Precision m_W and and weak mixing angle measurements with HL-LHC and Impact of LH(e)C PDFs

Ref.

Prospect for the Measurement of the W boson mass (ATL-PHYS-PUB-2018-026)

Prospect for the Measurement of the weak mixing angle (CMS-FTR-17-001)

Prospect for the Measurement of the weak mixing angle in $Z/\gamma^* \rightarrow e^+e^-$ (ATL-PHYS-PUB-2018-037)

HL-LHC Yellow Report :

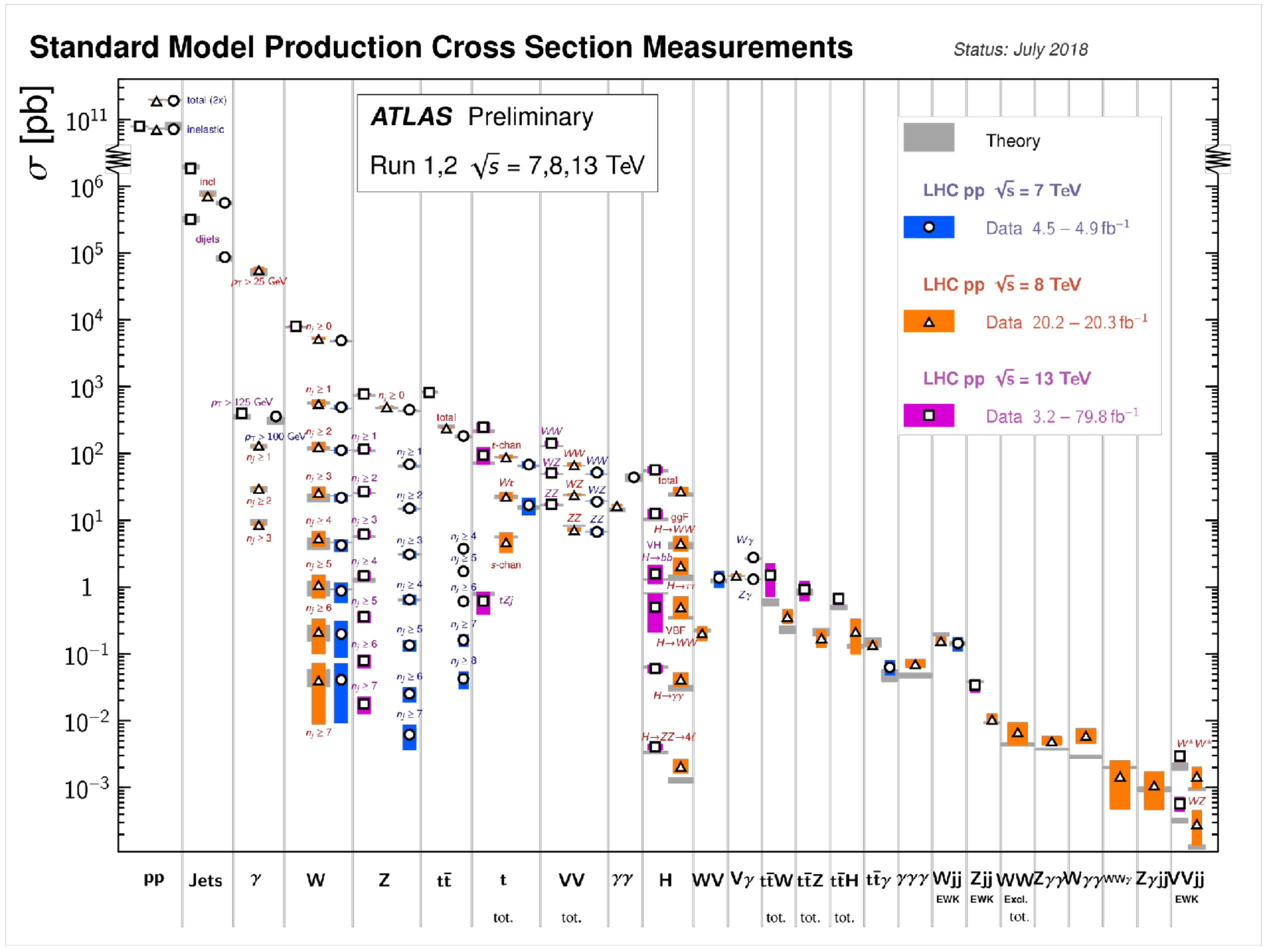
The physics potential of HL-LHC

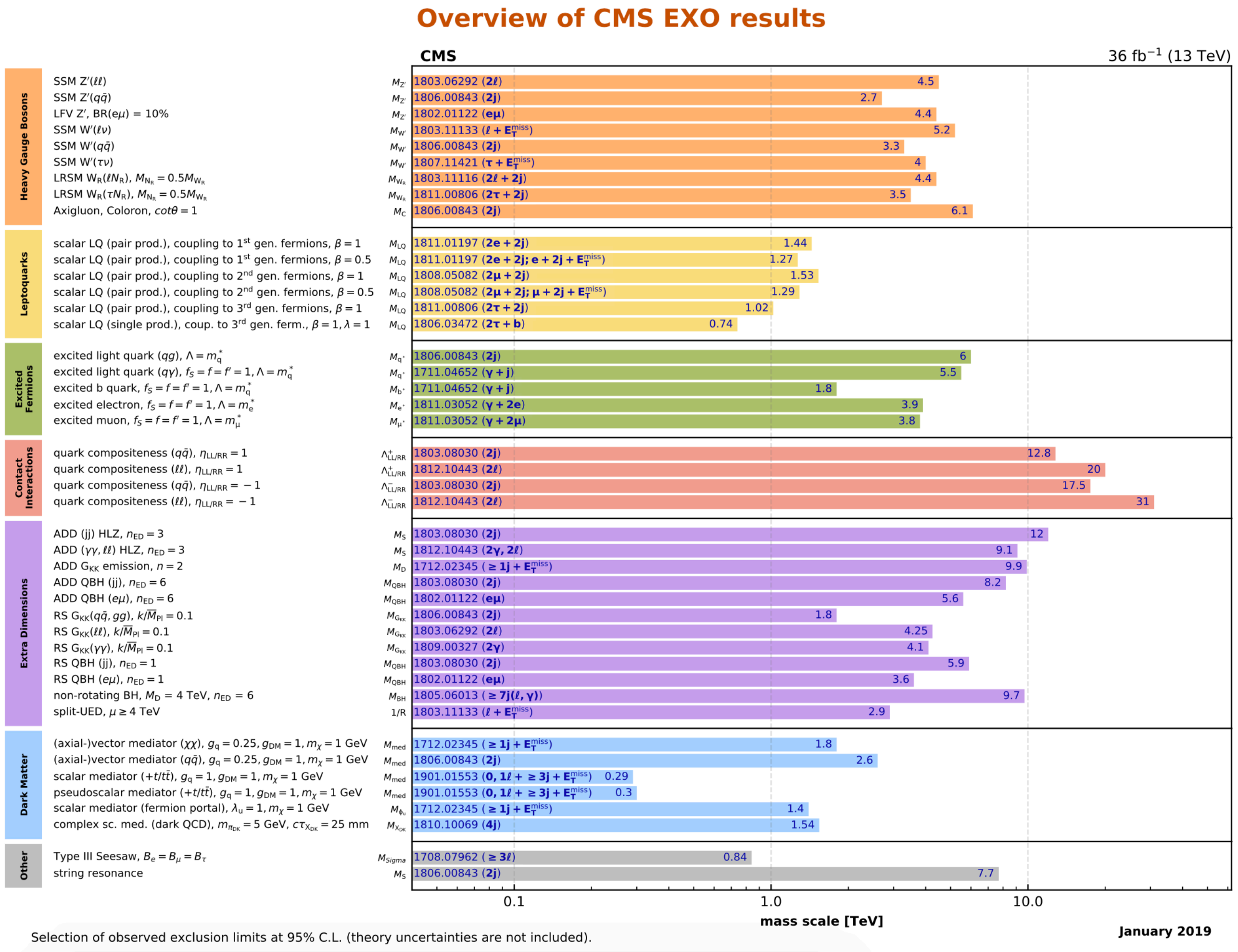
Collection of notes from ATLAS and CMS

Standard Model Physics at the HL-LHC and HE-LHC

Ludovica Aperio Bella

The duality of LHC physics program results

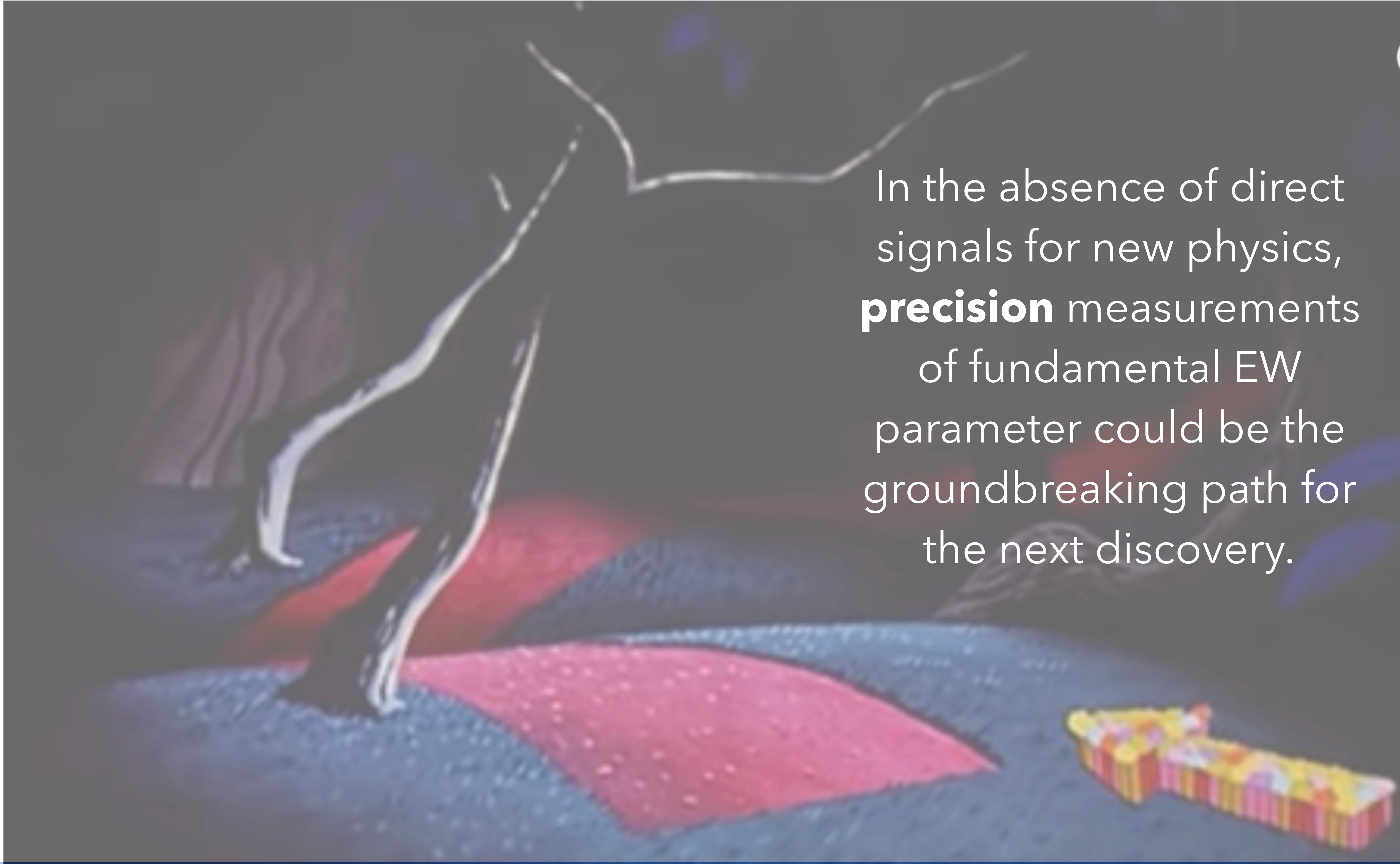




incredible validity range of SM

No direct sign of new physics

Precision physics

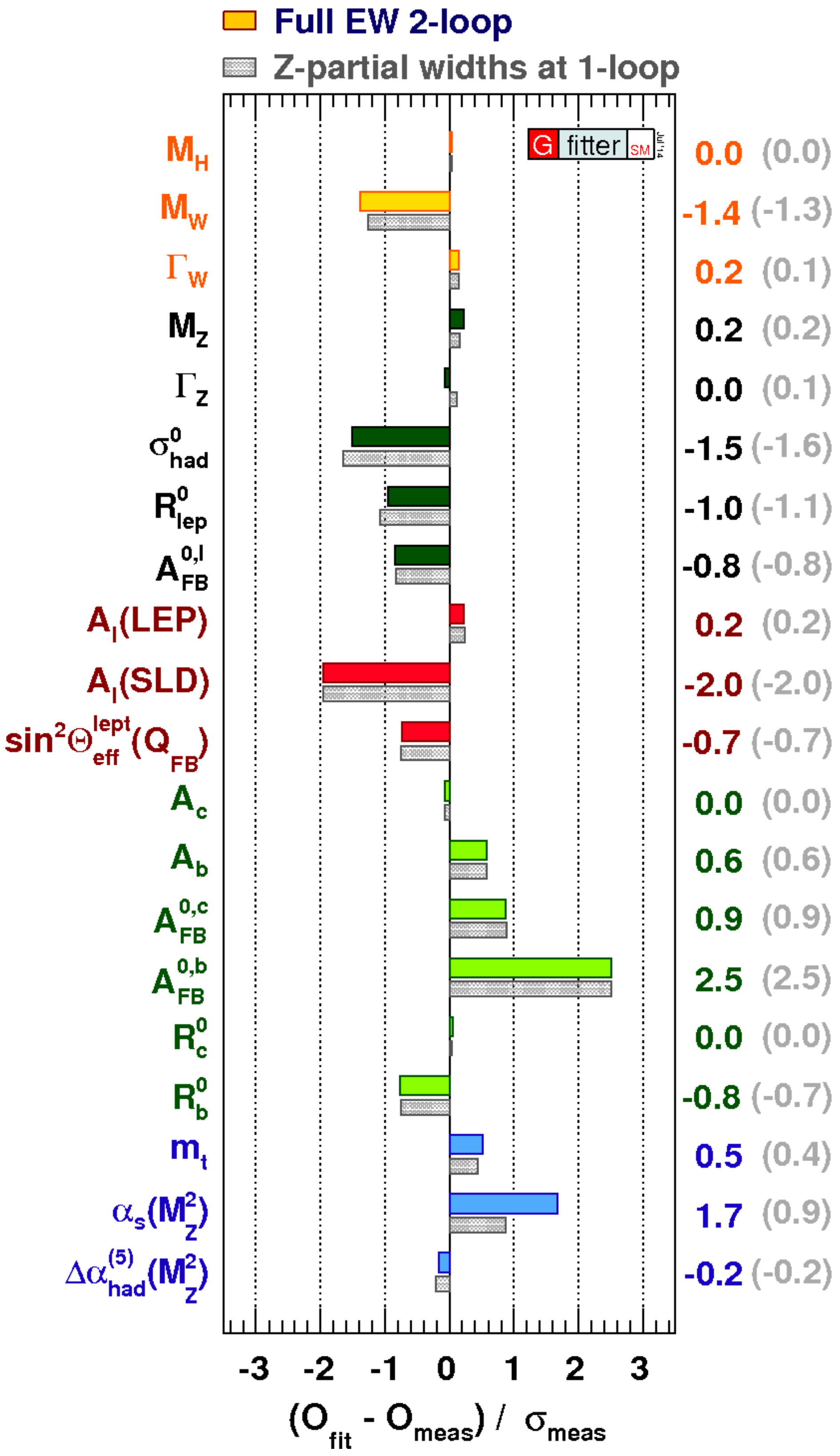


In the absence of direct signals for new physics, **precision** measurements of fundamental EW parameter could be the groundbreaking path for the next discovery.

How to test SM?

- In the recent past, the global electroweak fit was able to predict the masses of the top quark and Higgs boson before their discovery
- Relations between electroweak observables can be predicted now at 2-loop level
- Precise measurements of the electroweak parameters allow stringent test of the self consistency of the SM $\Longrightarrow$ Looking for hints of physics beyond the SM.

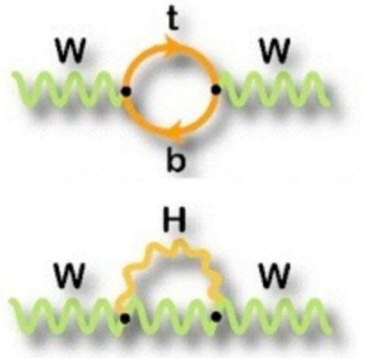
Indirect searches: *look for deviations from SM predictions* due to quantum loop effects of new virtual particles



The EW sector

The electroweak gauge sector of the Standard Model is constrained by three precisely measured parameters

$$\begin{aligned} \alpha &= 1/137.035999139(31) \\ G_F &= 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2} \\ m_Z &= 91.1876(21)\ \mathrm{GeV} \end{aligned}$$



At tree level, other EW parameters can be expressed as

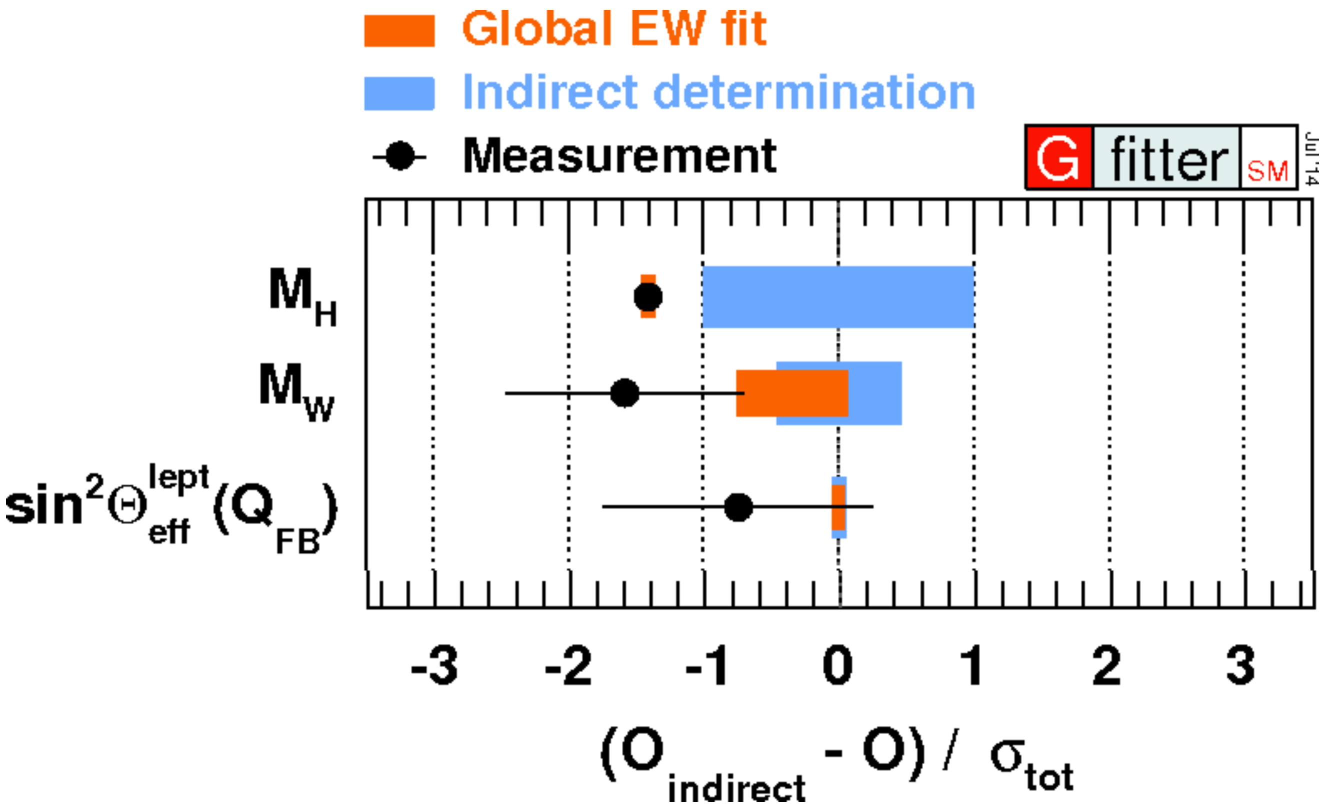
$$\left\{ \begin{aligned} m_W^2 &= \frac{\pi\alpha}{\sqrt{2} G_F \left(1 - m_W^2/m_Z^2\right) (1 - \Delta r)} \\ \sin^2_{\mathrm{eff}} \theta_W &= \left(1 - \frac{m_W^2}{m_Z^2}\right) \kappa \\ \Gamma_W &= \frac{3 G_F m_W^3}{2\sqrt{2}\pi} \rho \end{aligned} \right.$$

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

Higher order corrections modify these relations, and determine sensitivity to other particle masses and couplings

κ are EW loop corrections

key parameter of SM



Indirect determination of both m_W and $\sin^2\theta^{eff}$ more precise then the experimental measurement:

- This call for a precise direct Measurement

✓ Stringent test of the self consistency of the SM

  ✓ but extreme precision needed

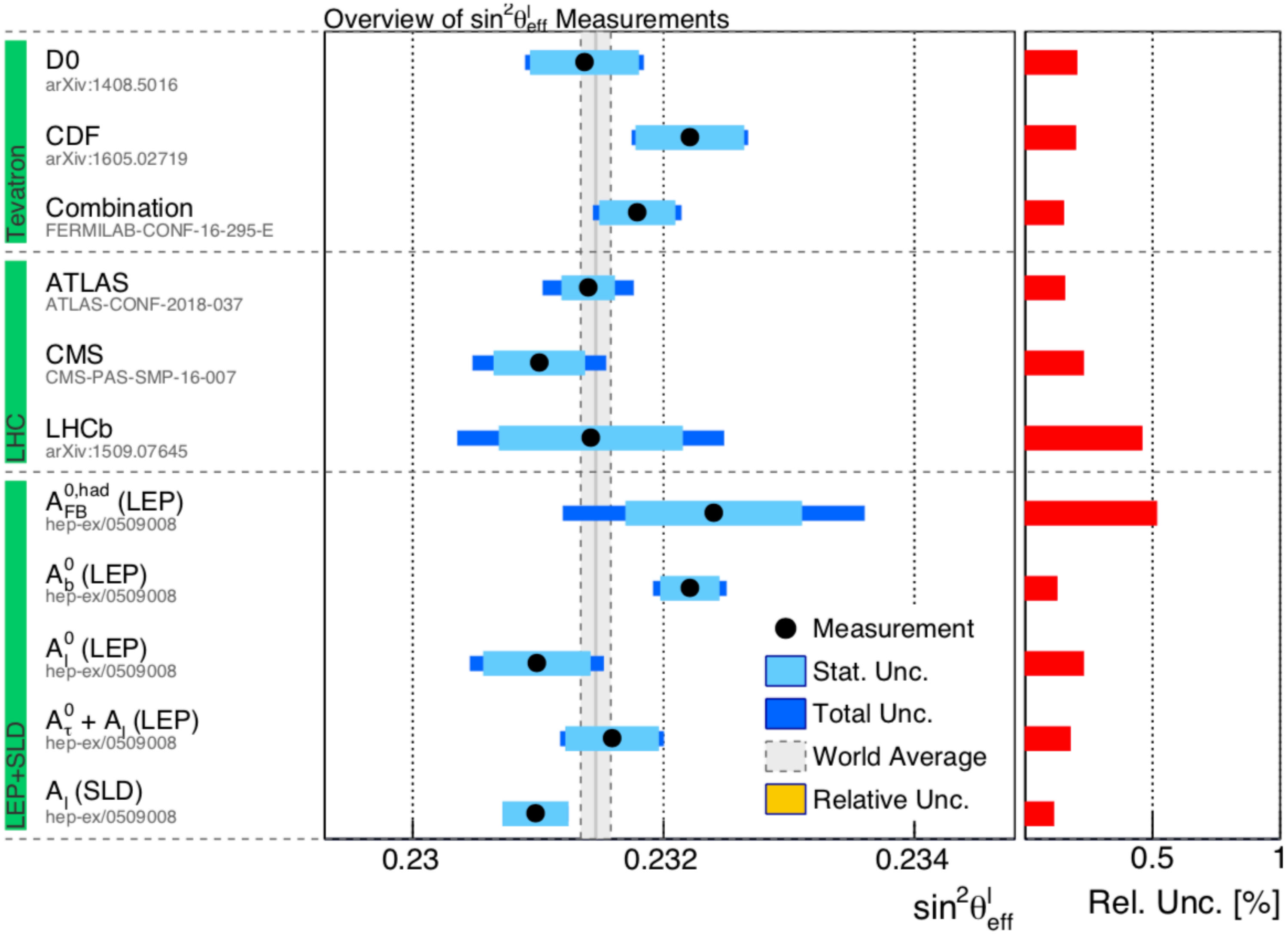
precision of indirect determination of m_W ±8 MeV → Call for $\delta m_W^{exp} < 10$ MeV

precision of indirect Determination of $\sin^2\theta_{eff} \pm 6\times10^{-5}$ → $\pm 20\times10^{-5}$ error in $\sin^2\theta^{eff}$ corresponds to ±10MeV error in m_W

LHC (or HL-LHC) is able to reach this level of precision ?

Weak Mixing Angle

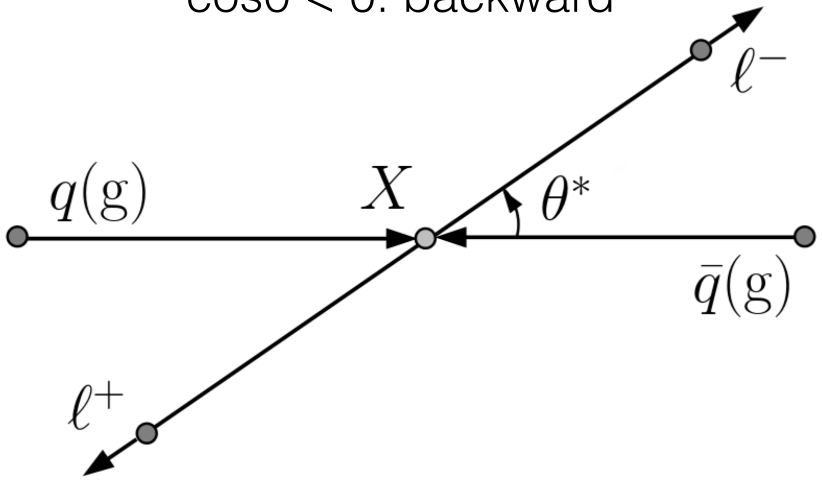
- Discrepancy of LEP and SLD measurement on $\sin^2\theta_W$ triggered quite some interest in recent years
- Problem at Hadron colliders: Do not know incoming fermion direction on an event-by-event basis
- to extract $\sin^2\theta_{eff}$ exploit forward-backward asymmetry **(A_{FB}) of DY process**



Indirect Determination:	$\sin^2\theta_{eff} = 0.23151 \pm 0.00006$
World average:	$\sin^2\theta_{eff} = 0.23151 \pm 0.00014$
Combination at hadron colliders:	$\sin^2\theta_{eff} = 0.23140 \pm 0.00023$

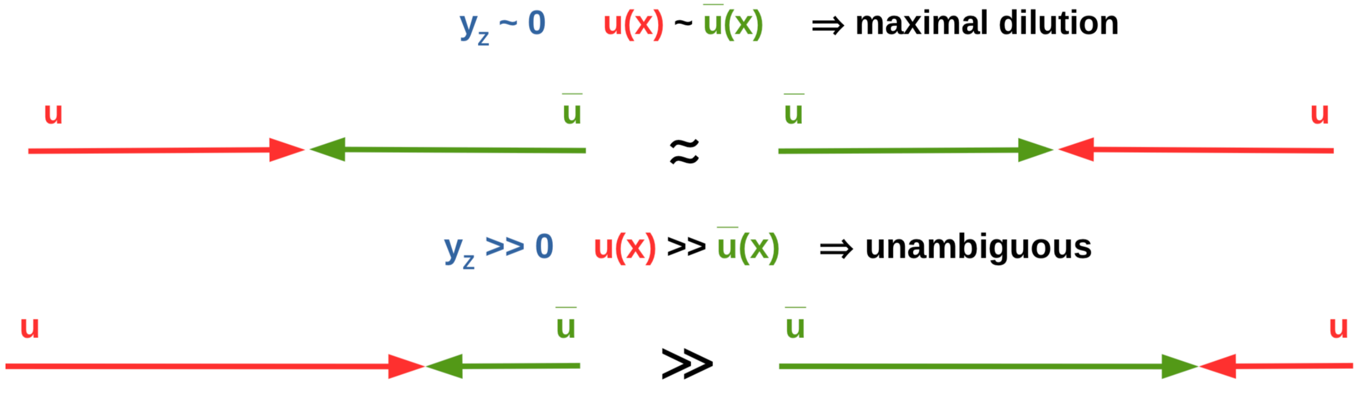
Z forward-backward asymmetry@LHC

cosθ > 0: forward
cosθ < 0: backward



$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8}\frac{B}{A}$$

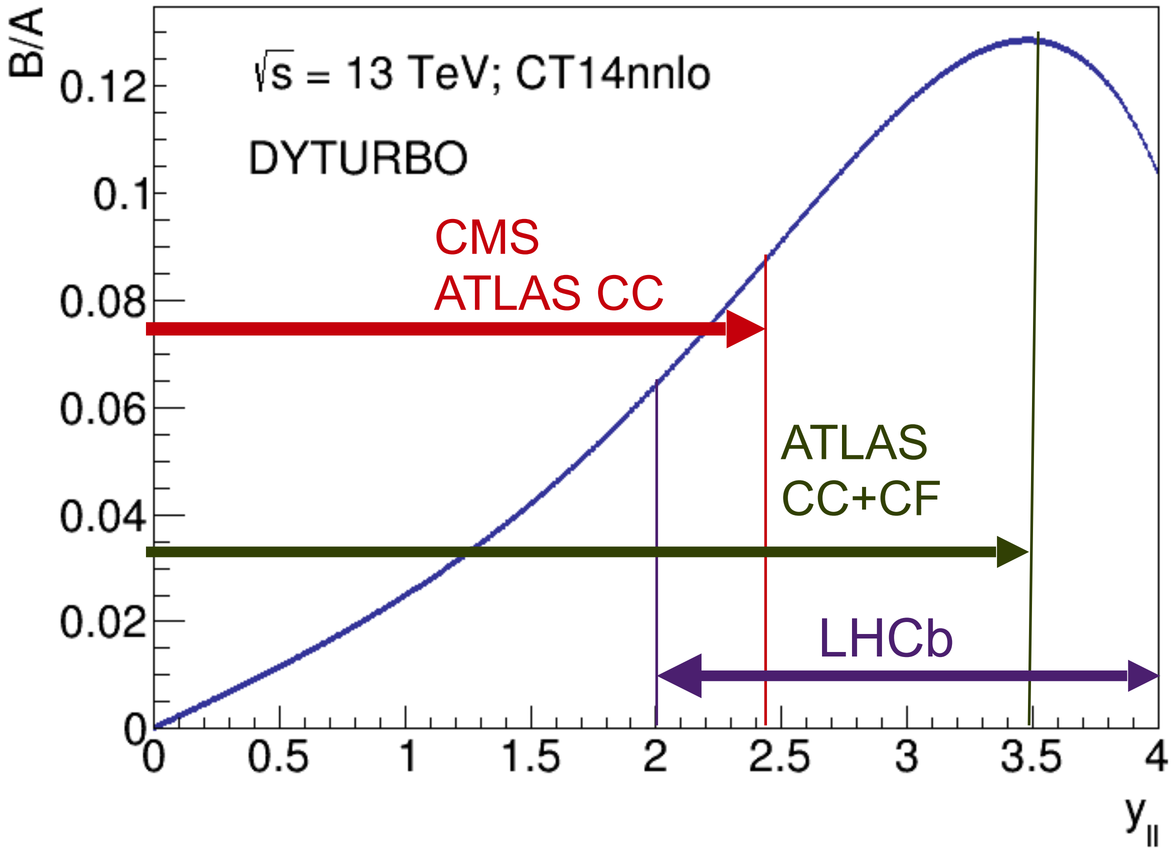
- The orientation of the incoming quark is unknown
  - Use θ* scattering angle defined in the Collins-Soper frame, with z-axis orientation defined by the Z rapidity
- In pp collisions, it is more likely to be in the same orientation as the Z boson, due to the u/ubar and d/dbar valence asymmetry



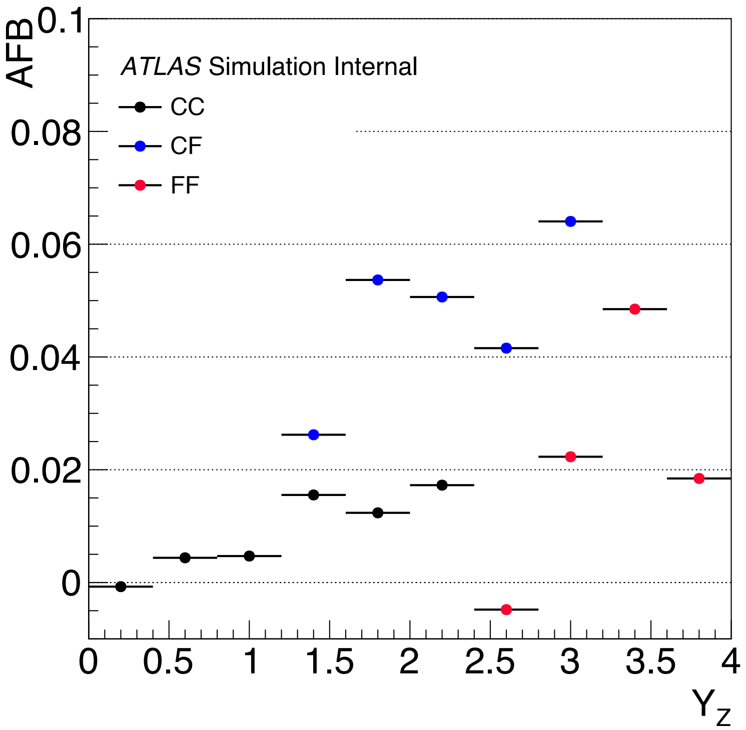
$y_z \sim 0$ $u(x) \sim \bar{u}(x)$ ⇒ **maximal dilution**

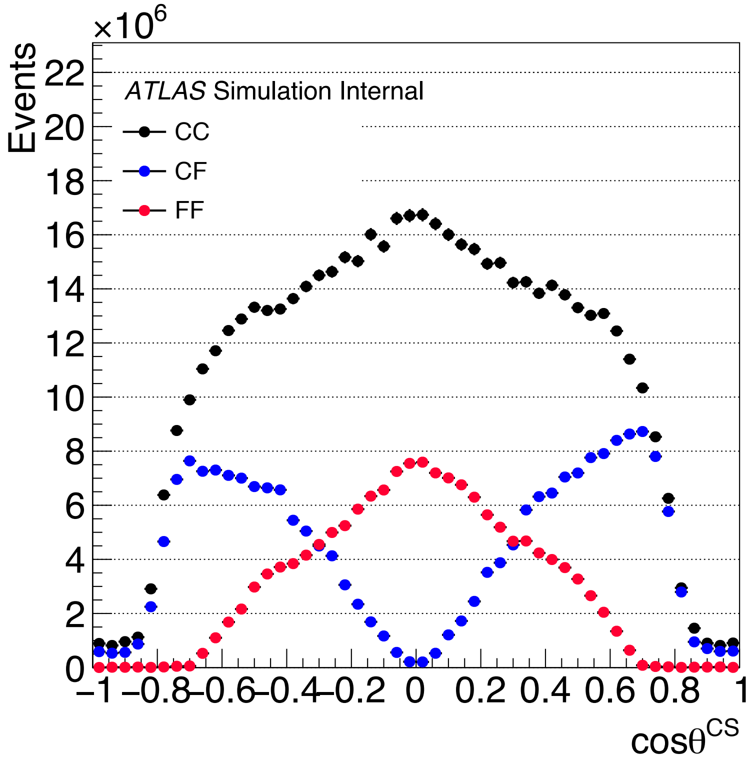
$y_z >> 0$ $u(x) >> \bar{u}(x)$ ⇒ **unambiguous**

Asymmetry as a function of boson y



Projection for Upgraded detector

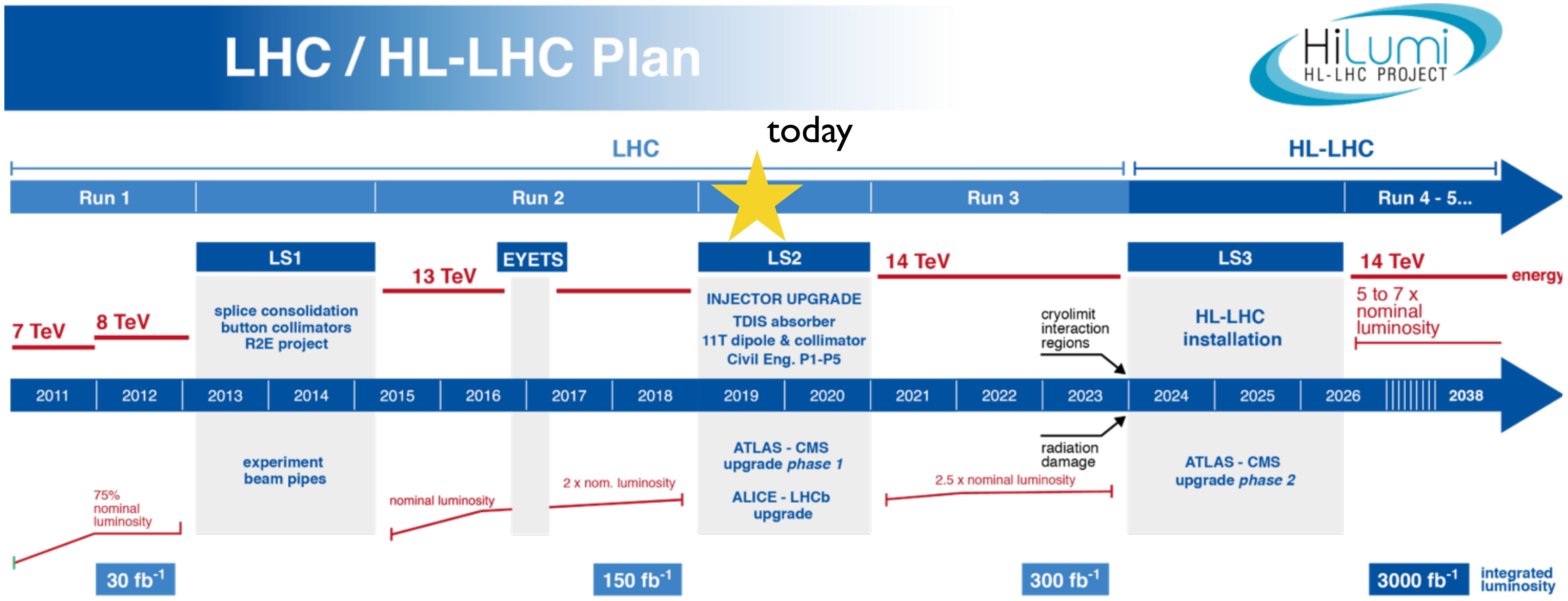


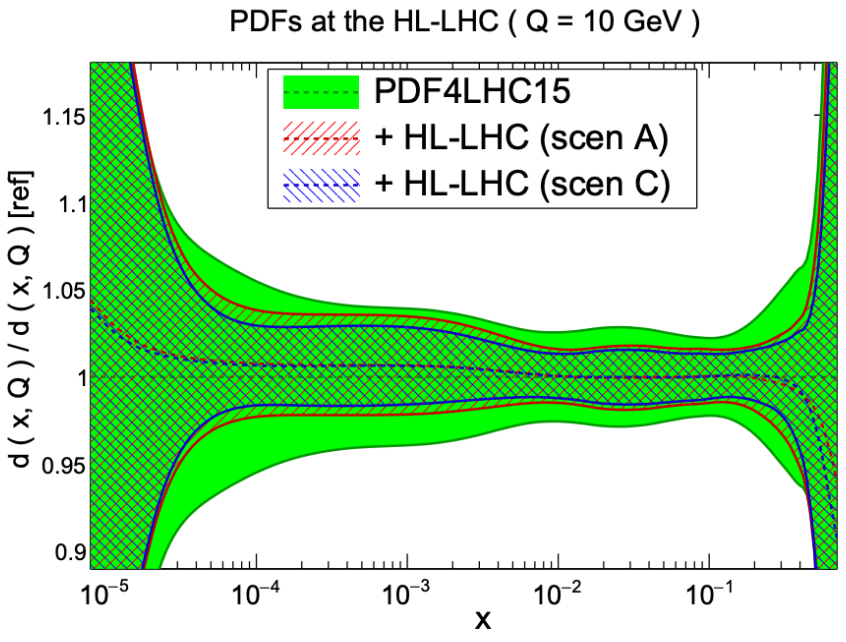


HLLHC scenario:

- infinite statistic
- benefit form extended trading coverage up to |η| < 4
- ancillary measurement to reduce current knowledge of PDF uncertainty

Projection for Upgraded detector



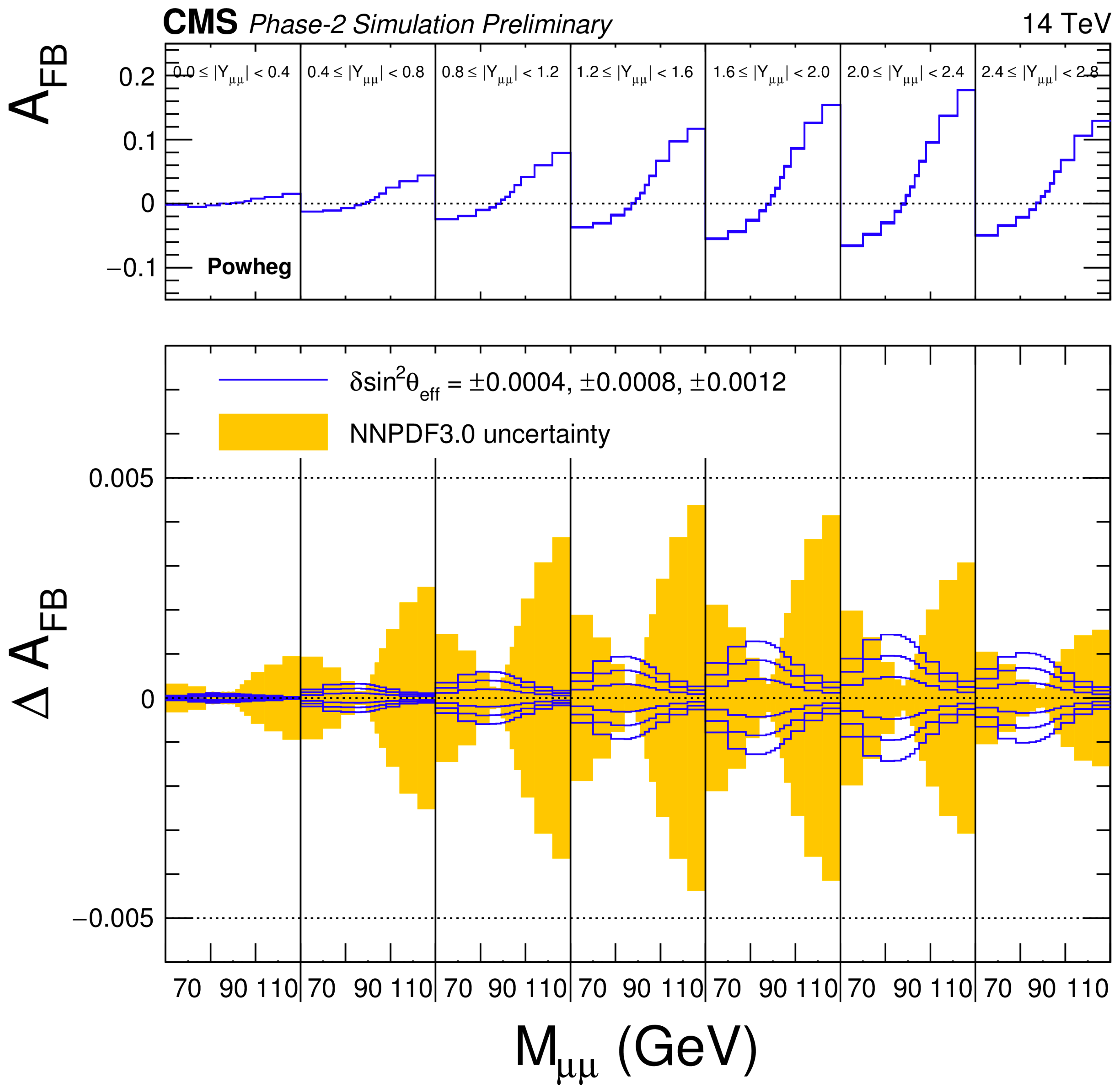


In the context of the Yellow Report for the HL-LHC: rospect PDF fits including HL-LHC pseudo-data of future PDF-sensitive measurements from ATLAS, CMS and LHCb were performed (compared with PDF4LHC15)

HLLHC scenario:

- infinite statistic
- benefit form extended trading coverage up to |η| < 4
- ancillary measurement to reduce current knowledge of PDF uncertainty

weak mixing angle @LHC

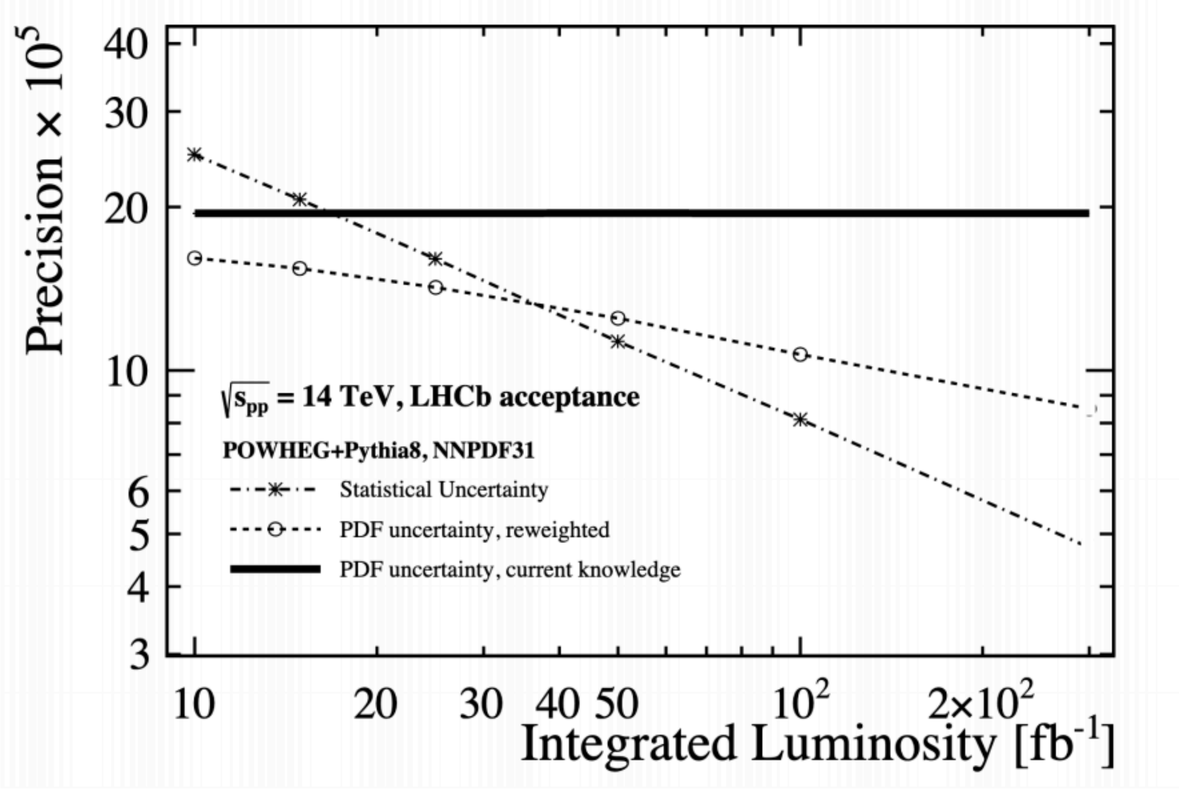


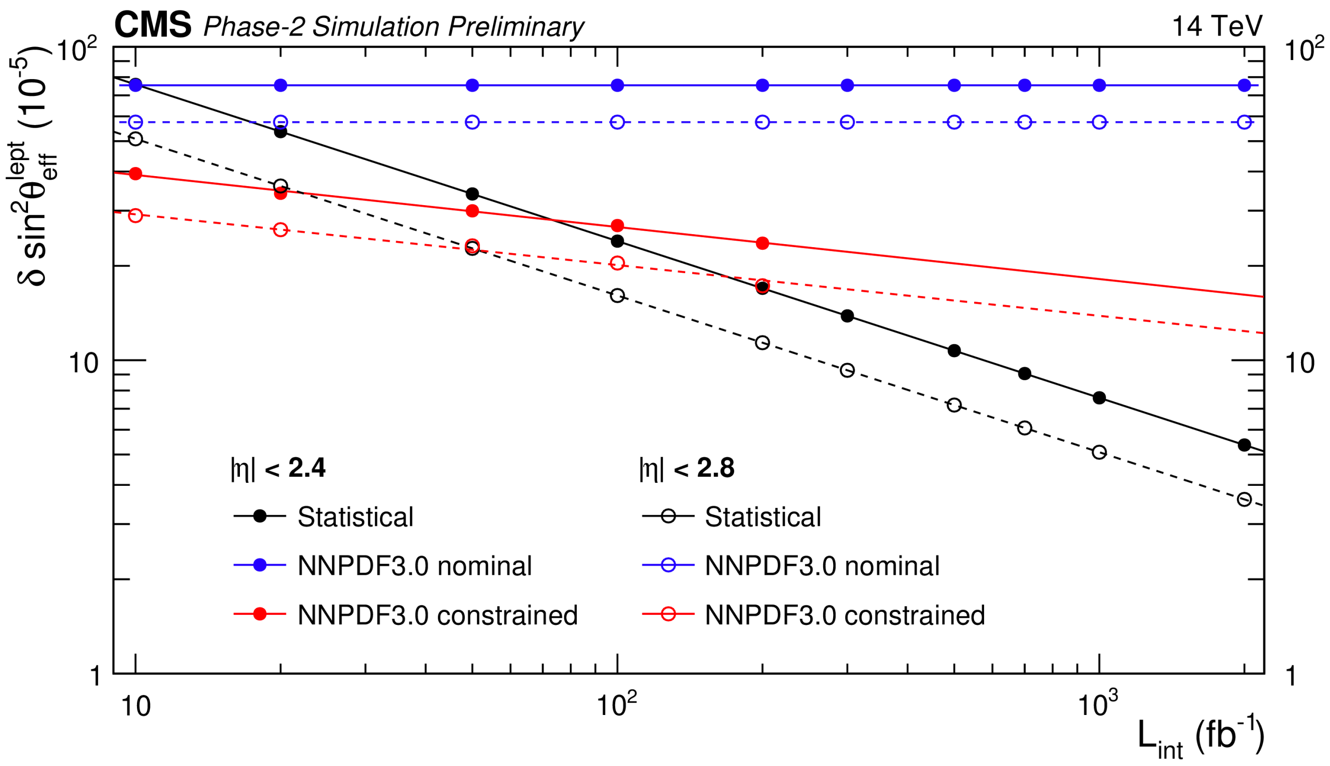
AFB strongly depend on PDF uncertainty ⇒ dominant systematic for the extraction of $\sin^2\theta_{eff}$

- different couplings of u- and d-type quarks
- yll direction depends on the relative content of valence and sea quarks

- The expected sensitivity to particle level A_{FB} as a function of m_{ll}
- PDF band correspond to PDF uncertainty without inset constraint.
  - The imperfect knowledge of the PDF results in sizeable uncertainties in A_{FB}, in particular in regions where the absolute value of the asymmetry is large, i.e. at high and low m_{ll}. On the contrary, near the Z boson mass peak, the effect of varying $\sin^2\theta_{eff}$ is maximal, while being significantly smaller at high and low masses.

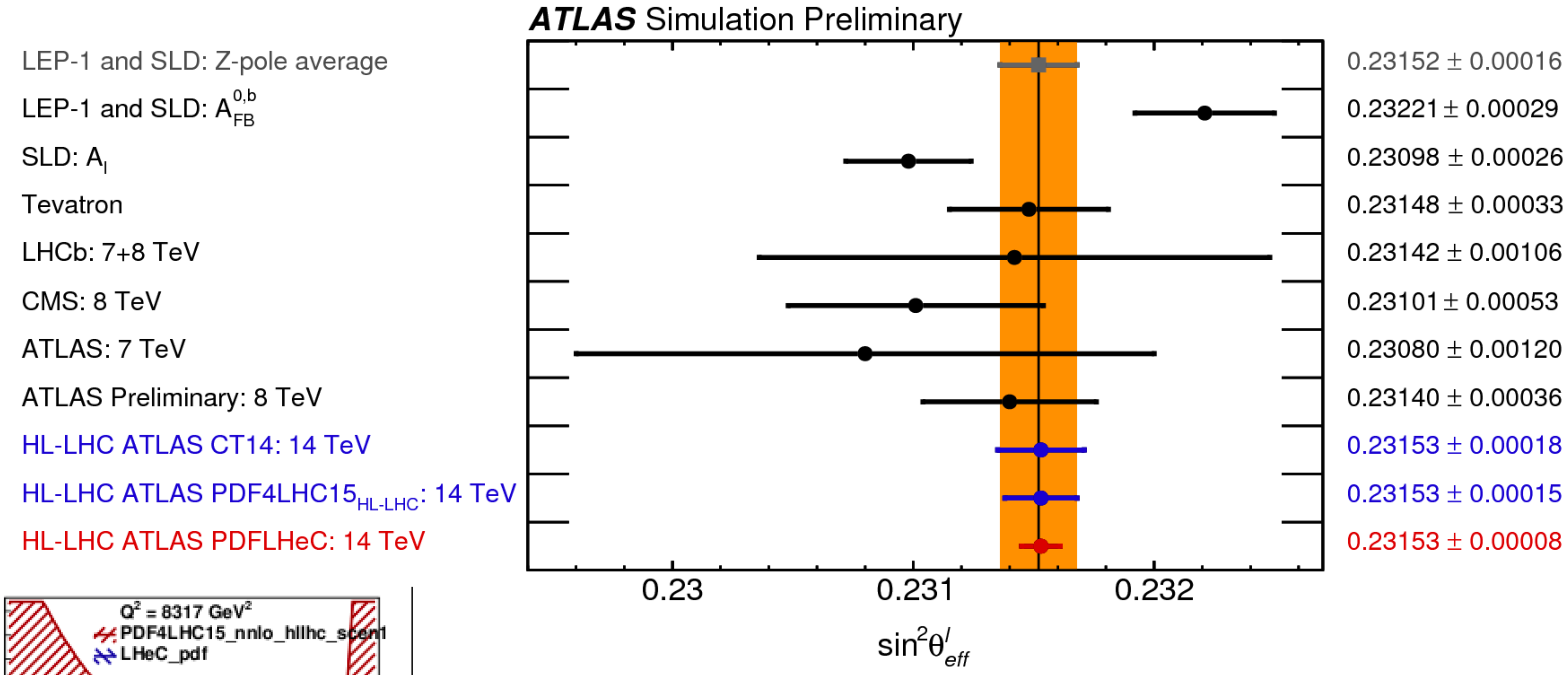
PDF reweighting and prospect of the results

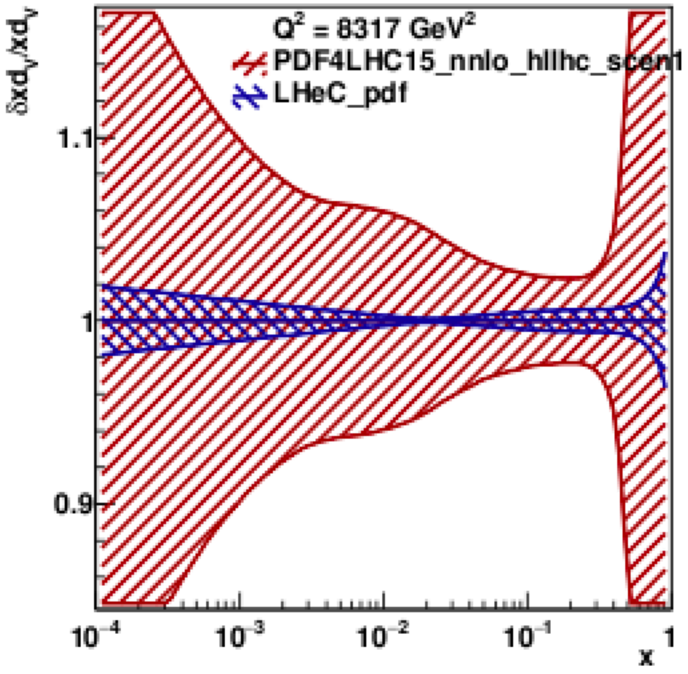




New analysis techniques, including in-situ PDF profiling and categorisation statistical and systematic uncertainties are significantly reduced relative to previous LHC measurements.

$\sin^2\theta_W$ extraction Prospect PDF sets

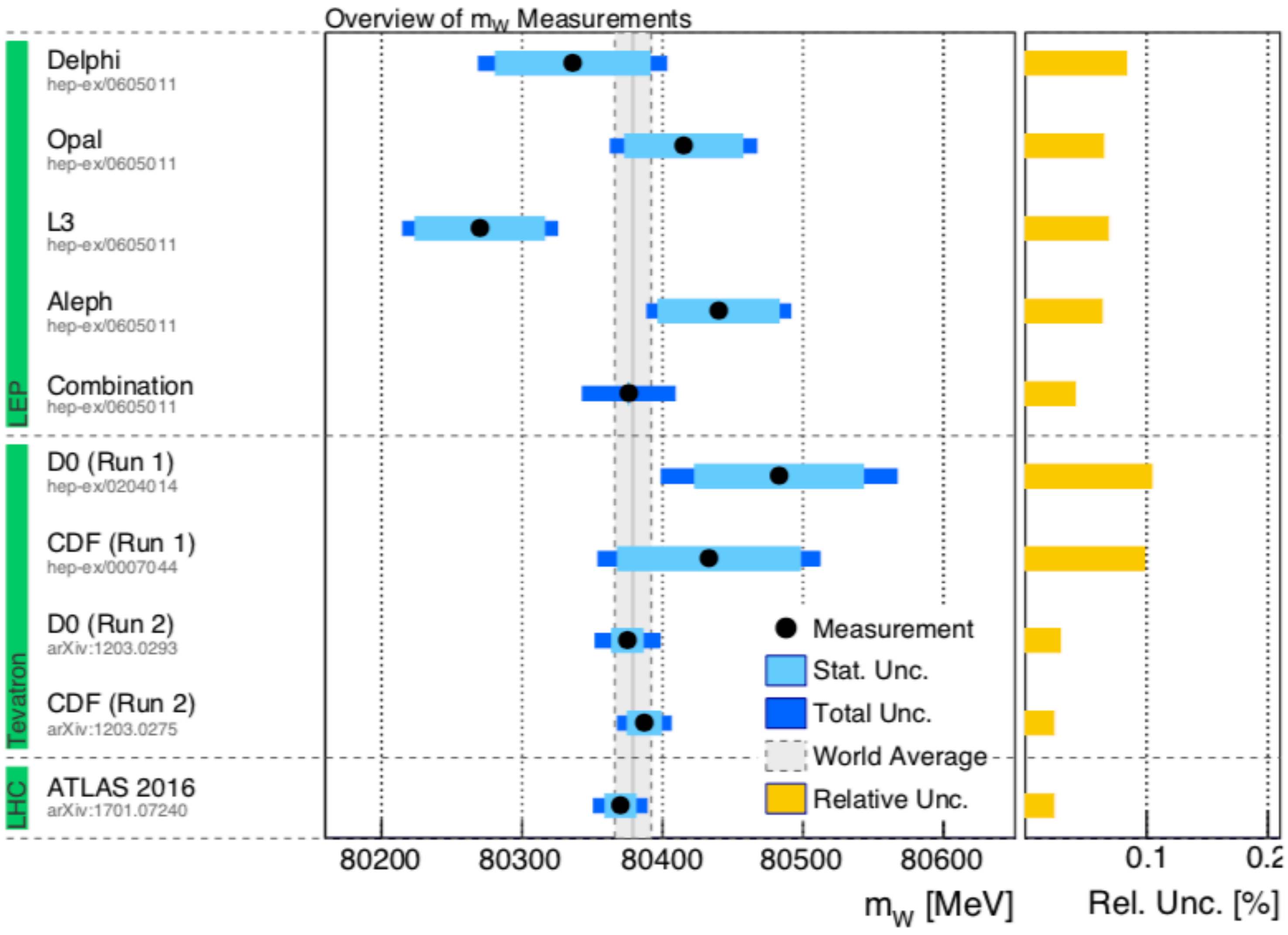




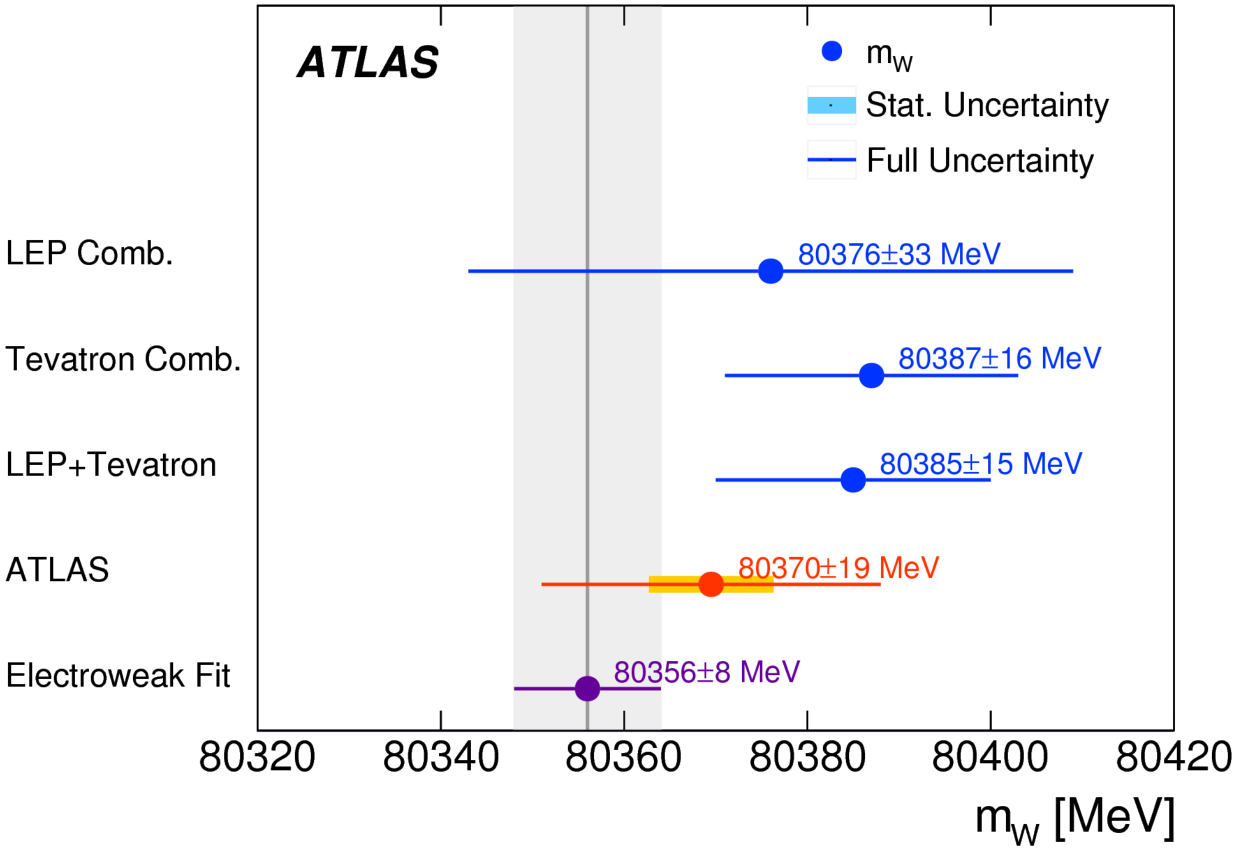
The expected sensitivity of the $\sin^2\theta_{eff}$ measurements is improved by **~20% using prospect PDF sets**. Including **LHeC** data: reduction of PDF (total) uncertainties by a factor of **~5 (2)** wrt to HL-LHC PDFs. Exceeding LEP precision

The W mass

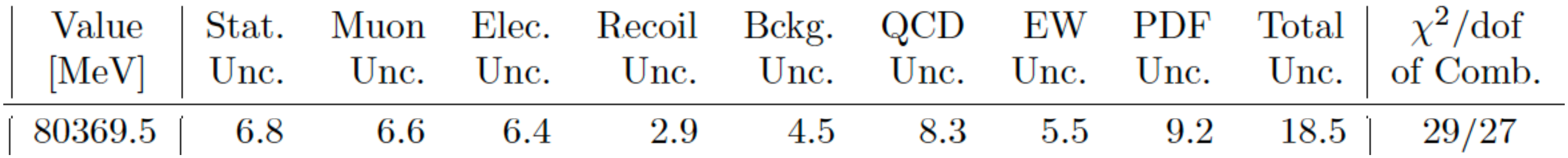
- Same basic measurement principle at Tevatron and LHC
  - Using a template fit approach to p^{l}_{T} and m_{T}
- Uncertainties dominated by model-uncertainties
  - PDFs, angular coefficients
  - Transverse momentum spectrum of the W boson
- Tevatron and LHC results currently at similar level of precision



W mass measurement with ATLAS Run1 data



19 MeV is still far from the target of 8 MeV set by the electroweak fit how can we improve ?



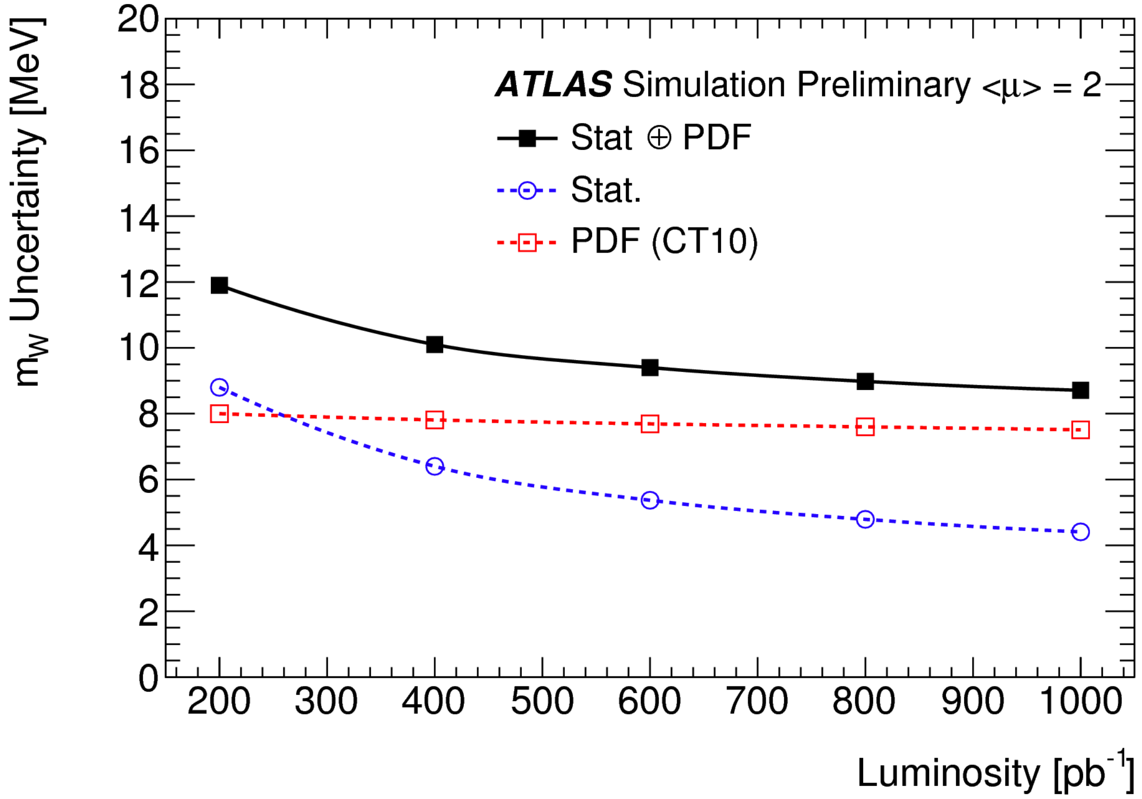
Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

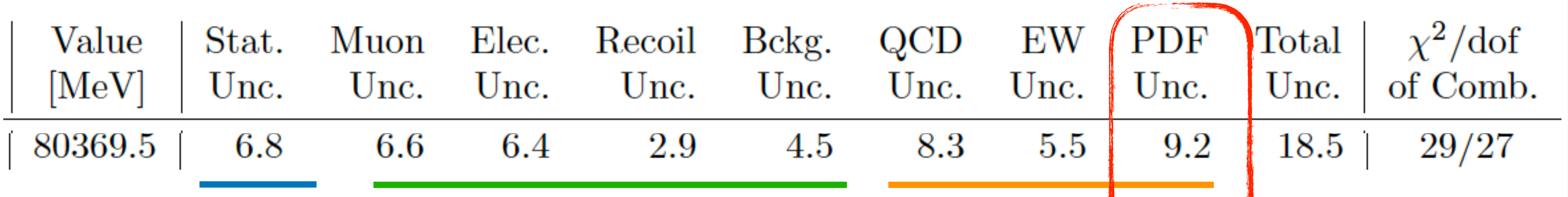
stat. = 6.8 MeV exp. syst = 10.6 MeV mod. syst =13.6 MeV

m_W = 80370 +- 19 MeV

W mass measurement with ATLAS Run1 data

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)





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stat. = 6.8 MeV exp. syst = 10.6 MeV mod. syst =13.6 MeV

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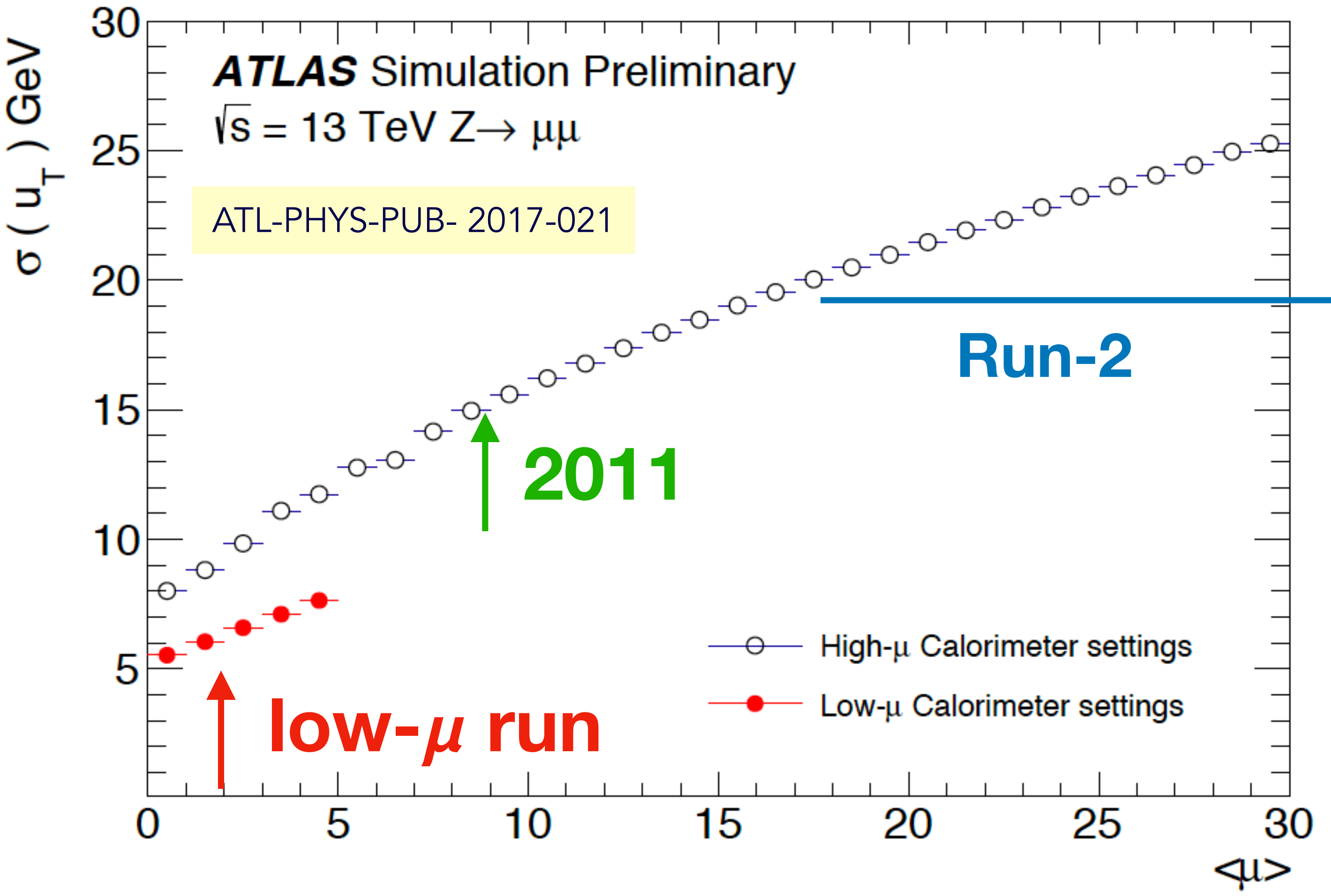
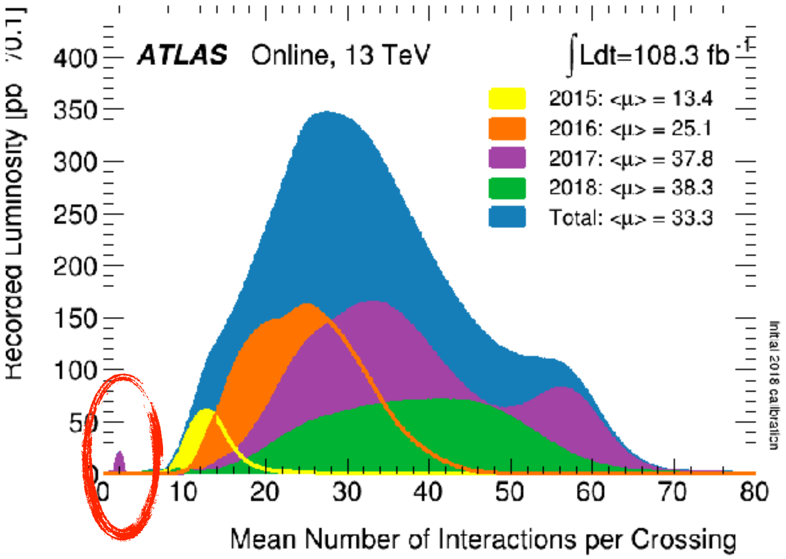
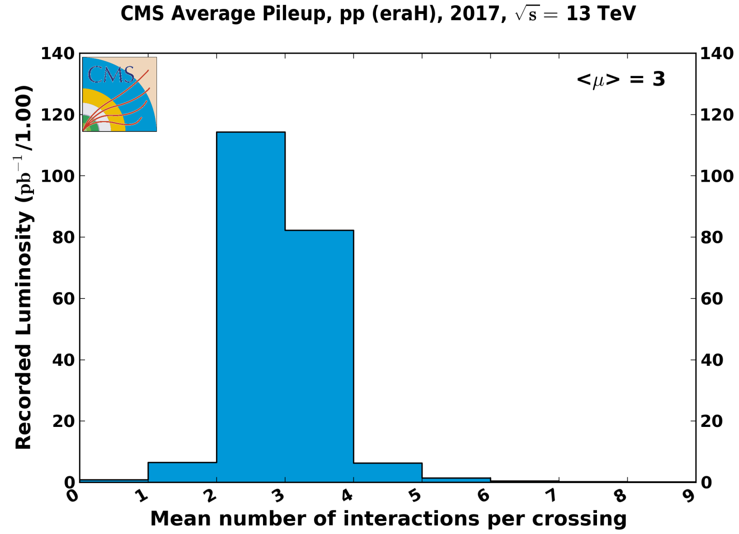
low-Pileup Data







Both ATLAS and CMS collected @340 pb^{-1} of data collected @13TeV with **low Pileup <μ> =2**

fantastic opportunity for W precision measurement!

better understanding the physics modelling of the W mass measurement will allow to reach **10 MeV precision !**

Futher in the future of W mass measurement

Study of potential of low pile-up runs, $<\mu>\sim 2$, at HL-LHC@14TeV and HE-LHC@27TeV. **200 pb-1** per week, yielding **~1M candidate/week**

- Major **reduction of uncertainty** can be achieved due to:
  - *Optimal reconstruction of missing transverse momentum → better recoil resolution*
  - *Extended coverage with new tracking detector → ITk coverage from* $|\eta| < 2.5$ *to* $|\eta| < 4$
  - *combining central and forward ranges brings significant reduction in the PDF unc. →probe new region of x at* $Q^2 \sim m_W$

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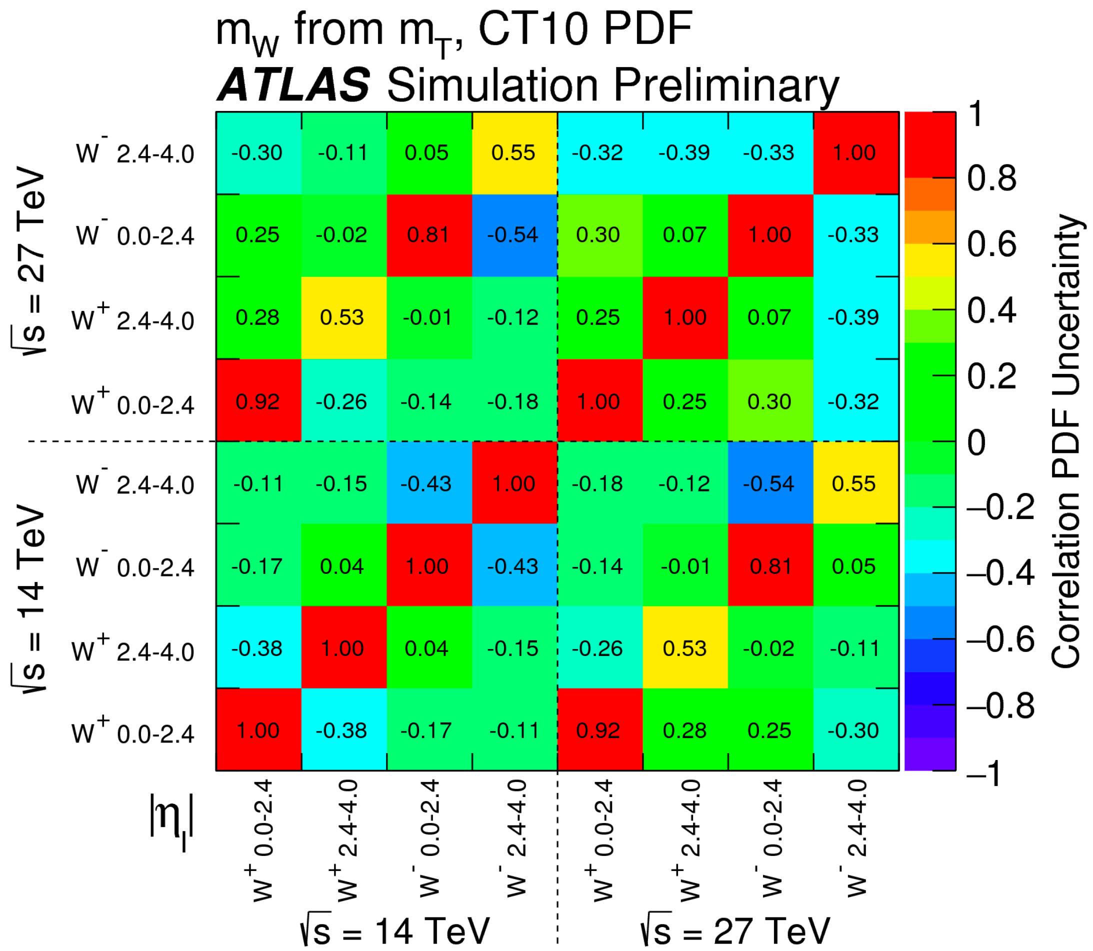
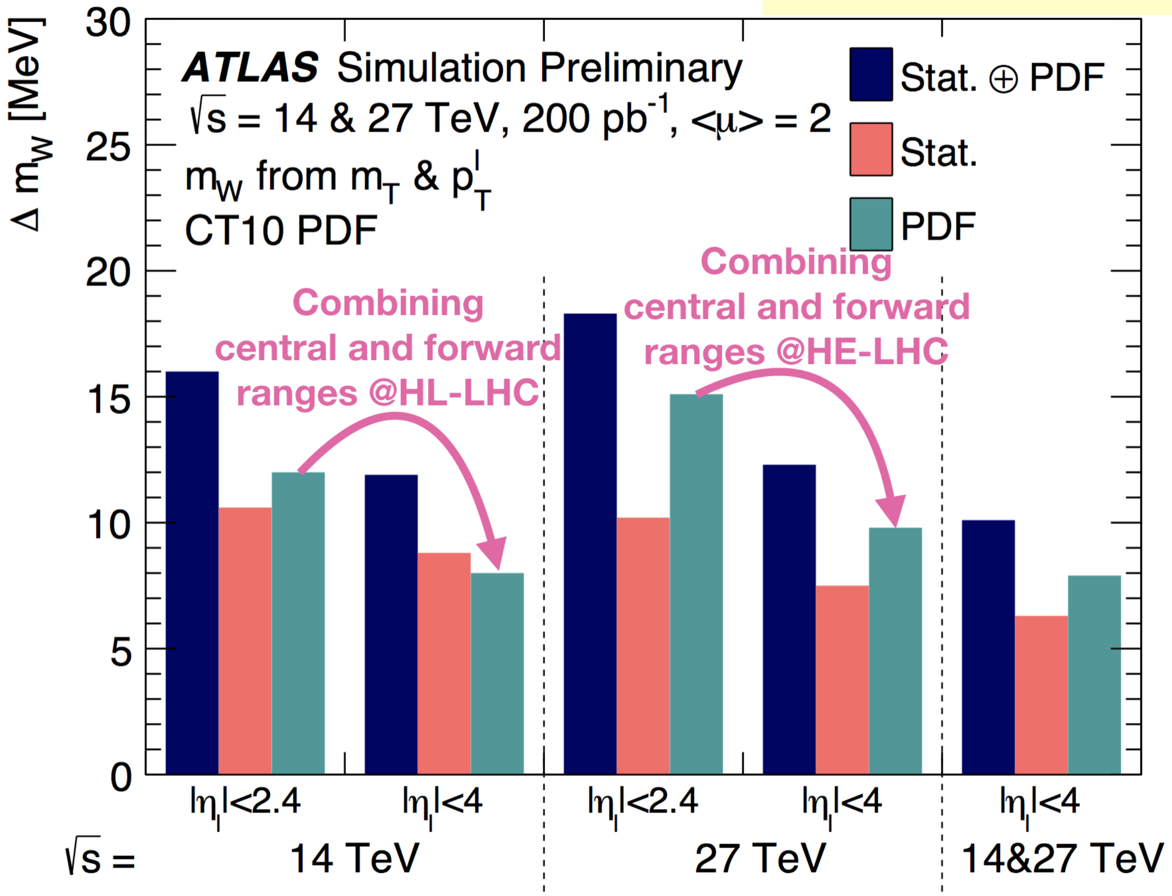


		14 TeV W^+ 0.0-2.4	14 TeV W^+ 2.4-4.0	14 TeV W^- 0.0-2.4	14 TeV W^- 2.4-4.0	27 TeV W^+ 0.0-2.4	27 TeV W^+ 2.4-4.0	27 TeV W^- 0.0-2.4	27 TeV W^- 2.4-4.0
$\sqrt{s}$ = 27 TeV	W^- 2.4-4.0	-0.30	-0.11	0.05	0.55	-0.32	-0.39	-0.33	1.00
	W^- 0.0-2.4	0.25	-0.02	0.81	-0.54	0.30	0.07	1.00	-0.33
	W^+ 2.4-4.0	0.28	0.53	-0.01	-0.12	0.25	1.00	0.07	-0.39
	W^+ 0.0-2.4	0.92	-0.26	-0.14	-0.18	1.00	0.25	0.30	-0.32
$\sqrt{s}$ = 14 TeV	W^- 2.4-4.0	-0.11	-0.15	-0.43	1.00	-0.18	-0.12	-0.54	0.55
	W^- 0.0-2.4	-0.17	0.04	1.00	-0.43	-0.14	-0.01	0.81	0.05
	W^+ 2.4-4.0	-0.38	1.00	0.04	-0.15	-0.26	0.53	-0.02	-0.11
	W^+ 0.0-2.4	1.00	-0.38	-0.17	-0.11	0.92	0.28	0.25	-0.30

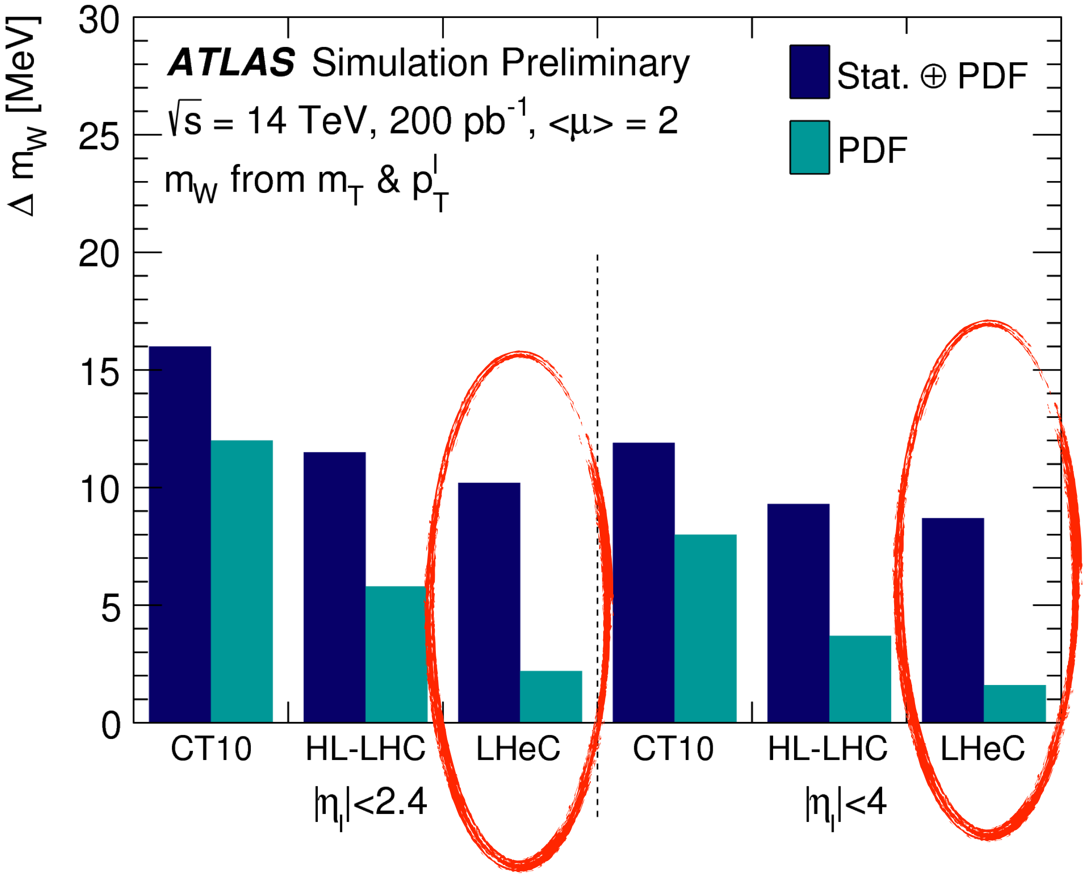


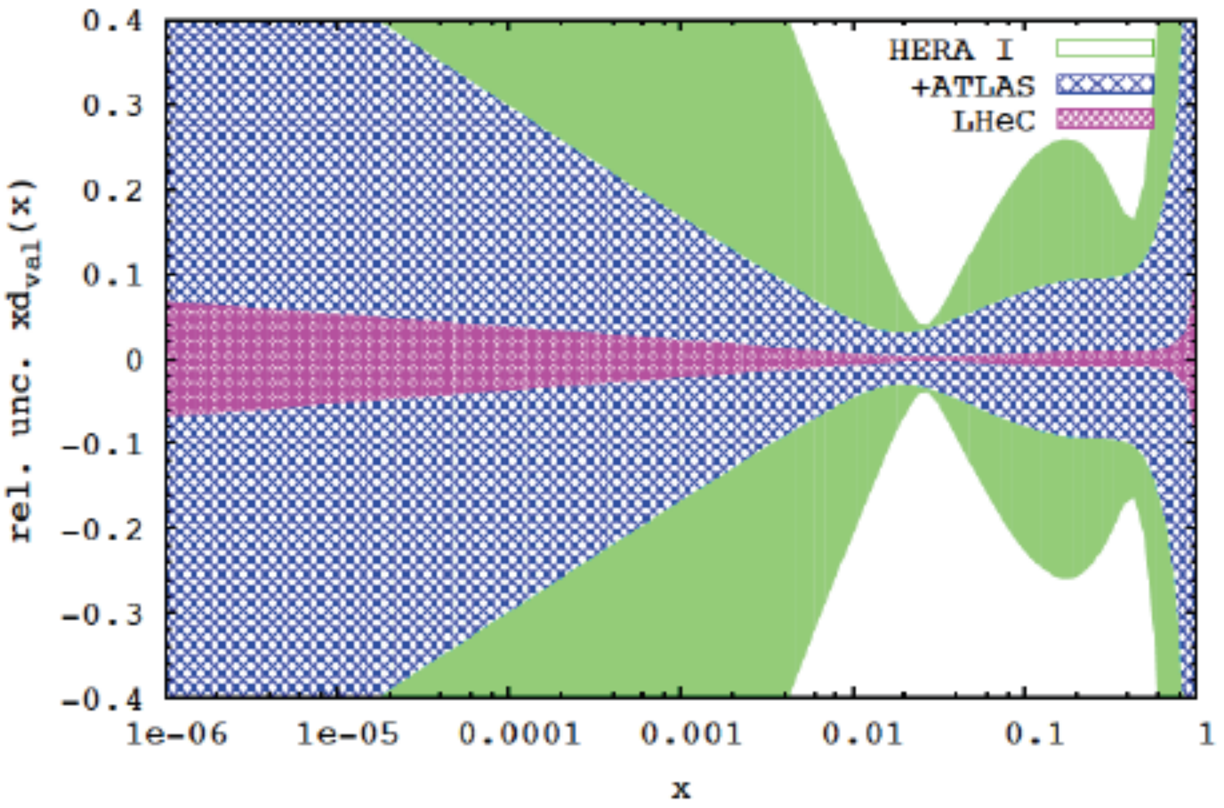
Prospect W mass

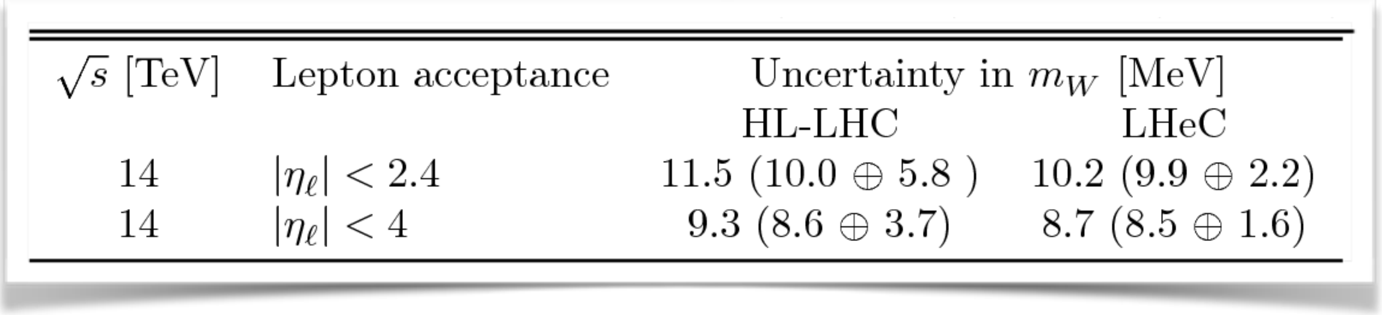
Total uncertainty of ~ **11 MeV** with 200 pb−1 of data @HL-LHC: **30% reduction** of PDF uncertainty with extended tracker.

Future HL-LHC PDF set would reduce PDF uncertainty by **factor of 2**.

Future **LHeC** PDF set from DIS data would reduce PDF uncertainty by **factor of 5-6**.







$\sqrt{s}$ [TeV]	Lepton acceptance	Uncertainty in m_W [MeV]	
		HL-LHC	LHeC
14	$\|\eta_\ell\| < 2.4$	11.5 (10.0 ⊕ 5.8)	10.2 (9.9 ⊕ 2.2)
14	$\|\eta_\ell\| < 4$	9.3 (8.6 ⊕ 3.7)	8.7 (8.5 ⊕ 1.6)

Conclusion

The EW precision measurements program at HL-LHC will highly benefit from more precise knowledge of PDF.

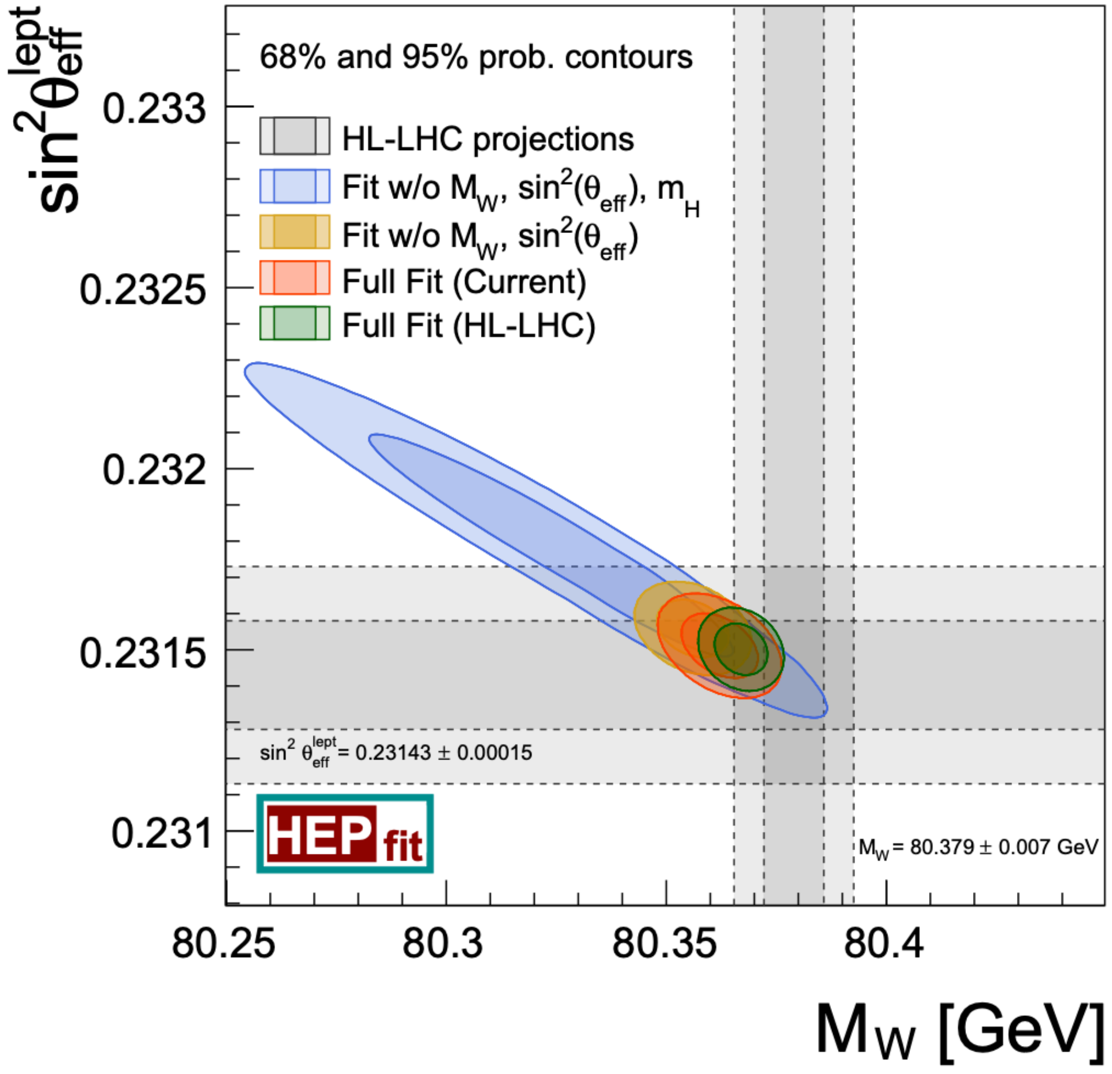
With 3000 fb-1 at 14 TeV the statistical precision of ***$\sin^2\theta_{eff}$*** measurements with ATLAS, CMS and LHCb will be better than **5 x10^{-5}.** The overall uncertainty will remain dominated by the PDFs, which can be reduced to **10-16 x10^{-5}** using in situ constraints, with an overall uncertainty below **18 x10^{-5}.**

The PDF uncertainty on $\sin^2\theta_{eff}$ can be reduced by 10%25% using the global fits to HL-LHC data.

Data from the LHeC collider would have the potential to reduce the PDF uncertainties by an additional **factor of 5**.

Dedicated low-pileup runs will provide the required conditions to reach the 8 MeV goal for a ***m_W*** measurement. Five to ten weeks of data taking in the course of the HL-LHC will lead to a statistical precision of about **3 MeV**.

Assuming the extended lepton coverage allowed by the HL-LHC detectors, the impact of PDF uncertainties on the mW measurement, using today's PDF sets, would amount to **5-8 MeV**. These uncertainties are further reduced to about **4 MeV** when using the HL-LHC prospect PDF set, leading to an overall HL-LHC target of **$\Delta m_W = \pm 6$ MeV**. LHeC measurements could further reduce the PDF systematics to **2 MeV**.



Backup

Prospect PDF for HL-LHC

- HL-LHC set incorporates the expected constraints from present and future LHC data; it starts from the PDF4LHC convention and comes in three scenarios corresponding to more or less optimistic projections of the experimental uncertainties.

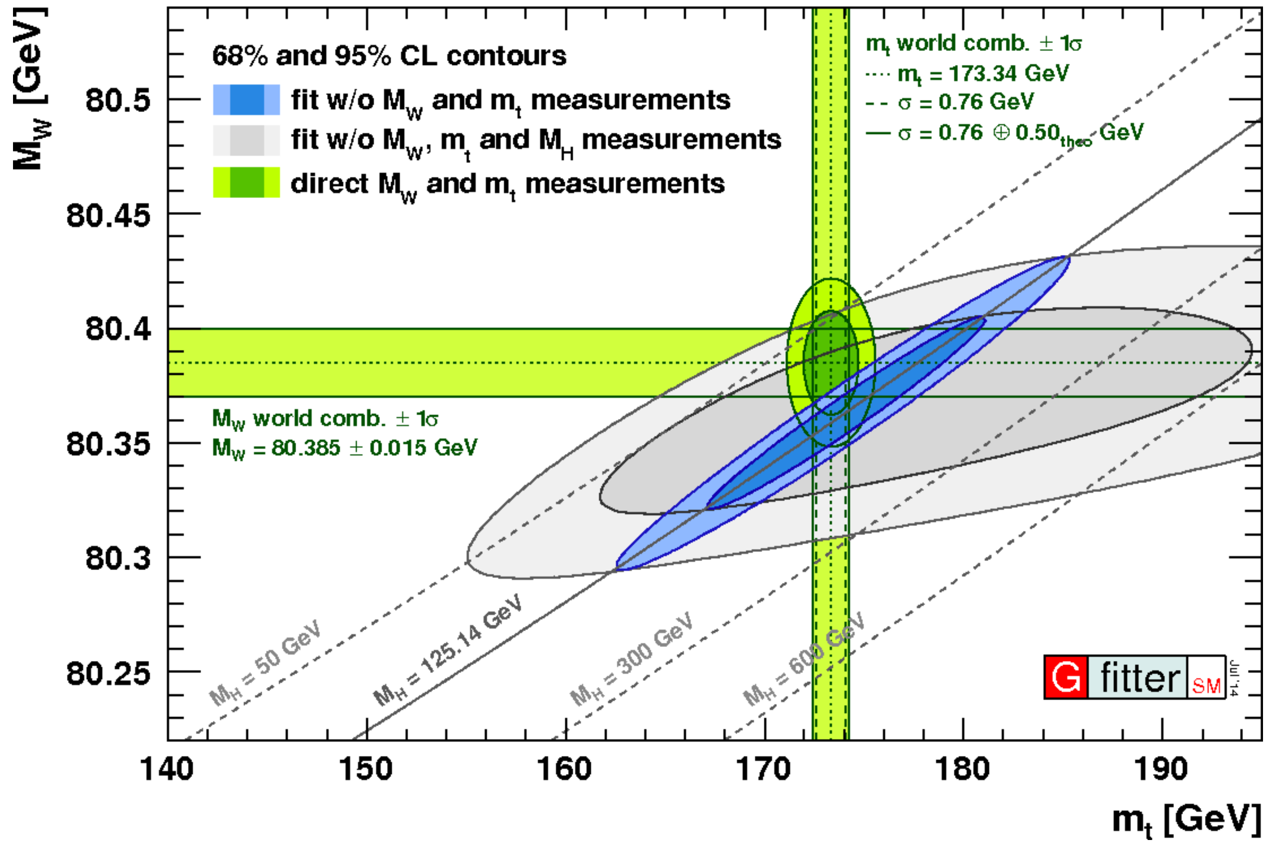
- The LHeC PDF set represents the impact of a proposed future high-energy, high-luminosity ep scattering experiment on the uncertainties in the proton structure, using the theoretically best understood process for this purpose.

New physics will shows up?

Big potential to collected critical datasets to do high precision EW physics:
this requires ultimate performance of detector at different energies and pileup
Often theoretical uncertainties are becoming the bottleneck for exploiting the full statistical power of a measurement

measurement of SM fundamental parameters

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



m_H	125.09 ± 0.24 GeV (ATLAS+CMS)	Uniquely measured at the LHC
m_t	172.84 ± 0.70 GeV (ATLAS) 172.44 ± 0.49 GeV (CMS)	Comparable with Tevatron precision
m_W	80.370 ± 0.019 GeV (ATLAS)	Competing with Tevatron precision
$\sin^2\theta_W$	0.23101 ± 53 10^{-5} CMS 0.23148 ± 106 10^{-5} LHCb 0.23140 ± 36 10^{-5} ATLAS	Not yet competitive with LEP and SLD

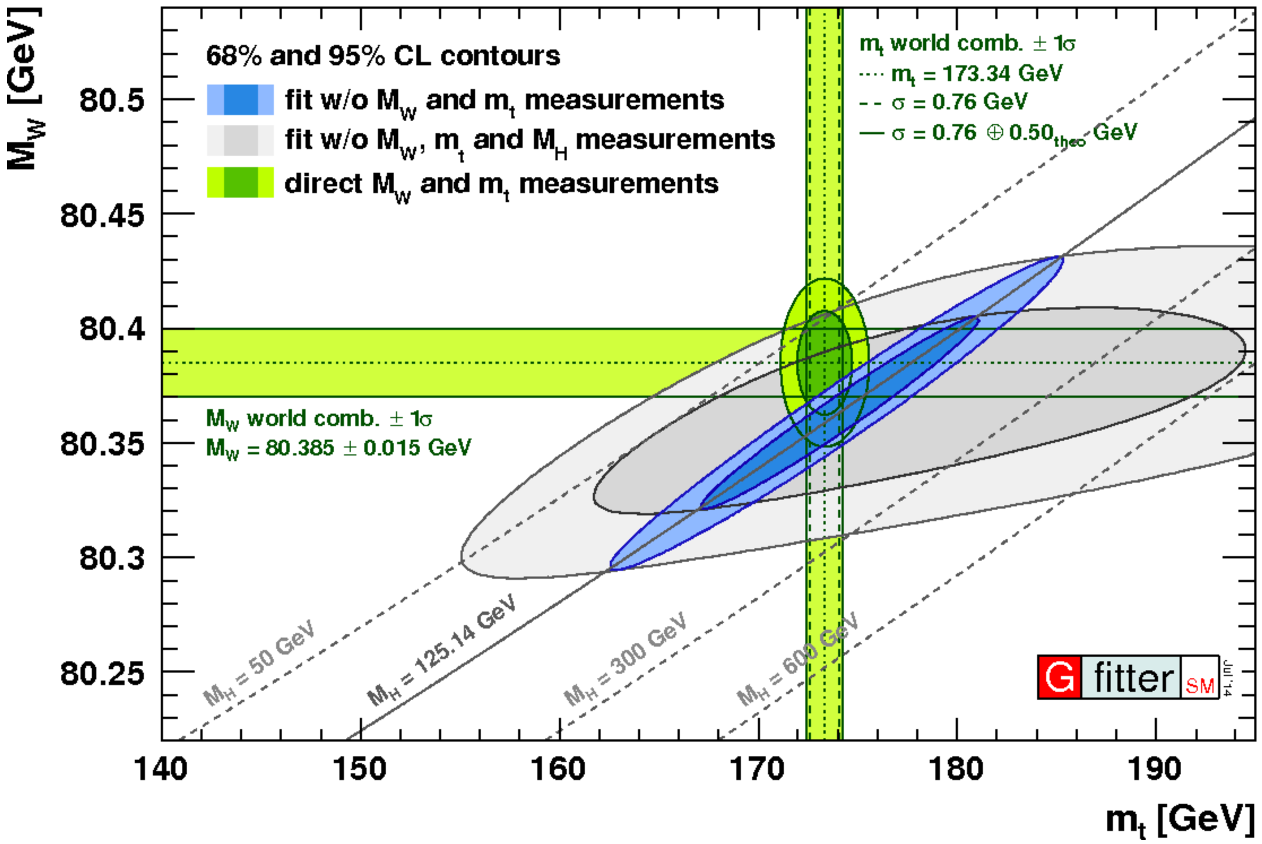
The measurement of $\sin^2\theta_W$ tests this relation:

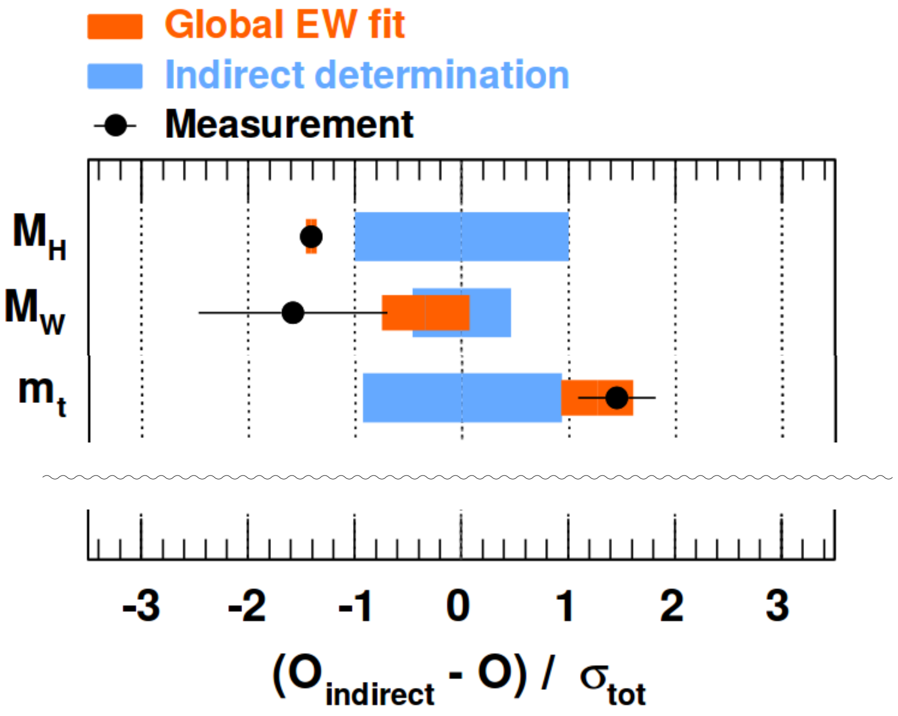
$$\sin^2_{\rm eff}\theta_W = \left(1 - \frac{m_W^2}{m_Z^2}\right)\kappa$$

± 20×10^{-5} error in $\sin^2\theta_{\rm eff}$ corresponds to ±10MeV error in M_W

relation between top, Higgs and W masses

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

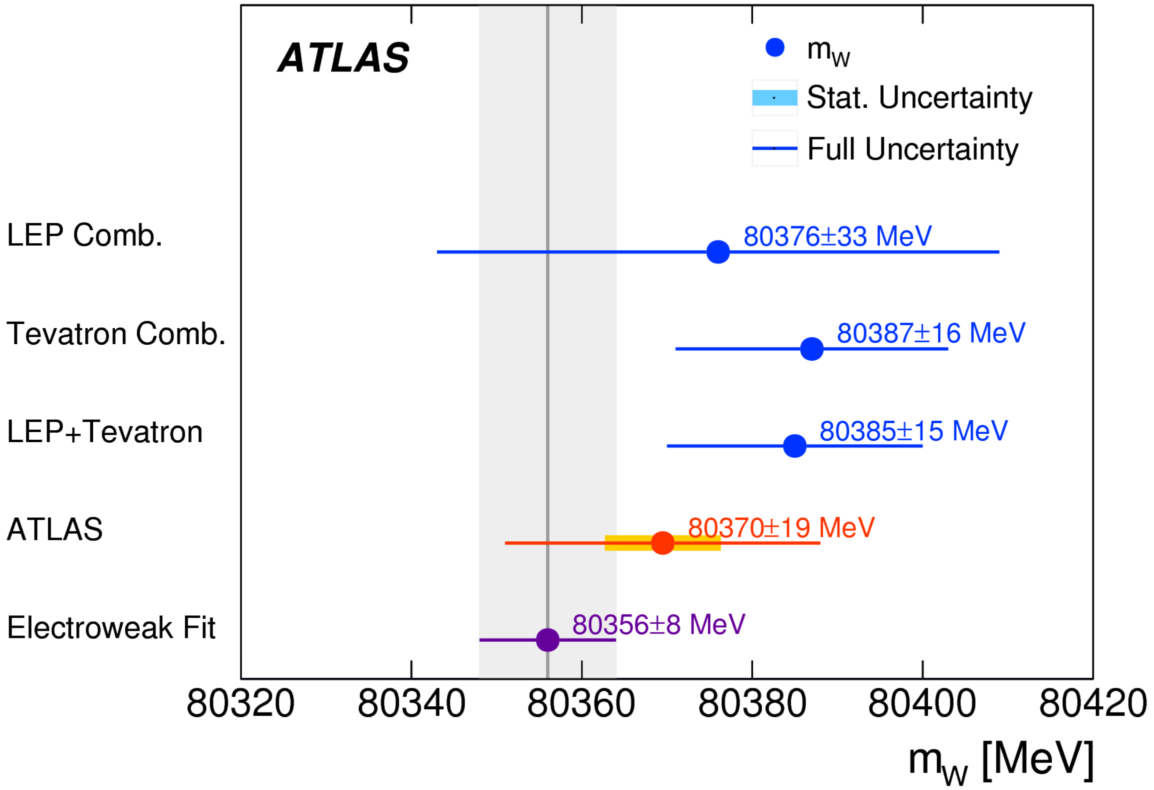




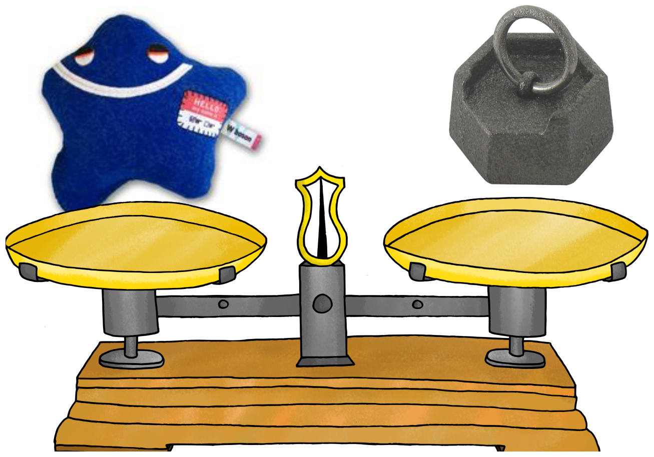
	Measurement	SM Prediction (*)
m_H	125.09 ± 0.24	102.8 ± 26.3
m_{top}	172.84 ± 0.70	176.6 ± 2.5
m_W	80.385 ± 0.015	80.360 ± 0.008

(*) arXiv:1608.01509

W mass



80370±19 MeV



$86\%\ p_T^l$, $14\%\ m_T$

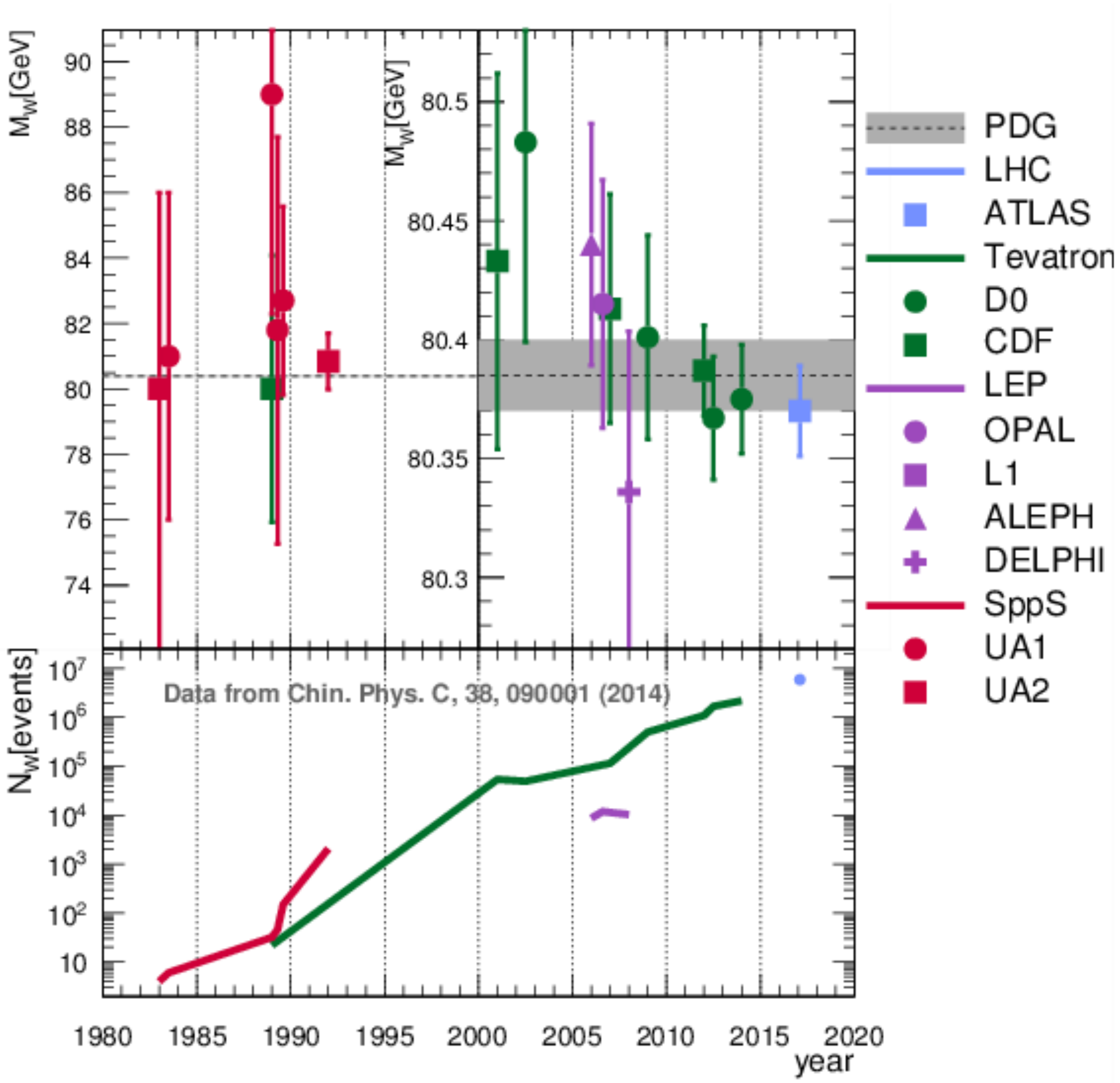
$$
\begin{aligned}
m_W &= 80369.5 \pm 6.8\,\text{MeV}(\text{stat.}) \pm 10.6\,\text{MeV}(\text{exp. syst.}) \pm 13.6\,\text{MeV}(\text{mod. syst.}) \\
&= 80369.5 \pm 18.5\,\text{MeV},
\end{aligned}
$$

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

Consistent with the SM expectation, compatible with the world average and comparable in precision to the currently leading measurements by CDF

Dominated by PDF and QCD model uncertainties (mainly p_T^W)

W mass history



- Only four W-boson mass measurements in the last 7 years

→ Complex measurements which require O(5-7) years

- 1983 CERN SPS – W discovery
- 1983 – UA1

  $m_W = 81 \pm 5$ GeV
- 1992 – UA2 (with mZ from LEP)

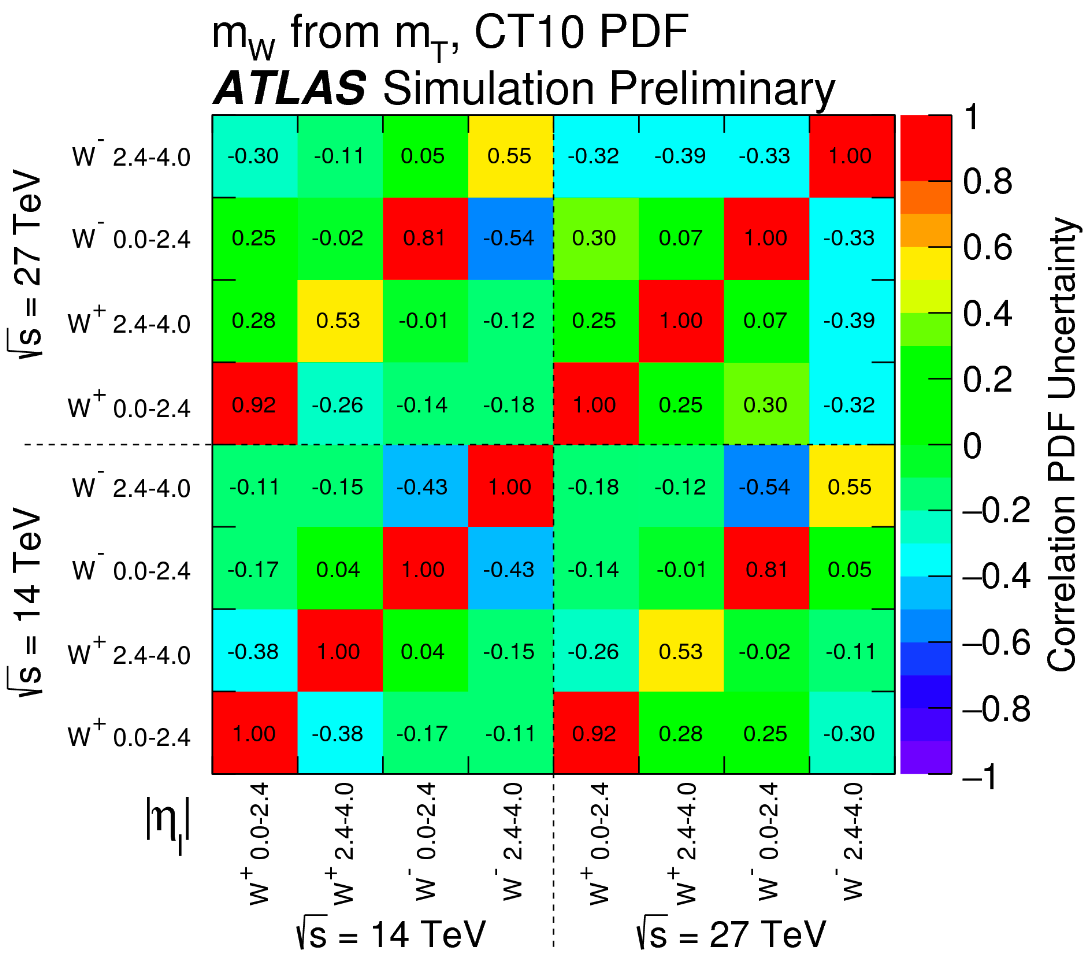
  $m_W = 80.35 \pm 0.37$ GeV
- 2013 – LEP combined

  $m_W = 80.376 \pm 0.033$ GeV
- 2013 – Tevatron combined

  $m_W = 80.387 \pm 0.016$ GeV
- 2017 – LHC (ATLAS)

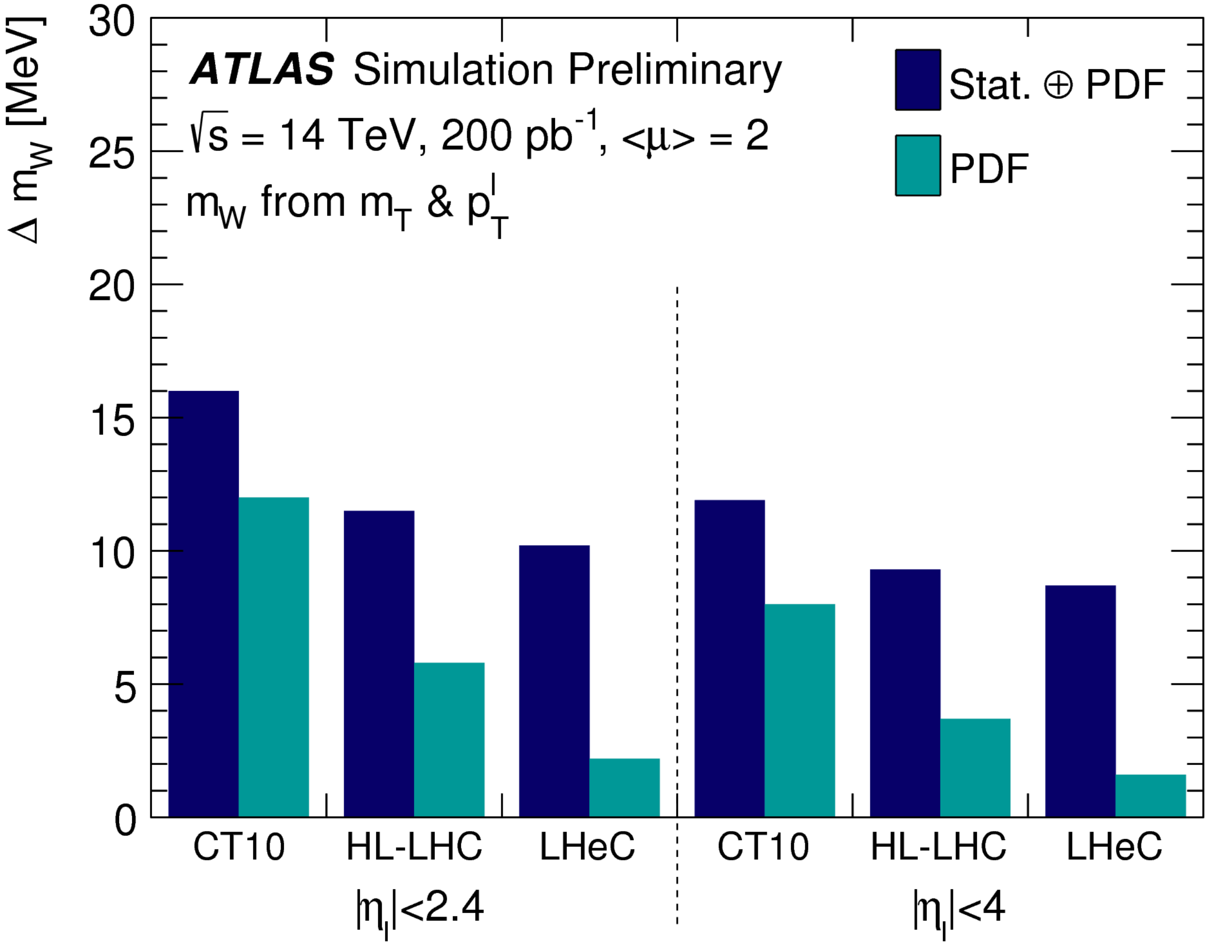
  $m_W = 80.370 \pm 0.019$ GeV

Prospect W mass



		$\sqrt{s}$ = 14 TeV W^+ 0.0-2.4	$\sqrt{s}$ = 14 TeV W^+ 2.4-4.0	$\sqrt{s}$ = 14 TeV W^- 0.0-2.4	$\sqrt{s}$ = 14 TeV W^- 2.4-4.0	$\sqrt{s}$ = 27 TeV W^+ 0.0-2.4	$\sqrt{s}$ = 27 TeV W^+ 2.4-4.0	$\sqrt{s}$ = 27 TeV W^- 0.0-2.4	$\sqrt{s}$ = 27 TeV W^- 2.4-4.0
$\sqrt{s}$ = 27 TeV	W^- 2.4-4.0	-0.30	-0.11	0.05	0.55	-0.32	-0.39	-0.33	1.00
	W^- 0.0-2.4	0.25	-0.02	0.81	-0.54	0.30	0.07	1.00	-0.33
	W^+ 2.4-4.0	0.28	0.53	-0.01	-0.12	0.25	1.00	0.07	-0.39
	W^+ 0.0-2.4	0.92	-0.26	-0.14	-0.18	1.00	0.25	0.30	-0.32
$\sqrt{s}$ = 14 TeV	W^- 2.4-4.0	-0.11	-0.15	-0.43	1.00	-0.18	-0.12	-0.54	0.55
	W^- 0.0-2.4	-0.17	0.04	1.00	-0.43	-0.14	-0.01	0.81	0.05
	W^+ 2.4-4.0	-0.38	1.00	0.04	-0.15	-0.26	0.53	-0.02	-0.11
	W^+ 0.0-2.4	1.00	-0.38	-0.17	-0.11	0.92	0.28	0.25	-0.30

Moderate or negative correlations, which will lead to reduced combined uncertainties, are observed between categories of different W-boson charges, and between central and forward pseudorapidities, at given $\sqrt{s}$
. As expected from the correlations, combining the central and forward pseudorapidity ranges brings significant reduction in the PDF uncertainties.
The PDF uncertainties can be reduced to about 4 MeV using HL-LHC PDF sets and to 2 MeV using LHeC PDF sets.



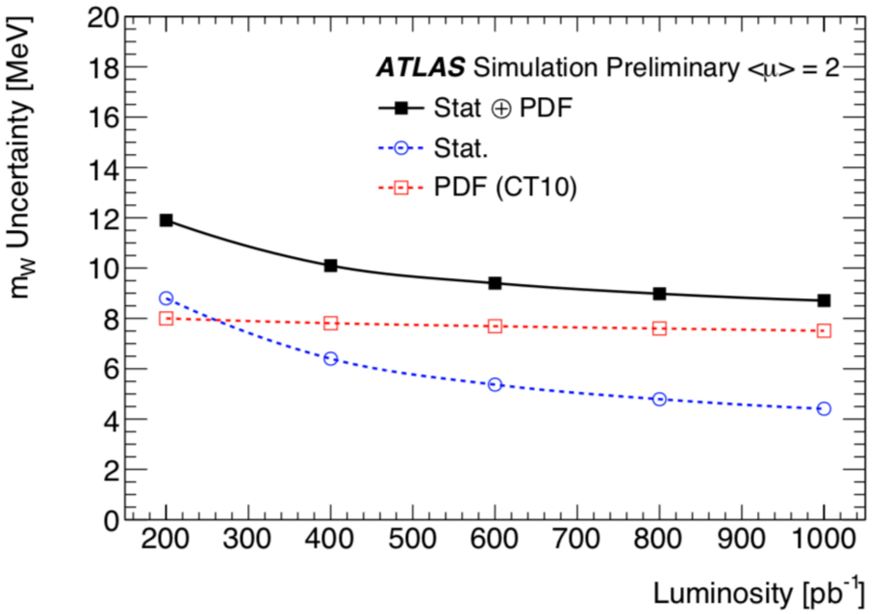
Total uncertainty of ~ 11 MeV with 200 pb−1 of data at each energy.

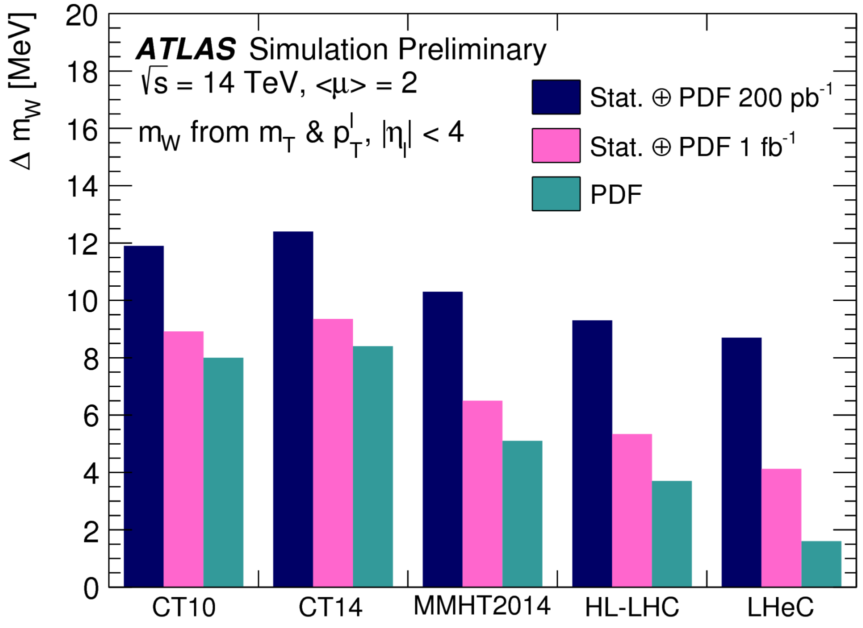
Future HL-LHC PDF set would reduce PDF uncertainty by factor of 2.

Future LHeC PDF set from DIS data would reduce PDF uncertainty by factor of 5-6.

Potential low pile-up runs at HL-LHC (14 TeV) and HE-LHC (27 TeV): 200 pb^{-1} per week

- Extended coverage with new tracking detector: $|\eta| < 4$ —> 30% reduction of PDF uncertainties

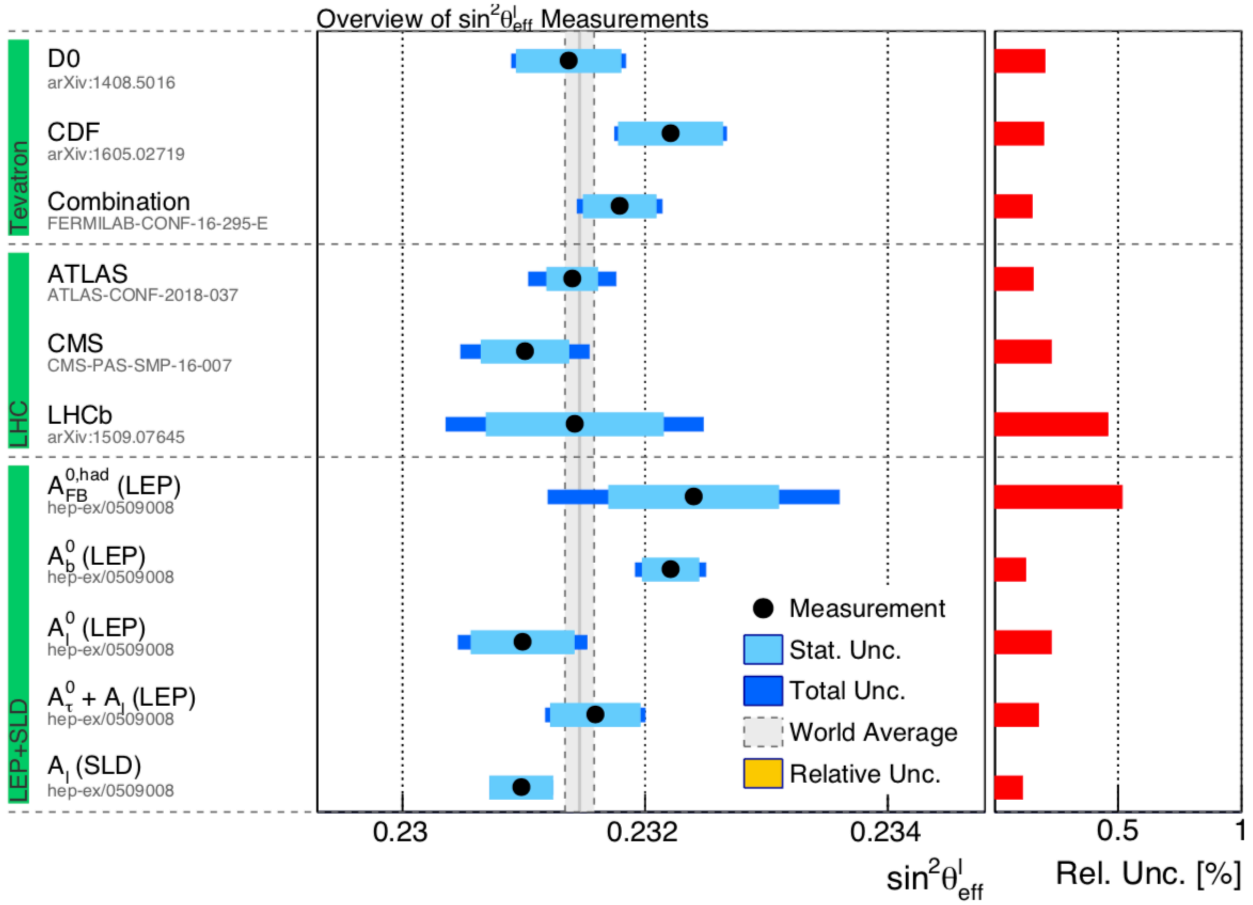




- The PDF uncertainties can be reduced to about 4 MeV using HL-LHC PDF sets and to 2 MeV using LHeC PDF sets.

Weak Mixing Angle

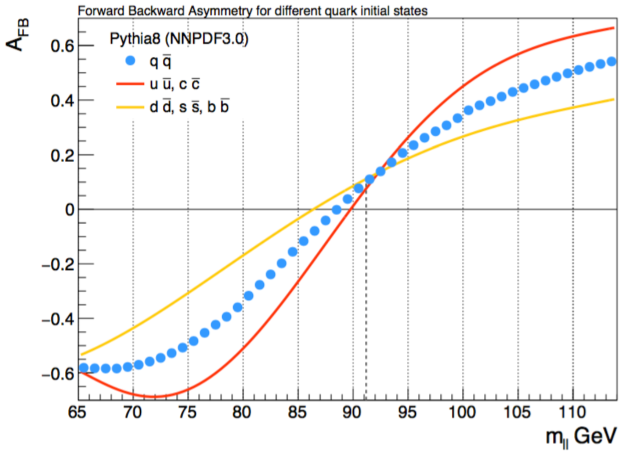
Indirect Determination:	$\sin^2\theta_{eff} = 0.23151 \pm 0.00006$
World average:	$\sin^2\theta_{eff} = 0.23151 \pm 0.00014$
Combination at hadron colliders:	$\sin^2\theta_{eff} = 0.23140 \pm 0.00023$

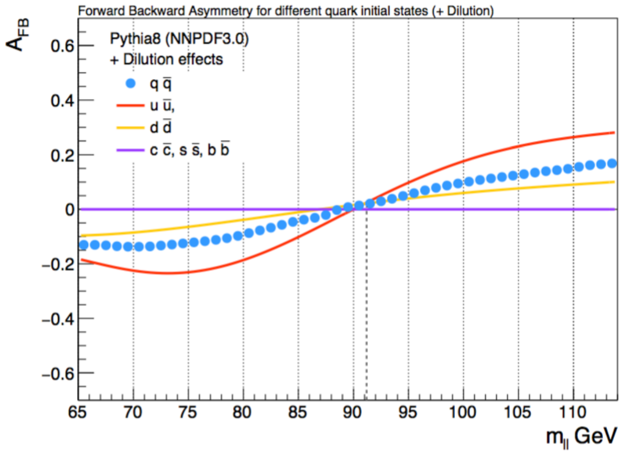


Discrepancy of LEP and SLD measurement on $\sin^2\theta_W$ triggered quite some interest in recent years

Problem at Hadron colliders: Do not know incoming fermion direction on an event-by-event basis

@Hadron colliders use forward-backward asymmetry (**A**$_{FB}$) to extract $\sin^2\theta_W$

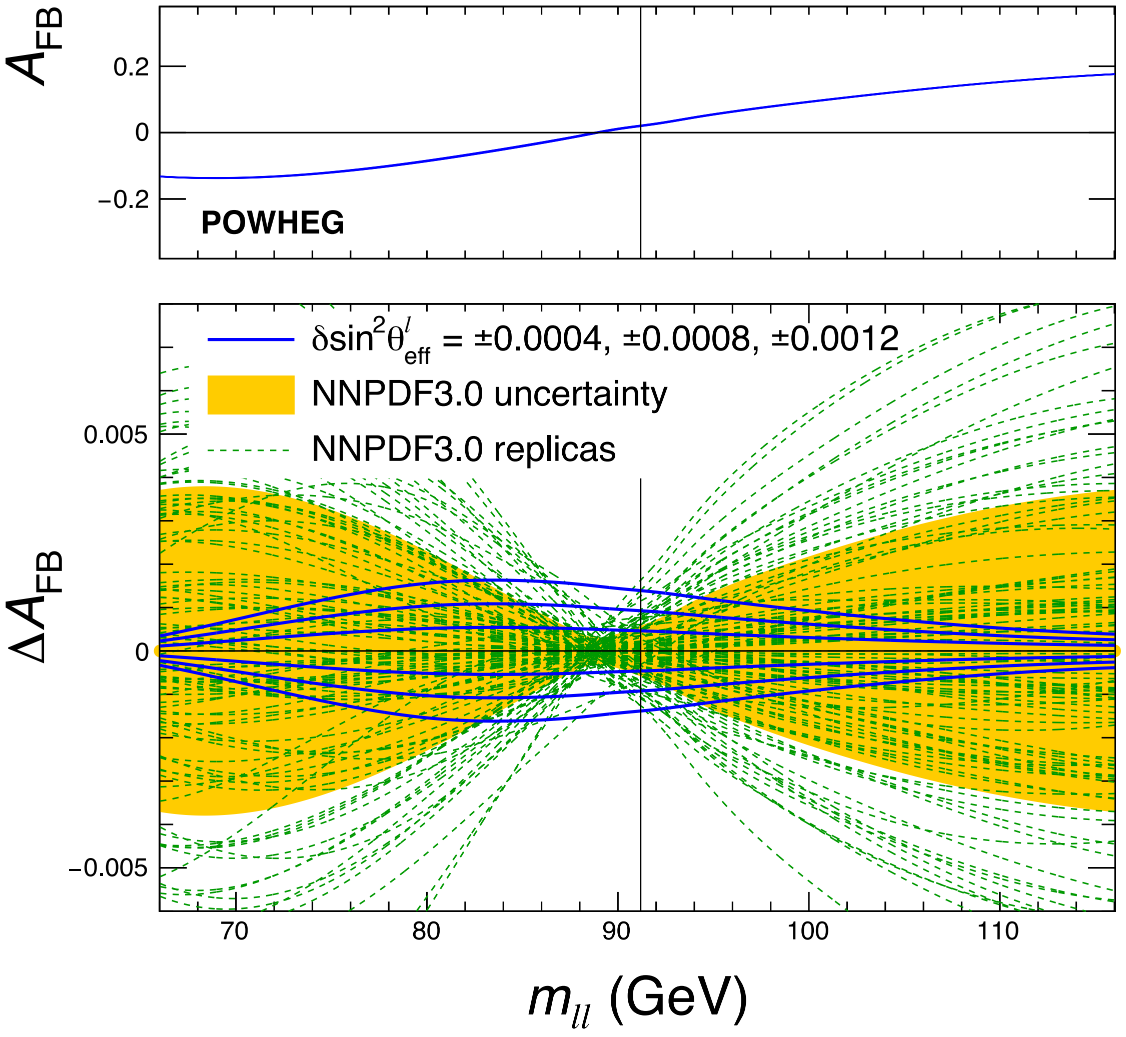




New analysis techniques, including in-situ PDF profiling and categorisation statistical and systematic uncertainties are significantly reduced relative to previous CMS and ATLAS measurements.

weak mixing angle @LHC

EPJC78(2018)701



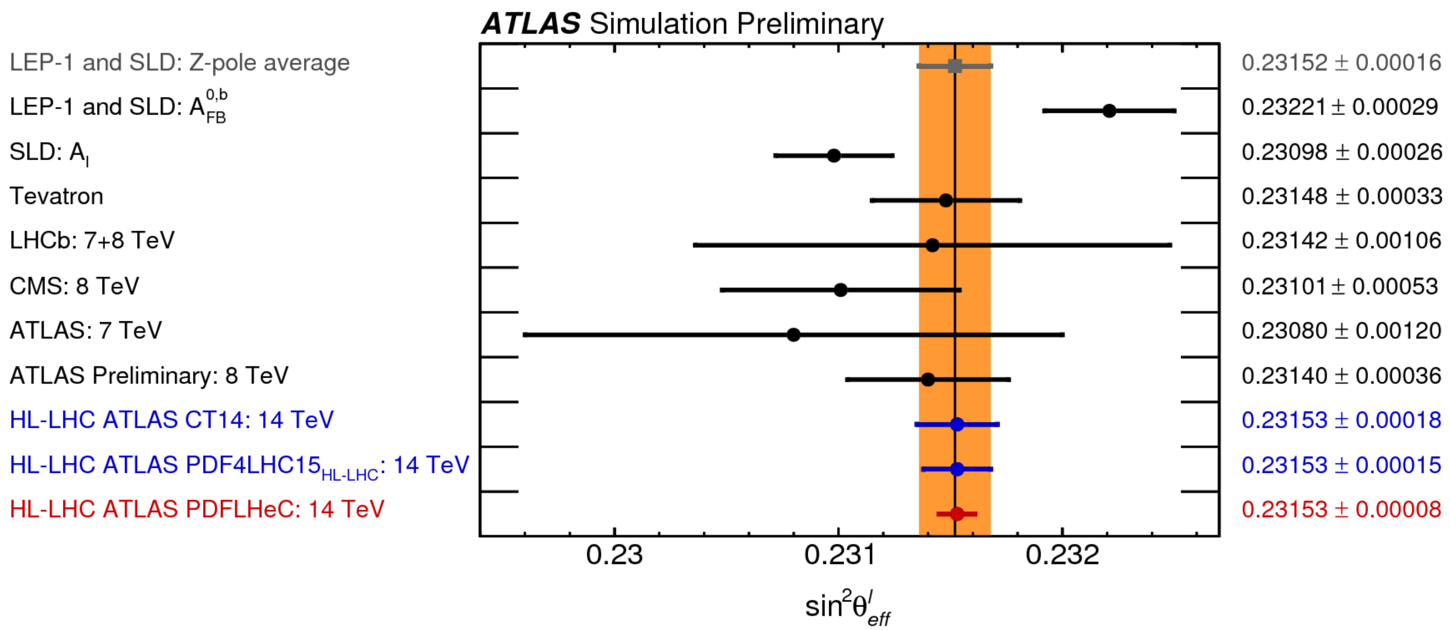
$\sin^2\theta_{eff}^{lept}$ -- key SM parameter

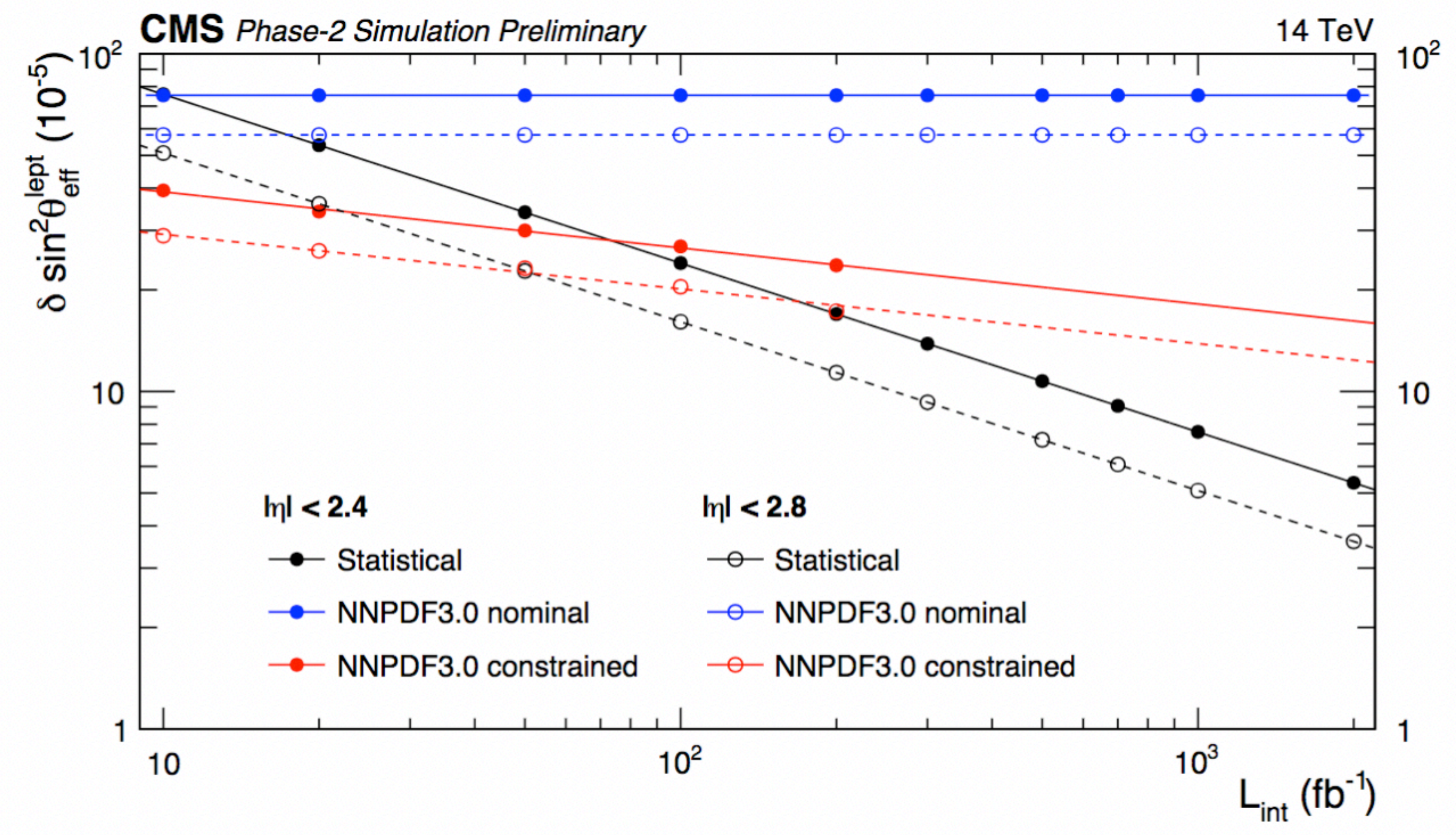
- Exploit forward-backward asymmetry (A_{FB}) in Drell-Yan ee/μμ events
  - ✦ Fit mass (Tevatron) or mass & rapidity (CMS) dependence of observed A_{FB} to SM predictions as function of $\sin^2\theta_{eff}^{lept}$
  - ✦ Extract from angular coefficient A_4 (ATLAS) in mass/rapidity bins

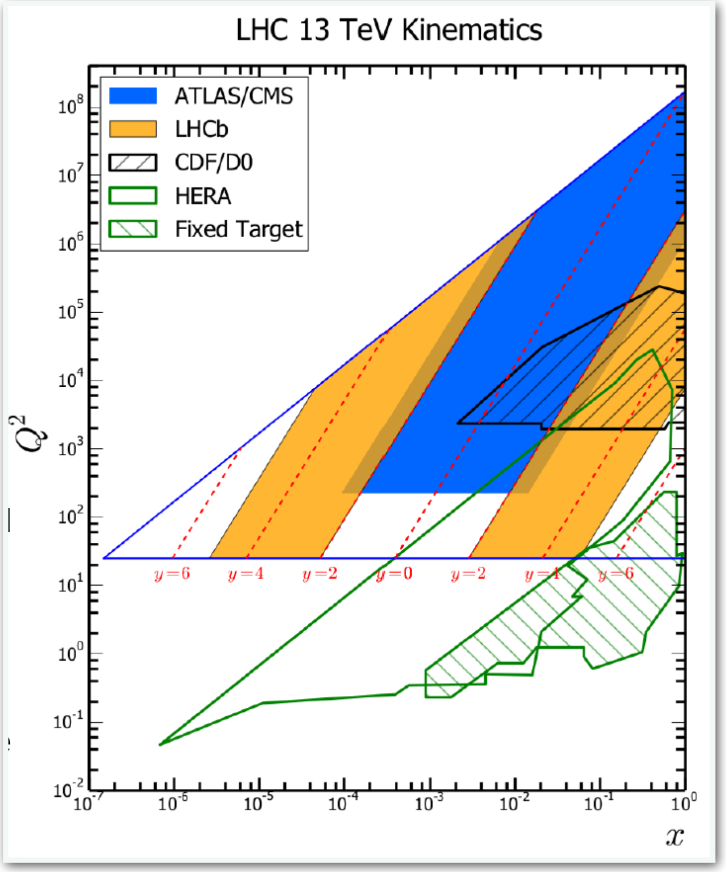
AFB,A4 strongly depend on PDF uncertainty ⇒ dominant systematic

- quark assigned based on Z rapidity
- largest at high y^Z where valence quark PDFs dominate at large x
- also depend on quark flavour, so on relative contributions of u and d PDFs

weak mixing angle extraction HL-LHC







relation between top, Higgs and W masses

The measurements of the m_H and m are currently more precise than their indirect determination from the global fit of the electroweak observables

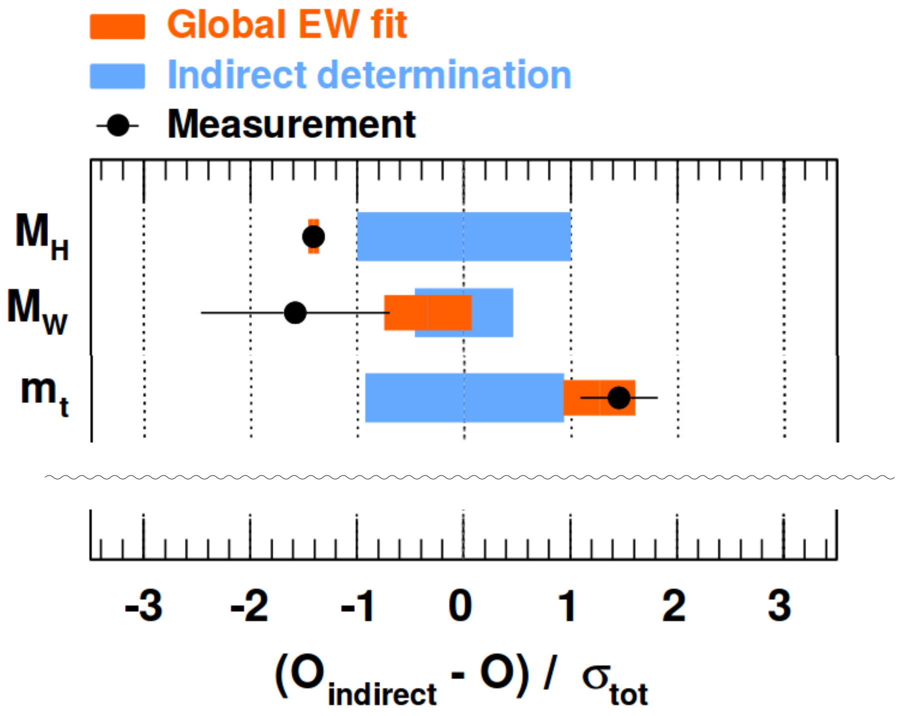
→

Improving precision will not increase sensitivity to new physics

Indirect determination of m_W (±8 MeV) is more precise than the experimental measurement

→

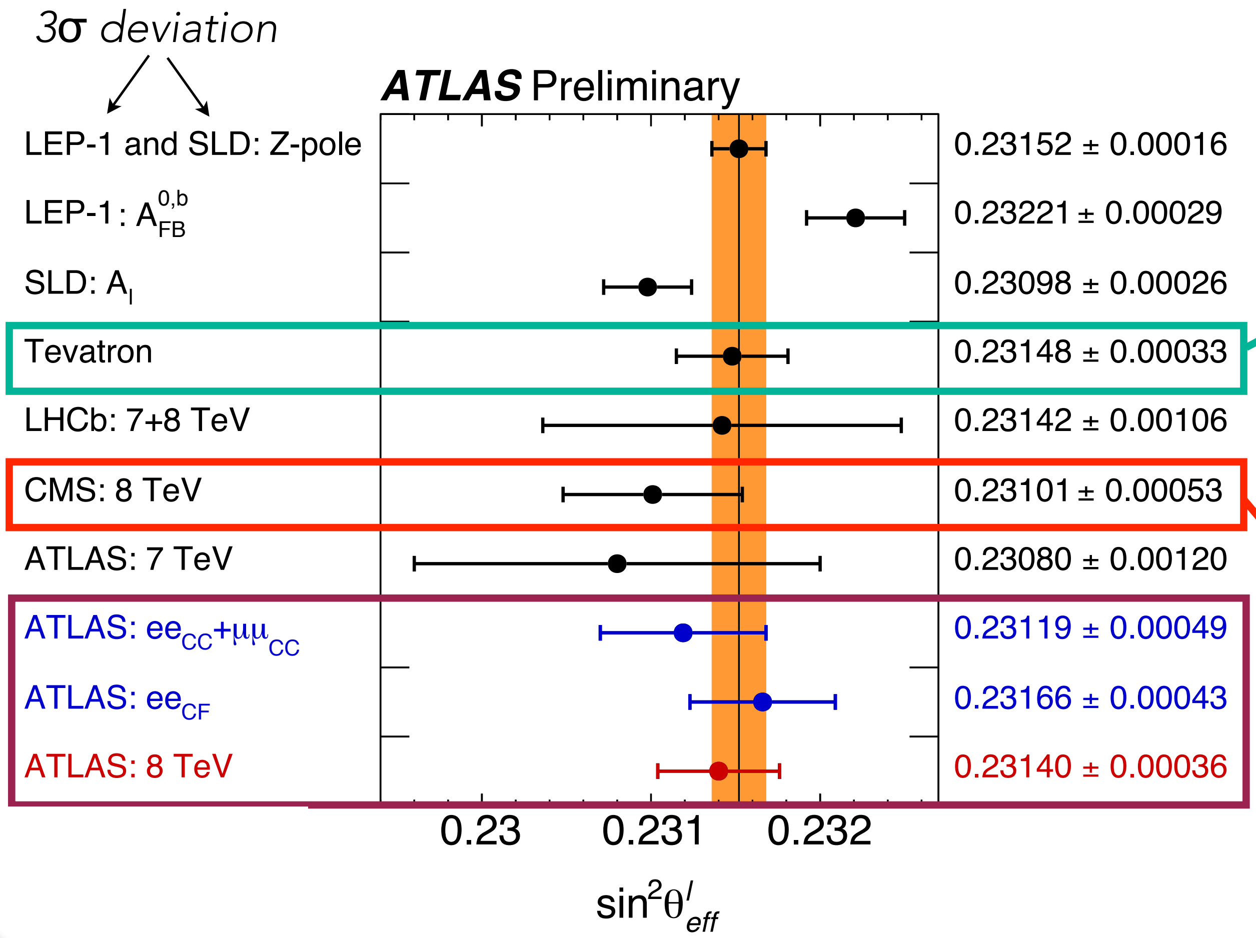
Call for $\delta m_W^{exp} < 10$ MeV

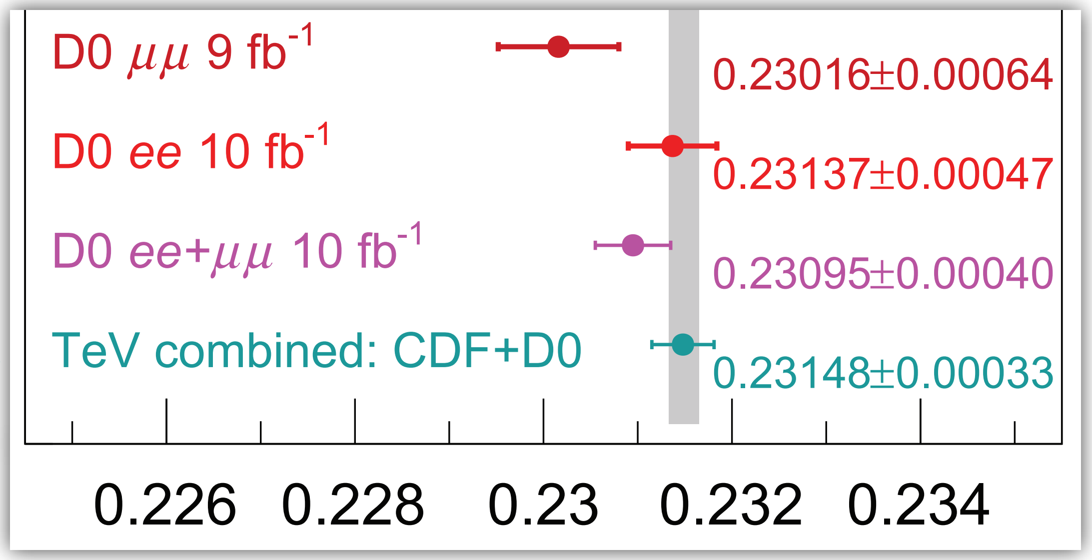


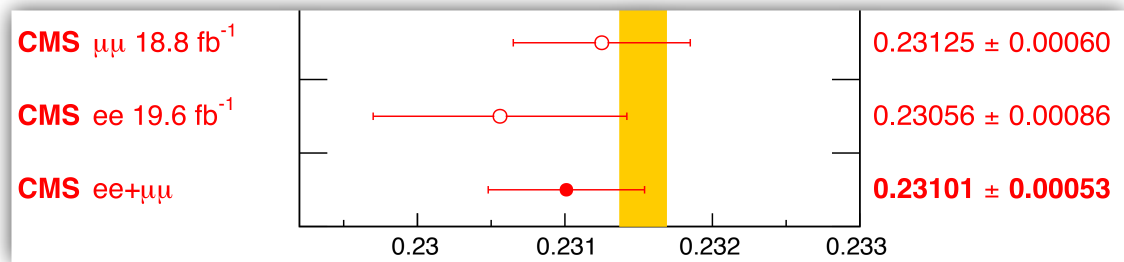
	Measurement	SM Prediction (*)
m_H	125.09 ± 0.24	102.8 ± 26.3
m_{top}	172.84 ± 0.70	176.6 ± 2.5
m_W	80.385 ± 0.015	80.360 ± 0.008

(*) arXiv:1608.01509

weak mixing angle @LHC





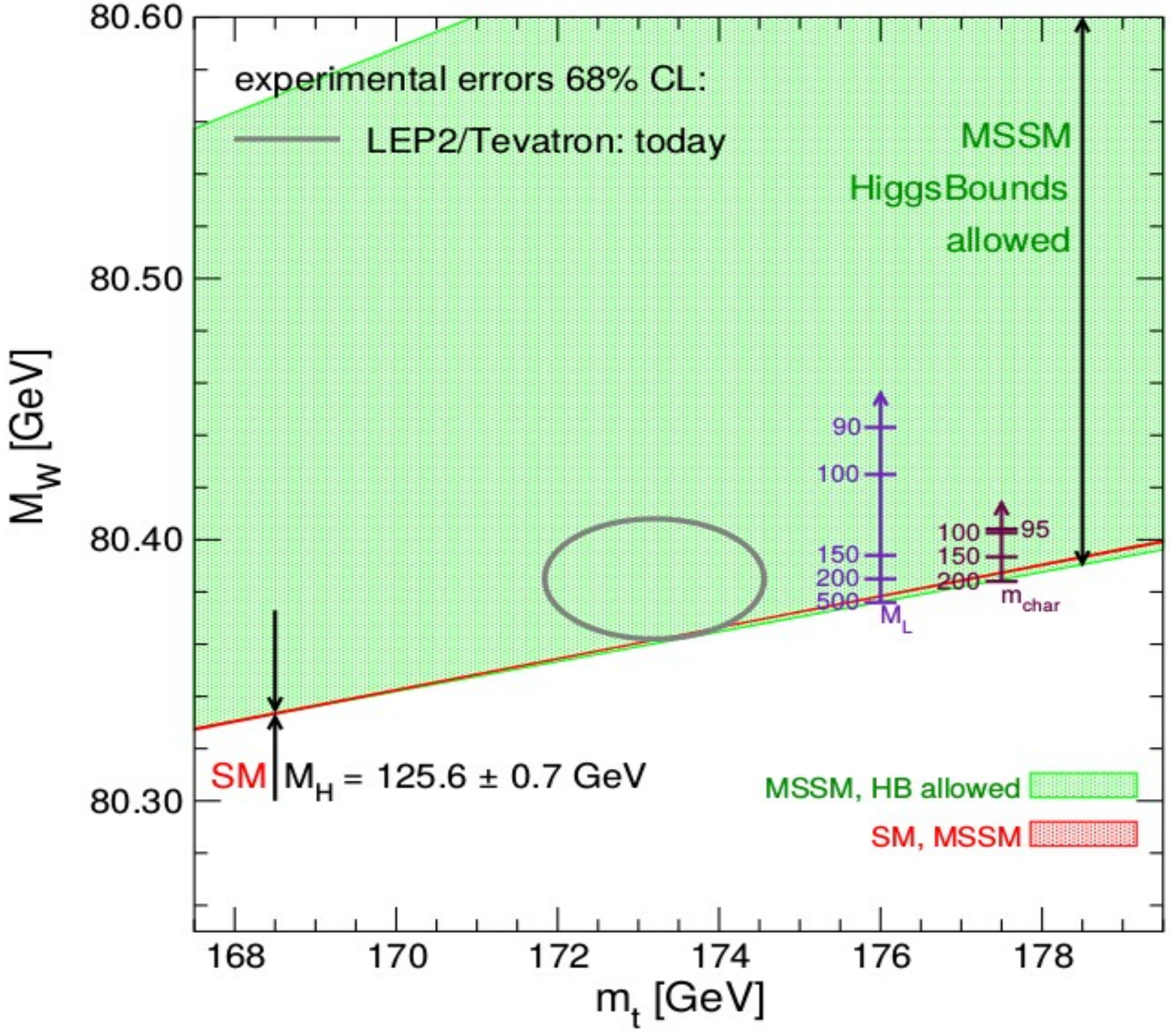


New analysis techniques, including in-situ PDF profiling and categorisation statistical and systematic uncertainties are significantly reduced relative to previous CMS and ATLAS measurements.

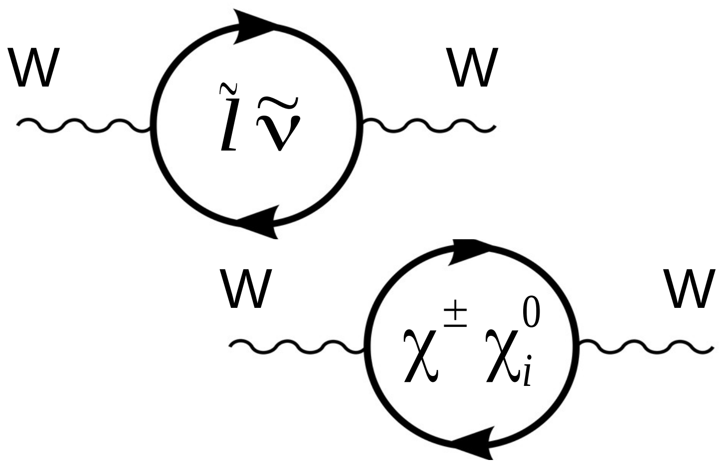
Approaching precision of Tevatron combination

SUSY scale

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



$$\Delta r = \Delta r^{SM} + \Delta r^{SUSY}$$



$\tilde{\nu}, \chi_1^0$: dark matter candidates

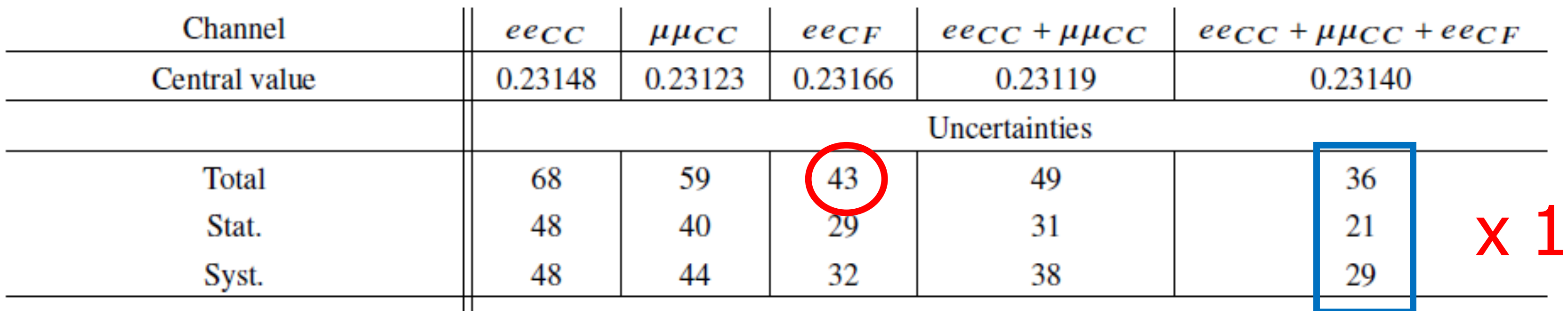
→ δm_W probes the scale of BSM physics

Ideally, δm_W < 10 MeV

How to approach the required sensitivity

(a) Excellent lepton performance:

- calibration: energy scale and resolution
    - In particular **forward electron** performance are very important and challenging

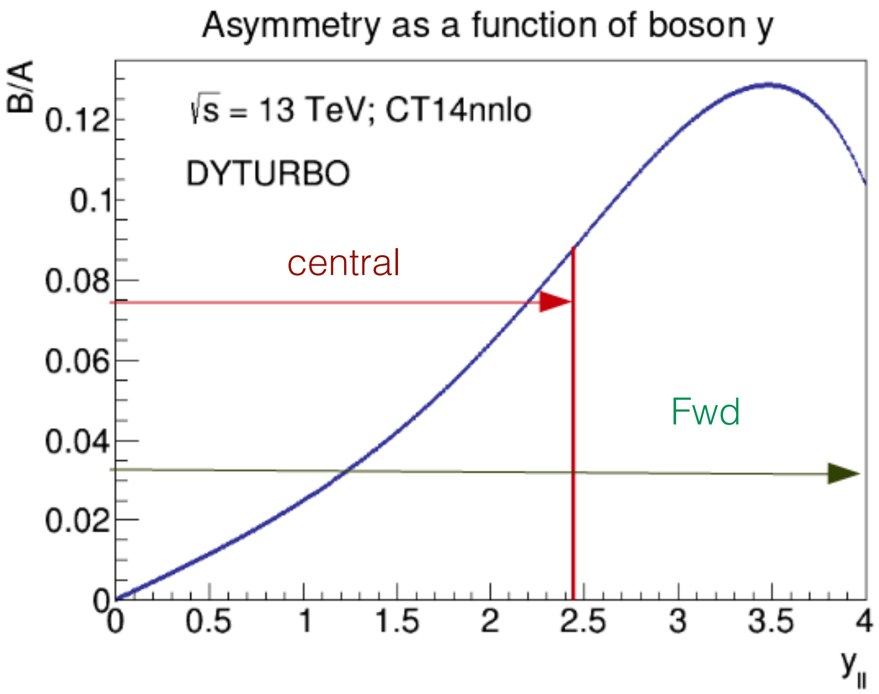


Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC}+\mu\mu_{CC}$	$ee_{CC}+\mu\mu_{CC}+ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
	Uncertainties				
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29

x 10^{-5}

ATLAS-CONF-2018-037 ee$_{CF}$ is most precise channel 1.5 M of events (13.5M ee+μμ) measurement uncertainty 36 x 10^{-5}

(b) Precise knowledge of the Z decay and production dynamics to constraint the main Theory uncertainty PDF.



The measurement will benefit from extended coverage in eta

Effective mixing angle from the lepton angular distributions

Factorized expression for Z boson production and decay at hadron colliders:

$$\frac{d^5\sigma}{dp_T^Z\, dy^Z\, dm^Z\, d\cos\theta\, d\phi}$$

Production

Decay

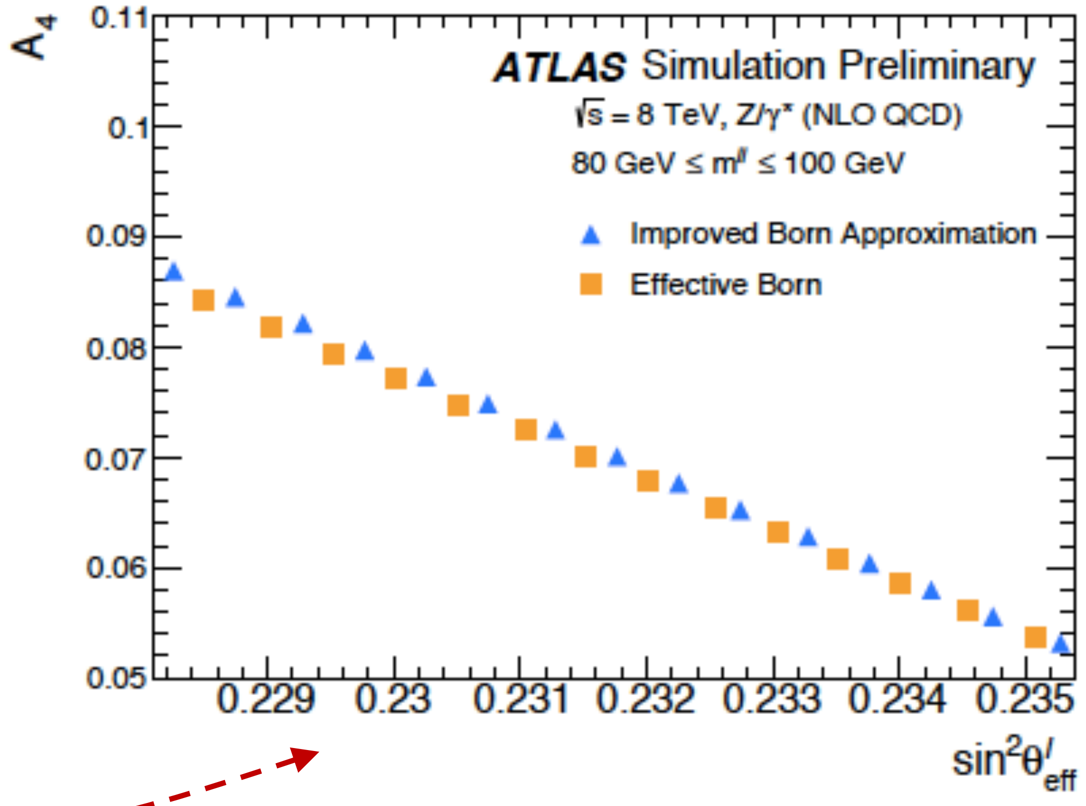
$$= \frac{3}{16\pi}\frac{d^3\sigma^{U+L}}{dp_T^Z\, dy^Z\, dm^Z}$$

$$\{\boxed{(1+\cos^2\theta)} + 1/2\ A_0(1-3\cos^2\theta) + A_1\ \sin 2\theta\ \cos\phi + 1/2\ A_2\ \sin^2\theta\ \cos 2\phi + A_3\ \sin\theta\ \cos\phi + \boxed{A_4\ \cos\theta} + A_5\ \sin^2\theta\ \sin 2\phi + A_6\ \sin 2\theta\ \sin\phi + A_7\ \sin\theta\ \sin\phi\}.$$

Unpolarized cross section

F/B asymmetry :

$A_4 = 8/3\ A_{FB} \sim a + b \sin^2\theta^l_{eff}$



PDF reweighting

- Bayesian Reweighting

  Discussion in the literature over weighting function to use:

  NNPDF: $w_i \propto \chi_i^{n-1} e^{-\frac{1}{2}\chi_i^2}$ See eg NNPDF collab., Nucl. Phys B 855, 608 (2012)

  Giele and Keller; Sato et al.: $w_i \propto e^{-\frac{1}{2}\chi_i^2}$ See eg Sato *et al*., Phys. Rev. D 89, 114020 (2014) and A. Bodek *et al.* EPJC76:115 (2016)

- PDF profiling See eg Paukkunen and Zurita, JHEP12(2014)100
  - More typically used with Hessian sets – mathematically can be shown as providing equivalent results to Giele and Keller weights in Bayesian reweighting.

- This `discrepancy of approach' within reweighting has not disappeared – the two weighting approaches – G&K and NNPDF – can give significantly different results, especially when reweighting gives large reductions in PDF uncertainty.
- In addition, we do not use "tolerances" when reweighting, so *we give our data more weight than the data used in the global fits*.

Forward-Backward asymmetry

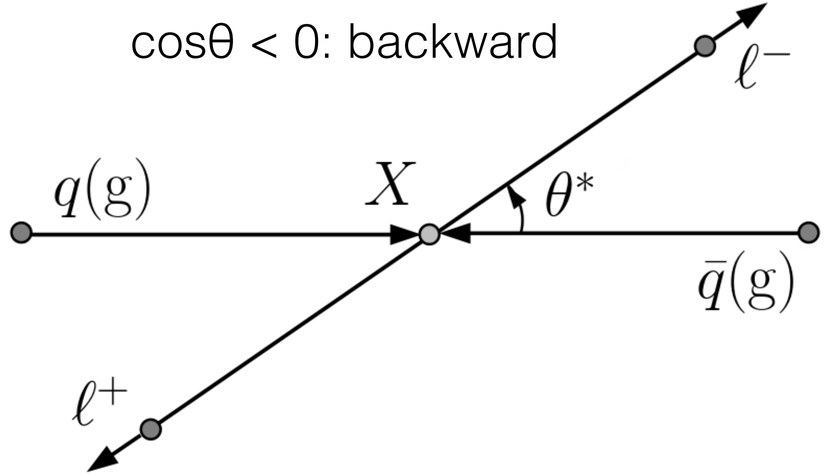
- The Drell-Yan production cross section as function of the scattering angle θ.

$$\frac{d\sigma}{d\cos\theta} = \frac{4\pi\alpha^2}{3s}\left[\frac{3}{8}(A(1+\cos^2\theta) + B\cos\theta\right]$$

$$B = -4Q_l g_A^q g_A^l \chi_1 + 8 g_A^q g_V^q g_A^l g_V^l \chi_2 \,,$$

B ~ Z/γ* and V-A interference

cosθ > 0: forward
cosθ < 0: backward



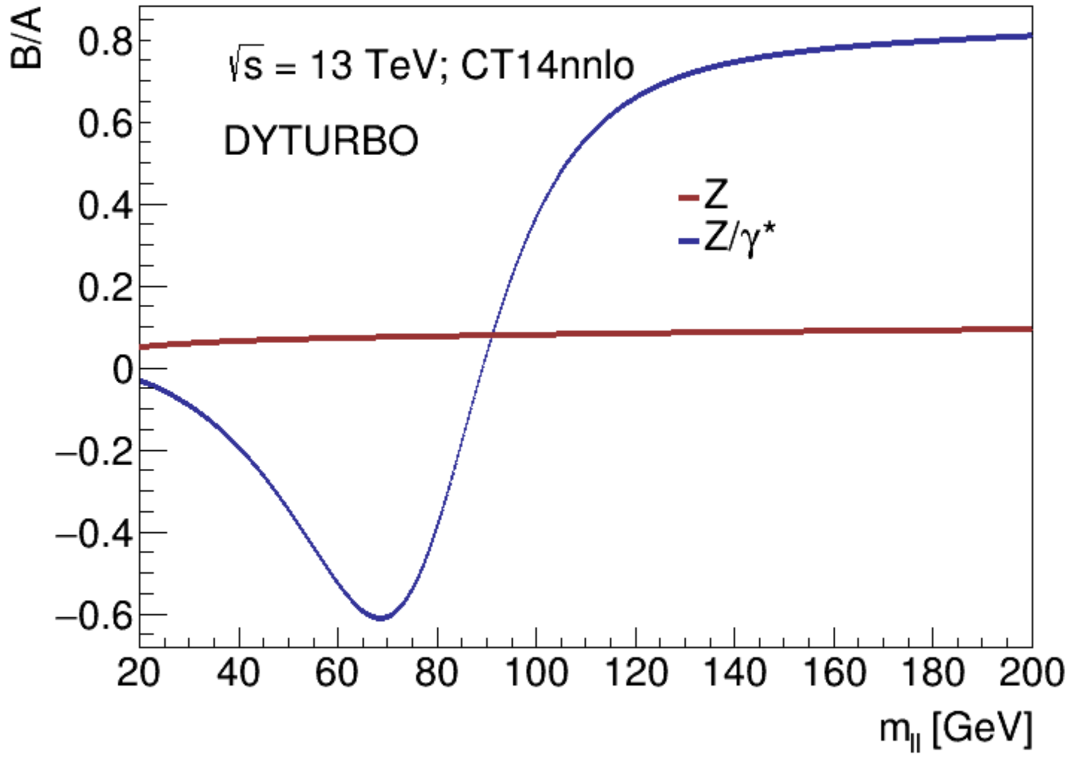
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8}\frac{B}{A}$$

- Linear term in cos(θ) give rise to non-vanishing forward-backward asymmetry
- The V-A interference contribution is proportional to g_V g_A, and depends on the weak mixing angle θ_W

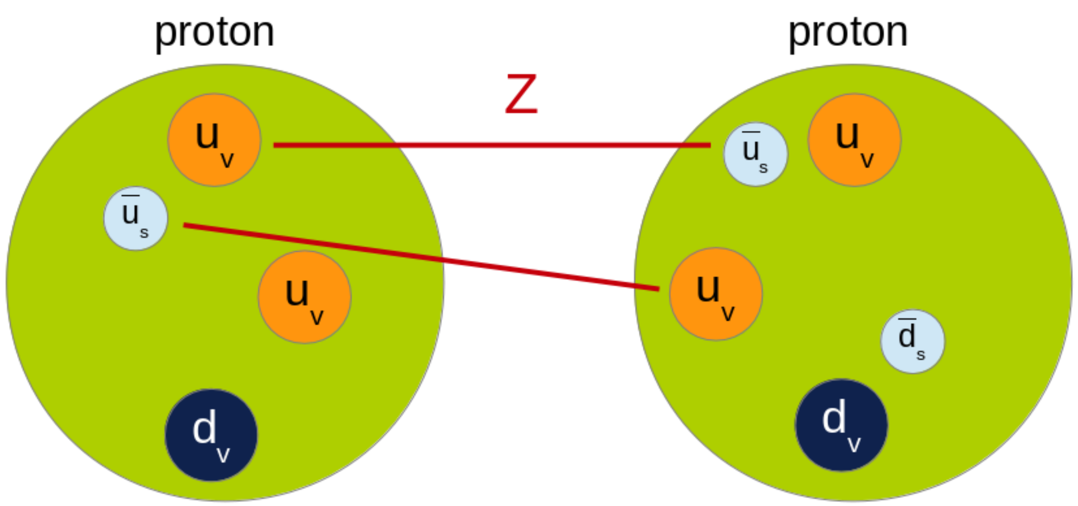
$$g_V^f = T_3^f - 2Q_f \sin^2\theta_W$$

- The Z/γ* interference contribution is proportional to (s - m_Z^2)

➡ A_{FB} changes sign at the Z pole

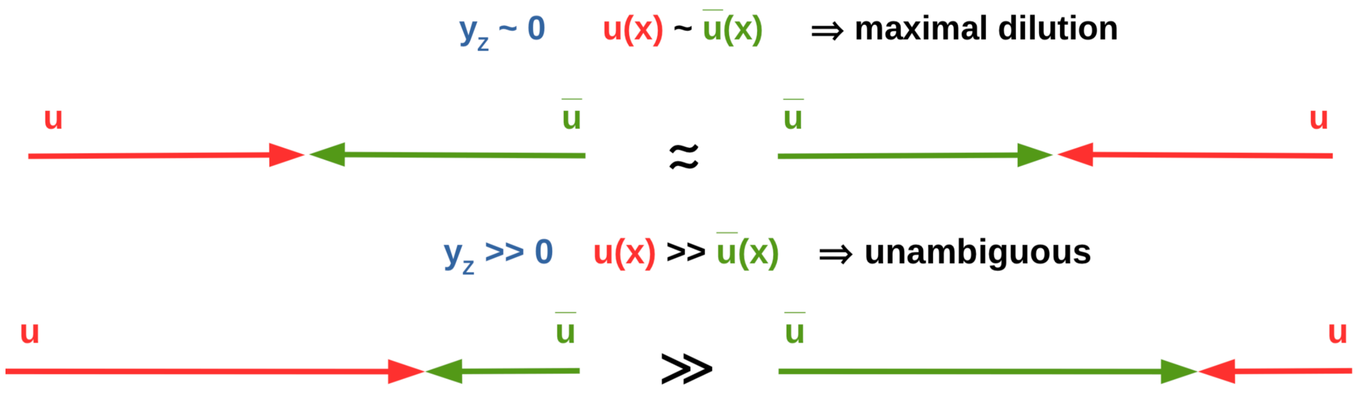


Z forward-backward asymmetry@LHC



- The orientation of the incoming quark is unknown
  - Use θ* scattering angle defined in the Collins-Soper frame, with z-axis orientation defined by the Z rapidity
- In pp collisions, it is more likely to be in the same orientation as the Z boson, due to the u/ubar and d/dbar valence asymmetry

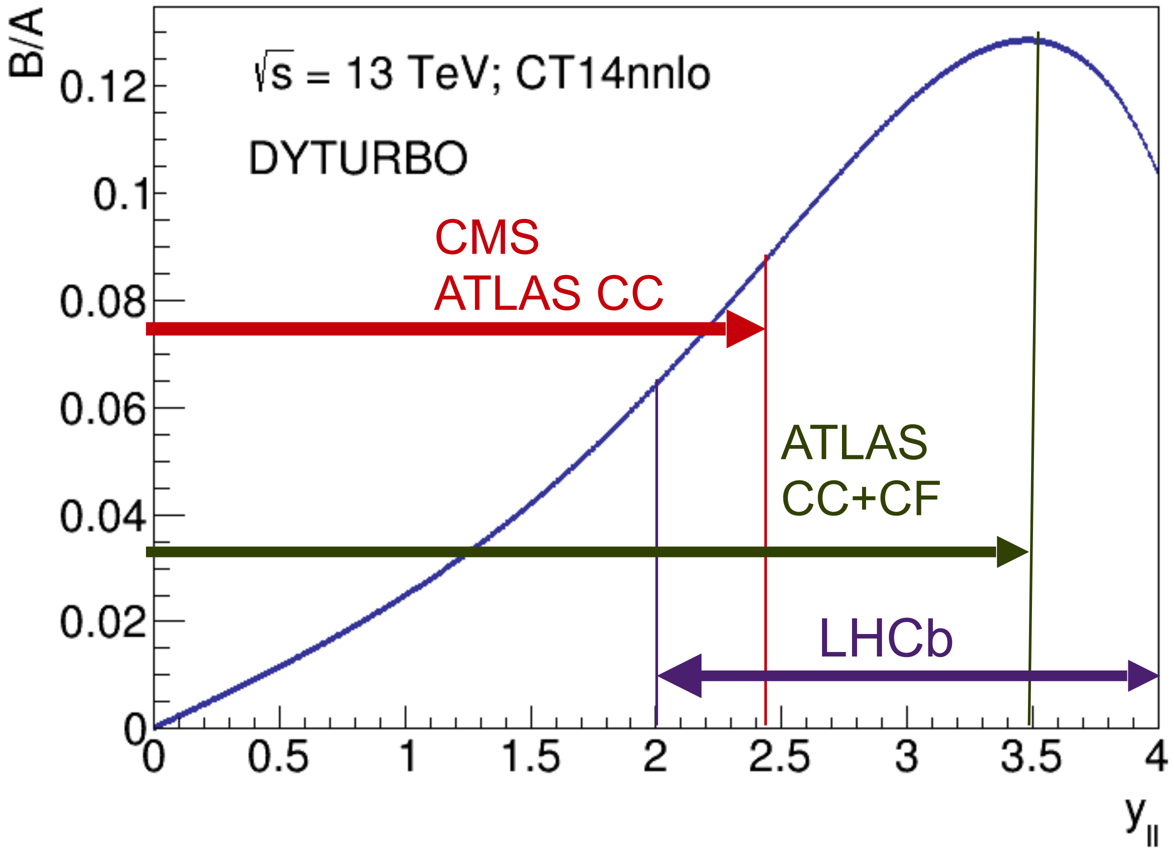
Challenge for LHC



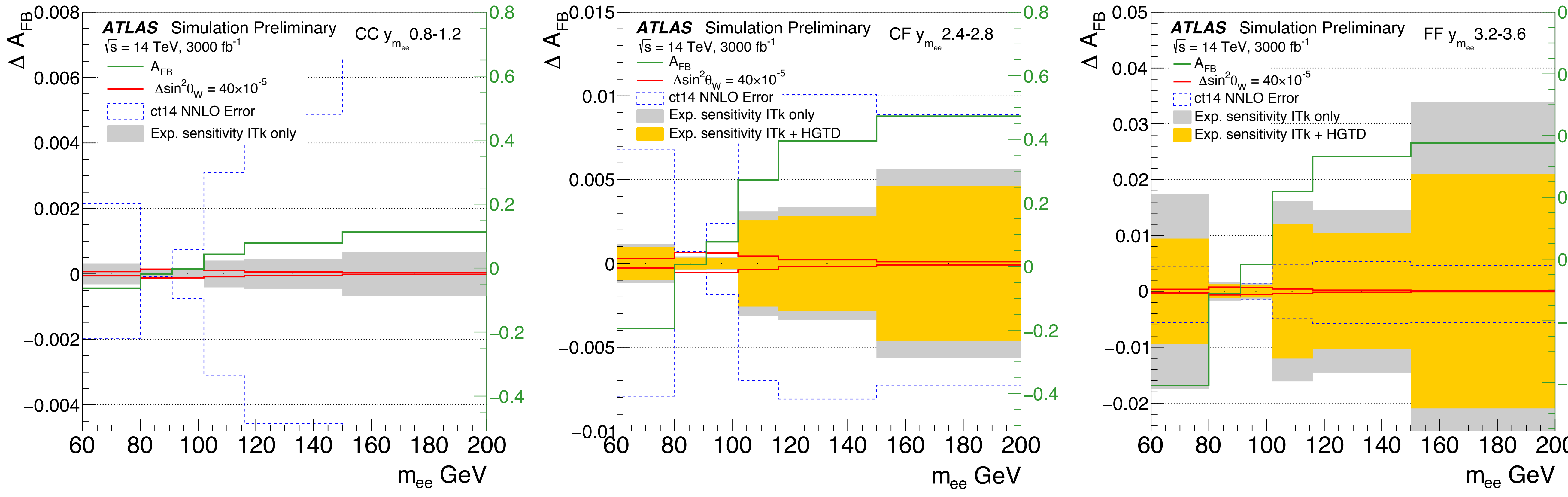
$y_z \sim 0$ $u(x) \sim \bar{u}(x)$ ⇒ maximal dilution

$y_z \gg 0$ $u(x) \gg \bar{u}(x)$ ⇒ unambiguous

Asymmetry as a function of boson y



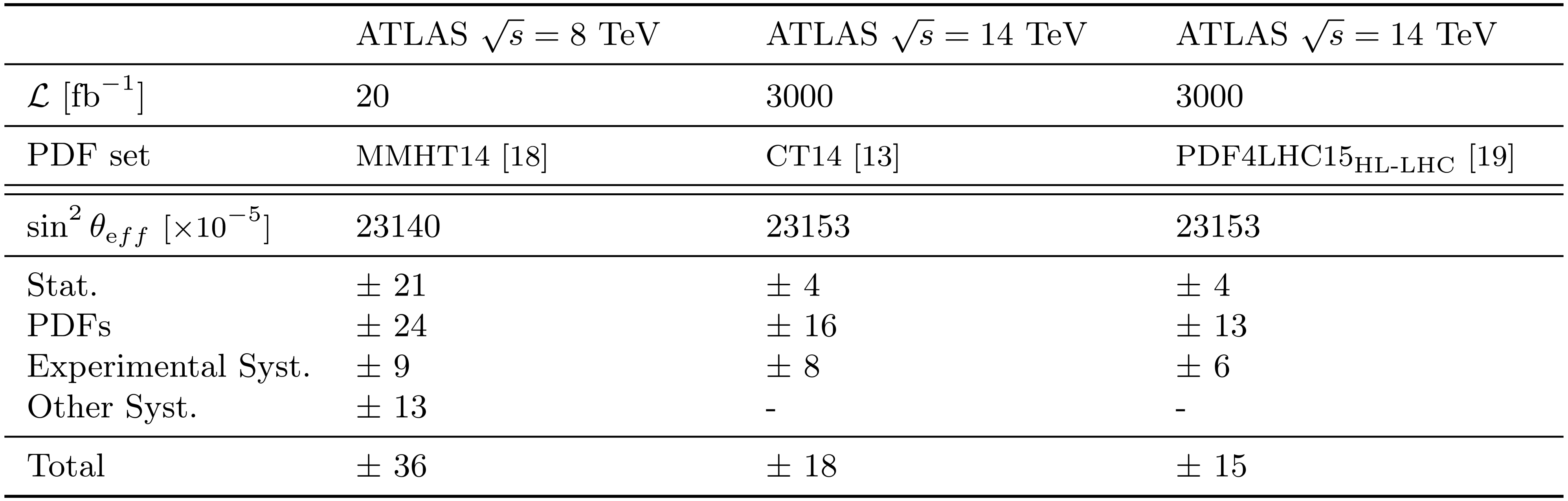
AFB Particle level CT14NNLO



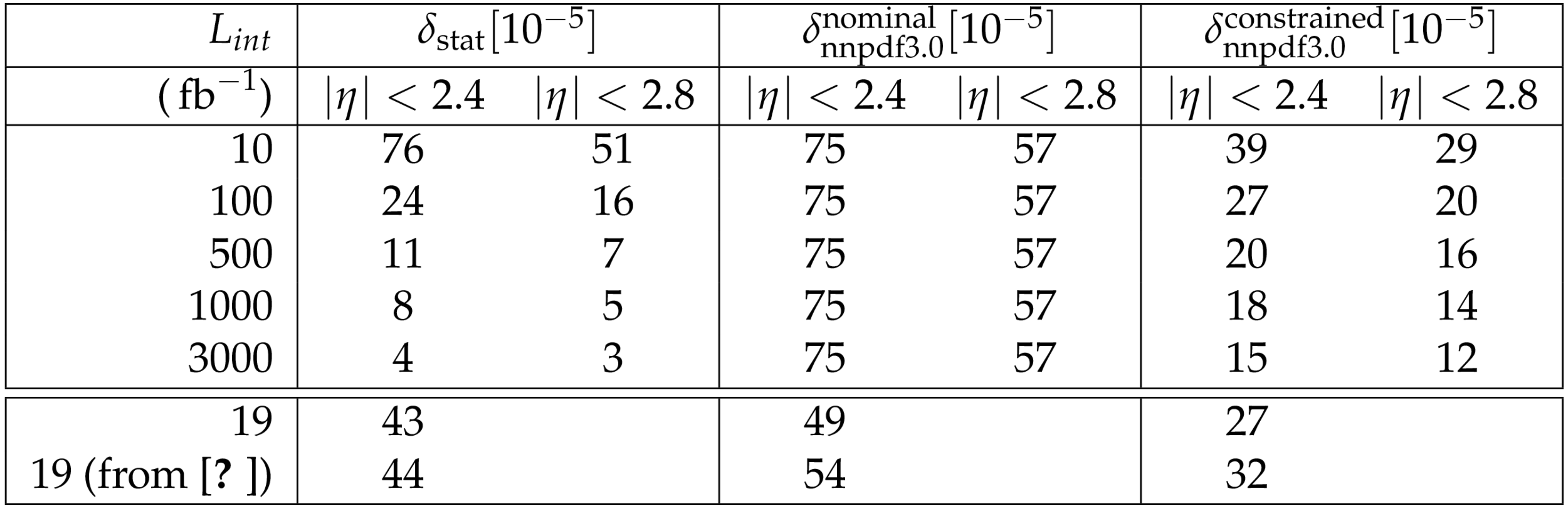
(a) Central-central (CC) (b) Central-forward (CF) (c) Forward-forward (FF)

- The expected sensitivity to particle level A_{FB} as a function of m_{ee} for each channel for a chosen rapidity bin.
- PDF band correspond to PDF uncertainty without inset constraint.
  - The imperfect knowledge of the PDF results in sizeable uncertainties in A_{FB}, in particular in regions where the absolute value of the asymmetry is large, i.e. at high and low m_{ll}. On the contrary, near the Z boson mass peak, the effect of varying $\sin^2\theta_{eff}$ is maximal, while being significantly smaller at high and low masses.

weak mixing angle @HL-LHC

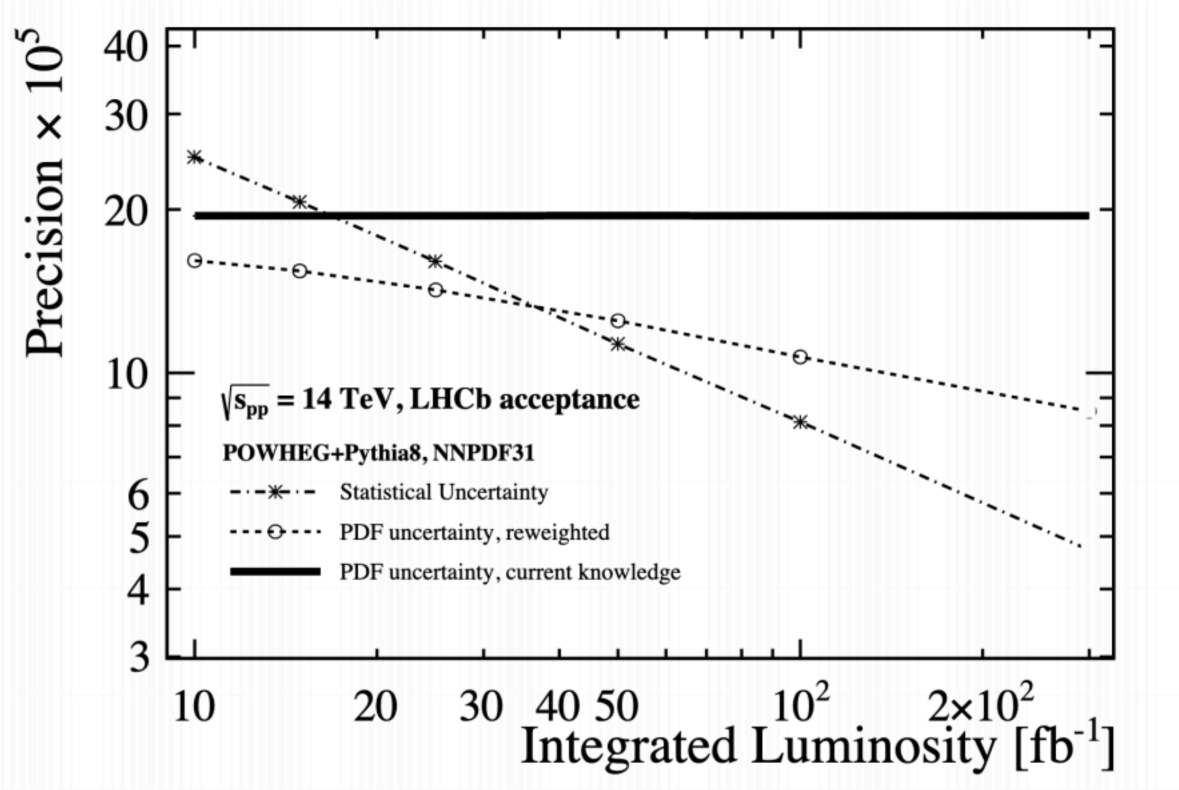


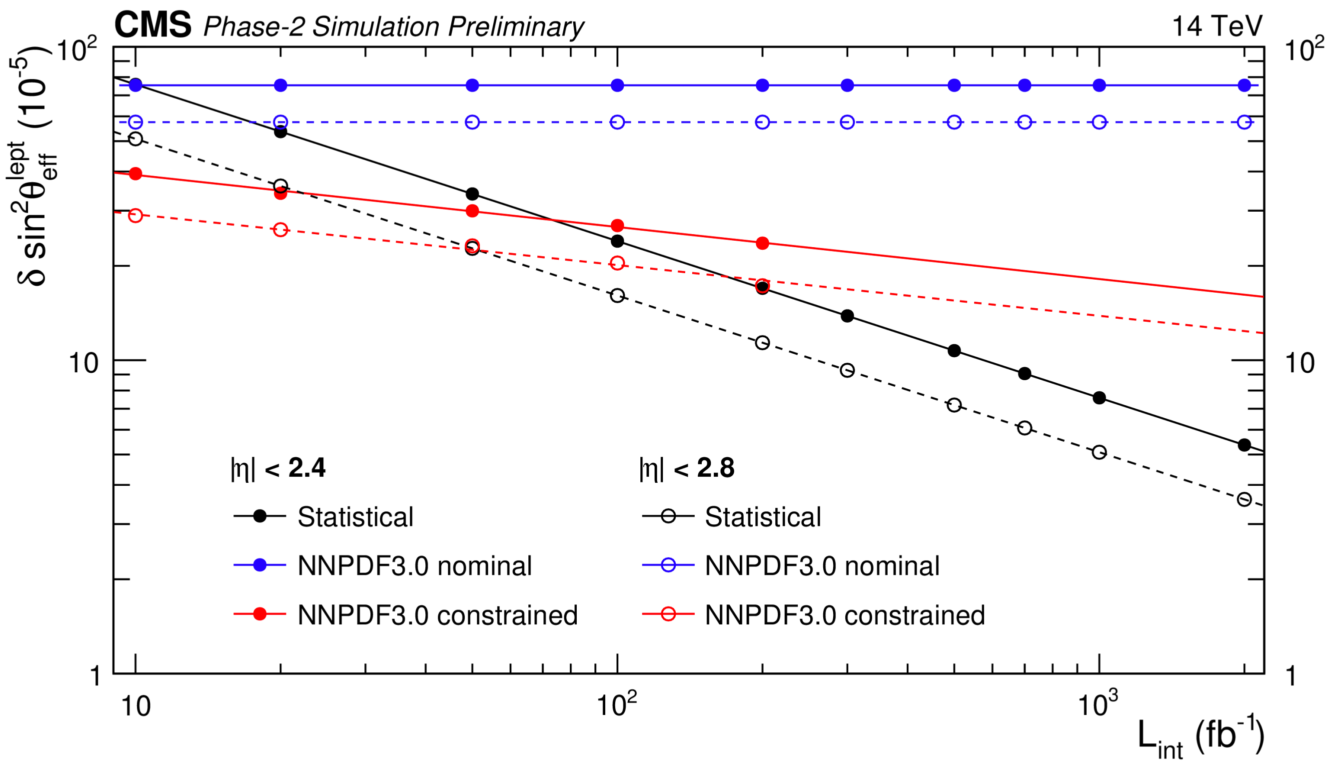
	ATLAS $\sqrt{s} = 8$ TeV	ATLAS $\sqrt{s} = 14$ TeV	ATLAS $\sqrt{s} = 14$ TeV
$\mathcal{L}$ [fb^{-1}]	20	3000	3000
PDF set	MMHT14 [18]	CT14 [13]	PDF4LHC15$_{\text{HL-LHC}}$ [19]
$\sin^2\theta_{eff}$ [$\times 10^{-5}$]	23140	23153	23153
Stat.	± 21	± 4	± 4
PDFs	± 24	± 16	± 13
Experimental Syst.	± 9	± 8	± 6
Other Syst.	± 13	-	-
Total	± 36	± 18	± 15

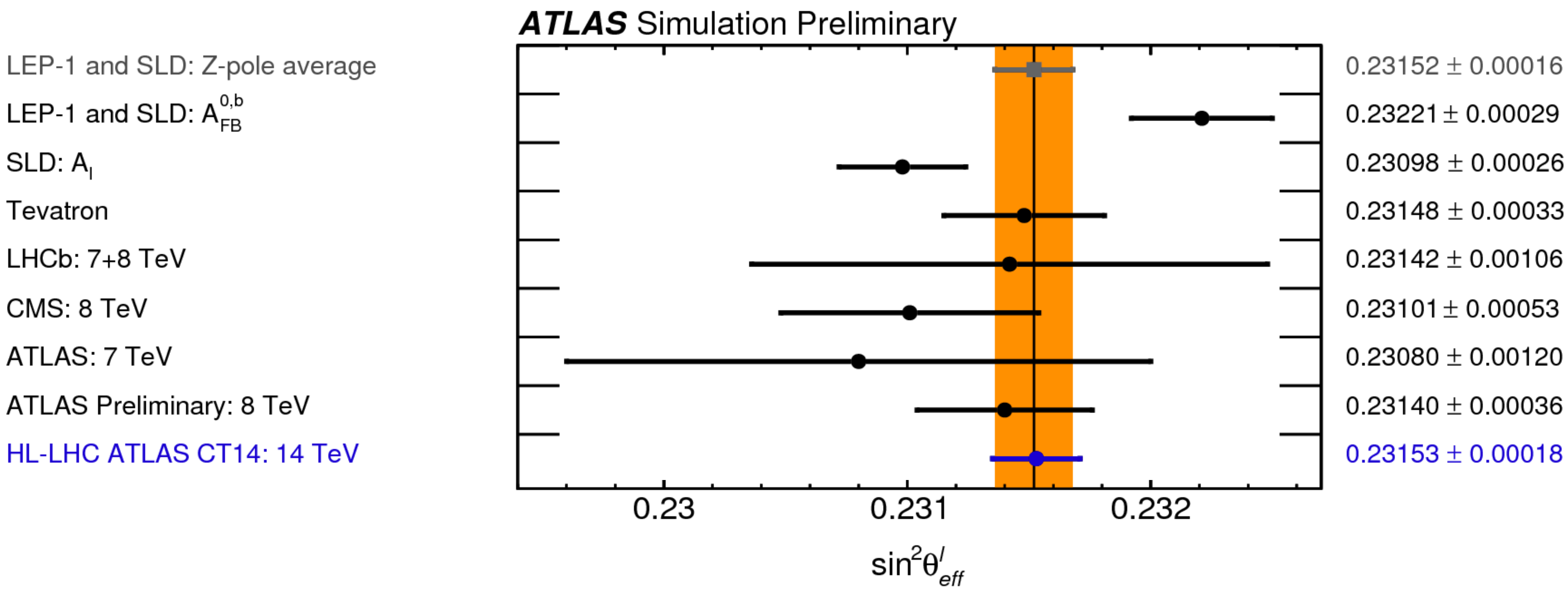


L_{int}	$\delta_{\text{stat}}[10^{-5}]$		$\delta^{\text{nominal}}_{\text{nnpdf3.0}}[10^{-5}]$		$\delta^{\text{constrained}}_{\text{nnpdf3.0}}[10^{-5}]$	
(fb^{-1})	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.8$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.8$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.8$
10	76	51	75	57	39	29
100	24	16	75	57	27	20
500	11	7	75	57	20	16
1000	8	5	75	57	18	14
3000	4	3	75	57	15	12
19	43		49		27	
19 (from [?])	44		54		32	

PDF reweighting and prospect of the results





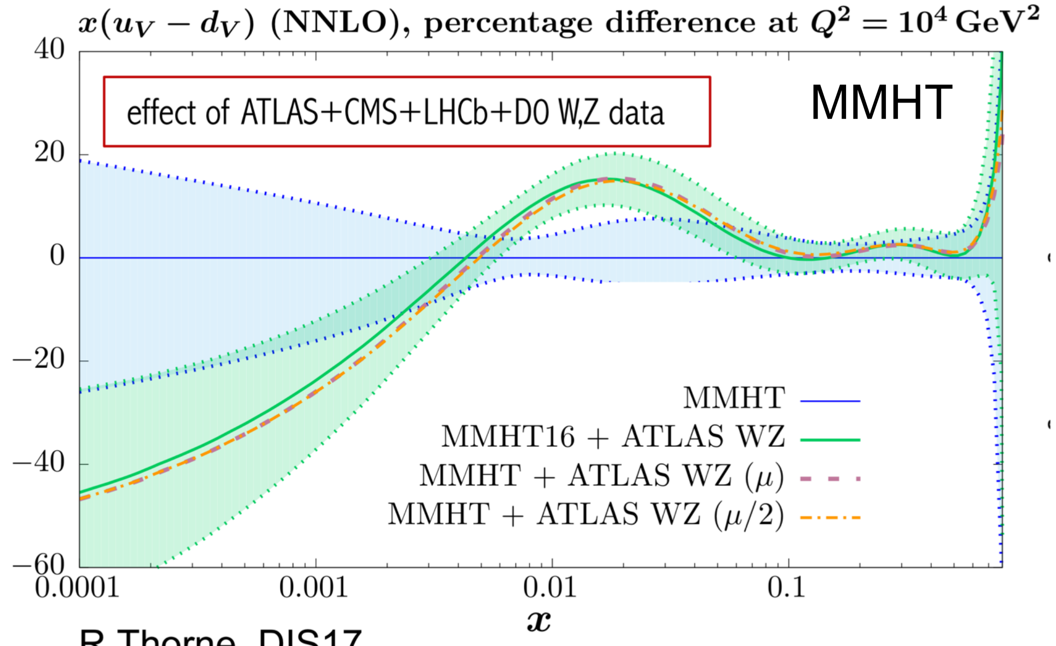


constraining PDFs with LHC data

LHC data has extensive and growing portfolio of pdf-sensitive measurements.

measurements of same process at different CM energies, and ratio measurements (EG. of different processes, or same process at different energies) with partially cancelling systematics can provide significant pdf constraints

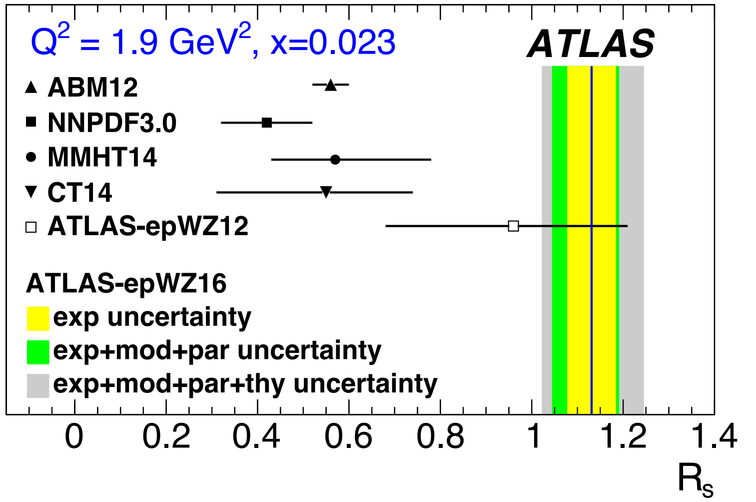
NNLO QCD calculations available for important physics processes – developments in grid technology (APPLfast) mean these data should be useable in rigorous NNLO pdf fits in the near future



R.Thorne, DIS17

→ ATLAS-epWZ16 pdf (available on lhapdf)

$$R_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)} \begin{cases} \approx 0.5 \text{ (from neutrino)} \\ \approx 1.0 \text{ (from ATLAS W,Z)} \end{cases}$$



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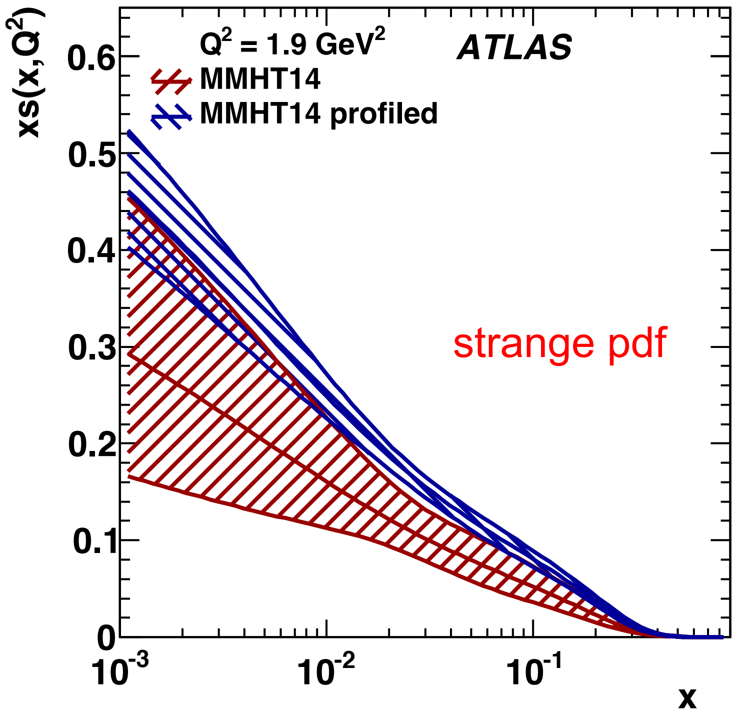
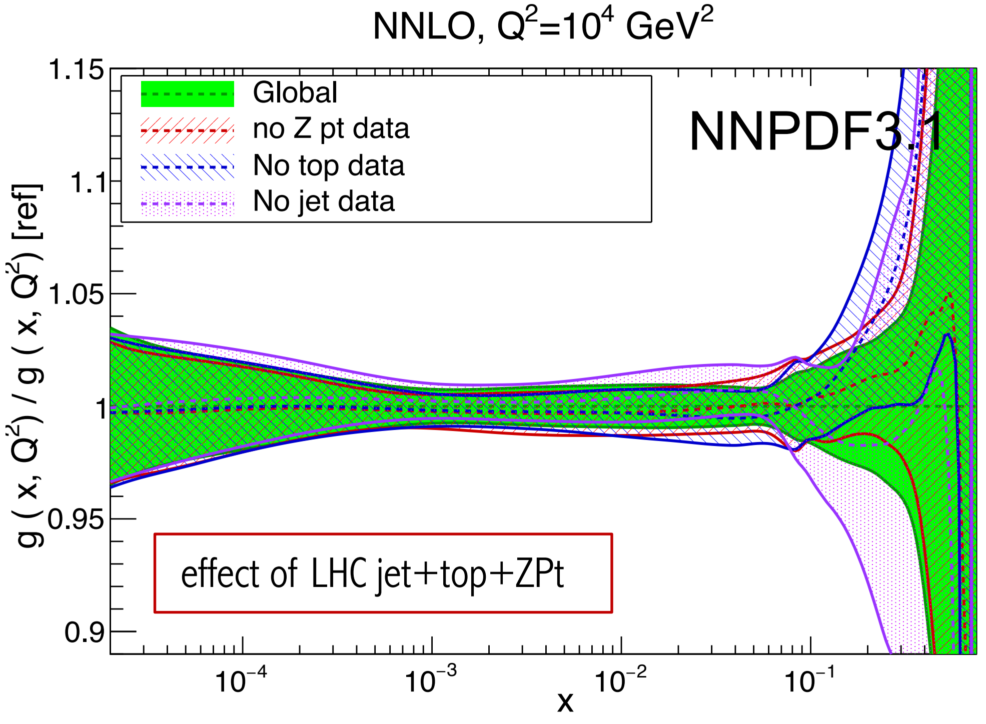




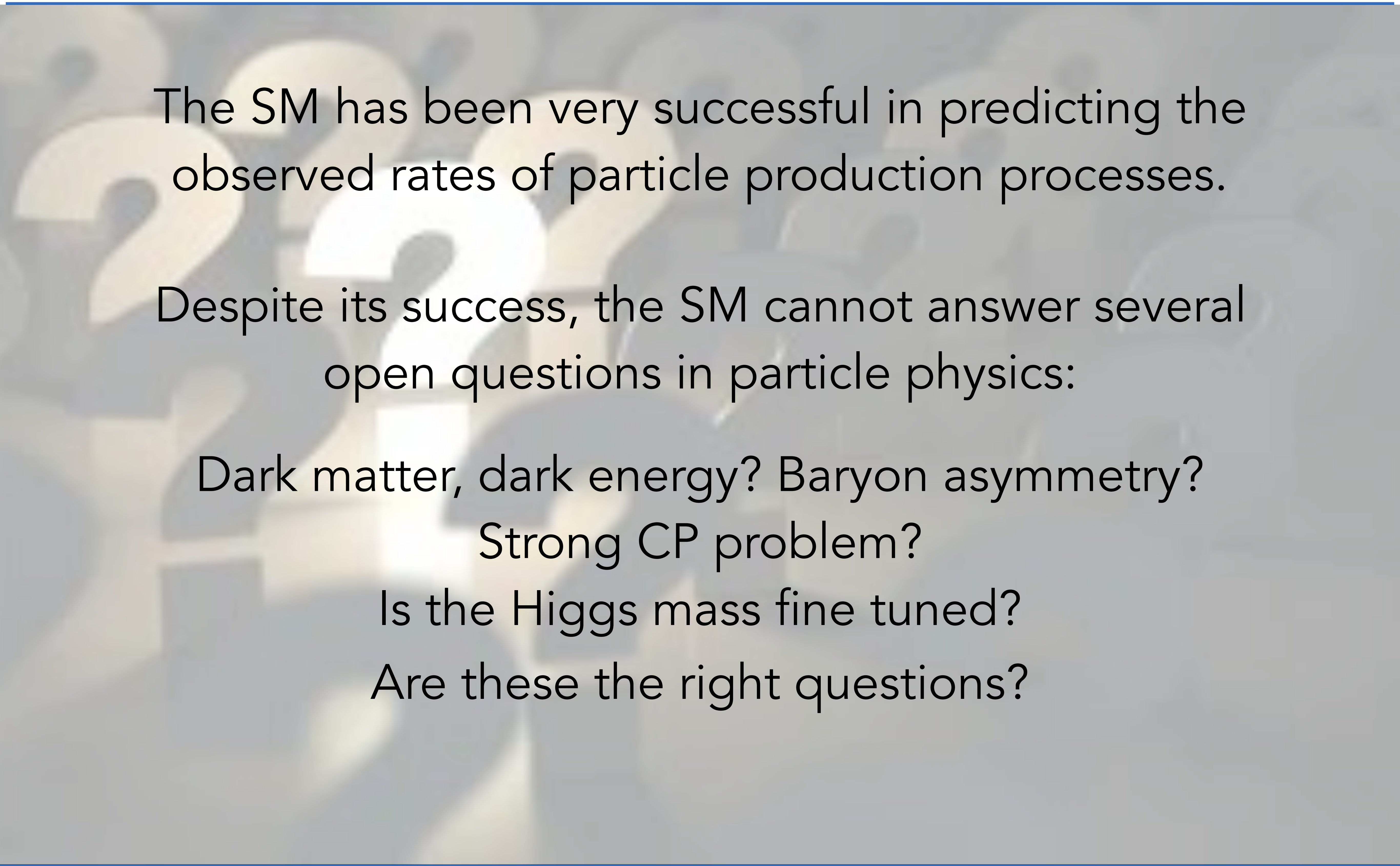
EPJ C77 (2017), 663

SM Physics Measurement

SM measurements play essential roles in testing our current understanding of the laws that govern the universe.

1. Measurements of the SM at LHC are looking at unexplored territory
   - Testing the validity of SM in challenging & previously unaccessible regions
     - High energy, rare processes
     - Difficult modelling: high-order/EW corrections
   - Tune MC generators, constraints PDFs, ...
2. Constrain, or observe, new physics contributions
   - Rare production processes
   - Processes sensitive to anomalous couplings
3. Background to all direct searches & Higgs measurements

Open questions

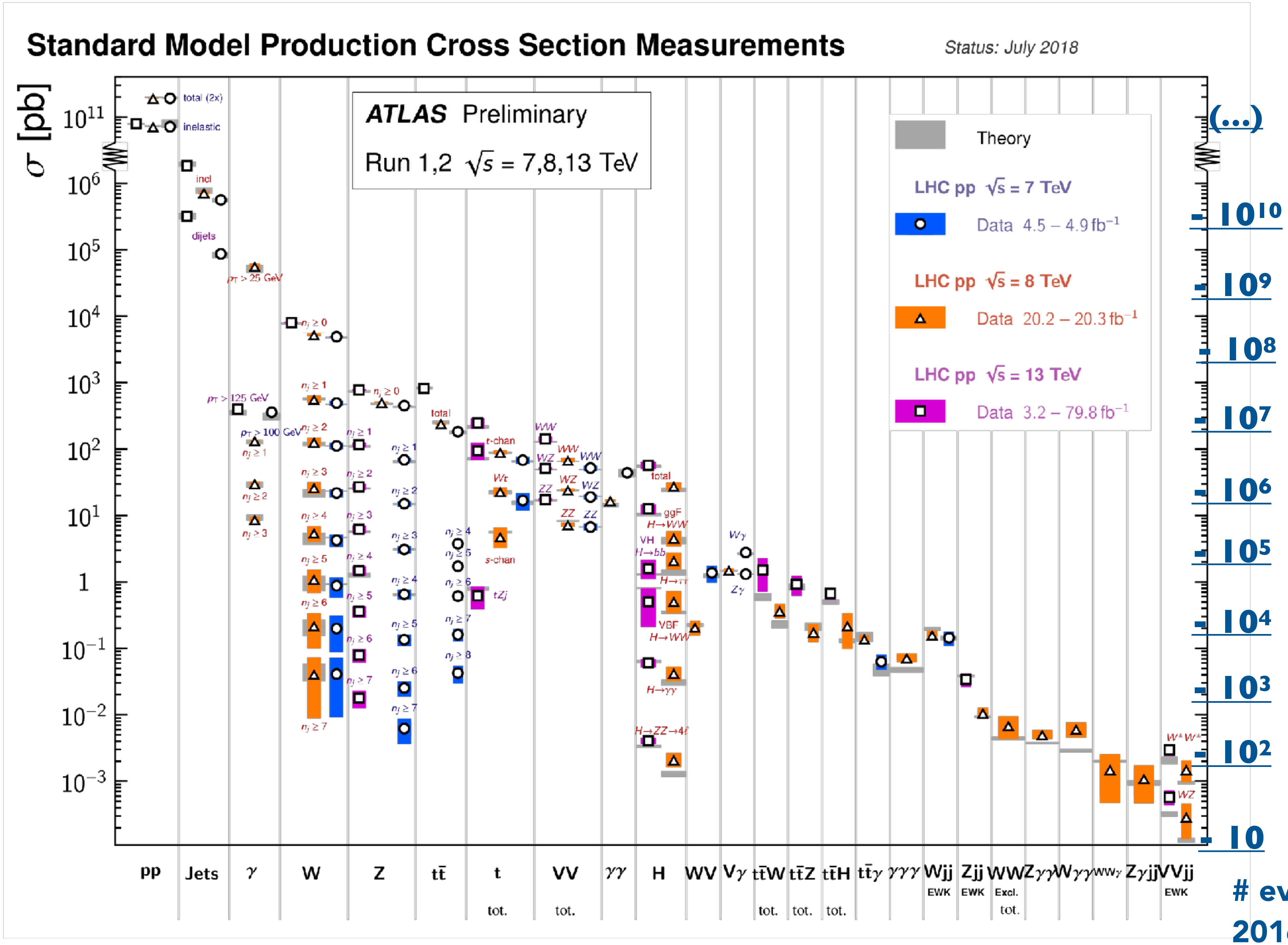


The SM has been very successful in predicting the observed rates of particle production processes.

Despite its success, the SM cannot answer several open questions in particle physics:

Dark matter, dark energy? Baryon asymmetry?
Strong CP problem?
Is the Higgs mass fine tuned?
Are these the right questions?

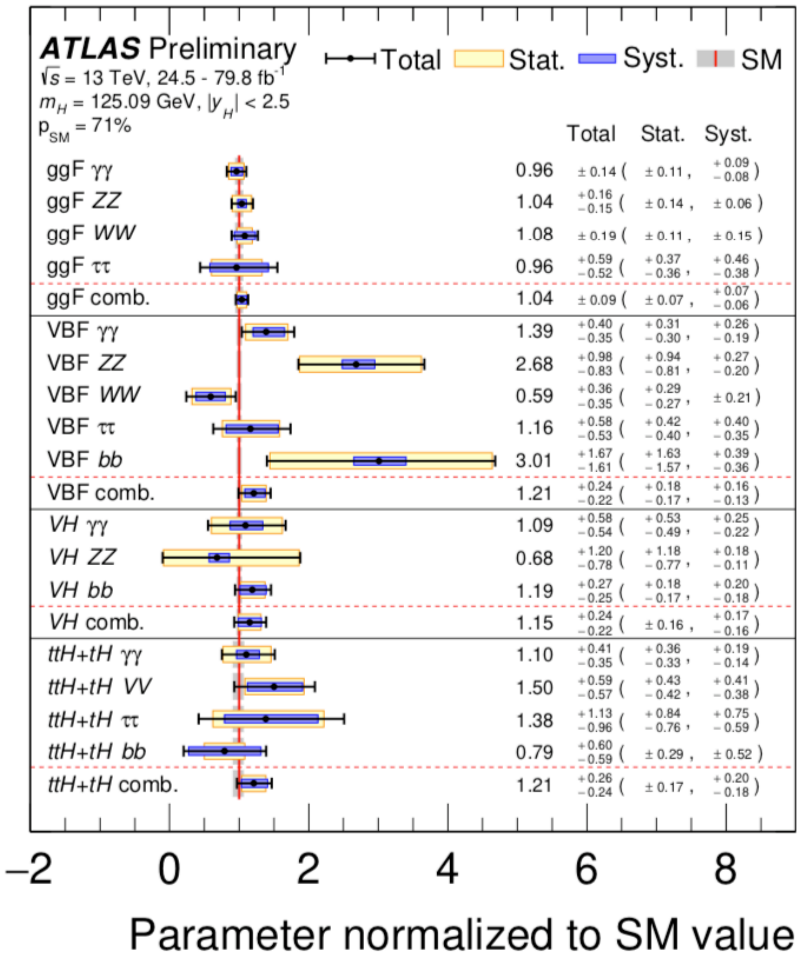
SM measurements validity range



 # events in 2016 dataset

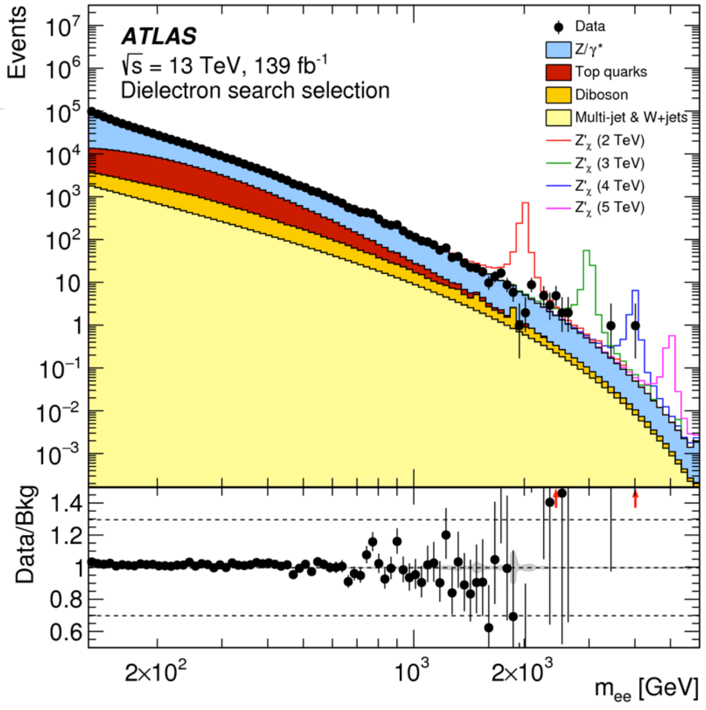
Direct searches

ATLAS-CONF-2019-005

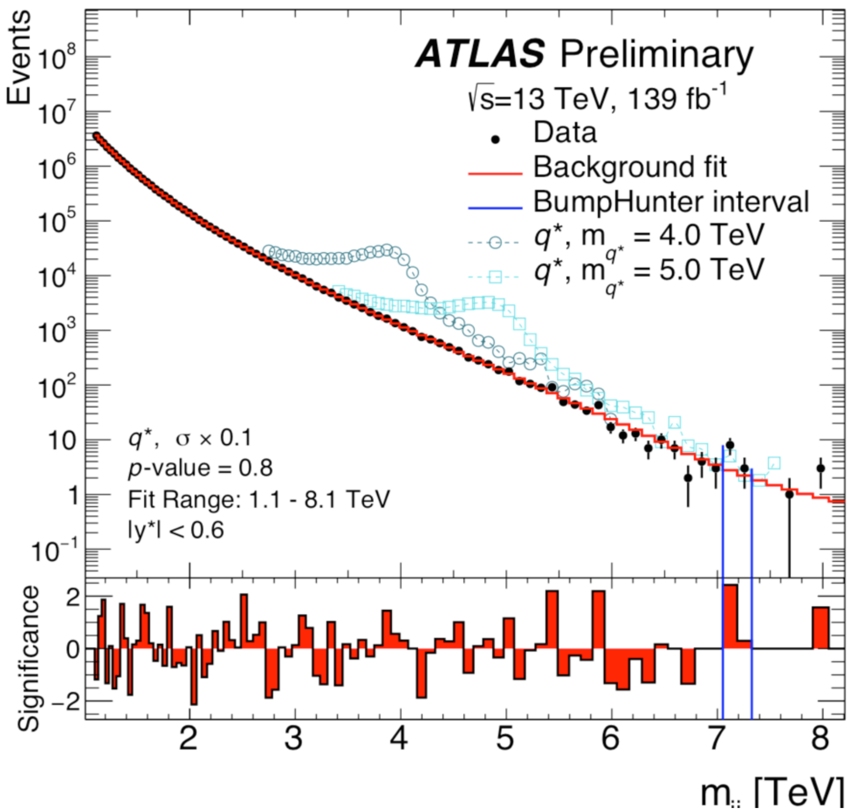


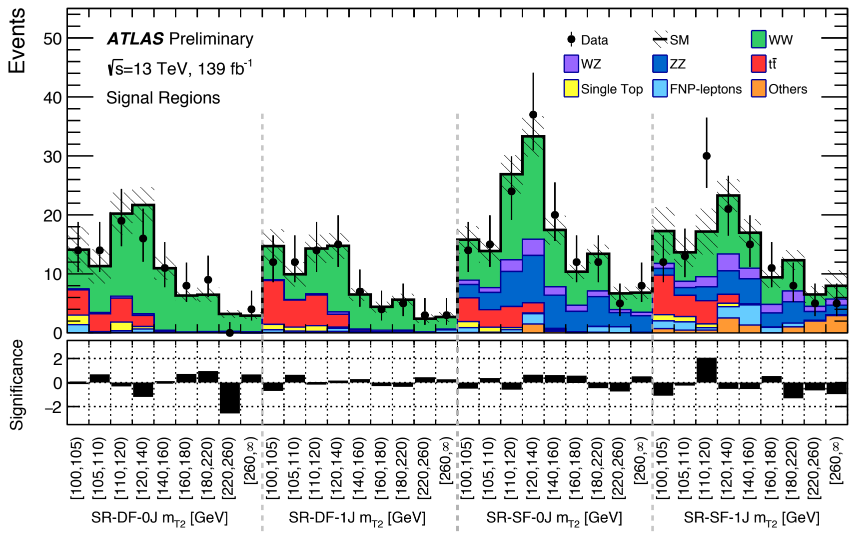
First full combination based on template cross sections (reduced theory uncertainty)

arXiv:1903.06248

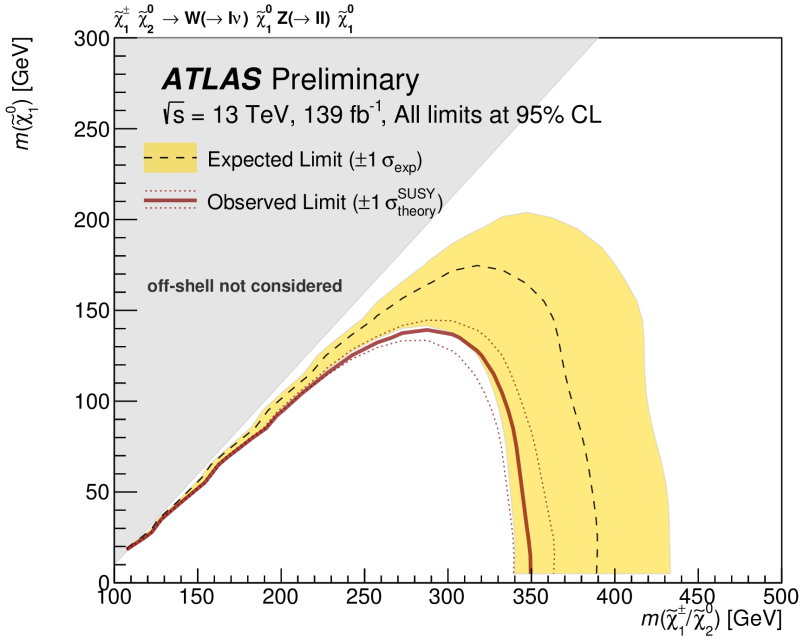


ATLAS-CONF-2019-007





Chargino / neutralino search; good agreement between data and SM expectations



Excess in tri-lepton channel in 2015-2017 data not confirmed