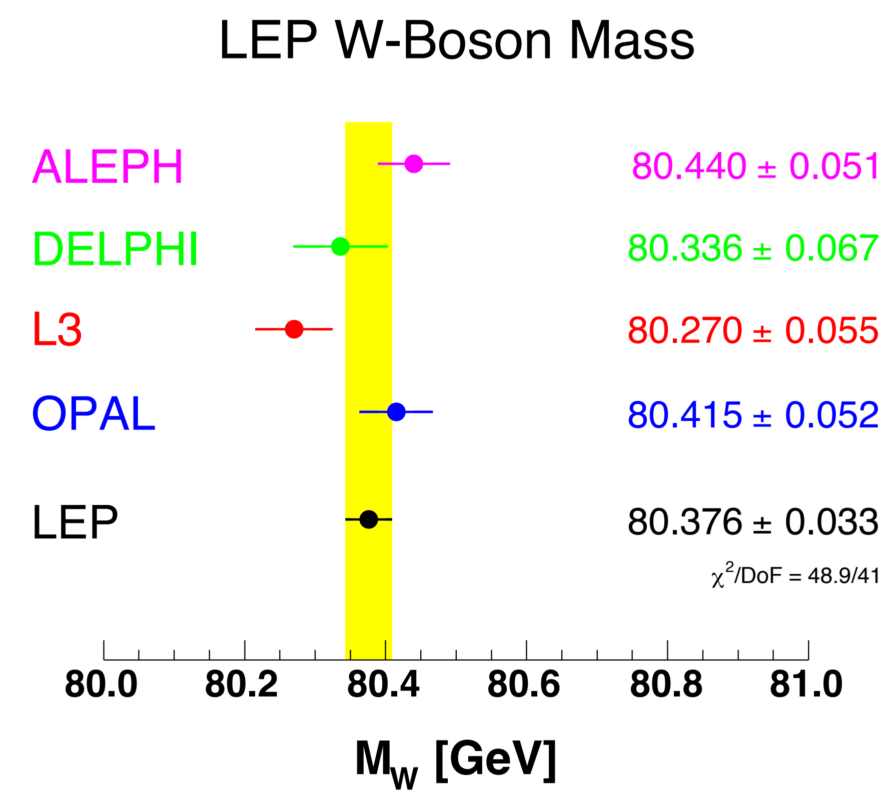


- the semi-leptonic channel was "golden" because
  - only two jets → unique invariant mass reconstruction
  - no colour reconnection of Bose-Einstein correlation problems

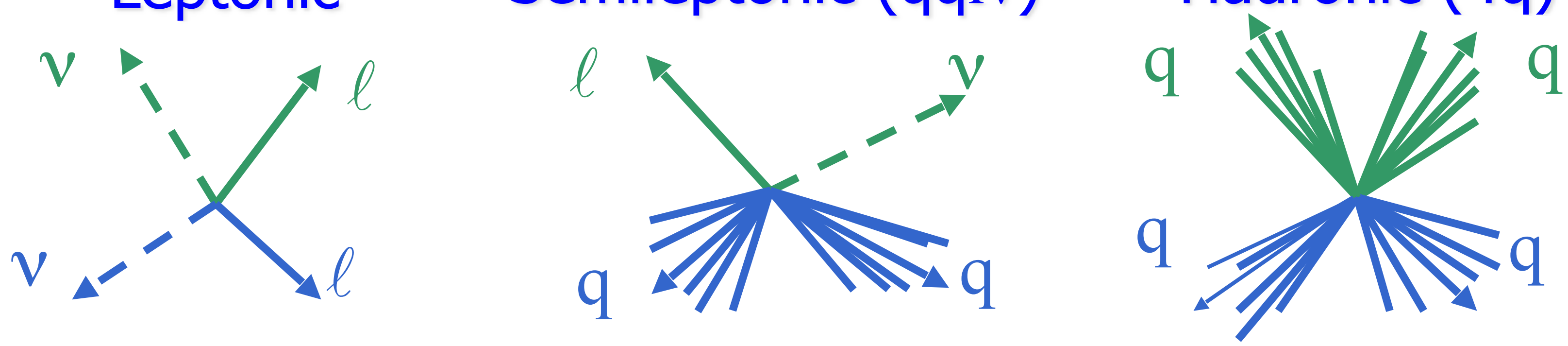
- LEP2 measurement mostly limited by statistics

Results from LEP2 for MW





Leptonic | Semileptonic (qqlν) | Hadronic (4q)



Low Mw sensitivity | 44% | 46%

- the semi-leptonic channel was "golden" because
  - ▹ only two jets → unique invariant mass reconstruction
  - ▹ no colour reconnection of Bose-Einstein correlation problems

- LEP2 measurement mostly limited by statistics