EW&Top@LHC – status, strategy, limitations and outlook

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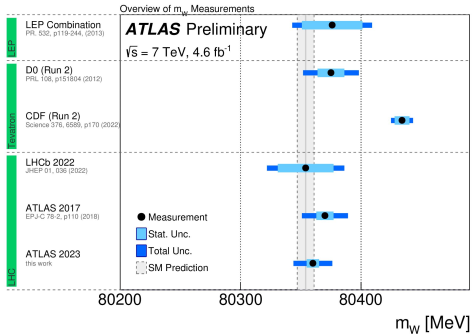
Synergy workshop between ep/eA and pp/pA/AA physics experiments
29.02.2024

With significant material from this weeks Theory precision WS

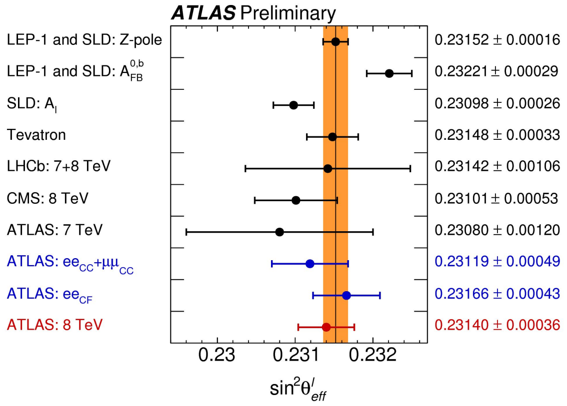
Precision measurements at the LHC

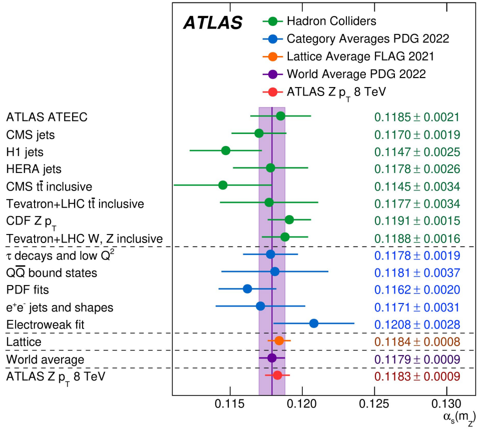
- LHC discovered the Higgs boson, being deeply studied
- No conclusive signs of BSM physics, yet
- But, many innovative studies of QCD and EW, many reaching or surpassing precision of theory despite huge efforts – theory in pp is difficult

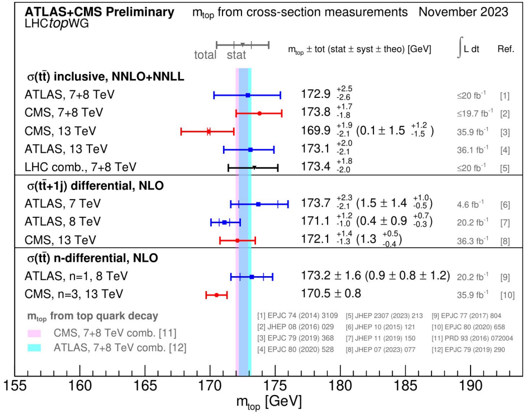


ATLAS-CONF-2023-004

Will mostly focus on impact and problems from PDFs







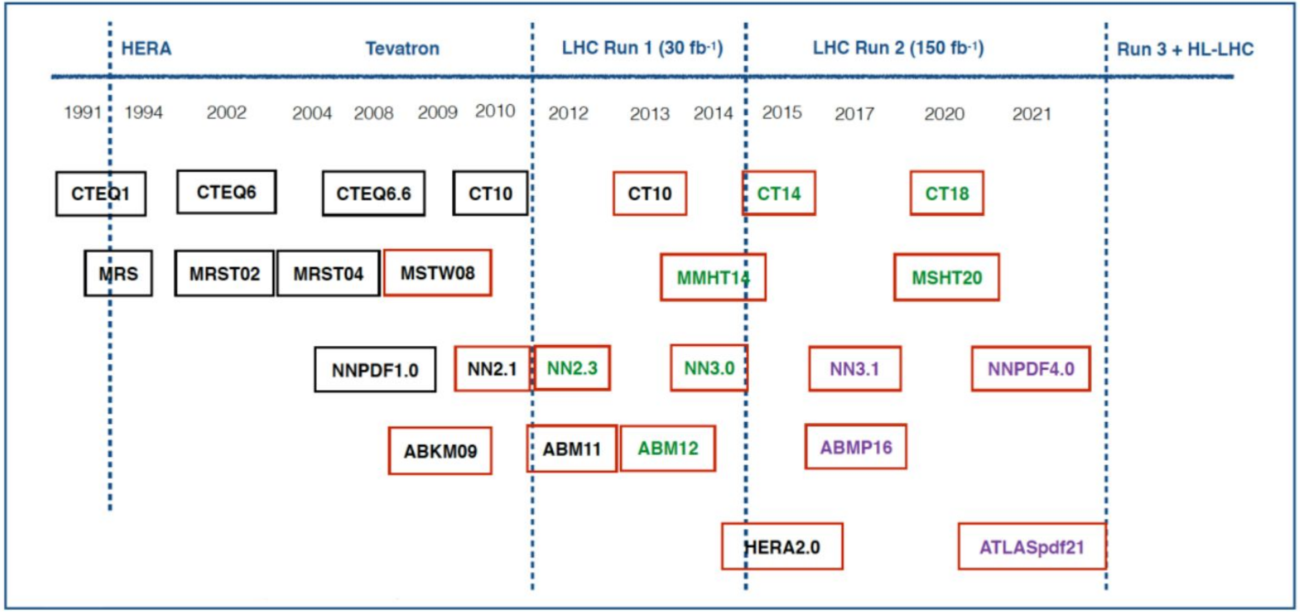
ATLAS-CONF-2018-037
Eur. Phys. J. C 78 (2018) 701

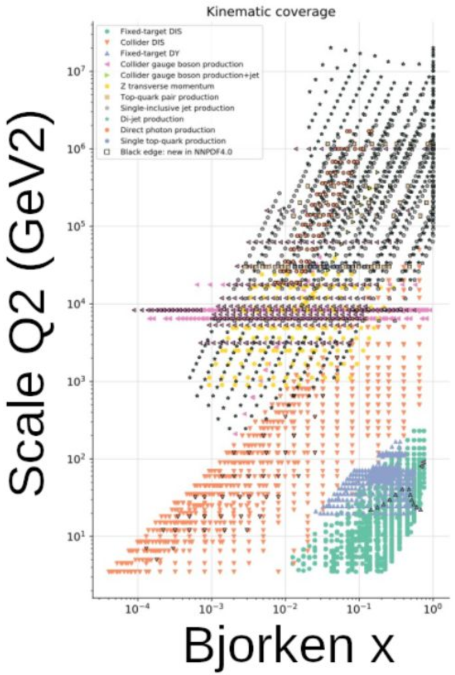
arXiv:2309.12986

PDFs for LHC physics

We've come a long way: theory progress, uncertainty estimates, data, benchmarking exercises…

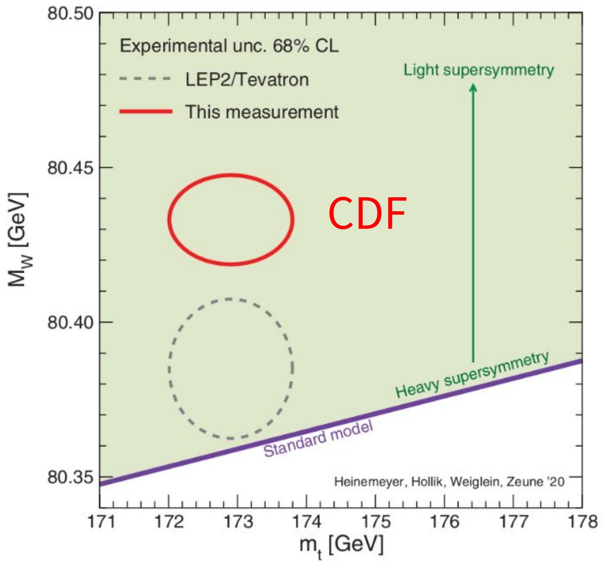
Yet, at precision level, differences between fits can be significant

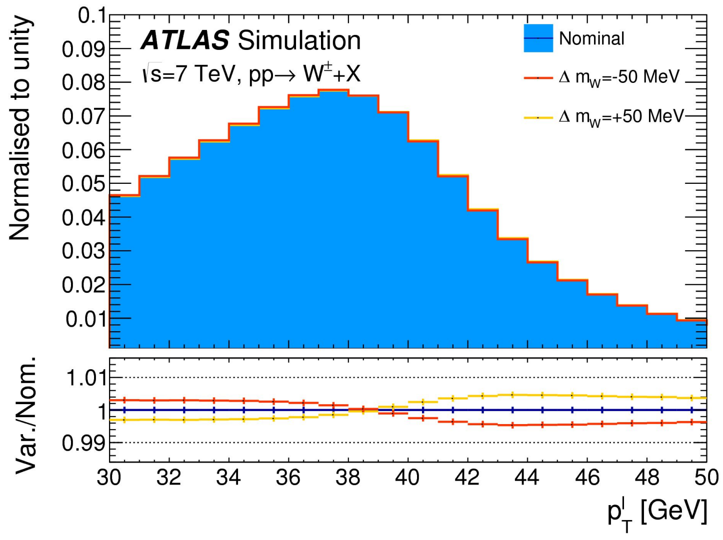




Current status of mW

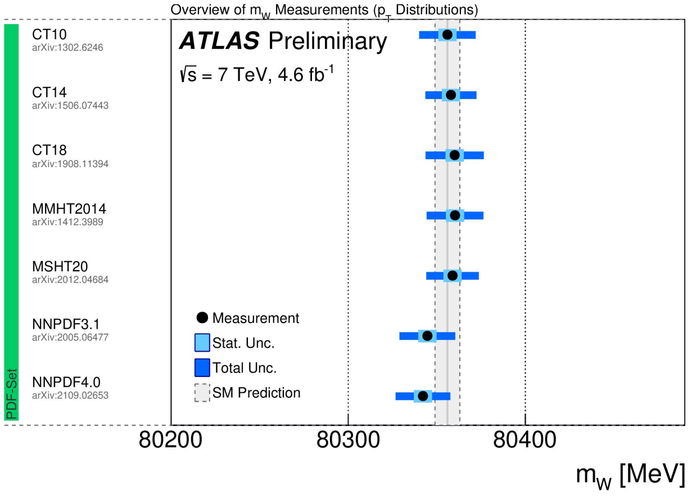
- Key parameter of SM: can we reach <10 MeV at hadron collider?
- Measurement requires high-precision QCD modelling of W production and decay – PDF uncertainties a key contribution, e.g. most recent ATLAS result quotes 8 MeV… PDFs not everything, but without precise PDFs no mW





PDF set dependence of mW

- Repeating the most recent ATLAS measurement for different PDF sets:
  - 15 - 20 MeV difference between CT18/MSHT20 and NNPDF3.1/4.0
  - Equal to the total measurement uncertainty
  - About twice the quoted PDF uncertainty
  - Clearly a ‘poor man’s approach’

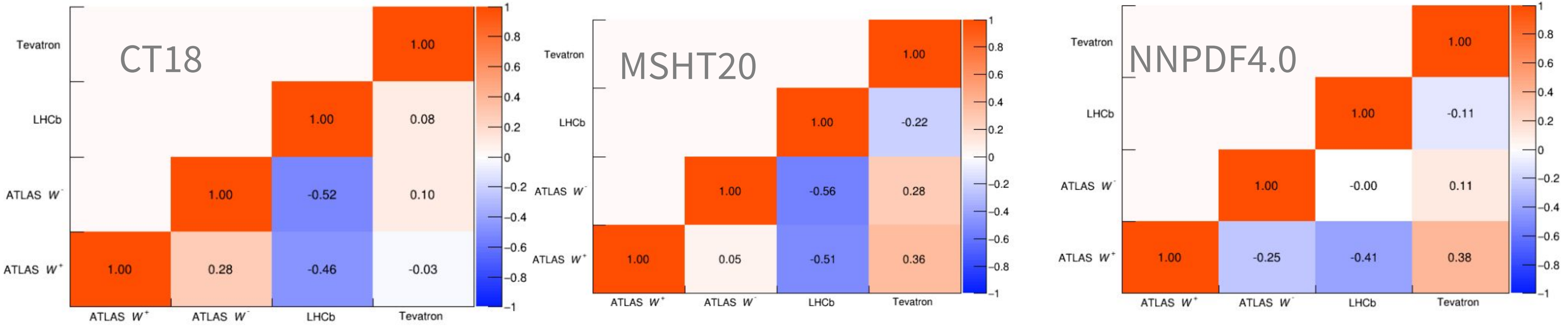


PDF-Set	p_T^ℓ [MeV]	m_T [MeV]	combined [MeV]
CT10	$80355.6^{+15.8}_{-15.7}$	$80378.1^{+24.4}_{-24.8}$	$80355.8^{+15.7}_{-15.7}$
CT14	$80358.0^{+16.3}_{-16.3}$	$80388.8^{+25.2}_{-25.5}$	$80358.4^{+16.3}_{-16.3}$
CT18	$80360.1^{+16.3}_{-16.3}$	$80382.2^{+25.3}_{-25.3}$	$80360.4^{+16.3}_{-16.3}$
MMHT2014	$80360.3^{+15.9}_{-15.9}$	$80386.2^{+23.9}_{-24.4}$	$80361.0^{+15.9}_{-15.9}$
MSHT20	$80358.9^{+13.0}_{-16.3}$	$80379.4^{+24.6}_{-25.1}$	$80356.3^{+14.6}_{-14.6}$
NNPDF3.1	$80344.7^{+15.6}_{-15.5}$	$80354.3^{+23.6}_{-23.7}$	$80345.0^{+15.5}_{-15.5}$
NNPDF4.0	$80342.2^{+15.3}_{-15.3}$	$80354.3^{+22.3}_{-22.4}$	$80342.9^{+15.3}_{-15.3}$

PDF correlations

arXiv:2308.09417

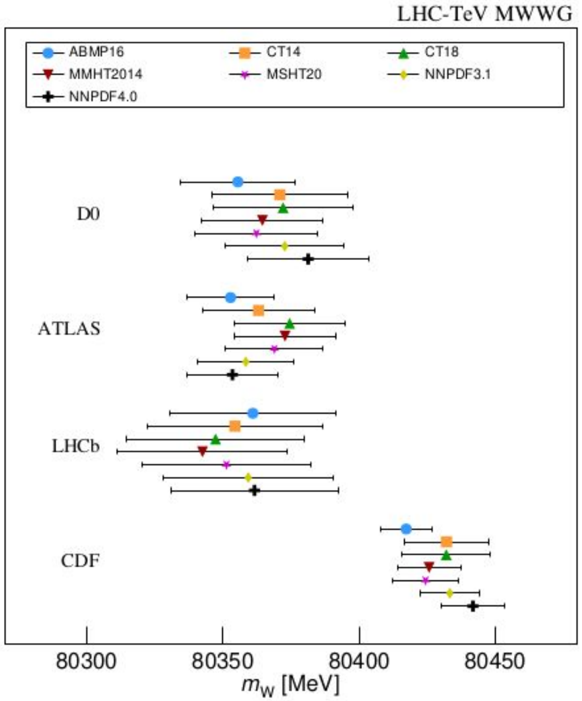
- Most LHC physics analyses these days performed with elaborate fits that constrain uncertainties ‘in-situ’ – is this enough to deal with PDFs?
  - It does not obviously improve the situation for the ATLAS mW example shown before
  - It does rely on very precise correlation model
- How far are PDF correlations controlled? Case study of mW measurements at TeVatron (1.96 TeV ppbar), ATLAS (7 TeV pp ‘central’), LHCb (13 TeV pp ‘forward’)
  - Clear differences observed

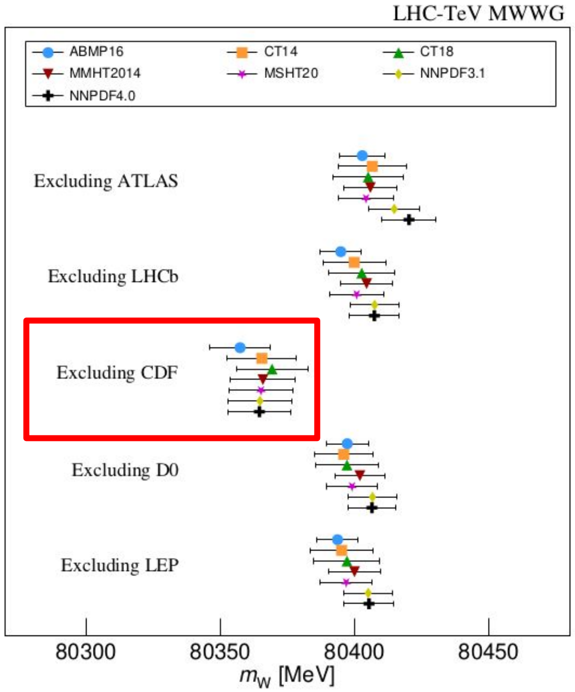


PDF correlations

arXiv:2308.09417

- Strong dependence in each set, CT18 set 'favoured' in benchmarking
- 'Small miracle' in combination: real effect or accident?





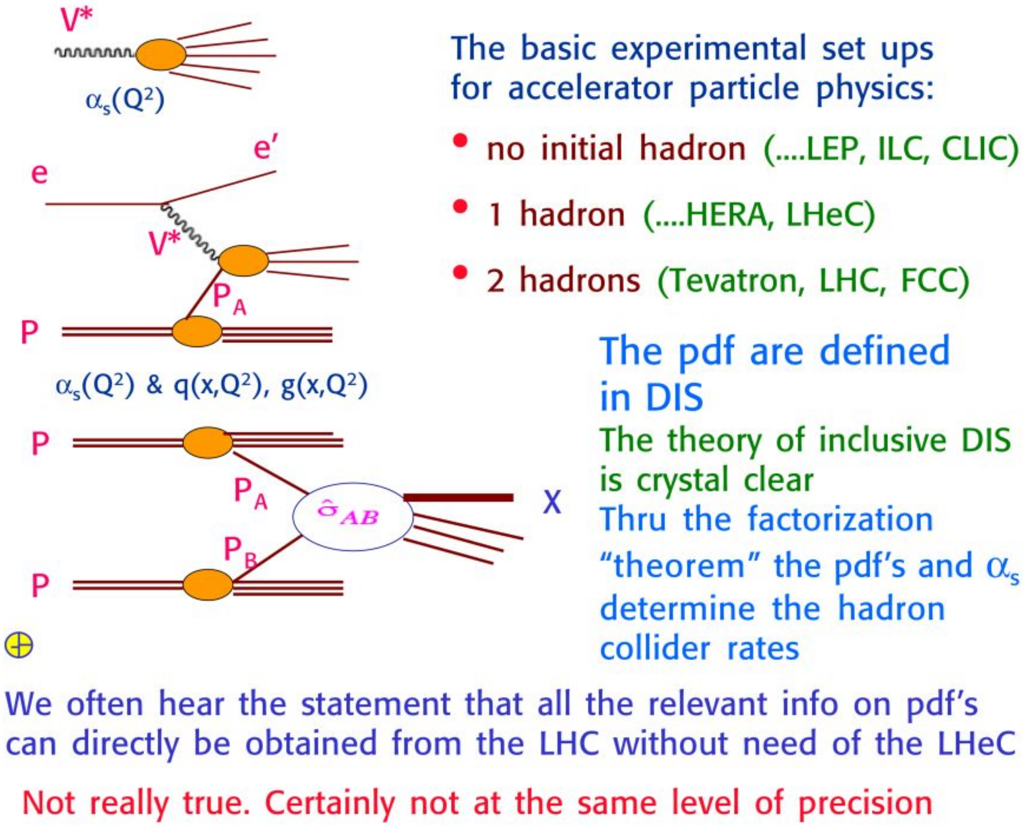
PDF ‘profiling’

Adapted from Simone & Maarten

- PDF fitters in fact tell us, that our ‘profiling procedure’ is not correct, issue of “Tolerance factors” applied in some PDF fits such as CT and MSHT
    - Deviate from canonical DeltaChi2 = 1 to accommodate deficiencies in the theory and/or tensions in the input data
- ‘Experimentalists’ include the impact of PDF eigenvectors in their likelihood/chi2 ignoring tolerances, effectively overestimating the impact of our data
    - Not clear that ‘dealing correctly’ with these tolerances improves the situation
    - Also has the detriment that it destroys all experimental precision
- Way out: PDF fit without tolerance criteria…

PDF set	Tolerance	m_W
NNPDF4.0	$\Delta\chi^2=1, T=1$	80364.5 ± 11.6
CT18	$\Delta\chi^2=1, T=1$	80369.2 ± 13.3
CT18	$\Delta\chi^2=100, T=10$	80374.8 ± 70.1

Guido Altarelli on Proton structure in ep and pp

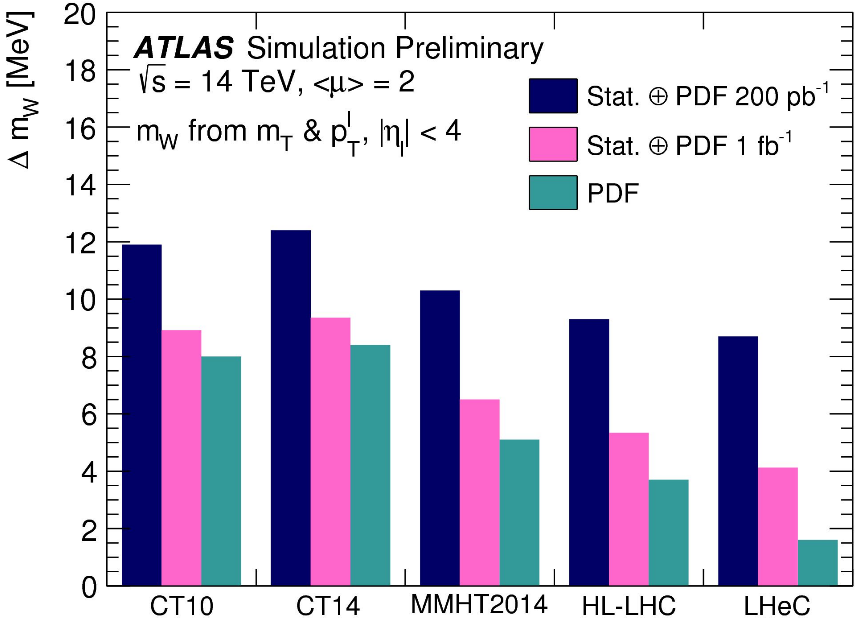


- Possible path to high-precision global PDF fits
  - New DIS data – **LHeC**
  - Carefully selected LHC data
  - N3LO theory
- A few more examples follow to illustrate the points made

Outlook for mW

E.g. ATL-PHYS-PUB-2018-026

- PDF uncertainties expected with LHeC data expected to be smaller by large factor
- This will be a game-changer for mW measurements at the LHC

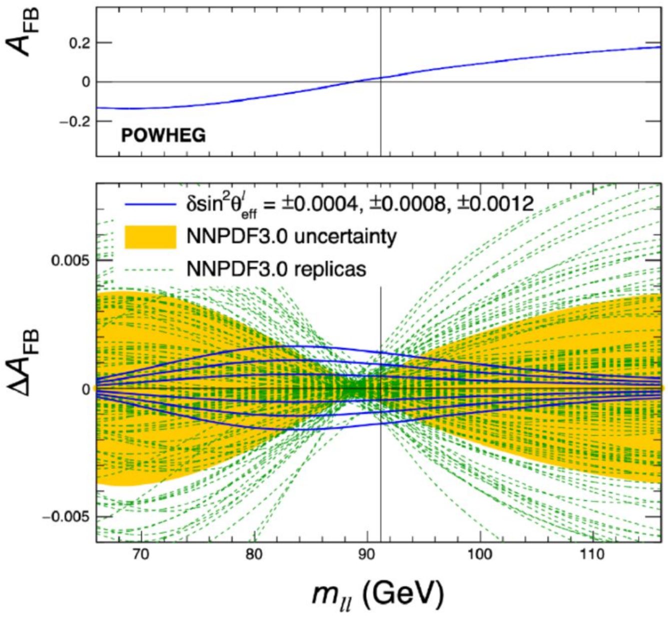


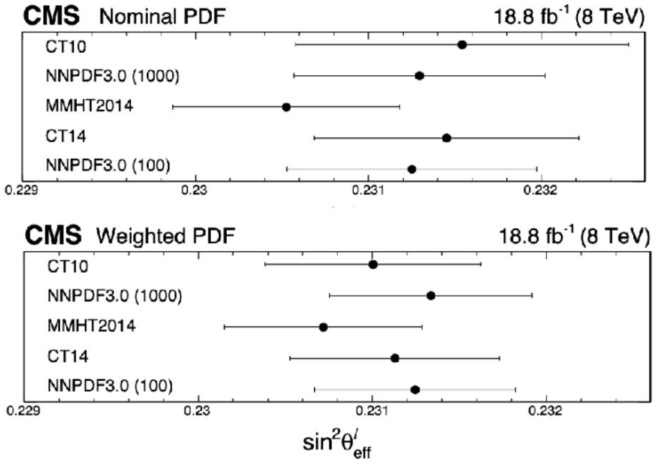
Weak mixing angle

E.g. [Eur. Phys. J. C 78 (2018) 701]

- Situation broadly similar to mW: ‘profiling’ usually built into the analyses
  - In case of CMS it improves the consistency, but spread remains

$$\sin^2\theta^{\ell}_{\rm eff} = 0.23101 \pm 0.00036\,({\rm stat}) \pm 0.00018\,({\rm syst}) \pm 0.00016\,({\rm theo}) \pm 0.00031\,({\rm PDF})$$



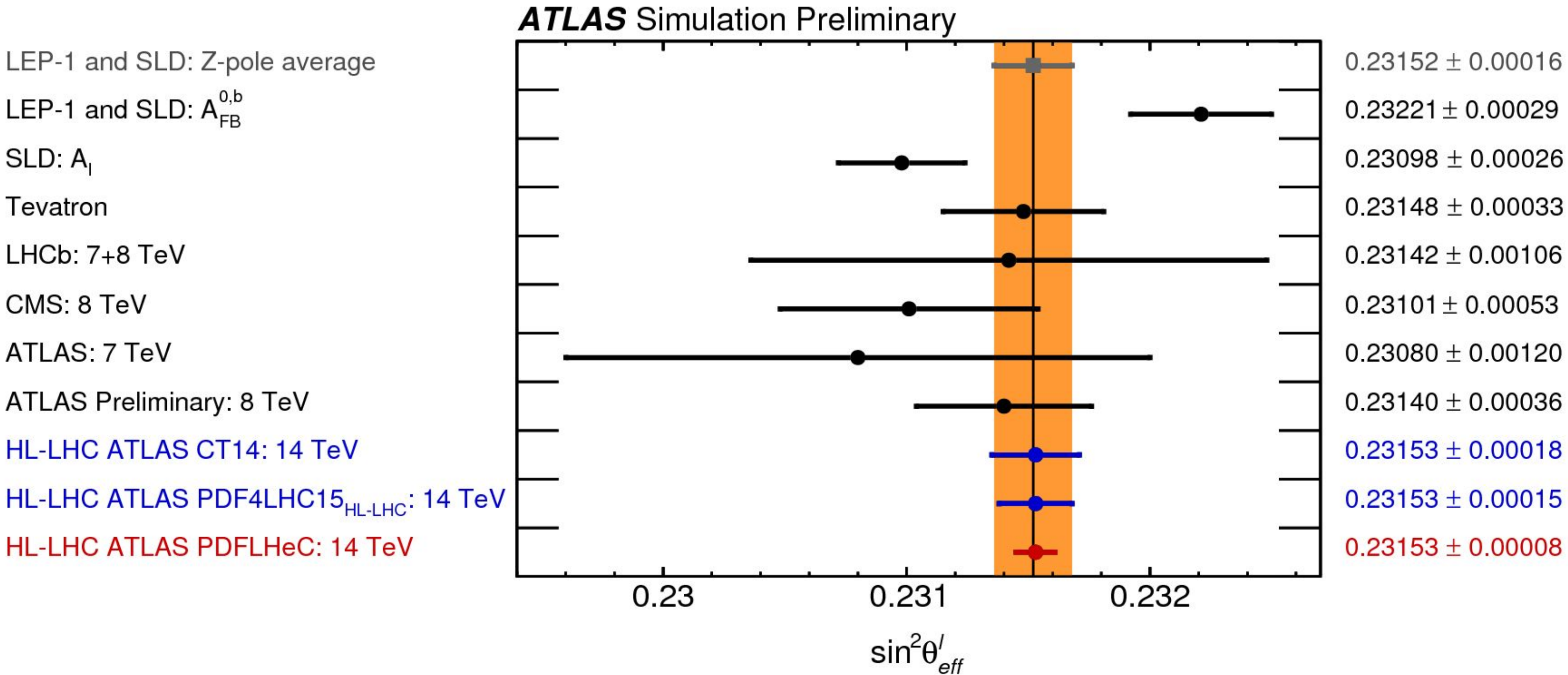


- PDF uncertainty of $3 \cdot 10^{-4}$ vs MSHT14/NNPDF30 spread of $6 \cdot 10^{-4}$

Weak mixing angle prospects

E.g. ATL-PHYS-PUB-2018-037

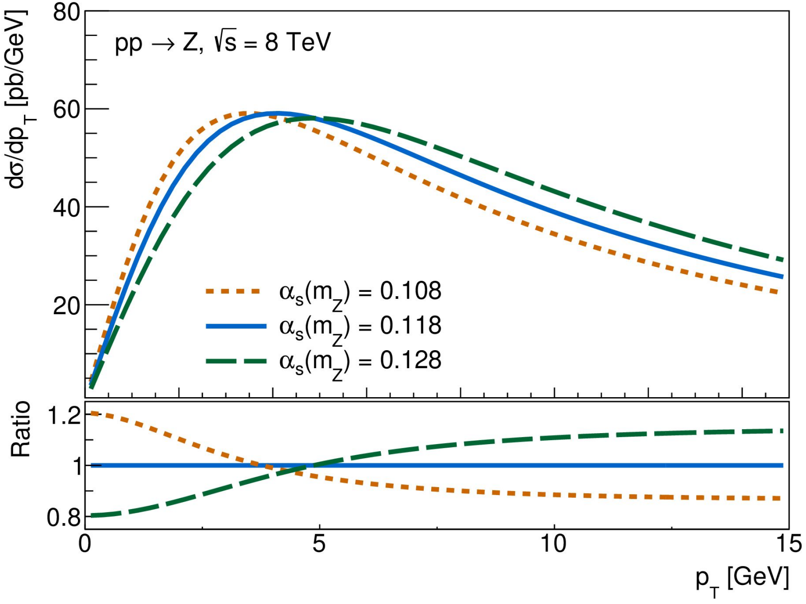
- HL-LHC promises very high precision
- As for mW, fundamental improvement of PDFs via LHeC will be a game changer
  - Also anticipating that one does not want to rely solely on ‘PDF profiling’

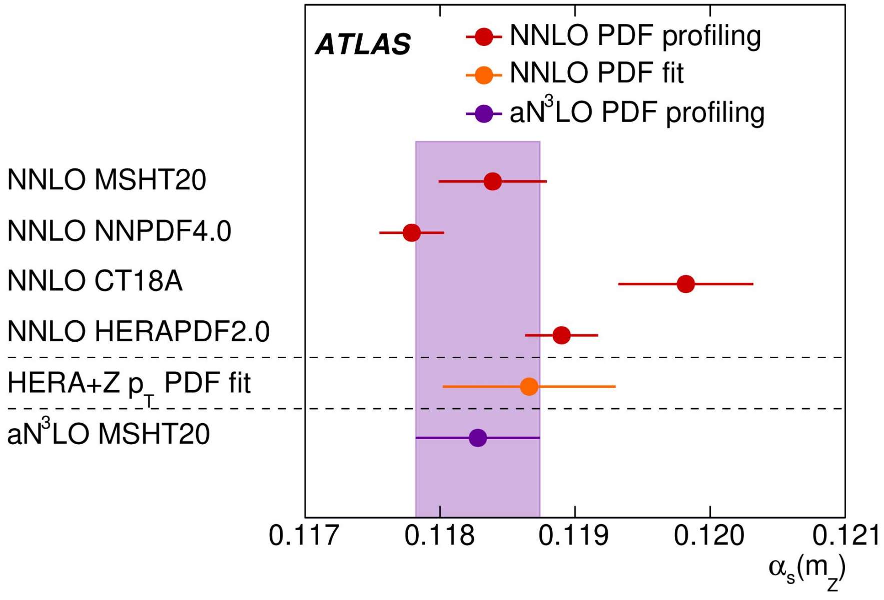


Strong coupling from pT(Z)

arXiv:2309.12986

- Clearly at the bleeding N3LO edge, while some ingredients only available at N2LO
- Yet, we see a similar effect: this time CT18 appears to be an outlier
- Stefano Camarda: “Indication that in the CT18 PDF set the gluon PDF is pulled away from what is preferred by DIS data, to accommodate tensions with other datasets sensitive to the gluon PDF”
  - Impact from e.g. jet cross section data?

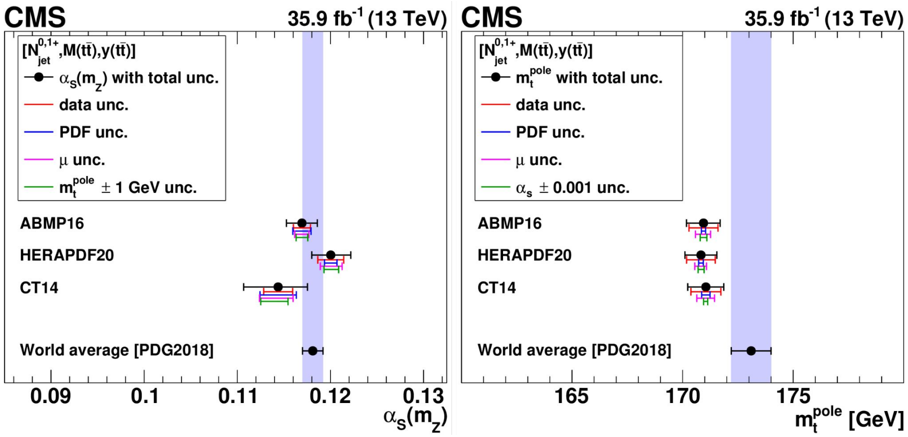


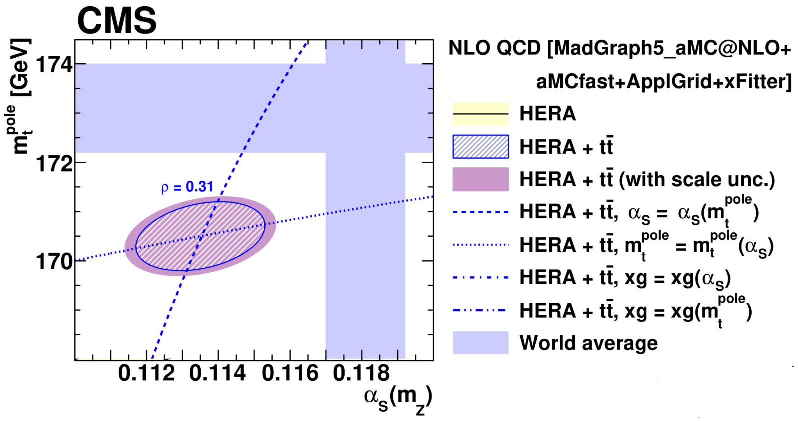


mTop

E.g. [Eur. Phys. J. C 80 (2020) 658]

- ‘Direct’ extractions (e.g. CMS Eur. Phys. J. C 83 (2023) 963) for once not limited by PDFs, but rather other experimental+modelling systematics
- Extraction from differential cross section data goes circumvents some conceptual questions: PDF effects appear, but subleading





Conclusions

- Clearly, high-energy high-luminosity ep has a huge physics program
- Because of personal bias, I focussed on impact of better PDFs on the pp program
  - Many other interesting topics where pp struggles
- For electroweak precision – mW and sin2theta – PDF model dependence appears to be a ‘killer’ beyond the current status:
  - Unclear how ‘significant’ differences between PDF sets are
  - Unclear how to deal correctly with ‘tolerance criteria’ in profiling analyses
- A deeper understanding of PDFs and their uncertainties is a must:
  - New DIS data from LHeC would put the effort on a new basis
  - It may allow to select pp data more carefully
  - Clearly, a lot of work on theory (N3LO+) and the fits will remain

DY data benchmarking

arXiv:2308.09417

- CT18 set ‘favoured’, used for recent mW values

Measurement	NNPDF3.1	NNPDF4.0	MMHT14	MSHT20	CT14	CT18	ABMP16
CDF y_Z	24 / 28	28 / 28	30 / 28	32 / 28	29 / 28	27 / 28	31 / 28
CDF A_W	11 / 13	14 / 13	12 / 13	28 / 13	12 / 13	11 / 13	21 / 13
D0 y_Z	22 / 28	23 / 28	23 / 28	24 / 28	22 / 28	22 / 28	22 / 28
D0 $W \to e\nu$ A_ℓ	22 / 13	23 / 13	52 / 13	42 / 13	21 / 13	19 / 13	26 / 13
D0 $W \to \mu\nu$ A_ℓ	12 / 10	12 / 10	11 / 10	11 / 10	11 / 10	12 / 10	11 / 10
ATLAS peak CC y_Z	13 / 12	13 / 12	58 / 12	17 / 12	12 / 12	11 / 12	18 / 12
ATLAS W^- y_ℓ	12 / 11	12 / 11	33 / 11	16 / 11	13 / 11	10 / 11	14 / 11
ATLAS W^+ y_ℓ	9 / 11	9 / 11	15 / 11	12 / 11	9 / 11	9 / 11	10 / 11
Correlated χ^2	75	62	210	88	81	41	83
Total χ^2 / d.o.f.	200 / 126	196 / 126	444 / 126	270 / 126	210 / 126	162 / 126	236 / 126
p(χ^2, n)	0.003%	0.007%	$< 10^{-10}$	$< 10^{-10}$	0.0004%	1.5%	10^{-8}

CTEQ view

Adapted from Simone

Augmented likelihood for PDFs with global tolerance

1. Start by defining the correspondence between $\Delta\chi^2$ and cumulative probability level: 68% c.l. $\Leftrightarrow$ $\Delta\chi^2 = T^2$.
2. Write the **augmented** likelihood density for this definition:

$$P(D_i|T_i) \propto e^{-\chi^2/(2T^2)}$$

3. When profiling 1 new experiment with the prior imposed on PDF nuisance parameters $\lambda_{\alpha,th}$:

$$\chi^2(\vec{\lambda}_{\rm exp}, \vec{\lambda}_{\rm th}) = \sum_{i=1}^{N_{pt}} \frac{\left[D_i + \sum_\alpha \beta_{i,\alpha}^{\rm exp}\lambda_{\alpha,\rm exp} - T_i - \sum_\alpha \beta_{i,\alpha}^{\rm th}\lambda_{\alpha,\rm th}\right]^2}{s_i^2} + \sum_\alpha \lambda_{\alpha,\rm exp}^2 + \sum_\alpha T^2\lambda_{\alpha,\rm th}^2. \qquad \beta_{i,\alpha}^{\rm th} = \frac{T_i(f_\alpha^+) - T_i(f_\alpha^-)}{2},$$

new experiment

priors on expt. systematics and PDF params

4. Alternatively, we can reparametrize $\chi^{2\prime} \equiv \chi^2/T^2$, so that 68% c.l. $\Leftrightarrow$ $\Delta\chi^{2\prime} = 1$. We have

$$P(D_i|T_i) \propto e^{-\chi^{2\prime}/2}$$

consistent redefinition

$$\chi^{2\prime}(\vec{\lambda}_{\rm exp}, \vec{\lambda}_{\rm th}) = \sum_{i=1}^{N_{pt}} \frac{\left[D_i + \sum_\alpha \beta_{i,\alpha}^{\rm exp}\lambda_{\alpha,\rm exp} - T_i - \sum_\alpha \beta_{i,\alpha}^{\rm th}\lambda_{\alpha,\rm th}\right]^2}{s_i^2\, T^2} + \sum_\alpha \frac{\lambda_{\alpha,\rm exp}^2}{T^2} + \sum_\alpha \lambda_{\alpha,\rm th}^2.$$

5. Inconsistent redefinitions:

$$\chi^{2\prime}(\vec{\lambda}_{\rm exp}, \vec{\lambda}_{\rm th}) = \sum_{i=1}^{N_{pt}} \frac{\left[D_i + \sum_\alpha \beta_{i,\alpha}^{\rm exp}\lambda_{\alpha,\rm exp} - T_i - \sum_\alpha \beta_{i,\alpha}^{\rm th}\lambda_{\alpha,\rm th}\right]^2}{s_i^2} + \sum_\alpha \lambda_{\alpha,\rm exp}^2 + \sum_\alpha \lambda_{\alpha,\rm th}^2.$$

and $P(D_i|T_i) \propto e^{-\chi^{2\prime}/2}$

or $P(D_i|T_i) \propto e^{-\chi^{2\prime}/(2T^2)}$

[equivalent to $s_i \to s_i/T$ or $\lambda_{\alpha,th} \to \lambda_{\alpha,th}T$ without $\beta_{i,\alpha,th} \to \beta_{i,\alpha,th}/T$]