Impact of PDF choices on LHC precision measurements

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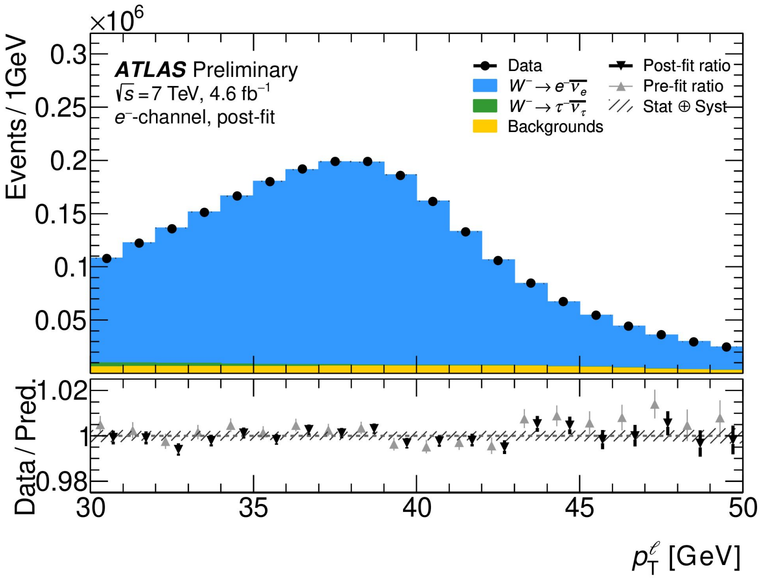
LHC-Tev MWWG LHC EWWG

Outline

- examples of precision measurements affected by PDF choices
- PDF uncertainty estimates and their impact
- (p_T resummation corrections)
- requests from the LHC experiments to the PDF community

Examples – mW at ATLAS



Recent ATLAS update (ATLAS-CONF-2023-004)

- now a simultaneous (PL) fit to mW and systematics)
- More detailed study of PDF dependence

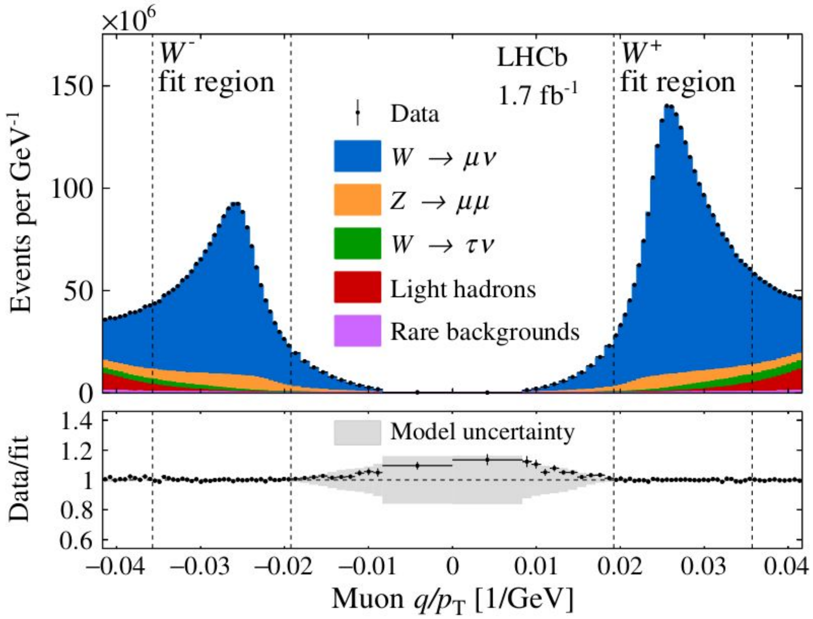
PDF-Set	p_T^ℓ [MeV]	m_T [MeV]	combined [MeV]
CT10	$80355.6^{+15.8}_{-15.7}$	$80378.1^{+24.4}_{-24.8}$	$80355.8^{+15.7}_{-15.7}$
CT14	$80358.0^{+16.3}_{-16.3}$	$80388.8^{+25.2}_{-25.5}$	$80358.4^{+16.3}_{-16.3}$
CT18	$80360.1^{+16.3}_{-16.3}$	$80382.2^{+25.3}_{-25.3}$	$80360.4^{+16.3}_{-16.3}$
MMHT2014	$80360.3^{+15.9}_{-15.9}$	$80386.2^{+23.9}_{-24.4}$	$80361.0^{+15.9}_{-15.9}$
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	$80342.2^{+15.3}_{-15.3}$	$80354.3^{+22.3}_{-22.4}$	$80342.9^{+15.3}_{-15.3}$

~17% improvement in uncertainty from using a profile likelihood analysis

Large PDF dependence; eg NNPDF4.0 and CT18 differ by 18 MeV.

Estimated PDF uncertainties 3 → 9 MeV.
What to do??

Examples – mW at LHCb



LHCb result for different PDF sets :

NNPDF3.1

$$m_W = 80362 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV},$$

CT18

$$m_W = 80350 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 12_{\text{PDF}}\ \text{MeV},$$

MSHT20

$$m_W = 80351 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 7_{\text{PDF}}\ \text{MeV},$$

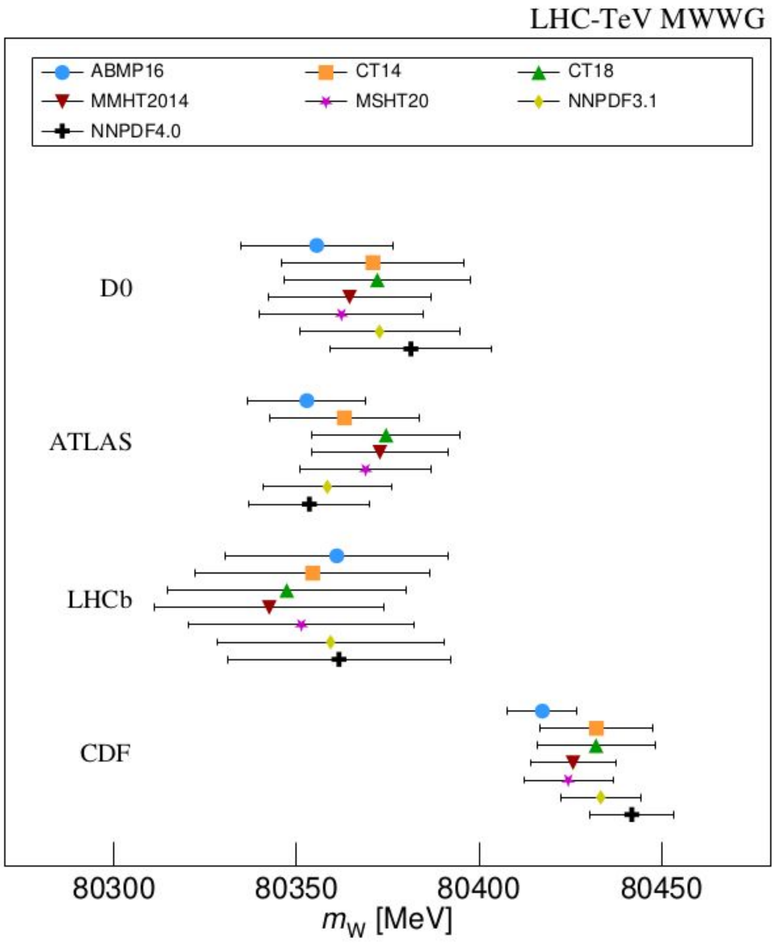
while the impact is modest given the total uncertainty, the difference between NNPDF and CT18/MSHT20 is large compared to the claimed PDF uncertainty.

A 1σ effect at face value, but what is the uncertainty in (m_W^{NNPDF31} - $m_W^{\text{CT18,MSHT}}$)?

Examples – mW combination

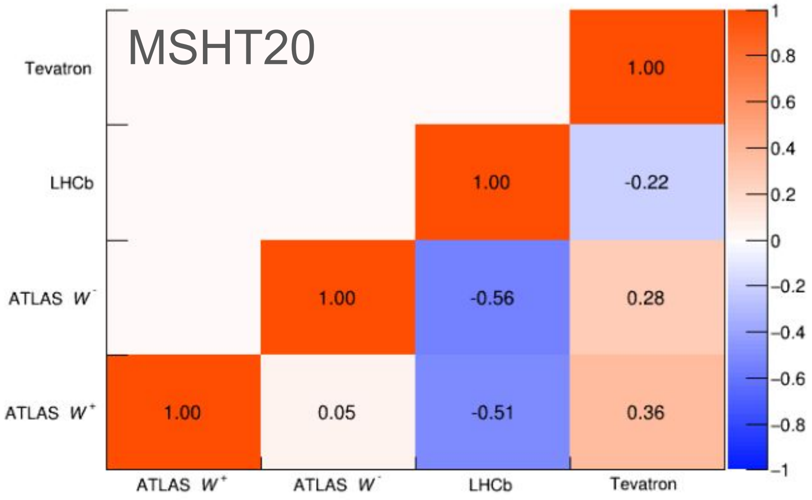
PDF dependence of world measurements (Tevatron, LHCb, ATLAS)

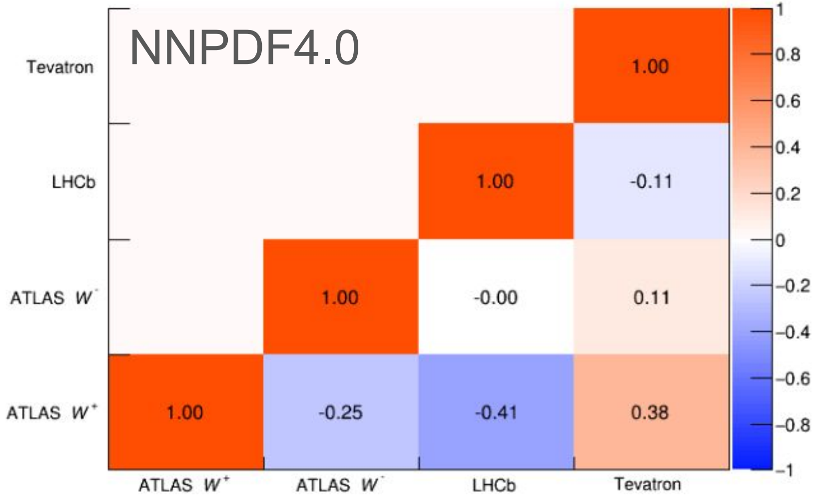
Variations typically of the order of the total measurement uncertainty; often larger than the quoted PDF uncertainty



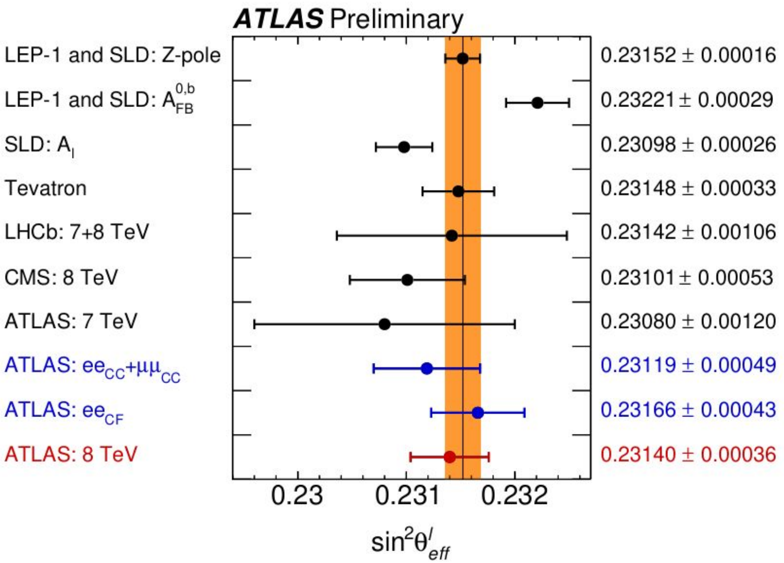
Examples – mW combination

PDF uncertainty correlations between experiments vary significantly from one PDF set to another :





Examples – $\sin^2\theta_{eff}$ (ATLAS)

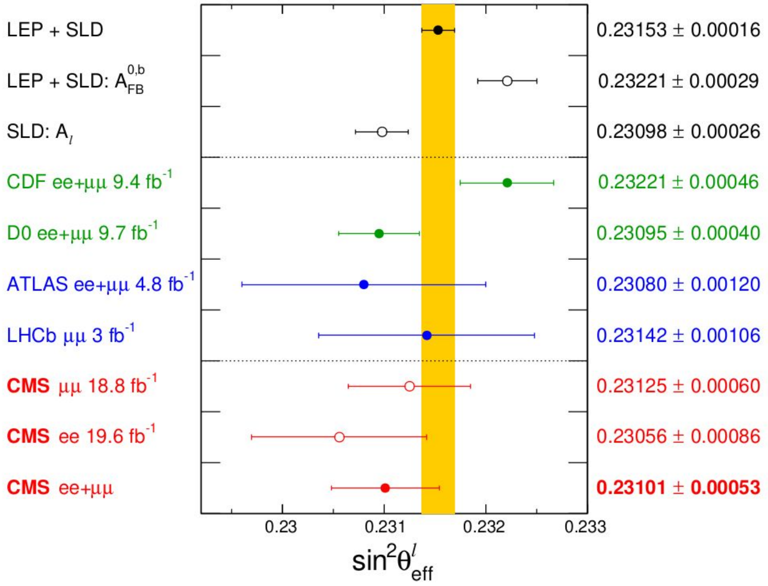


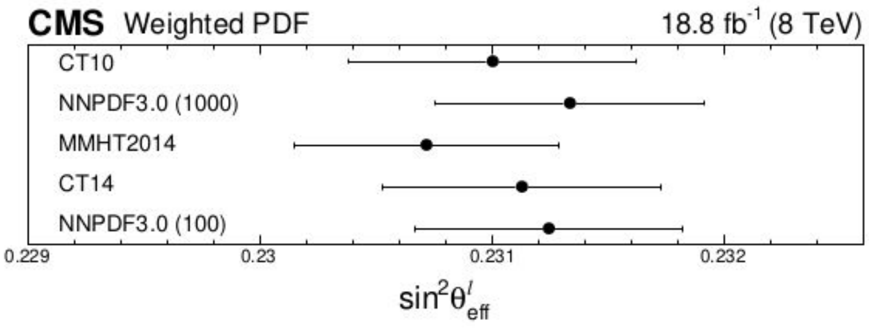
	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^\ell_{\rm eff}$	0.23118	0.23141	0.23140	0.23146
	Uncertainties in measurements			
Total	39	37	36	38
Stat.	21	21	21	21
Syst.	32	31	29	31

$$0.23140 \pm 0.00021\,(\text{stat.}) \pm 0.00024\,(\text{PDF}) \pm 0.00016\,(\text{syst.}),$$

PDF envelope 0.0028 – large, but driven by CT10. Outdated PDF sets in general...

Examples – $\sin^2\theta_{eff}$ (CMS)

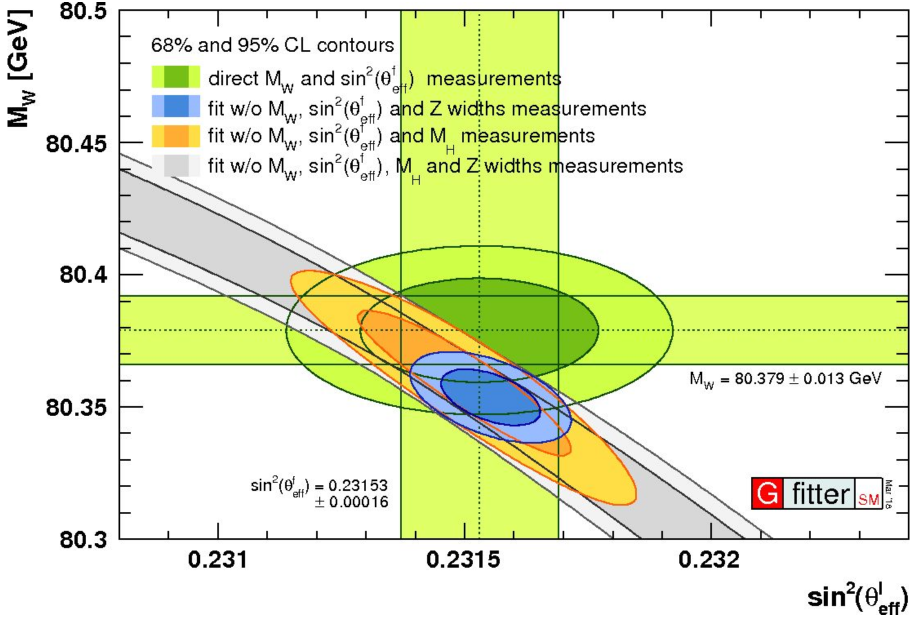


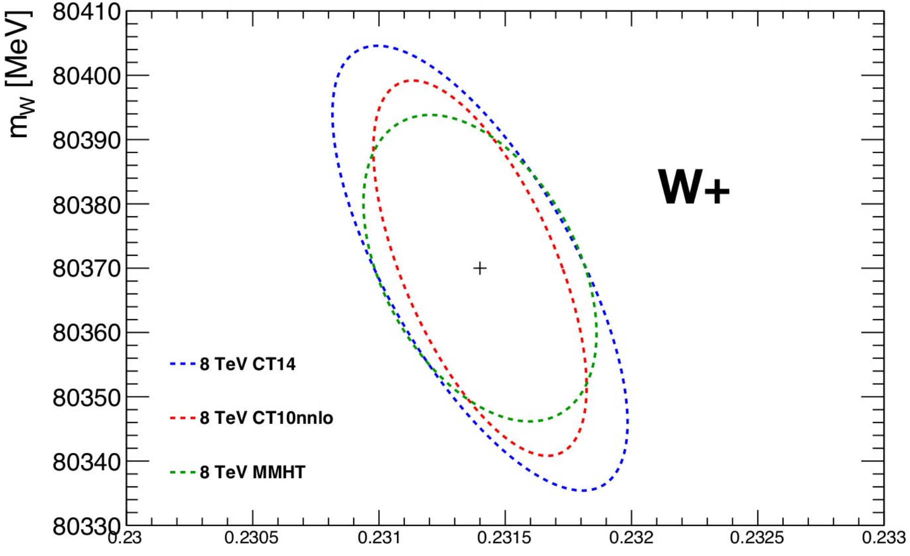


$$\sin^2\theta^\ell_{\rm eff} = 0.23101 \pm 0.00036\,({\rm stat}) \pm 0.00018\,({\rm syst}) \pm 0.00016\,({\rm theo}) \pm 0.00031\,({\rm PDF})$$

PDF envelope ~0.0006 (MMHT2014 – NNPDF3.0)

Examples – $\sin^2\theta_{eff}$ and mW

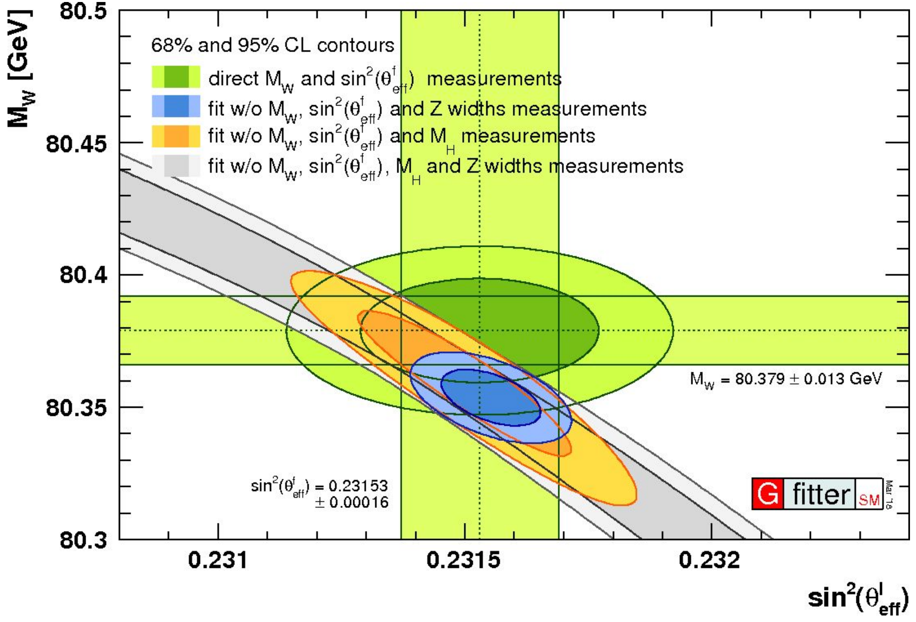


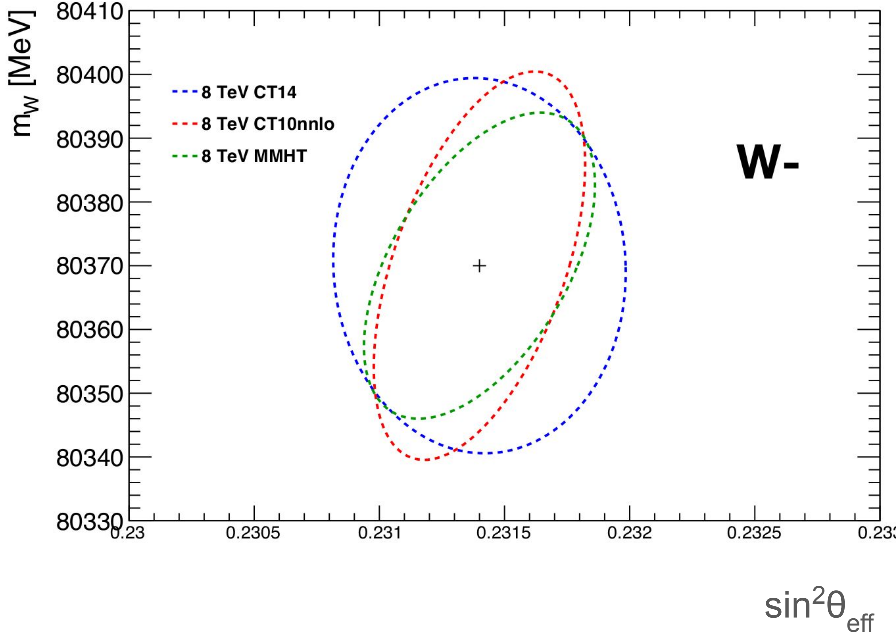


$\sin^2\theta_{eff}$

a “proper” experimental ellipse in this plot is required for for interpretation fits
LHC measurements correlated primarily through PDFs

Examples – $\sin^2\theta_{eff}$ and mW





a “proper” experimental ellipse in this plot is required for for interpretation fits
LHC measurements correlated primarily through PDFs

Examples – α_s extractions

- QCD coupling average from pre-averages from 7 categories of observables:
  $\alpha_s(M_z) = 0.1179 \pm 0.0009$ (±0.8%)

Hadronic tau decay (4 values):
$\alpha_s(M_z) = 0.1178 \pm 0.0019$ (±1.6%)

Quarkonia properties (4 values):
$\alpha_s(M_z) = 0.1181 \pm 0.037$ (±3.3%)

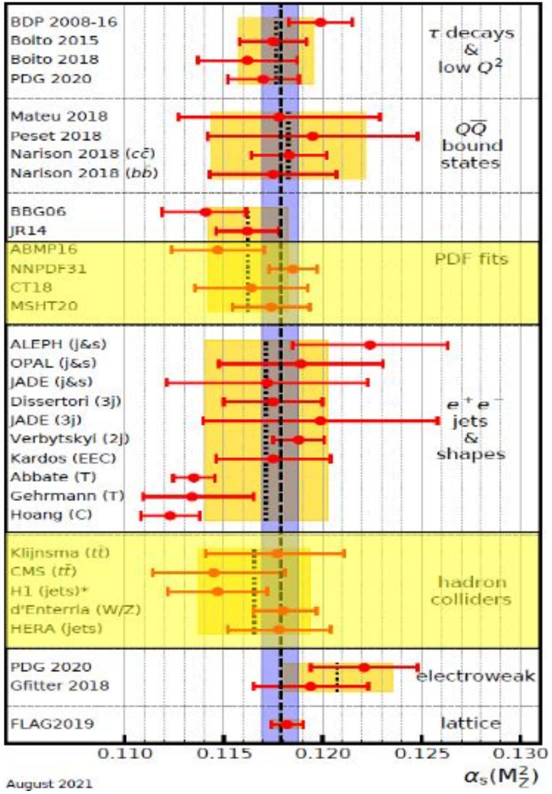
DIS & PDFs fits (6 values):
$\alpha_s(M_z) = 0.1162 \pm 0.0020$ (±1.7%)

$e^+e^- \rightarrow$ hadrons final states (10 values):
$\alpha_s(M_z) = 0.1171 \pm 0.0031$ (±2.6%)

Hadron collider measurements (5 values):
$\alpha_s(M_z) = 0.1165 \pm 0.0028$ (±2.4%)

Electroweak precision fits (2 values):
$\alpha_s(M_z) = 0.1208 \pm 0.0028$ (±2.3%)

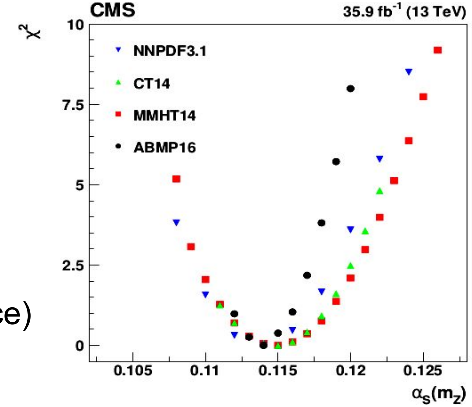
Lattice QCD (1 FLAG value):
$\alpha_s(M_z) = 0.1182 \pm 0.0008$ (±0.7%)

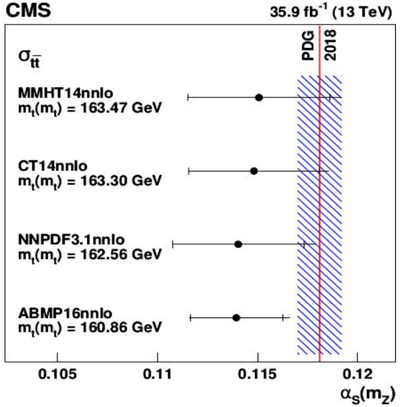


Examples – α_S from hadron collider observables (CMS)

σ_{tot}(ttbar)

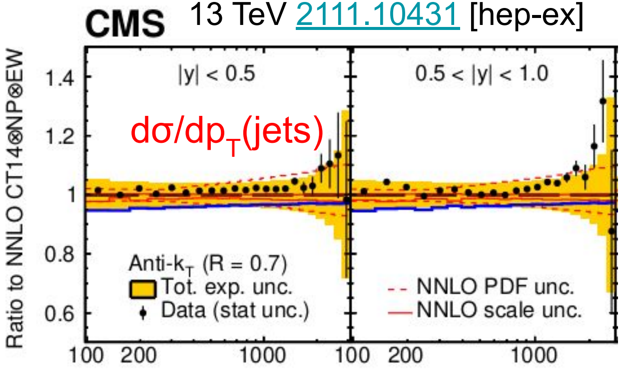
(also m_{top} dependence)





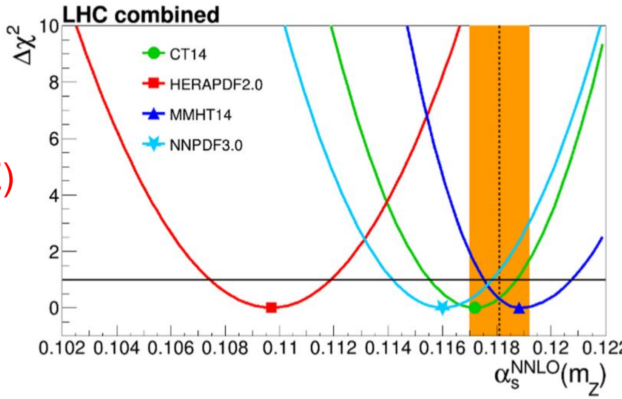
CMS 13 TeV 1812.10505 [hep-ex]

13 TeV 2111.10431 [hep-ex]



The leading TH uncertainty of hadron collider α_s extractions comes from the underlying PDFs in the NNLO calculations

σ_{tot}(W,Z)



D.d'E&Poldaru 1912.11733 [hep-ph]

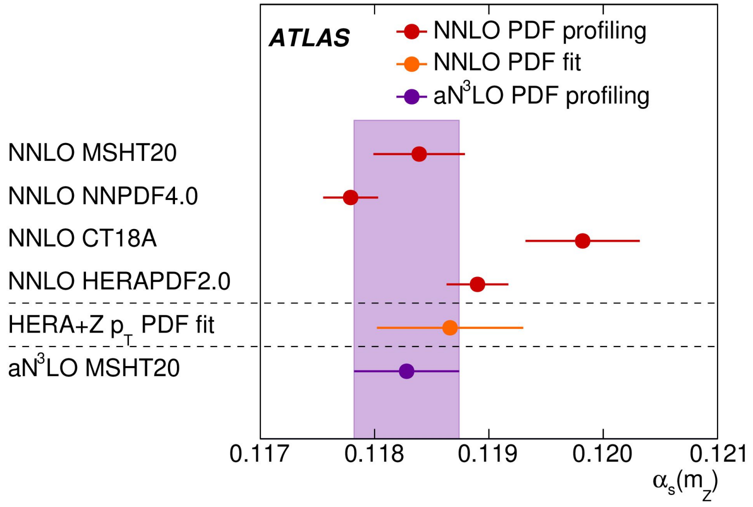
PDF	$\alpha_s(m_Z)$
CT14	$0.1172^{+0.0015}_{-0.0017}$
MMHT14	$0.1188^{+0.0019}_{-0.0013}$
HERAPDF2.0	$0.1097^{+0.0022}_{-0.0023}$
NNPDF3.0	0.1160 ± 0.0018

Examples – α_S from Z boson $d\sigma/dp_T$ peak (ATLAS)

Different NNLO PDF sets have a spread of ±0.00102, driven by the NNPDF4.0-CT18A difference (with CT14 the spread would be a factor of 2 smaller). CT18 is not compatible with the rest of PDFs within PDF uncertainties

Adding HERA data to the fit (counted twice), the spread is reduced to ±0.00016, around a central value of 0.11804

Would be interesting/possible to compare the nominal CT18 with a CT18 fit to only HERA data?



PDF set	$\alpha_s(m_Z)$	PDF uncertainty
MSHT20 [37]	0.11839	0.00040
NNPDF4.0 [84]	0.11779	0.00024
CT18A [29]	0.11982	0.00050
HERAPDF2.0 [65]	0.11890	0.00027

TEEC and ATEEC – Data / theory comparison

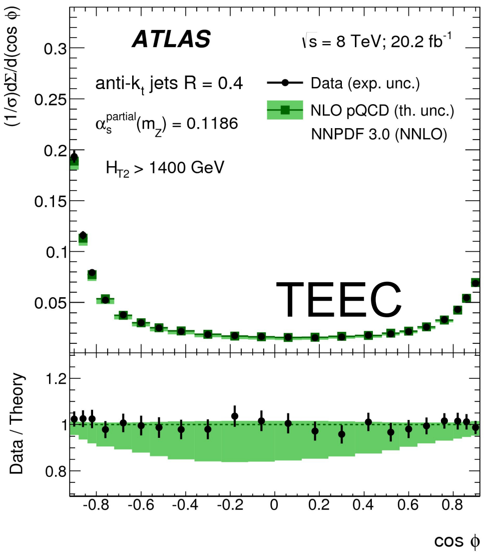
$$\frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d(\cos\phi)} x_{Ti}x_{Tj}dx_{Ti}dx_{Tj}$$

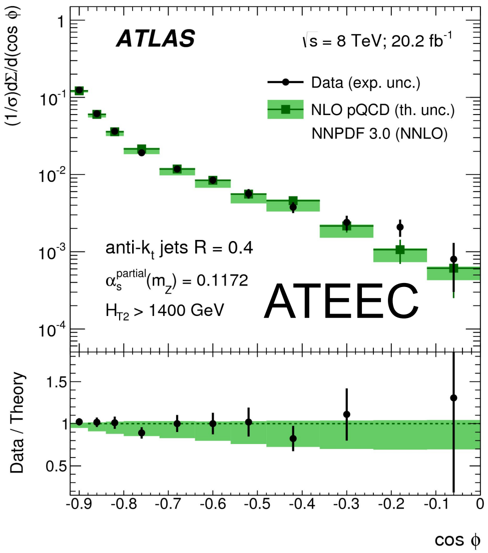
$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d(\cos\phi)} \equiv \frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)}\Big|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)}\Big|_{\pi-\phi}$$

→ Energy-weighted angular distributions:

$$w_{ij} = x_{Ti}x_{Tj} = \frac{E_{Ti}E_{Tj}}{\left(\sum_k E_{Tk}\right)^2}$$

arXiv:1707.02562





→ Theory prediction: NLOJet++ & NP corrections (PYTHIA6 & HERWIG++)

$$\frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)} = \frac{\sum_{a_i,b_i} f_{a_1}(x_1) f_{a_2}(x_2) \otimes \hat{\Sigma}^{a_1a_2\rightarrow b_1b_2b_3}}{\sum_{a_i,b_i} f_{a_1}(x_1) f_{a_2}(x_2) \otimes \hat{\sigma}^{a_1a_2\rightarrow b_1b_2}} \qquad \mu_R = \frac{p_{T1}+p_{T2}}{2};\quad \mu_F = \frac{p_{T1}+p_{T2}}{4}$$

TEEC and ATEEC – α_s results

PDF	$\alpha_s(m_Z)$ value	χ^2/N_{dof}	
MMHT 2014	0.1151 ± 0.0008 (exp.) $^{+0.0064}_{-0.0047}$ (scale) ± 0.0012 (PDF) ± 0.0002 (NP)	173 / 131	TEEC
CT14	0.1165 ± 0.0010 (exp.) $^{+0.0067}_{-0.0061}$ (scale) ± 0.0016 (PDF) ± 0.0003 (NP)	161 / 131	
NNPDF 3.0	0.1162 ± 0.0011 (exp.) $^{+0.0076}_{-0.0061}$ (scale) ± 0.0018 (PDF) ± 0.0003 (NP)	174 / 131	
HERAPDF 2.0	0.1177 ± 0.0008 (exp.) $^{+0.0064}_{-0.0040}$ (scale) ± 0.0005 (PDF) ± 0.0002 (NP) $^{+0.0008}_{-0.0007}$ (mod)	169 / 131	

PDF	$\alpha_s(m_Z)$ value	χ^2/N_{dof}	
MMHT 2014	0.1185 ± 0.0012 (exp.) $^{+0.0047}_{-0.0010}$ (scale) ± 0.0010 (PDF) ± 0.0004 (NP)	57.0 / 65	ATEEC
CT14	0.1203 ± 0.0013 (exp.) $^{+0.0053}_{-0.0014}$ (scale) ± 0.0015 (PDF) ± 0.0004 (NP)	55.4 / 65	
NNPDF 3.0	0.1196 ± 0.0013 (exp.) $^{+0.0061}_{-0.0013}$ (scale) ± 0.0017 (PDF) ± 0.0004 (NP)	60.3 / 65	
HERAPDF 2.0	0.1206 ± 0.0012 (exp.) $^{+0.0050}_{-0.0014}$ (scale) ± 0.0005 (PDF) ± 0.0002 (NP) ± 0.0007 (mod)	54.2 / 65	

→ Scale and PDF uncertainties > Experimental uncertainty

→ PDF uncertainty (eigenvectors) comparable to / smaller than PDF variations for global / all PDF sets

How significant are these differences between various PDF sets?

What fraction of the spread should be added as extra uncertainty?

PDF dependence, PDF uncertainty and their impact

Several, related issues:

- the PDF dependence of measurement results is too large, which points to underestimated uncertainties and “hidden” model dependence
- the significance of the PDF dependence of measurement results can not be calculated
- no well-defined prescription regarding the additional uncertainty to account for such effects

In summary, the error propagation is broken (or almost) at this point, with impact on our uncertainty estimates, averages, interpretation fits, etc

Requests & proposals – Correlations between PDF sets

Proposal to evaluate correlations between PDF sets, originating from common experimental inputs, using coherently-generated pseudo-experiments

Use the xFitter framework to generate pseudo-experiments fluctuating the statistical and systematic experimental uncertainties, taking into account correlations, for an inclusive sample of data (covering all the data used for the various PDF fits)

For each generated pseudo-experiment, select the data points used by each PDF fitting group and re-do the corresponding fit
(Only the nominal fit has to be determined at this stage, not the eigenvectors)

(After validation and cross-checks – see backup:)
Use the ensemble of fitted pseudo-experiments to determine correlations between the uncertainties of various PDF sets

"PDF benchmarking proposal for precision Drell-Yan" (PDF4LHC meeting, CERN, 2018)
"PDF benchmarking discussion" (LHC EW Precision sub-group workshop, IPPP Durham UK, 2019)
"PDF benchmarking report" (LHC Electroweak WG meeting, CERN, 2019)

Requests & proposals – “Bridge” PDFs?

While PDF analysis in general, and assigning PDF uncertainties in particular is well understood to be extremely challenging, it is critical for the experimental community to dispose of tools to understand what drives the differences.

Specifically, we need to understand, quantitatively, the specific impact of

- the choice of the datasets
- parametrisations
- theory : perturbative accuracy ; heavy-flavour mass schemes; …
- error treatment : tolerances, etc
- …

“Bridge” PDFs?

Naïvely :

PDF A
- data A
- param A
- HF scheme A
- Tolerance A
- …

→

PDF A’
- data B
- param A
- HF scheme A
- Tolerance A
- …

→

PDF B
- data B
- param B
- HF scheme B
- Tolerance B
- …

“Bridge” PDFs?

Naïvely :

PDF A
- data A
- param A
- HF scheme A
- Tolerance A
- …

PDF A”
- data A
- param B
- HF scheme A
- Tolerance A
- …

PDF B
- data B
- param B
- HF scheme B
- Tolerance B
- …

“Bridge” PDFs?

Naïvely :

PDF A
- data A
- param A
- HF scheme A
- Tolerance A
- …

PDF A’’’
- data A
- param A
- HF scheme B
- Tolerance A
- …

PDF B
- data B
- param B
- HF scheme B
- Tolerance B
- …

“Bridge” PDFs?

Naïvely :

PDF A	→	PDF A””	→	PDF B
- data A		- data A		- data B
- param A		- param A		- param B
- HF scheme A		- HF scheme A		- HF scheme B
- Tolerance A		- Tolerance B		- Tolerance B
- …		- …		- …

and/or combinations of variations…

“Bridge” PDFs?

In some cases, a common benchmark might be more practical :

PDF A	PDF A’	PDF B’	PDF B
- data A	- $\text{data}_{\text{common}}$	- $\text{data}_{\text{common}}$	- data B
- param A	- param A	- param B	- param B
- HF scheme A	- HF scheme A	- HF scheme B	- HF scheme B
- Tolerance A	- Tolerance A	- Tolerance B	- Tolerance B
- …	- …	- …	- …

“Bridge” PDFs?

In some cases, a common benchmark might be more practical :

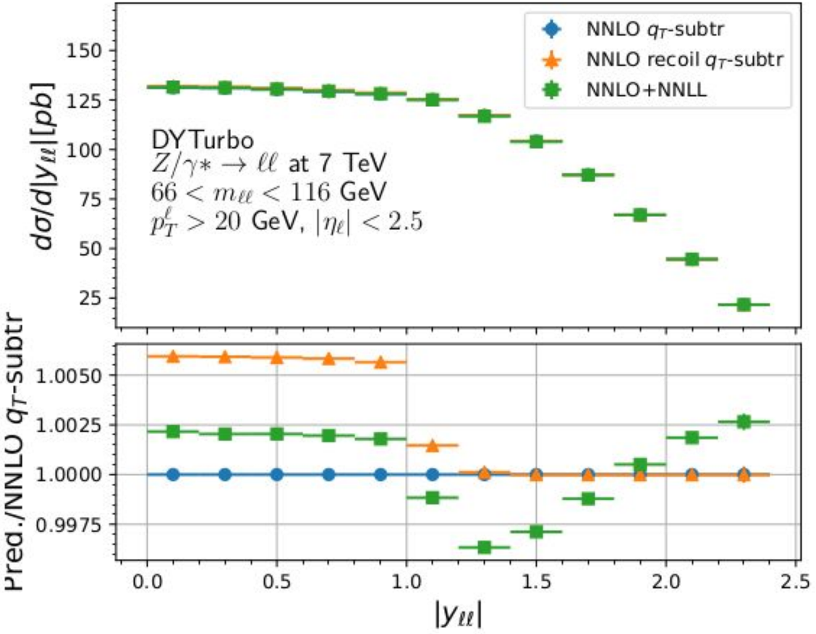
PDF A	PDF A’	PDF B’	PDF B
- data A	- data A	- data B	- data B
- param A	- param A	- param B	- param B
- HF scheme A	- HF scheme A	- HF scheme B	- HF scheme B
- Tolerance A	- $\Delta\chi^2=1$	- $\Delta\chi^2=1$	- Tolerance B
- …	- …	- …	- …

Tolerance variations ⇔impact on PDF uncertainty **and** measurement central value!

A separate point – p_T resummation corrections

ATLAS 7 TeV W,Z cross sections

EPJC (2017) 77:367, arXiv:2209.13535



CT14nnlo 68%CL			
Dataset	NNLO q_T-subtr.	NNLO recoil q_T-subtr.	NNLO+ NNLL
W^+ lepton rapidity	9.4/11	8.8/11	8.8/11
W^- lepton rapidity	8.2/11	8.7/11	8.2/11
Low mass, Z rapidity	11/6	7.2/6	7.5/6
Mass peak, central Z rapidity	15/12	10/12	7.7/12
Mass peak, forward Z rapidity	9.6/9	5.3/9	6.4/9
High mass, central Z rapidity	6.0/6	6.5/6	5.8/6
High mass, forward Z rapidity	5.2/6	5.6/6	5.3/6
Correlated χ^2	40	40	31
Log penalty χ^2	-4.33	-3.39	-4.20
Total χ^2/dof	99/61	88/61	77/61
χ^2 p-value	0.00	0.01	0.08

A separate point – p_T resummation corrections

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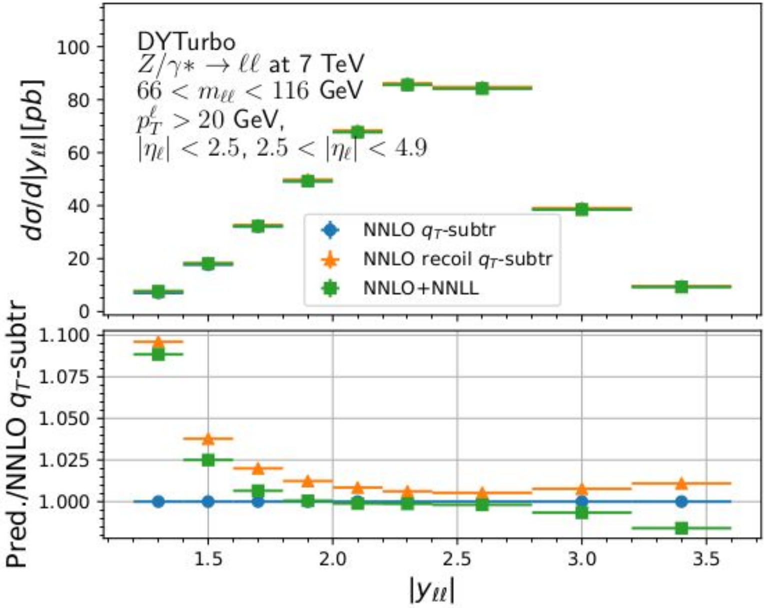
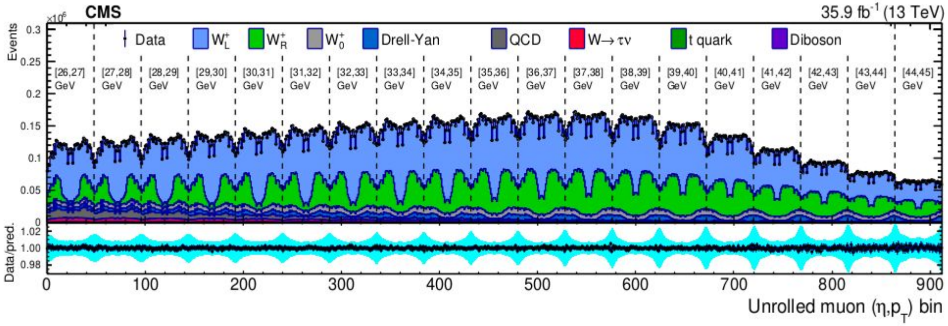
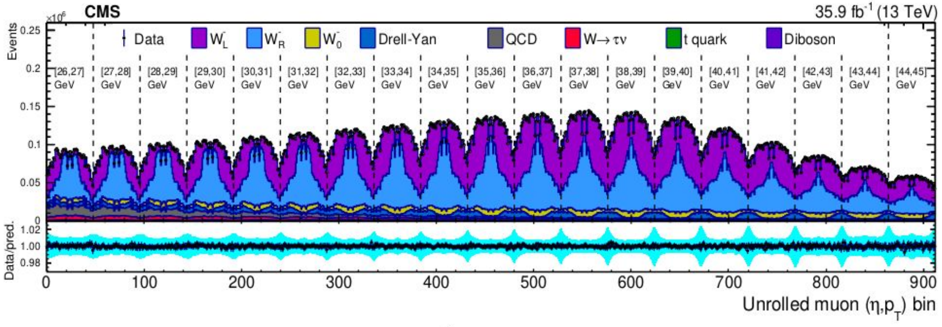


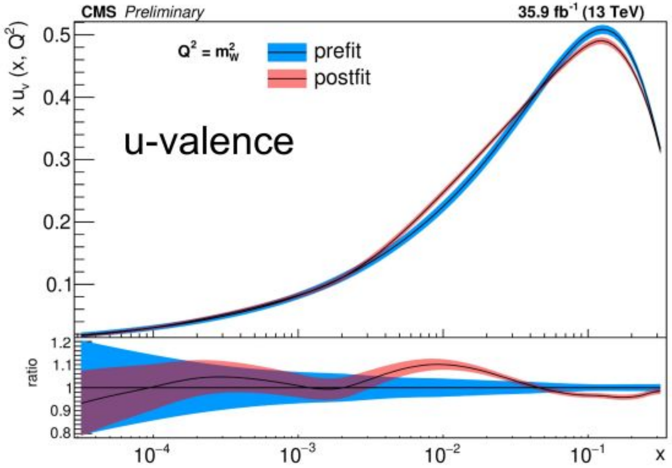
	CT14nnlo 68%CL		
Dataset	NNLO q_T-subtr.	NNLO recoil q_T-subtr.	NNLO+ NNLL
W^+ lepton rapidity	9.4/11	8.8/11	8.8/11
W^- lepton rapidity	8.2/11	8.7/11	8.2/11
Low mass, Z rapidity	11/6	7.2/6	7.5/6
Mass peak, central Z rapidity	15/12	10/12	7.7/12
Mass peak, forward Z rapidity	9.6/9	5.3/9	6.4/9
High mass, central Z rapidity	6.0/6	6.5/6	5.8/6
High mass, forward Z rapidity	5.2/6	5.6/6	5.3/6
Correlated χ^2	40	40	31
Log penalty χ^2	-4.33	-3.39	-4.20
Total χ^2/dof	99/61	88/61	77/61
χ^2 p-value	0.00	0.01	0.08

A separate point – p_T resummation corrections

CMS W helicity cross sections   Phys. Rev. D 102 (2020) 092012







Strong constraining power, but p_T resummation corrections mandatory for a consistent PDF analysis

Summary

The above picture is admittedly over-simplified and unaware of technical difficulties, PDF specificities, etc

- however, similar exercises have been performed in this forum in the past (cf. CT18', NNPDF3.1')
- in any case, a practical recipe for experiments is missing

The sketches above illustrate the essence of our needs. We are happy to rely on the concrete proposals of the PDF community.

We do not need to pin down the differences to the last digit :

- understanding ~90% of the difference between PDF sets using such "bridge" sets seems sufficient
- residual effects will be subleading, compared to other uncertainties, for the foreseeable future.

🔺 **we are not after reduced PDF uncertainties, but need better control of the correlations between them, and therefore of their breakdown into their main components.**

Conclusions & follow up

We are now deep into the LHC era, and have consolidated, yet ambitious goals for our precision measurement program:

$\delta m_W < 10$ MeV $\delta \sin^2\theta_{eff} \sim 10^{-4}$ $\delta m_Z \sim m_Z^{LEP}$ $\delta \alpha_S \sim 0.5\%$

To achieve these major end-goals, and quote well-understood uncertainties at this level, a proper understanding of the model dependence of measurement results, especially regarding PDFs, is **mandatory**.

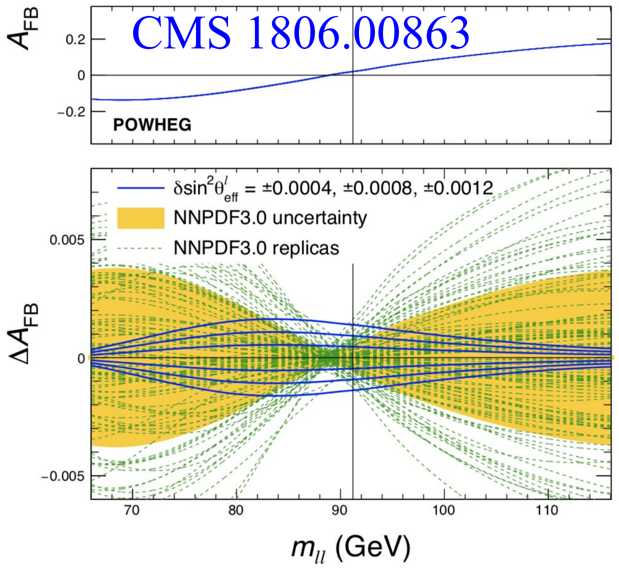
Obviously huge progress in PDF determination on many fronts! But the interface to the experiments is not sufficient at this point

- PDF “bridge” sets would be an extremely useful tool in this respect.
- PDF correlation studies seem very promising and should be concluded.

We would be happy to hear the PDF community’s view and proposals on this matter, and are eager to collaborate & follow up

Back up

$\sin^2\theta_W$



→ Extraction from experimental measurement using PDF profiling (complementary sensitivity to PDFs and $\sin^2\theta_W$)

ATLAS result (ATL-CONF-2018-037):

$0.23140 \pm 0.00021\,(\text{stat.}) \pm 0.00024\,(\text{PDF}) \pm 0.00016\,(\text{syst.})$

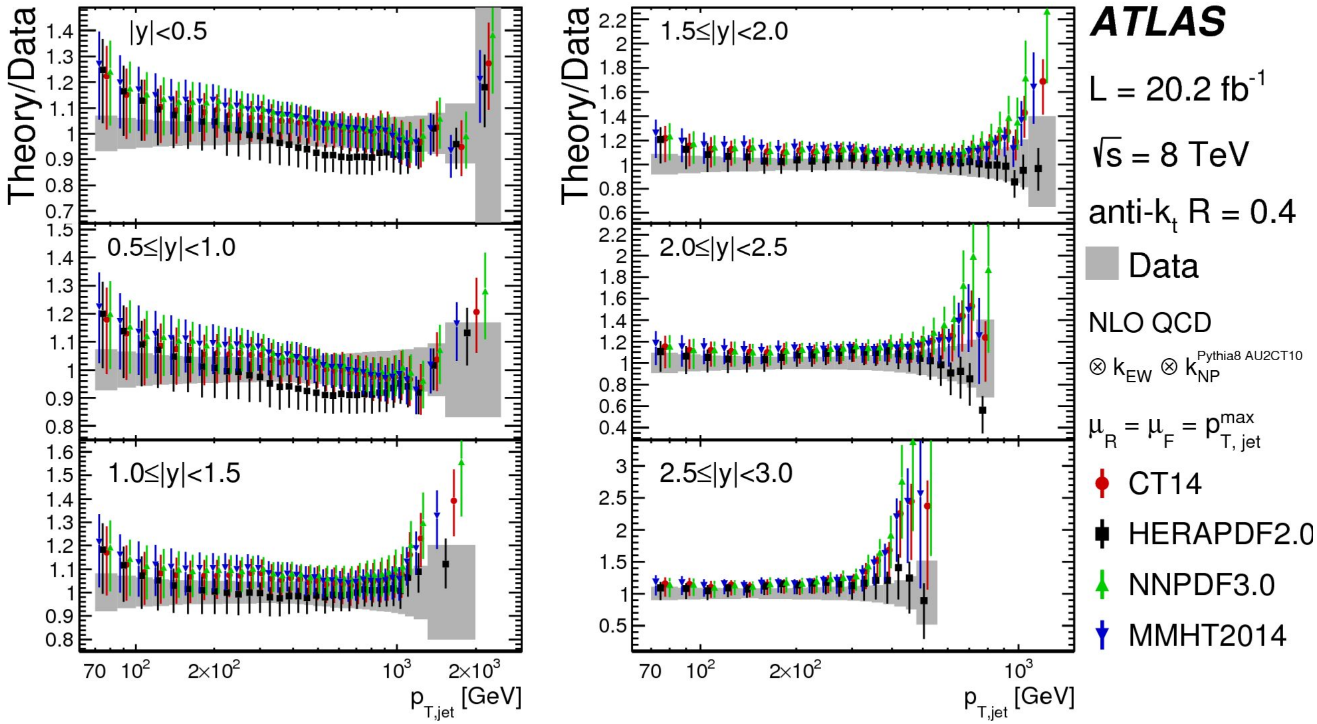
→ PDF uncertainty dominant: evaluated from MMHT14 nuisance parameters

	CT10	CT14	MMHT14	NNPDF31
$\sin^2\theta^\ell_{\text{eff}}$	0.23118	0.23141	0.23140	0.23146

→ Range of values for 4 PDF sets 0.00028: *are the differences significant?*

→ Similar questions need to be addressed for m_W

Quantitative comparison between data and NLO QCD+NP+EW



→χ^2 and p-values evaluated with full information on statistical and systematic uncertainties, experimental and theoretical, *with their correlations*

$$\chi^2(\mathbf{d};\mathbf{t}) = \min_{\beta_a}\left\{\sum_{i,j}\left[d_i - \left(1+\sum_a \beta_a \cdot \left(\boldsymbol{\epsilon}_a^{\pm}(\beta_a)\right)_i\right) t_i\right]\cdot\left[C_{\rm su}^{-1}(\mathbf{t})\right]_{ij}\cdot\left[d_j - \left(1+\sum_a \beta_a \cdot \left(\boldsymbol{\epsilon}_a^{\pm}(\beta_a)\right)_j\right) t_j\right] + \sum_a \beta_a^2\right\}$$

Quantitative comparison between data and NLO QCD+NP+EW

8 TeV – ATLAS inclusive jets (arXiv:1706.03192)

Rapidity ranges	P_{obs} CT14	MMHT2014	NNPDF3.0	HERAPDF2.0
Anti-k_t jets $R = 0.4$				
$\|y\| < 0.5$	44%	28%	25%	16%
$0.5 \leq \|y\| < 1.0$	43%	29%	18%	18%
$1.0 \leq \|y\| < 1.5$	44%	47%	46%	69%
$1.5 \leq \|y\| < 2.0$	3.7%	4.6%	7.7%	7.0%
$2.0 \leq \|y\| < 2.5$	92%	89%	89%	35%
$2.5 \leq \|y\| < 3.0$	4.5%	6.2%	16%	9.6%
Anti-k_t jets $R = 0.6$				
$\|y\| < 0.5$	6.7%	4.9%	4.6%	1.1%
$0.5 \leq \|y\| < 1.0$	1.3%	0.7%	0.4%	0.2%
$1.0 \leq \|y\| < 1.5$	30%	33%	47%	67%
$1.5 \leq \|y\| < 2.0$	12%	16%	15%	3.1%
$2.0 \leq \|y\| < 2.5$	94%	94%	91%	38%
$2.5 \leq \|y\| < 3.0$	13%	15%	20%	8.6%

→ Generally good agreement for individual |y| bins

χ^2/ndf	$p_T^{jet,max}$ $R = 0.4$	$p_T^{jet,max}$ $R = 0.6$	p_T^{jet} $R = 0.4$	p_T^{jet} $R = 0.6$
$p_T > 70$ GeV				
CT14	349/171	398/171	340/171	392/171
HERAPDF2.0	415/171	424/171	405/171	418/171
NNPDF3.0	351/171	393/171	350/171	393/171
MMHT2014	356/171	400/171	354/171	399/171
$p_T > 100$ GeV				
CT14	321/159	360/159	313/159	356/159
HERAPDF2.0	385/159	374/159	377/159	370/159
NNPDF3.0	333/159	356/159	331/159	356/159
MMHT2014	335/159	364/159	333/159	362/159
$100 < p_T < 900$ GeV				
CT14	272/134	306/134	262/134	301/134
HERAPDF2.0	350/134	331/134	340/134	326/134
NNPDF3.0	289/134	300/134	285/134	299/134
MMHT2014	292/134	311/134	284/134	308/134
$100 < p_T < 400$ GeV				
CT14	128/72	149/72	118/72	145/72
HERAPDF2.0	148/72	175/72	141/72	170/72
NNPDF3.0	119/72	141/72	115/72	139/72
MMHT2014	132/72	143/72	122/72	140/72

→Tension when including all |y| bins

How to treat correlations between JES uncertainties for different years?

when one set of LHC jet Xsec is used for the PDF fit and that PDF set is compared with (more recent) data

Available datasets in xFitter

→ Performed comparison with datasets used in the last PDF sets:

ABMP16 - 1701.05838 CT14 - 1506.07443

MMHT14 - 1412.3989 NNPDF31 - 1706.00428

General conclusions:

→ HERA datasets all present

→ Tevatron data mostly available

→ Neutrino experiments missing

→ All but the most recent ATLAS and CMS data are present
Missing most of the LHCb ones

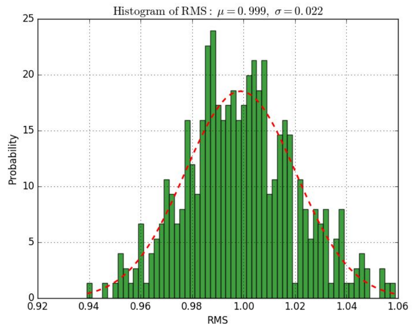
→ Some datasets actually available in private areas

Toys using xFitter datasets

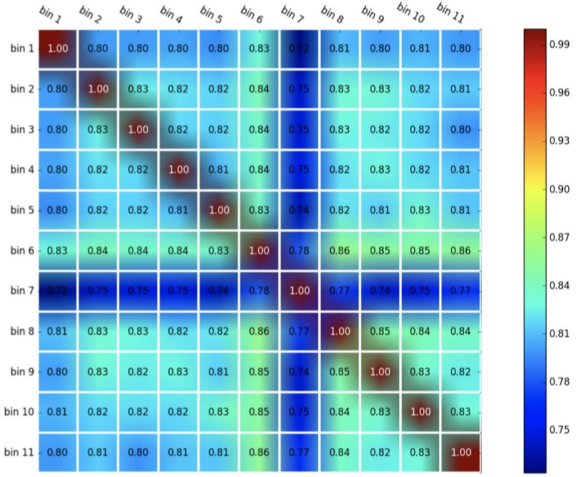
→ Code for toy generation and validation prepared by S. Mikhalcov, V. Novik and S. Amoroso: https://gitlab.cern.ch/smikhalc/test

→ Toy generation very fast

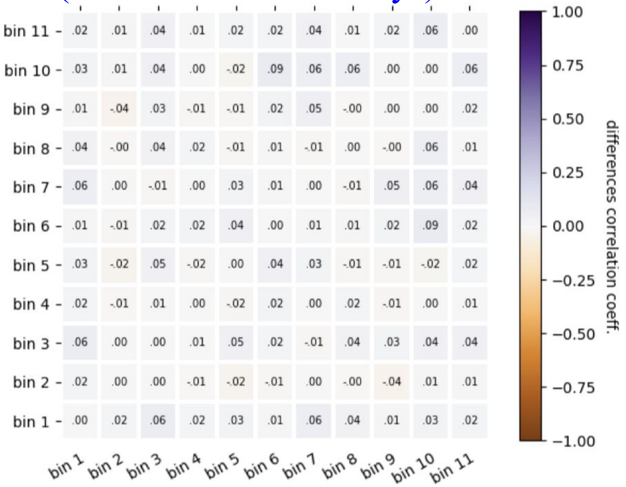
→ Performed cross-checks: total uncertainty and correlation matrix



Correlation matrix from toys



Correlation matrix difference (data uncertainties - toys)



Treatment of tolerances when measuring PDF correlations with toys

→ Based on needs of precision measurements: proposal to evaluate correlations between PDF sets, originating from common experimental inputs, using coherently-generated pseudo-experiments

→ Need to account for tolerance scaling factors, in order for the evaluated correlations to be relevant for the used PDF uncertainties

→ Proposal to do this without impacting the way the pseudo-experiments are generated: rescale the difference between the fits of the fluctuated data and the nominal fit

$$fit'^{Toy} = fit^{Nom} + \sum_{i=1}^{Ne.v.} \left\langle \left(fit^{Toy} - fit^{Nom} \right); e_i \right\rangle \cdot e_i \cdot t_i$$

$fit \equiv \mathrm{PDF}(x, Q^2)$ from fit of nominal or toy data

$\langle \ \rangle \equiv$ dot product: same binning as for e.v. decomposition

$e_i \equiv$ eigenvector (x, Q^2); orthogonal and unitary using $\langle \ \rangle; e_i \equiv V_i / \sqrt{\langle V_i; V_i \rangle}$

$t_i \equiv$ tolerance scaling factor for eigenvector V_i possibly with different values for +/- variations

Treatment of tolerances when measuring PDF correlations with toys

→ Rescaling relies on linear approximation, but that's already the case for the broadly-used eigenvector-based uncertainty propagation and pseudo- experiments do sample distribution tails where non-linear effects may occur

→ Possible cross-check:

- for a given PDF set, compute covariance of uncertainty for different / same PDF flavor at different / same $(x;Q^2)$ points, using pseudo-experiments
- compare with covariance evaluated based on eigenvectors

$$Cov\left(fit'_A(x_1,Q_1^2); fit'_B(x_2,Q_2^2) \right) = \sum_{i=1}^{N\ \text{e.v.}} V_{A,i}(x_1,Q_1^2) \cdot V_{B,i}(x_2,Q_2^2)$$

$$= \frac{\sum_{t=1}^{N\ toys} \left(fit'^{Toy,t}_A(x_1,Q_1^2) - \overline{fit'^{Toy}_A(x_1,Q_1^2)} \right) \cdot \left(fit'^{Toy,t}_B(x_2,Q_2^2) - \overline{fit'^{Toy}_B(x_2,Q_2^2)} \right)}{N\ toys}$$

$V_{A,i}(x_1,Q_1^2) \equiv$ eigenvector i for PDF flavor A, with tolerance factor applied

Treatment of tolerances when measuring PDF correlations with toys

→ Cross-check can be done in steps:

- diagonal uncertainties for PDFs
- correlations for PDF uncertainties
- uncertainties and correlations for various observables (e.g. Drell-Yan)

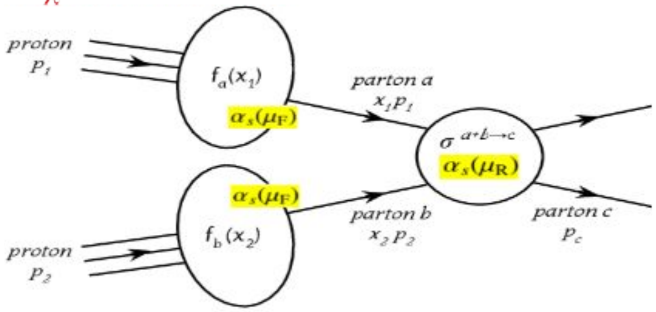
$$O_A^a = H^a(f_A)$$

$$Cov(O_A^a; O_B^b) = \frac{\sum_{t=1}^{N_{toys}} (O_A^{a,t} - \overline{O_A^a}) \cdot (O_B^{b,t} - \overline{O_B^b})}{N_{toys}}$$

→ For each of these can also compare the actual distributions used to fill each bin of the covariance matrices

Examples – α_s from hadron collider observables

- Method: (1) Compare σ(exp) to σ(NNLO) for varying PDFs+α_s
  (2) Extract α_s via χ^2 minimization



$$\sigma(pp \to X) = \sum_{\text{partons}} \int\int dx_1 dx_2\, f_1(x_1, \alpha_s(\mu_F))\, f_2(x_2, \alpha_s(\mu_F)) \left[\hat{\sigma}_{LO} + \alpha_s(\mu_R)\hat{\sigma}_{NLO} + \alpha_s^2(\mu_R)\hat{\sigma}_{NNLO} + \ldots\right]$$

pQCD accuracy: $\mathcal{O}$(50%) $\mathcal{O}$(20%) $\mathcal{O}$(2–5%)

- Global requirement:
  – x-section NOT incorporated/incorporable in global-PDF fits (avoid “double counting”)
- Theory requirements:
  – NNLO prediction: Few % scale uncertainty
  – Low non-pQCD & parametric (e.g. m_q) uncertainties & controlled EW corrections
- Exp. requirements:
  – Few % stat. uncertainty: Process with large cross sections (say $\sigma \gtrsim 100$ pb).
  – Few % syst. uncertainties: Ratios (luminosity & other systs. cancel out) better?