Prospects for precision EW measurements at the LHC

- Many thanks to the organisers for the invitation to present in this workshop an overview of what might be the panorama of precision EW measurements at the end of HL-LHC. Much of what I will show is based on the HL-LHC documentation and on recent work done in the context of the LHC precision EW working group over the past few years.

- I will focus mostly over the next 20' on the measurement of the masses of the W (and also Z and H bosons) and on the weak mixing angle.

- I wish to explicitly cover some theoretical issues which overlap to some extent with the work being done for FCCee. Much of what I will show has been shown in different presentations at the recent LHC SM working group meeting at https://indico.cern.ch/event/849342/

Prospects for precision EW measurements at the LHC

- **See in particular presentations by:**
  - M. Schott
  - N. Andari
  - A.J. Armbruster, W. Barter, A. Khukhunaishvili
  - V. Bertone
  - M. Boonekamp
  - S. Bondarenko
  - S.A. Yost
  - A. Vicini
  - E. Richter-Was
  - A. Glazov
- **Four main activities in LHC precision EW working group:**
  - **Resummation calculations of pTW/Z and of pTW/pTZ**
  - **QED/EW corrections at Z pole for weak mixing angle**
  - **Measurement of correlations between global PDF fits**
  - **Preparation of run-2 LHC/Tevatron combinations for m_W and weak mixing angle**
- **Goal is to have publications and overall report by late summer 20**

Precision measurements in the EW sector at the LHC

- At the LHC, the word precision has different meanings in different areas (note that mass measurements are a special case):
  - It means sub-percent precision in DY and in some aspects of flavour physics in LHCb
  - It means a few percent at best still for top physics
  - It means 10-40% for Higgs physics (eg couplings), at least for quite a while
- It is not a surprise therefore that DY measurements are the most demanding in terms of theoretical accuracy (far more than Higgs!).
- In a nutshell, there are two key difficulties we are confronted with:

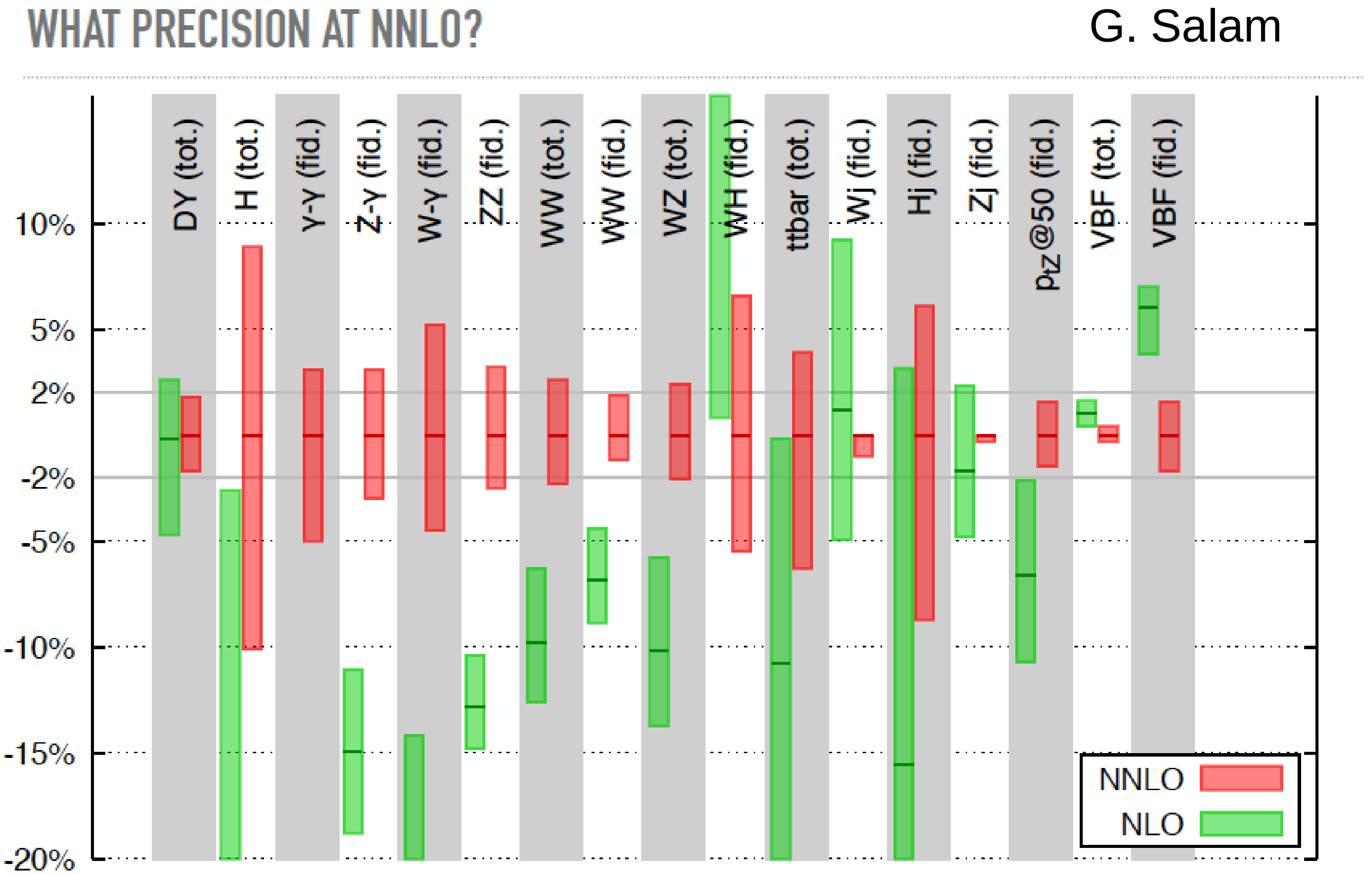
a) The lack of a MC generator tool for DY production which would include N...NLO+N…NLL QCD (and EW/QED) calculations, perfectly matched and merged to PS, with a UE model reproducing the data

b) The complexity of dealing with a large number of sources of theoretical uncertainty which are not always reliable nor stable

Can we be reasonably certain that full calculation would fall within red bands below?

More importantly, how can we be sure that this would be the case after acceptance cuts, which eg for searches select only small fraction of events?

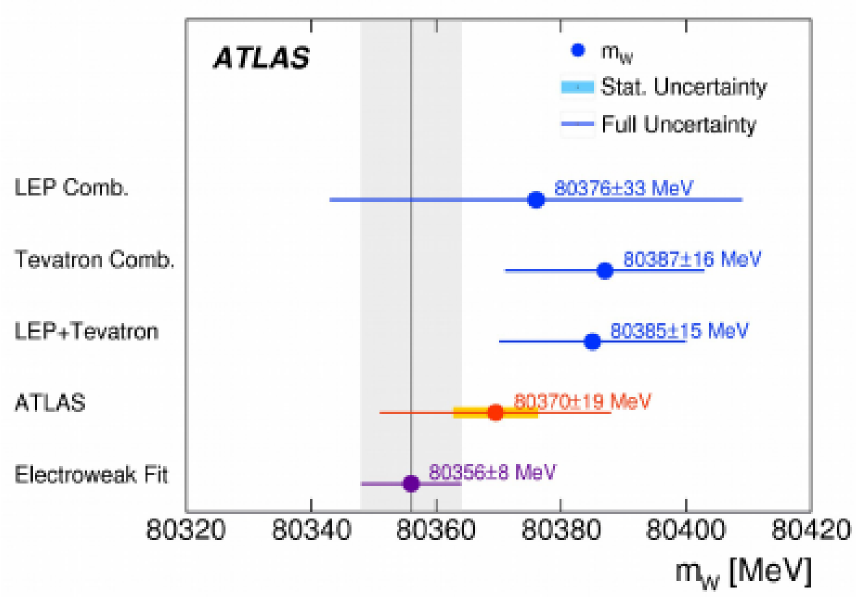
G. Salam

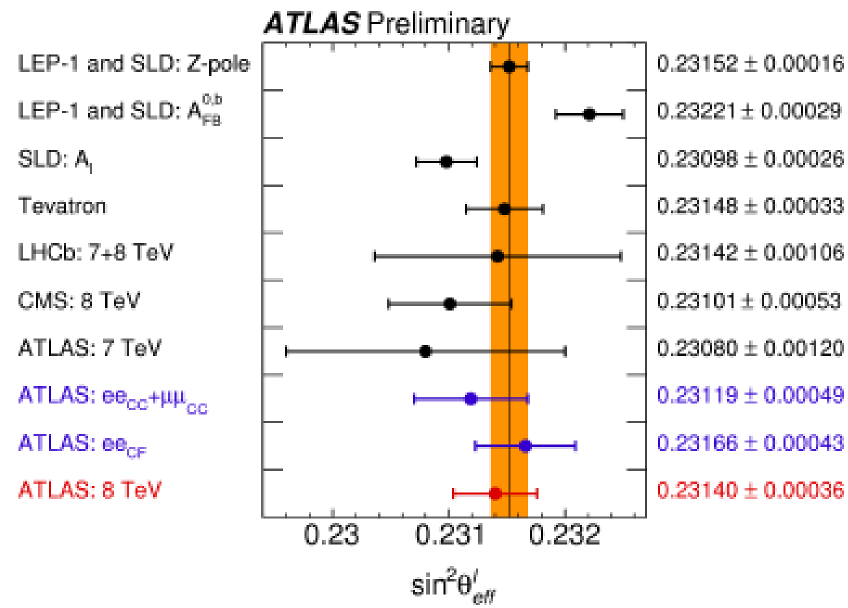


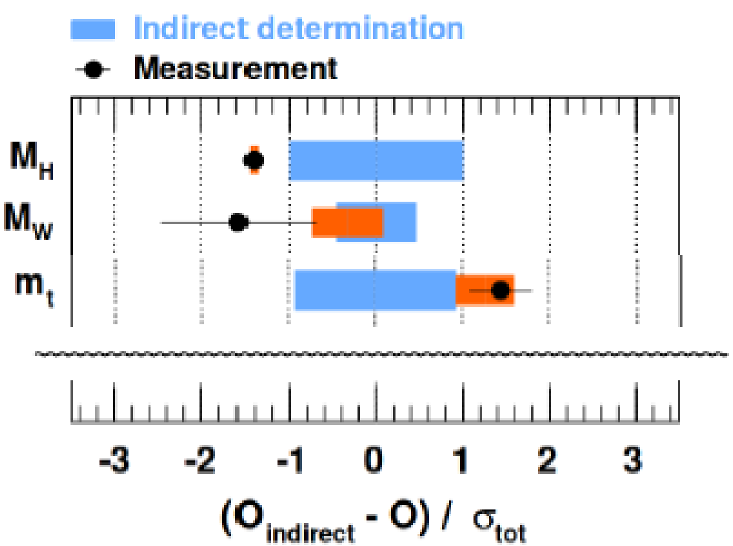
•D. Froidevaux, CERN/M

Prospects for precision EW measurements at the LHC

Where we are now







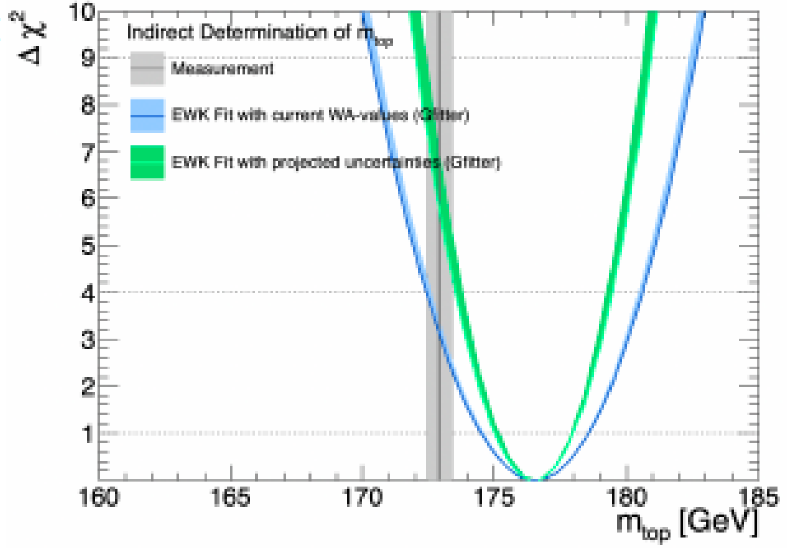
[GeV]	Measurement	SM Prediction (*)
m_H	125.1± 0.2	100.2 ± 22.5
m_{top}	173.06 ± 0.94	175.97 ± 2.11
m_W	80.379 ± 0.013	80.356 ± 0.008

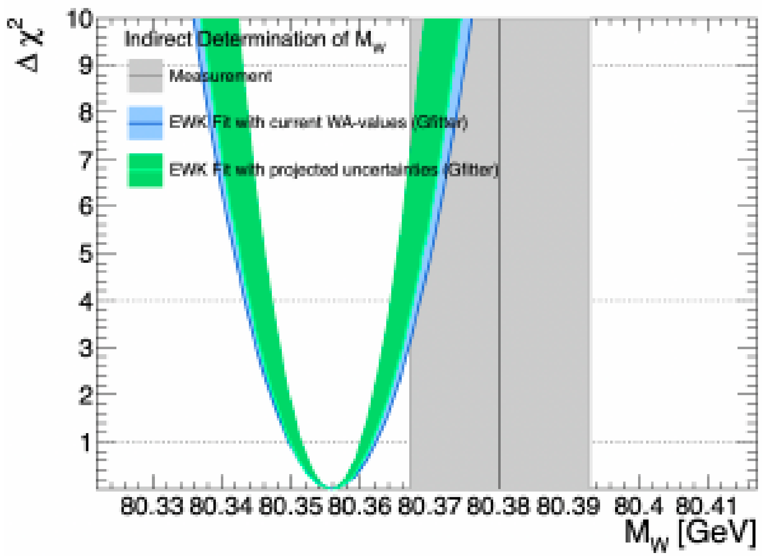
(*) arXiv:1803.01853

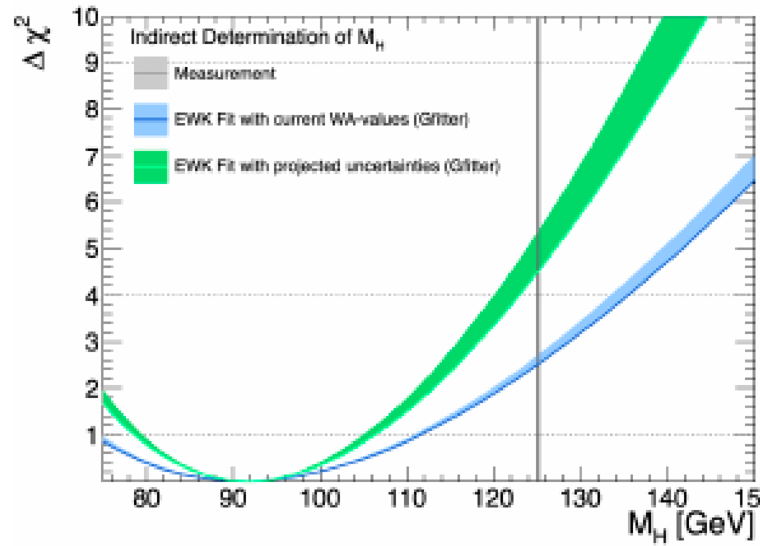
Prospects for precision EW measurements at the LHC

- By the end of the LHC, we (being optimistic) might have
  - $\Delta m_W \approx 8$ MeV
  - $\Delta m_{Top} \approx 300$ MeV
  - $\Delta \sin^2\Theta_W \approx 0.00012$

- … results in indirect precisions of
  - $\Delta m_W \approx 4$ MeV, $\Delta m_{Top} \approx 1.3$ GeV, $\Delta m_H \approx 13$ GeV
  - See also a detailed studfy from Gfitter from 2014: https://arxiv.org/abs/1407.3792







Prospects for precision EW measurements at the LHC

Two paths for future measurements of m_W with Run 2 samples

	High pileup	Low pileup
Most sensitive observable	p_T lepton	m_T
Theory challenge	W/Z p_T ratio, PDFs	PDFs
Experimental challenge	p_T lepton calibration	Recoil calibration
Dominant uncertainties	Physics modelling, PDFs	Recoil, stat, PDFs

- Can benefit from high stat of the full Run 2 sample
- Based on dedicated runs, provides measurement and data-driven modelling of p_T W

CMS 2016 **ATLAS 20167/2018**

- Orthogonal approaches with different dominant uncertainties
- Should be both pursued, will benefit from the combination

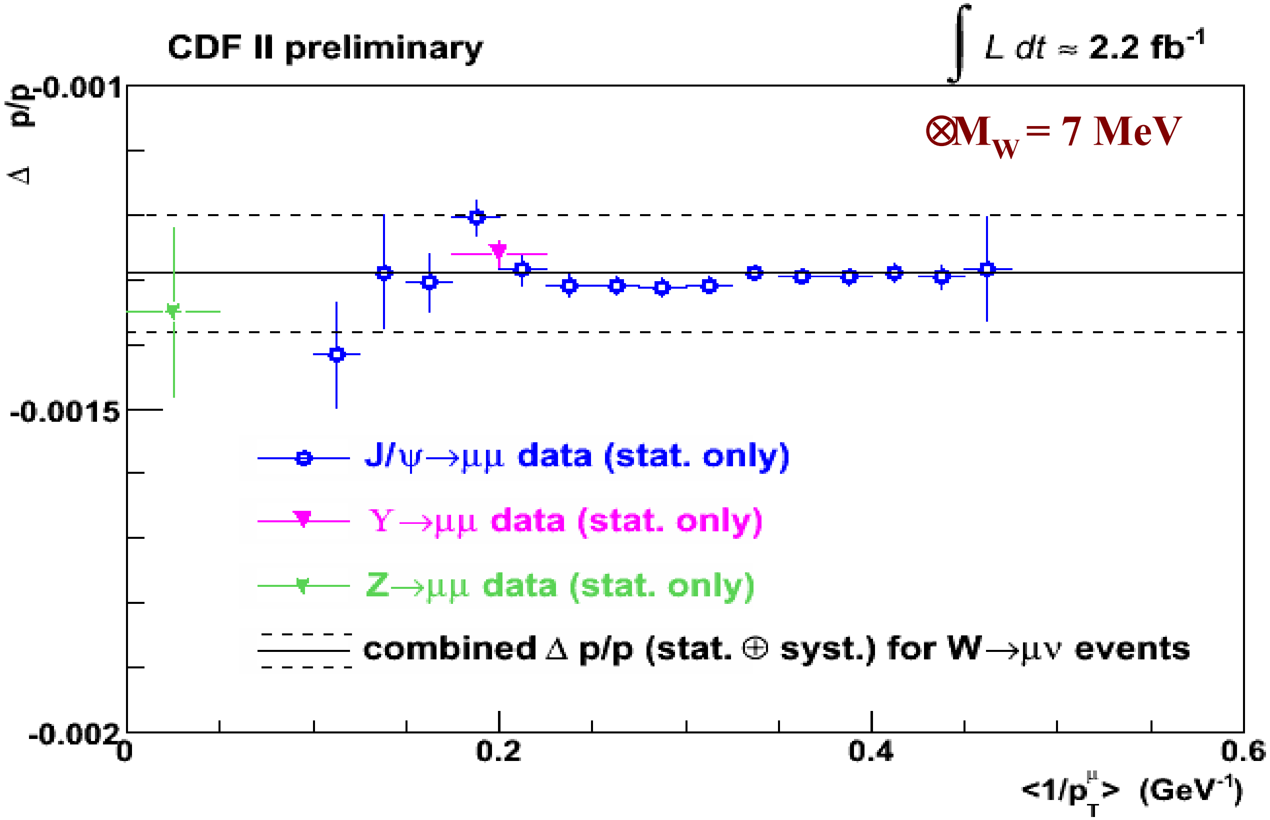
W-boson mass measurements: Tevatron versus LEP2

CDF: Tracker Linearity Cross-check & Combination

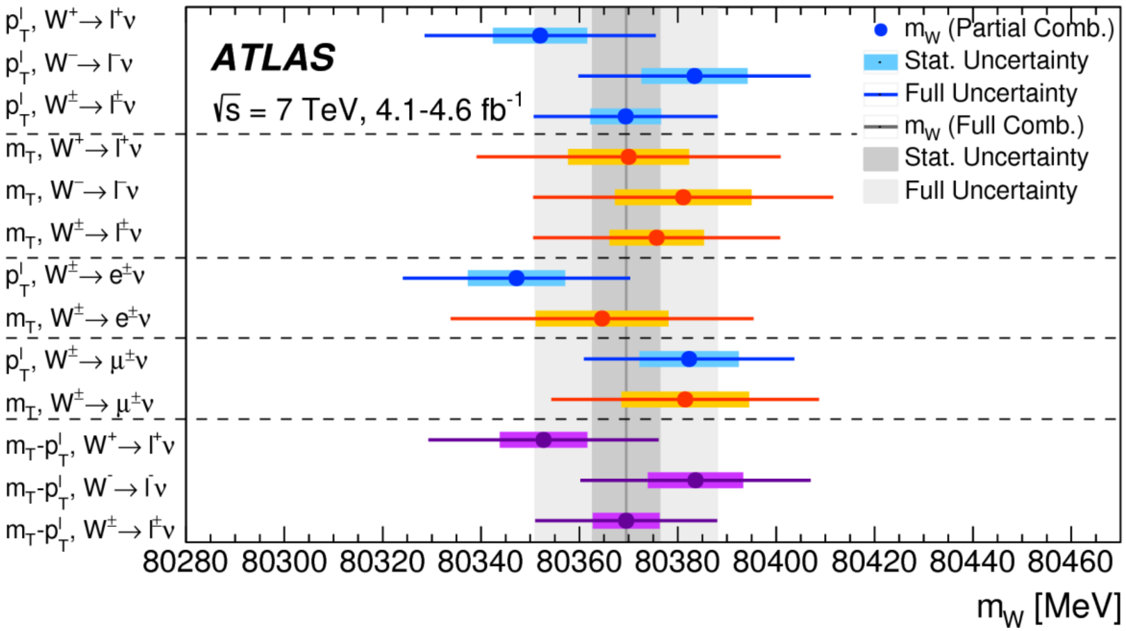
Final momentum calibration using the J/) , ®and Z bosons

Combined momentum scale correction:

- $\Delta p/p = (-1.29 \pm 0.07_{\text{independent}} \pm 0.05_{\text{QED}} \pm 0.02_{\text{align}}) \times 10^{-3}$



Relative importance of different measurements of m_W

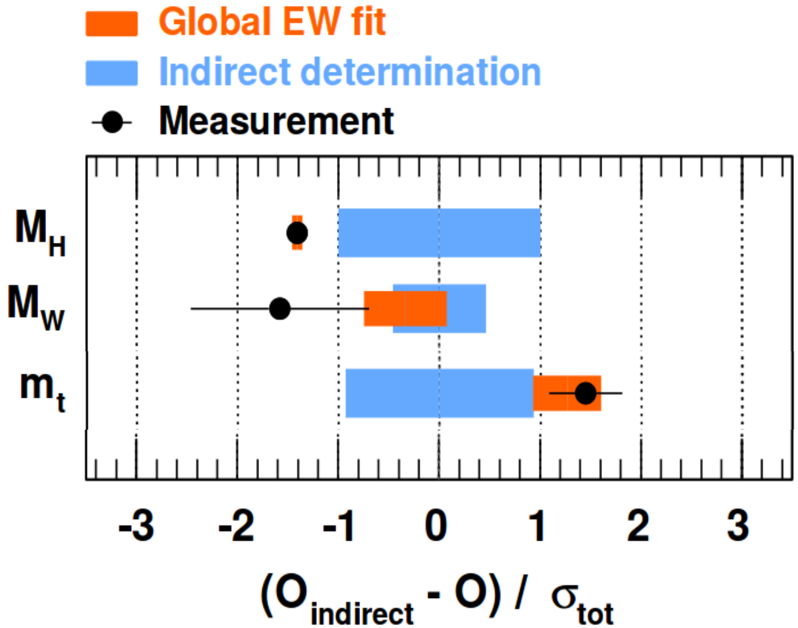


Combination	Weight
Electrons	0.427
Muons	0.573
m_T	0.144
p_T^ℓ	0.856
W^+	0.519
W^-	0.481

- **Measuring electrons AND muons provides a crucial set of closure constraints on the experimental systematic uncertainties. A number of experimental issues at the ~ 30-50 MeV level on m_W were resolved in both channels thanks to this.**

- **Even though the weight of the m_T measurement is much smaller than that of p_T^l, it plays an important role in the understanding of the theoretical modelling uncertainties on p_T^W**

Relation between top, Higgs and W masses



	Measurement	SM Prediction (*)
m_H	125.09 ± 0.24	102.8 ± 26.3
m_{top}	172.84 ± 0.70	176.6 ± 2.5
m_W	80.385 ± 0.015	80.360 ± 0.008

•(*) arXiv:1608.01509

The measurements of the Higgs and top-quark masses are currently more precise than their indirect determination from the global fit of the electroweak observables → **Improving precision will not increase sensitivity to new physics**

Indirect determination of m_W (±8 MeV) is more precise than the experimental measurement → **Call for $\delta m_W < 10$ MeV**

The W mass is nowadays the crucial measurement to improve the sensitivity of the global EW fits to new physics

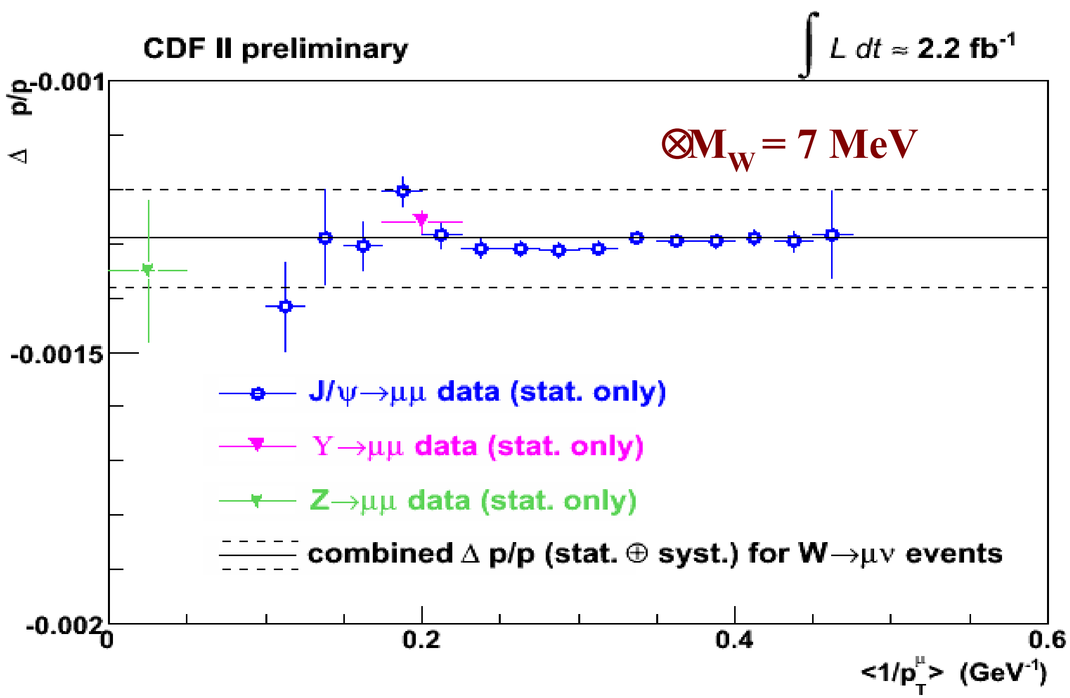
How well can LHC measure m_Z? Look back at Tevatron

CDF: Tracker Linearity Cross-check & Combination

Final momentum calibration using the J/) , ®and Z bosons

Combined momentum scale correction:

- $\Delta p/p = (-1.29 \pm 0.07_{independent} \pm 0.05_{QED} \pm 0.02_{align}) \times 10^{-3}$



Z → μμ sample used here by CDF corresponds to only ~ 10^5 events yielding the dominant contribution to the 7 MeV uncertainty on m_W

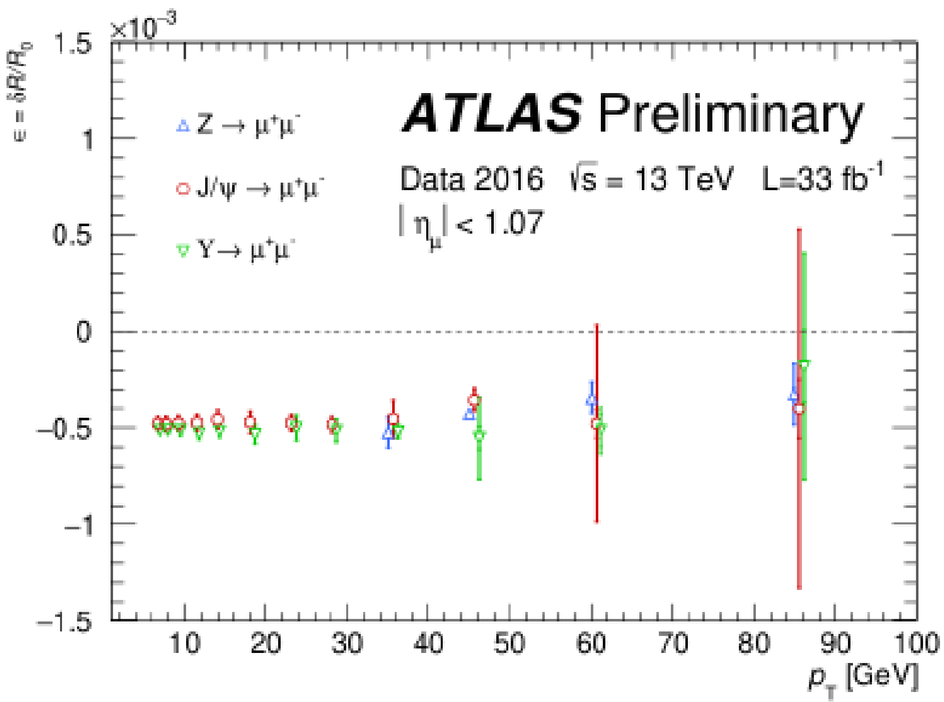
Note: this paves the way to a precision measurement of m_Z at hadron colliders, can LHC compete with LEP?

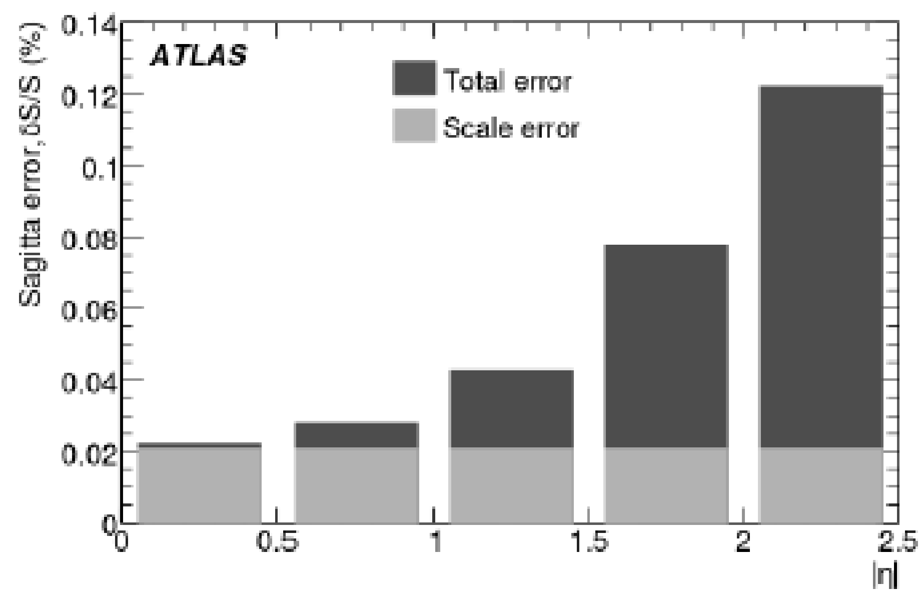
How well can LHC measure m_Z, m_H? The example of ATLAS

This is purely a muon performance issue, requiring a lot of work, but reaching a few MeV is not an impossible goal

- In Run 2 the muon momentum scale is uniform in pT and consistent between J/ψ, Y, and Z
- > 100 x 10^6 J/ψ events in Run 2 should allow calibrating the scale at a few 10^{-5}

There is still an open question on the magnitude of the scale correction: ~ 0.8×10^{-3}
→ The absolute value of the B-field is known at 2×10^{-4}





W-boson mass measurement at the LHC

The measurement of m_W at the LHC is extremely challenging and prone to many potential biases due to QCD effects

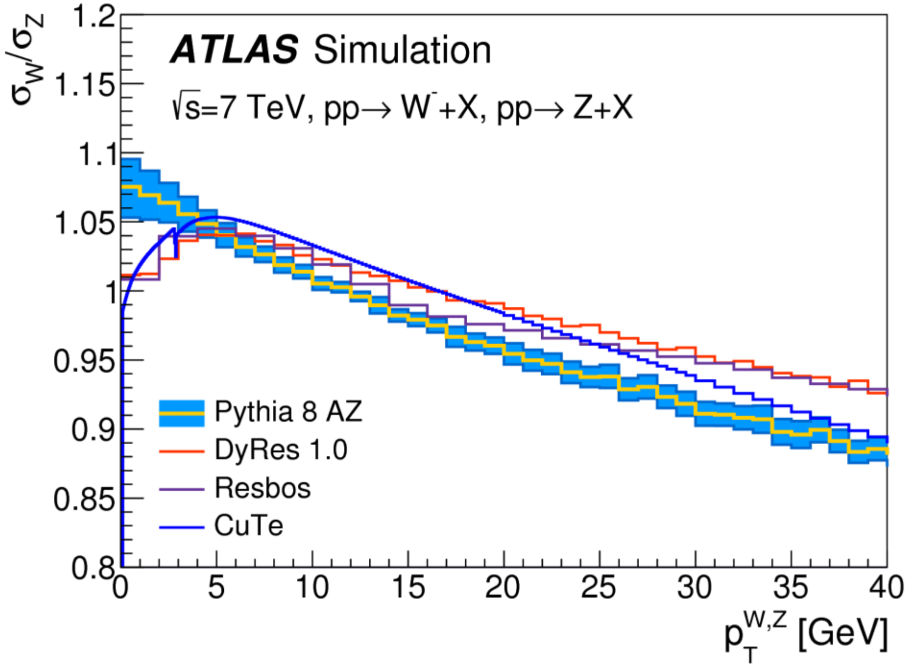
These affect all aspects of the measurement: detector calibration, transfer of theory predictions tuned to data from Z to W, PDF uncertainties, W polarisation, modelling of p_T^W

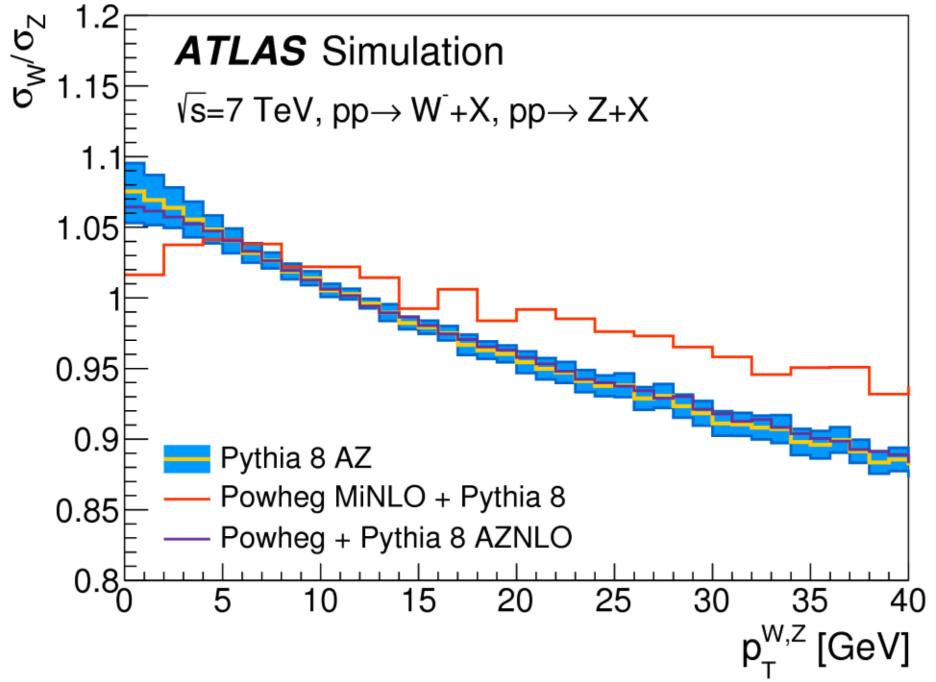
Need to design the measurement to be “as waterproof as possible” from the point of view of detector calibration and physics modelling

At the same time, the challenge makes the measurement hugely interesting, and provides a great occasion to improve the understanding of the detector performance and of QCD beyond that achieved by any other measurement or search at the LHC

Transverse momentum distribution

- **Theoretically more advanced calculations were also attempted**
  - **DYRES (and other resummation codes : ResBos, CuTe)**
  - **Powheg MiNLO + Pythia8**
- **All predict a significantly harder p_T^W spectrum for given p_T^Z distribution :**





- **This behaviour is disfavoured by data (see later); predictions discarded for now. As a result, no explicit uncertainty from missing fixed-order terms at $O(\alpha_s^2)$, but use data to place an upper bound on this effect.**

Summary of QCD predictions and uncertainties

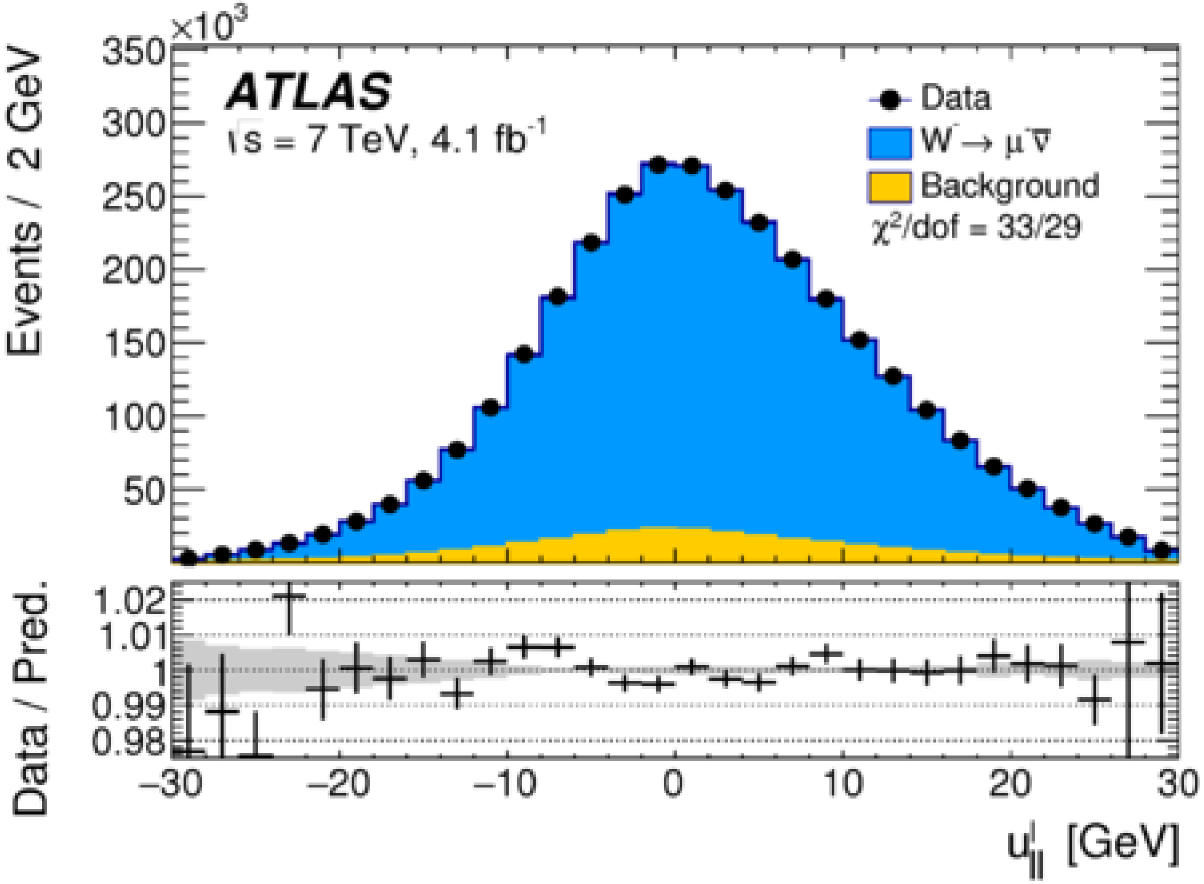
- **Baseline**
  - $d\sigma/dy$, $A_i(p_T, y)$: DYNNLO+CT10nnlo (fixed-order)
  - At given y, $d\sigma/dp_T$ is predicted using Pythia8 AZ

Validated by the data:
σ_W, σ_Z, p_T^Z, A_i ; also η_l, u_T, u_{ll}

- **Uncertainties**
  - CT10nnlo uncertainties (synchronised in DYNNLO and Pythia) + envelope comparing CT10 to CT14 and MMHT. Strong anti-correlation of uncertainties for W^+ and W^-!
  - AZ tune uncertainty; parton shower PDF and factorization scale; heavy-quark mass effects
  - A_i uncertainties from Z data; envelope for A2 discrepancy

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

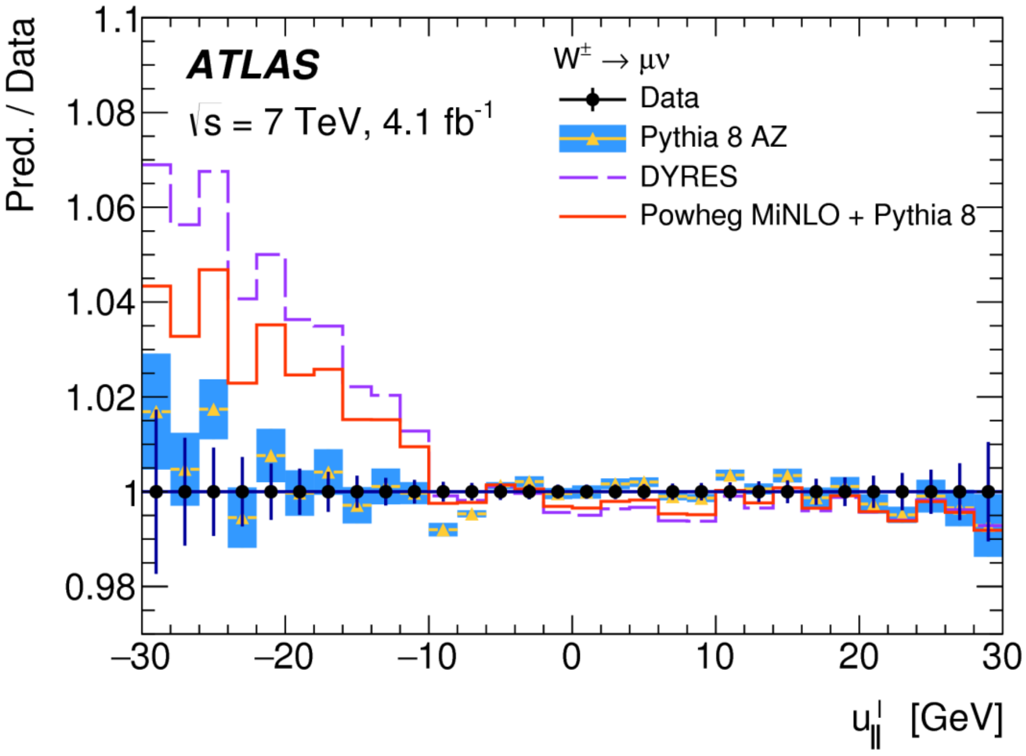
Control of p_T^W modelling : $u_{||}^e$, $u_{||}^\mu$

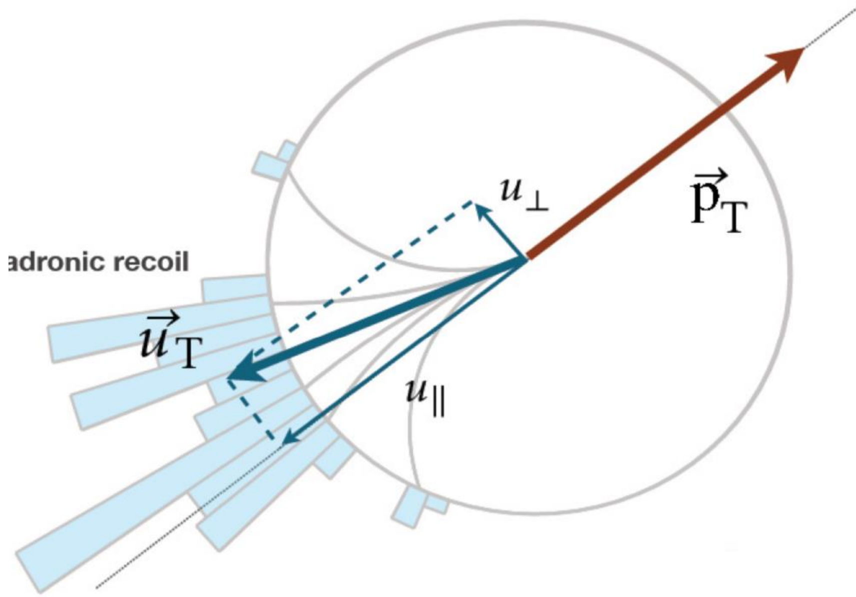


- The region $u_{//}^l$ < -10 GeV is sensitive to the physics modelling of the soft part of the p_T^W spectrum
- With a total of e.g. ~ 0.8M W to $\mu\nu$ decays, one can constrain modelling uncertainties to ~ 10 MeV

Control of p_T^W modelling : $u_{||}^e$, $u_{||}^\mu$

The $u_{||}^l$ distribution is very sensitive to the underlying p_T^W distribution, for $u_{||}^l < 0$. This feature can be exploited, even in a high pile-up environment to verify the accuracy of the baseline model, and to compare to alternative (more state-of-the-art?) models





Pythia 8 tuned to Z OK; DYRES, Powheg MiNLO disfavoured

Benchmarking of resummation calculations

$p_T^{W,Z}$ benchmarking activity

Main purpose of the benchmark

- We are now in the **precision phase** of the LHC.
- The present **accuracy** for *W*/*Z* production now is such that:
  - electroweak corrections become relevant,
  - **QCD** has to be pushed to its limits.
- **Resummation** allows us to include corrections to all orders in α_s:
  - necessary in the presence of large logs (typical in multiscale problems),
  - production of a *W*/*Z* with small q_T but large invariant mass Q ($q_T \ll Q$) is a typical example.
- Different **formalisms** provide resummation of $\log(q_T/Q)$:
  - need to understand **similarities/differences** and **uncertainties**.
- This will *eventually* allow for a **sensible comparison** to data:
  - reliable determination of the *W* mass through *W*/*Z* ratio.

Benchmarking of resummation calculations

Codes taking part

- SCETlib
  [https://confluence.desy.de/display/scetlib]
- CuTe
  [https://cute.hepforge.org]

} SCET

- DYRes/DYTURBO
  [https://gitlab.cern.ch/DYdevel/DYTURBO]
- ReSolve
  [https://github.com/fkhorad/reSolve]

} q_T-res.

- RadISH
  [https://arxiv.org/pdf/1705.09127.pdf]
- PB-TMD
  [https://www.xfitter.org/xFitter/]

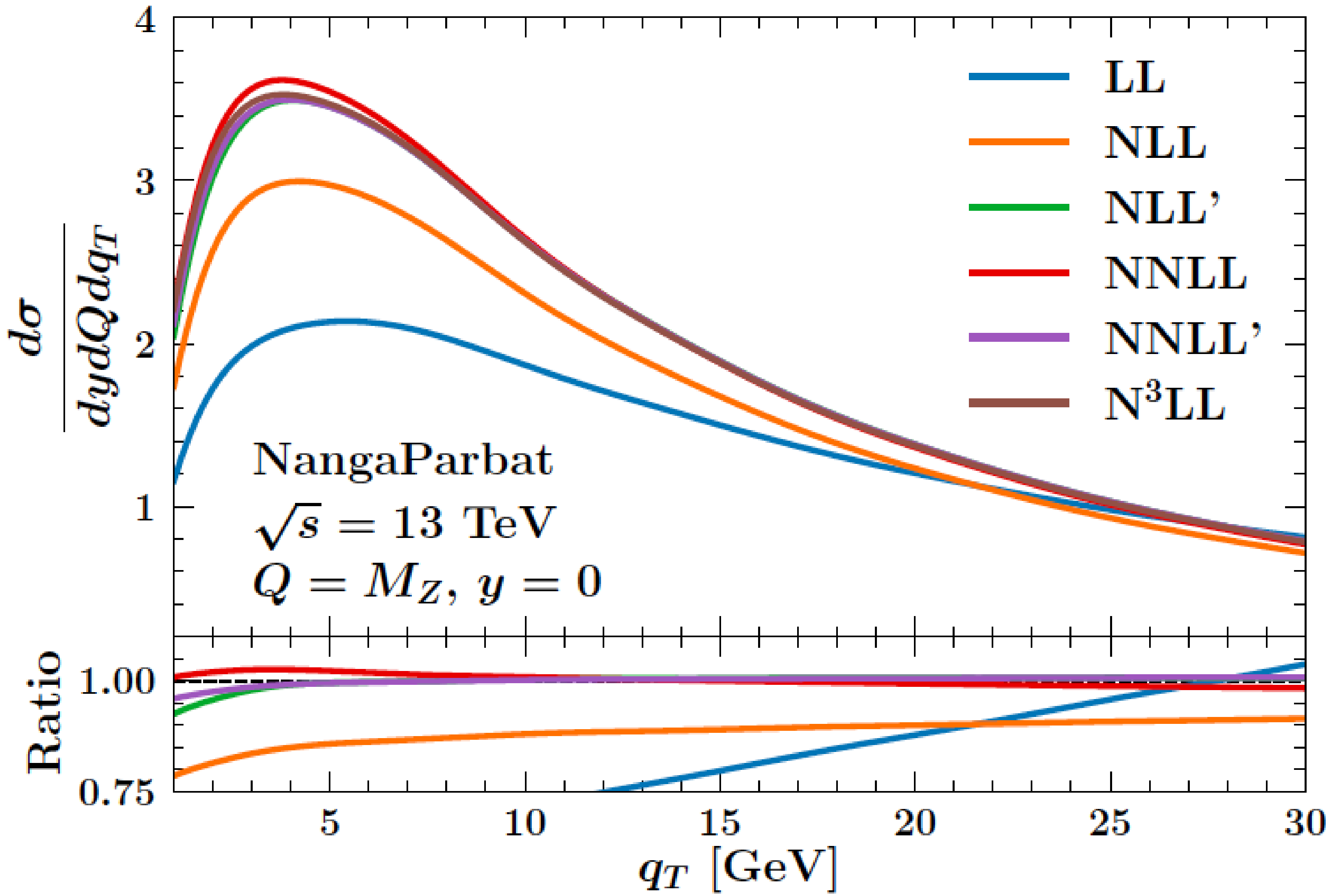
} PB

- NangaParbat
  [https://github.com/vbertone/NangaParbat]
- arTeMiDe
  [https://teorica.fis.ucm.es/artemide/]

} TMD

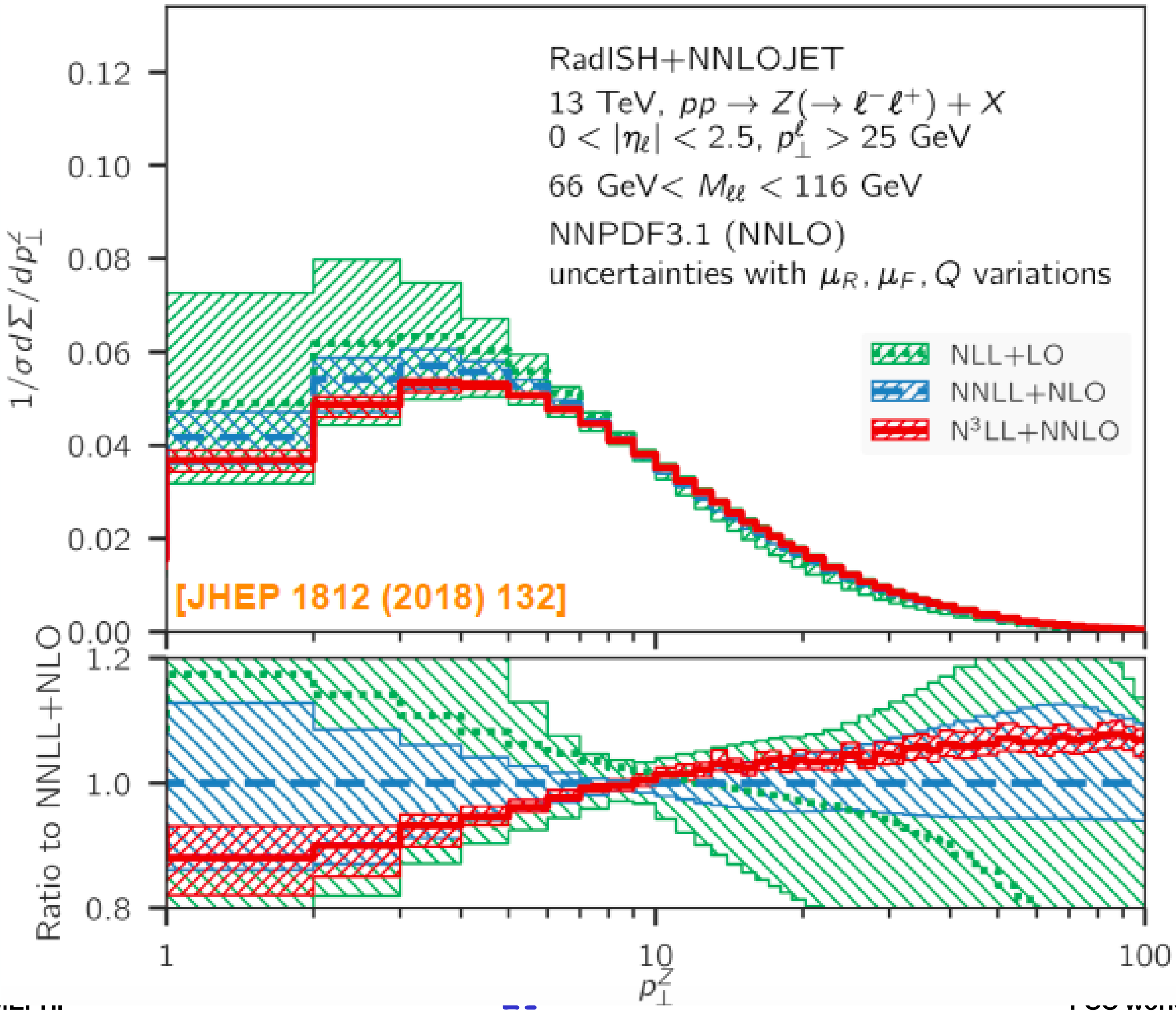
Benchmarking of resummation calculations

Perturbative convergence



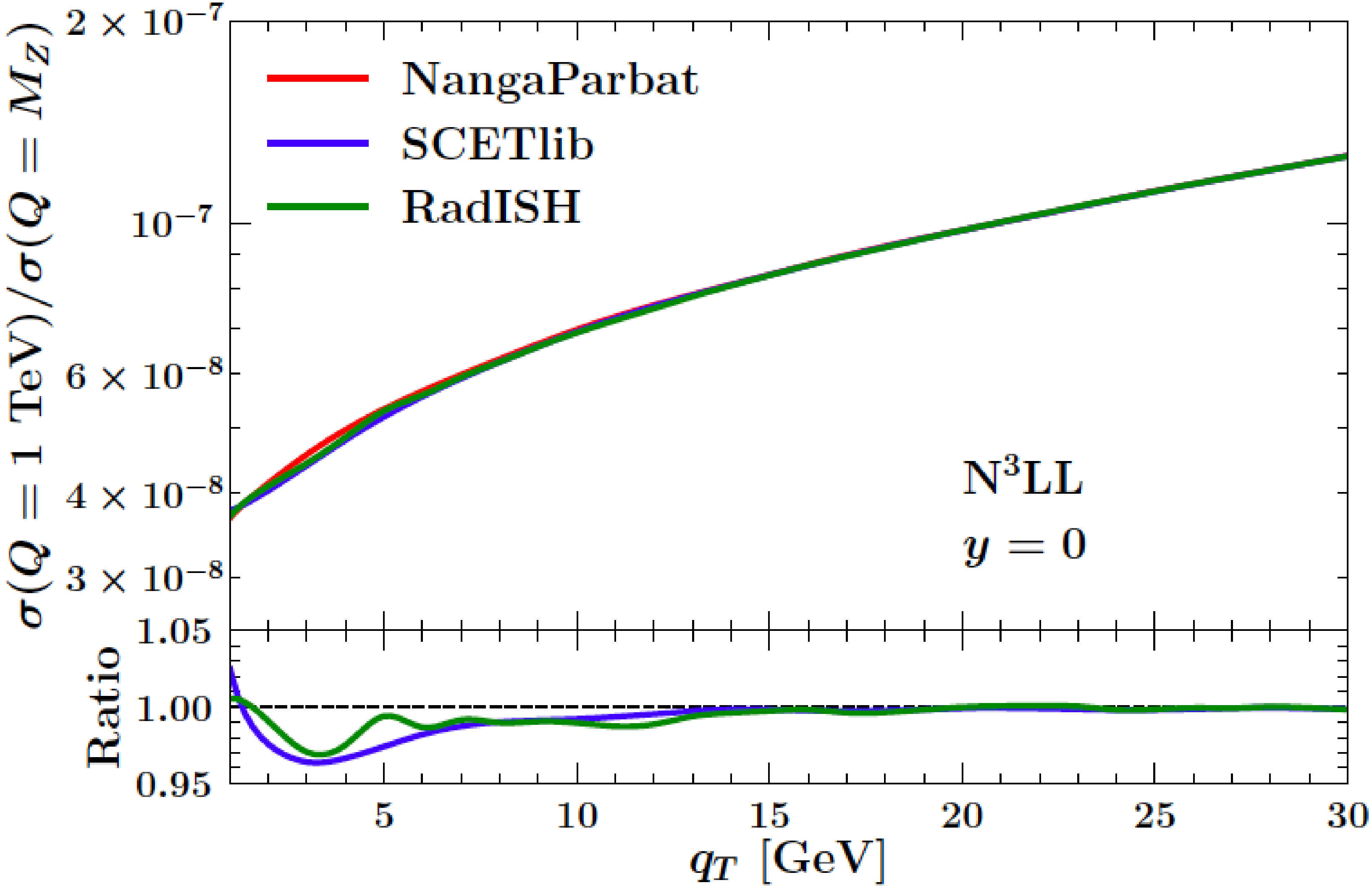
Benchmarking of resummation calculations

Perturbative convergence

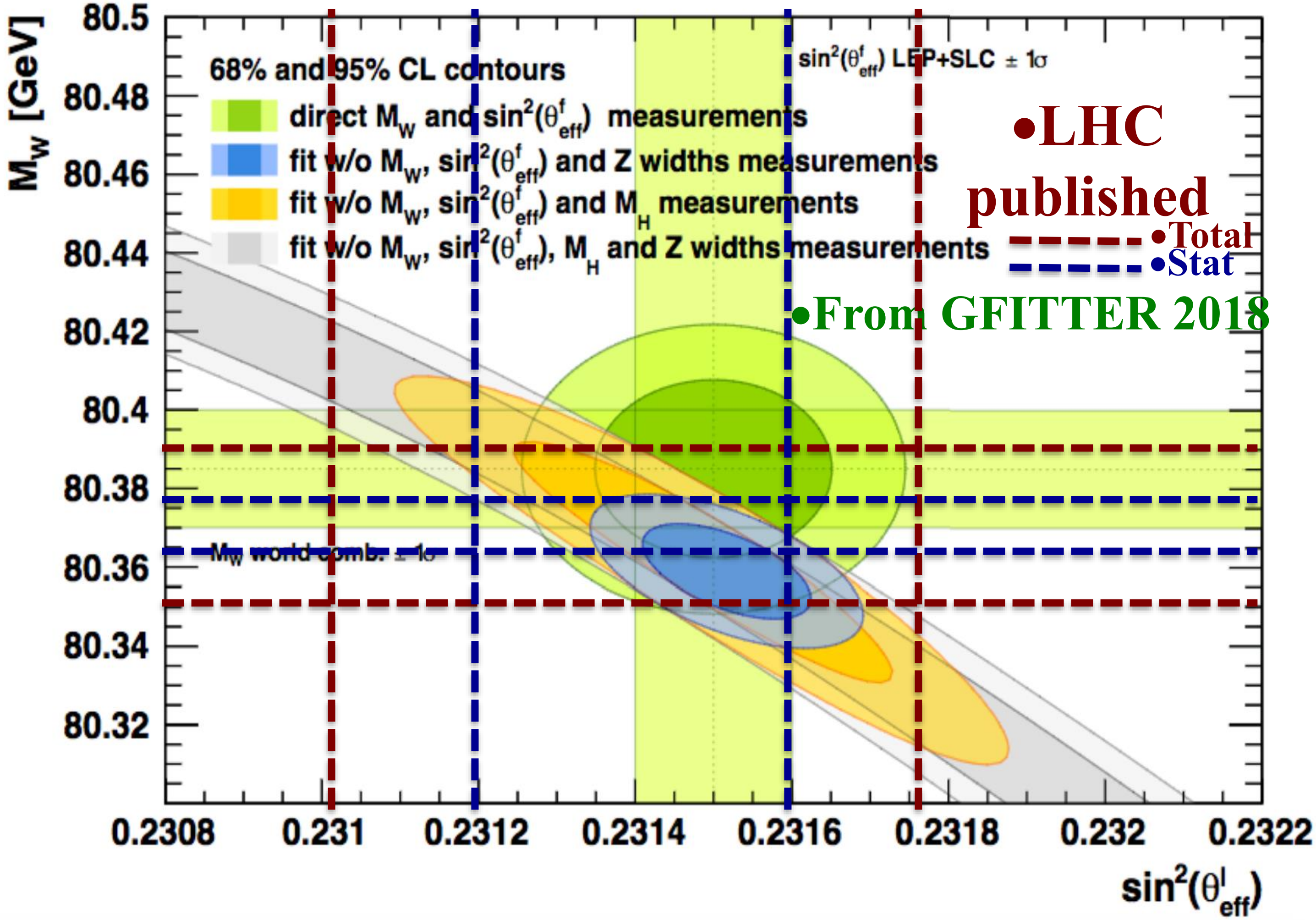


Benchmarking of resummation calculations

Kinematic evolution



Global EW fits in precision EW group



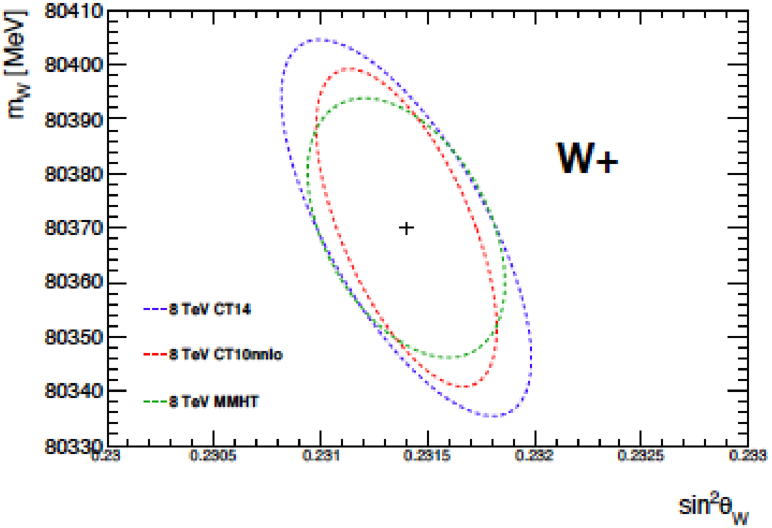
- One of goals would be to produce "proper" ellipse in this plot
  - Currently, direct measurements above are uncorrelated
- LHC measurements are correlated primarily through PDFs

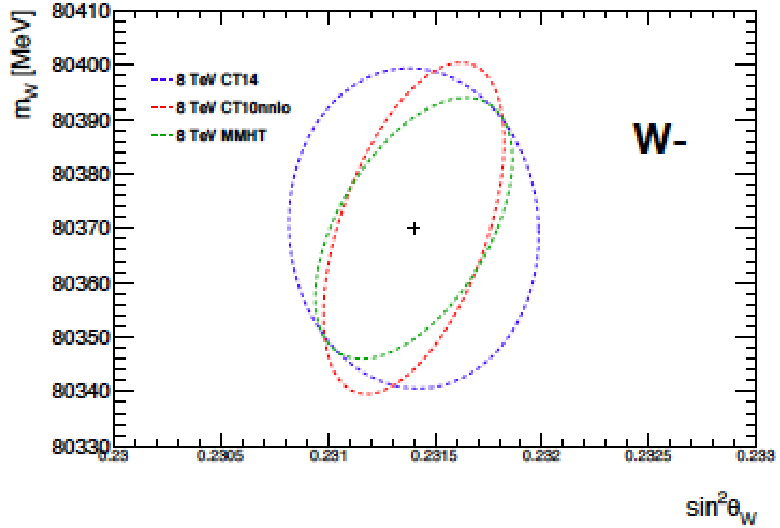
PDF correlations for EW fit

7 TeV mW
8 TeV sin2theta

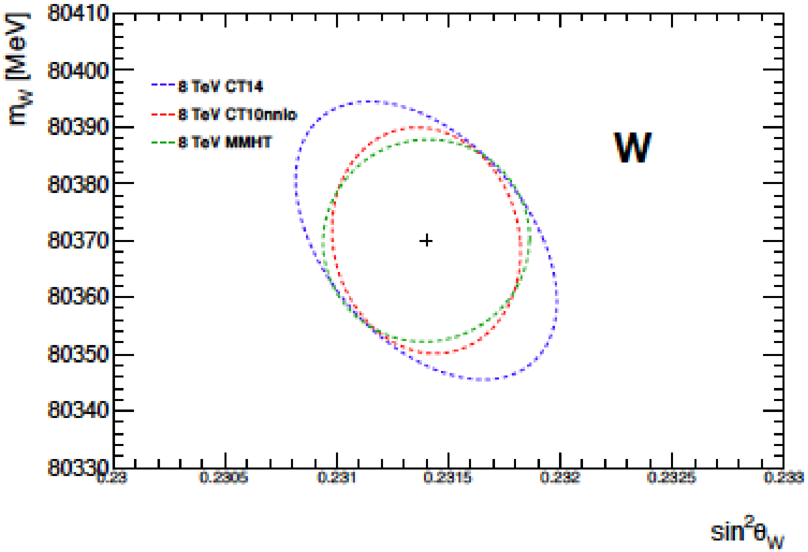
Correlation ellipses
(Preliminary)

Eur. Phys. J. C (2018) 78:110
ATL-CONF-2018-037





Opposite correlation W+/-



Only PDF uncertainties

QED/EW corrections at Z pole

Summary Status and Issues for (not only NLO) QED/EW corrections for weak mixing angle and mW

E. Richter-Was (IF UJ, Krakow)

- EW and QED corrections for $\sin^2_W$ measurement
  - EW schemes: from LEP to LHC
  - Observables, Pseudo-observables, $\sin^2\theta_{eff}$ at LHC
  - QED ISR/IFI
  - Photon induced processes
- EW and QED corrections for m_W measurement

Please note:

NLO EW is insufficient for both $\sin^2\theta_{eff}$ and m_W !

We know from LEP times that fixed-order is not necessarily the right way to access corrections for precision measurements sensitive to QED/EW corrections.

For m_W, QED FSR beyond state-of-art YFS or Photos calculations may be needed.

QED/EW corrections at Z pole

Genuine weak and lineshape corrections

wt^{EW} : TauSpinner + Dizet 6.21, 6.42, 6.45 ★

↑ with updated $\alpha(M_Z)$

wt^{EW}

MC events
EW LO

→ $\alpha(0)$ v0: LO, NLO+HO

→ $\alpha(0)$ v1: LO

→ G_μ: LO

→ $\sin^2_{eff}$: LO

Arbitrary
EW setup

Powheg_ew: QCD LO, Z

- $\alpha(0)$ v0: LO
- $\alpha(0)$ v1: LO, NLO, NLO+HO
- G_μ: LO, NLO, NLO+HO
- ★ $\sin^2_{eff}$: LO, NLO, NLO+HO

MCSANC: QCD LO, Z

- $\alpha(0)$ v1: LO, NLO, NLO+HO
- G_μ: LO, NLO, NLO+HO

★ New developments

QED/EW corrections at Z pole

EW schemes: benchmark input parameters

SM relation used to calculate EW LO parameters for different schemes. On-shell mass.

	LEP-legacy		LHC-paradigm		New scheme
Parameter	$(\alpha(0), G_\mu, M_Z)$ $\alpha(0)$ v0	$(\alpha(0), M_W, M_Z)$ $\alpha(0)$ v1	(G_μ, M_Z, M_W) G_μ	$(\alpha(0), s_W^2, M_Z)$ $\sin^2_{eff}$ v1	(G_μ, s_W^2, M_Z) sin^2_{eff} v2
M_Z (GeV)	91.1876	91.1876	91.1876	91.1876	91.1876
Γ_Z (GeV)	2.4952	2.4952	2.4952	2.4952	2.4952
Γ_W (GeV)	2.085	2.085	2.085	2.085	2.085
$1/\alpha$	137.035999139	137.035999139	132.23323	137.035999139	128.744939484
α	0.007297353	0.007297353	0.007562396	0.007297353	0.007767296
G_μ (GeV^{-2})	$1.1663787 \cdot 10^{-5}$	$1.1254734 \cdot 10^{-5}$	$1.1663787 \cdot 10^{-5}$	$1.09580954 \cdot 10^{-5}$	$1.1663787 \cdot 10^{-5}$
M_W (GeV)	80.93886	80.385	80.385	79.93886984	79.93886984
s_W^2	0.2121517	0.2228972	0.2228972	0.231499	0.231499
$\frac{G_\mu \cdot M_Z^2 \cdot 16 c_W^2 s_W^2}{\sqrt{2} \cdot 8\pi \cdot \alpha} = 1.0$ $s_W^2 = 1 - m_W^2/m_Z^2$	$\to s_W^2, M_W$	$\to G_\mu, s_W^2$	$\to \alpha, s_W^2$	$\to G_\mu, m_W$	$\to \alpha, m_W$
$\alpha_s(M_Z)$	0.120178900000	0.120178900000	0.120178900000	0.120178900000	0.120178900000

$$s_W^2 = 1 - m_W^2/m_Z^2$$

$$G_\mu = \frac{\pi\alpha}{\sqrt{2} M_W^2 s_W^2}$$

E. Richter-Was, IF JU CERN, LHC EW precision, 17.12.2019 5

- ongoing benchmarking with DIZET, MCSANC, POWHEG_EW on pure weak effects

QED/EW corrections at Z pole

QED ISR/IFI/FSR

- **QED FSR:**
  - Simulated with PHOTOS in the experimental analysis, now also available option of including pair-creation
  - Tests performed in the past with KKMC, Powheg-ew or HORACE confirmed its addequatenes for LHC precision physics.

- **QED IFI and ISR:**
  - HORACE, Powheg_ew, MCSANC, KKMC-hh.
  - Good progress on convergence between different codes. As expected effect small and will be accounted for as systematics of the $\sin^2\theta_{eff}$ measurement.
  - Present estimates for IFI is an effect of 10^{-4} on A_4 and 10^{-5} on A_{fb}.

QED/EW corrections at Z pole

Electroweak Pseudo-Observables at LHC: the meeting point between data and theory

ATL-CONF-2018-037

	$70 < m^{\ell\ell} < 80$ GeV			$80 < m^{\ell\ell} < 100$ GeV				$100 < m^{\ell\ell} < 125$ GeV		
$\|y^{\ell\ell}\|$	$0-0.8$	$0.8-1.6$	$1.6-2.5$	$0-0.8$	$0.8-1.6$	$1.6-2.5$	$2.5-3.6$	$0-0.8$	$0.8-1.6$	$1.6-2.5$
Central value (NNLO QCD)	-0.0870	-0.2907	-0.5970	0.0144	0.0471	0.0928	0.1464	0.1045	0.3444	0.6807
ΔA_4 (NNLO - NLO QCD)	0.0003	0.0010	0.0021	-0.0001	-0.0005	-0.0009	-0.0015	-0.0007	-0.0022	-0.0041
ΔA_4 (EW)	0.0008	0.0028	0.0056	0.0002	0.0007	0.0015	0.0026	-0.0008	-0.0026	-0.0048
$\Delta \sin^2\theta^{\ell}_{\rm eff}$ (EW)	0.00129	0.00130	0.00133	0.00024	0.00024	0.00025	0.00026	-0.00120	-0.00123	-0.00119
	Uncertainties			Uncertainties				Uncertainties		
Total	0.0035	0.0094	0.0137	0.0007	0.0017	0.0021	0.0021	0.0040	0.0102	0.0140
PDF	0.0034	0.0092	0.0127	0.0007	0.0016	0.0020	0.0019	0.0039	0.0100	0.0131
QCD scales	0.0006	0.0019	0.0052	0.0003	0.0003	0.0004	0.0008	0.0005	0.0022	0.0049

Pseudo-observables or observables:

cross-sections and asymmetries (Afb, A4) , (unfolded to truth level) in different Mll, Y bins.

Δ $\sin^2{}_{\rm eff}^{\rm lep}$ (scan) -> ΔA_4(EW, QCD) predicted -> A4 (measured/fitted) —> $\sin^2{}_{\rm eff}^{\rm lep}$ (best)

QED/EW corrections at Z pole

- As mentioned by Zbyszek yesterday, the work of keeping the link from LEP to LHC to FCCee has to be done now!

- LEP pseudo-observables cannot really be considered as solid if theory is evolving

- LHC measurements cannot be directly used in current EW fits. So they incorporate parametric uncertainties which is unavoidable in a hadron collider

- More discussions in the future would be profitable to all of us, experimentalists and theorists!

Back-up slides