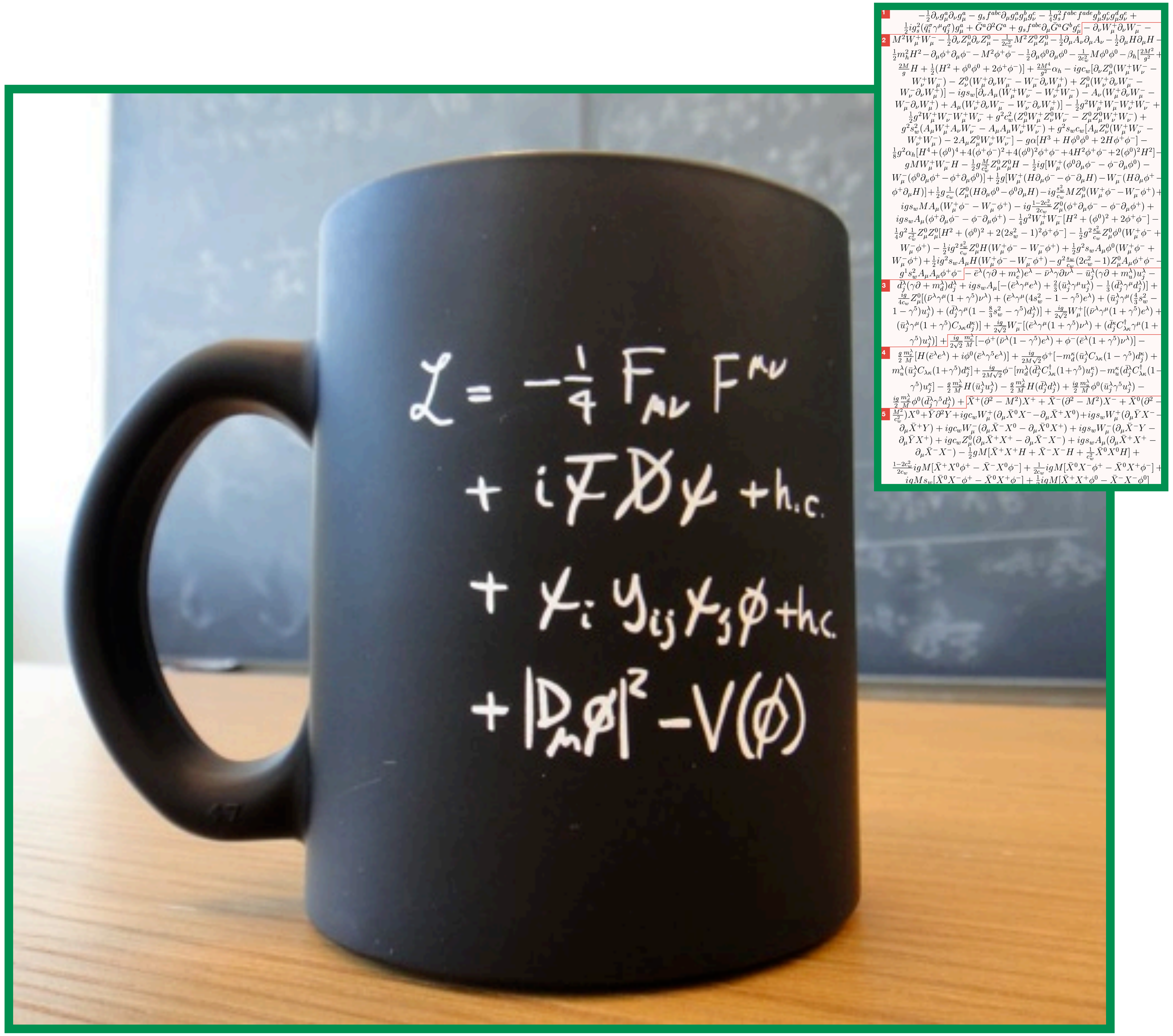
Precision EWK and QCD measurements from ATLAS, CMS, LHCb

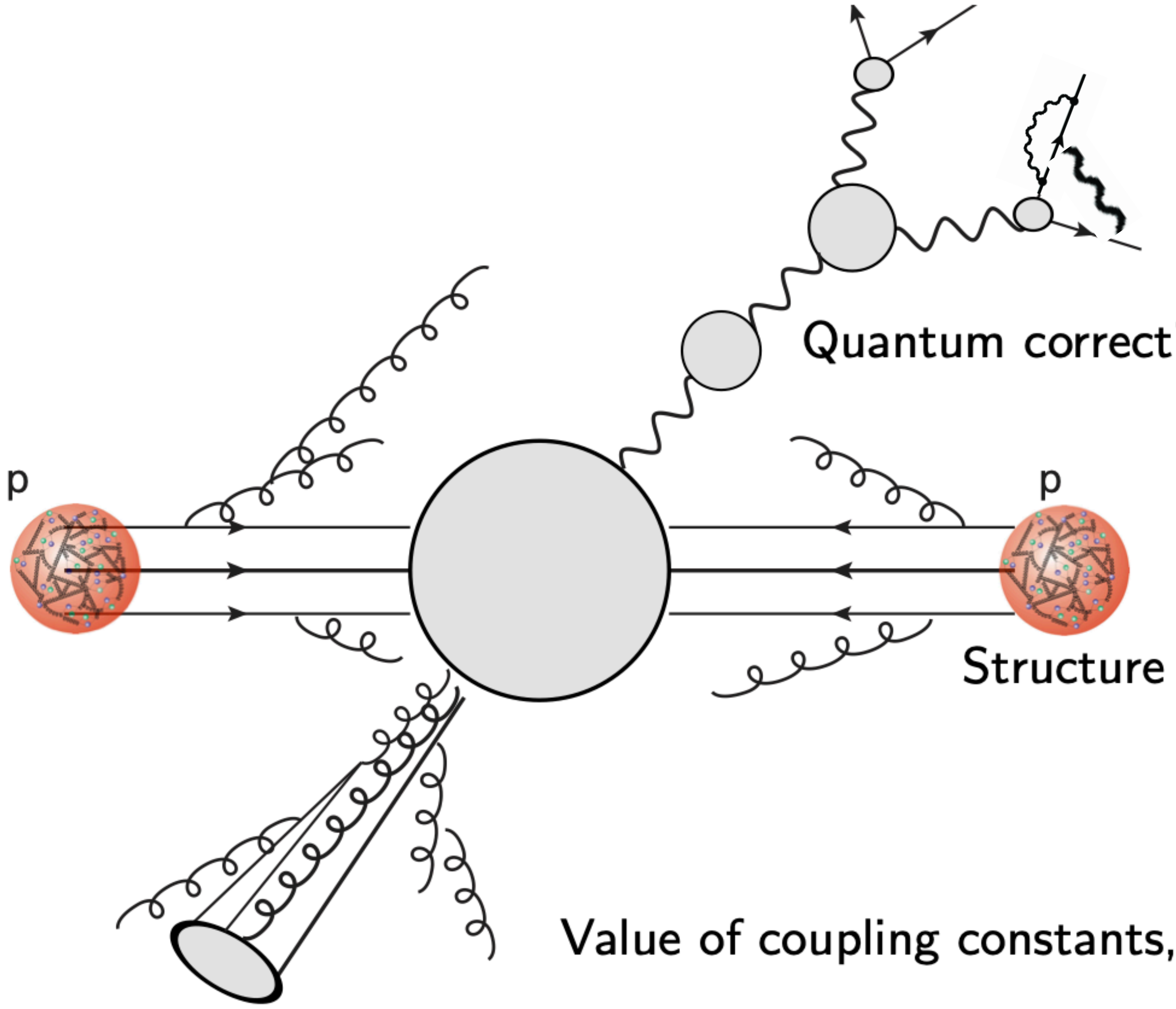
Valentina Guglielmi on behalf of ATLAS, CMS and LHCb

PIC2024, Athens, 22.10.2024

The standard model



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



Fermions and boson interactions and self-interactions

Quantum corrections to masses and couplings

Structure of the proton

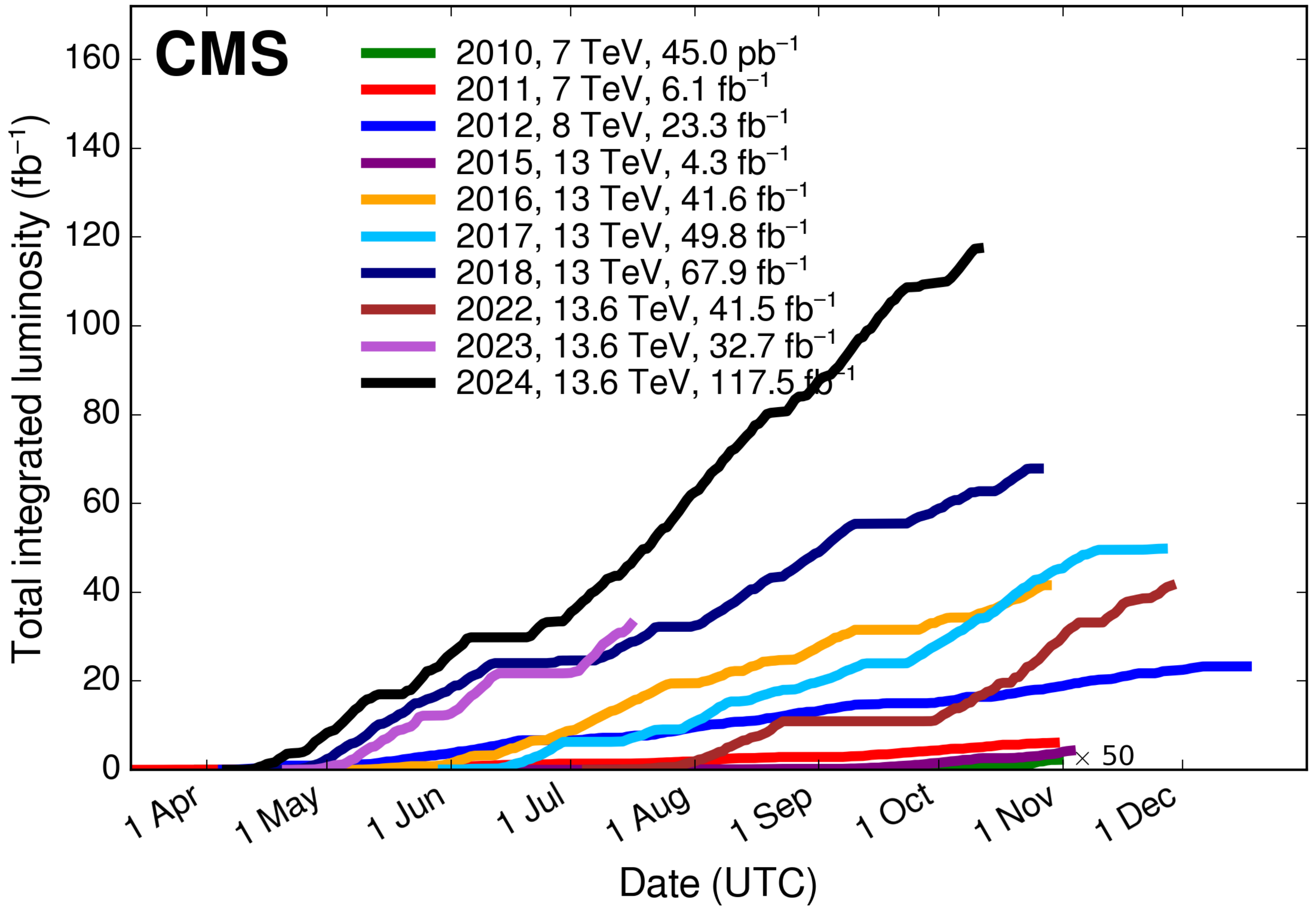
Value of coupling constants, e.g. α_S

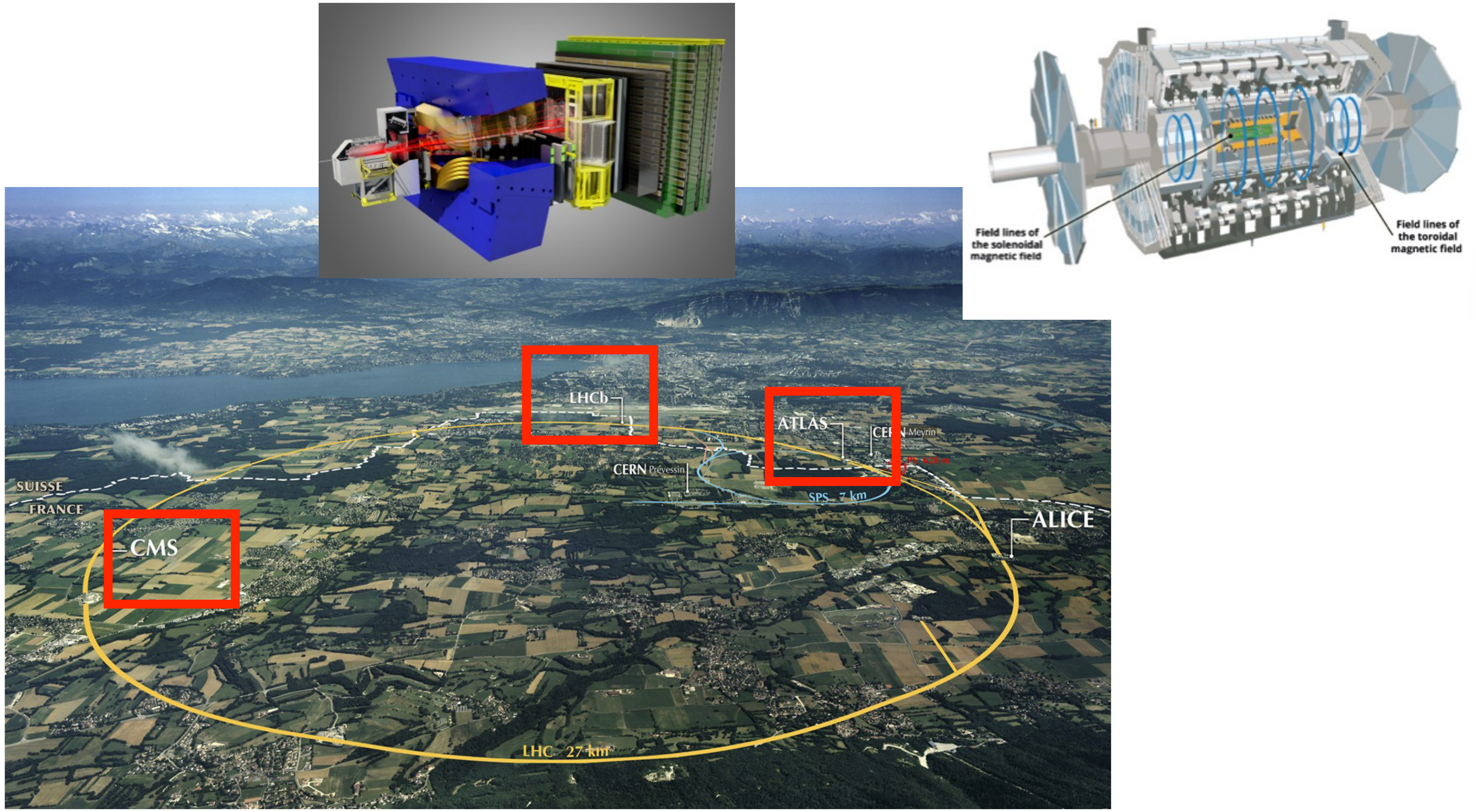
From Jan Kretzschmar, ICHEP2022

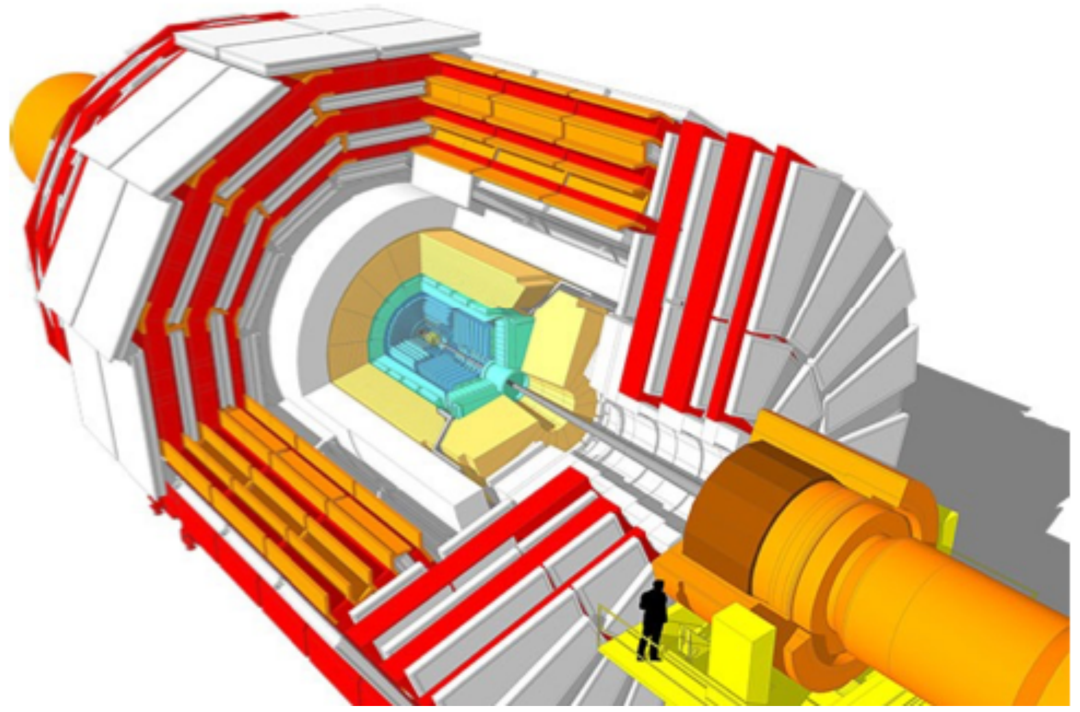
LHC and experiments

13 Years of successful data taking at the LHC covering many energies

twikiLumiPublicResults







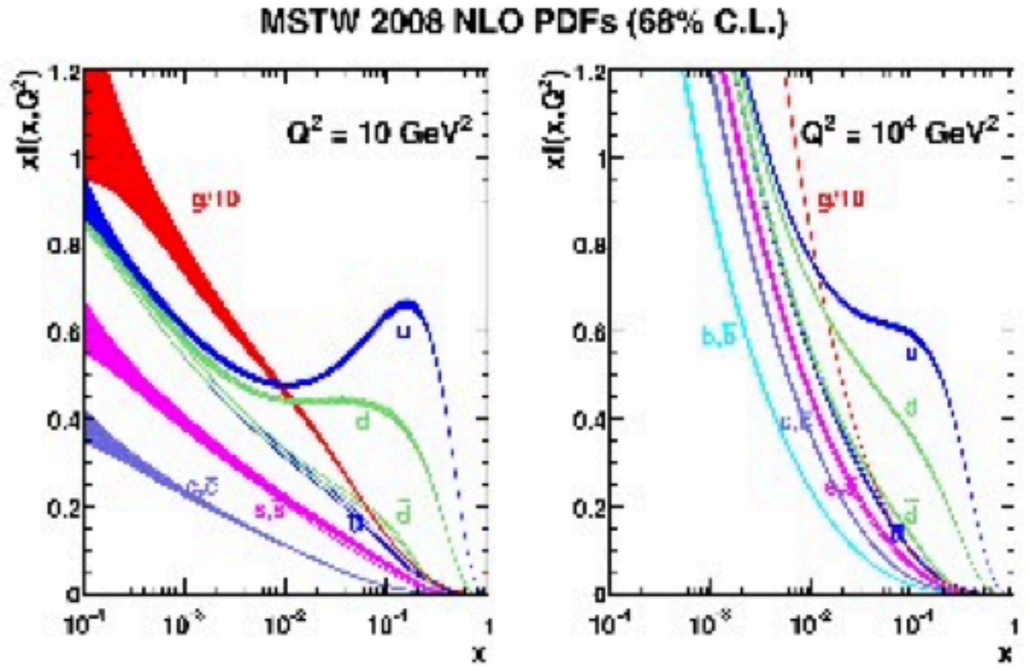
LHC: ring of ~27 km, in Geneva (Switzerland)

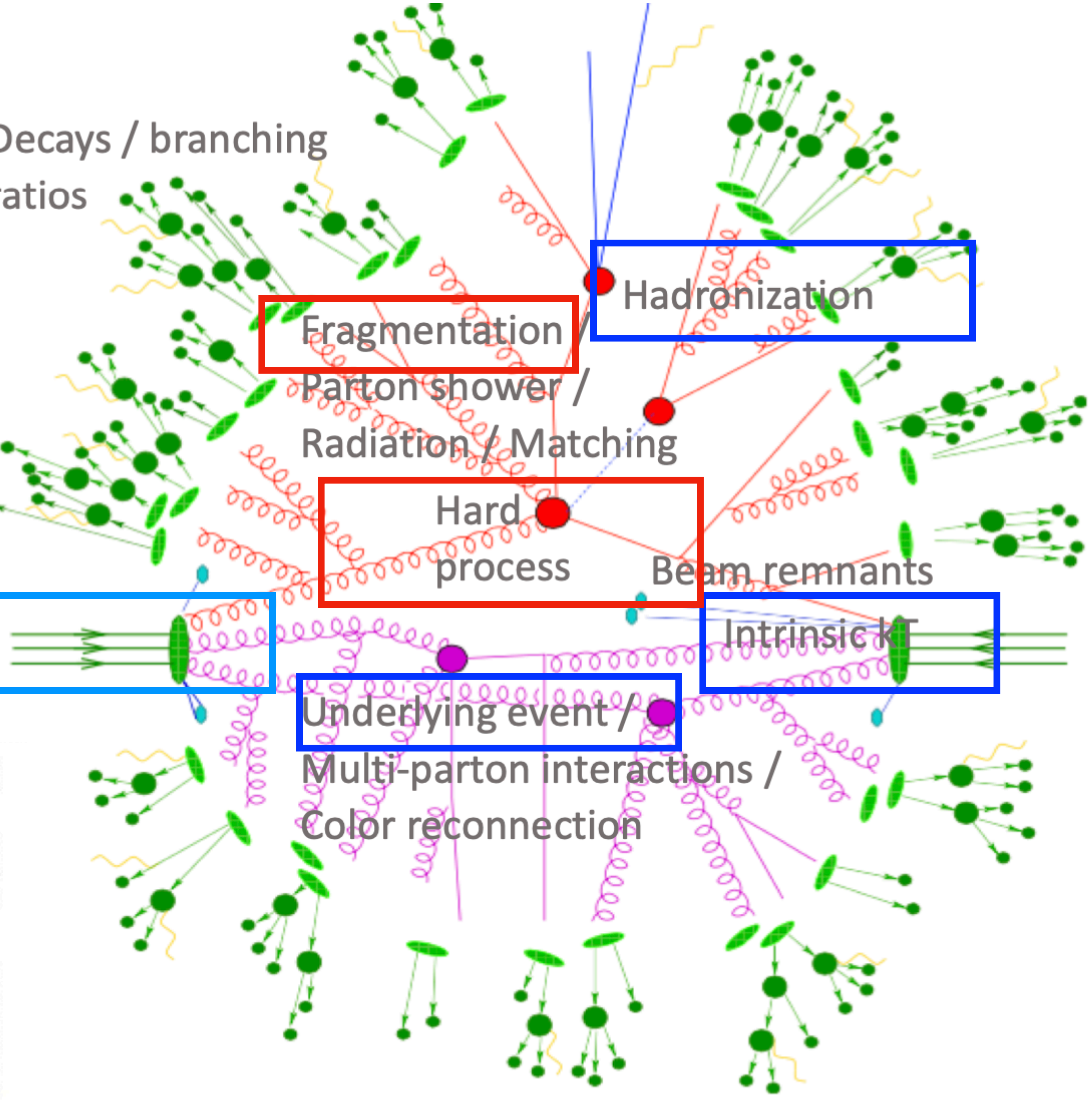
EW and QCD

- **EW physics at LHC can't forget about QCD**
- A good QCD model is a prerequisite for EW physics
- Precise EW measurements help to constrain QCD parameters and models

$$\sigma_{pp\to X} = \Sigma_{i,j}\int dx_1 dx_2 f_i^p(x_1,\mu) f_j^p(x_2,\mu) \times \sigma_{ij\to X}$$

Parton Distribution Functions (PDF)





Decays / branching ratios

Hadronization

Fragmentation / Parton shower / Radiation / Matching

Hard process

Beam remnants

PDFs

Intrinsic kT

Underlying event / Multi-parton interactions / Color reconnection

Introduction

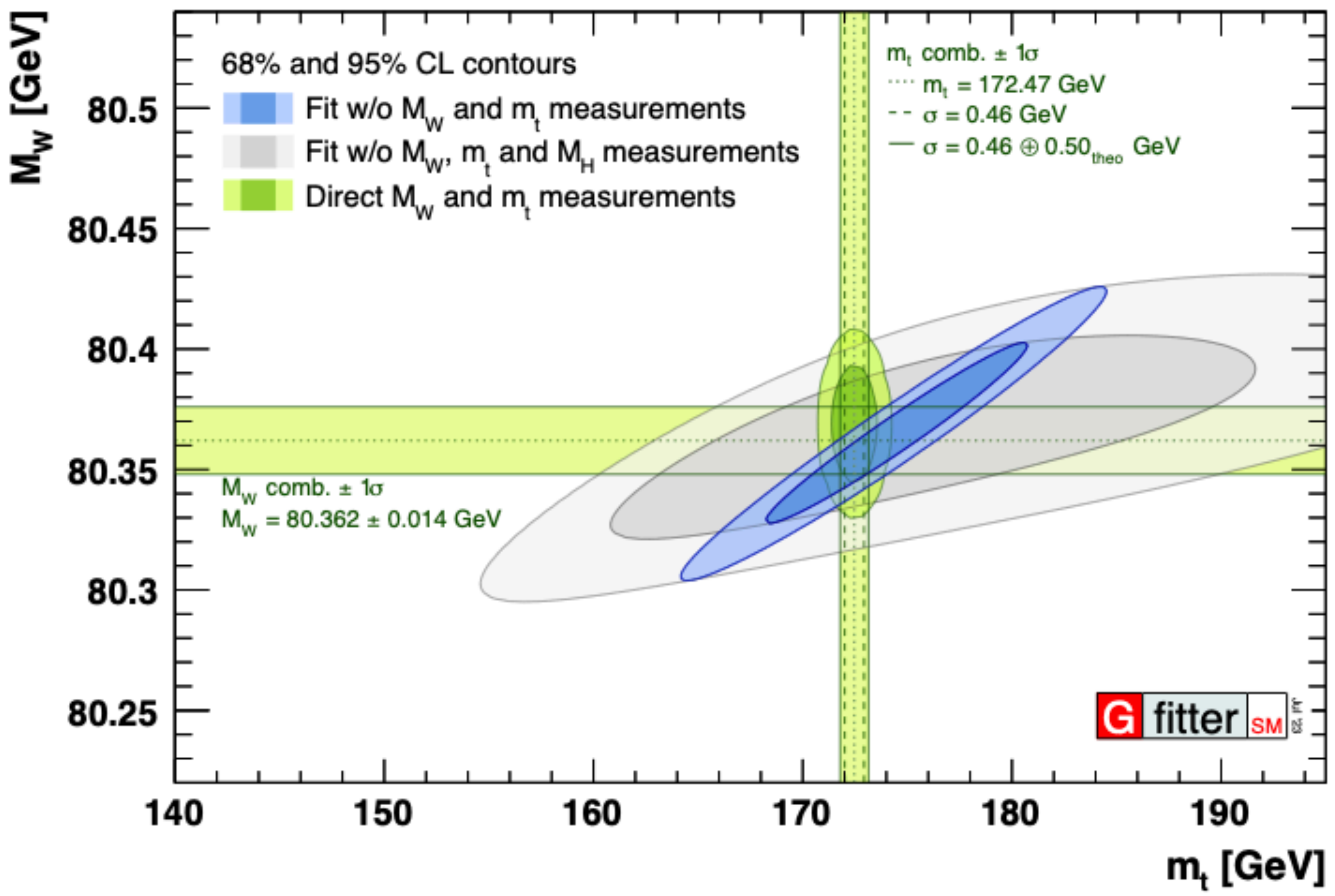
Gfitter,Y. Fischer et al., EPS 2023

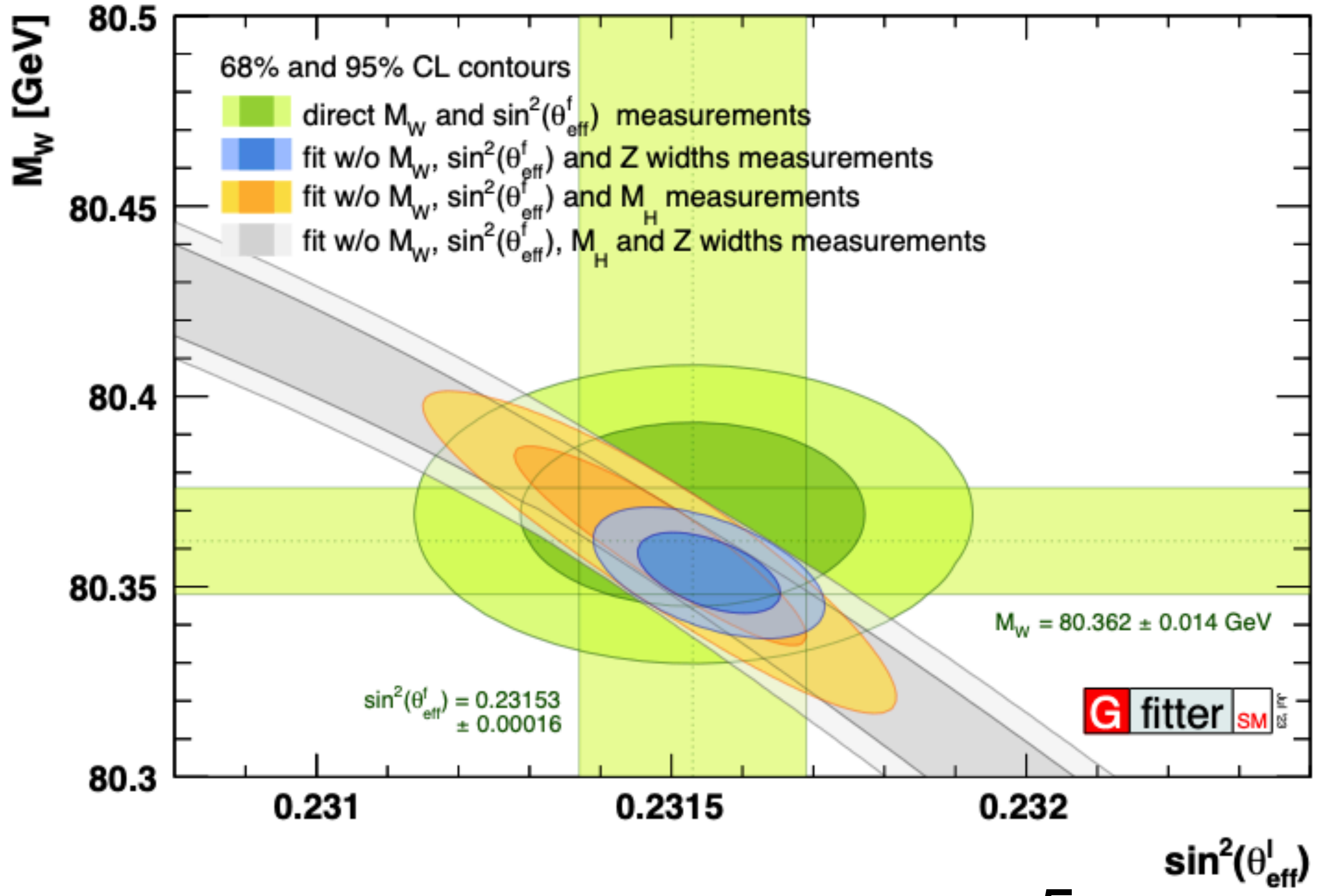
Parameters of SM interconnected with each other, e.g.

$$m_W = \left(\frac{\pi\alpha_{\mathrm{EM}}}{\sqrt{2}G_F}\right)^{1/2}\frac{\sqrt{1+\Delta r}}{\sin\theta_W}$$

α_{EM}: fine-structure constant
θ_{W}: weak mixing angle
G_{F}: Fermi coupling constant

Radiative corrections Δr with largest contributions from m_t^2, $log(m_H)$





Precision measurements:

→ Test self-consistency of SM theory in global EW fits

→ Tensions could be sign of BSM effects

→ Probe BSM at energies above those explored by searches

Outlook

Today I will focus on selection of most recent results

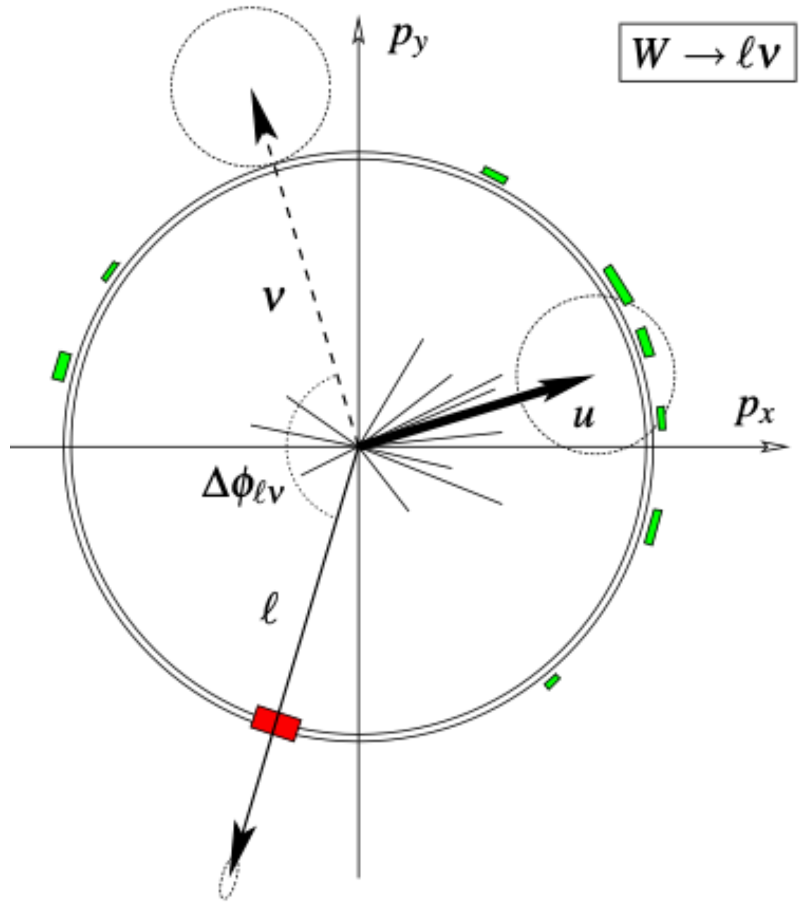
- **EW sector, focus on electroweak parameter measurements:**
  - W boson Mass and Width
  - Electroweak mixing angle
- Taus g-2
- **QCD sector, selection of determinations of $\alpha_S(m_Z)$:**
  - ATLAS Z p_T @8TeV
  - CMS Inclusive jets @2.76, 7, 8, 13 TeV
  - Summary of most recent determinations

Full publication list here: CMS, ATLAS, LHCb

ATLAS measurements of the W Boson Mass and Width

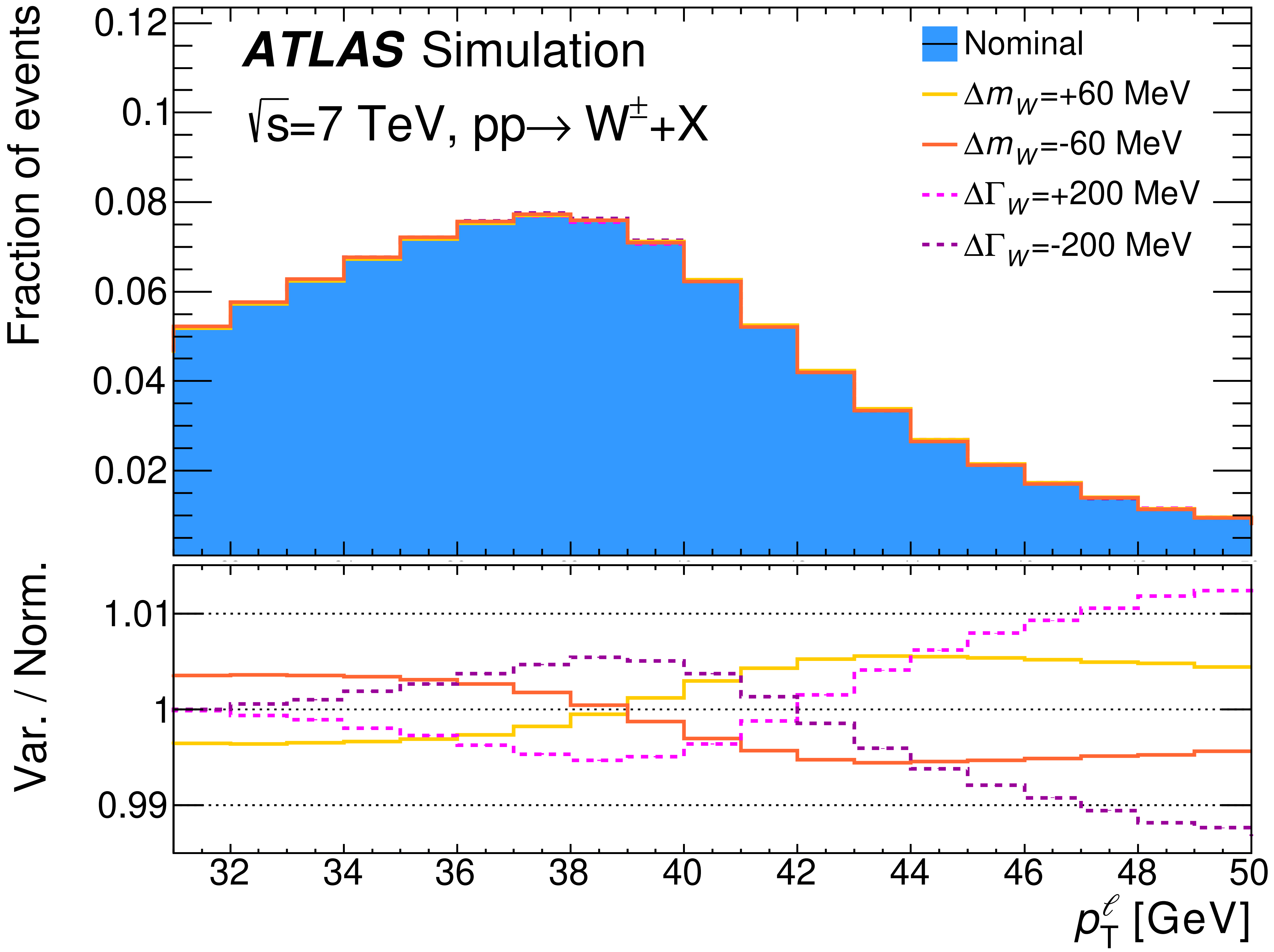
Revisit 2011 data for improved measurement of m_W and first measurement of Γ_W at LHC

- Measured from p_T^l and m_T^W distributions in $W \rightarrow l\nu$ decays ($l = e/\mu$)
- Rigorous checks of $p_T(W)$ modelling in dedicated measurements
- Progress in global PDF fits and theoretical calculations

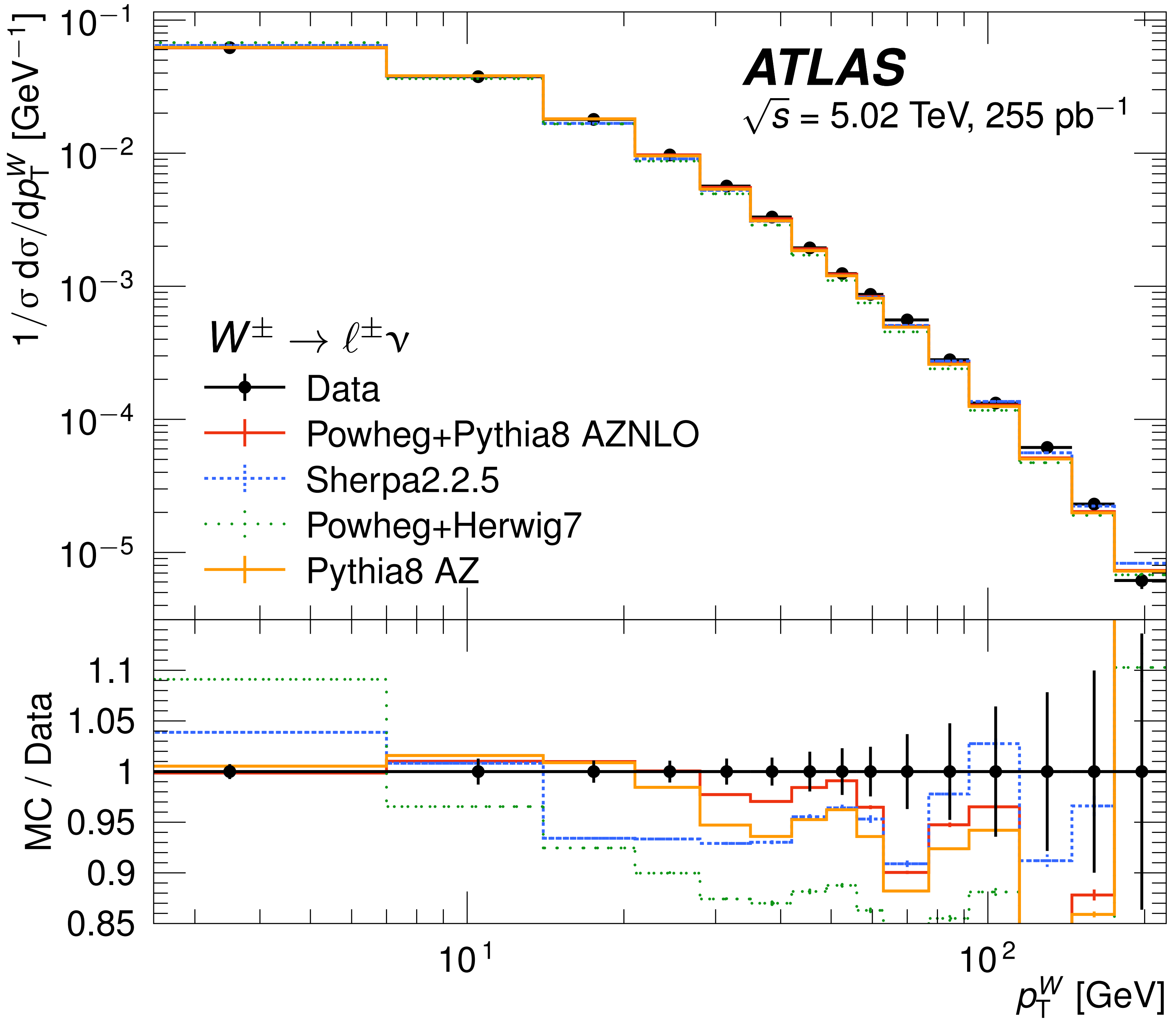


arXiv0901.0512

arxiv2403.15085

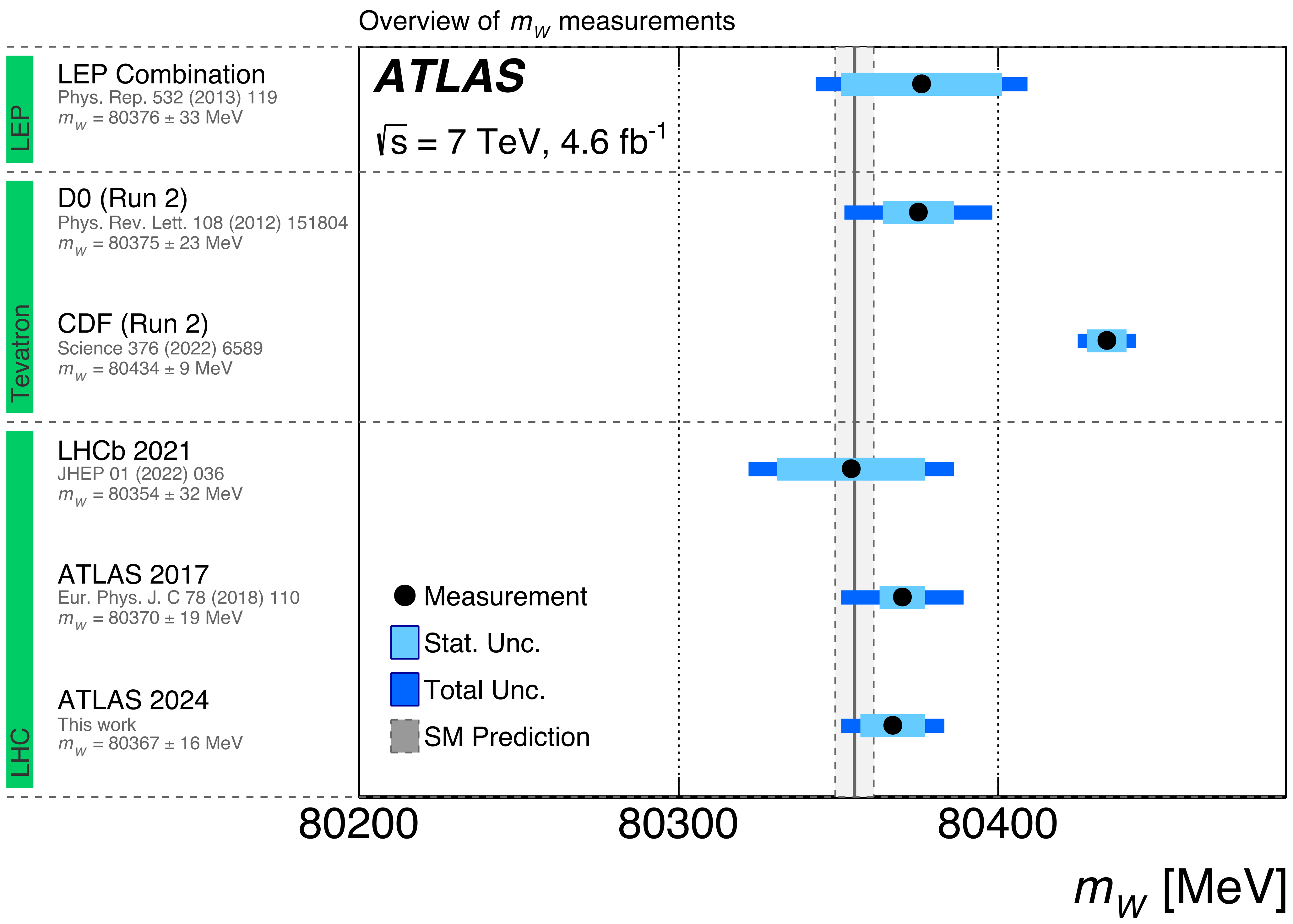


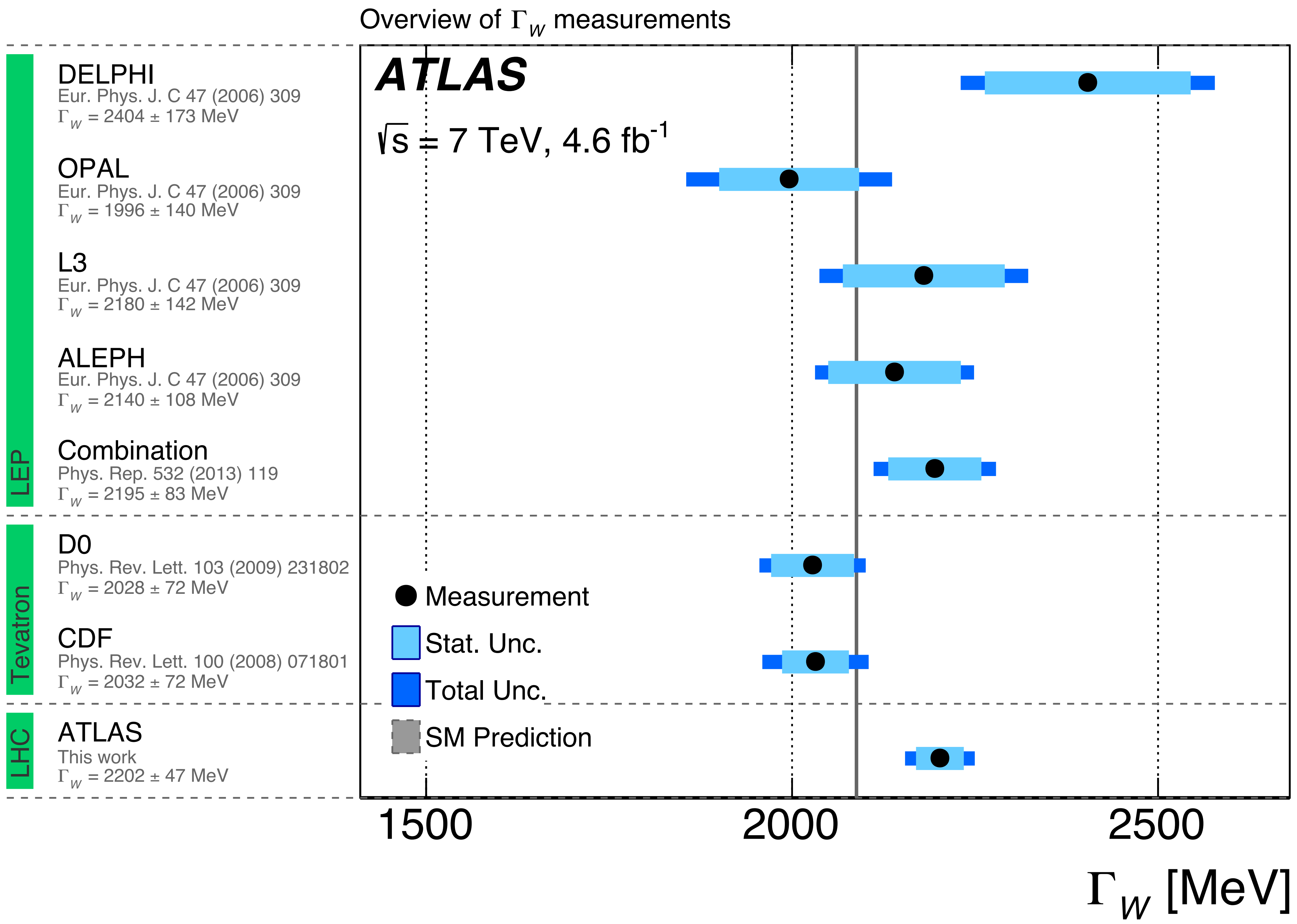
arXiv2404.06204



ATLAS results of the W Boson Mass and Width

arxiv2403.15085

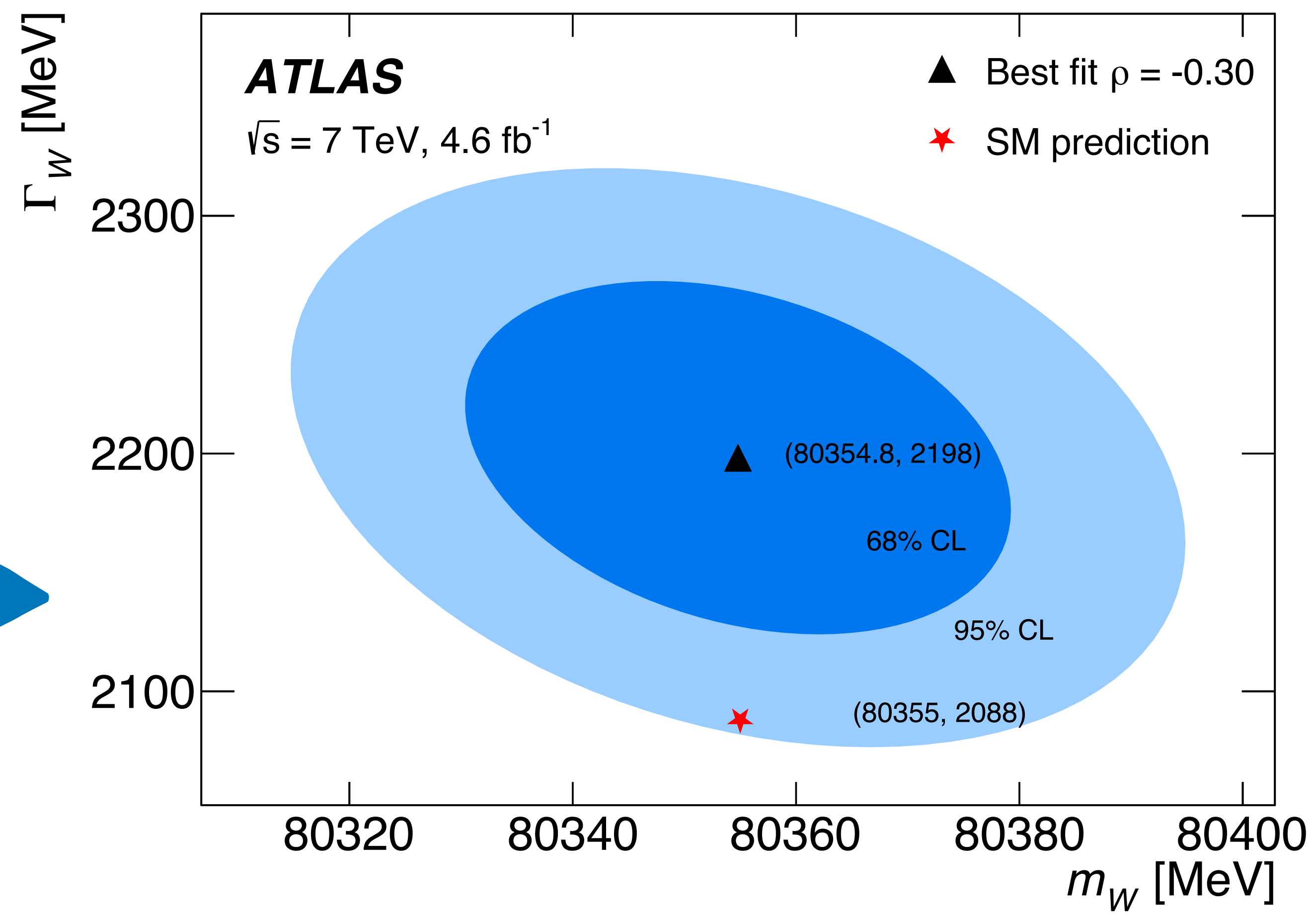




- Separate measurement of mass and width

$$m_W = 80366.5 \pm 15.9 \text{ MeV } (9.8 \text{ stat} + 12.5 \text{ syst})$$
$$\Gamma_W = 2202 \pm 47 \text{ MeV } (32 \text{ stat} + 34 \text{ syst})$$

- … as well as simultaneous extraction
- **Most precise single-experiment measurements of Γ_W**



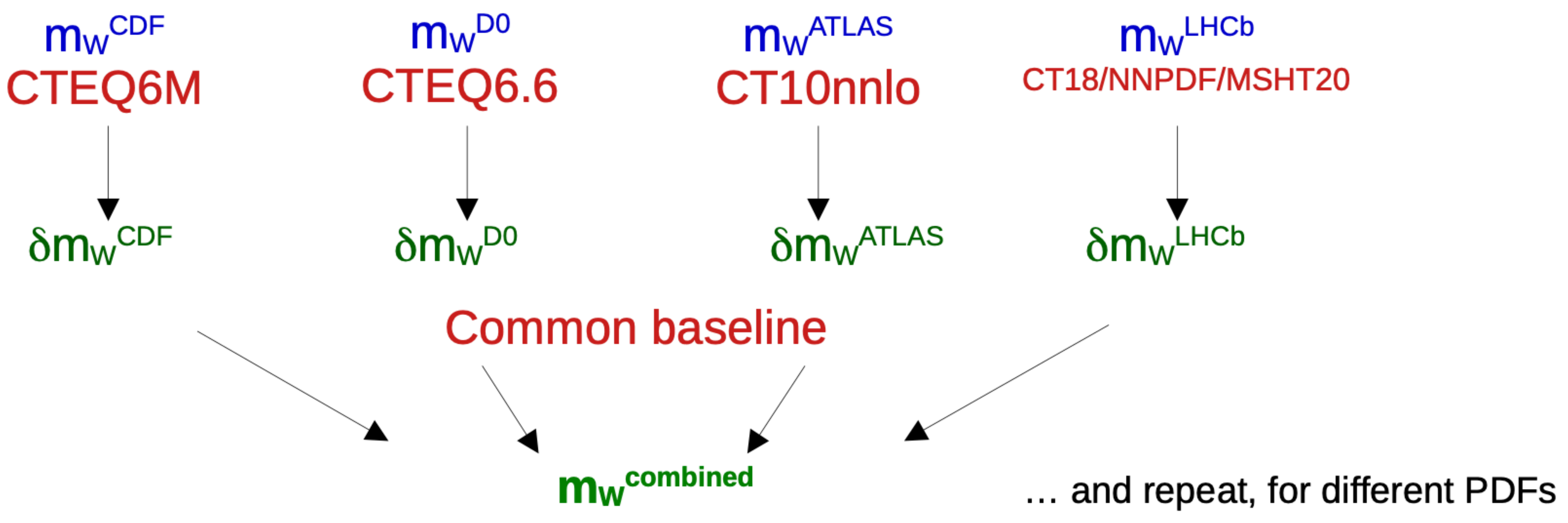
Combination of ATLAS, LHCb, D0 and CDF

EPJ C (2024) 84 451

Measurements performed at different times, using different baseline PDFs and QCD tools

→ **Existing result extrapolated to a common baseline**

- Correct to common theory and modelling
- Combine including correlations (proton structure)



m_W^{CDF} CTEQ6M → δm_W^{CDF}

m_W^{D0} CTEQ6.6 → δm_W^{D0}

m_W^{ATLAS} CT10nnlo → δm_W^{ATLAS}

m_W^{LHCb} CT18/NNPDF/MSHT20 → δm_W^{LHCb}

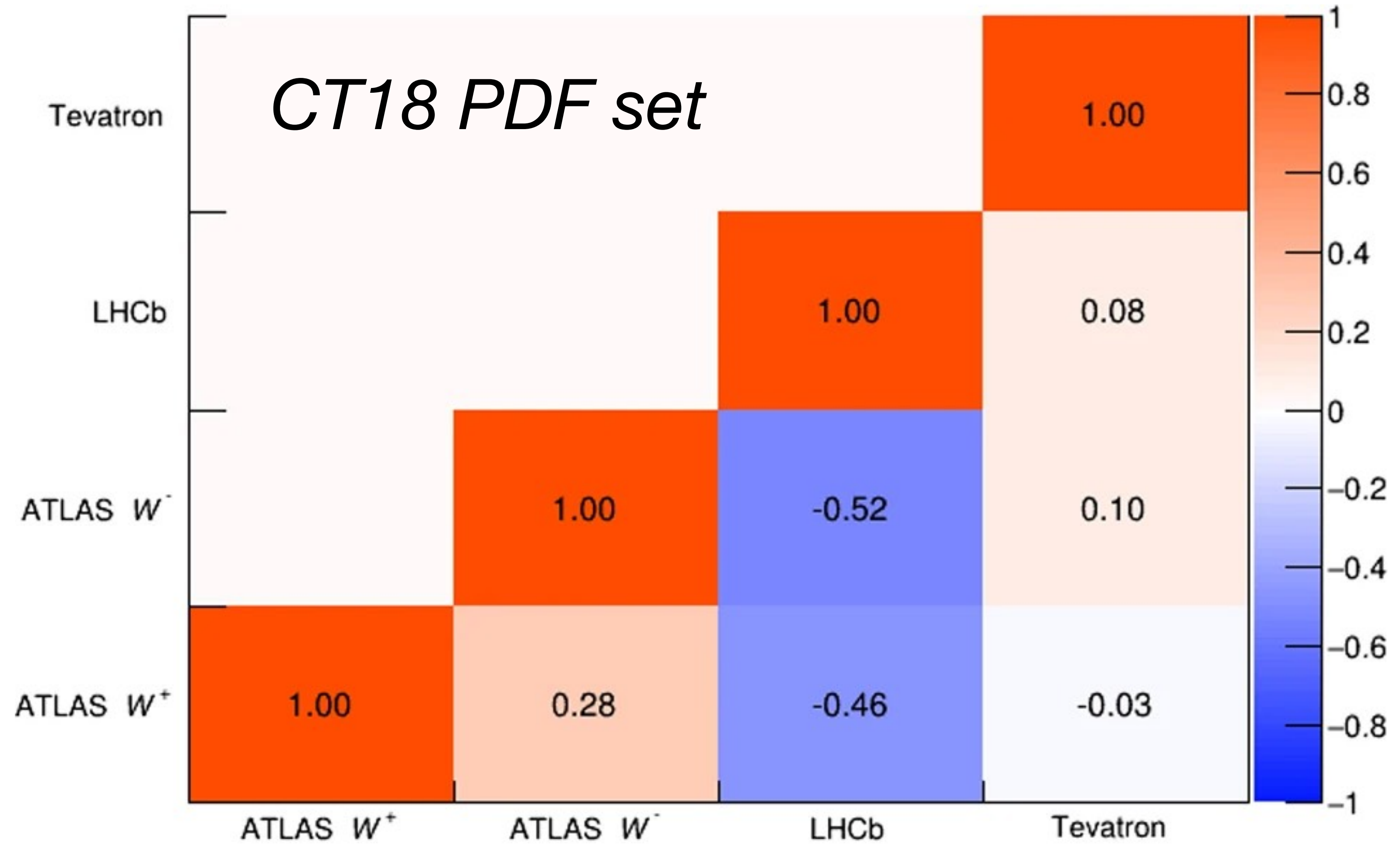
Common baseline

$m_W^{combined}$

… and repeat, for different PDFs

M. Boonekamp, LHC EW WG General Meeting, July 2024

PDF uncertainty correlation matrices



	ATLAS W^+	ATLAS W^-	LHCb	Tevatron
Tevatron				1.00
LHCb			1.00	0.08
ATLAS W^-		1.00	-0.52	0.10
ATLAS W^+	1.00	0.28	-0.46	-0.03

LHCb: m_W determination in forward acceptance suppresses PDF uncertainty in m_W average

m_W = **80364 ± 32 MeV** JHEP 01 (2022) 036

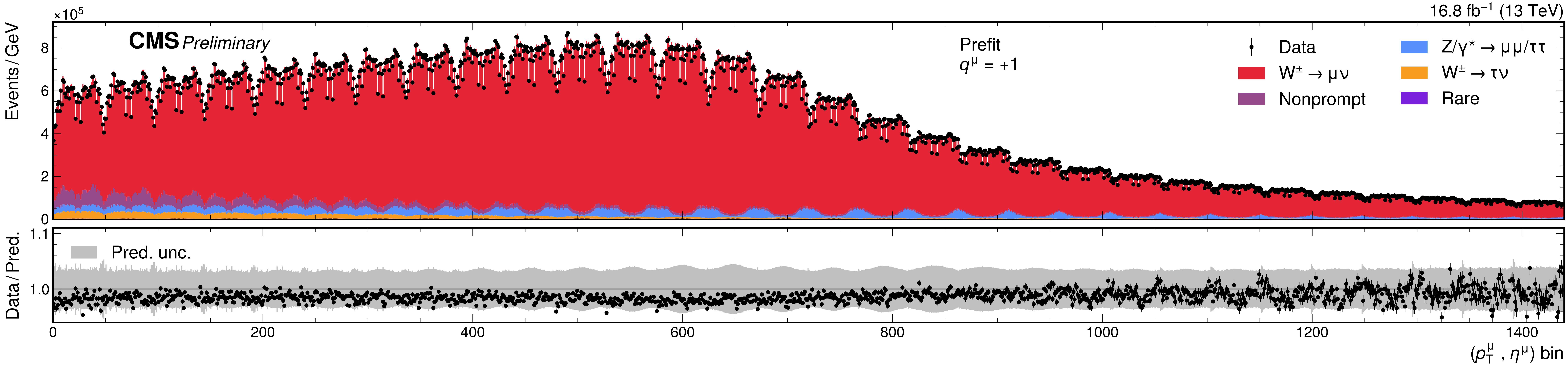
ATLAS, LHCb, D0: m_W = 80369.2 ± 13.3 MeV

Tension between ATLAS, LHCb, D0 combination and CDF is of 3.6 σ

CMS measurement of the W Boson Mass

CMS-PAS-SMP-23-002

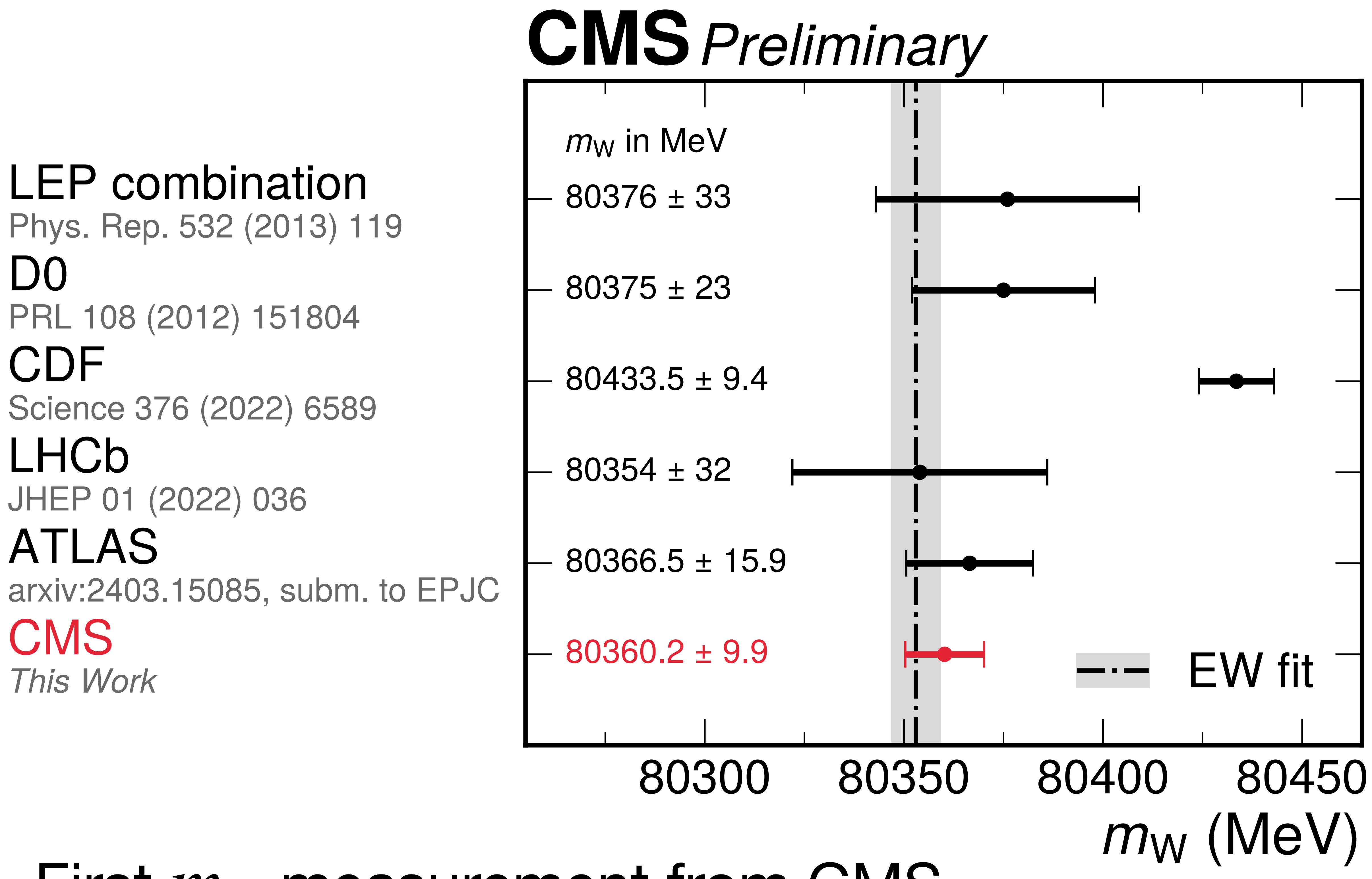
- Use **well-understood subset** of 13 TeV data
  - 16.8 fb^{-1} from later part of 2016 run
- p_T^μ **distribution in bins of** η_μ, separately for positive and negative muons
- Requires extremely good calibration of p_T^μ and understanding of p_T^W
- m_W extracted from profile likelihood fit to μ (η, p_T, charge)

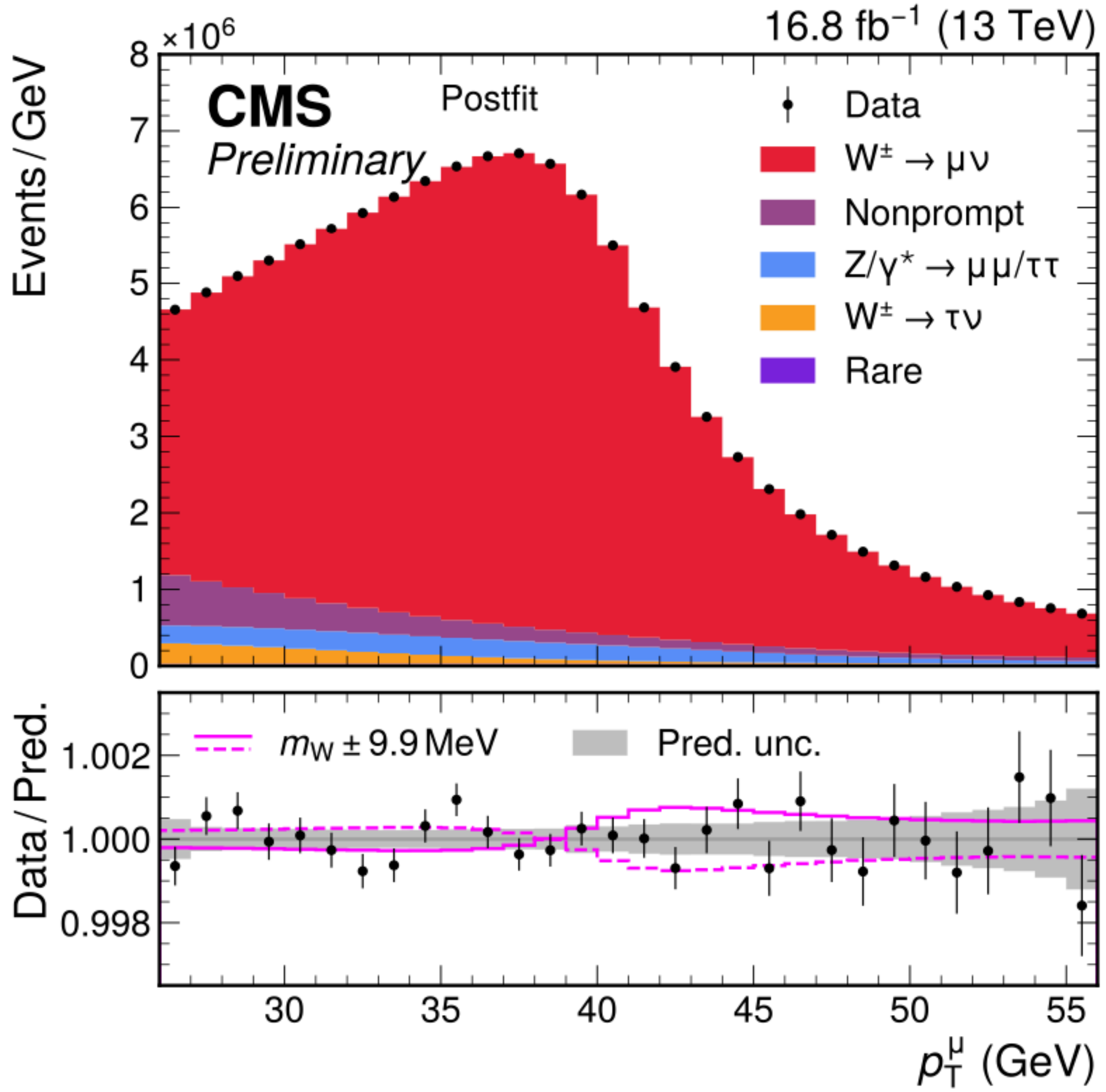


μ^+ prefit

CMS results of the W Boson Mass

CMS-PAS-SMP-23-002





- First m_W measurement from CMS
- Performed with ~10% of Run2 data
- Advances in experimental and theoretical techniques enable improved precision and lay the basis for future measurements

→ Most precise measurement from LHC m_W = 80360.2 ± 9.9 MeV, in agreement with SM

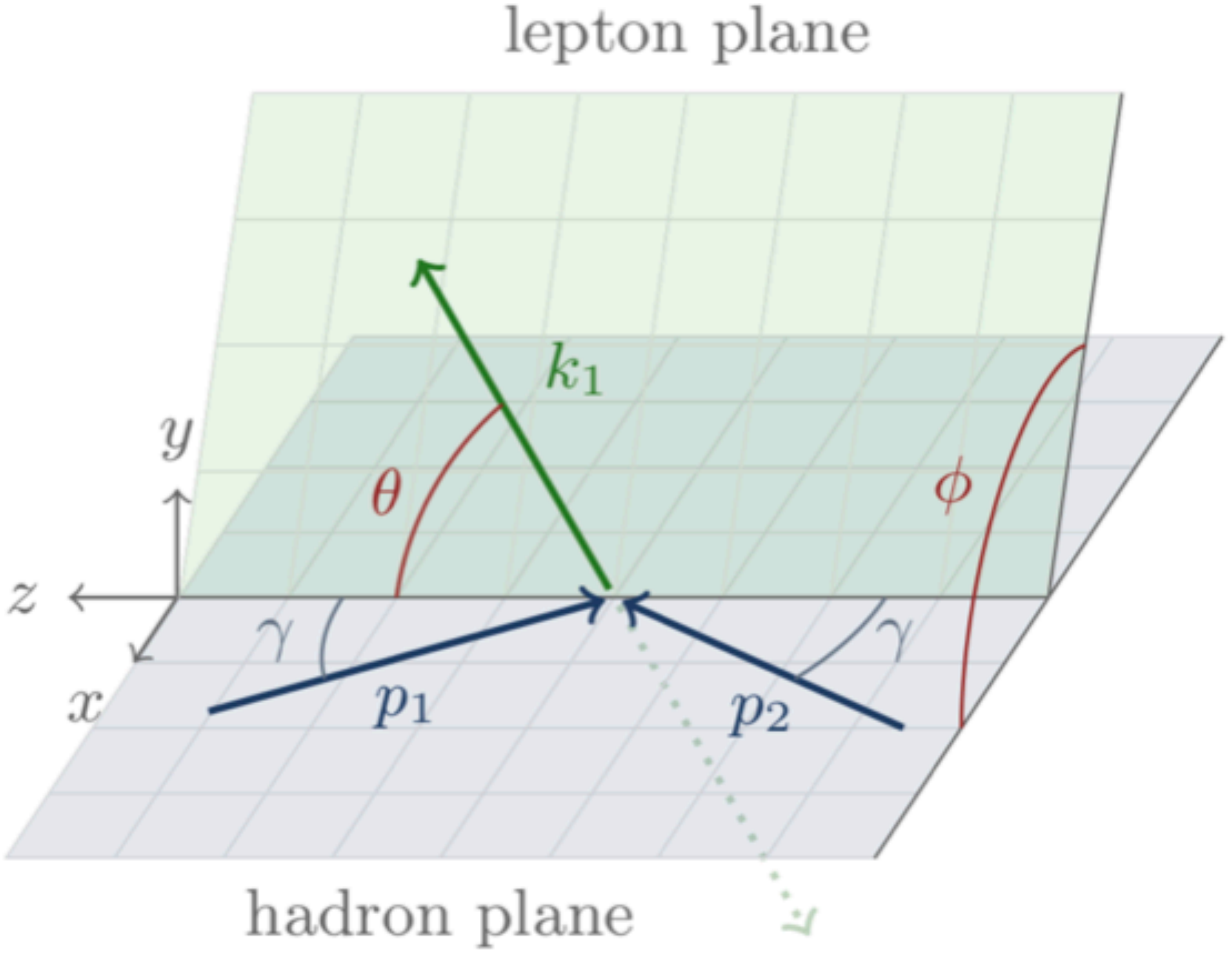
$$2.4\,(stat) \pm 9.6\,(syst)$$

The electroweak mixing angle

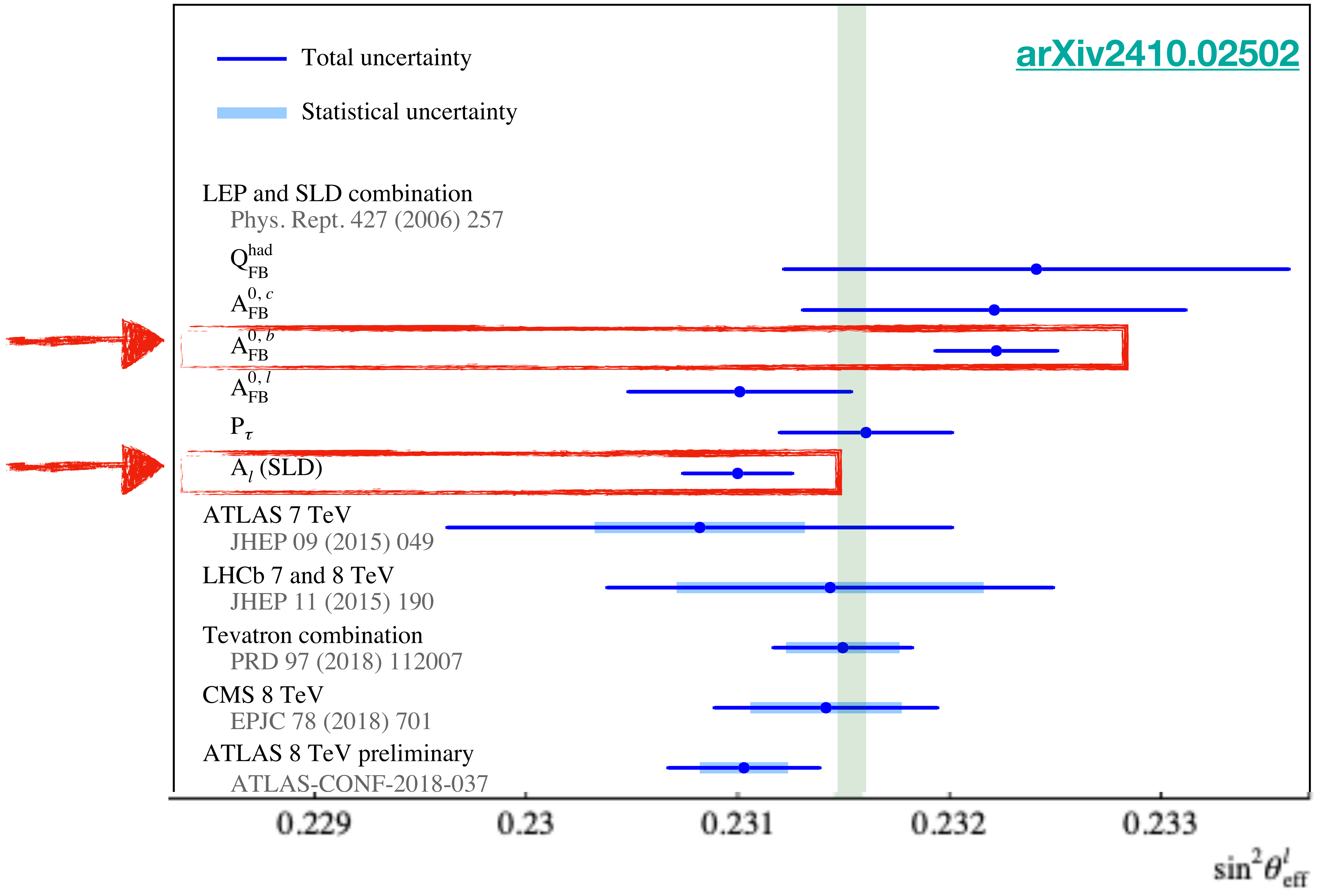
- At the heart of the Standard Model $sin^2\theta_W = 1 - m_W^2/m_Z^2$
- At higher order: $sin^2\theta^l_{eff} = k_f \cdot sin^2\theta_w$ (k_f flavour-dependent effective scaling factor absorbing higher order corr)
- At the LHC the effective mixing angle (leptonic) is measured with DY events in the Collin-Soper frame

$$\frac{d\sigma}{d\cos\theta} \sim 1 + \cos^2\theta + \frac{1}{2}A_0(1 - 3\cos^2\theta) + A_4\cos\theta$$

$$A_{FB} = 3A_4/8 \rightarrow \sin^2\theta^\ell_{eff}$$



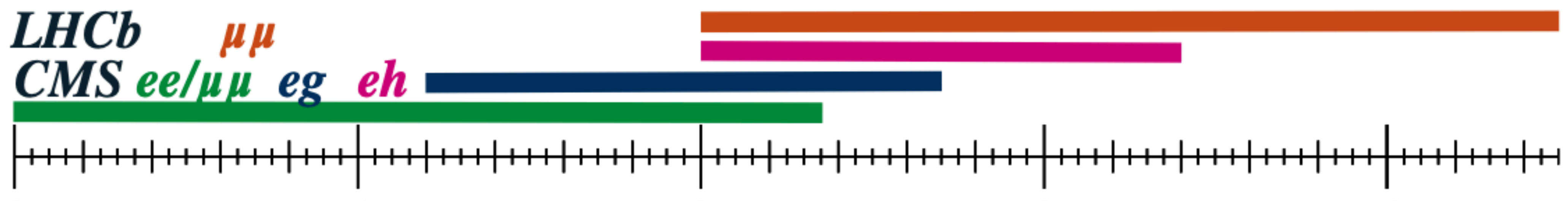
Two most precise exp. results from LEP/SLD differ by $\sim 3\sigma$

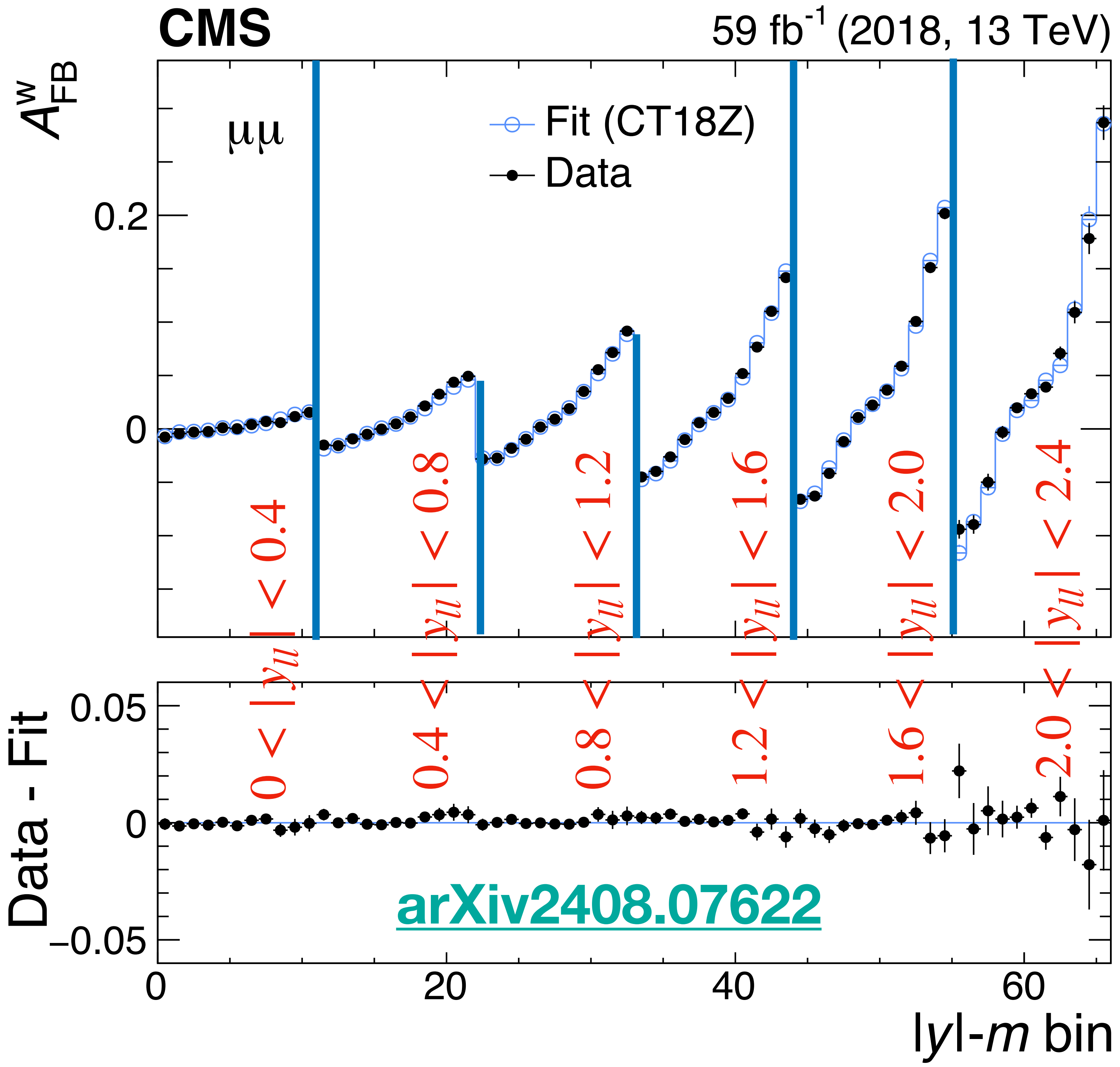


CMS and LHCb measurements of the effective weak mixing angle

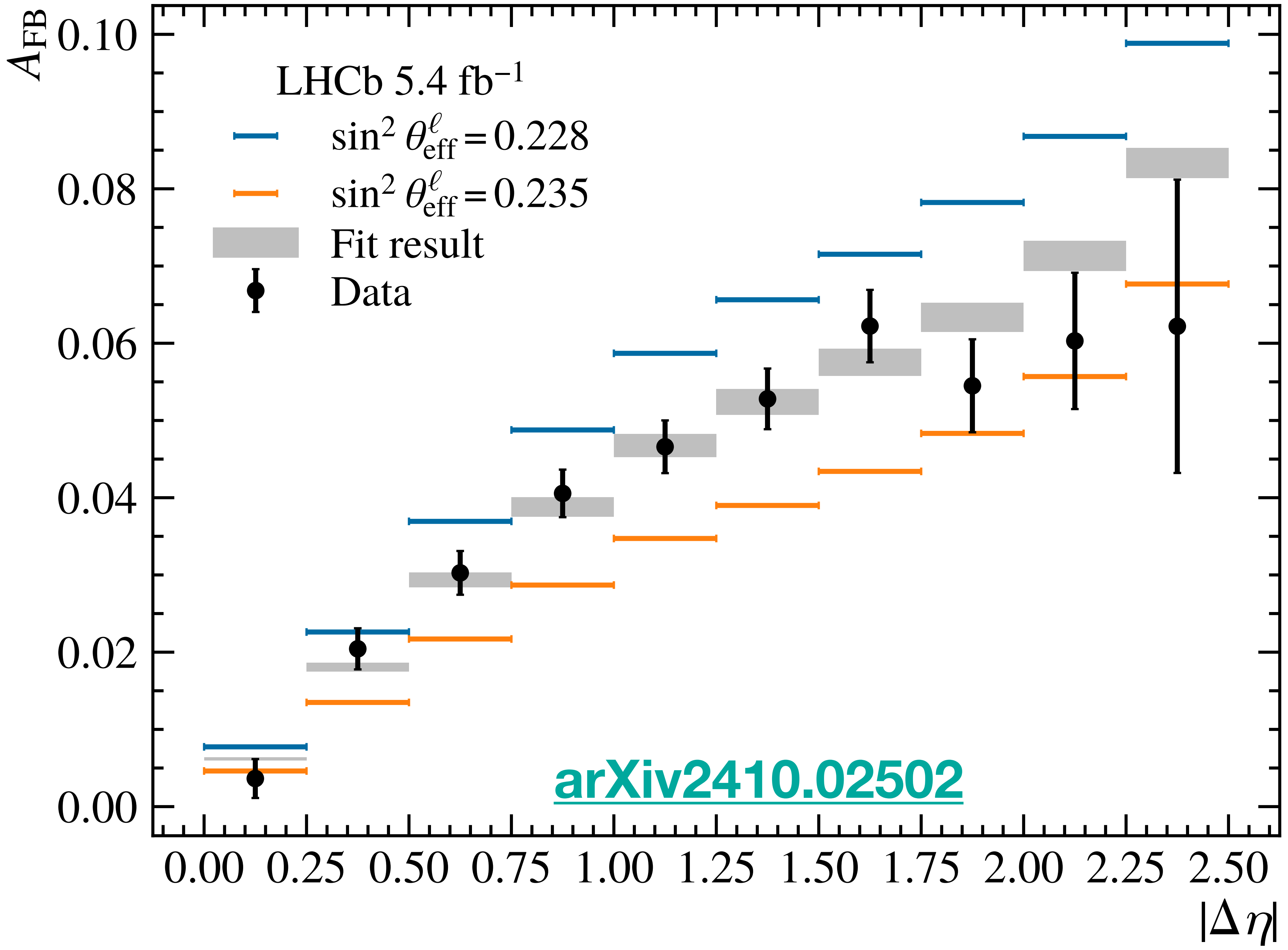
- Ambiguity in quark direction resolved through rapidity-dependent measurement
- Reconstruction of muons in CMS up to $|\eta| < 2.4$ and electrons extended to $|\eta| < 4.36$

  3 categories for electrons: “e” tracker only, “g” and “h” in forward calorimeters
- High quality muon reconstruction in LHCb in $2 < \eta < 4.5$





arXiv2408.07622

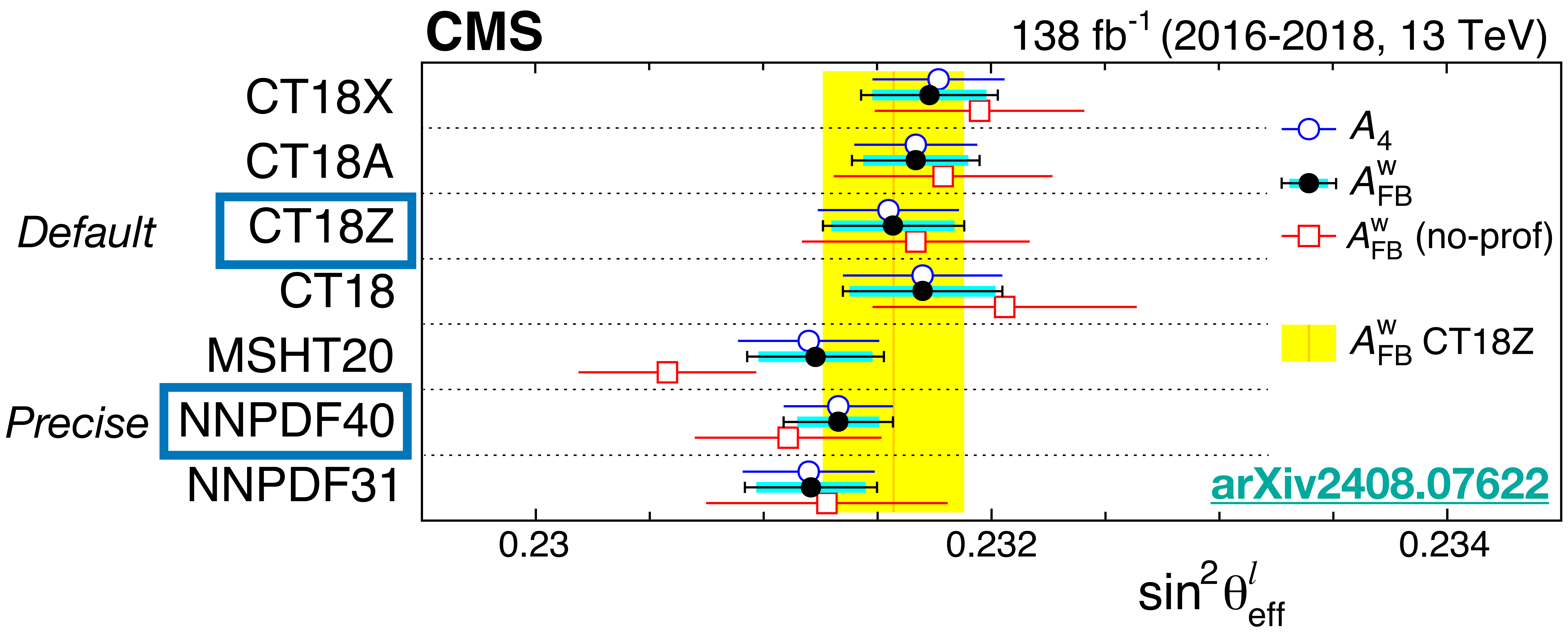


arXiv2410.02502

CMS and LHCb results of the effective weak mixing angle

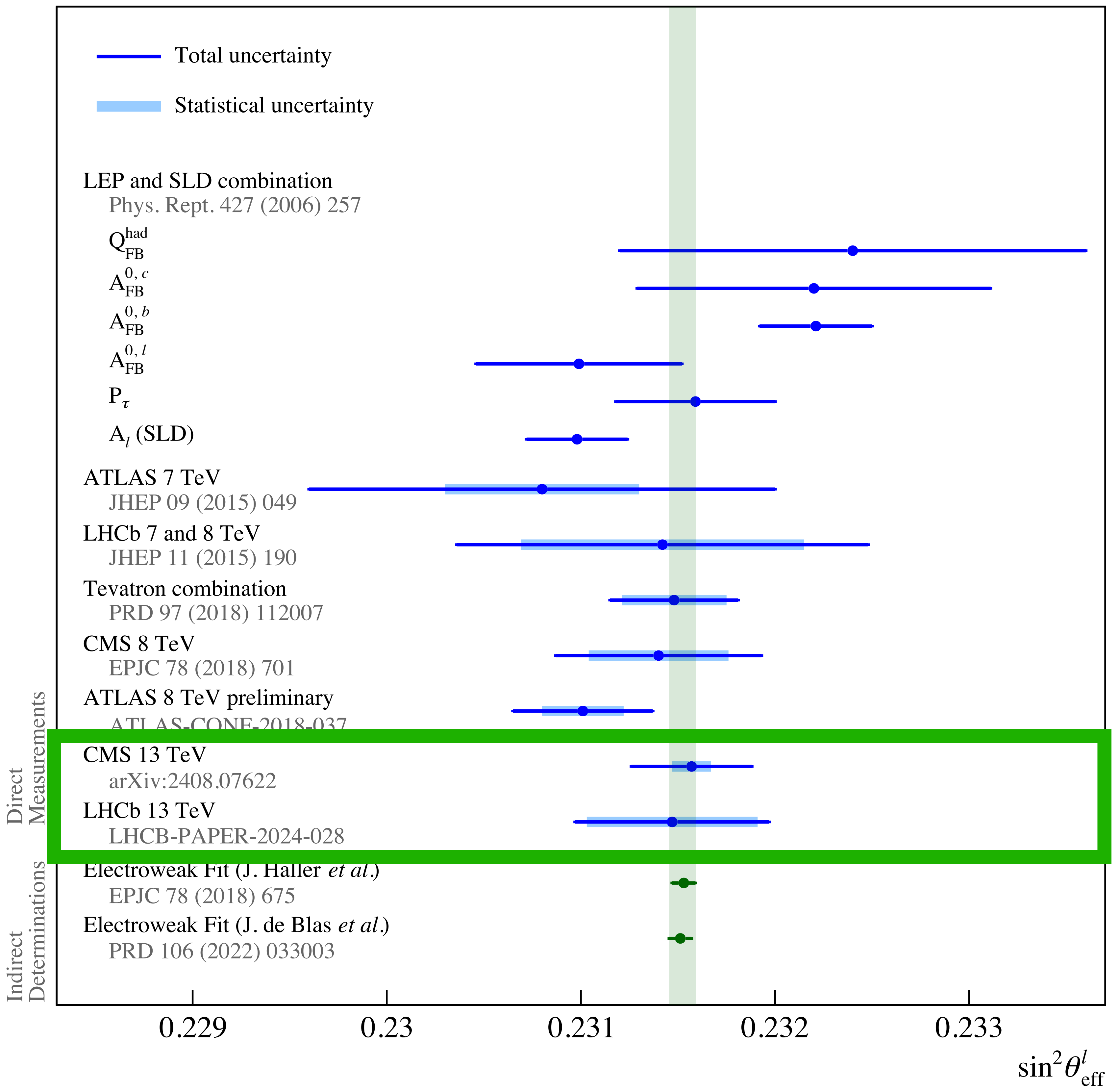
- In CMS PDF uncertainties profiled in fit of $\sin^2\theta^l_{eff}$

→ reduced differences between global PDF fits and reduced uncertainties



arXiv2408.07622

arXiv2410.02502



New, precise measurements from hadron colliders

$$\text{CMS}: \quad \sin^2\theta^{l}_{\text{eff}} = 0.23157 \pm 0.00010(\text{stat}) \pm 0.00015(\text{syst}) \pm 0.00009(\text{theo}) \pm 0.00027(\text{PDF})$$

$$\text{LHCb}: \quad \sin^2\theta^{l}_{\text{eff}} = 0.23147 \pm \boxed{0.00044(\text{stat})} \pm 0.00005(\text{syst}) \pm 0.00023(\text{theo/PDF})$$

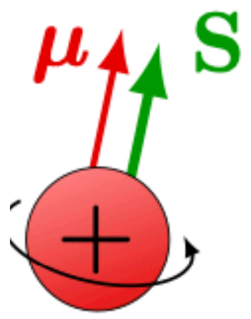
LHCb result dominated by statistics, very promising for Run3

CMS result most precise at hadron colliders

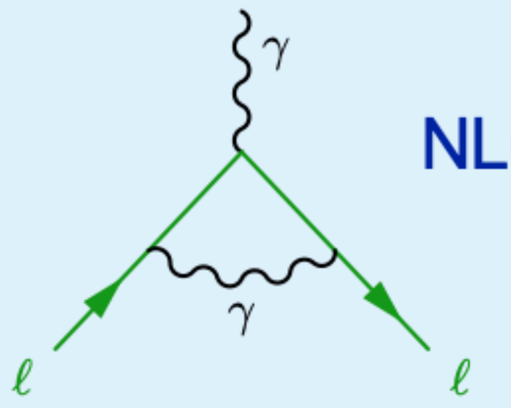
What is g-2?

- Particles with spin (S) have a magnetic moment (μ)
- For spin-½ particles, quantum corrections with a gyromagnetic factor, $g \approx 2.002\ 32$

→ anomalous magnetic moment $a = \dfrac{g-2}{2}$



$$\boldsymbol{\mu} = g\frac{e}{2m}\mathbf{S} \longrightarrow \begin{cases} g = 1: \ \text{classical} \\ g = 2: \ \text{Dirac} \\ g \approx 2.002: \ \text{QED} \end{cases}$$

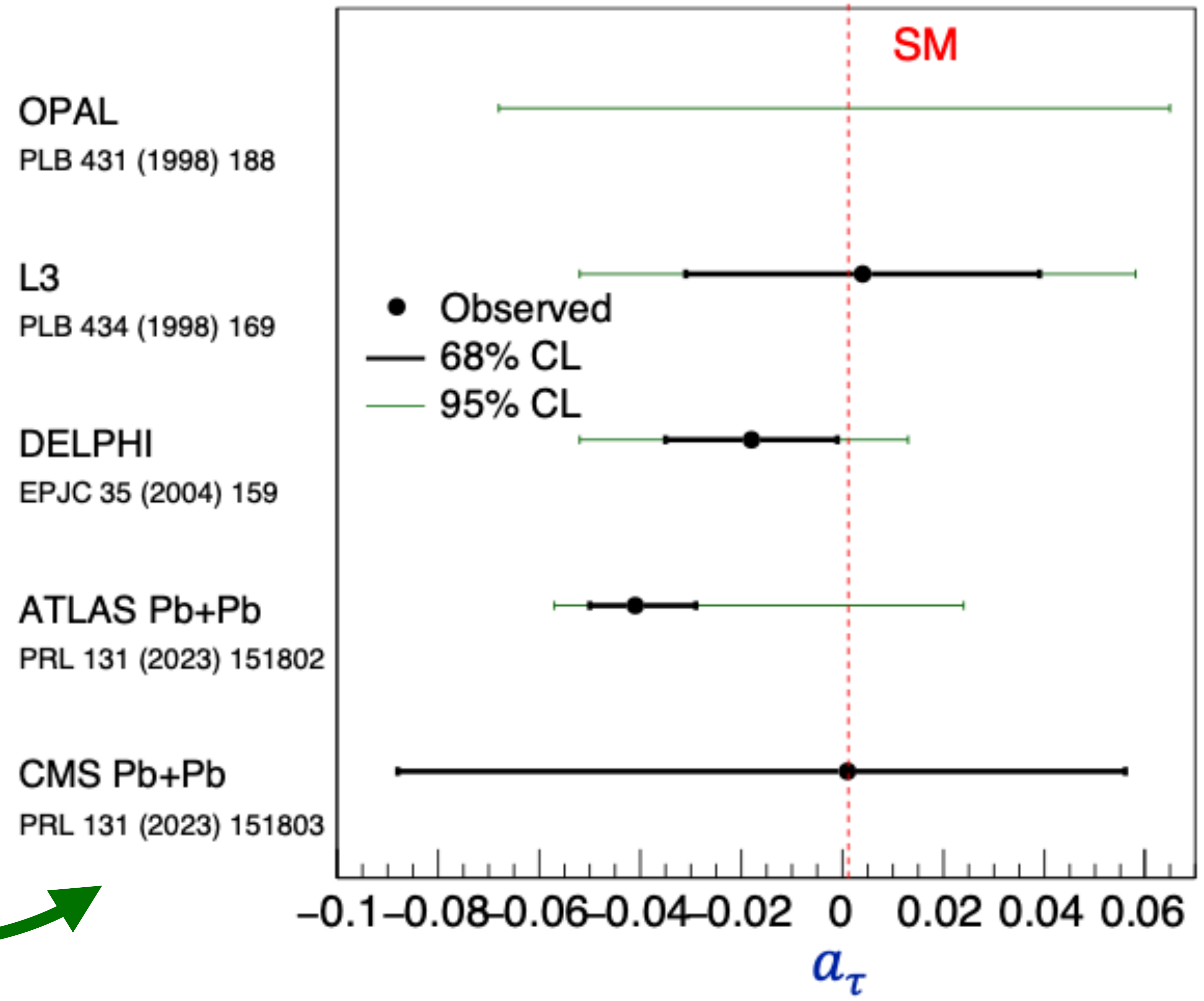


NLO correction (Schwinger)

$$a = \frac{\alpha}{2\pi} \approx 0.001\ 16$$

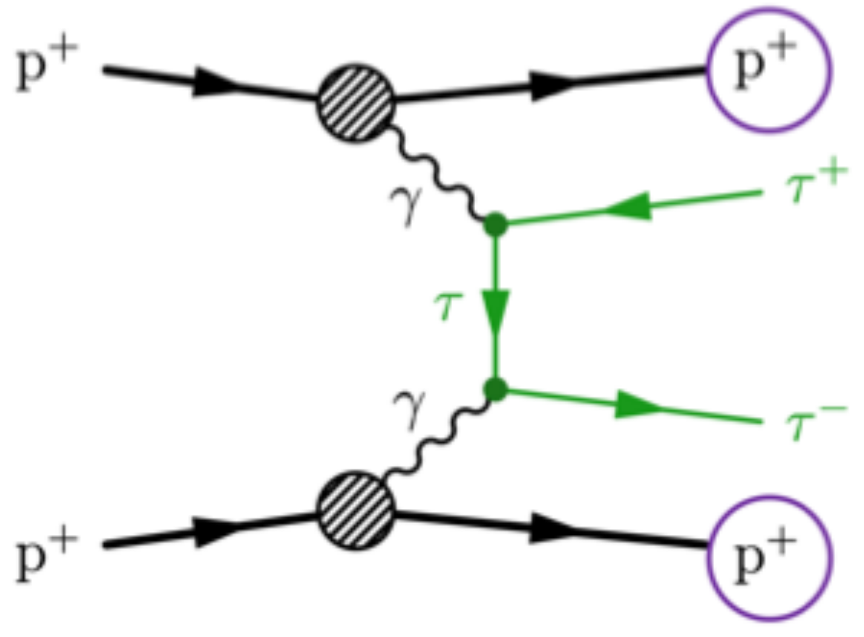
Key measurements:

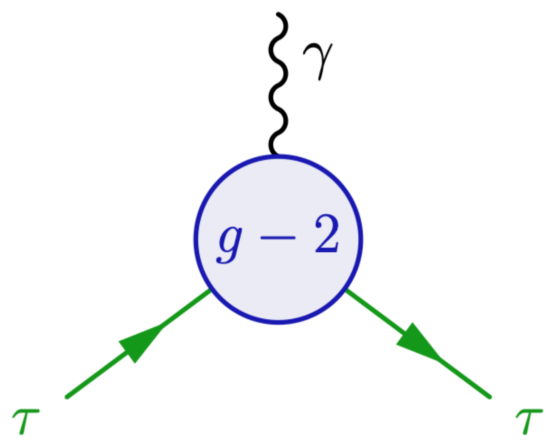
- **(g–2)e:** Measured in Penning traps
- **(g–2)μ:** Measured in storage rings
- **(g–2)τ:** Constrained in particle collisions (e^+e^- or PbPb)

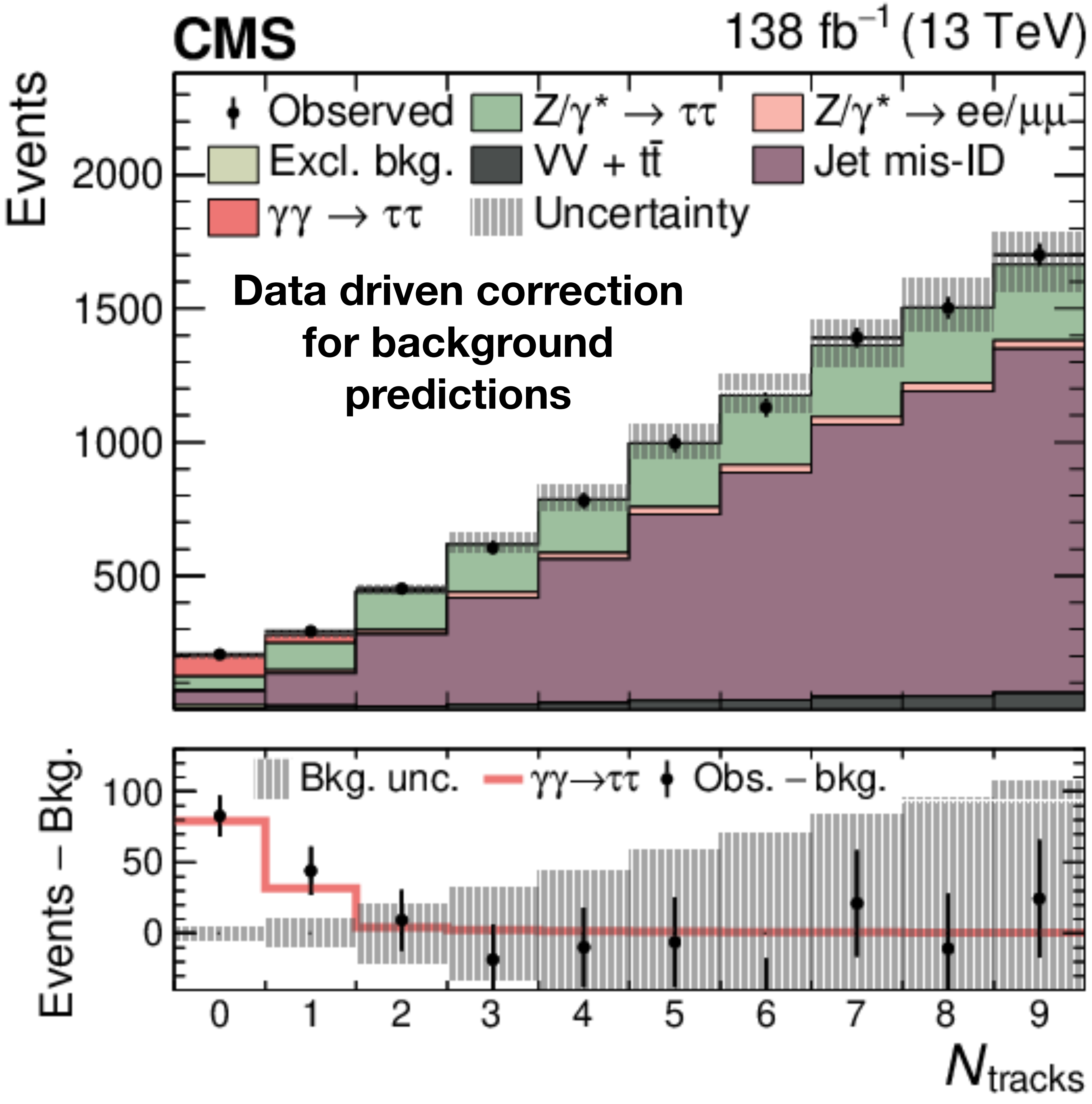


CMS as a photon collider experiment

- **Observed $\gamma\gamma \to \tau\tau$ production for the first time in pp collisions**
- Probed tau g-2 with unprecedented precision

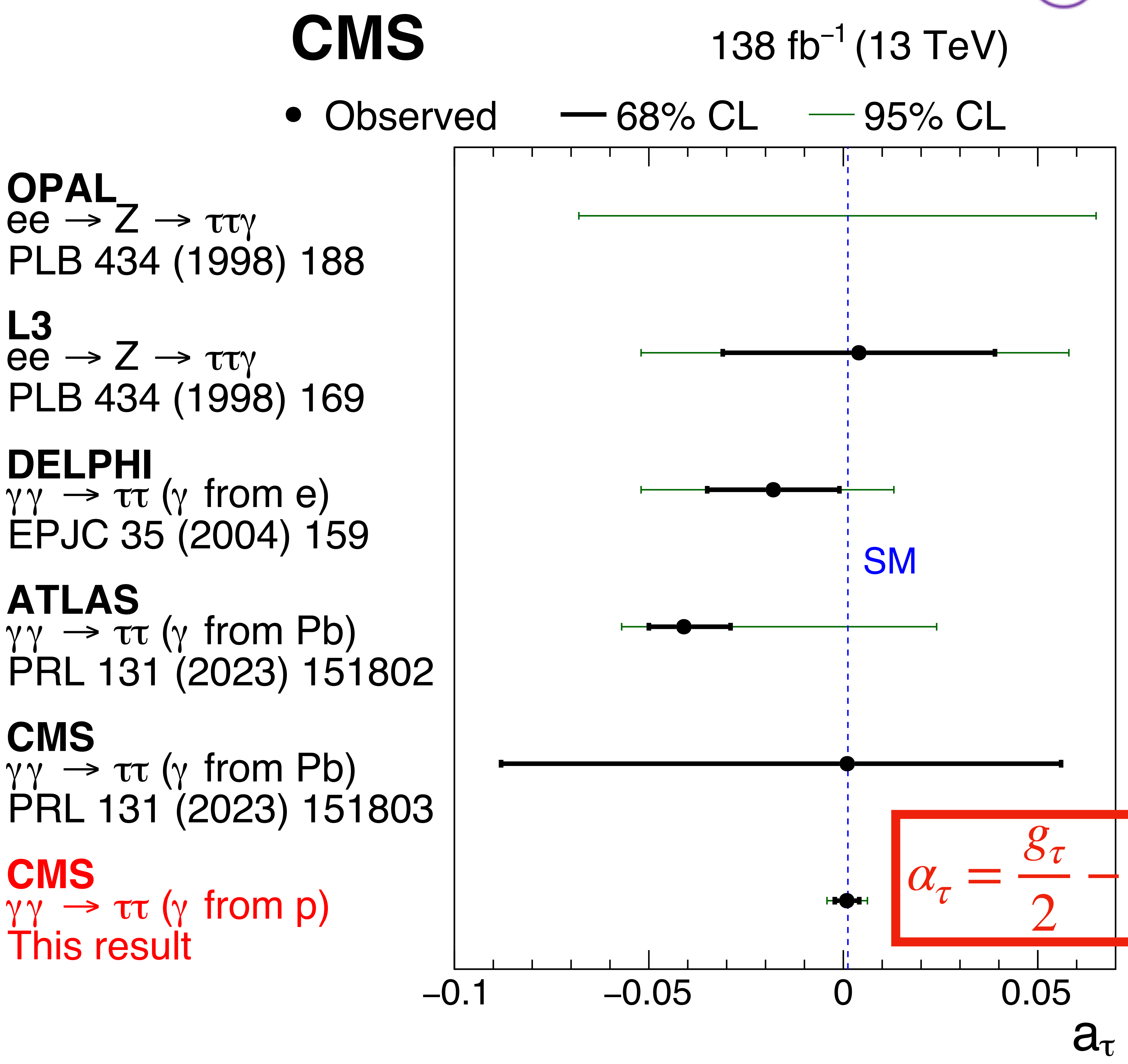






Data driven correction for background predictions

Isolate signal at low track multiplicity



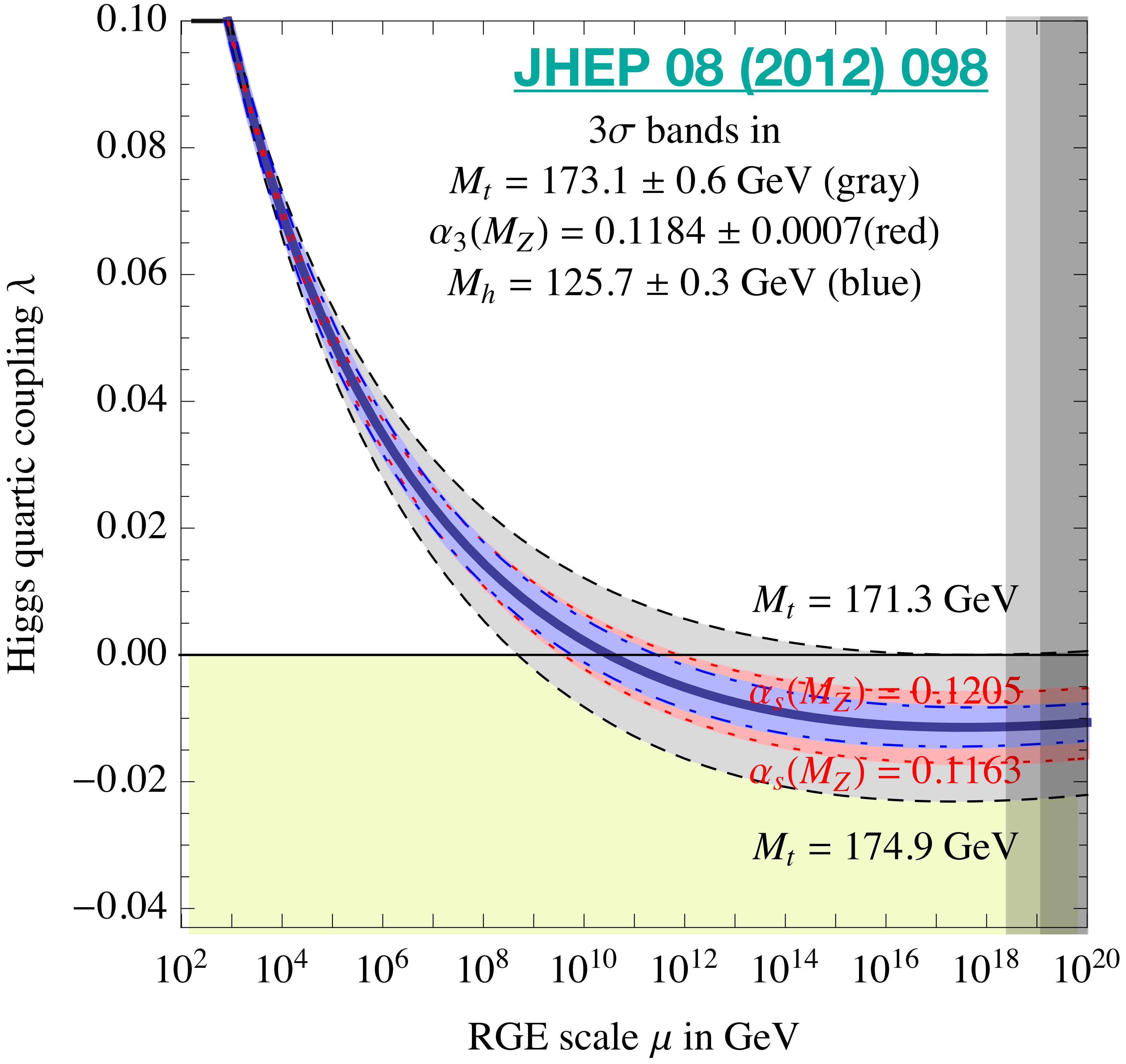
$$a_\tau = \frac{g_\tau}{2} - 1 = 0.0009^{+0.0032}_{-0.0031}$$

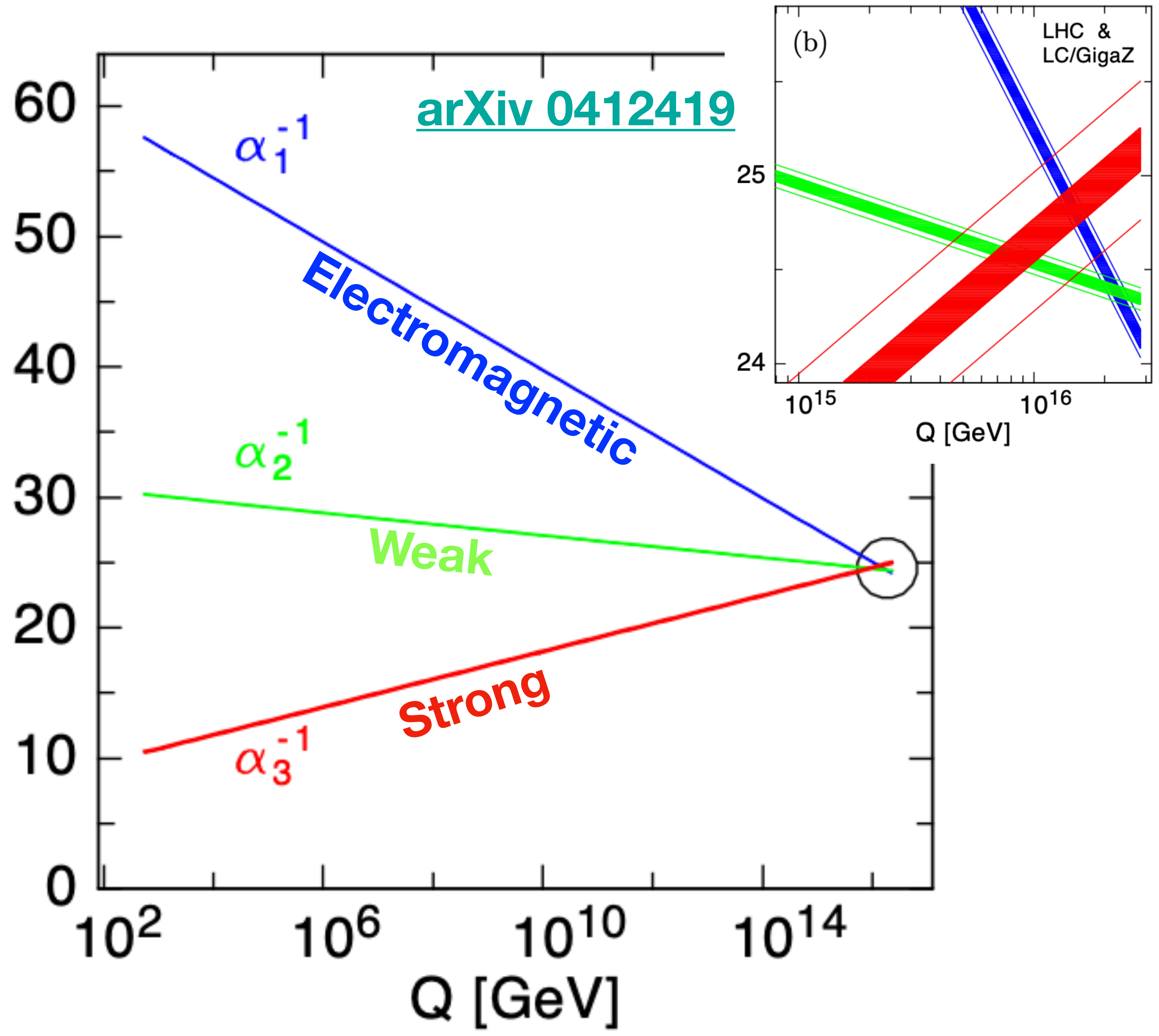
$$a_\tau = 0.0009^{+0.0016}_{-0.0015}\,(syst)^{+0.0028}_{-0.0027}\,(stat)$$

Rep. Prog. Phys. 87 (2024) 107801

Motivation for determining α_S

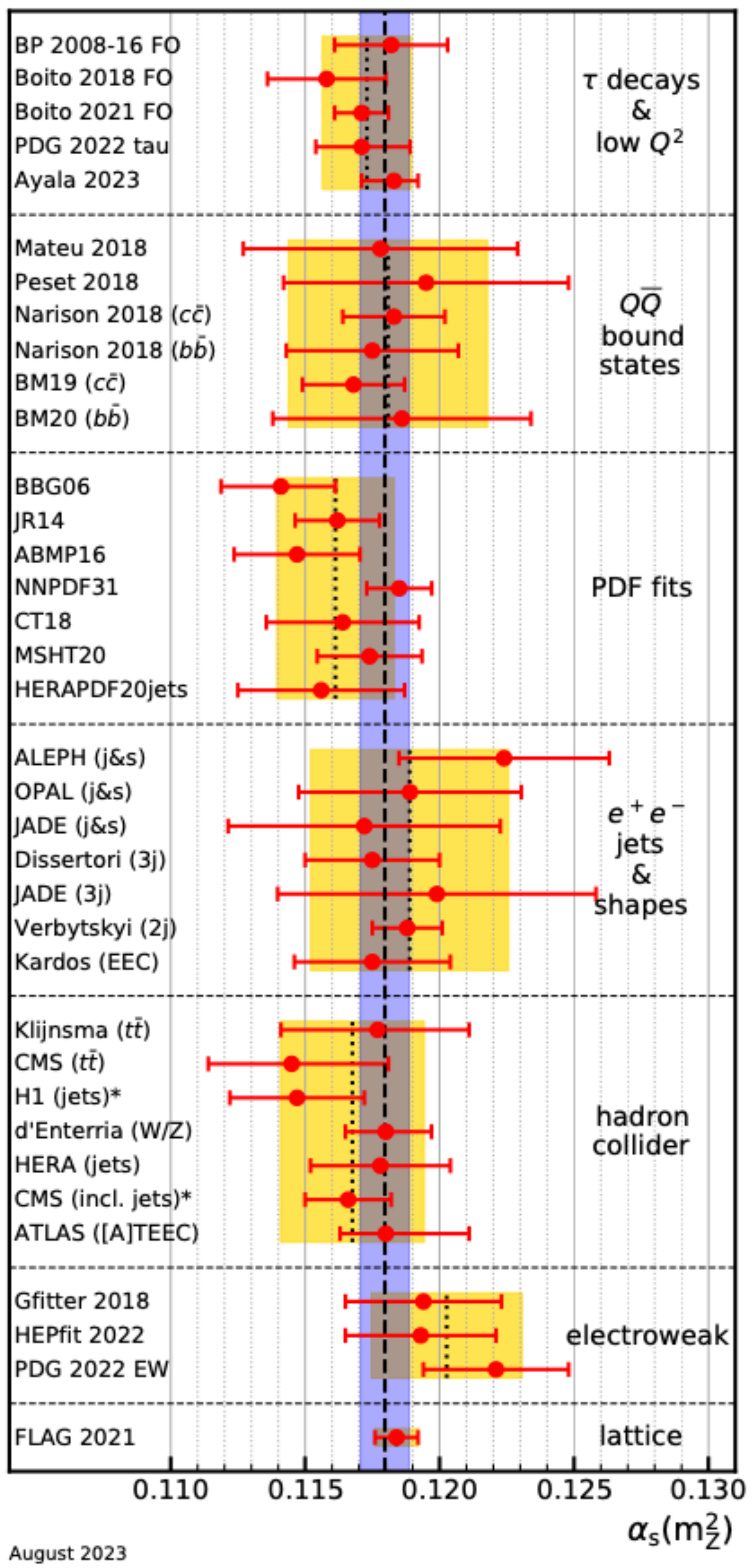
- Single free parameter of QCD in the $m_q \to 0$ limit
- Impact physics at the Planck scale: EW vacuum stability, GUT
- α_S is among the major uncertainties of many precision measurements: Higgs couplings at the LHC
- Currently, α_S is the less know interaction couplings

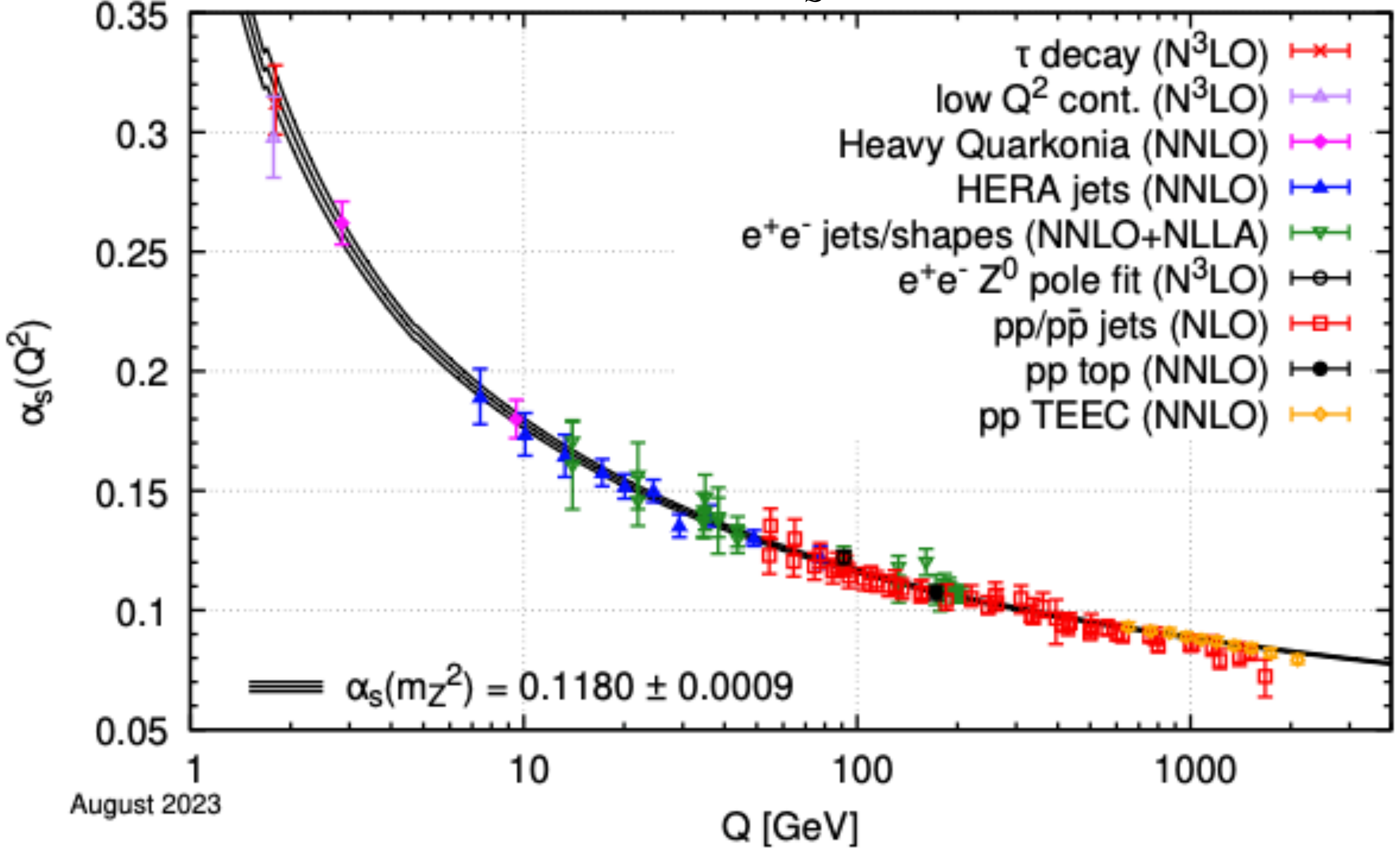

JHEP 08 (2012) 098


arXiv 0412419

The state of the art

QCD PDG Review 2024


Summary of $\alpha_S(m_Z)$


Running of α_S with Q

← World average **PDG 2024**: $\alpha_S(m_Z) = 0.118 \pm 0.0009$

→ α_S **"runs"** as $\approx \ln(\mathrm{Q}^2/\mathrm{L}^2)$ at LO, $\mathrm{L} \approx 0.2\ \mathrm{GeV}$

How to extract α_S at LHC?

$$\boxed{\sigma_{pp\to X}} = \sum_{ij} \boxed{f_i(x_1,\mu_F^2)\times f_j(x_2,\mu_F^2)} \otimes \boxed{\hat{\sigma}_{ij}(x_1,x_2,\alpha_S(\mu_R),\frac{Q^2}{\mu_R},\frac{Q^2}{\mu_F})} + O(\frac{\Lambda^2_{QCD}}{Q^2})$$

Data $\sigma(exp)$

PDFs $f_i(\mu,x)$

DGLAP eq.

Exp. measurements

Partonic XS (pQCD)

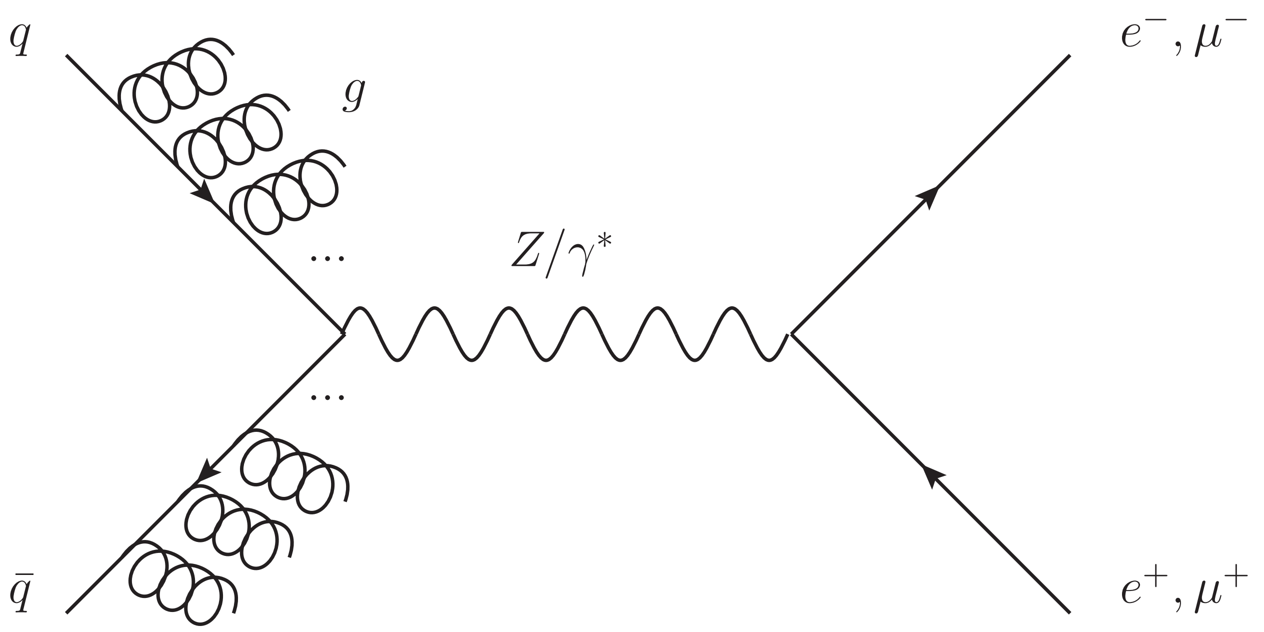
need to be corrected by non perturbative effects

Two methods to compare $\sigma(\mathrm{exp})$ to $\sigma(\mathrm{pQCD})$:

- **Profiling analysis using varying PDF+α_S** (predefined PDF from global PDF)
- **Simultaneous fit of α_S and PDFs**
  - Correlation between PDFs and α_S took into account
  - Reduced bias
  - BUT time consuming

ATLAS Z p_T

arXiv2309.12986

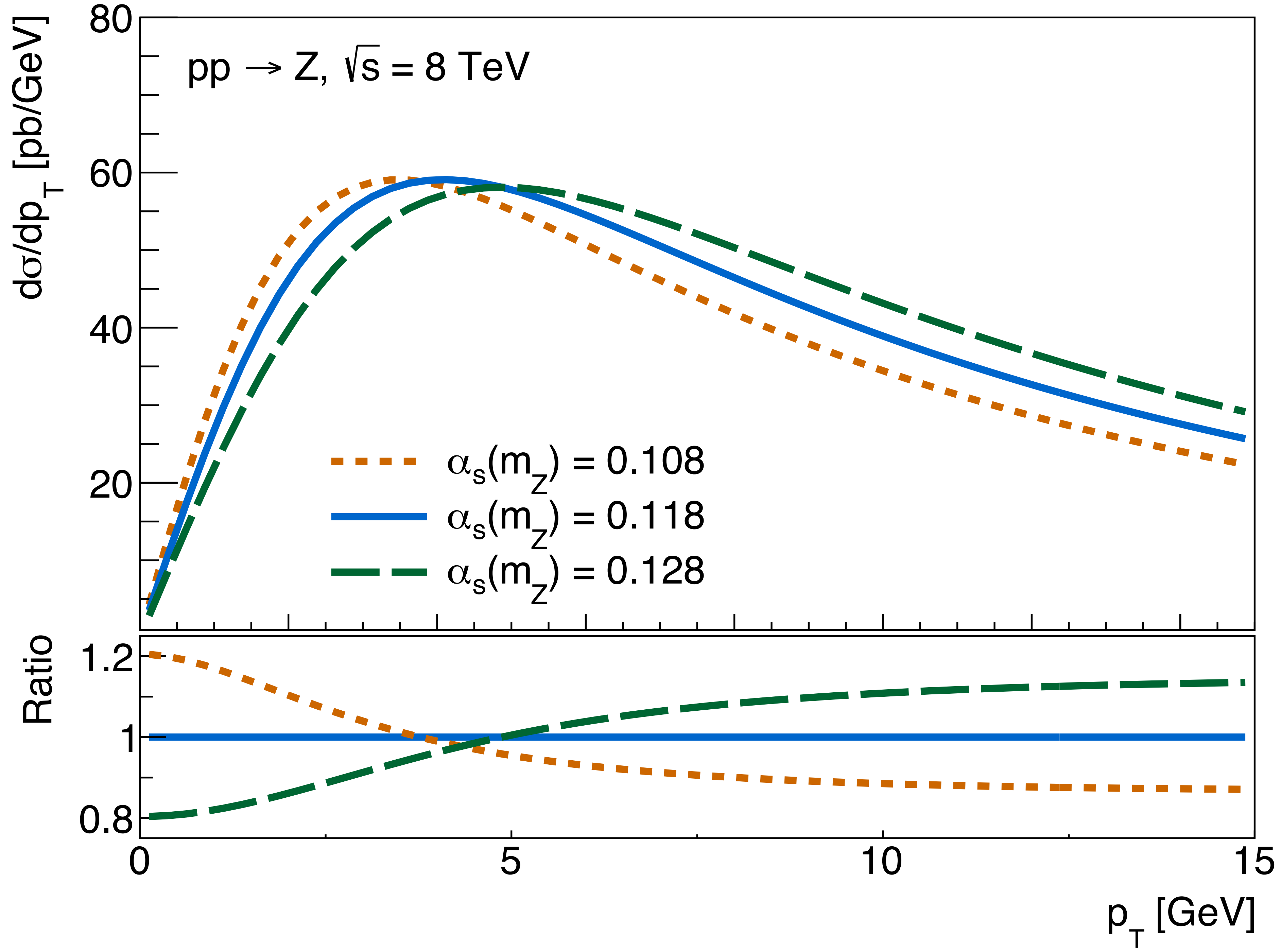


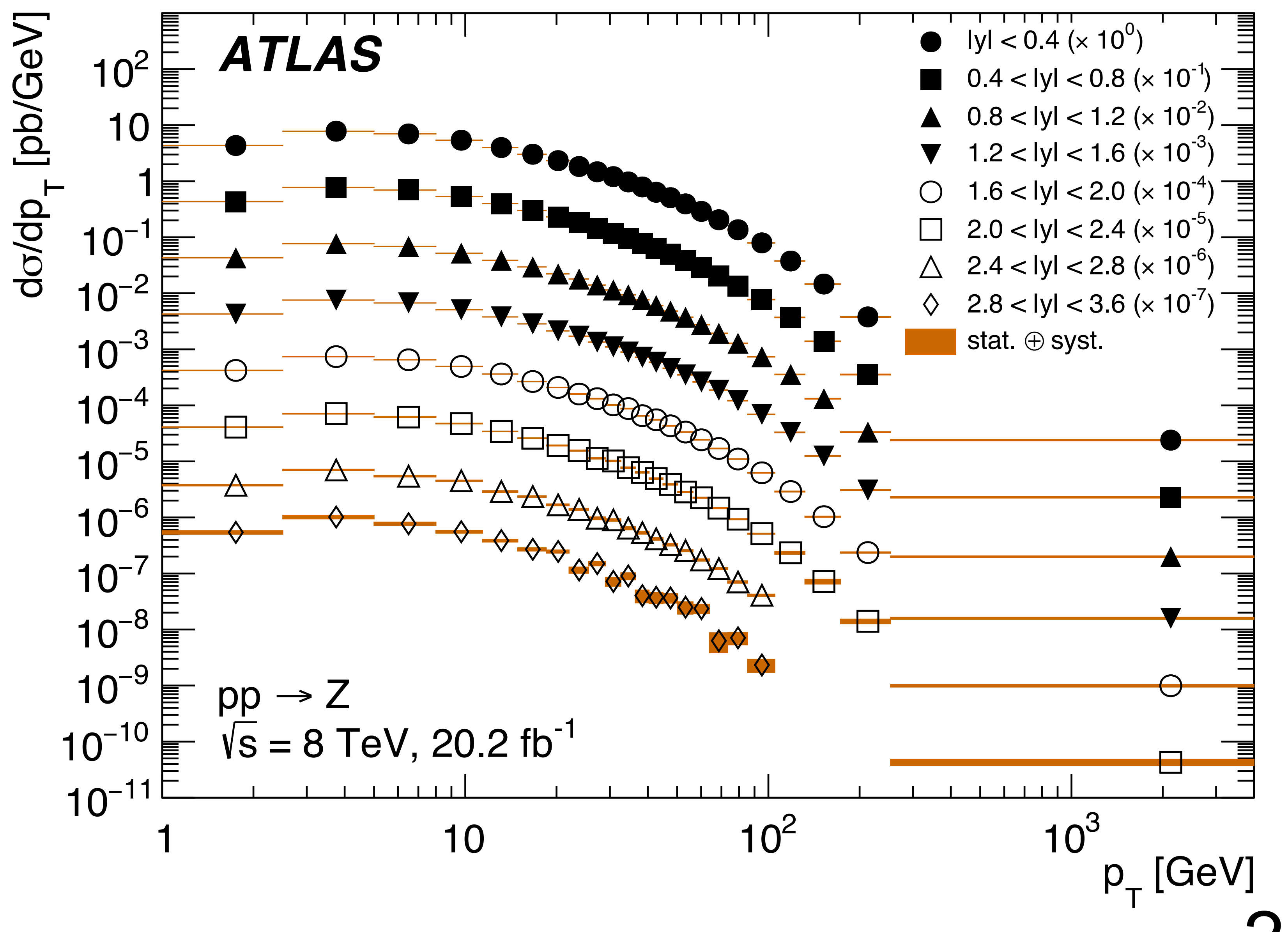
- **Z p_T sensitive to $\alpha_S(m_Z)$**
- Cross-sections in $p_T - \mathrm{y}$ in **full lepton phase space** at 8 TeV (EPJC 84 (2024) 315)
- **Theory predictions** at $\mathrm{N^4LLa + N^3LO}$

MSHT20aN3LO PDF set used to extract $\alpha_S(m_Z)$

Final result: $\alpha_S(\mathrm{m_Z}) = 0.1183 \pm 0.0009$

Most precise experimental measurement to date!

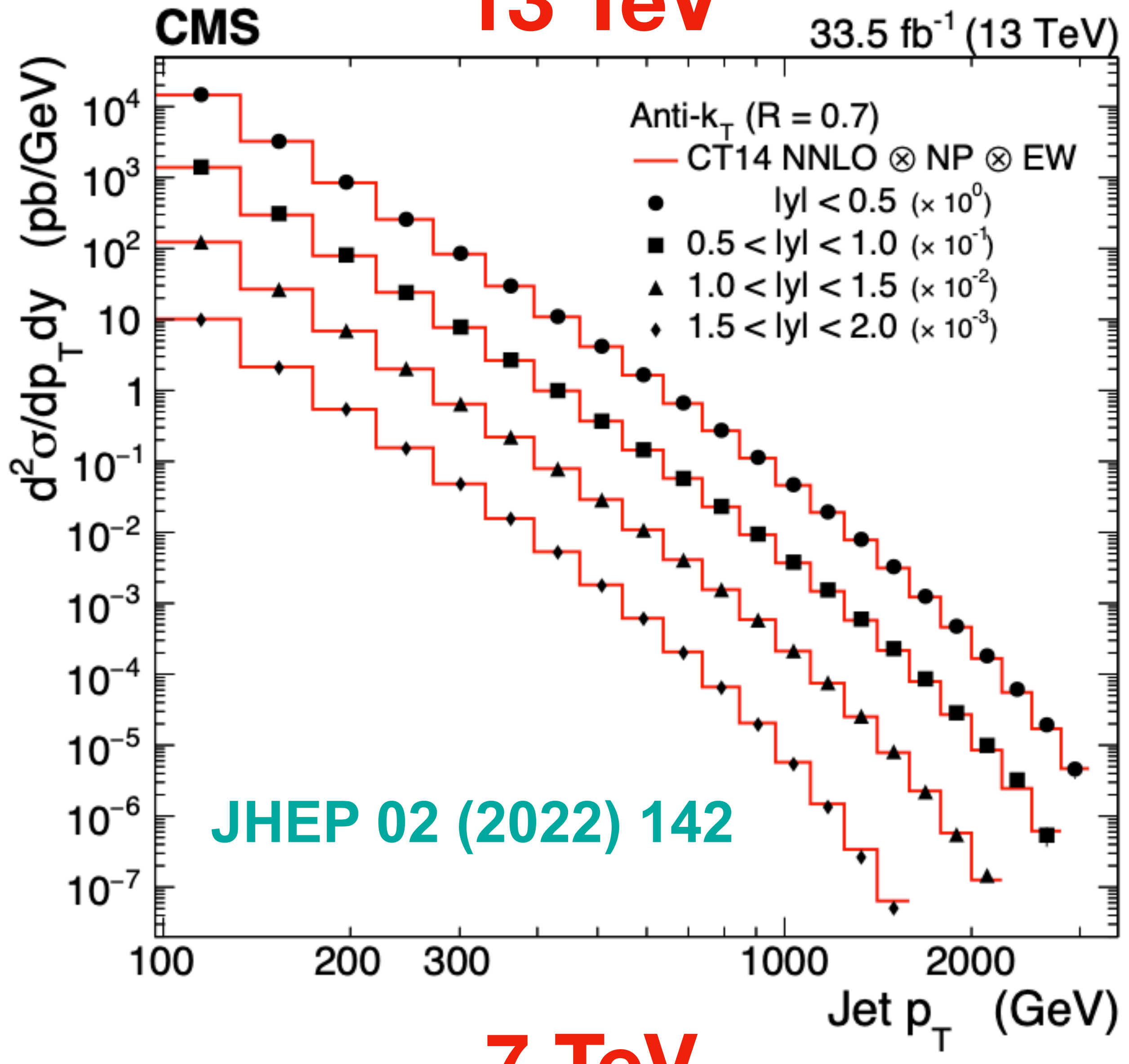




Combination of CMS Inclusive jets

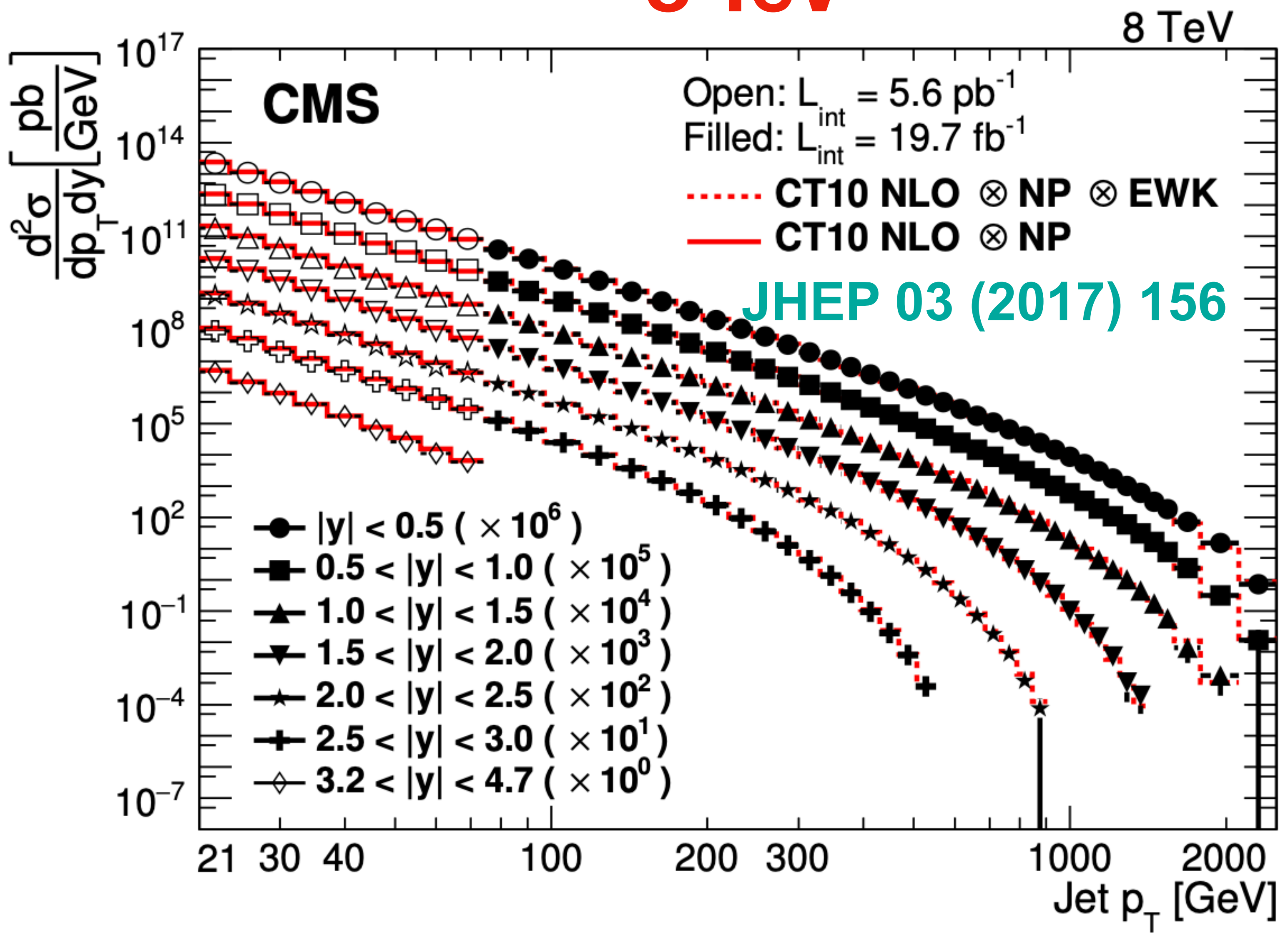
CMS-PAS-SMP-24-007

13 TeV



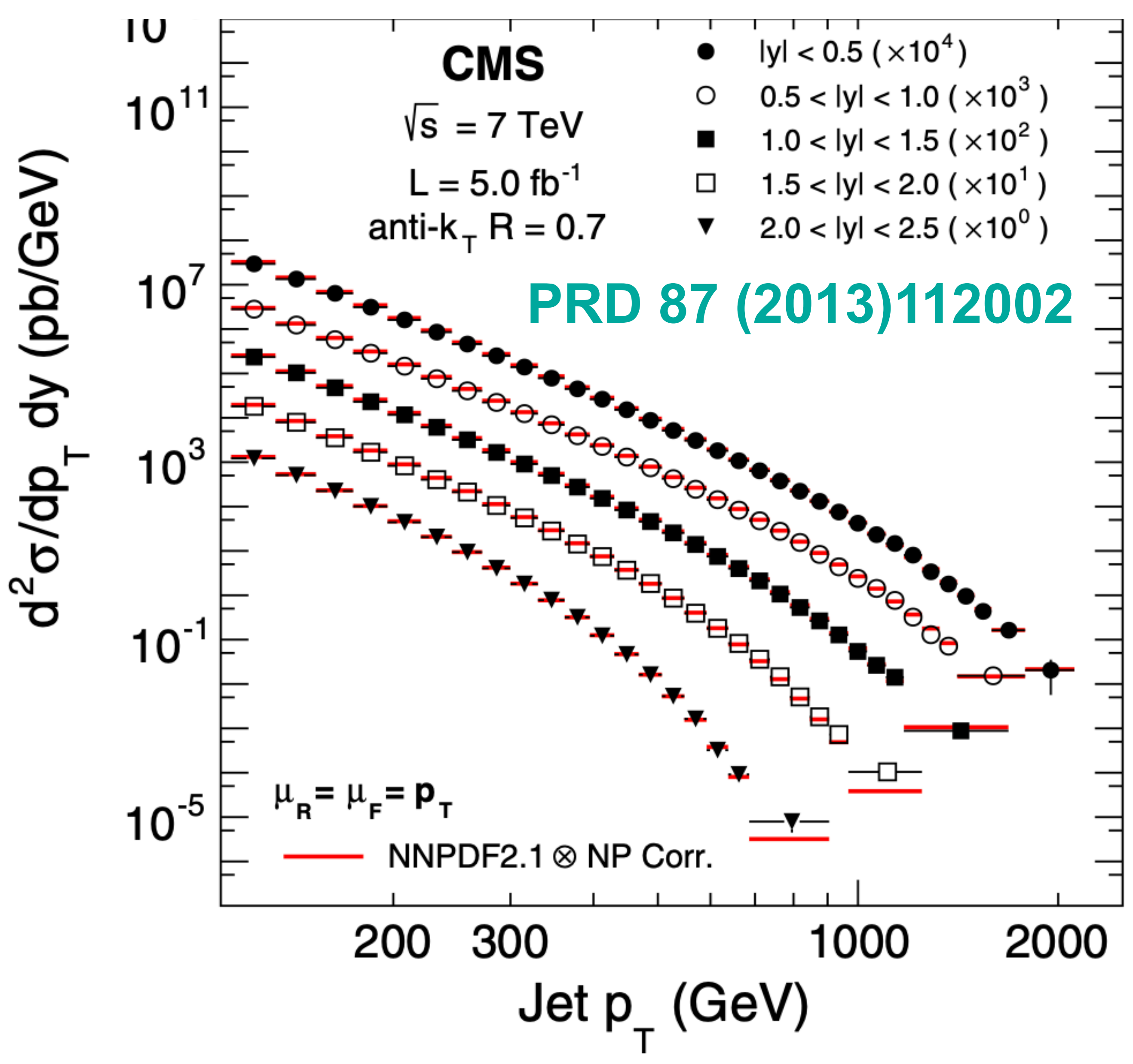
JHEP 02 (2022) 142

8 TeV



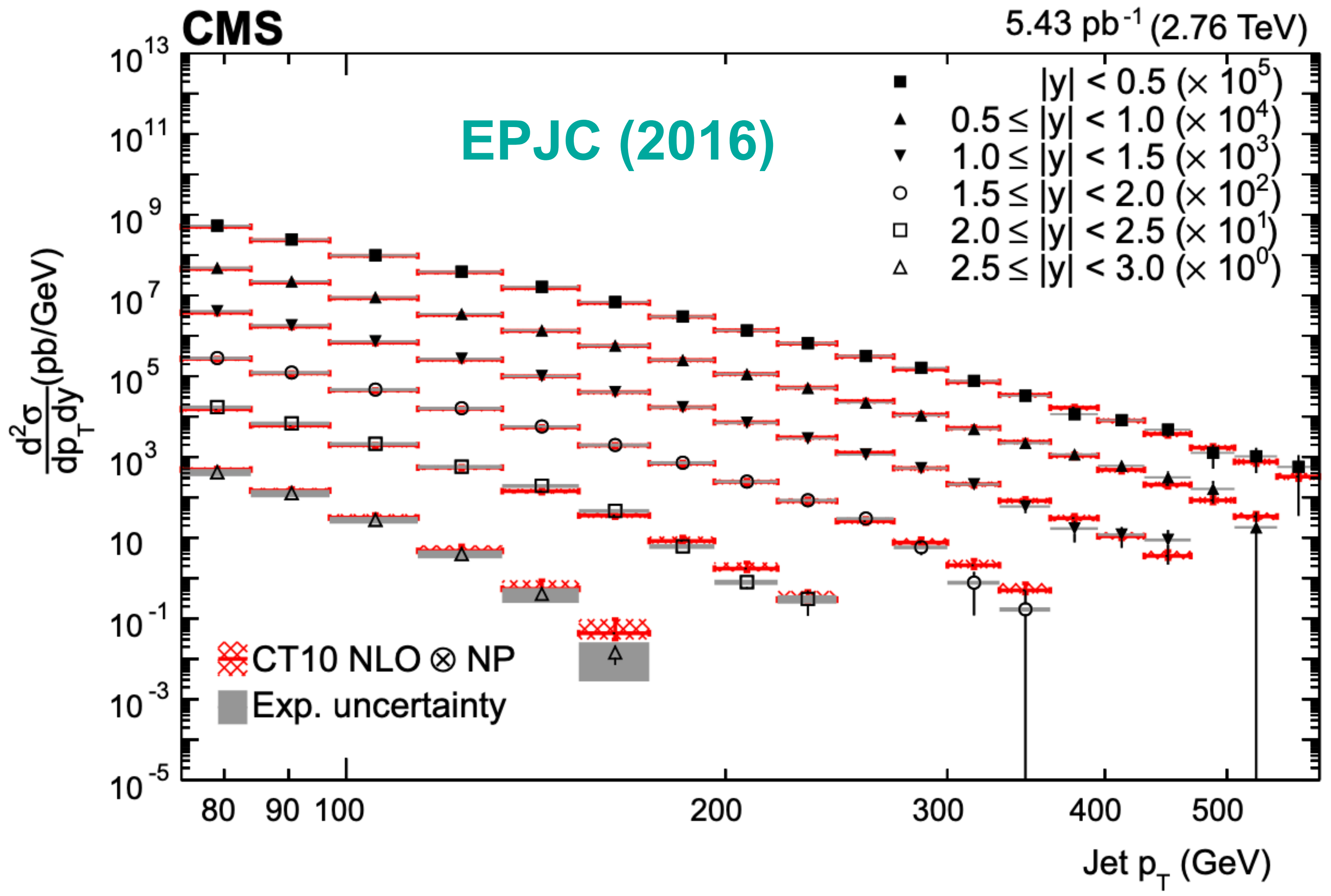
JHEP 03 (2017) 156

7 TeV



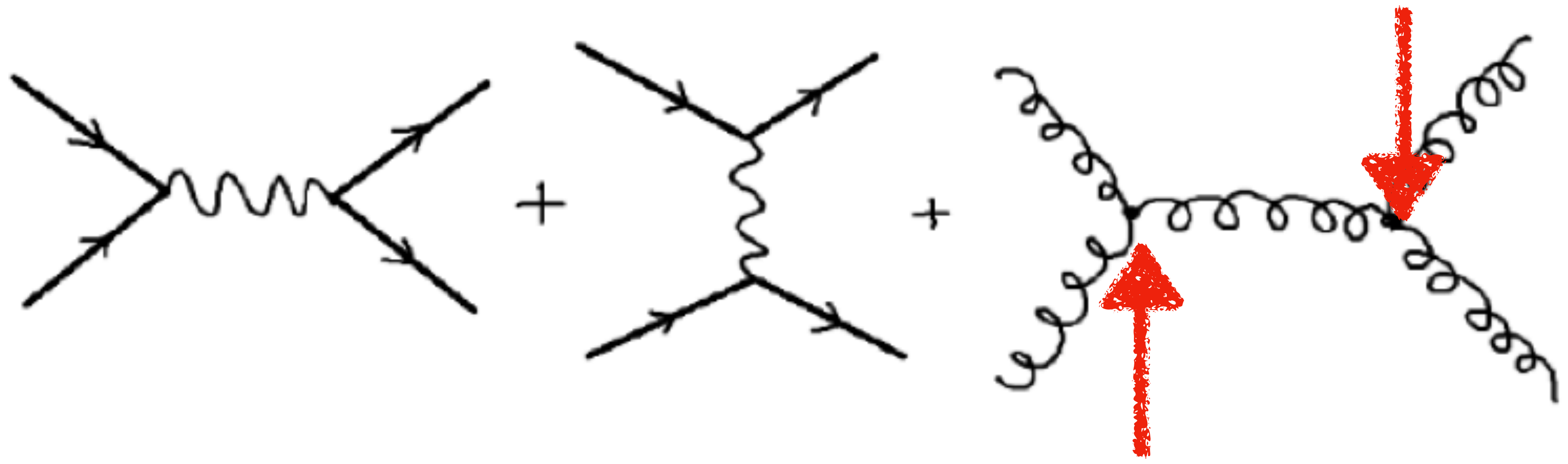
PRD 87 (2013)112002

2.76 TeV



EPJC (2016)

Each vertex sensitive to $\alpha_S(m_Z)$



Each line sensitive to PDFs

- **Simultaneous fit of PDF and $\alpha_S(m_Z)$ at NNLO** → correlation between PDFs and $\alpha_S(m_Z)$ taken into account
- **Correlation of jet measurements** studied

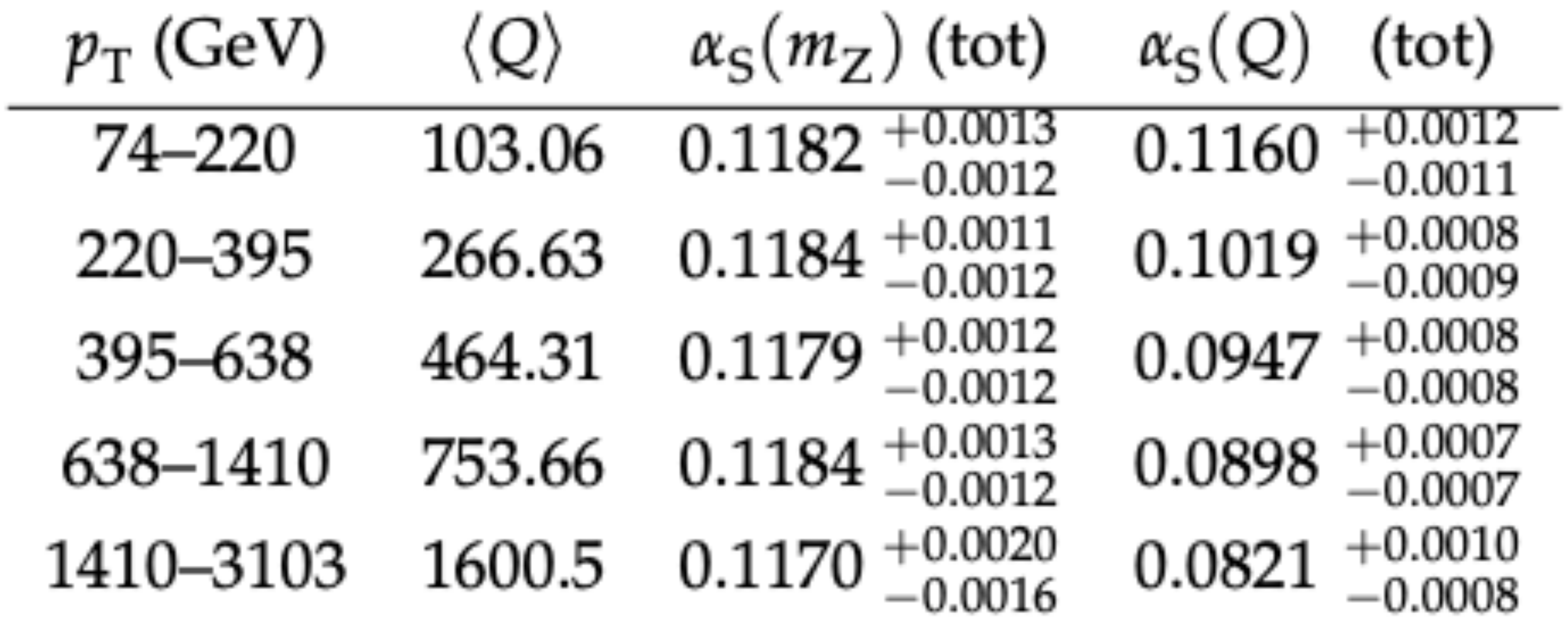
Final result: $\alpha_S(m_Z) = 0.1176^{+0.0014}_{-0.0016}$

Most precise measurement from jets!

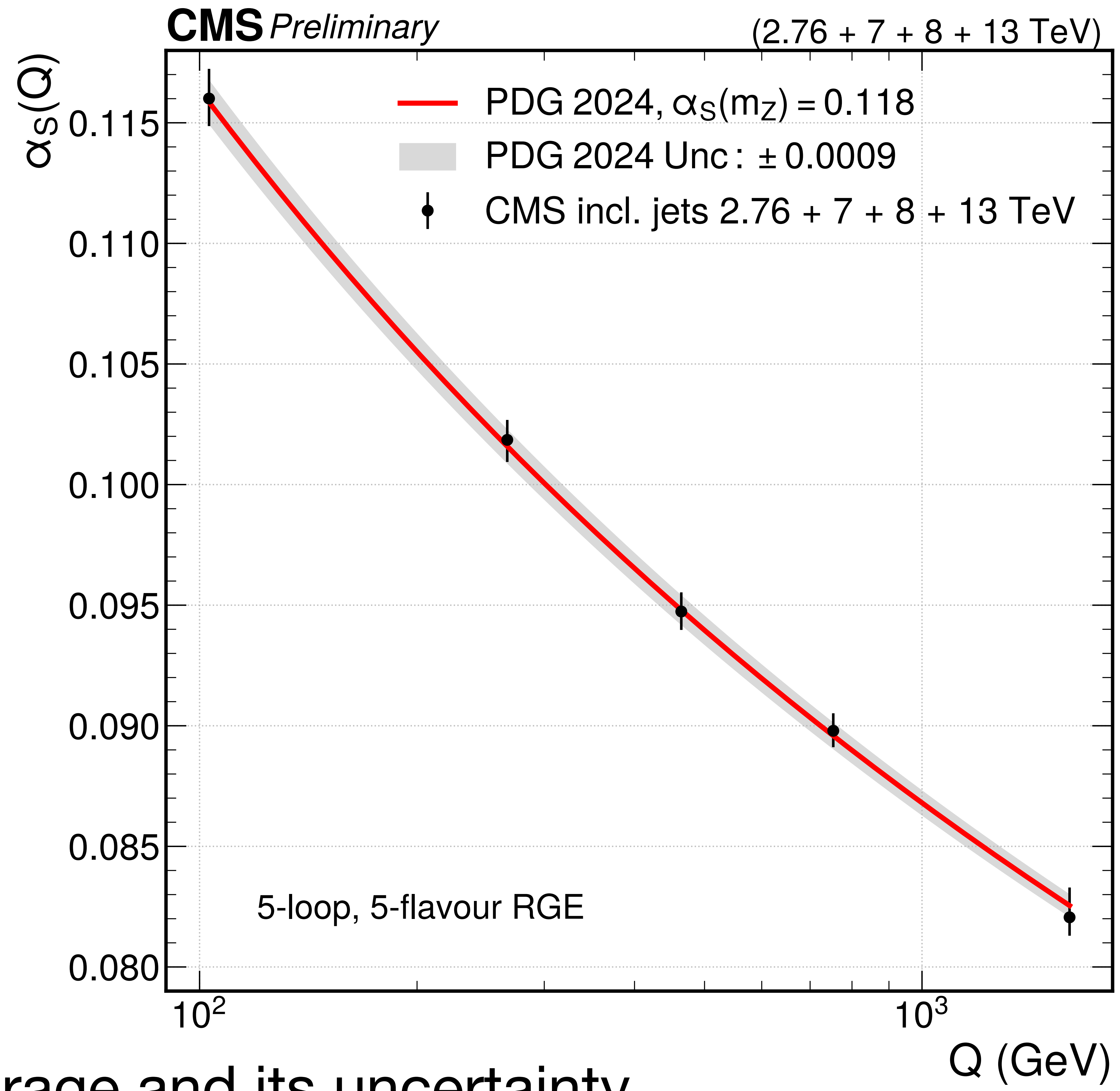
Extraction of α_S running CMS-PAS-SMP-24-007

Divide data into independent p_T ranges

- In each p_T range, fit PDFs and $\alpha_S(m_Z)$ simultaneously
- Define the center of gravity of each p_T range $< Q >$
- Evolve $\alpha_s(m_Z)$ to $< Q >$ (**CRunDec package**)



p_T (GeV)	$\langle Q \rangle$	$\alpha_S(m_Z)$ (tot)	$\alpha_S(Q)$ (tot)
74–220	103.06	$0.1182^{+0.0013}_{-0.0012}$	$0.1160^{+0.0012}_{-0.0011}$
220–395	266.63	$0.1184^{+0.0011}_{-0.0012}$	$0.1019^{+0.0008}_{-0.0009}$
395–638	464.31	$0.1179^{+0.0012}_{-0.0012}$	$0.0947^{+0.0008}_{-0.0008}$
638–1410	753.66	$0.1184^{+0.0013}_{-0.0012}$	$0.0898^{+0.0007}_{-0.0007}$
1410–3103	1600.5	$0.1170^{+0.0020}_{-0.0016}$	$0.0821^{+0.0010}_{-0.0008}$



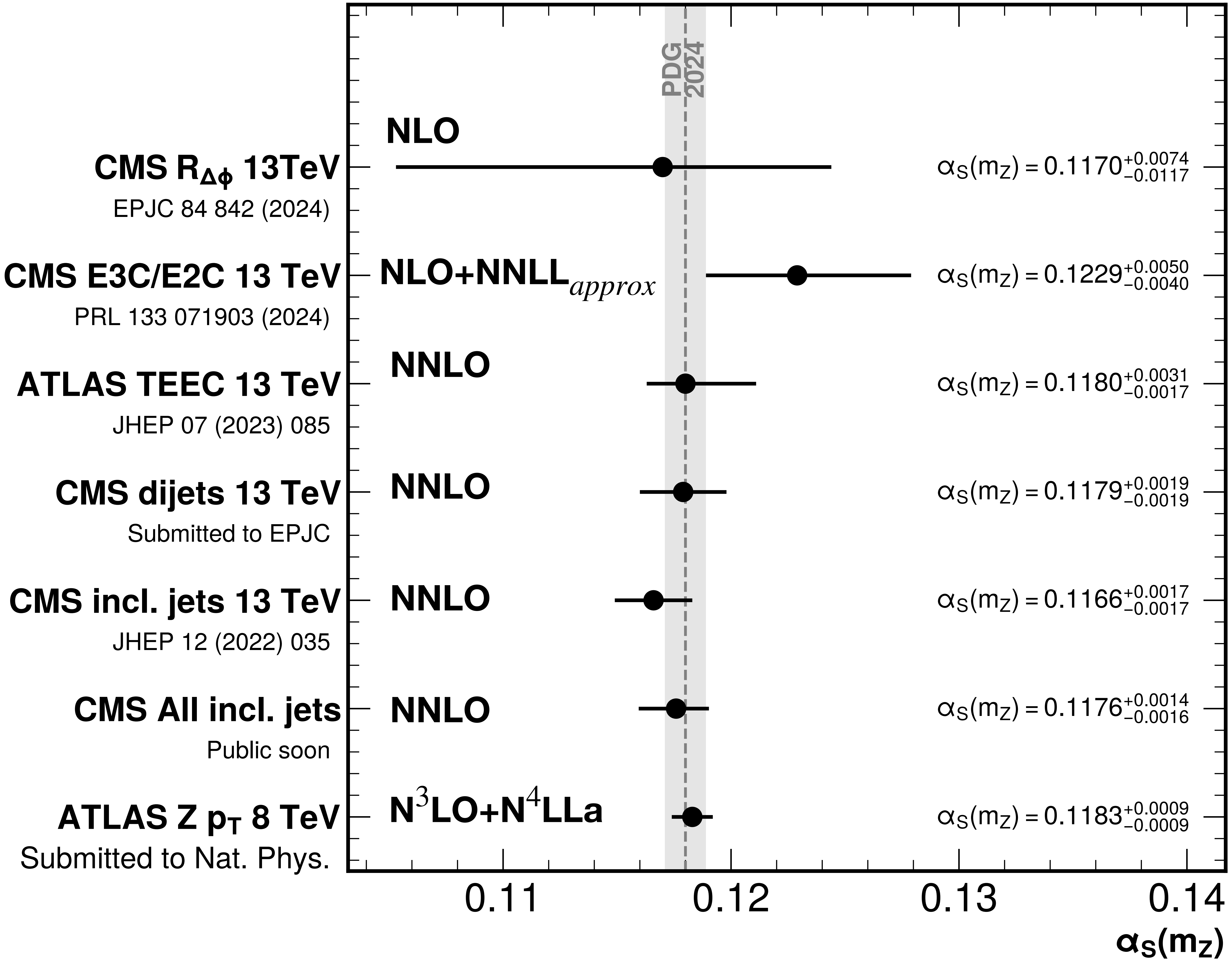
$\alpha_S(Q)$ in the five p_T ranges are compared to the world average and its uncertainty

→ **Running probed up to 1.6 TeV**

→ **Good agreement in the entire range**

Summary of $\alpha_S(m_Z)$

- ATLAS (A)TEEC @13TeV: JHEP 07 (2023) 085
- CMS dijets @13TeV: arXiv312.16669, *submitted to the EPJC*
- CMS azimuthal correlation $R_{\Delta\phi}$ @13TeV: EPJC 84 842 (2024)
- CMS energy correlators @13TeV: PRL 133 071903 (2024)



Summary and conclusions

- **EW and QCD are interconnected within each other**

- **Numerous results of precision electroweak and QCD physics in the last 12 months!**

- **LHC resulted to be a powerful precision machine for experimental SM measurements**
  - Facilitated by large datasets, detailed understanding of the detectors, dedicated reconstruction techniques and state-of-the-art theory predictions

- **New measurements of electroweak and QCD:** m_W, Γ_W, $sin\theta_W$, g-2, $\alpha_S(m_Z)$

Thank you

Backup

OTHER ANALYSES: single boson, multiboson and boson+jets

- CMS, Z invisible width, at 13 TeV: PLB 842 (2023) 137563
- ATLAS, Z invisible width, at 13 TeV: PLB 854 (2024) 138705
- ATLAS, ZZ at 13 .6 TeV: PLB 855 (2024) 138764
- CMS, WW at 13.6 TeV: PLB 855 (2024) 138764
- CMS, WZ, at 13.6 TeV: CMS-PAS-SMP-24-005
- CMS, Zy invisible and triple gauge couplings, at 13 TeV: CMS-PAS-SMP-22-009
- ATLAS, WZy, at 13 TeV: PRL132 (2024) 021802
- CMS, WWy, at 13 TeV: PRL132 (2024) 121901
- ATLAS, Z+jets, at 13 TeV: JHEP 06 (2023) 080
- CMS, Z+jets, at 13 TeV: EPJC 83 (2023) 722
- CMS, W Boson Decay Branching Fractions (SMP-24-009)
- LHCb, Z production cross-section, using 5.02 TeV: JHEP 02 (2024) 070

Effective weak mixing angle

- The Forward-Backward asymmetry AFB increases with the Z boson rapidity
  - Only valence quarks contribute to the AFB
- Ambiguity in quark direction resolved through rapidity-dependent measurement
- Experimentally defined as

CMS

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

LHCb

$$A_{\mathrm{FB}} = \frac{\mathrm{N}(\eta^- > \eta^+) - \mathrm{N}(\eta^- < \eta^+)}{\mathrm{N}(\eta^- > \eta^+) + \mathrm{N}(\eta^- < \eta^+)}$$

$\gamma\gamma \rightarrow \tau\tau$ in pp collisions

- **(g-2)$_\tau$ has a strong potential to probe new physics**
    - Expect large BSM enhancement at high p_T and $m_{\tau\tau}$

- ATLAS and CMS have put limits on α_τ using PbPb
    - $\sigma \approx Z^4$
    - Sensitive to m$_{\tau\tau}$<40GeV

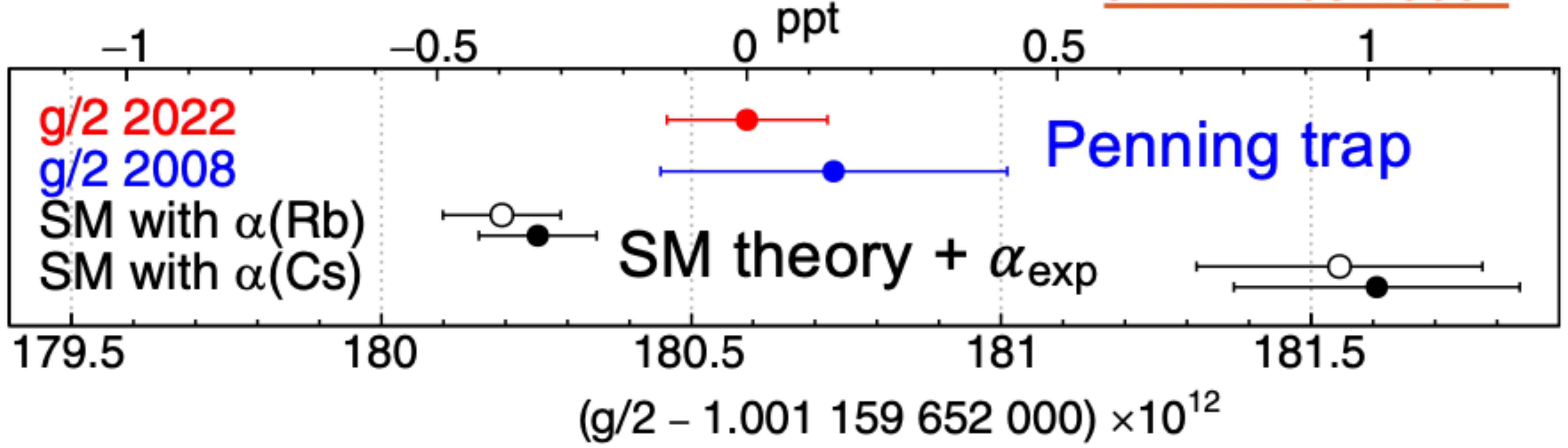
- New CMS results in pp collisions (Rep. Prog. Phys. 87 (2024) 107801):
    - Using exclusivity cuts on coplanarity and N$_{tracks}$
    - Fitting shape and yield in $m_{\tau\tau} > 50$GeV

- Electric dipole moment

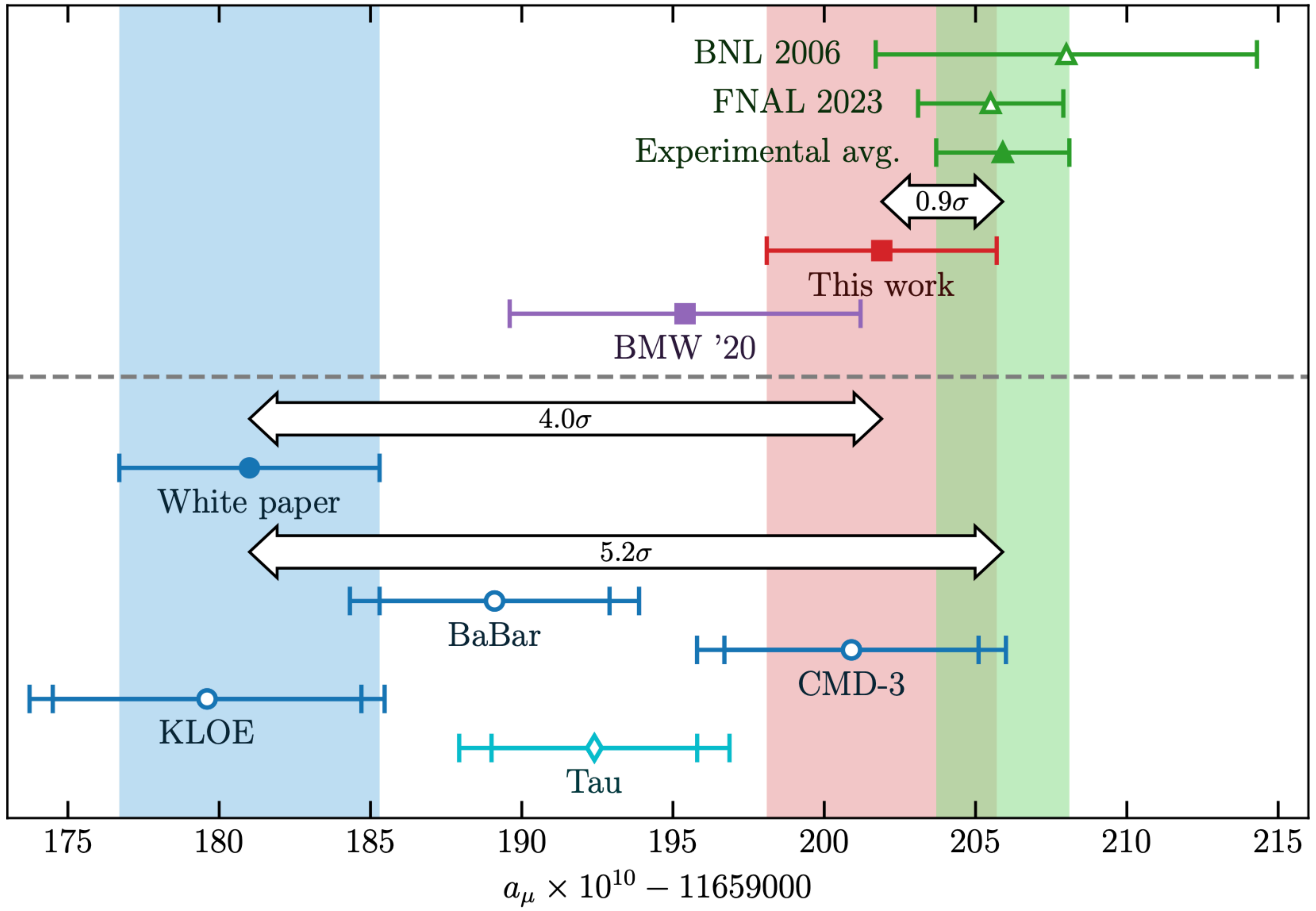
g-2

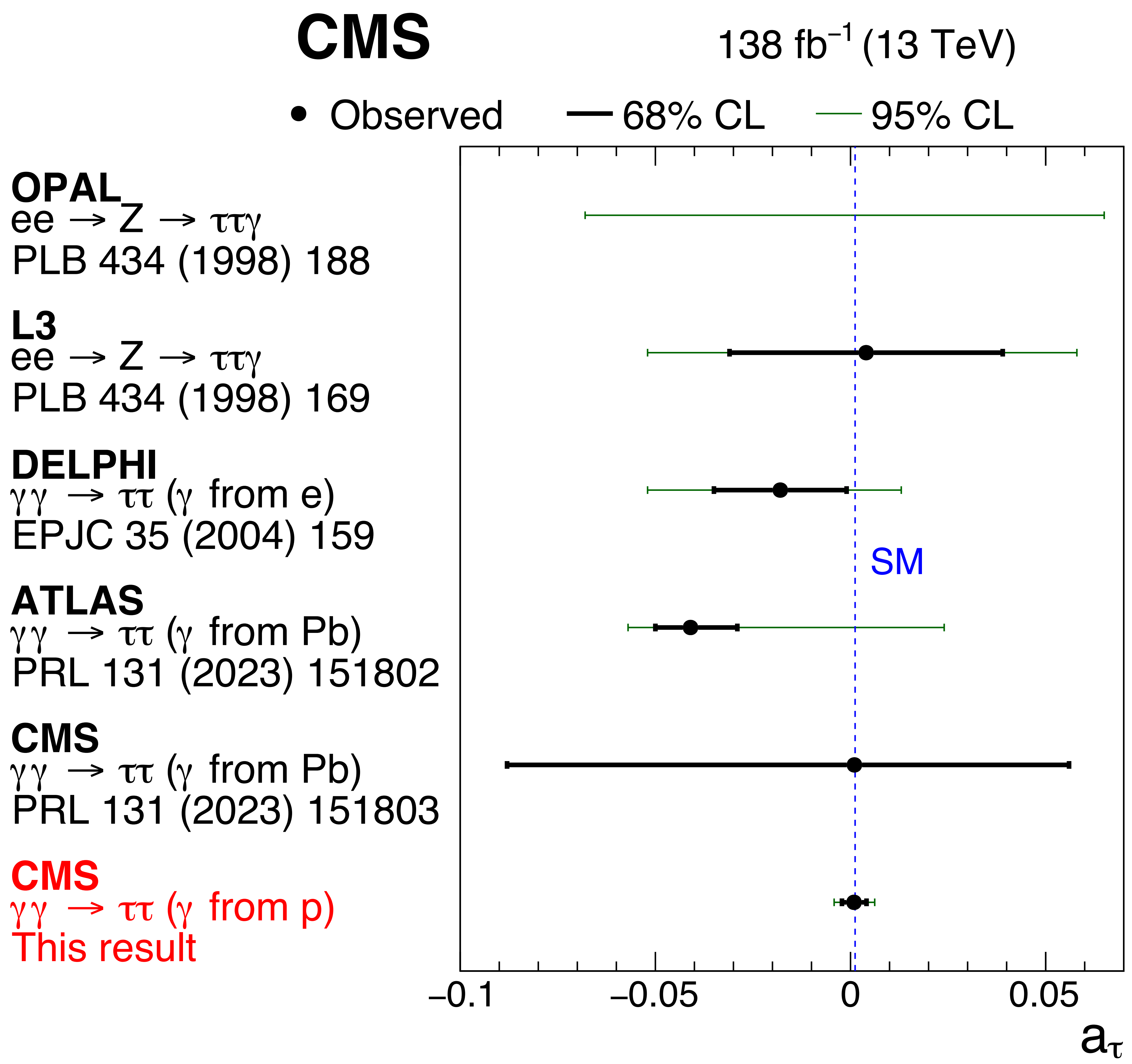
Rep. Prog. Phys. 87 (2024) 107801

arXiv:2209.13084



arxiv2407.10913





$$\boxed{\alpha_\tau = \frac{g_\tau}{2} - 1 = 0.0009^{+0.0032}_{-0.0031}}$$

Dominant contributions to uncertainty

- **CMS mW:** $80360.2 = 2.4\ (stat) \pm 9.6\ (syst) \rightarrow$ $\mathrm{p}_\mathrm{T}^{\mu}$ scale (4.8 MeV), PDF (4.4 MeV)
- **ATLAS mW:** dominated by PDF, EW and muon and electron calibration