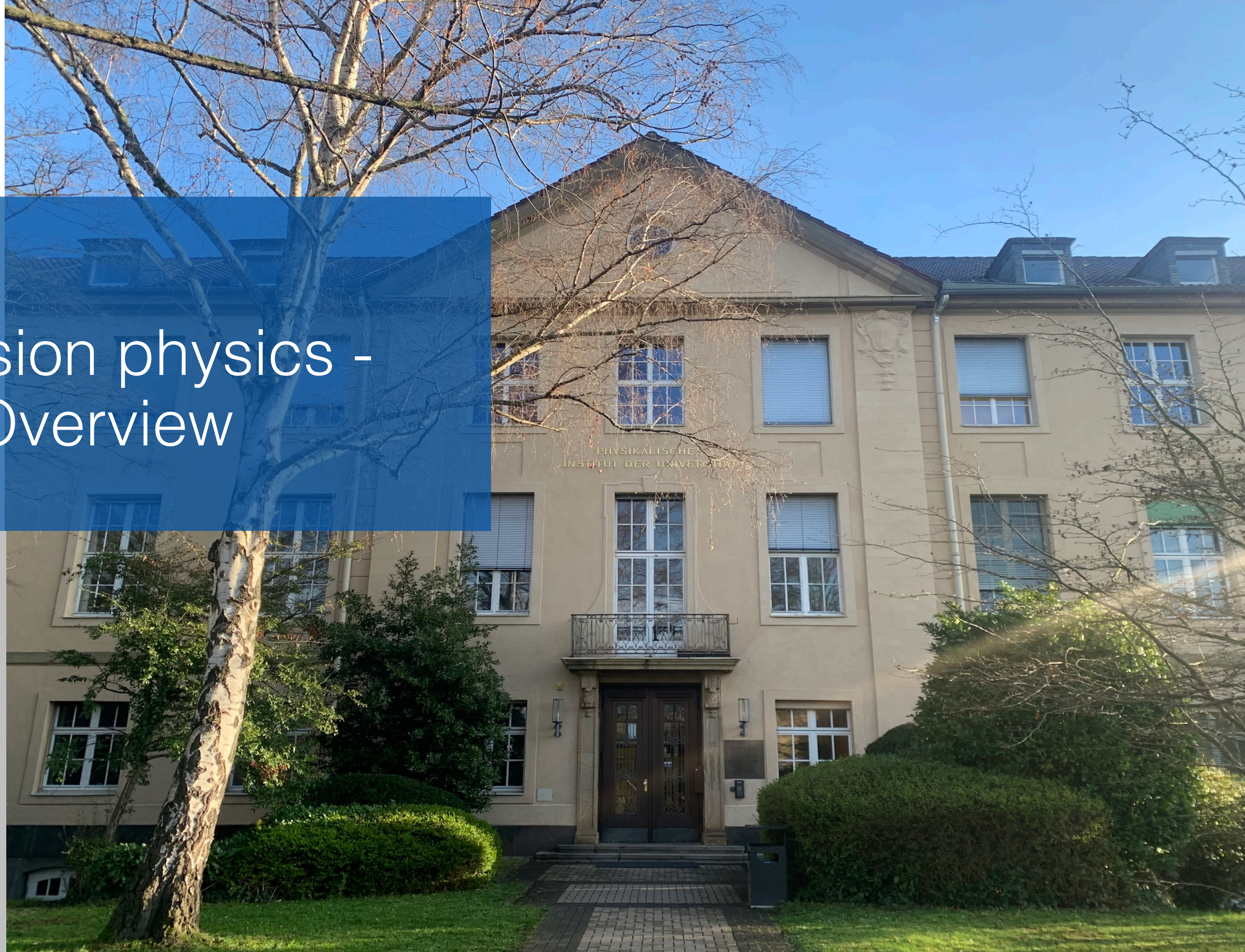




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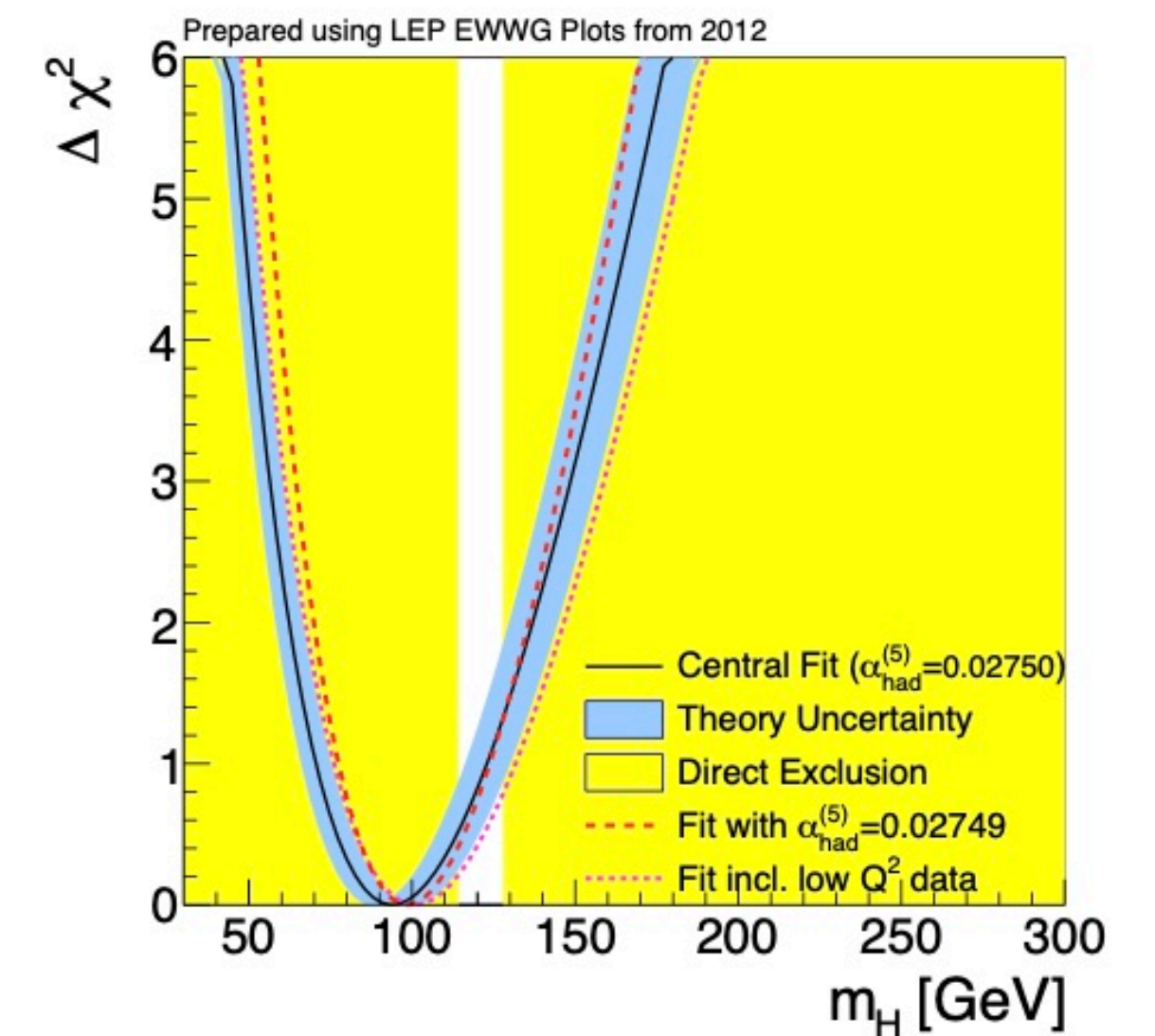
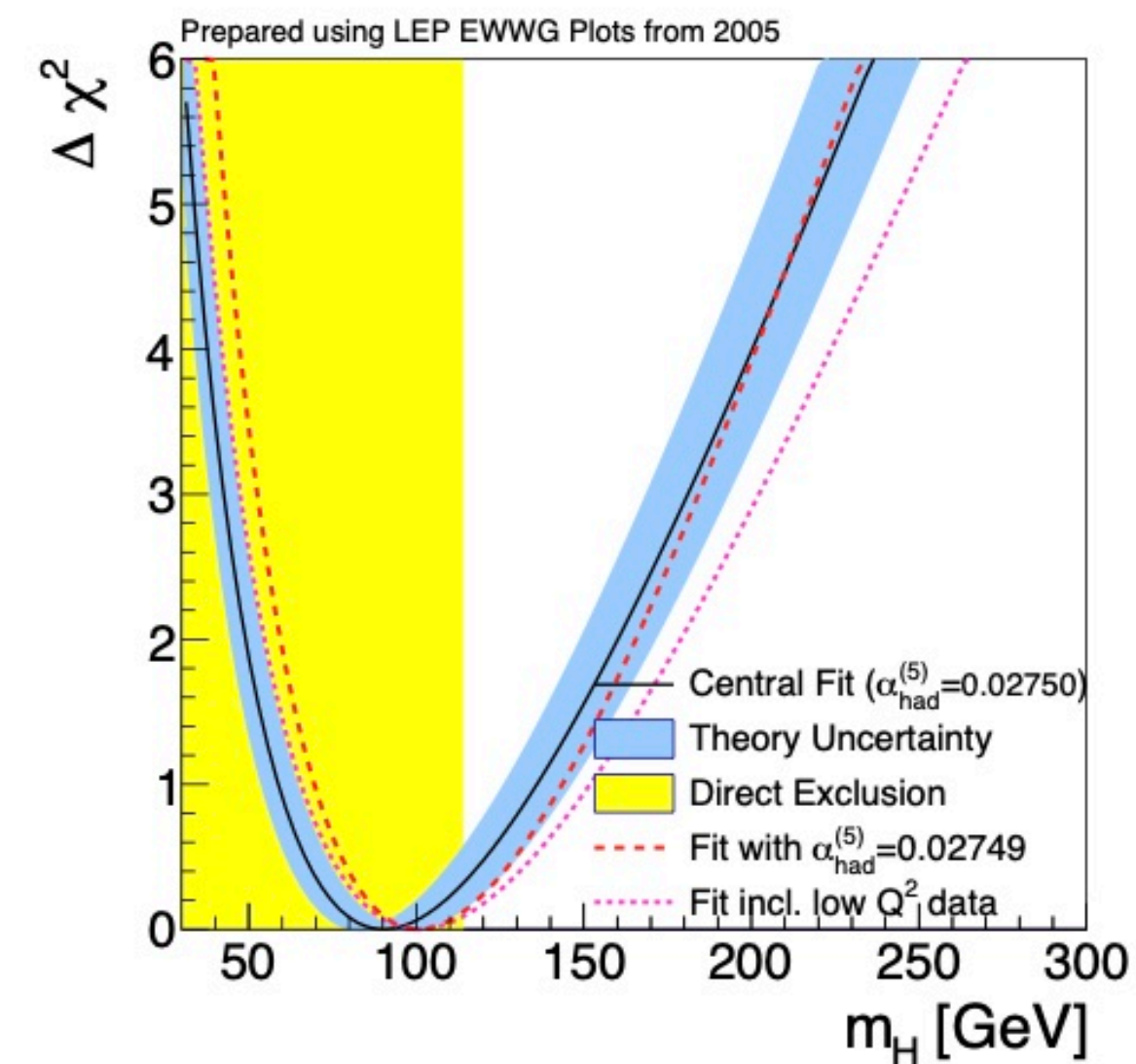
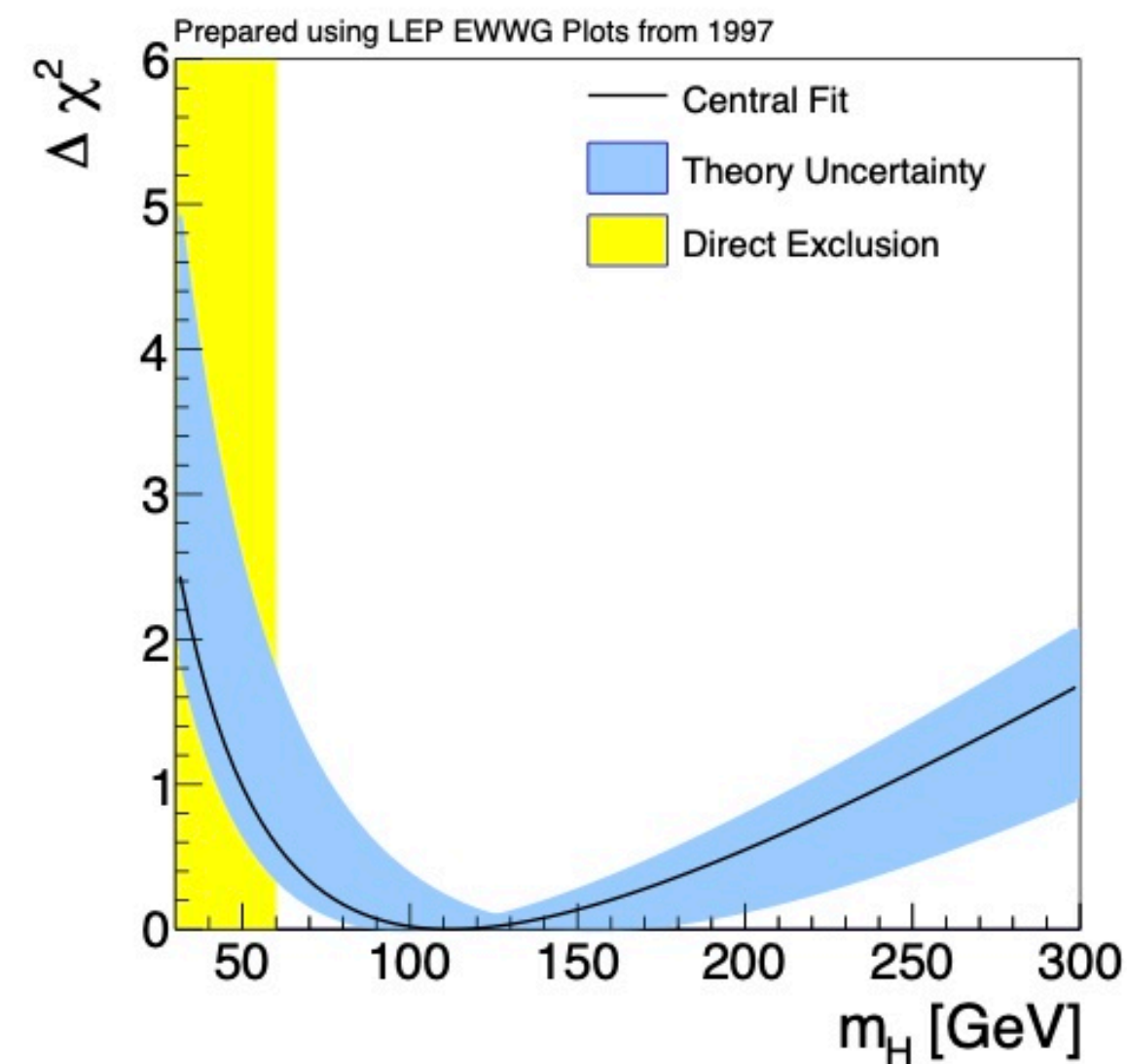
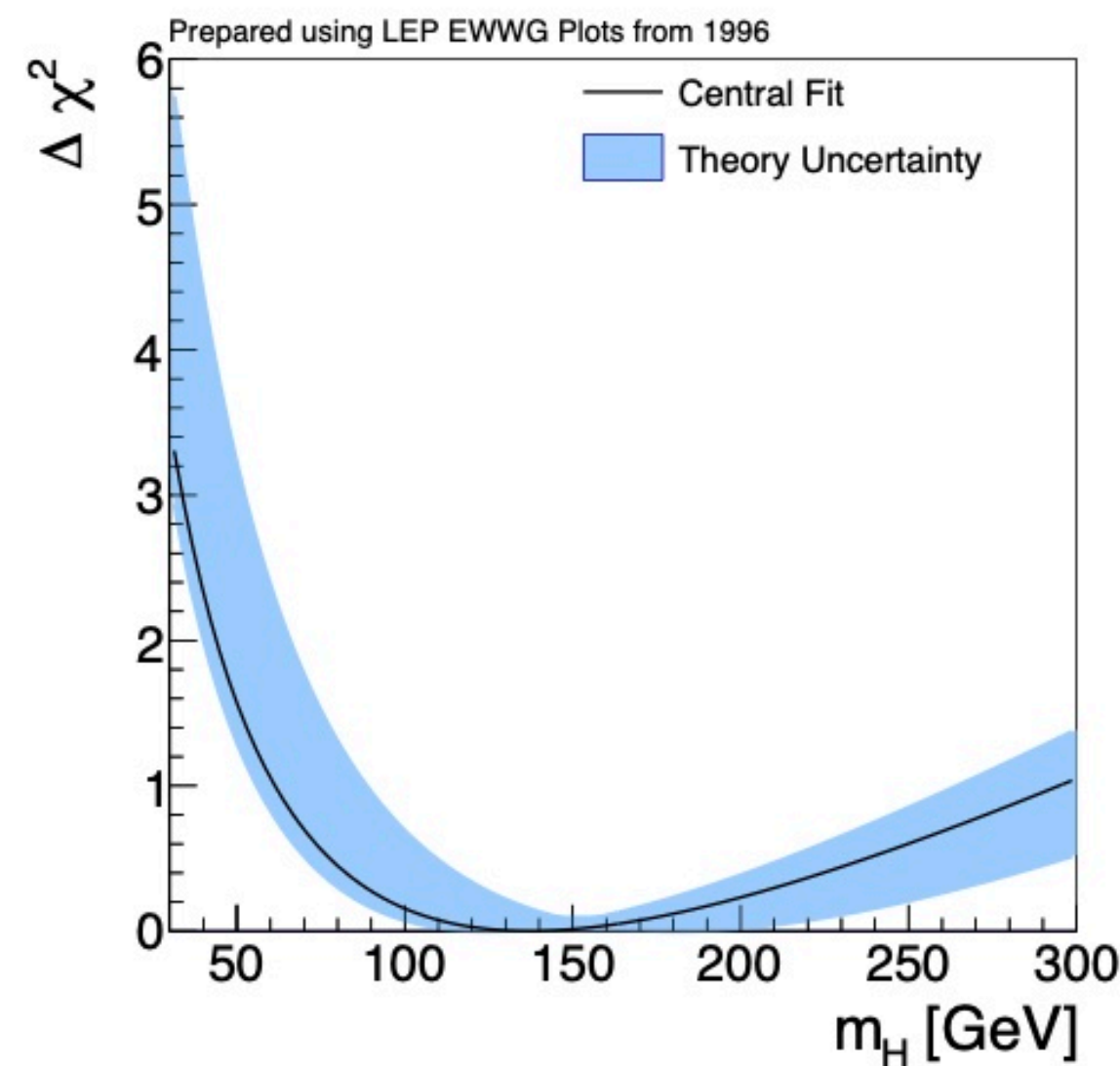
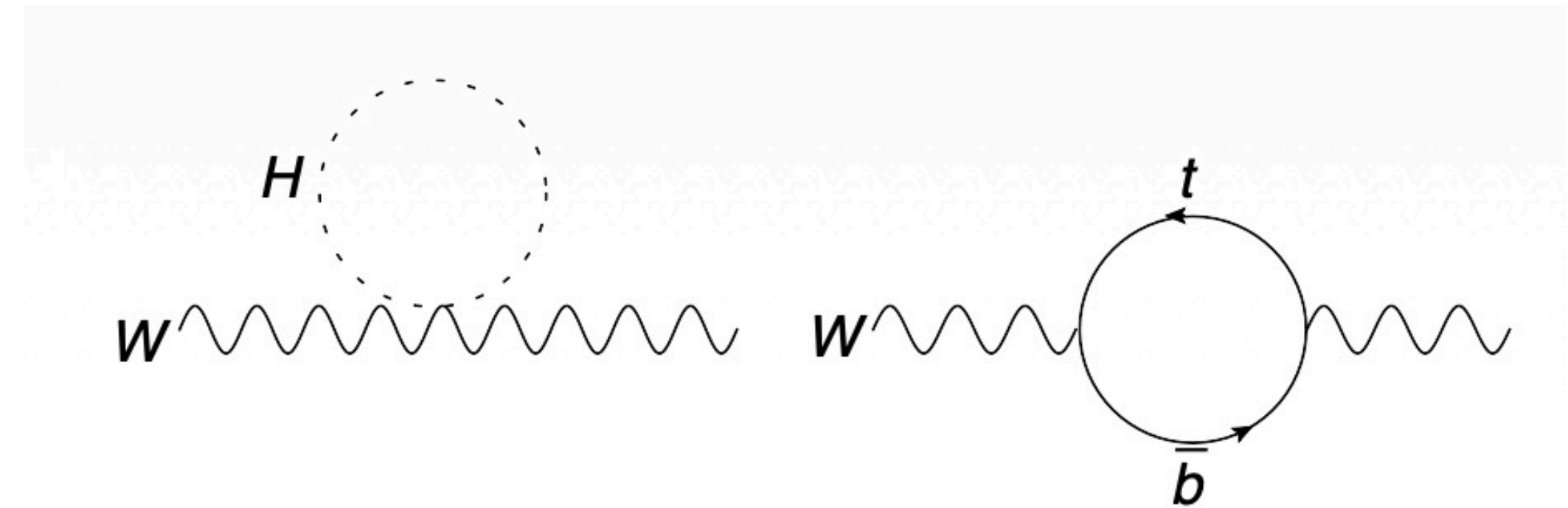
Matthias Schott

# LHC EW precision physics - Experimental Overview



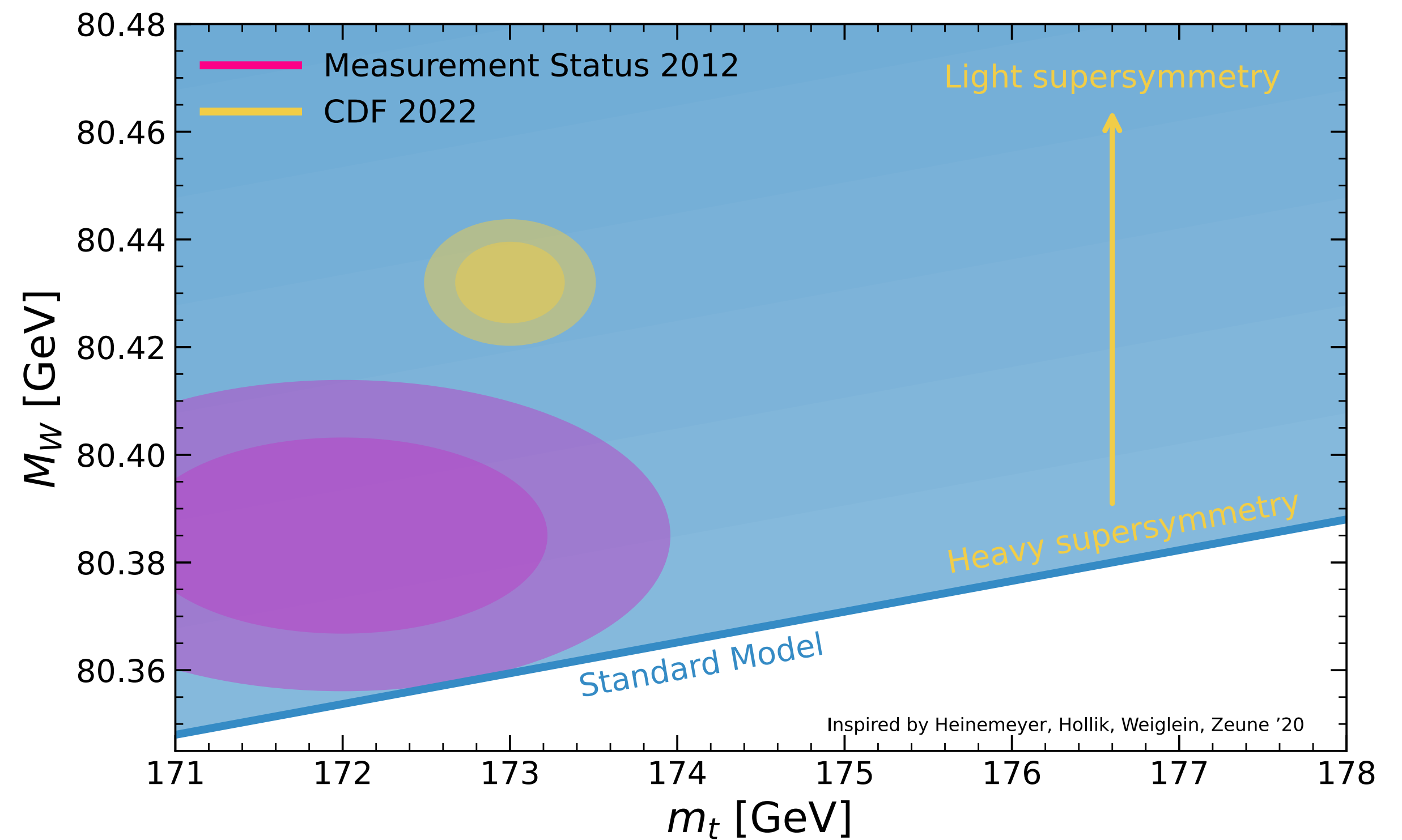
# The Slide which everybody knows

- Quantum loops yield corrections to the  $W$  boson mass (and other observables)
  - By comparing precision measurements of electroweak precision observables with predictions allow to constrain SM parameters / probe the SM consistency

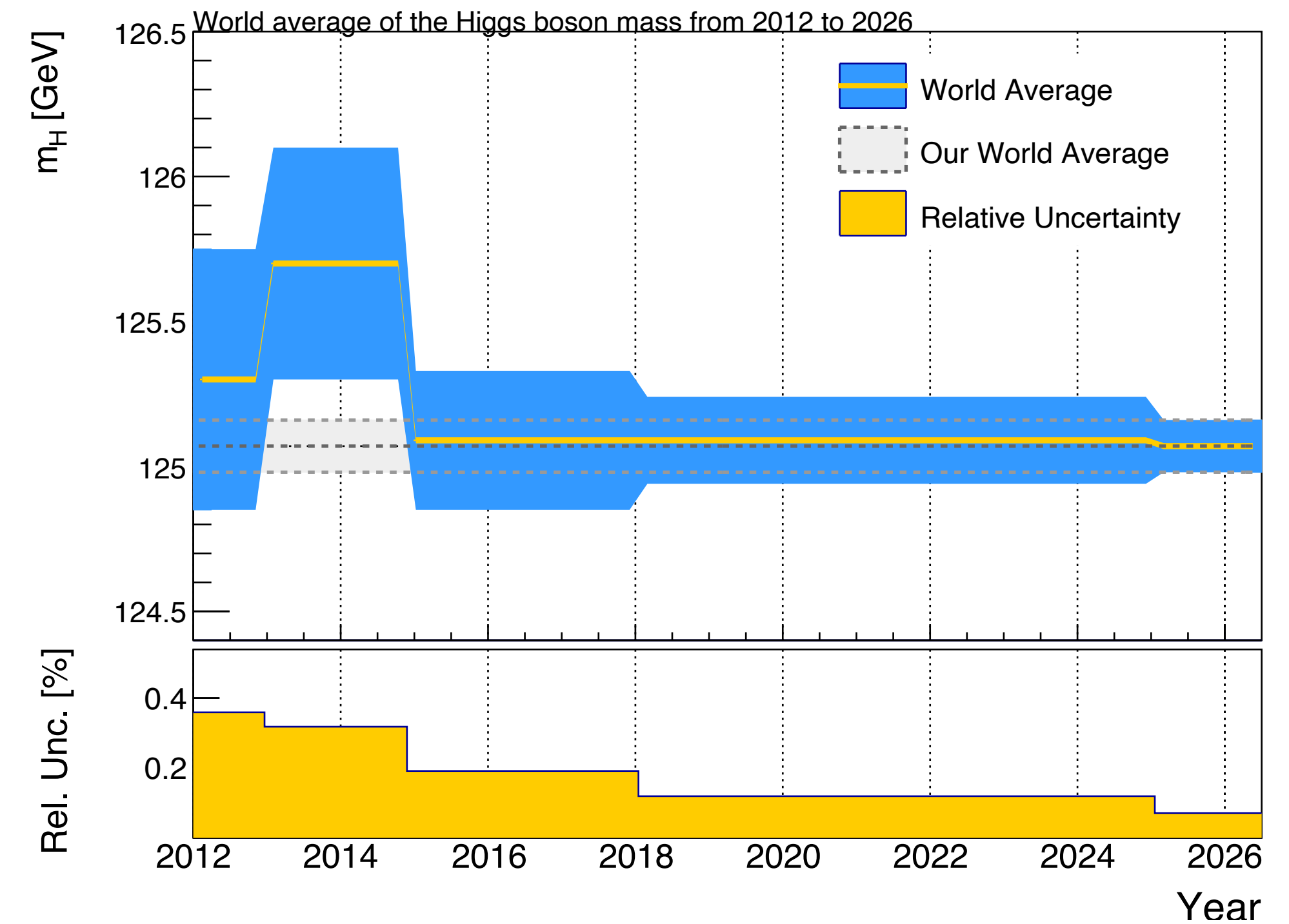
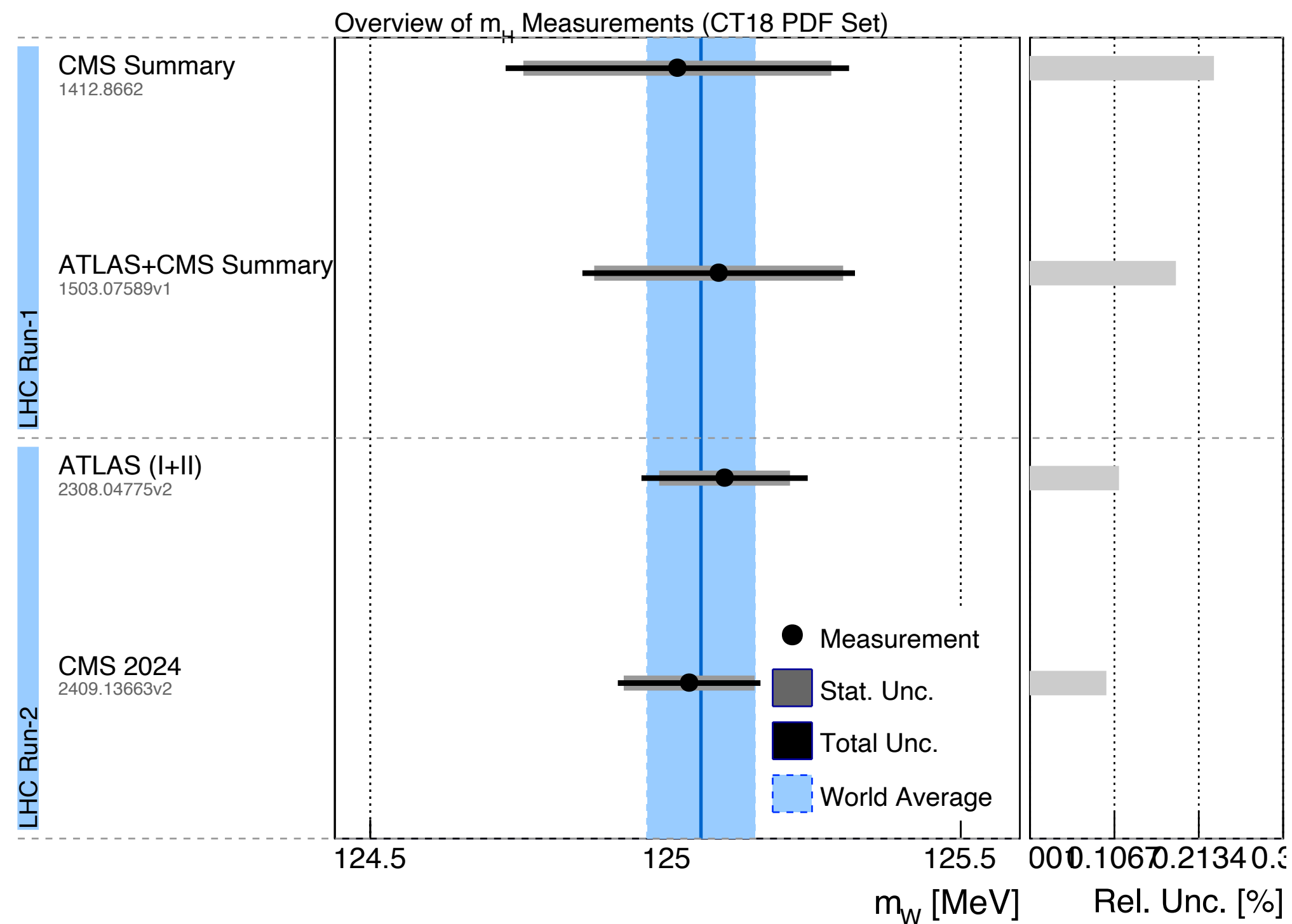


# Where it all started for me

- W boson mass in 2012
  - prediction was significantly more precise than the measurement
  - a slight tension between the SM prediction and the measurement

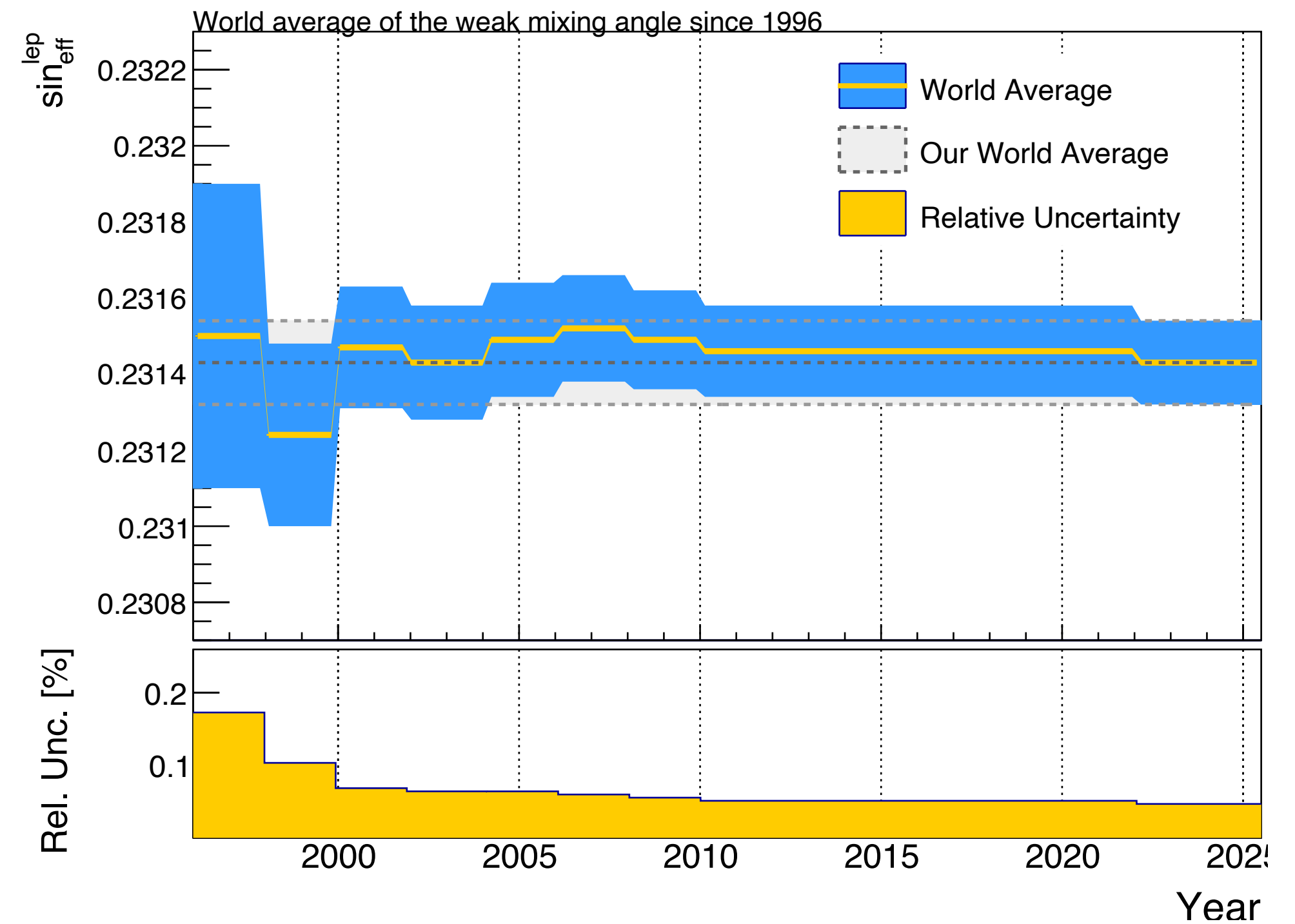
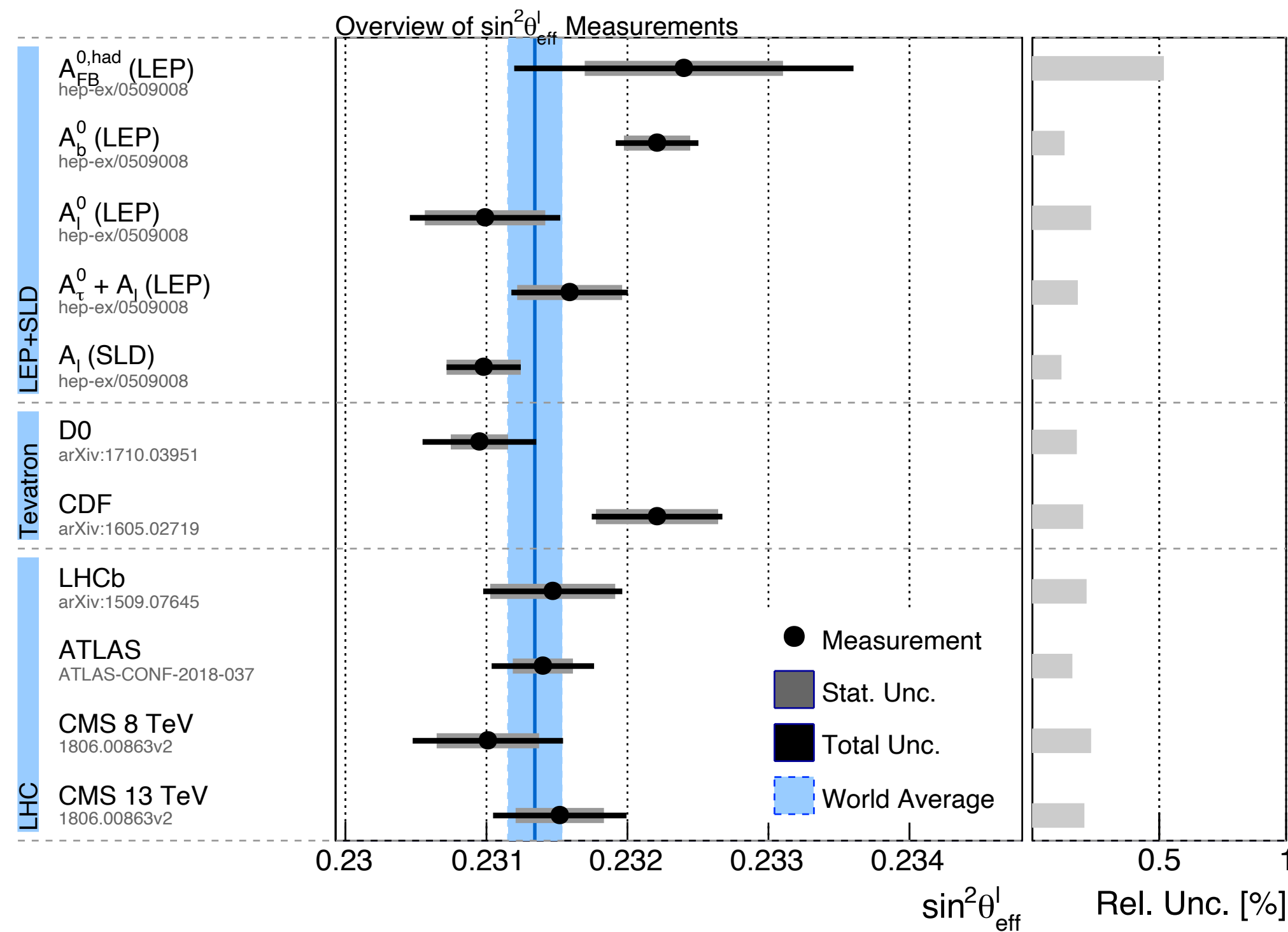


# Status of the Higgs Mass



- Higgs Combination based on Run-1 and most precise Measurements at Run 2
  - $m_H = 125.1 \pm 0.1$  GeV (p-value=0.9)
  - Only limited impact on Electroweak Fit

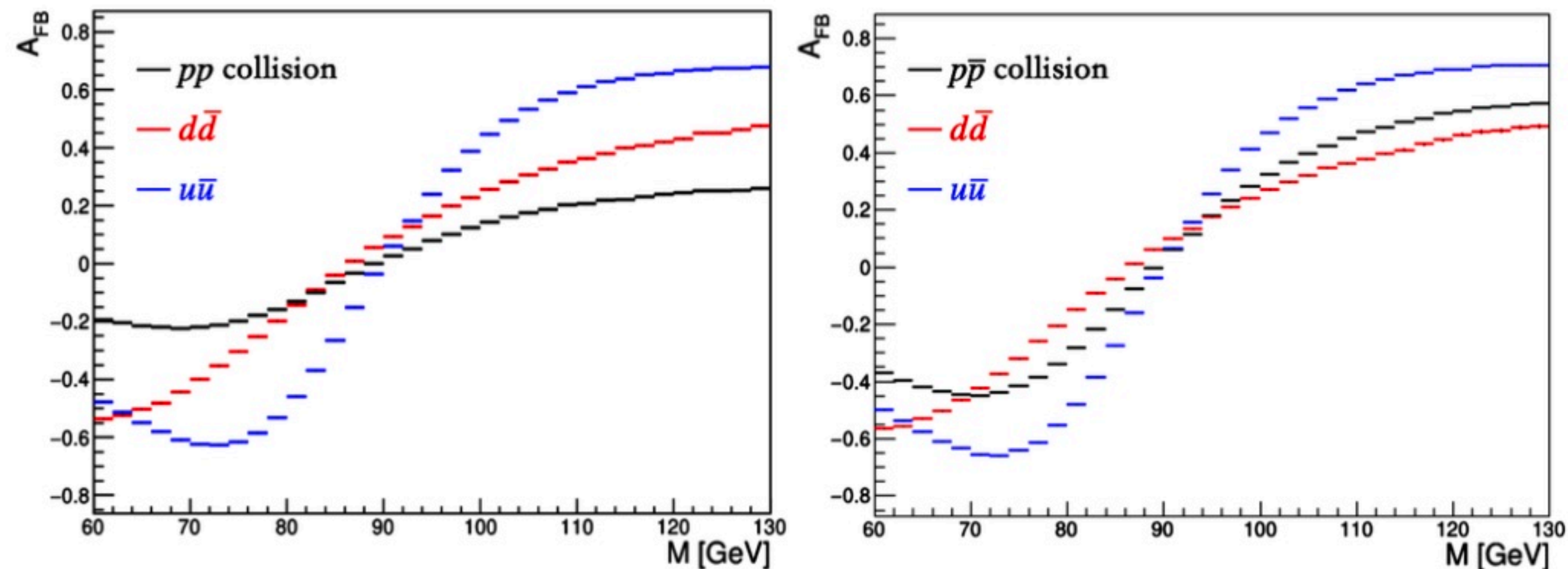
# Status of the (Leptonic) ElectroWeak Mixing Angle



- Including all measurements yields  $\sin^2\theta_W=0.231433\pm0.00013$ , but p-value of 0.1
- Excluding LEP and only use Hadron-Colliders yields  $\sin^2\theta_W=0.231343\pm0.00018$  with p-value of 0.9

# Impact of PDFs (taken from Liang Han's Talk in Bonn)

- Measurements at hadron colliders: systematics dominated by the PDF-induced uncertainties



- $\sin 2\theta_W[\text{Tevatron}] = 0.23148 \pm 0.00027 \text{ (stat.)} \pm 0.00005 \text{ (exp.)} \pm 0.00018 \text{ (PDF)}$
- $\sin 2\theta_W[\text{CMS-8}] = 0.23101 \pm 0.00036 \text{ (stat.)} \pm 0.00018 \text{ (exp.)} \pm 0.00016 \text{ (QCD)} \pm 0.00031 \text{ (PDF)}$
- $\sin 2\theta_W[\text{CMS-13}] = 0.23152 \pm 0.00010 \text{ (stat.)} \pm 0.00015 \text{ (exp.)} \pm 0.00008 \text{ (QCD)} \pm 0.00027 \text{ (PDF)}$

# Discussion of most precise experimental results

(Thanks to L. Han)

- As a combination of  $A_{FB}^u$  and  $A_{FB}^d$ , the observed  $A_{FB}^h$  at hadron colliders should be sensitive to the relative weight between the light quark  $u(\bar{u})$  and  $d(\bar{d})$  inside proton

$$A_{FB}^h = C_u[u(x); \bar{u}(x)] \times A_{FB}^u[\sin^2\theta_W] + C_d[d(x); \bar{d}(x)] \times A_{FB}^d[\sin^2\theta_W]$$

$\sin^2\theta_W$

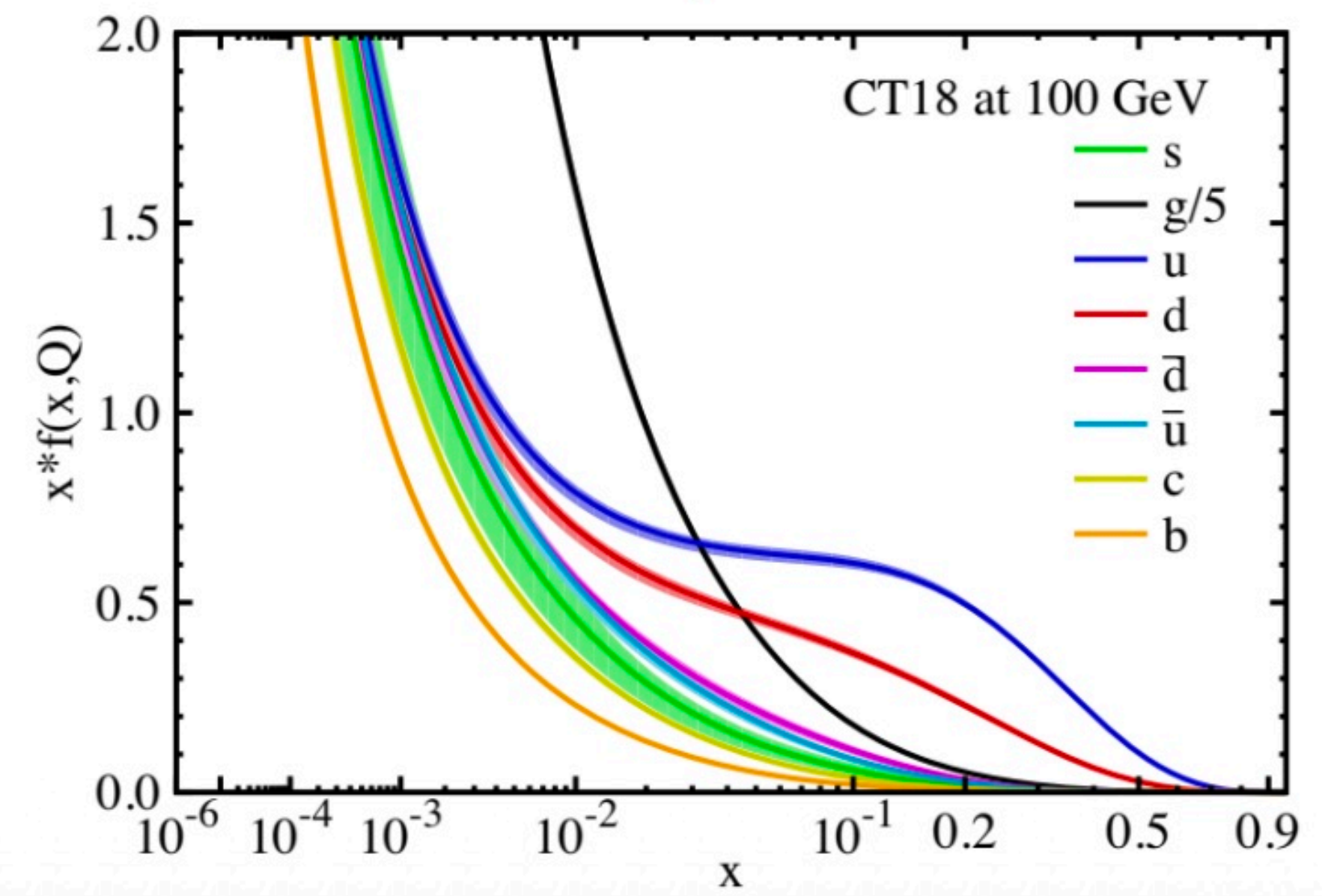
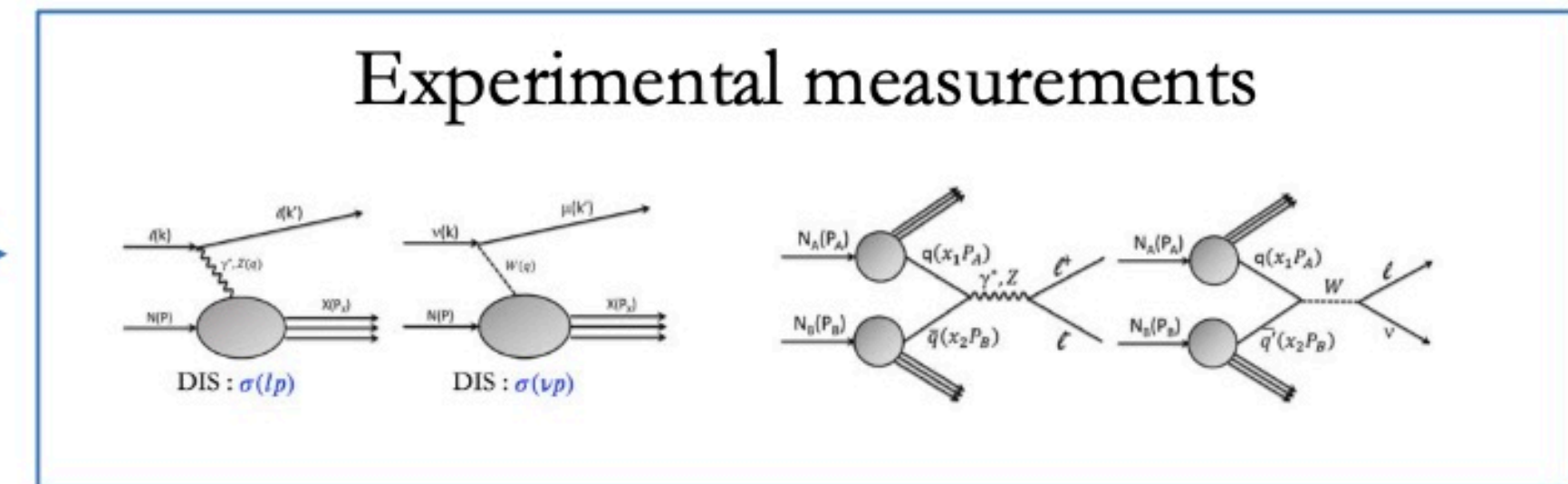
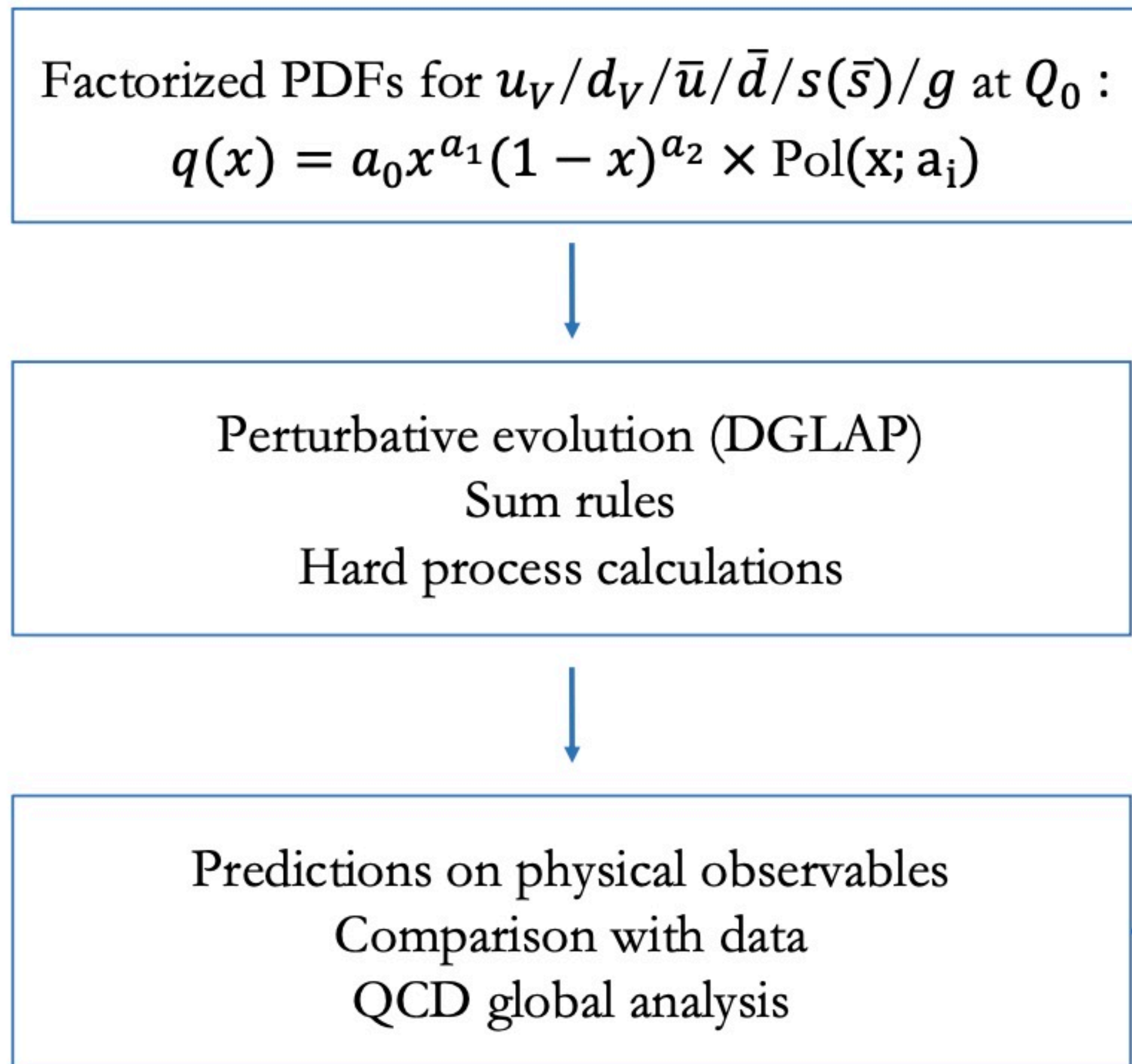


proton structure

- PDF-induced uncertainty on  $A_{FB}^h$  : the light quark ratio  $u(\bar{u})/d(\bar{d})$ , difficult to be experimentally constrained

# QCD global analysis on PDFs

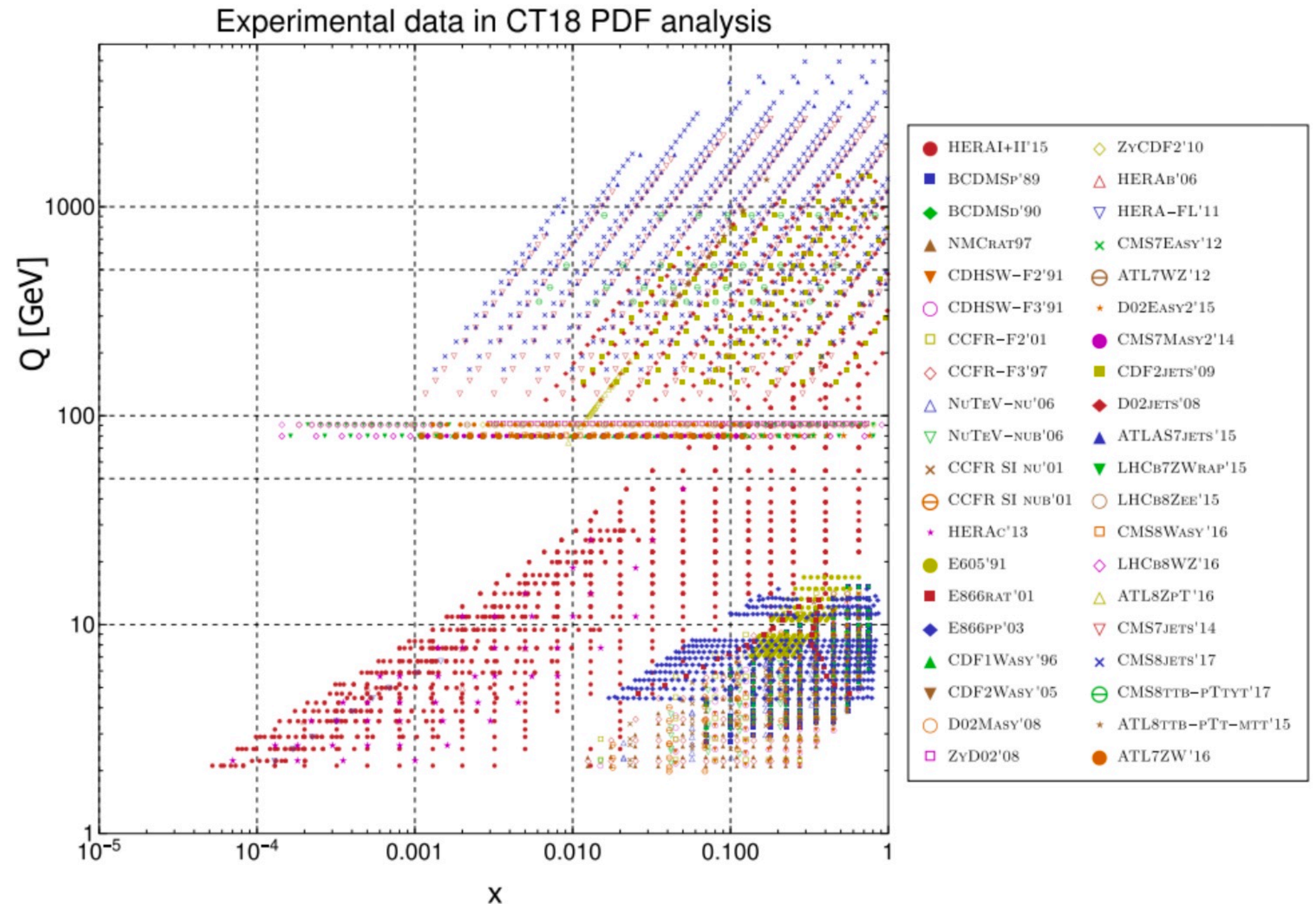
(Thanks to L. Han)



# Two categories of experimental inputs

(Thanks to L. Han)

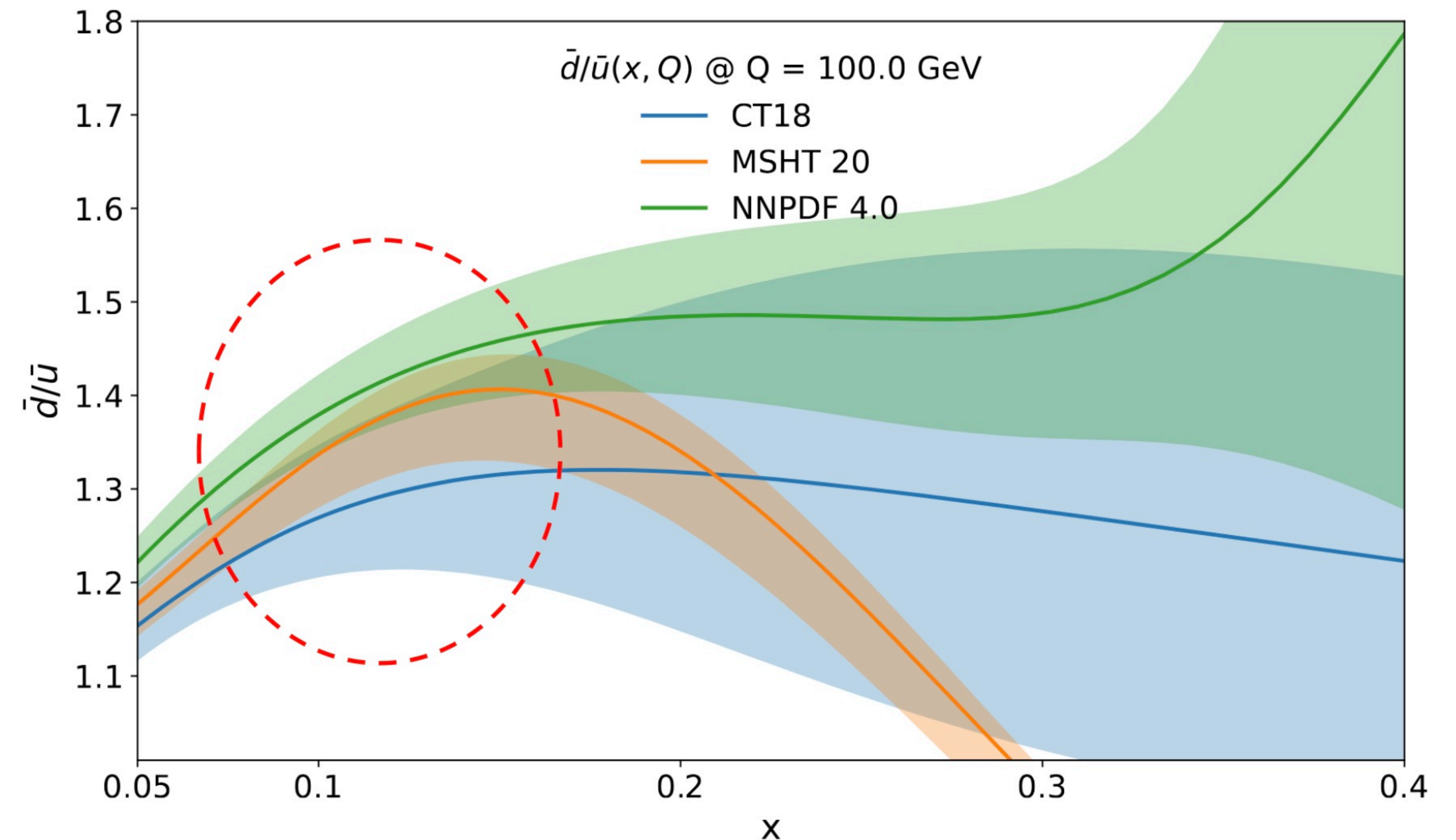
- Pure proton interactions: HERA/ Tevatron/LHC, constraints on quarks and gluon in small  $x$  region
- Various nuclear interactions: fixed target experiments, constraints on the light quarks in large  $x$  region, with assumptions on nuclear structure



# Two categories of experimental inputs

(Thanks to L. Han)

- SU(2) flavor asymmetry of light quark sea in proton, determined by Deuteron scattering experiments.
- Question: any way to verify the  $\bar{d}/\bar{u}$  asymmetry with unbiased pure proton data?



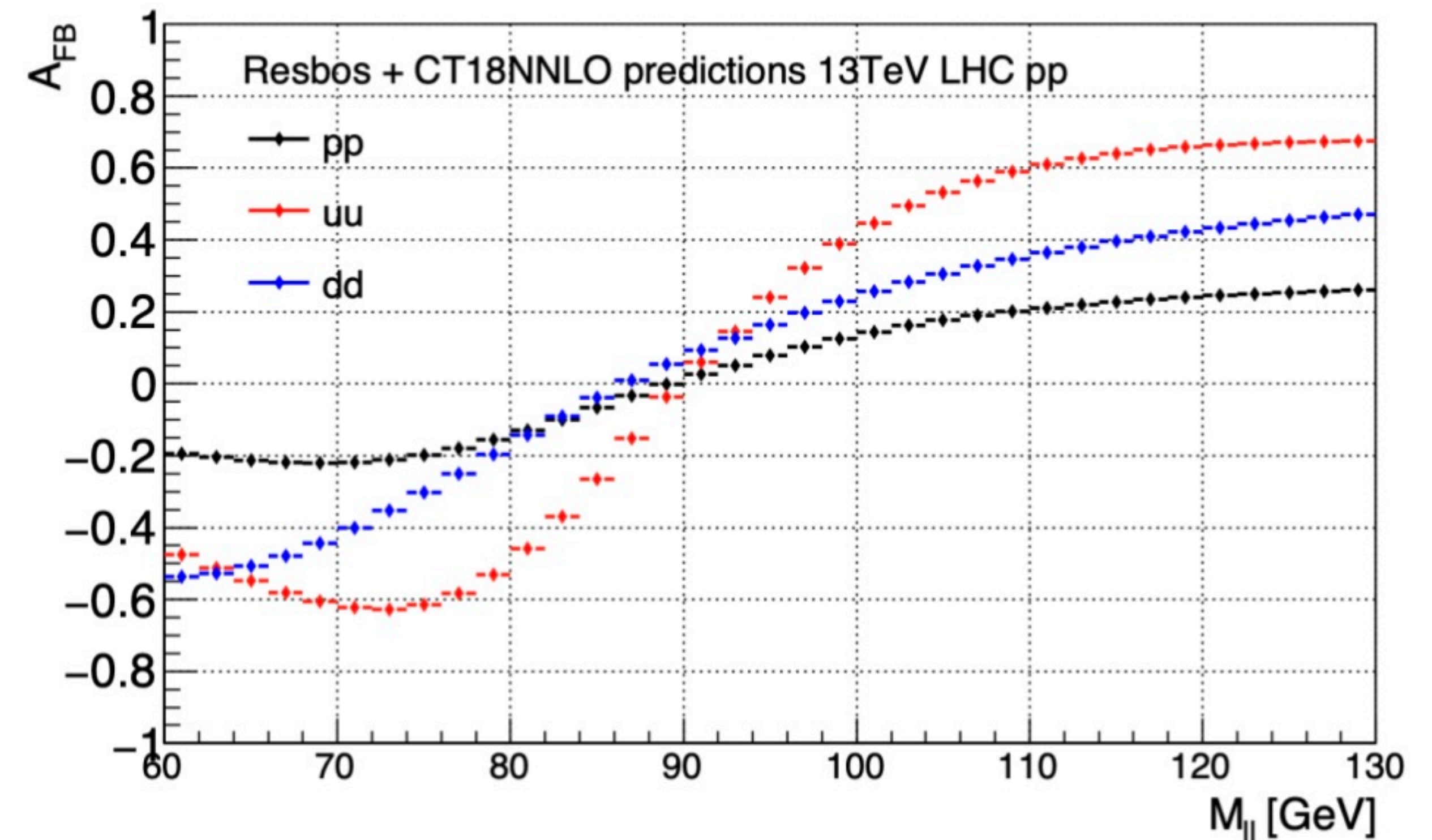
# Factorization and new proton structure observables

(Thanks to L. Han)

- The observed  $AFB_h$  can be factorized, with well-defined proton structure parameters :

$$A_{FB}^h = C_u(Y, M, Q_T) \times A_{FB}^u(Y, M, Q_T; \sin^2 \theta_W) \\ + C_d(Y, M, Q_T) \times A_{FB}^d(Y, M, Q_T; \sin^2 \theta_W)$$

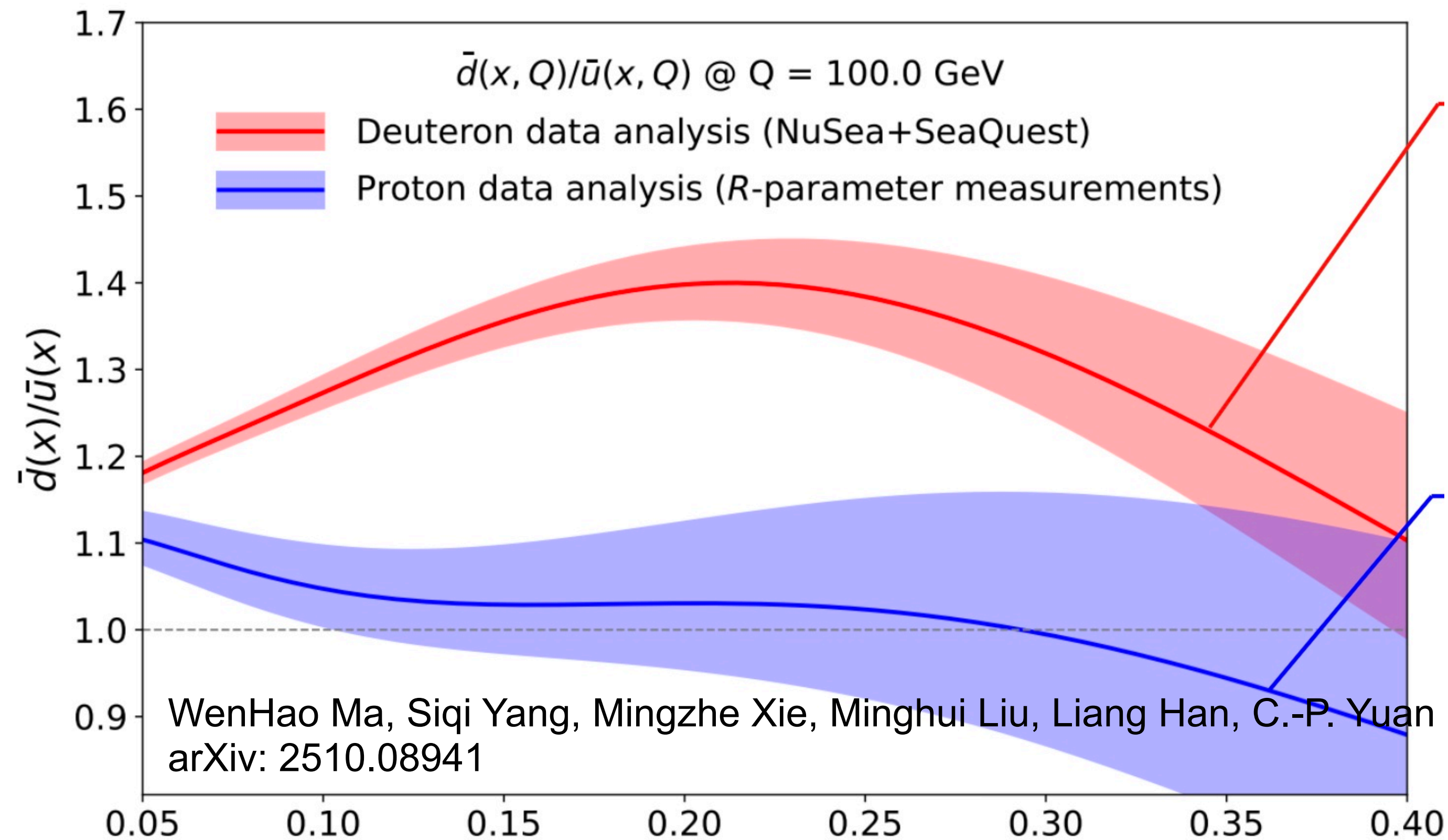
- strictly holds at all orders  $\rightarrow$  define new observables
- decouple EW and proton  $\rightarrow$  joint fit for  $\sin^2 \theta_W$
- $p$ -structure parameter  $C_u/C_d \rightarrow$  related to  $u/d$  respectively



- Chinese Phys. C 45 (2021) 053001
- Eur. Phys. J. C82 (2022) 368
- Phys. Rev. D106 (2022) 033001

# Global analysis of deuteron data vs. $A_{FB}^h$ Measurements

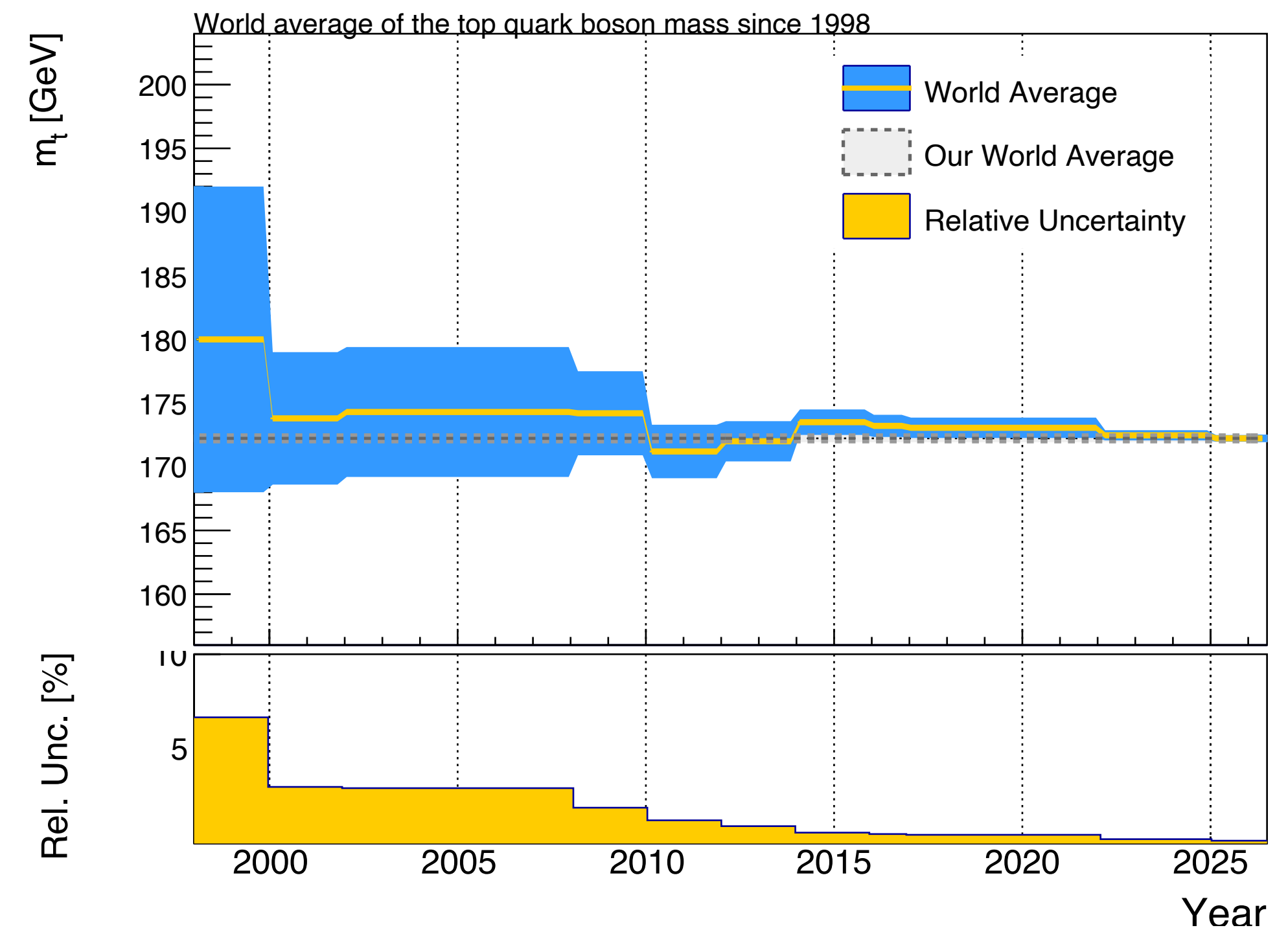
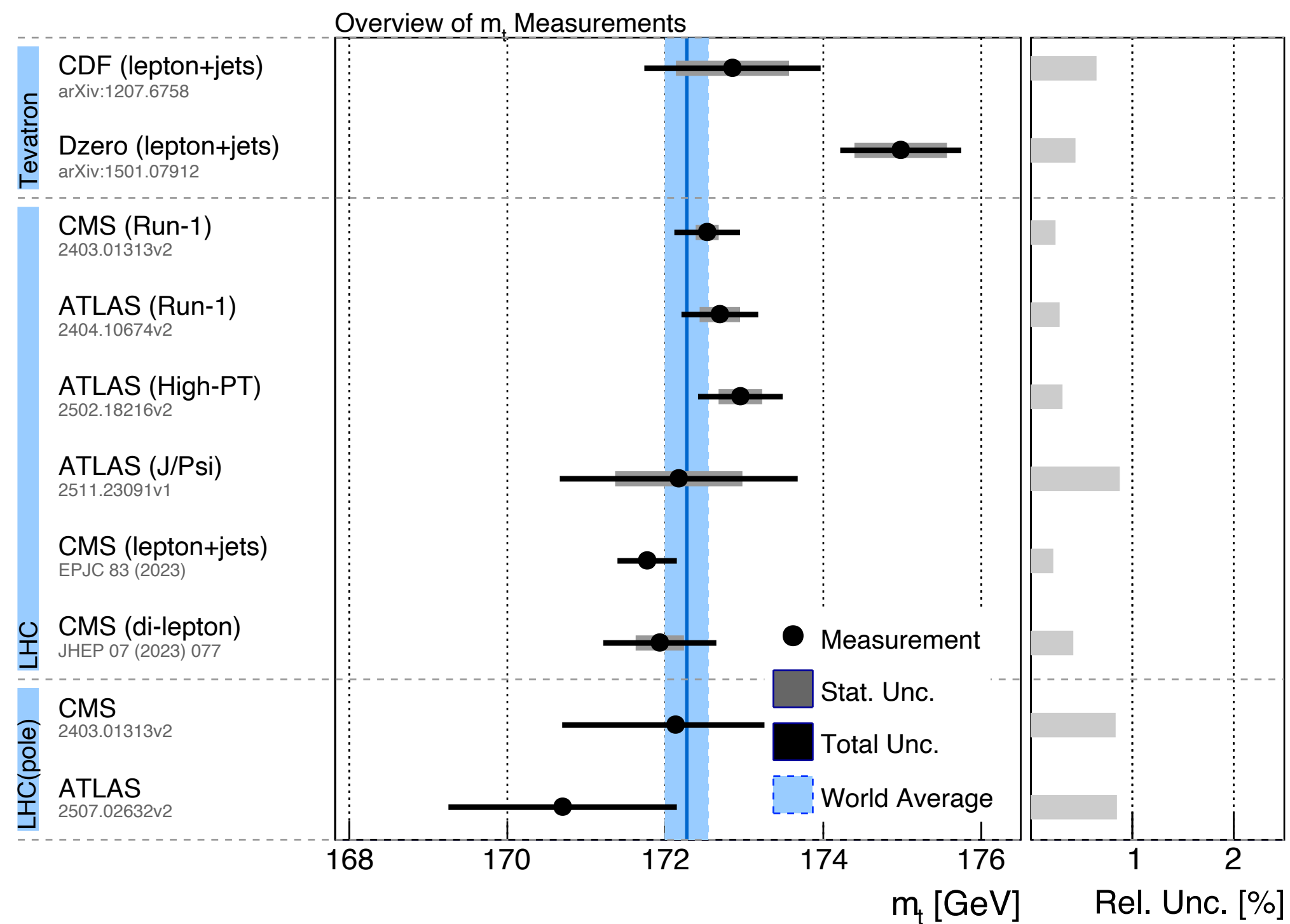
- The R-parameter measurements of  $A_{FB}^h$  yield a light sea  $\bar{d}/\bar{u}$  ratio close to unity



- Proton scattering  $\sigma_{lppp}$  baseline + NuSea/SeaQuest
- Deuteron: in high energy region, the classic D(n,p) picture may not be held
- Proton scattering  $\sigma_{lppp}$  baseline + D0/CMS R Measurement
- Proton: the sea quarks generated under pQCD, instead of SU(2) flavor asymmetry

- PDFs might indeed be a limiting factor, simply because we don't have enough data

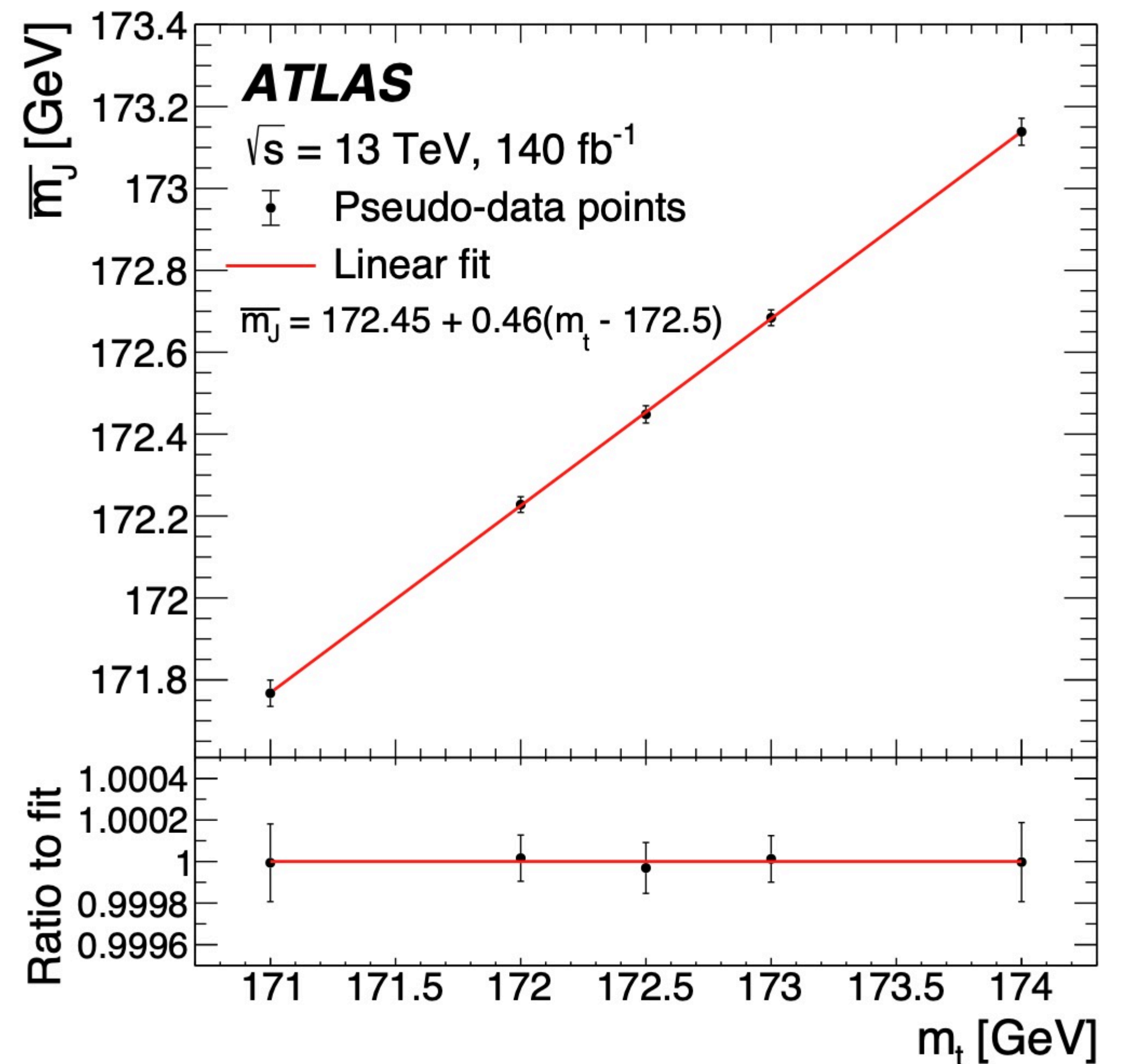
# Status of the Top Quark Mass



- LHC measurements of top-quark mass consistent:  $m_T = 172.27 \pm 0.27$  GeV (p-value 0.4)
  - Problem: need to interpret this as pole-mass (additional uncertainty of 0.1-0.5 GeV)
- Direct Pole-Mass measurements using cross-sections now also with  $\Delta m_T = 1$  GeV

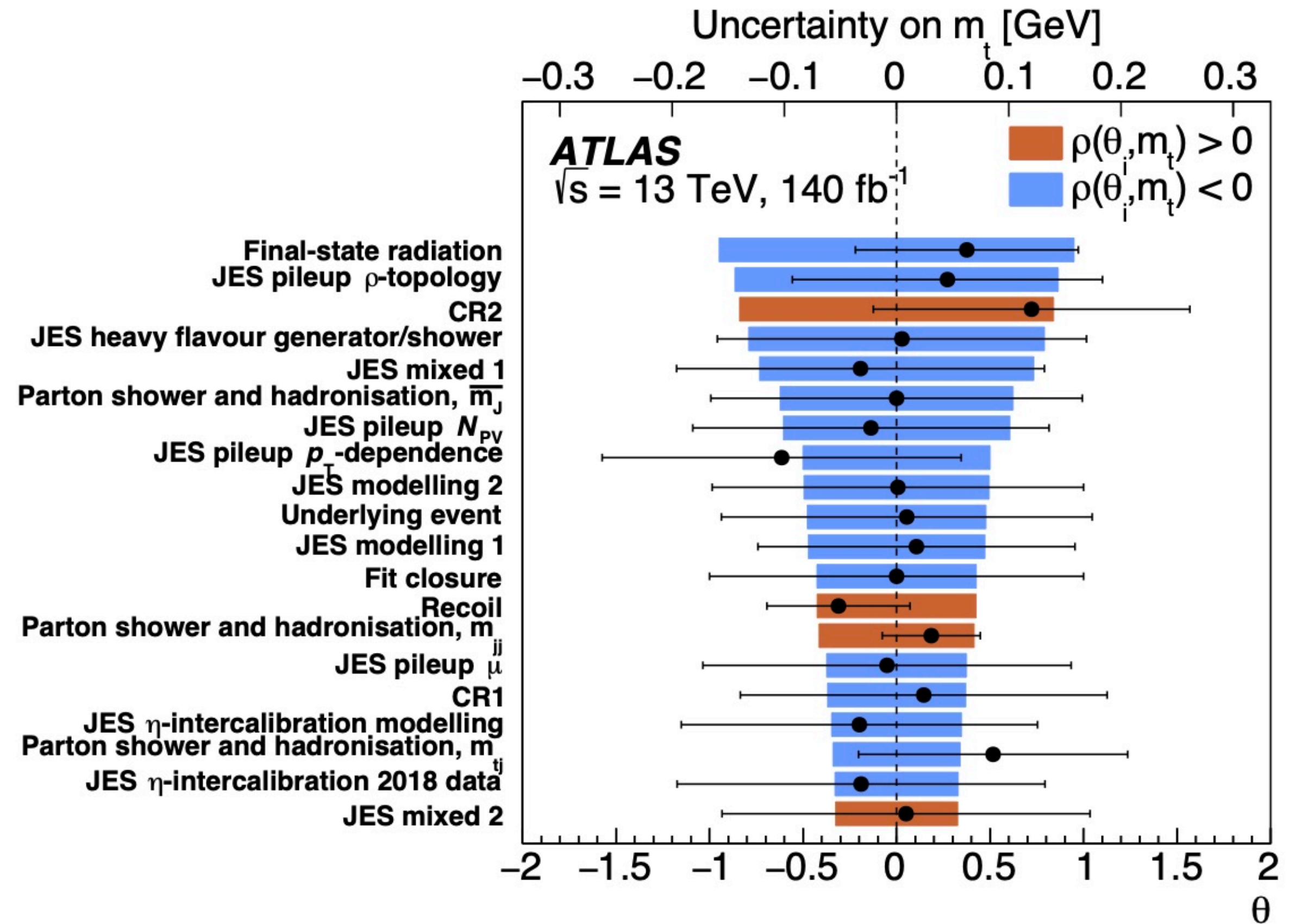
# Discussion of a selected high precision experimental results

- Measurement of the top quark mass with the ATLAS detector using top-quark pair events with a high transverse momentum top quark
  - <https://arxiv.org/abs/2502.18216>
  - $m_t = 172.95 \pm 0.53$  GeV
- The 13 TeV dataset enables studies in rare phase-space regions: tops have high pT
  - boosted regime, top-quark decay products become highly collimated.
  - These decay products are often reconstructed within a single large-radius (large- $R$ ) jet.
  - This simplifies the reconstruction of hadronically decaying top quarks.
  - this can reduce systematic uncertainties in the top-quark mass



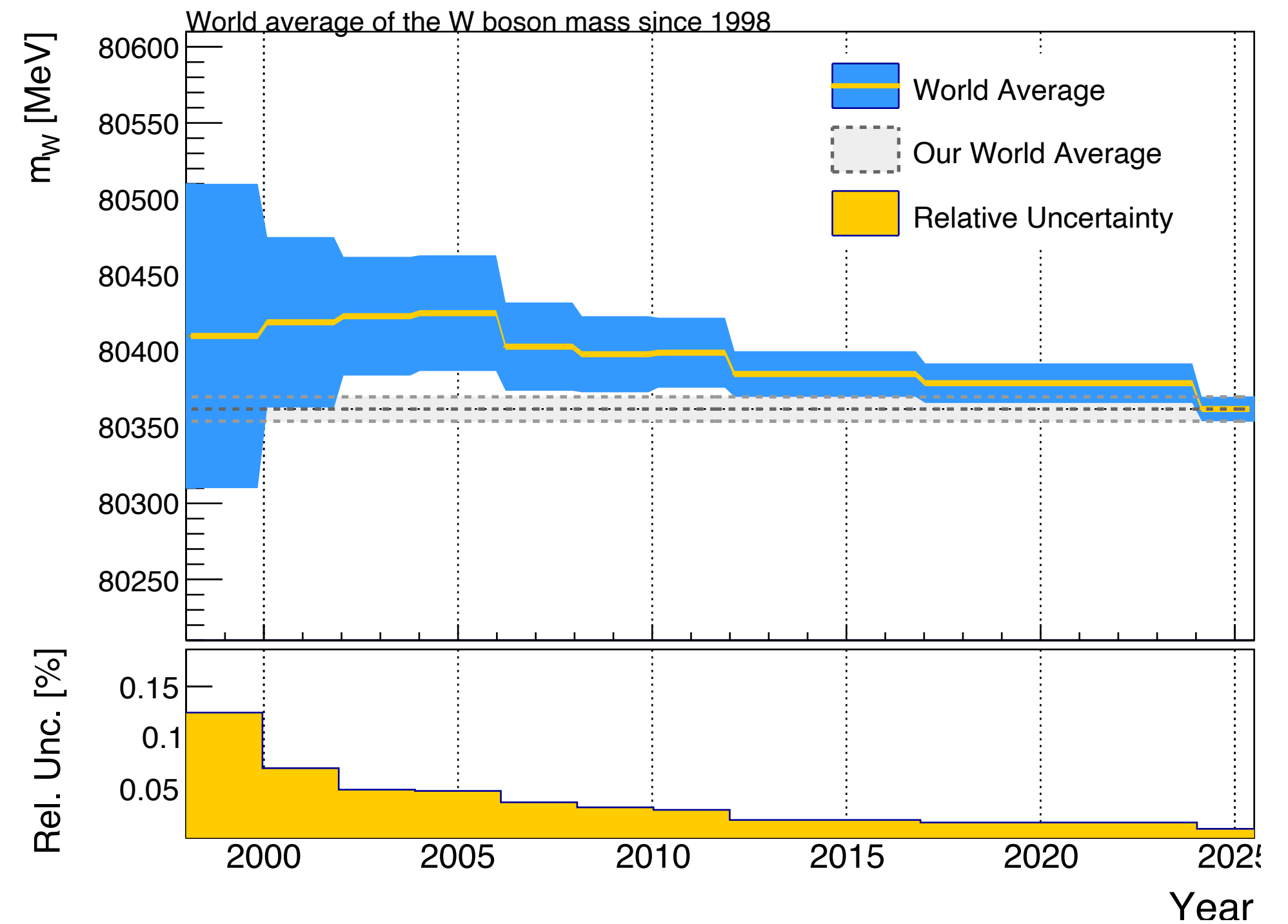
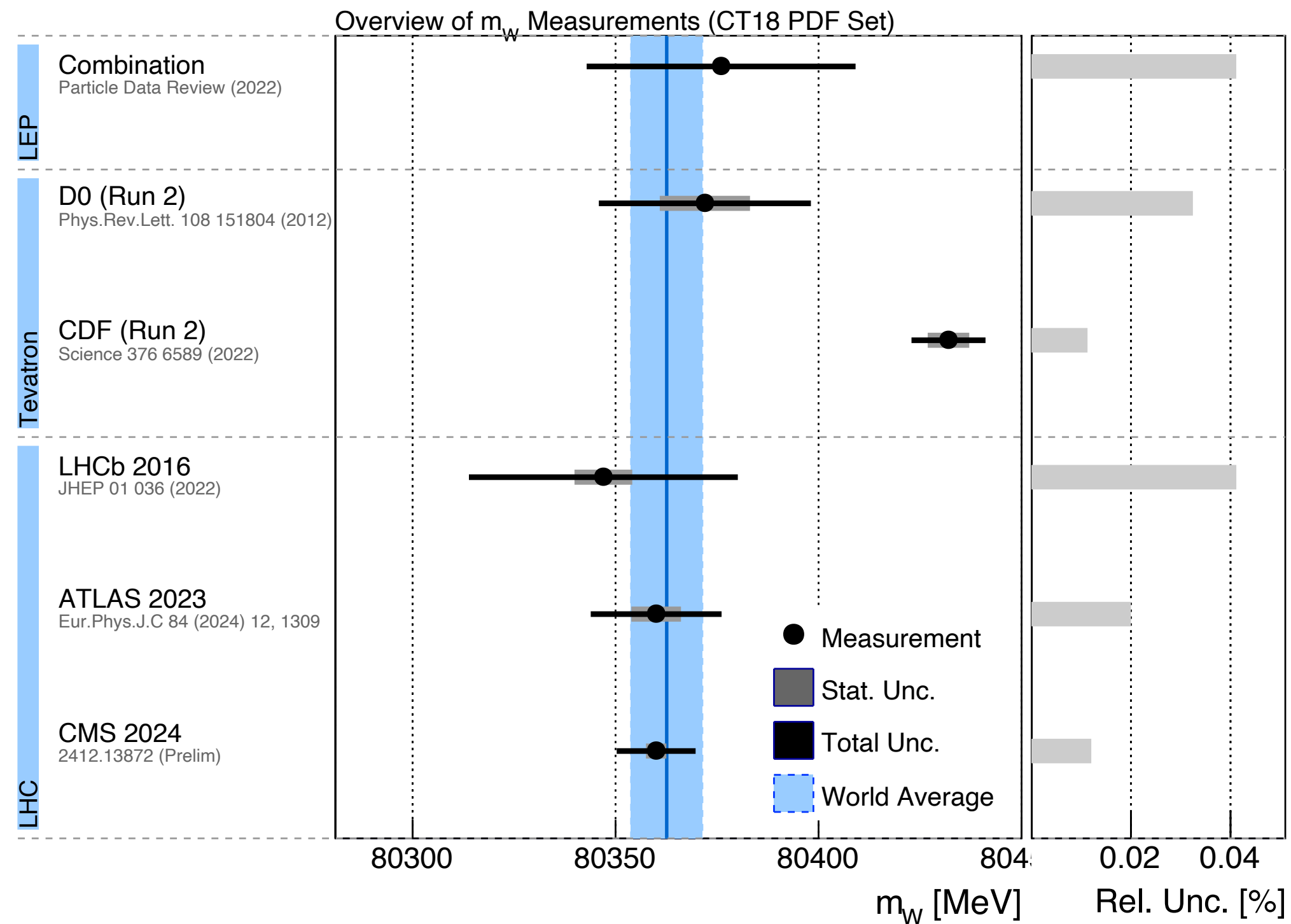
# Discussion of a selected high precision experimental results

Source	Uncertainty [GeV]
JES	$\pm 0.29$
Radiation (ISR and FSR)	$\pm 0.17$
Colour reconnection (CR1 and CR2)	$\pm 0.15$
JES heavy flavour	$\pm 0.14$
Parton shower and hadronisation model	$\pm 0.14$
JER	$\pm 0.10$
MC statistics	$\pm 0.08$
Underlying event	$\pm 0.08$
Recoil	$\pm 0.07$
Fit closure	$\pm 0.07$
Background modelling	$\pm 0.05$
Matrix element matching ( $p_T^{\text{hard}} = 1$ )	$\pm 0.04$
$b$ -tagging	$\pm 0.04$
Higher-order corrections	$\pm 0.02$
$E_T^{\text{miss}}$	$\pm 0.02$
Pileup	$\pm 0.01$
JVT	$\pm 0.01$
PDF	$\pm 0.01$
Leptons	$\pm 0.01$
Luminosity	$< 0.01$
<hr/>	
Total statistical	$\pm 0.27$
Total systematic	$\pm 0.46$
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Total	$\pm 0.53$



- JES uncertainties not only a experimental problem, but also due to flavor composition in shower
- Can be constrained by Control Regions

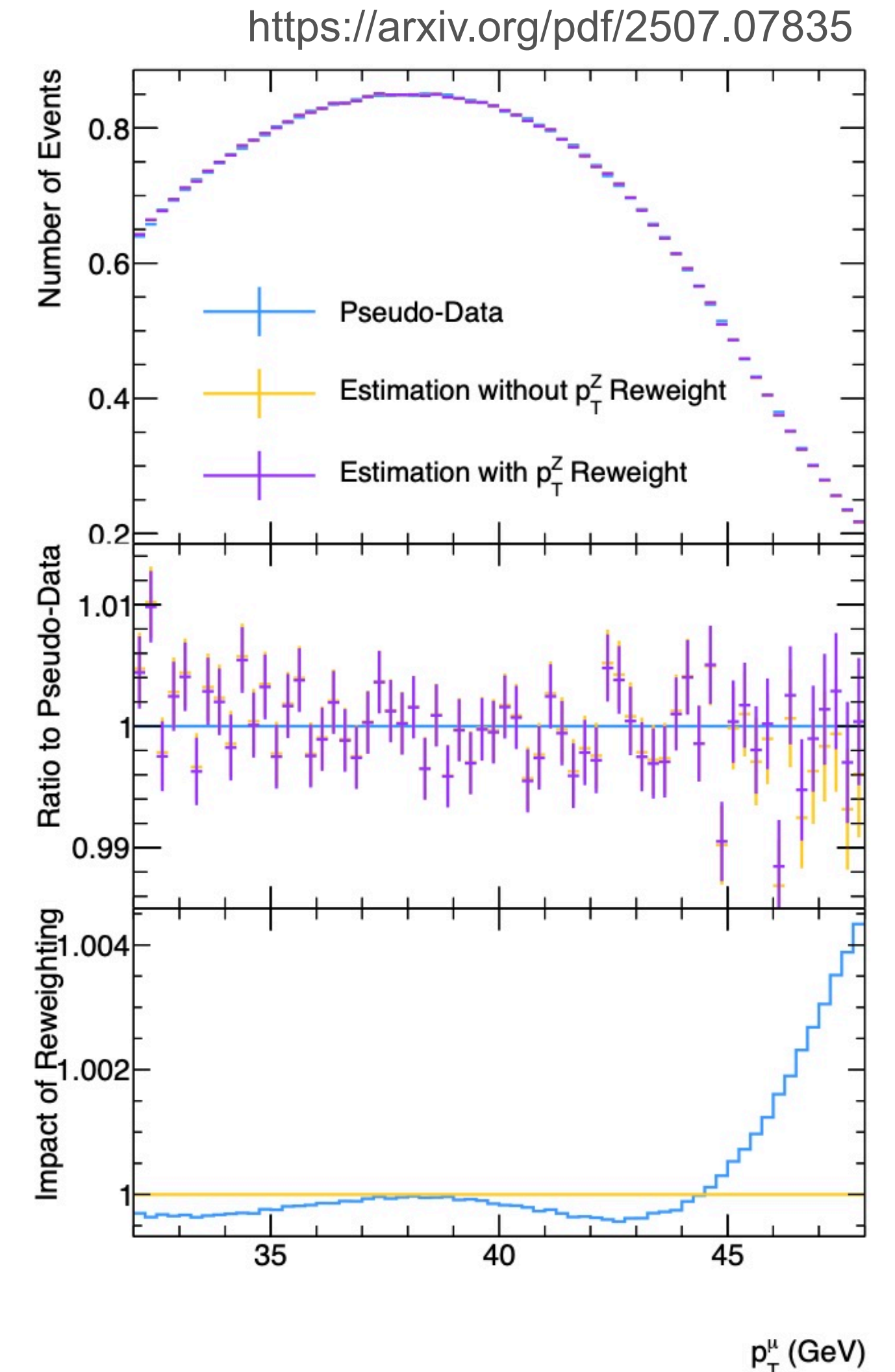
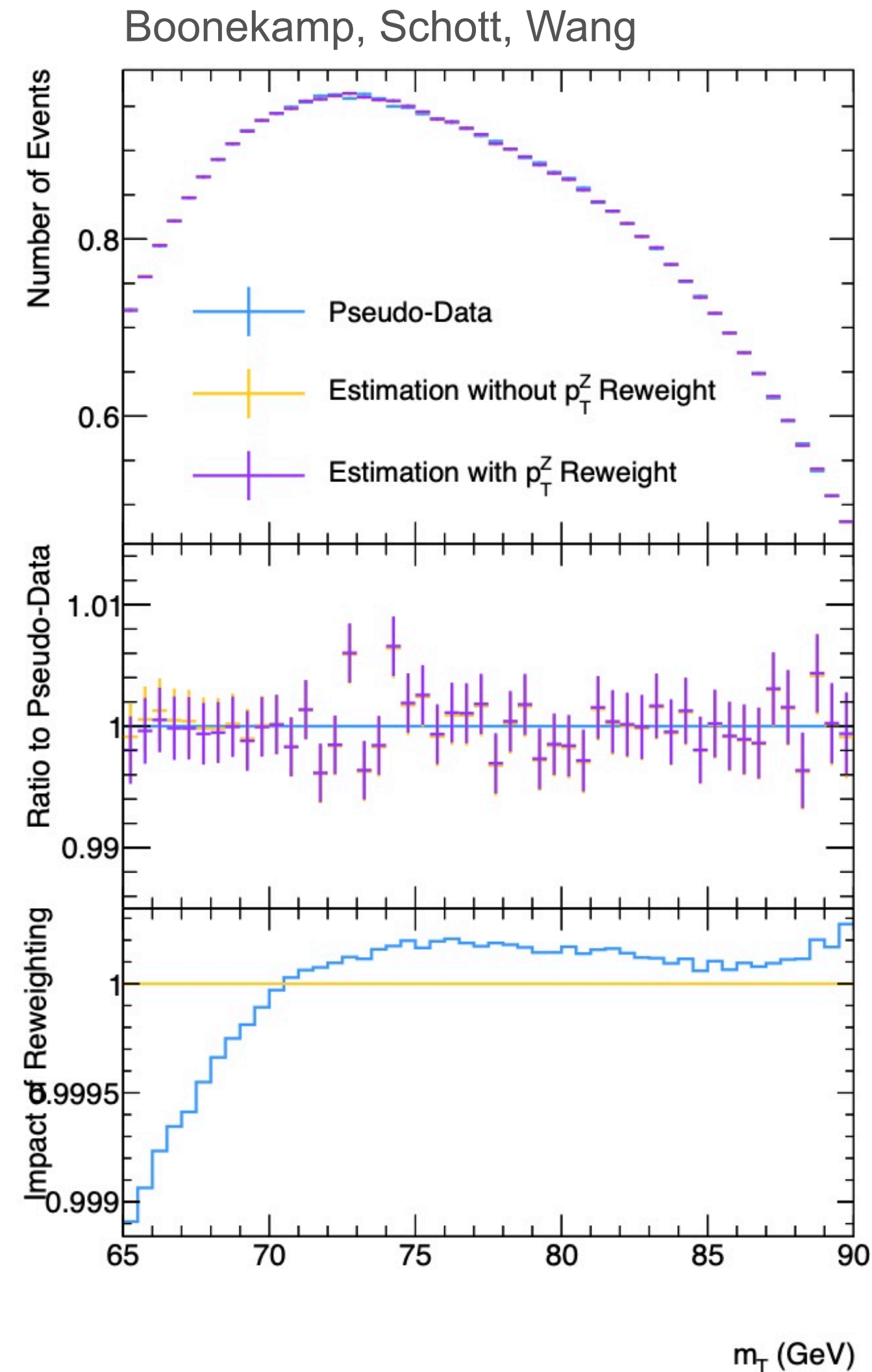
# A Preliminary W Boson Mass Combination



- W Boson mass combination perfectly consistent when ignoring the CDF result
  - $m_W = 80362.6 \pm 8.8$  MeV (p-value of 0.83)
  - Result consistent under different assumptions on correlation scenarios
  - When including CDF, the p-value drops below 0.001

# What do to with the CDF W Boson Mass

- CDF is an outlier to all other experiments, based on different approaches and experiments
- Several indications which require further studies
  - Signal Modelling
  - Background Modelling (up to 8 MeV)
- For the time being, we will not include the CDF measurement in our world average



# Discussion of most precise experimental results

- CMS: Profile likelihood fit using  $p_T$  in the muon channel
  - 13 TeV, 16.8 fb<sup>-1</sup>
- ATLAS: Profile likelihood fit using  $p_T / m_T$  in the electron and muon channel
  - 7 TeV, 4.6 fb<sup>-1</sup>
- Systematic Uncertainties compatible between both measurements
  - Exception EW corrections

Source of uncertainty	Impact (MeV)			
	Nominal		Global	
	in $m_Z$	in $m_W$	in $m_Z$	in $m_W$
Muon momentum calibration	5.6	4.8	5.3	4.4
Muon reco. efficiency	3.8	3.0	3.0	2.3
W and Z angular coeffs.	4.9	3.3	4.5	3.0
Higher-order EW	2.2	2.0	2.2	1.9
$p_T^V$ modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8
Nonprompt-muon background	—	3.2	—	1.7
Integrated luminosity	0.3	0.1	0.2	0.1
MC sample size	2.5	1.5	3.6	3.8
Data sample size	6.9	2.4	10.1	6.0
Total uncertainty	13.5	9.9	13.5	9.9

Unc. [MeV ]	Total	Stat.	Syst.	PDF	$A_i$	Backg.	EW	$e$	$\mu$	$u_T$	Lumi	$\Gamma_W$	PS
$p_T^\ell$	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
$m_T$	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

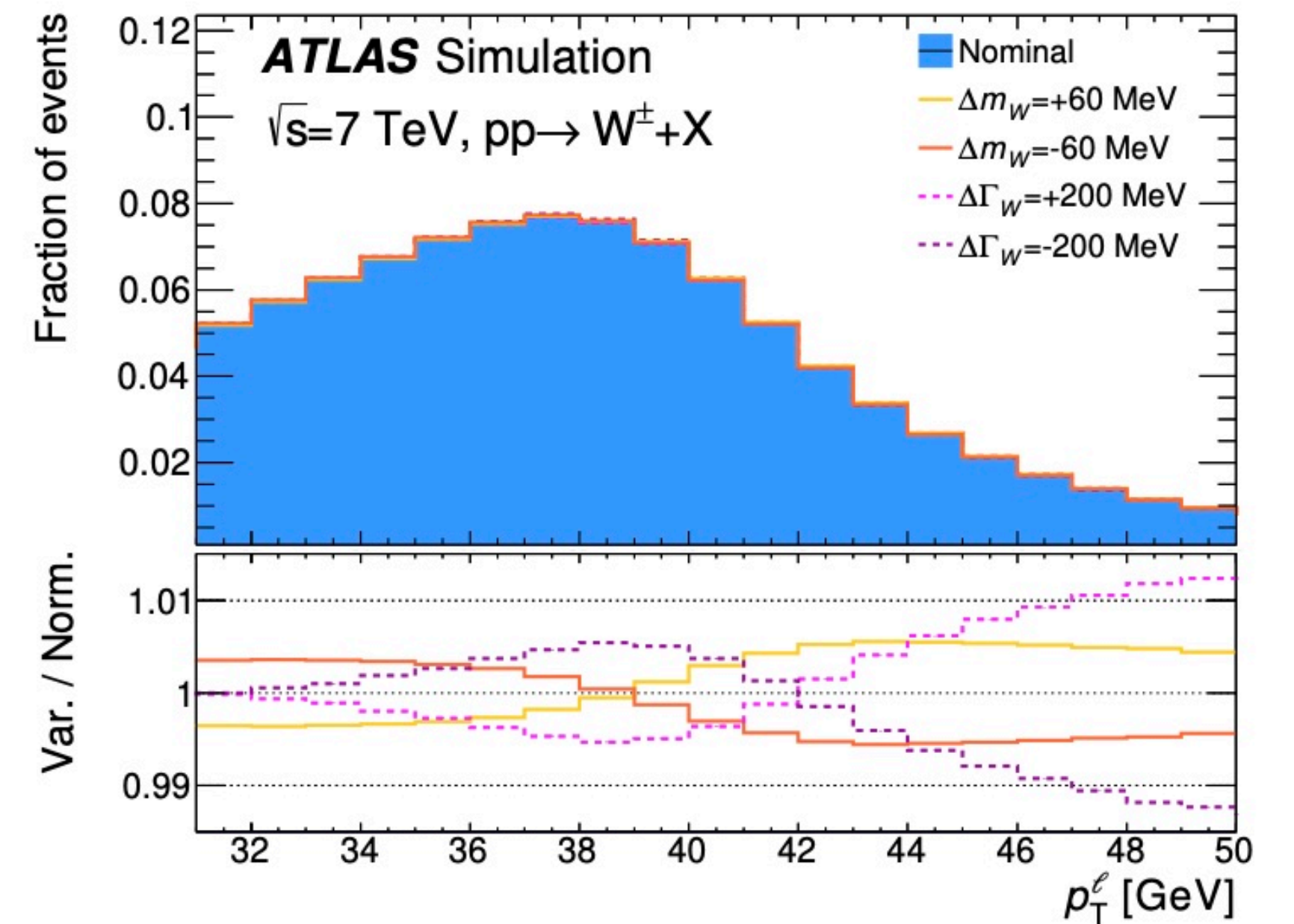
# Some aspects of Profiling

- Idea: We include all parameters which are required to describe data into a common fit
- Likelihood function (which is minimized) defined as

$$\mathcal{L}(\vec{n} \mid \mu, \vec{\theta}) = \prod_j \prod_i \text{Poisson}(n_{ji} \mid \nu_{ji}(\mu, \vec{\theta})) \cdot \text{Gauss}(\vec{\theta}).$$

- with the expected number of events defined as

$$\nu_{ji}(\mu, \vec{\theta}) = \Phi \times \left[ S_{ji}^{\text{nom}} + \mu \times (S_{ji}^{\mu} - S_{ji}^{\text{nom}}) \right] + \sum_s \theta_s \times (S_{ji}^s - S_{ji}^{\text{nom}}) \\ + B_{ji}^{\text{nom}} + \sum_b \theta_b \times (B_{ji}^b - B_{ji}^{\text{nom}}).$$

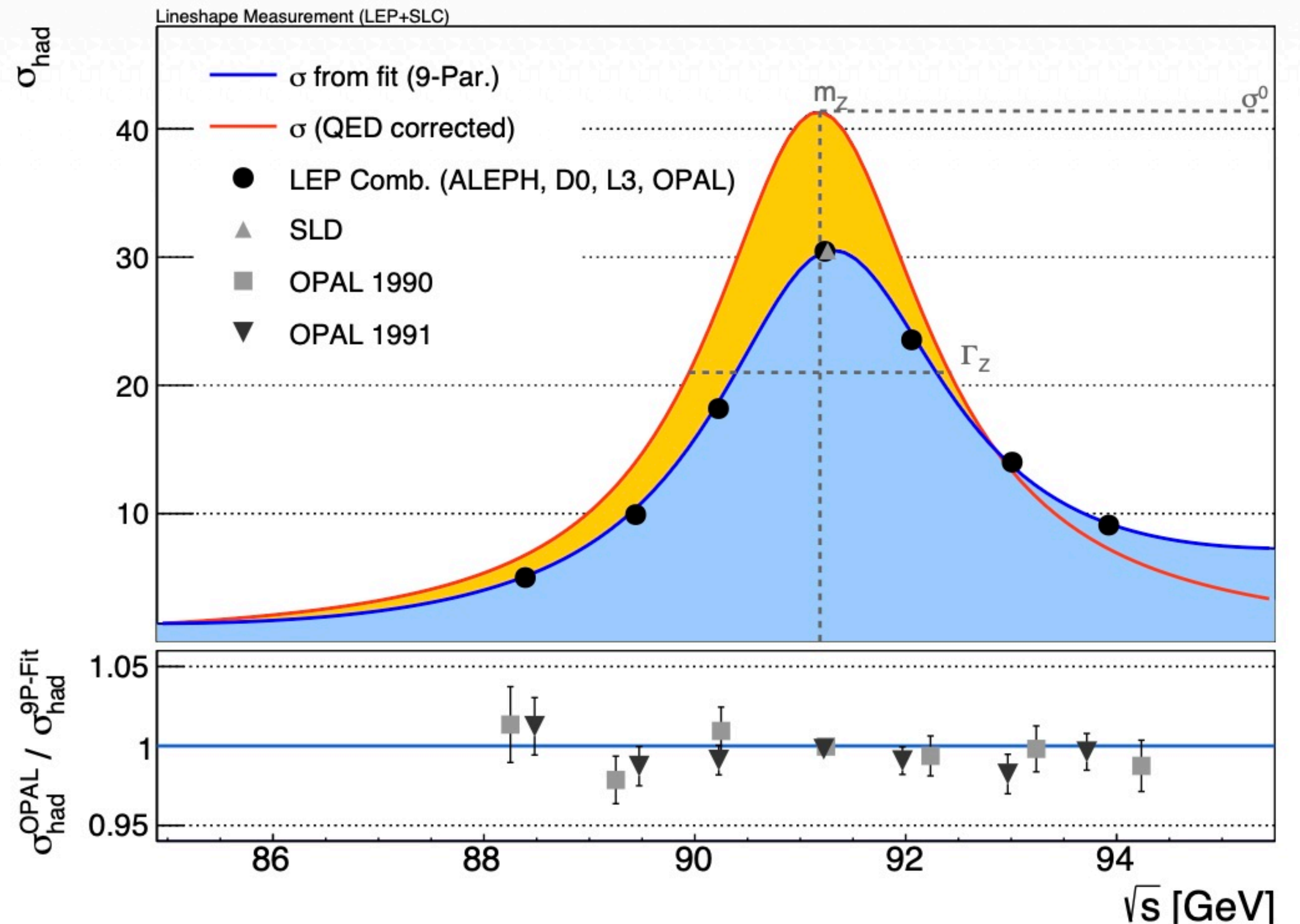


- The profiling will use the only the data under study to reduce systematic uncertainties
- IMHO Problem: Some model uncertainties (e.g. PDFs) are explicitly enlarged to be able to describe the full available range of experimental measurements

Solution in the far future:  
 Design a global fit, which includes all data and extracts everything at the same time

# Status of the Z Boson Mass

- The Z boson mass wasn't updated since LEP
  - ... long thought that it will never change until FCC-ee
- CDF and CMS W boson mass use J/Psi as calibration
  - Test their calibration at the Z boson and get close to LEP precision
- Likely that we will see an update on  $m_Z$  from LHC within the next decade



# Update of the Global Electroweak Fit

- Update of the Global Electroweak Fit with Gfitter

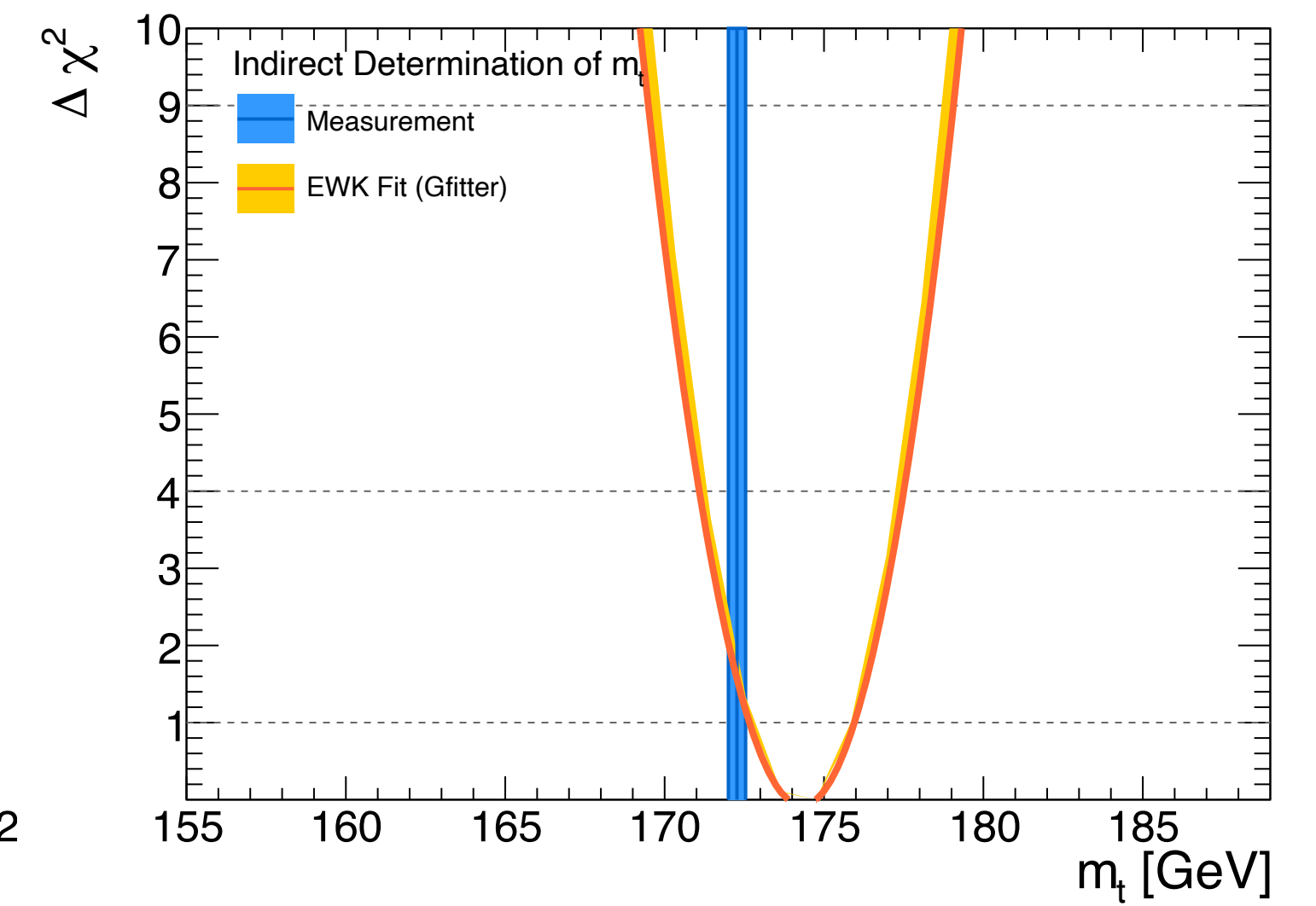
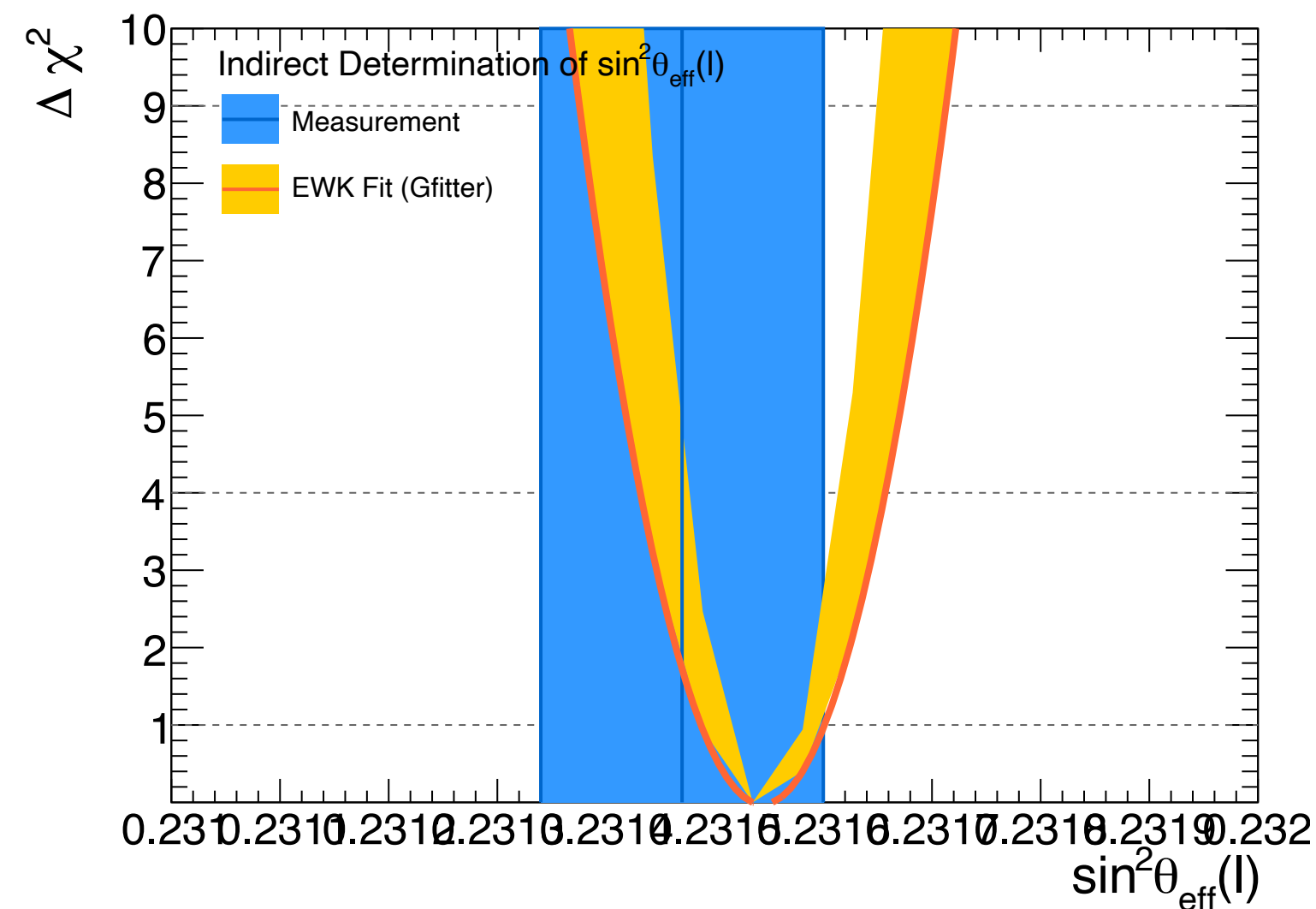
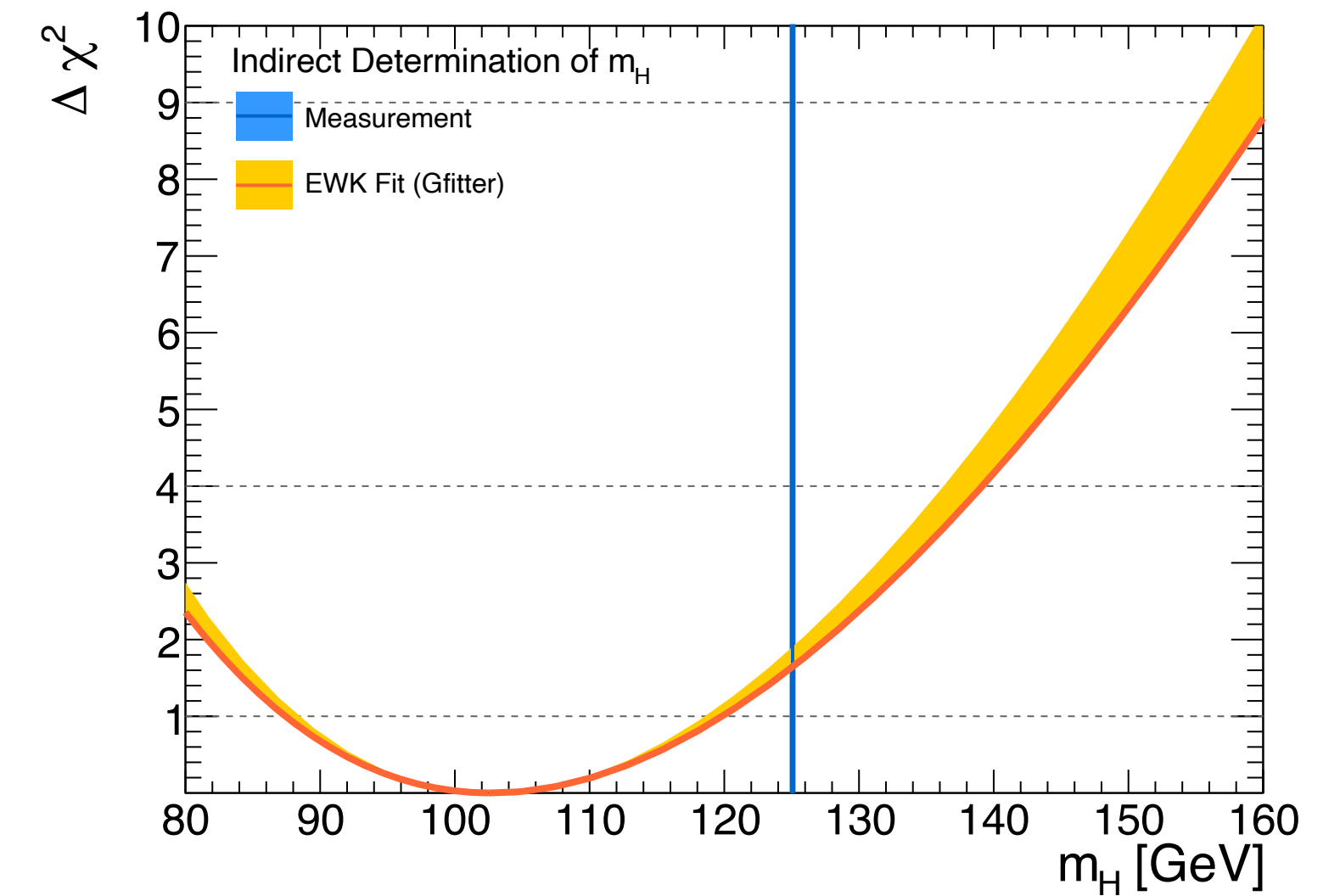
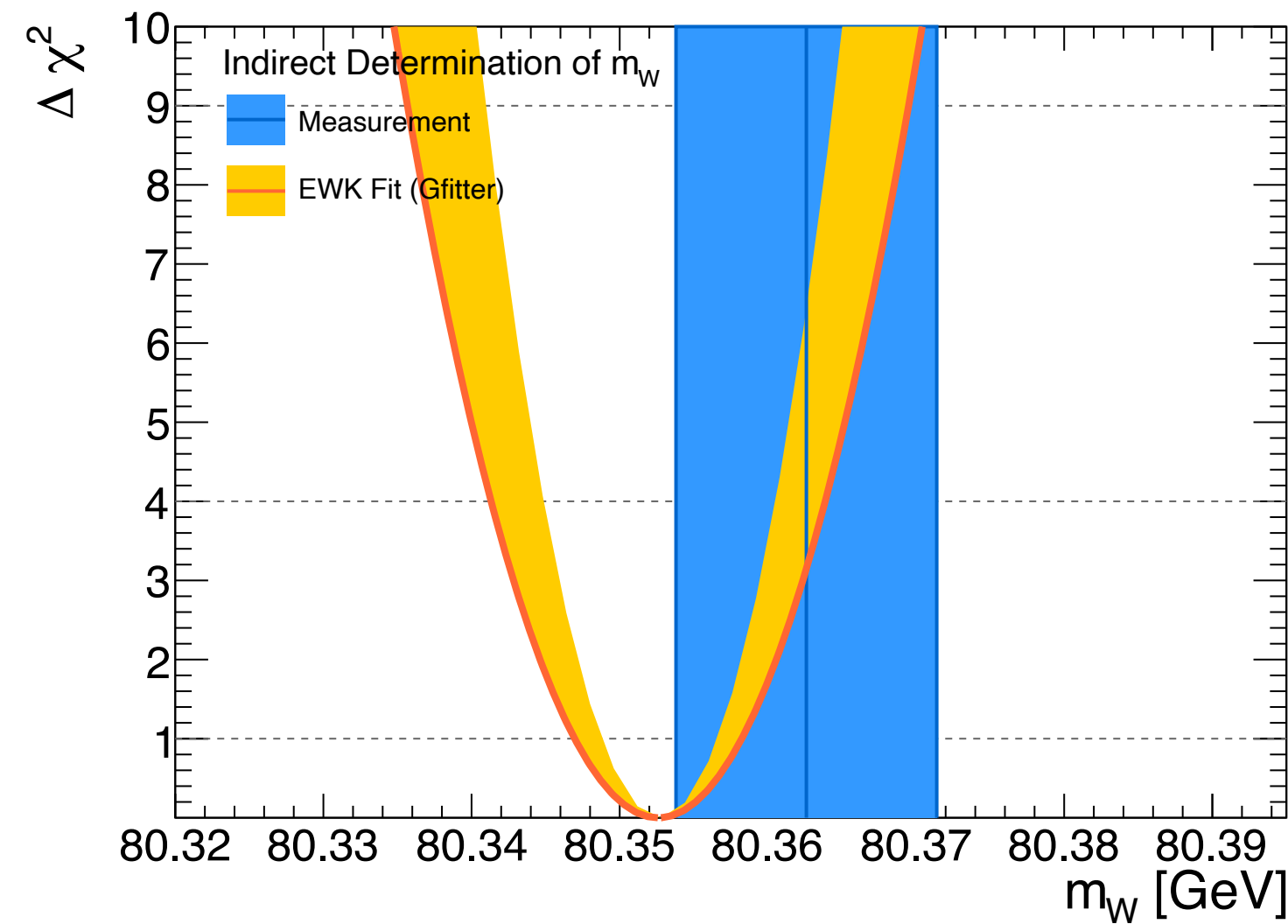
- <https://project-gfitter.web.cern.ch/>

- Indirect predictions for main observables

- $m_W = 80353 \pm 5.6$  MeV
  - $m_Z = 91195 \pm 7$  MeV
  - $m_T = 174.3 \pm 1.6$  GeV
  - $m_H = 102.7 \pm 16$  GeV
  - $\sin^2\theta_W = 0.231544 \pm 0.000056$

- Overall consistency of the SM Global Electroweak Fit

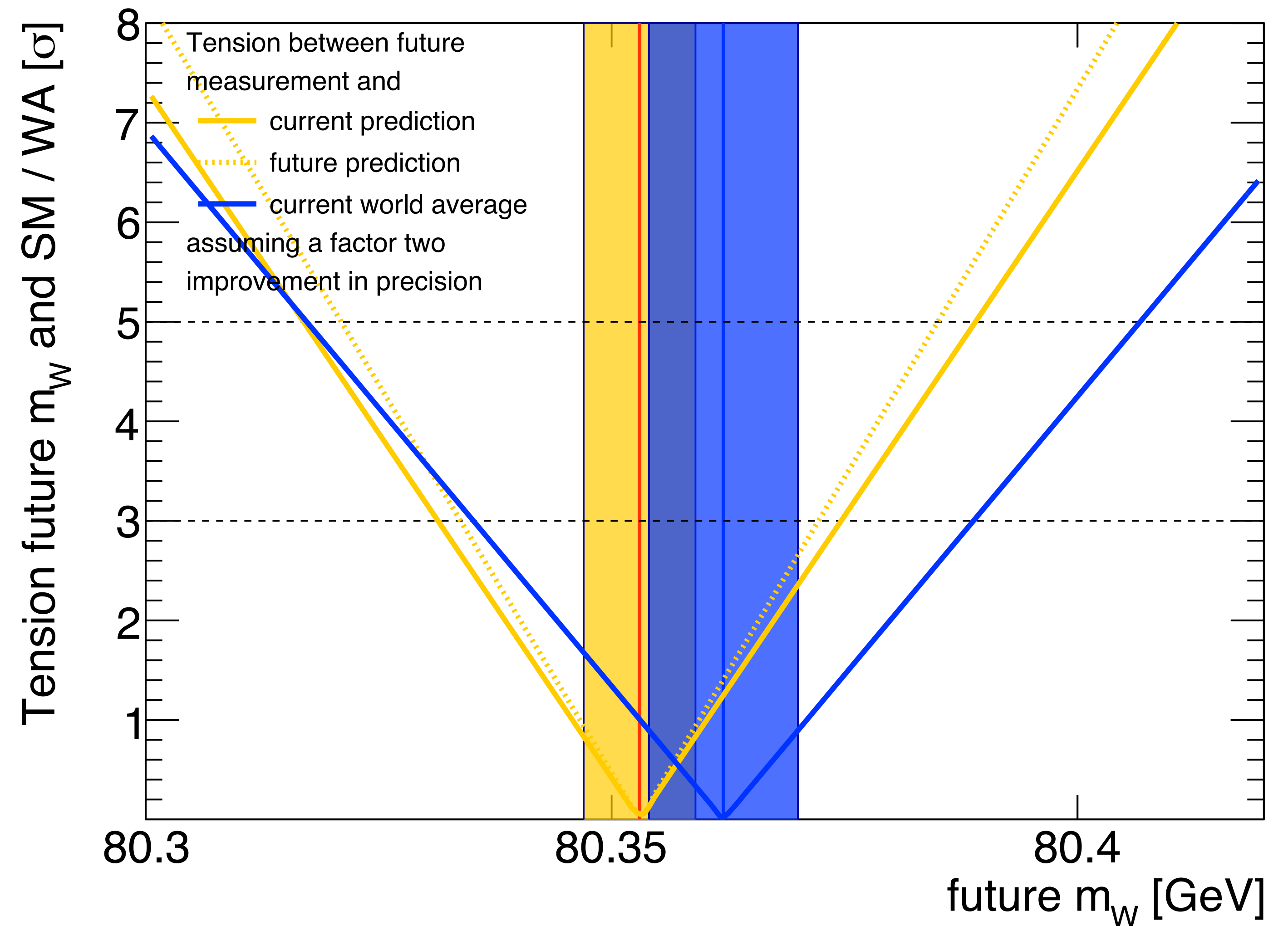
- $\chi^2/\text{ndf} = 17.1/14$  (p-value 0.25)



# The Future of the W Boson Mass

- Assumes experimental precisions after HL-LHC
  - $\Delta m_W = 4 \text{ MeV}$
  - $\Delta m_Z = 1 \text{ MeV}$
  - $\Delta m_\tau = 150 \text{ MeV}$  (unrealistic?)
  - $\Delta m_H = 50 \text{ MeV}$
  - $\Delta \sin^2 \theta_W = 0.00007$

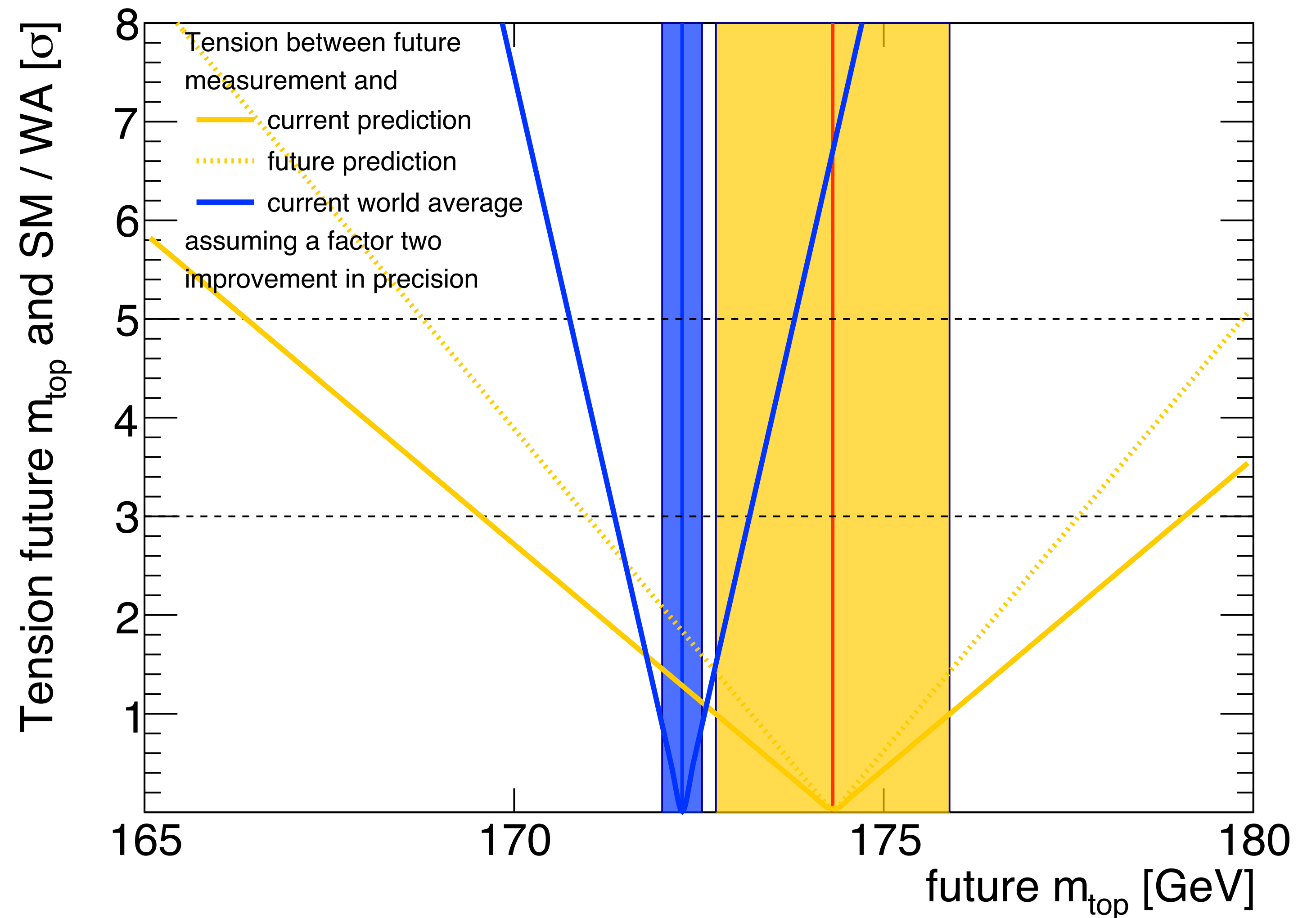
- Realistic future single measurements of  $m_W$  that are **incompatible with the SM** are also incompatible with the current WA



# The Future of the Top Quark Mass

- Assumes experimental precisions after HL-LHC
  - $\Delta m_W = 4 \text{ MeV}$
  - $\Delta m_Z = 1 \text{ MeV}$
  - $\Delta m_T = 150 \text{ MeV}$  (unrealistic?)
  - $\Delta m_H = 50 \text{ MeV}$
  - $\Delta \sin^2 \theta_W = 0.00007$

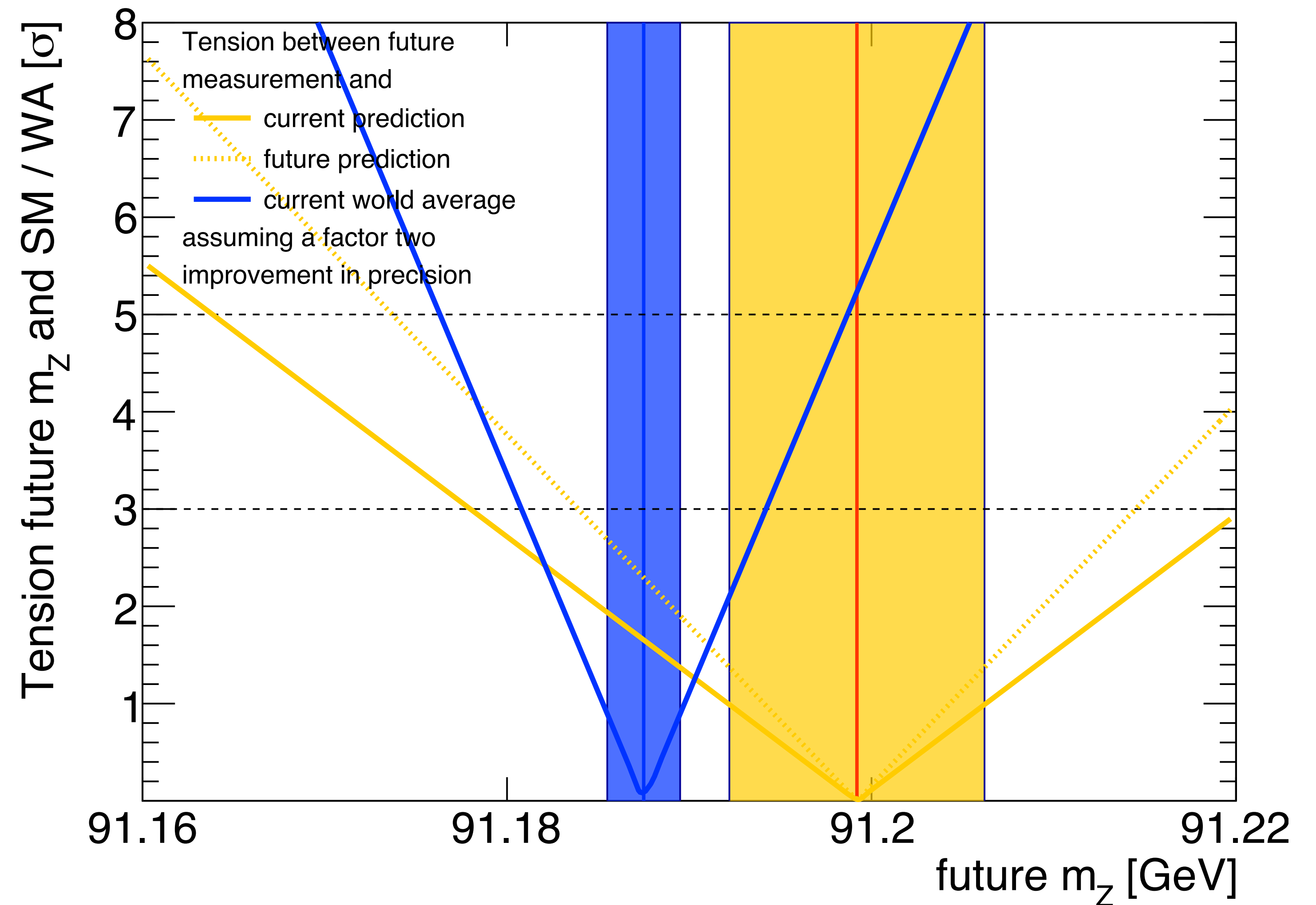
- Realistic future single measurements of  $m_{\text{Top}}$  that are **incompatible with the SM** are also incompatible with the current WA



# The Future of the Z Boson Mass

- Assumes experimental precisions after HL-LHC
  - $\Delta m_W = 4$  MeV
  - $\Delta m_Z = 1$  MeV
  - $\Delta m_\tau = 150$  MeV (unrealistic?)
  - $\Delta m_H = 50$  MeV
  - $\Delta \sin^2 \theta_W = 0.00007$

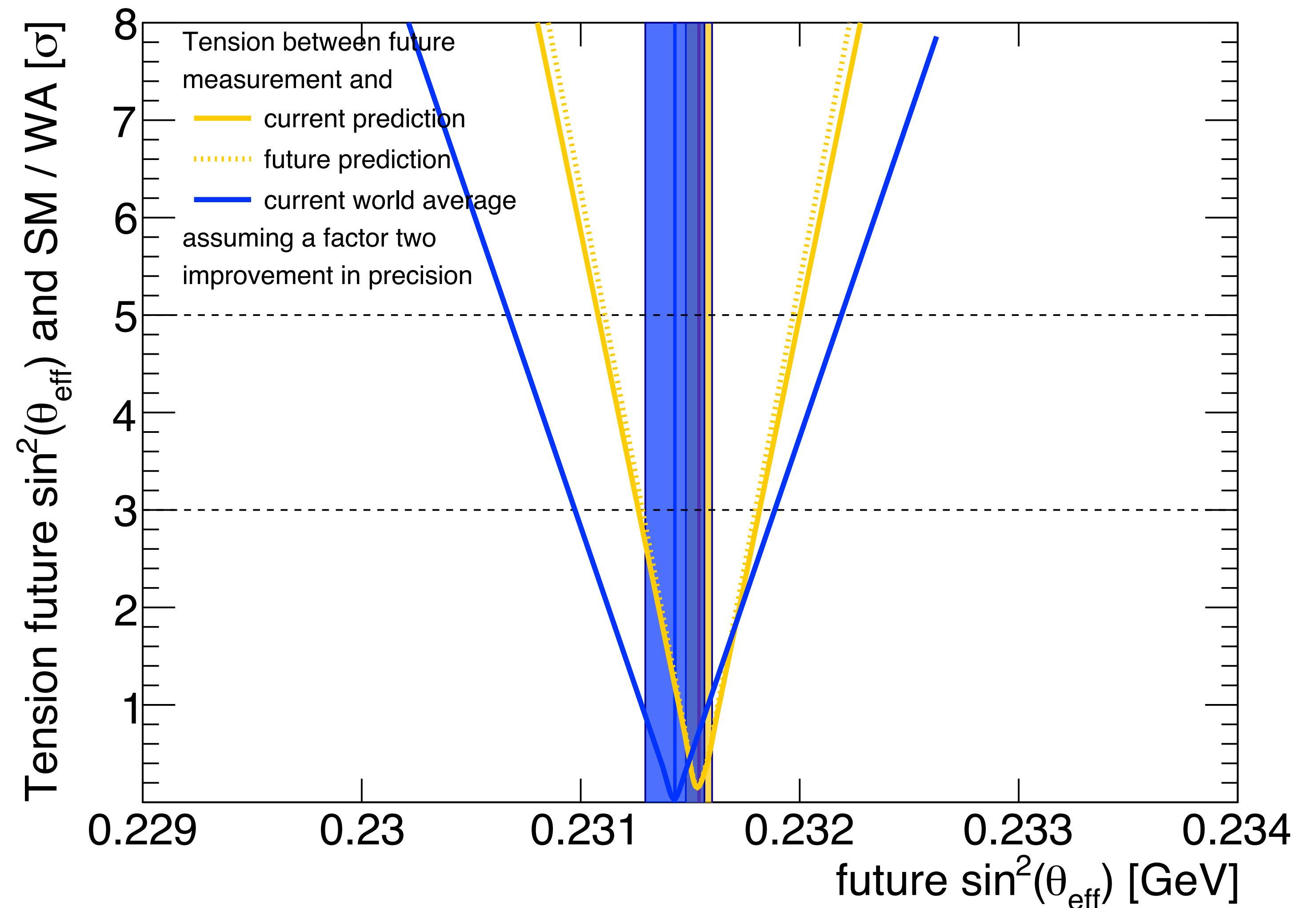
- Realistic future single measurements of  $m_Z$  that are **incompatible with the SM** are also incompatible with the current WA



# The Future of the Electroweak Mixing Angle

- Assumes experimental precisions after HL-LHC
  - $\Delta m_W = 4$  MeV
  - $\Delta m_Z = 1$  MeV
  - $\Delta m_\tau = 150$  MeV (unrealistic?)
  - $\Delta m_H = 50$  MeV
  - $\Delta \sin^2 \theta_W = 0.00007$

- Wait! Not so fast
- The weak mixing angle has indeed still a potential to see new physics at the HL-LHC



# What about Effective Field Theories?

- Moving beyond old LEP approaches (and no discoveries beyond the Higgs)

- Effective Field Theories
- extend SM Lagrangian by a operators  $O(d)$

$$L_{SMEFT} = L_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

- $\Lambda$ : scale of new physics
- $c_i$ : Willson coeff.: strength of BSM interaction

- EWPO involve relatively low energy scales  $E$  (compared to LHC energies)

- $\rightarrow$  higher-order corrections in  $E/\Lambda$  are small
- $\rightarrow$  leading terms of the SMEFT expansion as good approximation
- $\rightarrow$  EWPO important

- Setup of the SM Effective Field Theory Fit from Hannes (JHEP 07 (2025), 089)

- Input Data:

- $m_W, m_Z, \sin^2\theta_W, m_\tau, m_H + 27$  obs.
- $U(2)_q \times U(2)_u \times U(2)_d$  symmetry,  $\{m_W, m_Z, G_\mu\}$  input scheme

- SM Predictions based on

- I. Dubovyk, A. Freitas et. al, arXiv:1906.08815
- M. Awramik, M. Czakon and A. Freitas, arXiv:hep-ph/0608099
- M. Awramik, M. Czakon, A. Freitas and G. Weiglein, arXiv:hep-ph/0311148

- SMEFT parametrization based on

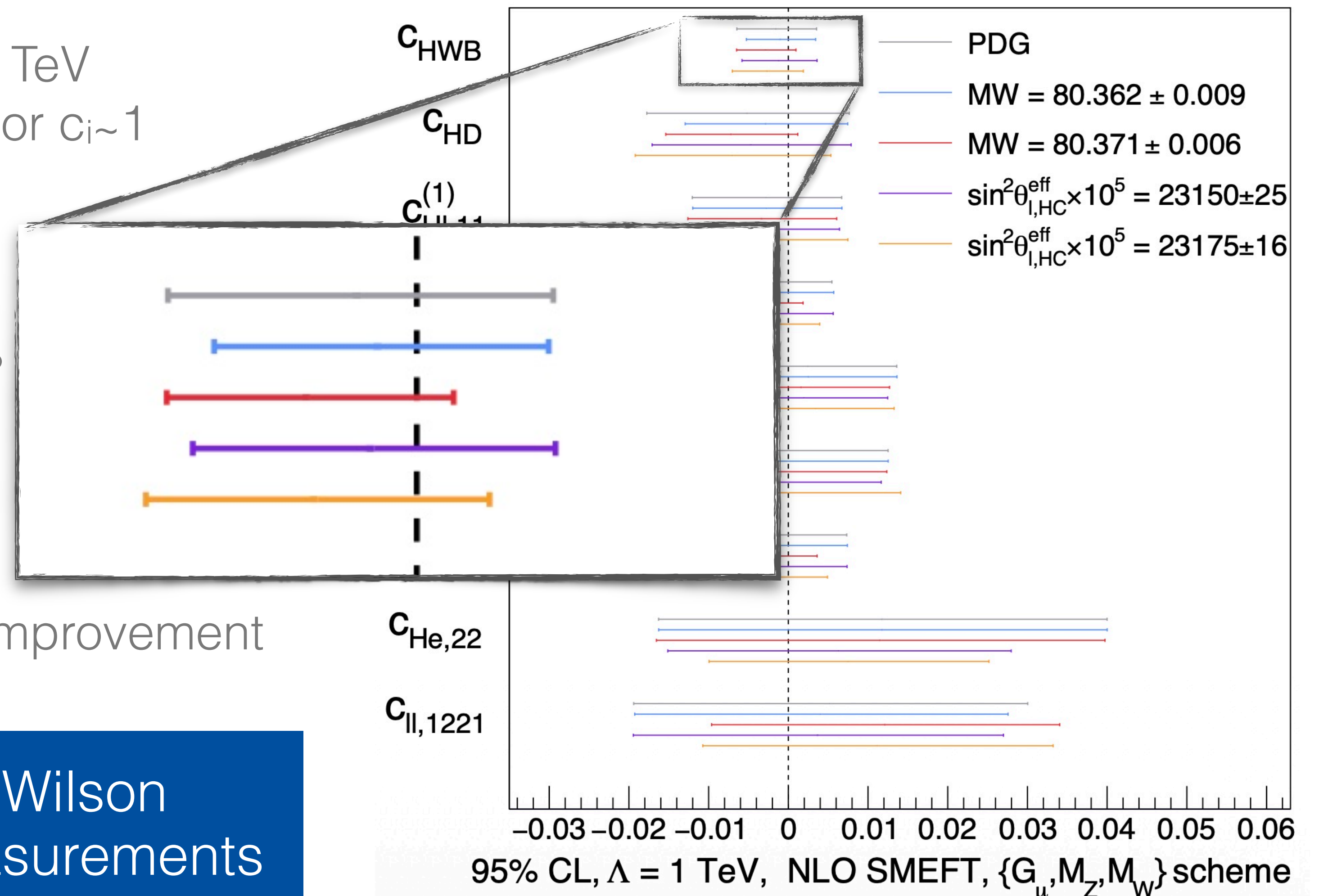
- A. Biekötter et. al., arXiv:2312.08446

# LHC Improvements

- Fit Results
  - One-at-a-time constraints for  $\Lambda = 1$  TeV
  - New physics exclusion:  $\Lambda \gtrsim 10$  TeV for  $c_i \sim 1$
- W Mass
  - First: Combined LHC
  - Second: shifted by  $+1\sigma$  with a 33% improvement
- Effective Weak Mixing Angle
  - First: Combined LHC+Tevatron
  - Second: shifted by  $+1\sigma$  with 33% improvement

■ Measuring significant non-zero Wilson coefficients requires future measurements to be incompatible with current EWPD

H. Mildner JHEP 07 (2025) 089

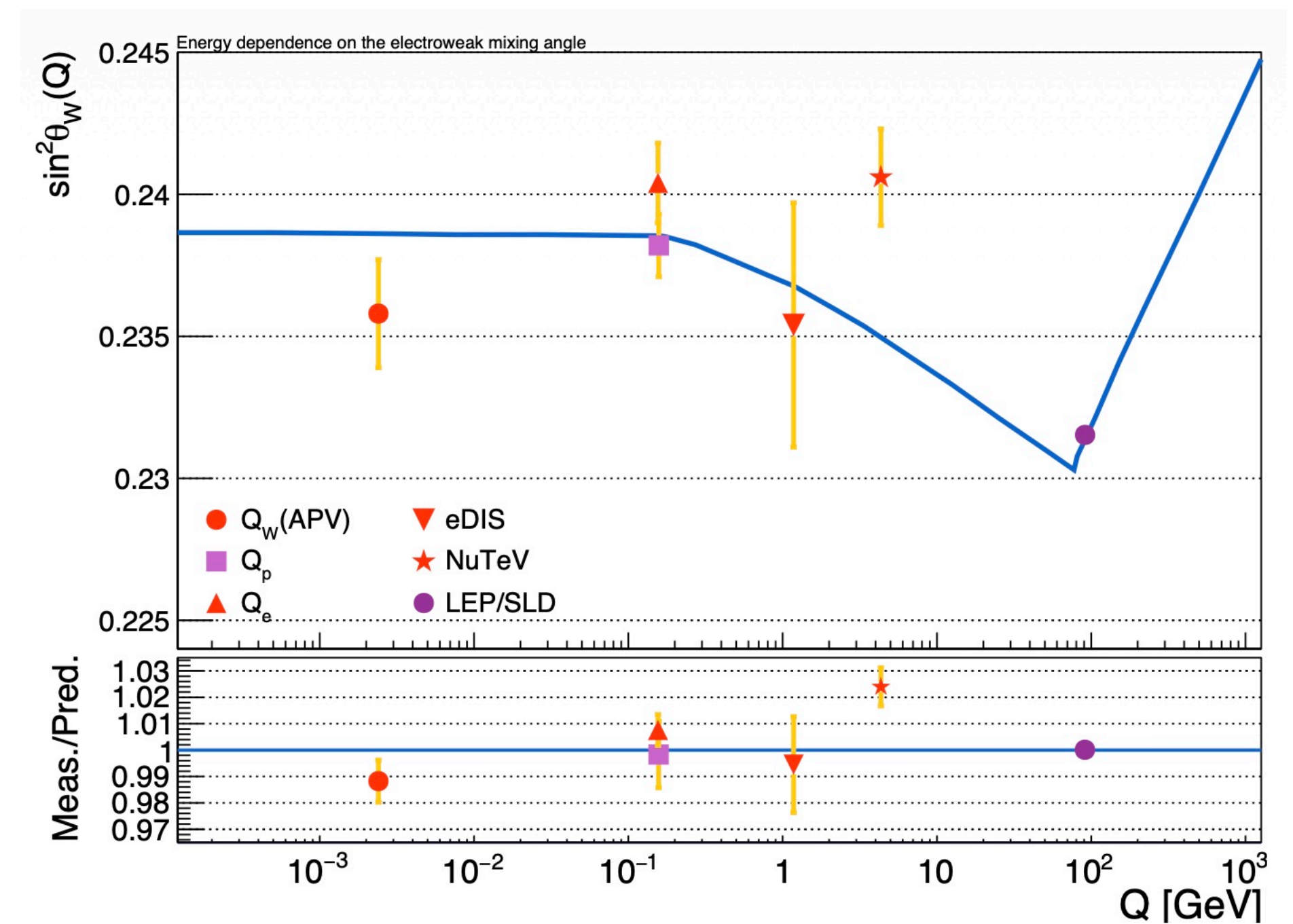


Wilson coefficients most affected shown

# The Future of Electroweak Precision Observables at the LHC



- Standard EWPO likely not a direct gate to NP, rather important input to SMEFT-Fits
  - but,  $\Lambda$  scales with  $(\text{precision})^{1/2}$
- Focus on running of couplings
  - Unique opportunity at HL-LHC



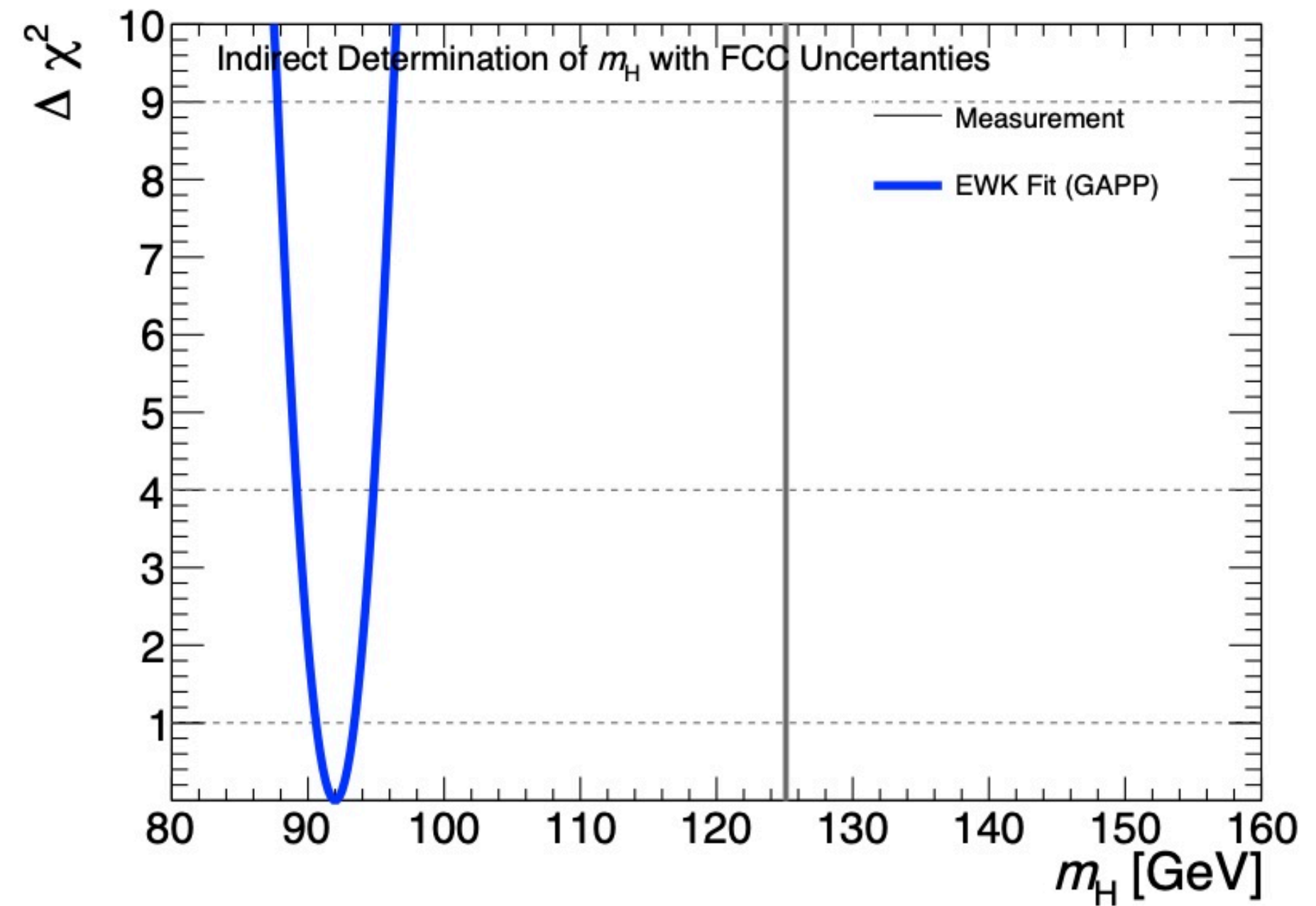
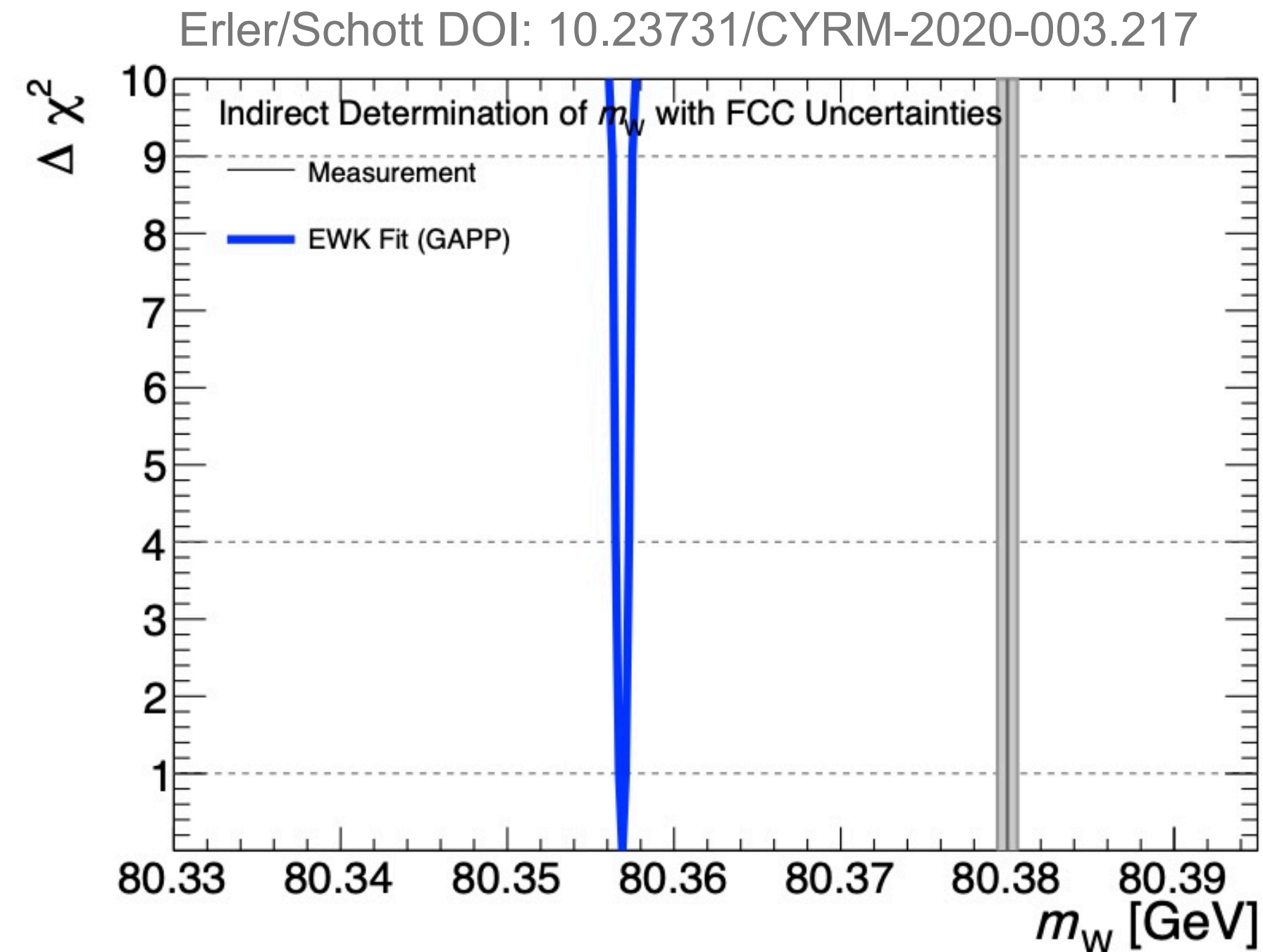
# Electroweak Precision Physics at the FCC-ee

- FCC-ee will be a game changer
  - Bringing back the Global EW Fit on stage

Parameter	Current value	FCC-ee unc.-target
$M_Z$	$91.1875 \pm 0.0021$ GeV	$<0.1$ MeV
$\Gamma_Z$	$2.4952 \pm 0.0023$ GeV	25 keV
$\sigma_{\text{had}}^0$	$41.540 \pm 0.037$ nb	0.004 nb
$R_b$	$0.21629 \pm 0.00066$	$<0.00006$
$A_{LR}^{\text{FB}}(b)$	$0.0992 \pm 0.0016$	$\pm 0.0001$

Parameter	Current value	FCC-ee unc.-target
$M_H$	$125.09 \pm 0.15$ GeV	$\pm 0.01$ GeV
$M_W$	$80.380 \pm 0.013$ GeV	$\pm 0.6$ MeV
$\Gamma_W$	$2.085 \pm 0.042$ GeV	$\pm 1.0$ MeV
$m_{\text{top}}$	$172.90 \pm 0.47$ GeV	$\pm 15$ MeV
$\Delta\alpha_{\text{had}}[\times 10^{-5}]$	$2758 \pm 10$	$\pm 3$

- SM Predictions at FCC-ee
  - $\Delta M_W = \pm 0.2$  MeV,
  - $\Delta m_{\text{Top}} = \pm 0.1$  GeV
  - $\Delta M_H = \pm 1.4$  GeV,





# Summary

- Most likely my last presentation on the Global Electroweak Fit for a while
- We should focus on the weak mixing angle and the running of couplings during the HL-LHC...
- ... and prepare step-by-step the FCC-ee program