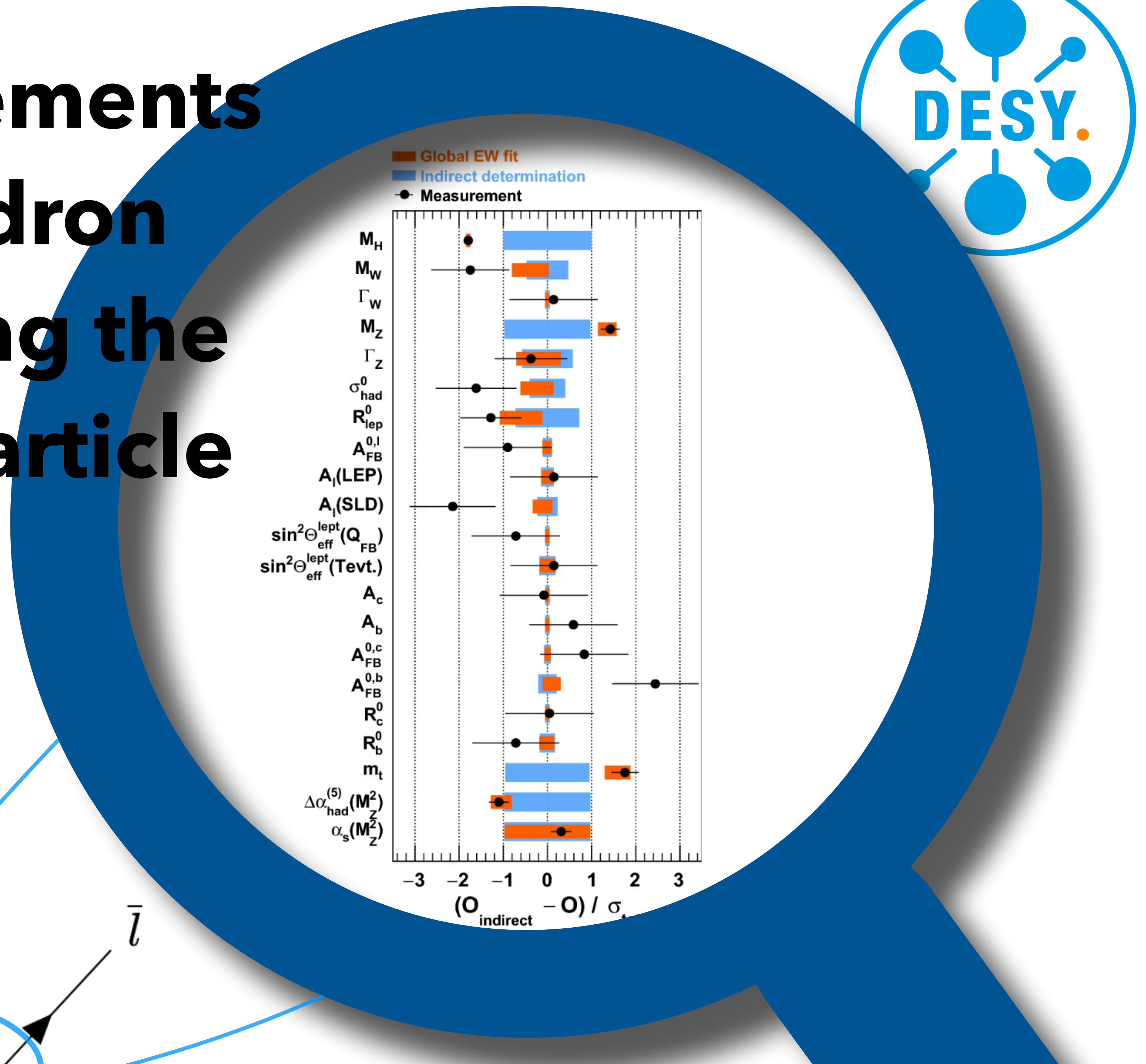
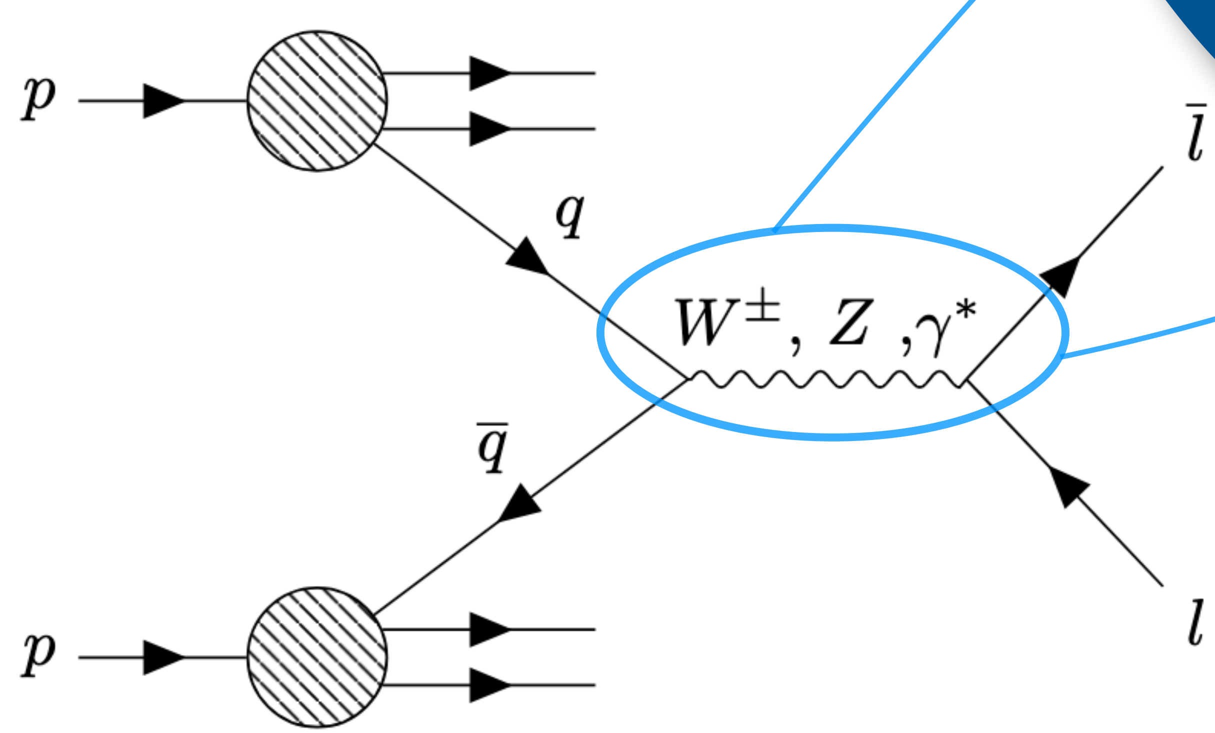
Precision Measurements at the Large Hadron Collider: Exploring the Foundations of Particle Physics





Ludovica Aperio Bella
Valencia - IFIC - 24/2/2026

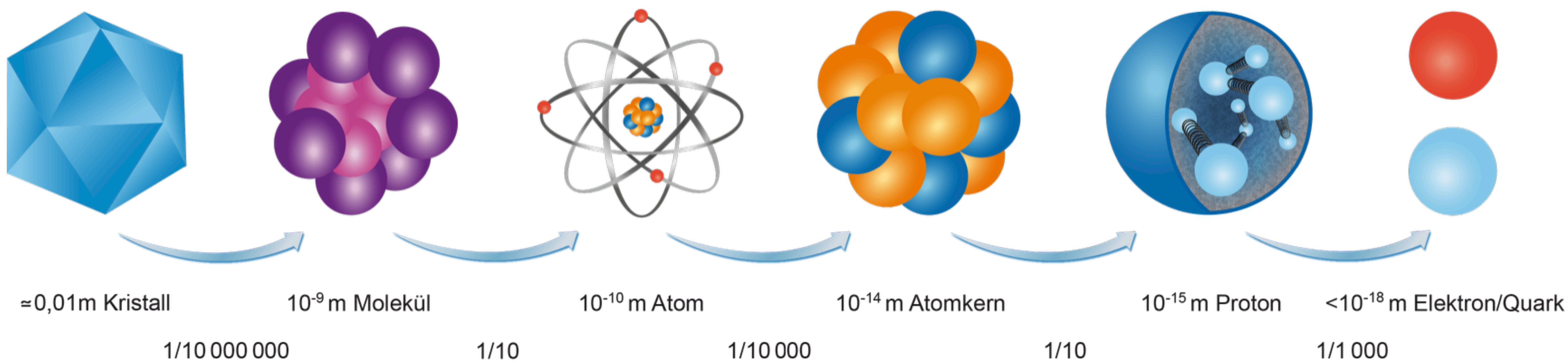
Precision Measurements at the Large Hadron Collider: Exploring the Foundations of Particle Physics

The experiments at the Large Hadron Collider (LHC) continue to confirm the Standard Model (SM) of particle physics with impressive precision, and no conclusive evidence for new physics at the TeV scale has yet been observed. In this context, precision measurements of electroweak observables provide a powerful and complementary approach to exploring physics beyond the SM.

The LHC experiments have delivered a broad and highly precise program of electroweak measurements, probing the internal consistency of the SM through fundamental quantities such as the W- and Z-boson masses, the effective weak mixing angle, and related electroweak parameters. More than forty years after their discovery, the W and Z bosons remain key laboratories for testing the SM, where even small deviations from predicted relations could point to new phenomena.

This talk will review recent high-impact ATLAS results in electroweak precision physics, highlighting both experimental and theoretical challenges and their relevance in the ongoing LHC physics program. Prospects for the High-Luminosity LHC, as well as the role of future collider projects, will also be discussed.

What is everything made of ?

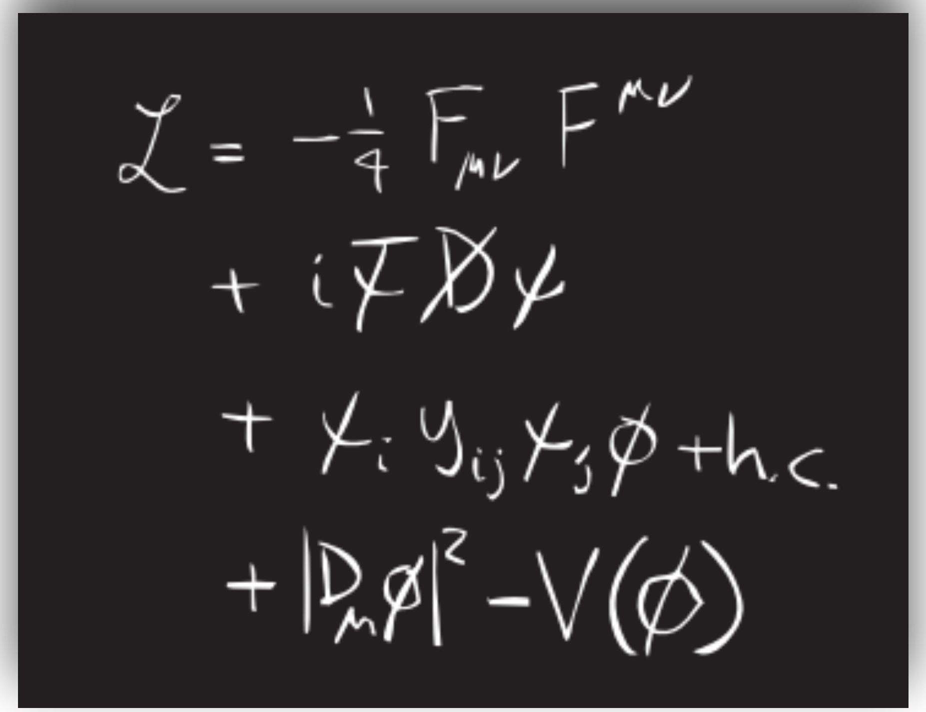


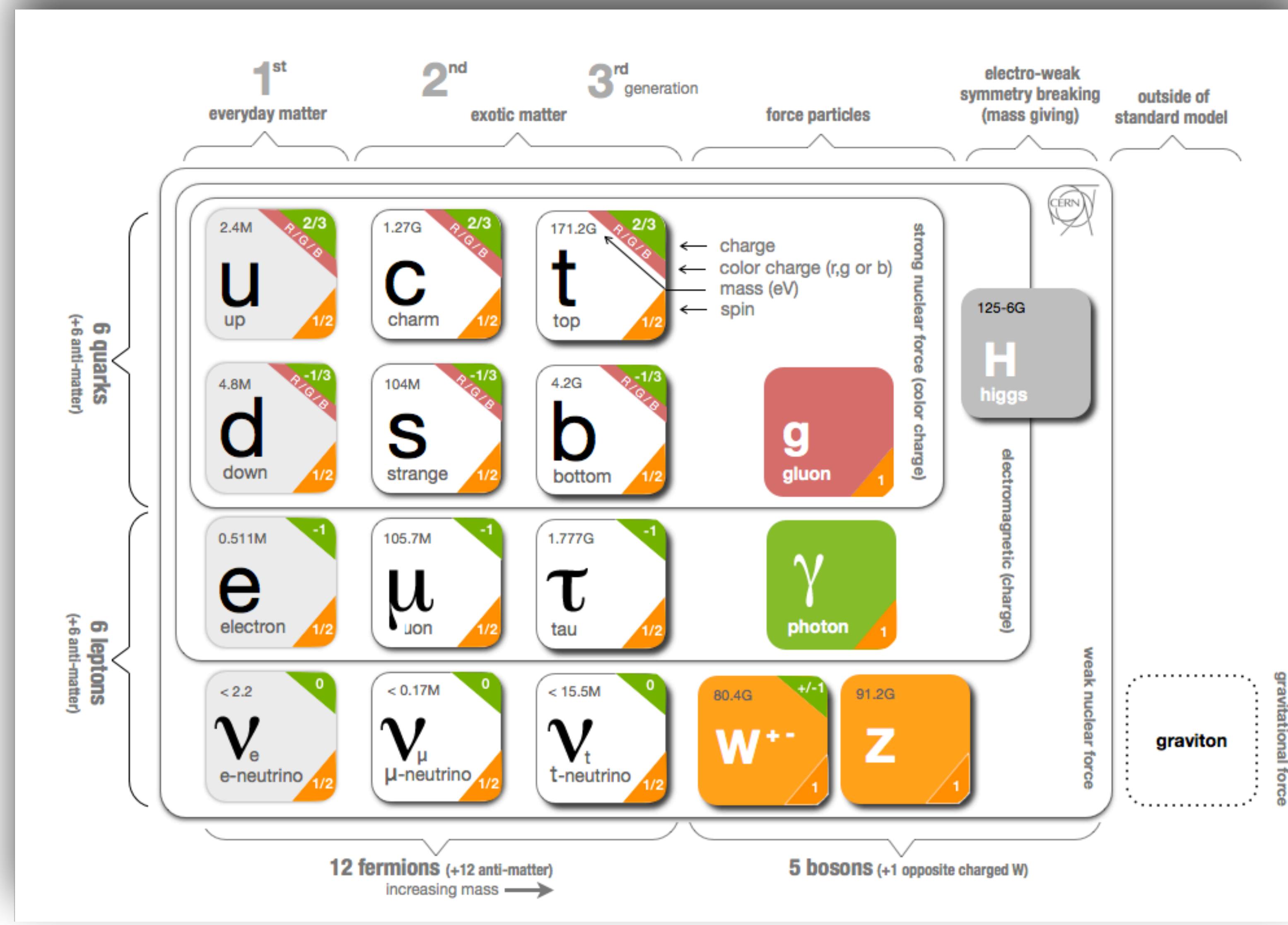
It's all made of a handful of particles and forces

Particle physics studies the elementary ***building blocks*** of matter

- **Particles** interact via forces caused by fields
- **Forces** are being carried by special particles called **"force mediators" (boson)**

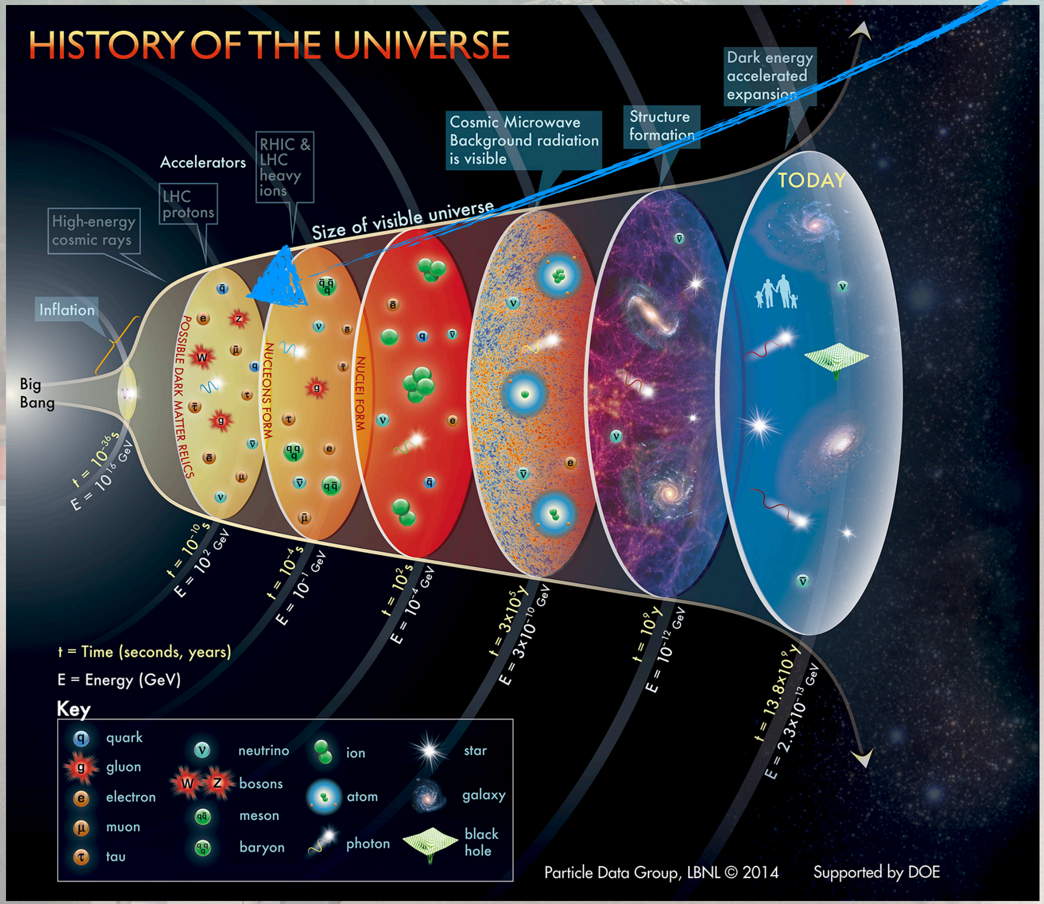
The theory of everything: the Standard Model





LHC a discovery machine at the energy frontier

- The **Large Hadron Collider** (**LHC**) is the world's largest and most powerful particle accelerator at date @ CERN in Geneva
  - it was build to reproduce the universe condition after the big-bang to help us understanding and study the fundamental component of matter and their interactions



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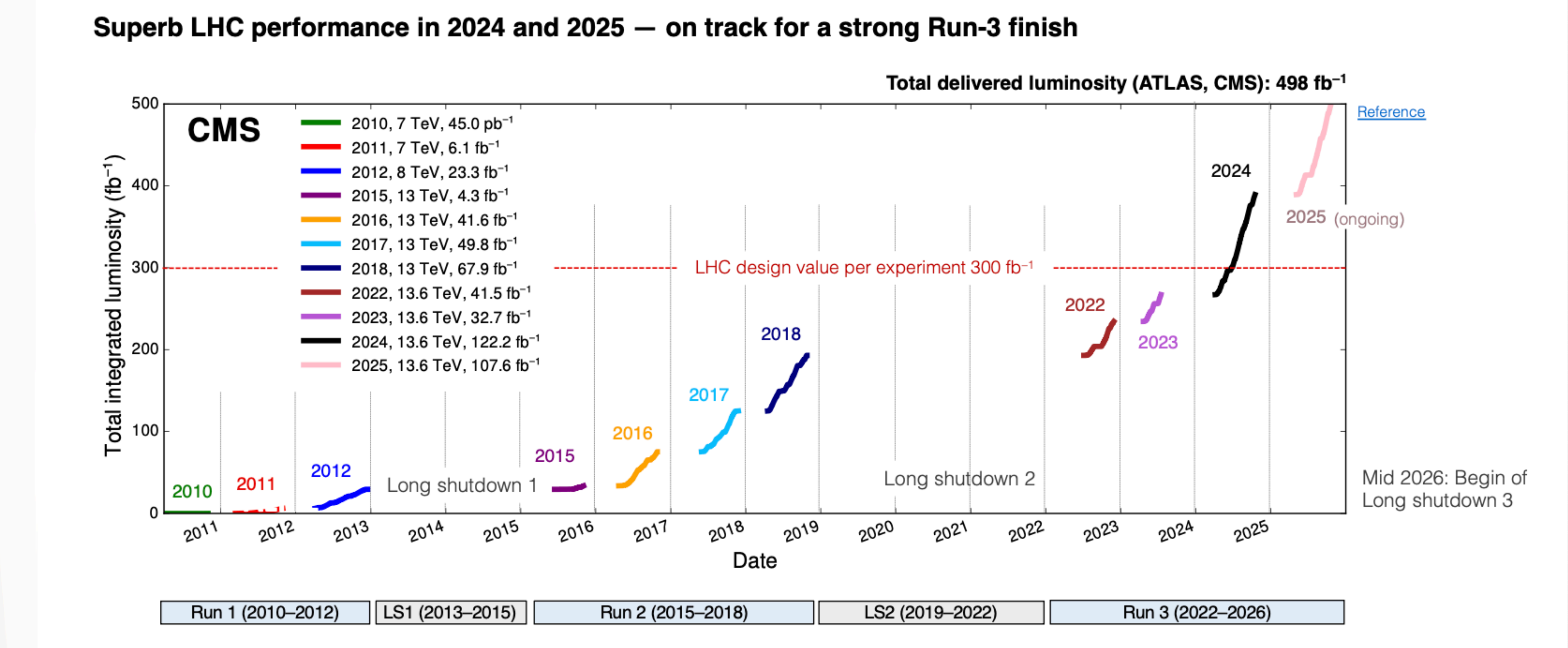
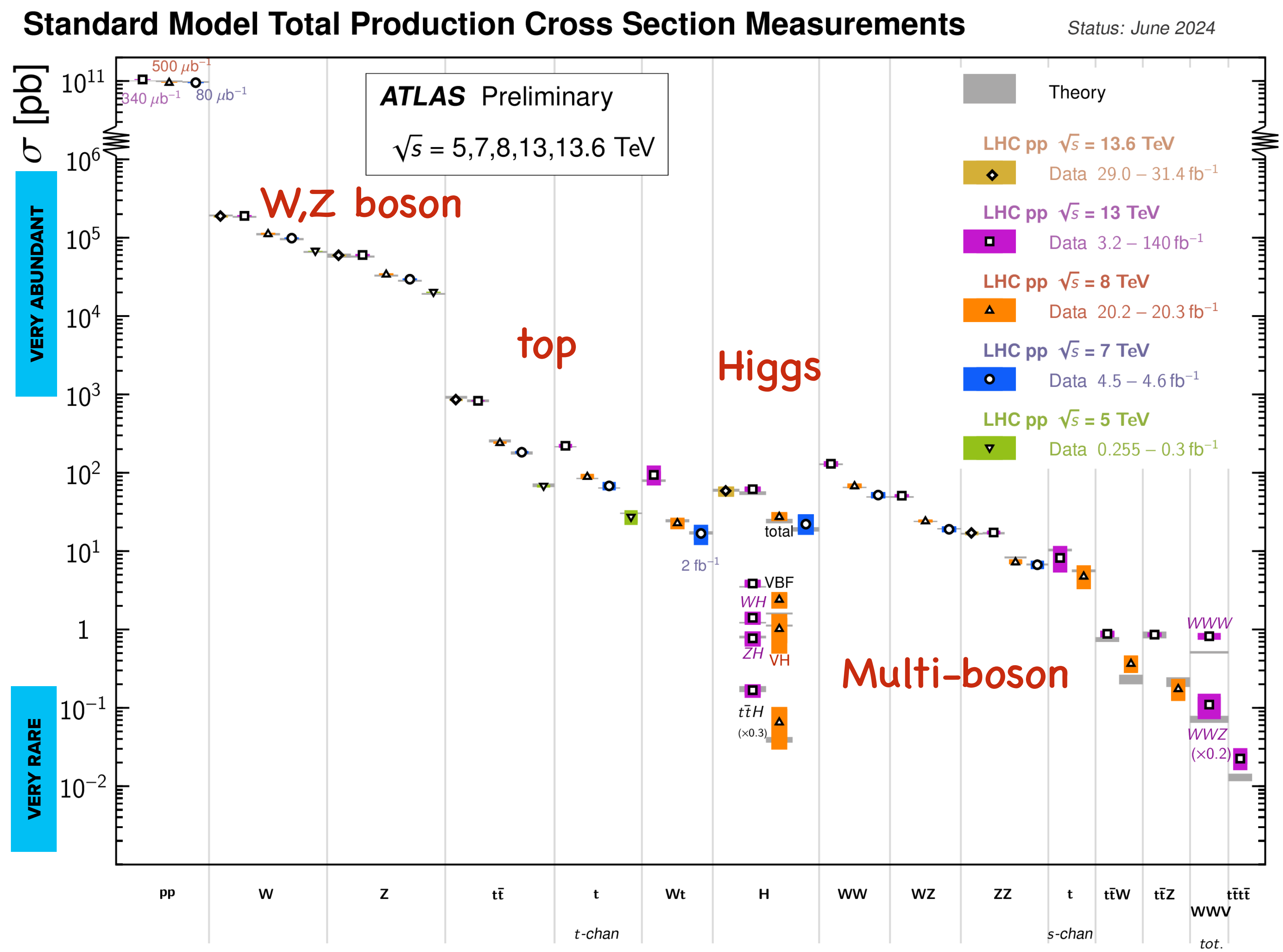


The LHC physics program

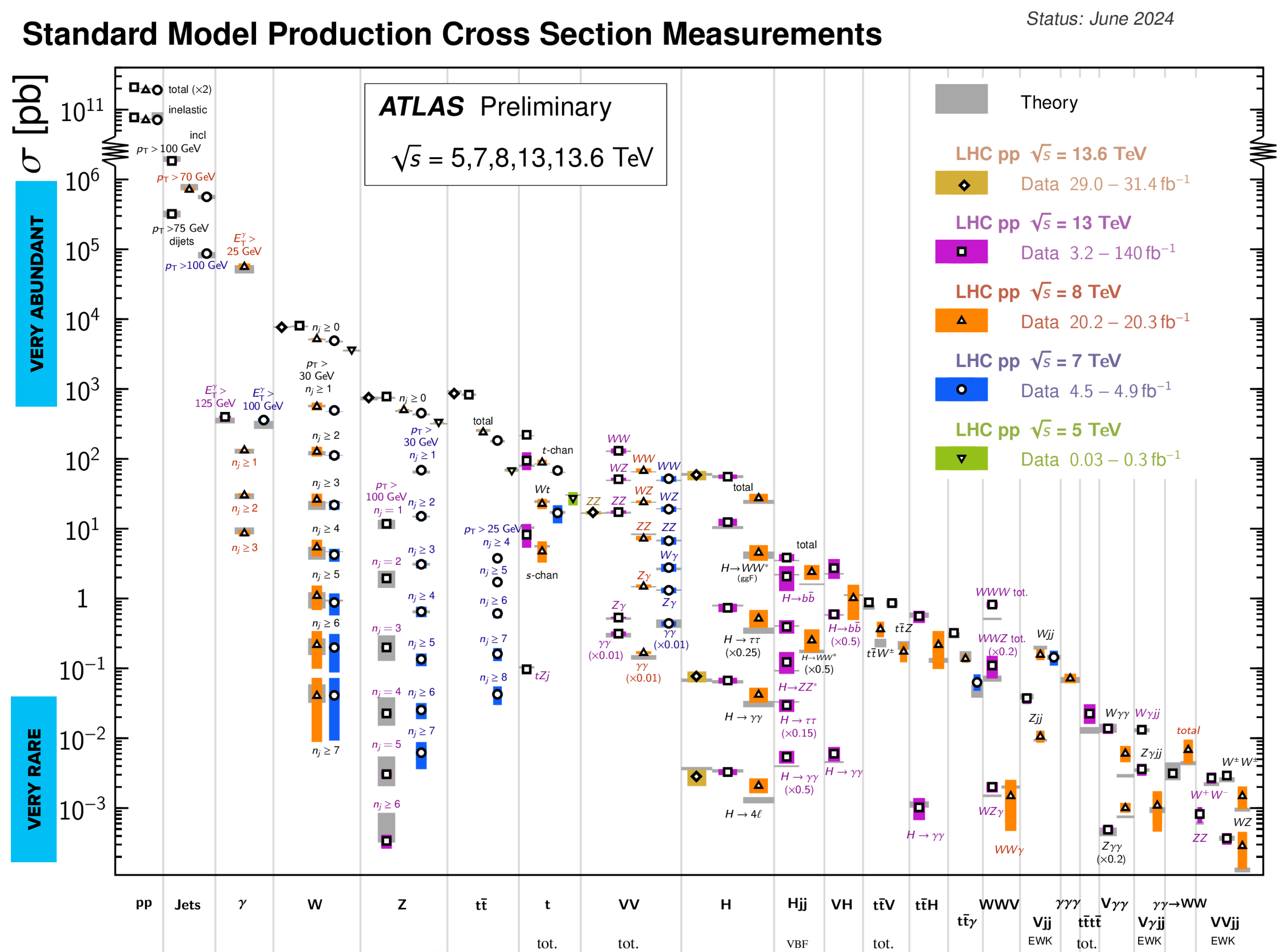
The LHC is an **everything** factory

LHC experiments got the <u>richest hadron collision data sample ever recorded</u> with production rates varying across an incredible 10 orders of magnitude!



The success of the SM

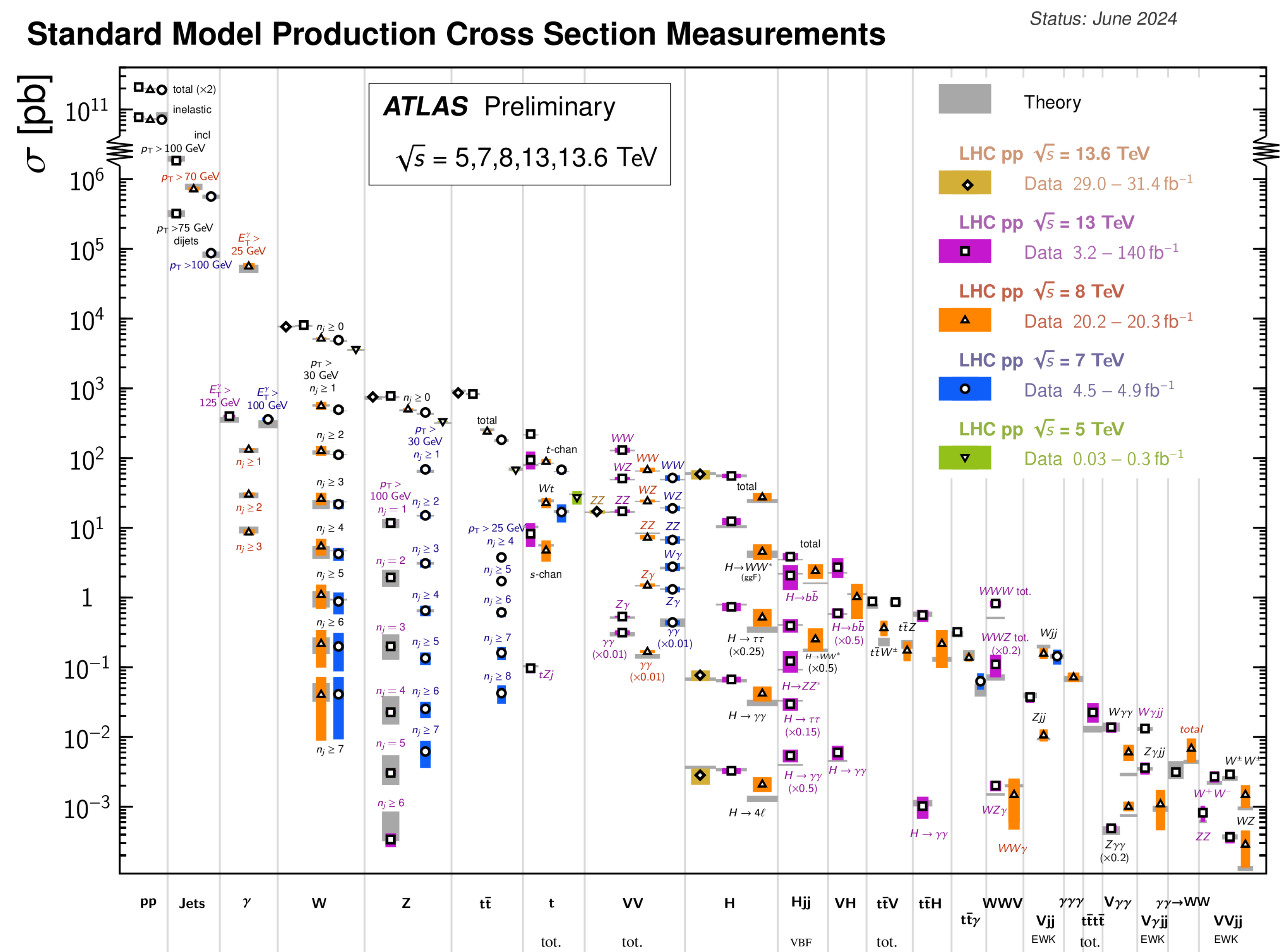
- Theory so far agrees with all measured cross sections across widely different processes
- and across centre-of-mass energies …
- ***Often data precision challenges the theory predictions…***



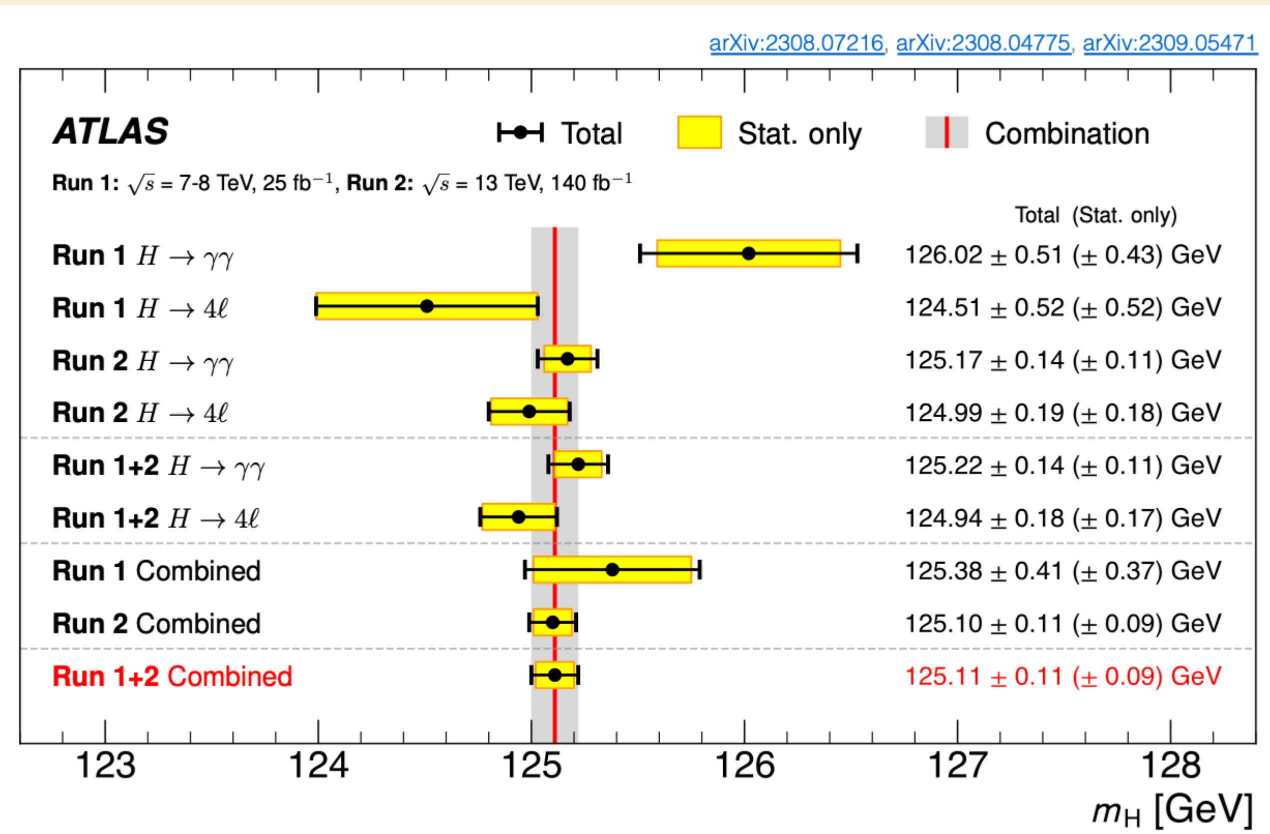
Can we consider now the LHC a "precision physics" machine ?

The success of the SM

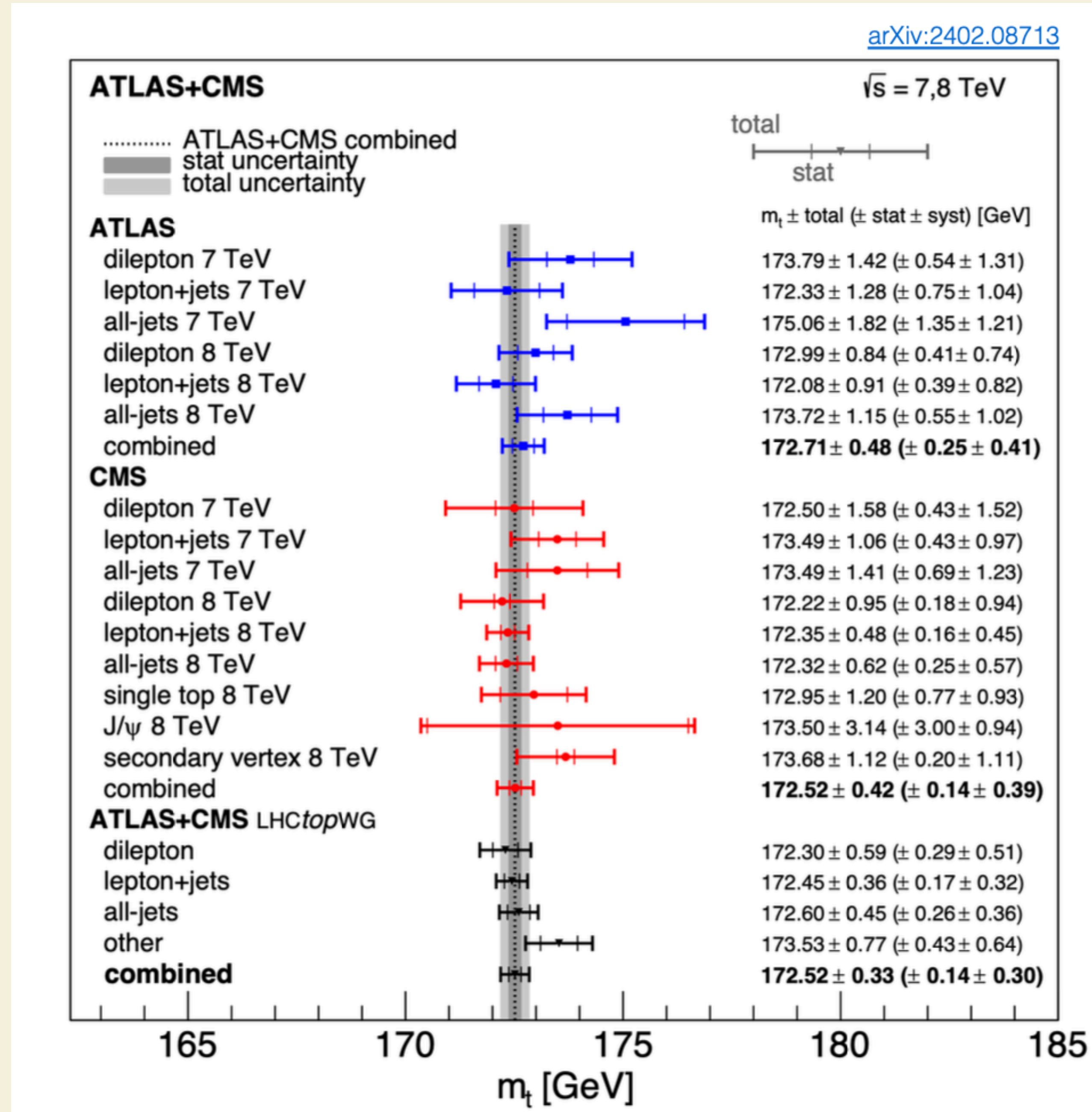
WHAT THE LHC-ERA IS CHANGING IS THE PERCEPTION OF THE TRUE COMPLEXITY OF THINGS AND THE ABILITY TO CARRY OUT QUANTITATIVE MEASUREMENTS OF KNOWN PRINCIPLE



Precision objects enable precision measurements



most precise Higgs mass measurement to date (0.1%)

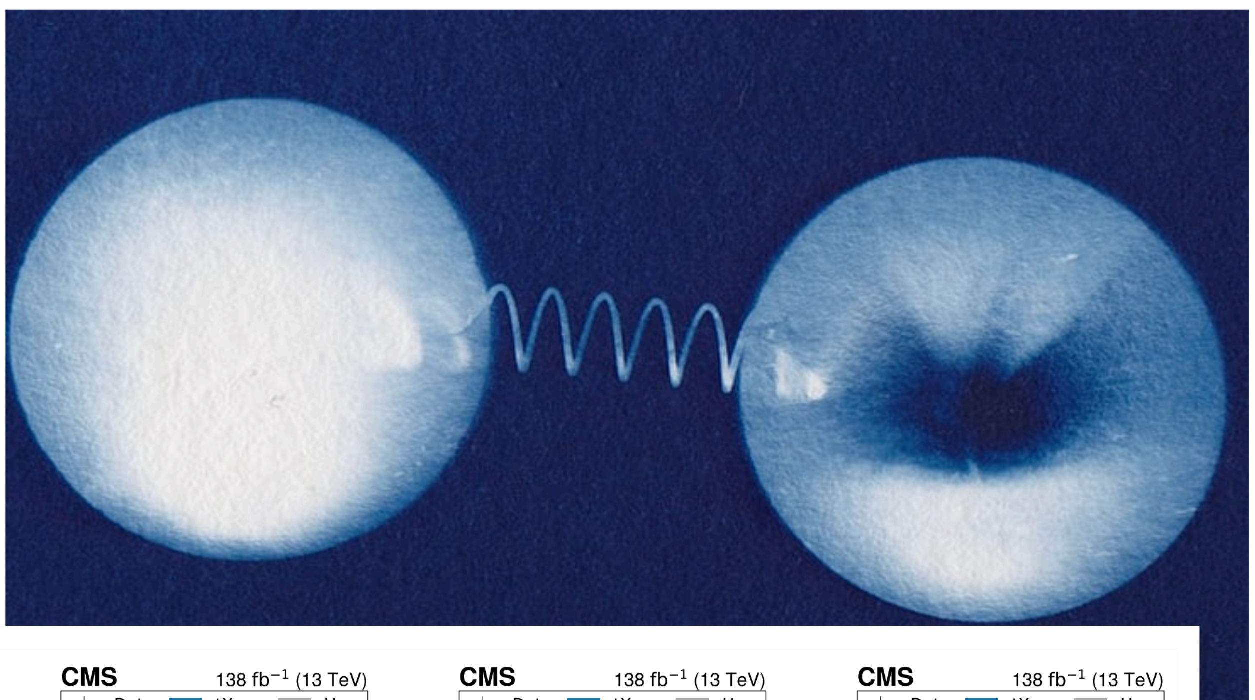


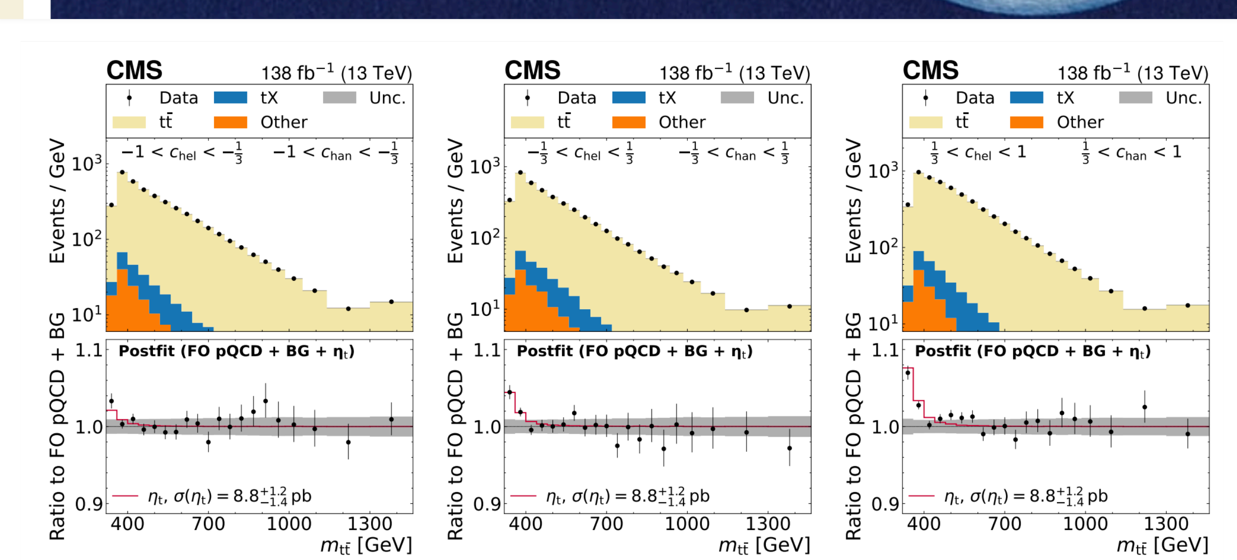
high-precision top mass measurements (0.2%)

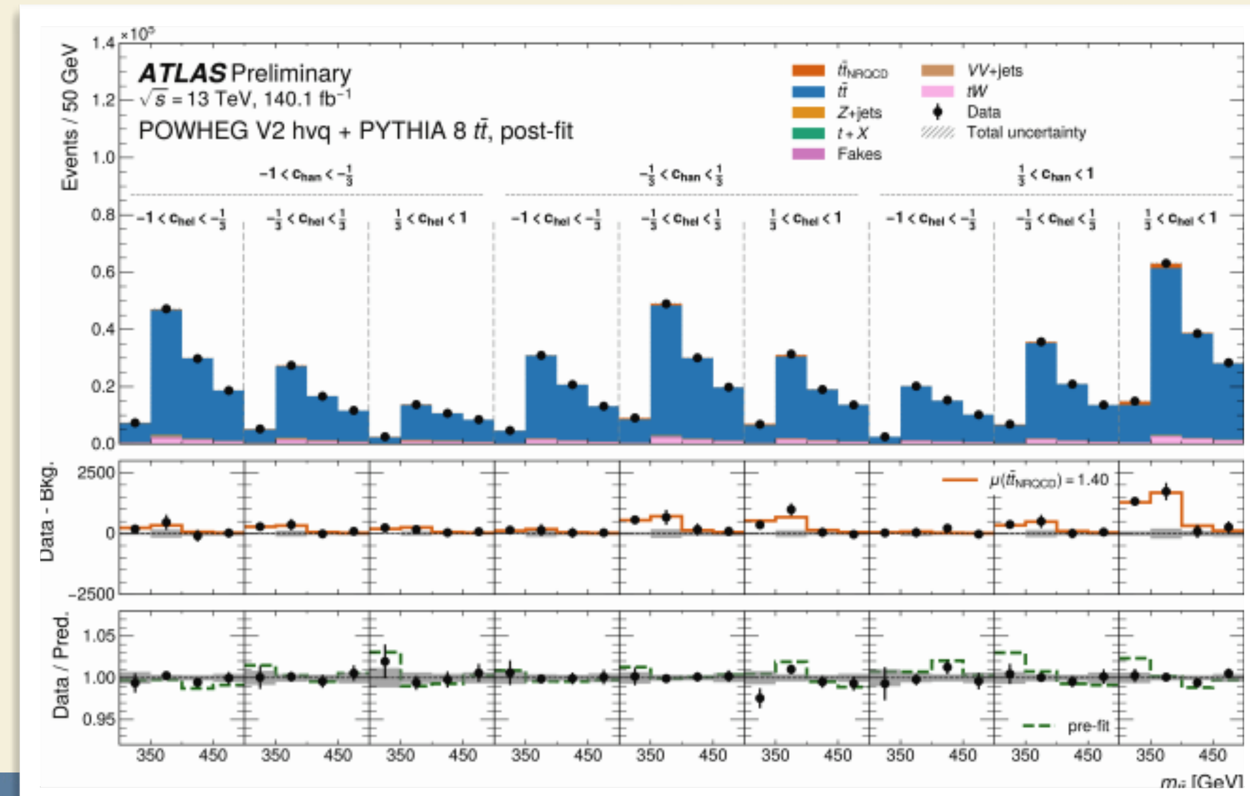
New observed state

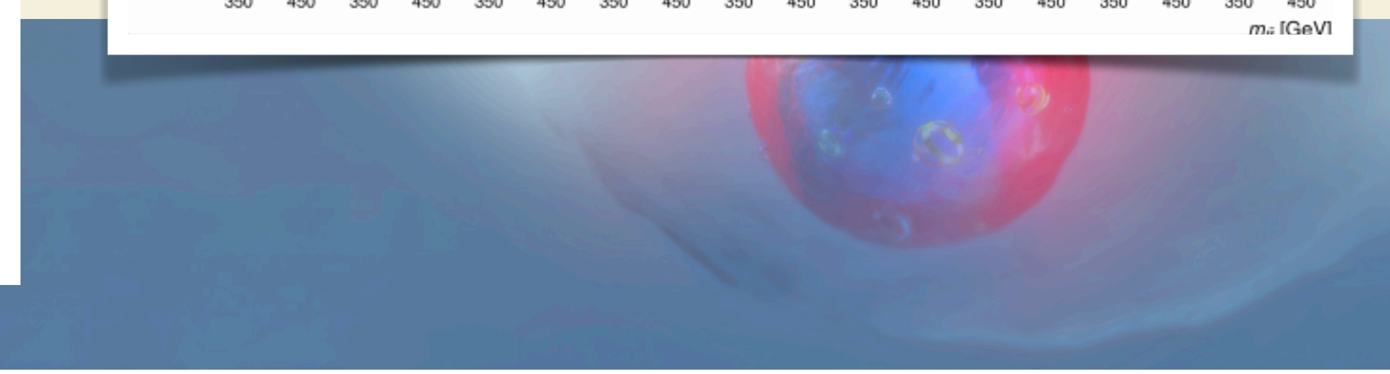
Non-relativistic QCD predicts highly compact, colour-singlet quasi-bound pseudoscalar tt states (negligible self-annihilation, top decays before)

Suddenly Visible: New Particle Challenges Long-Held Assumptions









Updates > Press Statement > Elusive romance of top-quark pairs observed at the LHC

Press Statement

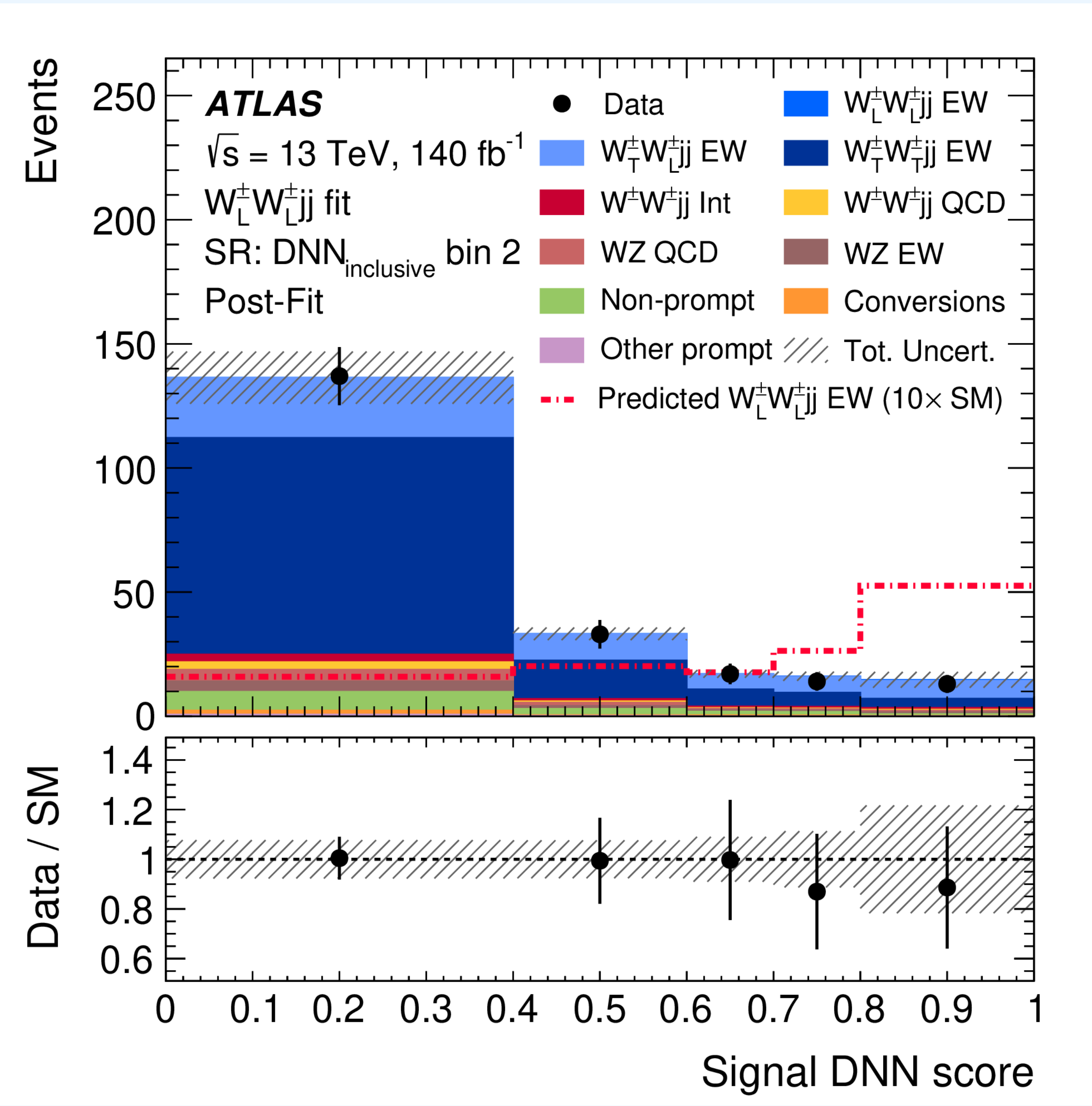
Tags:
EPS 2025,
top quark,
physics results

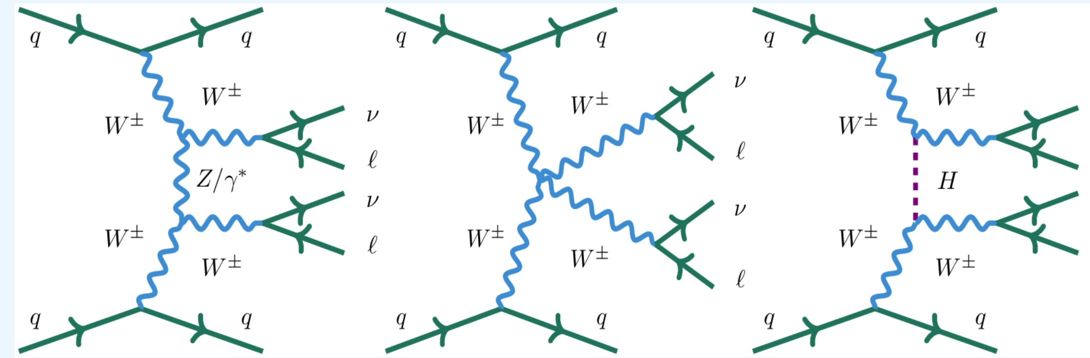
Elusive romance of top-quark pairs observed at the LHC

8 July 2025 | By CERN

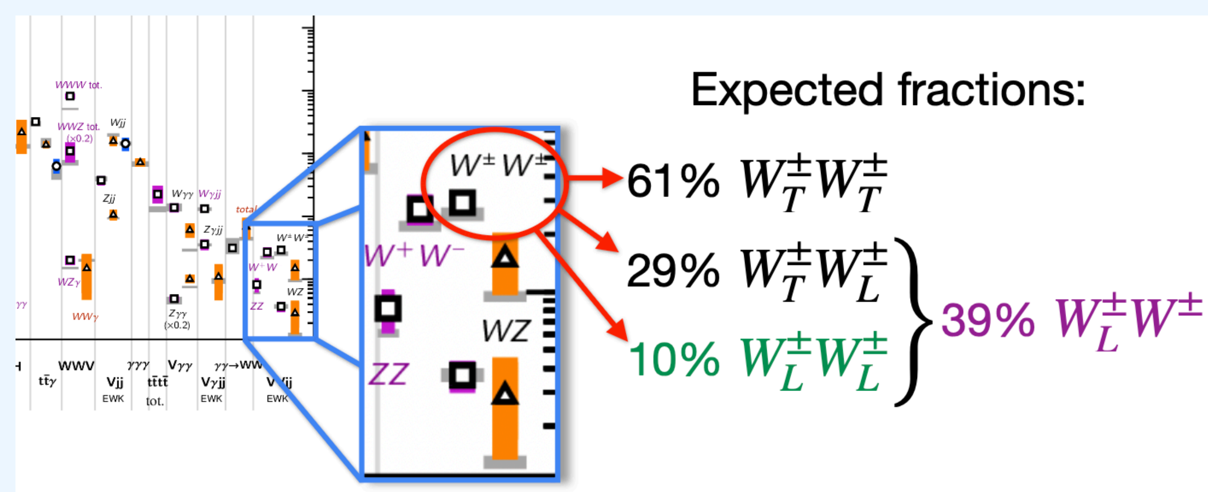
The CMS and ATLAS experiments at CERN's Large Hadron Collider have observed an unforeseen feature in the behaviour of top quarks that suggests that these heaviest of all elementary particles form a fleeting union.

Measurement of Super Rare process - longitudinal polarised WW - scattering

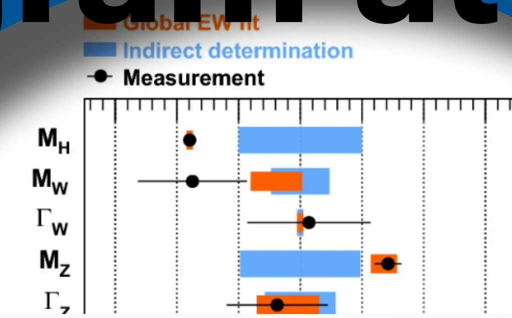




- First evidence of production of polarised WW where at least one of the bosons is longitudinally polarised (observed significance is 3.3 σ with a measured cross-section of **0.88 ± 0.30 fb**
- Most stringent limits to date for the fiducial cross-section of longitudinally polarised WW [observed (expected) 95 % CL upper limit of **0.45 (0.70) fb**]
-



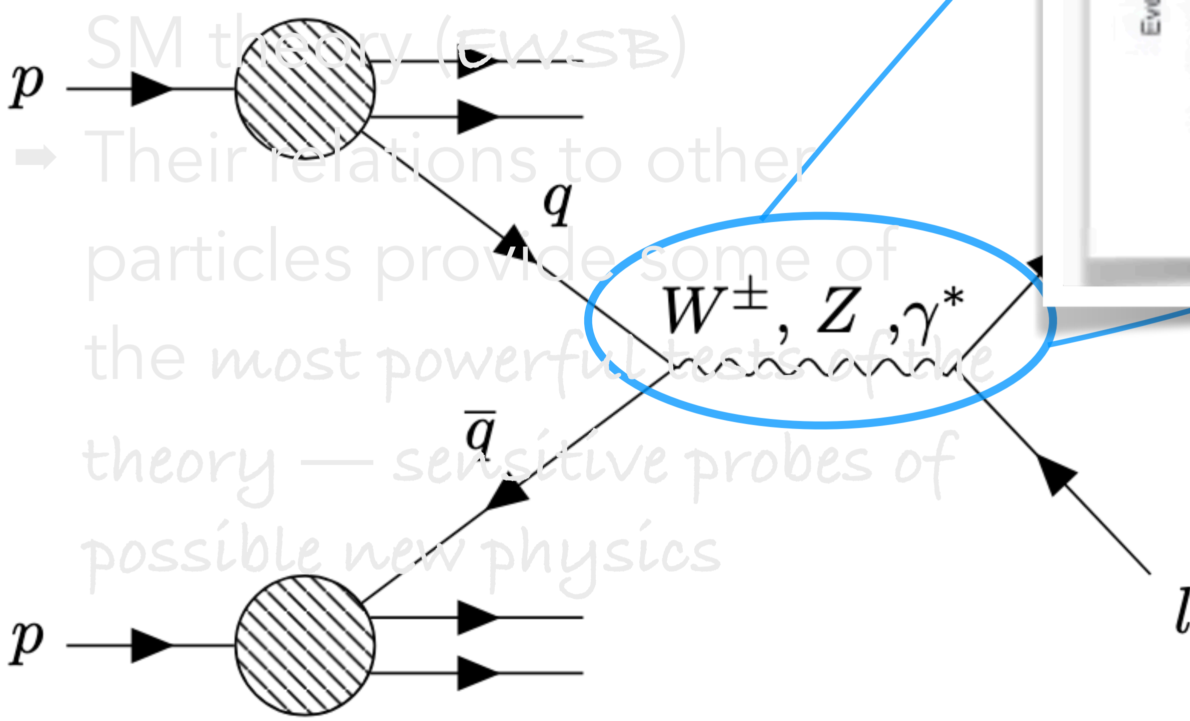
W,Z physics program at LHC

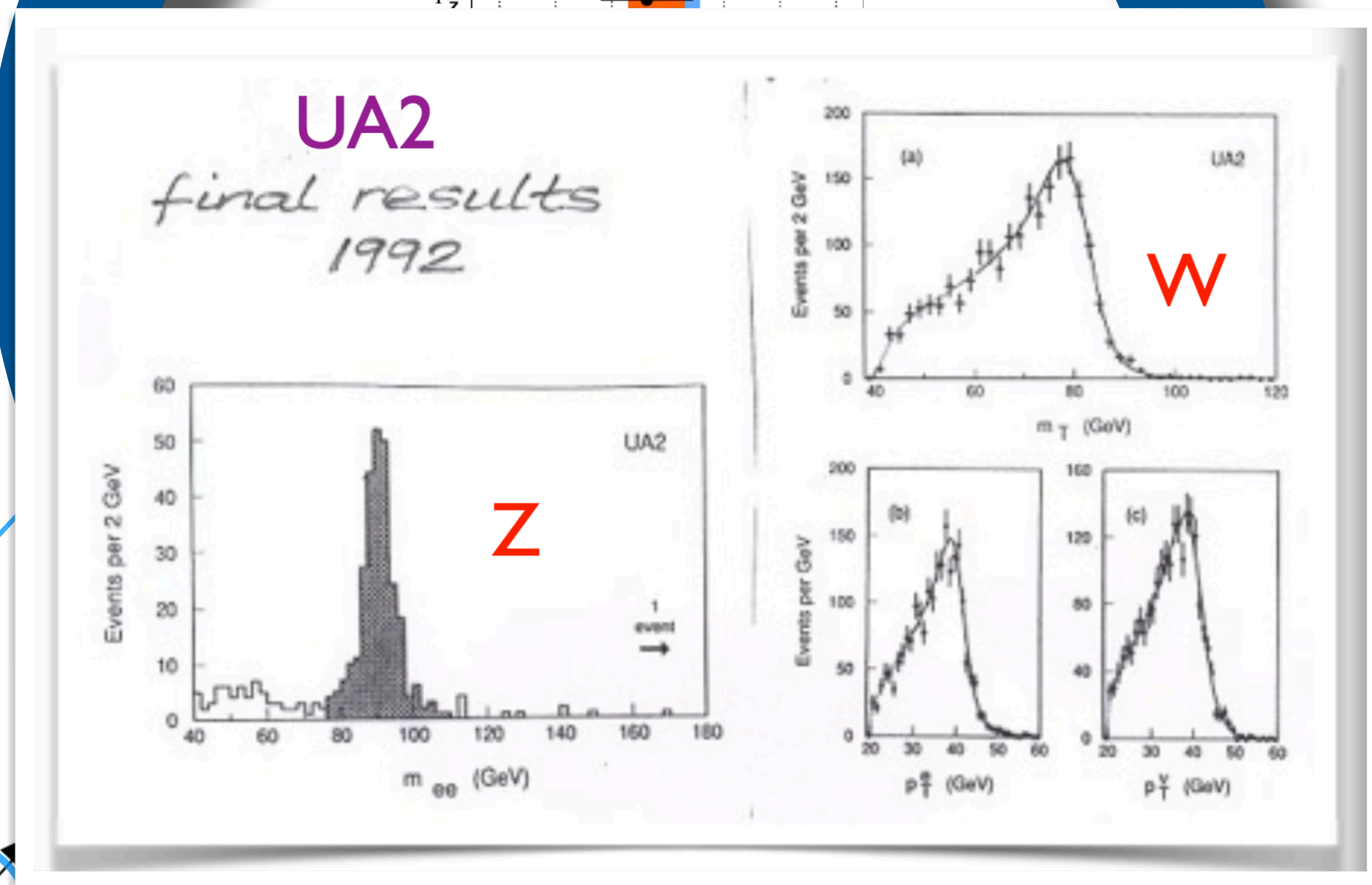


40 years after their discovery, the **W,Z bosons** are still at the heart of the LHC physics programme.

Why is this?

- ➡ W,Z properties are related to fundamental symmetries of SM theory (EWSB)
- ➡ Their relations to other particles provide some of the most powerful tests of the theory — sensitive probes of possible new physics





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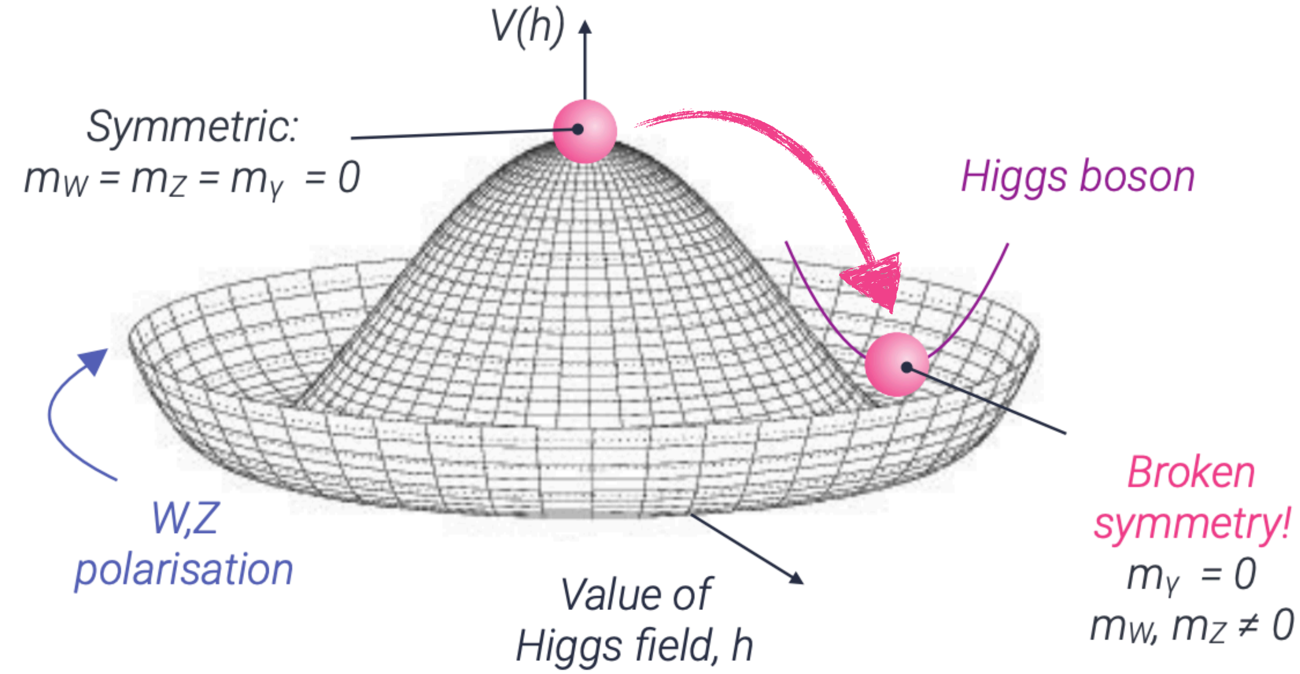

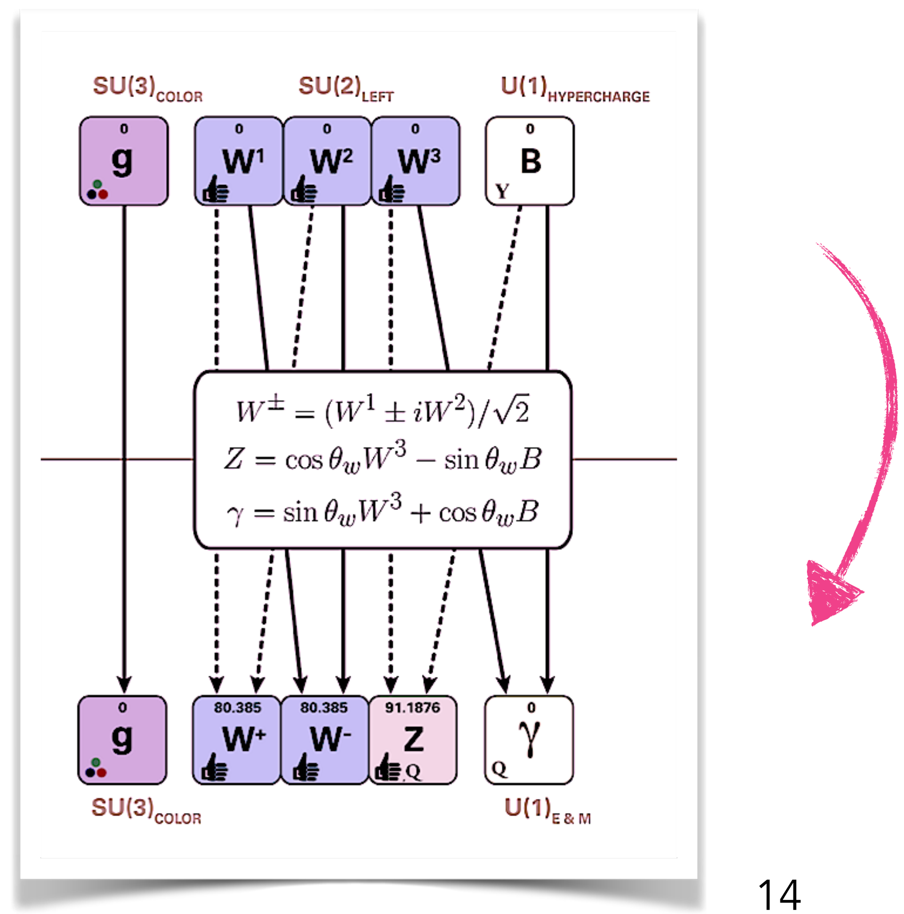

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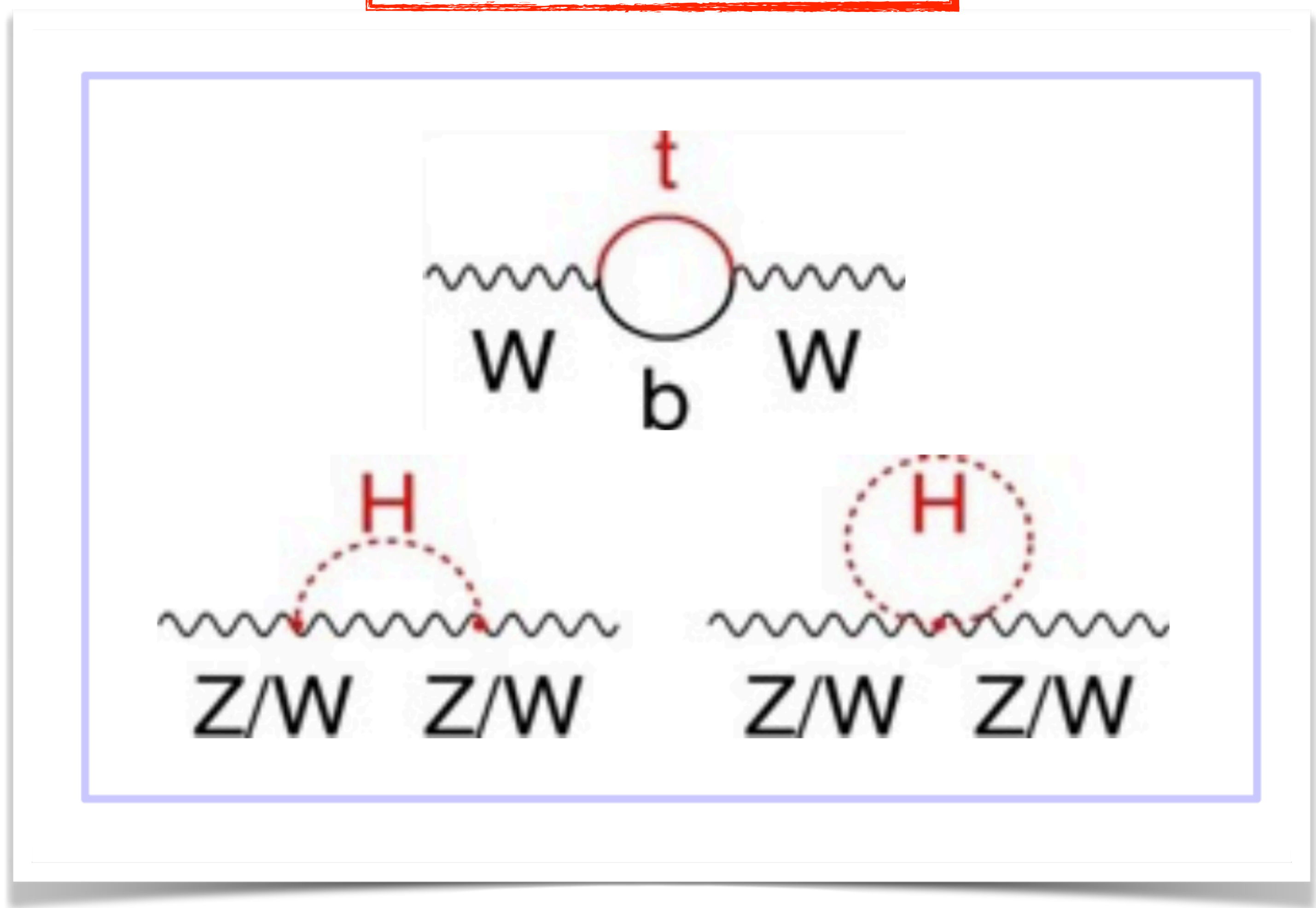
m_t, m_W, m_H related !



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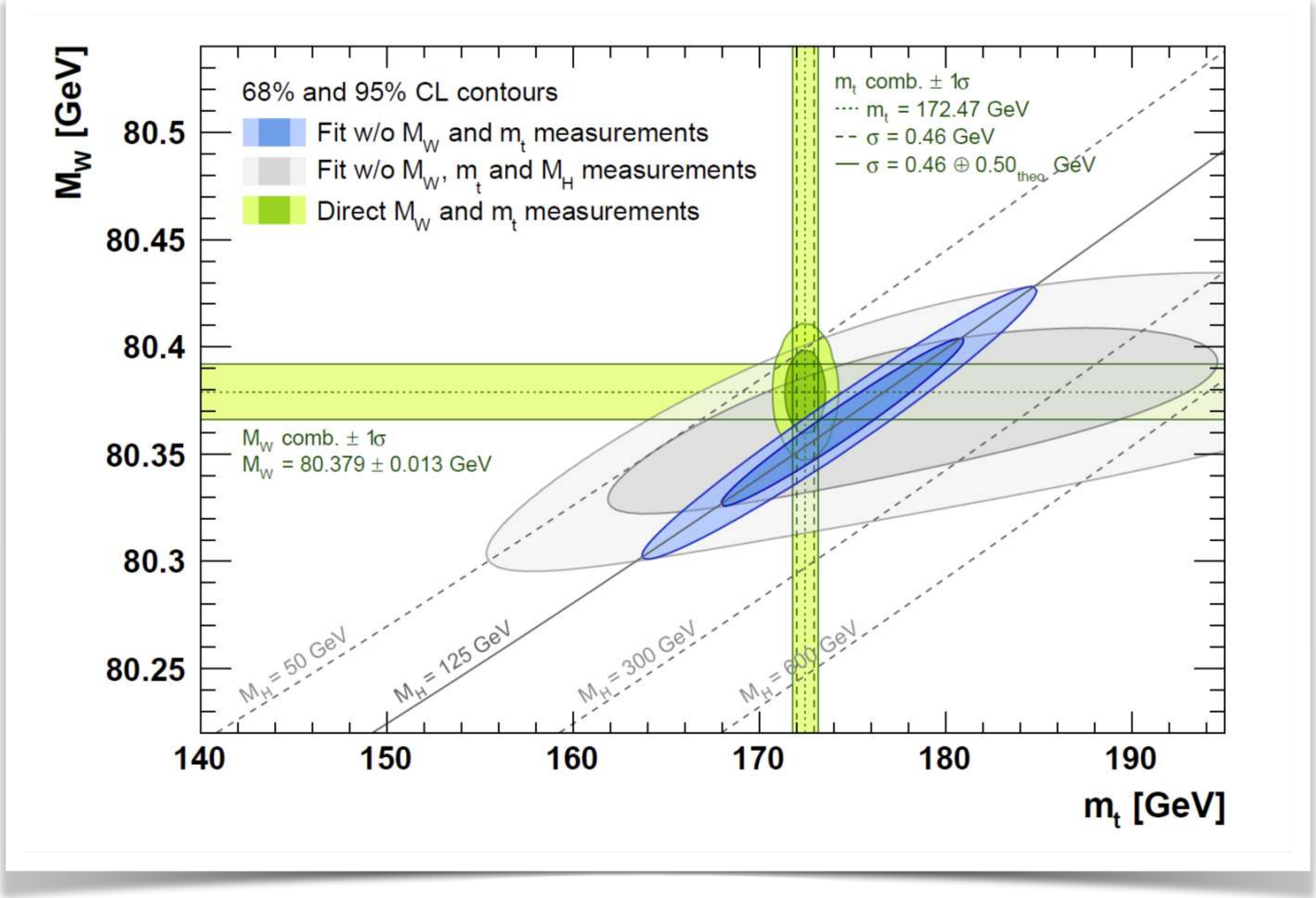
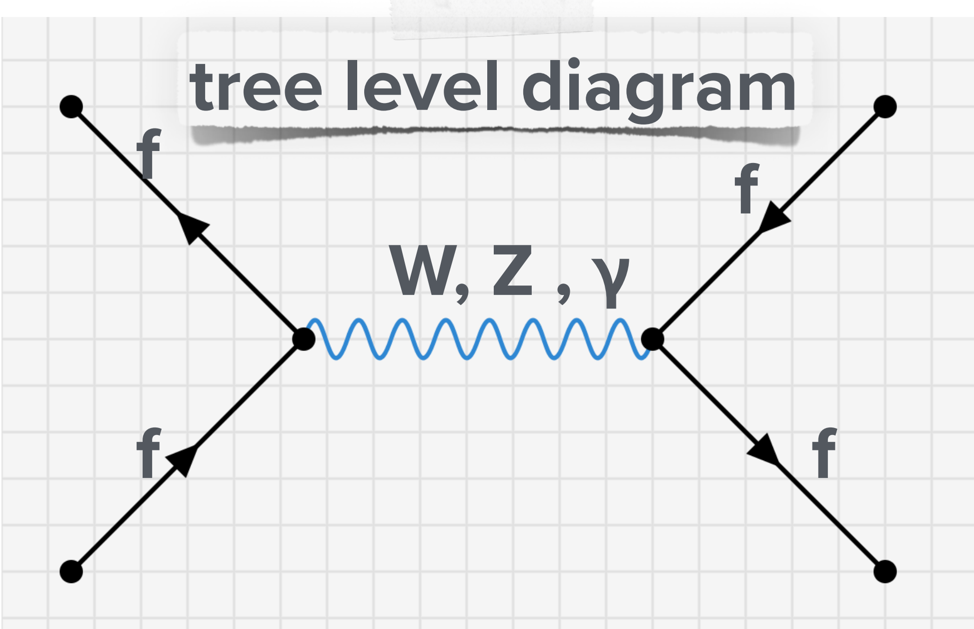


W,Z properties

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

		REL. UNC.
α	$= 1/137.035999139(31)$	$O(10^{-10})$
G_F	$= 1.1663787(6) \times 10^{-5}\ \text{GeV}^{-2}$	$O(10^{-7})$
m_Z	$= 91.1876(21)\ \text{GeV}$	$O(10^{-5})$



PROPERTIES OF THE W,Z BOSONS CAN BE EXPRESSED AS:

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

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

$$\Gamma_W = \frac{3G_F m_W^3}{2\sqrt{2}\pi}$$

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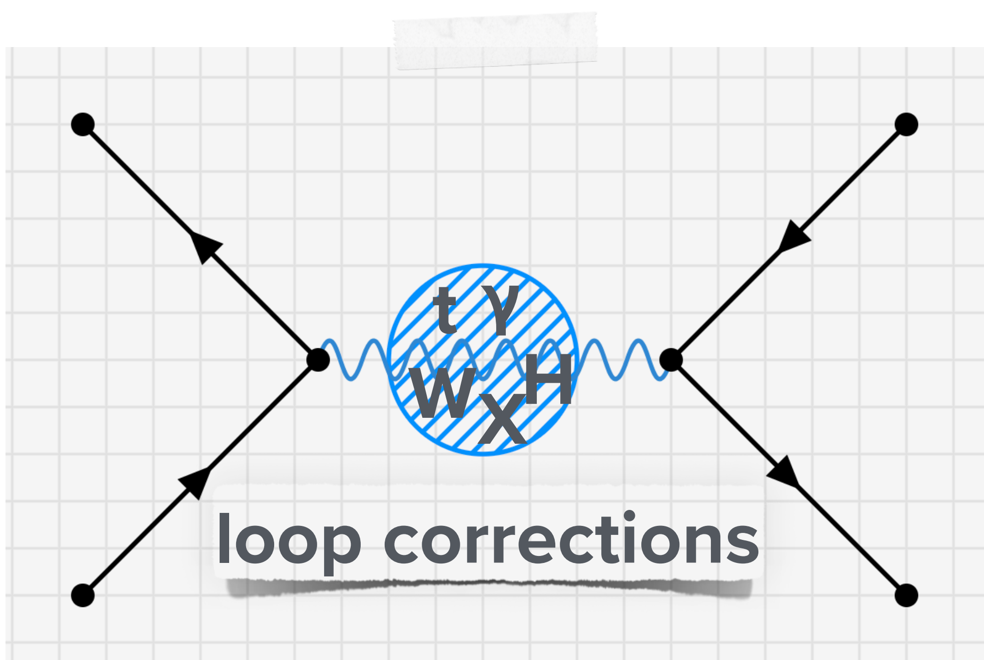
PROPERTIES OF THE W,Z BOSONS CAN BE EXPRESSED AS:

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F\,(1 - m_W^2/m_Z^2)\,(1-\Delta r)}$$

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

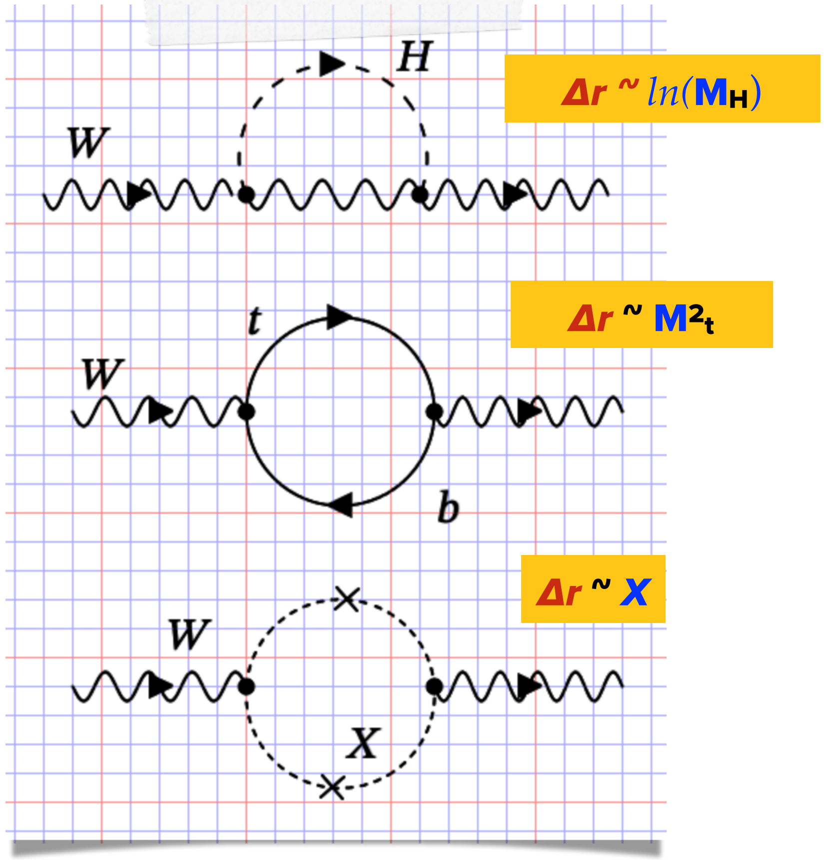
$$\Gamma_W = \frac{3G_F m_W^3}{2\sqrt{2}\pi}\rho$$



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

Loop corrections in m_W

$$= \frac{\pi\alpha}{\sqrt{2}G_F\,(1 - m_W^2/m_Z^2)\,(1 - \Delta r)}$$

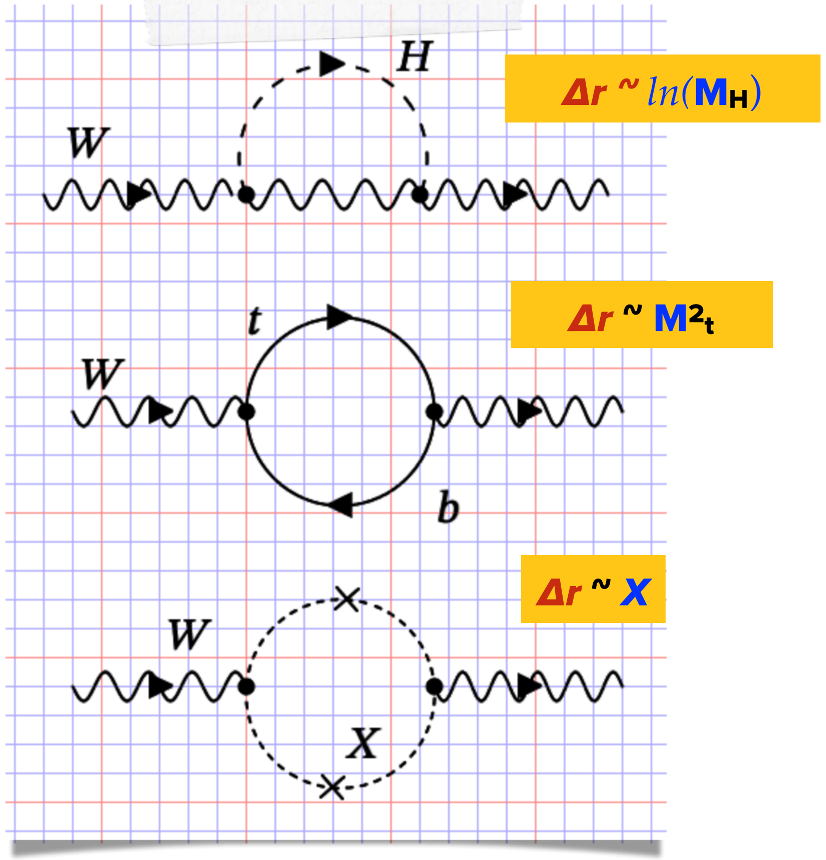


In SM, Δr correction on m_W reflects loop corrections and depends on m_t^2 and **$\ln(m_H)$ but can potentially also hide contributions from new physics**

- SM relation between m_t, m_W, m_H is the most popular way to test the predictive power of global fits in high-energy physics.
  - Historically has been used to predict m_t and put constraint on the m_H before they were discovered!

Predictivity of the SM

$$= \frac{\pi\alpha}{\sqrt{2}G_F\,(1 - m_W^2/m_Z^2)\,(1 - \Delta r)}$$



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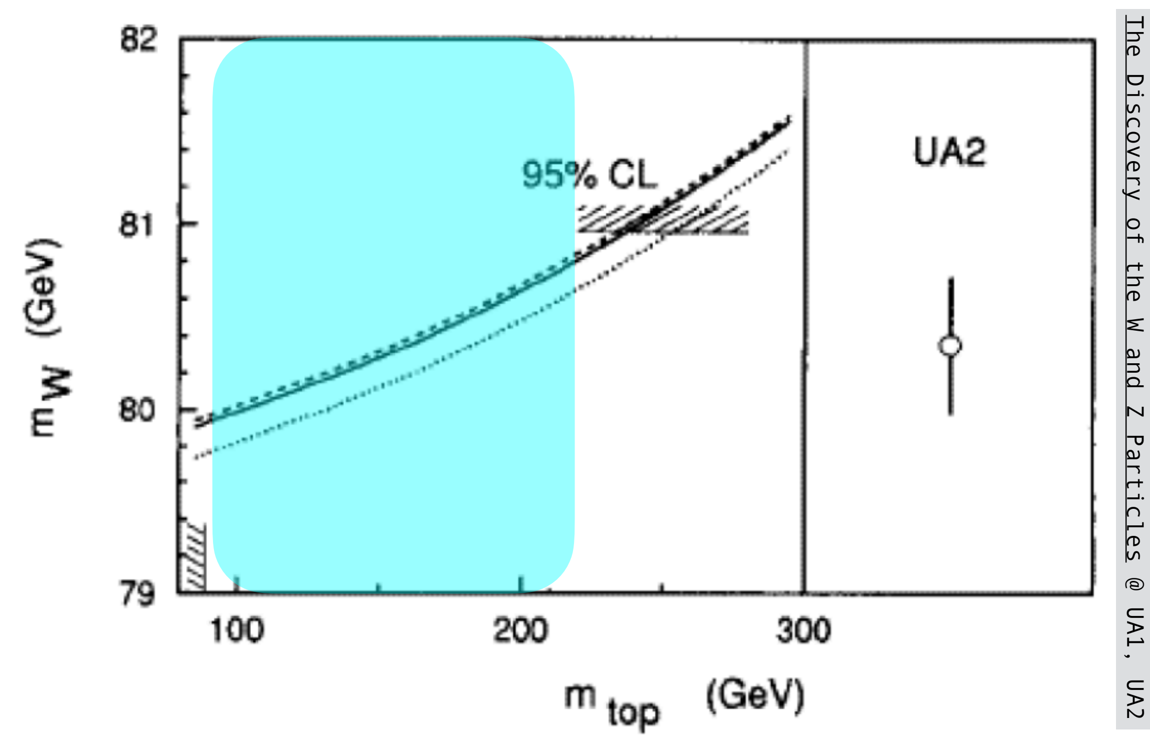
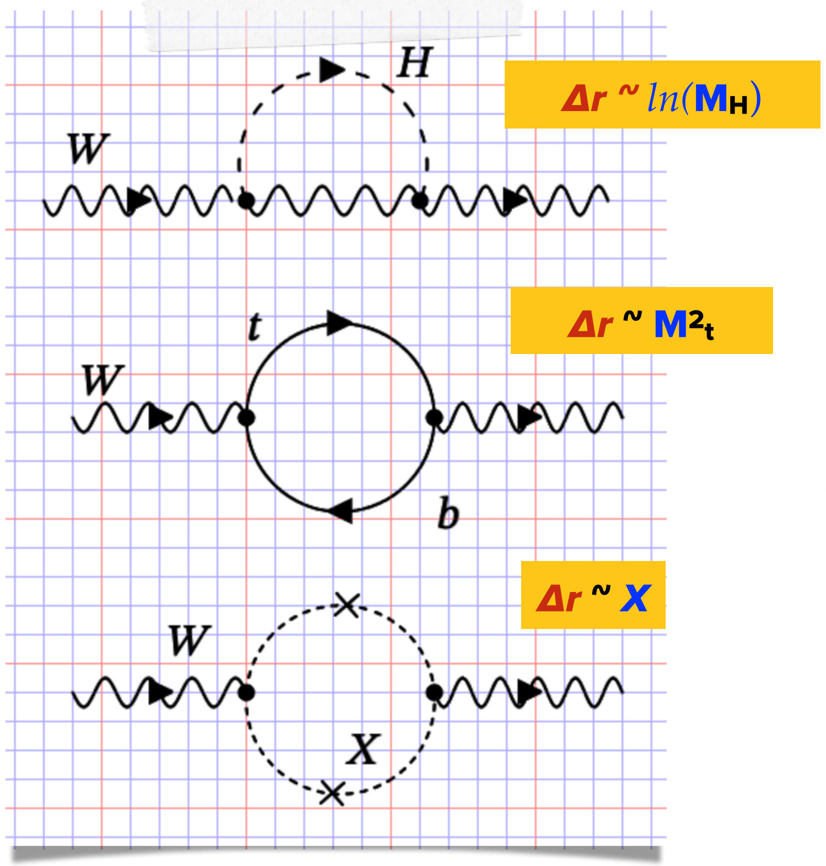


UA2 m_W measurement in 1983 Provide first stringent limits on the m_{top} 10 years before the first observation

Predictivity of the SM

$$= \frac{\pi\alpha}{\sqrt{2}G_F\,(1 - m_W^2/m_Z^2)\,(1 - \Delta r)}$$



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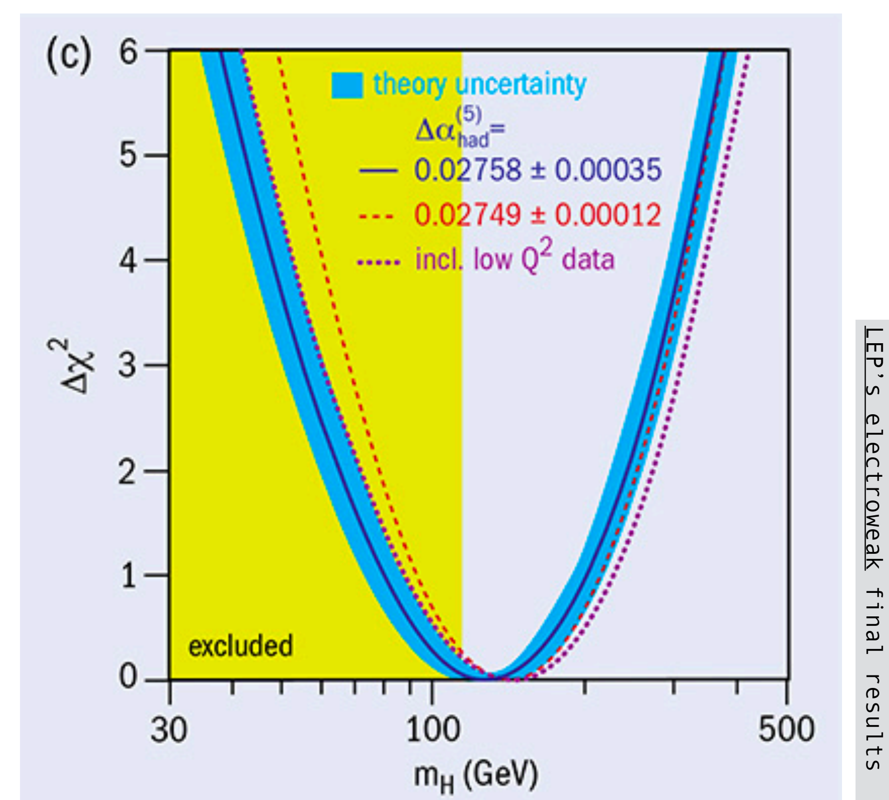
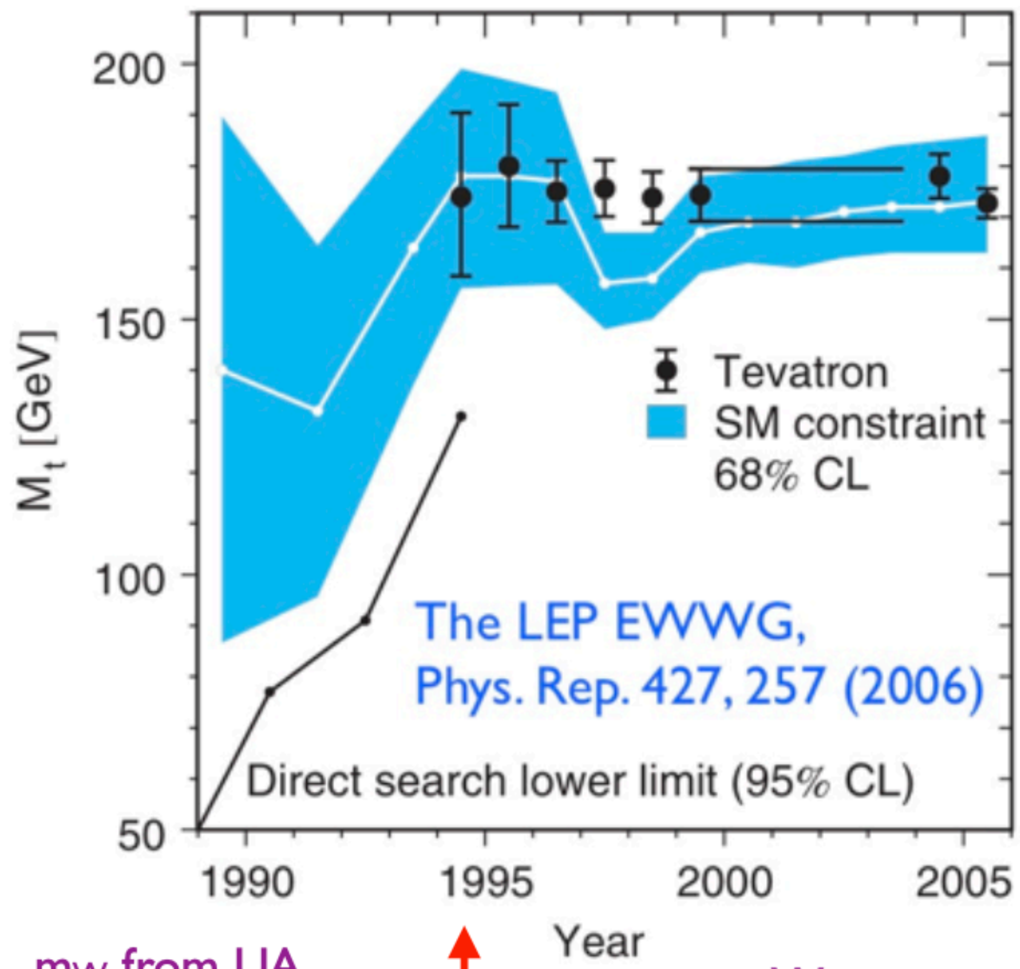


IN 2005 the legacy LEP results on m_W m_Z have been used to constrain the HIGGS boson mass (m_H) almost a decade before ITs discovery

Predictive Power of the SM early 2000

The Top Quark

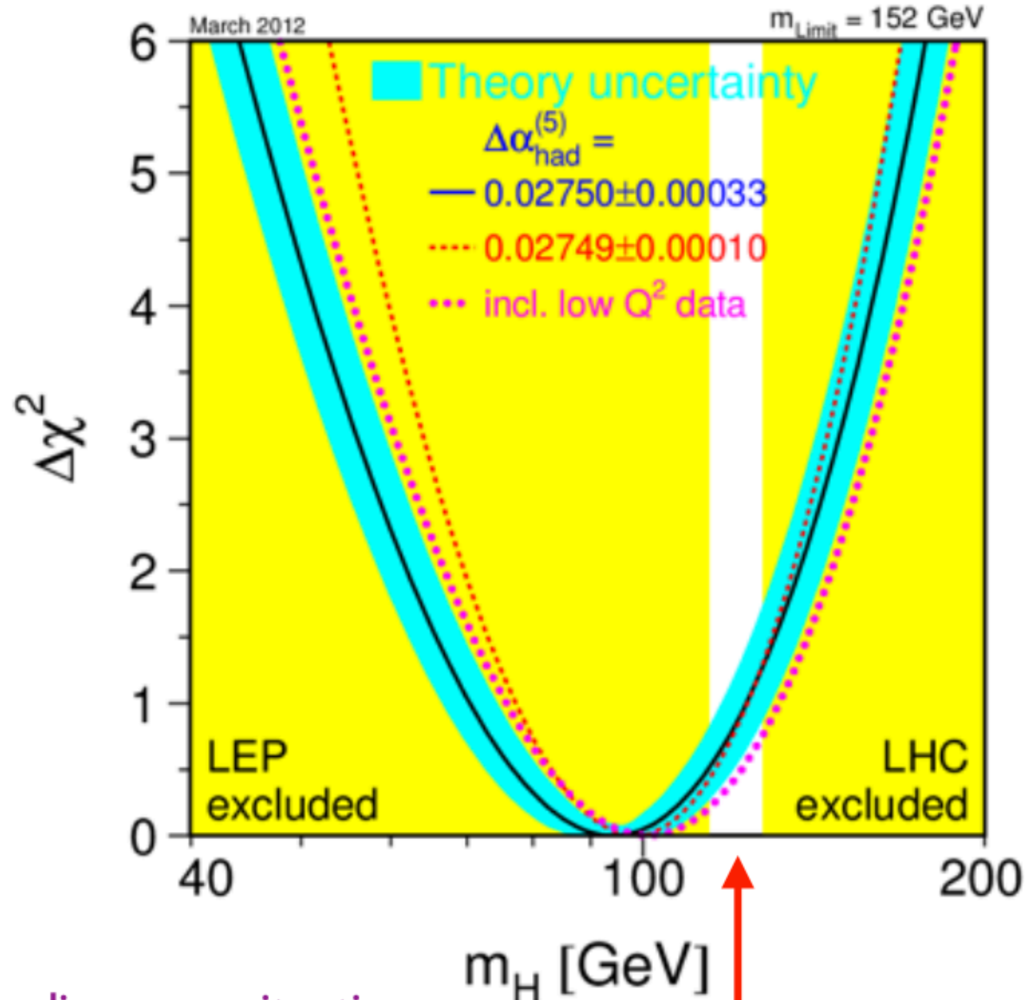


mw from UA
+ precision EW
from LEP-I

discovery
Tevatron
1994

W mass
from LEP-II

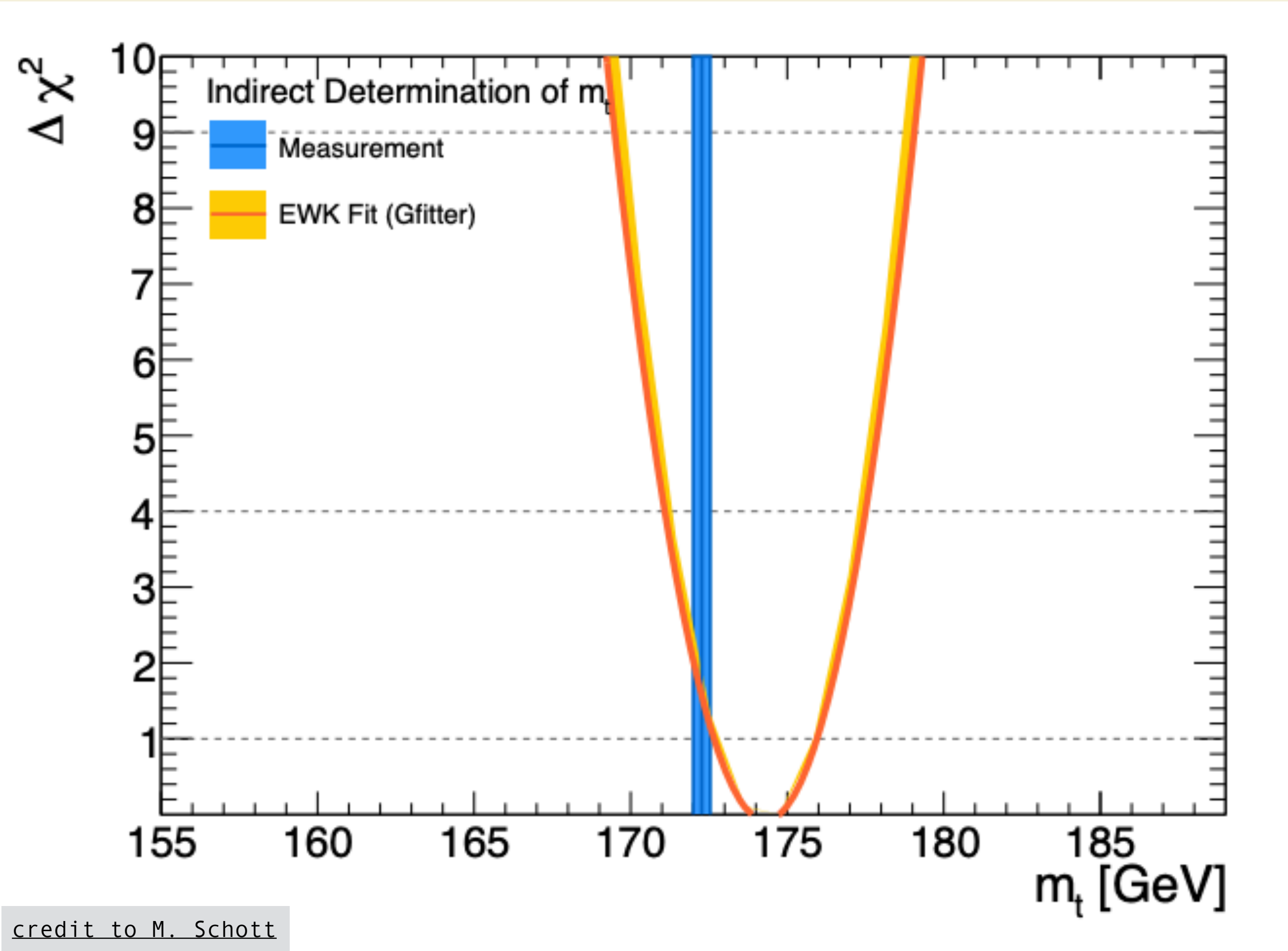
The Higgs Boson

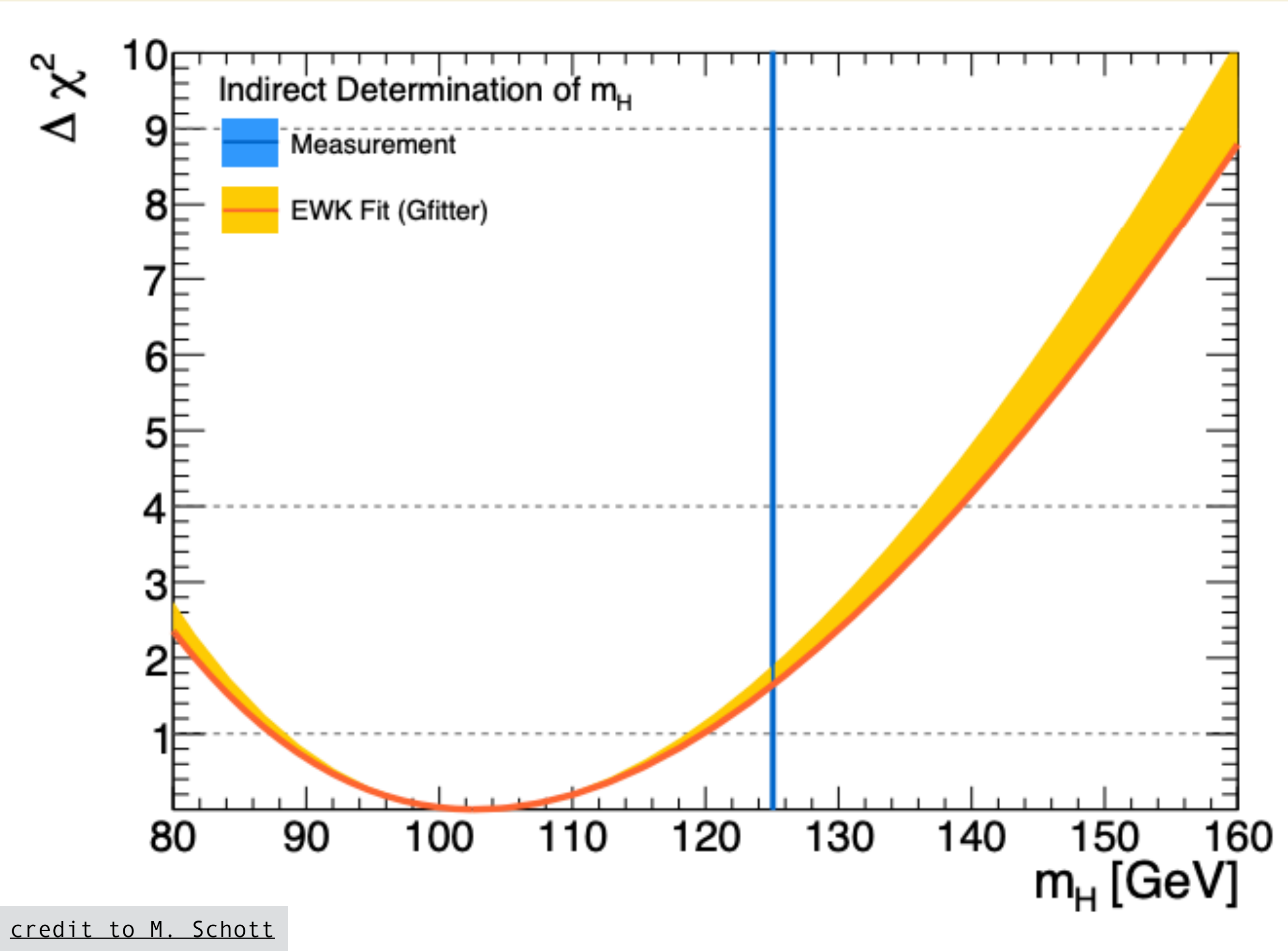


pre-discovery situation
(March 2012)

discovery LHC
2012

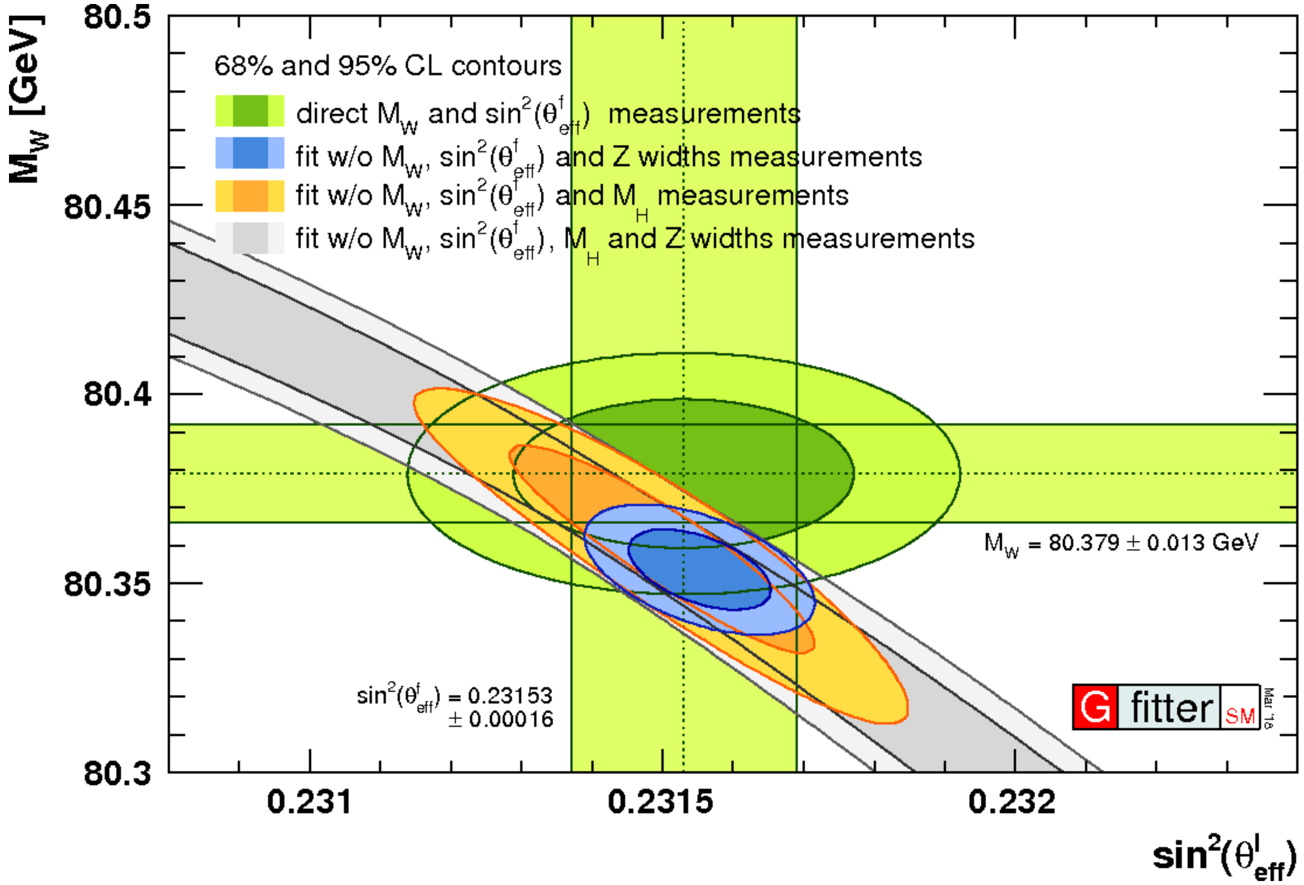
right now…





m_t and m_H are now so well-measured ($\delta m_t \sim 0.3$ GeV; $\delta m_H \sim 0.1$ GeV) that higher precision has minimal impact on the indirect determination of the others parameters

The custodial symmetry



https://arxiv.org/pdf/hep-ph/0302058

- The custodial symmetry protects this relation from large radiative corrections. All corrections to the ρ parameter are therefore proportional to terms that break the custodial symmetry (thought radiative correction)

$$\rho_0 \equiv \frac{M_W^2}{M_Z^2\,\hat{c}_Z^2\,\hat{\rho}}\,, \qquad \rho_0 = 1.00031 \pm 0.00019\,,$$

PDG , LEP legacy

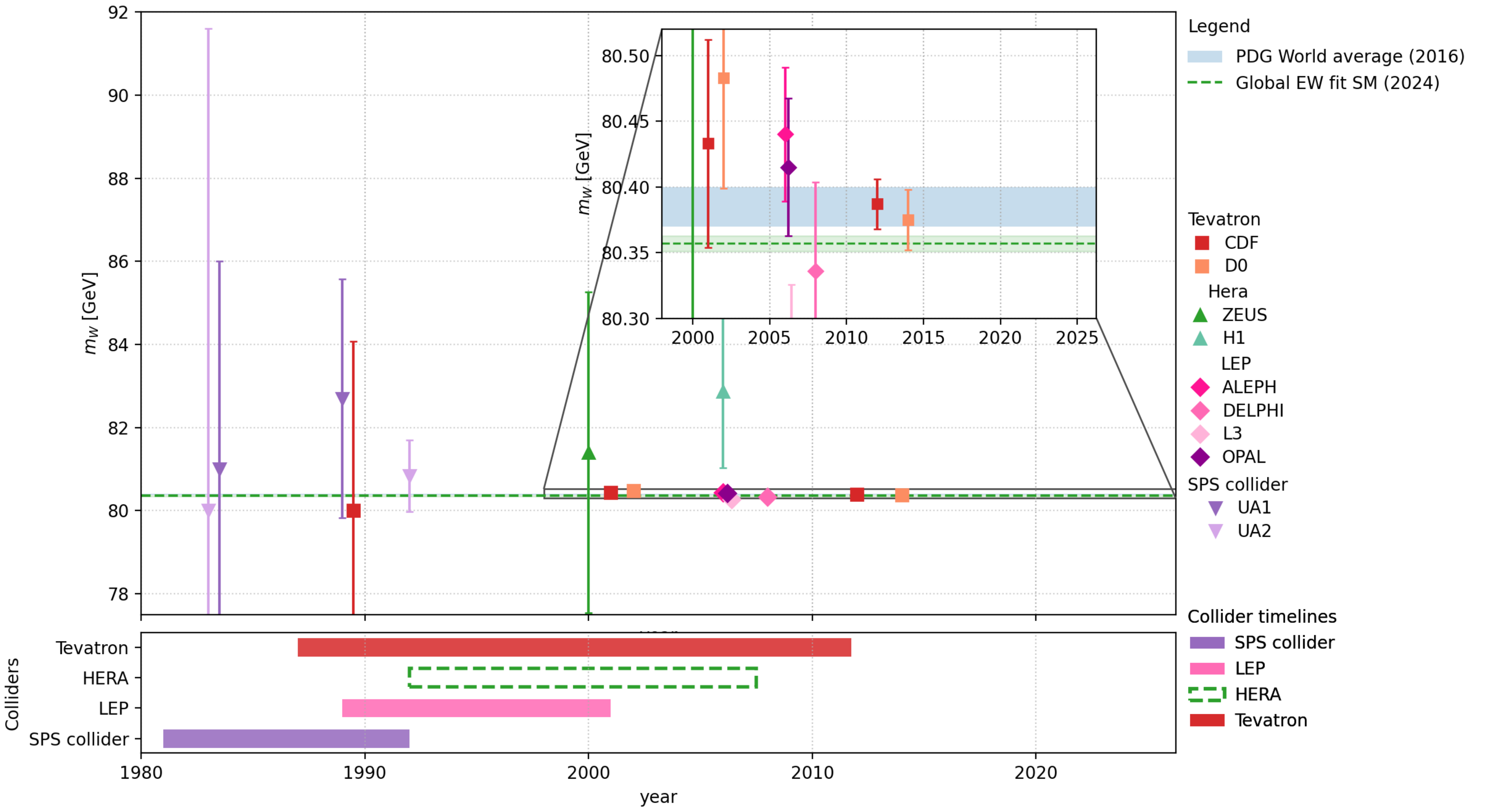
$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta} = 1.$$

ADDITIONAL SYMMETRY WHICH BOUND THE INDIRECT DETERMINATION OF M_W AND $\sin^2\theta_W$
➠ EW FIT DETERMINATION OF M_W AND $\sin^2\theta_W$ MORE PRECISE THAN THE EXPERIMENTAL MEASUREMENT

45 years of measurement

This is not the case for the W-boson mass

Situation of m_W measurements 10 years ago



(*) arXiv:1608.01509

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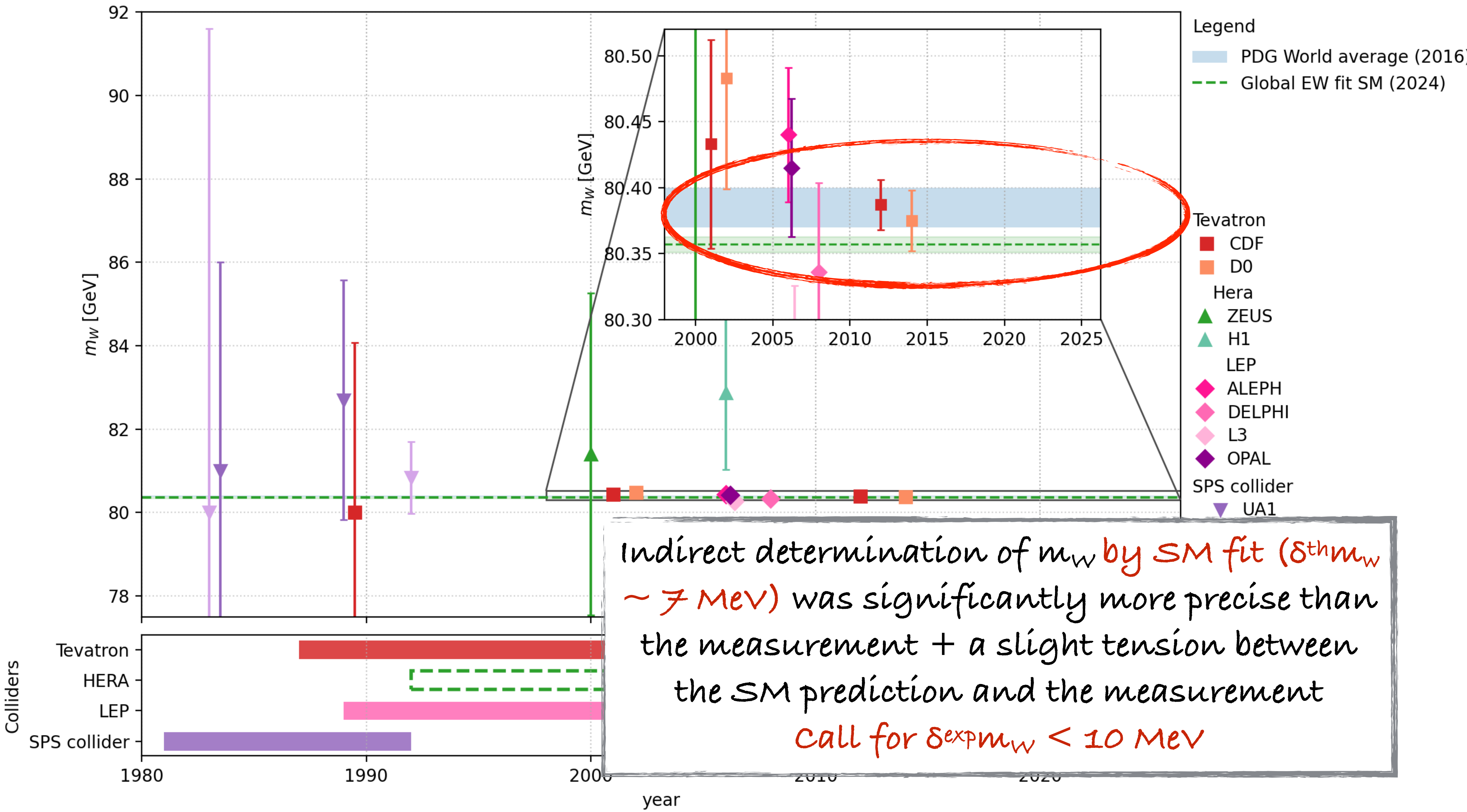

Indirect determination of m_W by SM fit ($\delta^{th} m_W \sim 7$ MeV) was significantly more precise than the measurement + a slight tension between the SM prediction and the measurement

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

45 years of measurement


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Life and Physics
Physics

This article is more than 8 years old

From gravity to the Higgs we're still waiting for new physics

Annual physics jamboree Rencontres de Moriond has a history of revealing exciting results from colliders, and this year new theories and evidence abound

Ben Allanach
Fri 24 Mar 2017 14.11 CET

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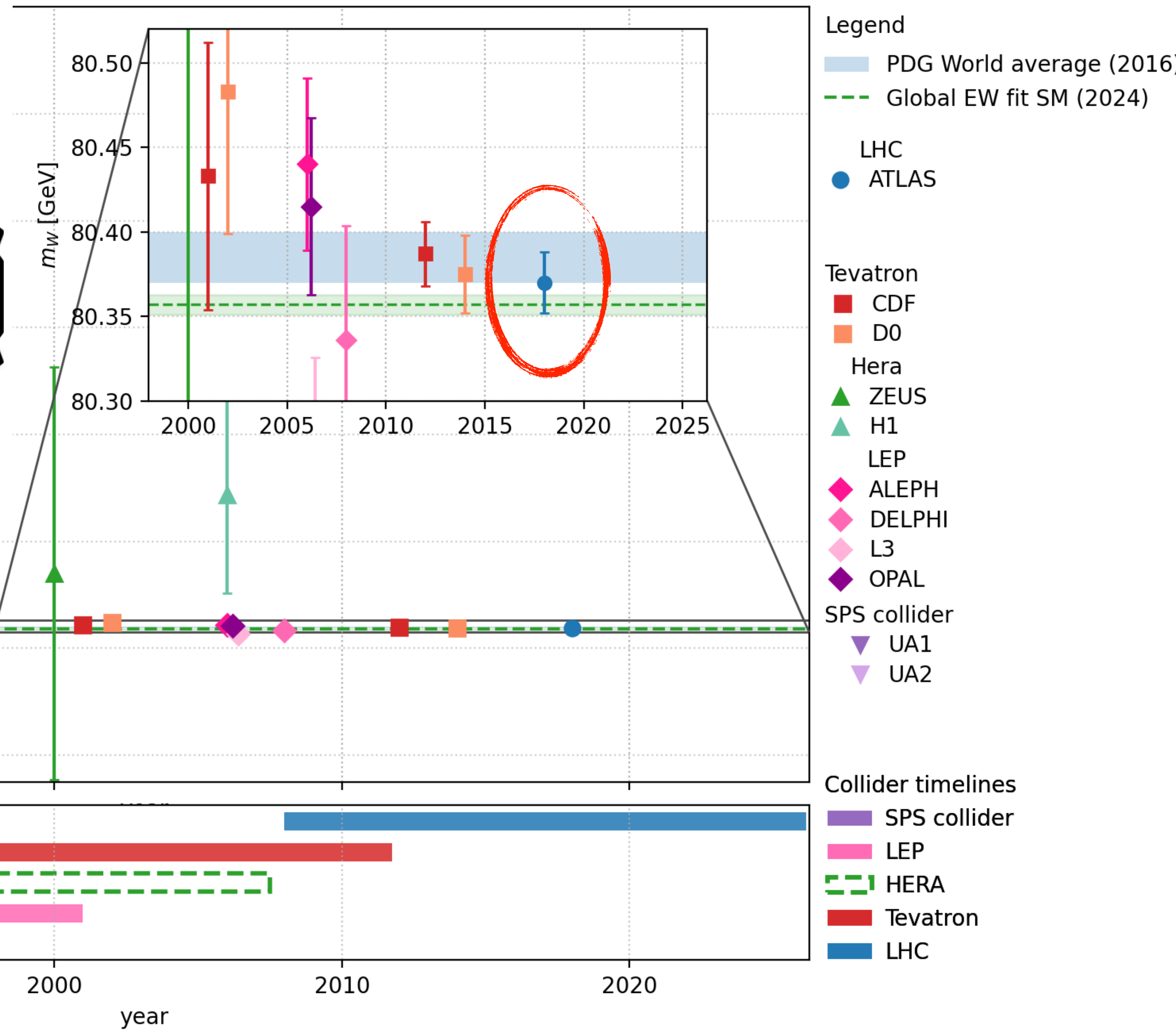
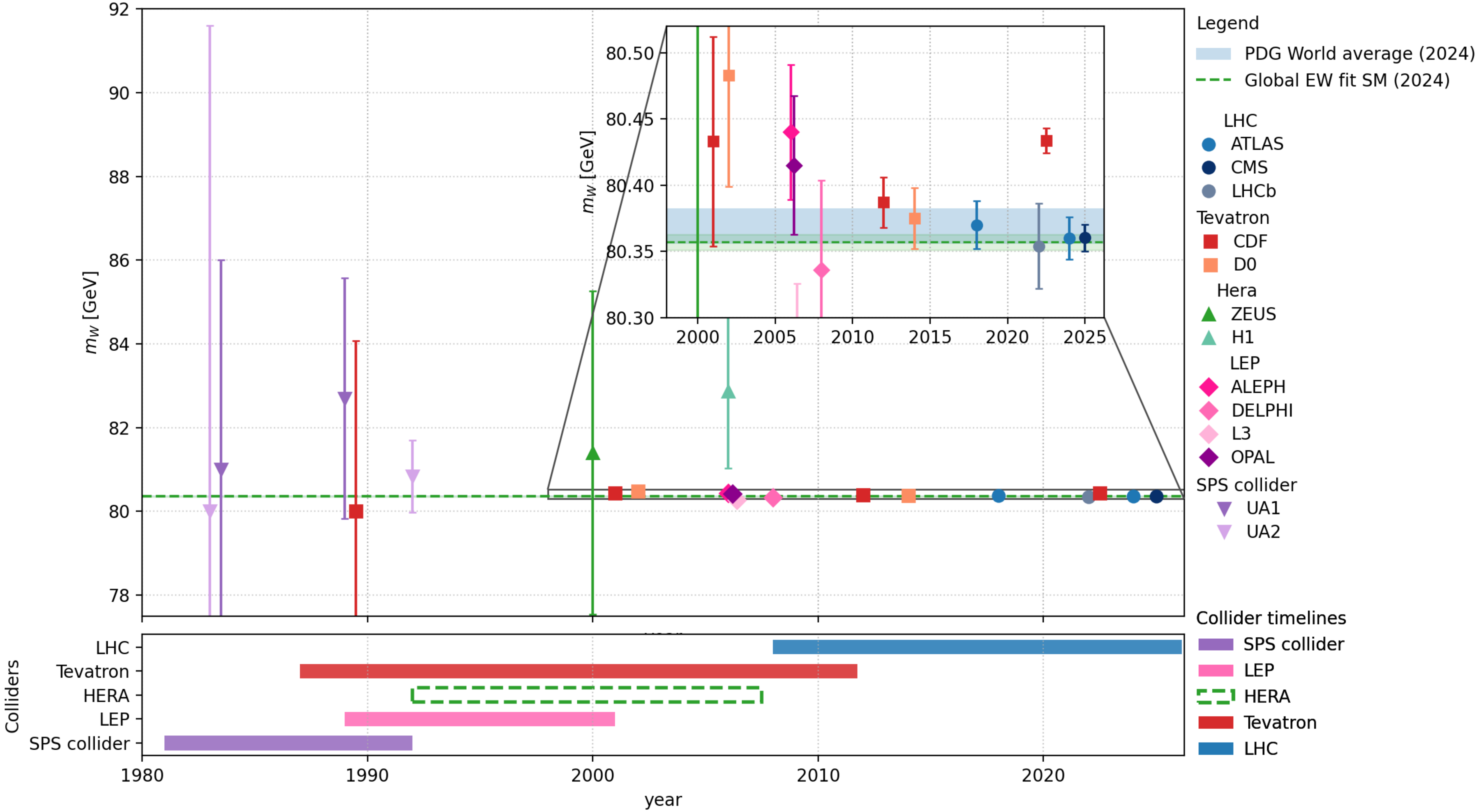
A new theoretical idea getting quite a bit of attention is A Clockwork Theory, invented by

March 2017



~~Much~~ better predicted then measured

Situation of m_W measurements today



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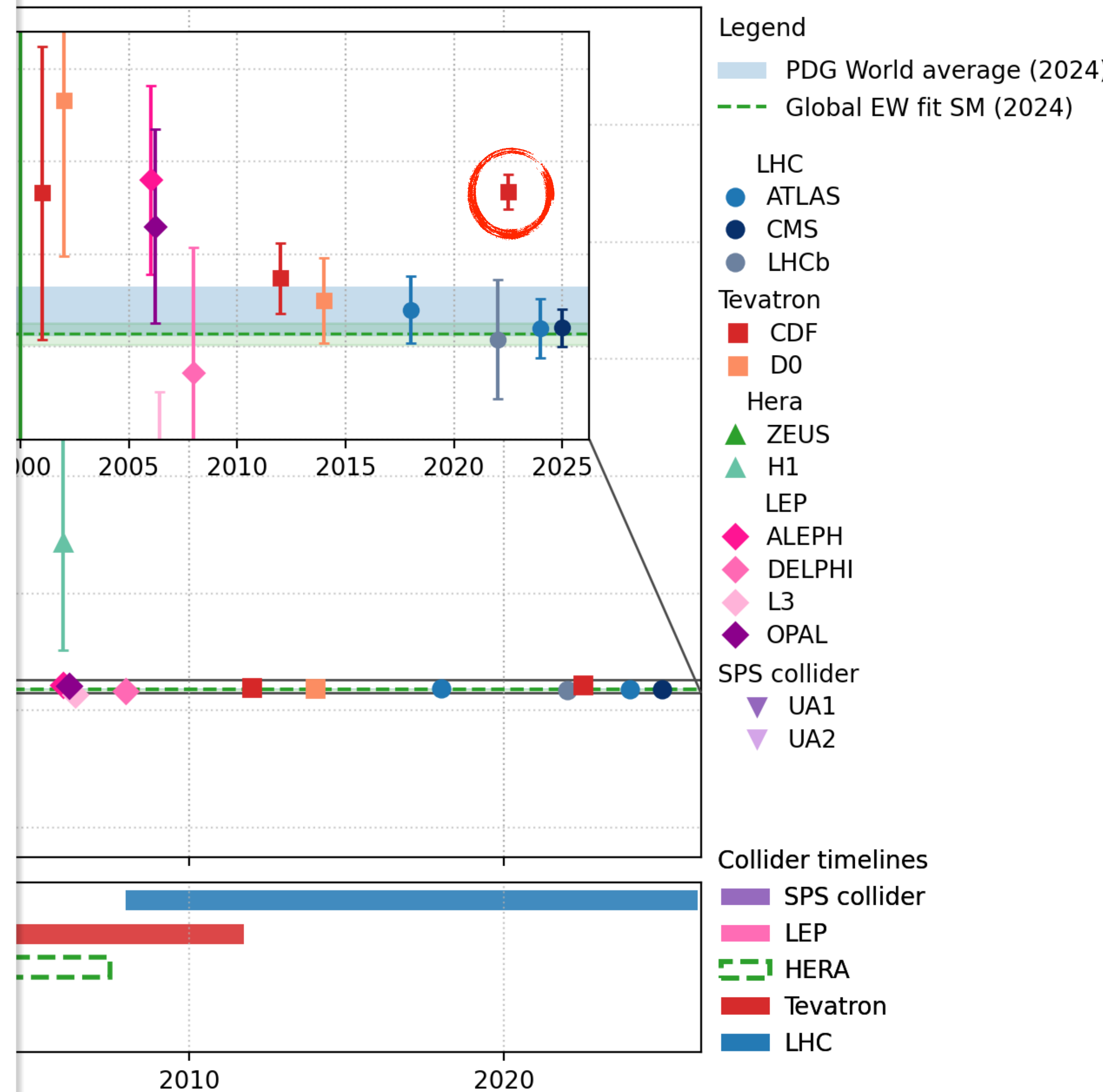


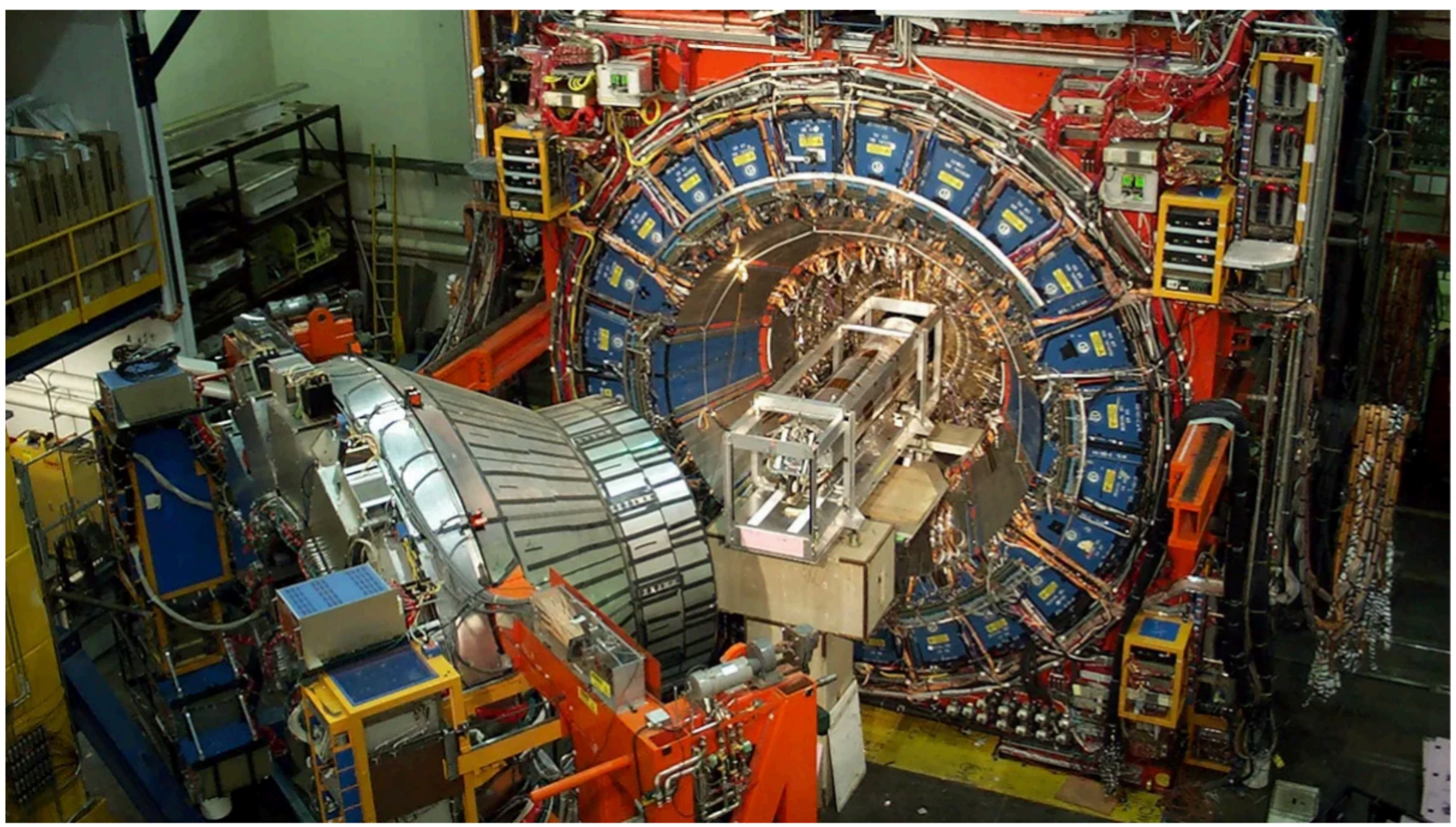
n measured

Science > Particle Physics

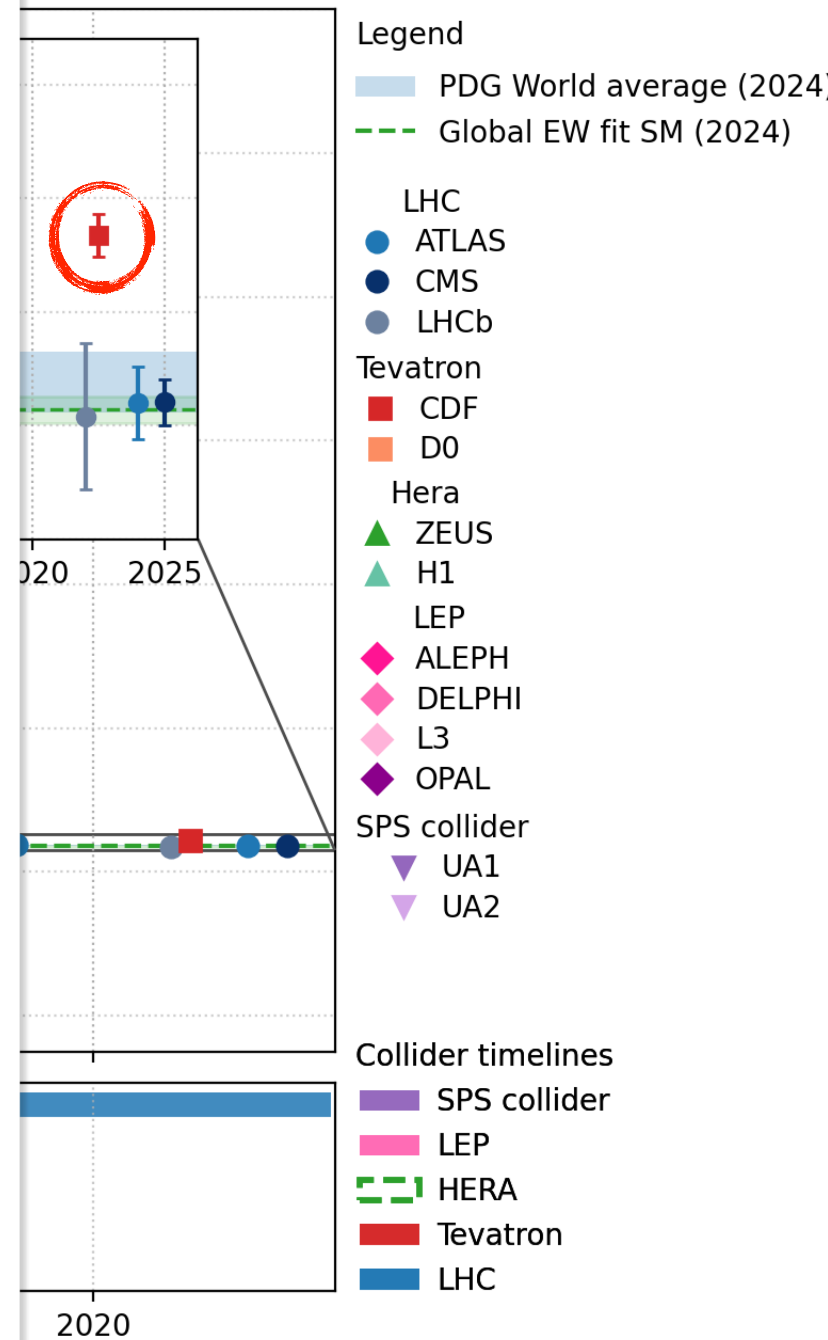
Surprise W boson measurement could rewrite particle physics

News By Tereza Pultarova published April 8, 2022

A subatomic particle called the W boson may be heavier than expected, a surprising finding that might lead to a shake-up of physics' grand model of how the world works on the microscale.



Physicists used the Tevatron collider at Fermilab to estimate the mass of the W boson. (Image credit: Fermilab)



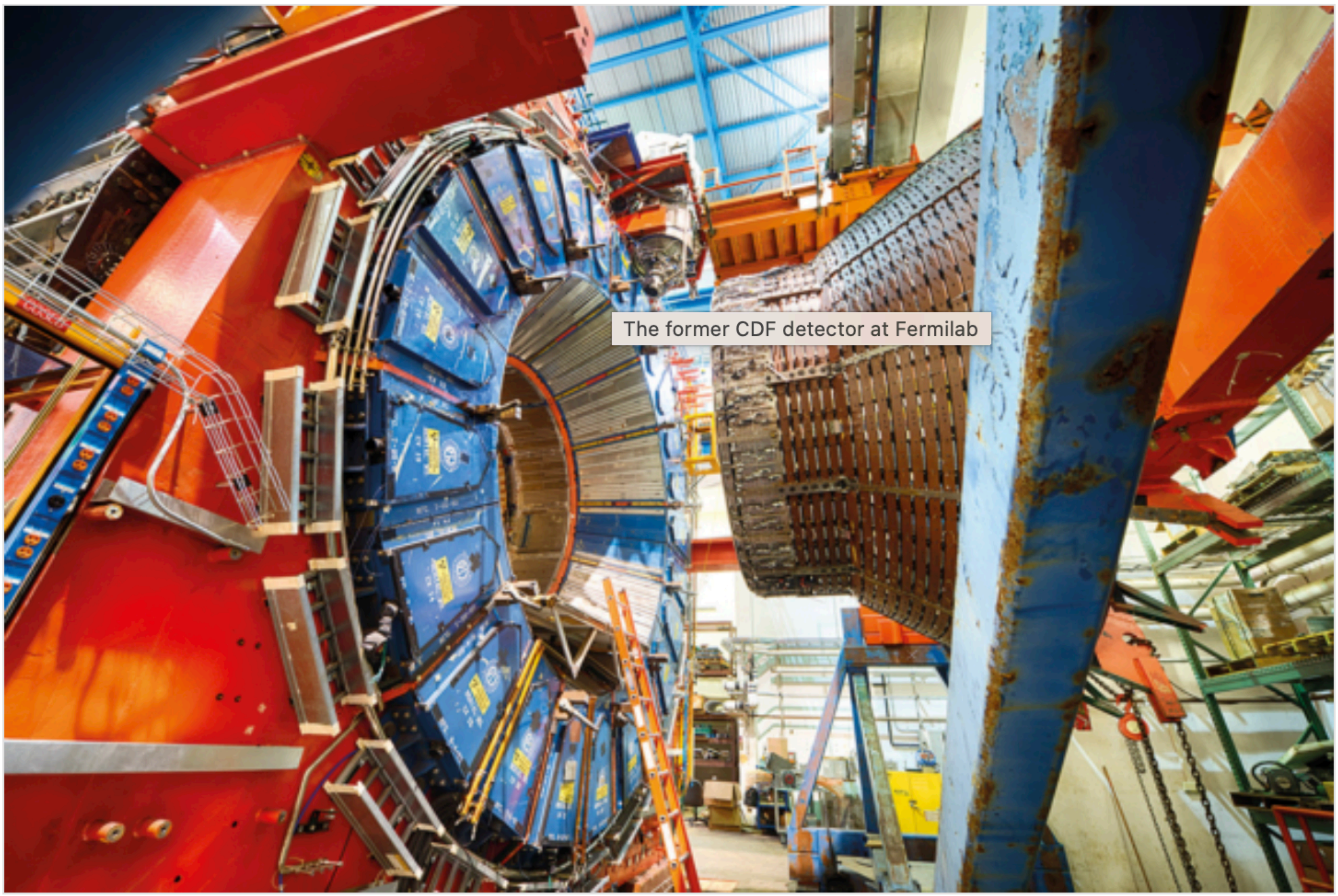
measured

HIGGS AND ELECTROWEAK | FEATURE

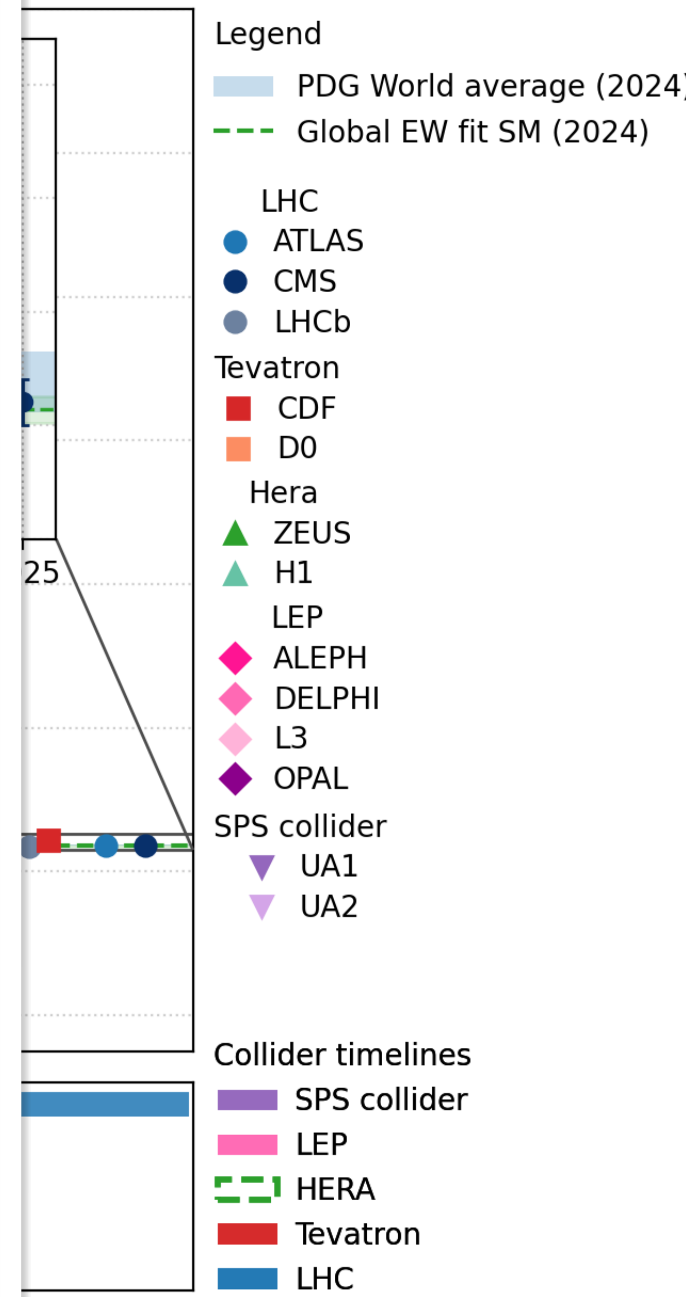
The W boson's midlife crisis

24 August 2023

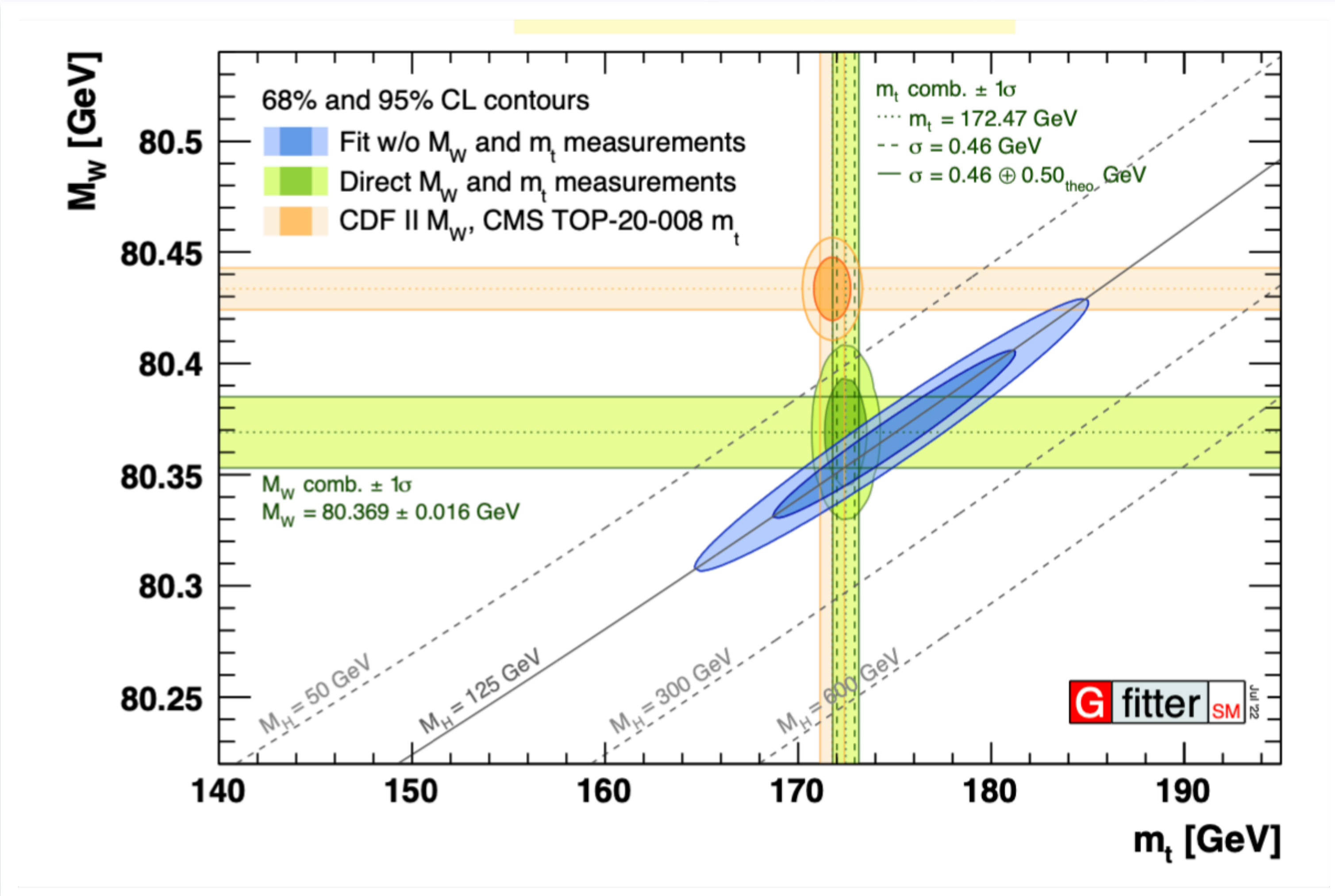
Forty years after its discovery, the W boson continues to intrigue. Chris Hays describes recent progress in understanding a surprisingly high measurement of its mass using data from the former CDF experiment.

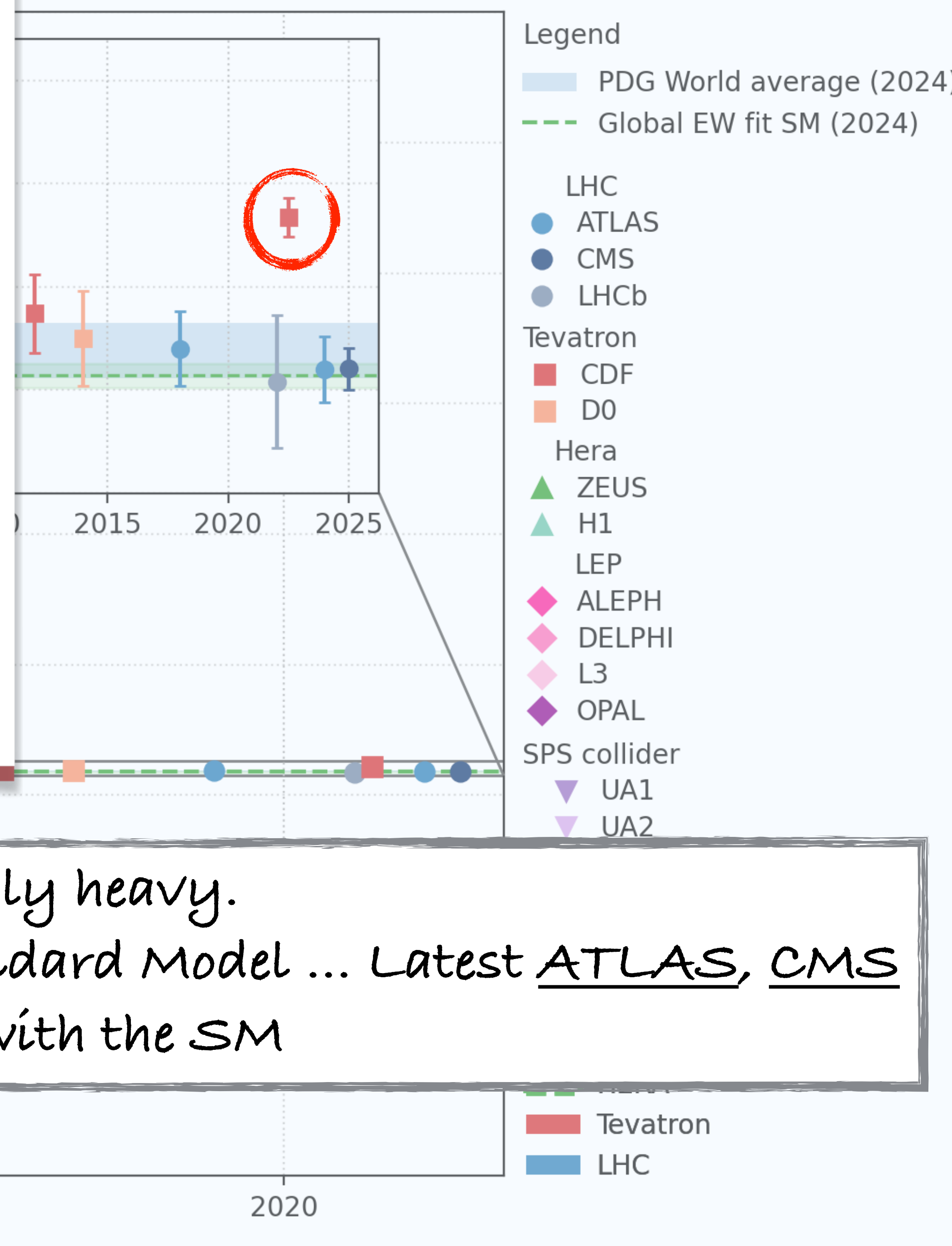


Massive The former CDF detector at Fermilab, data from which point towards an unexpectedly high value of the



Midlife crisis





Ultra-precise, surprisingly heavy.
The CDF m_W result stands in tension with the Standard Model … Latest ATLAS, CMS results restore agreement with the SM

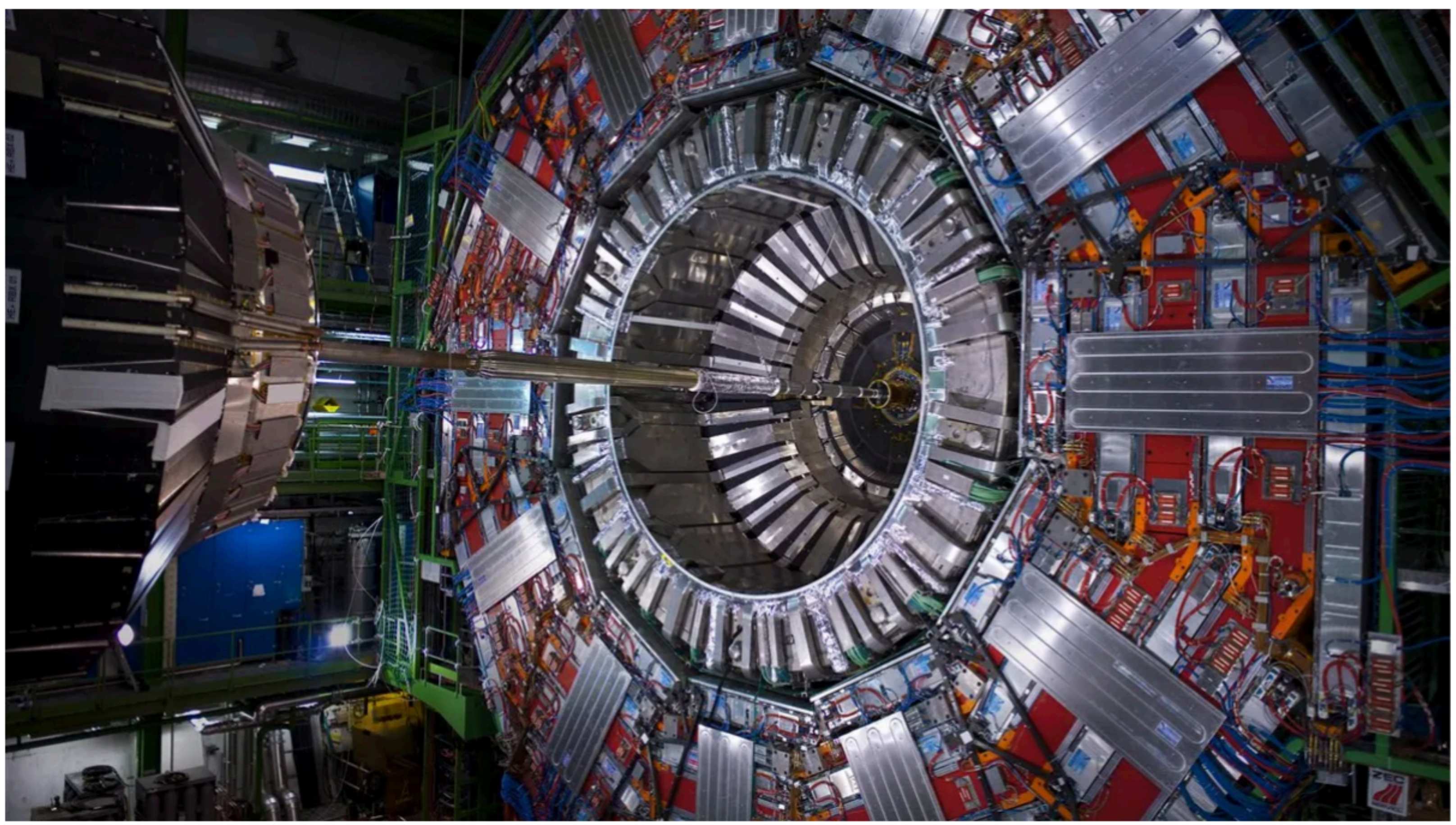
n measured

Science > Particle Physics

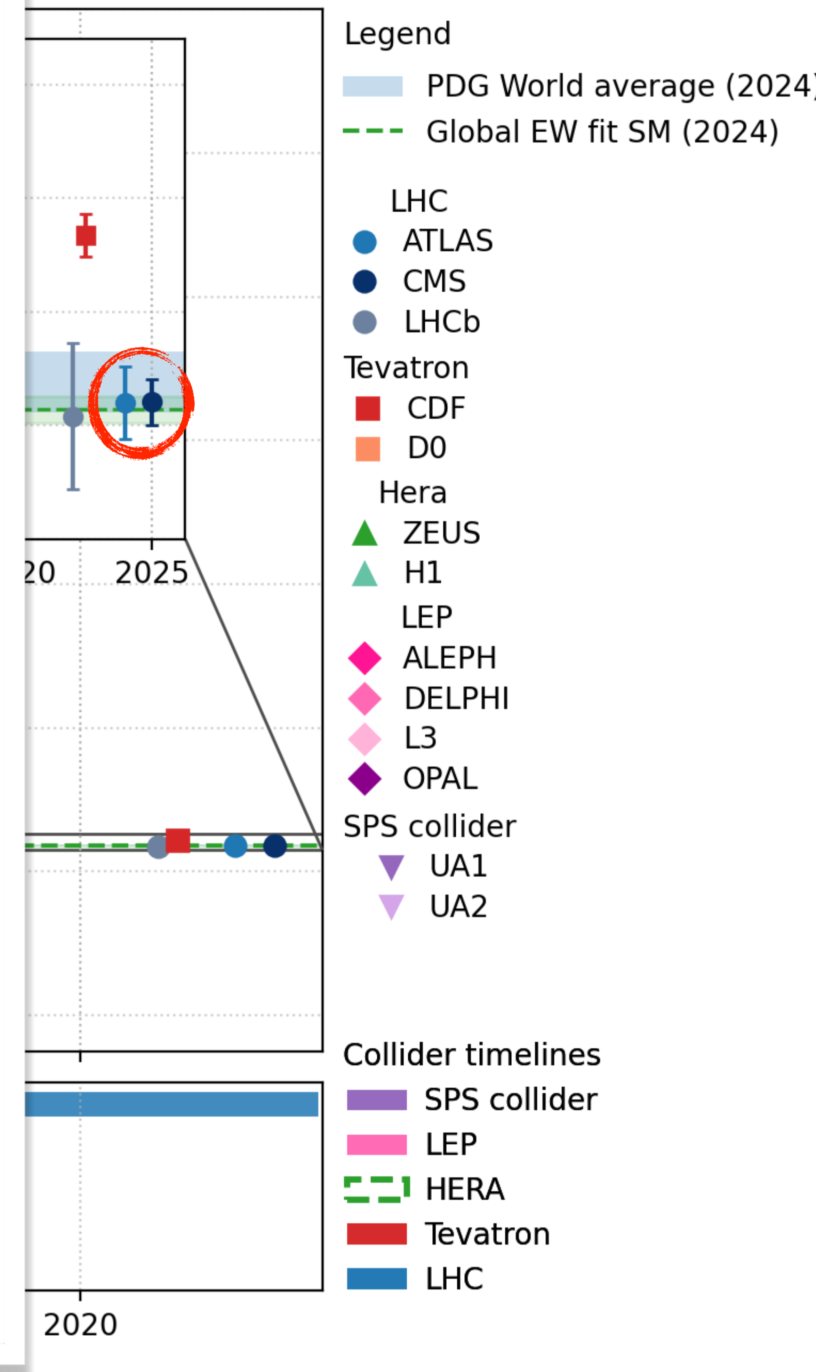
The W boson caused a particle mystery — but scientists have cracked the case

News By Keith Cooper published September 26, 2024

Large Hadron Collider has ended W boson fever. "We have to search for new physics elsewhere," one researcher says.



The giant Compact Muon Solenoid experiment at the LHC. The different rings of detectors, arranged a bit like an onion, measure different particles. (Image credit: CERN/Maximilien Brice)

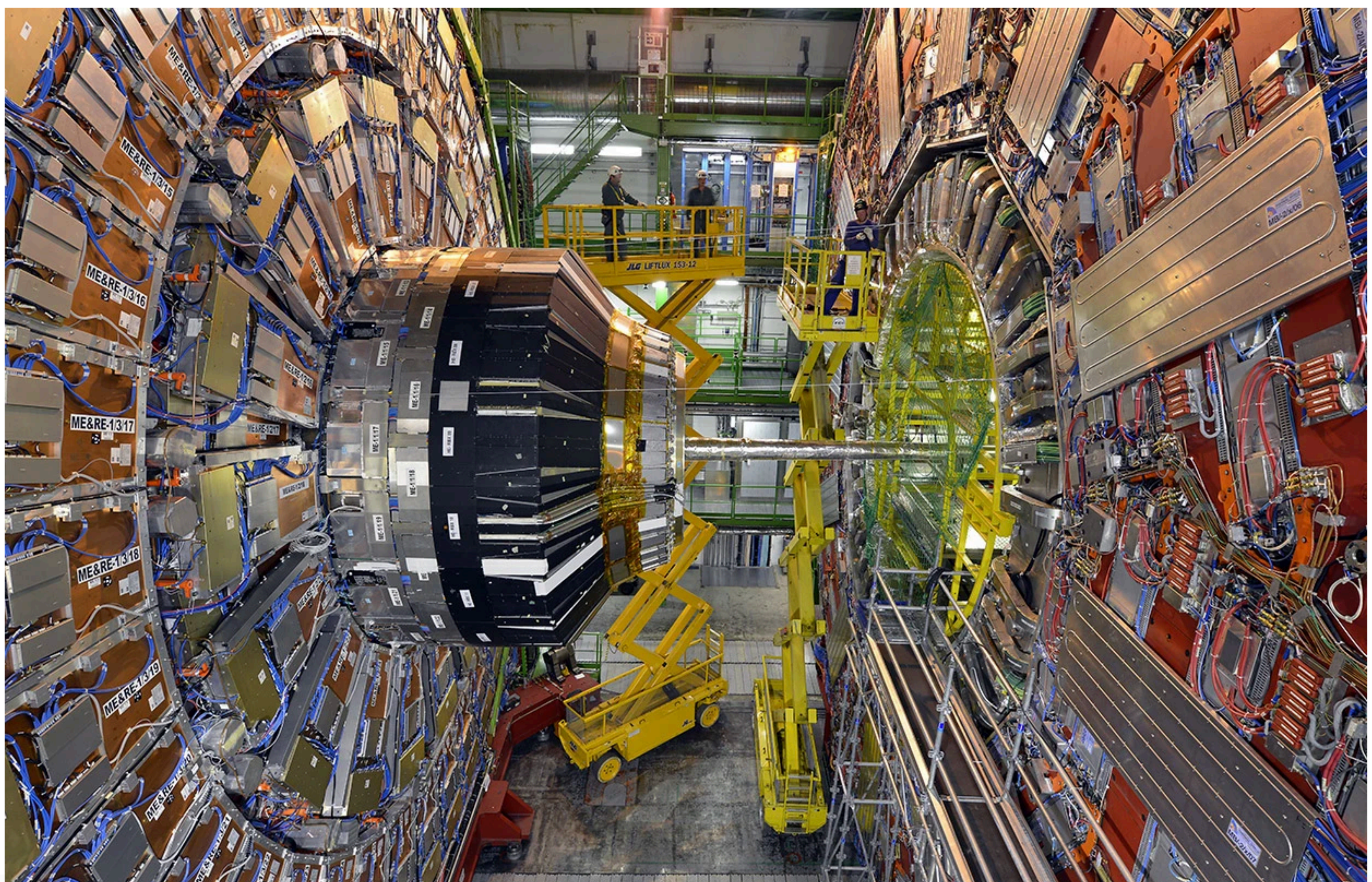


NEWS | 17 September 2024

‘The standard model is not dead’: ultra-precise particle measurement thrills physicists

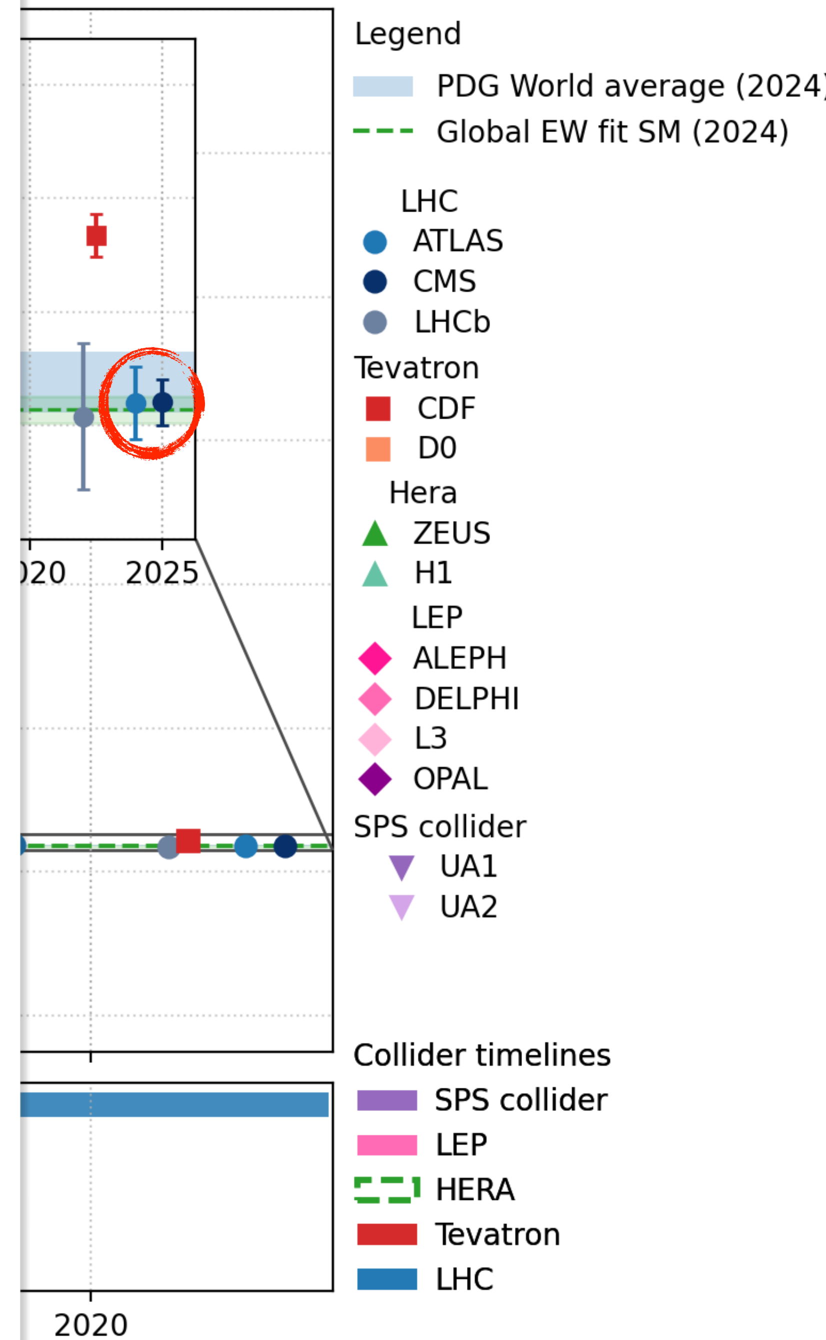
CERN’s calculation of the *W* boson’s mass agrees with theory, contradicting a previous anomaly that had raised the possibility of new physics.

By Elizabeth Gibney

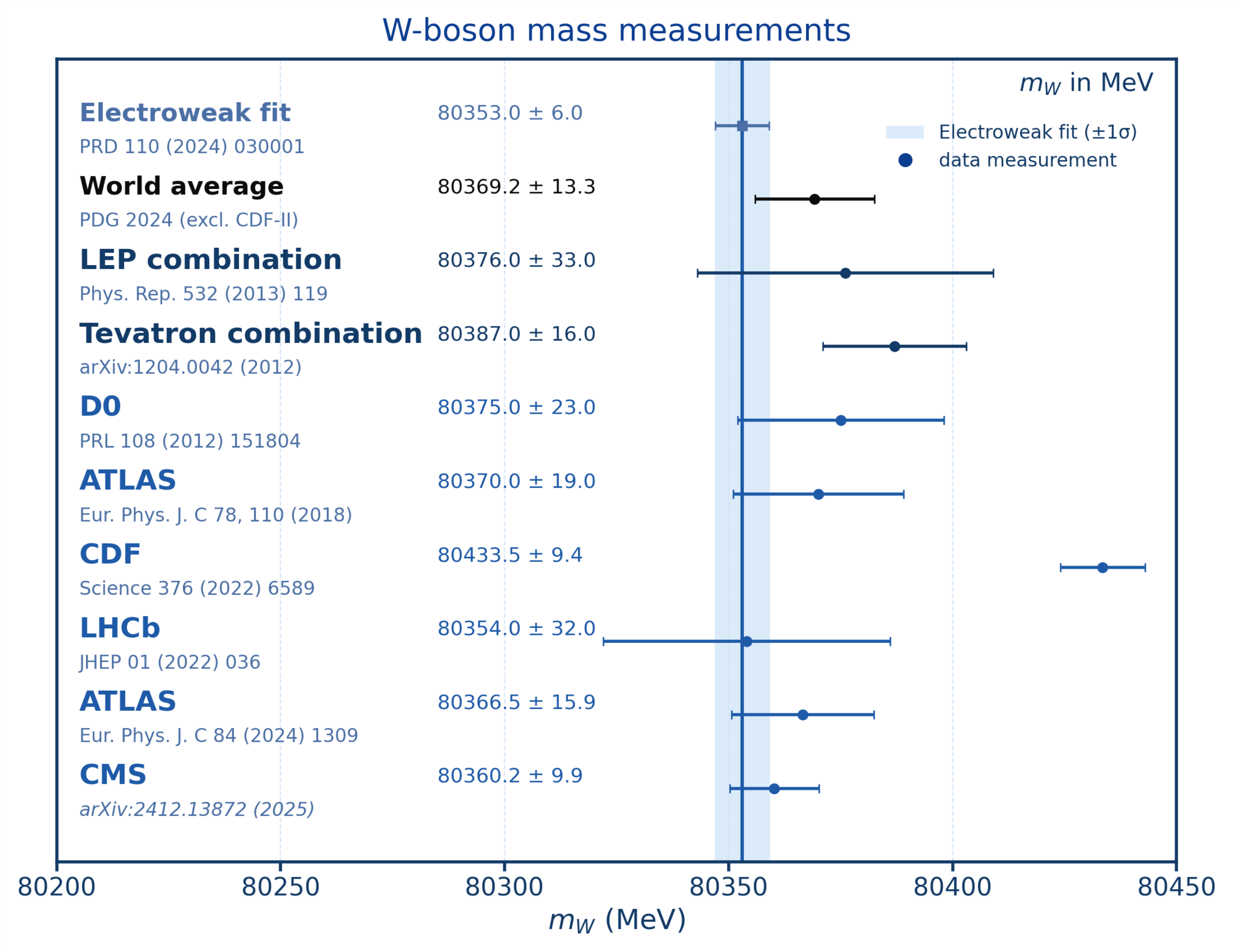


rement

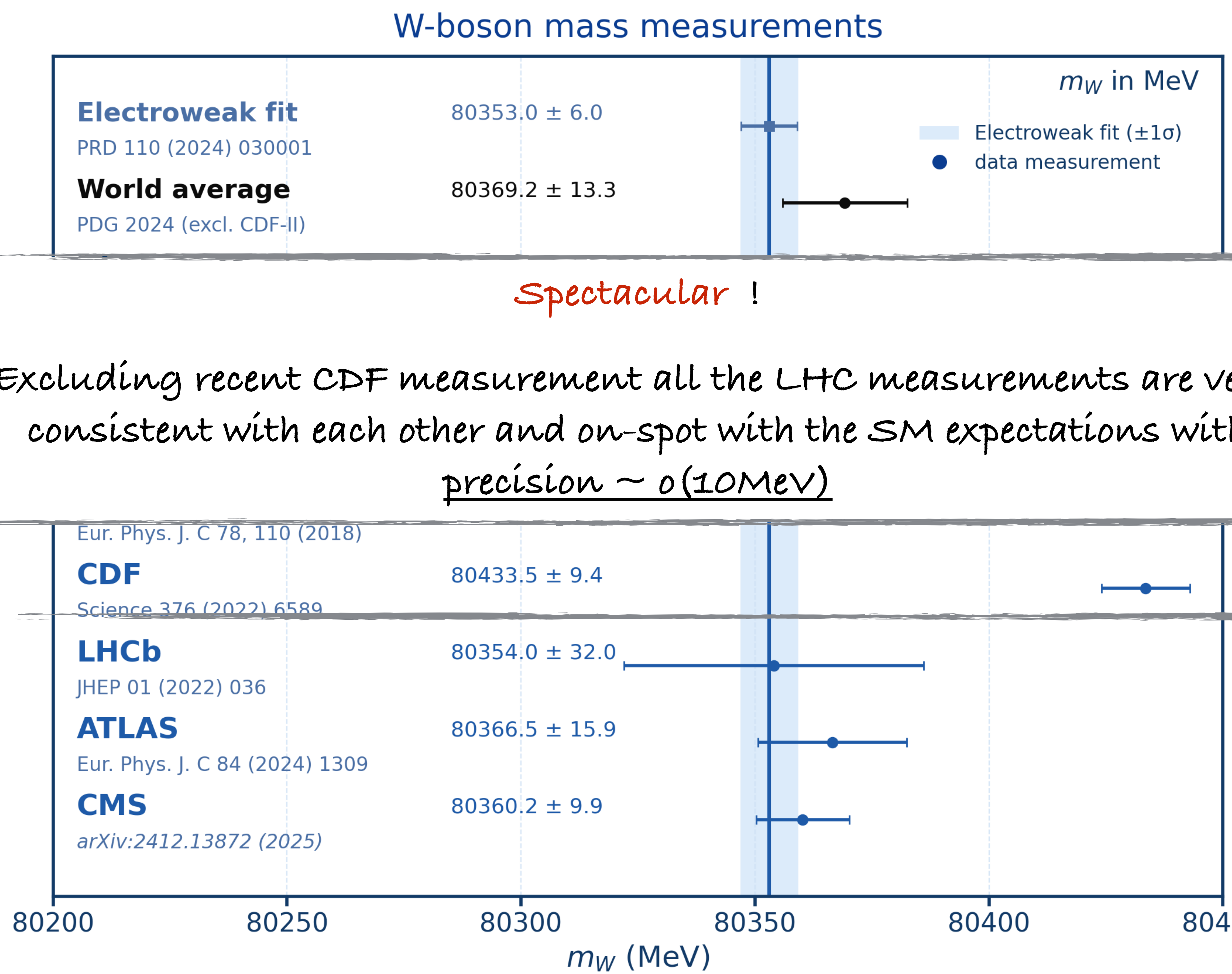
icted then measured



The W mass measurement at LHC



The W mass measurement at LHC



Spectacular !

Excluding recent CDF measurement all the LHC measurements are very consistent with each other and on-spot with the SM expectations with precision ~ o(10MeV)

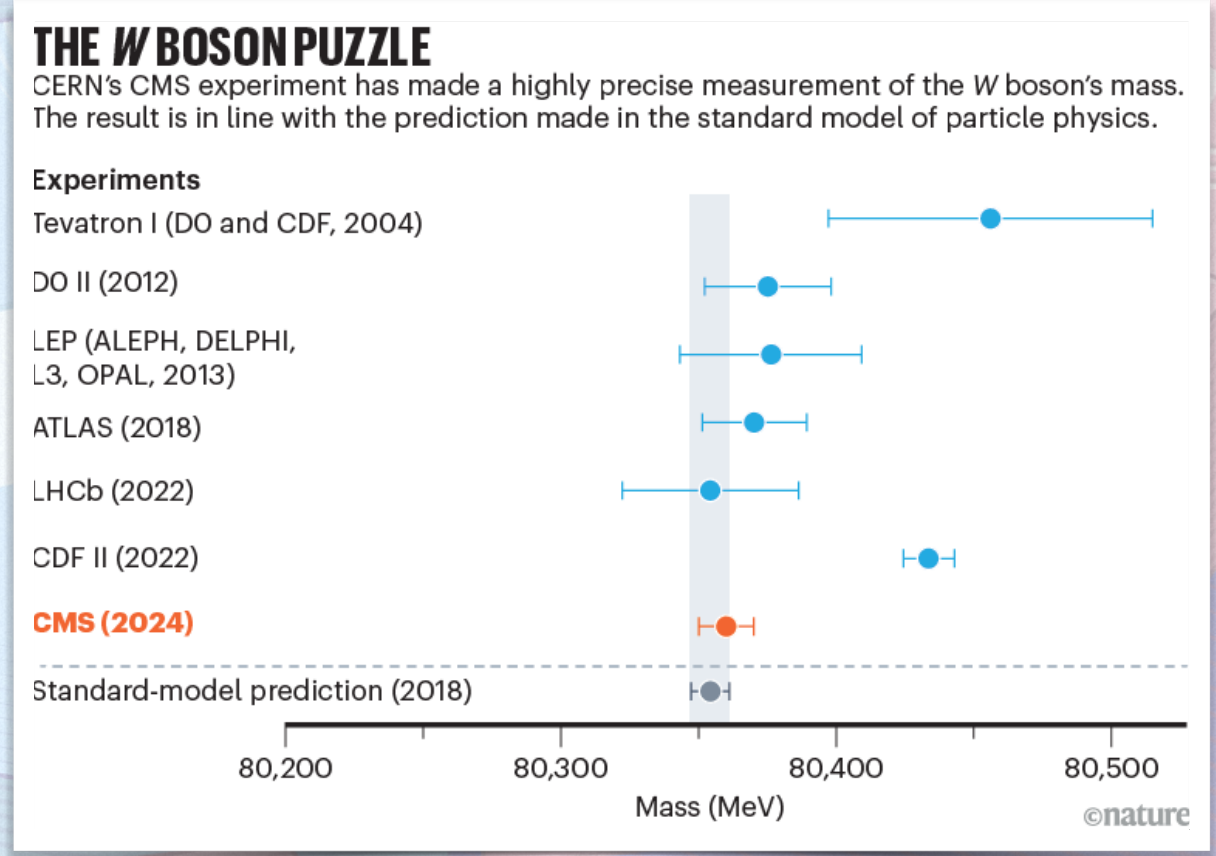
The W Boson mass at LHC

The W-boson mass is one of the most challenging measurements in high-energy physics.

- *At the start of the LHC era, today's precision seemed unattainable.*
  - ATLAS, CMS, and LHCb aim for **δm_W(10 MeV) → demanding extreme mastery of detector performance and systematics**
  - Its ultimate precision was limited by our **understanding of QCD**.

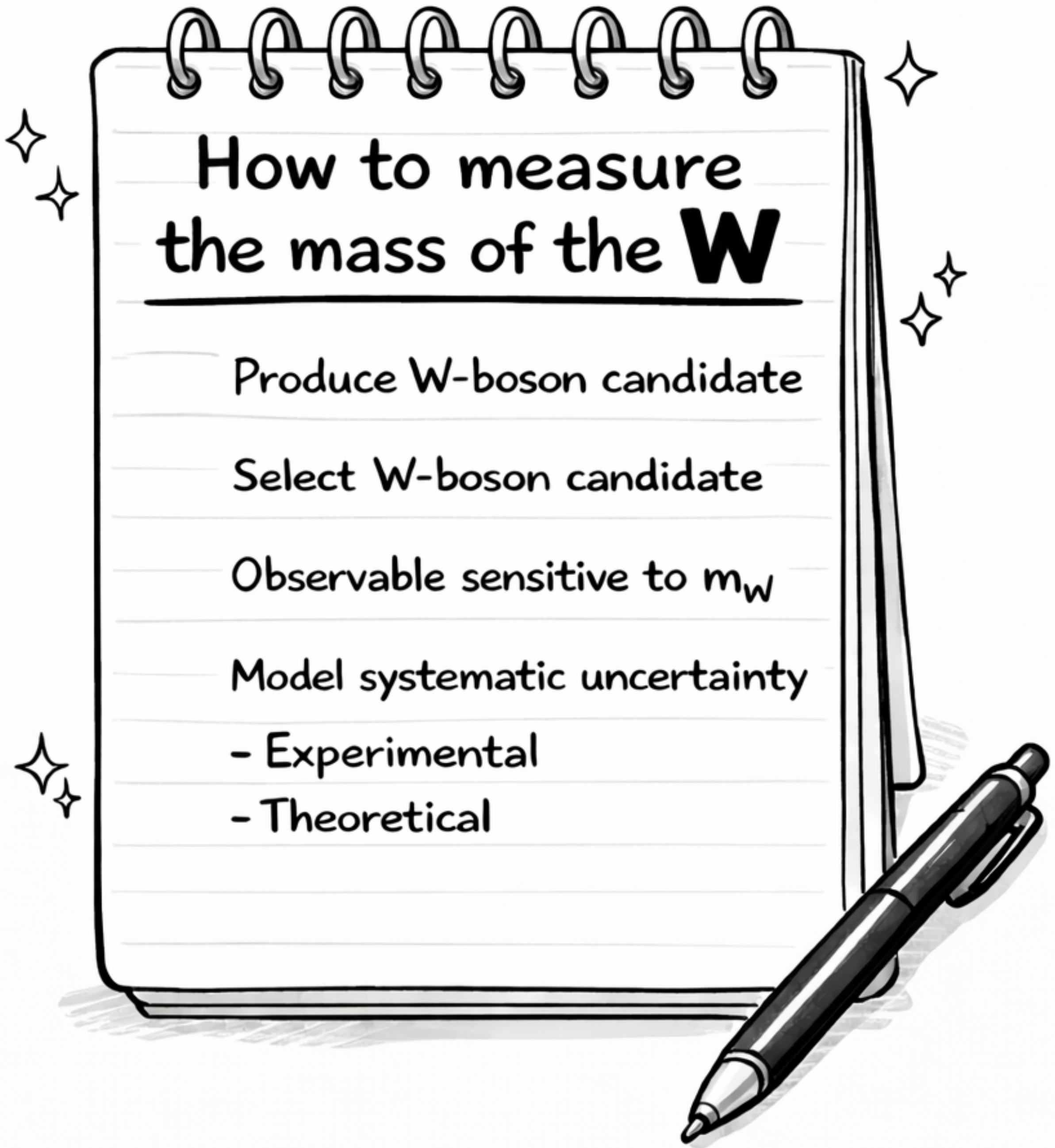
Ten years of LHC data have transformed the field:

- ☑ From discovery to precision → Detector control at the sub-‰ level using complementary methods and conditions
- ☑ Huge progress on theory methodologies in the past few years



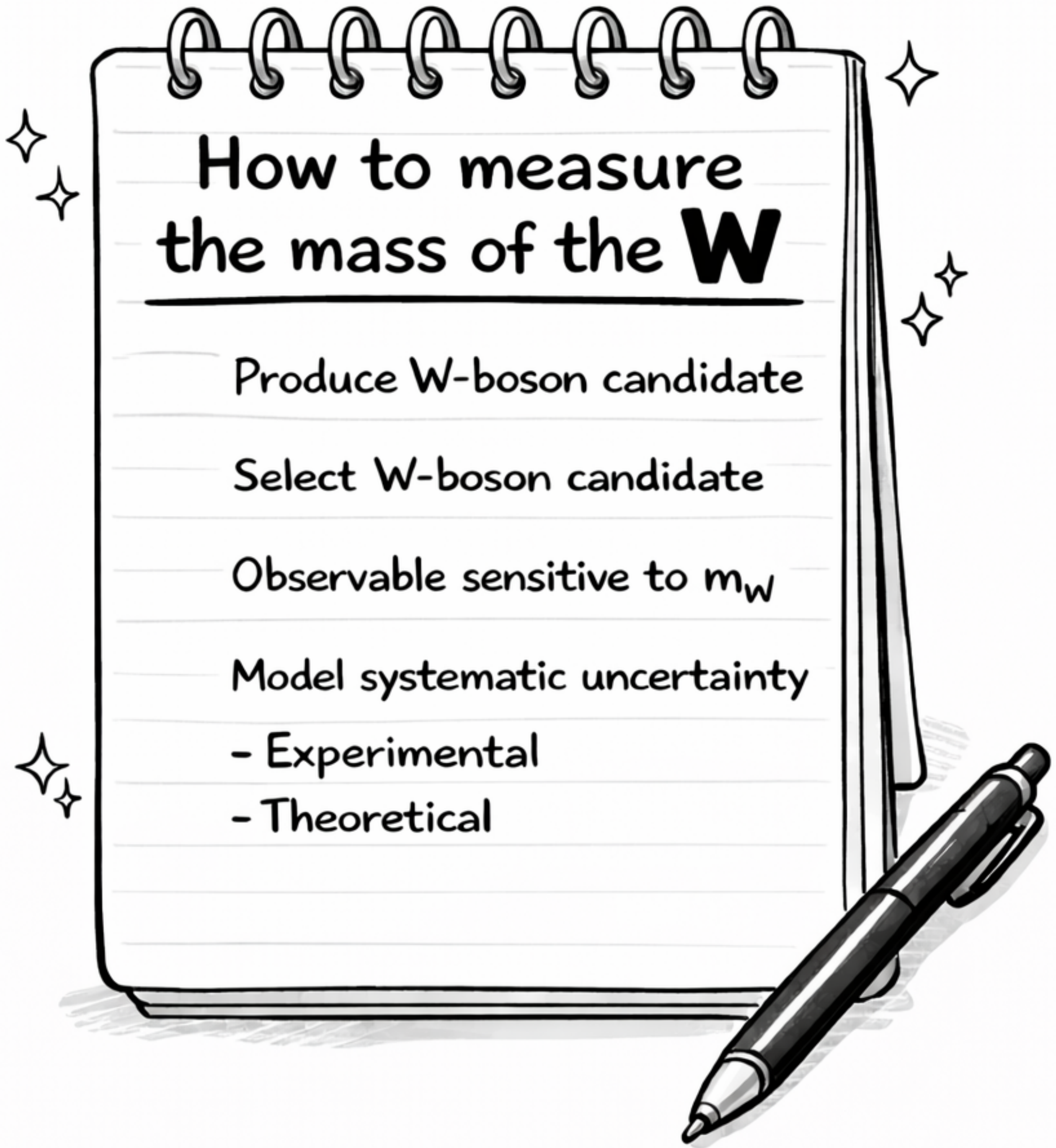
What are the challenges of the current W boson mass analyses @LHC ?

W mass analysis check-list



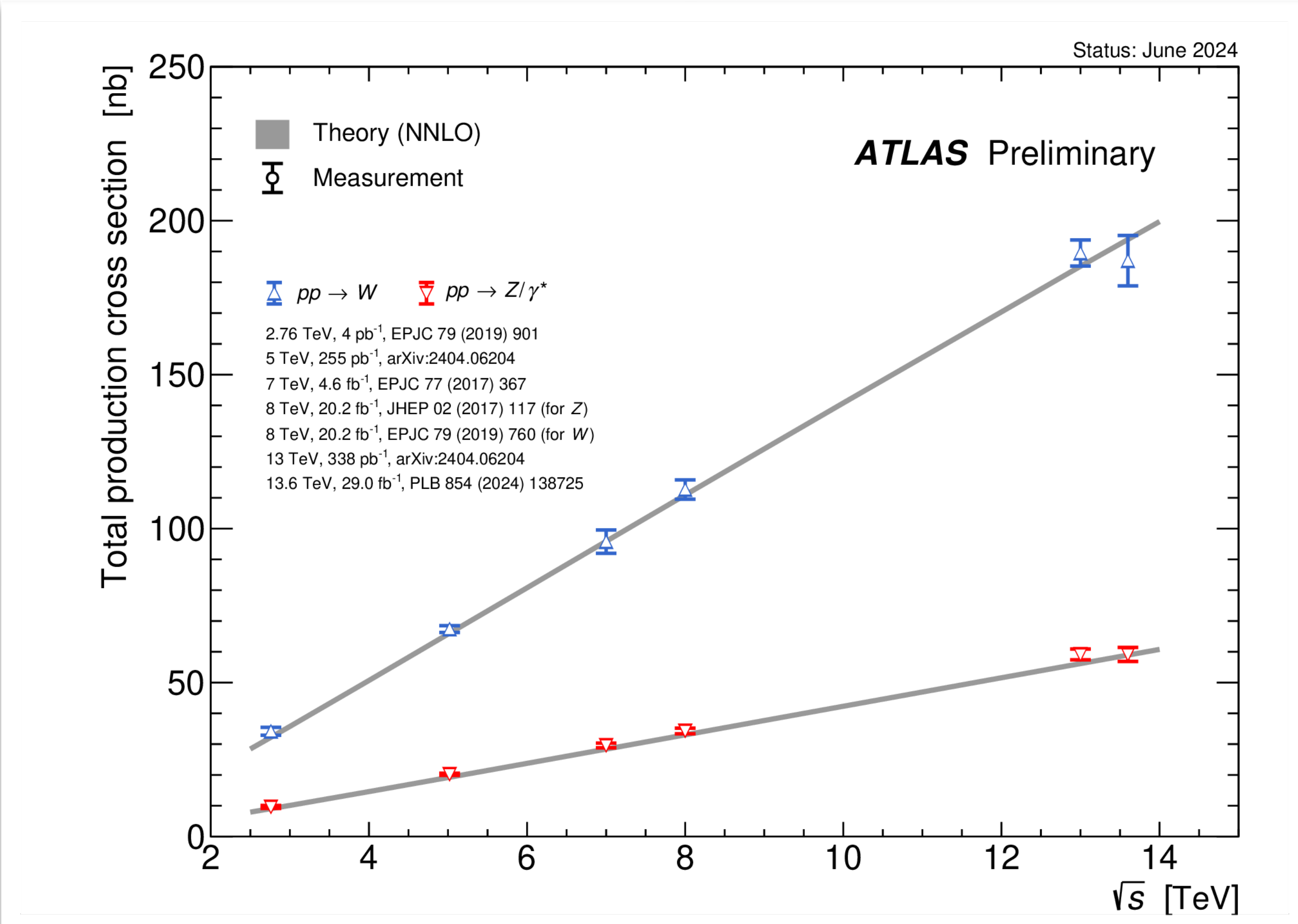
- High-performance software & computing: huge data-flow and complexity of the fit (> 10^3 bins + 10^4 NP)
- Super-precise detector calibration and response control
- Robust physics modelling: Percent-level theoretical precision → Careful treatment of many uncertainty sources
- Extensive program of ancillary measurements

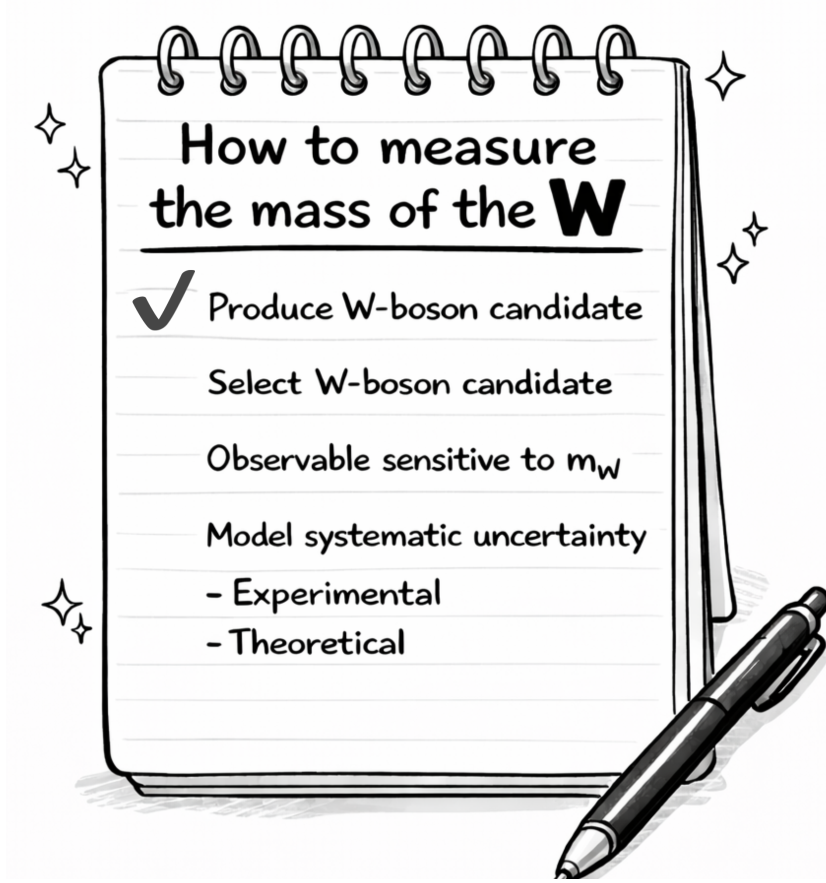
W mass analysis check-list



- High-performance software & computing: huge data-flow and complexity of the fit (> 10^3 bins + 10^4 NP) → **W boson prod. is ≈O(1000)x greater than Higgs production @LHC**
- Super-precise detector calibration and response control → **Often 1 order of magnitude better precision that std. analysis**
- Robust physics modelling: Percent-level theoretical precision → **Data precision challenge the progress of the theory community**
- Extensive program of ancillary measurements → **Do you believe on what they predict ? 10-20 year in the past nobody would never believe it.**

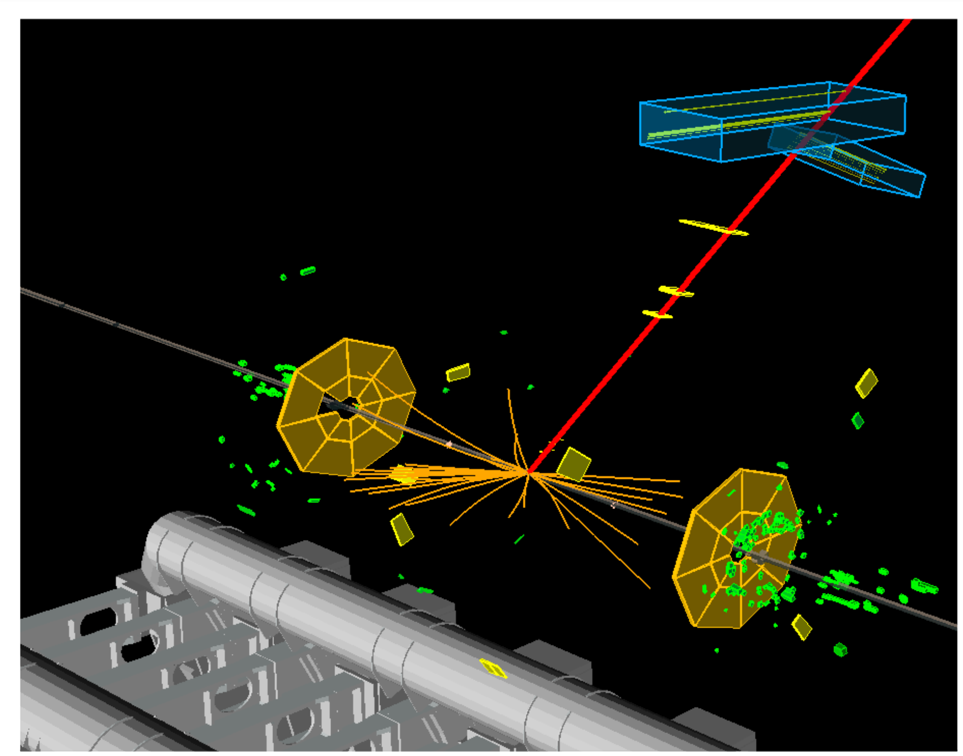
Produce W candidate





$$\mathrm{BR}(Z \to e^+e^-) \simeq \mathrm{BR}(Z \to \mu^+\mu^-) \simeq 3.37\,\%$$
$$\mathrm{BR}(W \to e\nu) \simeq \mathrm{BR}(W \to \mu\nu) \simeq 10.8\,\%$$

$$\frac{dN}{dt} = \mathscr{L}_{\text{inst}} \times \sigma$$

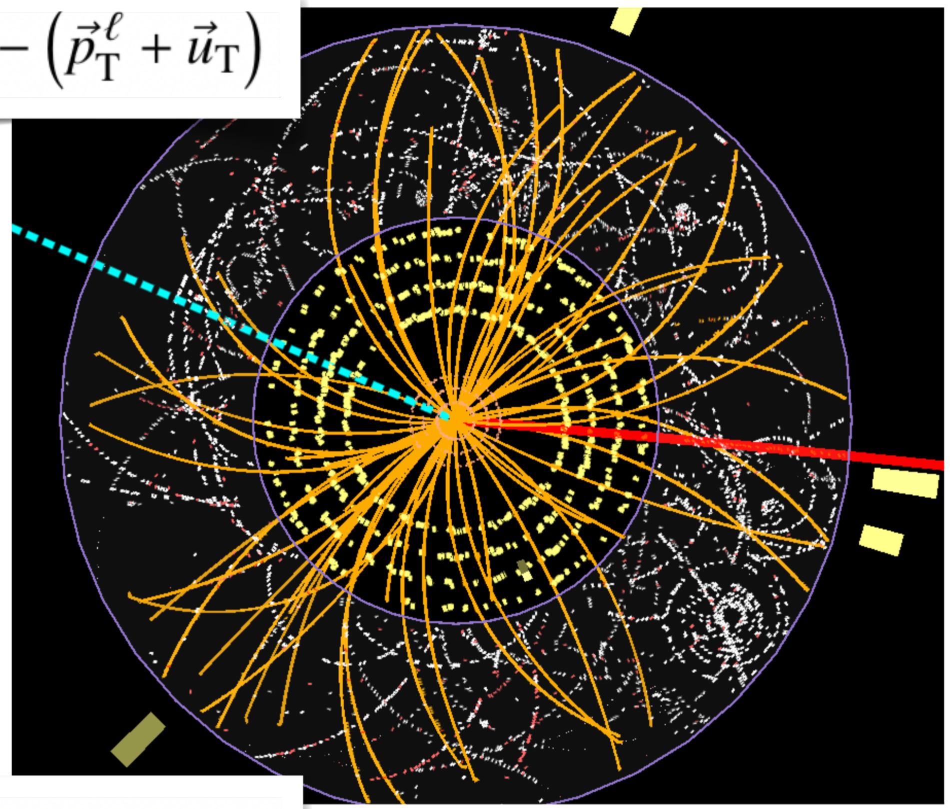


Event produced per fb-1 (total, σ×BR)

√s	W→ℓν (ℓ = e/μ) events/fb-1	Z → ℓℓ (ℓ = e/μ) events/fb-1
5 TeV	7.3×10^6	0.68×10^6
7 TeV	10.7×10^6	1.0×10^6
13 TeV	20.5×10^6 ≈ 115 events/second	2.03×10^6 ≈ 11 events/second

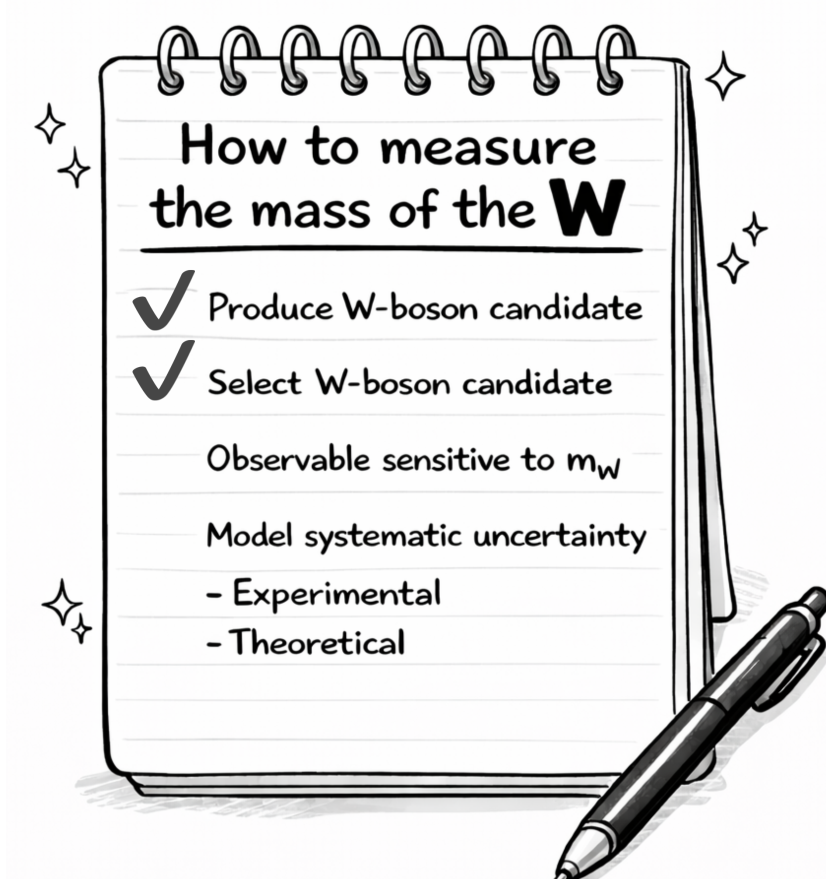
Select W candidate

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right)$$



$$\vec{p}_T^{\,\ell}$$

$$\vec{u}_{\mathrm{T}} = \sum_i \vec{E}_{\mathrm{T},i}$$

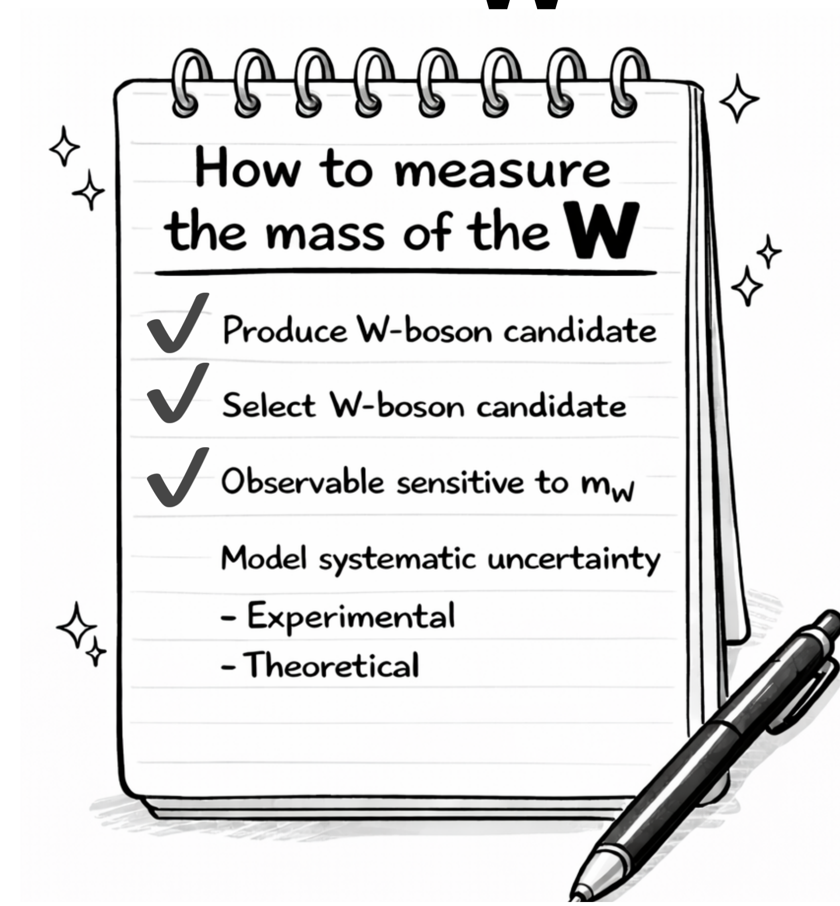


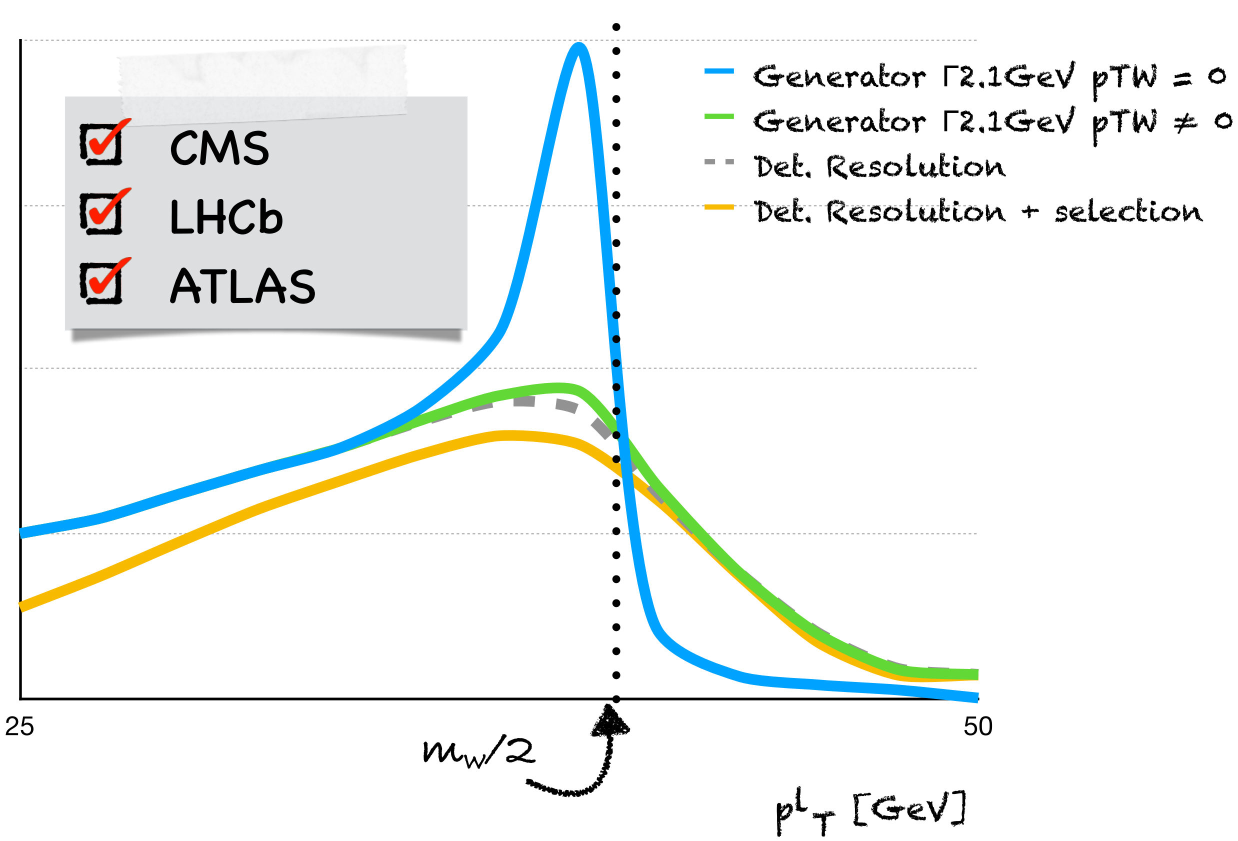
selected events	CMS	ATLAS	LHCb
Dataset	17 fb^{-1} @13TeV μ=30	5 fb^{-1} @7TeV μ=9	1.7 fb-1 @13TeV
W → μν	117 M	7.8 M	2.4 M
W → eν	X	5.9 M	X
Z→ μμ	7.5 M	1.2 M	0.2 M
Z →ee	X	0.6 M	X

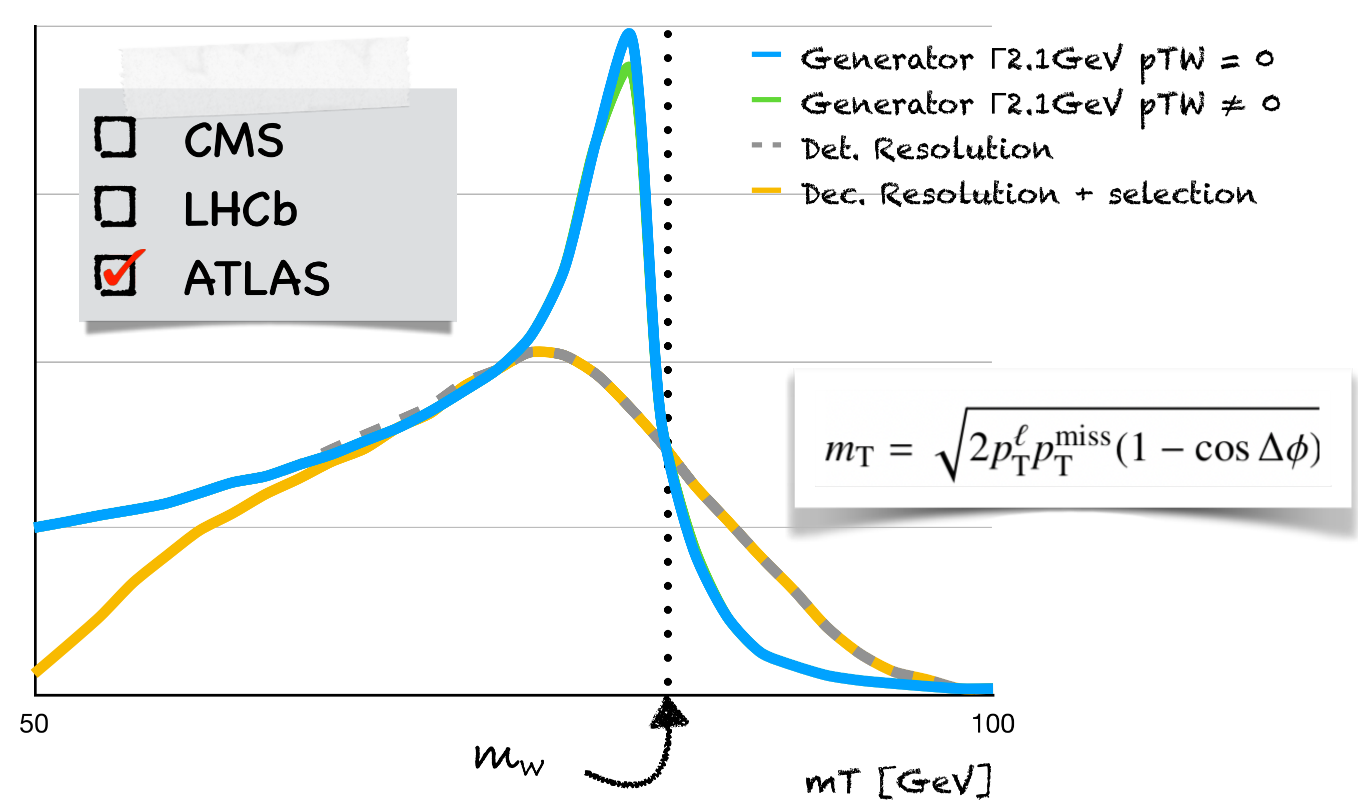
Observables sensitive to m_W

p^{l}_{T} and m_T observable are complementarity against:

- Pile-up dependence,
- experimental systematic,
- Modelling effects







Observables sensitive to m_W

p^l_T and m_T observable are complementarity against:

- Pile-up dependence,
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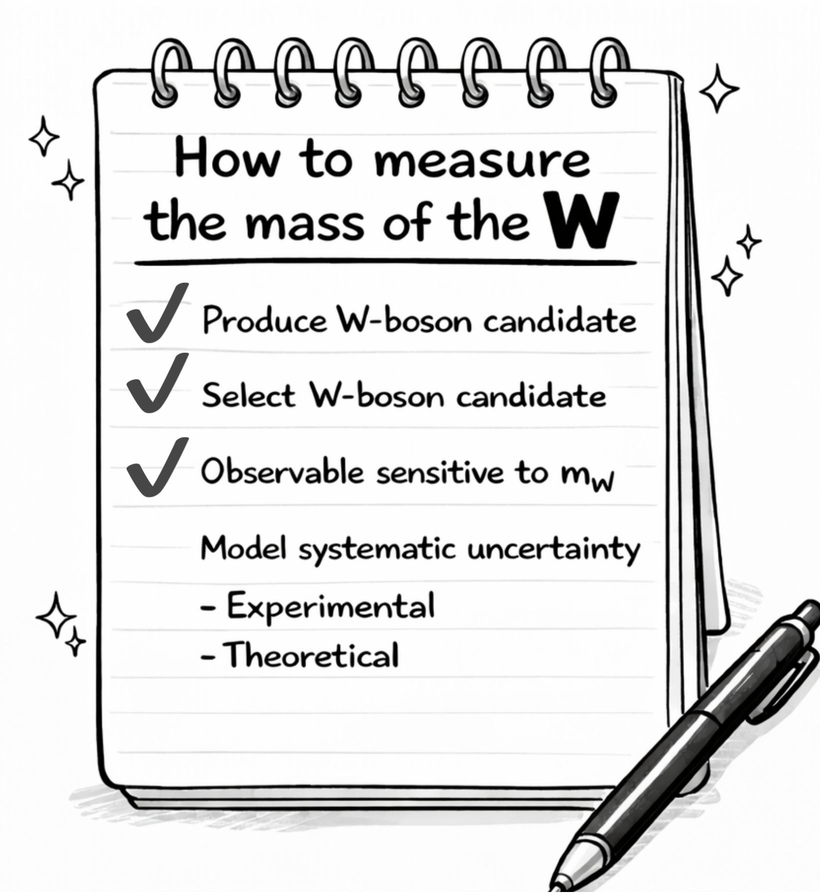
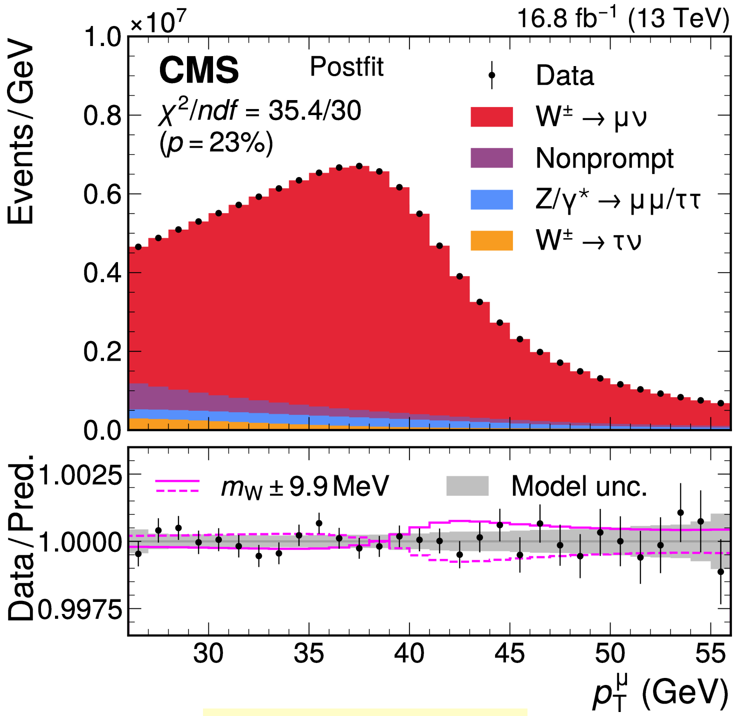
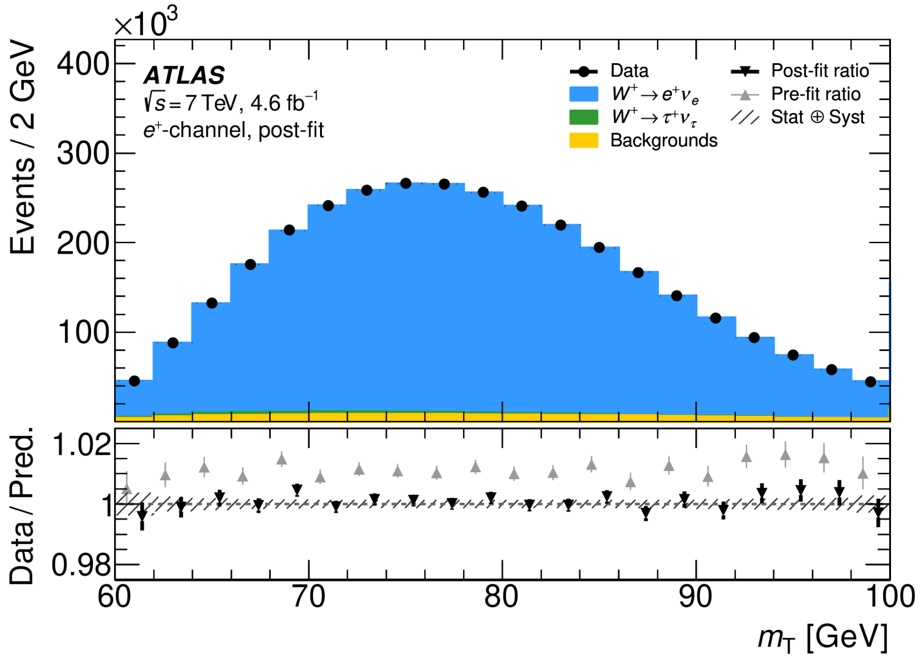
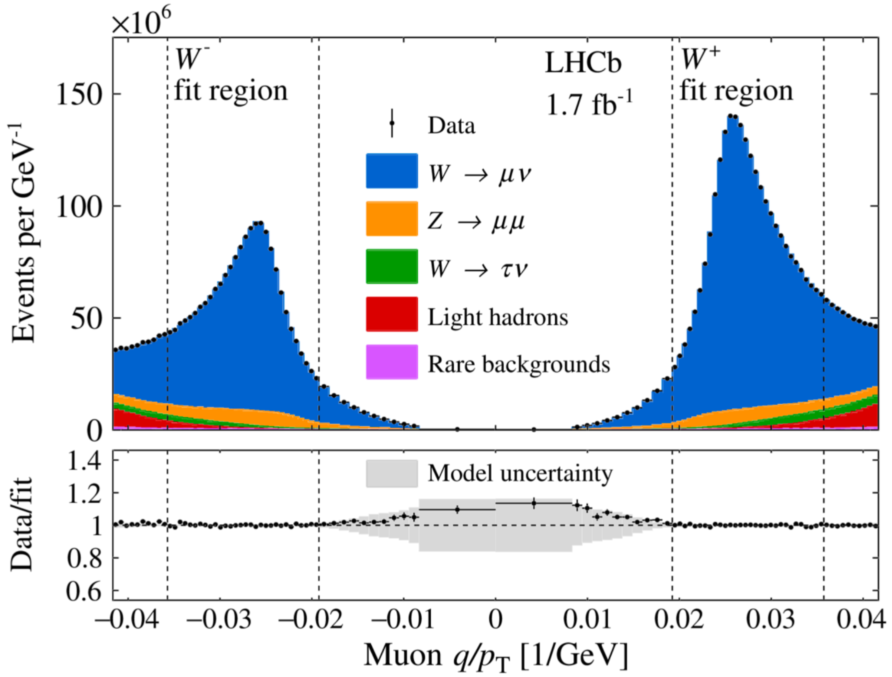




arXiv:2412.13872



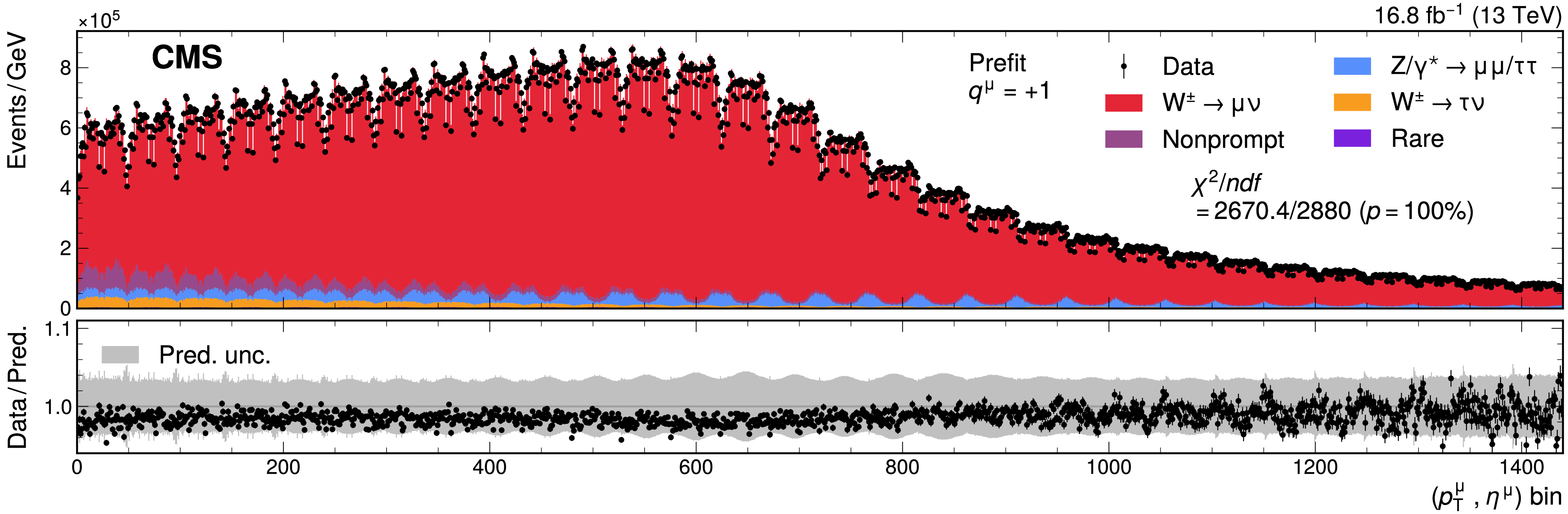
Eur. Phys. J. C 84 (2024) 1309



JHEP 01 (2022) 036

Event category

➡Events are split in several categories to maximise the sensitivity to the mW and to Model and Experimental sys (qμ,e, ημ,e, pTμ,e, mTμ,e)



Decay channel	$W \to e\nu$	$W \to \mu\nu$
Kinematic distributions	p_T^{ℓ}, m_T	p_T^{ℓ}, m_T
Charge categories	W^+, W^-	W^+, W^-
$\lvert\eta_\ell\rvert$ categories	[0, 0.6], [0.6, 1.2], [1.8, 2.4]	[0, 0.8], [0.8, 1.4], [1.4, 2.0], [2.0, 2.4]

Software challenges

in CMS 13TeV data ~120M of W-events

➡Extract mass from fit to (qμ, ημ, pTμ) distribution

~2000 bins and 4000 nuisance parameters

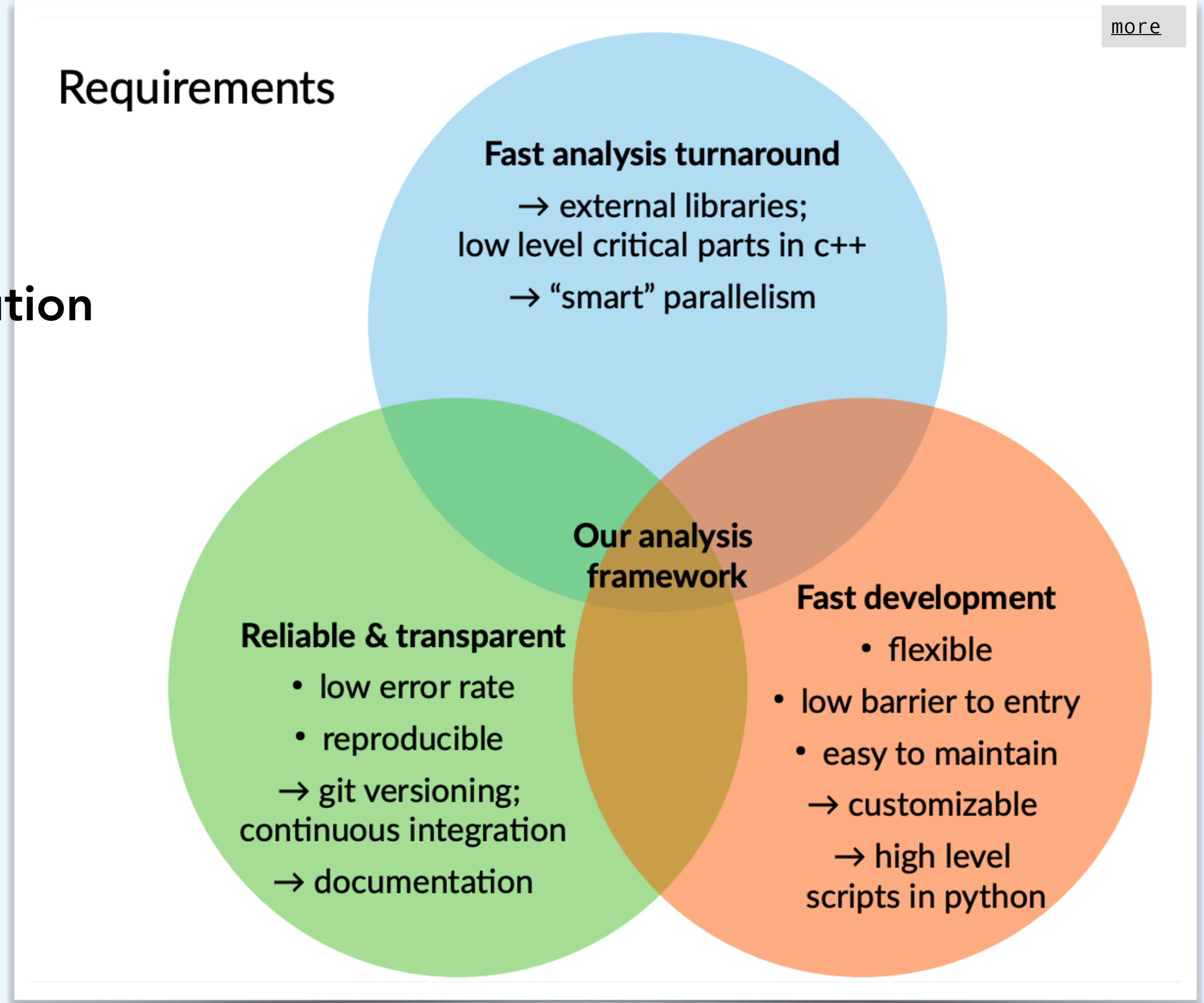
➡Major computational challenge

Increasing amount of data opens new opportunities

- Software must stay ahead to exploit data potential
- RDataFrame as efficient and flexible framework
- Optimisation of low-level critical parts [histogram implementation]
- Single high-performance node with fast SSDs and 100 Gbit/s networking for efficient I/O. [Future multi-core CPUs (e.g. EPYC Turin) will further improve scalability.]

Collaboration & Reliability

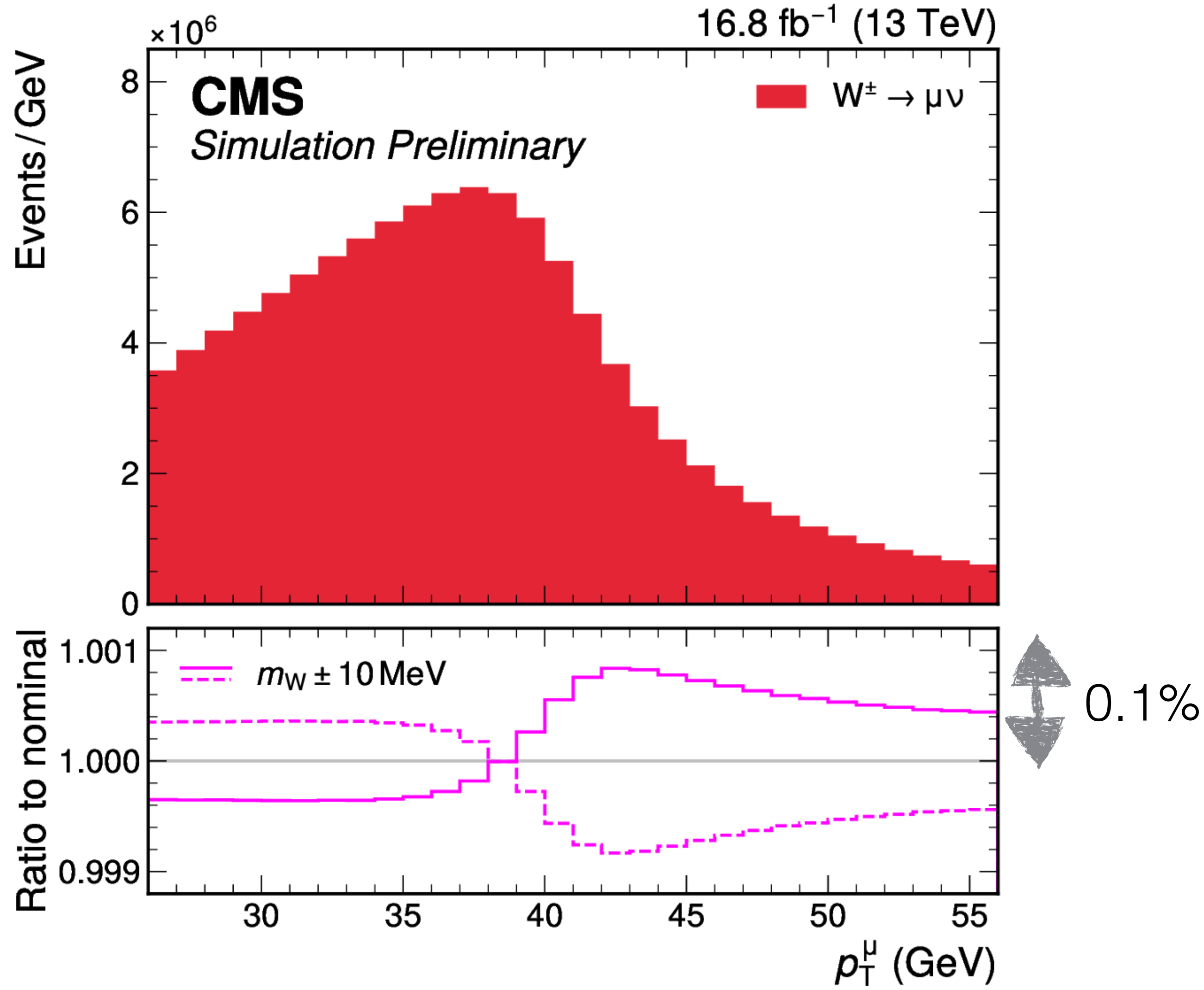
- GitHub CI/CD pipeline extremely useful
    - Early bug detection
    - Easy rollback of changes
    - Stable implementation across configurations



The precision we need

General measurement strategy: *produce models ("templates") of the final state distributions for different W-mass hypotheses to compare to* ***data***

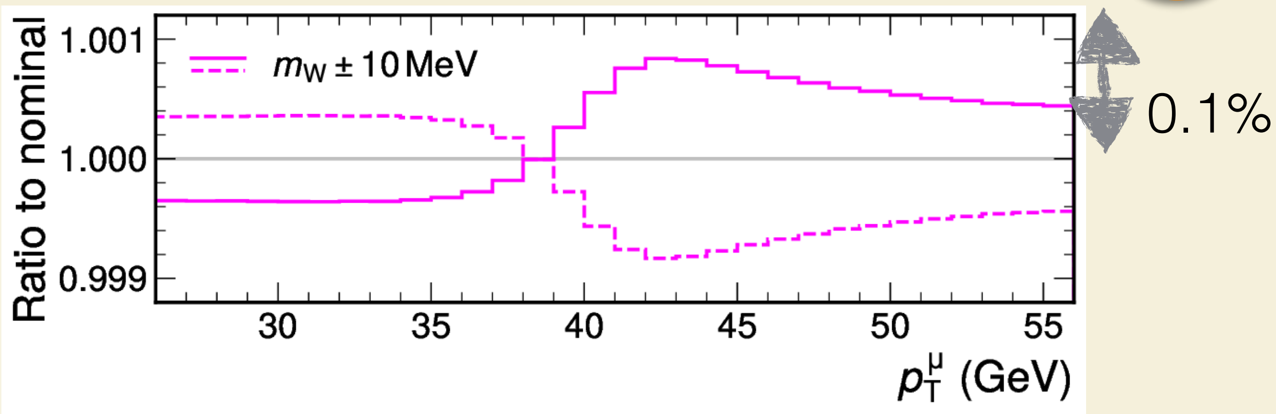
10 MeV precision in m_W need per mille precision!

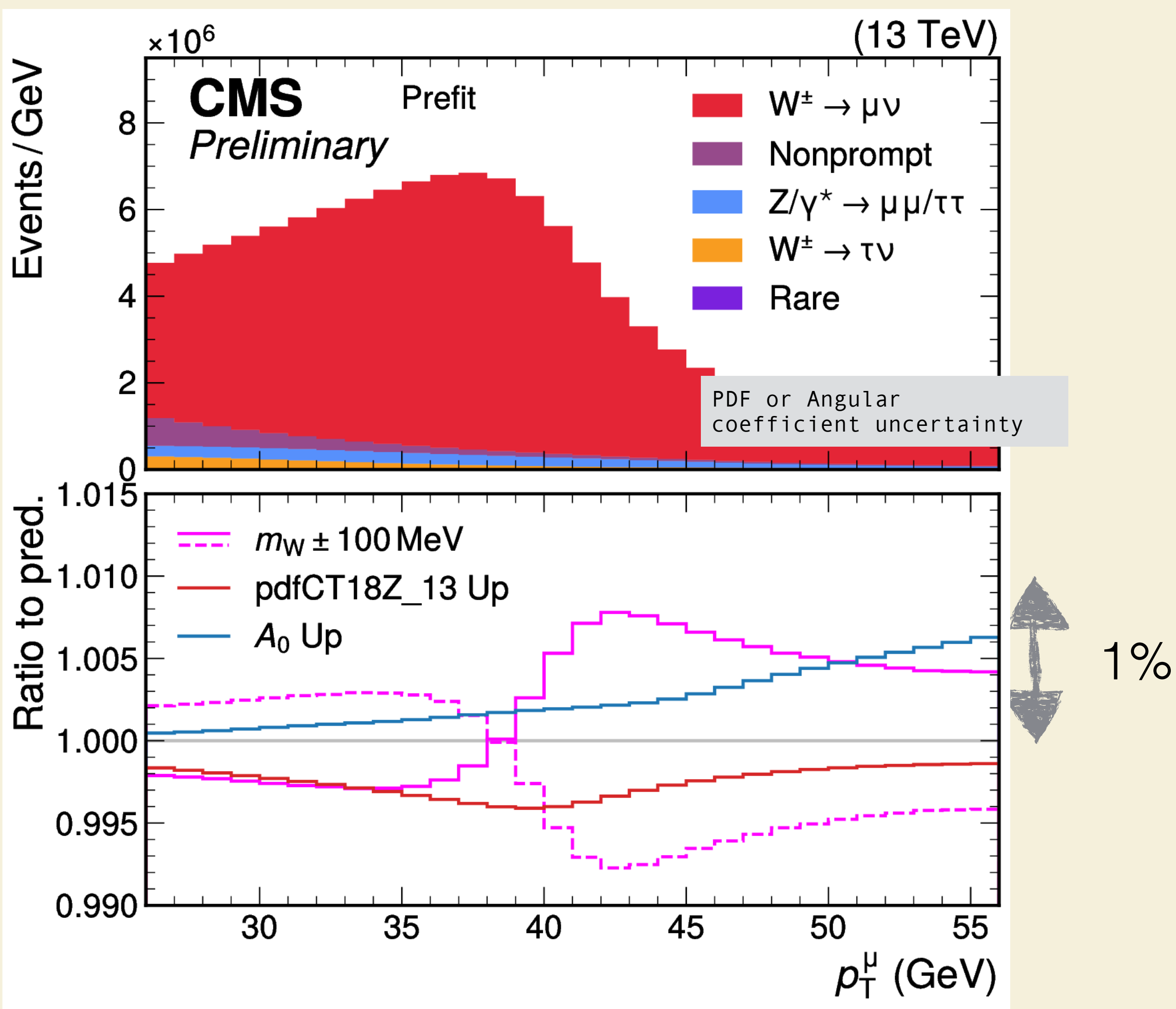


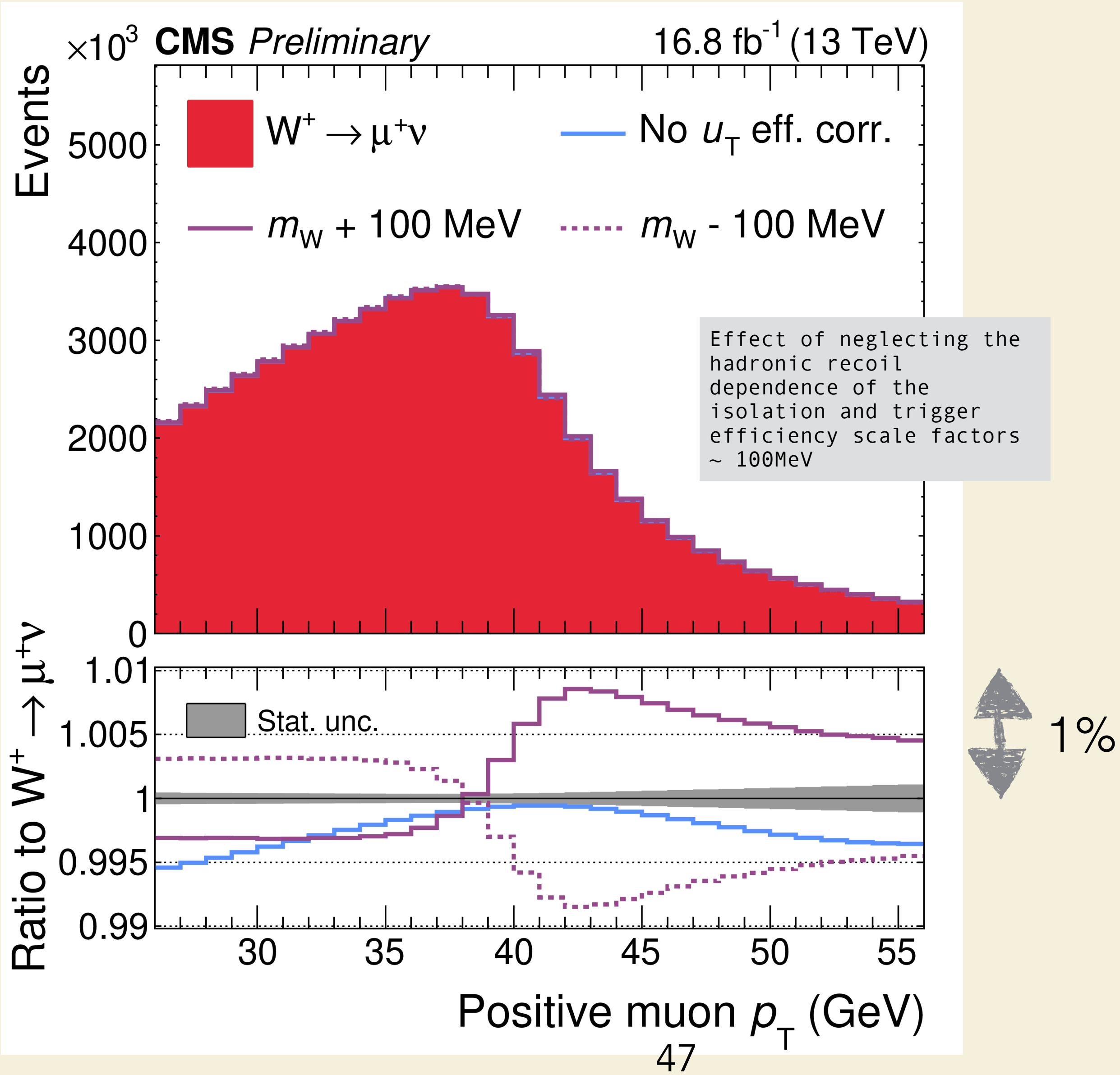
	CMS	ATLAS	LHCb
Dataset	17 fb^{-1} @13TeV μ=30 (10% 2016)	5 fb^{-1} @7TeV μ=9	1.7 fb-1 @13TeV (no pileup) 2016 only
Channels	**only** muons	**electron & muons**	**only** muons 2.2 < η^μ < 4.4
Observable	**only** p_T lepton	p_T , m_T	q/p_T
Modelling	**TNP** (theoretical nusciance parameters)	Z↔W extrapolation of the model	simultaneous fit to Z→μμ events binned in $\phi^* \approx p_T/M$

The precision we need

10 MeV precision in m_W need per mille precision in the observable

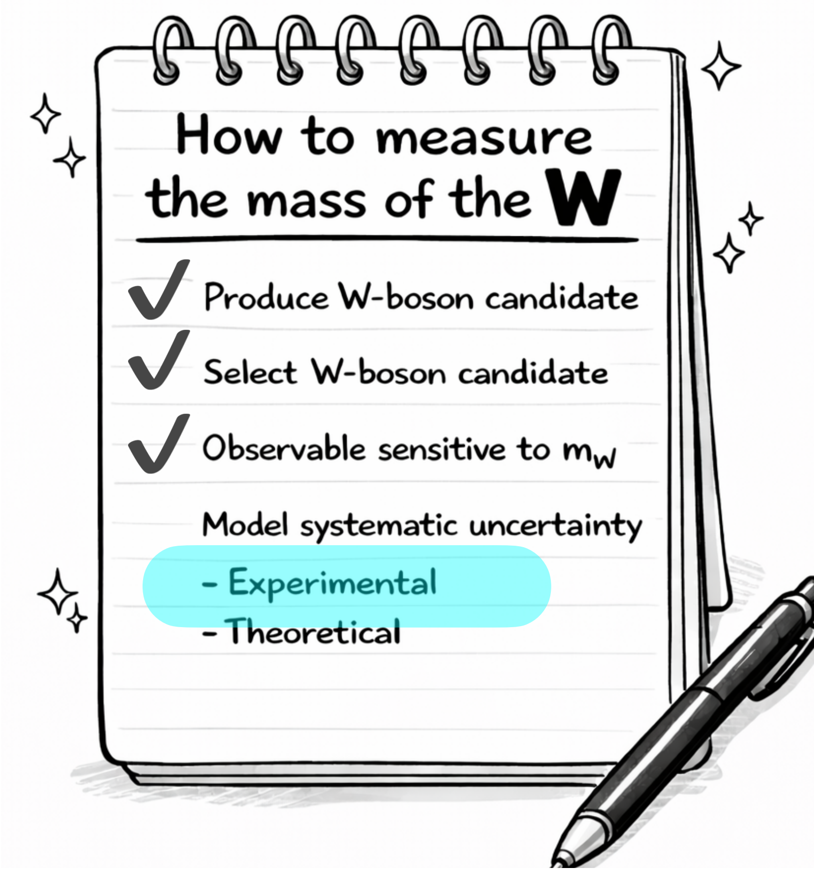






Experimental precision

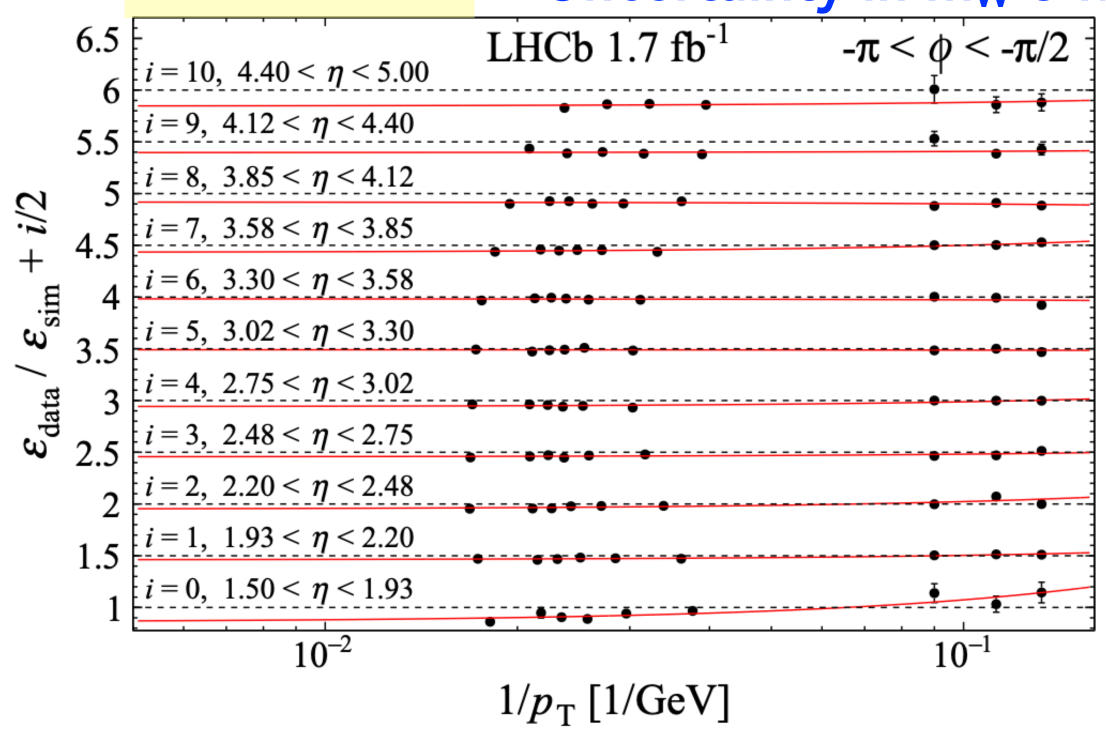
- The mW measurement is the culmination of an extensive program of **performance measurements** :
- **Lepton**:
  - Highly granular and precise estimation of lepton reconstruction/ID/Trigger **efficiency**
  - Calibration of **absolute p_T scale** (electron $\delta E_T \sim 10^{-4} \Longrightarrow \delta m_W \sim 8$ MeV)
    - > x10 better than typical ATLAS/CMS/LHcb analysis
- **Calibration of the hadronic-Recoil - p_T^{miss}**
  - challenge of the pile-up → % precision required
- Accurate estimation of **backgrounds**
  - primarily heavy flavour decays and jets mis-ID'd leptons



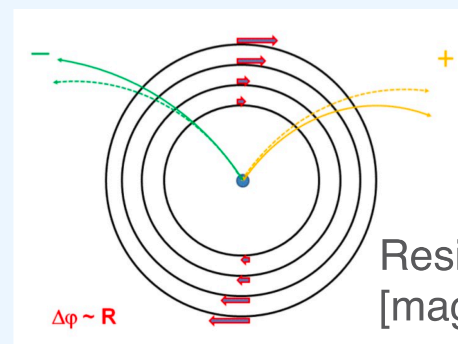
	CMS	ATLAS	LHCb
Dataset	17 fb^{-1} @13TeV μ=30	5 fb^{-1} @7TeV μ=9	1.7 fb−1 @13TeV
muon performance	Z to validate calibration (J/ψ, Y(1S))	Z samples for calibration	Z to validate calibration (J/ψ, Y(1S))
electron performance	X	Z samples for calibration	X
hadronic recoil	X	Z samples for calibration	X

Lepton performances

JHEP 01 (2022) 036 ➡ Uncertainty in m_W 6 MeV

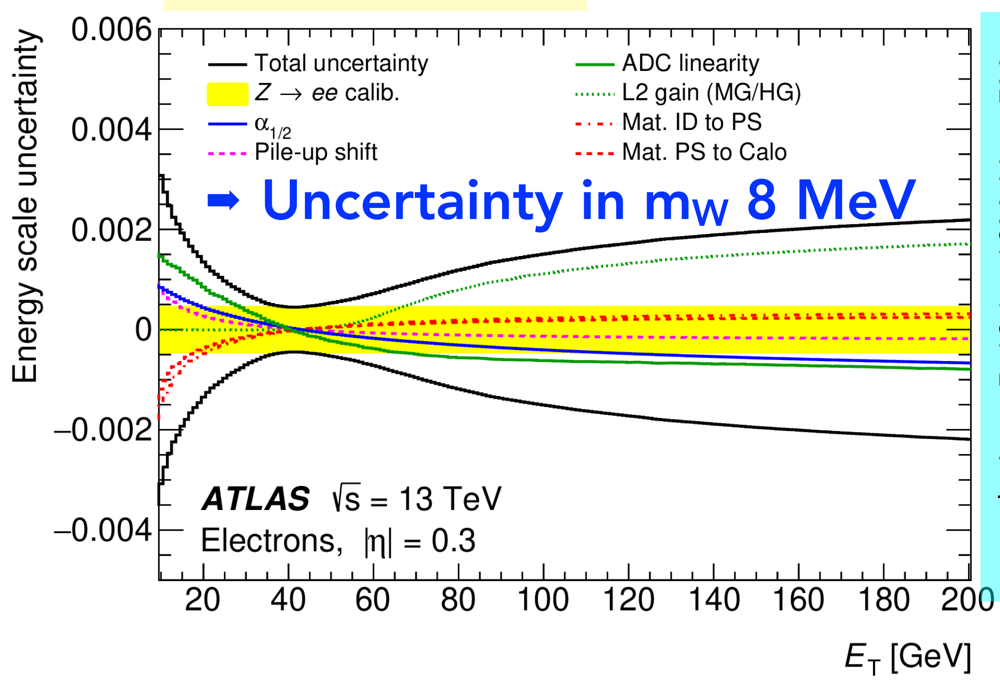


Outstanding experimental precision reached



Residual scale differences for charge-independent **A'** [magnetic-field-like difference], and charge-dependent **M'** comparison [misalignment-like term]

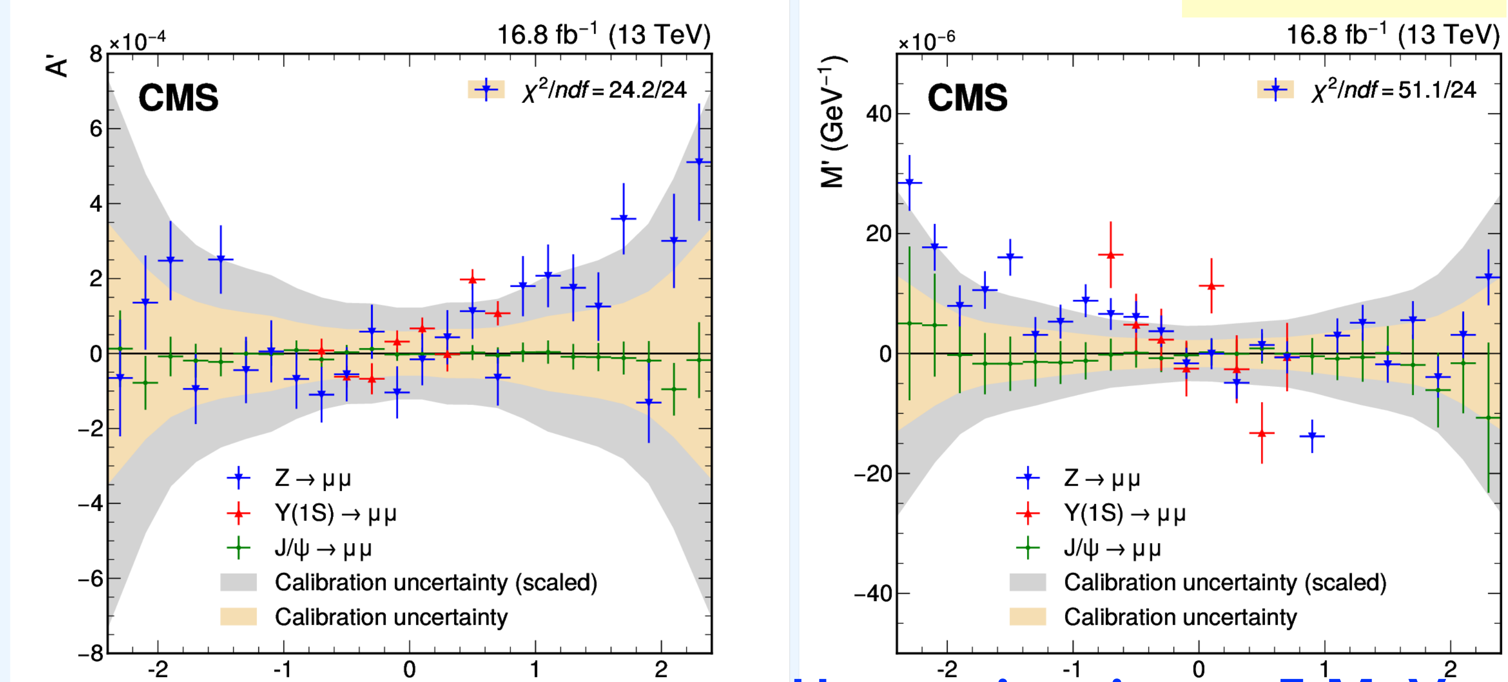
JINST 19 (2024) P02009



➡ Uncertainty in m_W 8 MeV

naively $\Delta\alpha \sim 5\times10^{-4} \sim$ 10MeV on δM_W

arXiv:2412.13872

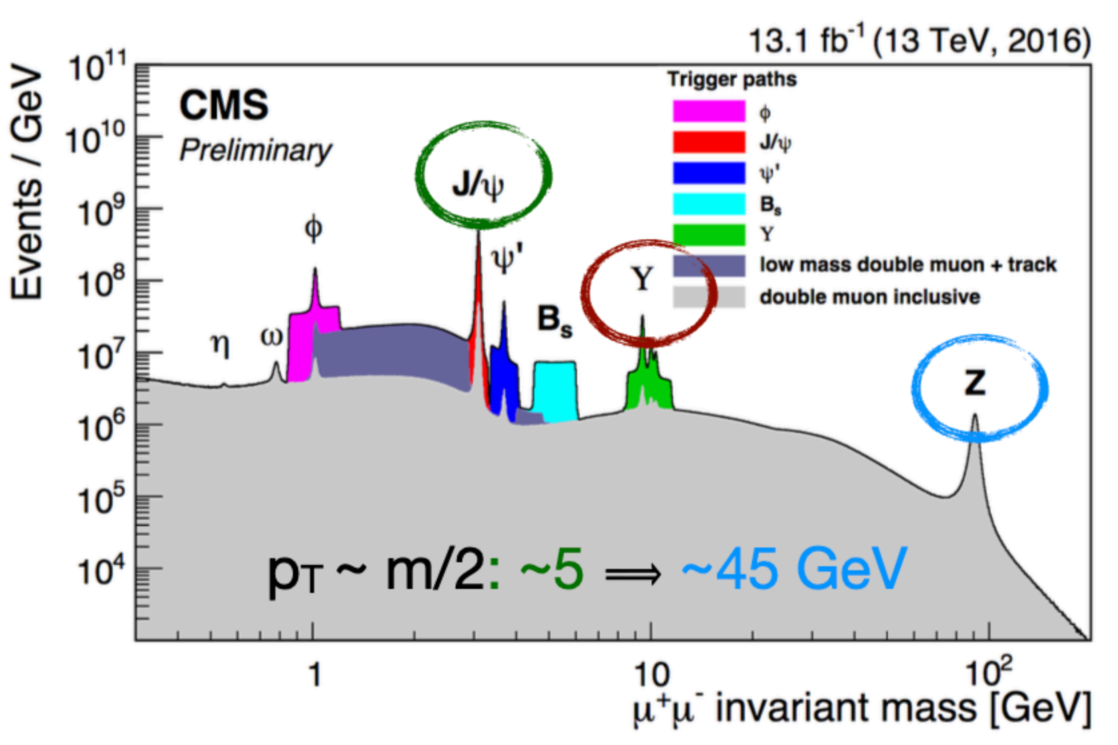


➡ Uncertainty in m_W 5 MeV

calibration challenges - muon scale

$$k_{corr} = Ak + qM + \frac{k}{1+ek}$$

$$\delta k/k \approx A + qM/k - ek$$



Calibration from quarkonia and extrapolation to W/Z momentum range requires precise control over momentum dependence of the calibration.

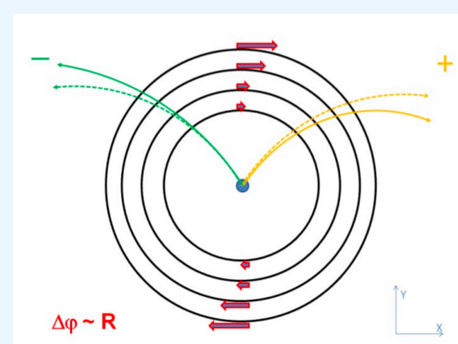
Canonical expression for curvature bias $\delta k/k$

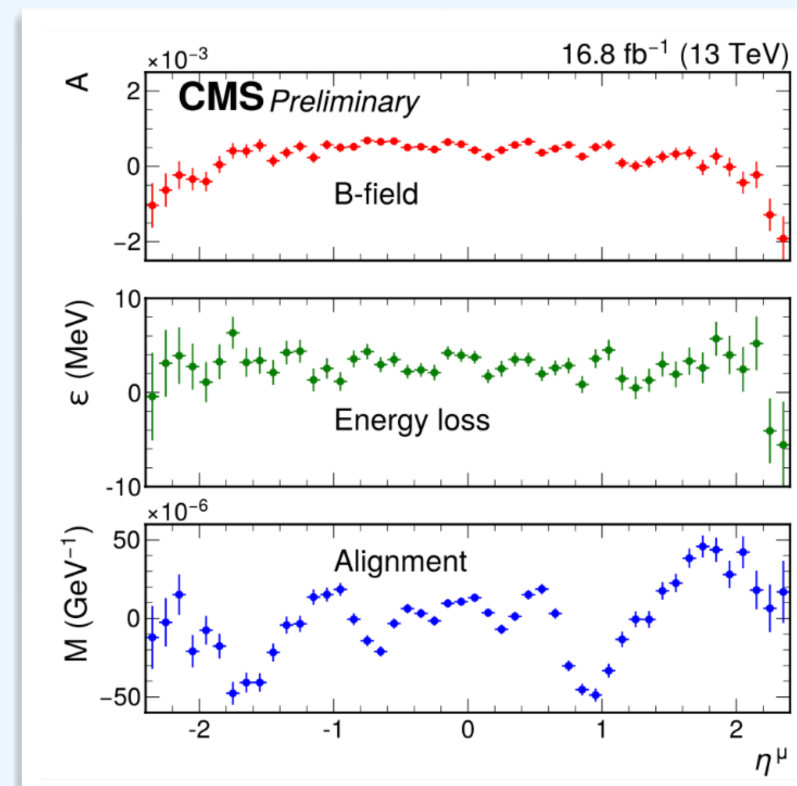
Parameterize by small differences in

B-field

Alignment

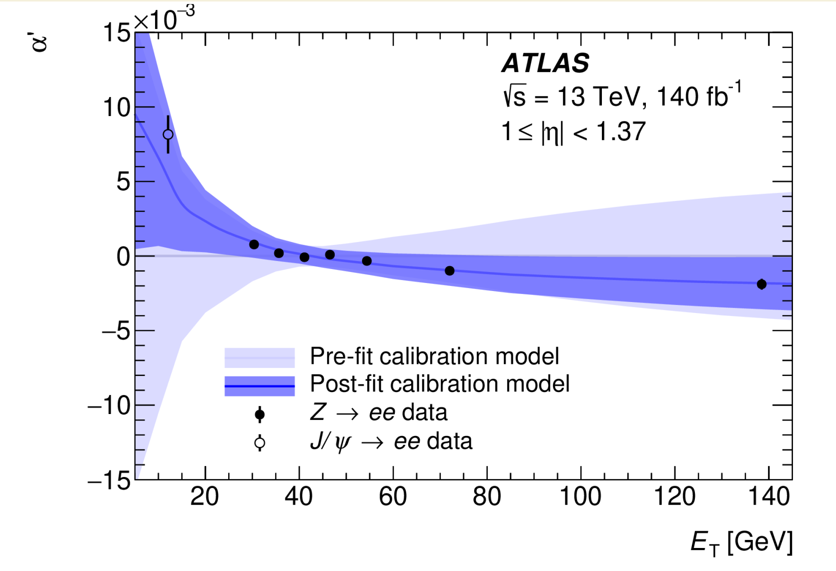
Energy loss (material)

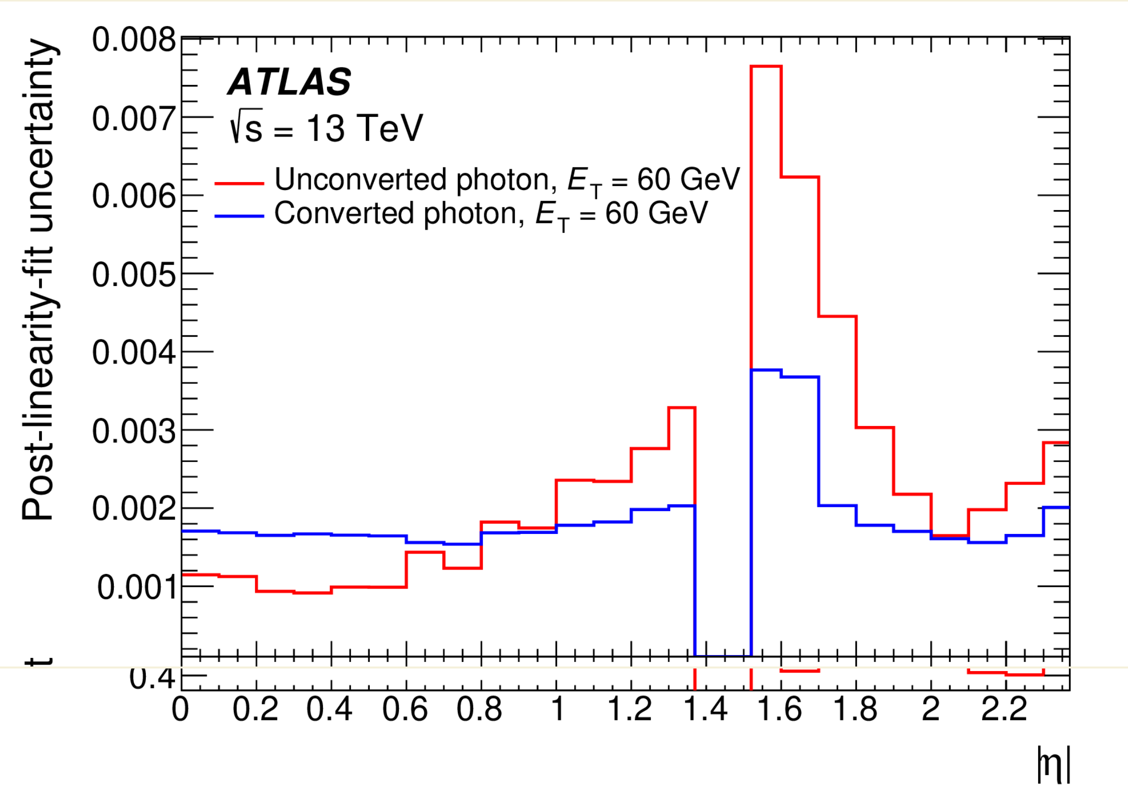




- ➡ Uncertainty in m_W 4.8 MeV
- ➡ final precision scale for Z mass 5×10^{-5}

e/γ performances

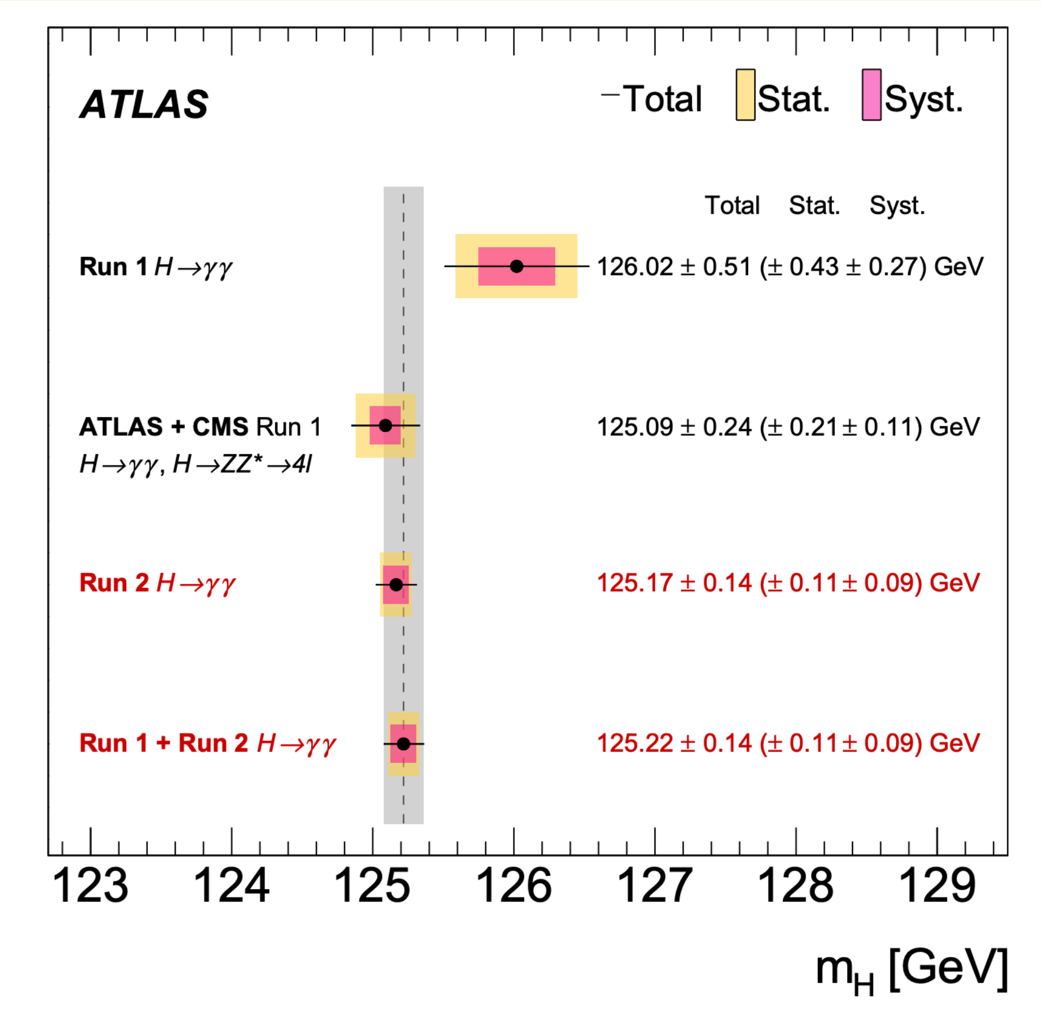




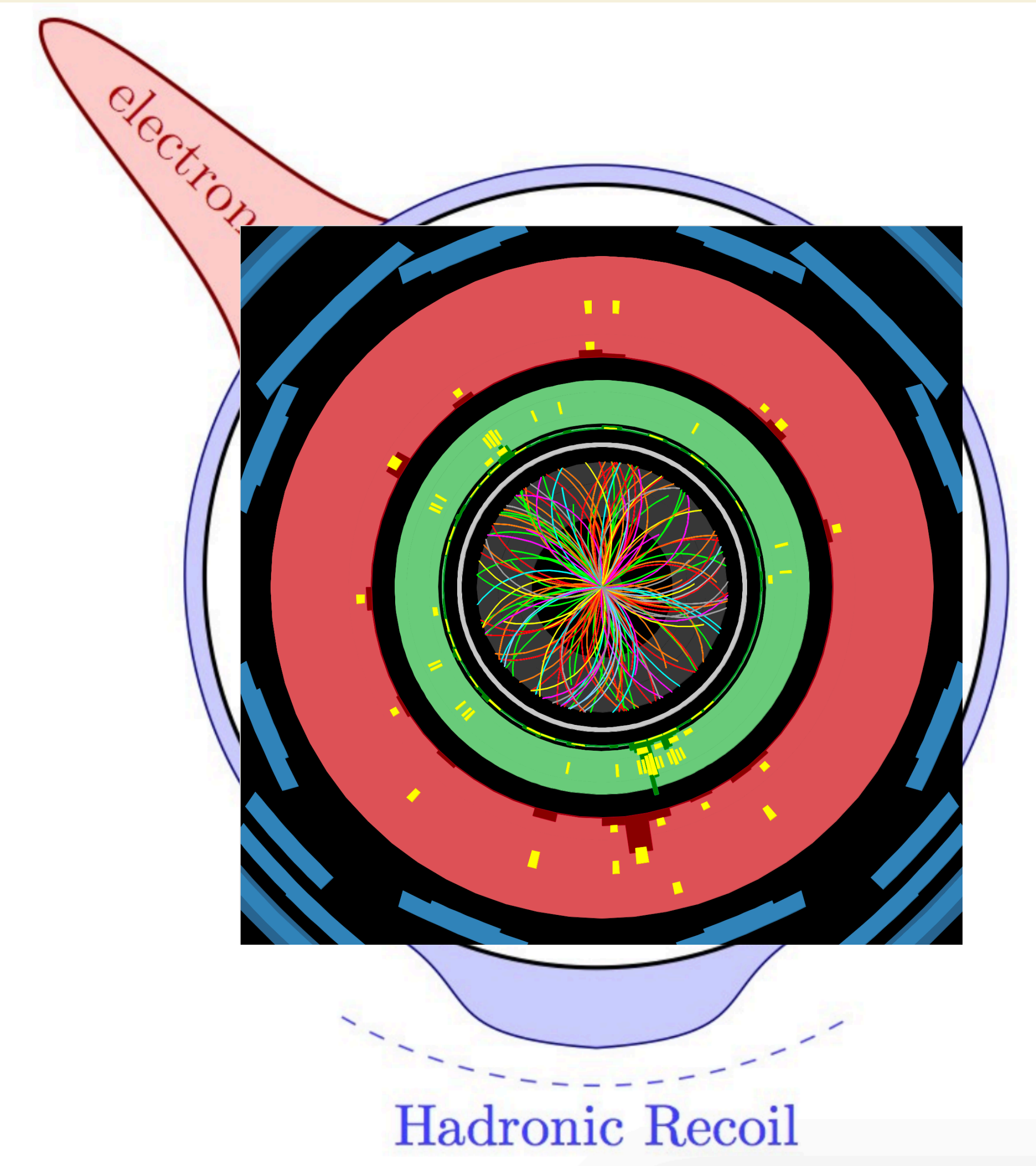
JINST 19 (2024) P02009

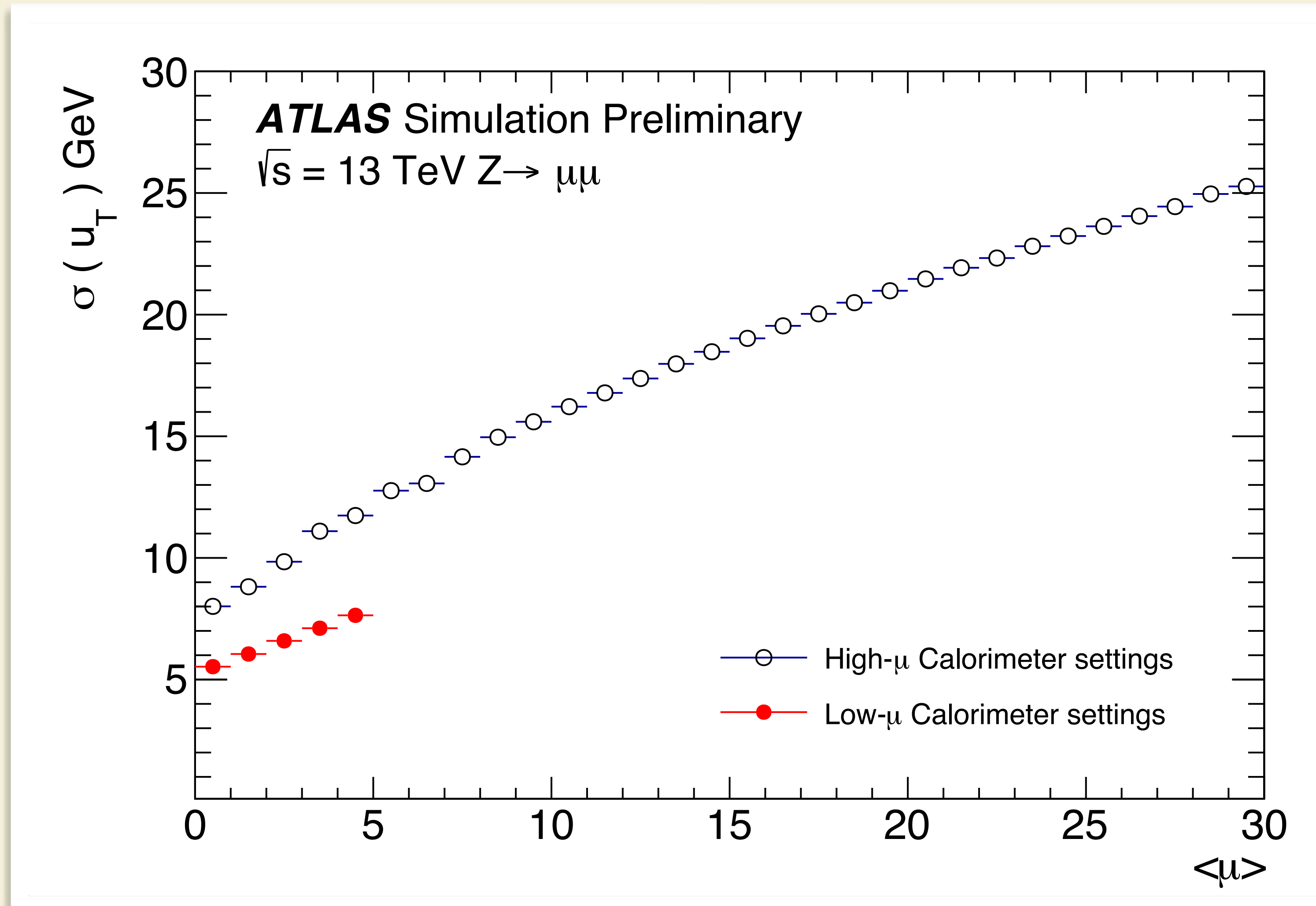
Detailed photon energy calibration enabled most precise Higgs mass measurement to date (90 MeV (0.07%) systematic uncertainty in $H \to \gamma\gamma$)

Phys. Lett. B 847 (2023) 138315



W mass sensitivity and pileUp

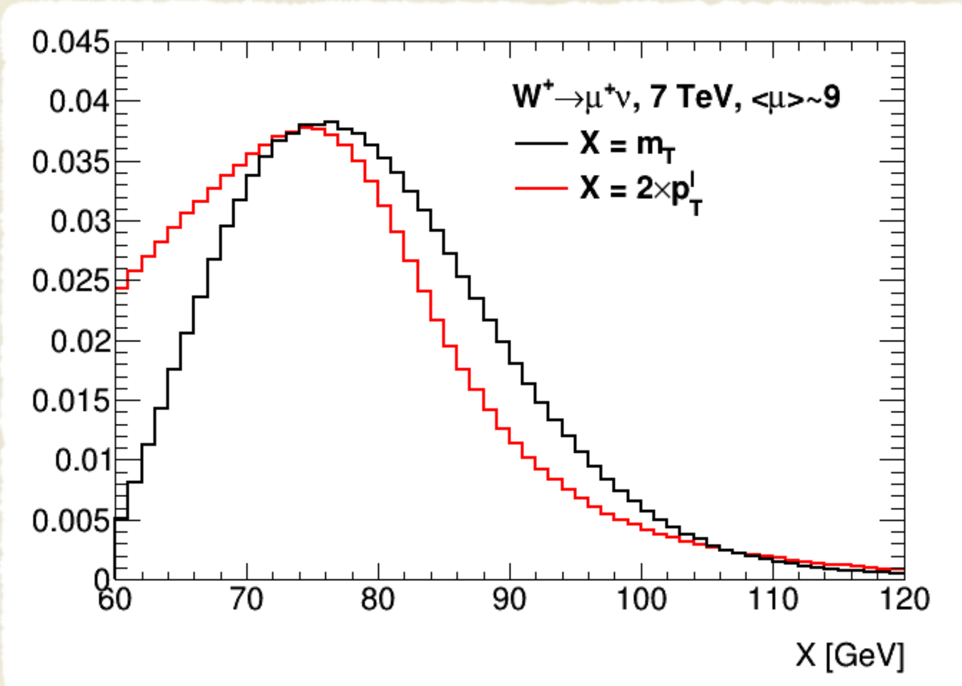


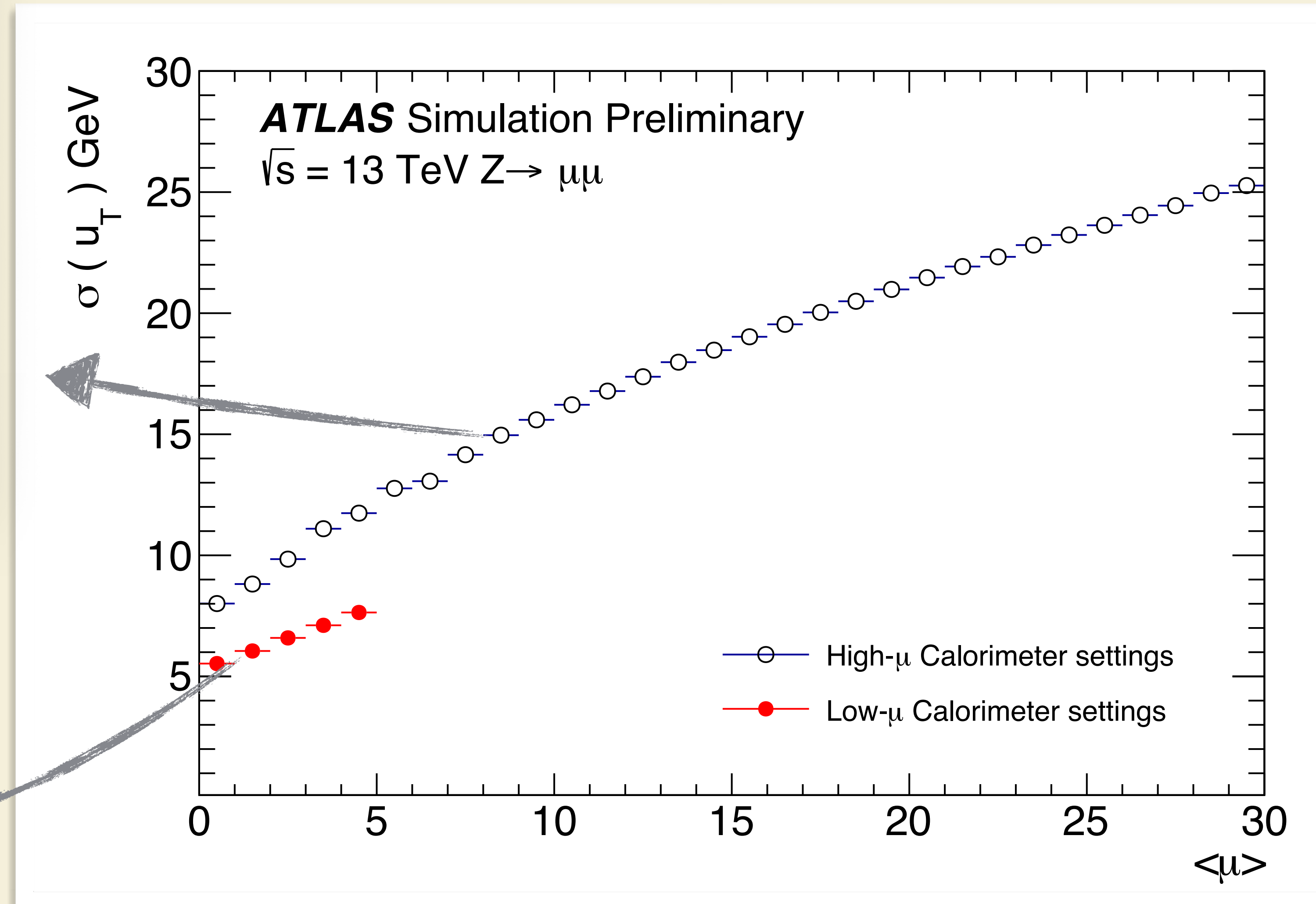


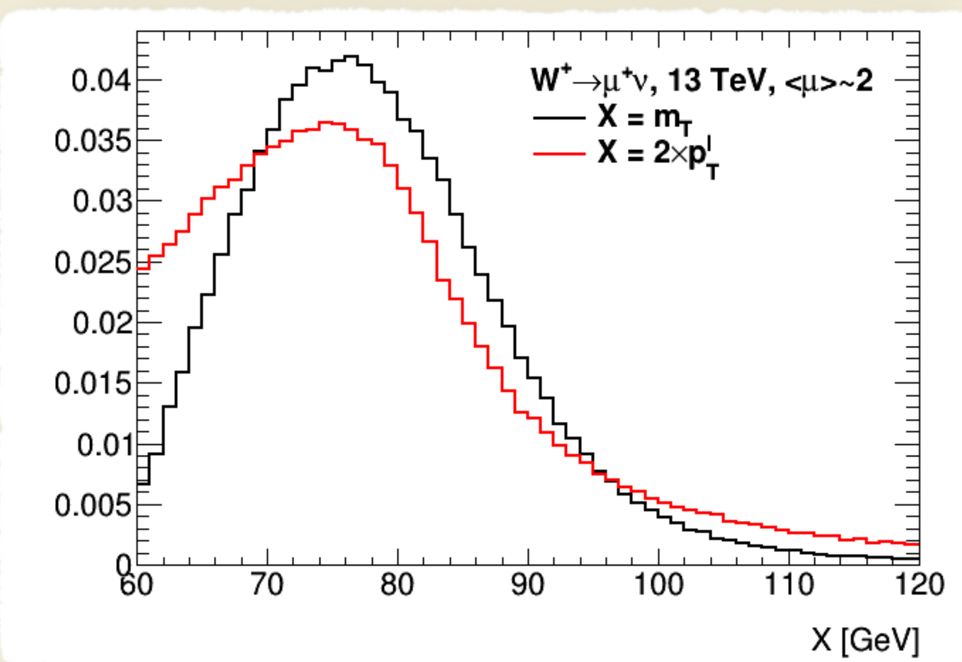
$$\vec{u}_{\mathrm{T}} = \sum_i \vec{E}_{\mathrm{T},i}$$

- u_T **resolution** strongly depends on $\mathbf{\Sigma E_T}$ (~ total event activity)
  - At low p_T^W, underlying event & **pileup** <μ> contribute to deterioration of the recoil resolution → **therefore to the statistical sensitivity to m_W**

W mass sensitivity and pileUp





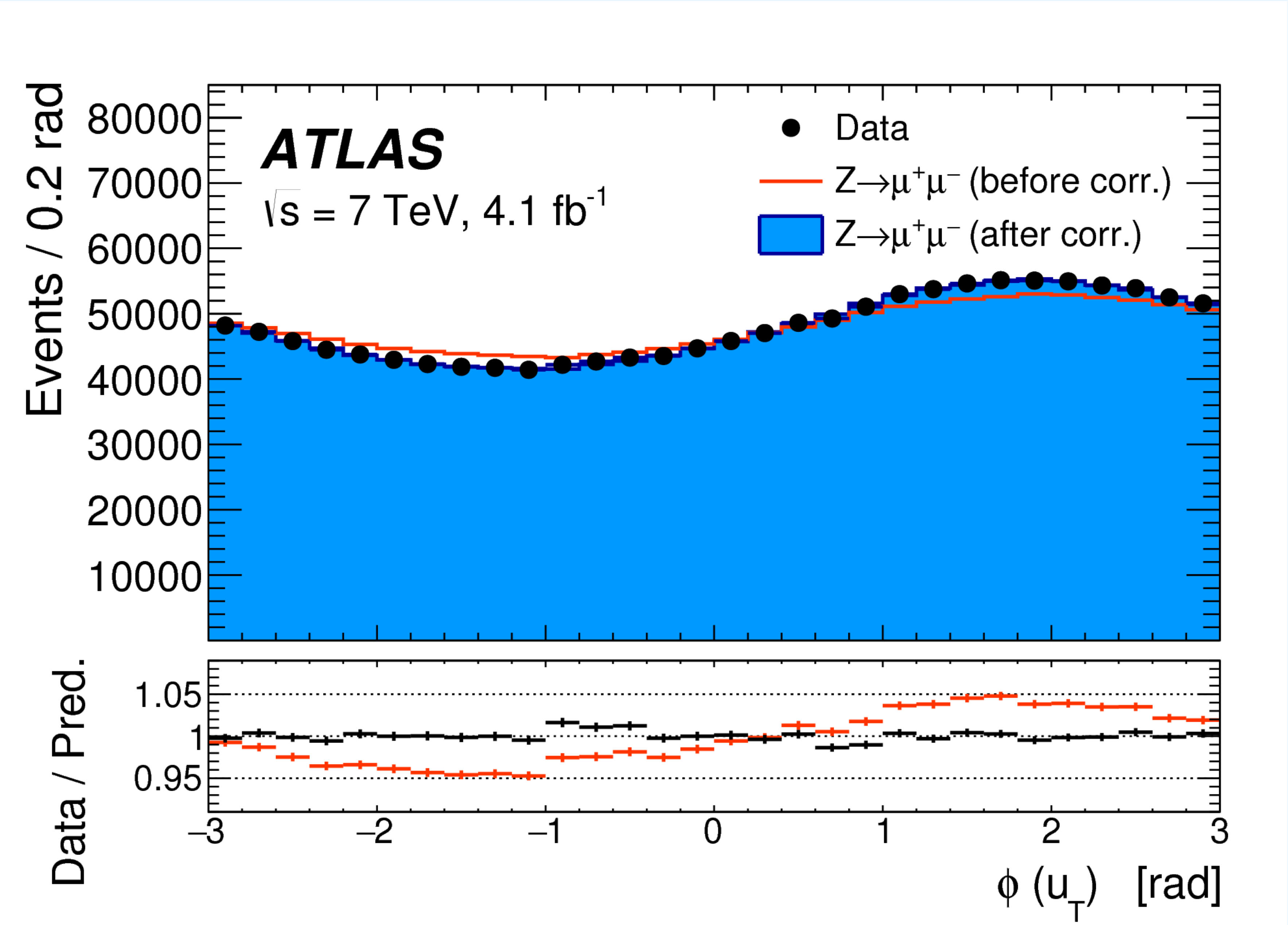


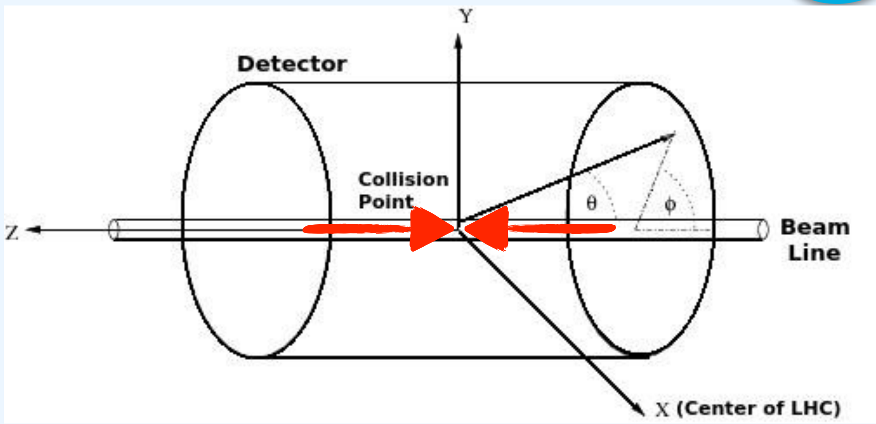
2.5 x better $\sigma(u_T)$
7TeV vs 5TeV
<μ> = 9 vs <μ> = 2

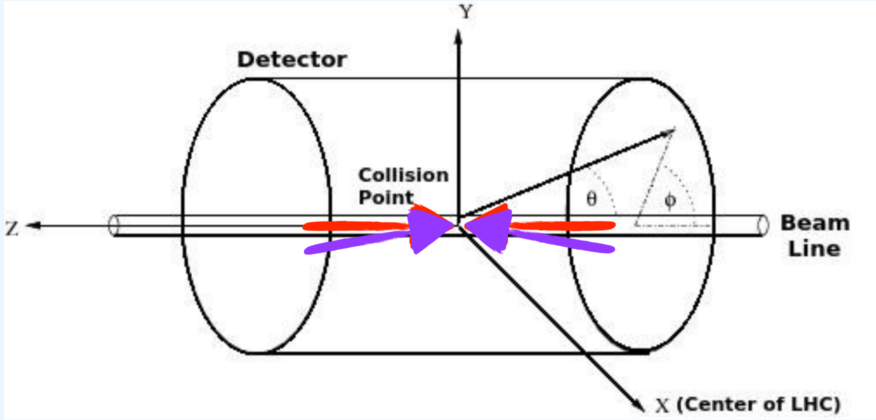
u_T resolution strongly depends on **ΣE_T** (~ total event activity)

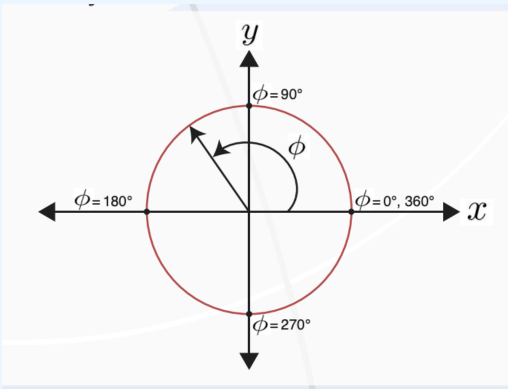
- At low p_T^W, underlying event & **pileup** <μ> contribute to deterioration of the recoil resolution → **therefore to the statistical sensitivity to m_W**

bonus: perfect knowledge of our detectors ?



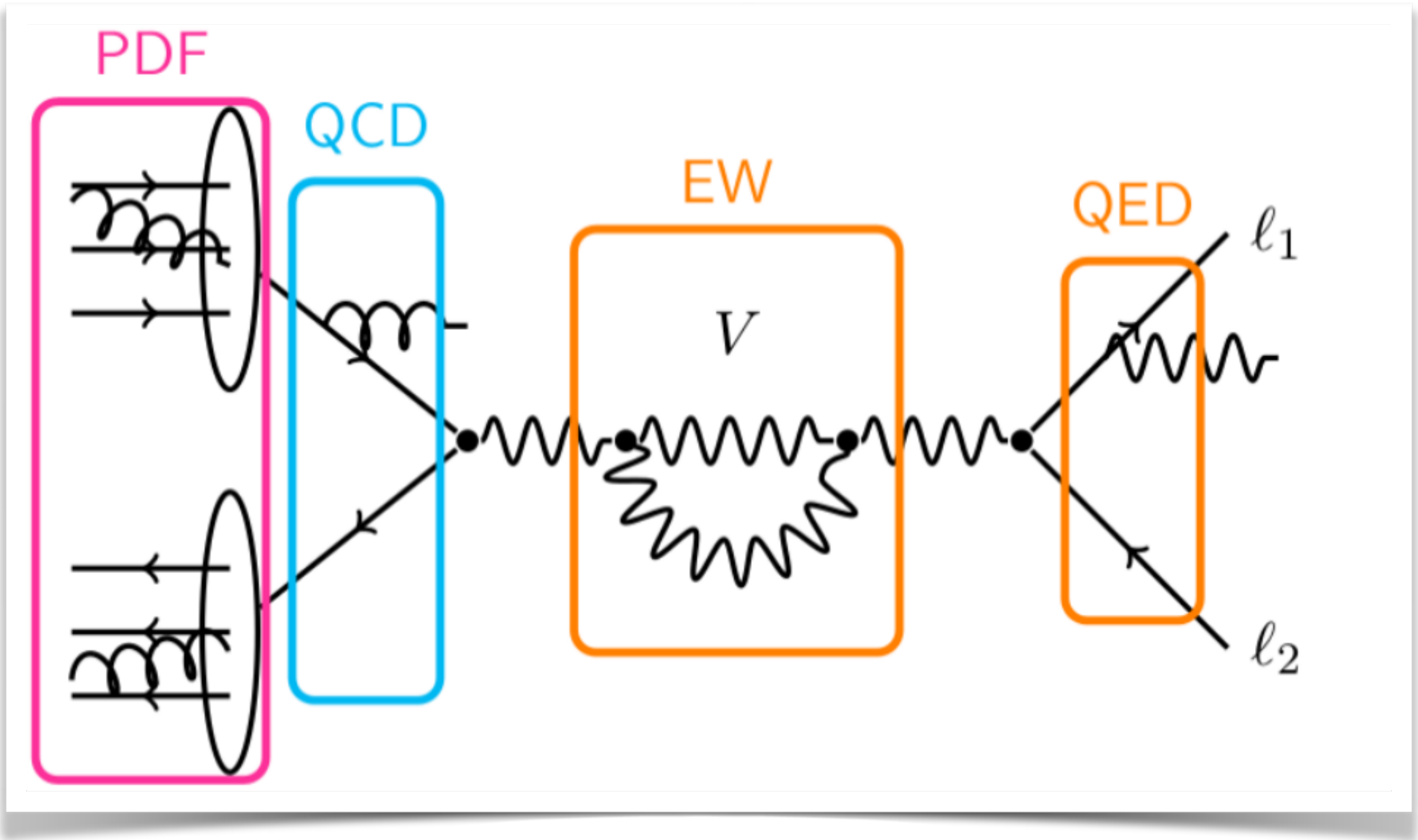


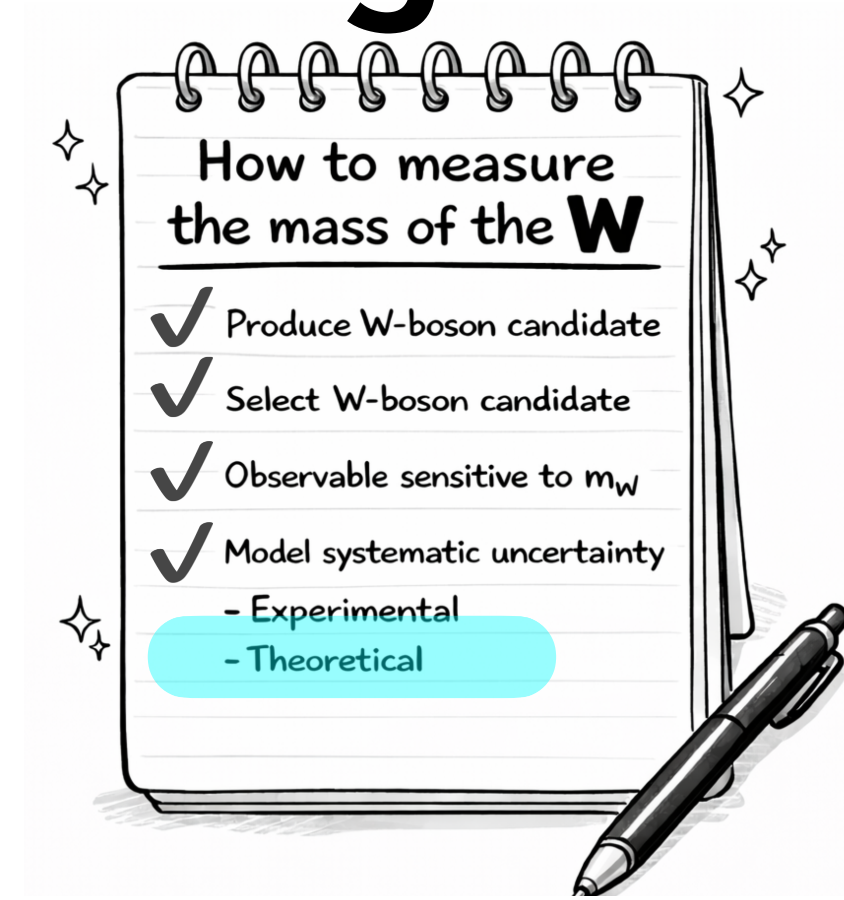




In the ideal case of beams coinciding with the z-axis, the physical transverse momentum of W and Z bosons is uniformly distributed in ϕ. However, an offset of the interaction point with respect to the detector centre in the transverse plane, the non-zero crossing angle between the proton beams, and ϕ-dependent response of the calorimeters generate anisotropies in the reconstructed recoil distribution.

The W physics modelling

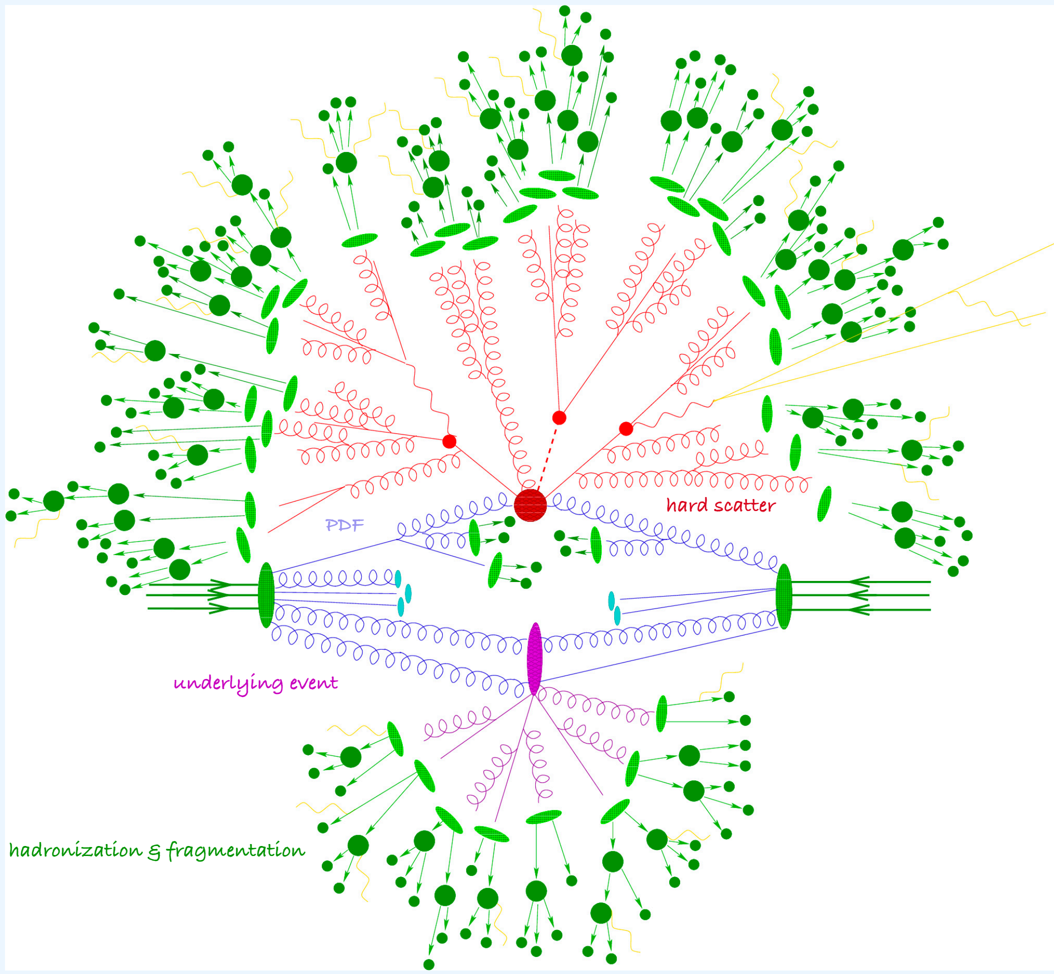




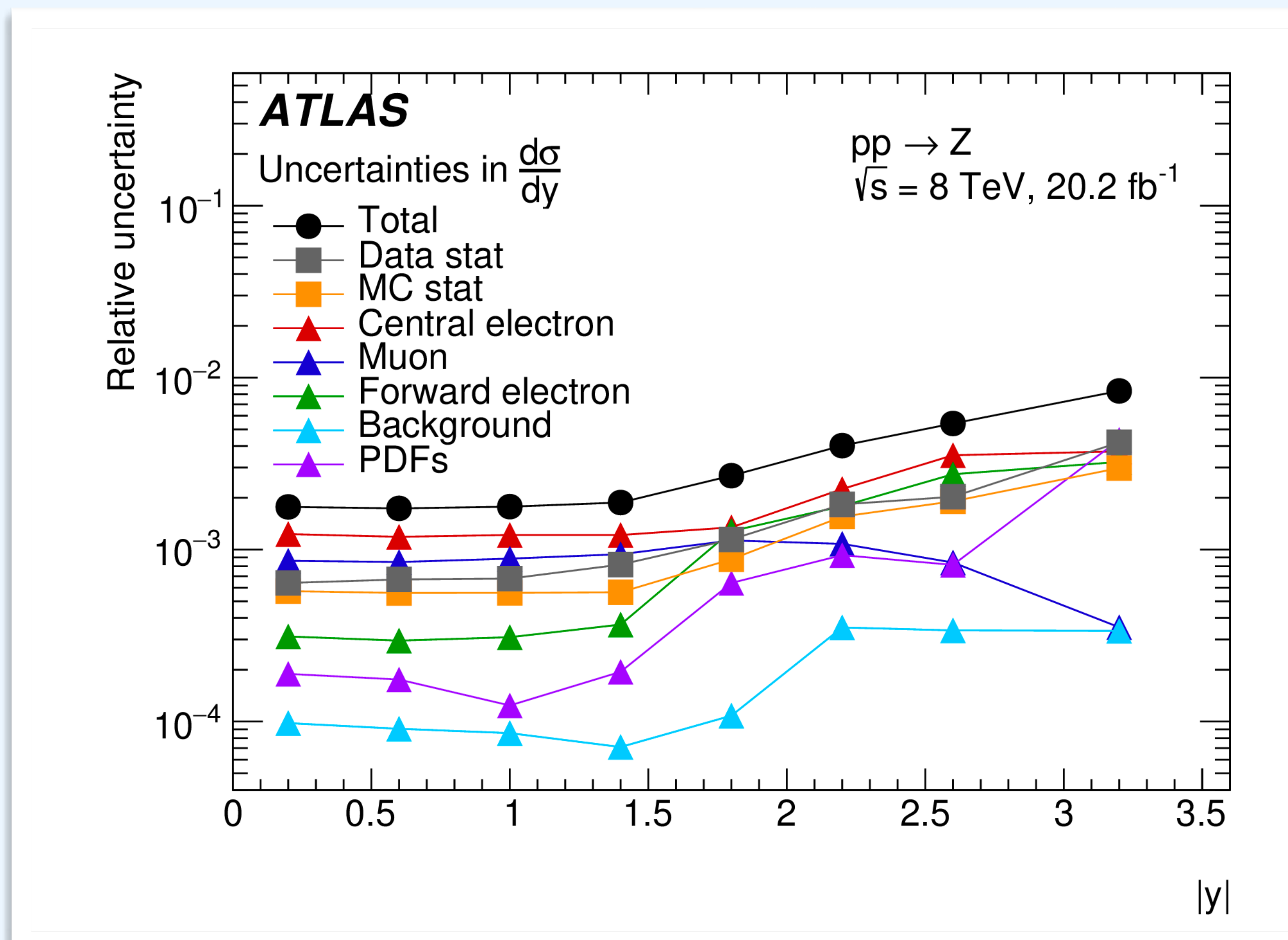
δm_W< 10 MeV precisions required ~0.1-0.2% control on the kinematics of the W production, sub-percent accuracy of predictions for PDF ; p_T^W modelling and W polarisation (Ai) is extreme challenge for QCD theory!

Theory advancement

Tremendous progress in theory in the past 10 years !



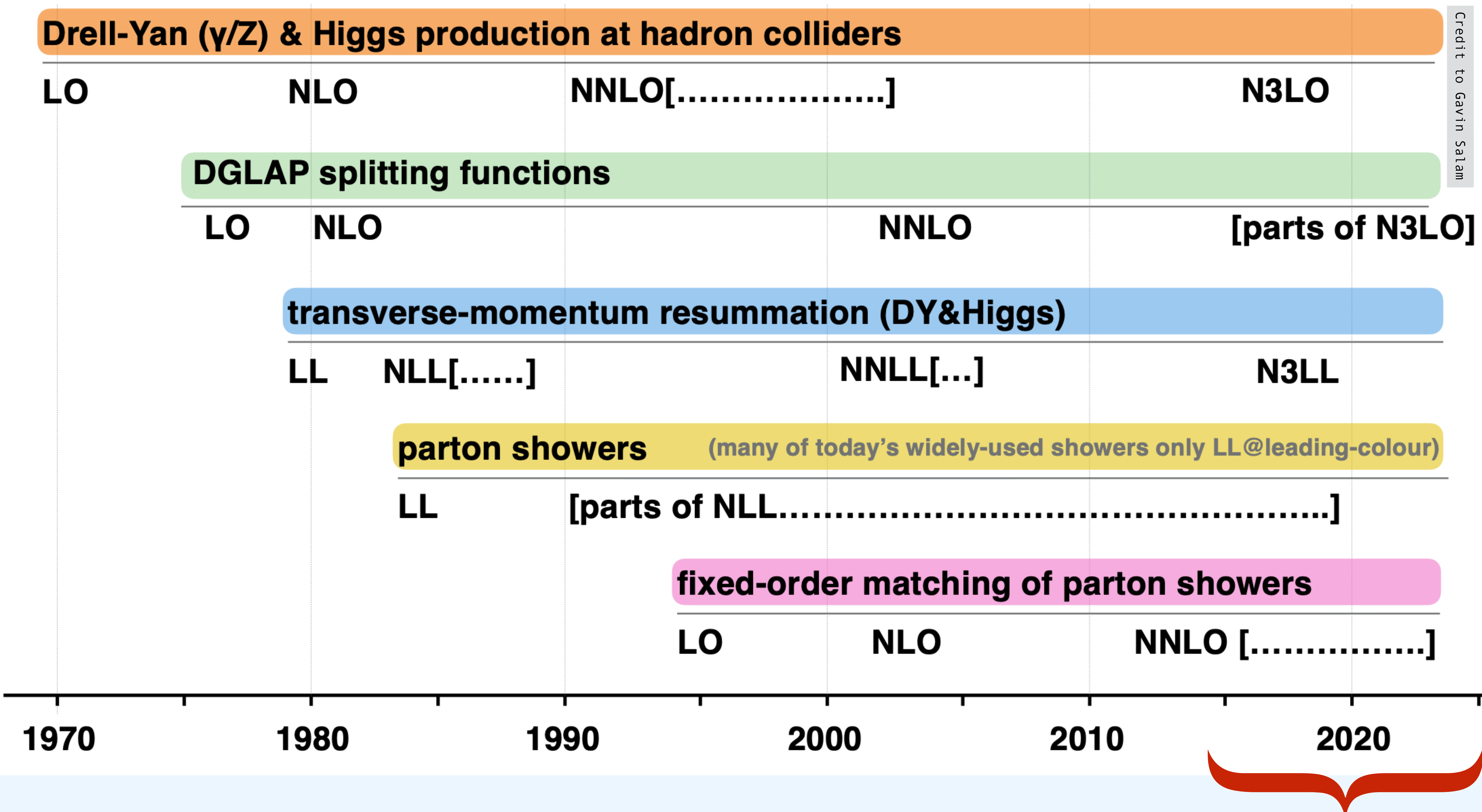
At the **level of precision achieved by LHC experiments,** pushing the **theory frontier for all contributors to our predictions essential**



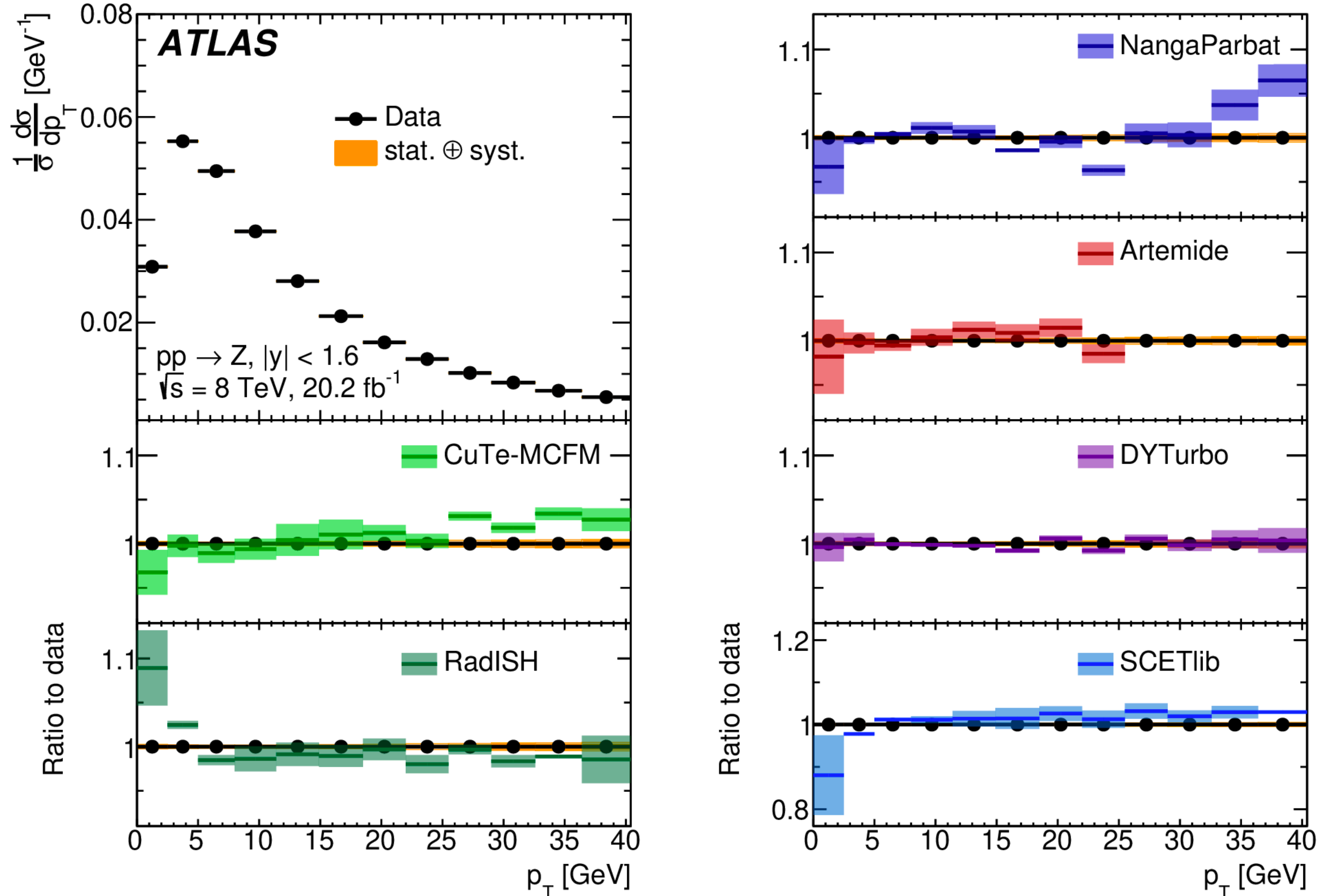
differential X-section measurement of Z boson production
‰ accuracy in the central $|y^Z|$ region below % uncertainties up to $|y^Z| < 3.6$

Theory advancement

Tremendous progress in theory in the past 10 years !



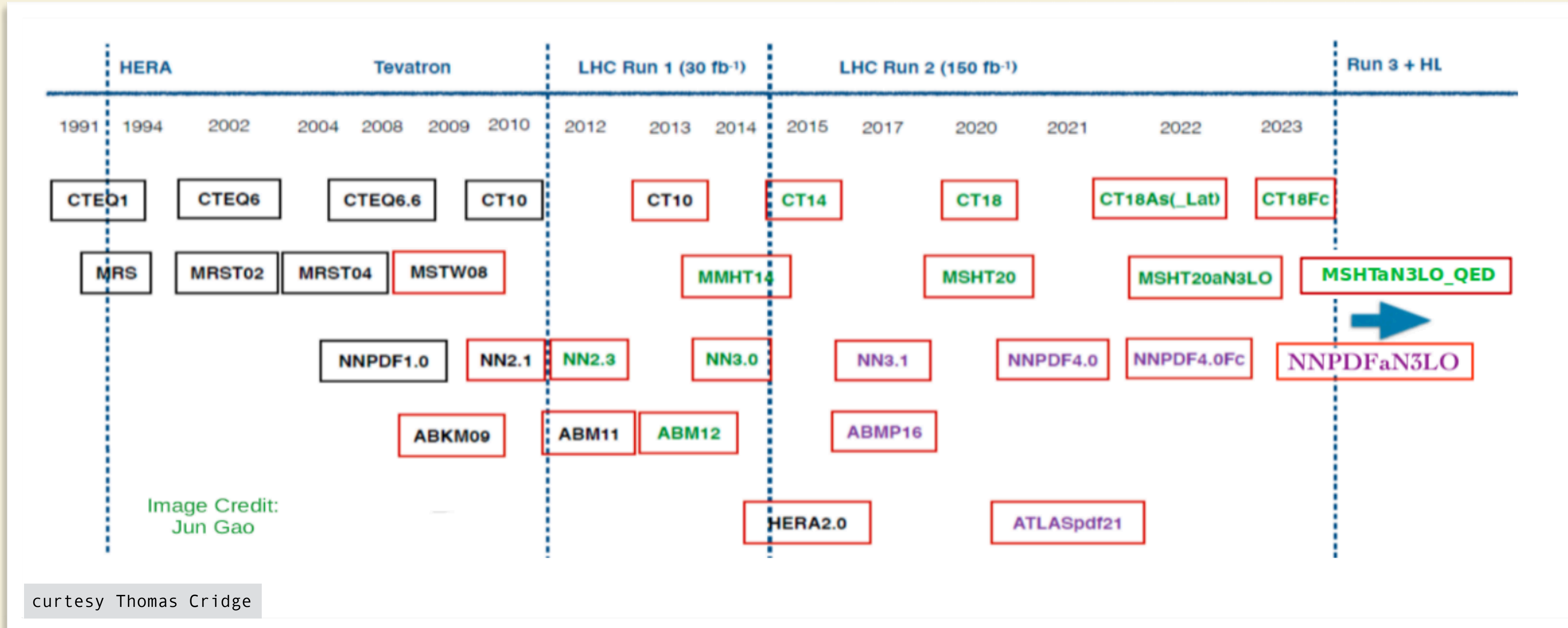
NNLO outdated →N3LO + resummation

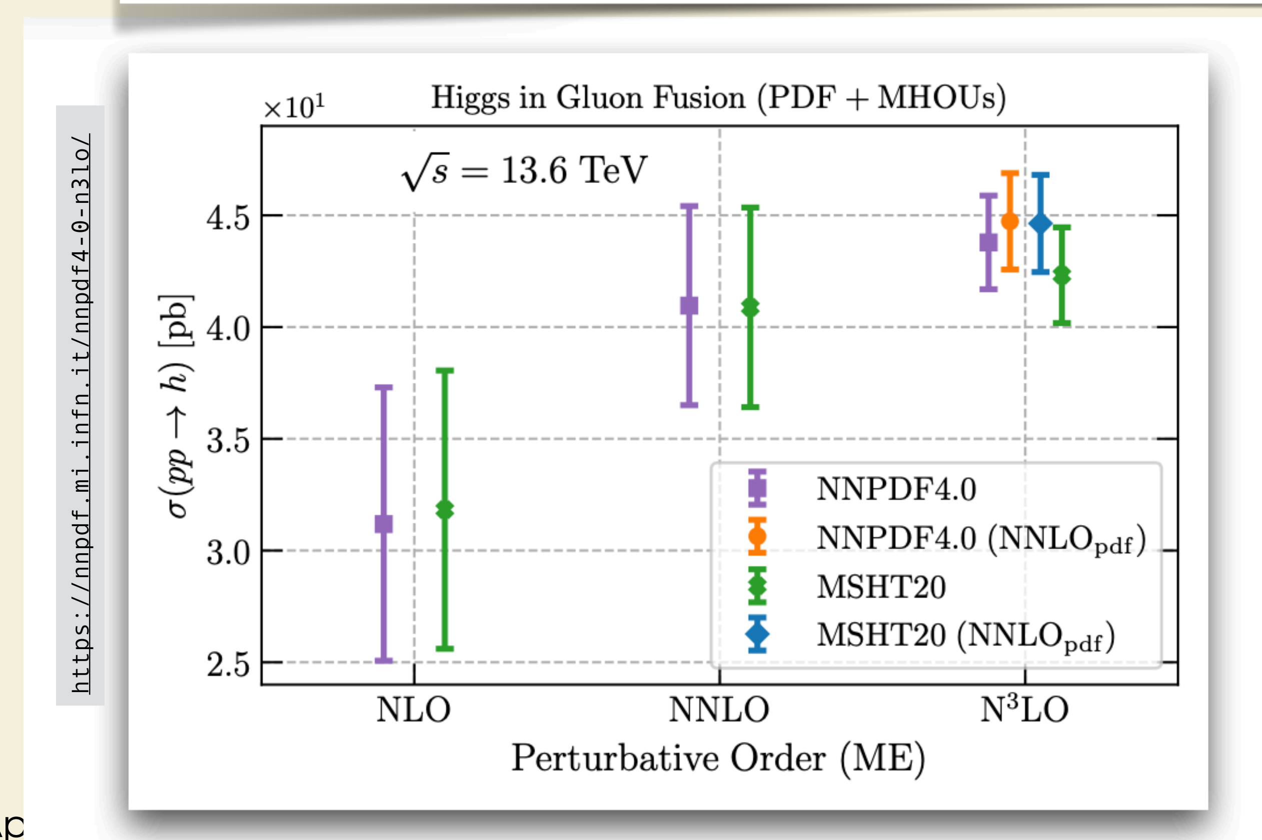


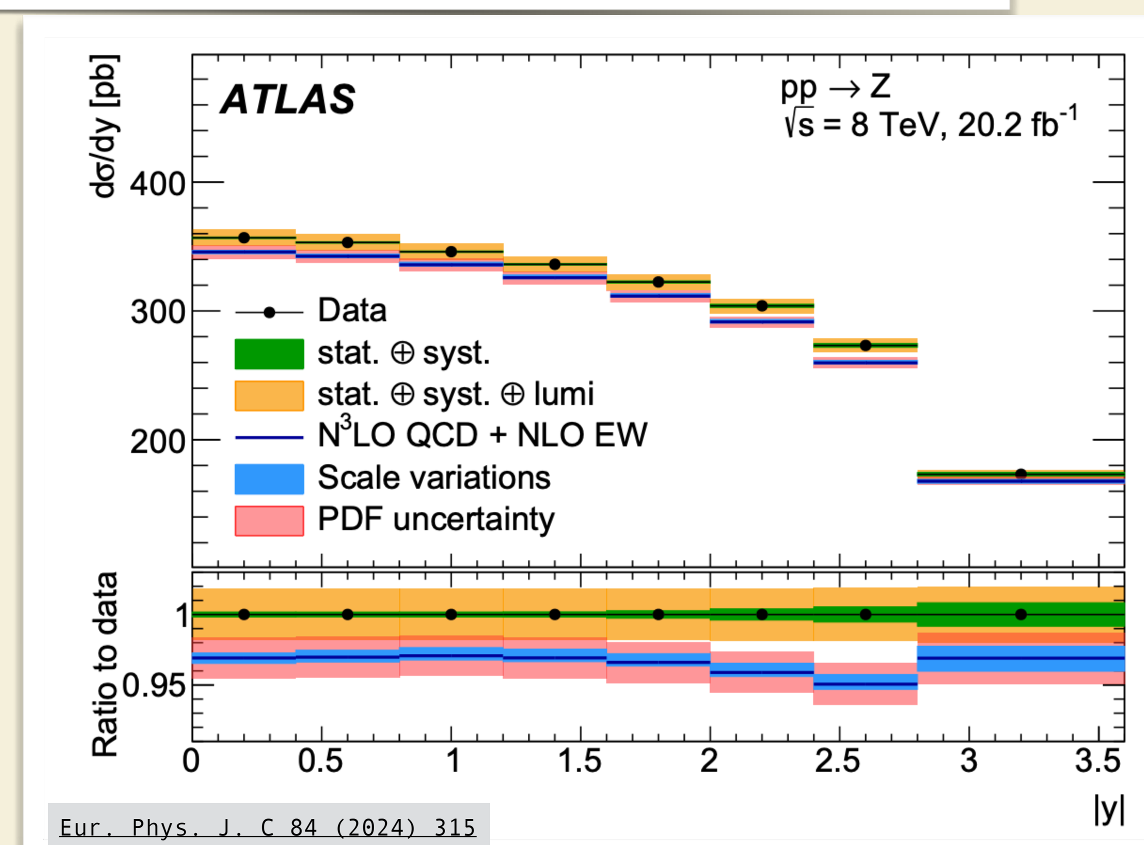
[Eur. Phys. J. C 84 (2024) 315]

The Z-boson normalised $d\sigma/dp_T$ measurement compared with different state-of-the-art QCD perturbative calculations based on qT resummation @ approximate N4LL accuracy.

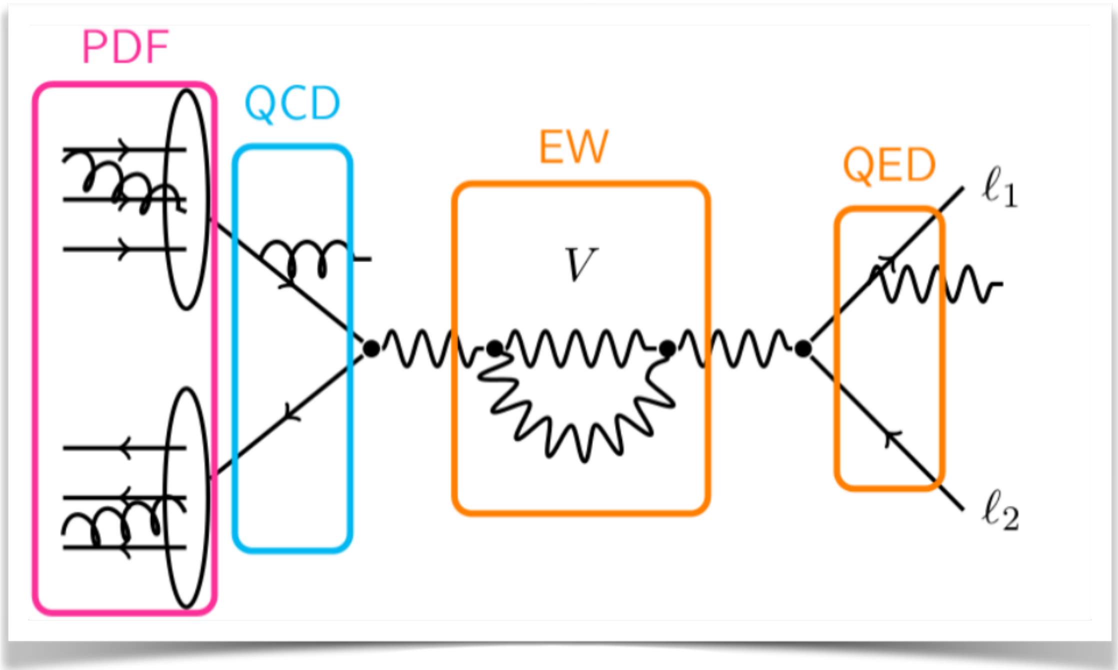
NNLO outdated →N3LO in PDF

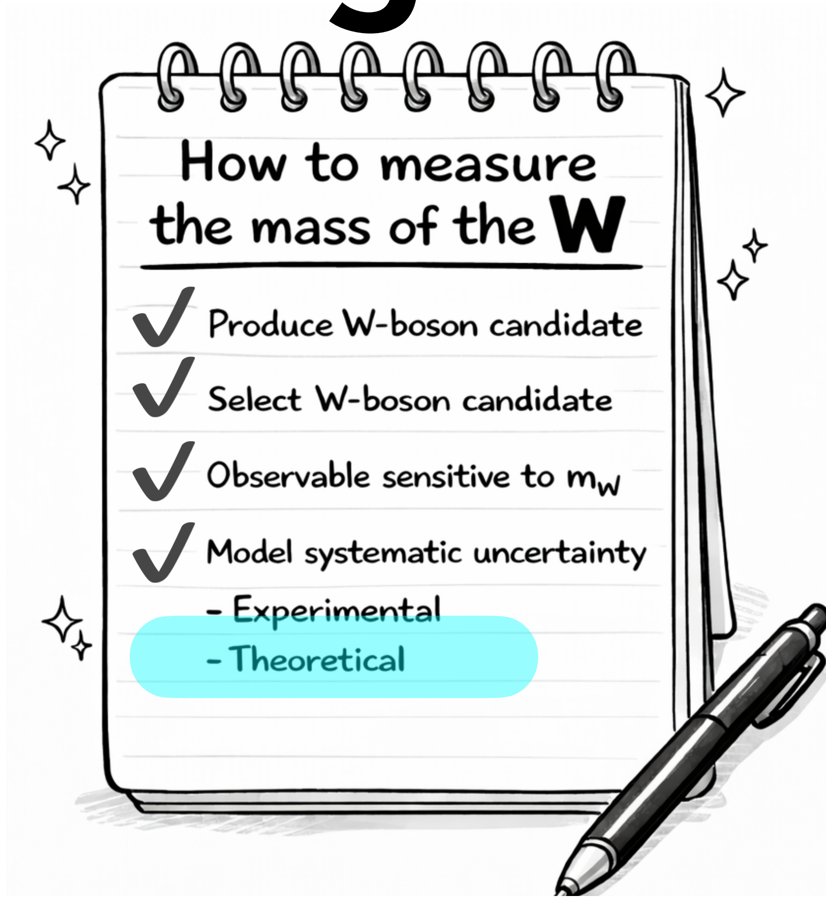






The W physics modelling

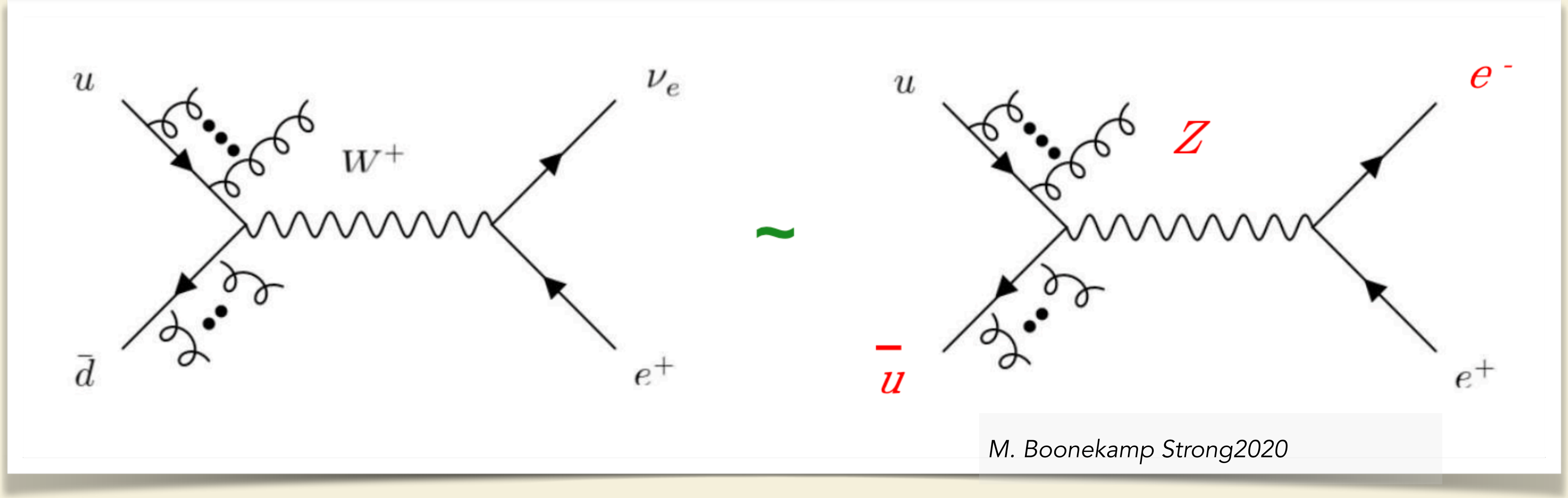


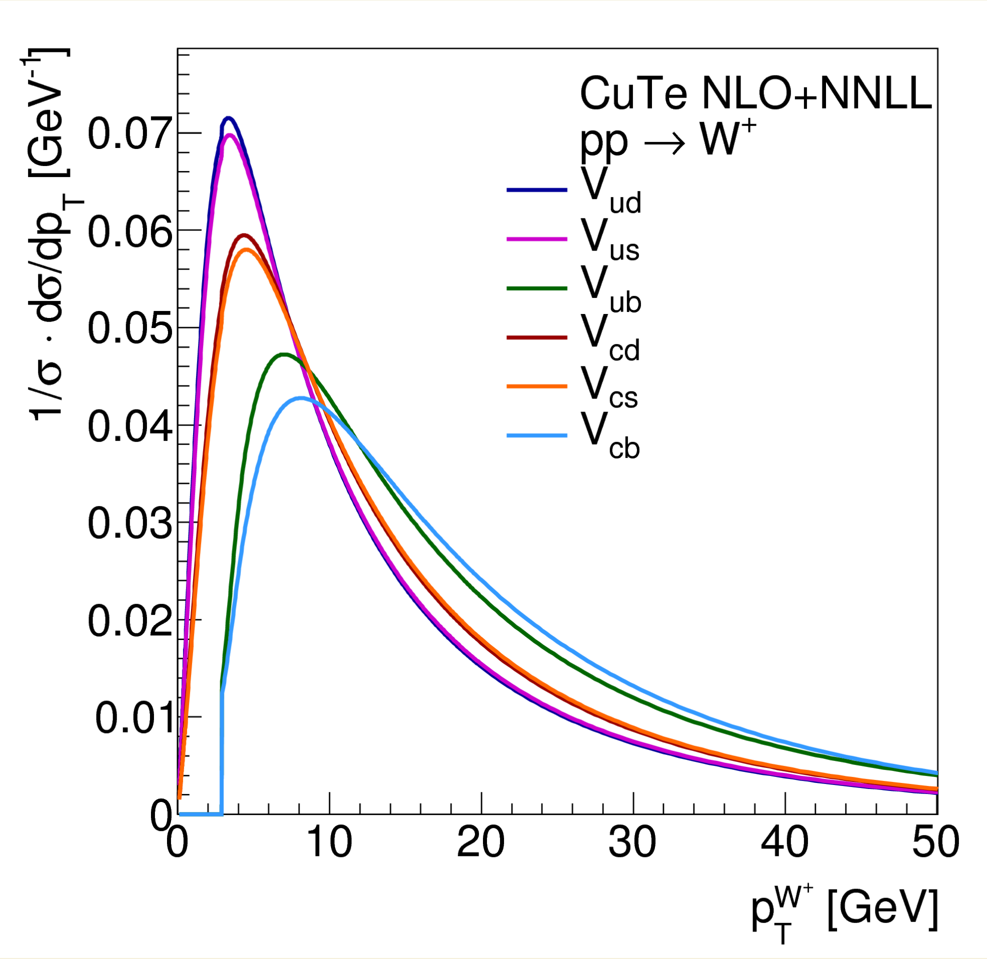


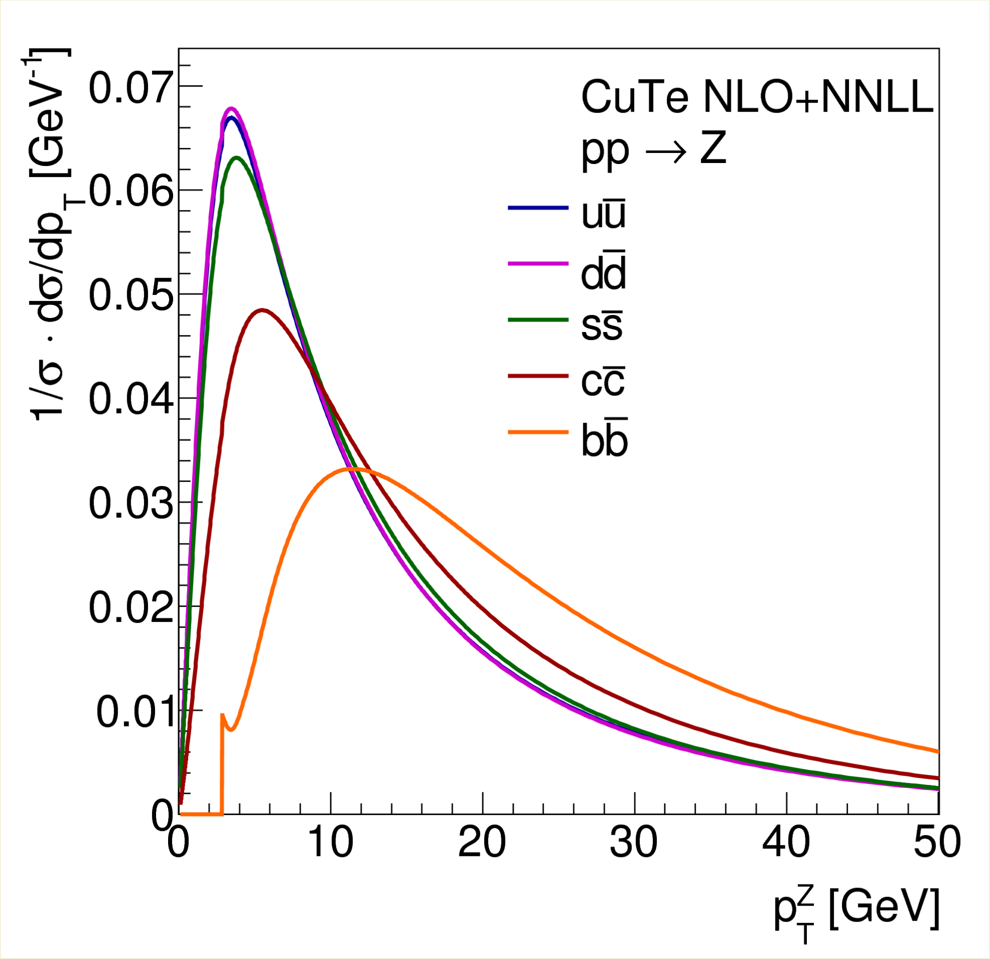
- @LHC W mass physics modelling is described using a **composite model** :
- Start from the NLO/NNLO generators + LL parton-shower (Pythia8) and apply corrections to reach the state of the art accuracy.
  - Using an useful decomposition: factorising the dynamic of the boson production and the kinematic of the boson decay.

$$\frac{d\sigma}{dp_1 dp_2} = \left[\frac{\mathrm{d}\sigma(\mathrm{m})}{\mathrm{dm}}\right]\left[\frac{\mathrm{d}\sigma(\mathrm{y})}{\mathrm{dy}}\right]\left[\frac{\mathrm{d}\sigma(\mathrm{p_T})}{\mathrm{dp_T}}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7} A_i(p_T, y, m)\, P_i(\cos\theta, \phi)\right]$$

QCD it is not identical for W and Z boson



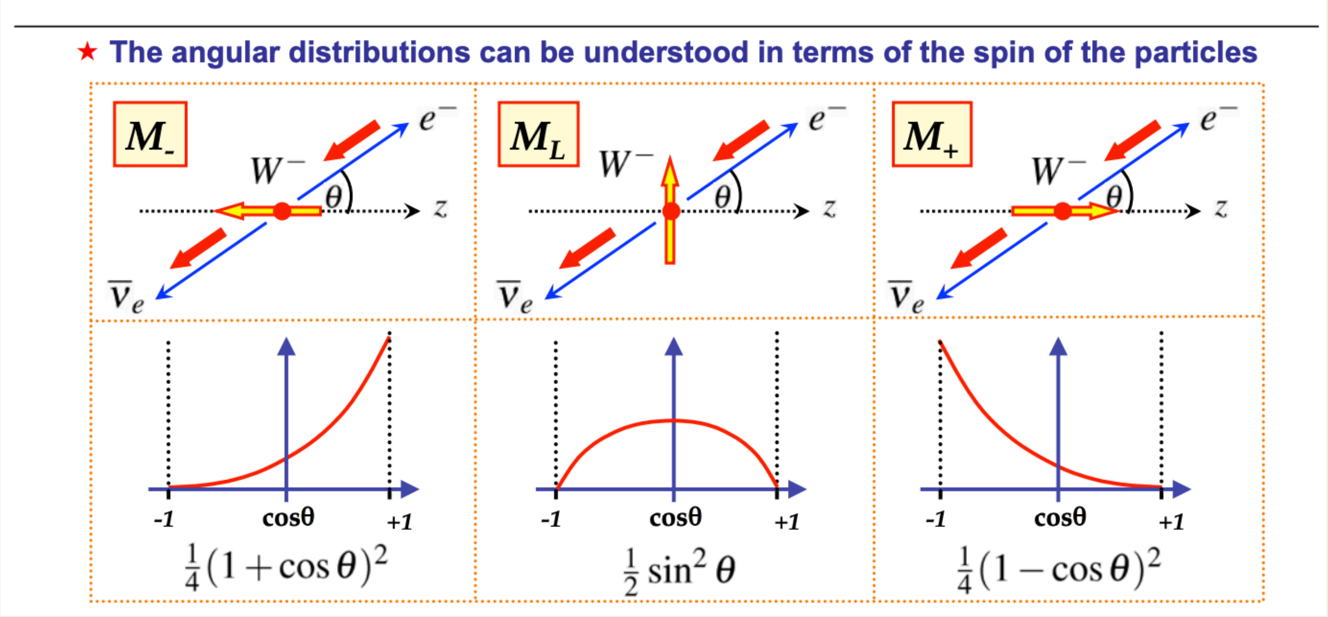


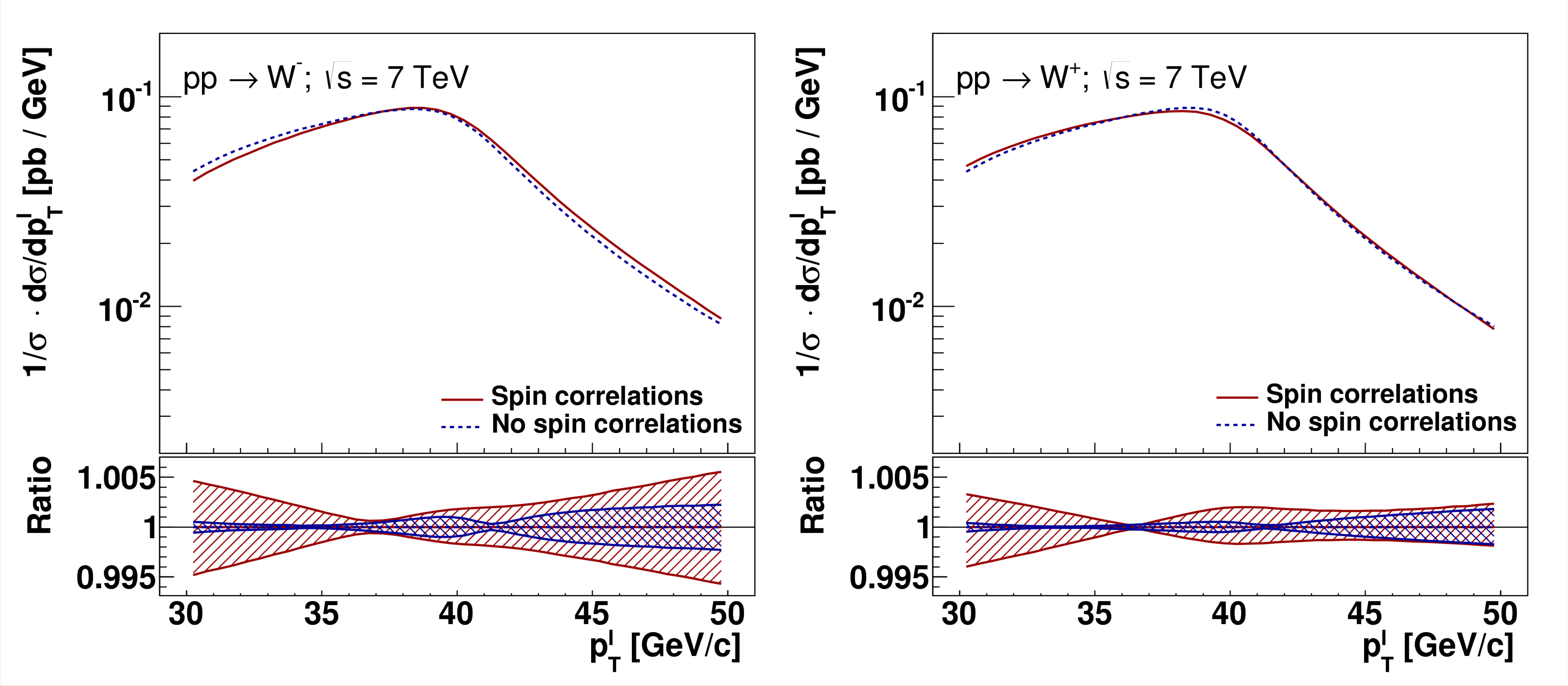


More Info

W+, W- and Z are produced by different light flavour fractions

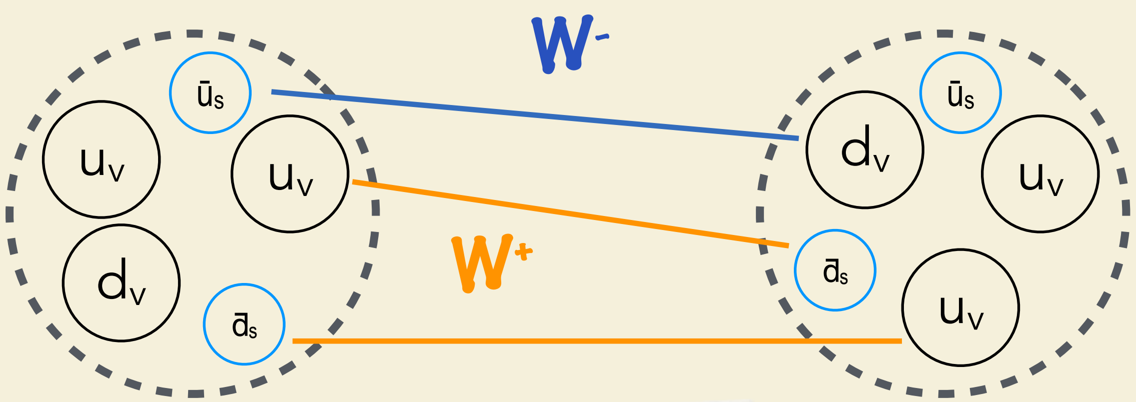
Spin correlation





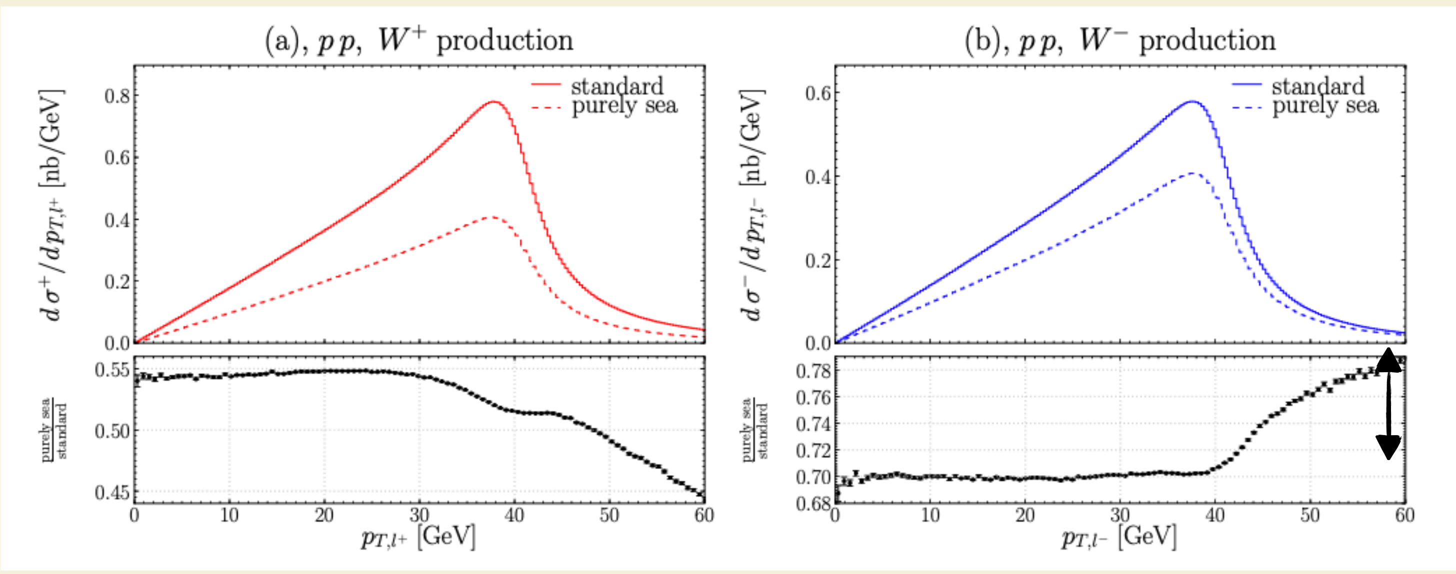
More Info

PDF



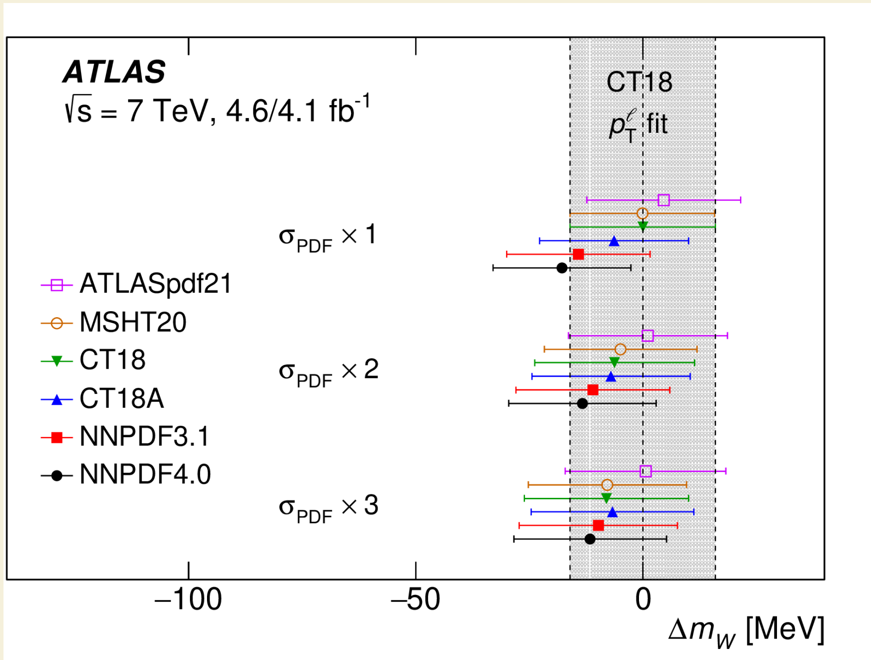
In pp collision: different cross section for W+ and W- and different dynamics.

Eur. Phys. J. C 69 (2010) 379-397



- Difference between u,d valence and the see distributions determine the W-boson rapidity distributions → affects acceptance and fiducial volume
  - kinematic distributions & signal yields in the different categories have additional constraining power on the PDFs unc. (*in situ constraint*)

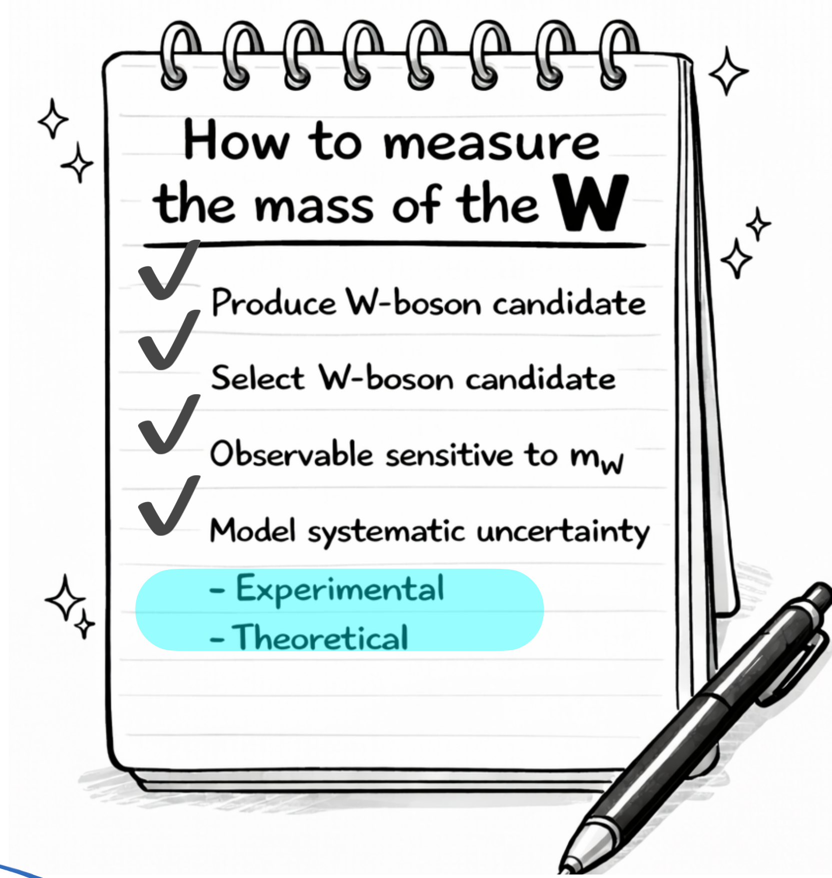
- Profiling of PDF uncertainty:
  - **reduction** of **Δm_W PDFs envelope**
  - **reduction** impact of PDF uncertainties
    (*previous measurement* $\delta_{(PDF)}$ m_W = *9-10 MeV*)
  - **CT18 PDF** set **baseline**: $\delta_{(PDF)}$ m_W = *7.7 MeV [ATLAS] , 4.4 MeV [CMS]*



The W physics modelling

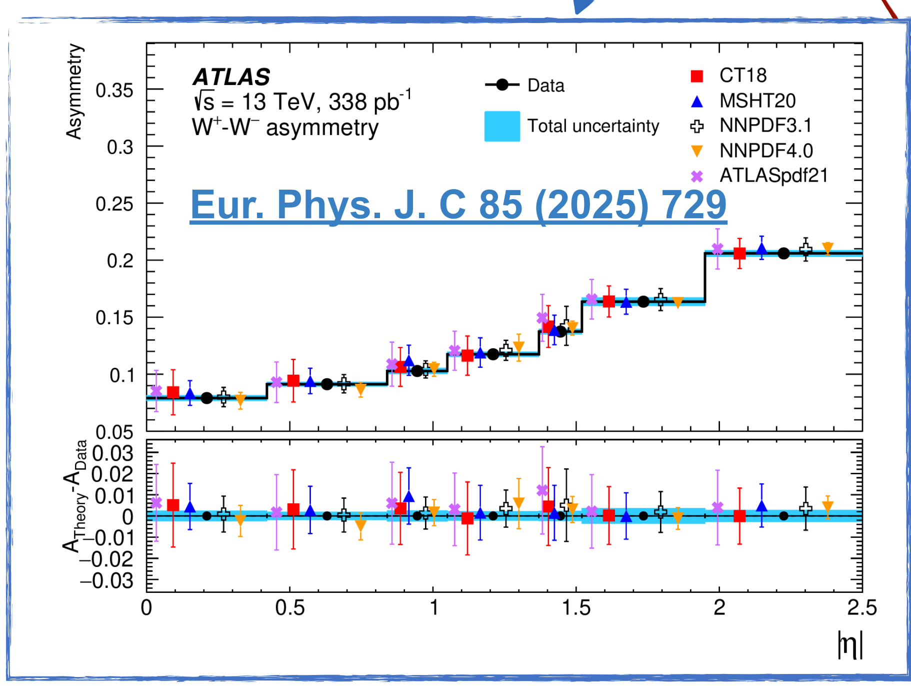
ATLAS/LHCb

- start Powheg+Pythia8 [NLO+LL (PS)] and apply corrections ⇒ NNLO pQCD accuracy
  - **Use ancillary measurements of Drell-Yan processes to validate (and tune) the model and assess systematic uncertainties.**

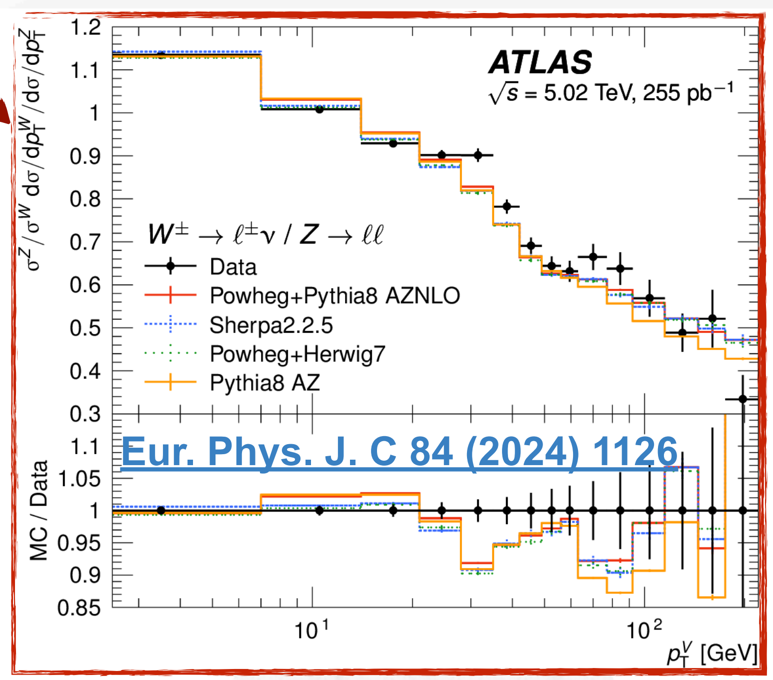


$$\frac{d\sigma}{dp_1 dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T)}{dp_T}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y, m)\, P_i(\cos\theta, \phi)\right]$$

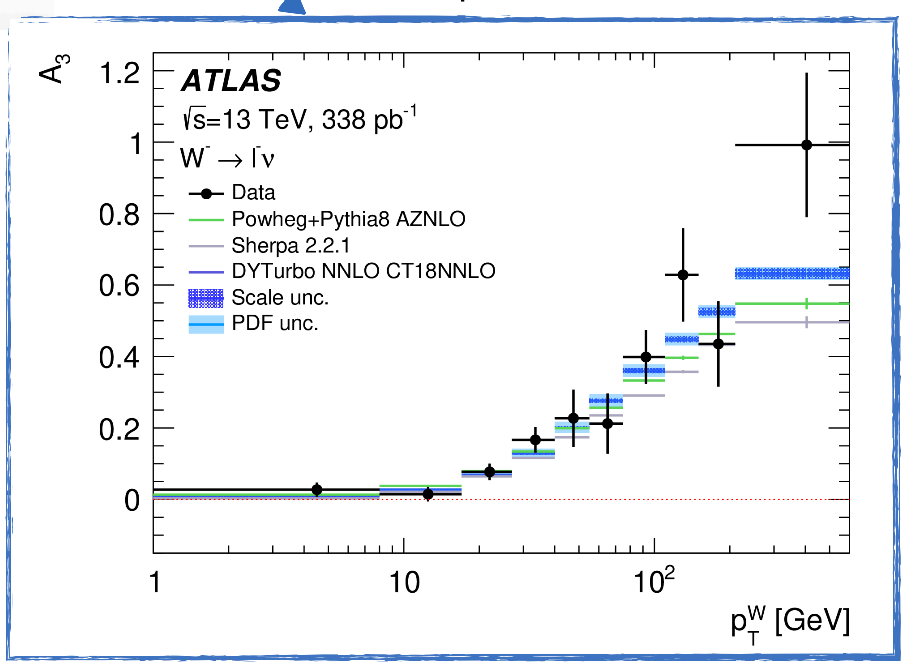
e-print arXiv:2509.13759



Eur. Phys. J. C 85 (2025) 729

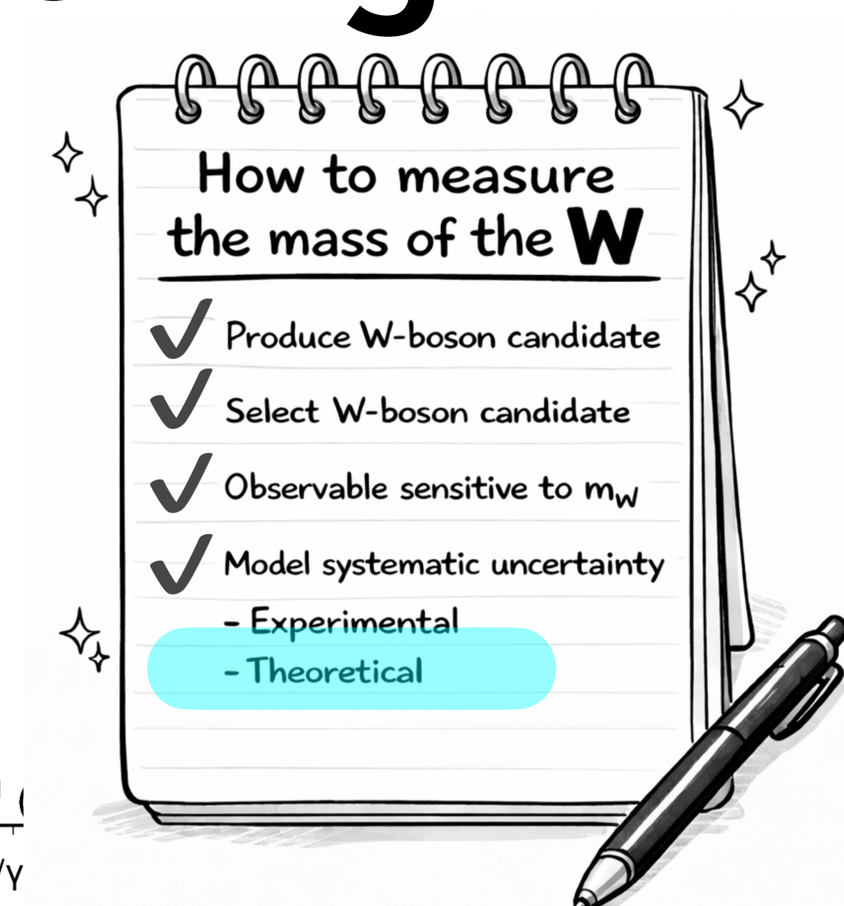


Eur. Phys. J. C 84 (2024) 1126



Incredible set of new extremely precise measurement of W boson production

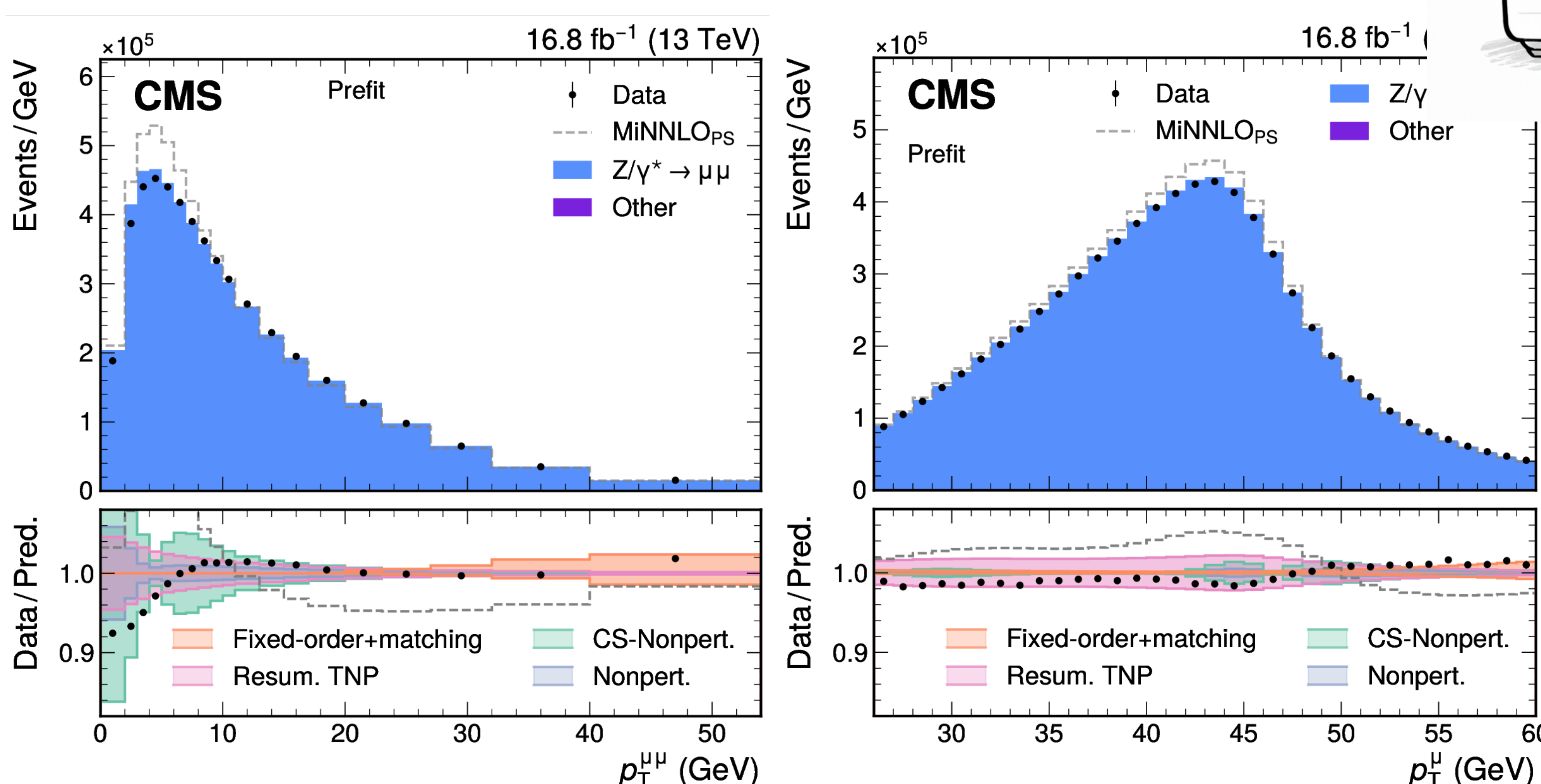
The W physics modelling



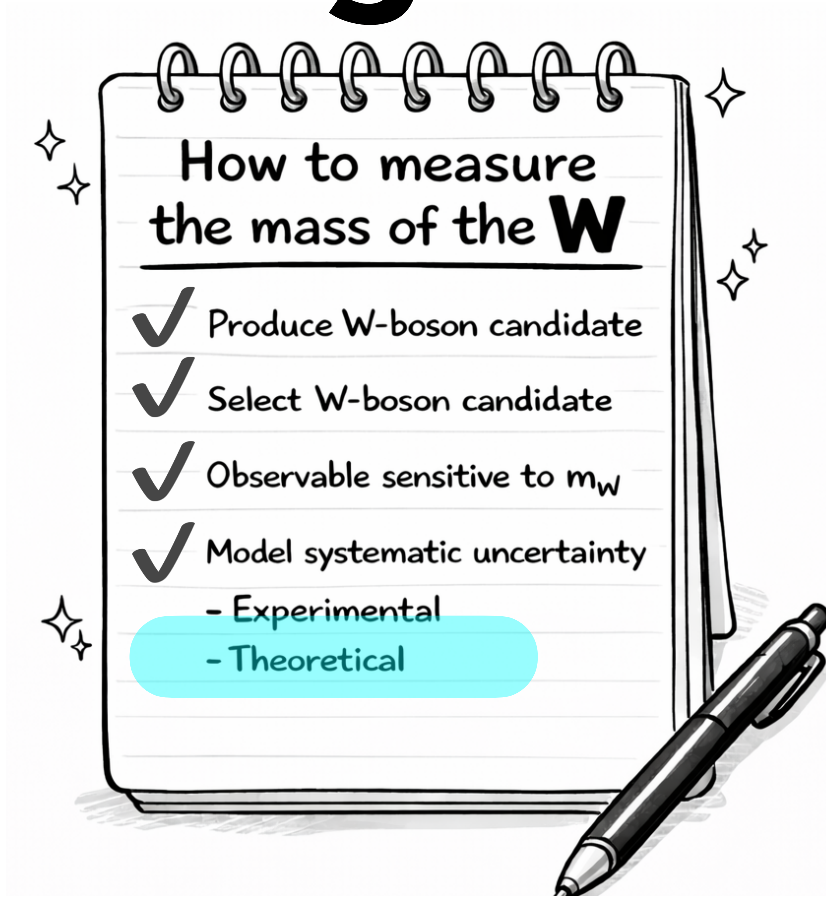
CMS strategy

Fully simulated MC samples with MiNNLOPS+Pythia8 O(α_s^2) accuracy

- p_T^W not directly measured but same procedure applied on W ➜ **Validate with Z boson measurements**



The W physics modelling



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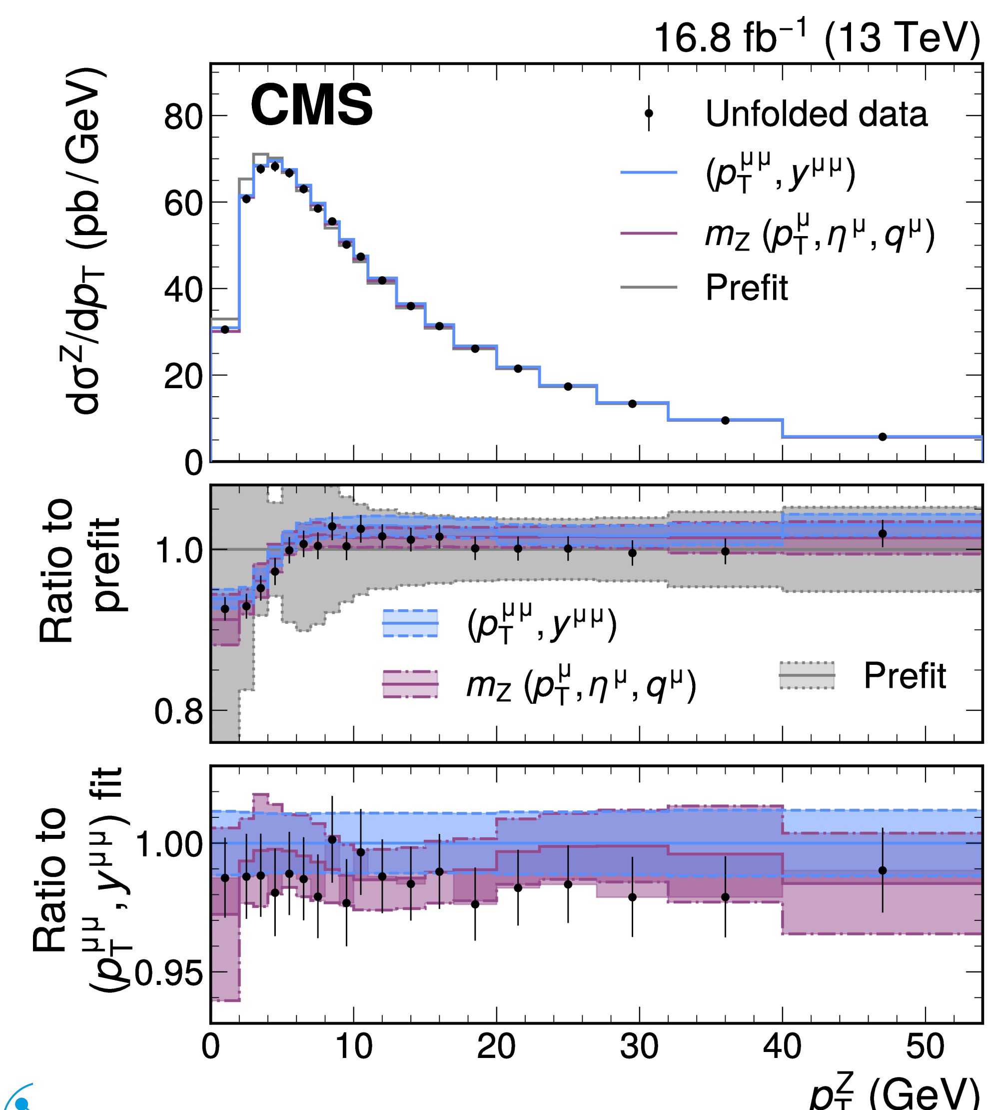
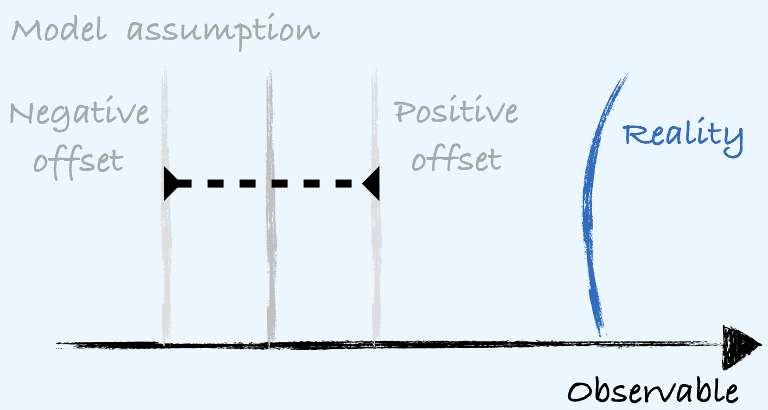


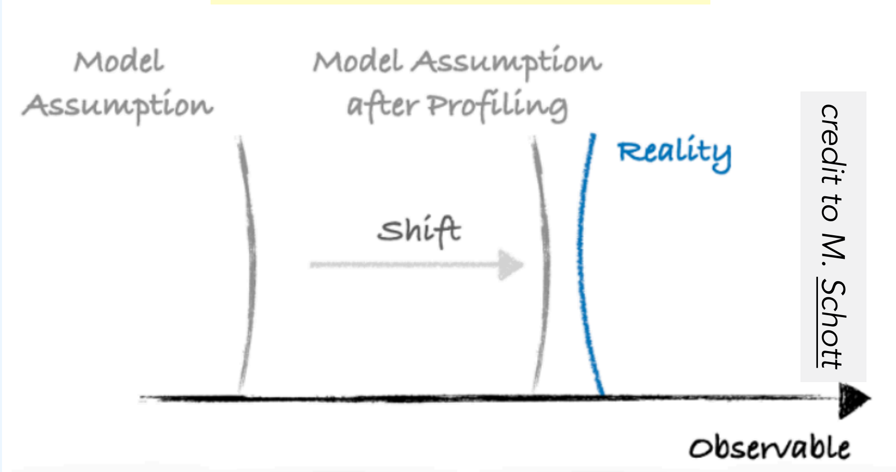
Rely on theory [SCETLIB prediction matched to fixed order DYTurbo prediction (N3LL + NNLO)] and on the *constraining power of the very high statistic of the data* samples

A quantitative example

χ^2 offset fit

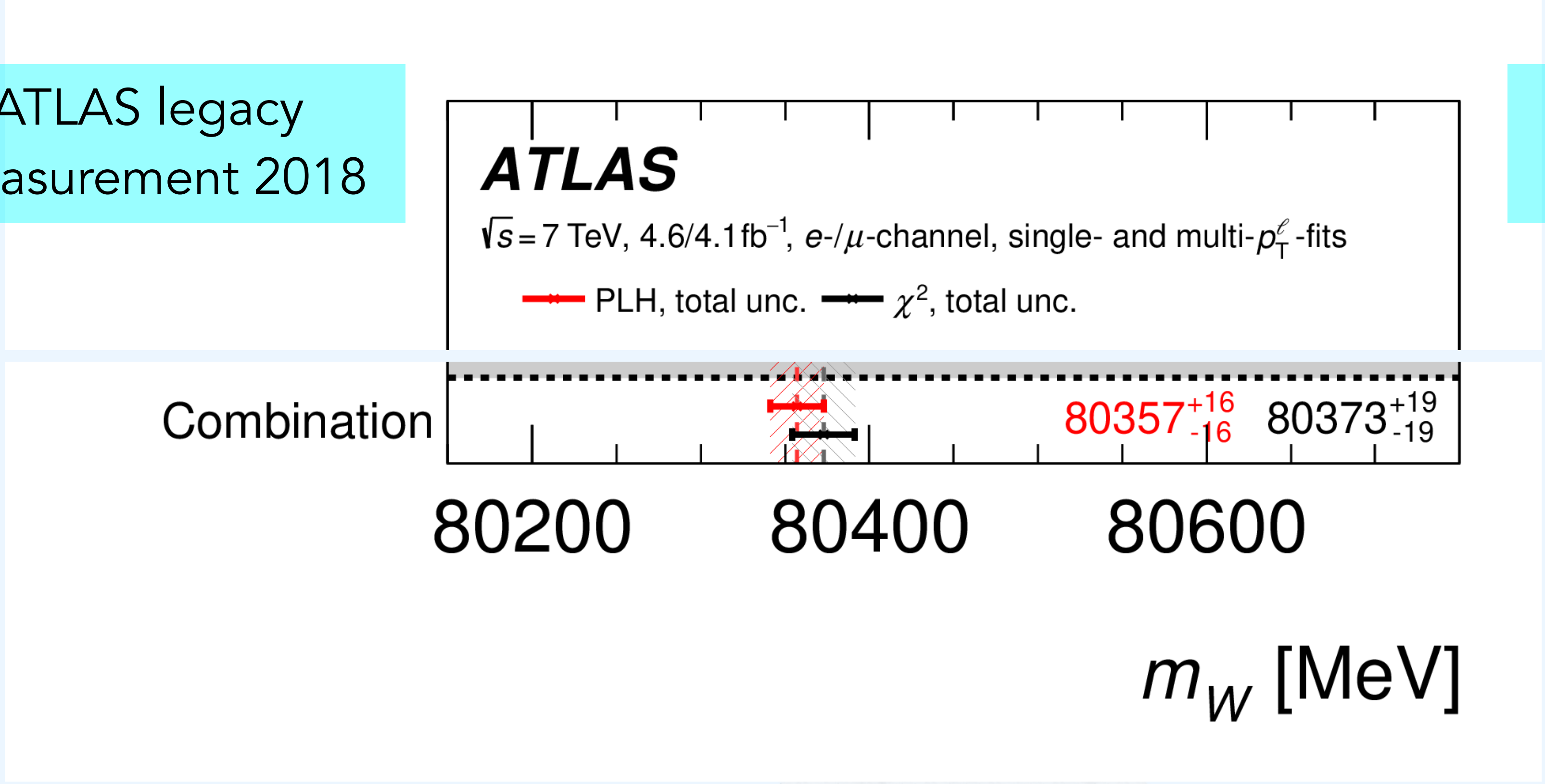


Profiled Likelihood fit



ATLAS legacy measurement 2018

ATLAS improved measurement 2024

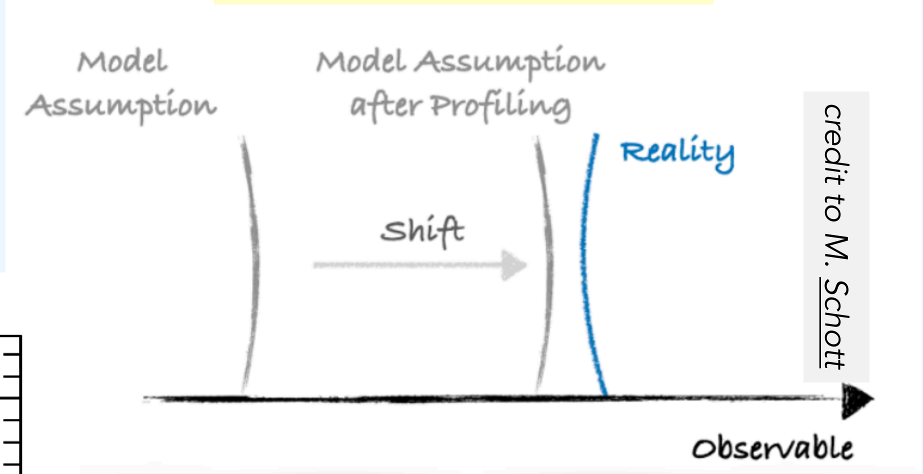


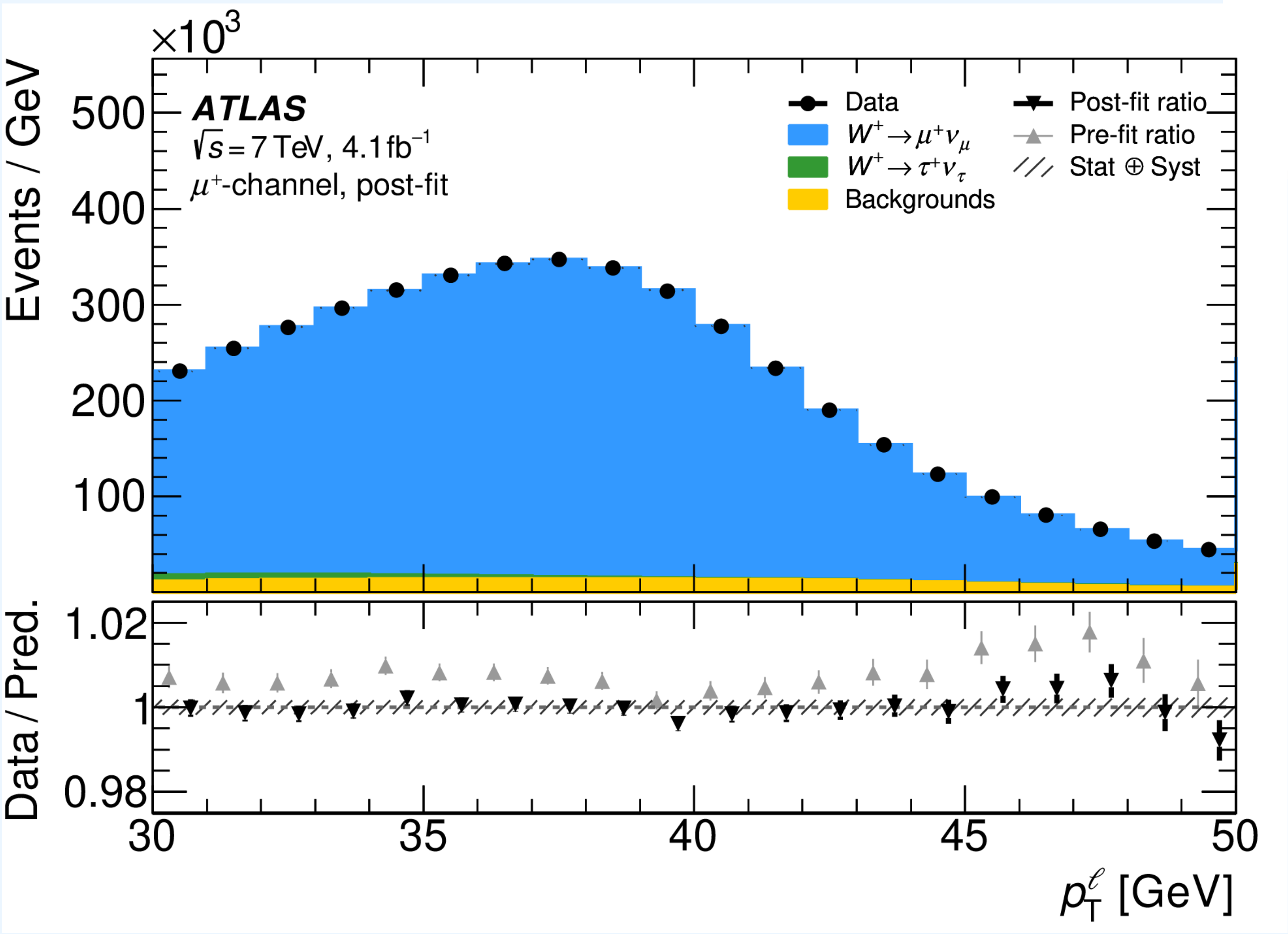
PLH allows simultaneous determination of POI together with NP taking account correlation in each category

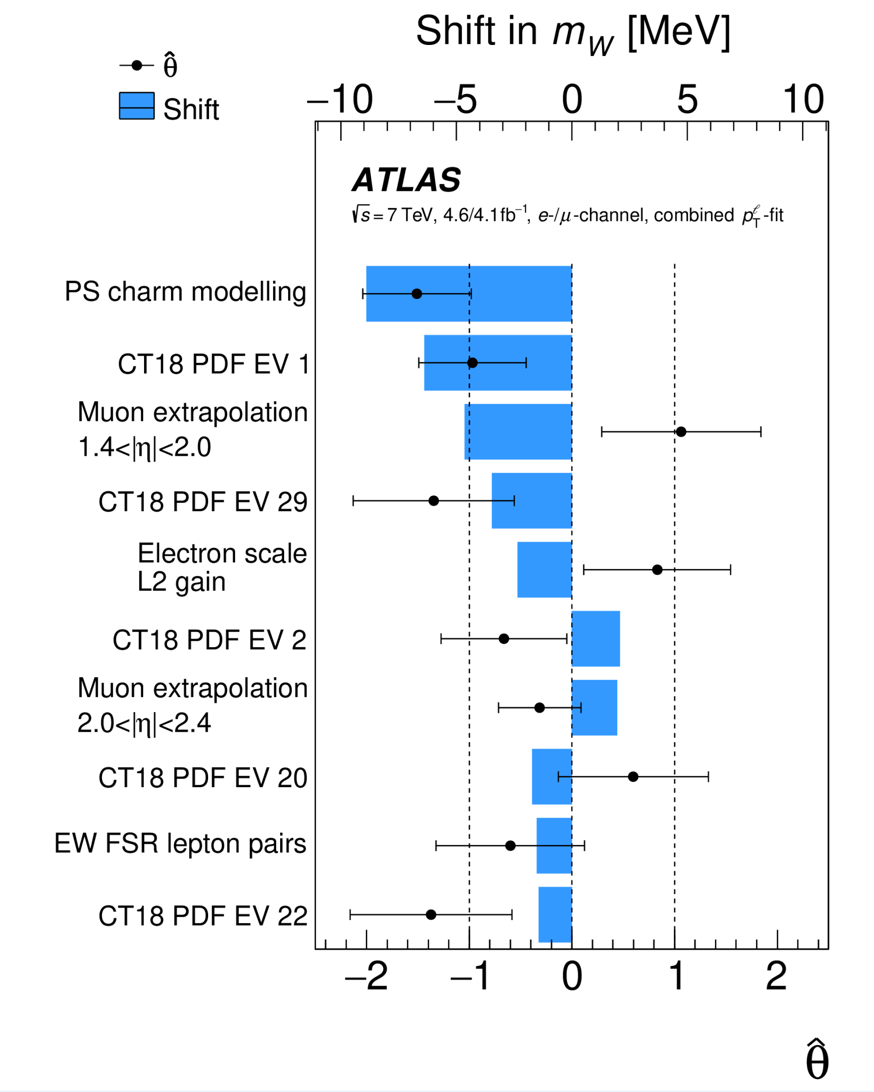
expected allowed shift m_W ±16 (±23) MeV for p_T^l (m_T)

A quantitative example

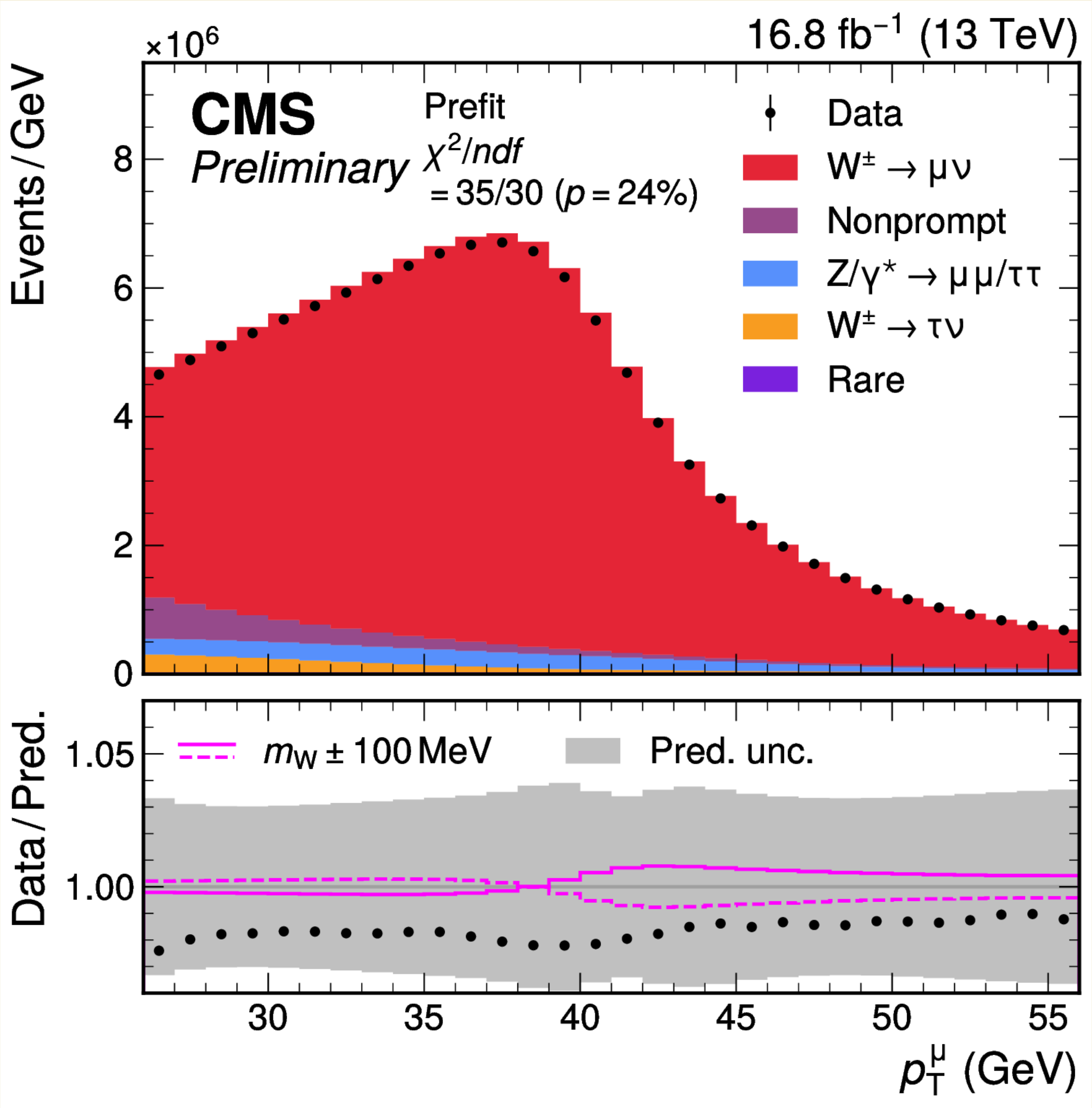
Profiled Likelihood fit



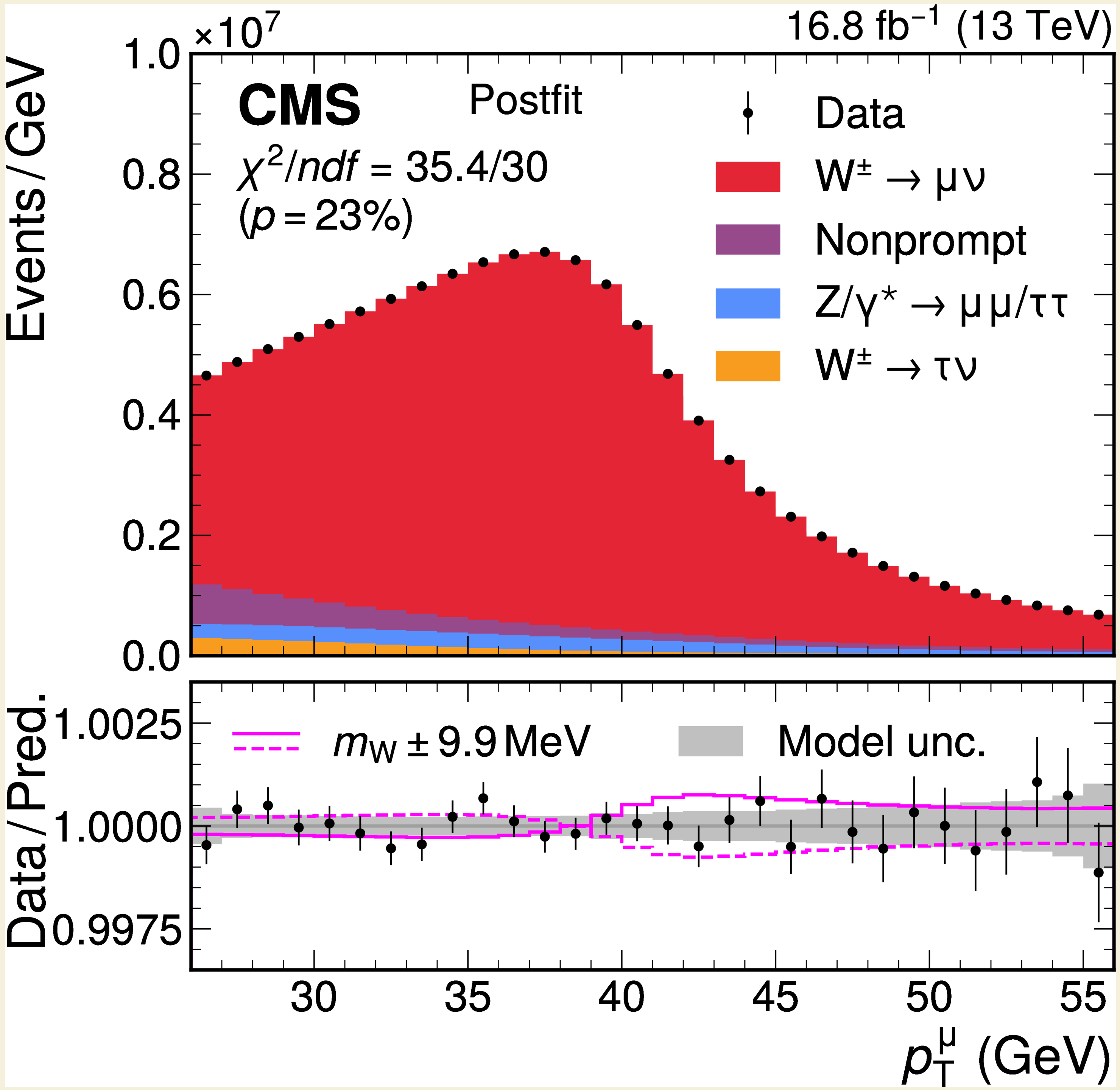




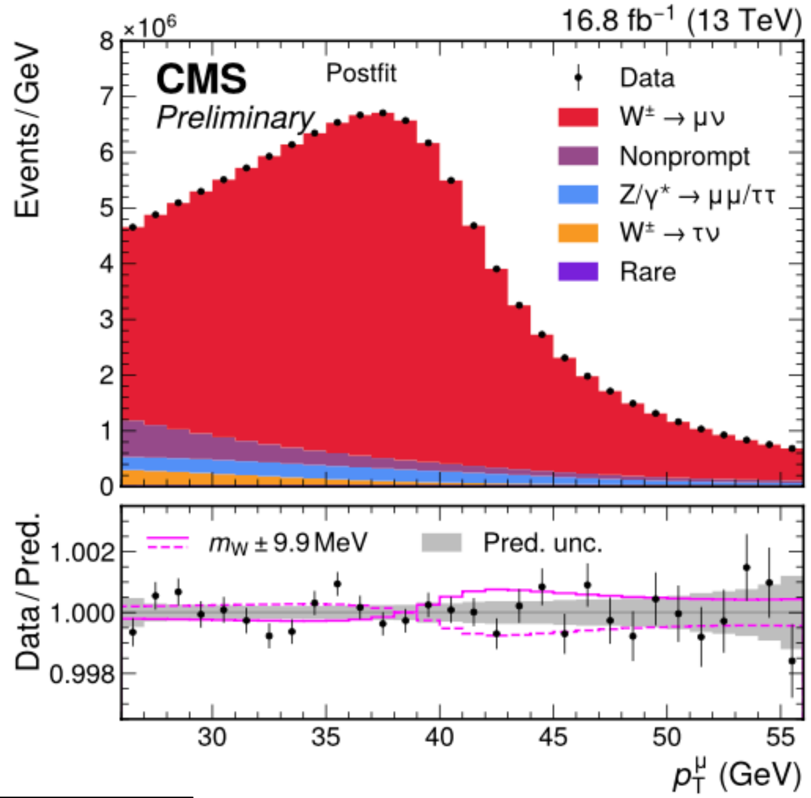
A quantitative example



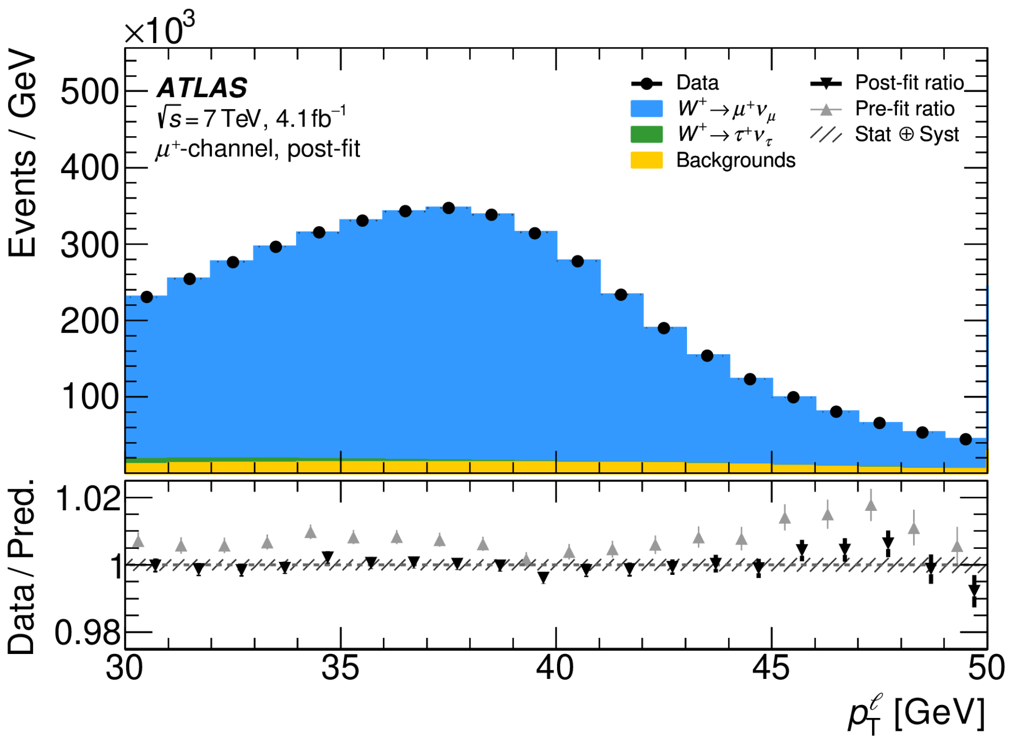
A quantitative example



Uncertainty decomposition

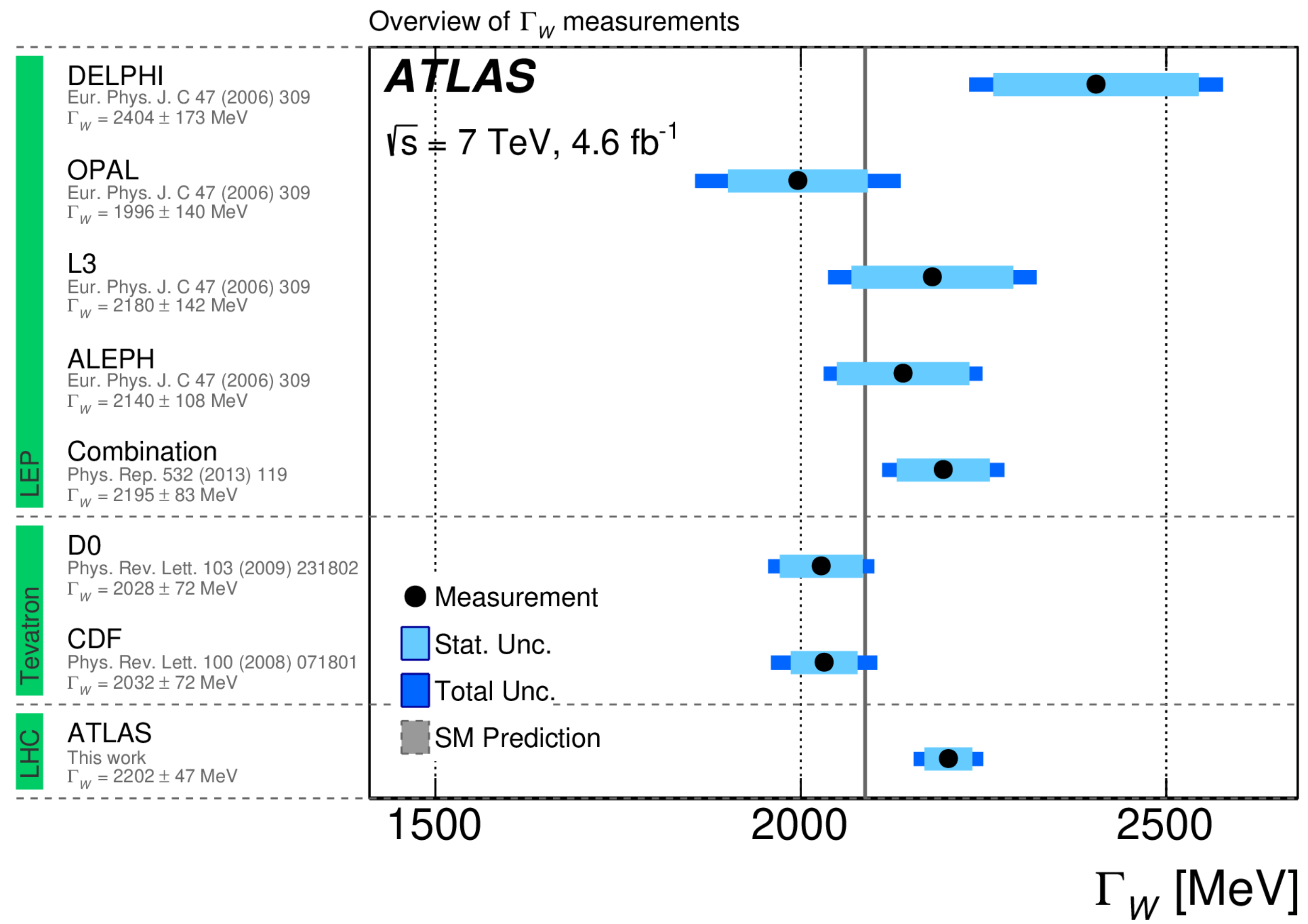


Source of uncertainty	Impact (MeV) Nominal	Global
Muon momentum scale	4.8	4.4
Muon reco. efficiency	3.0	2.3
W and Z angular coeffs.	3.3	3.0
Higher-order EW	2.0	1.9
p_T^V modeling	2.0	0.8
PDF	4.4	2.8
Nonprompt background	3.2	1.7
Integrated luminosity	0.1	0.1
MC sample size	1.5	3.8
Data sample size	2.4	6.0
Total uncertainty	9.9	9.9



. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	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

Bonus: W width measurement



$$\Gamma_W = 2202 \pm 47 \text{ MeV}$$

First LHC measurement of W width also the most precise one !

mT observable has best sensitivity to width Γ_W

Mass of the W treated as NP

$m_W^{SM} = 80355 \pm 6$ MeV

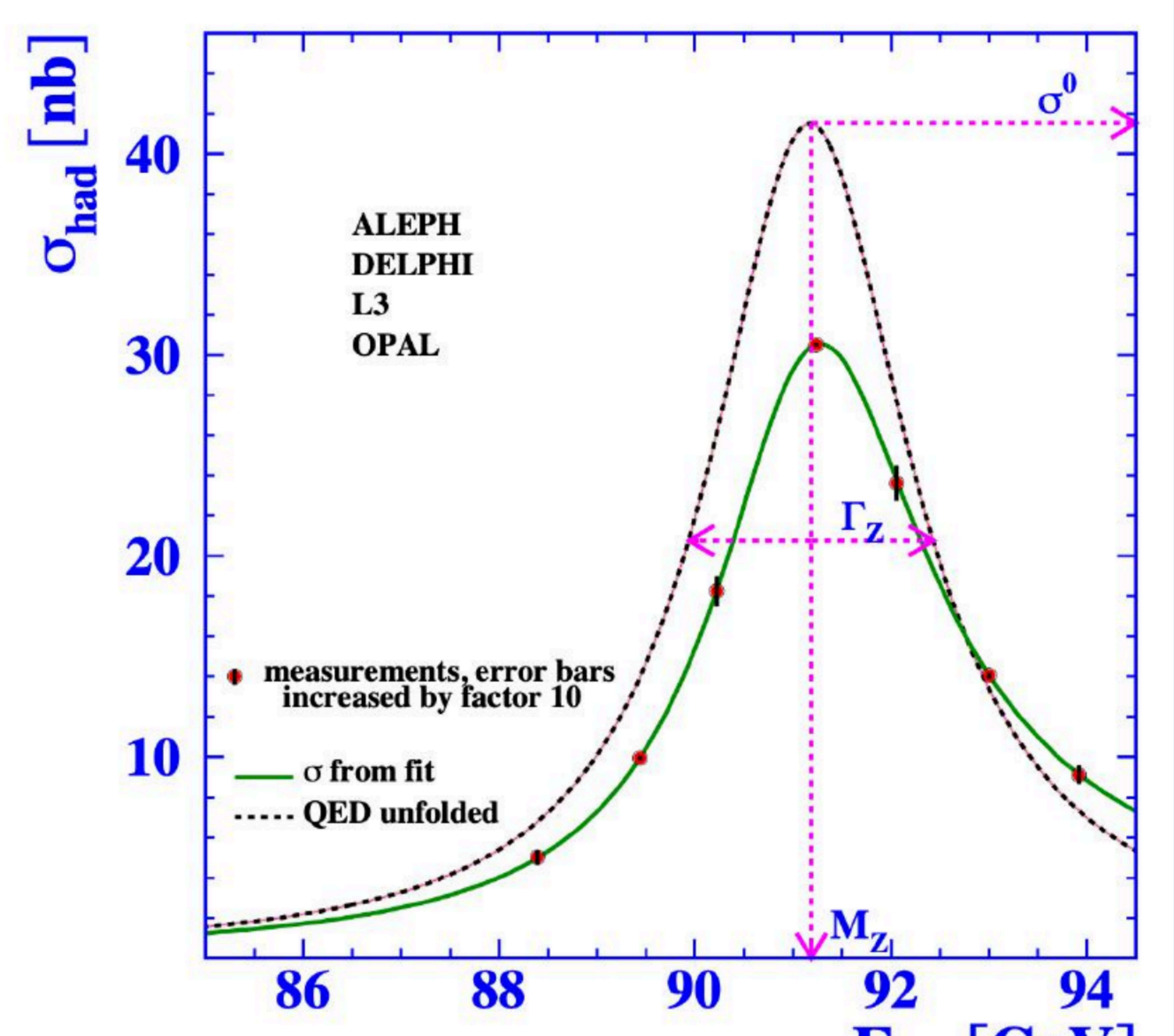
the measurement agrees with the SM expectation of $\Gamma_W^{SM} = 2088 \pm 1$ MeV within 2.4σ

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	72	27	66	21	14	10	5	13	12	12	10	6	55
m_T	48	36	32	5	7	10	3	13	9	18	9	6	12
Combined	47	32	34	7	8	9	3	13	9	17	9	6	18

Bonus: The Z mass

Large Electron Positron collider LEP (1989 – 2000 @ CERN)

- e^+e^- collider, tuned to Z resonance~ 17 million Z bosons
  - Access via energy scan



Phys. Rept. 427 (2006) 257

The LEP legacy

m_Z = 91187.6 ± 2.1 MeV

- uncertainty dominated by Beam-energy calibration.

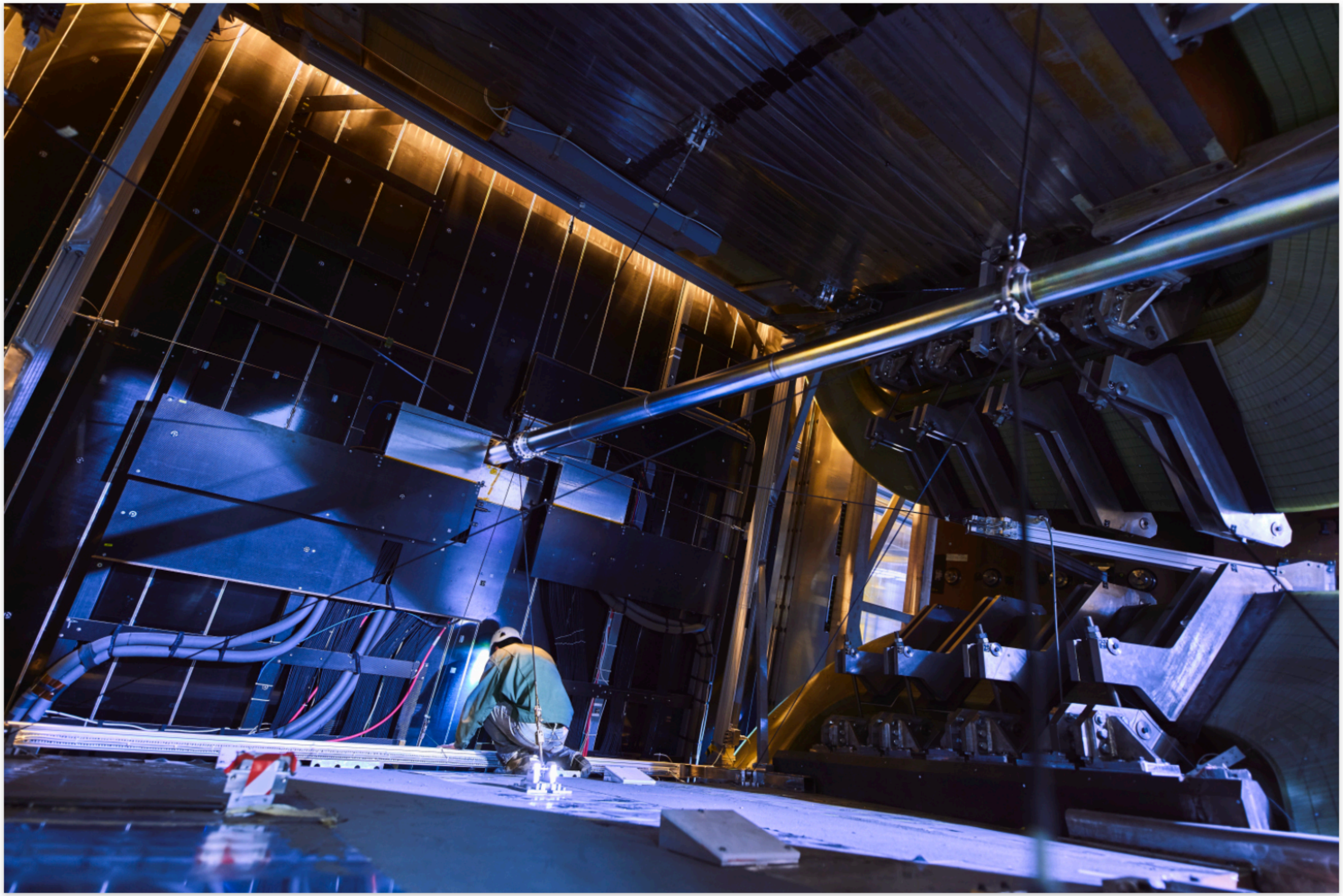
Reminder Indirect measurement m_Z = 91201.7 ± 8.9 MeV [Phys. Rev D. 106.033003]

LHCb weighs up the Z

New measurement of the mass of the Z boson showcases the Large Hadron Collider's growing role in precision physics

6 JUNE, 2025 | By Ana Lopes

Recent LHCb measurements (2025)



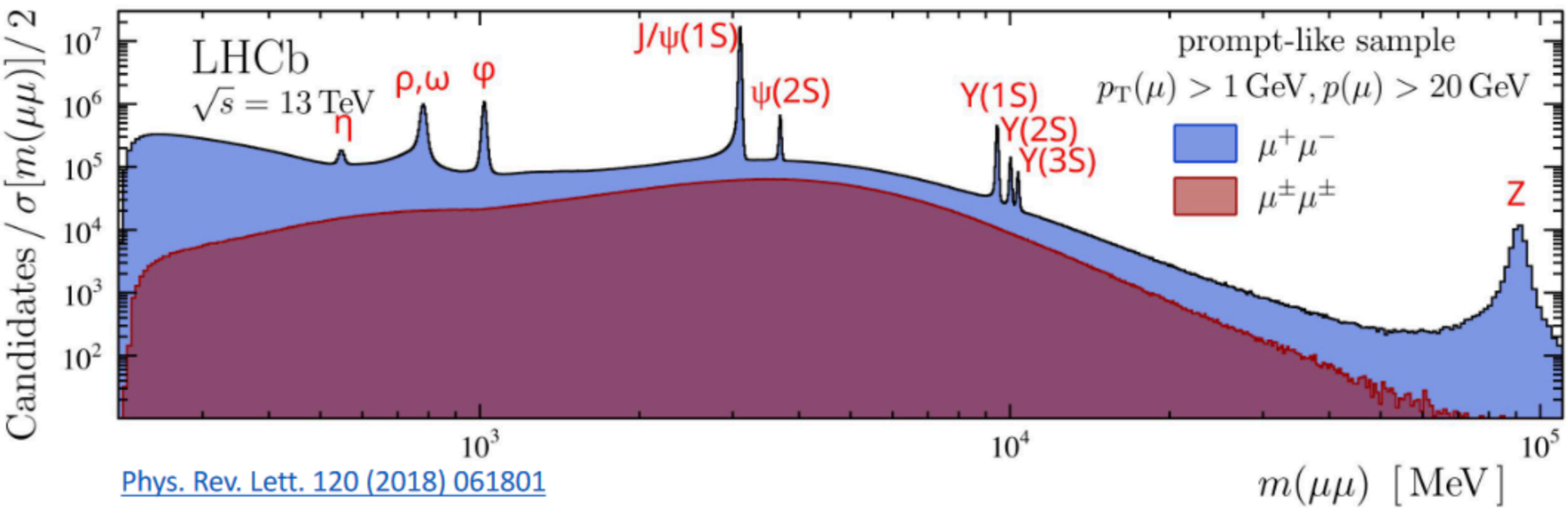
The LHCb detector in 2018. (Image: CERN)

Di-muon mass spectrum

- At Hadron collider the mass of the Z is extracted from final state kinematics.
- The di-muon mass spectrum become the key observable

@13TeV 1.7 fb^{-1}	LHCb Candidates
$\Upsilon(1S) \to \mu^+\mu^-$	190×10^3
$J/\psi \to \mu^+\mu^-$	48×10^3
$Z \to \mu^+\mu^-$	170×10^3

for more info



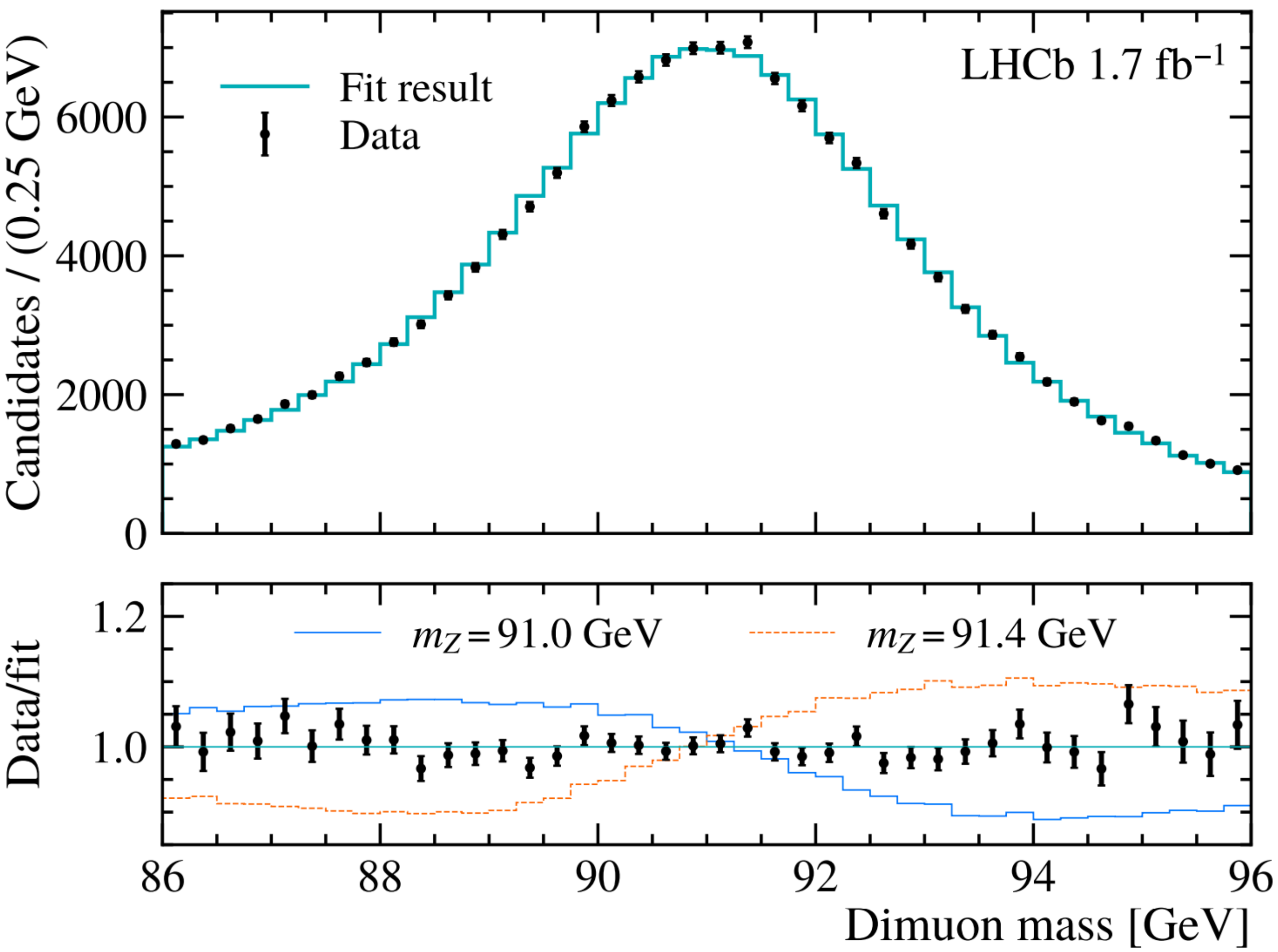
Phys. Rev. Lett. 120 (2018) 061801

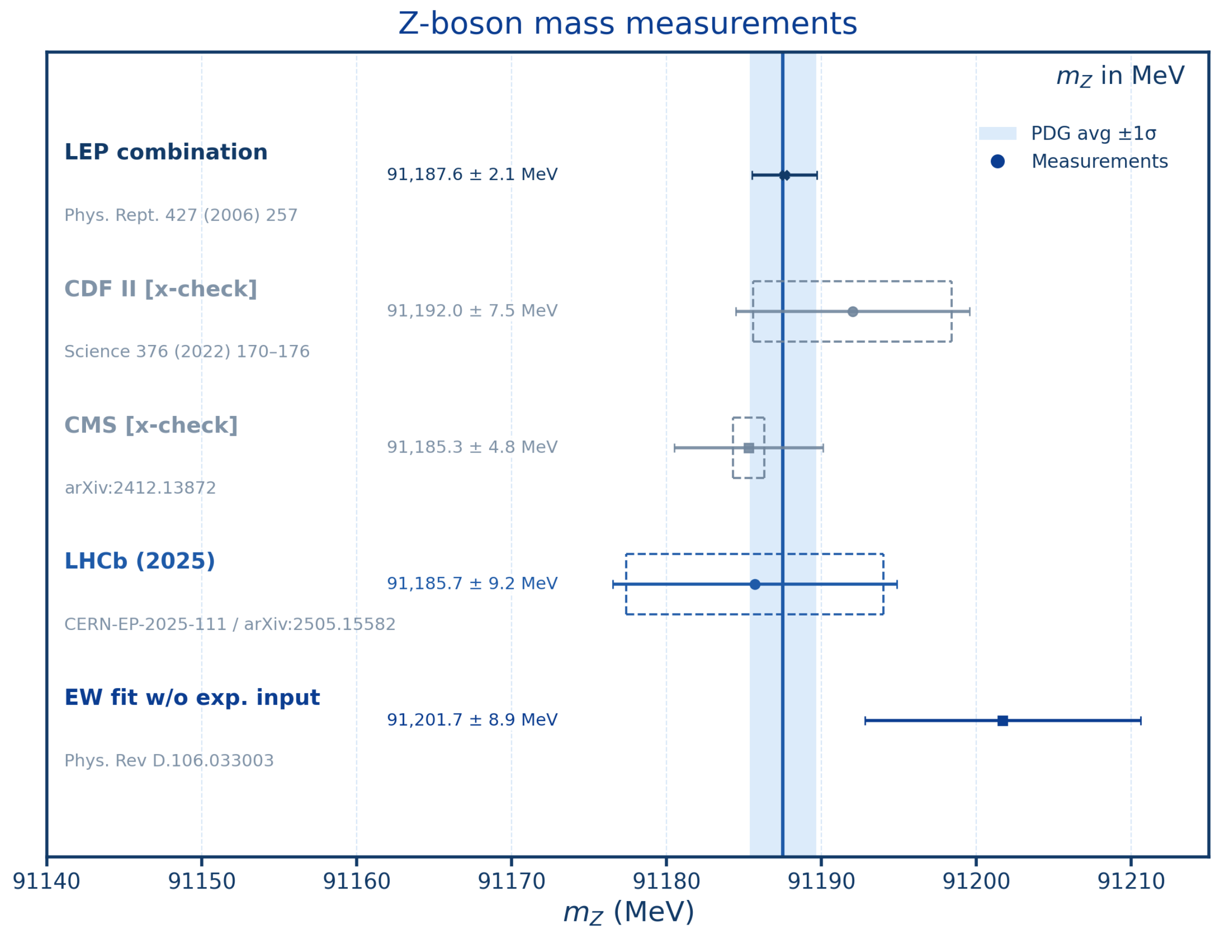
Standard muon momentum calibration for LHCb achieves a relative uncertainty of 3×10^{-4}

For the Z mass analysis muon momentum calibration uncertainty reached 4×10^{-5} (dominated by the detector material description in the simulation) ⇒ δm_Z = 3.6 MeV

LHCb m_Z measurement

Rev. Lett. 135 (2025) 161802





The resulting measurement of the Z-boson mass is **m_Z = 91185.7 ± 8.3 (stat) ± 3.9 (sys) MeV**

… to summarise

➡The mW measurement is the culmination of an extensive precision physics program

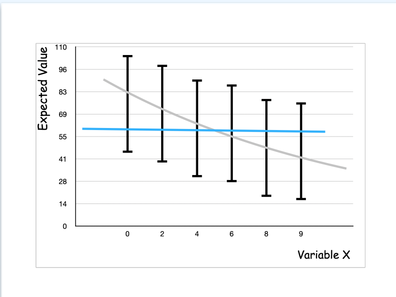
- LHC experiments are reaching unprecedented precisions on the measurement of fundamental parameter of the SM
- Individual experiments now approach — or even surpass — the precision of the combined LEP, SLD, and Tevatron electroweak results.

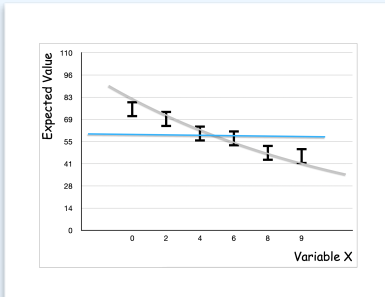
What Makes It Possible ?

- Incredible understanding of detector response across energies and pileup conditions.
- The measurement relies on extremely complex, multi-differential analyses.
  - almost ∞ data statistic is used to test and constrain state of the art prediction:
    - PDF uncertainties
    - p_T^W modelling

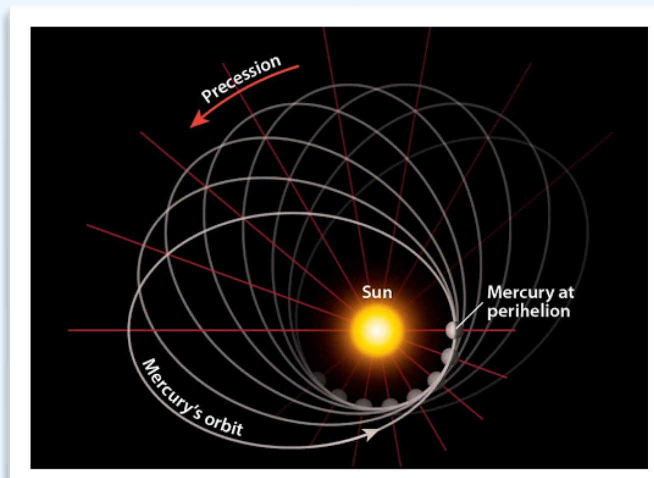
Backup

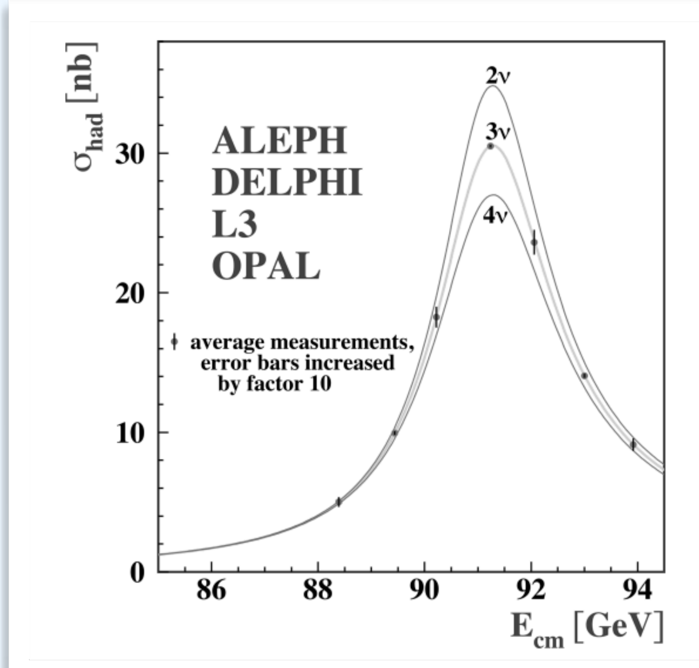
Precision Experiments: Revealing New Frontiers

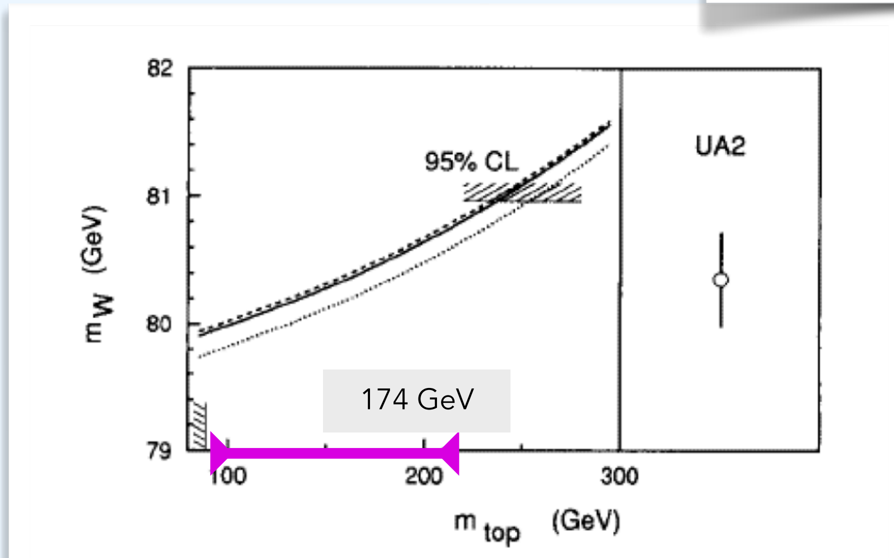




- ★ **Ruling Out Theories**
  (1860') Mercury's precession measured at 1.56° per century—Newtonian physics explained most of it but missed **0.01194°**. This gap led to the triumph of **General Relativity**!
- ★ **Confirming Theories**
  Precision measurements of the (1990') confirmed the existence of **3 families of neutrinos (3‰)**, pushing the boundaries of established facts of the SM.
- ★ **Paving the Way for Discoveries**
  First precise measurement of the **W boson mass** in the 1990s paved the way for the discovery of the **top quark**.







LHC experimental data

Now — after an outstanding Run 2 — the LHC experiments have in their hands the richest hadron collision data sample ever recorded

Particle	Produced in 140 fb^{-1} pp at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.8 million	
Top quark	275 million	(115 million $t\bar{t}$)
Z boson	8 billion	($\rightarrow \ell\ell$, 270 million per flavour)
W boson	26 billion	($\rightarrow \ell\nu$, 2.8 billion per flavour)
Bottom quark	~160 trillion	(significantly reduced by acceptance)

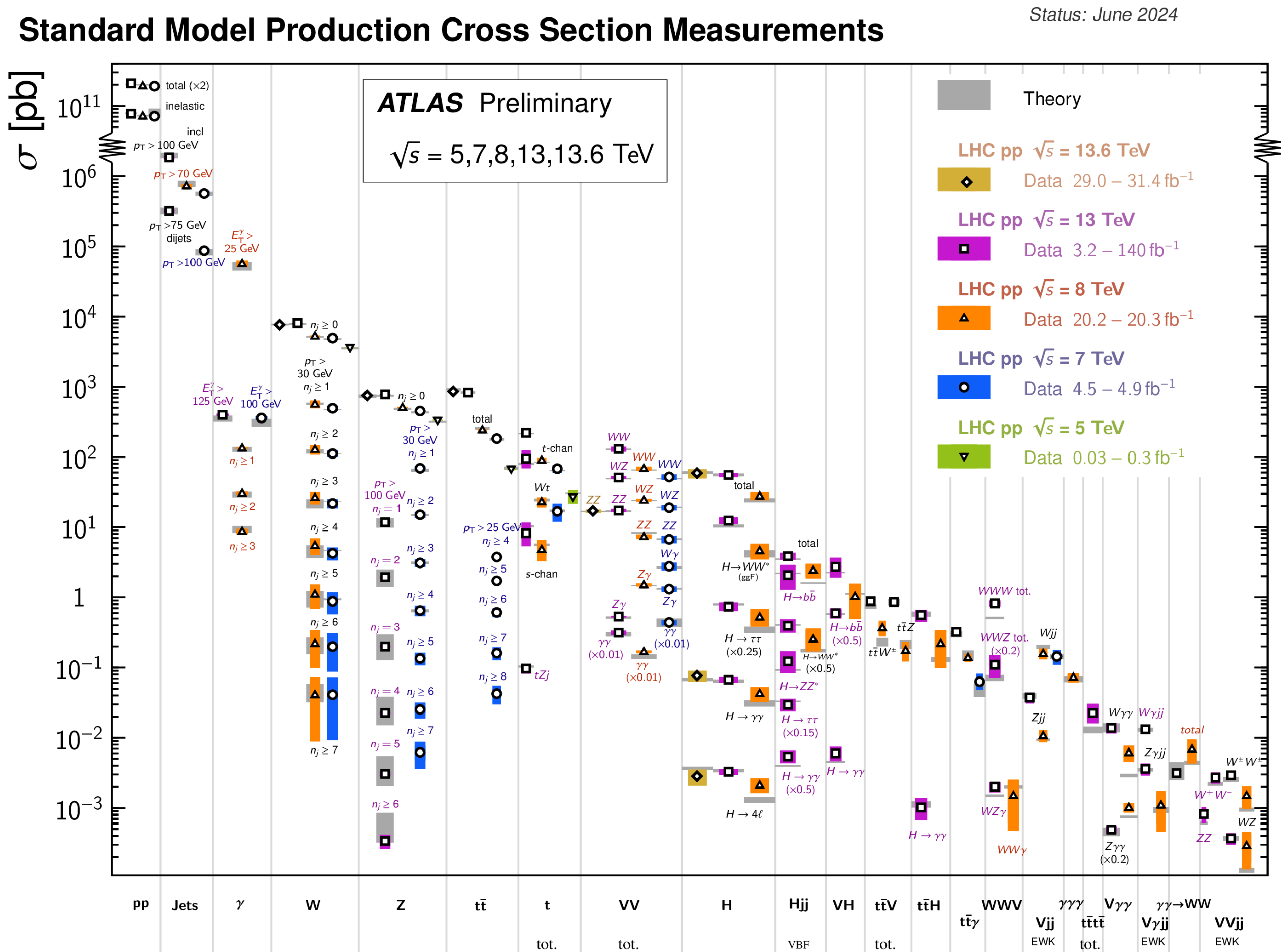
credit to A. Hoecker

The LHC is an **everything** factory

Vast and reach program at High energy frontier.

- *Probing with high-precision Standard Model processes self consistency of the SM*
- *detecting very rare processes*
- *exploring new physics via direct and indirect measurements*

The SM of particle physics @LHC



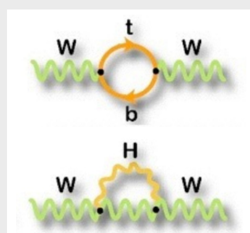
- Theory so far agrees with all measured cross sections across widely different processes
- and across centre-of-mass energies …
- ***Often data precision challenges the theory predictions…***

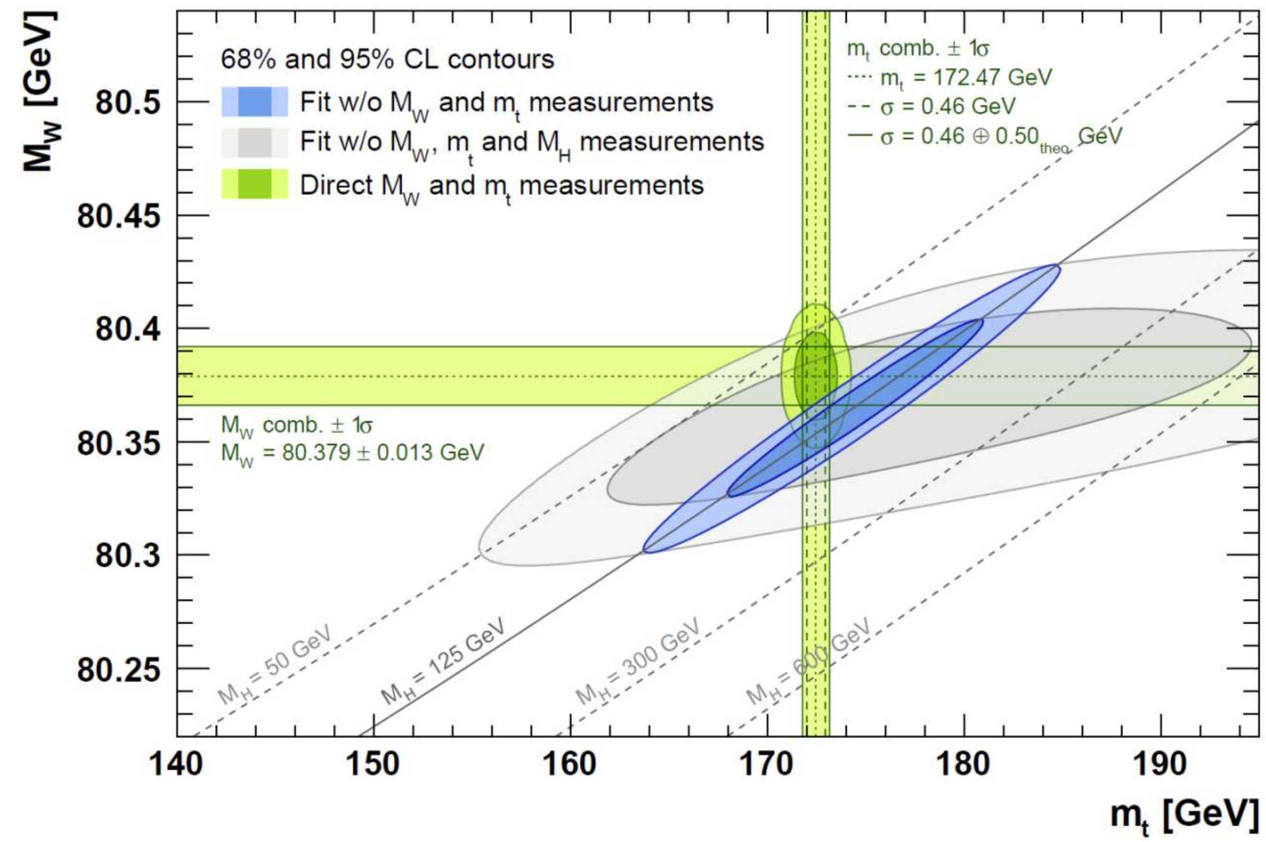
Can we consider now the LHC a "precision physics" machine ?

The EW sector: m_t m_W and m_H

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F\,(1 - m_W^2/m_Z^2)\,(1 - \Delta r)}$$

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

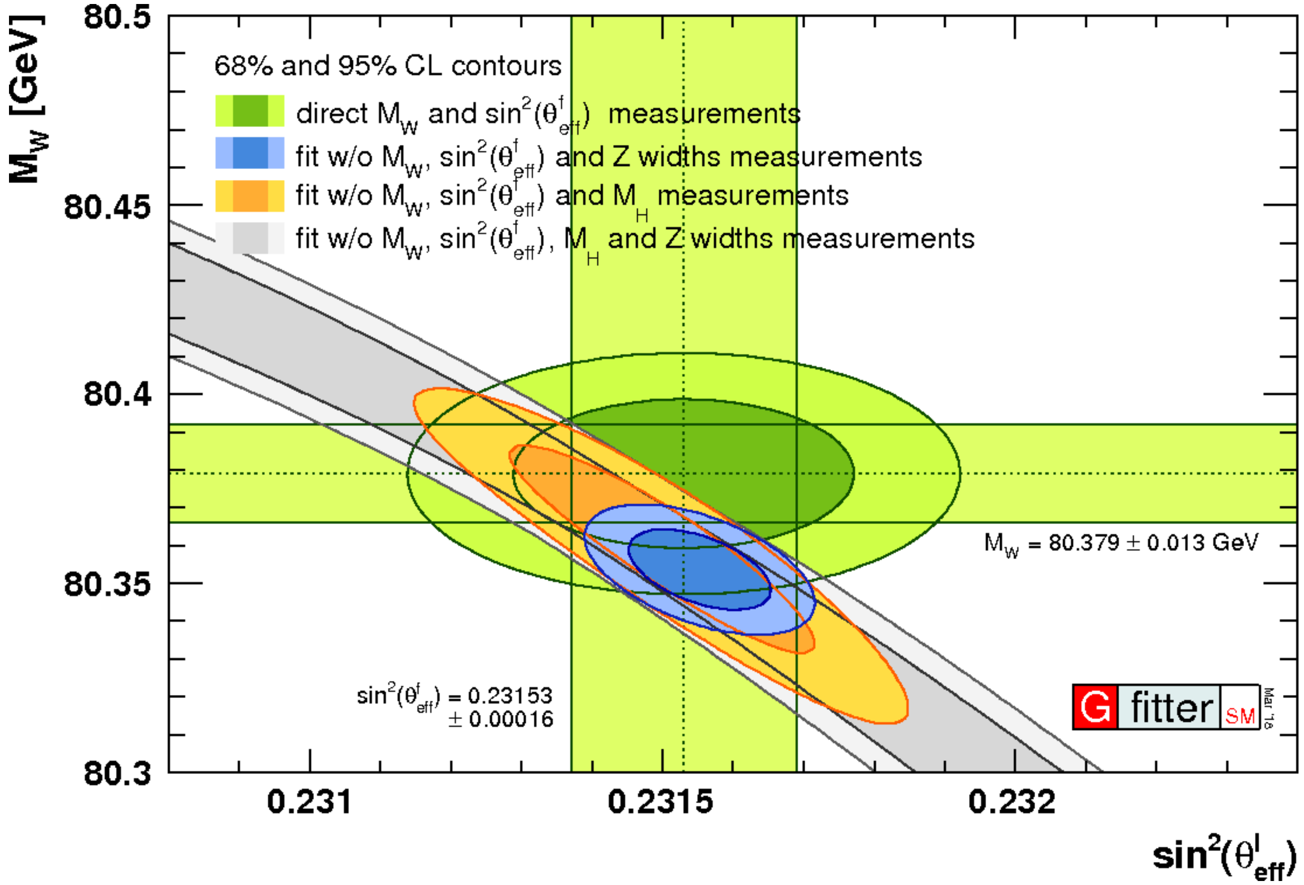




- m_t, m_W, m_H interrelation is the most popular way to test the predictive power of global fits in high-energy physics.
  - Historically, SM relation between fundamental parameters has been used to predict m_t and put constraint on the m_H before they were discovered!

*m_t **and** m_H **are now so well- measured (δ**m_t ~0.5/0.4 GeV; **δ**m_H ~ 0.2 GeV) that higher precision has minimal impact on the indirect determination of the others, however m_W is more precisely determined by SM fit **δ**$^{th}m_W$ 7 MeV …*

The custodial symmetry



https://arxiv.org/pdf/hep-ph/0302058

TEST OF THE CONSISTENCY OF THE EW SECTOR IN THE SM THROUGH PRECISION MEASUREMENTS OF ITS FUNDAMENTAL PARAMETERS IS ONE OF THE GOAL OF LHC PHYSICS PROGRAM.

- Indirect determination of both m_W and $\sin^2\theta_W$ more precise than the experimental measurement

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta} = 1.$$

- The custodial symmetry protects this relation from large radiative corrections. All corrections to the ρ parameter are therefore proportional to terms that break the custodial symmetry (thought radiative correction H,top$_{mass}$)

$$\rho_0 \equiv \frac{M_W^2}{M_Z^2\,\hat{c}_Z^2\,\hat{\rho}}\,,$$

PDG , LEP legacy

$$\rho_0 = 1.00031 \pm 0.00019\,,$$

EW radiative correction

Electroweak parameters

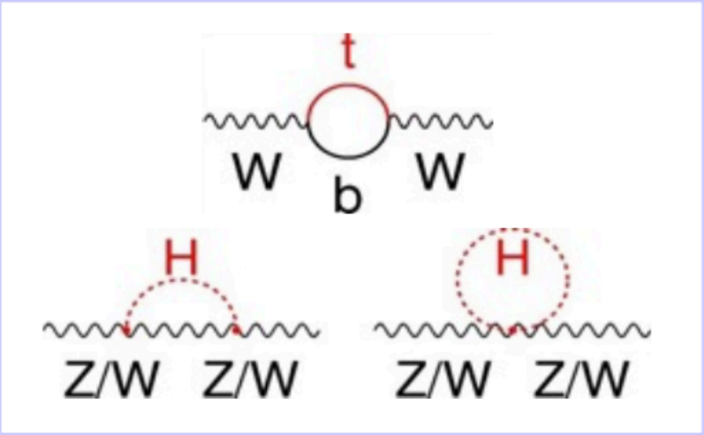
$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \quad (= 1) \qquad s_W^2 \equiv 1 - \frac{m_W^2}{m_Z^2} \quad (= \sin^2\theta_W)$$

Physical quantities

$$\bar{\rho} = 1 + \Delta\rho$$

$$M_W^2 = m_W^2\,(1 + \Delta r) \quad \text{and} \quad \sin^2\theta_W^{\text{eff}} = s_W^2(1 + \Delta\kappa)$$

with $\Delta r, \Delta\rho, \Delta\kappa = f(m_t{}^2, \ln(m_H), \ldots)$



$$\Delta\rho_t \simeq 0.01 \times [\,m_t/(175\ \text{GeV})\,]^2$$

$$\Delta\rho_H \simeq -0.0015 \times \log(\,m_H/M_W\,)$$

the electroweak radiative correction parameters are of the order of the percent and involve contributions from top quark and Higgs boson loops

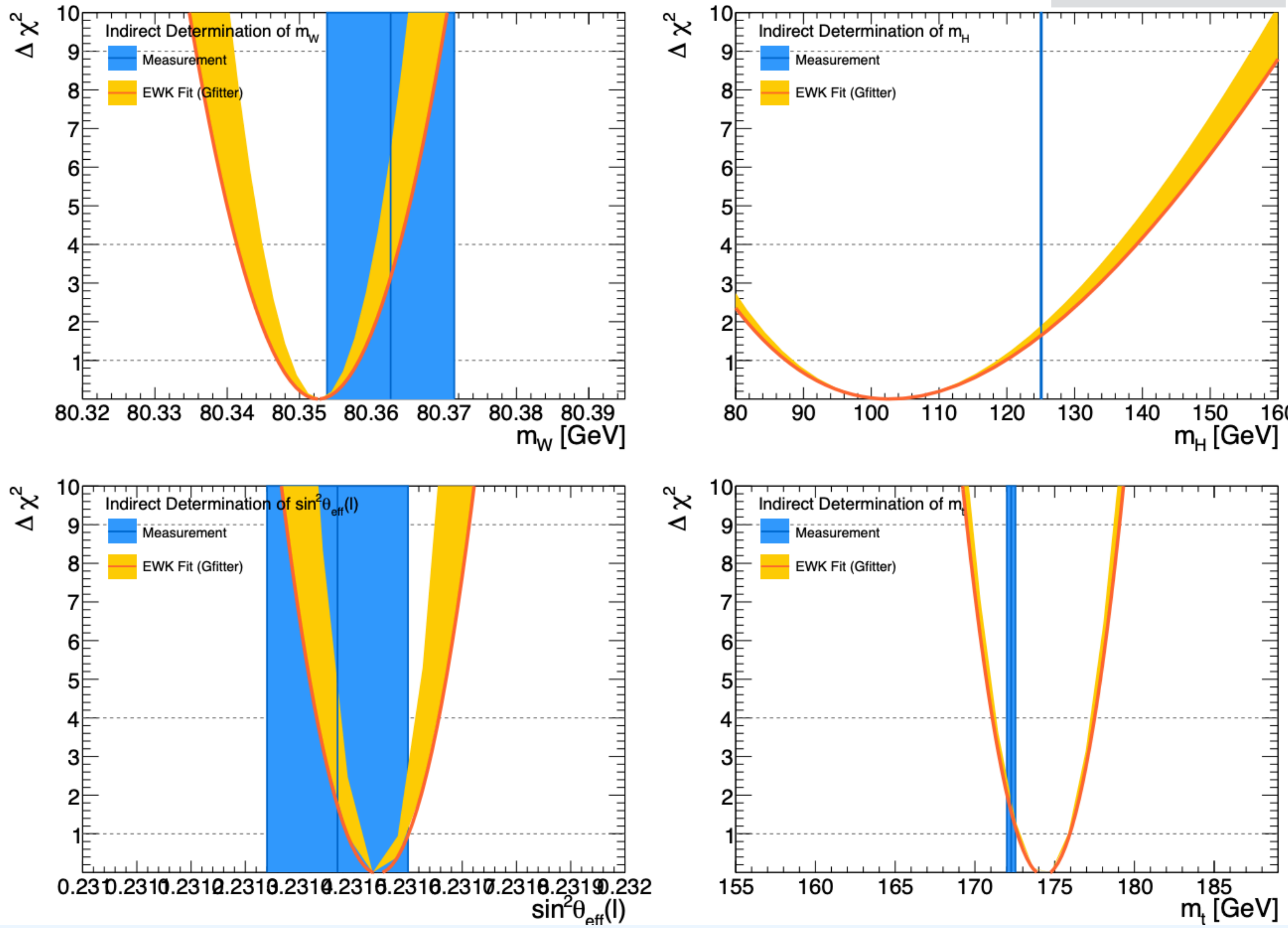
The electroweak theory predicts relations between experimentally measurable quantities

Observables can be calculated in the SM in term of a finite number of parameters to be determined experimentally (coupling constants, masses of fermions, CKM and M_H)

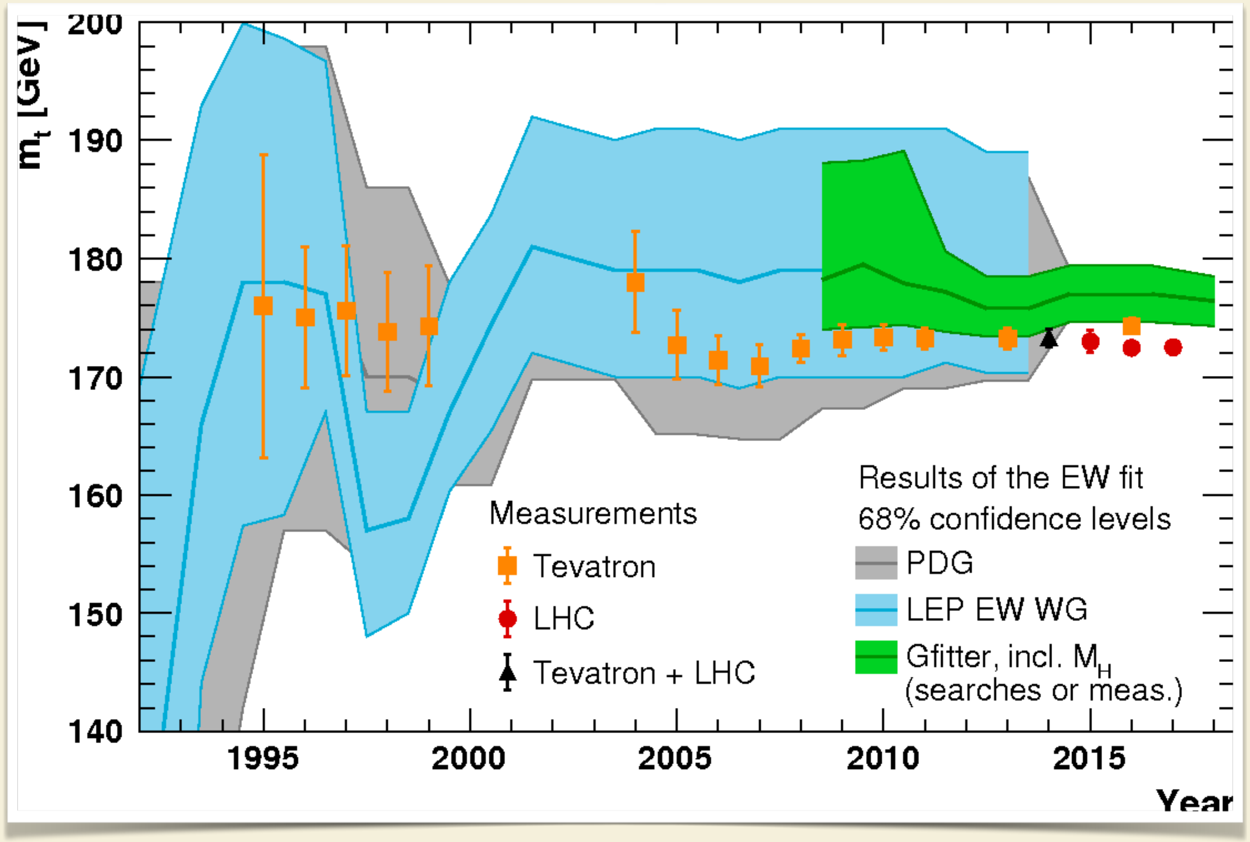
Update of the Global EW Fit (2026)

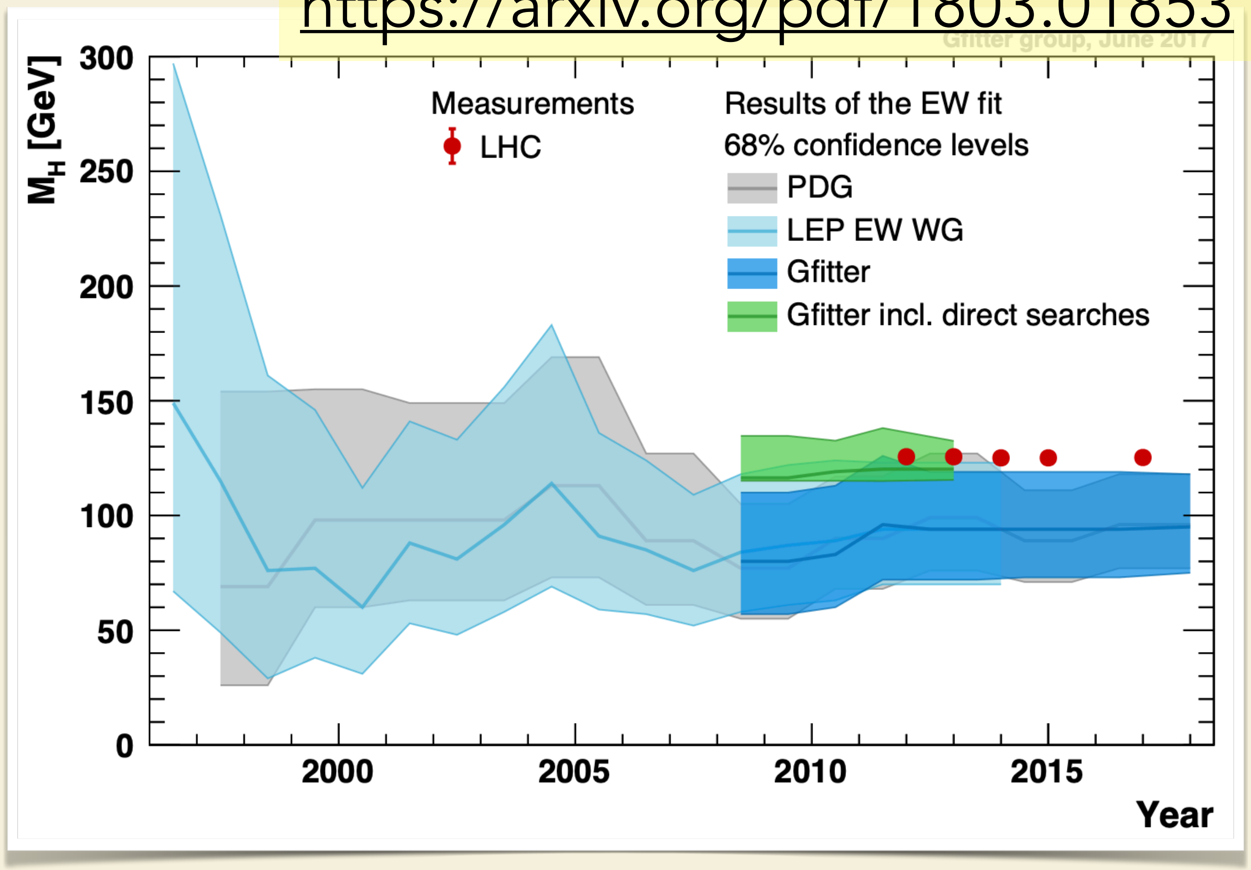
credit to M. Schott

- 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
  - χ^2/ndf=17.1/14 (p-value 0.25)



right now…

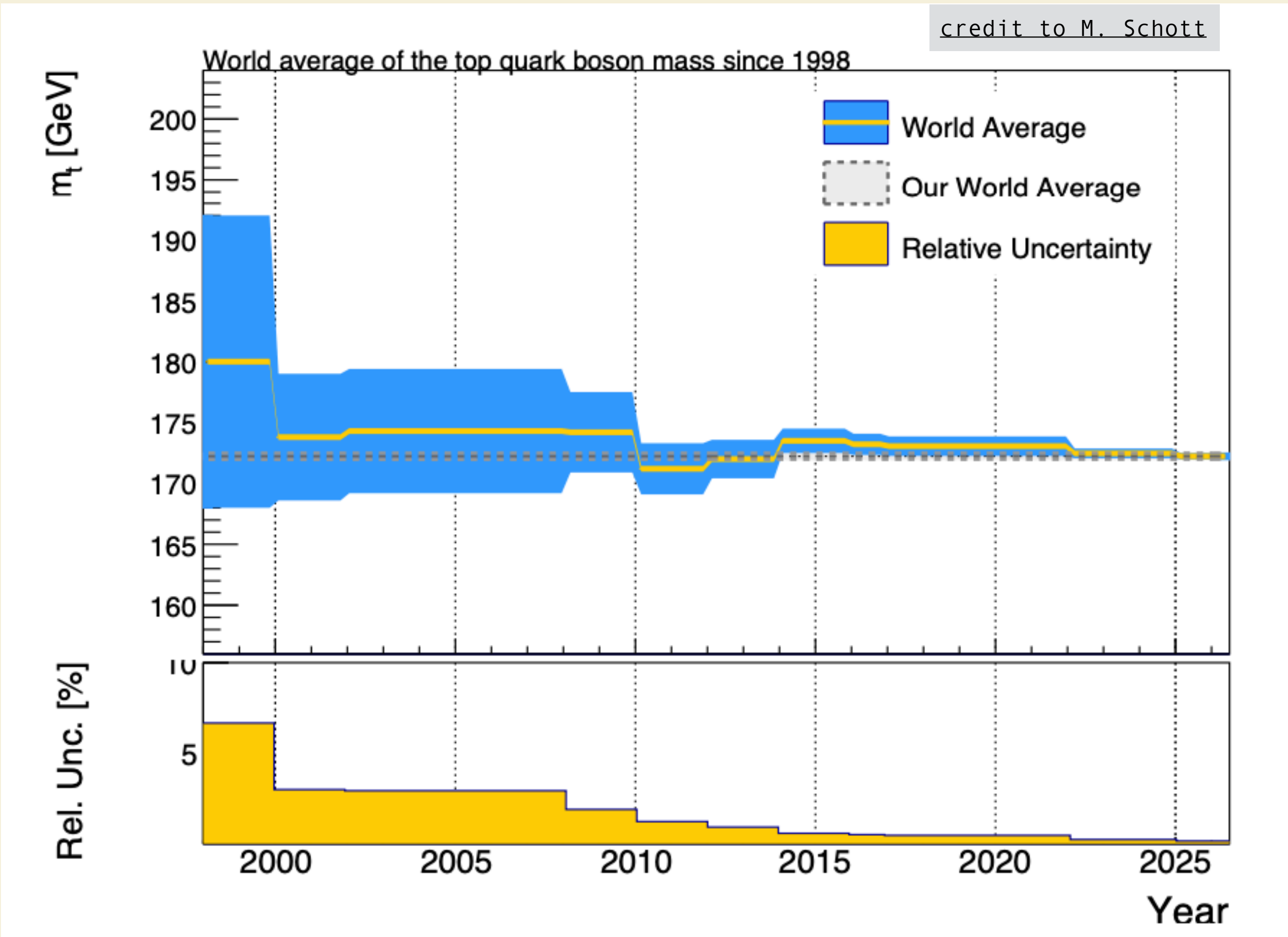


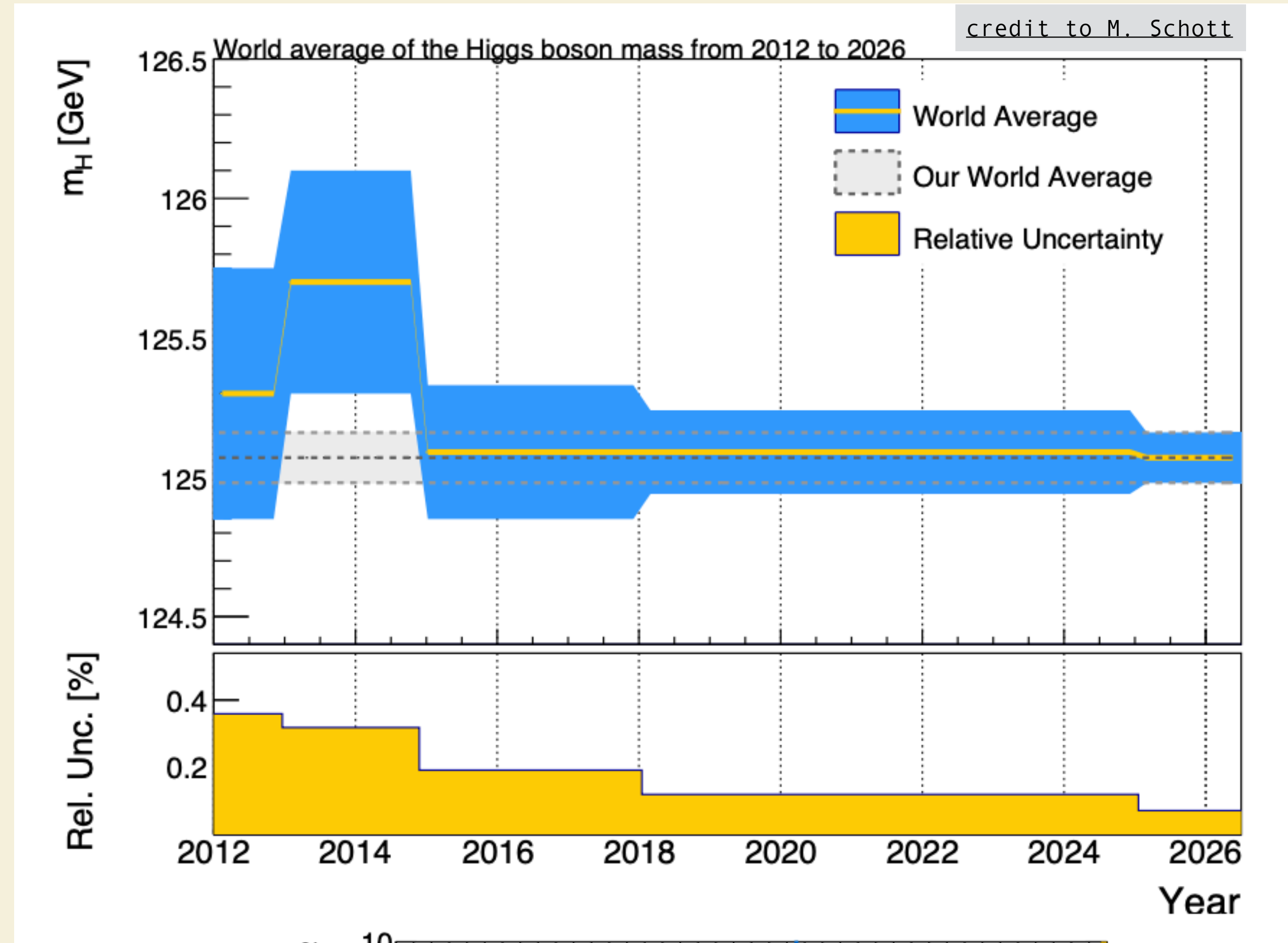


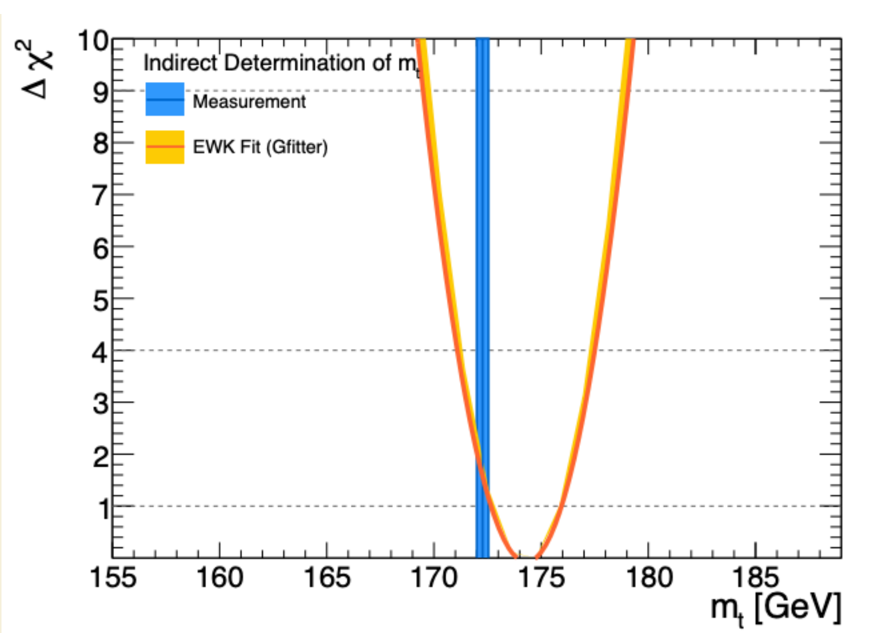
https://arxiv.org/pdf/1803.01853

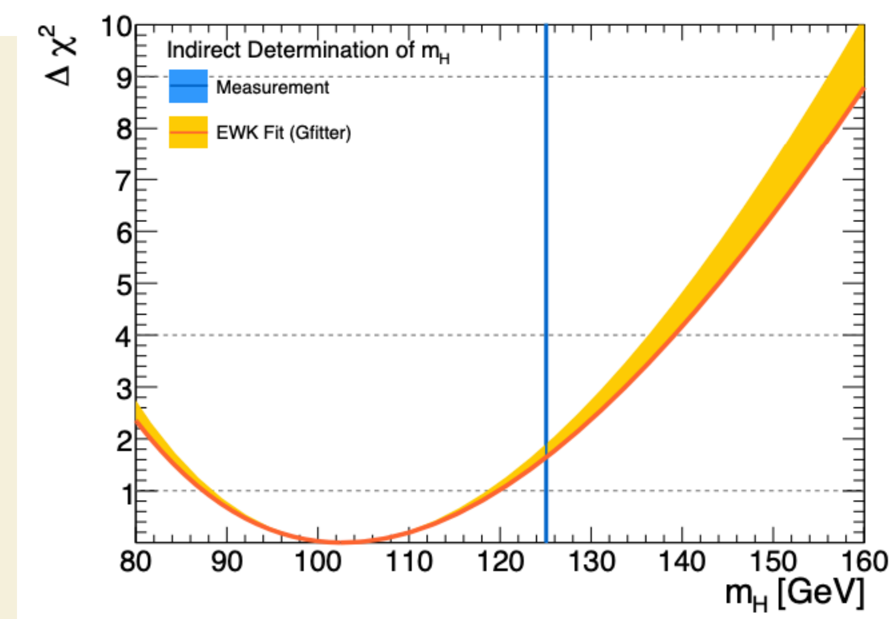
m_t and m_H are now so well-measured ($\delta m_t \sim 0.3$ GeV; $\delta m_H \sim 0.1$ GeV) that higher precision has minimal impact on the indirect determination of the others parameters

Predictive Power of the SM today

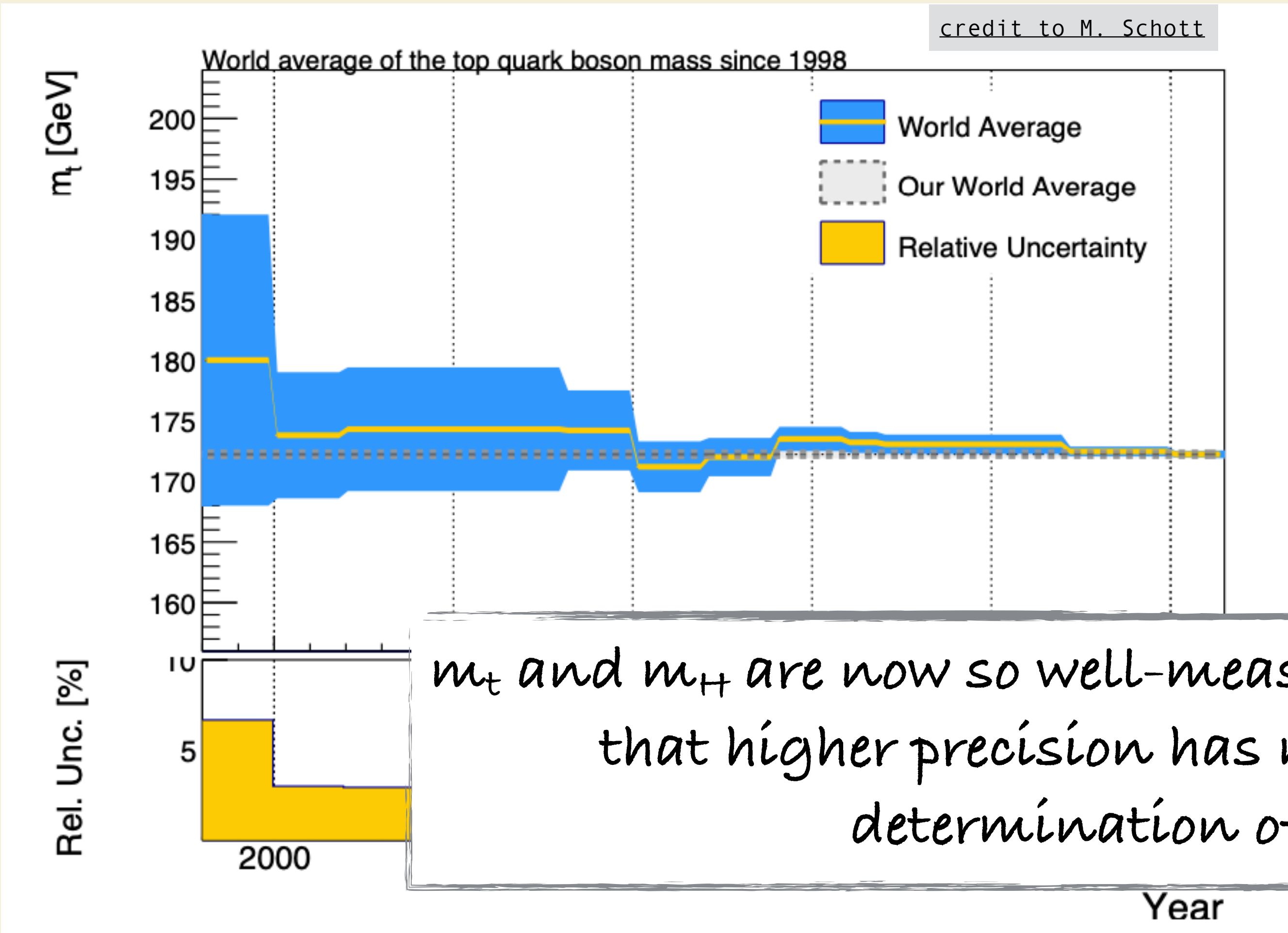


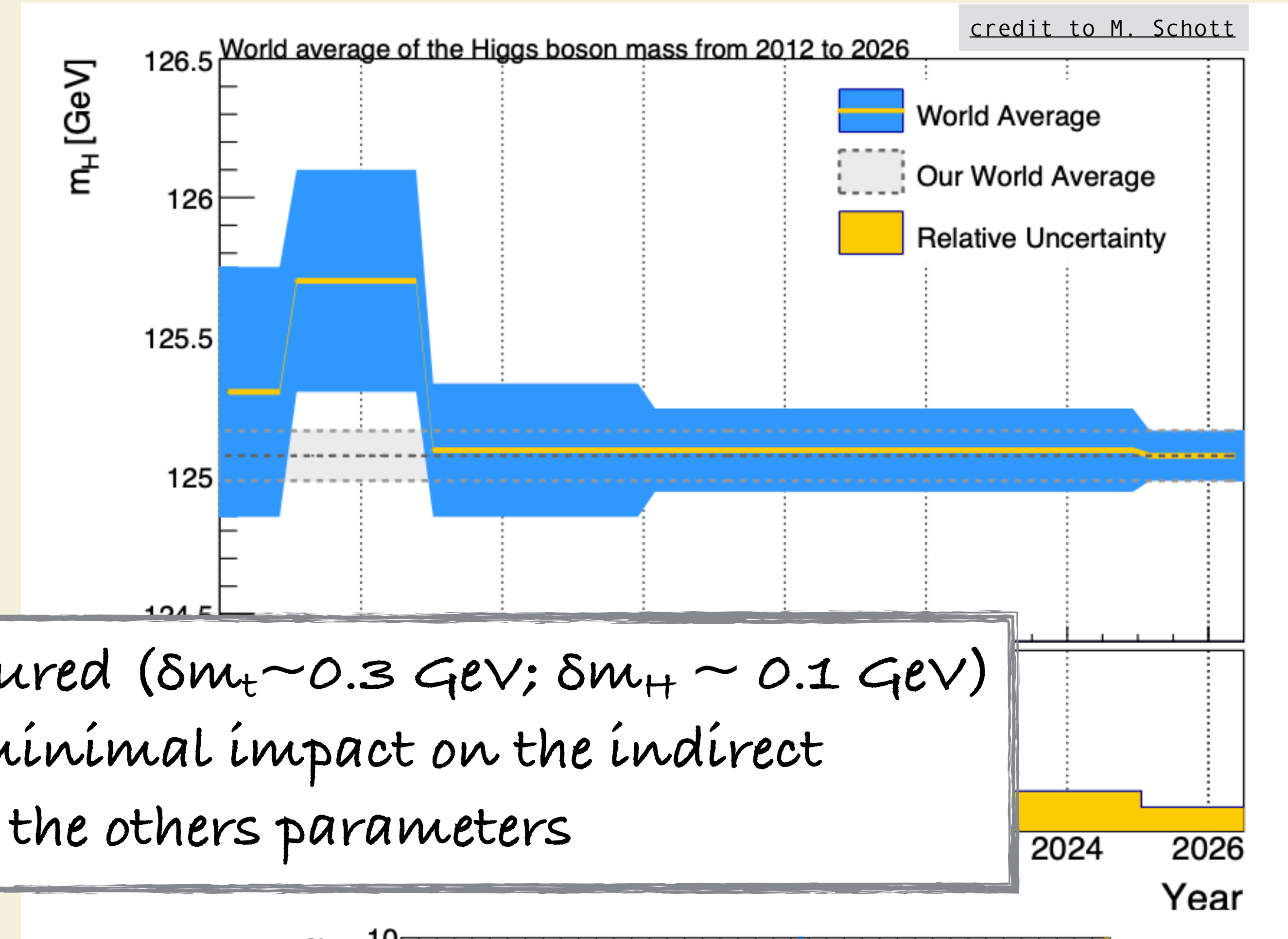






Predictive Power of the SM today





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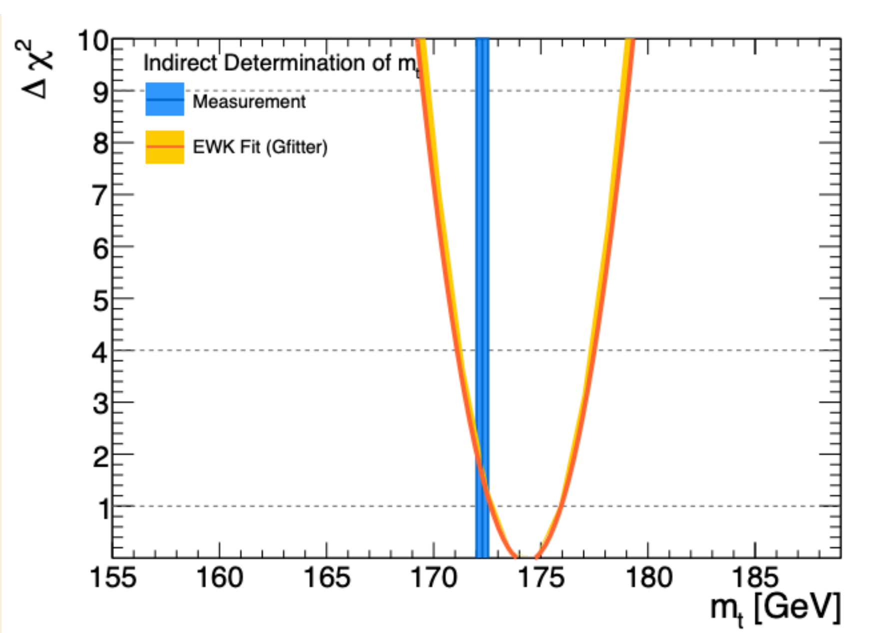
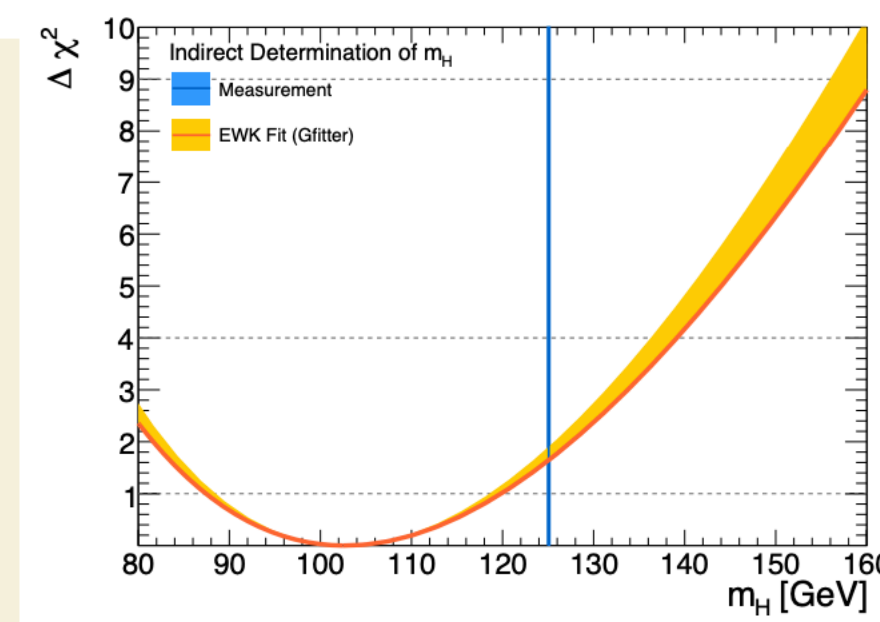
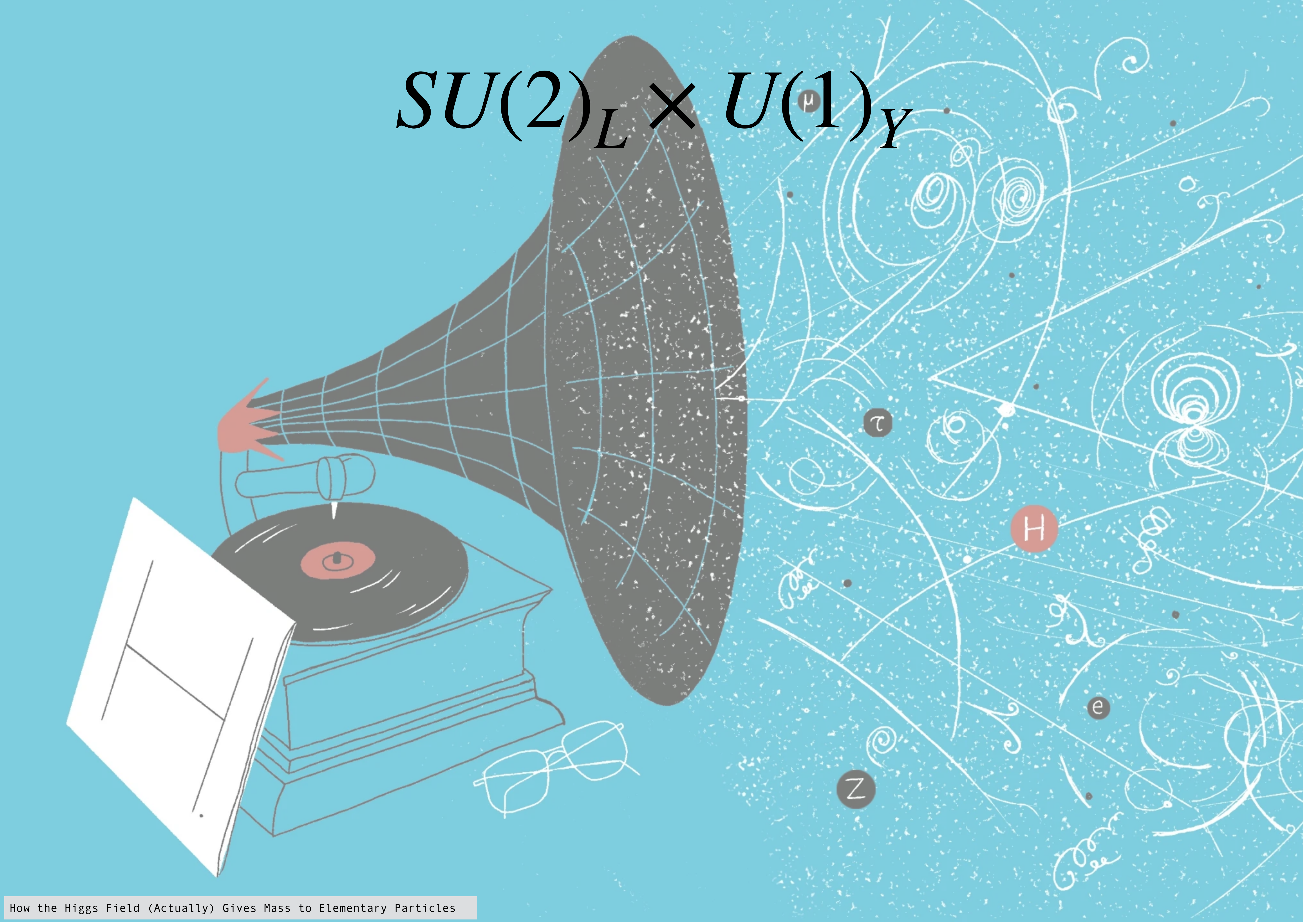


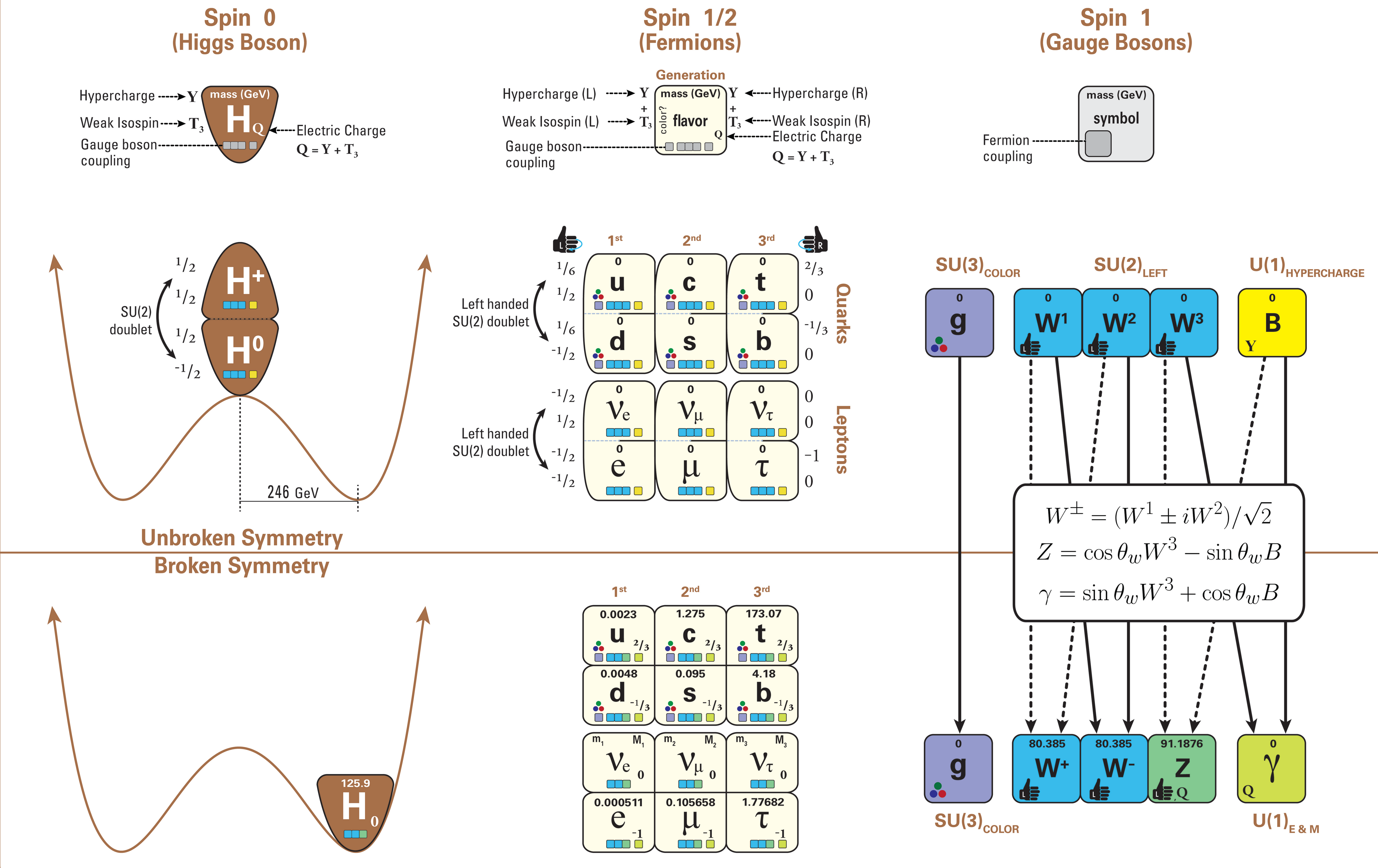


$$SU(2)_L \times U(1)_Y$$

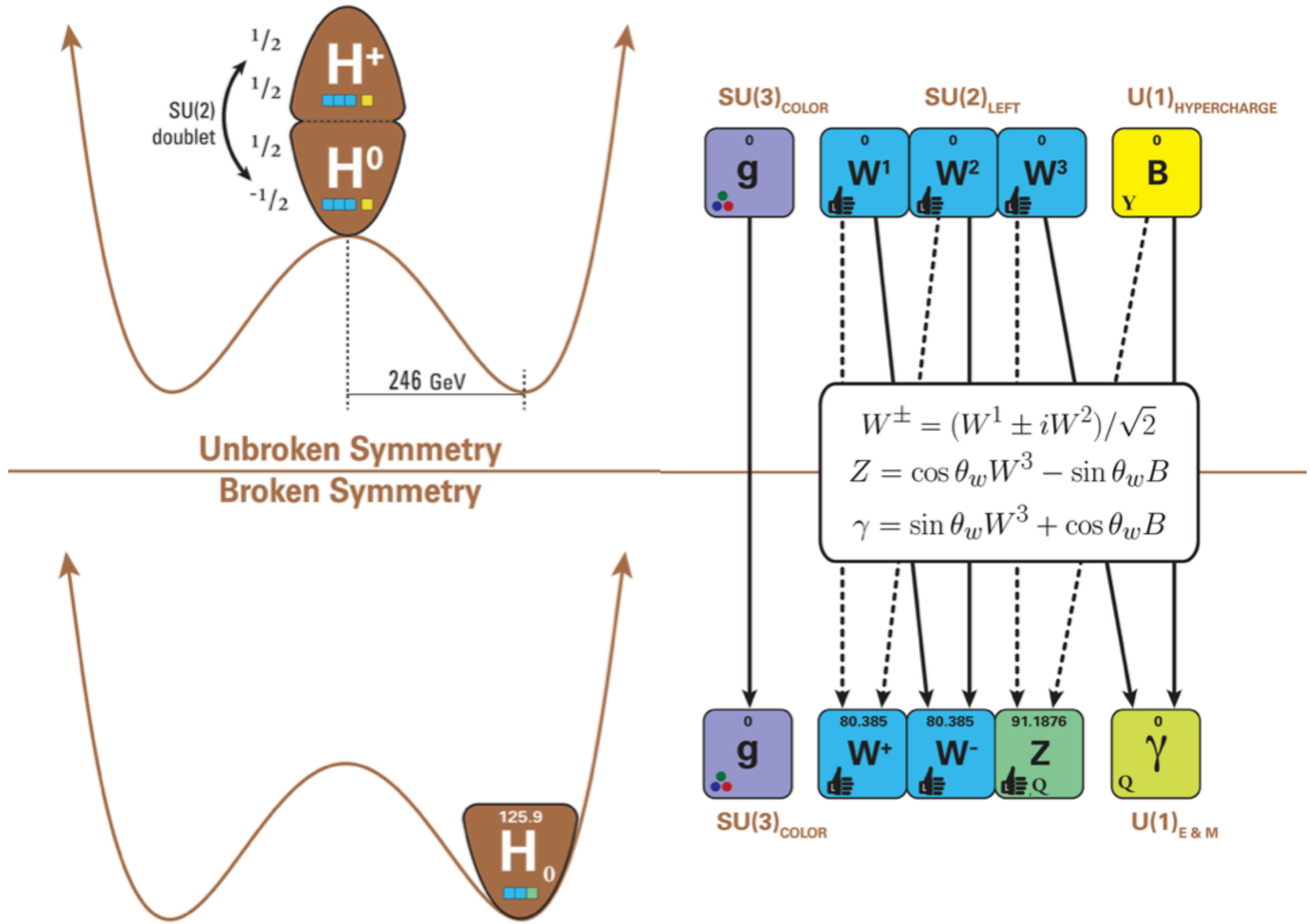


How the Higgs Field (Actually) Gives Mass to Elementary Particles

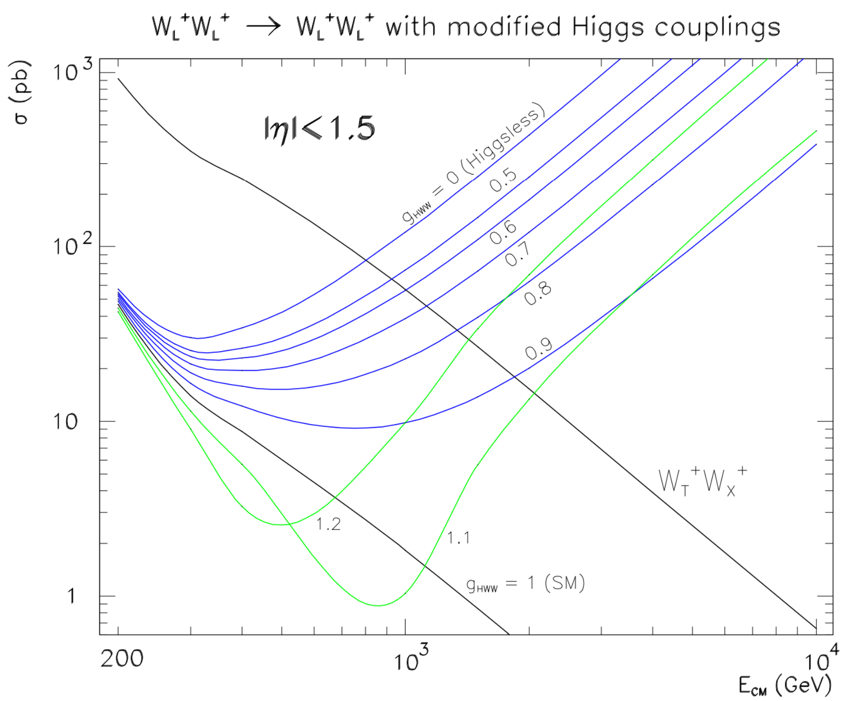
The Standard Model of Particle Physics



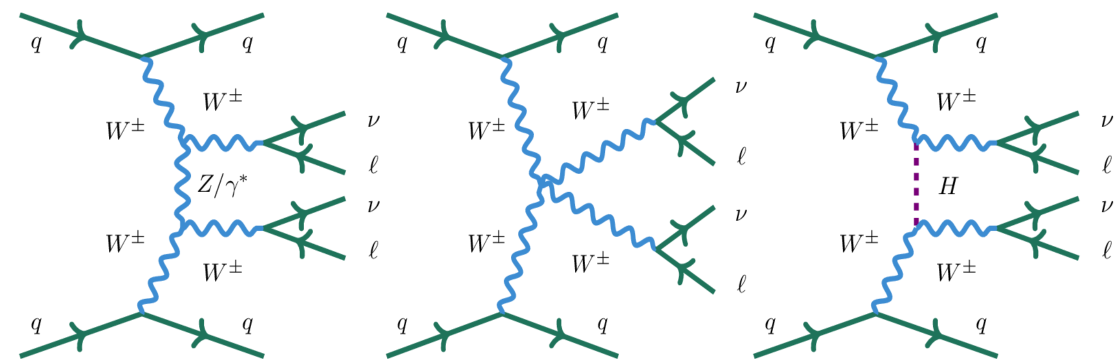
$SU(2)_L \times U(1)_Y$



longitudinal polarised WW - scattering



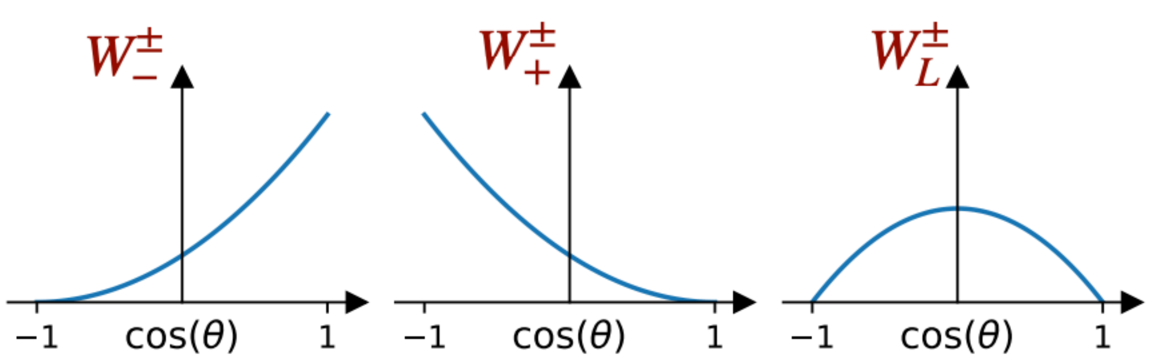
https://arxiv.org/pdf/1412.8367

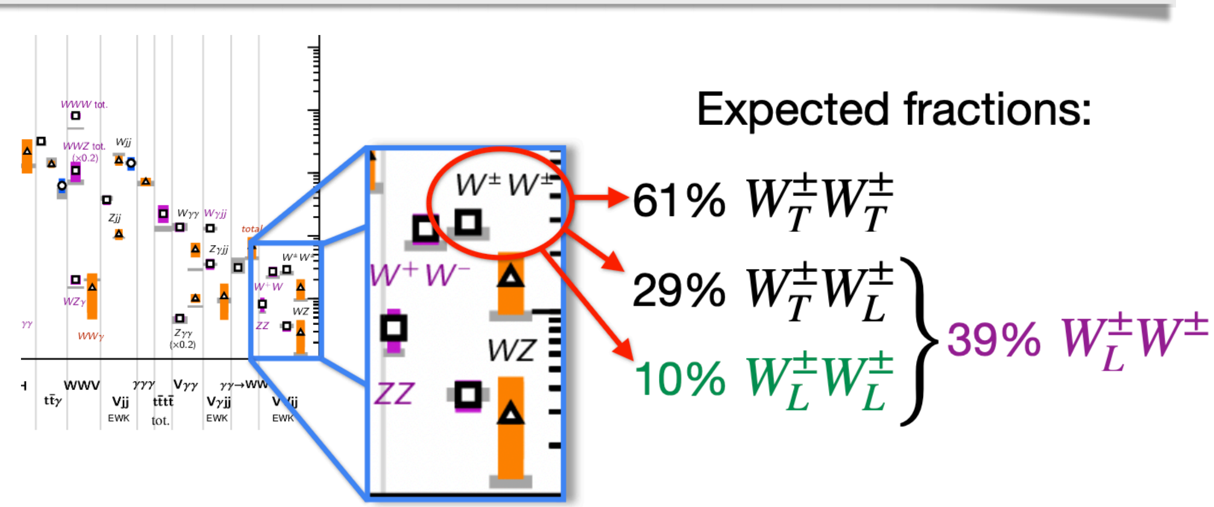


Higgs mechanism (eg. EW symmetry breaking) result in longitudinal polarised vector bosons:

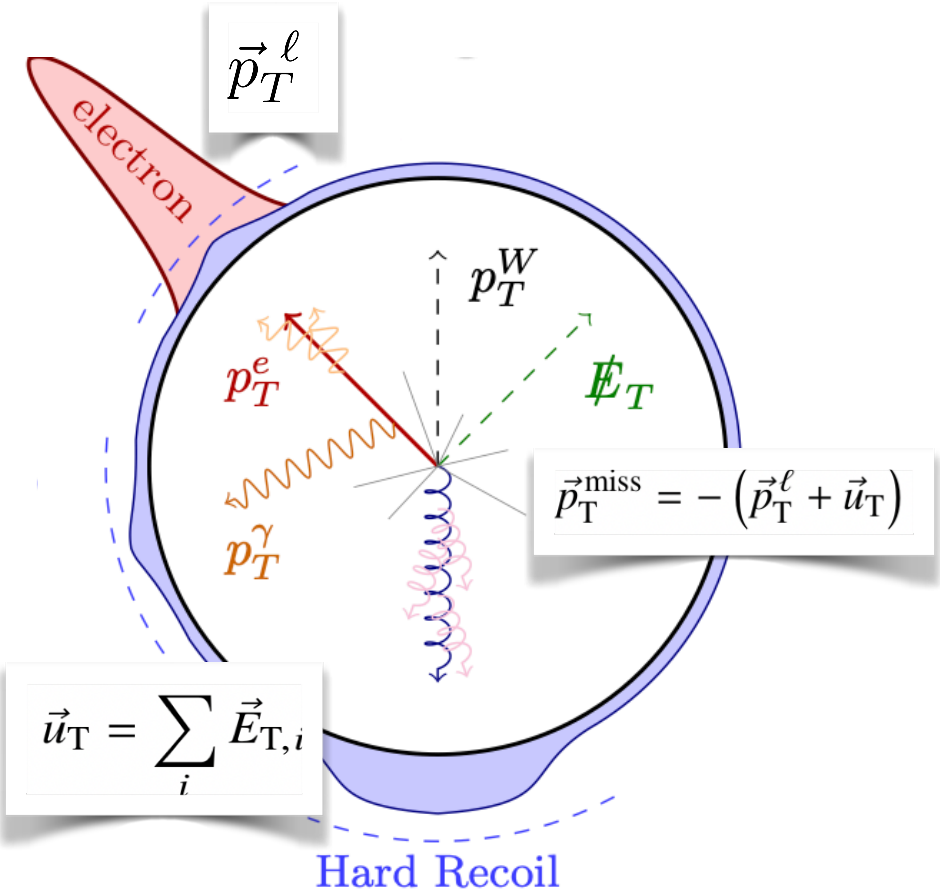
$W_L^\pm W_L^\pm \rightarrow W_L^\pm W_L^\pm$ scatter would violate unitarity if Higgs coupling deviates from SM prediction

➡ is a unique opportunity to probe electroweak symmetry-breaking



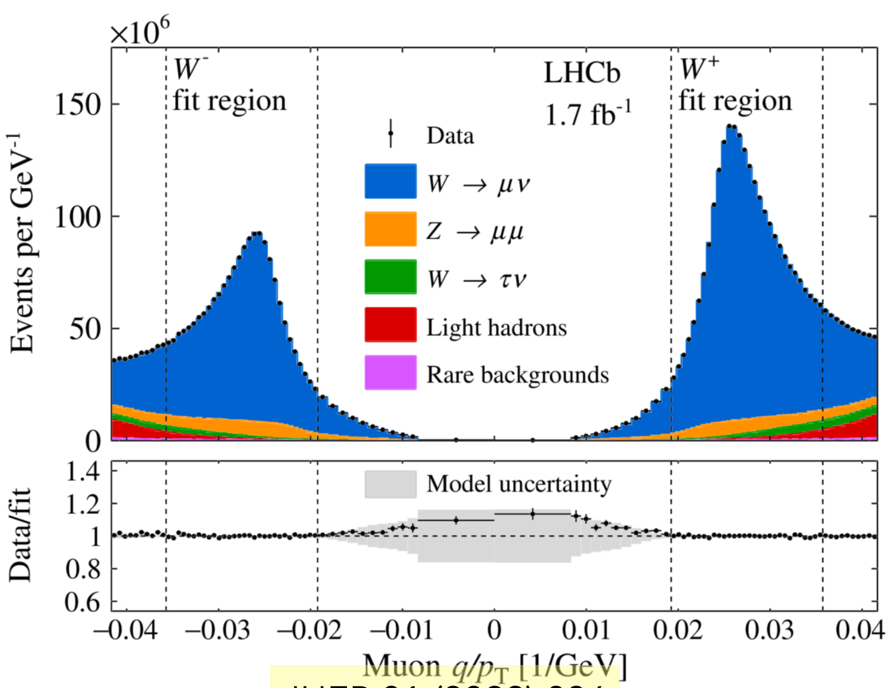


The W Boson mass at LHC

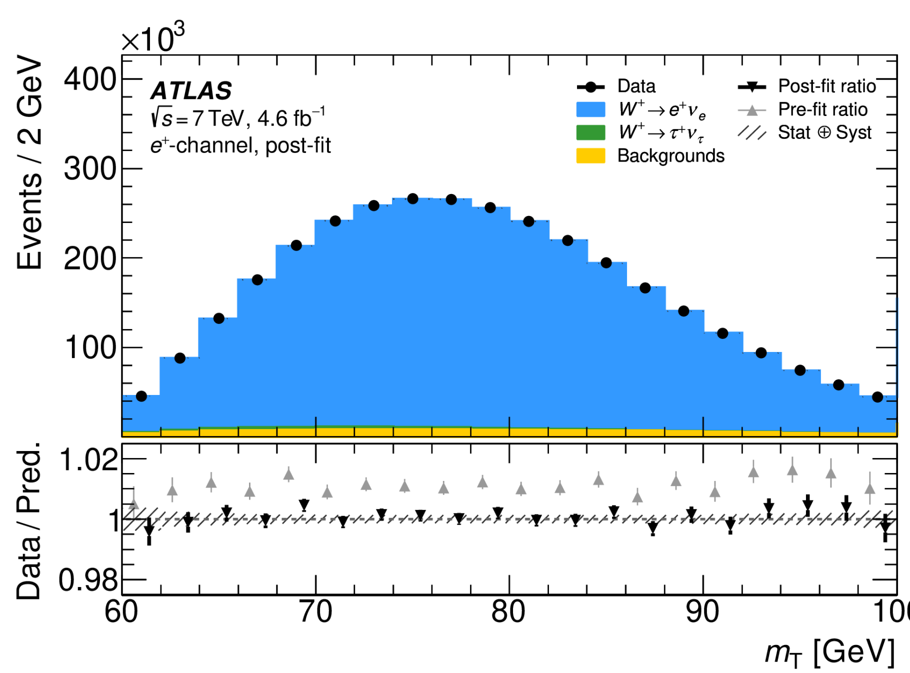


W boson signature: Incomplete kinematics (missing neutrino) no invariant mass: rely on measured quantities (p_T^ℓ, u_T) and exploit momentum conservation in the transverse plane (p_T^{miss} , m_T)

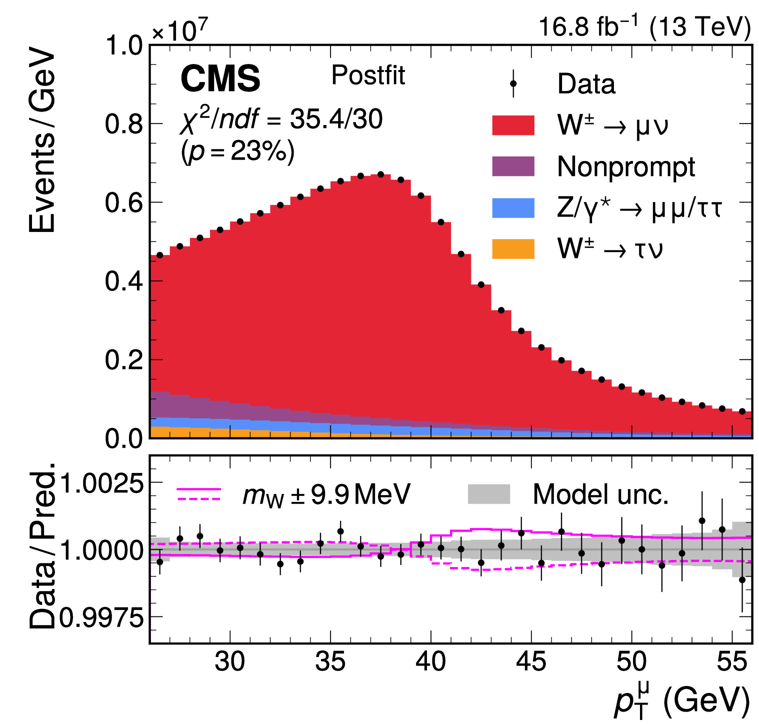
$$m_{\rm T} = \sqrt{2 p_{\rm T}^{\ell} p_{\rm T}^{\rm miss} (1 - \cos \Delta\phi)}$$



JHEP 01 (2022) 036

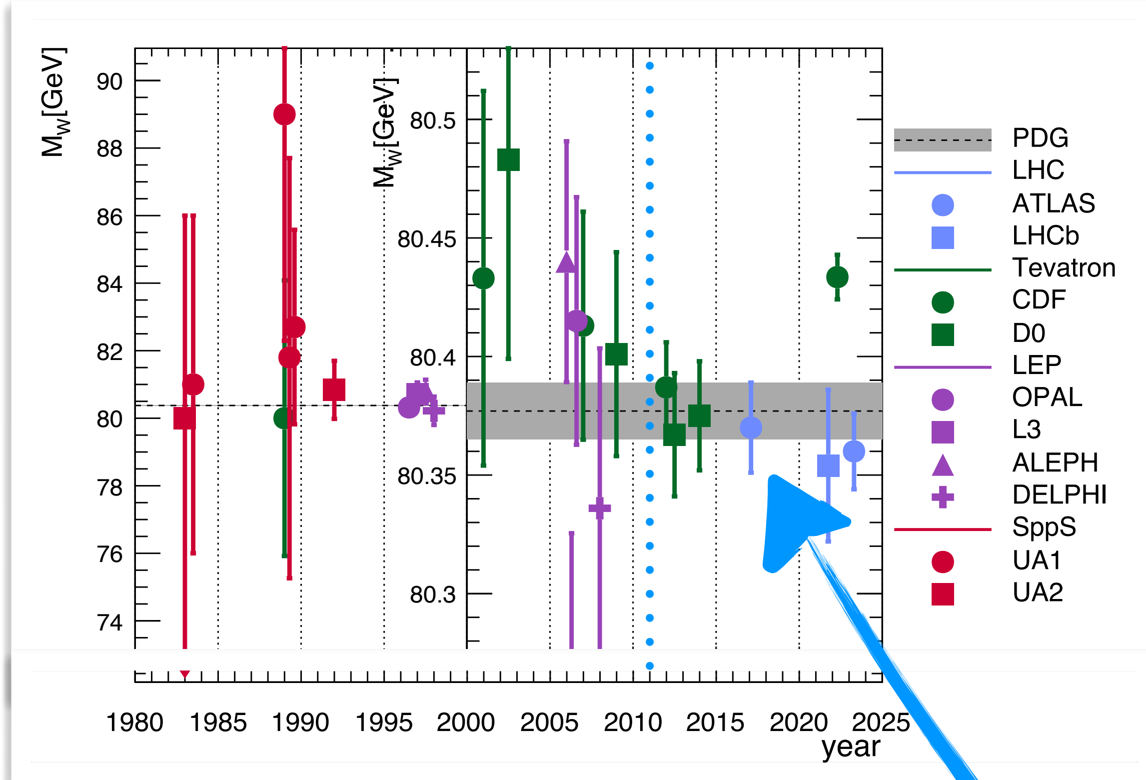


Eur. Phys. J. C 84 (2024) 1309



arXiv:2412.13872

The road map of the first **LHC** m_W measurement



2008 Eur.Phys.J.C 57
ATLAS Potential on m_W

2014 JHEP 09 (2014) 145
Z Boson Transverse Momentum at 7 TeV

2012 Start of the m_W analysis Efforts

2016 Eur. Phys. J. C 77 (2017) 367
W and Z Boson Production at 7 TeV

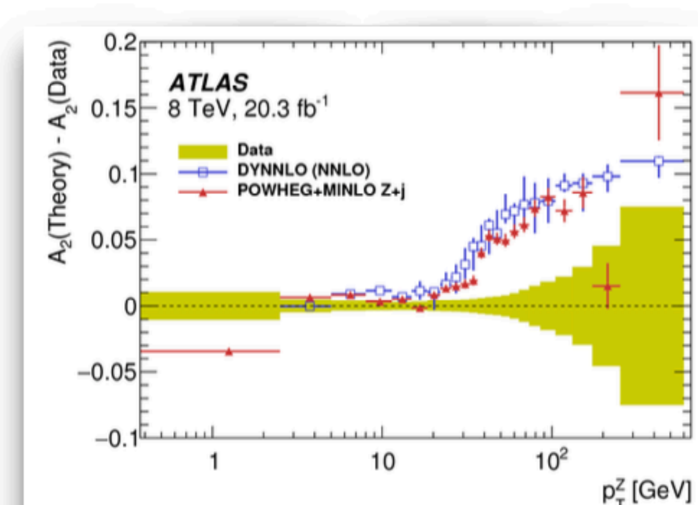
2016 JHEP 08 (2016) 159
Z Boson Angular Coefficients

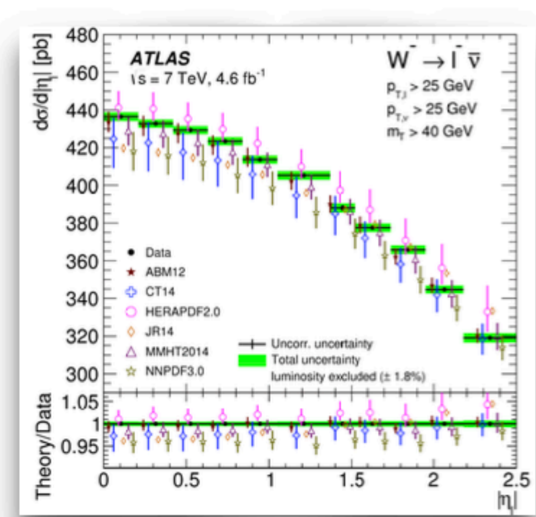
2017 Eur.Phys.J.C 78 (2018)
First Measurement of m_W

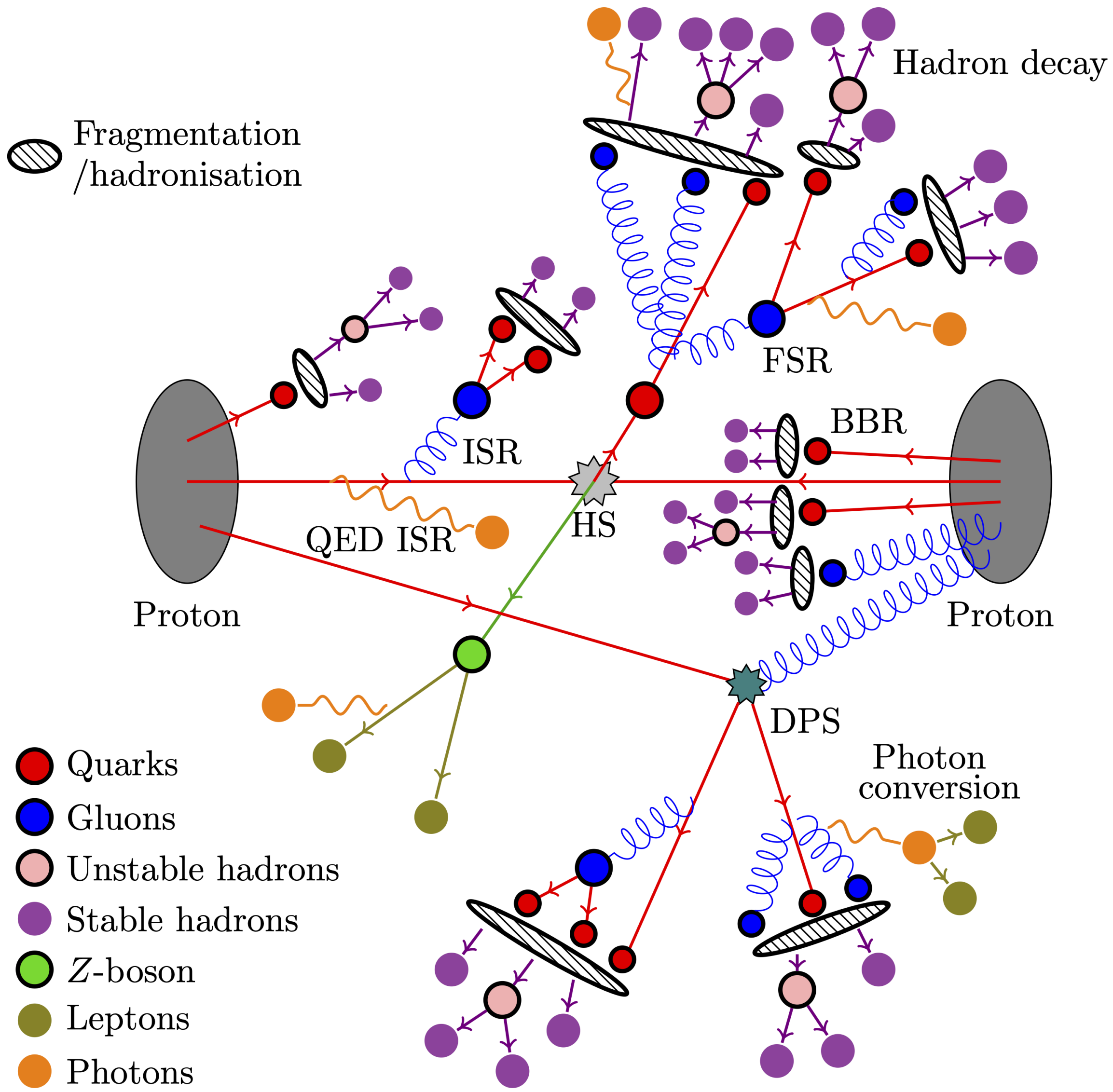
2018 Start of the m_W Re-analysis Efforts

2019 A. Düdder
PhD Theses
2020 L. Adam
PhD Thesis
2022: P. König
PhD Thesis

2023 This Work
Reanalysis of m_W

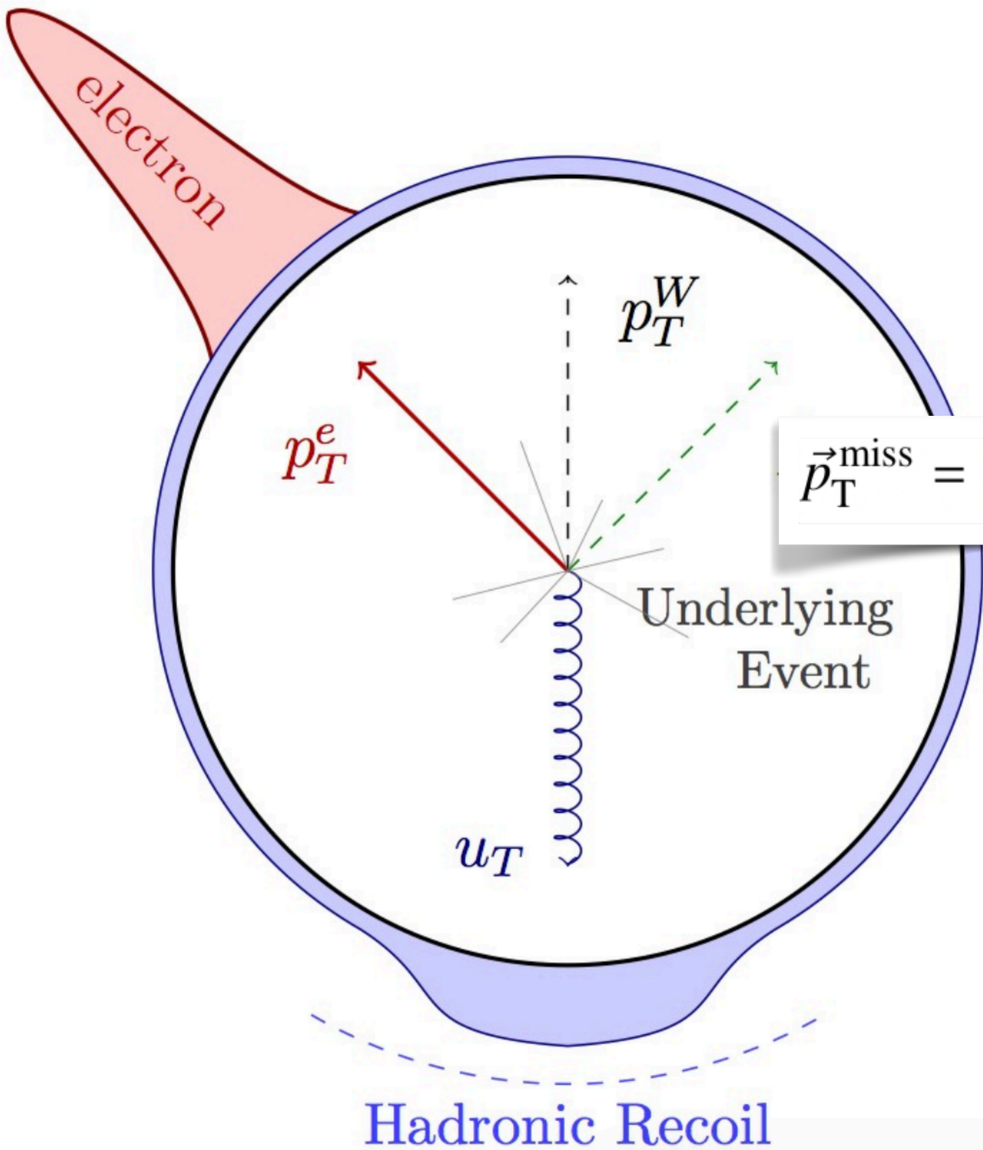






Hadronic recoil

Experimental challenge: W boson signature



$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right)$$

$$\vec{u}_{\mathrm{T}} = \sum_i \vec{E}_{\mathrm{T},i}$$

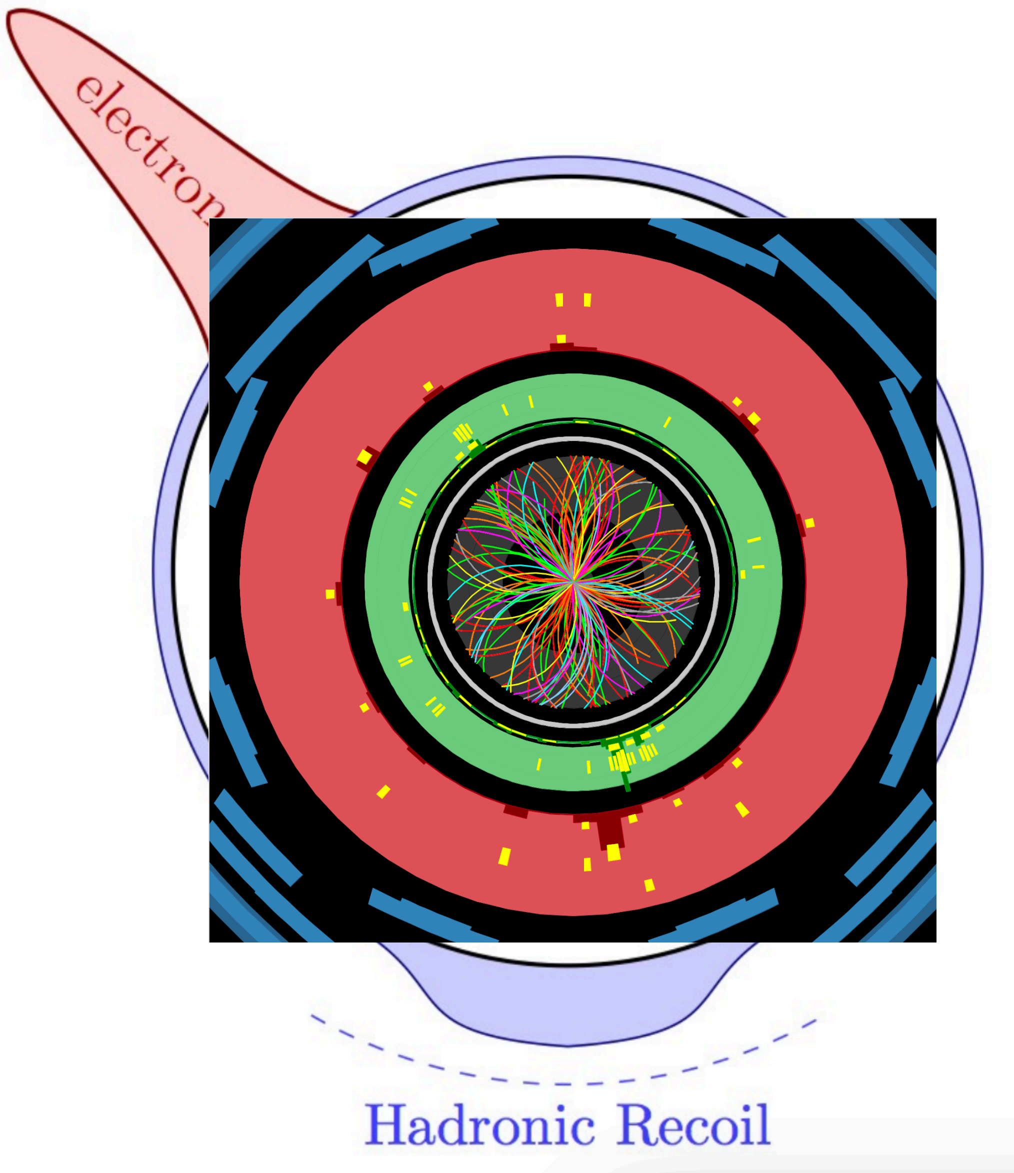
Incomplete kinematics (missing **neutrino**):

- no invariant mass
- measured quantities
  - Prompt and isolated **lepton** (e or μ)
  - *Hadronic*-**Recoil** (u_T): sum of "everything else" reconstructed in the calorimeters;
- exploit momentum conservation in the transverse plane to reconstruct p_T^{miss} and transverse mass (m_T)

+ Pileup …

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi)}$$

W boson signature



$$\vec{u}_{\rm T} = \sum_i \vec{E}_{{\rm T},i}$$

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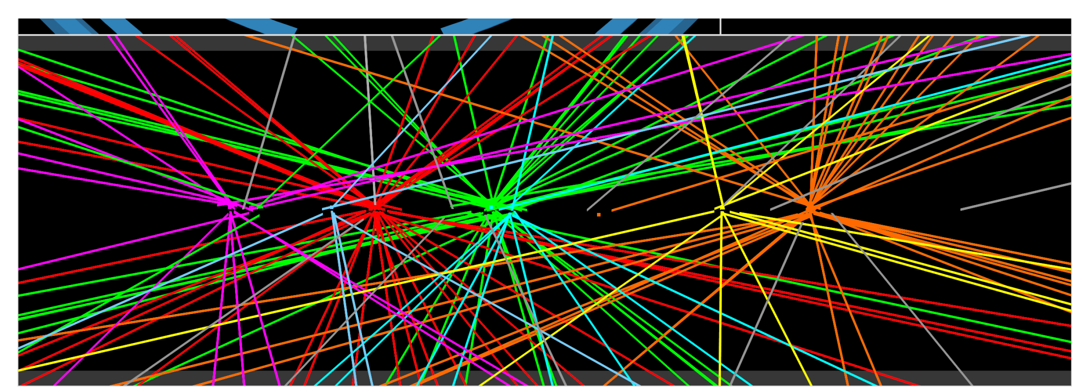
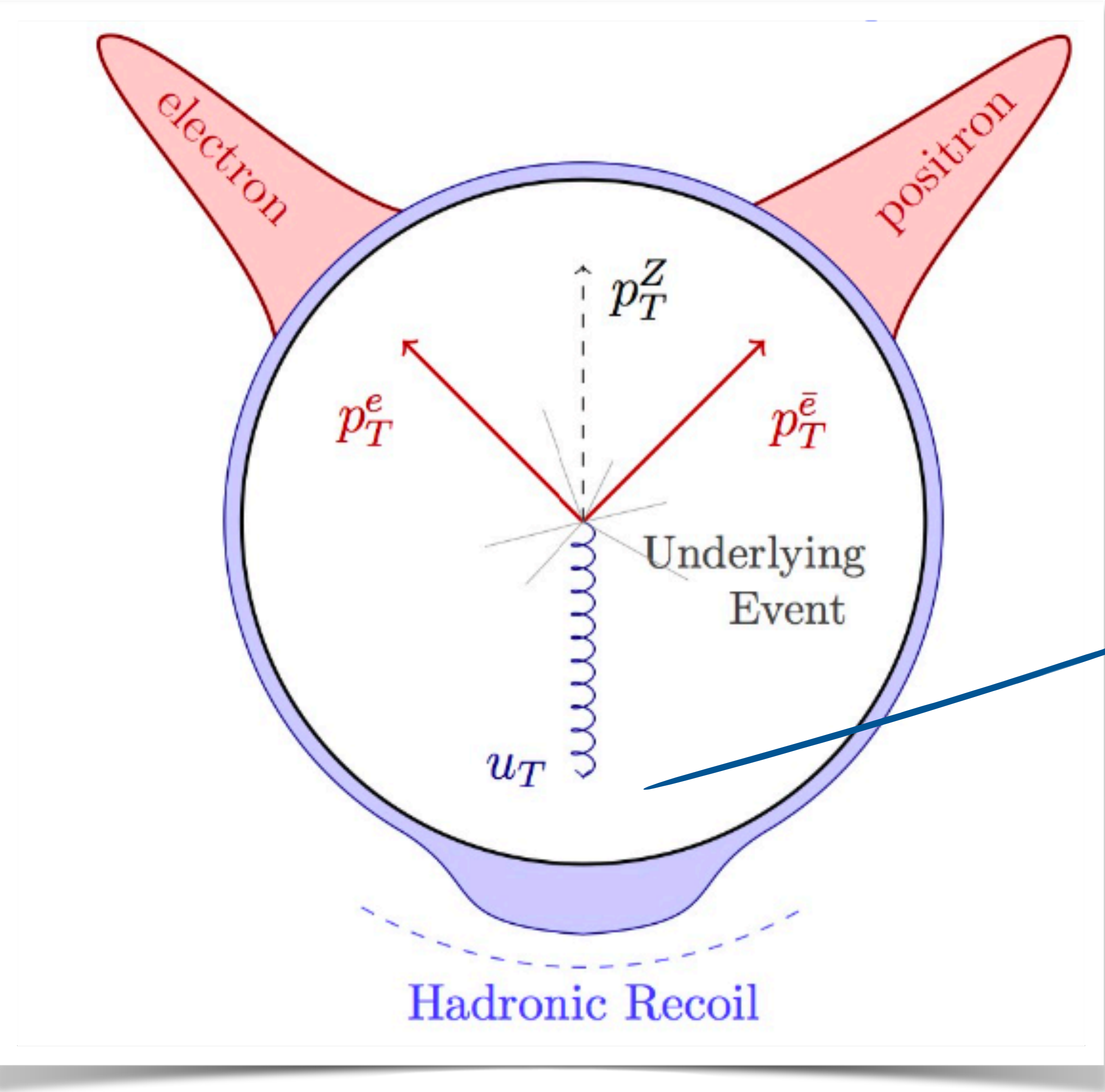


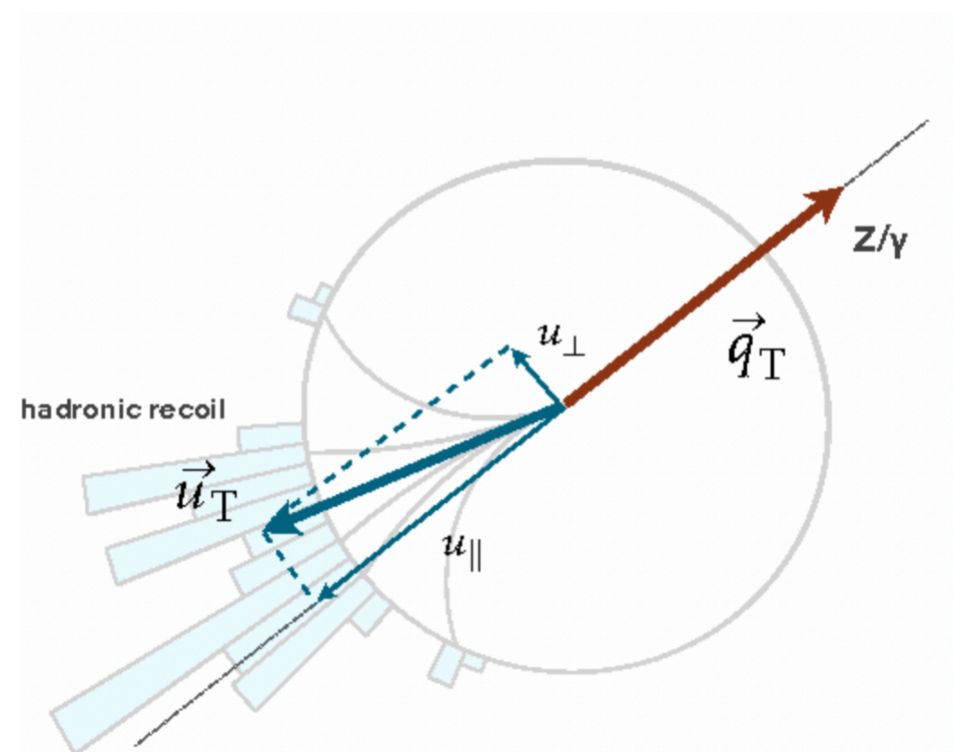
Hadronic recoil calibration with Z events



In Z-events

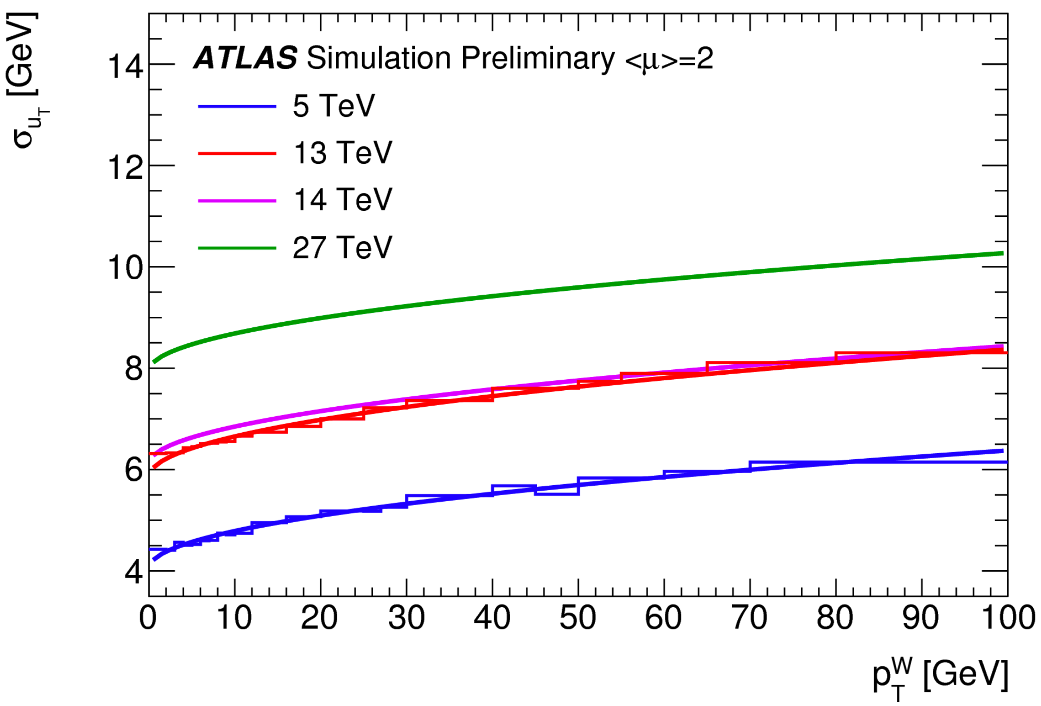
- exploit momentum conservation in the transverse plane to measure in data the u_T response using the p^Z_T balance in Z events

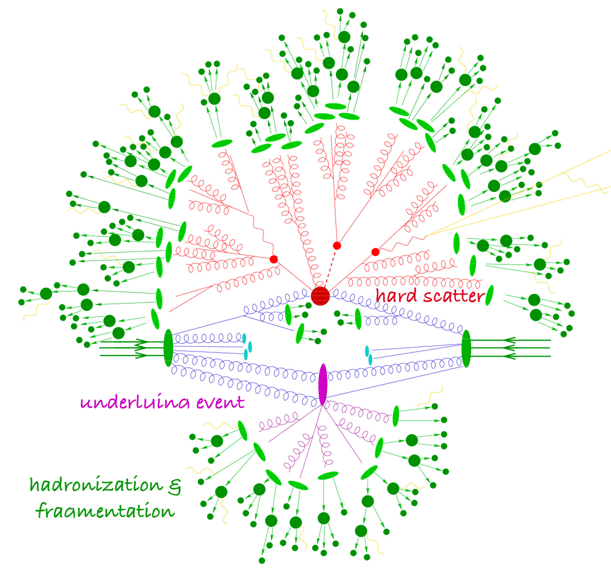
$$p_T^Z = p_T^{\ell\ell} = -u_T$$



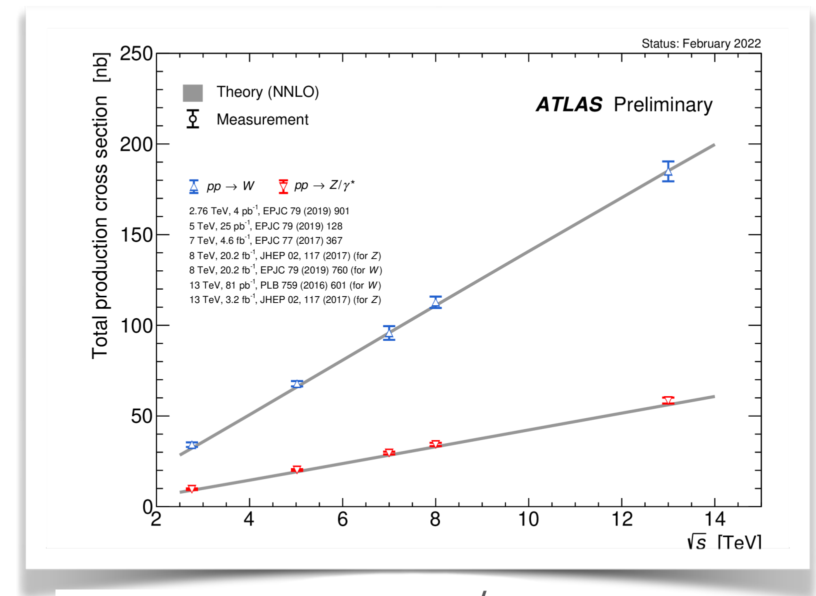
u_T scale and resolution are characterise by the // and ⊥ projection of the recoil into the p^Z_T axis

Underlying event and Pileup contribution to the recoil

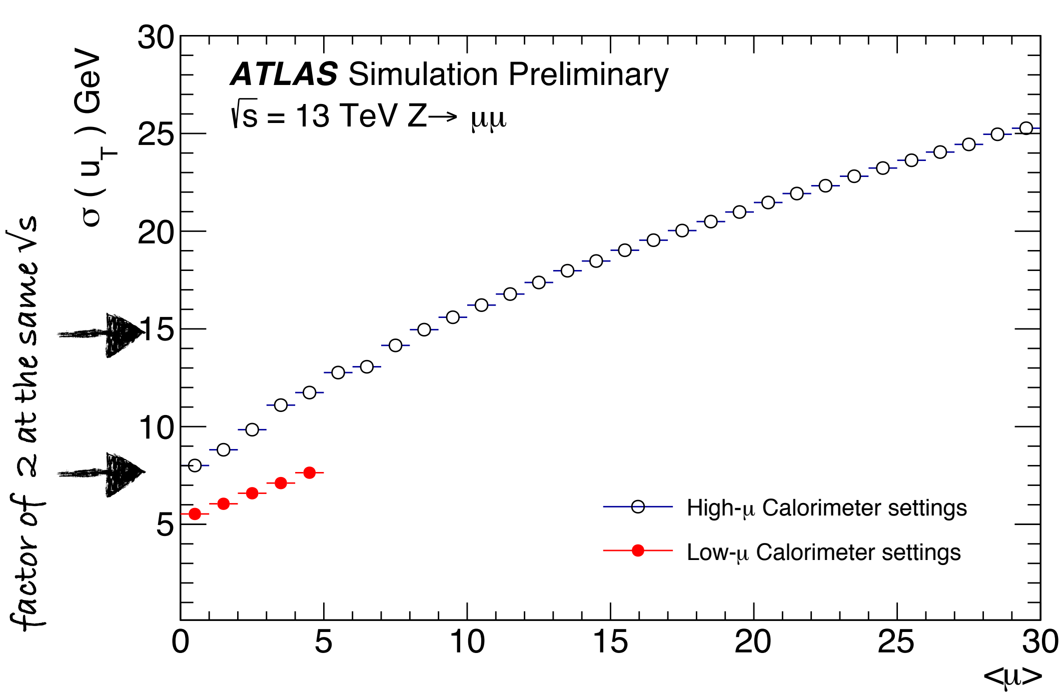


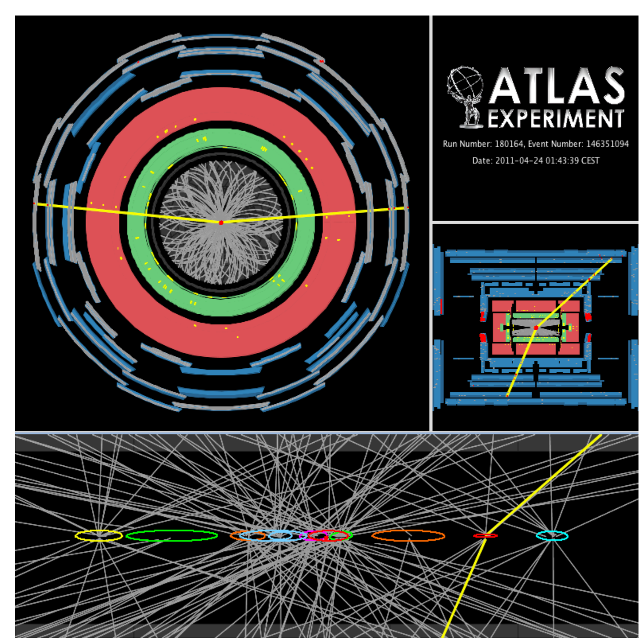


underlying events grows with √s

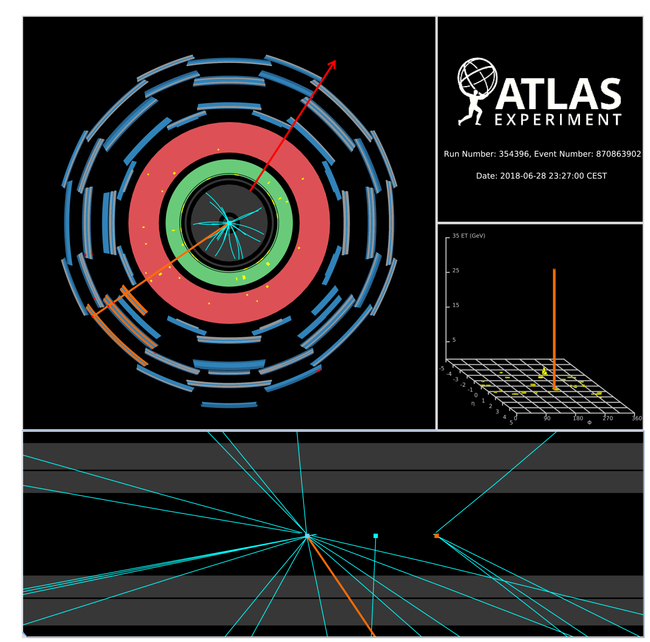


X-section grows with √s





9 additional reconstructed vertices

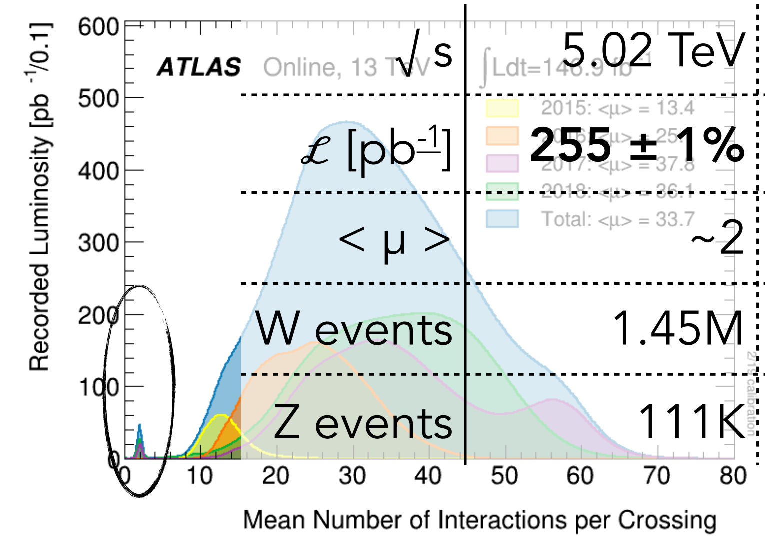


2 additional reconstructed vertices

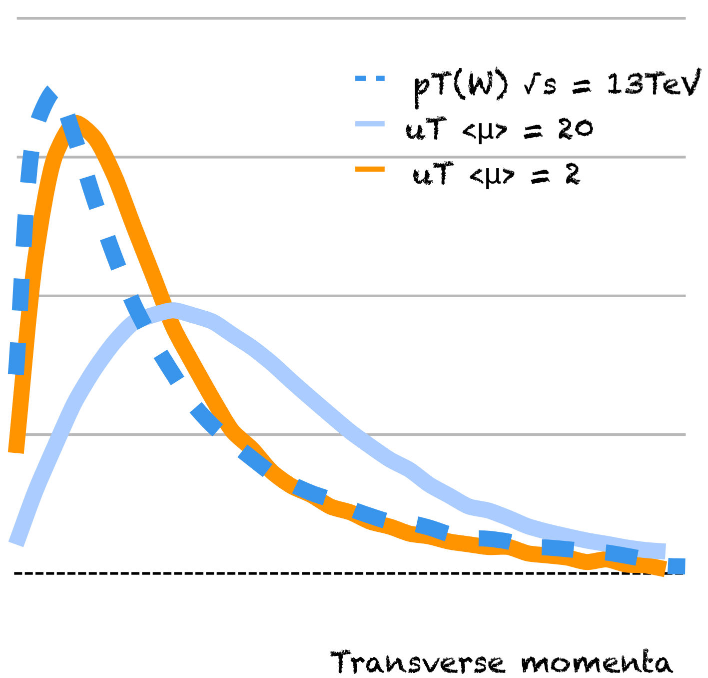
Low-μ dataset

In Run-2 ATLAS collected ~ 500 pb^{-1} at <μ> ~ 2

fantastic opportunity for W precision physics!

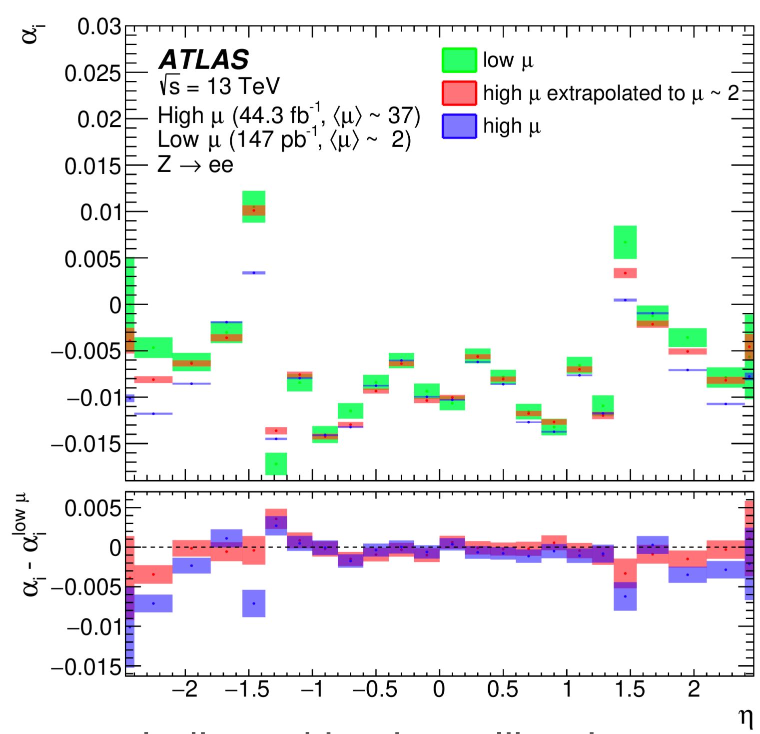


$\sqrt{s}$	5.02 TeV	13 TeV
$\mathcal{L}$ [pb^{-1}]	**255 ± 1%**	**338 ± 0.92%**
< μ >	~2	2 (levelled)
W events	1.45M	4.36M
Z events	111K	366K

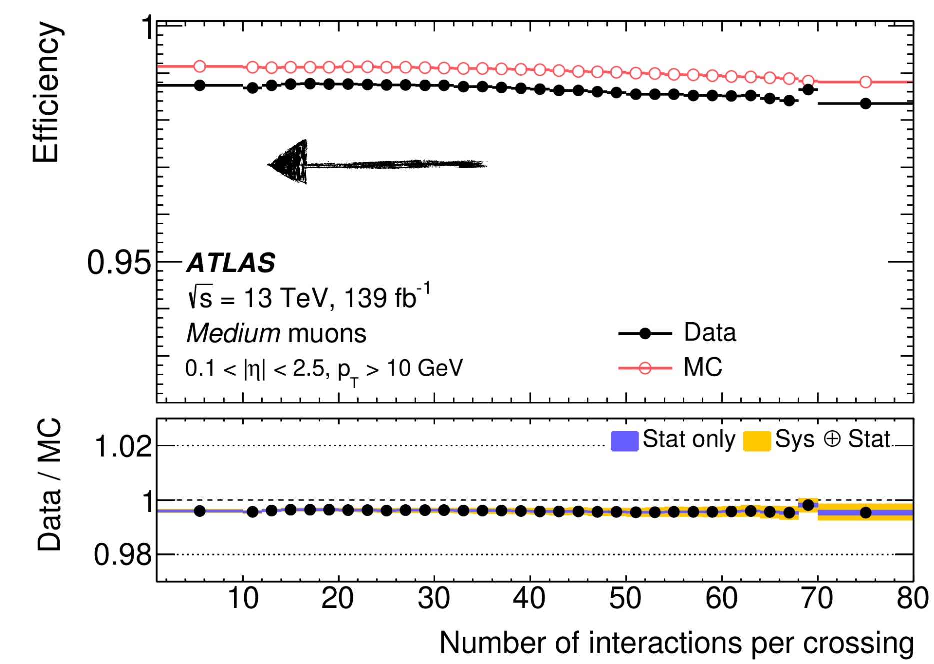


- *Unique* recoil resolution
- Benefit from ***super precise*** **luminosity** uncertainty
- *Dedicated* set of detector calibration and performances

leptons performance accuracy limited by the Z sample statistic



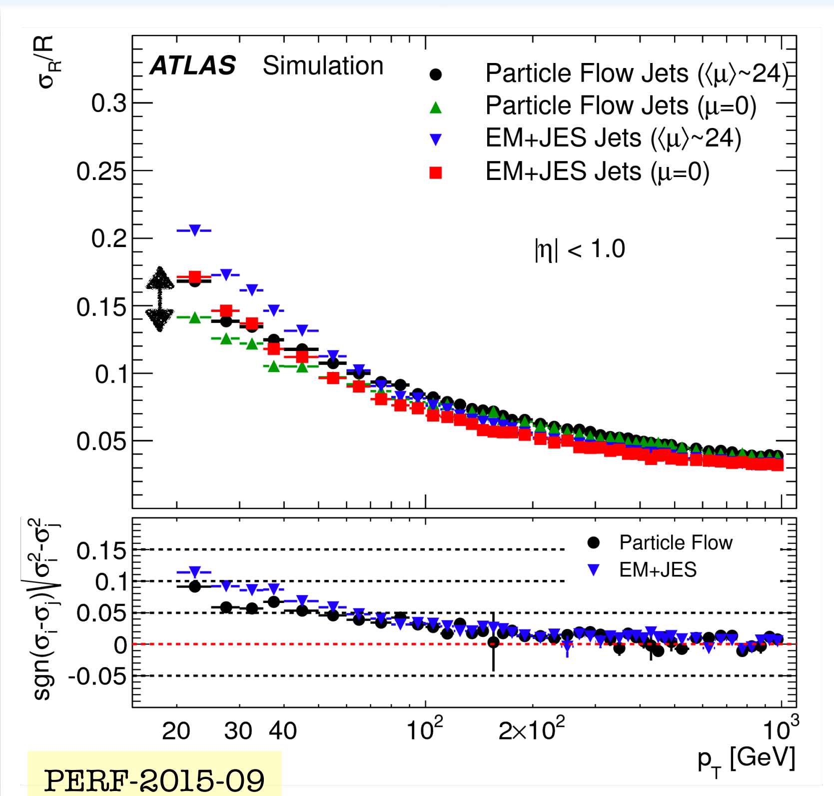
dedicated in-situ calibrations

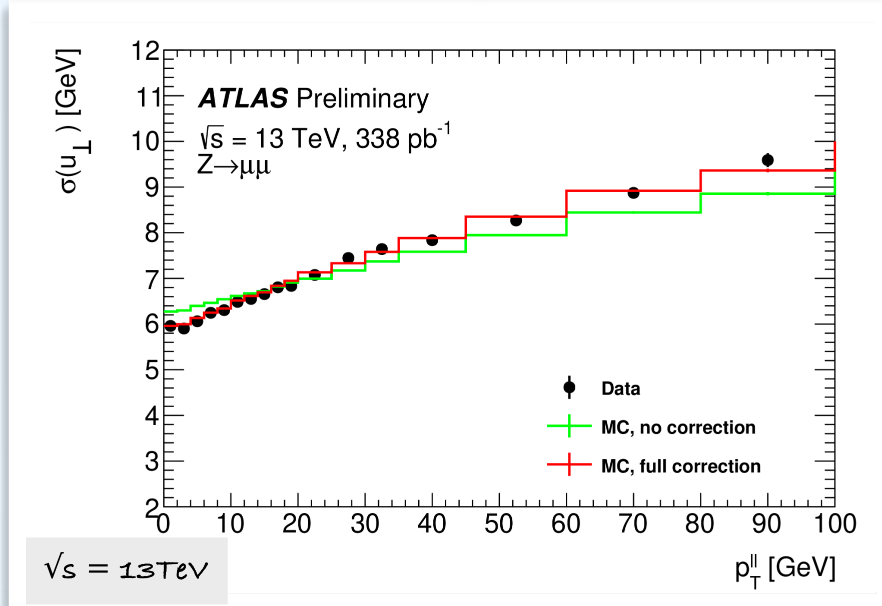


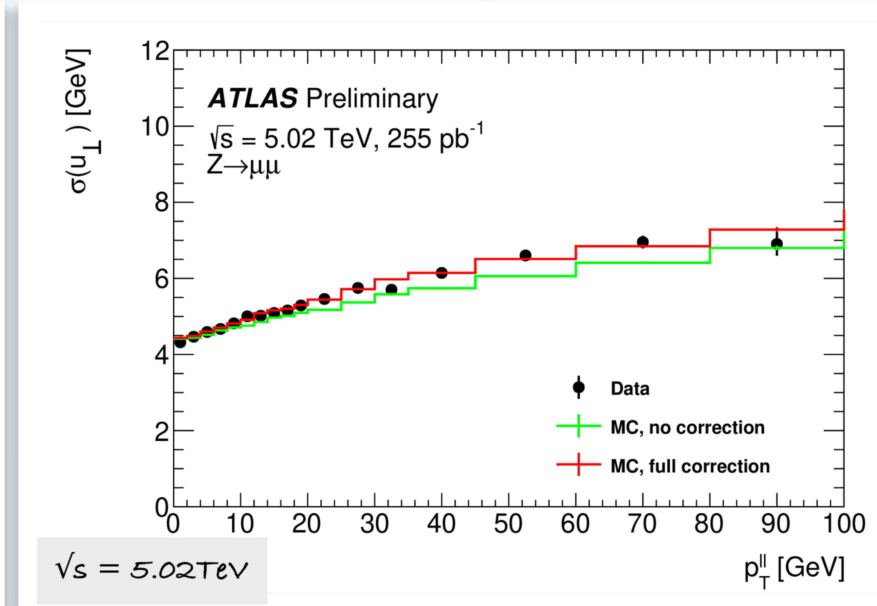
wherever possible extrapolated high-μ to low-μ conditions

Hadronic recoil performances

A) Particle flow objects (**PFOs**) for recoil **reconstruction** *up to 5% improvement in resolution*



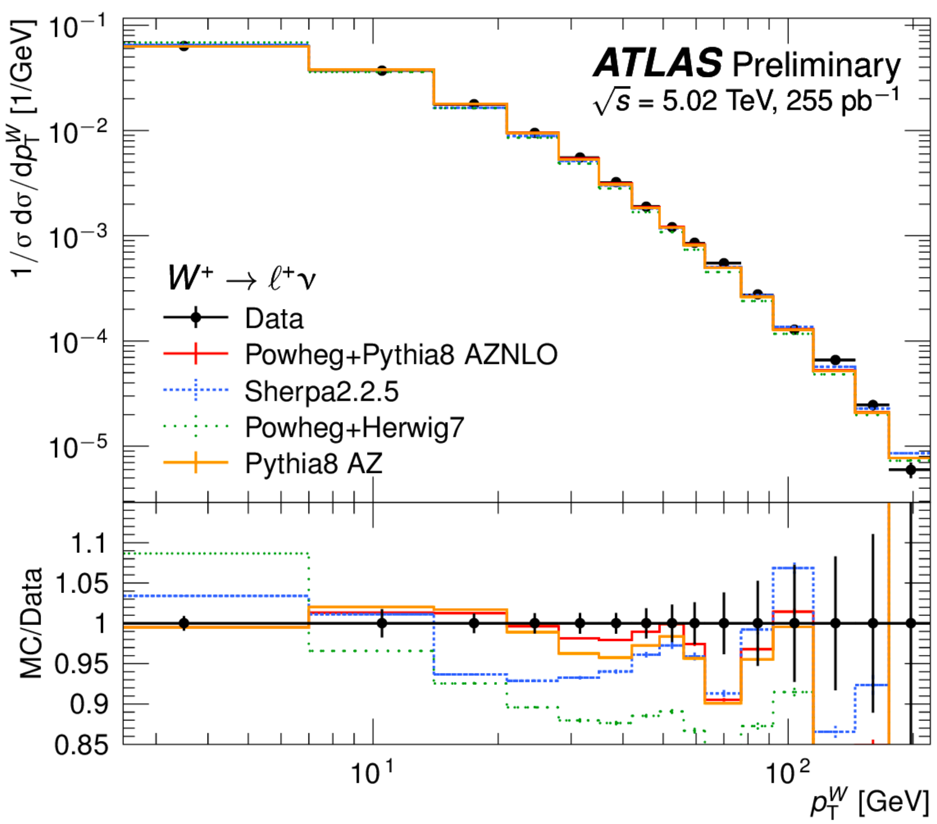


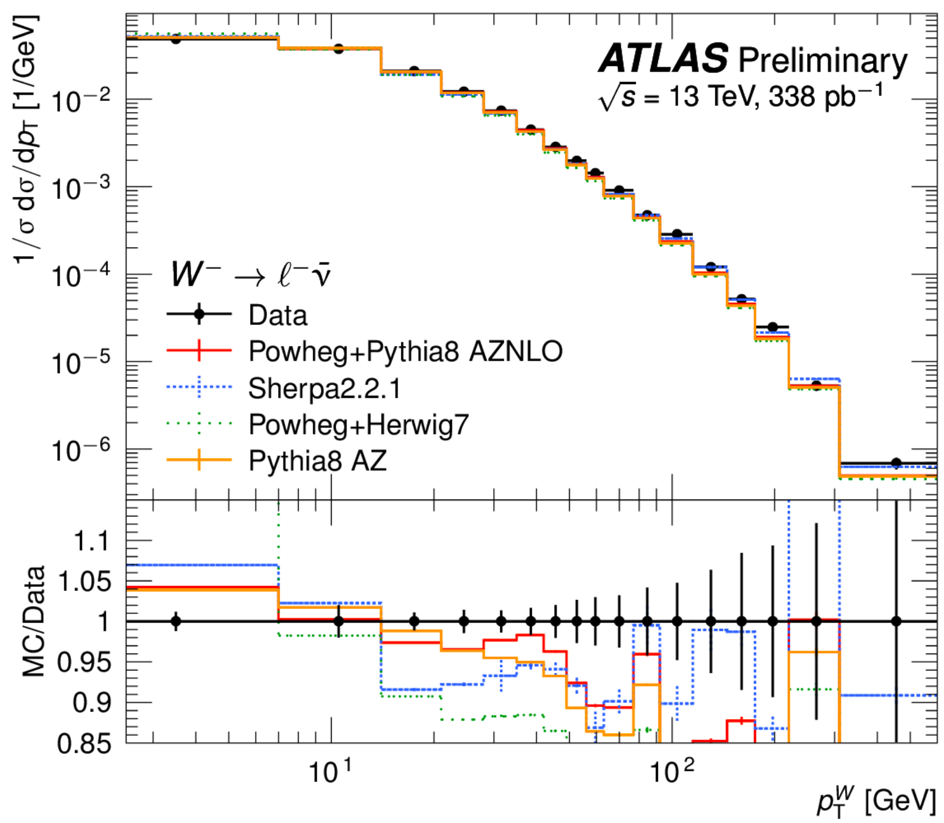


B) in-situ in $Z\to\ell\ell$ events used to **Calibrate** the recoil response:

- Modelling of underlying activity from data
- Correcting response non-uniformity in the calorimeter (beam displacement, beam-crossing angle. azimuthal angle)
- Equalising response and resolution differences between data/MC
- Correcting for residual non-Gaussian tails in the response

Hadronic-recoil uncertainties have sub-percent level impact on p_T^W < 50 GeV
(@ 5TeV limited stat of the Z samples is the dominant source)

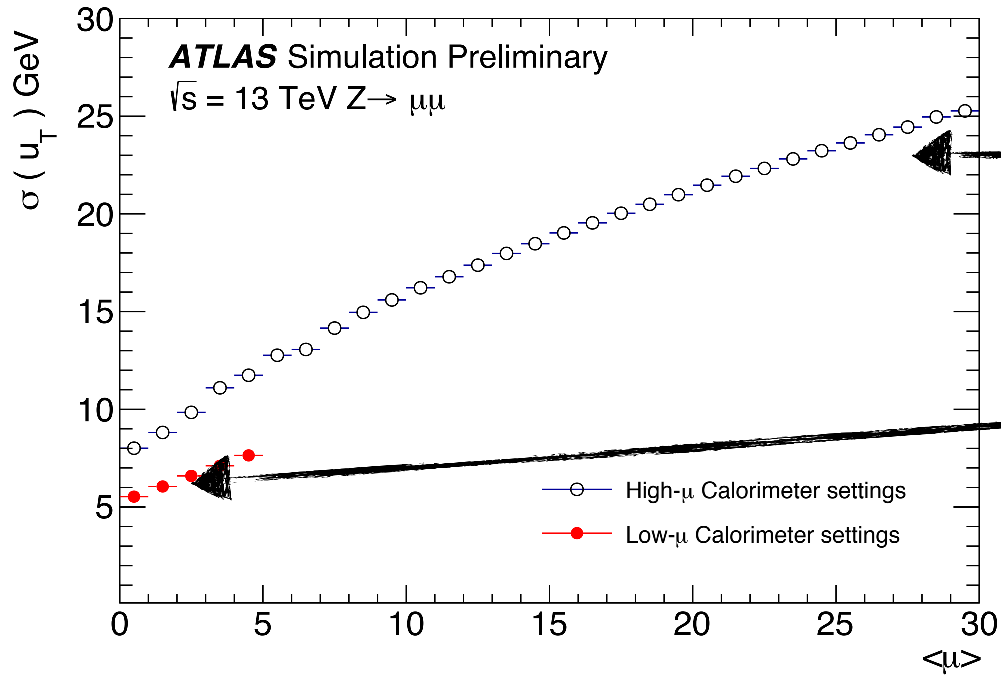


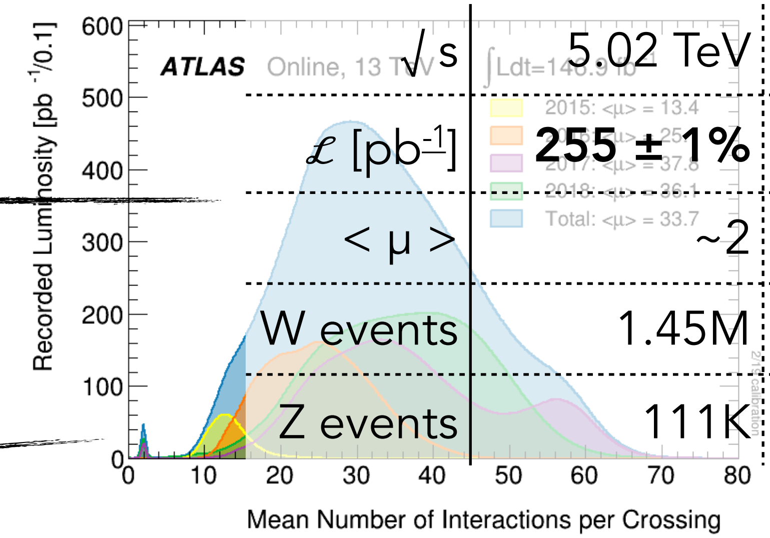


Eur. Phys. J. C 84 (2024) 1126

The p^W_T measurement

Low mu





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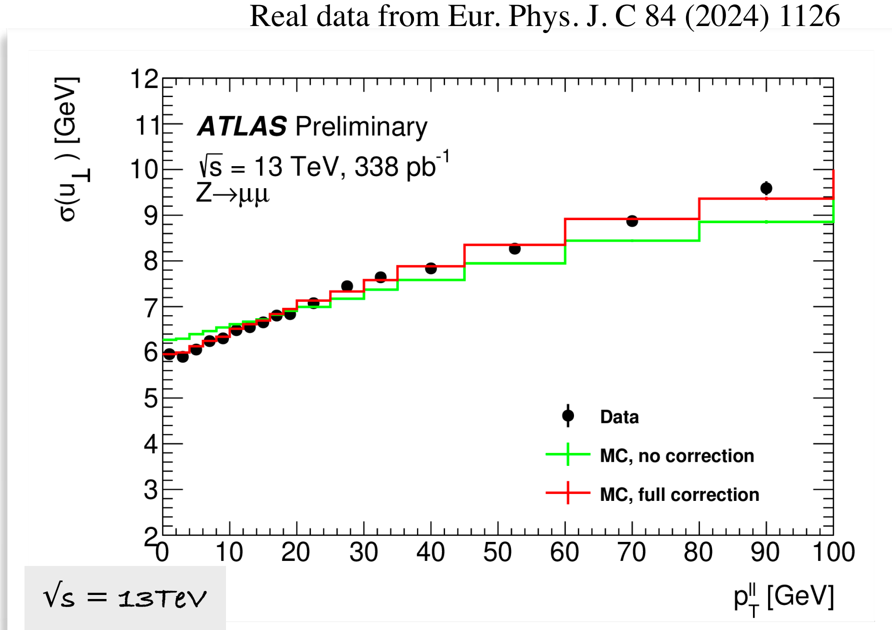
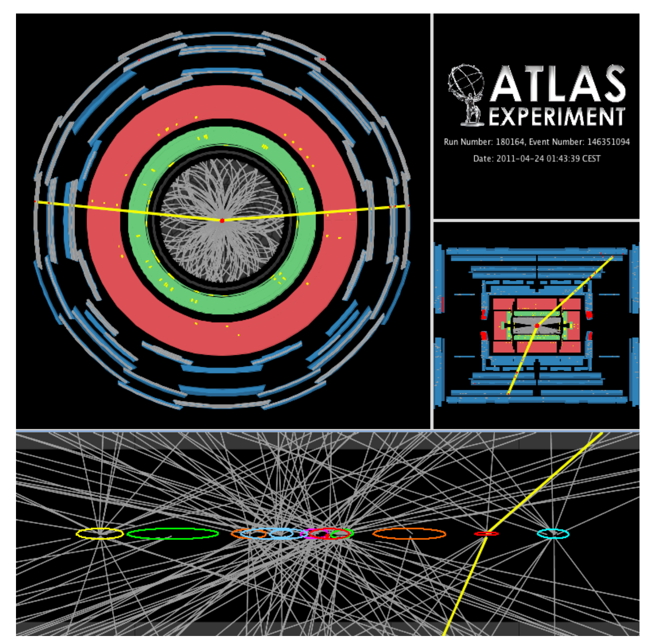
$\mathcal{L}$ [pb^{-1}]	**255 ± 1%**	**338 ± 0.92%**
$<\mu>$	~2	2 (levelled)
W events	1.45M	4.36M
Z events	111K	366K

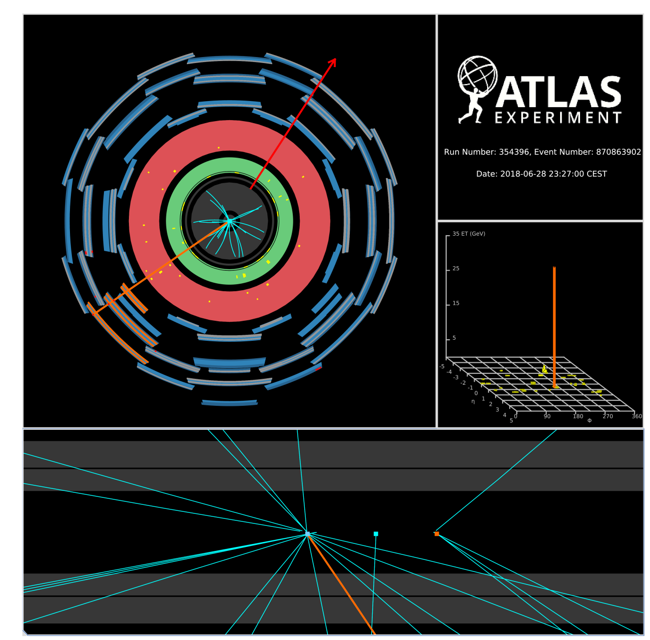
Run2-luminosity

Real data from Eur. Phys. J. C 84 (2024) 1126





9 additional reconstructed vertices



2 additional reconstructed vertices

Wp_T measurements

lepton p_T > 25 GeV
lepton $|\eta|$ < 2.5
W : p^{ν}_T >25 GeV ; m_T> 50 GeV
Z : 66 < $m_{\ell\ell}$ < 116 GeV

Detector level distributions unfolded at particle level in fiducial volume:

- **Bayesian unfolding** of u_T (W) ; $p^{\ell\ell}_T$ (Z) , separately for e/μ channels
  - Bin width/iterations **optimise to reduce uncertainty of unfolding prior bias**
  - 9 (25) iterations, ⊢7GeV⊣ bin at low p_T^W at 5.02 (13) TeV
  - 2 iterations, ⊢2GeV⊣ bin width at low p_T^Z
- electron and muon channels combined with BLUE, all giving good $\chi 2$

Most precise integrated fiducial measurement of the W± and Z boson @ 5.02 and 13 TeV:

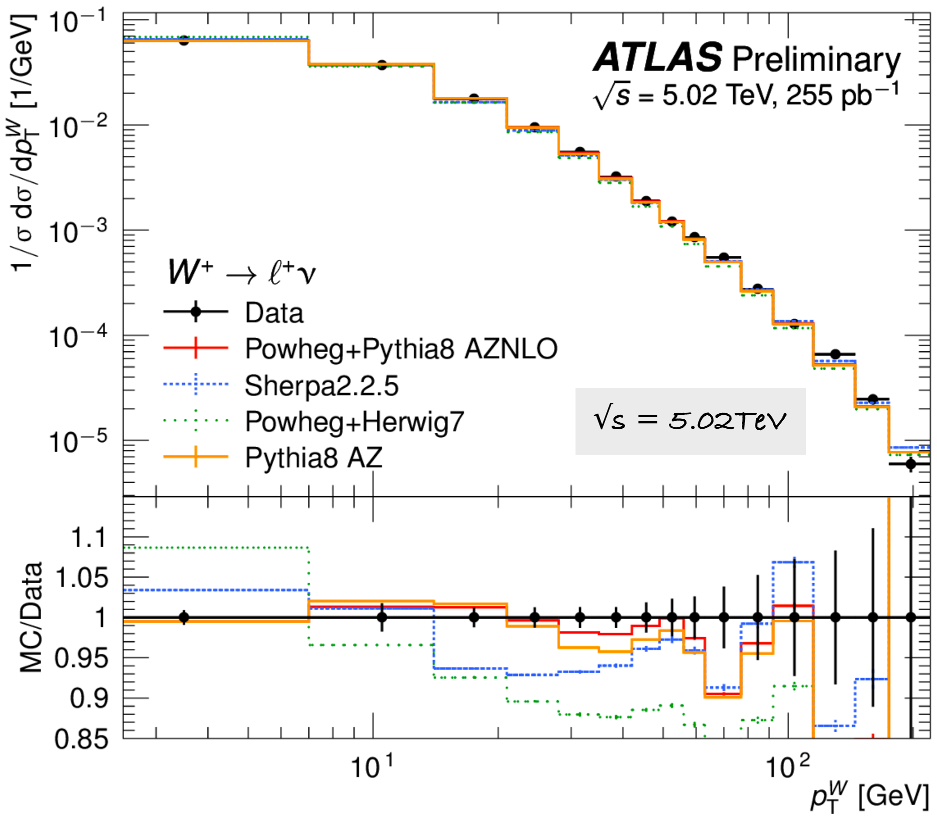
Process	Cross section at $\sqrt{s} = 5.02$ TeV [pb]	Cross section at $\sqrt{s} = 13$ TeV [pb]
$W^- \to \ell\nu$	1385 ± 2 (stat.) ± 5 (sys.) ± 15 (lumi.)	3486 ± 3 (stat.) ± 18 (sys.) ± 34 (lumi.)
$W^+ \to \ell\nu$	2228 ± 3 (stat.) ± 8 (sys.) ± 23 (lumi.)	4571 ± 3 (stat.) ± 21 (sys.) ± 44 (lumi.)
$Z \to \ell\ell$	333.0 ± 1.2 (stat.) ± 2.2 (sys.) ± 3.3 (lumi.)	780.3 ± 2.6 (stat.) ± 7.1 (sys.) ± 7.1 (lumi.)

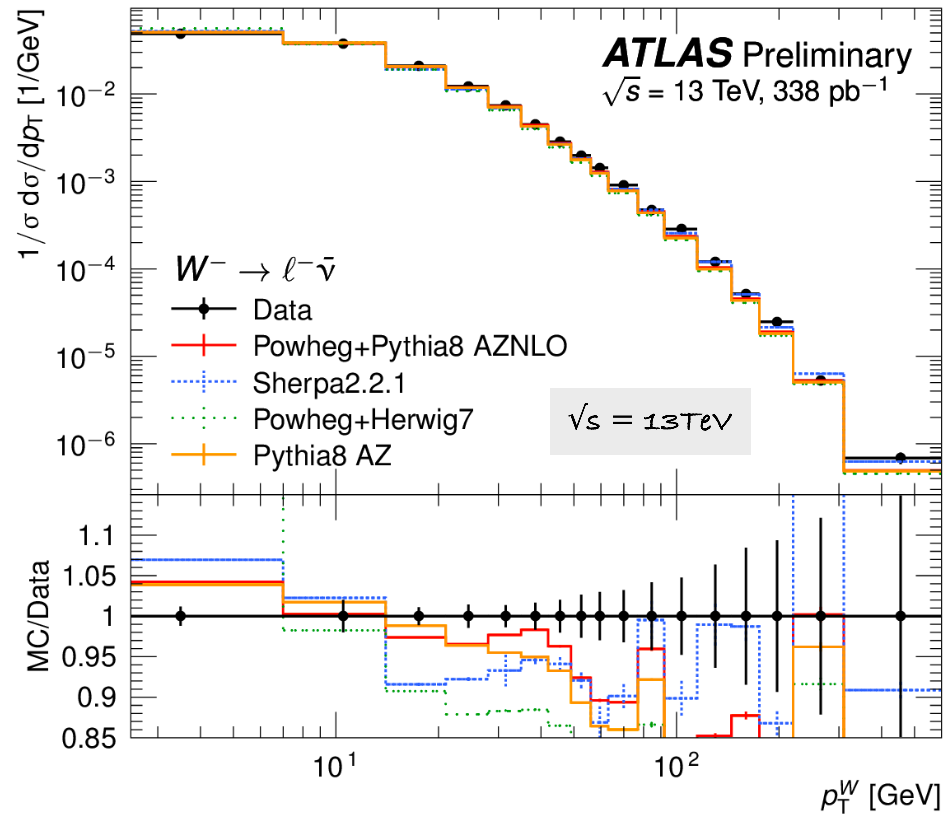
experimental accuracy 0.4 - 0.5 % with 1% lumi
factor of 2 (3.5) better then previous W X-section at 5.02 (13TeV)
good agreement with DYTURBO [NNLO+NNLL] prediction with 3 different PDF sets

W± and W∓ transverse momentum measurement

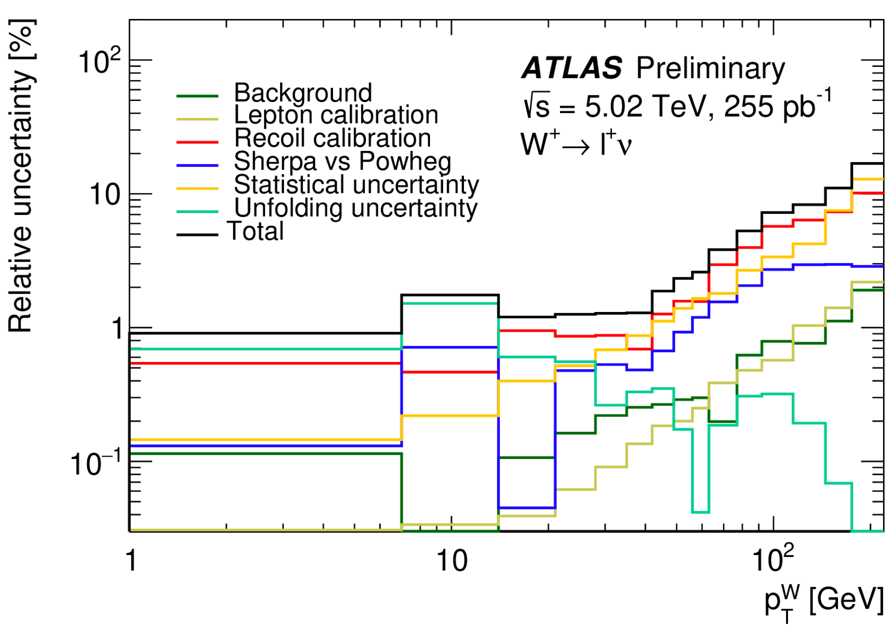
W±

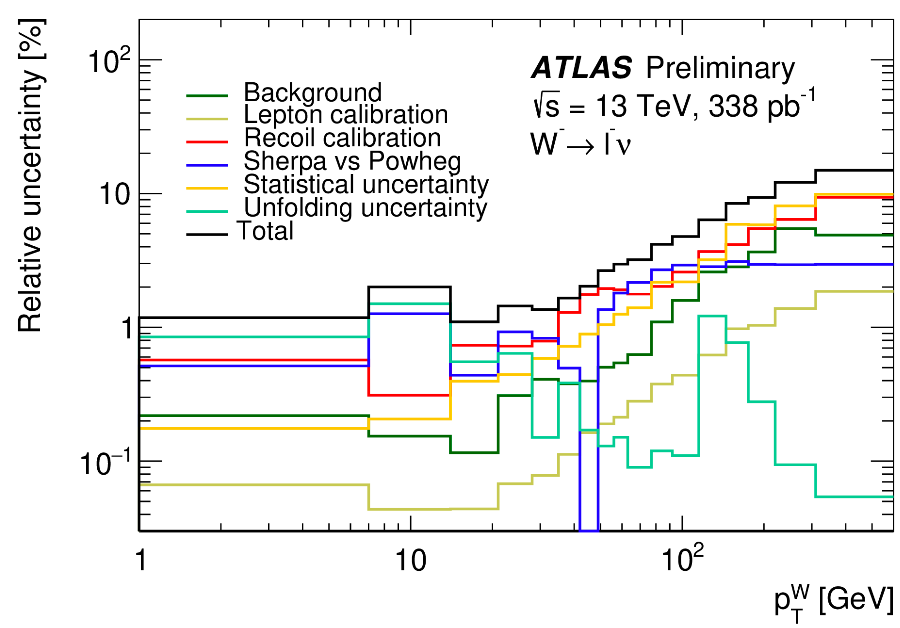
W∓





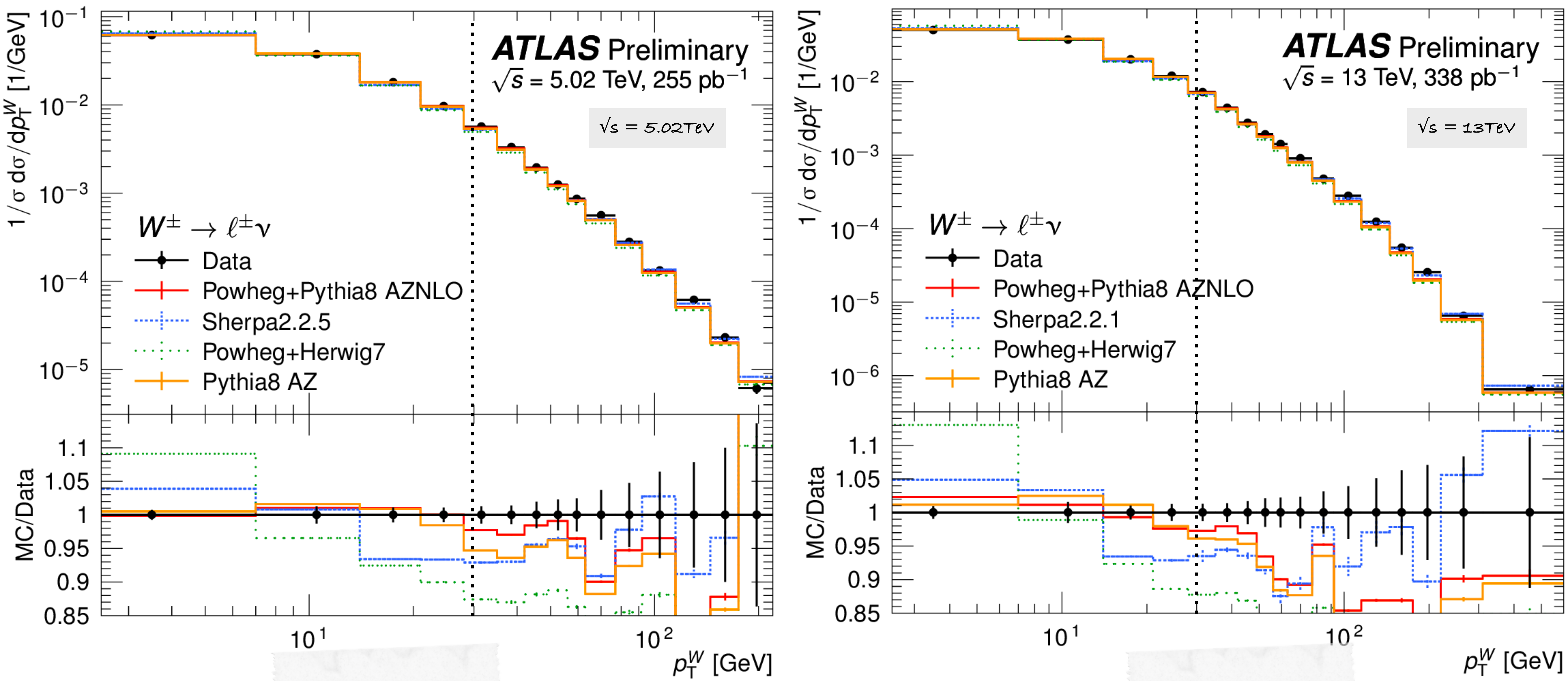
- Normalised differential distributions in data are compared to several predictions





overall data precision:
~ 1% at low pT,
~ 10% towards the end of the spectrum.

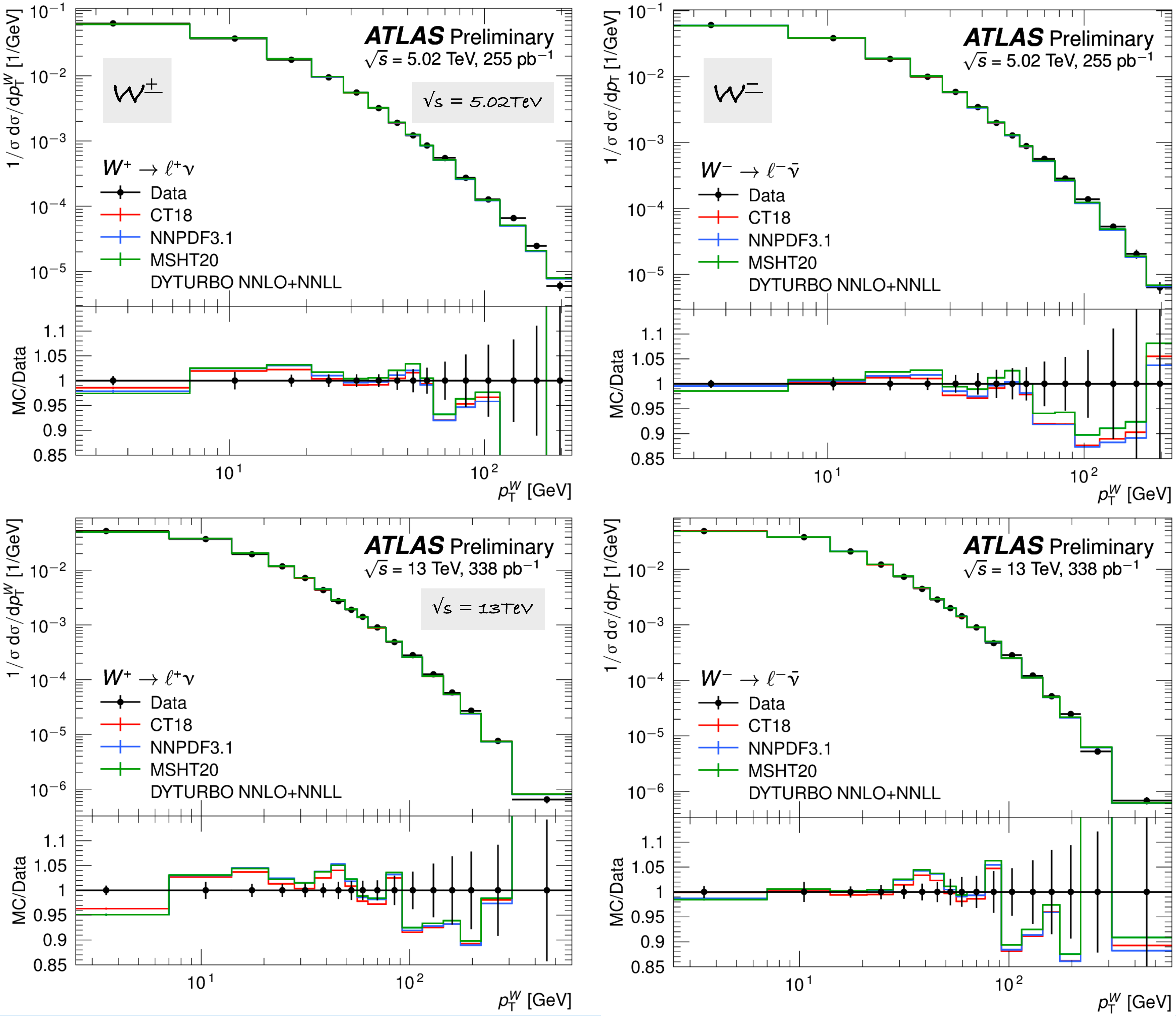
Validation of the m_W physic modelling



W mass pTW physics modelling [Powheg+Pythia 8 AZNLO ; Pythia 8 AZ] describe well the data in the low-pT region @5TeV

W mass pTW physics modelling [Powheg+Pythia 8 AZNLO ; Pythia 8 AZ] a bit worst agreement @13TeV ⇒ PS retuning needed.

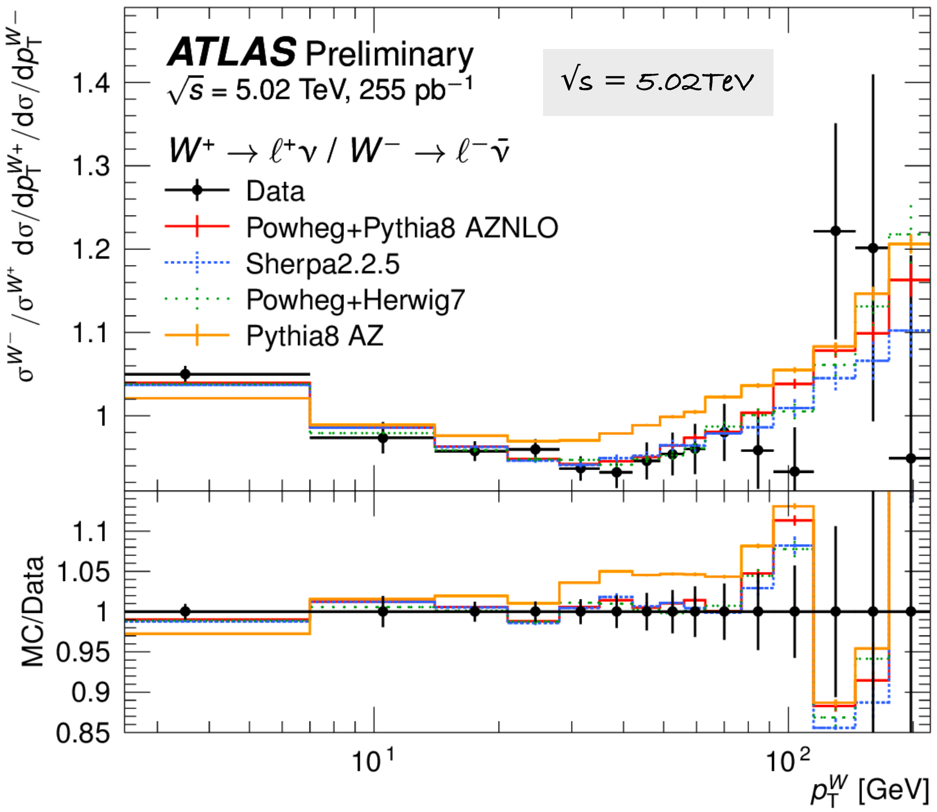
W± and W∓ transverse momentum measurement

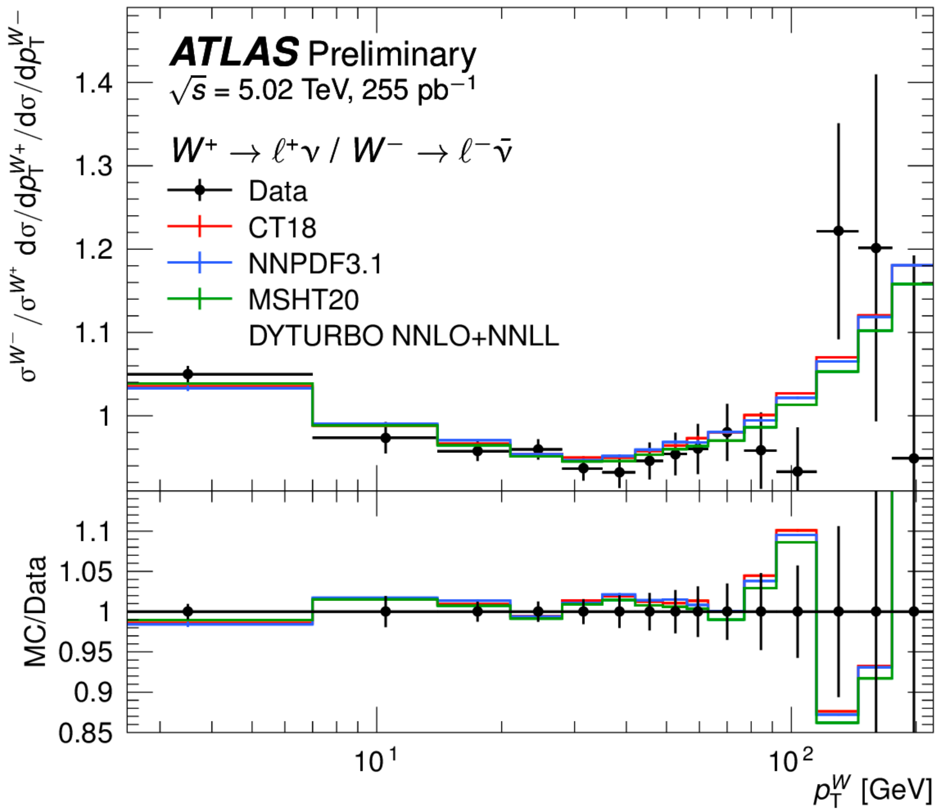


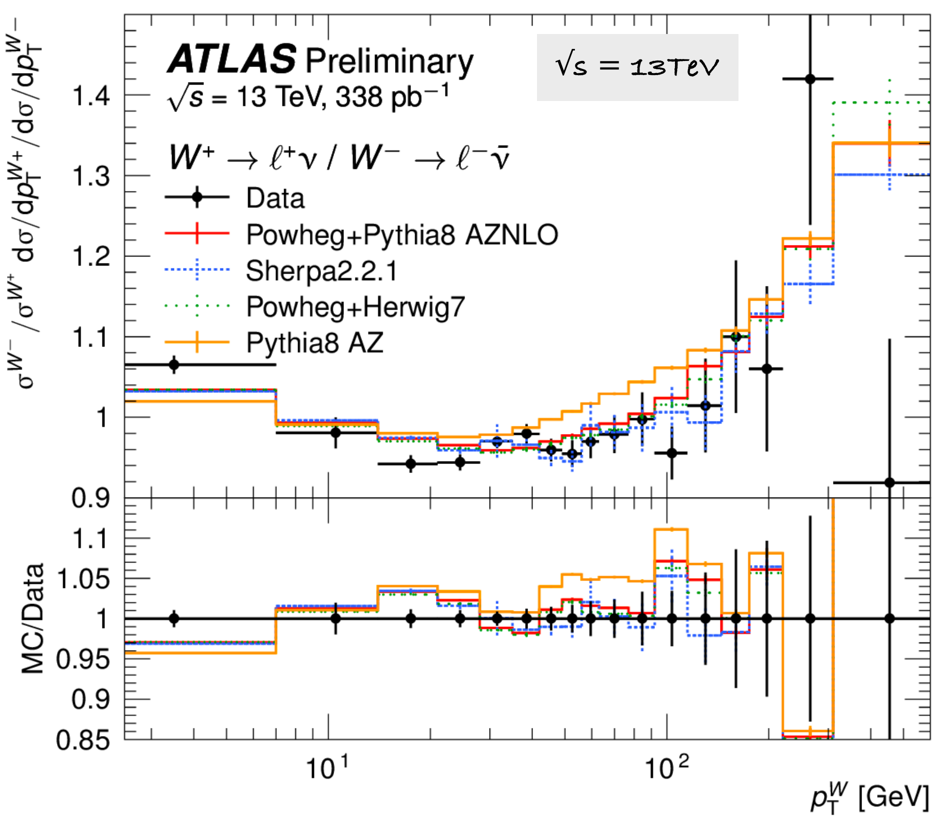
- Data distributions are compared with DYTURBO predictions [NNLO + NNLL]
  - Effect of PDF estimate comparing 3 recent PDF sets

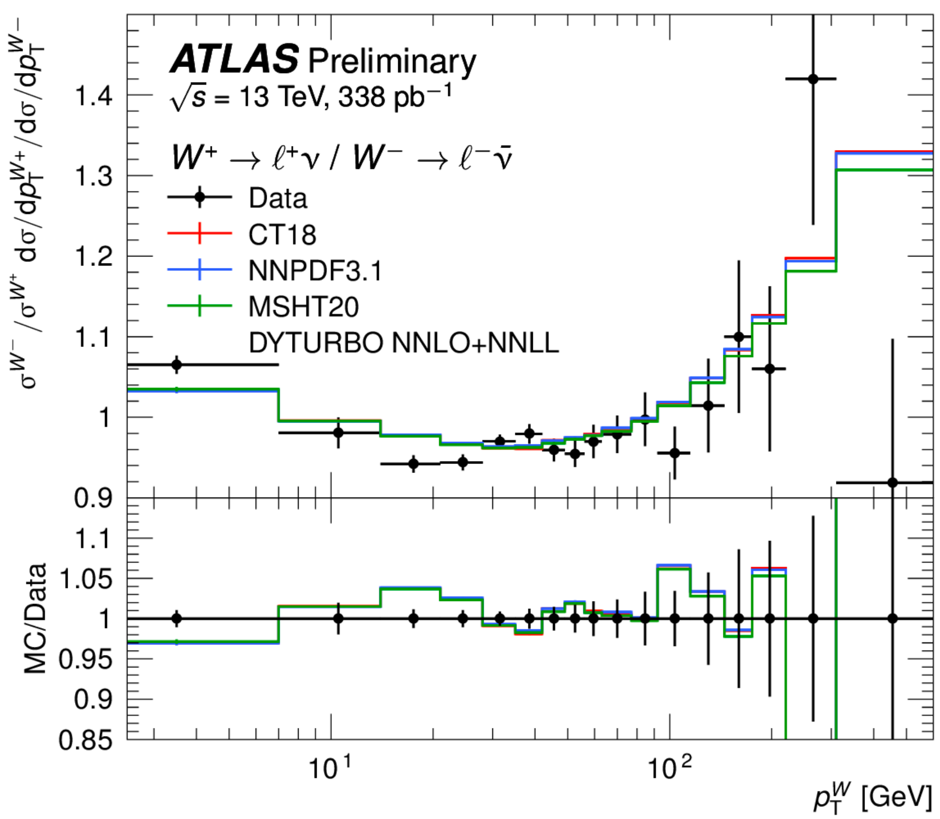
reasonable good agreement in the whole spectra →showing the improvements on analytic resummation programs!

W+/ W− ratio



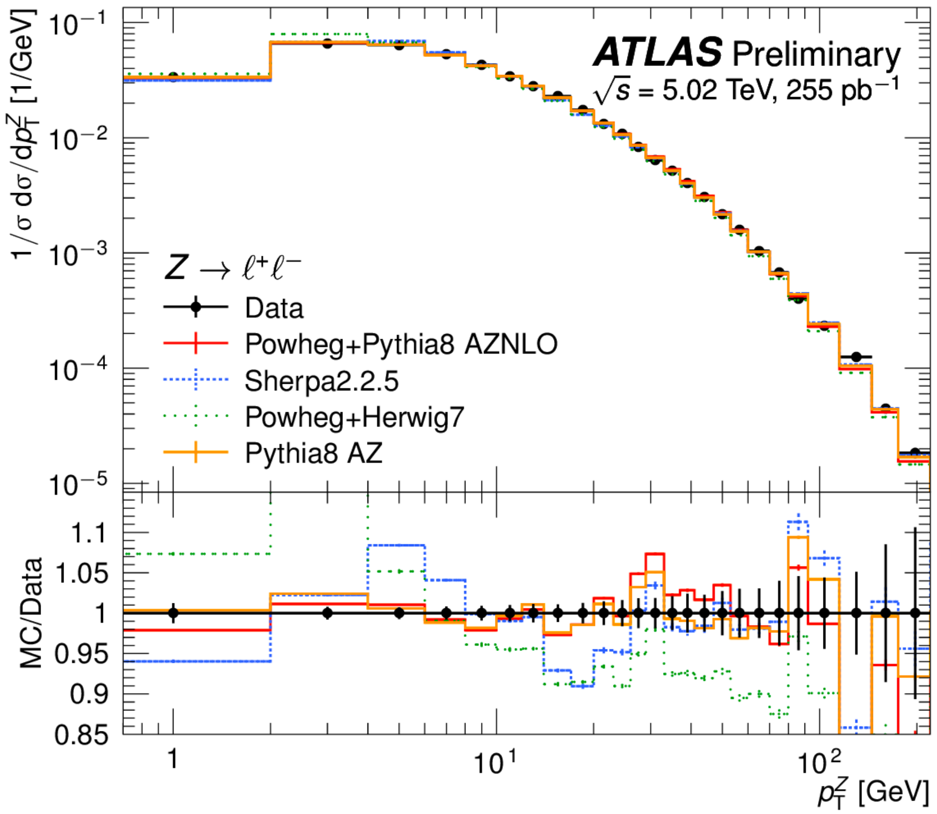


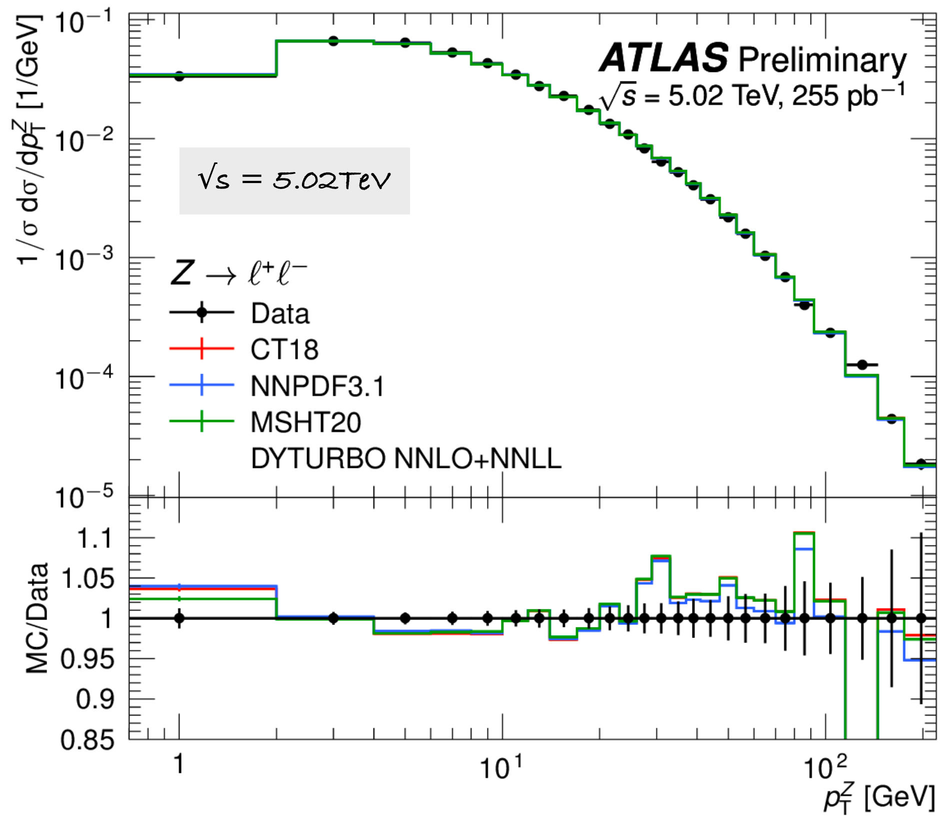


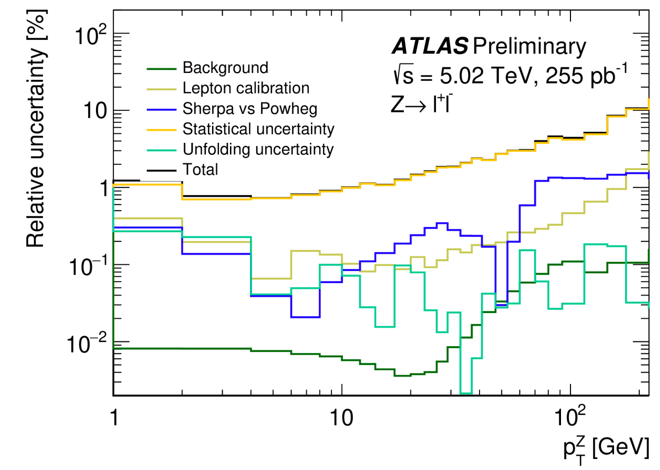


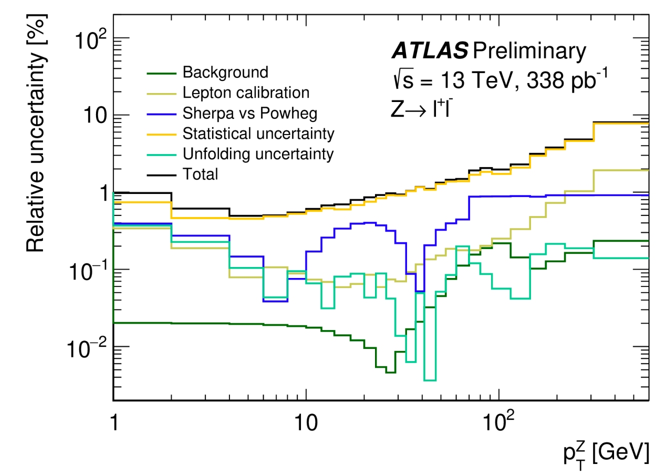
The W+ /W− ratio is expected to be relatively insensitive to universal resummation effects, but the low-pT range is sensitive to the different initial quark flavours. Exp precision ~ 1%

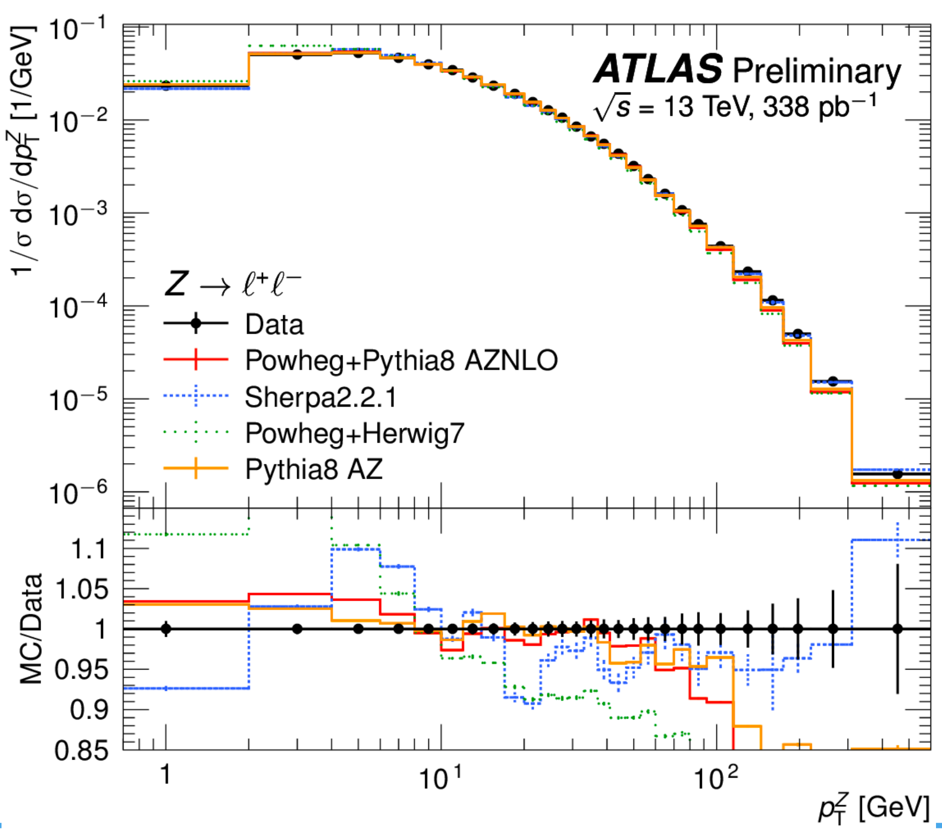
Z transverse momentum differential measurement

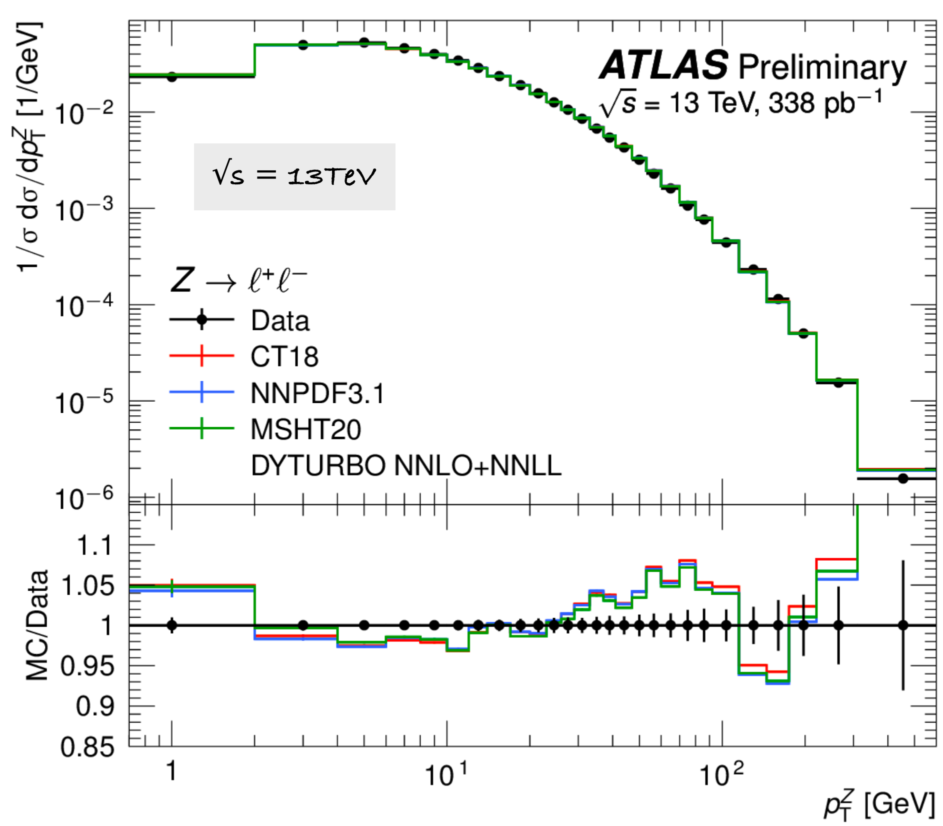








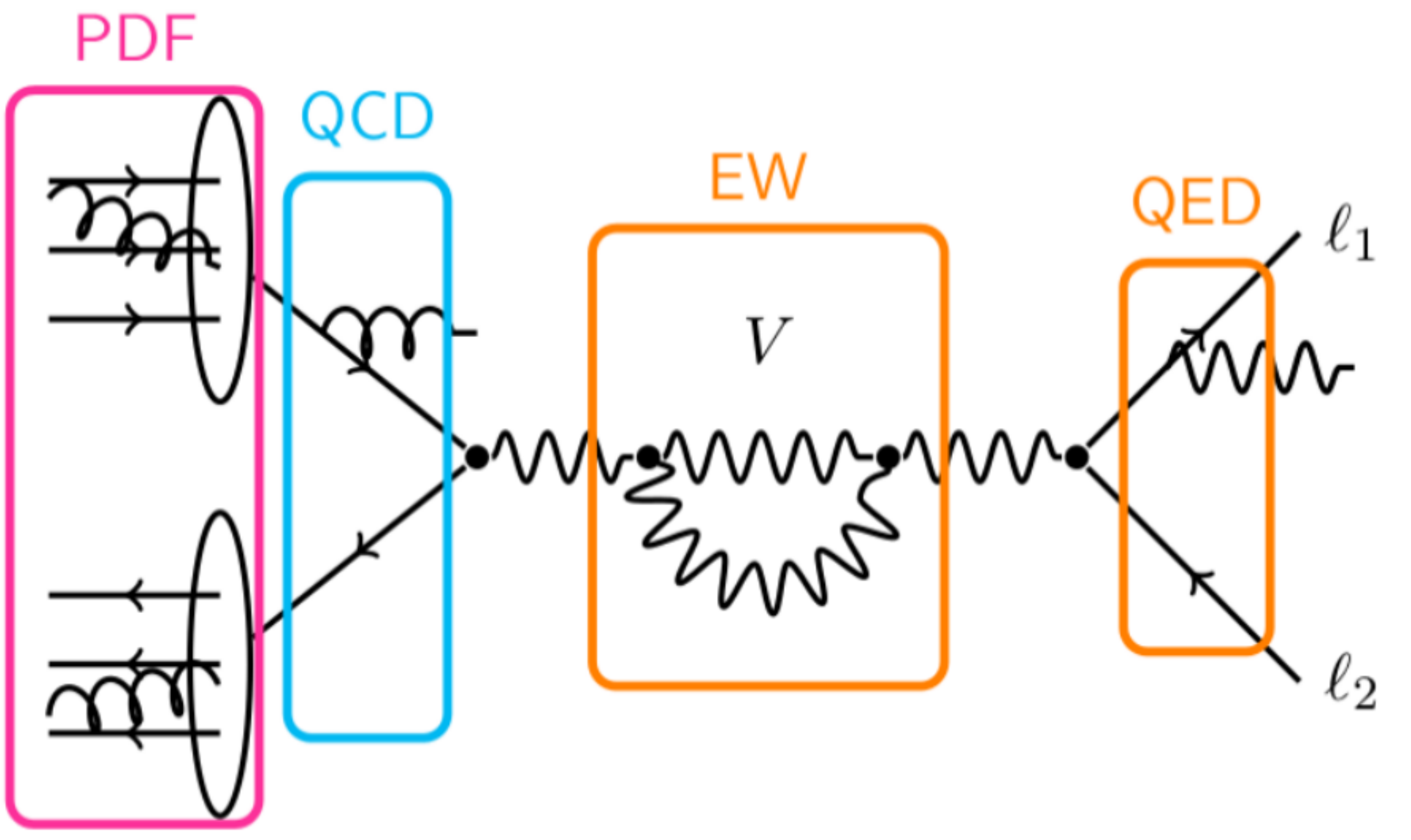




The comparison to MC sample/resummed predictions shows a variety of deficiencies most of which are common for all vector bosons. The agreement is better at $\sqrt{s}$ = 5.02 TeV

Physics Modelling

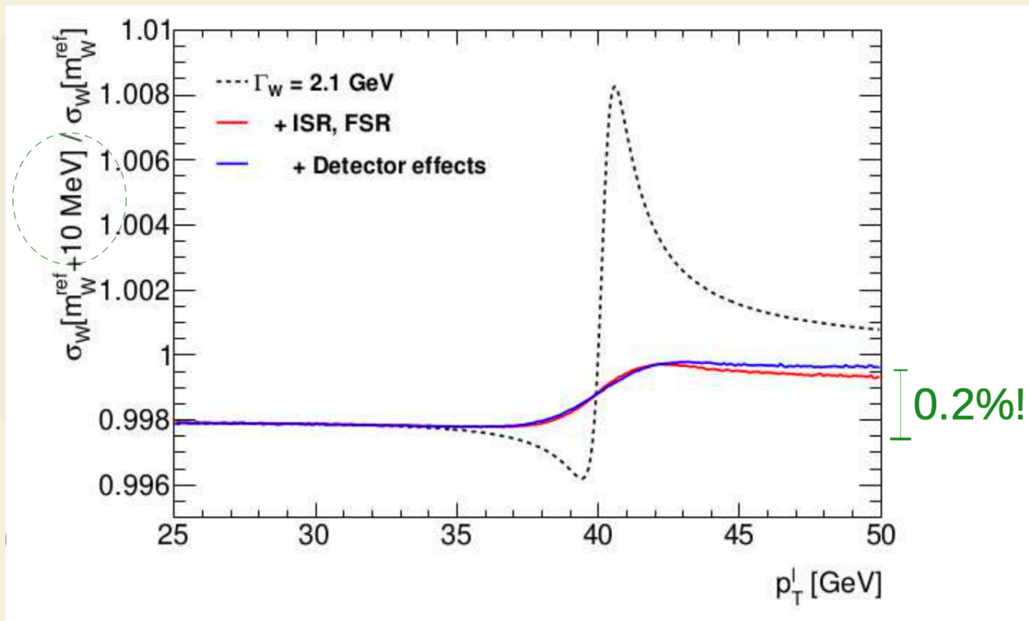
reminder limiting factor in the legacy 2018 first mW ATLAS publication



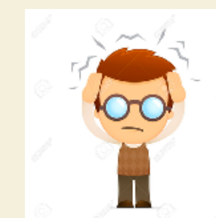
$$\frac{d\sigma}{dp_1 dp_2} = \left[\frac{\mathrm{d}\sigma(\mathrm{m})}{\mathrm{dm}}\right]\left[\frac{\mathrm{d}\sigma(\mathrm{y})}{\mathrm{dy}}\right]\left[\frac{\mathrm{d}\sigma(\mathrm{p_T})}{\mathrm{dp_T}}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y, m)\, P_i(\cos\theta, \phi)\right]$$

Complexity of the physics modelling

credit to M. Boonekamp



- **< 10 MeV precisions required ~0.1-0.2% control on the kinematics of the W production**
- sub-percent accuracy of predictions for PDF ; p_T^W modelling and W polarisation (Ai) is extreme challenge for QCD theory!

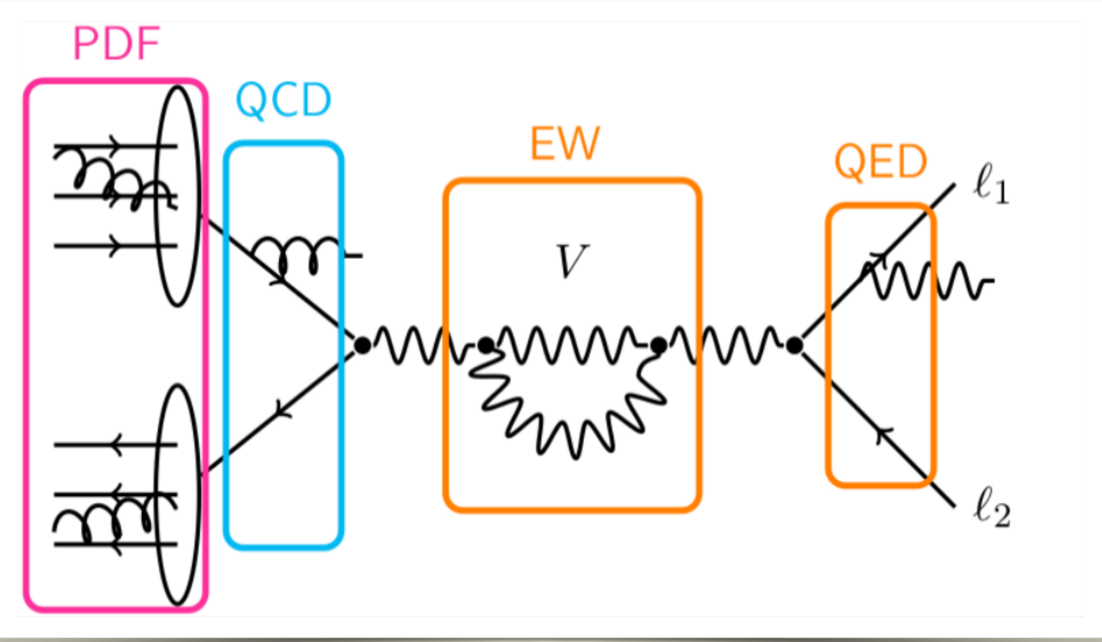


- @LHC W mass physics modelling is described using a **composite model** :
- Start from the NLO/NNLO generators + LL parton-shower (Powheg+Pythia8) and apply corrections to reach the state of the art accuracy.
  - The Drell-Yan cross-section can be decomposed by factorising the dynamic of the boson production and the kinematic of the boson decay.

$$\frac{d\sigma}{dp_1 dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T)}{dp_T}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y, m)\, P_i(\cos\theta, \phi)\right]$$

*Use **ancillary measurements** of Drell-Yan processes to validate (and tune) the model and assess systematic uncertainties.*

Complexity of the physics modelling



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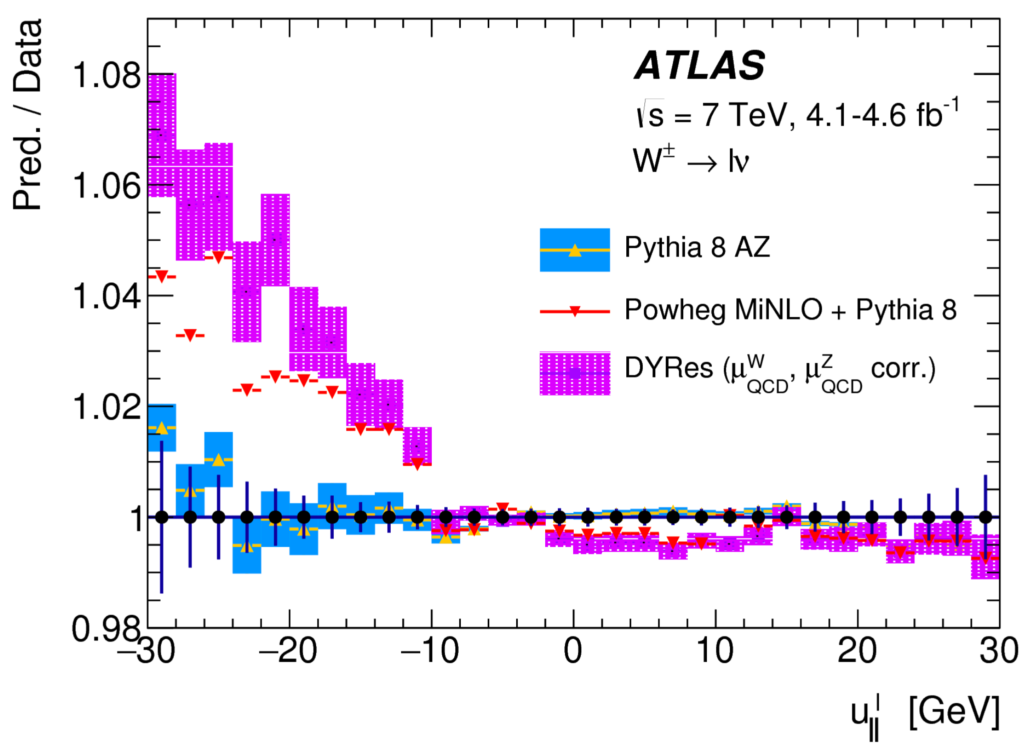
The p_T^W modelling

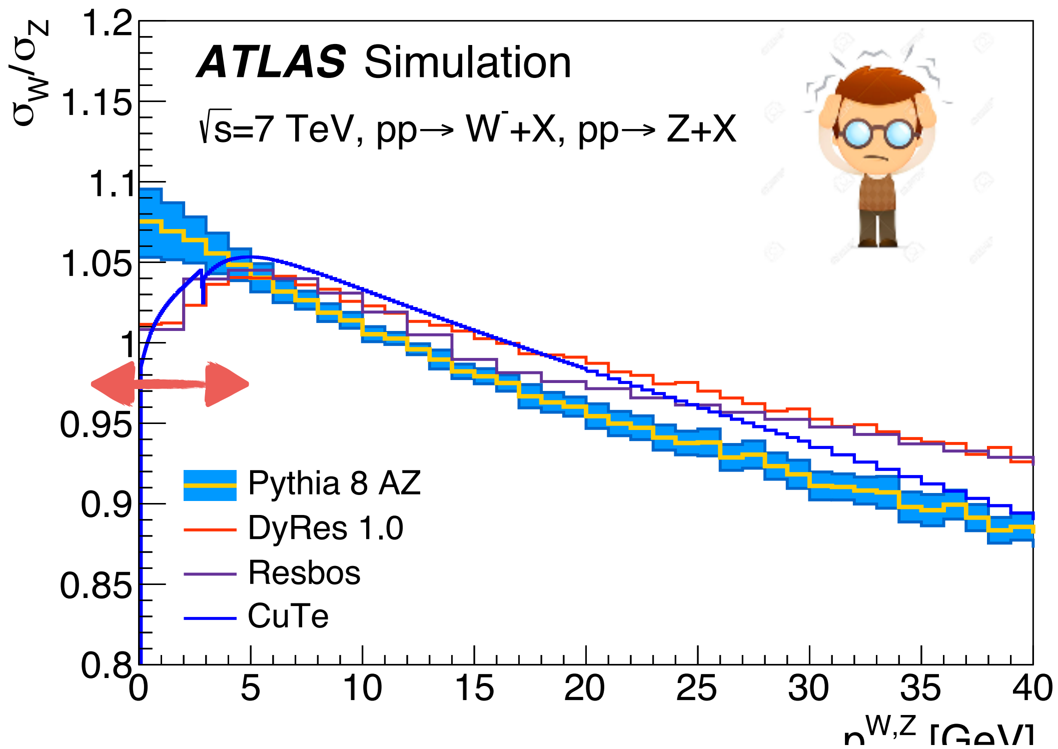
- **p_T^W modelling is a challenge for QCD theory** (resummation, heavy flavour, multiple scale, no pQCD)
  - Experimentally very precise p_T^Z measurement (W limited by recoil resolution)
- **Approach: adjust model parameters using Z events → extrapolate to W production**

$$R_{W/Z}(p_T) = \left(\frac{1}{\sigma_W}\cdot\frac{d\sigma_W(p_T)}{dp_T}\right)\left(\frac{1}{\sigma_Z}\cdot\frac{d\sigma_Z(p_T)}{dp_T}\right)^{-1}$$



@time of the first measurement: analytic resummed predictions were **strongly disfavoured** by the recoil distribution in data.

+



@time of the first measurement: low p_T W/Z ratio very different between analytic resummed predictions and PS model tuned with Z data

Addressing the difficulties of p_T^W modelling

- **p_T^W modelling is a challenge for QCD theory** (resummation, heavy flavour, multiple scale, no pQCD)
  - Experimentally very precise p_T^Z measurement (W limited by recoil resolution)
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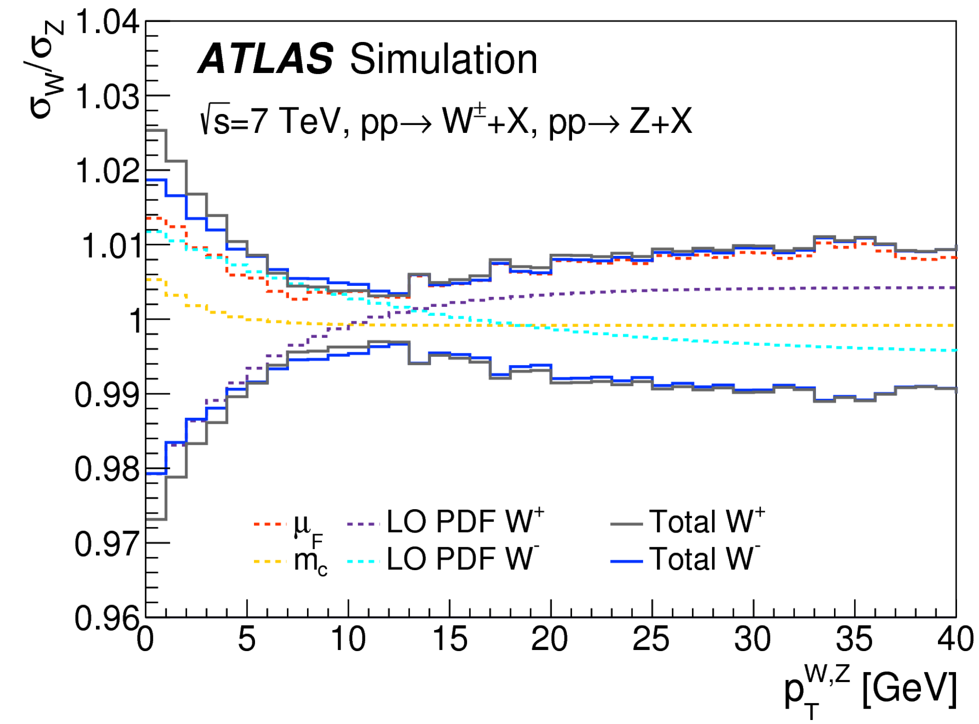
ATLAS m_W $d\sigma/dp_T$ modelling uses **Pythia parton shower**

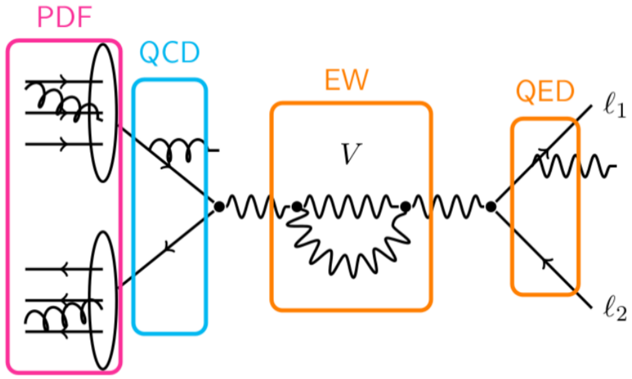
- PS parameters tune on 7TeV p_T^Z data (AZ tune)
- Fairly good modelling of the W-data, **but hard to improve on uncertainties** (mostly related to model limitations)



CMS modelling strategy

"agnostic" approach eg. relay on constraining power of the DATA

- **Overall strategy:** construct the best possible theoretical model for the *W* and constrain in-situ directly with the W data
- Z data is "only" used for validation



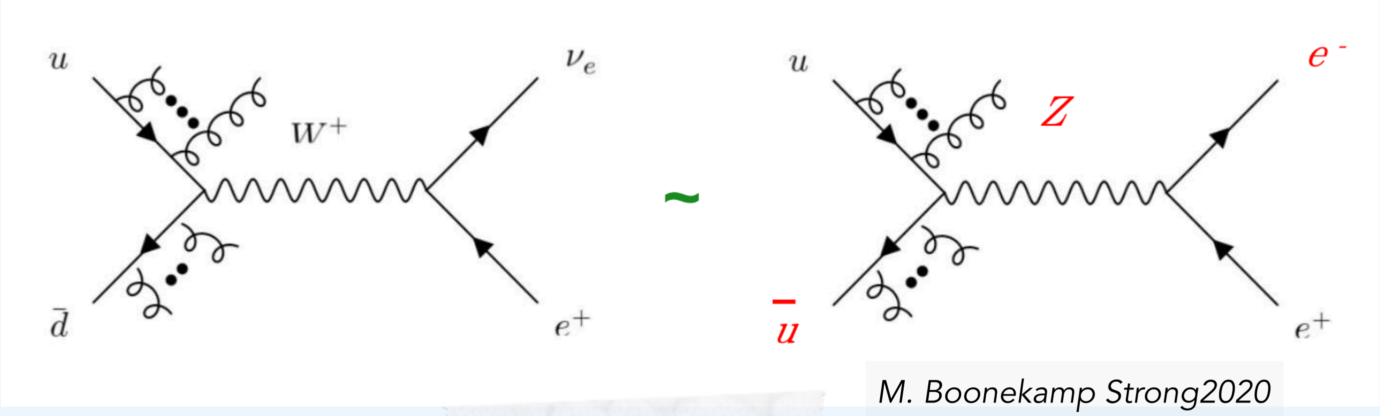
- **Nominal Theory uncertainties:**
  - Perturbative QCD
  - PDFs
  - Additional non-perturbative QCD (e.g. transverse momentum of partons within proton)
  - Electroweak effects

similar decomposition as ATLAS

- **In addition:** Helicity cross section fit is used as a cross-check which augments or replaces the theory uncertainties by directly varying the different components of the angular decomposition
  - Reduced theory/model-dependence at the cost of increased statistical uncertainty

W mass: p^W_T modelling

- QCD Initial state radiation involves large corrections (perturbative and non-perturbative).
  - Experimental measurement limited by the resolution of the recoil…
- Approach: adjust model parameters using Z events (can be measured precisely) extrapolate to W production



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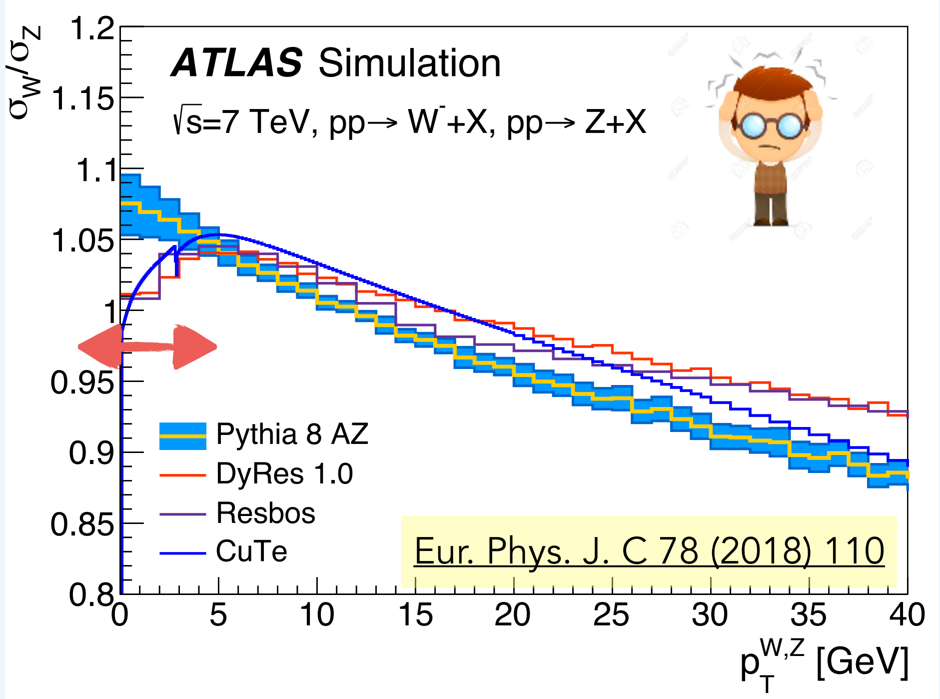
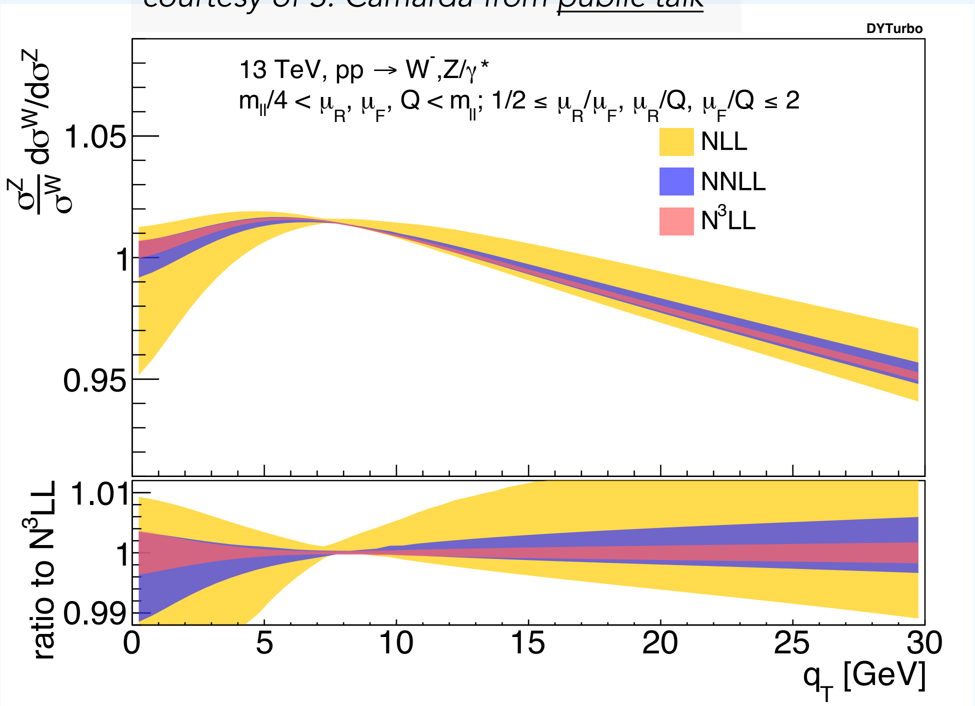


courtesy of S. Camarda from public talk

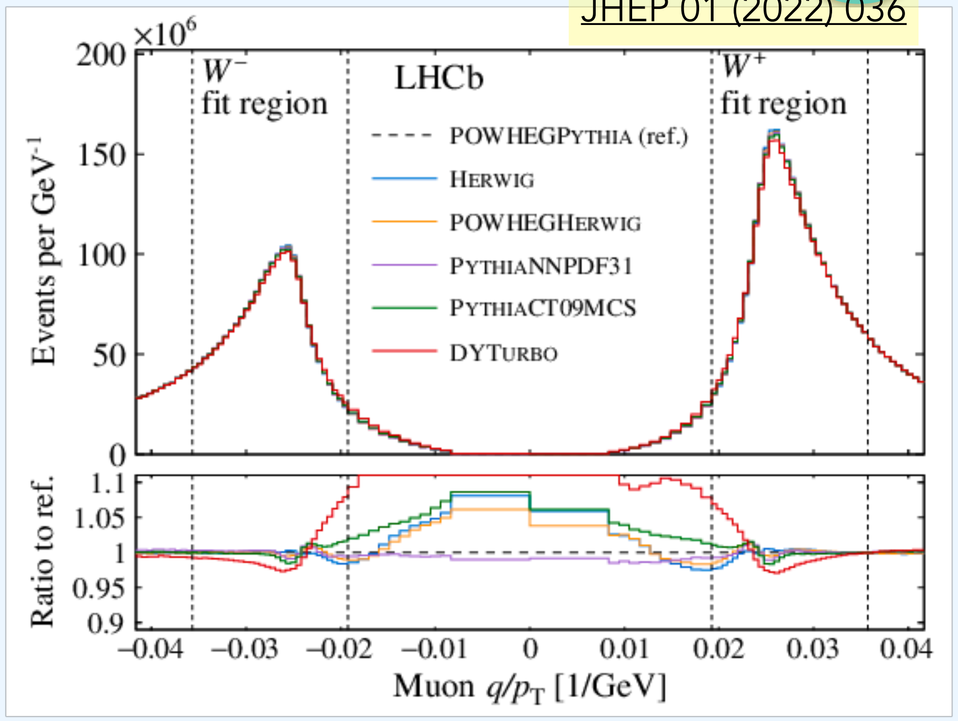


current days several improvements done on analytic resummation programs (improved treatment of HFI production, higher orders etc)

NEW era of analytic resummation models

able to predict/be flexible enough to fit W/Z p_T ratio in data or exploiting constraining power of data providing TNP [theory nusssiance parameter] for the fit

W mass: p^W_T modelling



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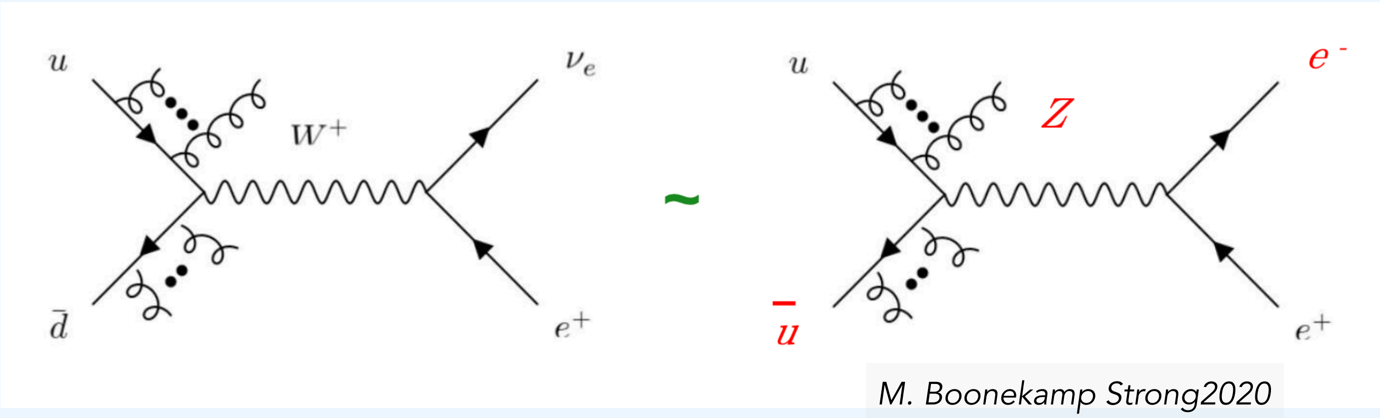
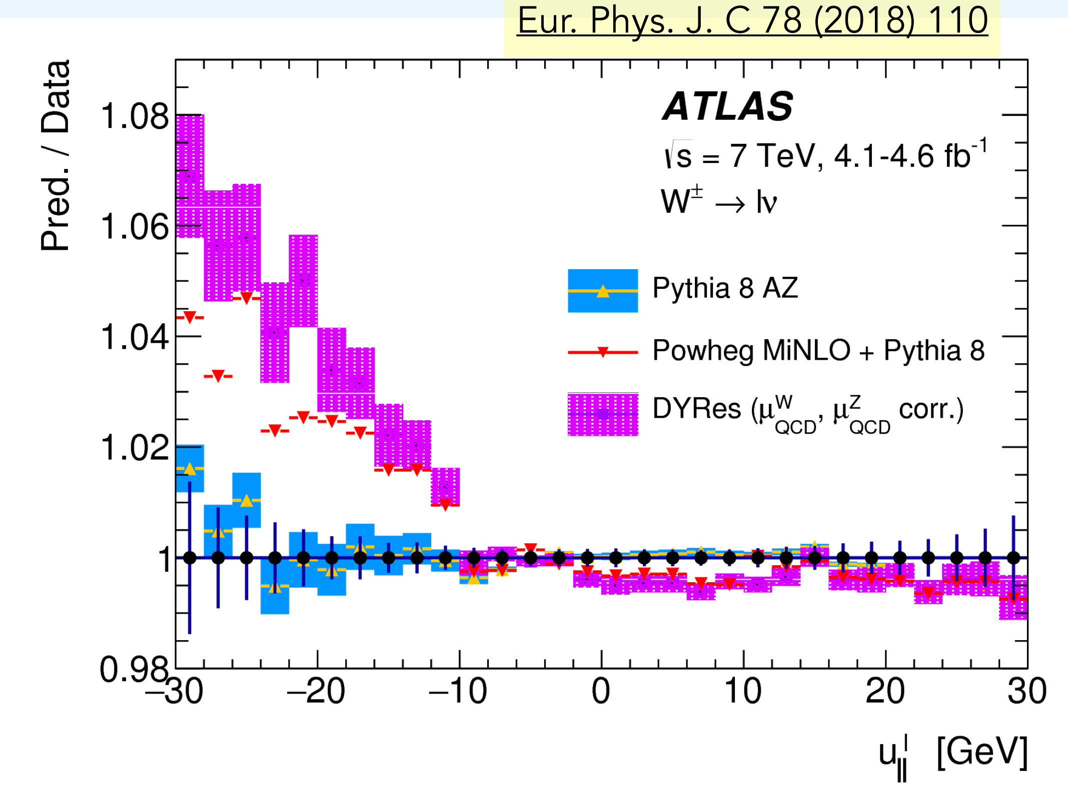


- Current mW physics modelling uses Pythia parton shower for $d\sigma/dp_T$
  - p^Z_T data are used to tune the parameters of the model (AZ tune)
- Fairly good modelling of the W-data, **but hard to improve on uncertainties**, which are mostly related to theory limitations :
  - Based on parton shower which is only (N)LL accurate
  - Limited to LO PDFs
  - No scale variations (meaningless at LL)
  - No handles on heavy-flavour initiated production
- at the time of the measurement analytic resummed predictions (Resbos, Cute, and DyRes) are **strongly disfavoured** by the recoil distribution in data.



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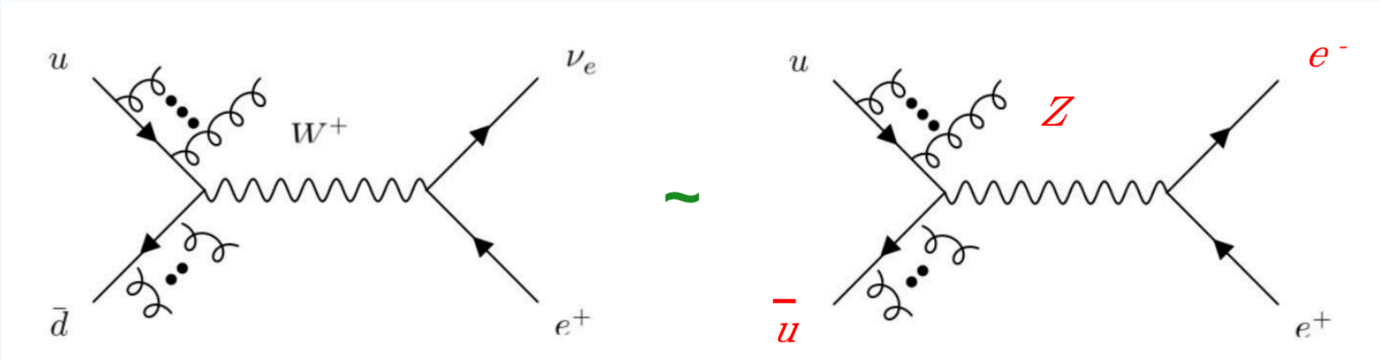
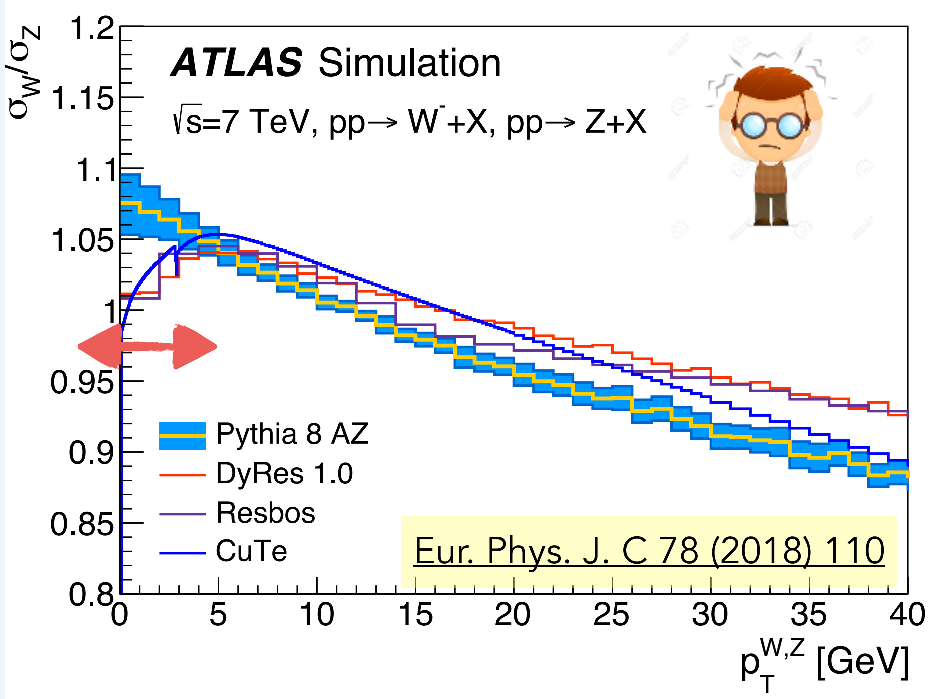
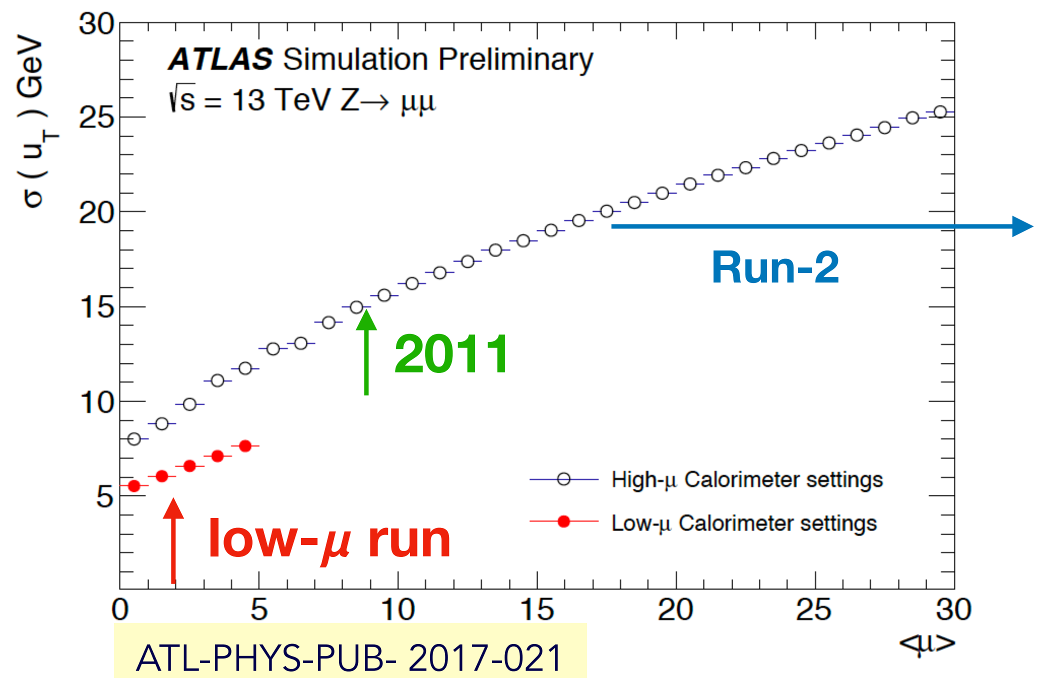
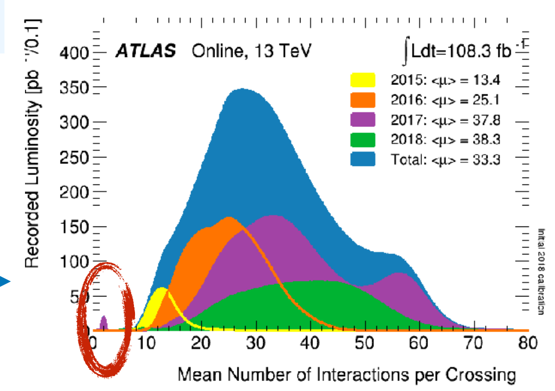


M. Boonekamp Strong2020



A ***measurement*** *able to resolve W p_T in bins of 5 GeV with 1% uncertainty would provide a direct probe of the W/Z p_T ratio and a crucial experimental input to understand this issue.*



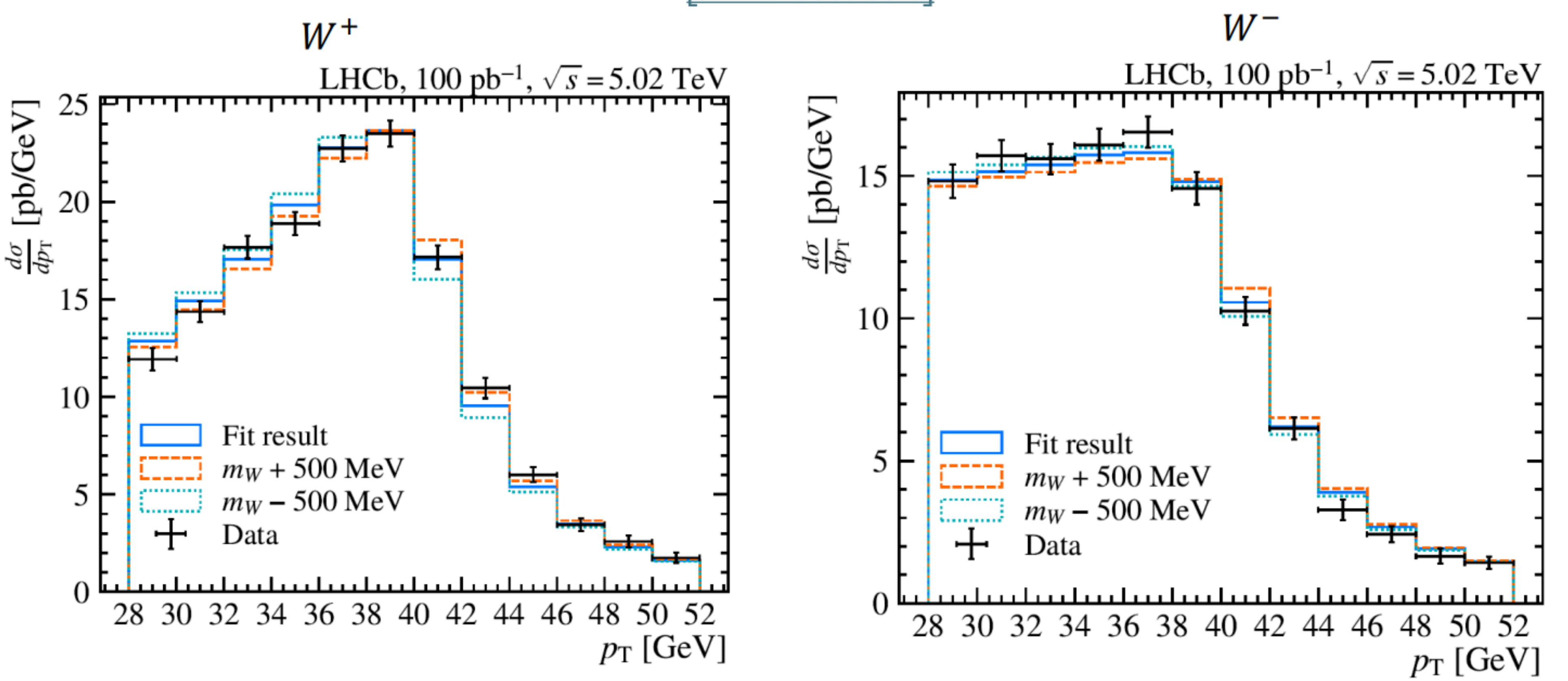


Both ATLAS and CMS collected ~500(200) pb-1 of data with low-μ ! fantastic opportunity for W precision physics!

- NB In order to resolve W p_T at 5 GeV we need to achieve a experimental resolution of the Hadronic recoil of the same order.

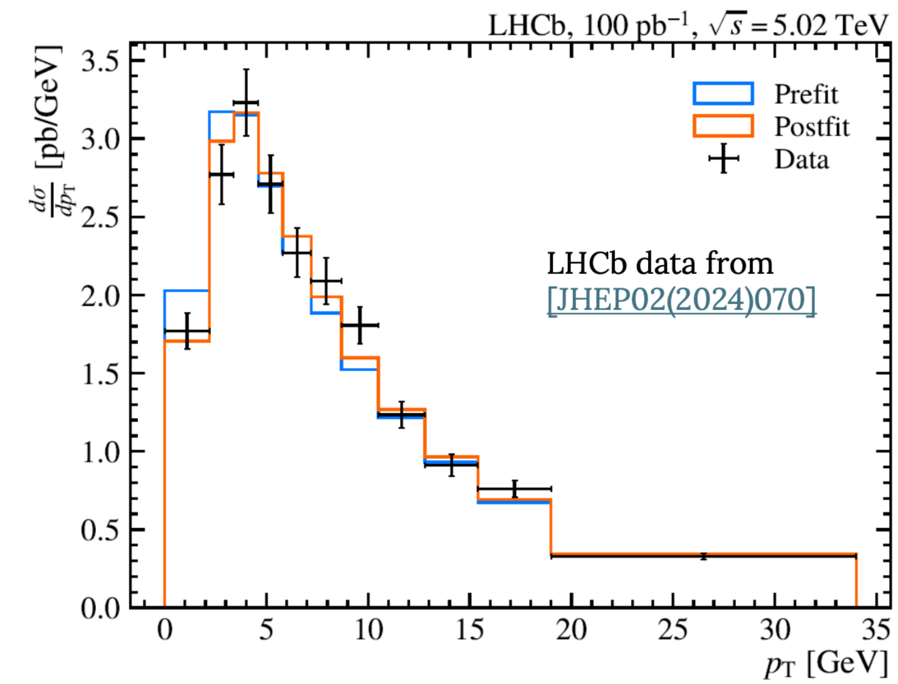
proof of principle - LHCb

[arXiv:2509.18817]



LHcb extract the differential cross-section of W boson decays as a function of the muon pT

- Can later fit the W boson mass (model-independent way)
- Ensures long-term reusability of the cross-section measurement for evolving models
- More power to the community (particularly theorists)



Z boson auxiliary measurement crucial the to constrain QCD modelling (αs and g parameters)

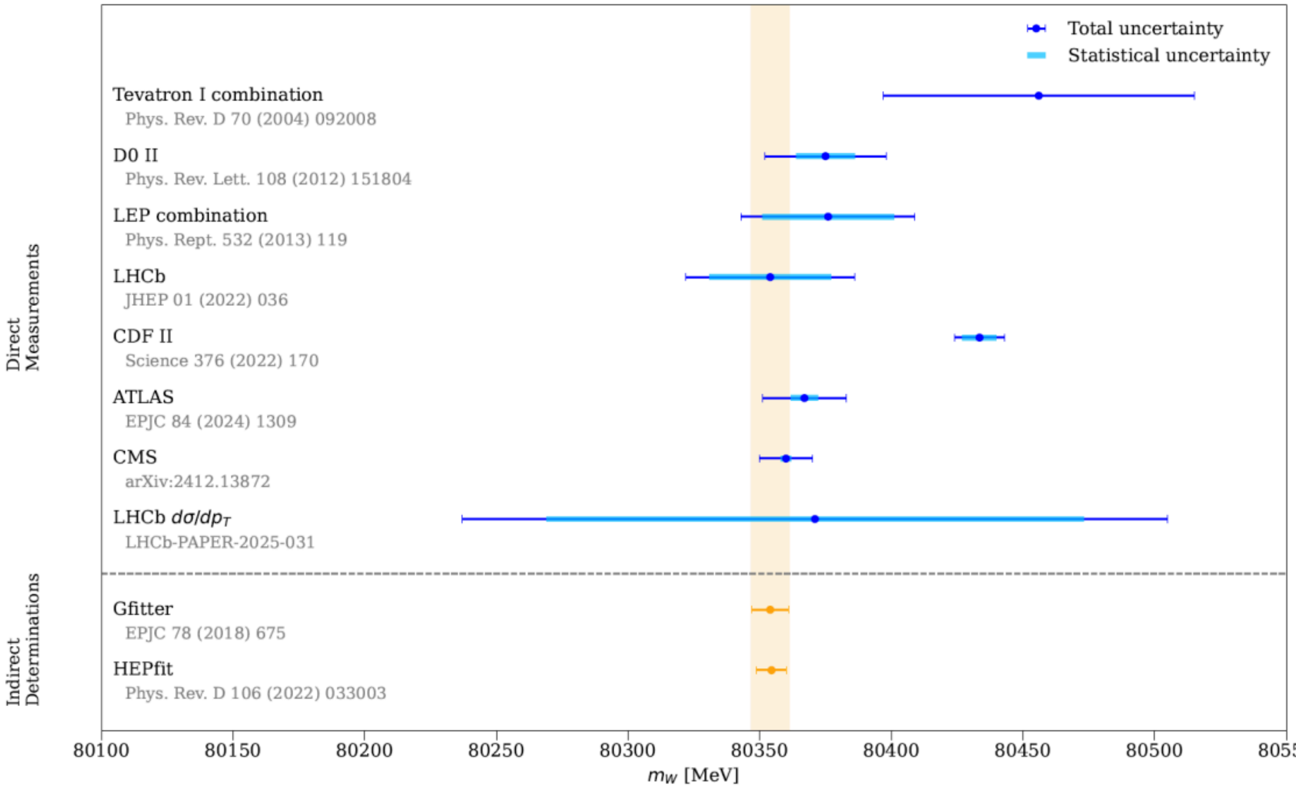
proof of principle - LHCb

The final m_W result is a simple average of the results from using the 3 PDF sets:

PDF set	χ^2/ndf	m_W	σ_{theory}	σ_{PDF}
NNPDF3.1	25.6/21	80366 ± 130 MeV	25 MeV	28 MeV
MSHT20	27.2/21	80380 ± 129 MeV	25 MeV	15 MeV
CT18	23.9/21	80362 ± 130 MeV	25 MeV	23 MeV

$$m_W = 80371 \pm 130_{stat+syst} \pm 32_{theo*}$$
(~100 MeV stat)

- **Submitted to JHEP**
- **Now onto full Run 2 analysis!**
  (at $\sqrt{s} = 13$ TeV)



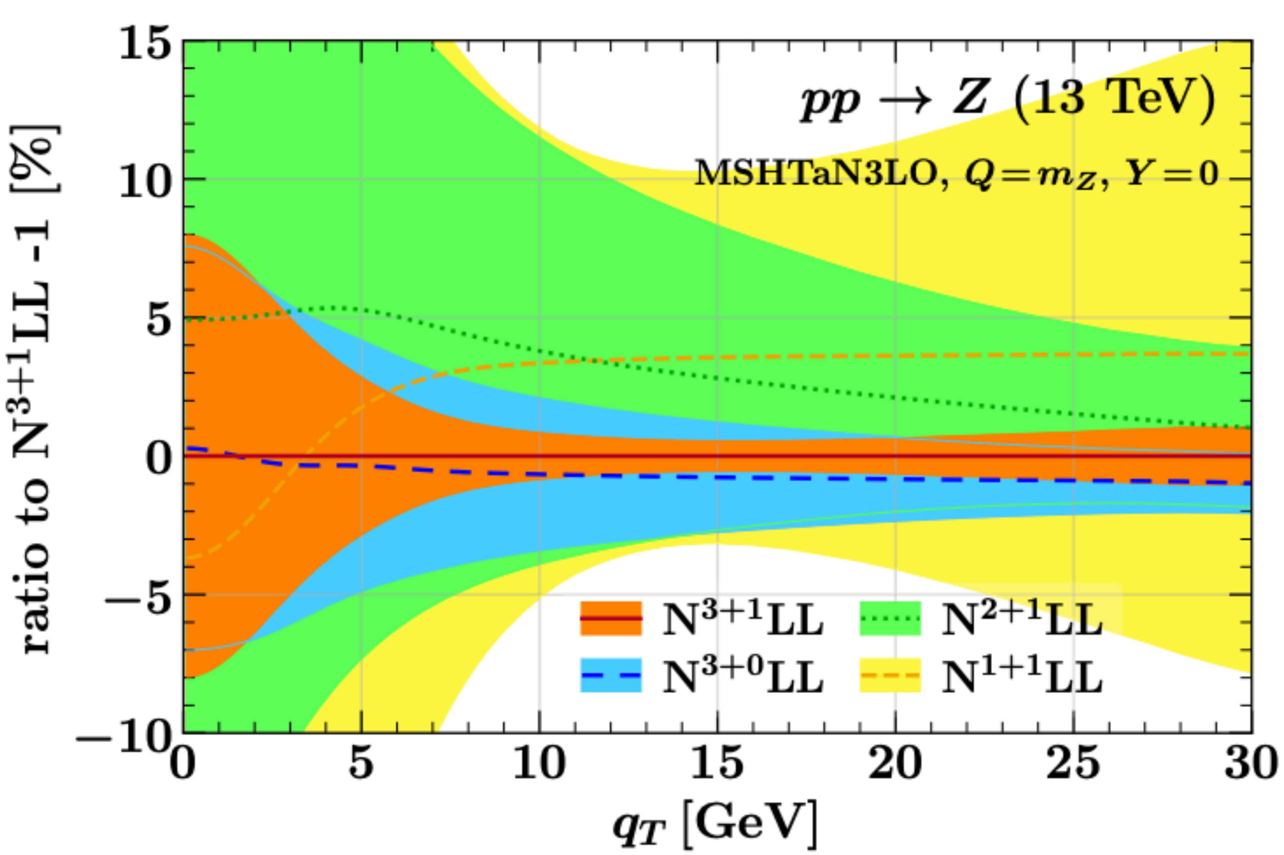
*The theory uncertainty is the combination of the PDF members uncertainty and other variations (namely, varying α_s+ QED FSR radiation + the 7-point variation of the DYTurbo QCD scale factors)

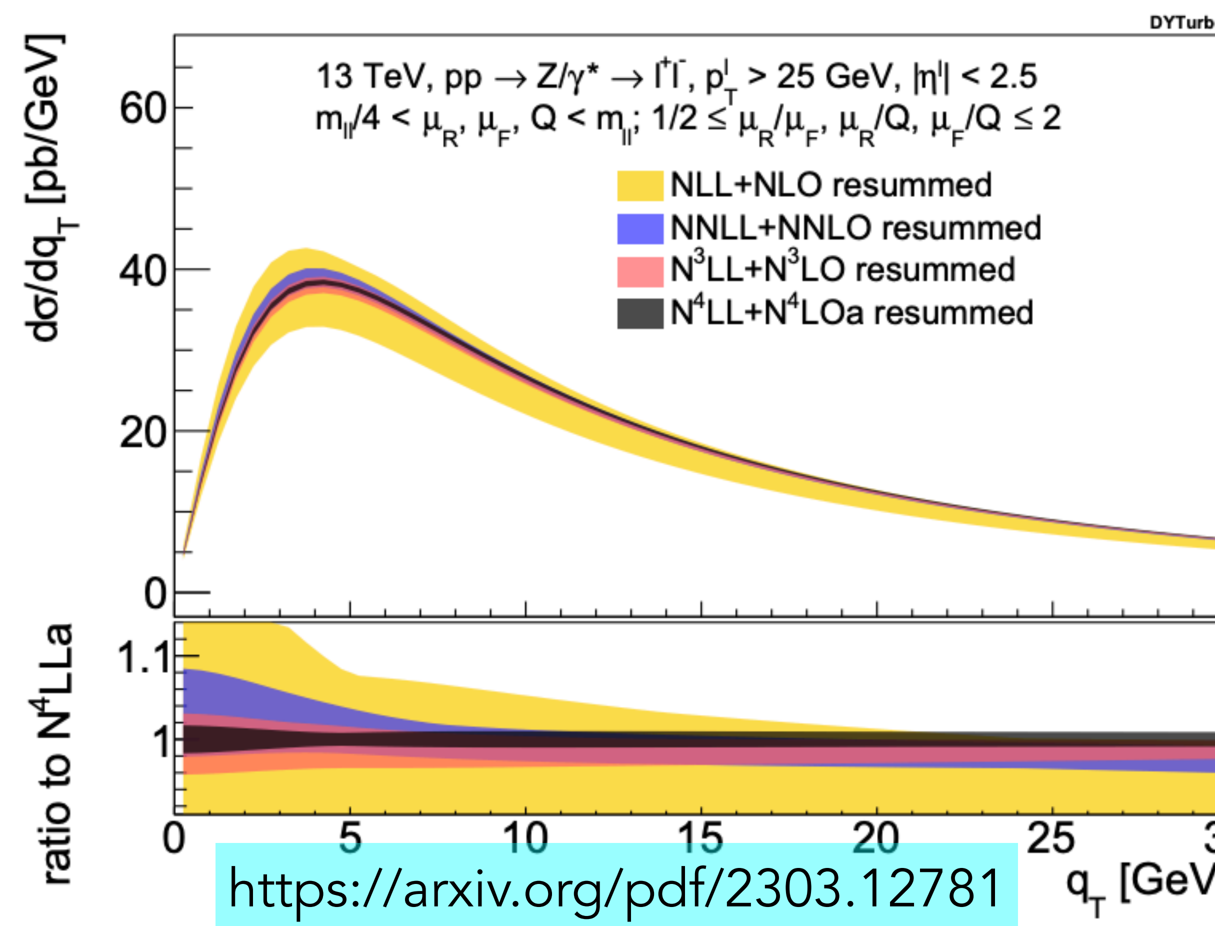
Theory advancement

Tremendous progress in theory in the past 10 years !

At the **level of precision achieved by LHC experiments,** pushing the **theory frontier for all contributors to our predictions essential**

https://arxiv.org/pdf/2411.18606



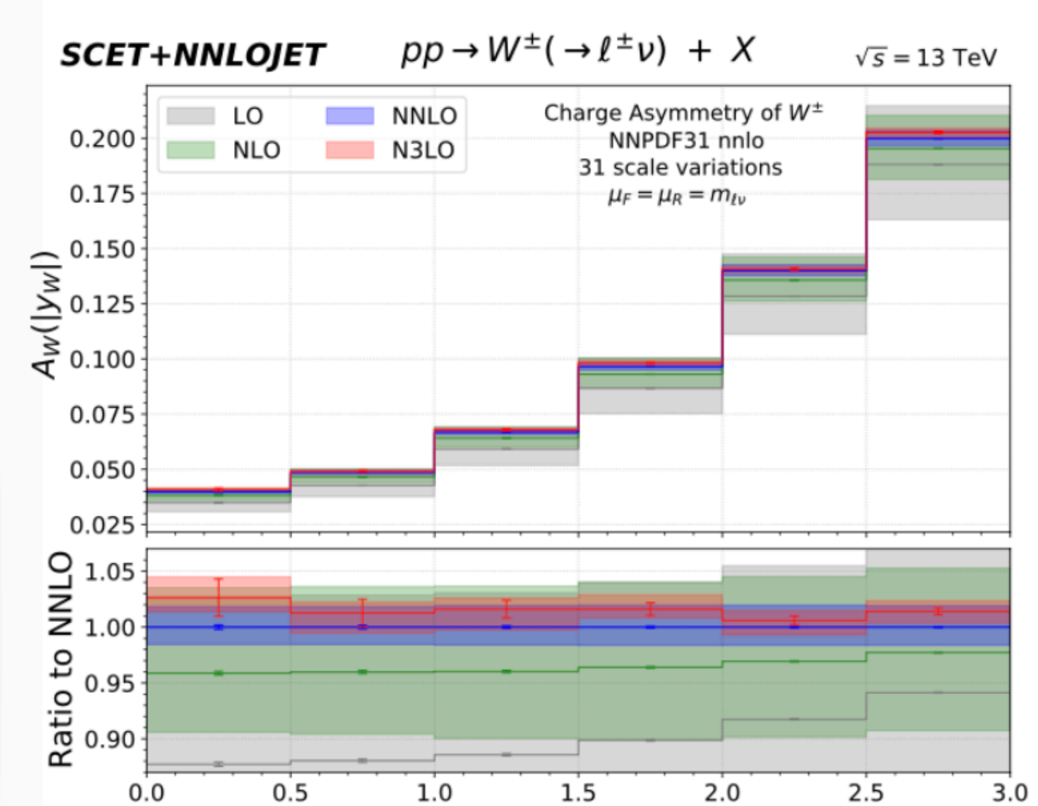


https://arxiv.org/pdf/2303.12781

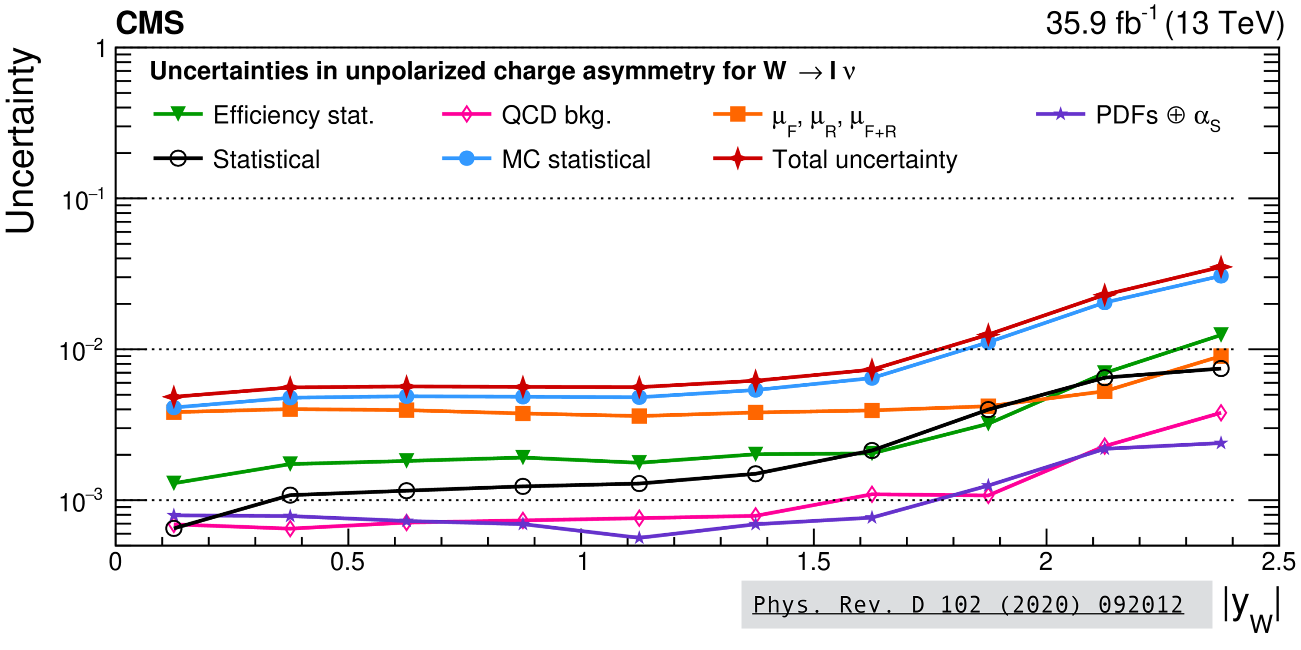
NNLO outdated →N3LO

Tremendous progress in theory in the past 5~10 years !

At the **level of precision achieved by LHC experiments,** pushing the **theory frontier for all contributors to our predictions essential**
theory & model uncertainties already now **limiting factor** for many LHC analyses



https://arxiv.org/pdf/2205.11426



Phys. Rev. D 102 (2020) 092012

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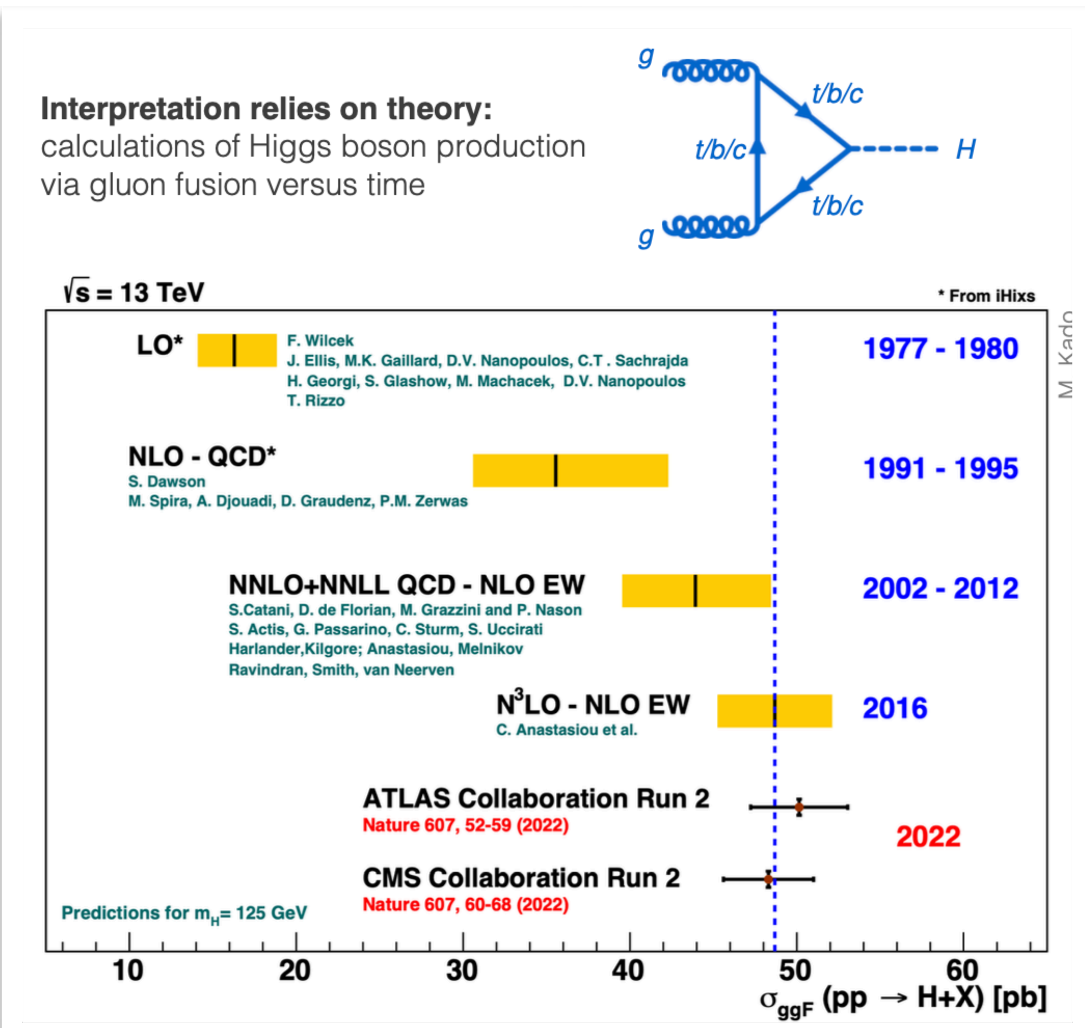
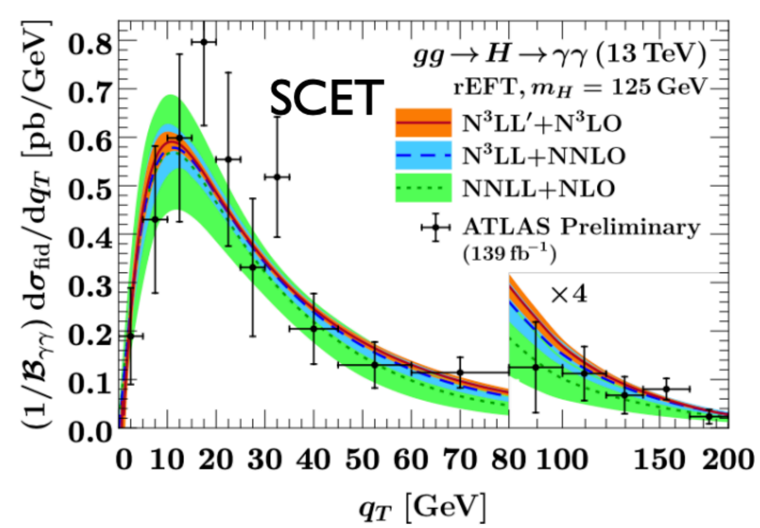
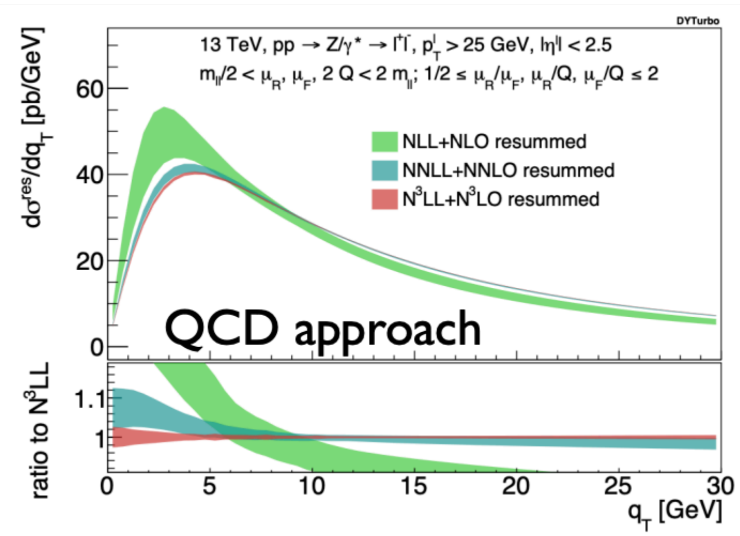


At the **level of precision achieved by LHC experiments,** pushing the **theory frontier for all contributors to our predictions essential**



Billis, Denhadi, Ebert, Michel, Tackmann (2021)

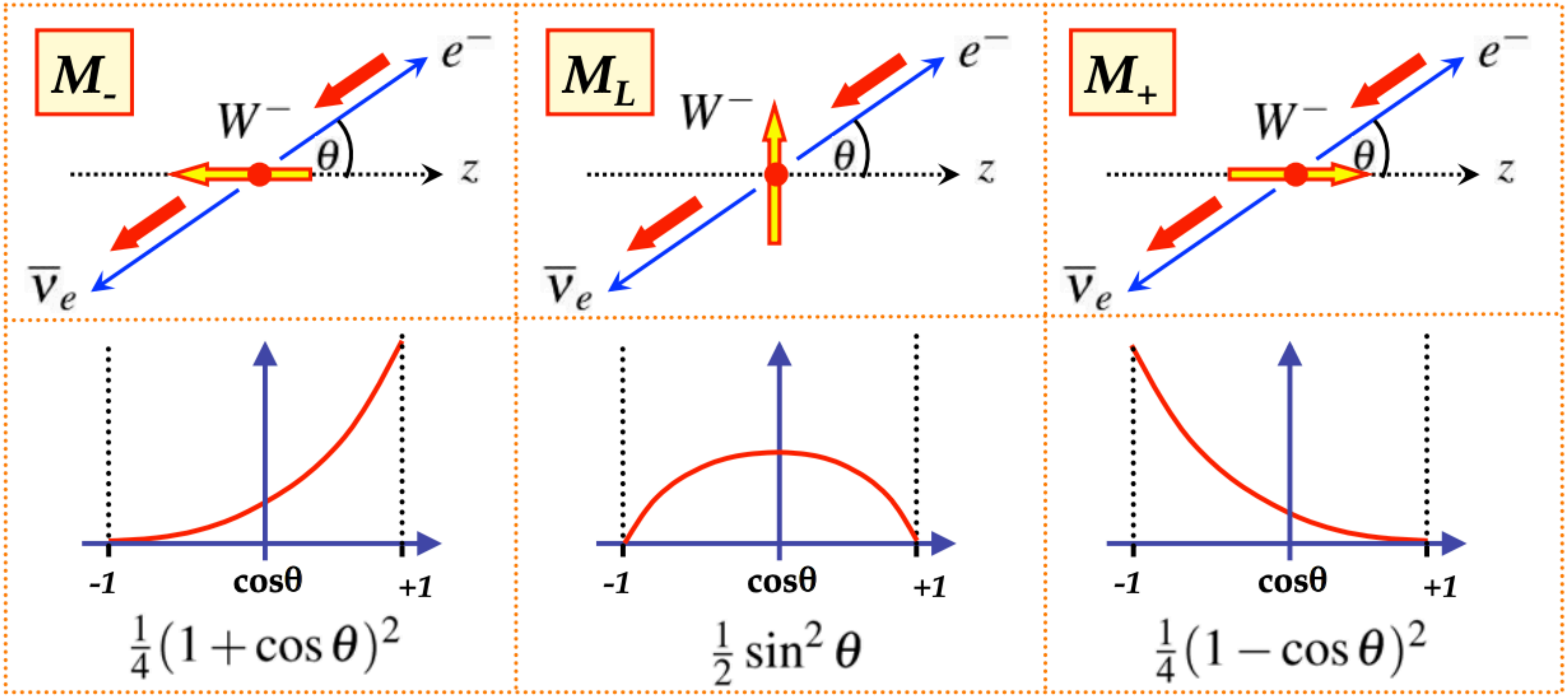
N3LL' resummation + N3LO



Camarda, Cieri, Ferrera (2021)

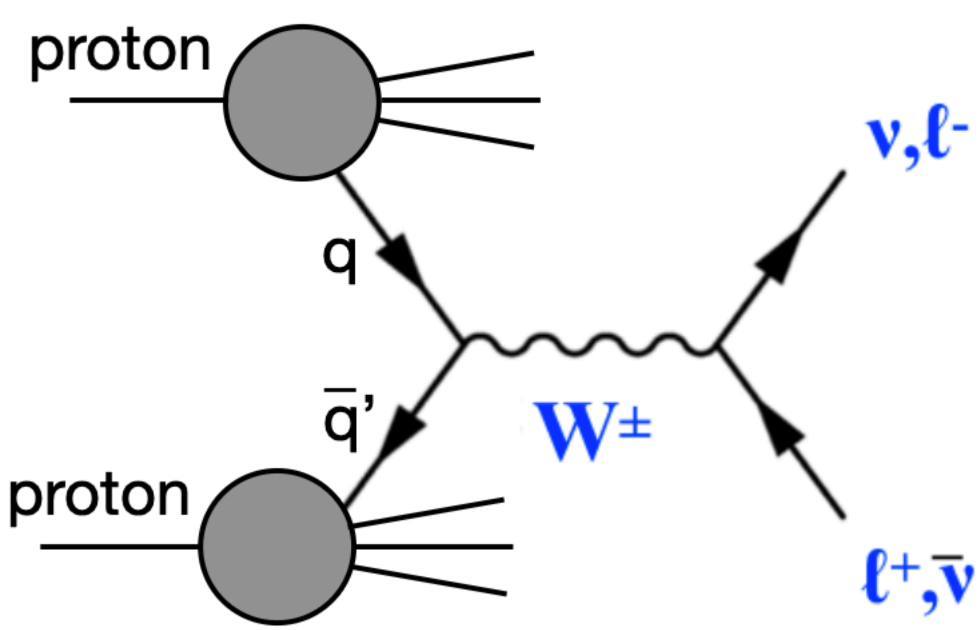
N3LL resummation + N3LO

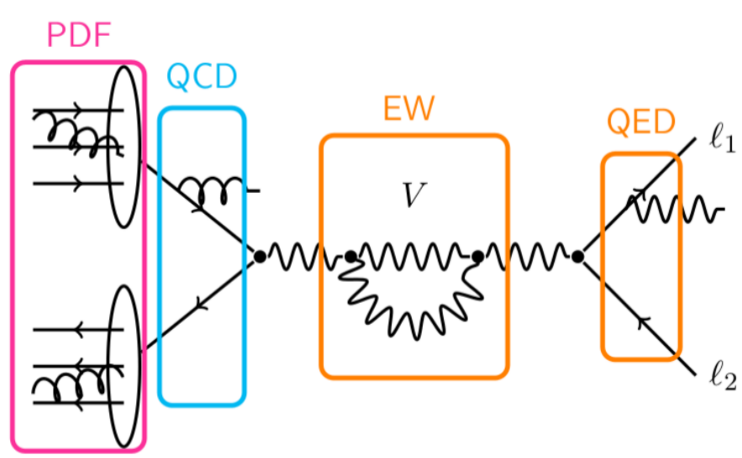
★ **The angular distributions can be understood in terms of the spin of the particles**



W - Polarisation

W production at LHC



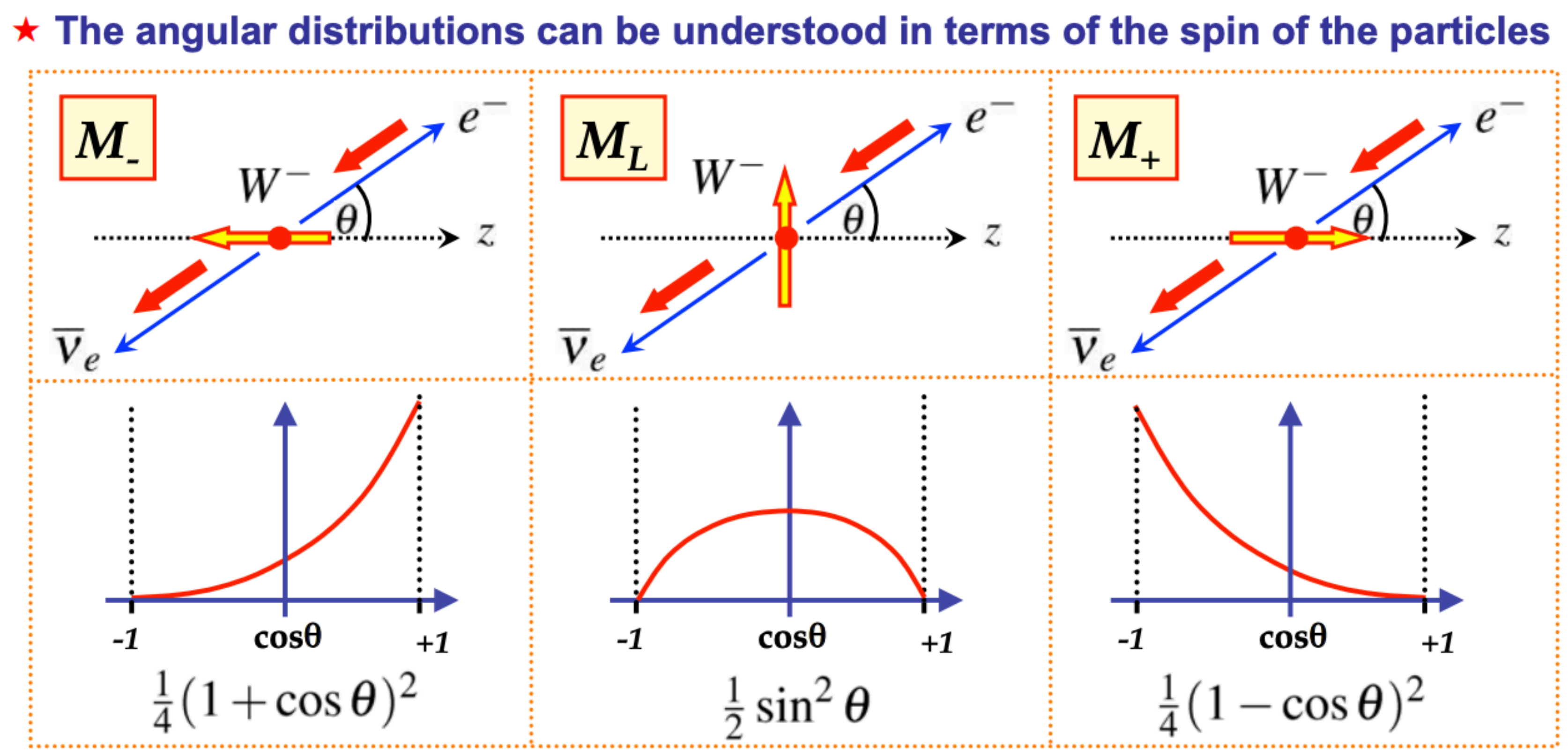


$$\frac{d\sigma}{dp_1 dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T)}{dp_T}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y, m)\, P_i(\cos\theta, \phi)\right]$$

Measuring the polarisation of particles is crucial for understanding their production mechanisms.

- At hadron colliders, W bosons with small transverse momentum are mainly produced by
  $u\bar{d} \rightarrow W^+$ and $d\bar{u} \rightarrow W^-$
  eg. leading order electroweak processes and decay governed by V-A structure of weak interaction ~ (A4)
  - production depends on quark kinematics → parton distribution functions (PDFs)
    - interesting at LHC (pp): anti-quark must be a sea quark
    - we will see: lepton kinematics carry information about the PDFs!
- At high transverse momenta the production mechanism are :
  $u\bar{d} \rightarrow W^+ g$, $g\bar{d} \rightarrow W^+\bar{u}$ or $ug \rightarrow W^+ d$
  - higher QCD order are needed and full Helicity decomposition is needed (because of the vector nature of the gluon)

reminder polarisation



- W decays: governed by V-A couplings
  → angular distributions of W decay products: not random, but correlated with W

$$\frac{dN}{d\cos\theta^*_{W,l}} \propto (1 + \mathrm{sgn}(h_l \times h_W)\cos\theta^*_{l,W})^2 = (1 \pm \cos\theta^*_{l,W})^2$$

@ leading order!

- sign determined by product of W boson and lepton helicities
- W helicity depends on the incoming quarks:
  1) leading x quark/anti-quark determines the (longitudinal) W boost direction
  2) W(-) spin direction is fixed to direction of motion of incoming anti-quark

Vector boson polarisation

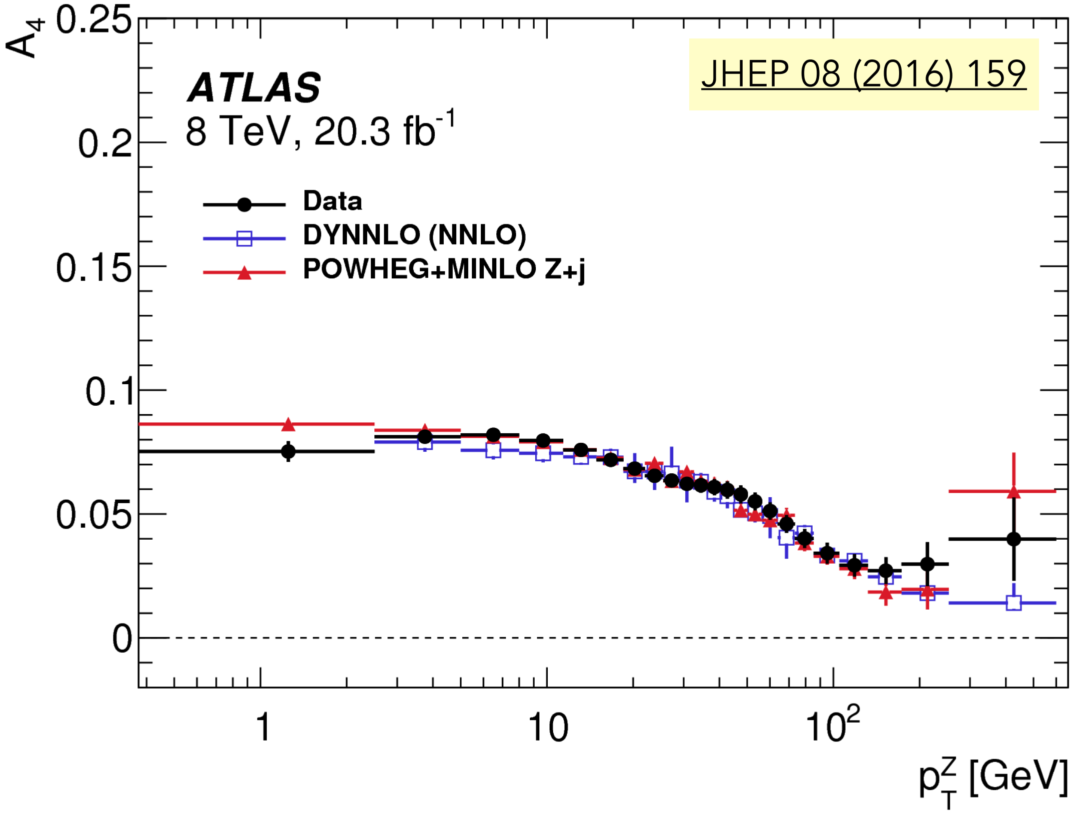
Feature	W	Z
No Longitudinal polarisation at LO Purely transverse V [J^{+-}]	A_0 ~ longitudinal fraction	A_0 ~ longitudinal fraction
Coupling structure	Pure V–A	Vector + axial
Parity violation	Maximal (V–A)	Partial (V+A mix)
Forward–backward asymmetry	A_4 → parity violation sensitive to PDF [different for W^+ W^-]	A_4 → proportional to $\sin^2\theta_W$
Lam–Tung holds at $O(\alpha_s)$	$A_0 - A_2 \neq 0$ → higher-order QCD effects	$A_0 - A_2 \neq 0$ → higher-order QCD effects

$p_T^V = 0$ → No orbital angular momentum → Both W and Z are **purely transverse**

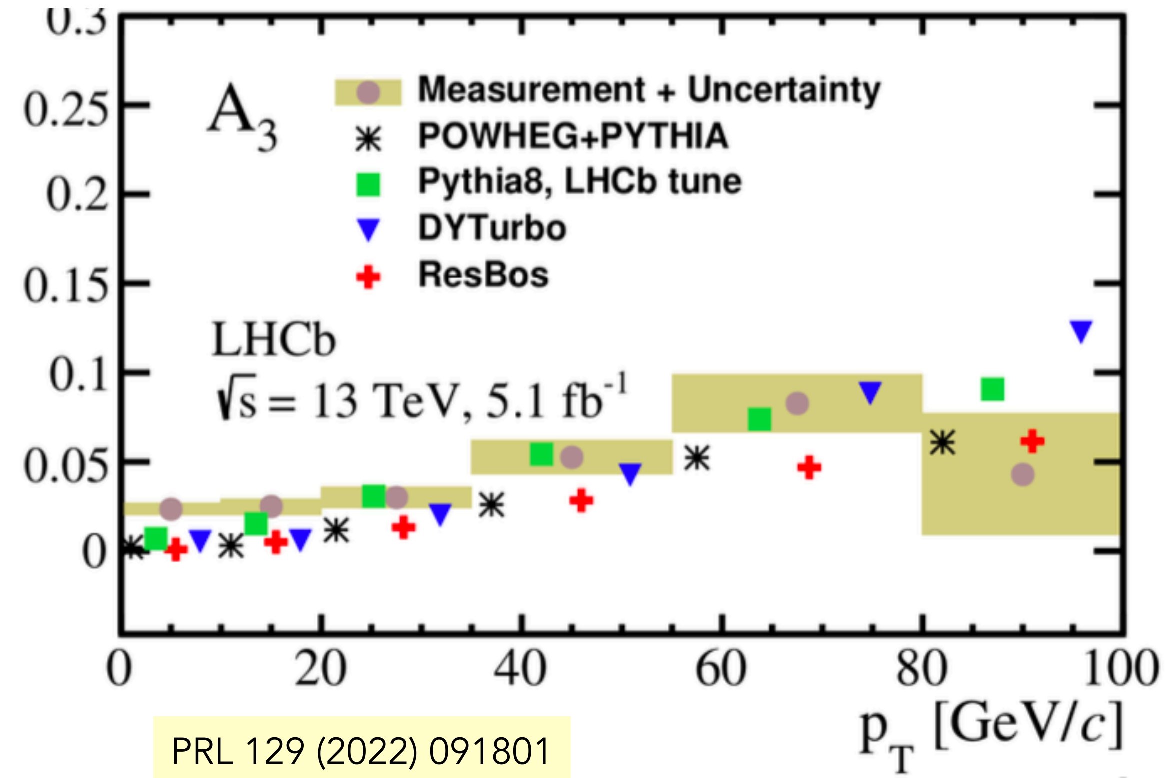
W mass: Angular coefficients

- The DY cross section can be reorganised by factorising the dynamic of the boson production, and the kinematic of the boson decay

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma}{dp_T dydm} \sum_i A_i(y, p_T, m) P_i(\cos\theta, \phi)$$



- Current m_W physics modelling has the angular coefficients (Ai) modelled with fixed order perturbative QCD at NNLO
- Ai predictions are validated by comparisons to the Z measurement
  - **Suboptimal for A4: fixed order prediction down to low pT** ?
    - Nowadays A4 can be predicted including resummation effects
  - LHCb m_W measurement accounts for A3 data/prediction discrepancy [cf. Recent LHCb measurement of Ai in $Z \to \ell\ell$]



PRL 129 (2022) 091801

The analysis motivation

Measure W angular coefficients in 340 pb^{-1} **@ 13TeV ATLAS low-μ data**

- Precise measurements of DY production dynamics through the measurement of the angular distributions → connected with the W **polarisation**
  - Stringent **test of QCD and physics modelling for m_W**
- **NEW** measurement never exploited before in W events!
  - Analysis strategy follow the Moments Method from Eur. Phys. J. C 84 (2024) 315 + Dedicated set of lepton&hadronic recoil performances correction from the WpT/ZpT measurement and **low mu**-W mass effort (more info)
    - For the first time extraction of the W-boson angular coefficient (A^0- A^4) & at the same full phasespace differential cross-section vs p_T^W
  - **More challenging** wrt Z boson (JHEP08(2016)159) due to the missing neutrino and the poor MET resolution (**ambiguity sign of cosθ solved using m_W kinematic constraint requirement**)
    - Benefit from new techniques / low-μ environment to have O(5) better hadronic recoil reconstruction

A convenient decomposition

A convenient way of expressing the radiation-inclusive DY cross section is through the factorisation of the production dynamic and the decay kinematic properties of the dilepton system.

$$\frac{d^3\sigma^{U+L}}{dp_T dy dm}\left(1+\cos^2\theta+\sum_{i=0}^{7} A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$

The **unpolarised cross sections** do not depend on lepton variables, they are defined in "full-lepton phase space", only by cuts (or bins) in pT,y,m of the boson

Measuring the **angular coefficients** correspond to building a synthetic "quantized" representation of the (cosθ,ϕ) kinematic space decompose in helicity cross sections

Smart idea: Exploit the angular variables decomposition to perform a simultaneous pT measurement of unpolarised full-lepton phase space cross sections + extraction of angular coefficients

- **Very powerful:** trade systematics for statistics
- **Very useful:** provides analytic extrapolation of lepton cuts and enables a rich interpretation programme

Angular coefficients

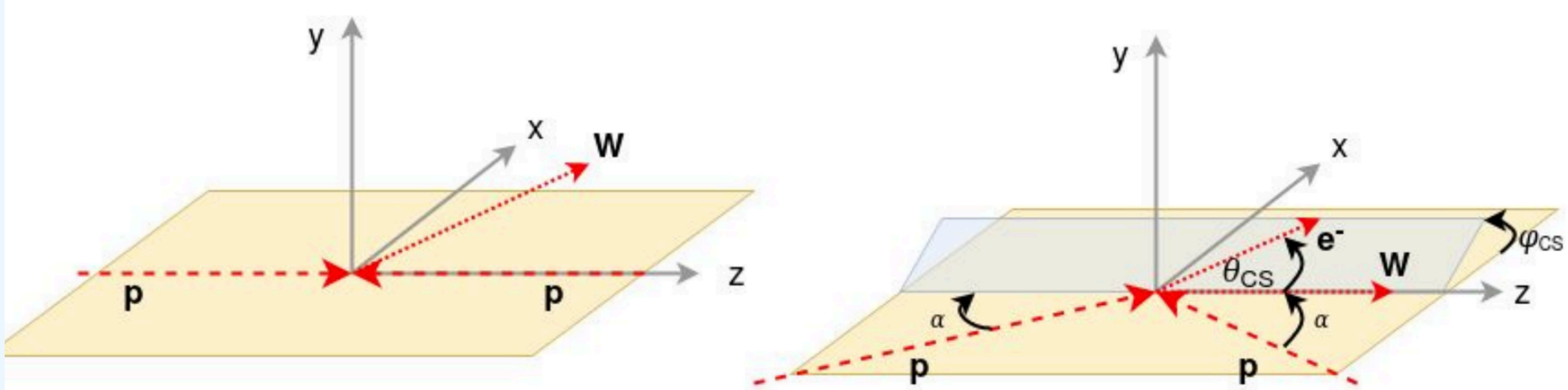
$$\frac{d\sigma}{dp_T^W\, dm^W\, dy^W\, d\cos\theta\, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^W\, dm^W\, dy^W} \Big\{ \left(1+\cos^2\theta\right) + \frac{1}{2}A_0\left(1-3\cos^2\theta\right) + A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi + A_4\cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \Big\} .$$

Non-zero at LO

Non-zero at NLO

Non-zero at NNLO

Collins Soper Frame



Lab Frame CS Frame

Special W boson rest frame where angles are defined by lepton and proton kinematics.
Both incoming partons share the same transverse momentum (ie. maximally symmetric)
Define using “negative” lepton, so for W^+ case this is the neutrino

about the ambiguity in sign

→ Missing neutrino pz information —> results in a sign ambiguity in the determination of cosθ

How to infer the Neutrino pZ information?

$$E_T^{\vec{miss}} = \vec{p_T}^{\nu} = -\left(\vec{u_T} + \vec{p_T}^{\ell}\right)$$

Solving for the Neutrino Pz:

- W mass constraint: quadratic equation

$$(p^\mu + q^\mu)^2 = m_W^2 \quad \Rightarrow \quad q_z(1,2) = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

for Δ = (b^2 −4ac) :

A. Δ = 0 → 1 solution

B. Δ > 0 → 2 solutions

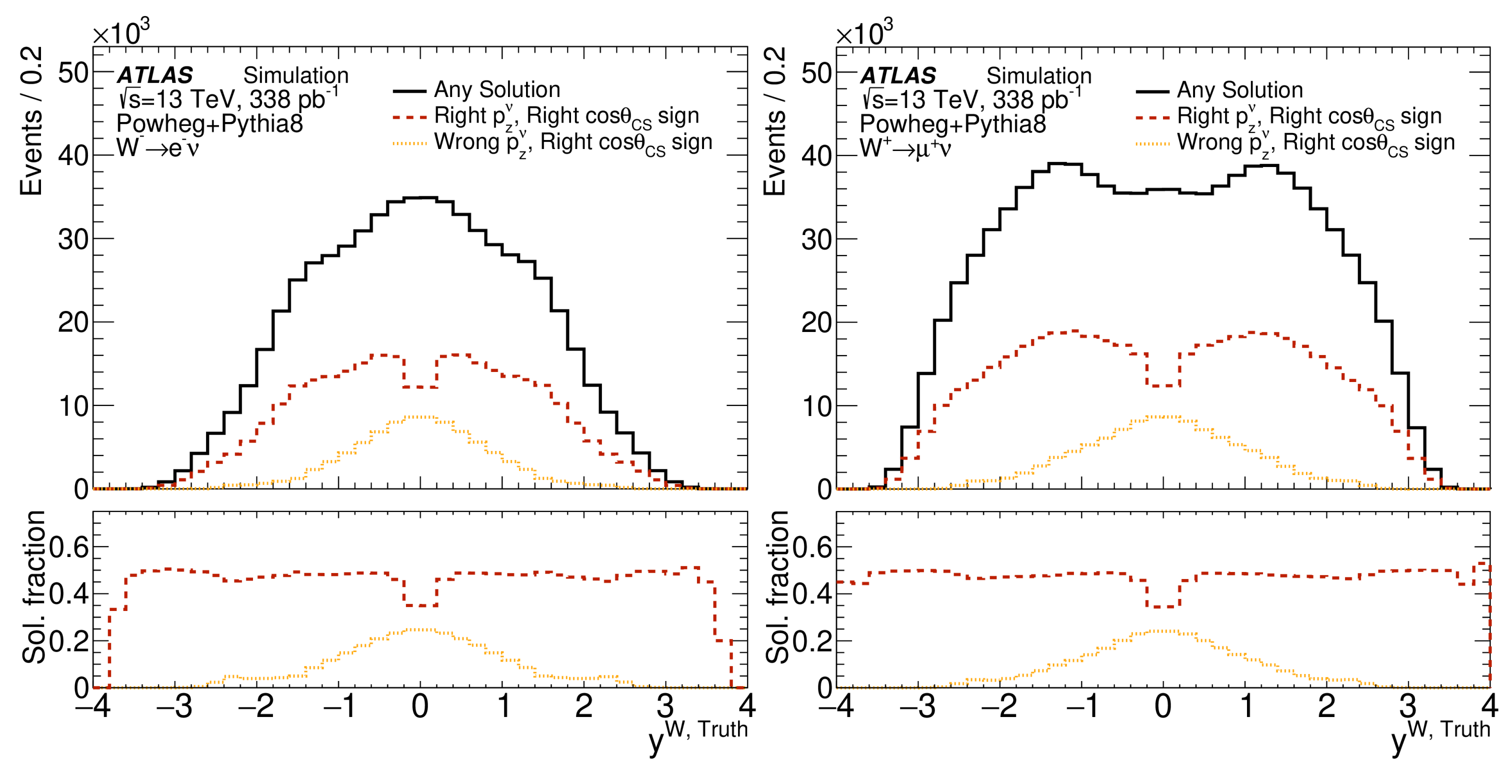
C. Δ < 0 → no real solution

NO solution Δ < 0 :

when we can not infer the neutrino pTz information we keep the sign ambiguity in cosθ definition

NB. when $mT^{reco} > mW \Rightarrow \Delta < 0$ and

this appears more often at high pTW because of bad recoil resolution



about the ambiguity in sign

→ Missing neutrino pz information —> results in a sign ambiguity in the determination of cosθ
How to infer the Neutrino pZ information?

2 solution Δ > 0 :

when we have 2 solution <u>pick one at random</u>

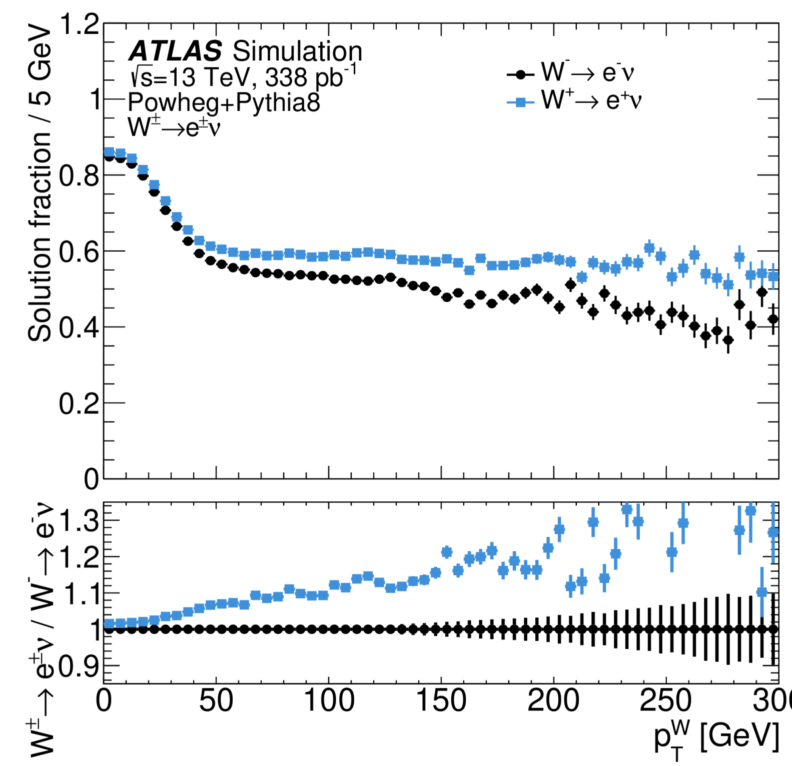
$$\cos\theta = 2\frac{(l^{+}\bar{l}^{-} - l^{-}\bar{l}^{+})\cdot \text{sign}(y_{\ell\ell})}{m_{\ell\ell}\sqrt{m_{\ell\ell}^{2}+\vec{p}_{T}^{\,2}}},$$

$l^{\pm} = E \pm p_z$ for the lepton/neutrino
$\bar{l}^{\pm} = E \pm p_z$ for the antilepton/antineutrino

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

Choosing a solution at random can result in ambiguity in the sign of $\cos\vartheta_{cs}$, but with enough statistic we can overcome this to solve the sign ambiguity. There are 3 cases :

1. Both solutions change sign to $\cos\vartheta_{cs}$ and y_w (50% chance to get the right solution)
2. Only y_w have sign ambiguity the sign ambiguity of the 2 solutions in $\cos\vartheta_{cs}$ cancels
3. One solution is unphysical ($x_{Bjorken} > 1$)



Likelihood FIT

Likelihood **Fit**

$$N^{n}_{\text{exp}}(A,\sigma,\theta) = \left\{ \sum_{j=0}^{N^{p_T^W}_{\text{bins}}} \sigma_j \times L \left[T^{n}_{8,j}(\beta) + \sum_{i=0}^{7} A_{ij} \times T^{n}_{ij}(\beta) \right] \right\} \times \gamma^{n} + \sum_{B}^{\text{bkgds}} T^{n}_{B}(\beta)$$

Cross-section parameters

Ai parameters

Polynomial Templates

Bkgd Templates

Expected Events

$$\mathcal{L}(A,\sigma,\theta|N_{\text{obs}}) = \prod_{n}^{N_{\text{bins}}} \{ P(N_{\text{obs}}|N^{n}_{\text{exp}}(A,\sigma,\theta)) P(N^{n}_{\text{eff}}|\gamma^{n} N^{n}_{\text{eff}}) \} \times \prod_{m}^{M} G(0|\beta^{m},1)$$

Observed Events

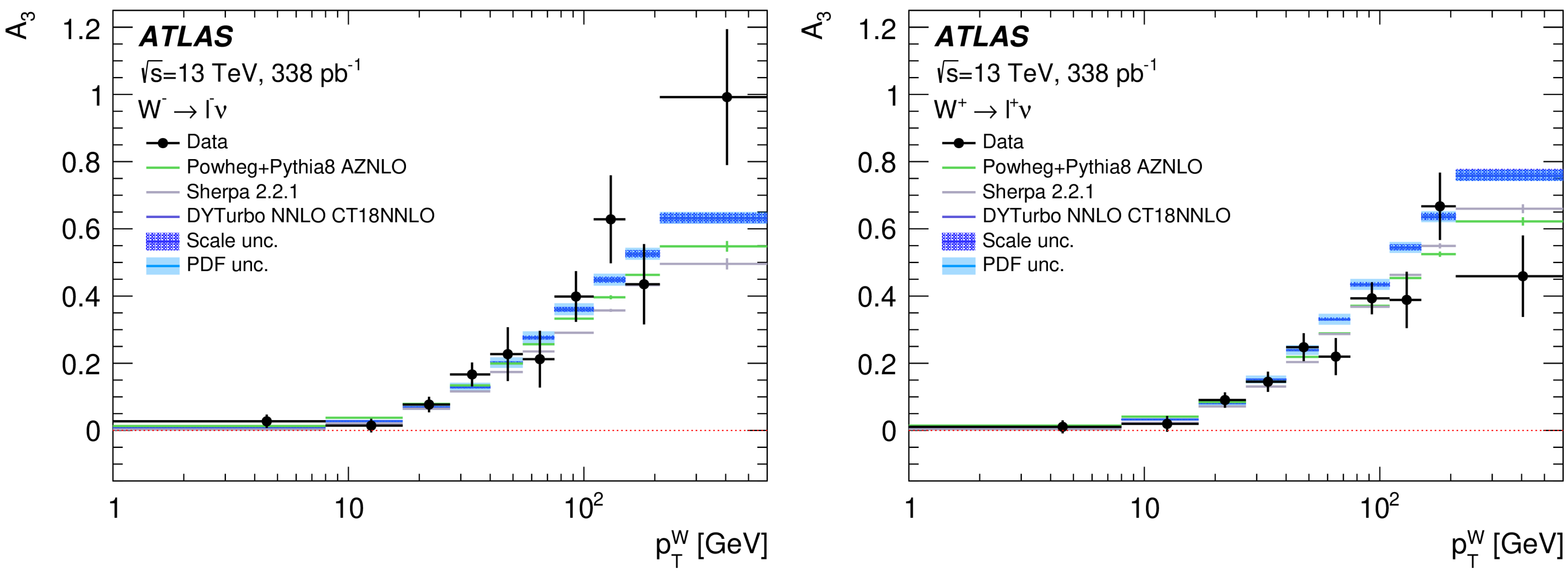
MC Stat

Syst NPs

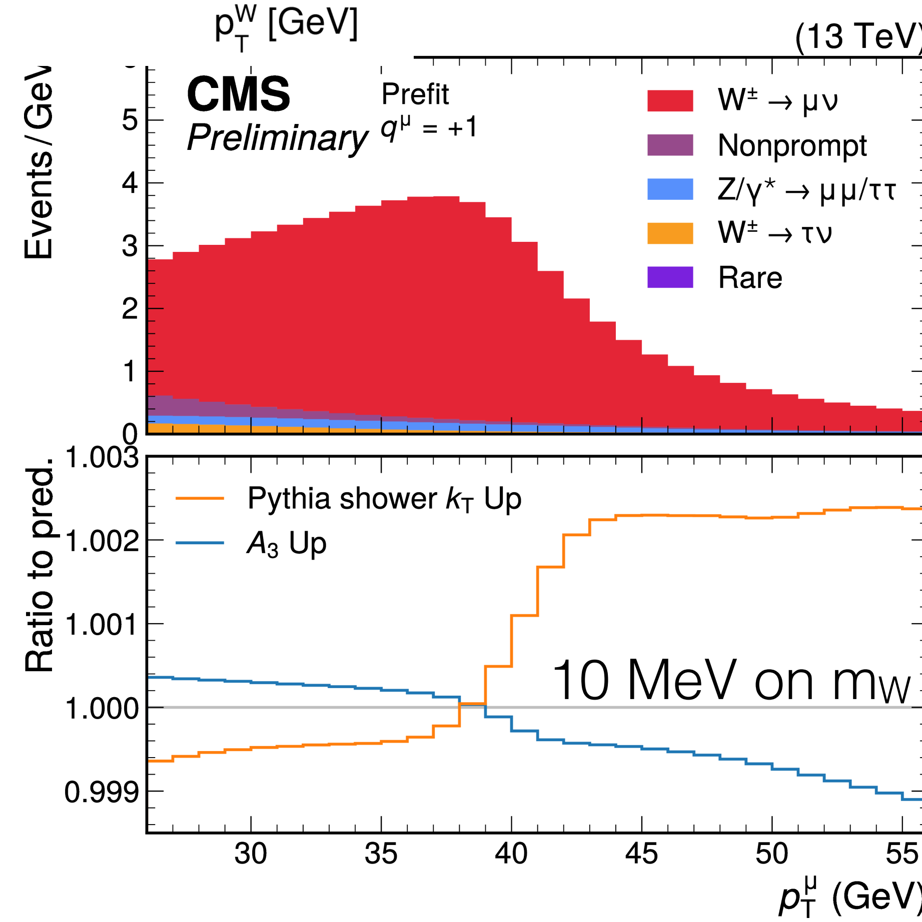
Product of all Poisson probabilities for each p_T^W, $\cos\theta_{CS}$, ϕ_{CS} bin and NP constraints

Minimized using binned NLL to calculate first and second derivatives to calculate Hessian, $H = \nabla^2(-\ln L)$ to find a solution for $\nabla(-\ln L) = 0$

First measurement of full set of angular coefficient in W production



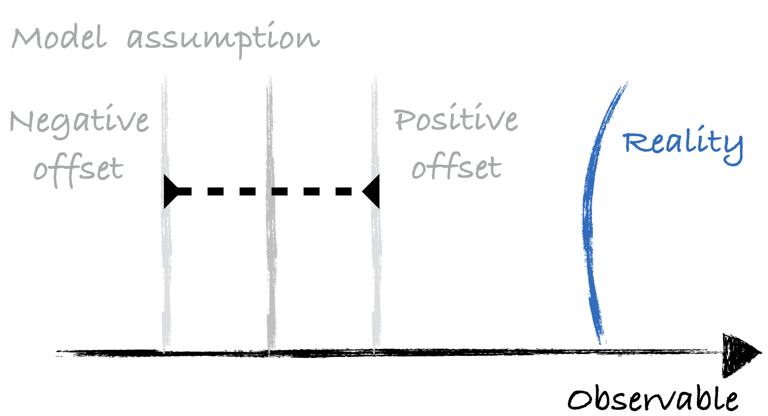
e-print [arXiv:2509.13759](https://arxiv.org/abs/2509.13759)



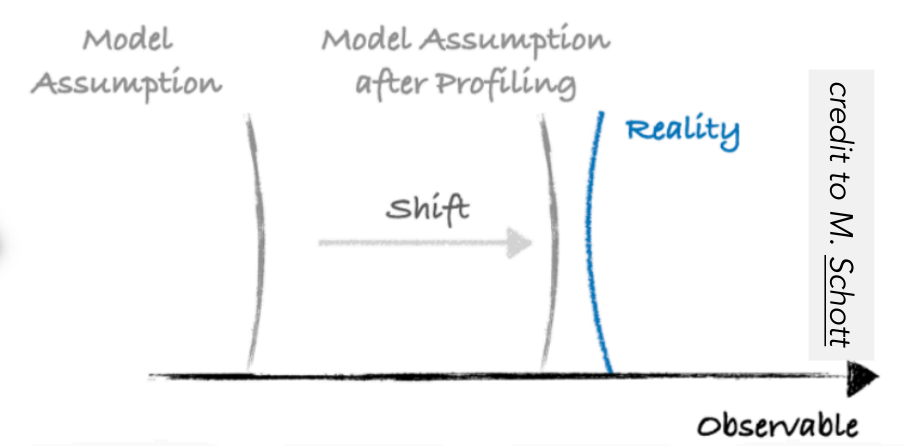
- For the first time extraction of the full set of W-boson angular coefficient (A_0- A_7)
- First direct measurement of A0 and A4 vs p_T^W
- Improvement for A2 and A3 Precision exceeds that of any previous measurement
- Measurement of p_T^W spectra in full phase space for W^+ and W^- at 13 TeV with %level accuracy

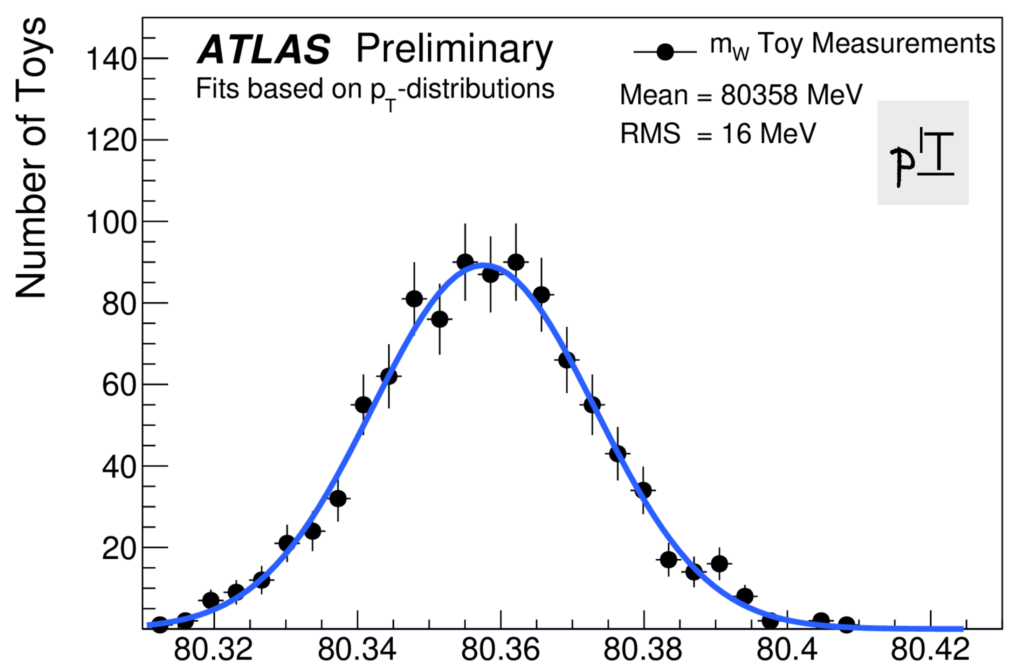
The improvement of the analysis

χ^2 offset fit

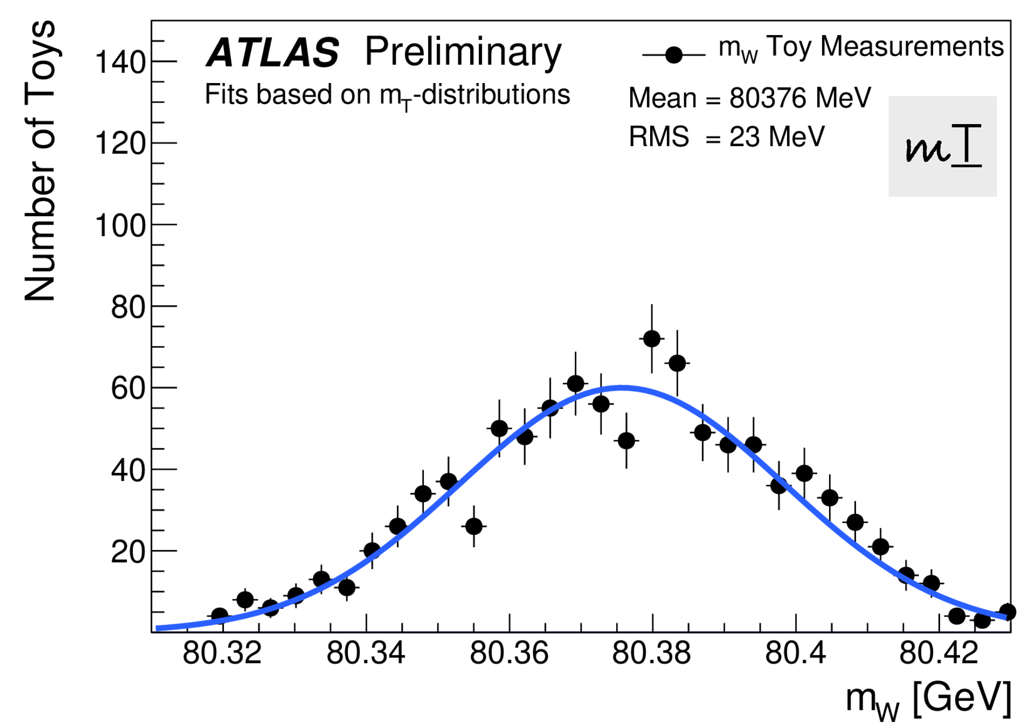


Profiled Likelihood fit



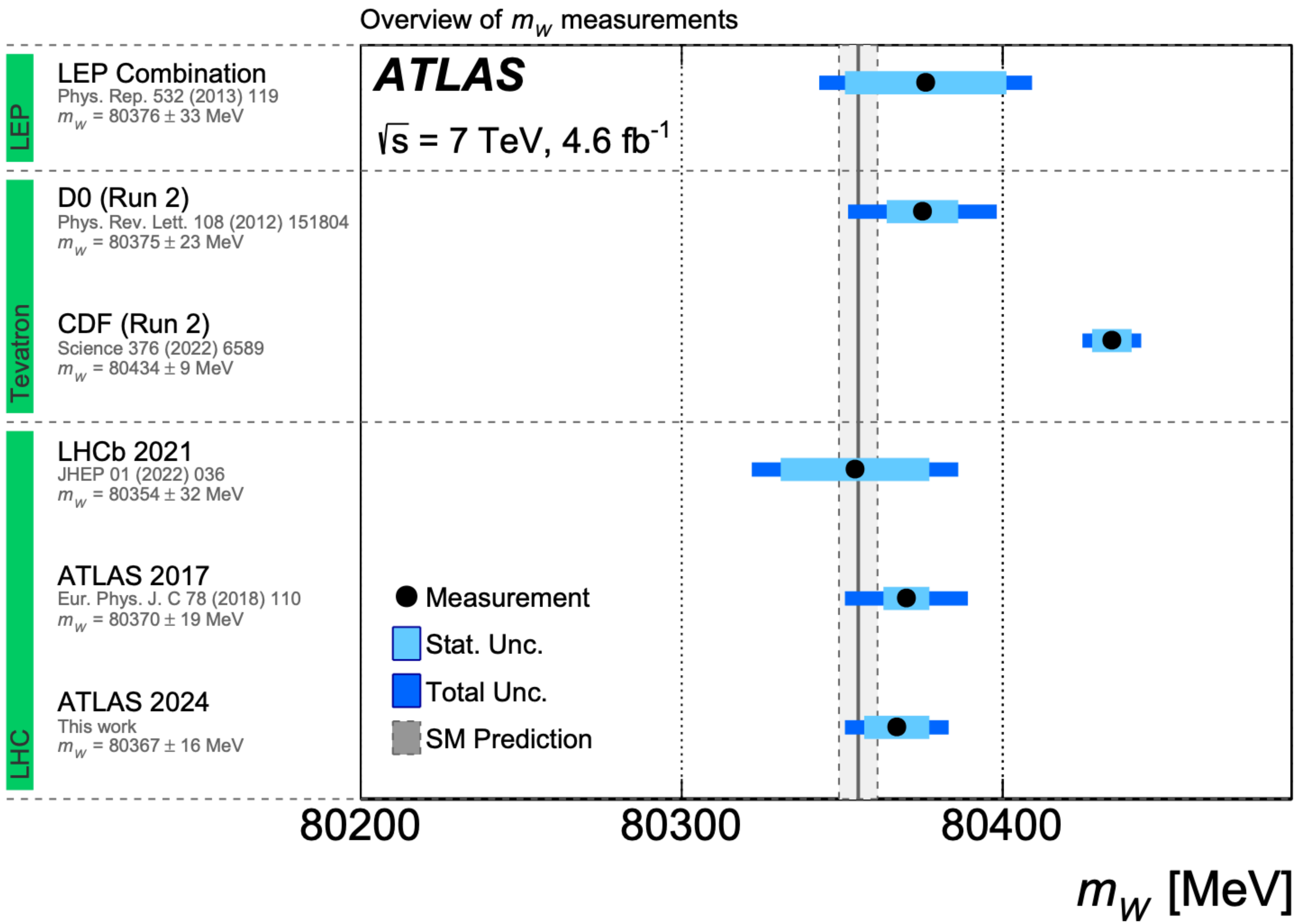


MC Toy study of sys. spread using CT10 PDFs



PLH allows simultaneous determination of POI together with NP taking account correlation in each category

expected allowed shift m_W ±16 (±23) MeV for p_T (m_T)



W mass re-analysi

ATLAS W boson mass

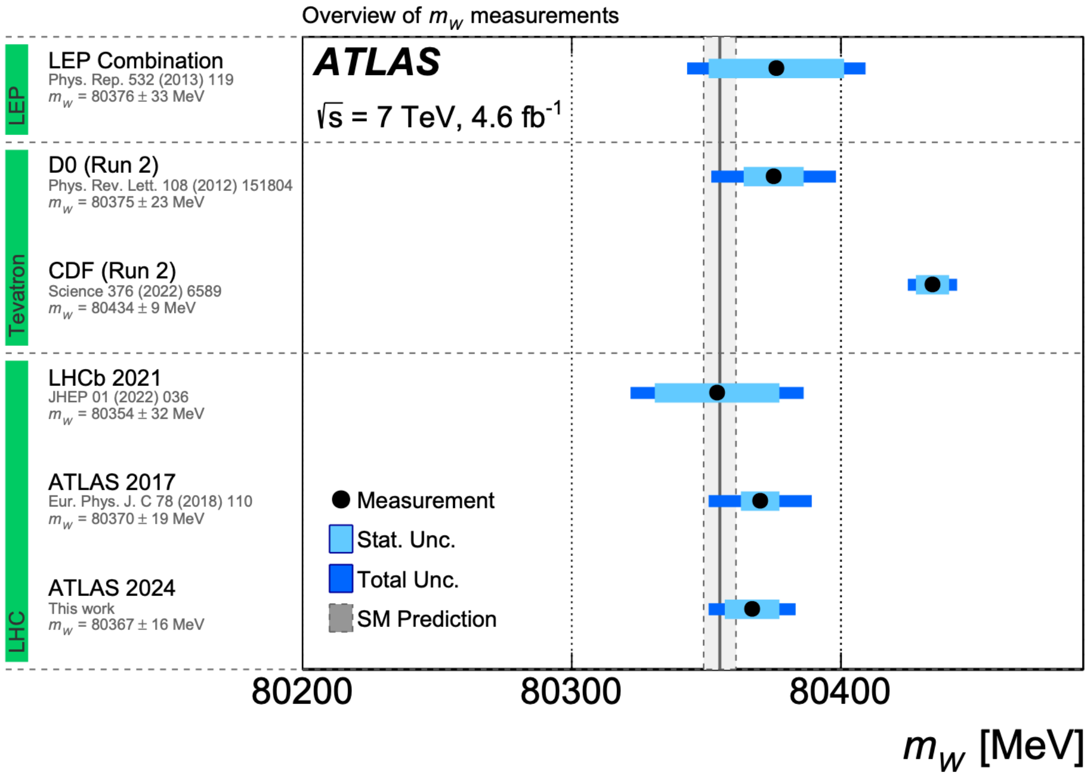
- p_T^ℓ and m_T measurement are compatible at 1.2σ level
  - correlation between the 2 measurements ρ = 0.63

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	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

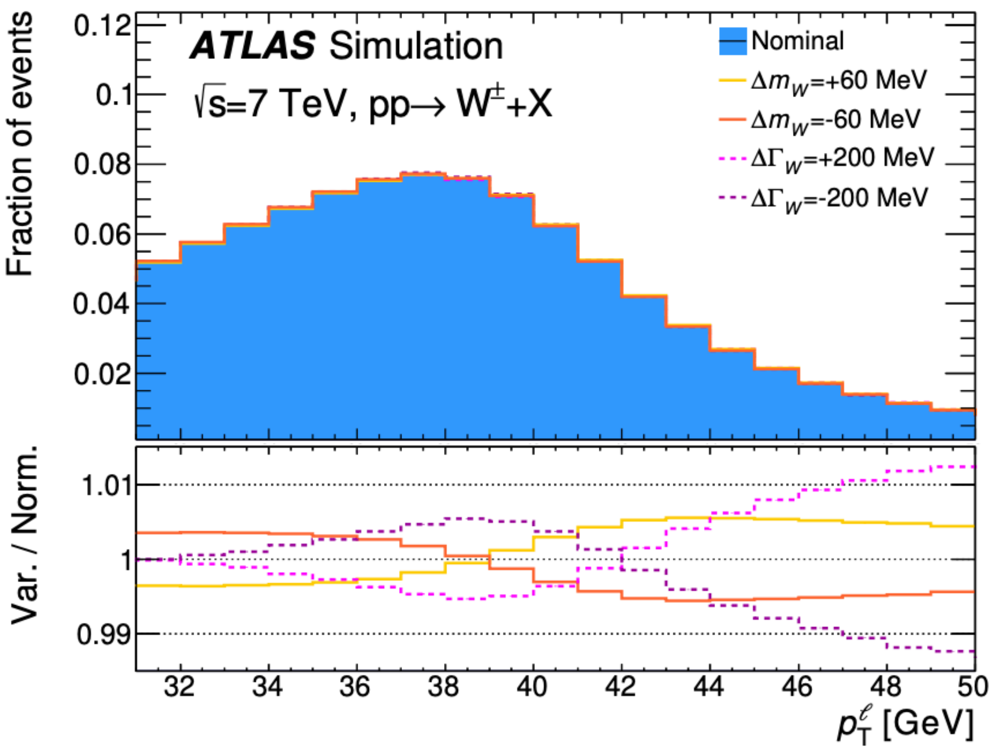
BLUE Combination for p_T^ℓ and m_T results

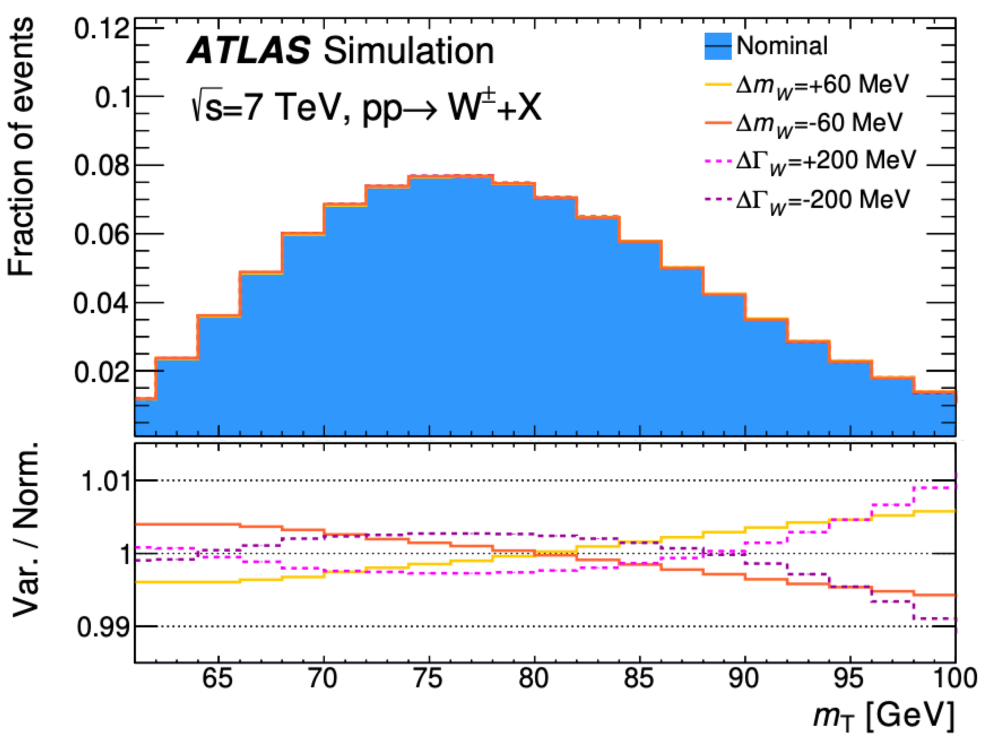
- The p_T^ℓ fit largely dominates the final result (95% weight

$m_W = 80360 \pm 5(\text{stat.}) \pm 15(\text{syst.}) = 80360 \pm 16$ MeV

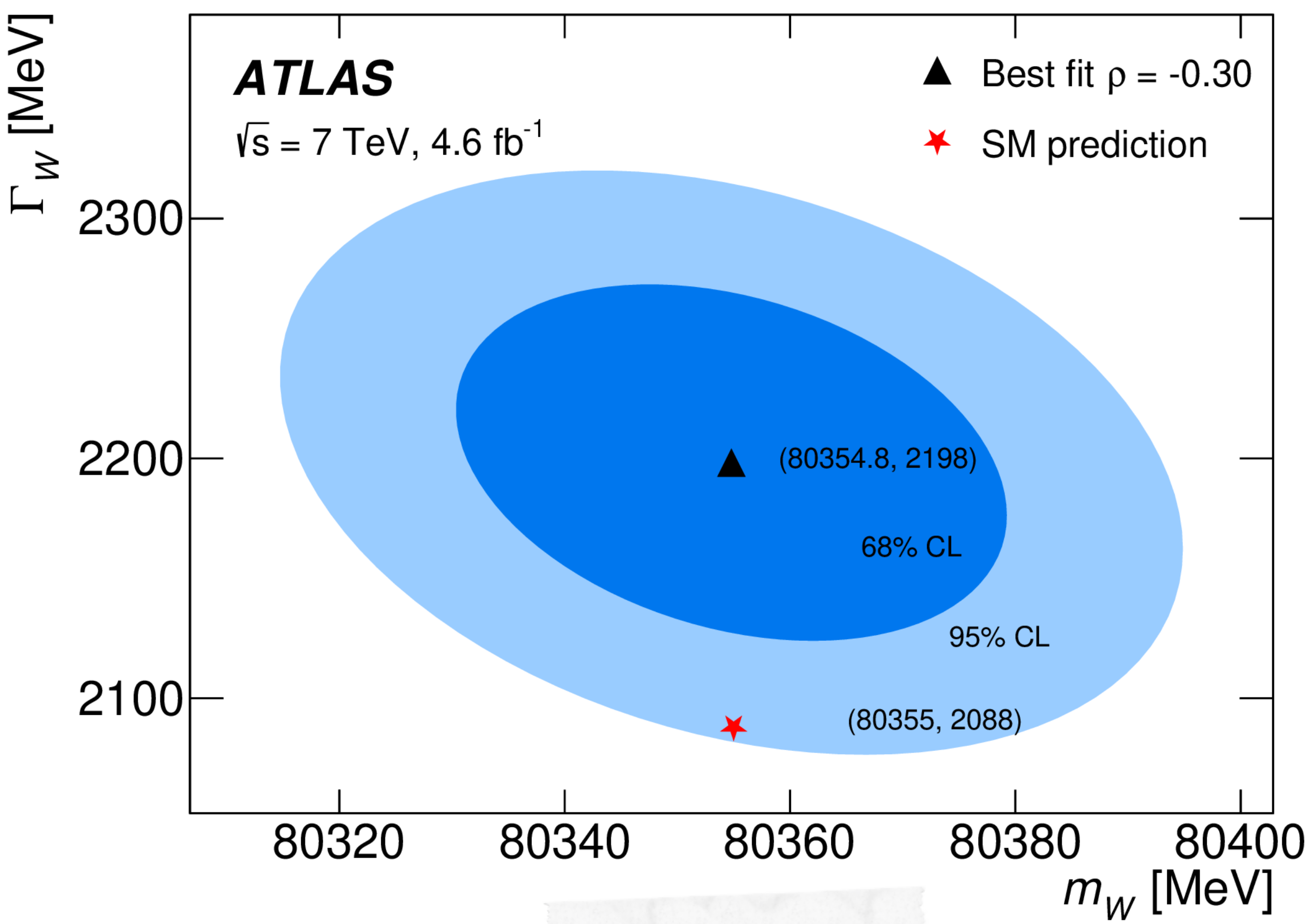


simultaneously extracting Mass and width





Contrary to mW, the fitted value of Γ_W depends more strongly on the assumed value of the mass $\Delta\Gamma_W = -1.25\ \Delta m_W$



For the CT18 PDF set, the combination yields values of m_W = 80354.8 ± 16.1 MeV Γ_W = 2198 ± 49 MeV,

Uncertainty decomposition

arXiv:2307.04007

Interpreting Uncertainties in Profile-Likelihood Fits

- The usual separation into "statistical" and "systematic" components can be misleading.
  - Statistical-only fits **underestimate** the true statistical uncertainty when systematics are included.
  - Systematic impacts **overestimate** the genuine systematic contribution.
  - Impact plots should **not** be used directly for combinations or interpretation fits.
- The Gaussian approximation [Global in the CMS decomposition] give a consistent split of uncertainties consistent with other method.

Example ATLAS :

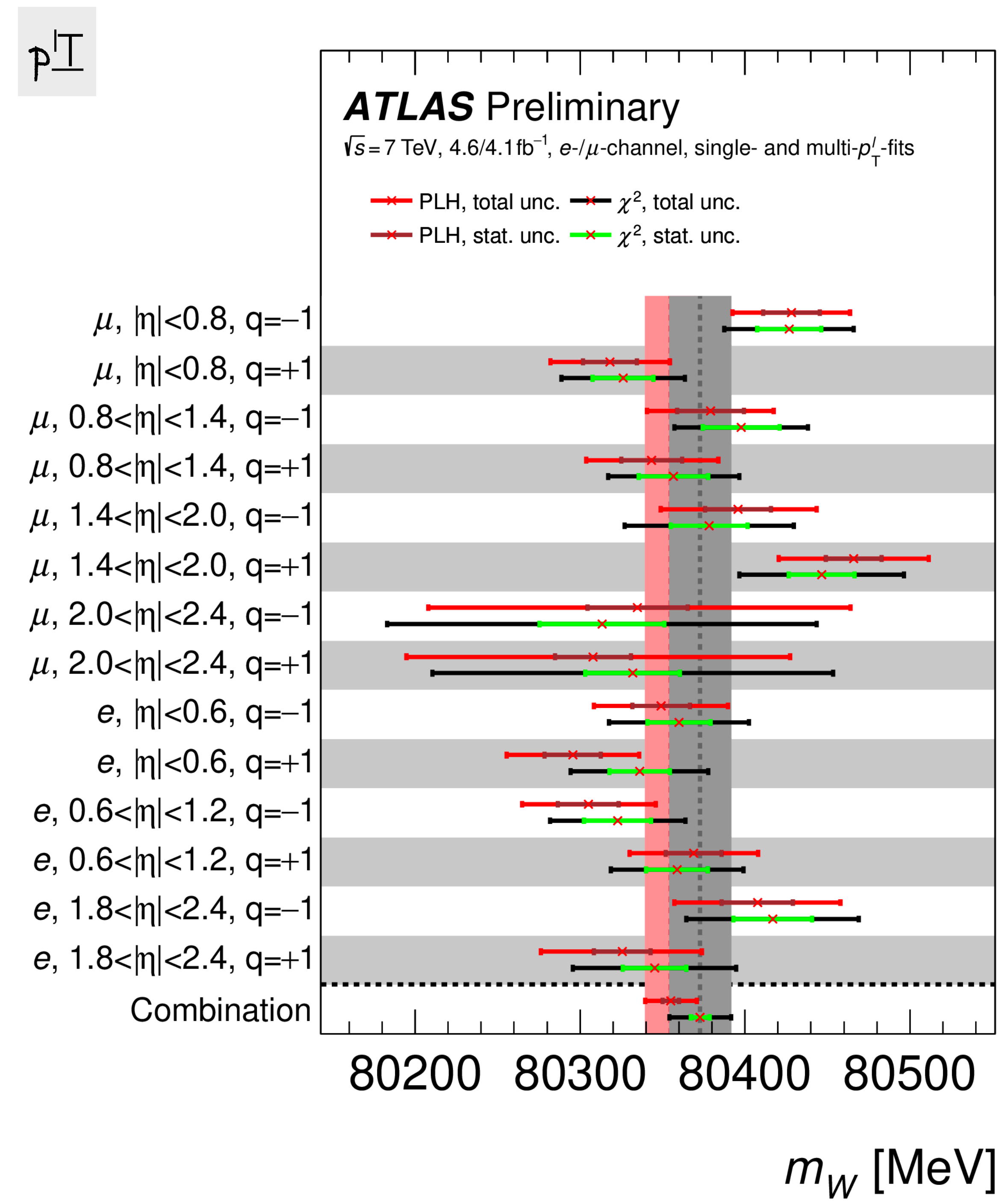
- The statistical uncertainty on final m_W analysis is ~10 MeV in the full profile-likelihood fit
  - Larger than the 6 MeV from statistical-only fits (with nuisance parameters fixed)
  - The genuine systematic uncertainty is ~13 MeV — smaller than conventional "impact" estimates.

Test consistency PLH fit

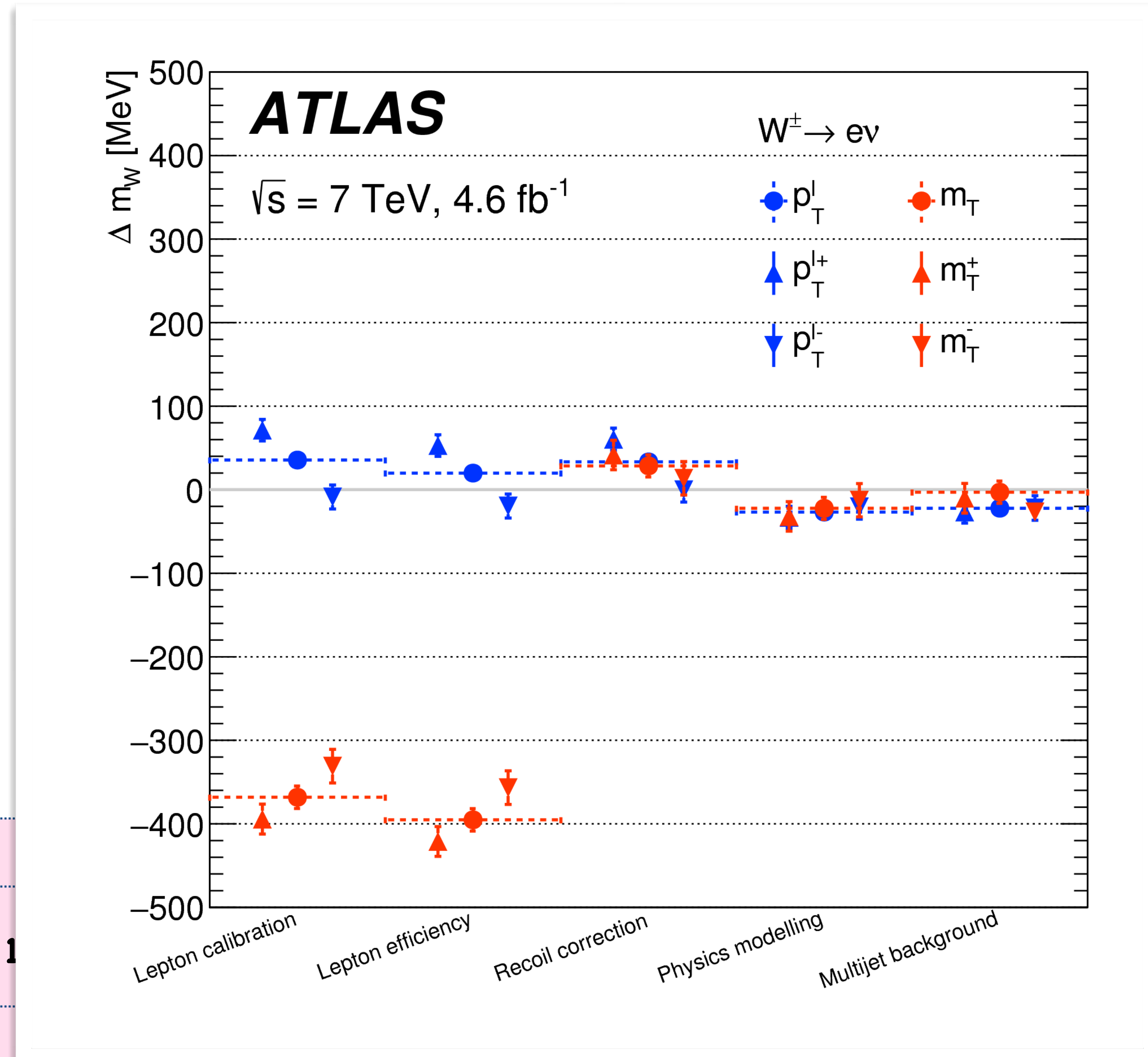
- PLH fit **mW = 80355.1 ± 15.6 MeV** (CT10nnlo PDF)
  - Δmw = -14.4 MeV **(mW** 2017 **= 80369.5 ± 18.5 MeV)**
  - Profiling of systematic uncertainties reduce δmW by 15%

Δ(mW) well within the expectation from Toys studies.

PLH fit validation using CT10 PDFs

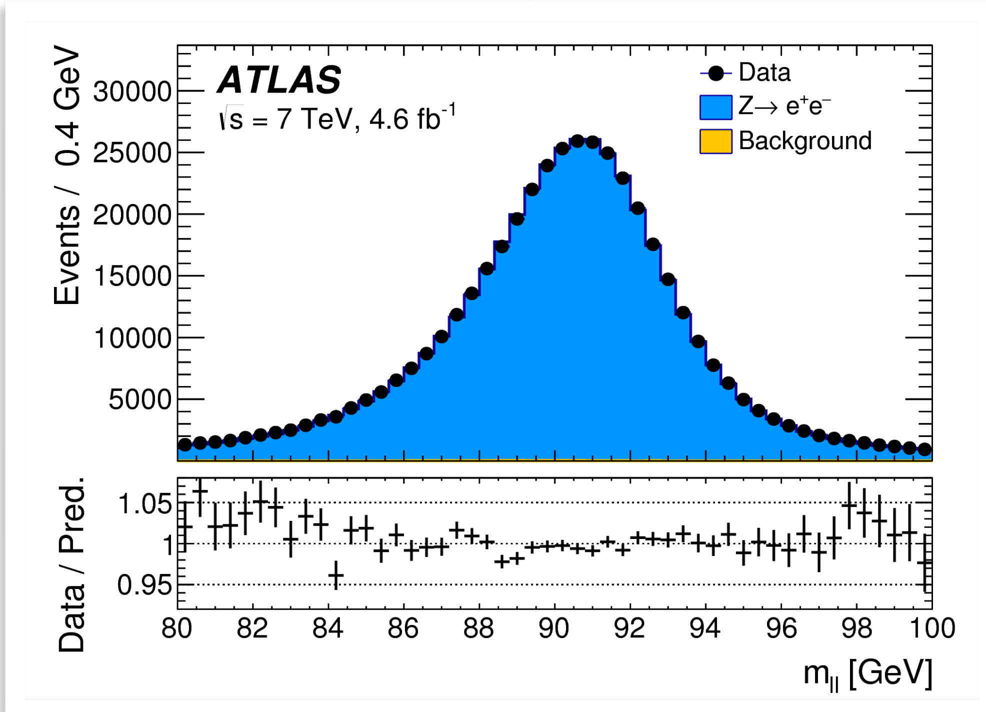


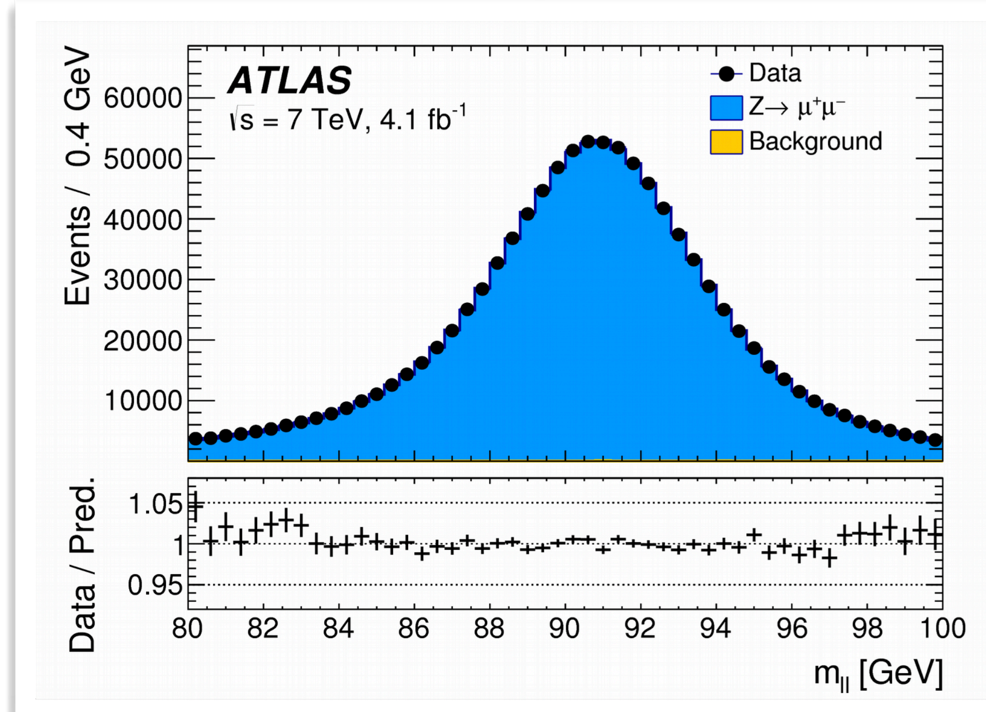
The precision we need

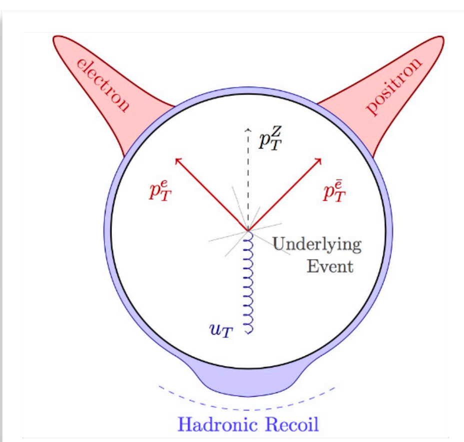


			LHCb
Dataset	17 fb^{-1} @1		7 fb-1 @13TeV pileup) 2016 only
Channels			uons 2.2 < η^{μ} < 4.4
Observable	only p_T lepton	p_T , m_T	q/p_T
Modelling	TNP (theoretical nuscìance parameters)	Z↔W extrapolation of the model	simultaneous fit to $Z\rightarrow\mu\mu$ events binned in $\phi^{*}\approx p_T/M$

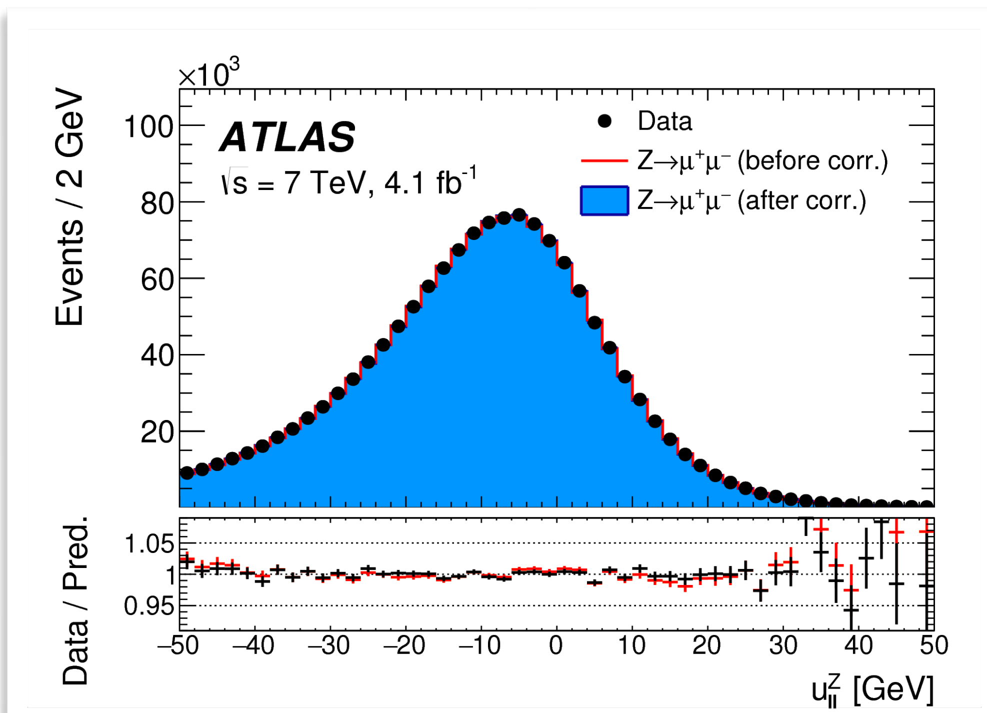
in ATLAS - Z samples





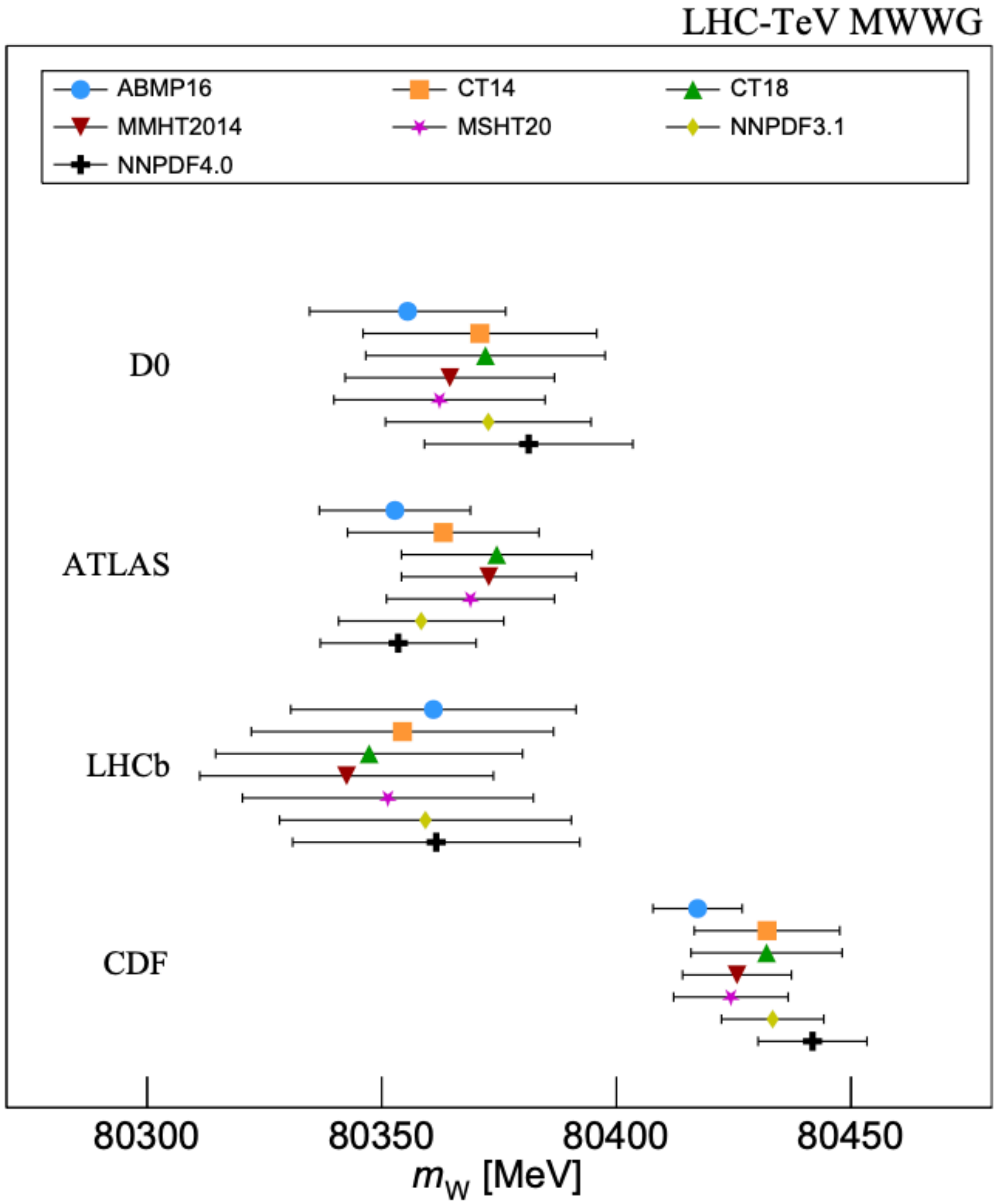


The response of u_T is measured in data using the p^Z_T balance in Z events



- Z boson events are used to derive detector calibrations.
- **Experimental precision :**
  - Lepton performances at sub-‰ level ⇒ $\delta m_W \sim$ 7-10 MeV
  - Hadronic Recoil calibration at % level ⇒ $\delta m_W \sim$ 12 MeV

often objects-calibration precision is trade of between clean environment and Z samples statistic [particularly true for low-μ]



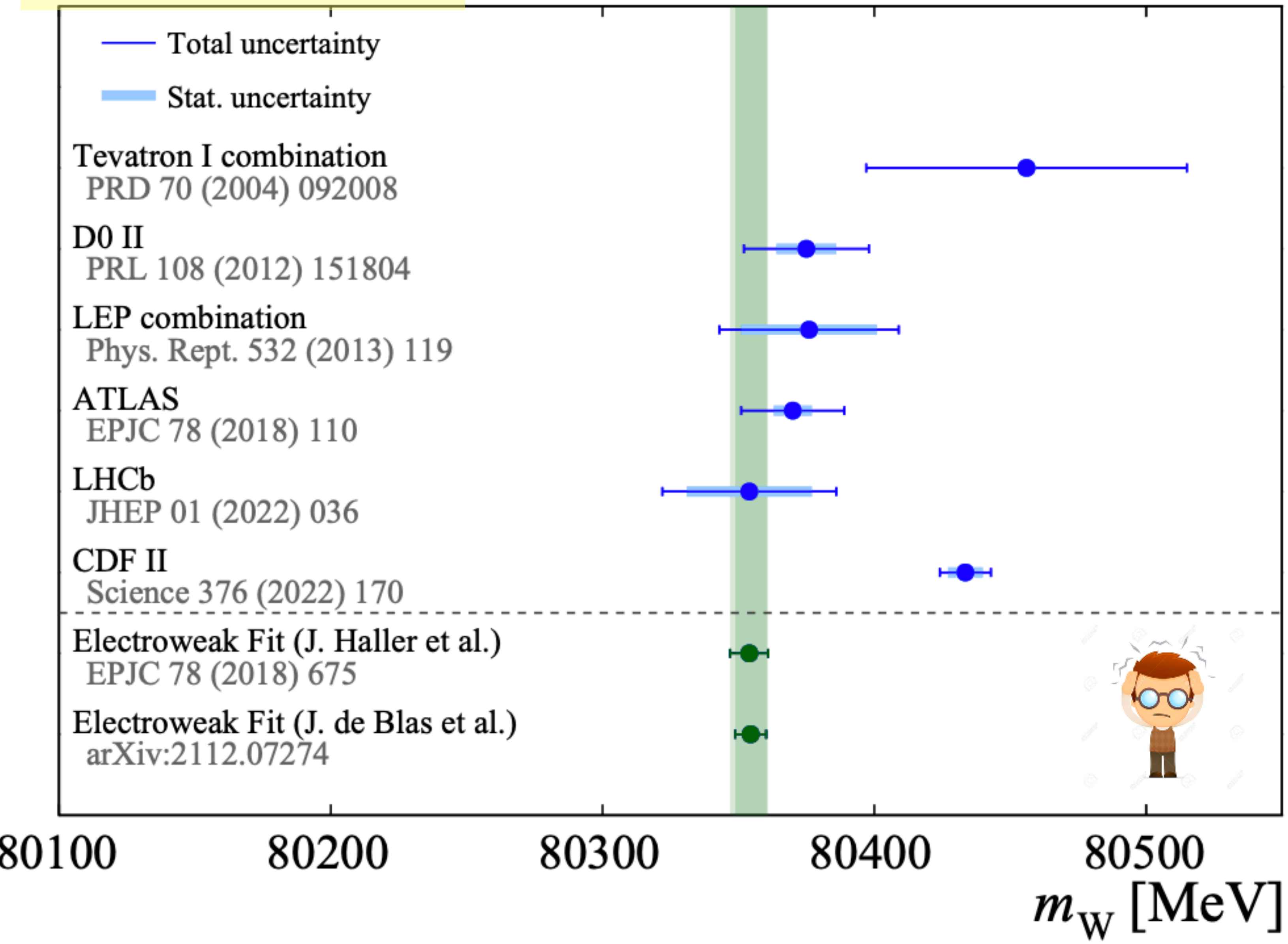
Eur. Phys. J. C (2024) 84: 451

LHC-EW WG

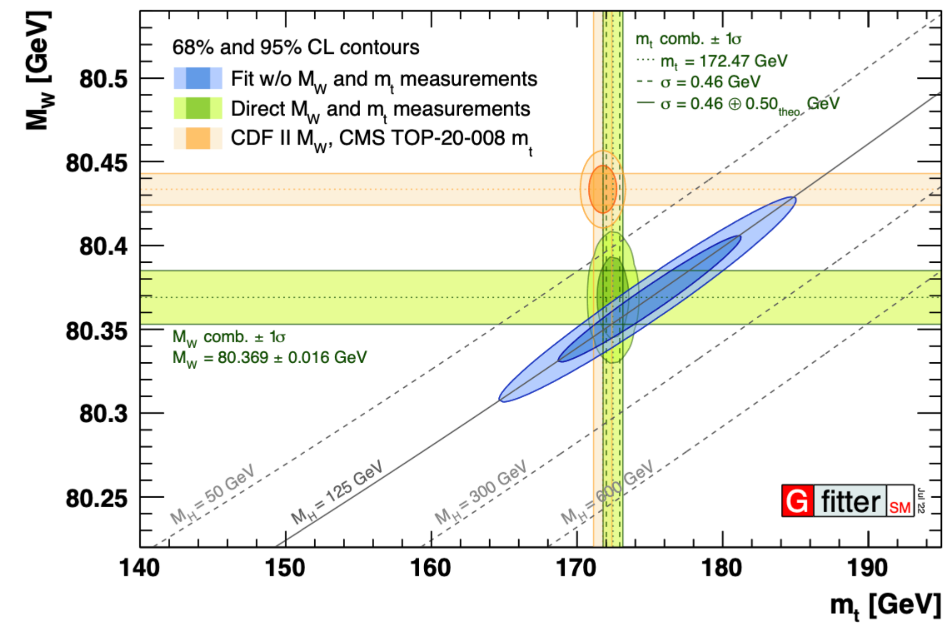
W mass combination

Tevatron/LHC W-mass combination

[LHCB-FIGURE-2022-003]



R.Kogler ICHEP2022



- *Measuring mW at the LHC (pp) is more challenging than at the Tevatron (pp-bar)*
  - *PDF-induced polarisation uncertainty*
  - *2^{nd} generation quarks*
- *3(2) sigma tension between CDF and ATLAS(LHCb)*

Tevatron/LHC W-mass combination

- Ongoing LHC/TeVatron Electroweak WG effort towards combination
  - Crucial to understand theoretical correlations between measurements: prime examples **PDFs** and lepton angular correlations (**Ai**)

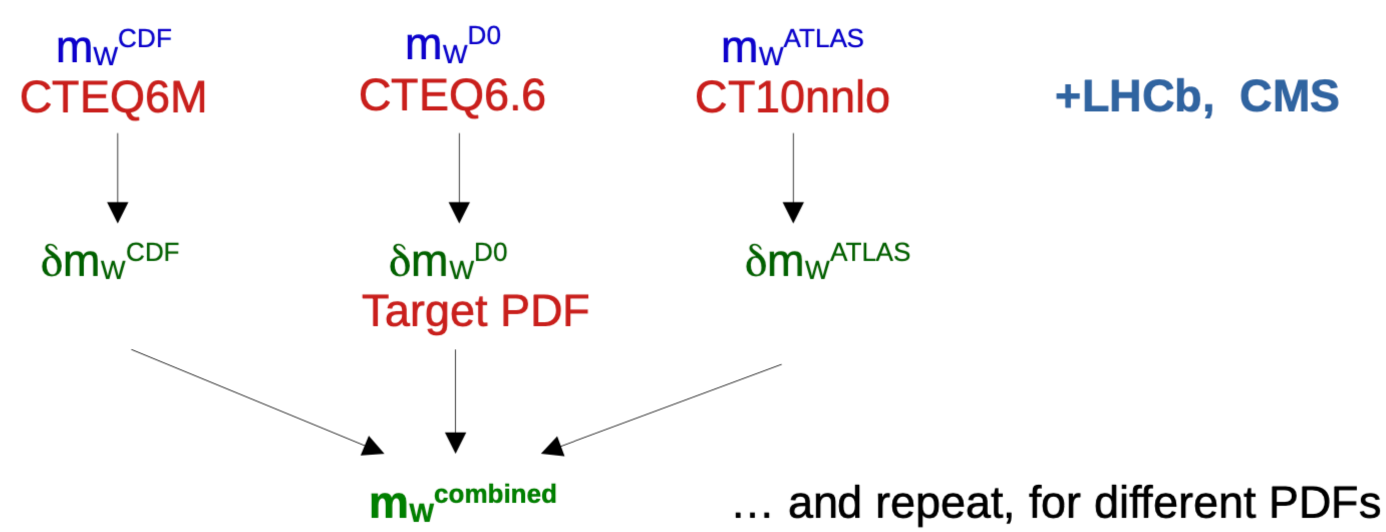
$$m_W^{new} = m_W^{ref} - \delta m_W^{QCD} - \delta m_W^{PDF}$$

published value — Improved predictions — PDF extrapolation

δm_W^{PDF} correction to reference PDF

δm_W^{QCD} correction to QCD modelling beyond quoted uncertainties

- **PDFs main source of correction and uncertainty correlations**
- Other sources very small (EW corrections) or mostly decorrelated (pT W/Z)
- Correction applied in a two-step procedure:
  1. Correct all measurements to a common PDF/QCD
  2. Combine them properly including correlations



CERN-LPCC-2022-06

Tevatron/LHC W-mass combination

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  - Crucial to understand theoretical correlations between measurements: prime examples **PDFs** and lepton angular correlations (**Ai**)

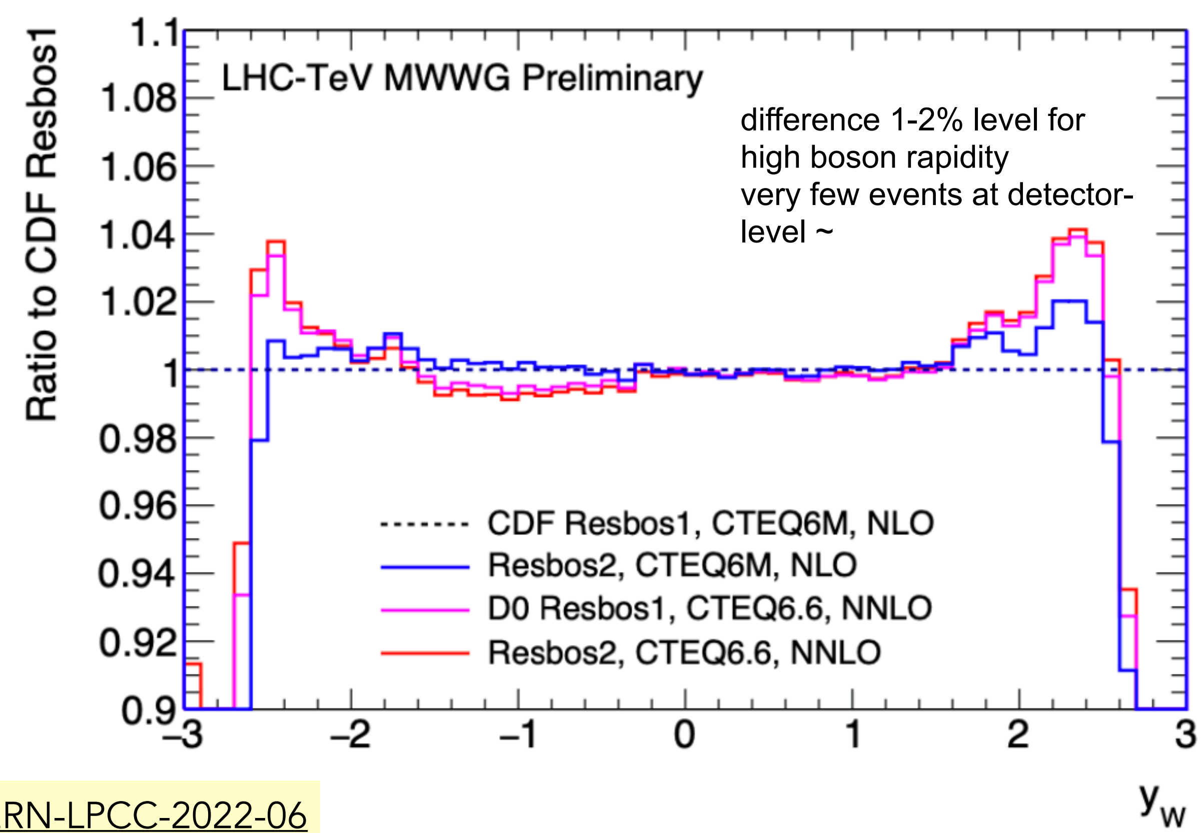
$$m_W^{new} = m_W^{ref} - \delta m_W^{QCD} - \delta m_W^{PDF}$$

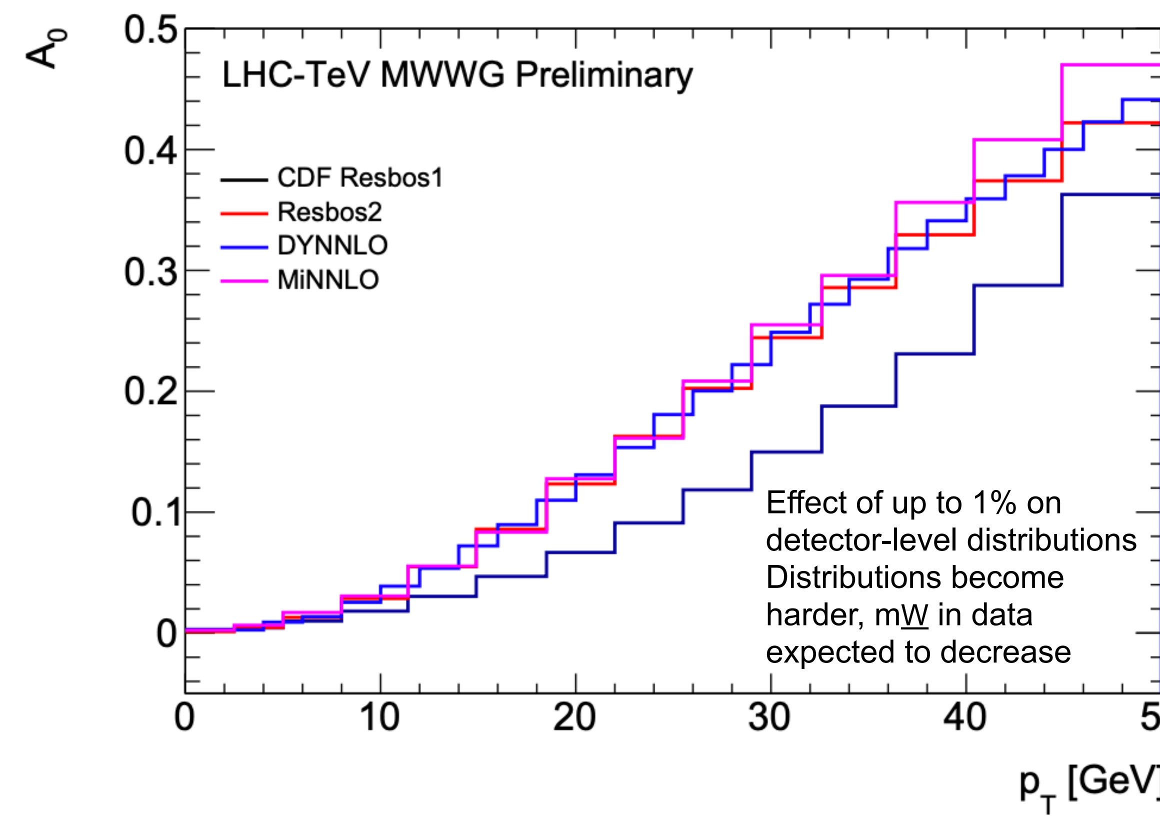
published value | Improved predictions | PDF extrapolation

δm_W^{PDF} correction to reference PDF

δm_W^{QCD} correction to QCD modelling beyond quoted uncertainties

- **Boson polarisation** in legacy Resbos different from Resbos2 and other codes: E.g. description of *W Ai* in legacy Resbos codes not ideal, motivates of O(10 MeV) correction of Tevatron measurements





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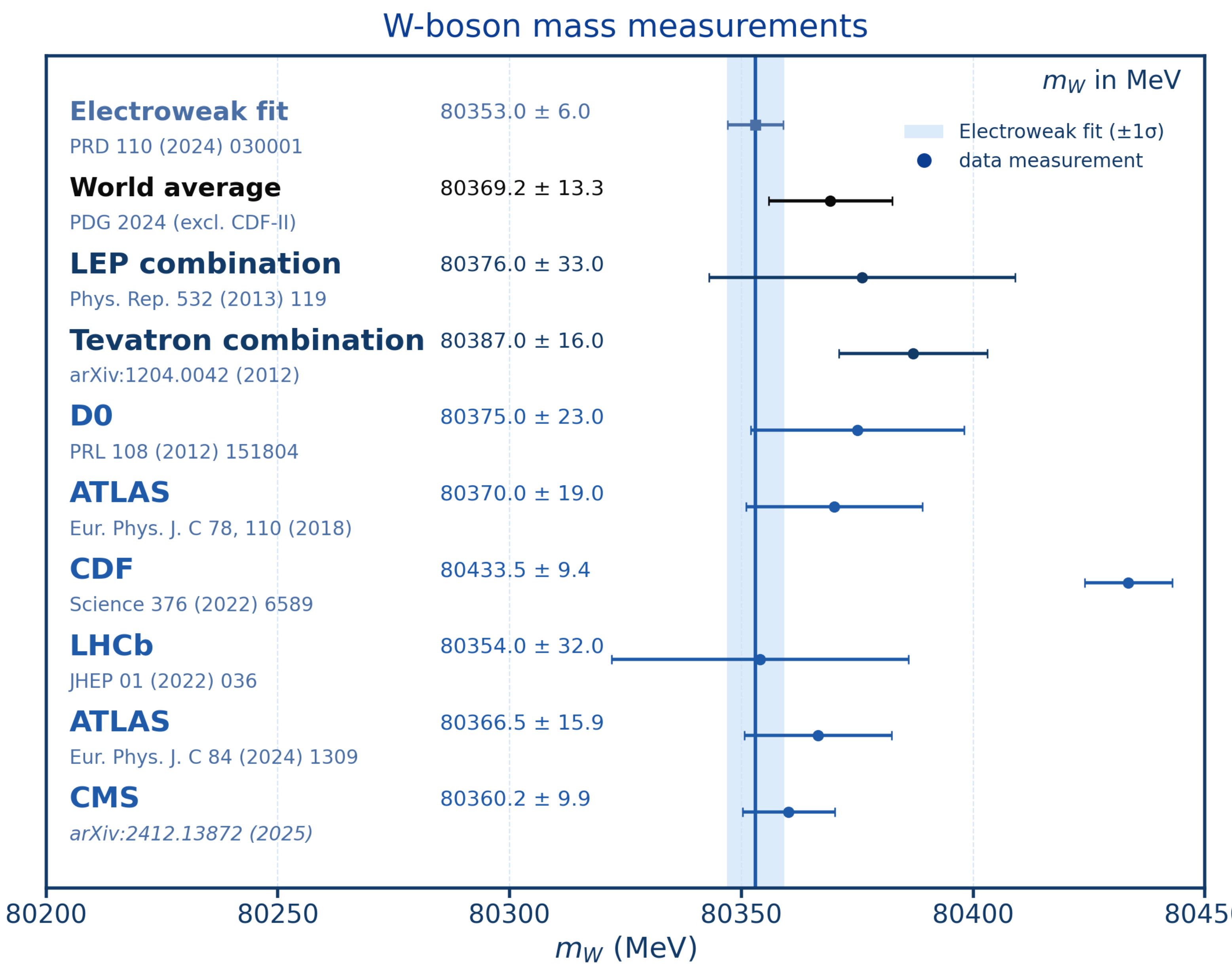
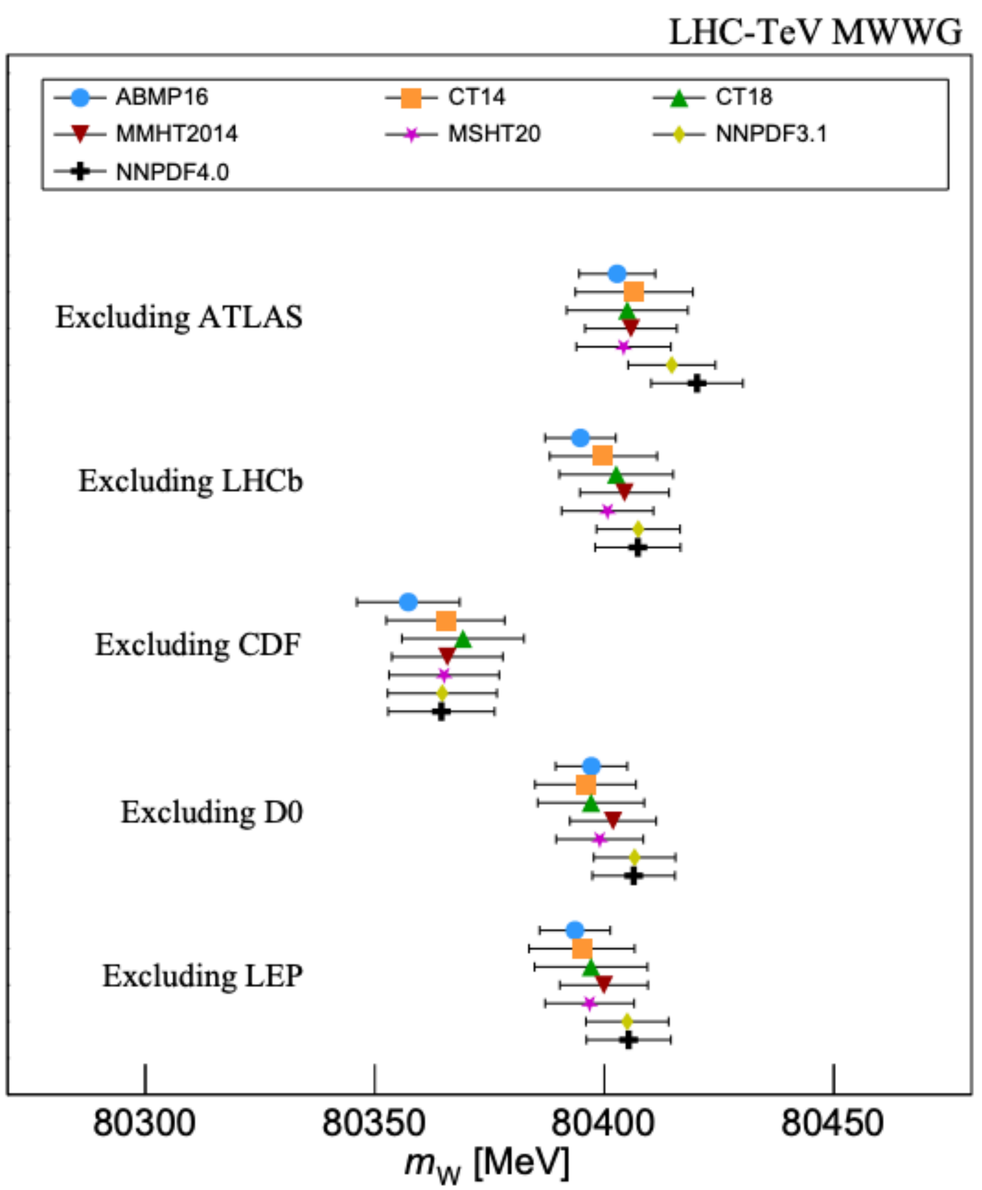
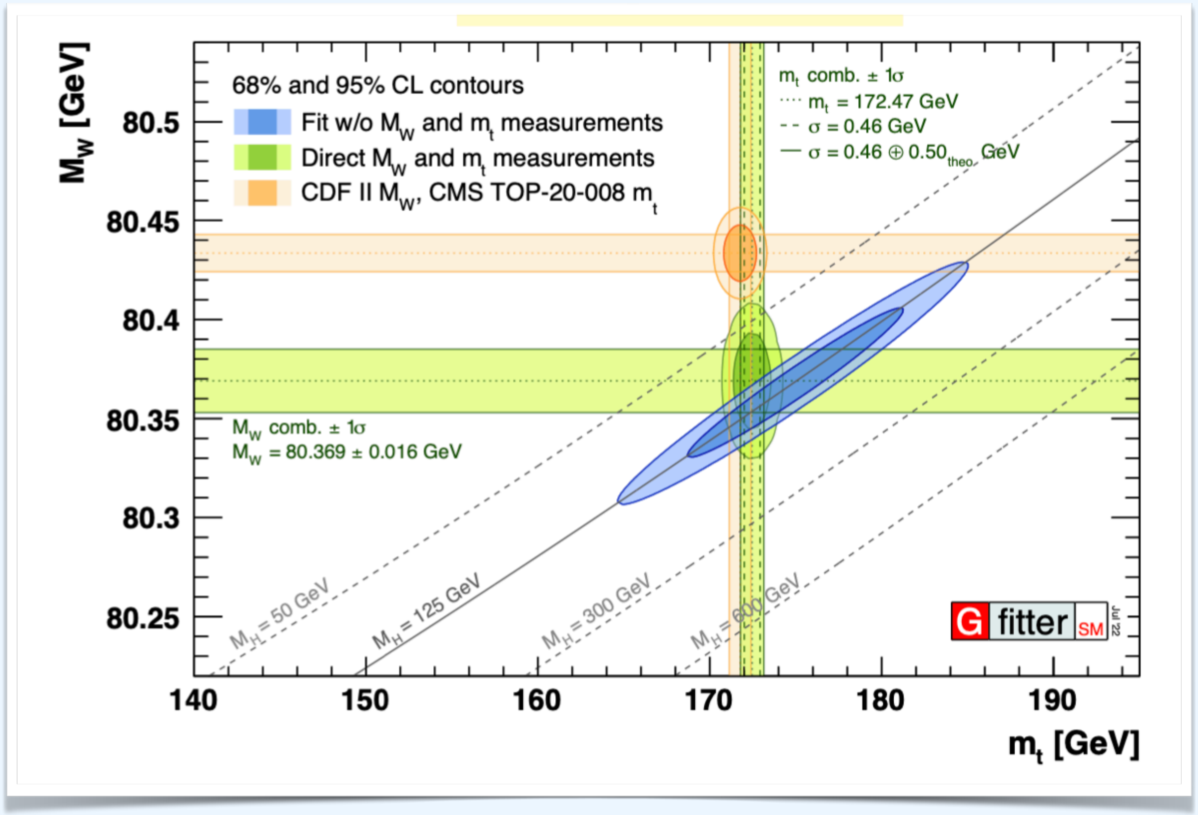
The W mass combination

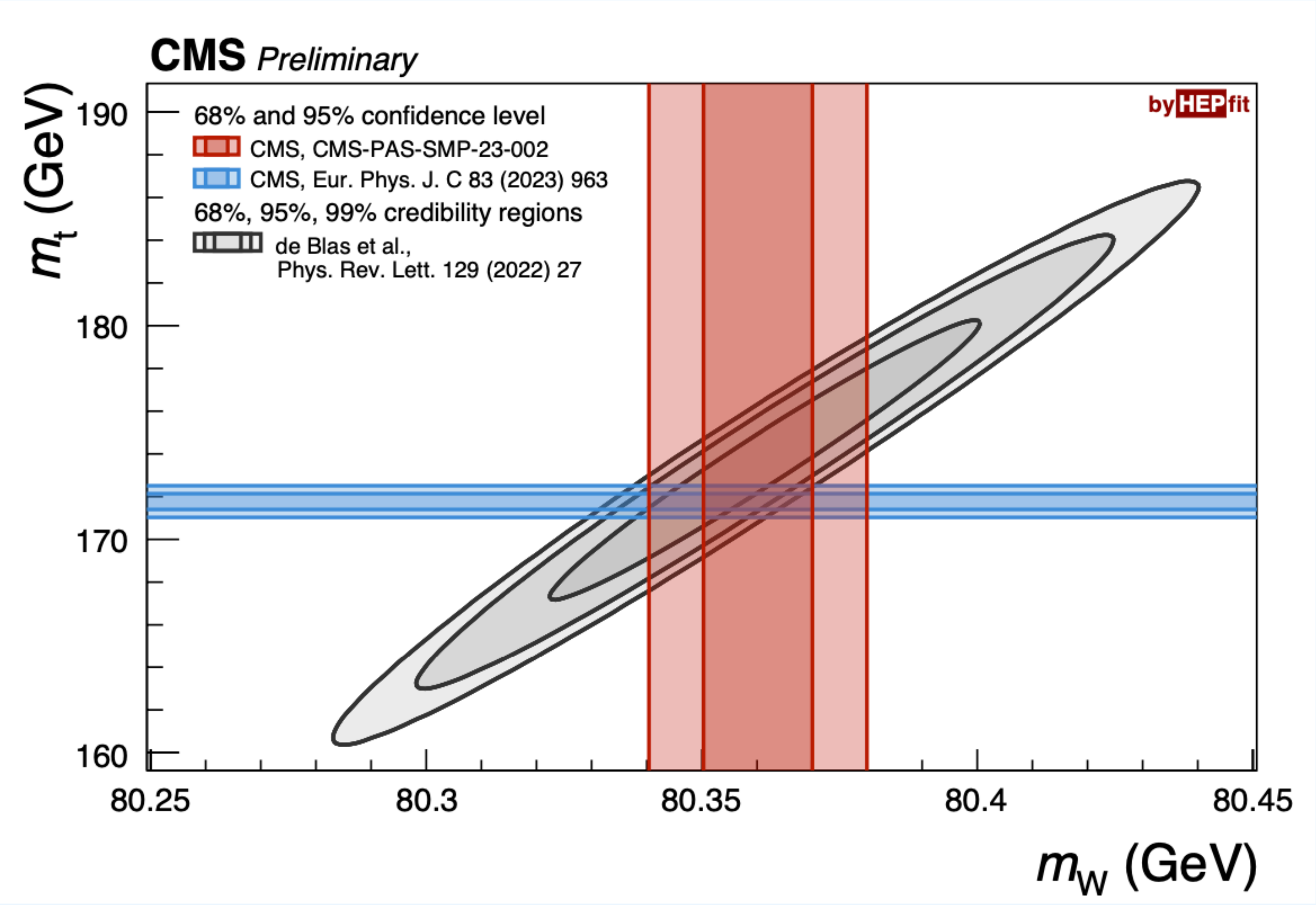




https://arxiv.org/pdf/2308.09417

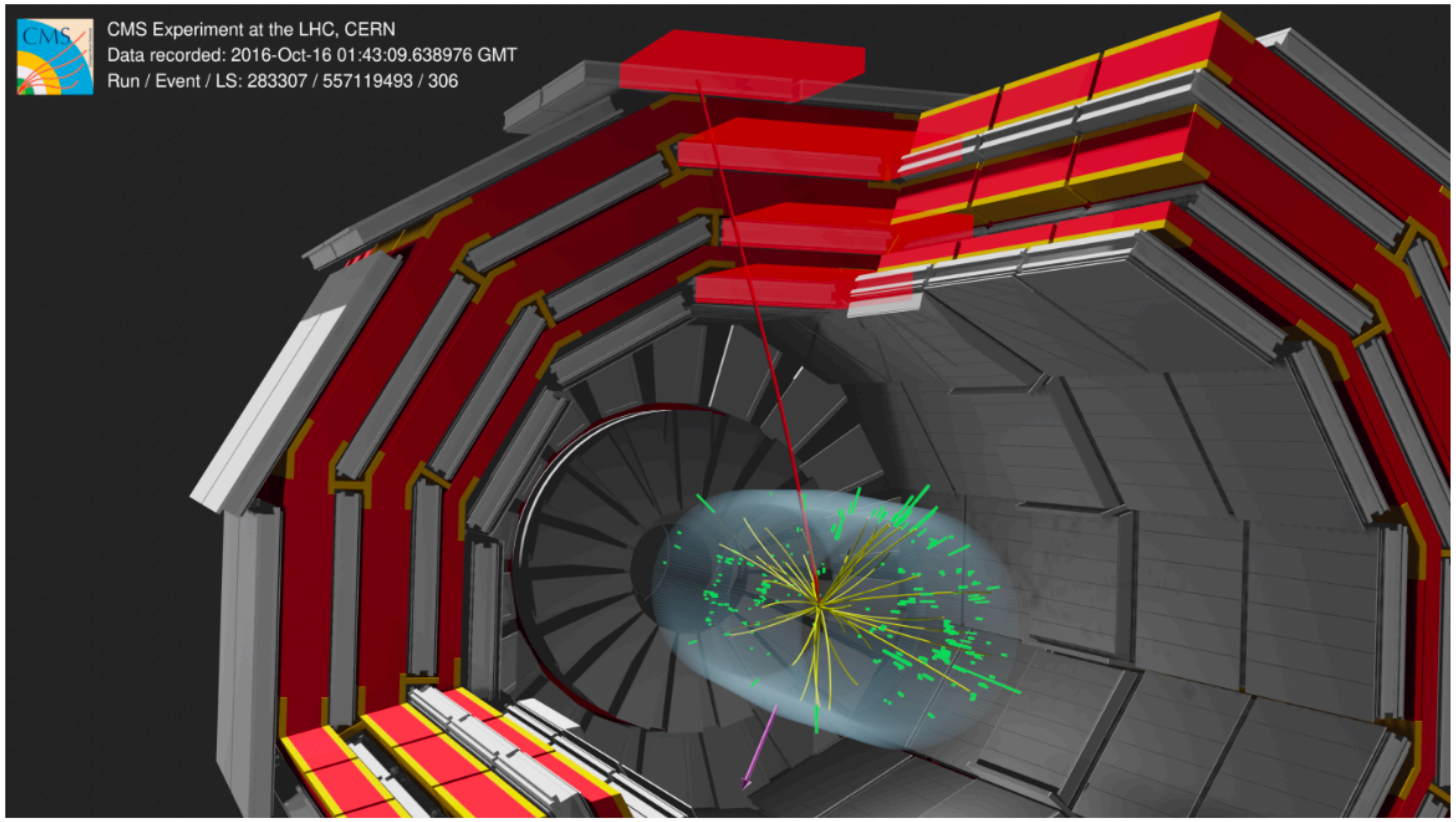
SM is restored

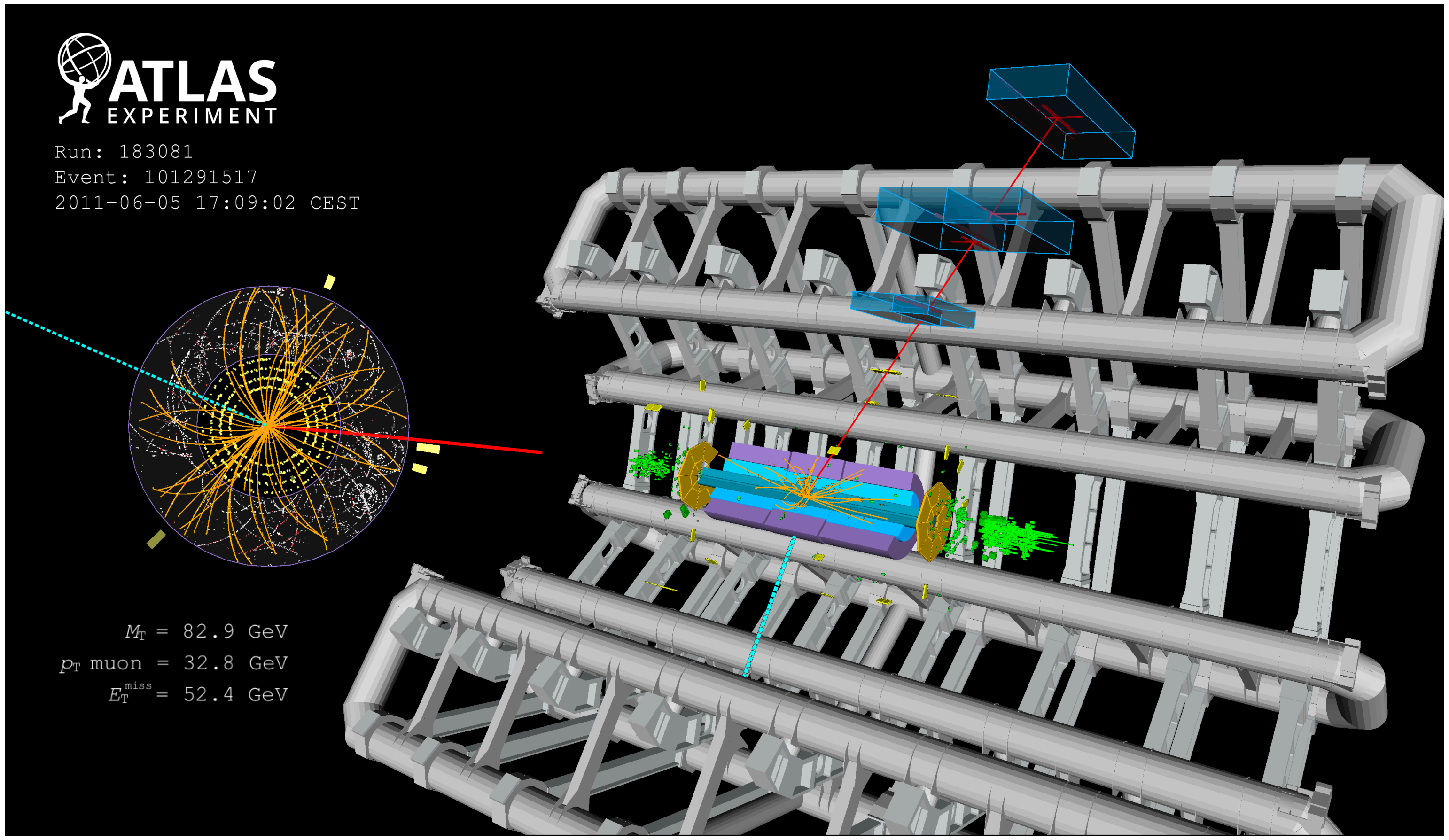




Ultra-precise. Surprisingly heavy.
The CDF m_W result stands in tension with the Standard Model … Latest ATLAS, CMS results restore agreement with the SM

Experimental challenges



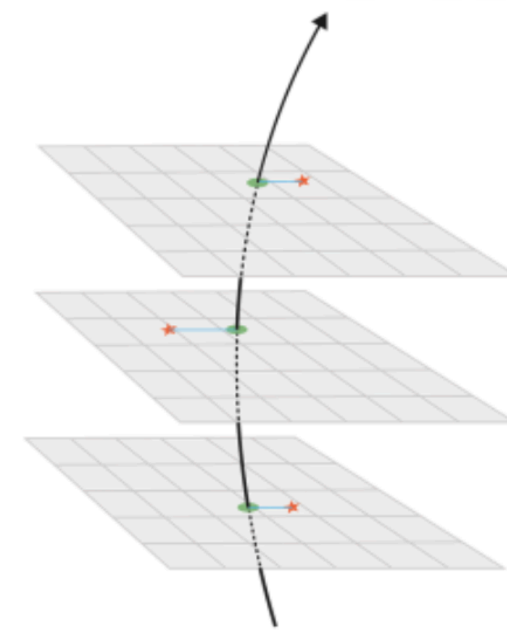


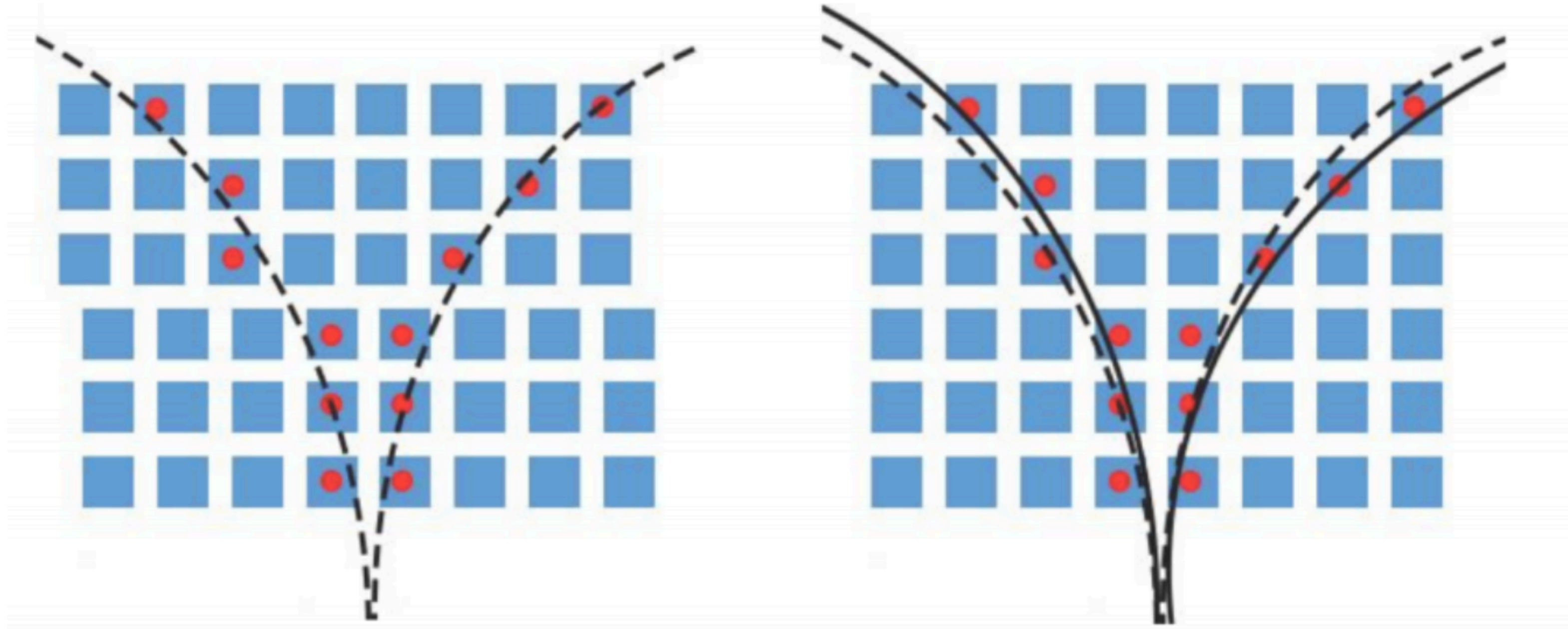
challenges of tracking calibration

- Knowing location and quantity of material, and relative alignment of 12k tracker modules also crucial
  - Need to know material traversed—not just silicon, but electronics, cables, support structure…

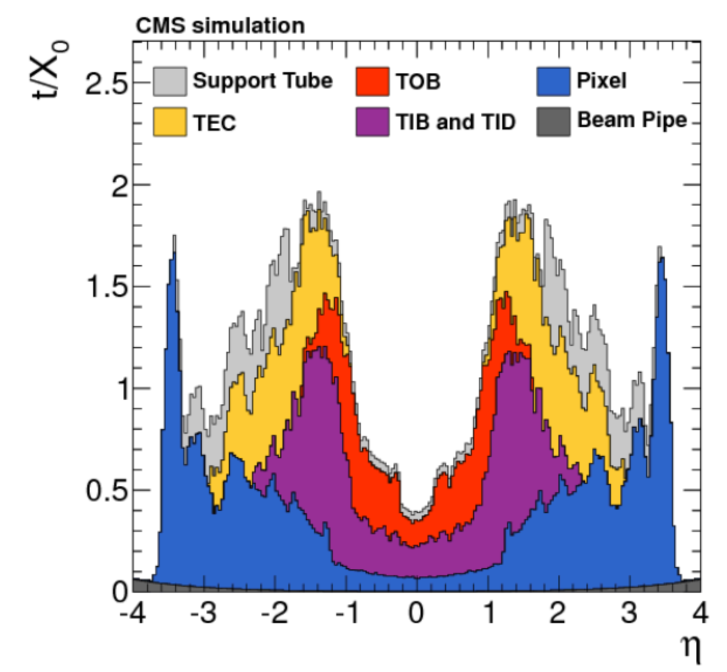
    ➡**5 MeV of bias equivalent to ~Δ5 mm of iron in the tracker volume**
  - Relative shifts from gravity, opening of the detector, modify alignment

    ➡**5 MeV uncertainty is a ~0.4 μm misalignment**





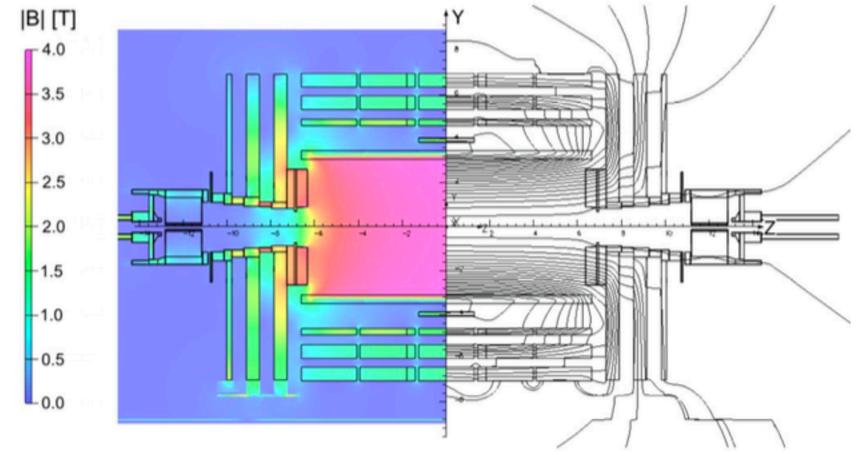
If the tracker is misaligned and we don't know it… …the track will be reconstructed as if the tracker was aligned

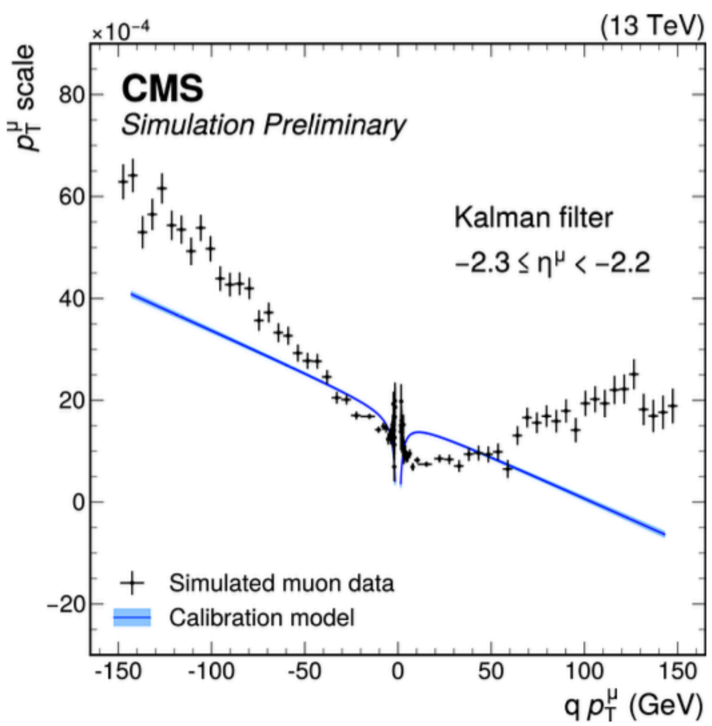


CMS

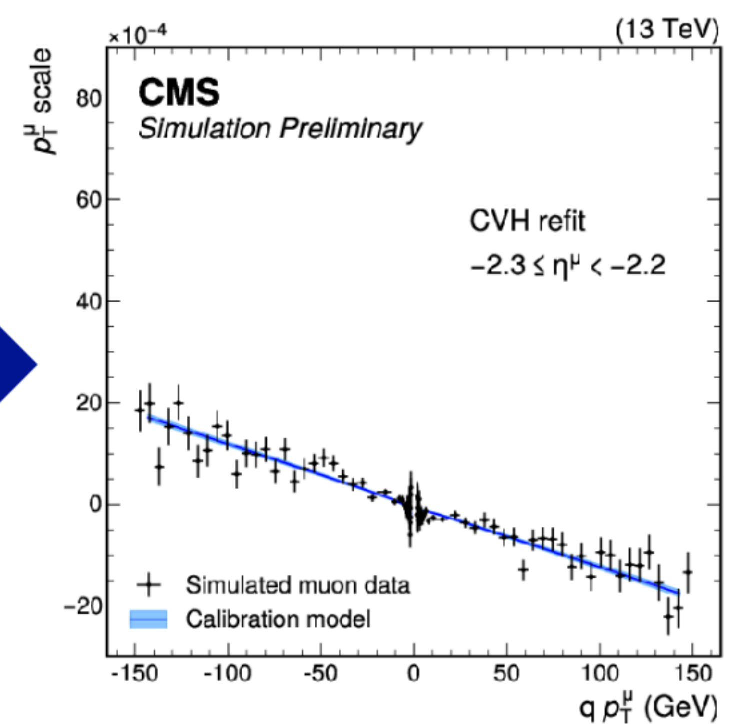
- **Refit muon hits using custom "Continuous Variable Helix" fit**
- **Model material in helix fit with Geant4**+additional params for B-field
  - Increase Geant precision wrt standard CMS reco.
- **Use of high-precision B-field map** (lower speed wrt standard reco.)

➡Extract and apply per-module parameter corrections

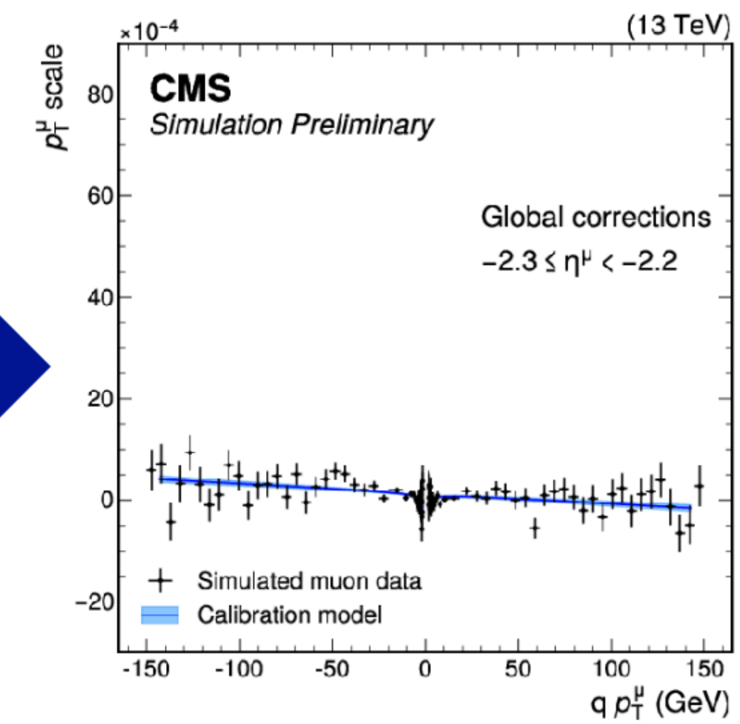




CMS standard reco.



CVH refit

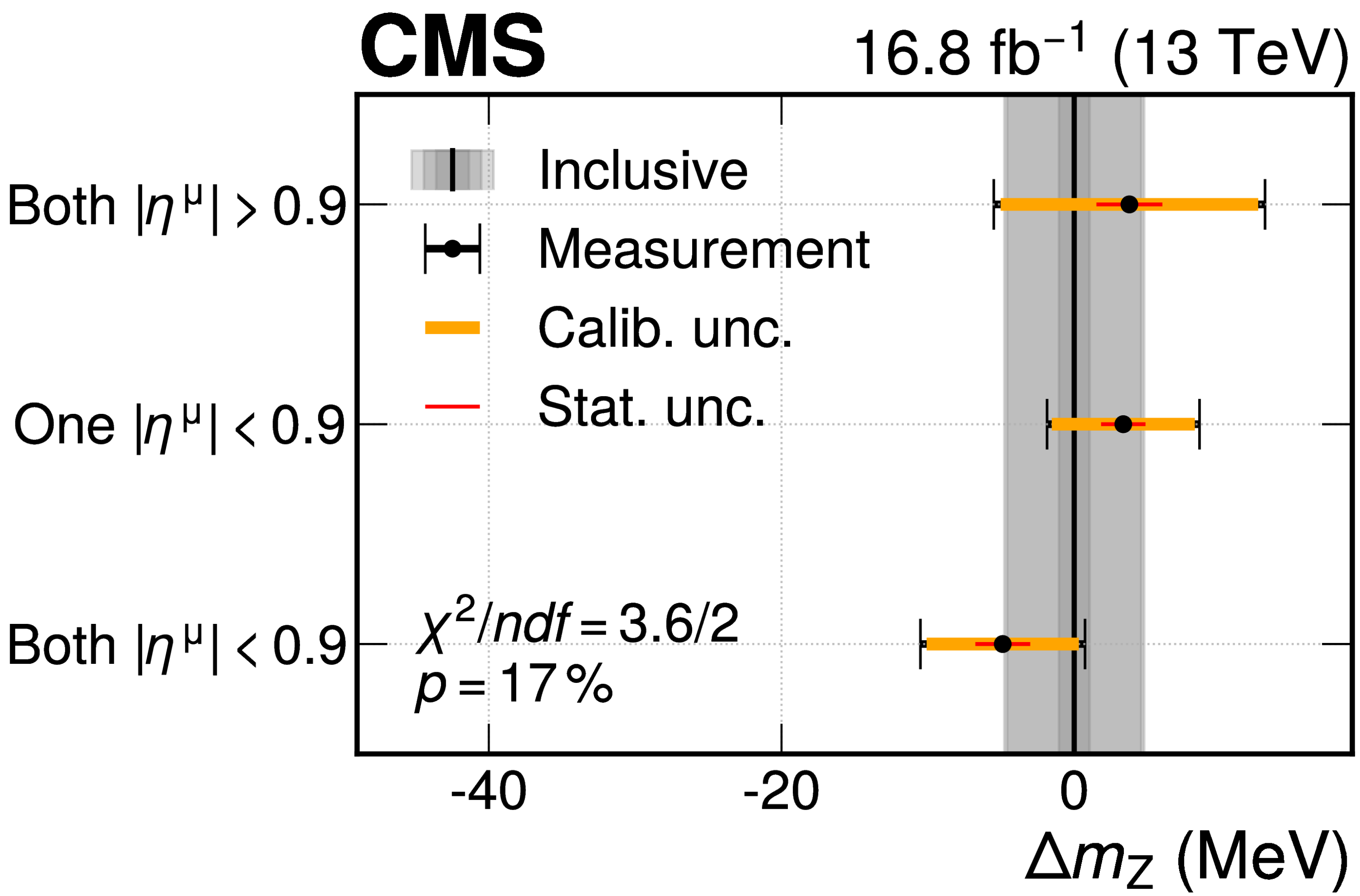


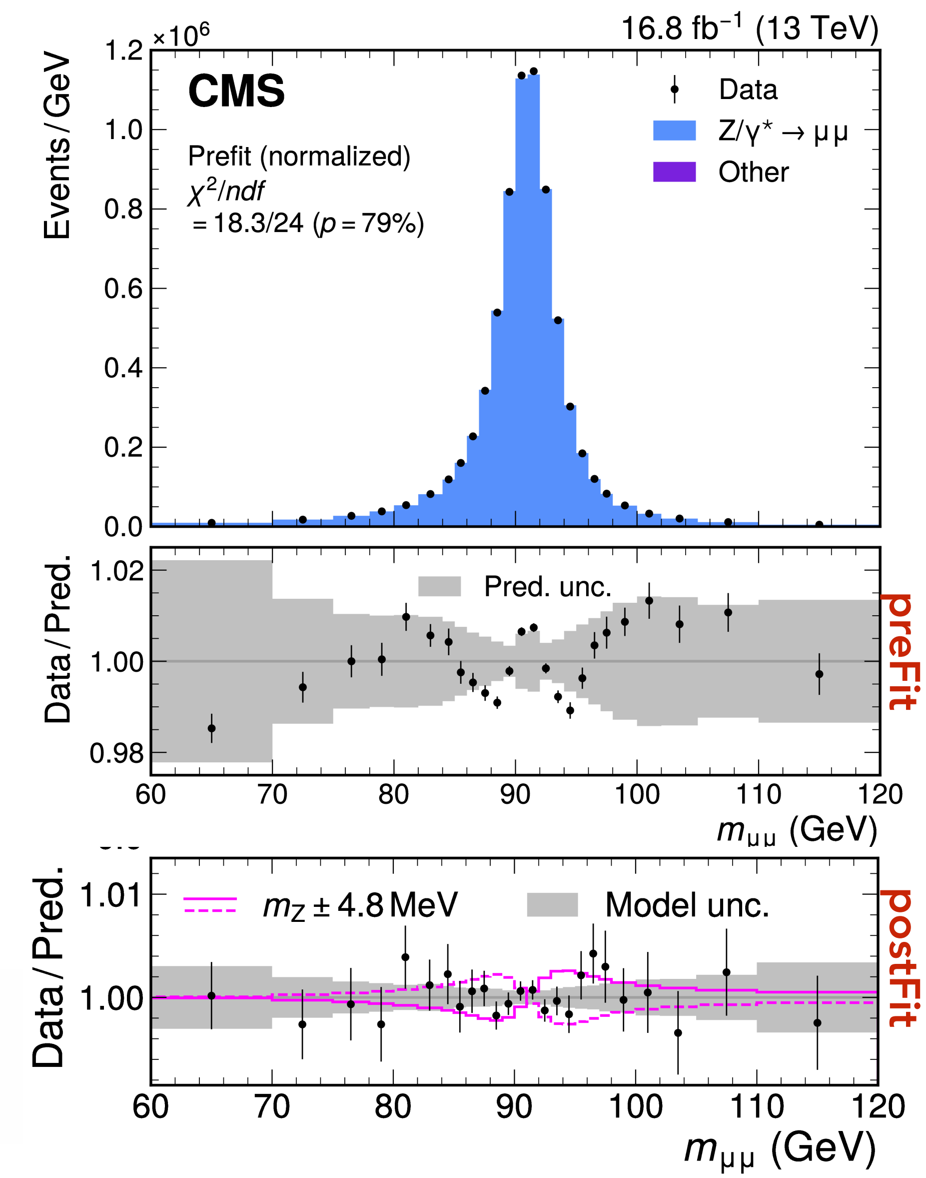
CVH refit+corr.

Z boson mass

Final validation of calibration uncertainties by extracting m_Z from the di-muon spectra → 2D profile-likelihood fit in $m_{\mu\mu}$:η

Since J/ψ vs Z closure was used to tune calibration and enters the uncertainty model, not (yet) a fully independent measurement for inclusion in world average.





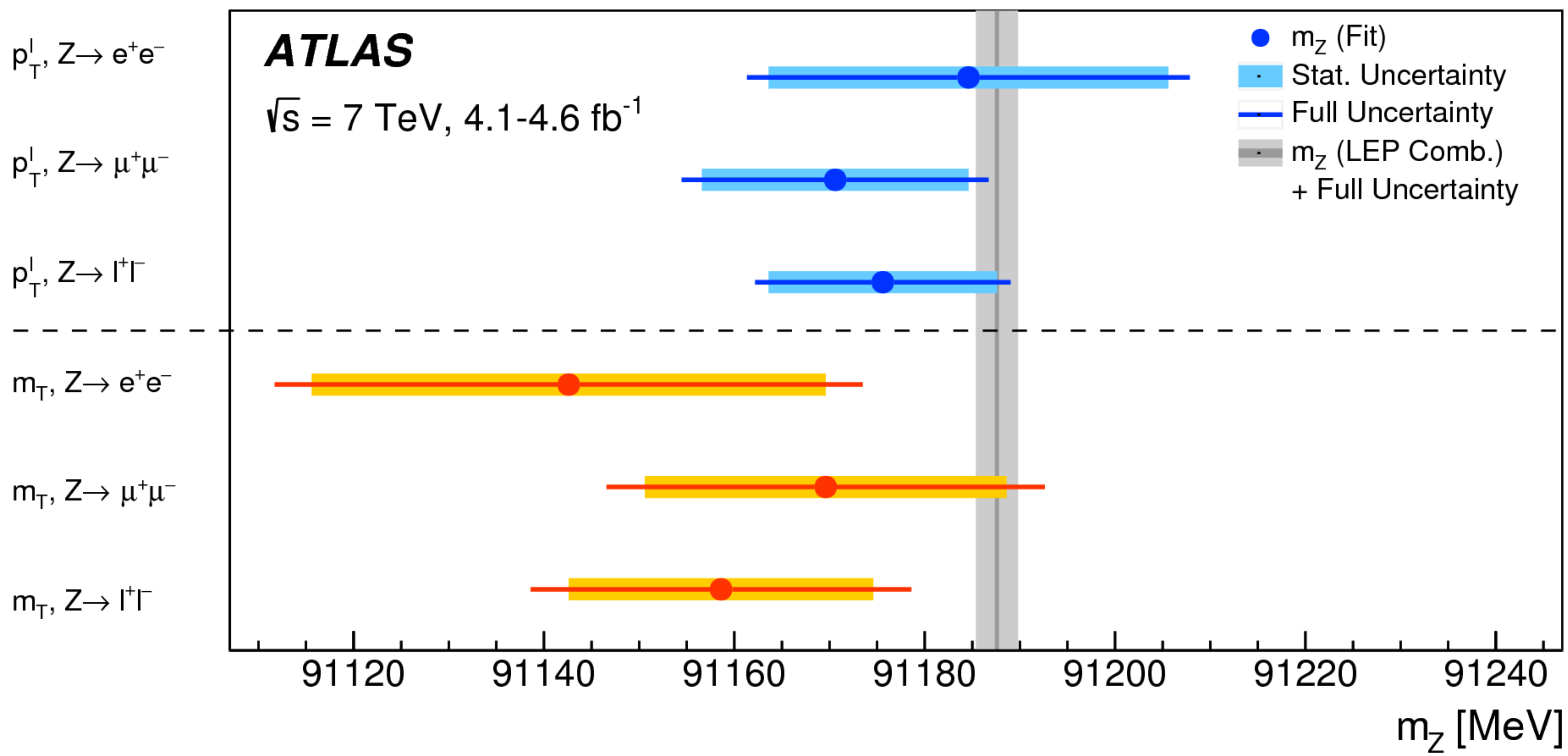
$$\mathbf{m_Z - m_Z^{PDG} = -2.2 \pm 4.8\ MeV} = -2.2 \pm 1.0\ (\text{stat}) \pm 4.7\ (\text{syst})\ \text{MeV}$$

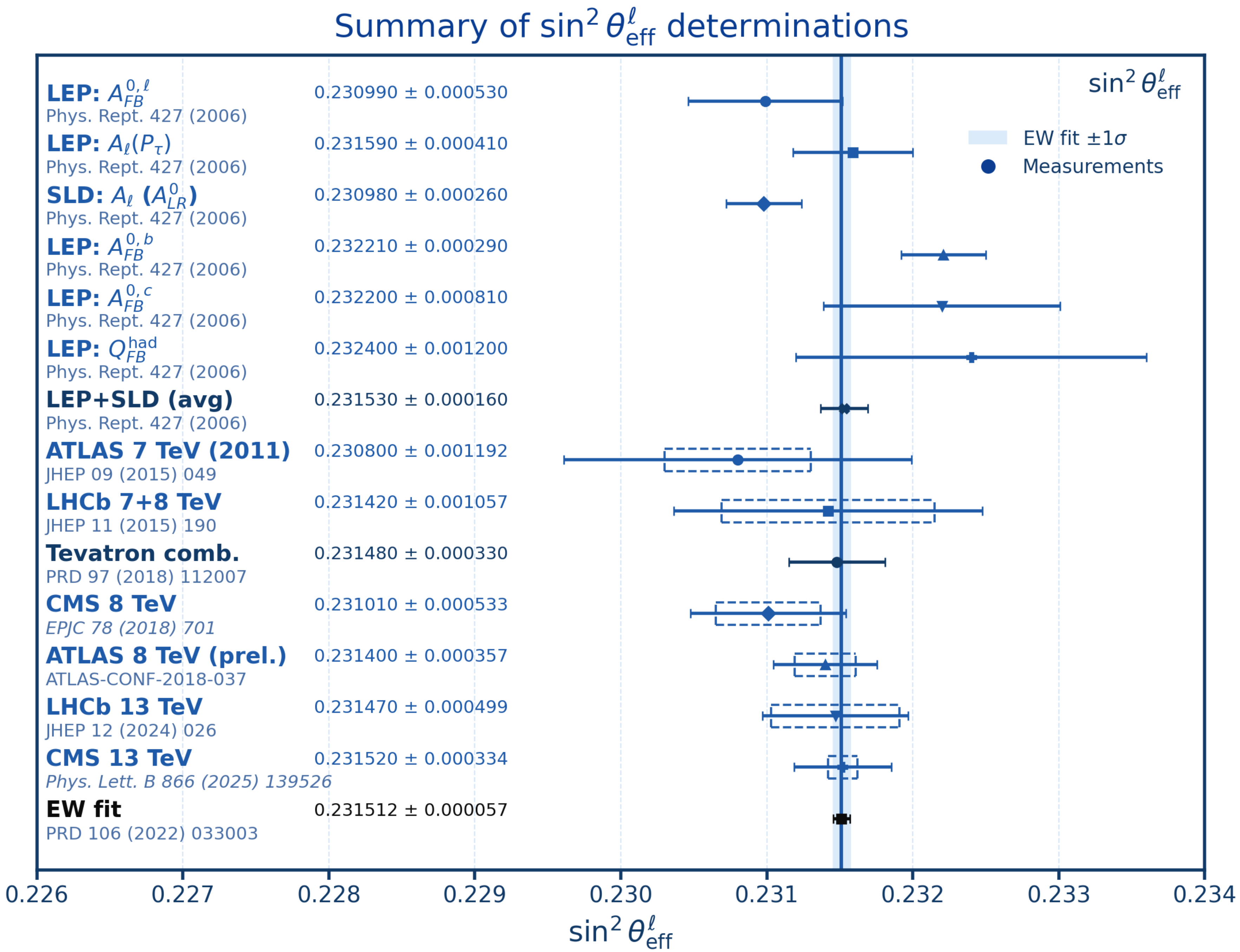
Great statistical sensitivity in CMS measurement

W-like sample with Z boson events

The measurement strategy is tested using Z-boson events to get a measurement of Mz.

- One of the charged leptons from Z-decay is treated as a neutrino
- The precision of this validation is limited by the Z-boson statistics, 10 times smaller than for W-boson





weak mixing angle

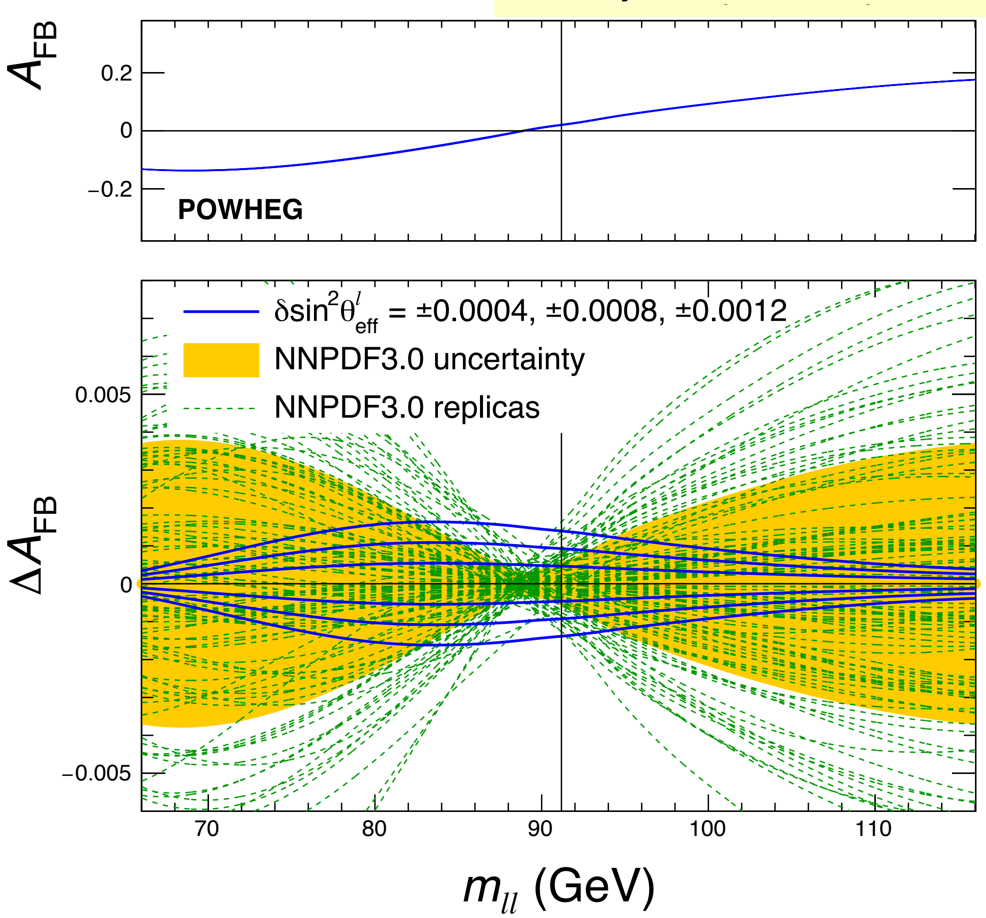
The weak mixing angle @LHC

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

κ are EW loop corrections

- ± 20x10^{-5} error in $\sin_{\text{eff}}^2\theta_W$ corresponds to ±10MeV error in m_W
  - another extremely powerful test of the EW sector of the SM.
  - another measurement quite challenging @LHC

Eur. Phys. J. C 78 (2018) 701



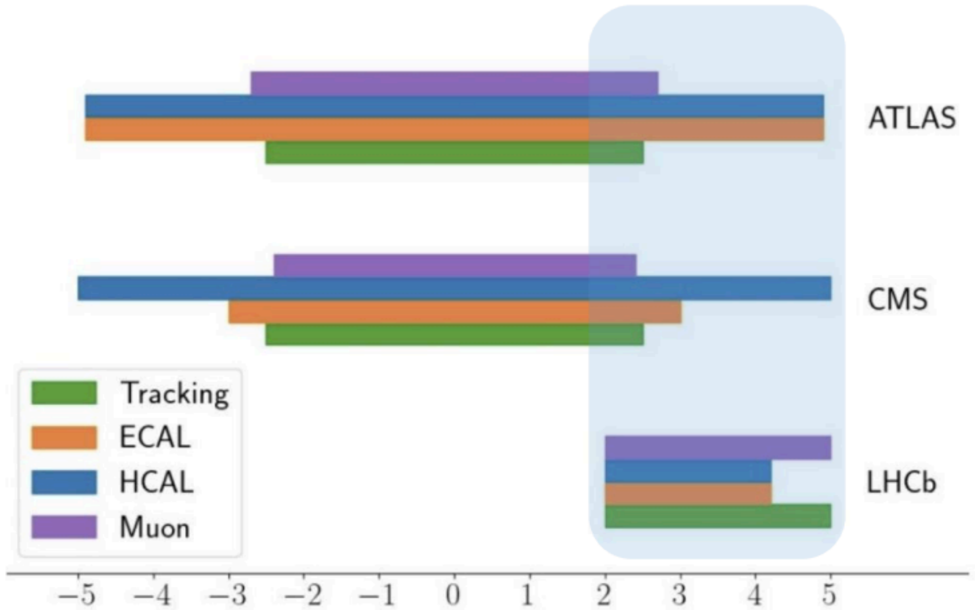
- $\sin_{\text{eff}}^2\theta_W$ extracted from forward-background asymmetry in DY events: AFB,A4 (extraction is done in m_{ll},y_{ll} bins)
- **Challenge:** strongly depends on PDF uncertainty.
  - At the **LHC** the colliding proton beams are FB symmetric → **the asymmetry vanishes at central rapidity, and grows as a function of rapidity**
    - Asymmetry largest at high y^Z where valence quark PDFs dominate at large x → ATLAS benefit from extending the acceptance of electron reconstruction for |η|>2.5.
  - also depend on quark flavour, so on relative contributions of u and d PDFs

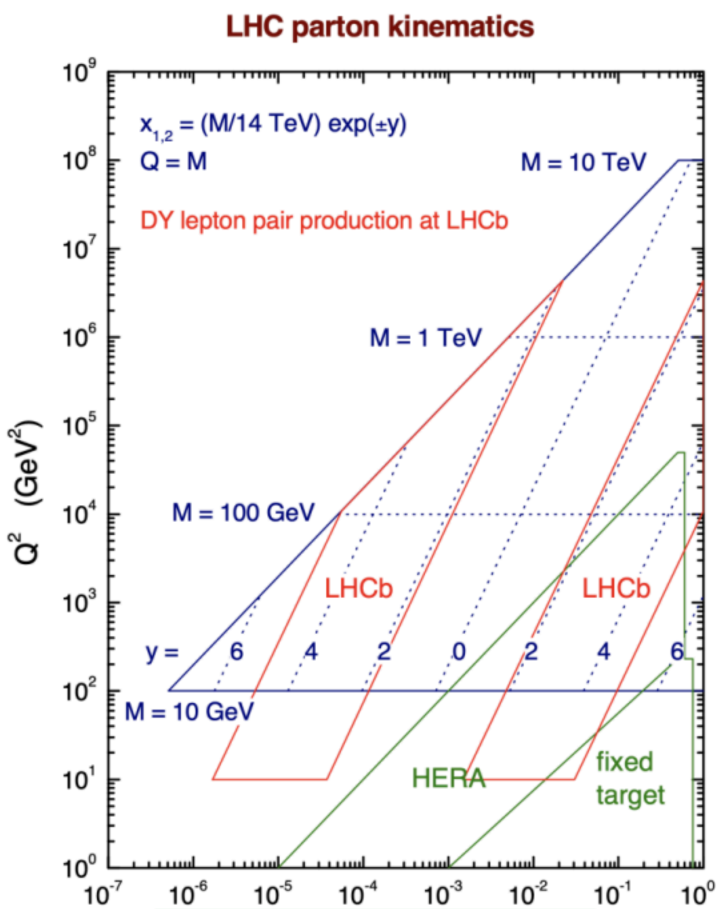
unique acceptance of LHCb

The $\boldsymbol{x}$ value of interacting partons is correlated with the boson rapidity Rapidity $y = \frac{1}{2} ln \frac{x_1}{x_2}$

- Large rapidity: either very large x or very small x

ATLAS/CMS and LHCb: complementary to each other





arXiv:0808.1847

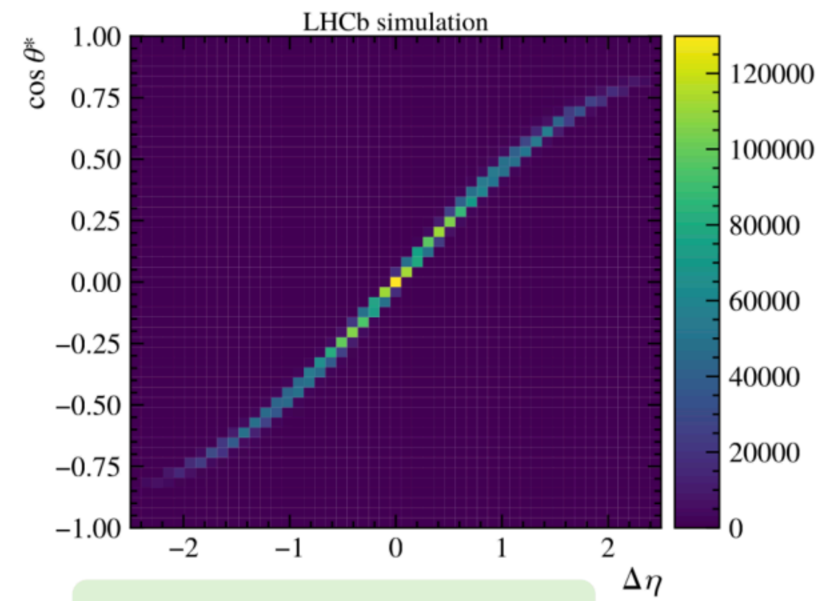
4

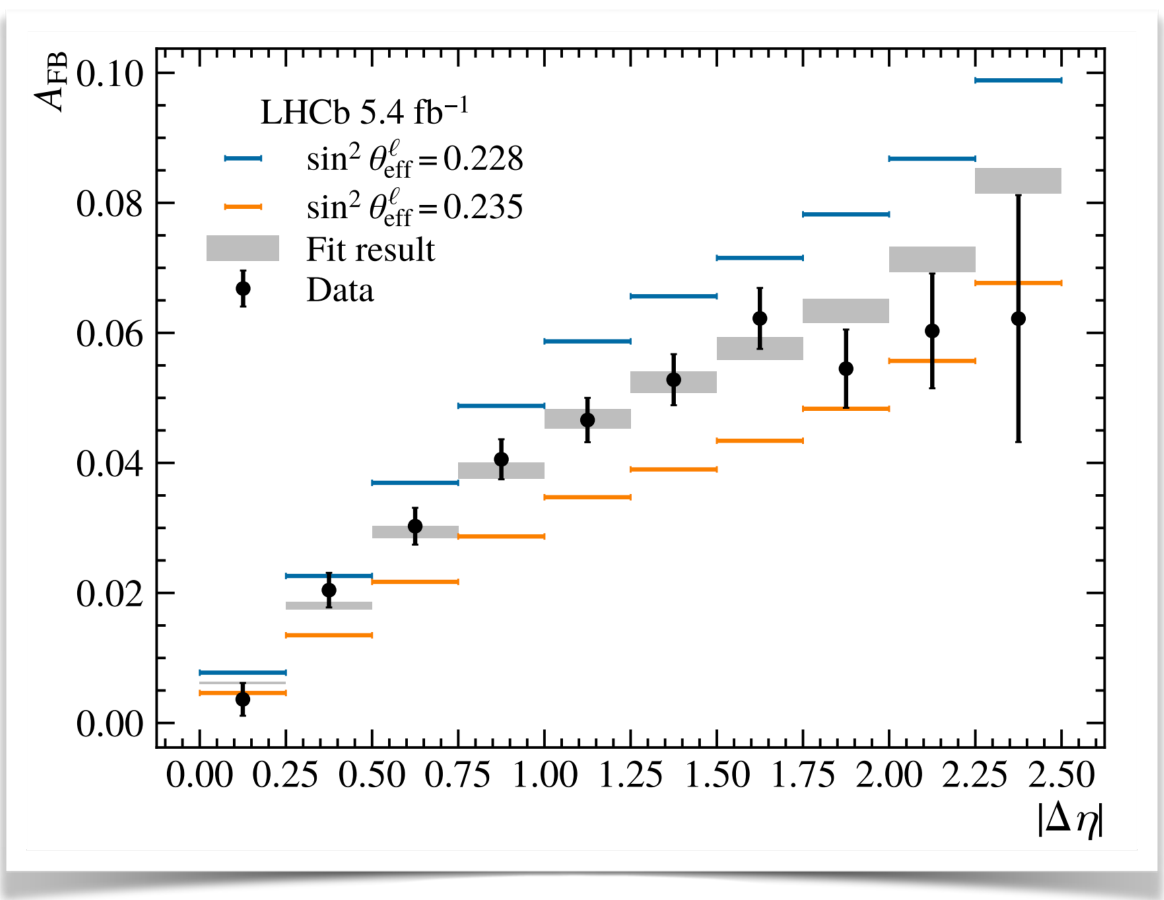
NB: PDF uncertainty are largely uncorrelated or anti-correlated between ATLAS-CMS and LHCb → highly beneficial for combination

LHCb

JHEP 13 (2024) 026

- small |cosθ*| mostly dilute the measurement
- $\cos\theta^* \sim \tanh(|\Delta\eta|/2)$, $\Delta\eta = \eta^- - \eta^+$
- **Improves the precision of the $sin^2\,\theta^{\ell}_{eff}$ measurement by 14% in simulation**





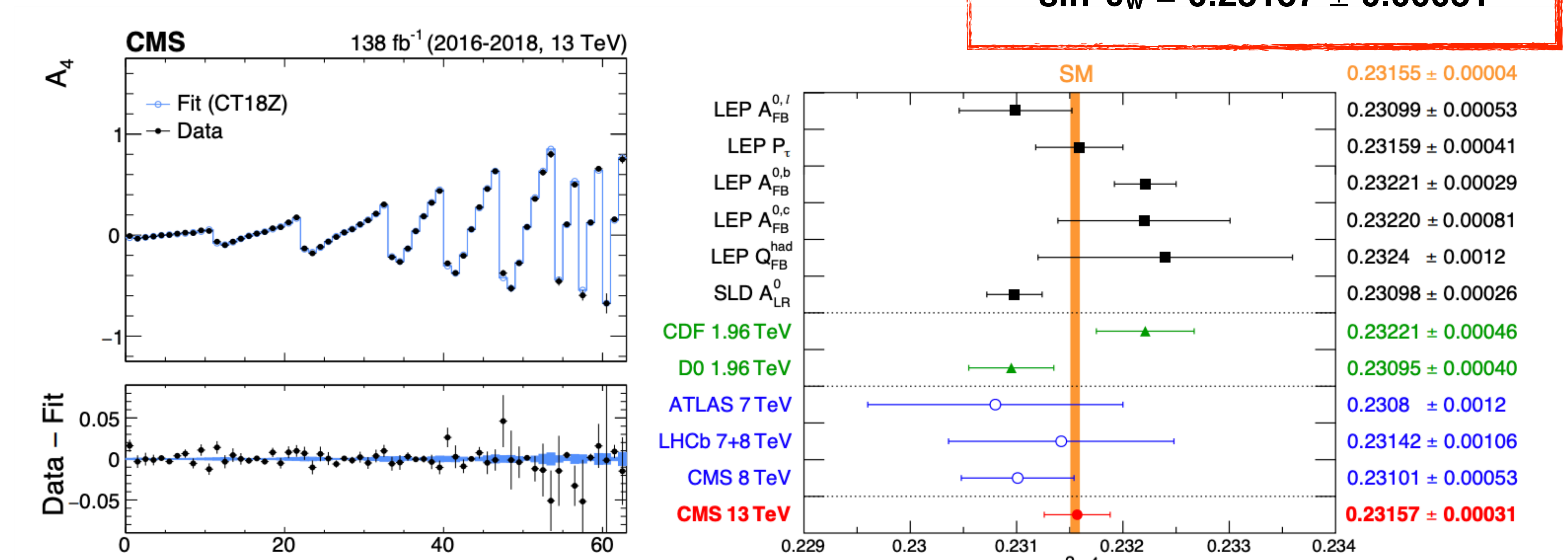
sin2tW 0.23147 ± 0.00044 (stat.) ± 0.00005 (syst.) ± 0.00023 (theory)

CMS

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

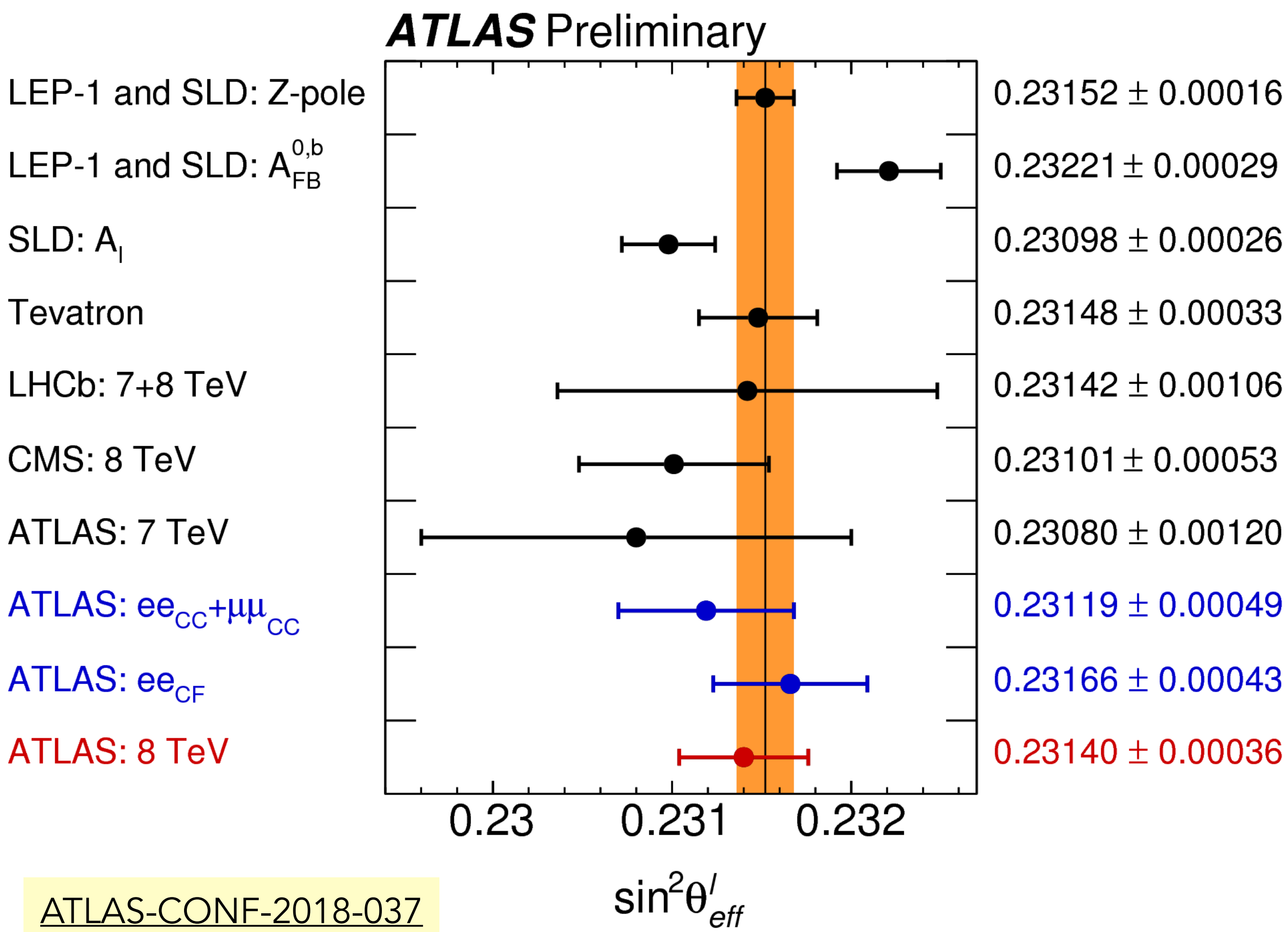
$\sin^2\theta_W = 0.23157 \pm 0.00031$



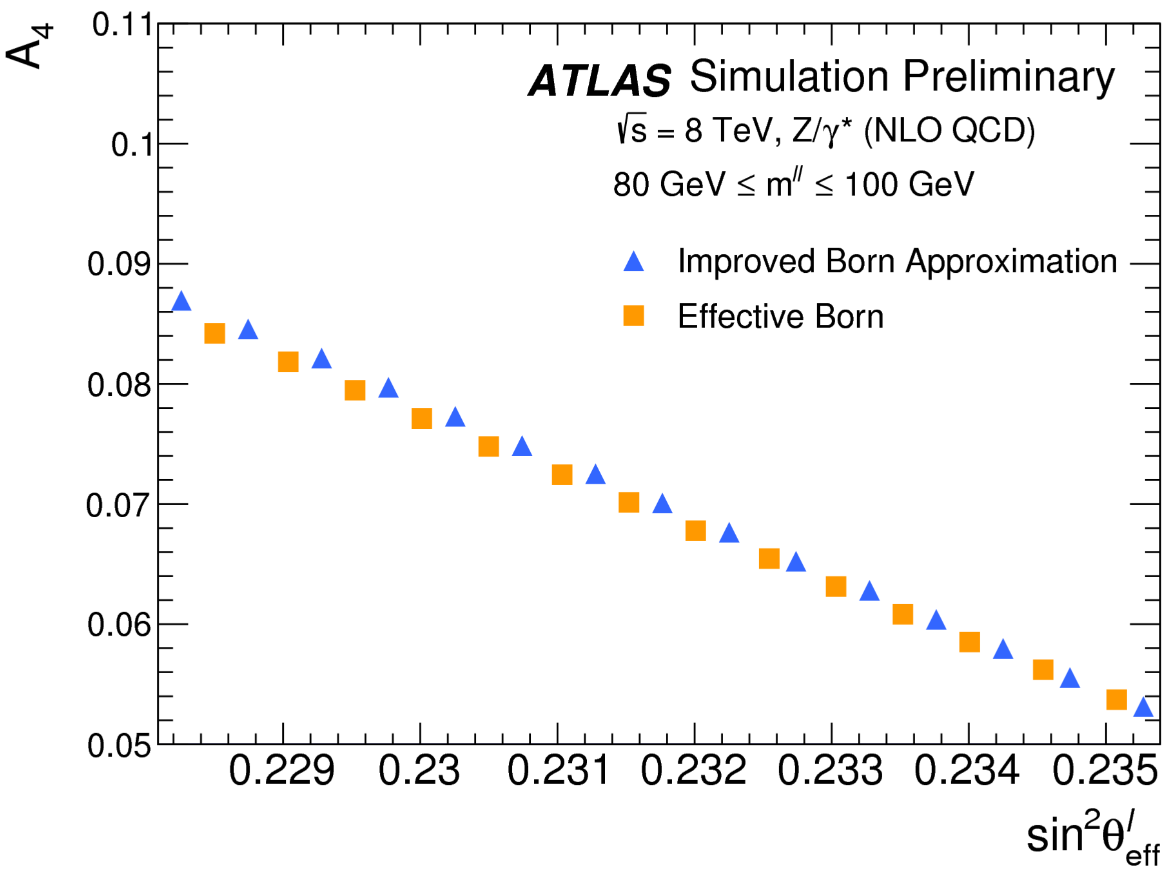
Phys. Lett. B 866 (2025) 139526

(*) PDF uncertainties are constrained in the interpretation exploiting their different dependence on mll, yll

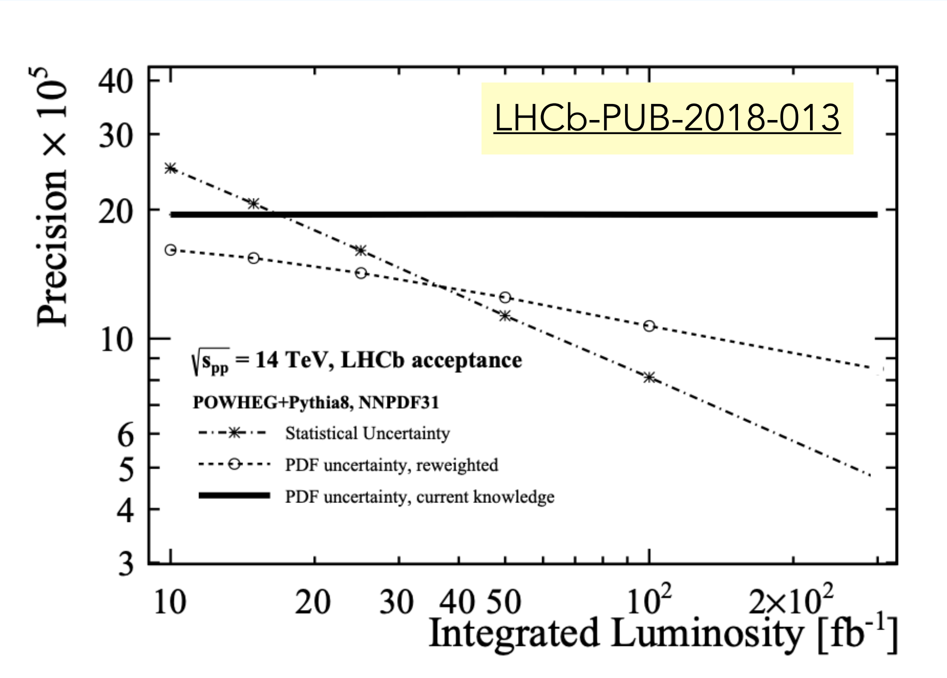
ATLAS

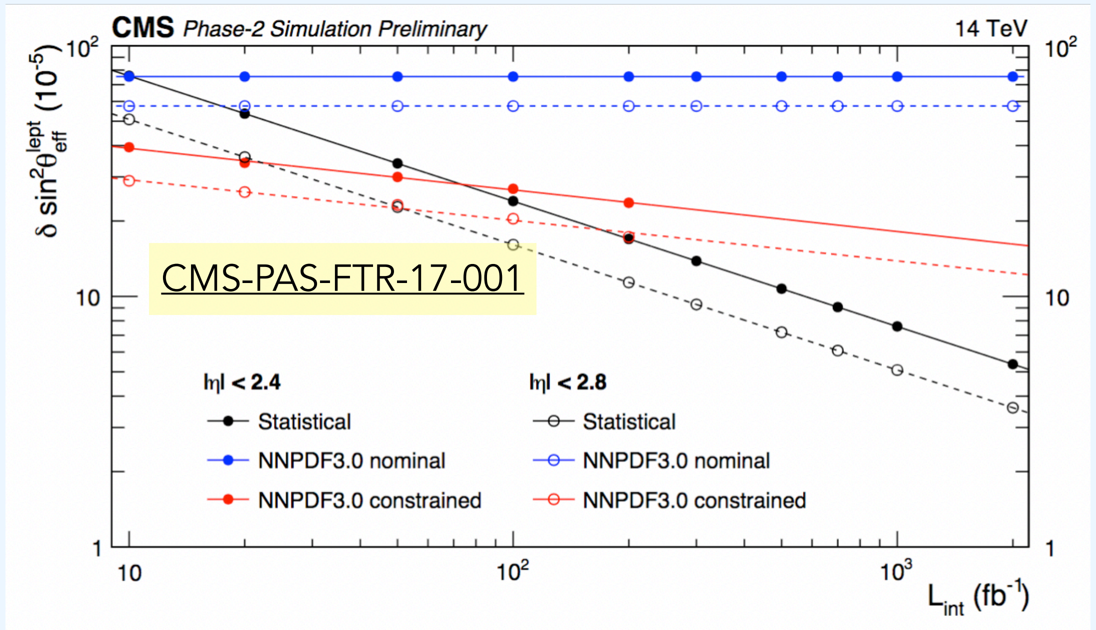


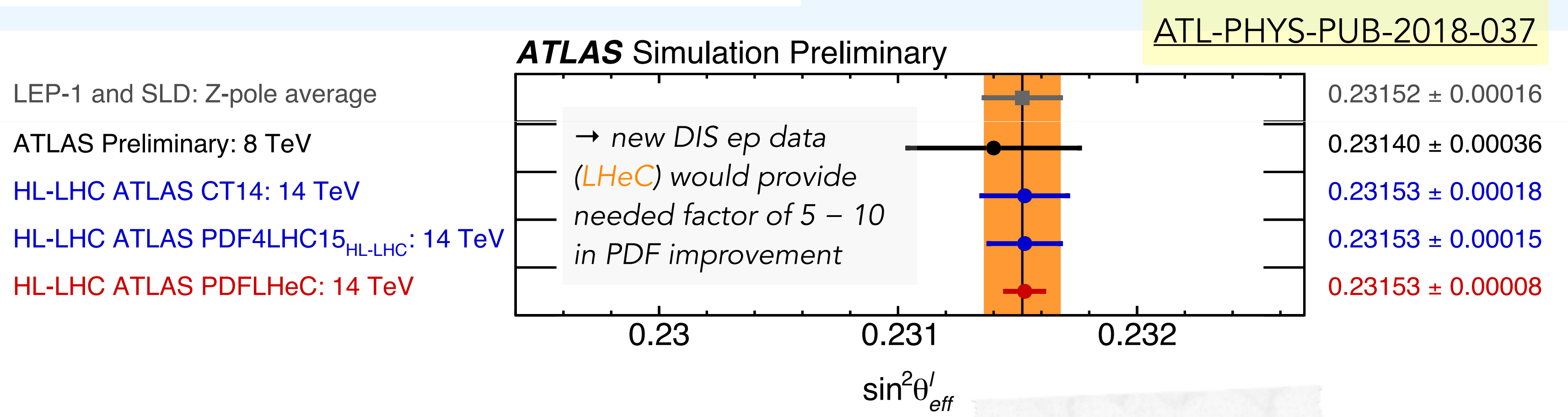
ATLAS-CONF-2018-037



$\sin^2\theta_W$ prospects studies







- LHC experiments officially entered the **precision electroweak race**: current measurement limited by PDF uncertainty
- PDFs and their uncertainties can not any longer be treated as a black box, need similar or even bigger scrutiny, in terms of uncertainty decomposition and correlations, as exp. uncertainties.

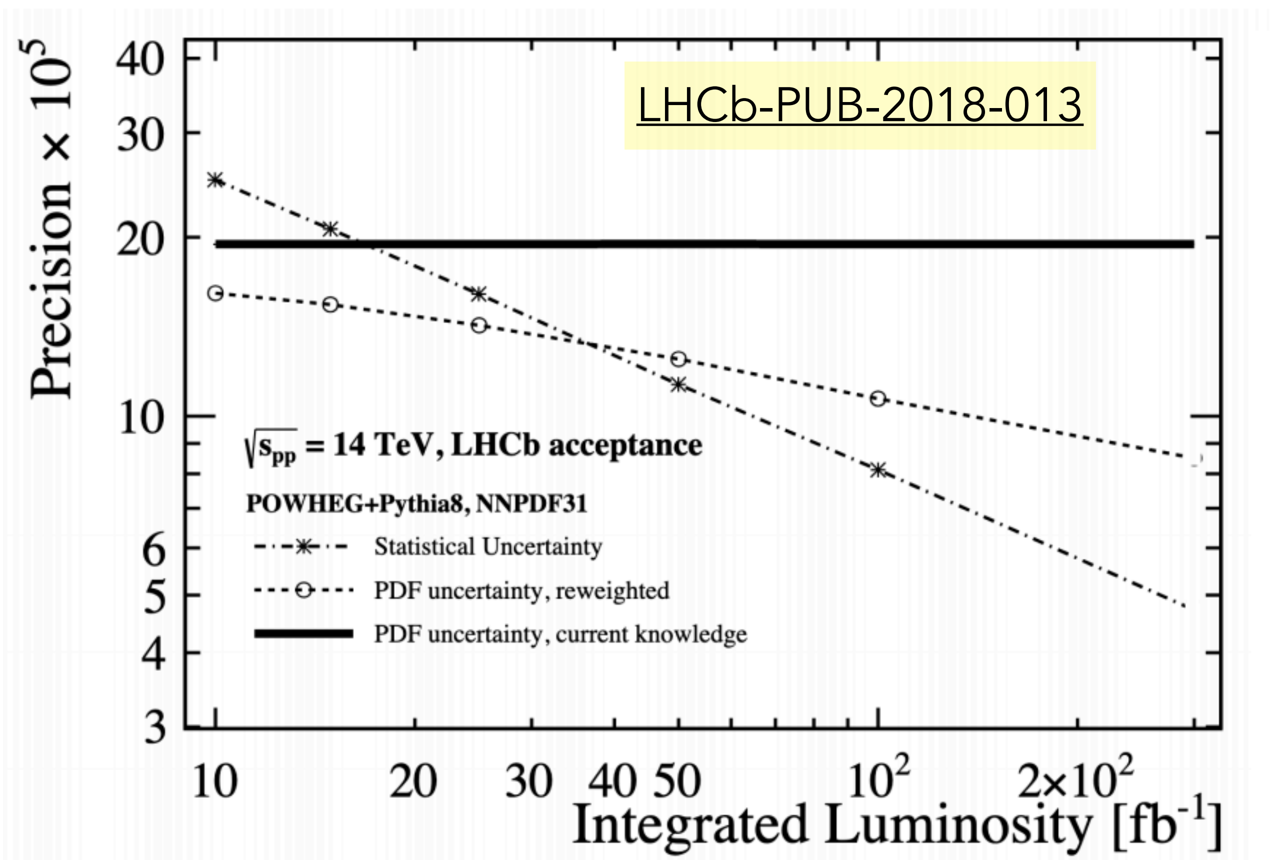
Towards LHC combination : Including **LHCb acceptance** (low dilution in forward region) offers a crucial handle by examining at precision a region where the PDF uncertainty is intrinsically small.

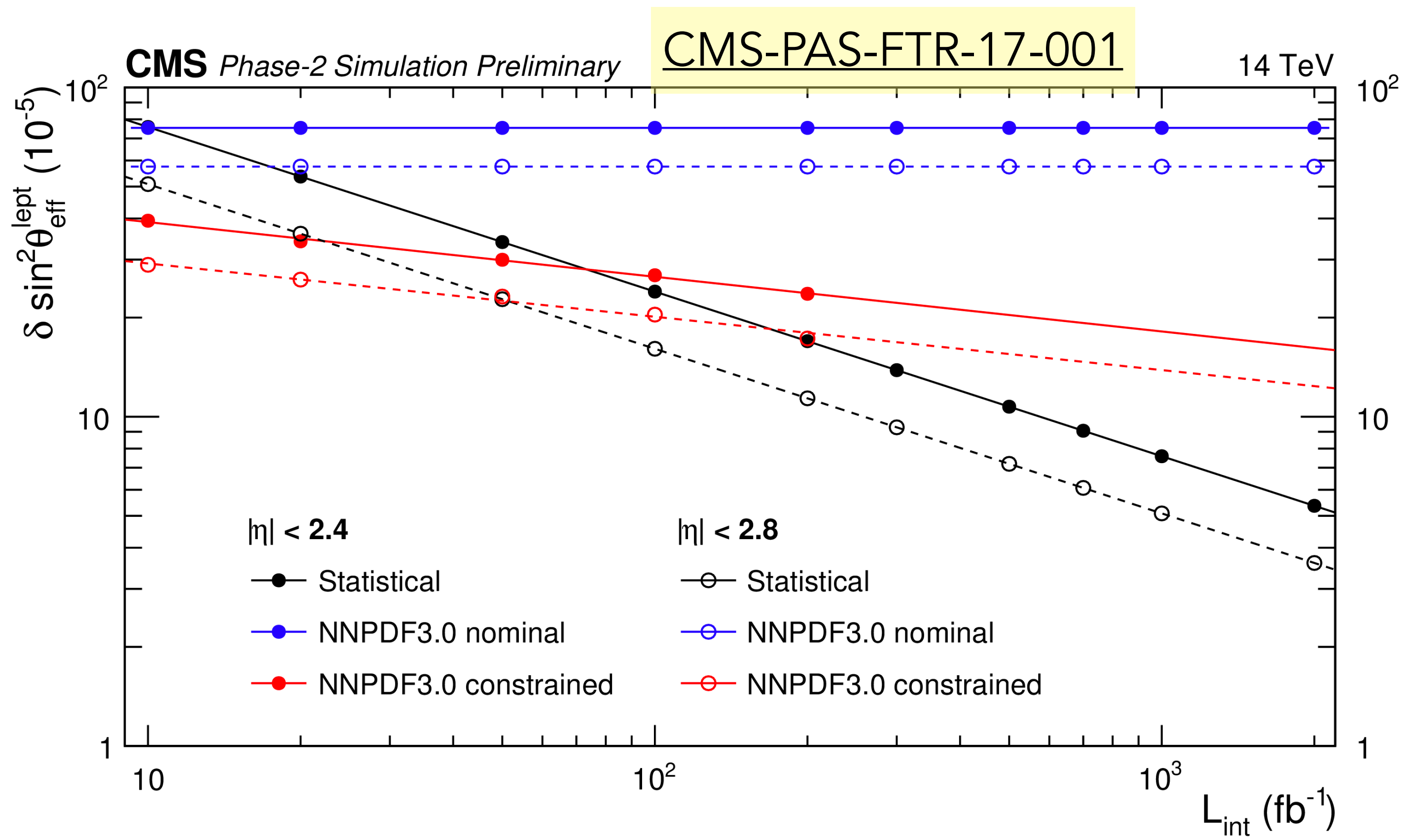
Work ongoing in **LHC-EW working group and PDF4LHC forum** to investigate:

- EW/QED NLO+h.o. accuracy corrections, benchmark NNLO and resummed calculations and uncertainties
- PDF differences and correlations

Weak mixing angle @HL-LHC

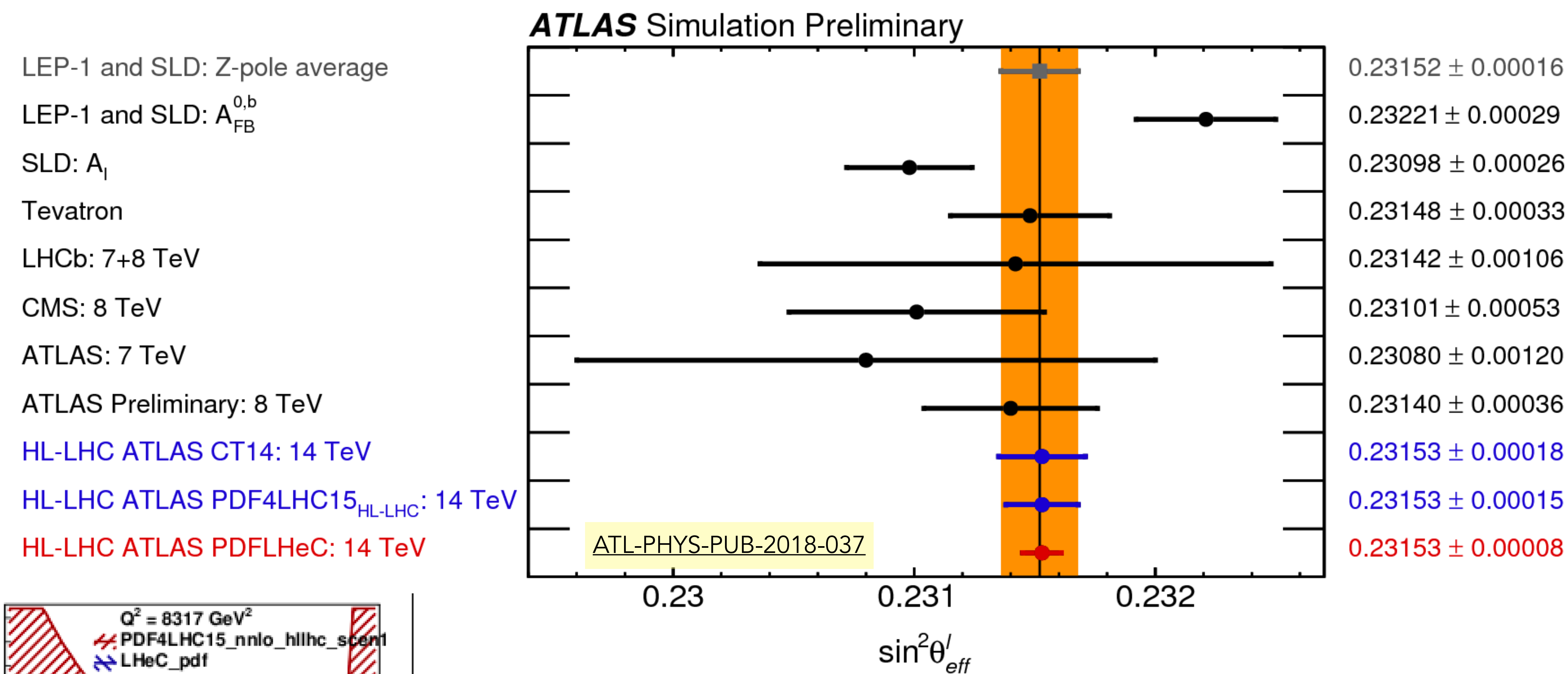
LHC experiments entered the precision electroweak race: New analysis techniques, including in-situ PDF profiling and event categorisation substantially reduced statistical and systematic uncertainties wrt previous LHC measurements.

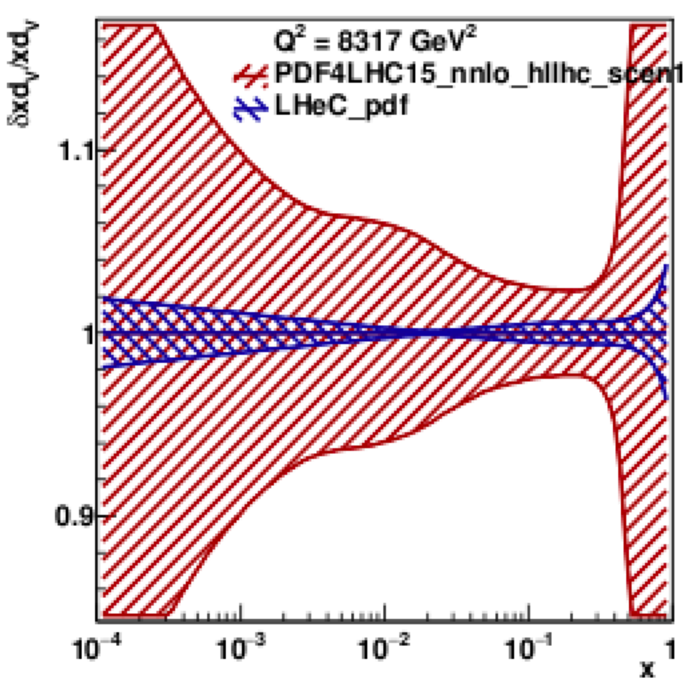




Current and future measurement at pp collider limited by PDF uncertainty

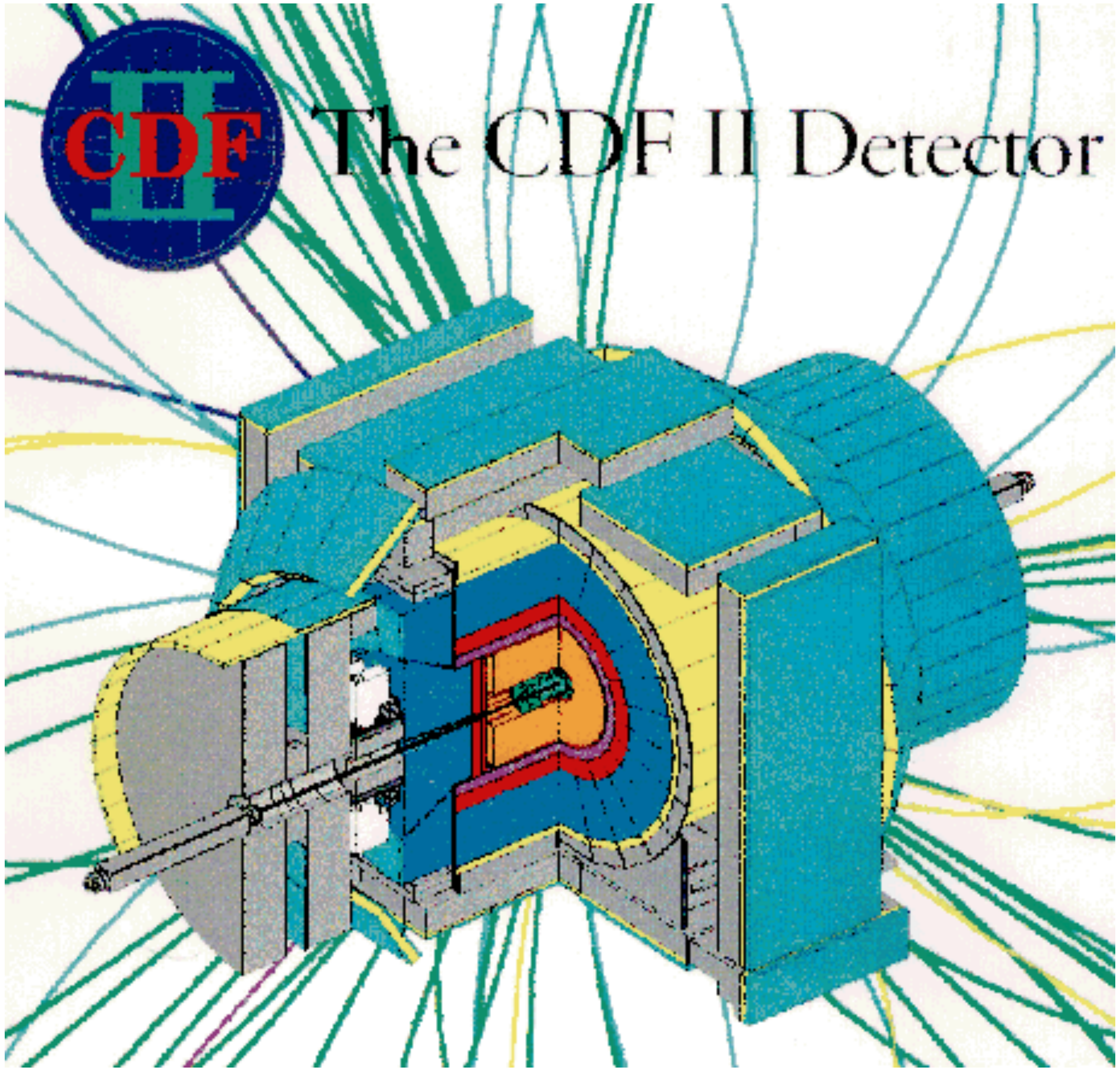
$\sin^2\theta_W$ extraction with LHeC data





The expected sensitivity of the $\sin^2\theta_{eff}$ measurements is improved by **~20% using HL-LHC data/PDF sets**.

→ new DIS ep data (LHeC) would provide needed factor of 5 – 10 in PDF improvement to **exceed LEP precision**

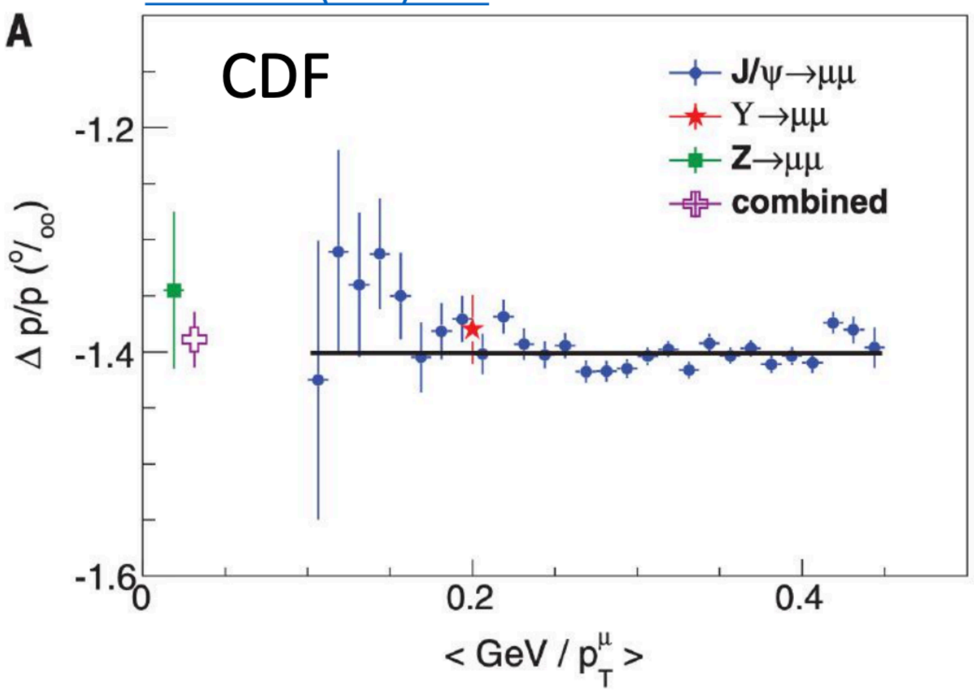


CDF II

Tevatron

CDF

Science 374 (2021) 6568



$m_Z = 91192.3 \pm 7.1$ MeV

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

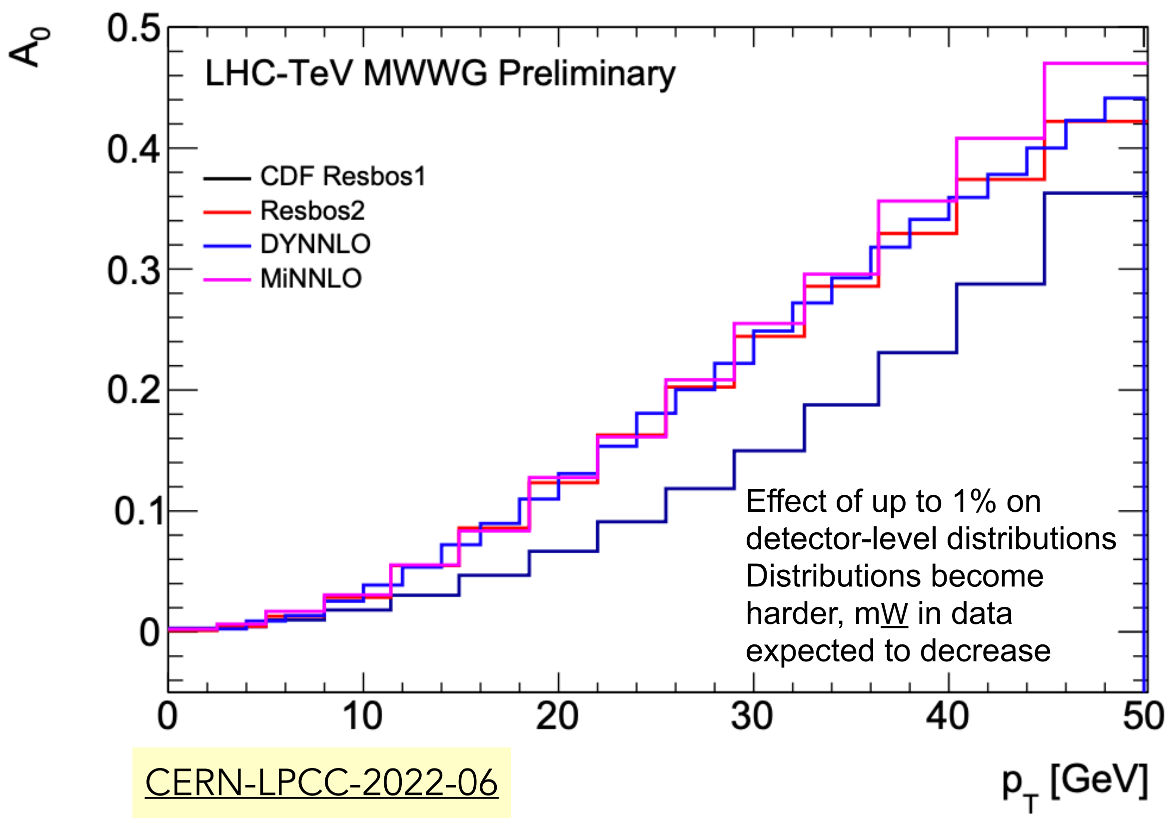
CDF has advantages from $p\bar{p}$, lower E, PU

- PDFs better understood (valence quarks)
- Less hadronic activity (simpler recoil calibration)
- Low tracking material aids lepton calibration

CDF

Several indications of potential bias in CDS measurement which require further studies

- Signal Modelling
- Z→μμ Background Modelling (up to 8 MeV)



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https://arxiv.org/pdf/2507.07835