Measurement of the W boson mass

Based on [2403.15085] (ATLAS) and [2412.13872] (CMS)

15th Course on Physics at the LHC

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LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
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Outline

Introduction

- **The W Boson:** Fundamental mediator of the weak force (e.g., nuclear beta decay).
- **Mass ($m_W \approx$ 80.4 GeV):** Dictates the range and strength of the weak interaction.
- **Width ($\Gamma_W \approx$ 2.1 GeV):** Directly linked to its extremely short lifetime ($\sim 3 \times 10^{-25}$ s) via the uncertainty principle.
- **LHC Production:** Primarily quark annihilation decaying into leptons ($q\bar{q}' \to W \to \ell\nu$).

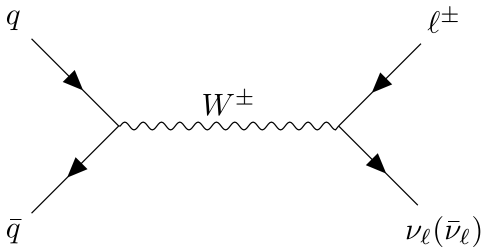

Figure 1: Dominant W boson production channel via quark-antiquark annihilation at the LHC.

Why Measure m_W?

- **Electroweak Consistency:** In the Standard Model, m_W is fundamentally tied to the core parameters m_Z, α, and G_F.
- **The Mass Relation:**

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

- **Quantum Loop Corrections:** The parameter Δr accounts for radiative corrections. It is highly sensitive to the top quark mass ($\Delta r \propto m_t^2$) and the Higgs boson mass ($\Delta r \propto \ln m_H$).

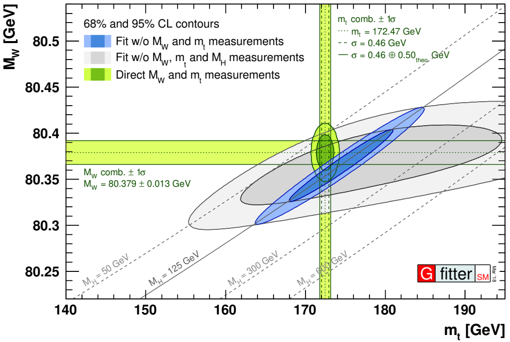

Figure 2: Global electroweak fit contour in the (m_t, m_W) plane, comparing indirect SM predictions (ellipse) with direct experimental measurements (bands).

The CDF Anomaly

- **2022 Result:** The CDF II collaboration (Tevatron) reported an ultra-precise measurement: $m_W = 80433.5 \pm 9.4$ MeV
- **Severe Tension:** This value stands in a sharp 7σ deviation from the Standard Model global electroweak fit prediction (80355 ± 6 MeV).
- **The Physics Crisis:** A discrepancy of this magnitude ($> 5\sigma$) strongly implies either unmodeled systemic effects or new heavy Beyond the Standard Model (BSM) physics.

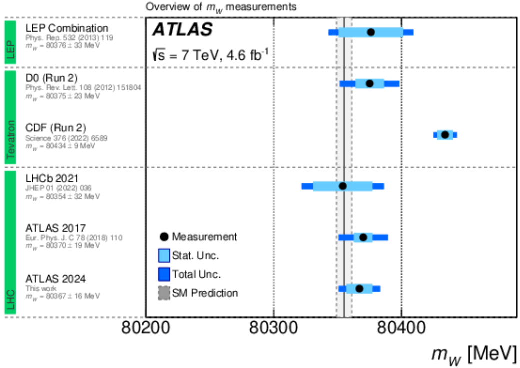

Figure 3: Comparison of historical and recent m_W measurements against the Standard Model prediction, highlighting the stark tension introduced by the CDF II result.

Measurement Strategy

The Jacobian Peak

- **Unreconstructable Mass:** Initial parton longitudinal momentum is unknown at a hadron collider, and the neutrino escapes undetected.
- **Transverse Mass Equation:**

$$m_T = \sqrt{2p_T^{\ell} E_T^{\text{miss}} (1 - \cos \Delta\phi)}$$

- **The Jacobian Edge:** The kinematic phase-space projection creates a sharp singular drop-off near m_W. This edge contains the maximum statistical sensitivity for extracting the mass.

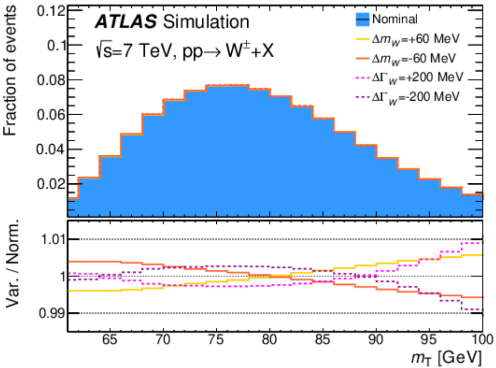

Figure 4: Simulated kinematic distributions of m_T in $W^{\pm} \to \mu^{\pm}\nu$ events, for W-boson mass and width values of $m_W = 80399$ MeV and $\Gamma_W = 2085$ MeV.

Statistical Approach - The Paradigm Shift

- **Legacy Method:** Previous measurements minimized a χ^2 distribution considering statistical errors only, adding systematic uncertainties a posteriori via the “offset” method.
- **Profile Likelihood:** The updated framework implements a global PLH fit to simultaneously optimize m_W or Γ_W across all event categories.
- **The Main Advantage:** Profiling allows systematic uncertainties to be constrained directly by the data, shrinking the total error margin.

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

Profiling & Template Morphing

- **Nuisance Parameters:** Systematics are embedded directly into the likelihood as nuisance parameters ($\vec{\theta}$) governed by Gaussian constraint terms.
- **Breit-Wigner Morphing:** Arbitrary mass and width templates are constructed dynamically by reweighting the underlying W-boson Breit-Wigner distribution.
- **Interpolation:** A polynomial morphing procedure handles interpolation between nominal and shifted systematic templates during the minimisation phase.

$$
\begin{aligned}
v_{ji}(\mu, \vec{\theta}) = \Phi \times \Big[S_{ji}^{\text{nom}} + \mu \times (S_{ji}^{\mu} - S_{ji}^{\text{nom}})\Big] \\
+ \sum_{s} \theta_s \times (S_{ji}^{s} - S_{ji}^{\text{nom}}) \\
+ B_{ji}^{\text{nom}} + \sum_{b} \theta_b \times (B_{ji}^{b} - B_{ji}^{\text{nom}})
\end{aligned}
$$

ATLAS

ATLAS Detector & Dataset

- **Data Sample:** 2011 proton-proton collisions collected at a center-of-mass energy of $\sqrt{s} = 7$ TeV, corresponding to 4.6 fb^{-1} (electron channel) and 4.1 fb^{-1} (muon channel).
- **Low-Pileup Advantage:** Characterized by an exceptionally low average interaction rate ($\langle \mu \rangle \approx 9$) per bunch crossing.
- **Hadronic Recoil Resolution:** Low pileup is critical for precise resolution of the soft recoil vector.
- **Subdetector Systems:** Reconstructed using the Inner Detector tracking systems, LAr EM calorimeters, and the Muon Spectrometer.

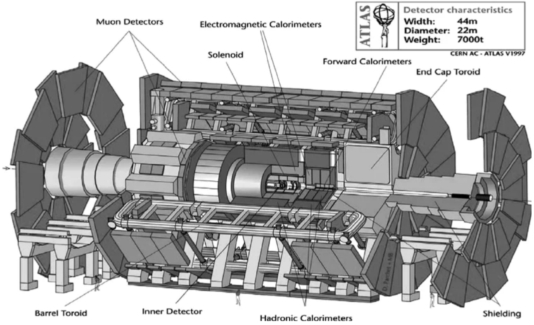

Figure 5: Schematic view of the ATLAS detector.

ATLAS Event Selection & Signatures

Leptonic Topologies

- Targets clean $W \to e\nu$ and $W \to \mu\nu$ decay modes to heavily suppress massive QCD multi-jet backgrounds.

Neutrino Signature

- Reconstructed from single isolated high-momentum tracks balanced by a large missing transverse momentum vector ($\vec{p}_T^{\text{miss}}$).

Enormous Dataset

- **Electron Channel:** $\approx 5.89 \times 10^6$ events
- **Muon Channel:** $\approx 7.84 \times 10^6$ events

Selection Thresholds

Lepton $p_T^\ell > 30$ GeV

Missing $p_T^{\text{miss}} > 30$ GeV

Transverse Mass $m_T > 60$ GeV

Max Recoil $u_T < 30$ GeV

Calibration & Uncertainties

- **Lepton Scale Anchoring:** Precision lepton energy/momentum scales are calibrated in-situ using massive $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ control samples.
- **Hadronic Recoil Tuning:** The soft hadronic recoil vector ($\vec{u}_T$) mimics the neutrino's missing momentum. It is calibrated using the transverse momentum balance against $p_T^{\ell\ell}$ in Z events to fix detector resolution.
- **Efficiency Mapping:** Detailed lepton trigger, reconstruction, isolation, and identification efficiencies are extracted from data using strict tag-and-probe methods.
- **Uncertainty Reduction:** The global profile likelihood fit maps over 100 systematic variations to uncorrelated nuisance parameters, allowing data to constrain the errors.
- **Experimental Drivers:** Dominant errors stem from tracking/muon alignment, electron calorimeter energy calibration, and hadronic recoil system scale variations.
- **Modeling & Theory:** Large impacts arise from Parton Distribution Functions (PDFs), electroweak corrections, and theoretical QCD factorization/renormalization scales.

ATLAS m_W Result

- **Baseline Measurement:** The finalized combined mass result using the standard CT18 PDF set is extracted as:

$$m_W = 80366.5 \pm 15.9 \text{ MeV}$$

- **Error Decomposition:** The result achieves unprecedented precision at the LHC, split into:
  - **Statistical Error:** ± 9.8 MeV
  - **Systematic Error:** ± 12.5 MeV
- **Mass-Width Cross-Dependence:** The fit assumes the SM value for the width ($\Gamma_W^{SM} = 2088 \pm 1$ MeV). Changing this baseline shifts the mass minimally via:

$$\Delta m_W = -0.06\, \Delta\Gamma_W$$

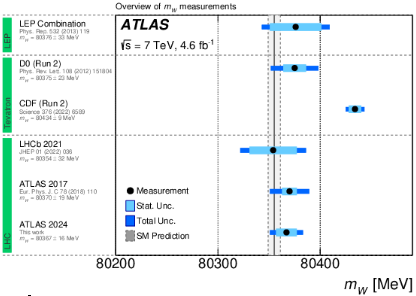

Figure 6: Comparison of m_W results. The new ATLAS measurement aligns perfectly with the SM electroweak fit, resolving the CDF II tension.

ATLAS m_W Result

- **Standard Model Compatibility:** Fully compatible with the global electroweak fit prediction (80355 ± 6 MeV) and historical LEP combinations.
- **The CDF Anomaly:** Aligns closely with the SM expectation, strongly challenging the tension created by the ultra-high CDF II result (80433.5 ± 9.4 MeV).
- **Superseding Legacy Work:** Profiling and updated PDFs reduce the total uncertainty of the original 2017 ATLAS publication from 19 MeV down to 16 MeV.

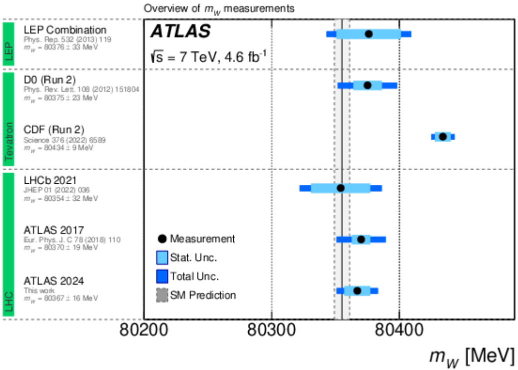

Figure 7: Comparison of m_W results. The new ATLAS measurement aligns perfectly with the SM electroweak fit, resolving the CDF II tension.

ATLAS Γ_W Result

- **First LHC Measurement:** Marks the historic first direct measurement of the W-boson width using LHC data.
- **The Central Value:** Extracted using the baseline CT18 PDF set:

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

- **Error Decomposition:** Highly balanced statistical and systematic error bars:
  - **Statistical Error:** ± 32 MeV
  - **Systematic Error:** ± 34 MeV
- **Mass Fit Dependency:** The width fit relies on fixing the mass parameter to the SM value ($m_W^{SM} = 80355 \pm 6$ MeV). Deviations scale strongly via:

$$\Delta\Gamma_W = -1.25\,\Delta m_W$$

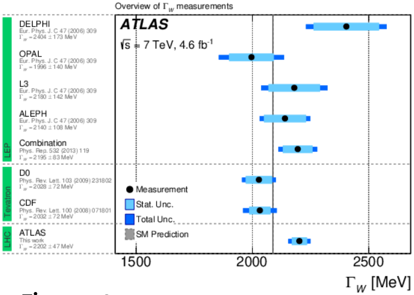

Figure 8: The final ATLAS Γ_W result compared against historical world measurements and the Standard Model expectation.

Simultaneous $m_W + \Gamma_W$

- **Unconstrained Approach:** Both parameters float freely at the same time, completely removing the model-dependent constraints used in the standalone fits.
- **Combined 2D Fit Results:** Using the baseline CT18 PDF set, the global multi-distribution combination yields:

$$m_W = 80354.8 \pm 16.1 \text{ MeV}$$

$$\Gamma_W = 2198 \pm 49 \text{ MeV}$$

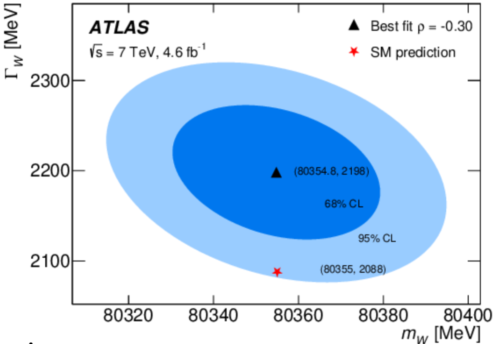

Figure 9: The 68% and 95% CL uncertainty contours for the simultaneous determination of m_W and Γ_W combining the p_T^ℓ and m_T distributions.

CMS

CMS Detector & Dataset

- **Superconducting Solenoid:** Houses a massive 3.8 T magnet enclosing both the inner tracker and the calorimeter systems.
- **All-Silicon Tracker:** High-granularity pixel and strip layers providing exceptional track reconstruction and vertex resolution.
- **Muon Spectrometer:** Interleaved within the iron return yoke using DT, CSC, and RPC systems for clean muon identification.
- **Homogeneous ECAL:** Uses high-density lead tungstate ($PbWO_4$) crystals to deliver premier electron and photon energy resolution.

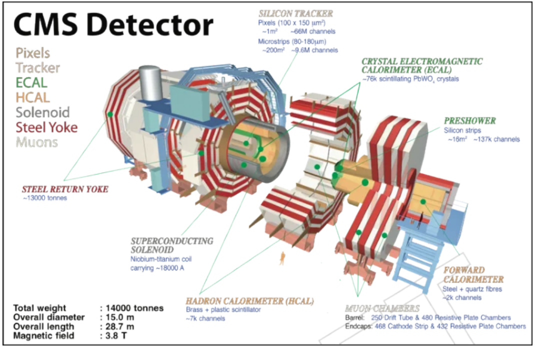

Figure 10: Schematic view of the CMS detector.

CMS Detector & Dataset

- **Center-of-Mass Energy:** Analyzes a targeted proton-proton collision sample recorded at $\sqrt{s} = 13$ TeV during the 2016 running period.
- **Pileup Profile:** Operates in a controlled, moderate pileup environment with an average interaction rate of $\langle \mu \rangle \approx 25$ per bunch crossing (with a tail extending up to 44).
- **Advanced Particle Flow:** Leverages the global Particle-Flow algorithm to reconstruct the soft hadronic recoil vector ($\vec{u}_T$) by combining information from all subdetectors, successfully overcoming the severe pileup noise.

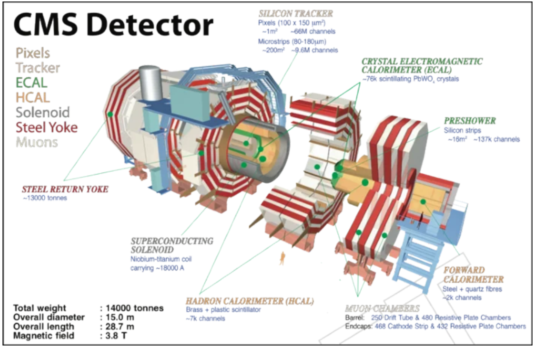

Figure 11: Schematic view of the CMS detector.

CMS Event Selection & Signatures

Leptonic Topologies

- Focuses strictly on the $W \to \mu\nu$ decay mode to exploit the maximum track precision of the all-silicon tracking system.

Neutrino Signature

- Evaluates the invisible neutrino kinematics using advanced data-driven tracker isolation and high-pileup vertex reconstruction algorithms.

Enormous Dataset

- **Muon Channel:** $\approx 117 \times 10^6$ events
- **Statistical Advantage:** One of the world's largest data sample ever recorded for a single W-boson kinematic distribution.

Selection Thresholds

Muon p_T^μ	$\in [26, 56]$ GeV
Acceptance $\lvert\eta^\mu\rvert$	< 2.4
Transverse Mass m_T^W	> 40 GeV
Trigger p_T^μ	> 24 GeV

Muon Momentum Calibration

Primary Calibration Anchor

- Reconstructed track curvatures are calibrated exclusively using high-statistics samples of $J/\psi \to \mu^+\mu^-$ resonance decays.

The Extrapolation Problem

- J/ψ decays calibrate low-p_T muons (a few GeV), but W decays sit near 40 GeV. Transferring resolution corrections across this range, where multiple scattering shifts drastically, is the dominant residual challenge.

Extrapolation Validation

- $Z \to \mu^+\mu^-$ and $\Upsilon(1S) \to \mu^+\mu^-$ channels are strictly treated as independent cross-checks to validate the momentum scale across a wide kinematic range.

Calibration Parameters

Primary Calibration Sample	$J/\psi \to \mu^+\mu^-$
Validation Samples	$\Upsilon(1S) \to \mu^+\mu^-$ $Z \to \mu^+\mu^-$
Reconstruction	Silicon tracker only
Impact on m_W	$\pm$ 4.8 MeV

CMS In-Situ Theory Constraints

Theory Challenges at 13 TeV

- Higher collision energies heavily amplify theoretical modeling uncertainties originating from Parton Distribution Functions (PDFs) and missing higher-order QCD corrections on the p_T^W spectrum.

Direct W-Data Profiling

- Rather than correcting the p_T^W prediction using Z boson data, CMS profiles the p_T^W spectrum directly from the $W \to \mu\nu$ sample itself within the maximum-likelihood fit.

$Z \to \mu^+\mu^-$ as Closure, Not Input

- The precise $Z \to \mu^+\mu^-$ measurement is used strictly to validate the theoretical modeling and uncertainty framework, but it never directly reweights or modifies the primary W-boson signal templates.

Constraints Framework

Primary Challenge	PDFs and QCD Scales
Constraint Source	$W \to \mu\nu$ Data (in-situ)
Fit Strategy	In-Situ Profiling
$Z \to \mu\mu$ **Role**	Closure/validation only

CMS 3D Fit & Validation

The 3D Fit Machinery

- **The 3D Fit Observables:** Instead of basic 1D histograms, CMS aggregates data and simulation into a highly granular 3D distribution mapping muon track momentum (p_T^μ), pseudorapidity (η^μ), and electric charge (q^μ).
- **High-Granularity Grid:** The distribution is divided into 48 spatial η^μ bins, 30 momentum p_T^μ bins, and 2 charge categories, producing exactly 2880 unrolled analysis bins.
- **Computational Engine:** Built using the TensorFlow framework with automatic differentiation, allowing the fit to handle approximately 4000 nuisance parameters simultaneously.

Validation & Control Channels

- **Standard Dimuon Mass Check:** Directly extracts the Z boson mass (m_Z) from the $Z \to \mu^+\mu^-$ invariant mass peak to validate baseline track reconstruction and absolute scale calibrations.
- **The "W-like" Z Measurement:** Drops one of the two muons from a real Z decay and treats it as an invisible neutrino to perfectly mimic the experimental limits of the W analysis channel.
- **LEP World-Average Closure:** Proving that both measurements yield flawless mathematical consistency with the legacy LEP world-average m_Z value anchors the entire extraction framework.

CMS m_W Result

- **Final Measured Value:** 80360.2 $\pm$ 9.9 MeV. Split into an ultra-precise statistical error of $\pm$2.4 MeV and a systematic envelope of $\pm$9.6 MeV.
- **Standard Model Validation:** Exhibits flawless compatibility with the global Electroweak Fit prediction of 80353 $\pm$ 6 MeV.
- **The CDF Discrepancy:** Directly challenges and strongly disagrees with the anomalously high mass value reported by the CDF II Collaboration (80433.5 $\pm$ 9.4 MeV).

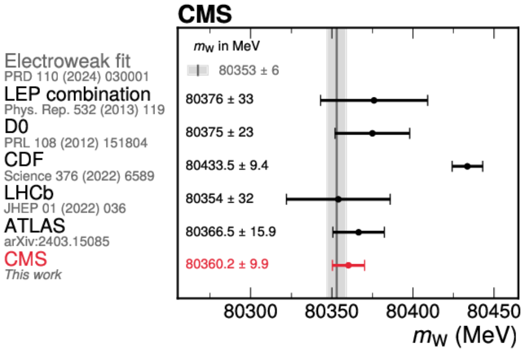

Figure 12: Overview of the W mass puzzle. The 13 TeV CMS measurement provides competitive precision to the CDF anomaly while reinforcing standard model electroweak expectations.

Comparison

ATLAS vs CMS Comparison

ATLAS: Precision via Clean Environments

- **Kinematic Dataset:** Analyzes proton-proton collisions at a lower center-of-mass energy of $\sqrt{s} = 7$ TeV with an integrated luminosity of 4.6 fb^{-1} (electron channel) and 4.1 fb^{-1} (muon channel).
- **Pileup Conditions:** Benefits from a pristine, low-pileup run ($\langle\mu\rangle \approx 9$) critical for the precise resolution of the soft hadronic recoil vector $\vec{u}_T$.
- **Leptonic Topologies:** Targets both electron ($W \to e\nu$) and muon ($W \to \mu\nu$) decay channels to maximize statistics and suppress backgrounds.
- **Fit Methodology:** Relies on a template-morphing fit applied directly to 1D transverse mass (m_T) and lepton momentum (p_T^ℓ) projections.

CMS: Precision via Statistical Power

- **Kinematic Dataset:** Analyzes a 2016 dataset of pp collisions at $\sqrt{s} = 13$ TeV, corresponding to 16.8 fb^{-1}.
- **Pileup Conditions:** Operates under moderate pileup ($\langle\mu\rangle \approx 25$, with a tail extending to 44), reconstructed via the global Particle-Flow algorithm.
- **Leptonic Topologies:** Focuses strictly on a muon-only topology ($W \to \mu\nu$), bypassing electron systematic variations to exploit pristine tracker resolution.
- **Fit Methodology:** Implements an unrolled 3D profile likelihood fit (p_T^μ, η^μ, q^μ), with p_T^W profiled in-situ from $W \to \mu\nu$ data rather than corrected via Z.

All Measurements vs SM

The Global Electroweak Landscape

- **LHC Symmetrical Cluster:** The three independent LHC measurements (ATLAS, CMS, LHCb) form a highly consistent cluster.
- **Standard Model Triumph:** Excluding the Tevatron anomaly, the combined global database (LEP, D0, and LHC) demonstrates incredible alignment with the global EW fit.
- **Isolation of the Anomaly:** The ultra-high CDF II result is now isolated by a multi-channel wall of high-precision data, shifting the weight of evidence back to the SM.

Quantitative Compatibility

- **LHC vs. Theory Fit:** The combined LHC results show a minor $\approx 0.5\sigma$ pull relative to the central Standard Model prediction (80353 ± 6 MeV).
- **The Tevatron Tension:** The standalone CDF II anomaly remains pulled away by more than 7σ from the rest of the world average.
- **Future Convergence:** Resolving this residual tension now shifts away from new-physics claims and focuses heavily on investigating undetected experimental systematics.

Conclusions

Summary

Group / Model	m_W (MeV)	Total	Stat	Syst	Γ_W (MeV)	Total	Stat	Syst
ATLAS	80366.5	$\pm$ 15.9	$\pm$ 9.8	$\pm$ 12.5	2202	$\pm$ 47	$\pm$ 32	$\pm$ 34
CMS	80360.2	$\pm$ 9.9	$\pm$ 2.4	$\pm$ 9.6	—	—	—	—
CDF II	80433.5	$\pm$ 9.4	$\pm$ 6.4	$\pm$ 6.9	—	—	—	—
Standard Model	80353.0	$\pm$ 6.0	—	—	2088	$\pm$ 1.0	—	—

Key Experimental Nuances:

- **CMS Width Handling:** While ATLAS performs the first LHC measurement of Γ_W, CMS's analysis does not extract the width independently, its fit focuses solely on m_W, with Γ_W held fixed to the SM prediction.
- **Error Budgets:** Both experiments remain heavily limited by systematic errors, but the in-situ profiling framework engineered by CMS yields a massive reduction in the final systematic uncertainty.

Outlook

Experimental Opportunities

- **Joint LHC Combination:** Establishing a dedicated cross-collaboration working group to perform a unified ATLAS-CMS-LHCb W mass combination.
- **Statistical Scaling:** Utilizing upcoming high-luminosity data streams to access massive control datasets, improving tracker calibration limits.
- **Expanded Acceptance:** Exploiting upgraded forward subdetectors to reconstruct leptonic decays and capture previously inaccessible kinematic ranges.

Theory & Modeling Alignment

- **PDF Modeling Updates:** Integrating ultra-precise 13 TeV Drell-Yan data into global updates to systematically reduce baseline PDF uncertainties.
- **Template Stabilization:** Refining in-situ profiling configurations to further constrain production parameters directly within the fit.
- **Systematic Investigations:** Shifting emphasis away from new-physics claims to focus heavily on identifying undetected experimental or tuning discrepancies.

Thank You

Questions?