QCD-related uncertainties on precision measurement of electroweak parameters

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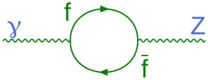
Assemblée générale 2024 du GDR QCD

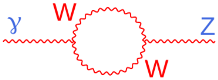
May 26, 2024

Electroweak precision measurements

- The electroweak sector of the SM is overconstrained by precision measurements of the weak and Higgs boson masses and properties
- Best measured parameters ($\alpha(0)$ scheme):
  - $\alpha = 1/137.03599139(31)$
  - $G_F = 1.1663787(6) \times 10^{-5}\,\text{GeV}^{-2}$
  - $m_Z = 91.1876(21)\,\text{GeV}$
- Relation between these parameters:

$$m_W^2\left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha(0)}{\sqrt{2}G_F}(1 + \Delta)$$

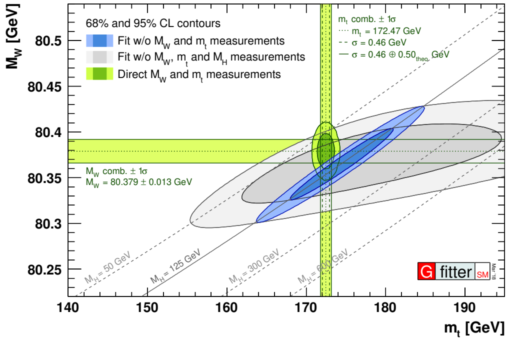


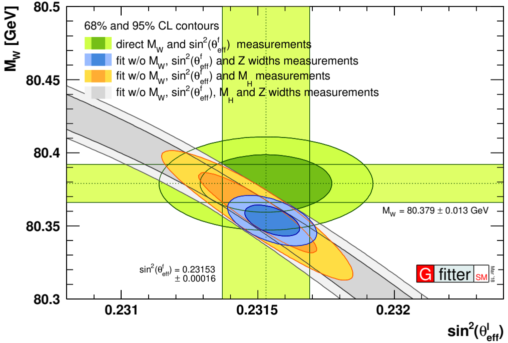


  - Predicting the value for one parameter based on the measurement of the others
  - Internal consistency checks of the SM
  - Radiative corrections Δ: test new physics in the loops

Global electroweak Standard Model fits

GFitter

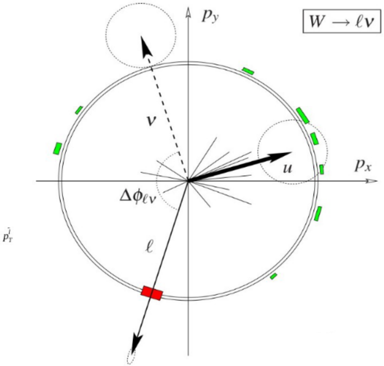


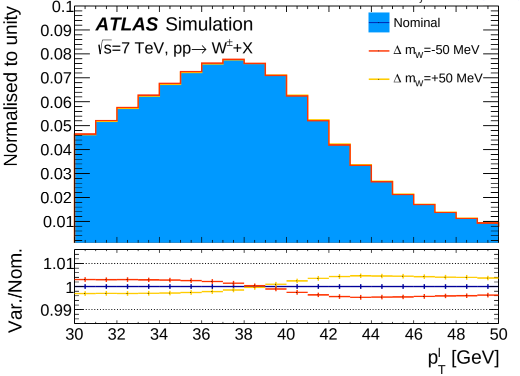


Comparing direct measurements (horizontal and vertical bands) with Standard Model predictions using other data (ellipses)

How to measure the W mass

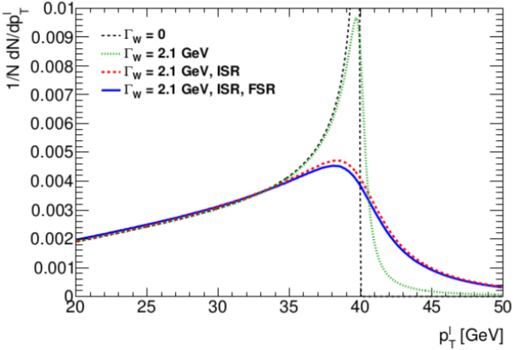
2403.15085, EPJC 78 (2018) 110

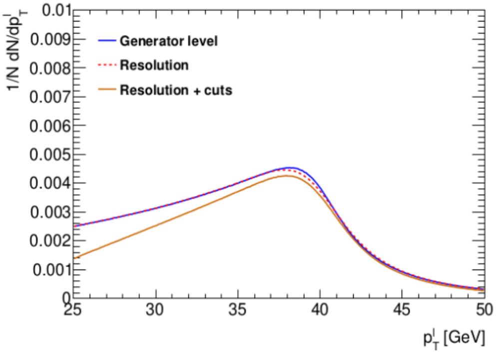




- Main observables: p_T^ℓ and m_T
  - Physics modelling (W p_T and helicity states, PDFs) $\rightarrow$ larger impact on p_T^ℓ
  - Hadronic recoil (reconstruction of particles recoiling against the W boson, needed for p_T^ν) $\rightarrow$ larger impact on m_T
  - Need $\lesssim$ permil precision on all effects!

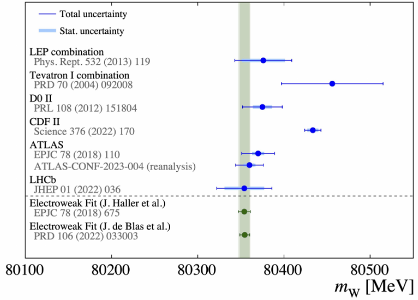
Ingredients to the W mass measurement

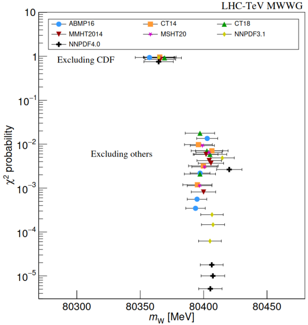




- Physics corrections: width, ISR (nonzero p_T^W), FSR (QED)
- Detector effects: lepton calibration and resolution, missing transverse energy resolution ($\rightarrow$ recoil; for m_T), efficiencies and acceptance
- All with uncertainties!

W mass combination





2308.09417

- Clear interest in combining measurements from different experiments (e.g. very different PDF effects)
- However they are in clear tension
- Need also to bring the measurements to a common QCD framework (PDFs, etc.)

Update to common PDF

Additional (small) updates

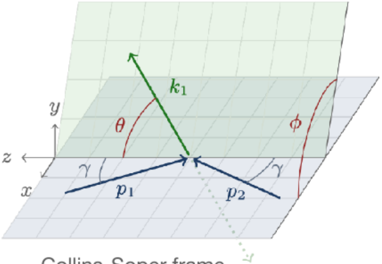
$$m_W^{update} = m_W^{ref} + \delta m_W^{PDF} + \delta m_W^{pol} + \delta m_W^{other}$$

Published value

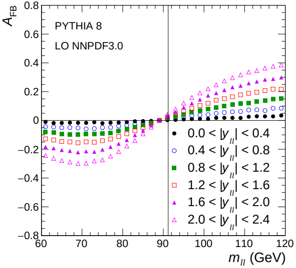
Common W boson polarization update

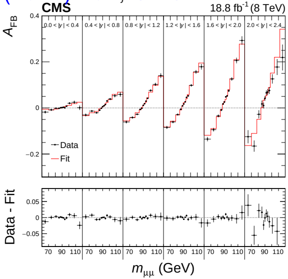
Effective meaxing angle in a nutshell

EPJC 78 (2018) 701, CMS-PAS-SMP-22-010



Collins-Soper frame





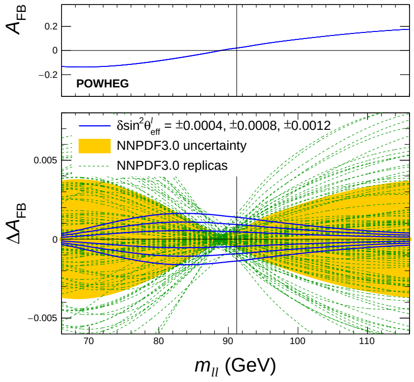
- Parity-violating vector coupling of the Z to fermions $\rightarrow$ non-vanishing forward-backward asymmetry:

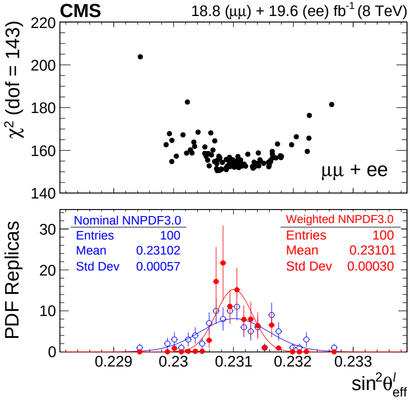
$$A_{FB} = \frac{N_{\text{fwd}} - N_{\text{bwd}}}{N_{\text{fwd}} + N_{\text{bwd}}} \propto 1 - 4\sin^2\theta_W$$

- "forward" vs "backward": defined in the Collins-Soper frame (rest frame of the Z boson)
- q vs $\bar{q}$ disambiguation: better at high $|y_Z|$ (high-x valence q vs low-x sea $\bar{q}$)
  - Large $|\eta_\ell|$ acceptance crucial for high precision

Weak mixing angle and PDFs

- The forward-backward asymmetry depends strongly on the initial state quark flavour and on the dilepton rapidity and mass
- At large $|y_Z|$ the sensitivity is larger
- Can exploit the different dependence on y, m to disentangle PDF effects



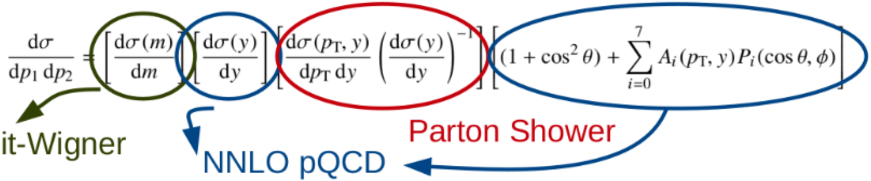


QCD modelling for W and Z measurements

Precision measurements of electroweak parameters at the LHC (e.g. $\sin^2\theta^\ell_{\mathrm{eff}}$, m_W) require excellent QCD modelling of the data

- Distributions to be modeled:
  - m_W: p_T^ℓ, $m_T = \sqrt{2p_T^\ell p_T^\nu(1-\cos\Delta\phi)}$
  - $\sin^2\theta^\ell_{\mathrm{eff}}$: A_{FB} (forward-backward asymmetry in the Collins-Soper frame)

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$



QCD uncertainties in m_W and $\sin^2\theta^{\ell}_{\text{eff}}$ measurements

W mass

QCD modelling uncertainties:

W-boson charge Kinematic distribution	W^+ p_T^ℓ	 m_T	W^- p_T^ℓ	 m_T	Combined 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

Weak mixing angle

Theoretical uncertainties (excluding PDFs):

Modeling parameter	Muons	Electrons
Dilepton p_T reweighting	0.00003	0.00003
μ_R and μ_F scales	0.00011	0.00013
POWHEG MiNLO Z+j *vs.* Z at NLO	0.00009	0.00009
FSR model (PHOTOS *vs.* PYTHIA 8)	0.00003	0.00005
Underlying event	0.00003	0.00004
Electroweak $\sin^2\theta^{\ell}_{\text{eff}}$ *vs.* $\sin^2\theta^{\text{u,d}}_{\text{eff}}$	0.00001	0.00001
Total	0.00015	0.00017

PDF uncertainties (profiling them or not):

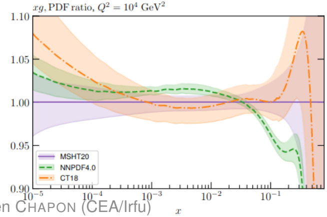
Channel	Not constraining PDFs	Constraining PDFs
Muons	0.23125 ± 0.00054	0.23125 ± 0.00032
Electrons	0.23054 ± 0.00064	0.23056 ± 0.00045
Combined	0.23102 ± 0.00057	0.23101 ± 0.00030

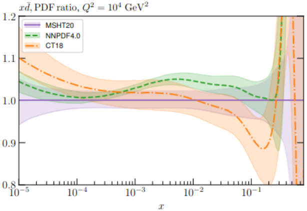
Parton distribution functions

L. Harland-Lang @ DIS2024

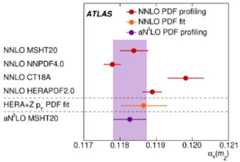
$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}_{ij}(x_1 p_1, x_2 p_2, Q, \mu_F^2)$$

- Assuming collinear factorisation (universality), PDFs can be fitted from data (fixed target, HERA DIS, collider incl. LHC)
- High precision PDFs require high precision theory (NNLO–N^{3}LO QCD + NLO EW)
- Different PDF groups use different methodologies and different parametrisations
- Uncertainties: incredibly difficult to assess
  - Basic idea is simple: typically χ^2 (data, theory+PDF) scan
  - Methodology (“tolerance” dealing with tensions / inconsistencies between datasets)? Parametrisation? Missing higher orders? Correlations with new physics, SM params?



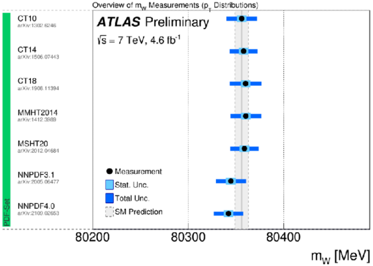


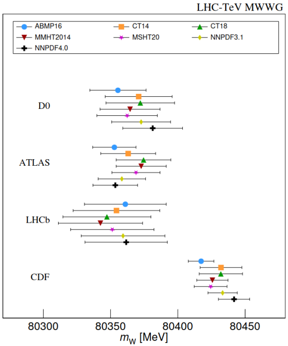
ATLAS $\alpha_S(m_Z)$ FROM Z PT

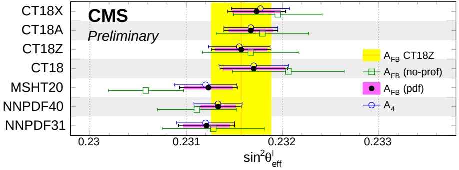


Parton distribution functions: impact on W/Z measurements

2308.09417, CMS-PAS-SMP-22-010



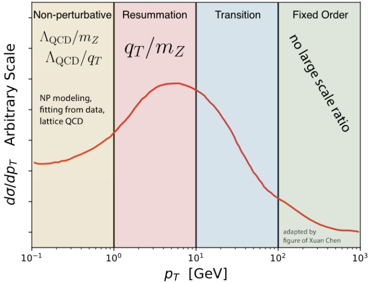


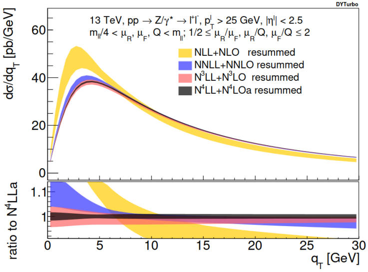


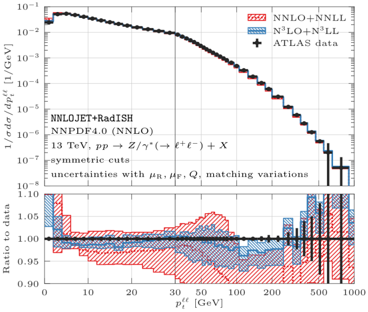
- PDFs have a very large impact on the results
- Recent PDFs are very precise... but tensions between different groups
- Is profiling OK? How to handle results from different PDF groups?

Boson p_T modelling

Xuan Chen



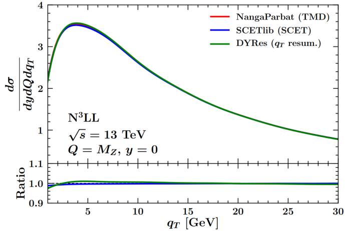




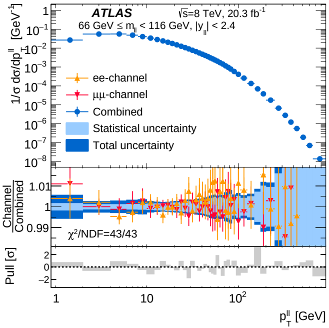
- Several codes reaching N^{3}LO QCD accuracy and beyond
  - DYTurbo, NNLOJet, CuTe-MCFM...
  - NNLO $\alpha_{EW} \times \alpha_S$ also studied (but beware of factorisation!)
  - Resummation: N^{3}LL or beyond

Boson p_T modelling

V. Bertone



EPJC 76 (2016) 291



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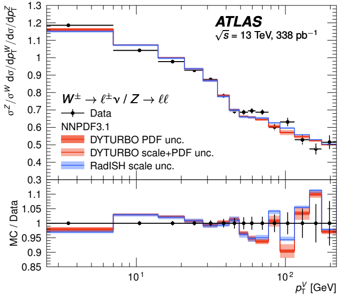
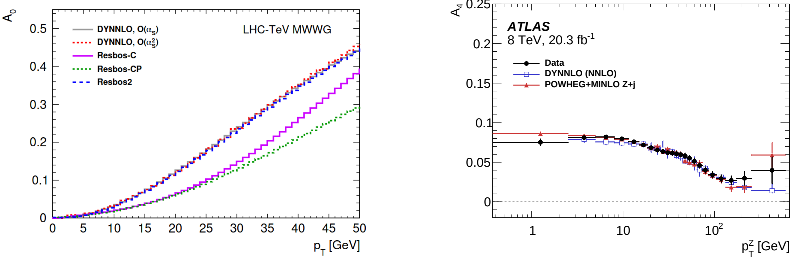


- Several ways to handle large Λ_{QCD}/q_T logs at low q_T
  - q_T resummation, SCET, TMDs
  - Good agreement found between different formalisms
- Event generators use parton shower
- For W: tune generators to very precise p_T^Z and use p_T^W/p_T^Z from theory
  - ATLAS found PYTHIA 8 AZ to be the best model
  - W → Z: critical to handle (heavy) flavour and EW effects
  - Also directly measured (same data as used for next ATLAS m_W)

Angular coefficients

2308.09417, JHEP 08 (2016) 159



- The cross section for the production of a spin-1 resonance can be expanded to all orders in QCD into an angular coefficients decomposition:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{dm\,dp_T\,dy}[(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta$$
$$+ A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi]$$

- Well predicted by pQCD (N^{3}LO) and measured in data
- However inaccurate in old event generators (Resbos1) $\rightarrow$ care needed in m_W combination

Summary

- Precision measurements of EW parameters $\rightarrow$ stringent tests of the SM consistency
- Very challenging measurements experimentally
- Many challenges on the theoretical side too
- Very active community with frequent discussions between experiments and theorists (e.g. LHC-EWWG)

A few interesting papers and talks:

- ATLAS measurement of m_W (2403.15085, superseding EPJC 78 (2018) 110)
- W mass combination (2308.09417)
- CMS measurement of $\sin^2\theta^{\ell}_{\text{eff}}$ (CMS-PAS-SMP-22-010, 2024)
- Joint session with GDR QCD at 2023 IRN Terascale workshop
- Orsay 2023 W mass workshop
- Discussion on theoretical systematics in LHC precision measurements (LHC-EWWG, 2024)

Thank you

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