Impact of LHeC PDFs on W mass and weak mixing angle measurements

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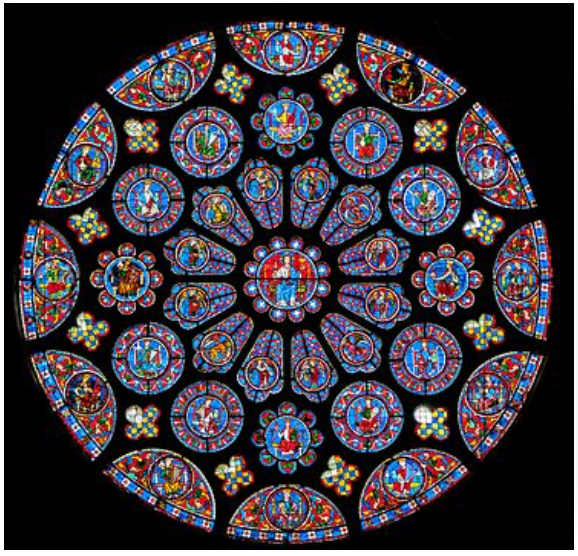
Thanks to J. Kretzschmar, L. Aperio Bella, Z. Zhang, M. Boonekamp, S. Camarda for help and inputs

Outline

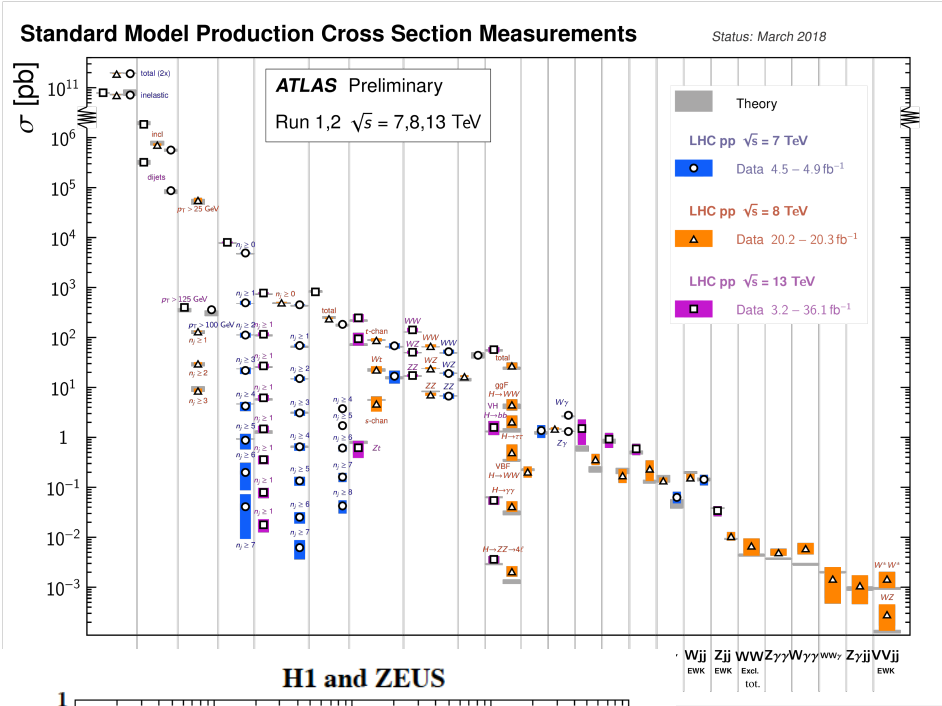
- Why high precision is important?
- W-boson mass measurement in ATLAS
- HL-LHC prospects for a W-boson mass measurement
- LHeC importance in the precise W-boson mass determination
- Weak mixing angle measurement
- HL-LHC prospects for a weak mixing angle measurement
- LHeC importance in a weak mixing angle measurement

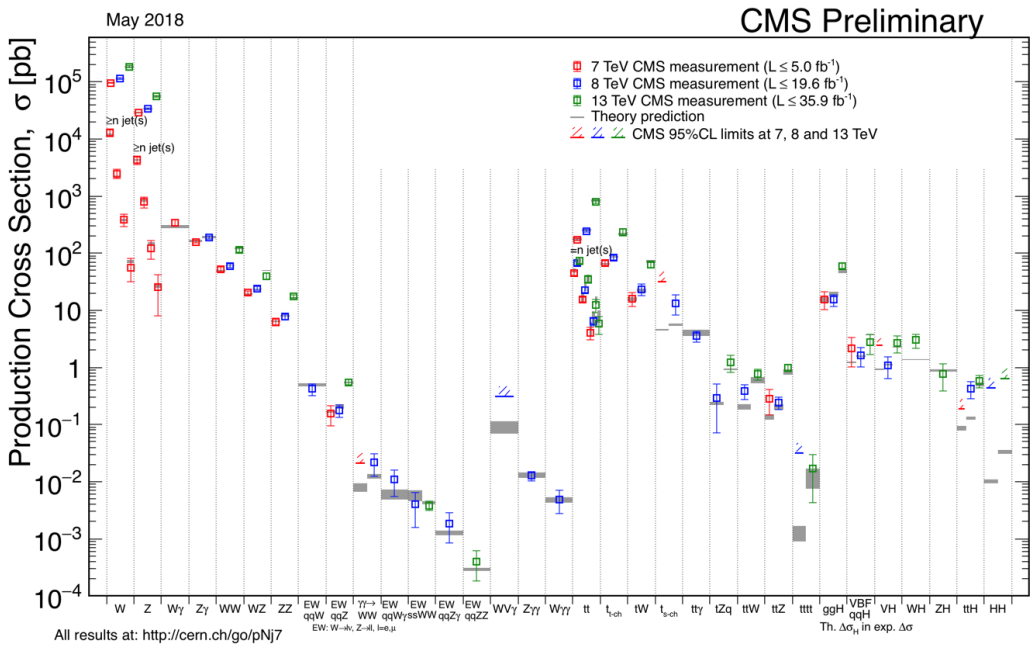
Why do we need precision?

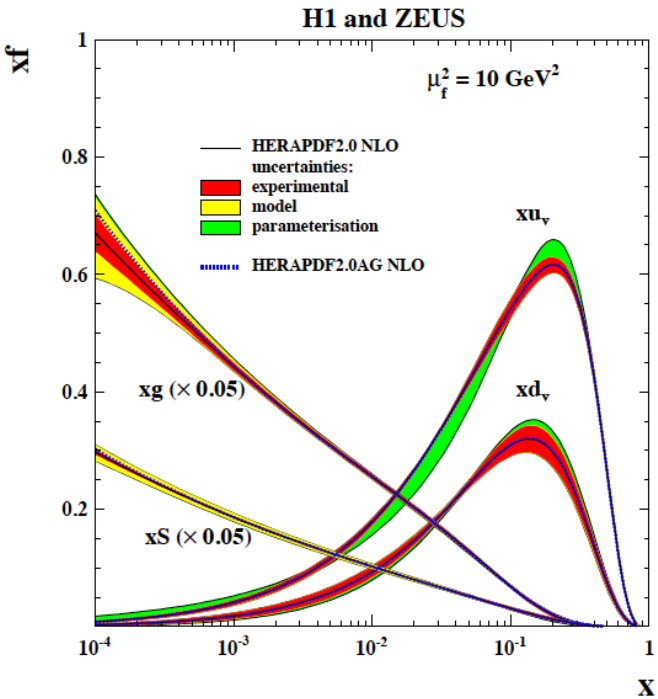
Nature and beauty are always about precision !

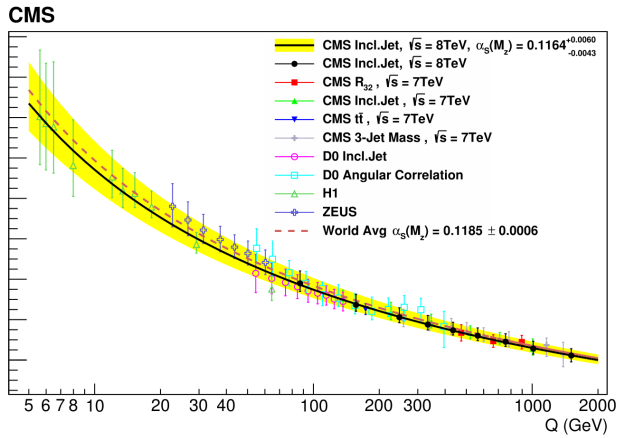


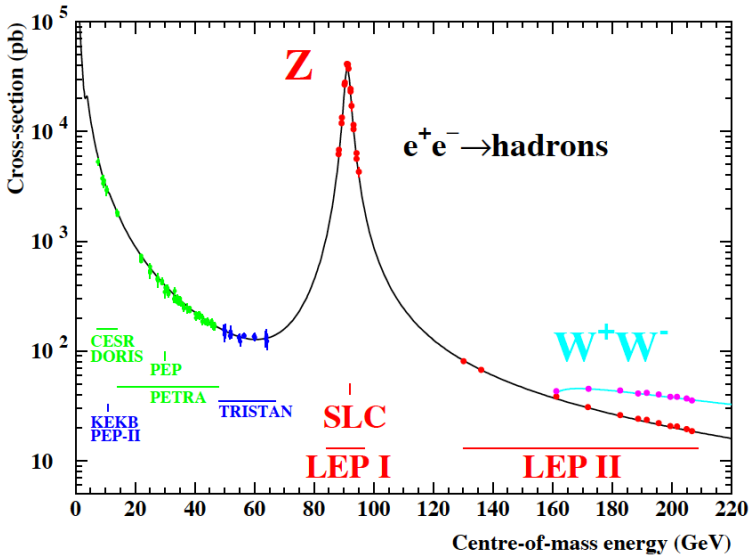
Precision measurements: examples





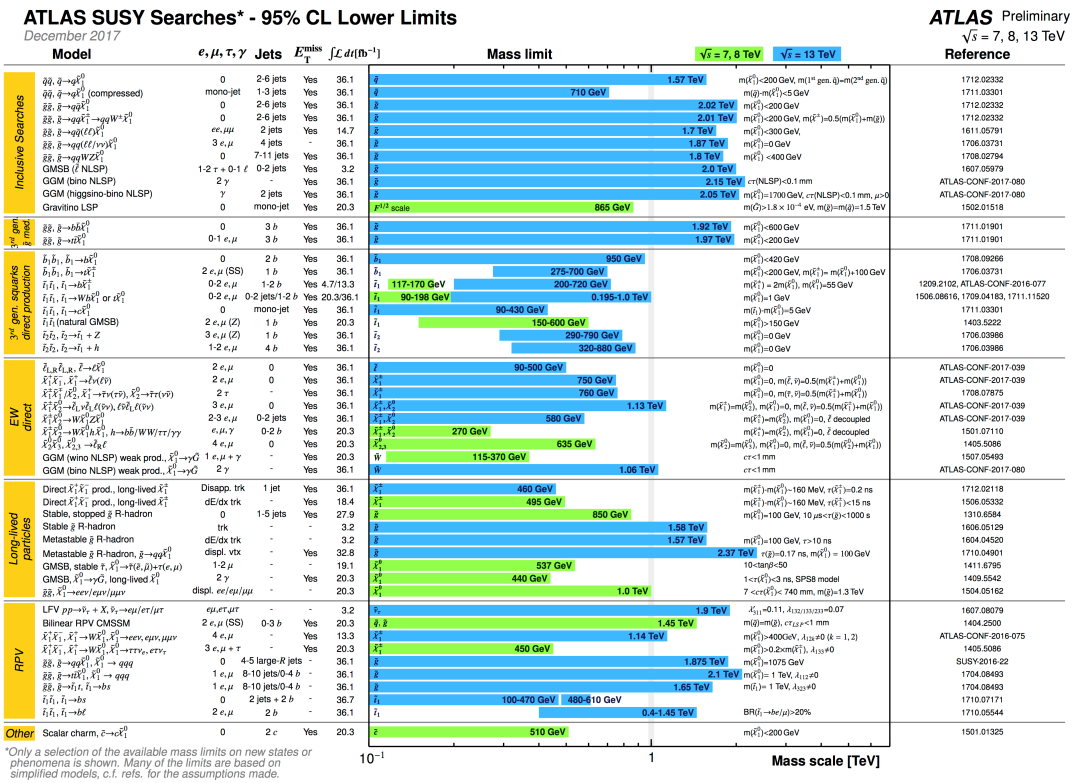


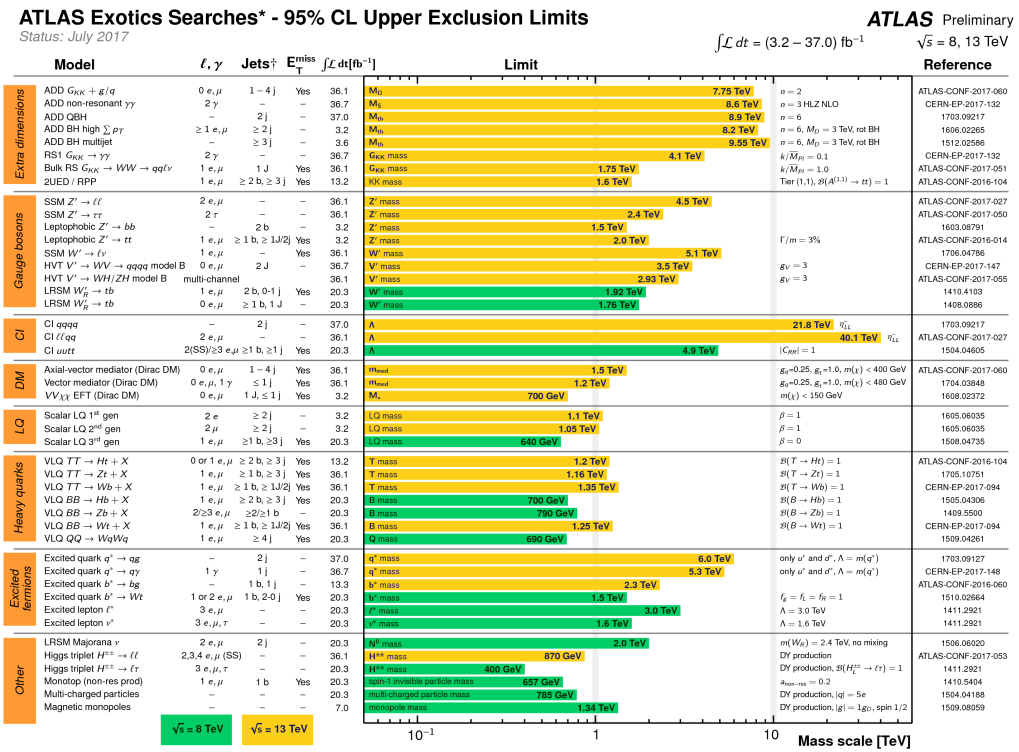




Direct searches

Huge numbers of new results from the LHC - astonishing achievement. No significant signals - updated limits. More still to come with future data.





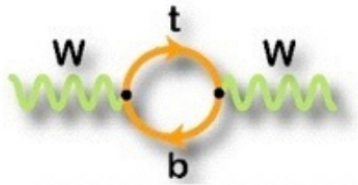
Indirect searches: precision measurements in EW sector (Higgs couplings, $\sin^2\theta_W$, m_W…)

W-boson mass

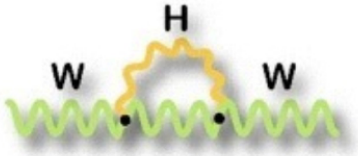
W-boson mass

In the electroweak sector of the SM, the W mass at the tree level:

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

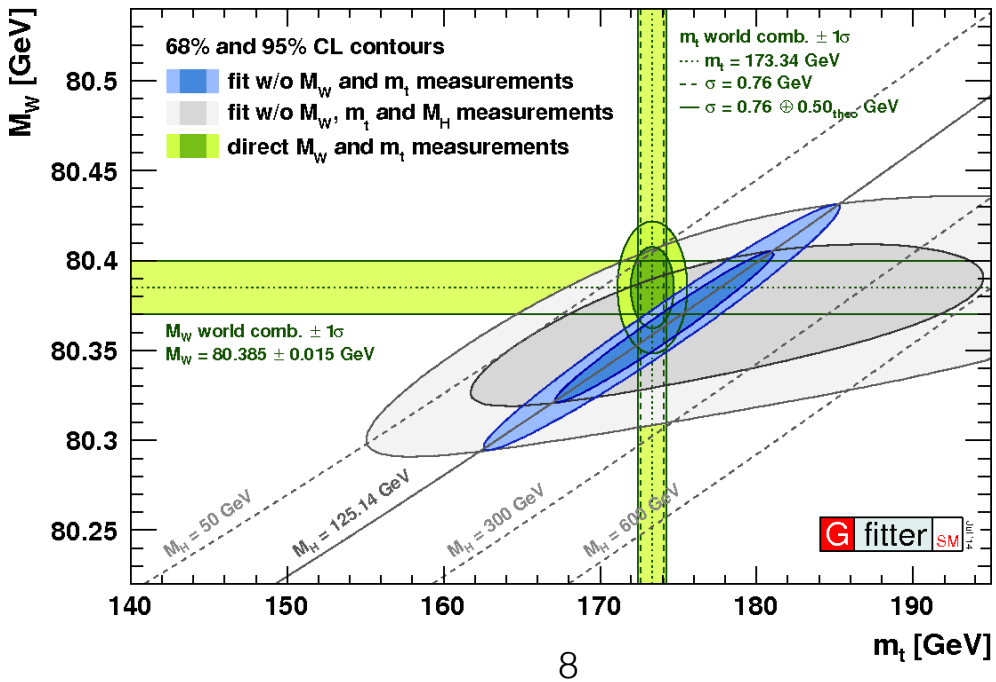


at the loop level: $$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



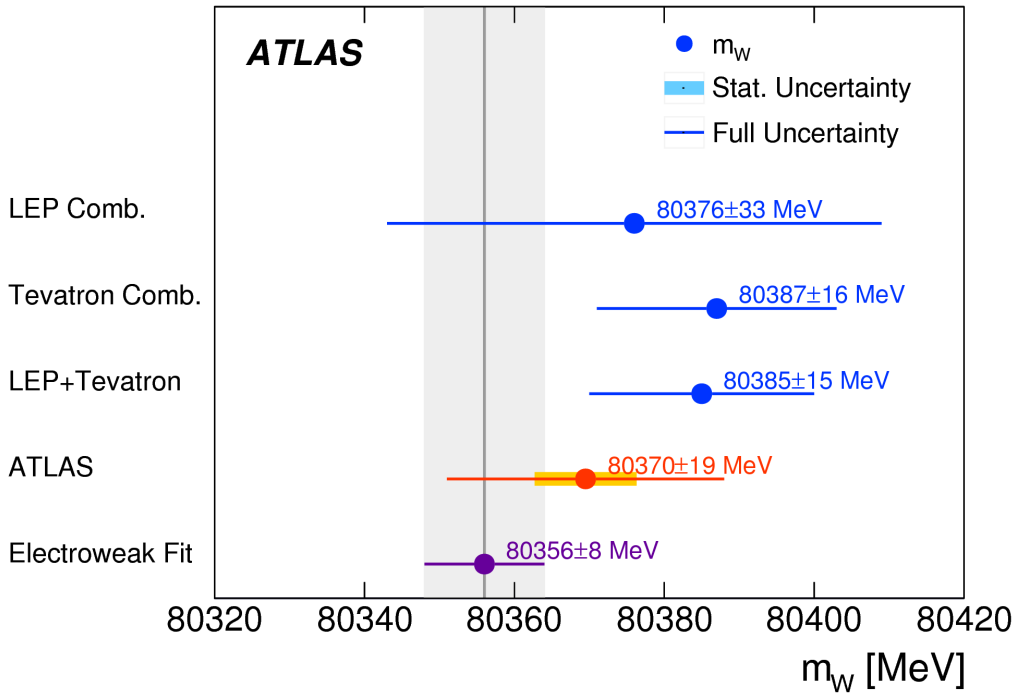
In SM, Δr reflects loop corrections and depends on m_t^2 and $\ln m_H$

The relation M_W, m_t, and M_H provides stringent test of the SM and is sensitive to NP



W-boson mass measurement

Eur.Phys.J.C (2018) 78:110



LEP+Tevatron: M_W uncertainty~ 15 MeV
Best individual measurement:
CDF M_W uncertainty 19 MeV

Long thought as not possible to reach high precision at the LHC: challenging measurement due to pp collisions and high pile-up environment.

Measurement by ATLAS:

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

The ATLAS result is consistent with the SM expectation, compatible with the world average and competitive in precision to the currently leading measurements by CDF

ATLAS W-boson mass measurement

Dominant uncertainties:

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EWK Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

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

PDF variations (25 error eigenvectors) of CT10nnlo, very similar between p_T^l and m_T but strongly anti-correlated between W^+ and W^-. Dominated by knowledge of valence quark PDFs (in particular d_v)

ATLAS W-boson mass measurement

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p_T^W modelling related uncertainties are also important

Strangeness

Second generation quark PDFs play a larger role at the LHC *(25% of the W-boson production is induced by at least one second generation quark s or c)* than at the Tevatron.

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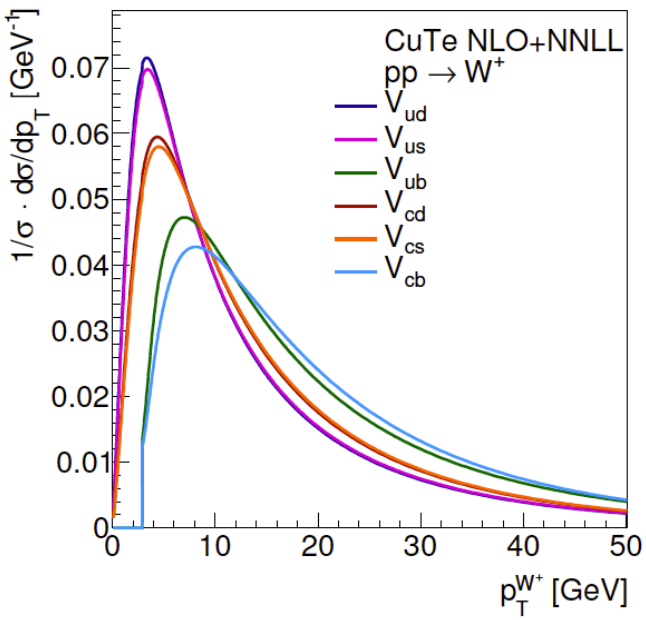
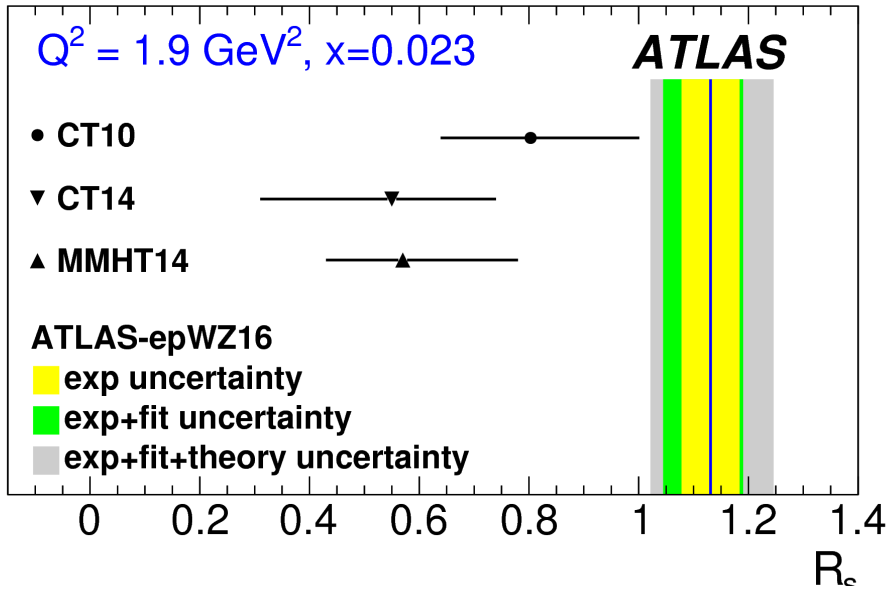
ATL-PHYS-PUB-2014-015





$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$$

Precision cross-section measurement: probe of strong interaction and the proton structure (PDFs)

ATLAS W,Z data suggests a larger than expected strange-quark sea contribution: $R_s>1$ —> impact on p_T^W modelling from least known strange PDF

Future improvements

- Combination with CMS *(when available)* and Tevatron…

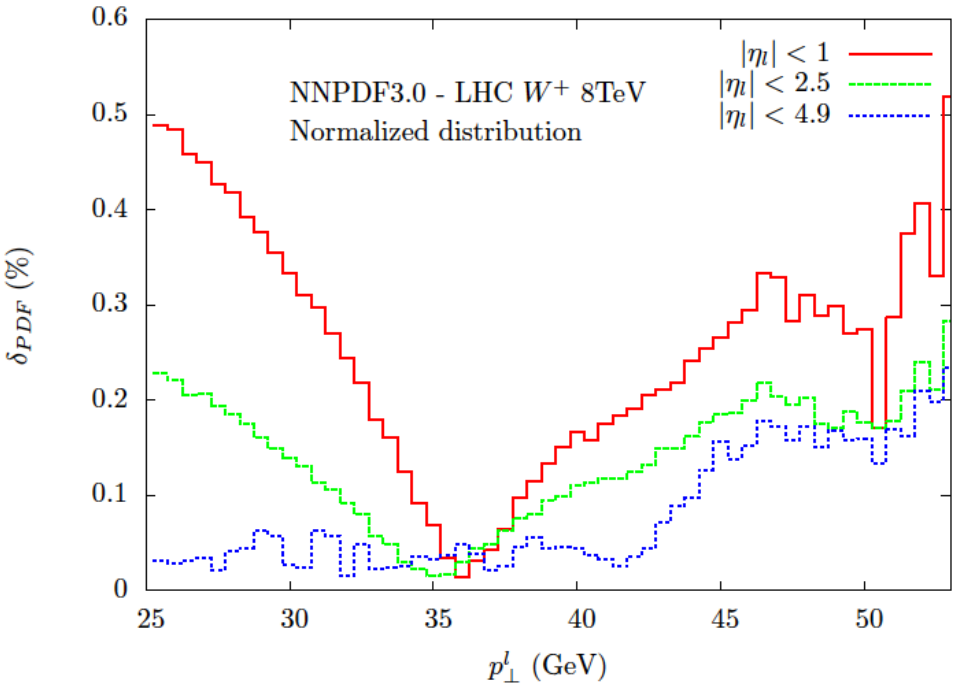
- More data are available with the 8 and 13 TeV datasets which can be used to improve the analysis and to further constrain the PDFs *(even though we are getting at the limit of what the current theory can do)*. Experimentally, with the increase of the statistics in Z sample, most of the experimental uncertainties can be reduced. Still challenging: the recoil resolution is worsened with the increased pileup.

- Low pileup data were taken in ATLAS at 5 (~250 pb^{-1} μ=0.5-4) and 13 TeV (~150 pb^{-1} μ=2) which will allow a measurement of the W transverse momentum at low p_T to 1% and to measure the W mass using m_T ATLAS-PUB-2017-021 with a statistical uncertainty of 13 MeV. More low pileup data to come probably shortly.

Beyond the LHC

- W mass measurement at the HL-LHC extremely challenging (μ=200) but might be possible if a low pileup run is foreseen to benefit from increase in the detector acceptance up to |η|=4.

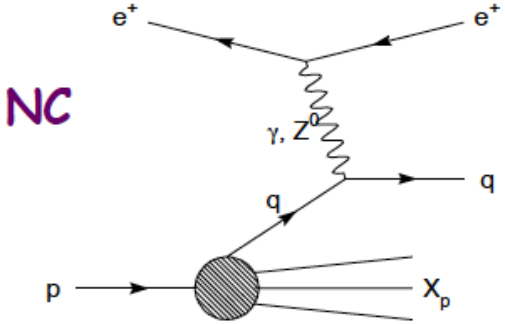
Bozzi, Citelli, Vicini
arXiv:1501.05587v2

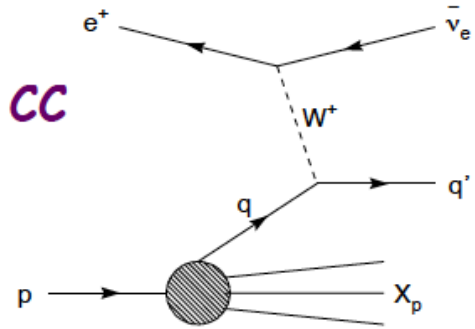


normalized distributions			
cut on $p_\perp^W$	cut on $\lvert\eta_l\rvert$	CT10	NNPDF3.0
inclusive	$\lvert\eta_l\rvert < 2.5$	$80.400 + 0.032 - 0.027$	80.398 ± 0.014
$p_\perp^W < 20$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.027 - 0.020$	80.394 ± 0.012
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.017 - 0.018$	80.395 ± 0.009
$p_\perp^W < 10$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.392 + 0.015 - 0.012$	80.394 ± 0.007
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 1.0$	$80.400 + 0.032 - 0.021$	80.406 ± 0.017
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 2.5$	$80.396 + 0.017 - 0.018$	80.395 ± 0.009
$p_\perp^W < 15$ GeV	$\lvert\eta_l\rvert < 4.9$	$80.400 + 0.009 - 0.004$	80.401 ± 0.003
$p_\perp^W < 15$ GeV	$1.0 < \lvert\eta_l\rvert < 2.5$	$80.392 + 0.025 - 0.018$	80.388 ± 0.012

Of course experimentally, the picture is more complicated, but still some gain (to be quantified soon) is expected

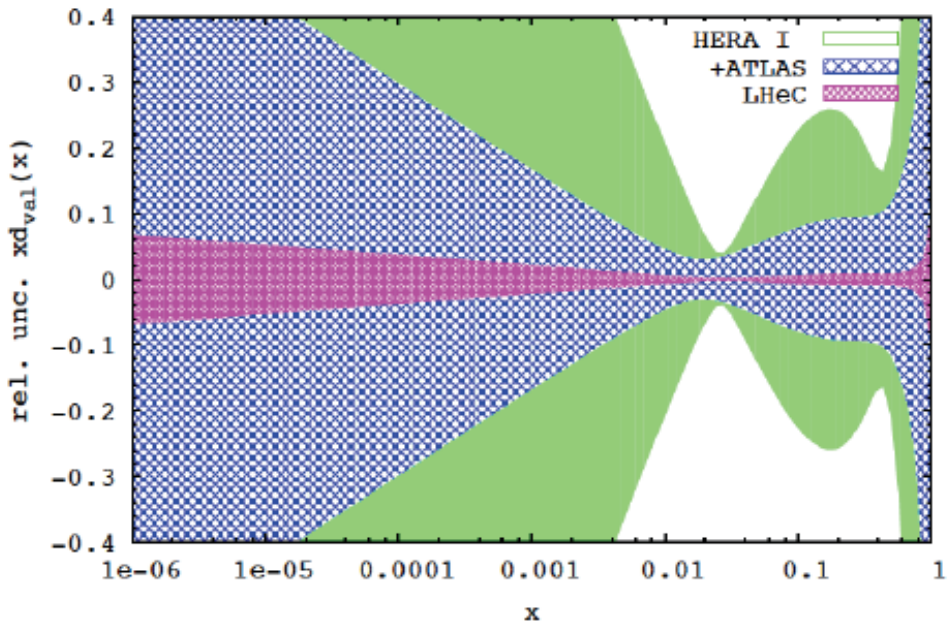
LHeC importance

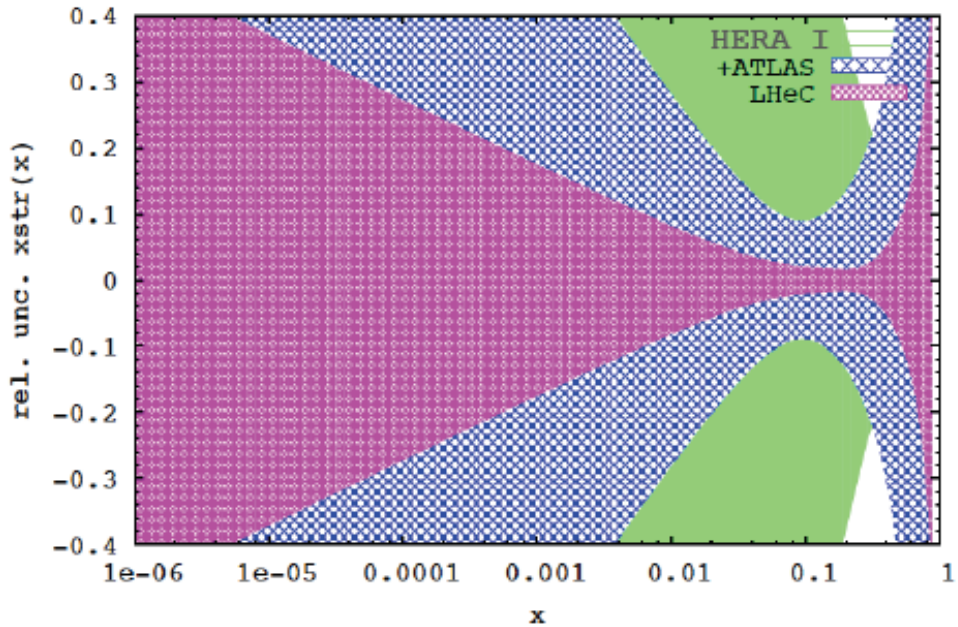




LHeC NC and CC measurements will improve PDF knowledge by large factor in a largely extended kinematic region.
LHeC CC DIS Ws—>c with charm tagging would provide good measurement of s and s^- quarks (and test u^-/d^-)

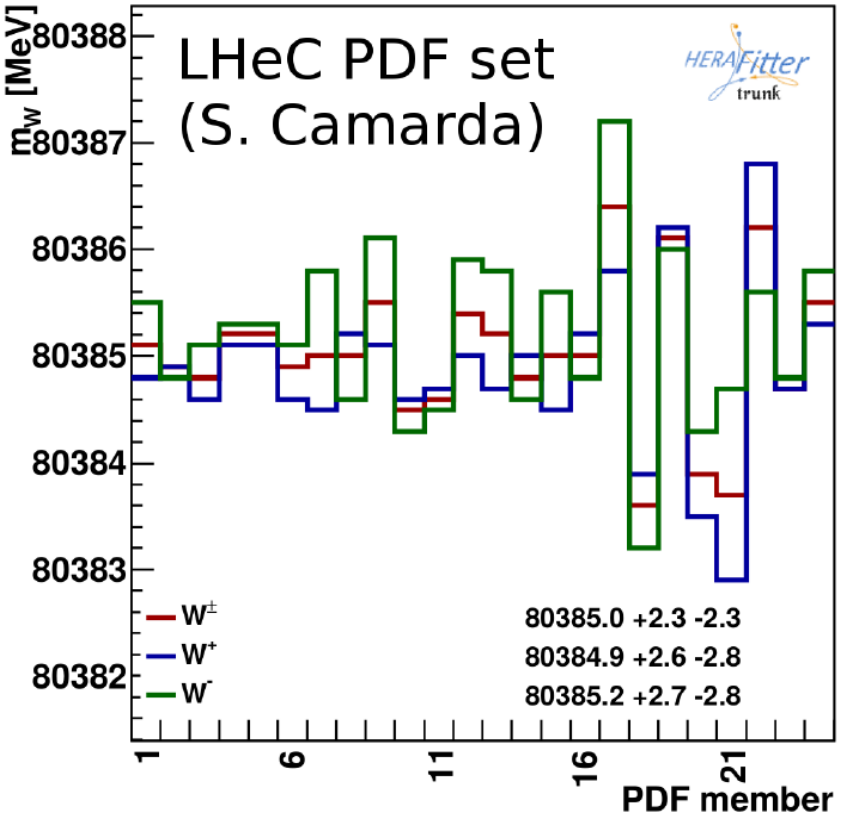
CERN-OPEN-2012-015
LHeC-Note-2012-002 GEN

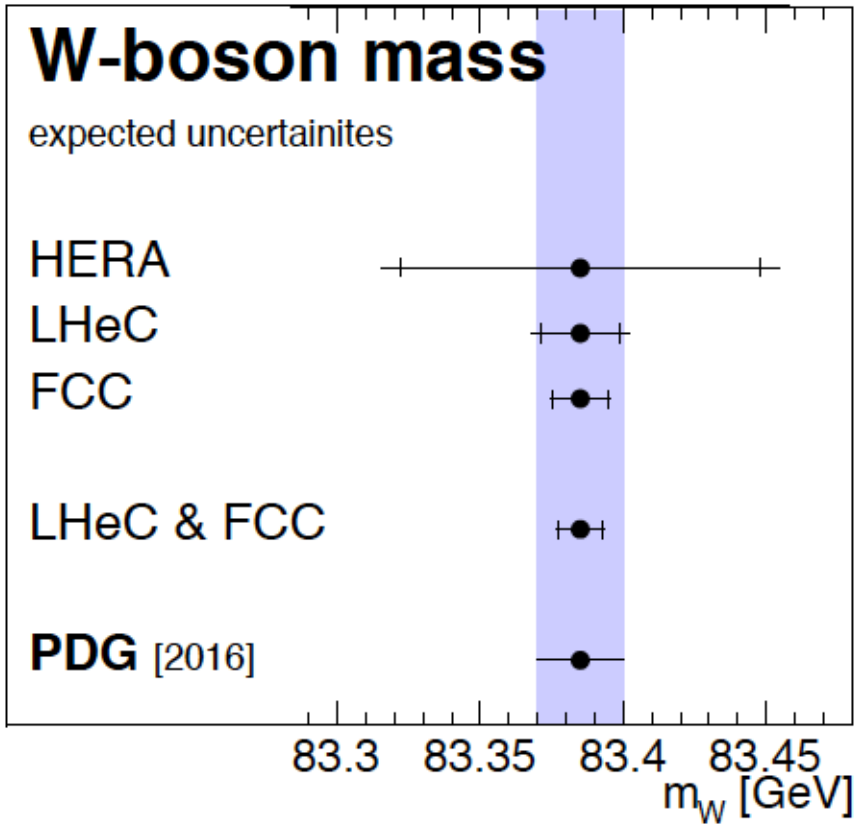




m_W with LHeC

Using PDF set from LHeC gives a ~3 MeV uncertainty on the W mass measurement (no categories used), very interesting input to LHC/HL-LHC m_W measurements





W mass can be fitted from PDF + EW parameter fits in the space-like regime using *ep* data providing a complementary testing ground.

Weak mixing angle

Weak mixing angle

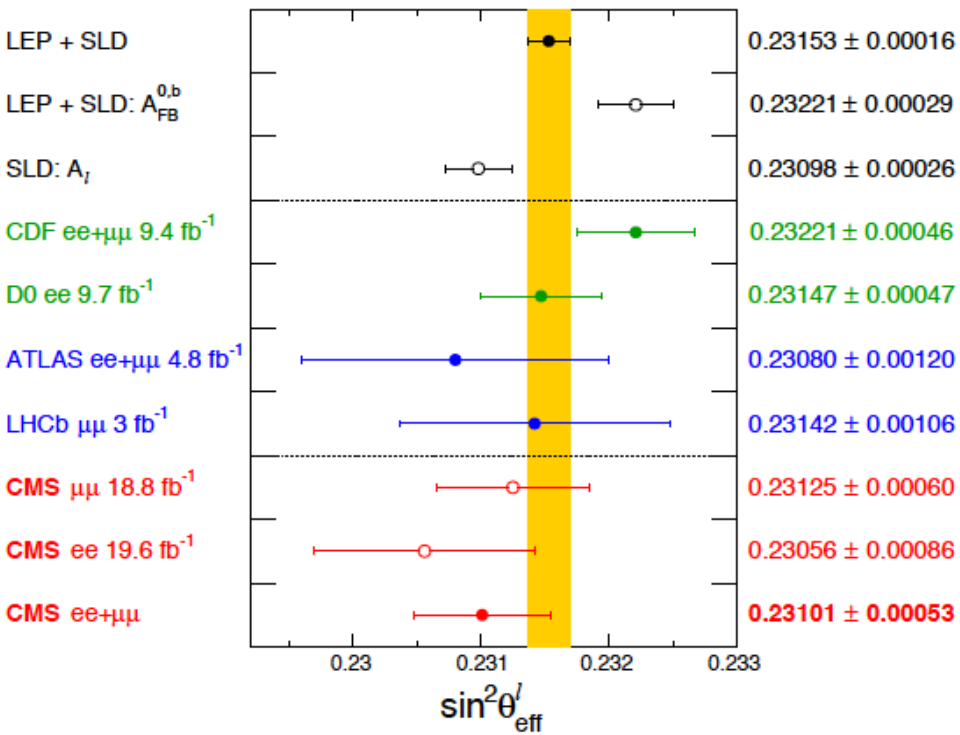
Another key parameter in EW sector of SM

At tree level: $\sin^2(\theta_W) = (1 - \frac{m_W^2}{m_Z^2})$

At higher orders, vertex corrections lead to the effective weak mixing angle:

$$\sin^2\left(\theta_{\text{eff.}}^{\text{lept.}}\right) = \kappa_f \sin^2(\theta_W)$$

arXiv:1806.00863v1



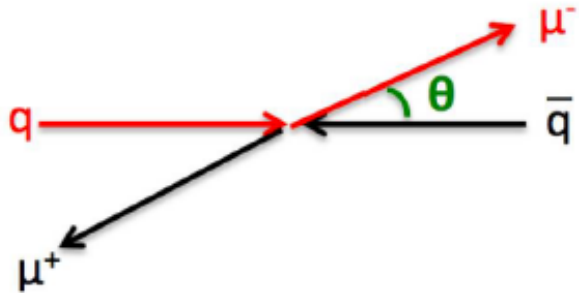
The two most precise measurements (LEP, SLD) disagree by about 3 sigmas

Provides also an indirect measurement of the W mass: $16*10^{-5}$ corresponds to a precision of 8 MeV on the W mass

Weak mixing angle: LHC

Presence of vector and axial-vector couplings introduces a forward-backward asymmetry.

$$A_{FB} = \frac{N(\cos\theta^*>0) - N(\cos\theta^*<0)}{N(\cos\theta^*>0) + N(\cos\theta^*<0)}$$



The AFB distributions are different for different flavour quarks and thus depend on PDFs

CMS result:

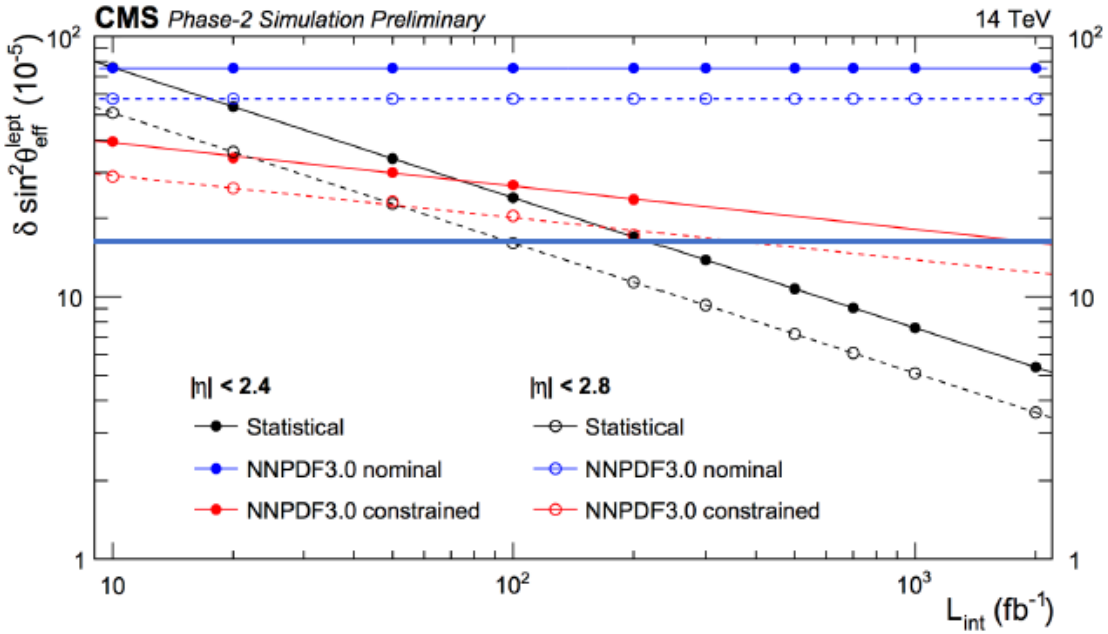
$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23101 \pm 0.00036\,(\text{stat}) \pm 0.00018\,(\text{syst}) \pm 0.00016\,(\text{theo}) \pm 0.00031\,(\text{PDF})$$

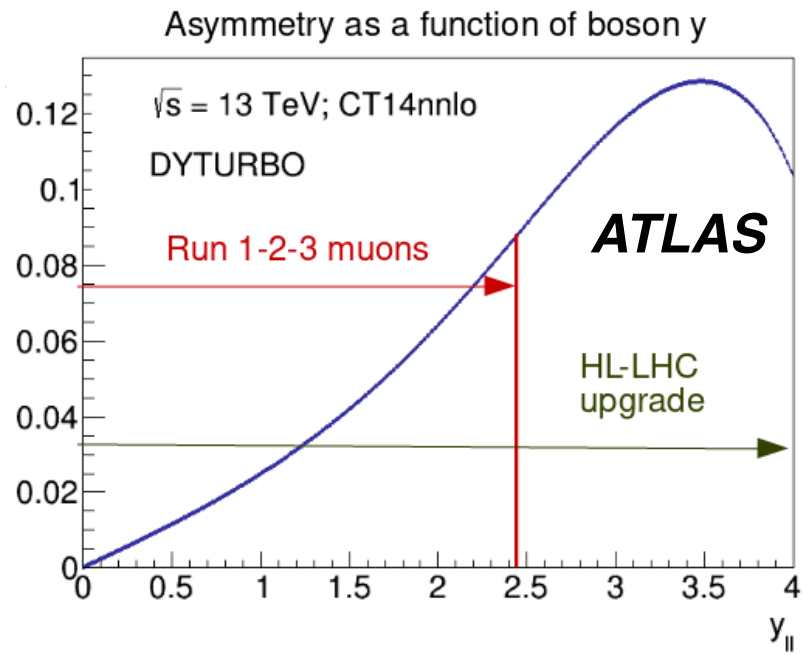
The dominant systematic uncertainty is due to PDF uncertainties

Weak mixing angle: HL-LHC

CMS, FTR-17-001-PAS

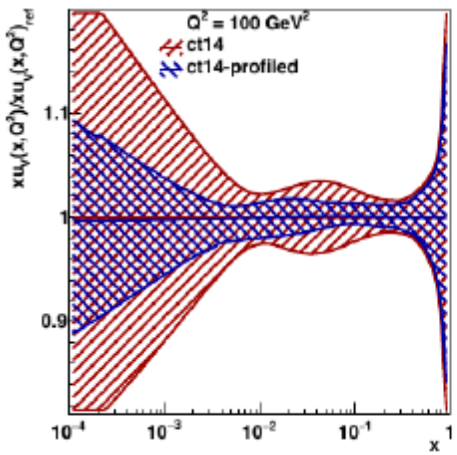
https://indico.cern.ch/event/702717/contributions/2897074/attachments/1611646/2559385/zafb_hllhc.pdf

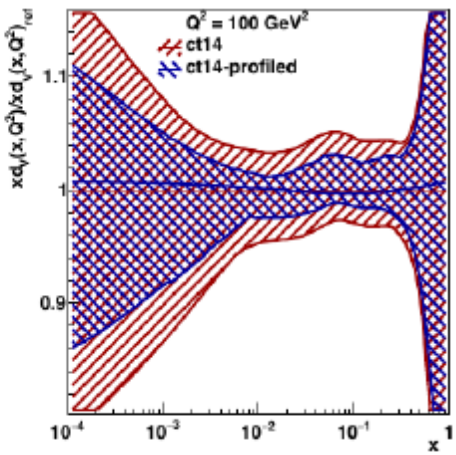




CMS: muon channel (CC and extended up to |η|<2.8) PDF constraints replicas

ATLAS: electron channel (CC, CF, FF up to |η| <4.2) PDF profiling —> estimates total uncertainty $19*10^{-5}$ dominated by PDF uncertainties $17*10^{-5}$





Using full HL-LHC program, reach similar precision than LEP+SLD (more gain combining experiments). We expect that using HL-LHC in-situ analysis like W asymmetry we can in principle to improve the PDF uncertainty by a ~factor 2.

Weak mixing angle: LHeC

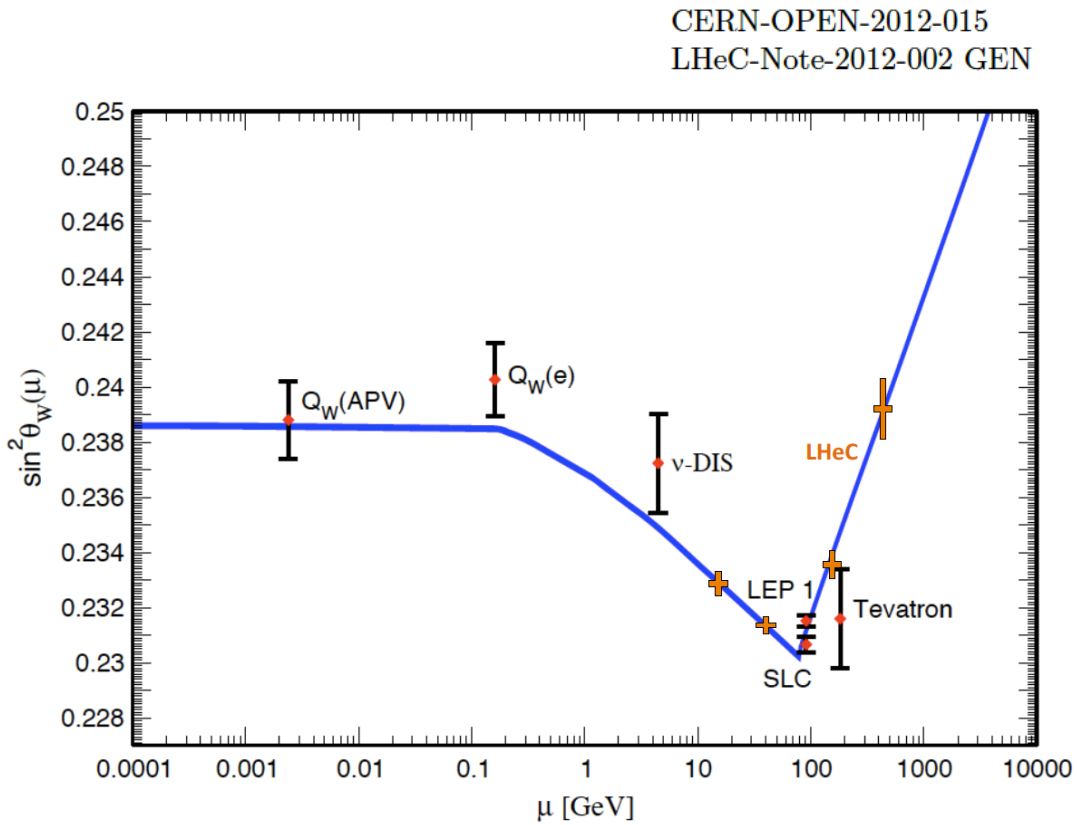
https://indico.cern.ch/event/702717/contributions/2897074/attachments/1611646/2559385/zafb_hllhc.pdf

Using LHeC prospect PDFs, the PDF uncertainties are expected to be reduced by a factor of ~10 and the total uncertainty by a factor of 5. If using HL-LHC prospect result expect: $4*10^{-5}$ —> more than a factor of 4 better than LEP + SLD combination.

High luminosity ep data may directly constrain the weak mixing angle through PDF+EW fits.

ep data can probe the scale dependence of the weak mixing angle using polarisation asymmetry.

The LHeC measurements are expected to be precise and to cover a large energy range.



Conclusions

Van Gogh *"Nuit étoilée sur le Rhône"*
Musée d'Orsay

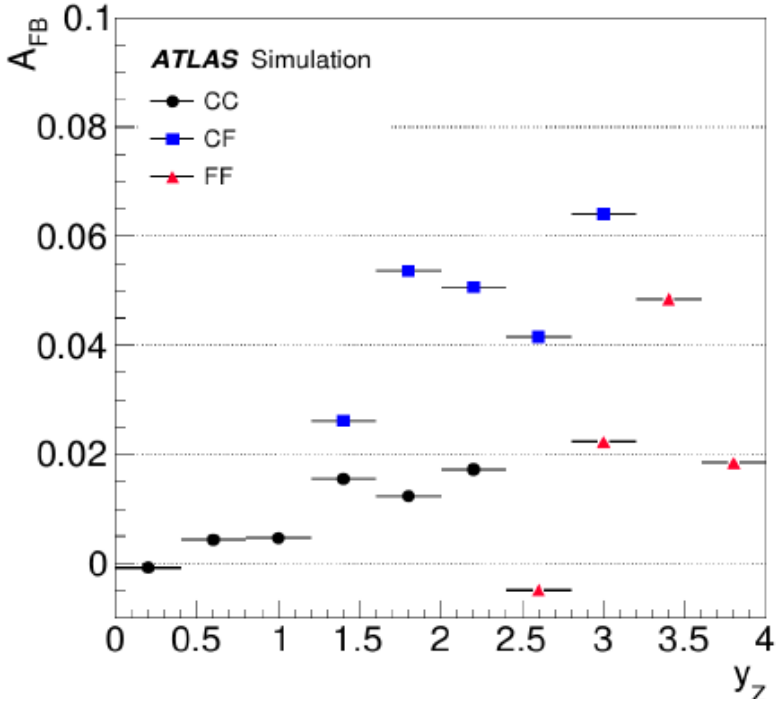
- The LHeC project provides an unprecedented precision in PDF for a large range of kinematics

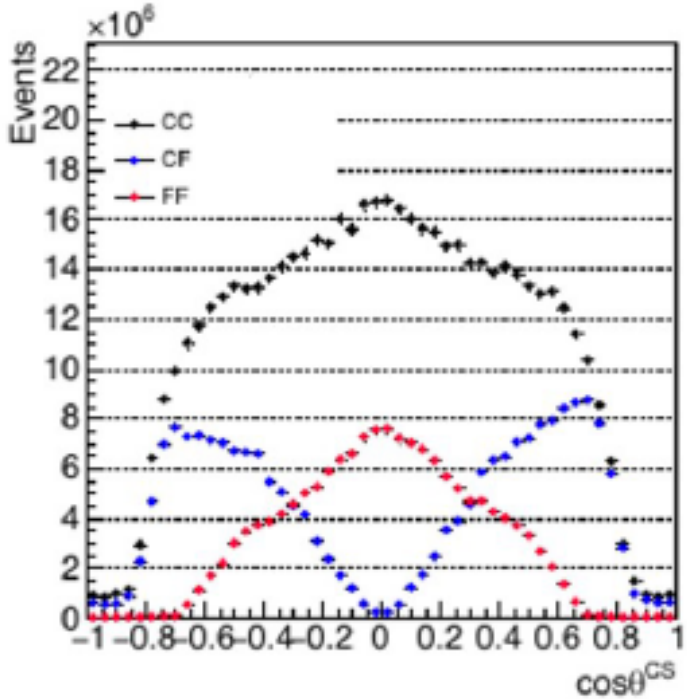
- The LHeC would provide a very important input to the LHC/HL-LHC results

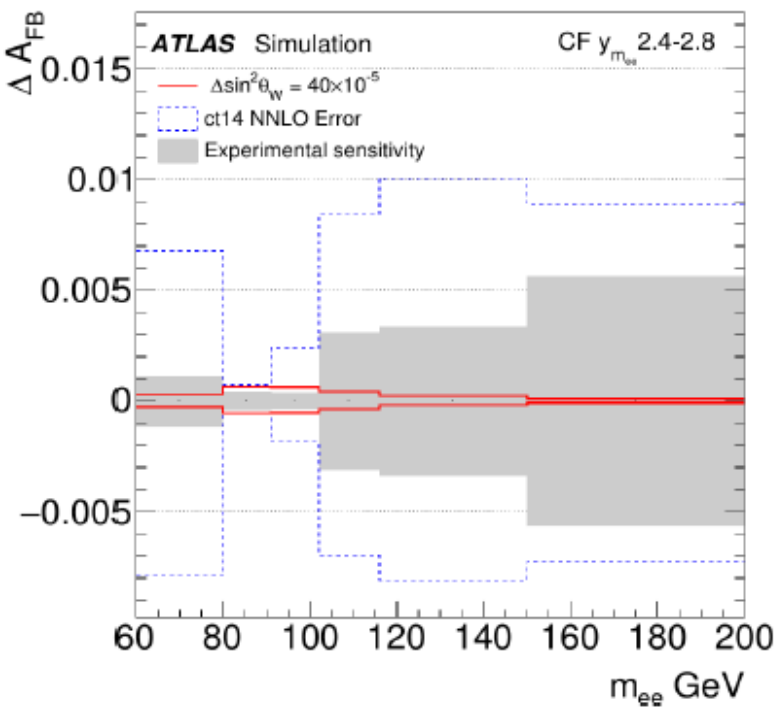
- In particular, EW precision measurements such as W-boson mass and weak mixing angle are limited by PDF uncertainties and would highly benefit from the LHeC improvements.

- The LHeC therefore is a rich and complementary program for the LHC/HL-LHC. It will for sure be essential to explore new physics.

Backup Slides



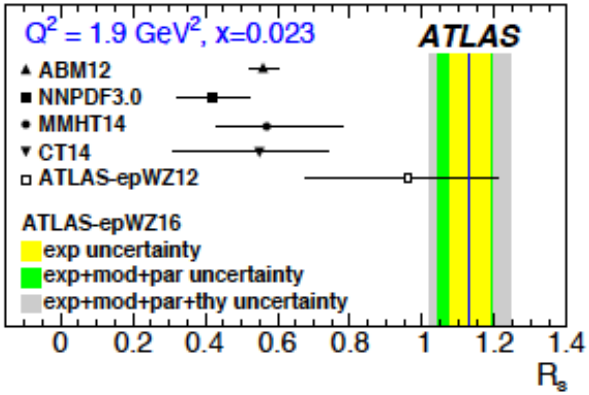




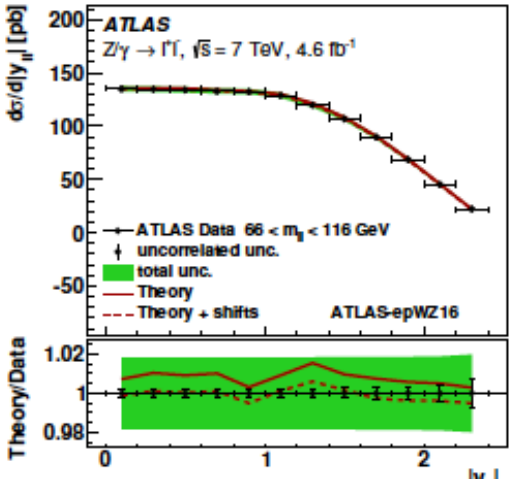
In ATLAS we consider 3 categories: CC, CF, FF, where C is a central ($|\eta| < 2.5$) and F is a forward ($2.5 < |\eta| < 4.2$) electron, with pT > 25 GeV

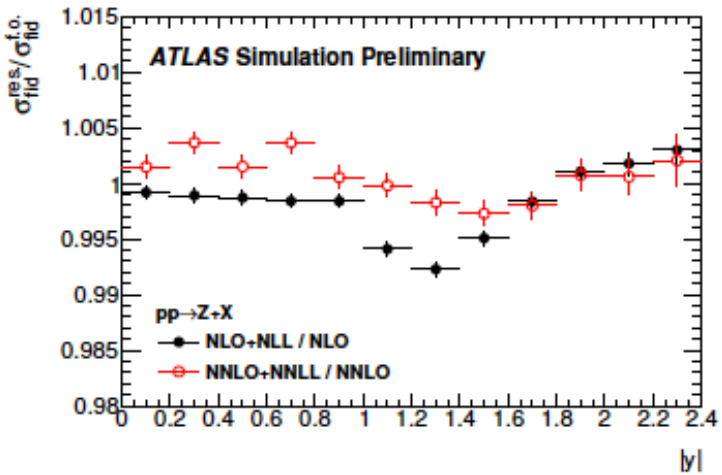
J.K.

- Precise differential W, Z data can constrain PDFs, especially the strange-quark density
- ATLAS-epWZ16 fit fixed-order NNLO QCD + NLO EW: theory uncertainty dominant



- Differences between predictions at fixed-order and with boson $p_{T,V}$ resummation $\sim 0.5\%$ effect similar to experimental precision — ensure predictions in PDF fits consistent with application to parton shower MCs to extract results

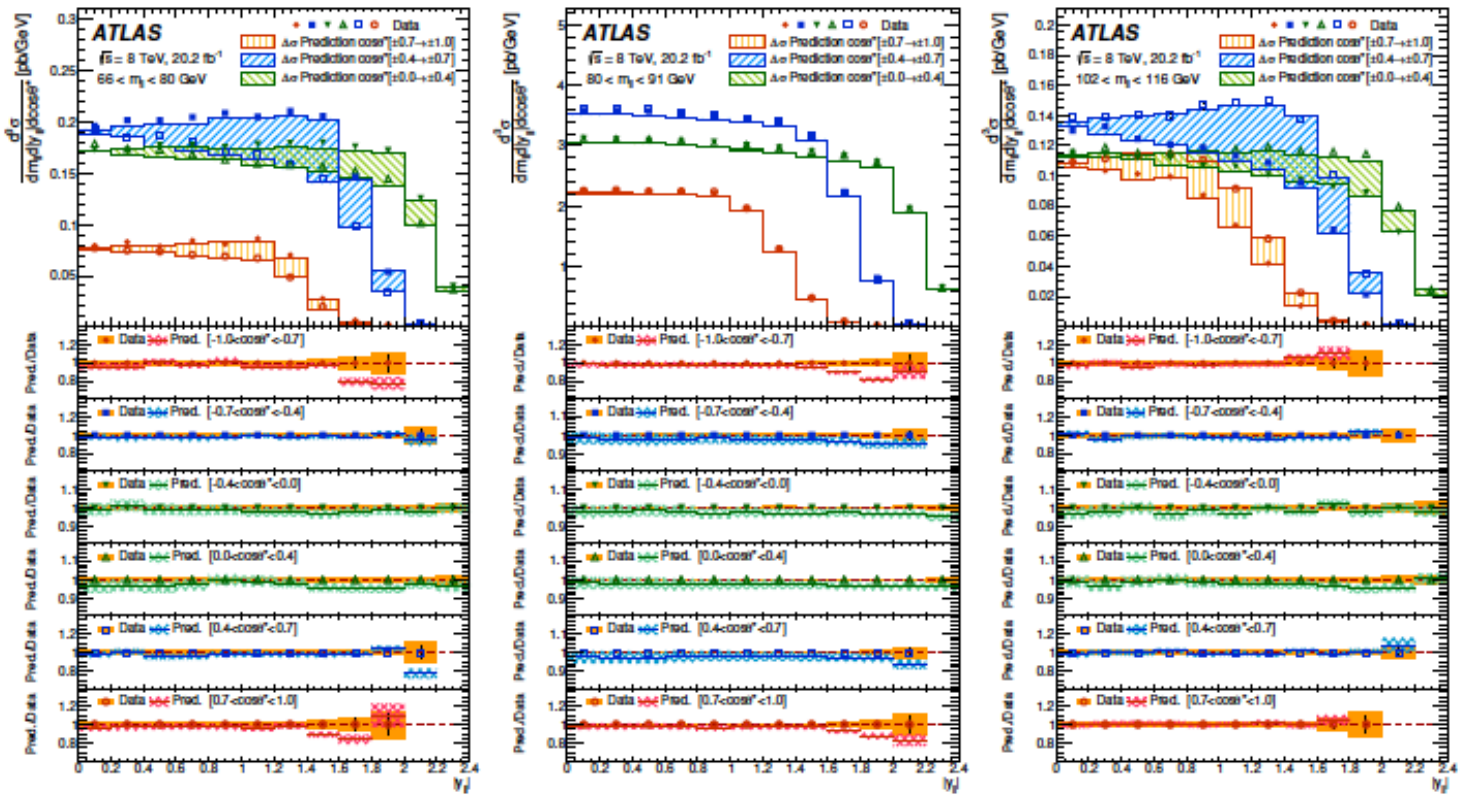




Multi-differential $Z/\gamma^* \to \ell\ell$

[JHEP 12 (2017) 059, CMS-PAS-SMP-16-007]

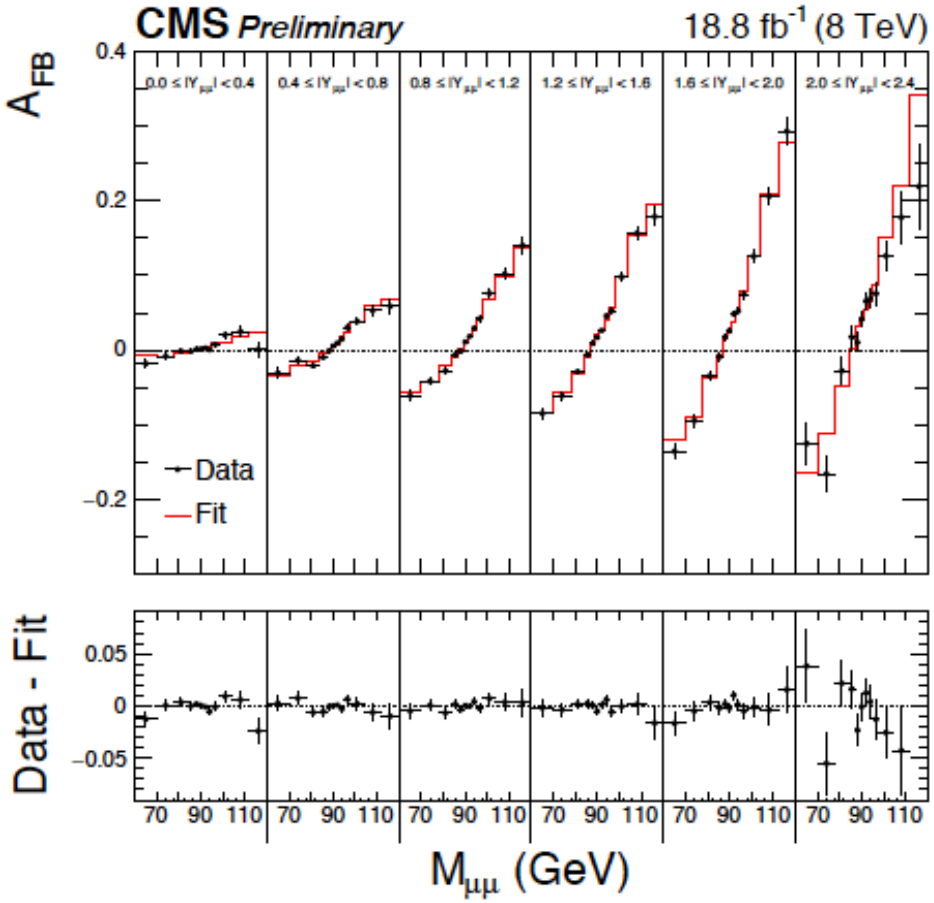
- Simultaneous measurement as function of dilepton mass $m_{\ell\ell}$ and rapidity $y_{\ell\ell}$ and $\cos\theta^*$ in Collins–Soper frame
- Sensitive to PDFs as well as $\sin^2\theta_W$ through forward-backward asymmetry A_{FB}



Multi-differential $Z/\gamma^* \to \ell\ell$

[JHEP 12 (2017) 059, CMS-PAS-SMP-16-007]

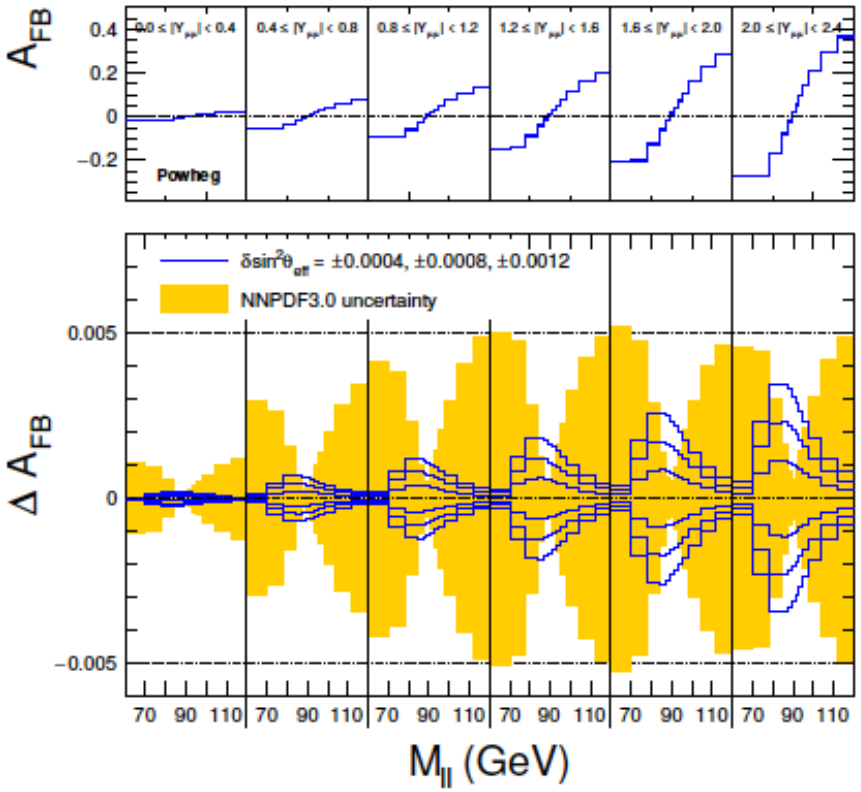
- Simultaneous measurement as function of dilepton mass $m_{\ell\ell}$ and rapidity $y_{\ell\ell}$ and $\cos\theta^*$ in Collins–Soper frame
- Sensitive to PDFs as well as $\sin^2\theta_W$ through forward-backward asymmetry A_{FB}

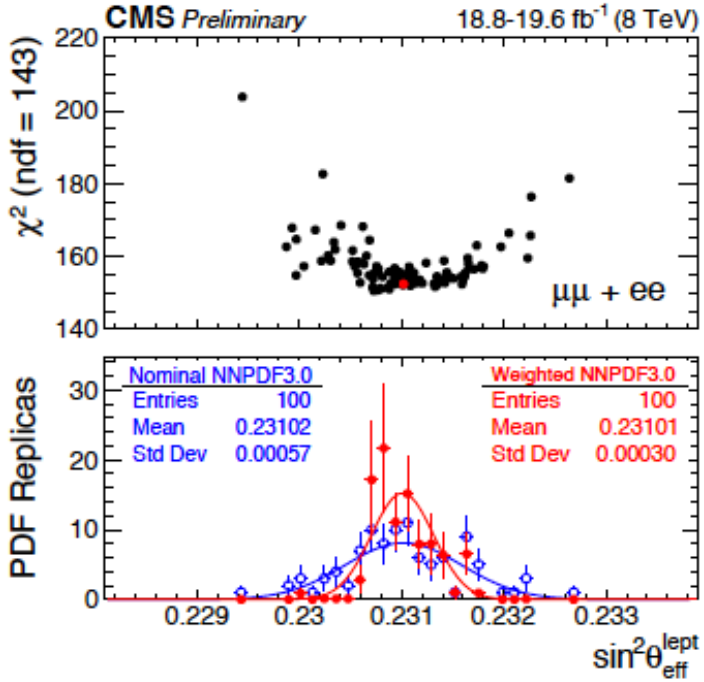


PDFs for $\sin^2\theta_W$

[CMS-PAS-SMP-16-007, CMS-PAS-FTR-17-001]

- Valence-quark shape determines the "dilution" of A_{FB} and is a significant uncertainty
- In-situ constraint using the $m_{\ell\ell}$–$y_{\ell\ell}$ dependence by factor ~ 2
- Differences between PDFs similar to NNPDF3.0 uncertainty





Final result: $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.23101 \pm 0.00036(\mathrm{stat}) \pm 0.00018(\mathrm{syst}) \pm 0.00016(\mathrm{theory}) \pm 0.00030(\mathrm{pdf})$