

Precision Tests as Windows to New Physics

From Anomalies to Rare Higgs Decays

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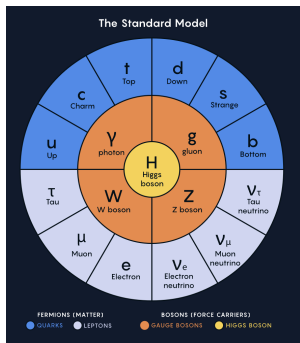


September 11, 2026

OUTLINE

- 1 WHY PRECISION?
- 2 PRECISION TESTS AND ANOMALIES
- 3 FROM ANOMALIES TO HIGGS PRECISION
- 4 ANALYSIS AND RESULTS
- 5 CONCLUSIONS

THE STANDARD MODEL: REMARKABLY SUCCESSFUL, YET INCOMPLETE



A remarkably successful theory of particles and interactions

SOME FUNDAMENTAL QUESTIONS REMAIN

- What is **dark matter**?
Recent LZ result: intriguing candidate event,
– not yet a discovery
- Why do **neutrinos** have mass?
- Why is there more **matter** than **antimatter**?
- Why are the electroweak and Planck scales so widely separated?
- How does **gravity** fit into the quantum description?

Where should we look for physics beyond the Standard Model?

TWO COMPLEMENTARY FRONTIERS FOR DISCOVERING NEW PHYSICS

ENERGY FRONTIER

Produce new particles directly

Higher
collision energy



Access to
new states

Increase the collision energy and search for new particles, resonances and interactions.

Direct search for new physics

PRECISION FRONTIER

Look for tiny deviations

Precision
measurement



New-physics
sensitivity

New particles can modify precisely measured quantities through quantum effects, even without being produced directly.

Indirect probe of new physics



**New physics may first appear
as a new particle or as a small deviation.**

PRECISION PHYSICS HAS WORKED BEFORE

BEFORE THE TOP-QUARK DISCOVERY

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1 \quad \text{in SM at tree level}$$

Virtual top-quark loops modify the W and Z propagators, shifting their tree-level relation :

$$\Delta\rho \simeq \frac{3G_F m_t^2}{8\sqrt{2}\pi^2}$$

Precision electroweak fits [hep-ex/9407002]:

$$m_t^{\text{indirect}} \simeq 177 \pm 13 \pm 19 \text{ GeV}$$

before top discovery.

**Top quark discovered at the Tevatron in
1995**

BEFORE THE HIGGS DISCOVERY

The Higgs boson also contributes to the W and Z vacuum polarizations.

EW corrections from Higgs Boson:

$$\delta_{\text{EW}}^H \sim \ln\left(\frac{m_H}{m_Z}\right)$$

Precision electroweak fit [PDG 2010]:

$$m_H^{\text{indirect}} = 87^{+35}_{-26} \text{ GeV}$$

$$m_H < 157 \text{ GeV} \quad (95\% \text{ CL})$$

Precision data preferred a light Higgs

**Higgs boson discovered at the LHC in
2012**

QUANTUM LOOPS: INDIRECT WINDOWS TO NEW PHYSICS

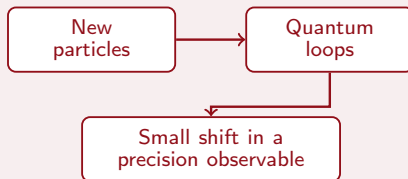
THE BASIC IDEA

A measured quantity receives quantum-loop corrections

$$\mathcal{O} = \mathcal{O}_{\text{leading}} + \Delta\mathcal{O}_{\text{quantum}}$$

Precision makes these small effects observable.

WHERE CAN NEW PHYSICS ENTER?



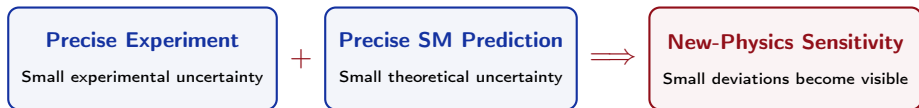
Virtual effects can remain observable even when the new particle is beyond the direct-production reach.

Examples:

$$M_W \quad \bullet \quad (g-2)_\mu$$

$$h \rightarrow \gamma\gamma \quad \bullet \quad h \rightarrow Z\gamma$$

WHAT MAKES A POWERFUL PRECISION TEST?



Significance of the difference:

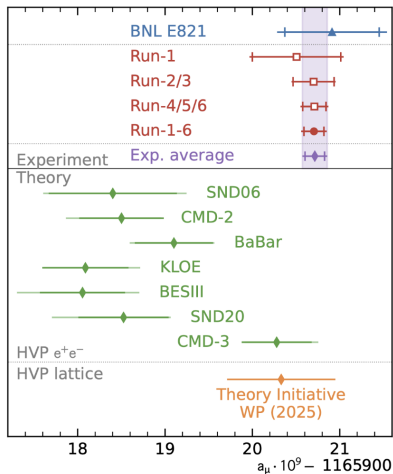
$$\text{Significance} \sim \frac{|\text{measurement} - \text{SM prediction}|}{\text{total uncertainty}} = \frac{|\mathcal{O}_{\text{exp}} - \mathcal{O}_{\text{SM}}|}{\sigma_{\text{tot}}}$$

σ_{tot} : total uncertainty associated with the comparison.

A deviation can become significant if it is
large compared with the total uncertainty.

Precision requires both precise measurements and precise theoretical predictions.

MUON $g - 2$: AN EVOLVING PRECISION TEST



Experiment

Successive Fermilab runs have greatly improved the experimental precision, leading to a very precise world average.



Theory

The SM prediction depends critically on the hadronic vacuum-polarization contribution.

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$$

$$= (0.38 \pm 0.64) \times 10^{-9}$$

Muon $g - 2$ Collab., PRL 135, 101802 (2025);

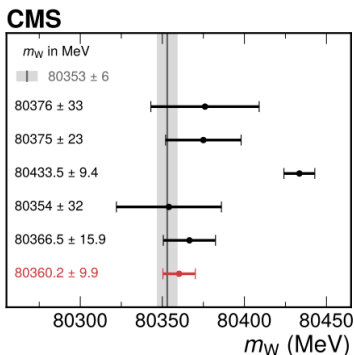
Muon $g - 2$ Theory Initiative, Phys. Rep. 1143, 1 (2025)

THE LESSON

An apparent anomaly can evolve as either the **experimental measurement** or the **theoretical prediction** improves.

W-BOSON MASS: A CHANGING EXPERIMENTAL PICTURE

Electroweak fit
PRD 110 (2024) 030001
LEP combination
Phys. Rep. 532 (2013) 119
D0
PRL 108 (2012) 151804
CDF
Science 376 (2022) 6589
LHCb
JHEP 01 (2022) 036
ATLAS
EPJC 84 (2024) 1309
CMS
This work



Electroweak fit

$$M_W^{\text{EW}} = 80.353 \pm 0.006 \text{ GeV}$$

CDF II (2022)

$$M_W = 80.4335 \pm 0.0094 \text{ GeV}$$

Strong tension with the EW fit.

CMS (2026):

$$M_W = 80.3602 \pm 0.0099 \text{ GeV}$$

CMS Collab., Nature 652, 321 (2026)

Consistent with the EW fit.

THE LESSON

Independent precision measurements are essential before interpreting a discrepancy as evidence for new physics.

HIGGS PRECISION FRONTIER

Higgs Sector – Increasingly Important Precision Frontier

WHY THE HIGGS?

- The most recently discovered fundamental particle of the Standard Model.
- Its couplings probe the mechanism of electroweak symmetry breaking and mass generation.
- Measurements so far are broadly consistent with the Standard Model, but room for new physics remains.

Higher precision $\Rightarrow$ greater sensitivity

A PARTICULARLY SENSITIVE WINDOW

Loop-induced Higgs decays

$$h \rightarrow \gamma\gamma$$

$$h \rightarrow Z\gamma$$

New charged particles



Additional loop contributions



Modify the decay rates

Indirect sensitivity to new physics

OUR RESEARCH QUESTION

Can the same new-physics framework produce observable effects across precision measurements

$$h \rightarrow \gamma\gamma \qquad h \rightarrow Z\gamma$$

while remaining consistent with **electroweak precision data** and other **experimental constraints**?

Loop-induced Higgs decays as complementary precision probes

With: Hrishabh Bharadwaj, Sukanta Dutta and Ashok Goyal

Related work: *Phys. Rev. D 110 (2024); arXiv:2504.04265 [hep-ph]; and ongoing work*

MODEL FRAMEWORK

Field content

$$\boxed{2\text{HDM } (\Phi_1, \Phi_2) + \text{complex singlet } \Phi_3 + \text{vector-like charged lepton } \chi}$$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_{\text{SM}} + \phi_1^0 + i\eta_1^0) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(\phi_2^0 + i\eta_2^0) \end{pmatrix}, \quad \Phi_3 = \frac{1}{\sqrt{2}}(v_s + \phi_3^0 + i\eta_3^0).$$

- Φ_1 and Φ_3 acquire VEVs, while Φ_2 remains inert: $\langle \Phi_2 \rangle = 0$.
- Discrete Z_2 assignments: $\Phi_1 : +, \quad \Phi_2 : -, \quad \Phi_3 : -, \quad \chi_L : -, \quad \chi_R : +$.
- χ is a singlet vector-like charged lepton: $\chi_{L,R} \sim (1, 1, -1)$.

After symmetry breaking

$$(\phi_1^0, \phi_3^0) \xrightarrow{\theta_{13}} (h_1, h_3), \quad (\eta_2^0, \eta_3^0) \xrightarrow{\theta_{23}} (A^0, P^0),$$

$$h_1 \text{ identified with the 125 GeV Higgs boson } h \quad \phi_2^0 \equiv h_2, \quad \phi_2^\pm \equiv H^\pm.$$

The extended scalar and VLL sectors can leave correlated signatures in Higgs precision observables.

NEW INTERACTIONS

Beyond the SM Yukawa sector

$$-\mathcal{L}'_{\text{Yukawa}} \supset y_1 \bar{\ell}_L \Phi_2 e_R + \text{h.c.}$$

,

$$\mathcal{L}^{\text{VLL}}_{\text{Yukawa}} \supset -y_2 \bar{\chi}_L \chi_R \Phi_3 - y_3 \bar{\chi}_L e_R \Phi_3 + \text{h.c.}$$

- ▶ y_1 : couples the additional scalar sector to SM charged leptons and explicitly breaks Z_2 .
- ▶ y_2, y_3 : explicitly breaks the global $U(1)$.

New physical states

Neutral scalars : $h_2, h_3,$

Charged scalar : $H^\pm,$

Pseudoscalars : $A^0, P^0,$

Vector-like charged lepton : $\chi.$

Where do they show up?

- ▶ The **extended scalar spectrum and its mass splittings** are constrained by electroweak precision observables.
- ▶ The charged states $H^\pm$ and χ give additional loop contributions to the Higgs decays

$$h_1 \rightarrow \gamma\gamma, \quad h_1 \rightarrow Z\gamma.$$

Before studying the Higgs decays, the model must satisfy electroweak precision constraints.

PHYSICAL PARAMETER BASIS

Rather than scanning directly over the relevant parameters of the scalar potential, we express them in terms of **physical masses, mixing angles and trilinear couplings**, together with the Yukawa couplings.

Lagrangian parameters $\Rightarrow$ **Physical parameter basis** $\Rightarrow$ **Phenomenological scan**

Observed Higgs: $h_1 \equiv h_{\text{SM-like}}, \quad m_{h_1} = 125 \text{ GeV (fixed)}.$

Parameter Space

6 MASSES

$$m_{h_2}, \quad m_{h_3}, \\ m_{H^\pm}, \quad m_{A^0}, \quad m_{P^0}, \\ m_\chi$$

2 MIXING ANGLES

$$\theta_{13}, \quad \theta_{23}$$

5 COUPLINGS

$$y_1, \quad y_2, \quad y_3, \\ \lambda_{h_1 H^+ H^-}, \\ \lambda_{h_3 H^+ H^-}$$

These parameters determine the precision observables and Higgs decay amplitudes .

THEORETICAL CONSISTENCY

Before applying experimental constraints, each parameter point is required to satisfy the theoretical consistency conditions of the model.

► Vacuum stability / Copositivity

The scalar potential is required to be bounded from below. We impose the full copositivity conditions on the quartic couplings. In the physical parameter basis, one of these conditions separates the allowed parameter space into two branches:

$$\text{Region I: } m_{h_2}^2 > m_{A0}^2 + m_{P0}^2, \quad m_{H^\pm}^2 > m_{A0}^2 + m_{P0}^2,$$

$$\text{Region II: } m_{h_2}^2 < m_{A0}^2 + m_{P0}^2, \quad m_{H^\pm}^2 < m_{h_2}^2.$$

We explore Region I in this work.

► Perturbativity

The underlying scalar and Yukawa couplings are required to remain in the perturbative regime. We use the conventional coupling-size criteria:

$$|\lambda_i| < 4\pi, \quad i = 1, 2, 3, 4, 5, 8, 11, 13 \quad \text{and} \quad |y_i| < \sqrt{4\pi}, \quad i = 1, 2, 3.$$

HIGGS SIGNAL STRENGTH AND THE EVOLVING $H \rightarrow Z\gamma$ PICTURE

Higgs measurements are commonly expressed in terms of the signal strength defined as

$$\mu_{XY} \equiv \frac{\text{measured rate for } pp \rightarrow h \rightarrow XY}{\text{SM expectation for } pp \rightarrow h \rightarrow XY} \simeq \frac{\sigma(pp \rightarrow h)}{\sigma(pp \rightarrow h)_{\text{SM}}} \frac{\text{BR}(h \rightarrow XY)}{\text{BR}(h \rightarrow XY)_{\text{SM}}}$$

$\mu_{XY} = 1$
SM-like rate

$\mu_{XY} > 1$
enhanced rate

$\mu_{XY} < 1$
suppressed rate

Experimental picture for $H \rightarrow Z\gamma$

ATLAS + CMS

Run-2 combination

$$\mu_{Z\gamma} = 2.2 \pm 0.7$$

First evidence for $H \rightarrow Z\gamma$

ATLAS + CMS, PRL 132, 021803 (2024)

CMS Preliminary

Run 2 + partial Run 3

$$\mu_{Z\gamma} = 1.10^{+0.52}_{-0.61}$$

Updated dedicated $Z\gamma$ analysis

CMS, CMS-PAS-HIG-25-010 (2026)

Run-2 preference for enhancement $\rightarrow$ newer data move the central value towards the SM

HIGGS SIGNAL STRENGTHS IN THE MODEL

The observed Higgs state is identified with h_1 , with $m_{h_1} \simeq 125$ GeV.
Its SM-like couplings are universally rescaled by the singlet-mixing angle θ_{13} .

SM-like decay channels

For $XY = f\bar{f}, WW^*, ZZ^*, gg$,

$$\mu_{XY} = \cos^4 \theta_{13} \frac{\Gamma(h^{\text{SM}} \rightarrow \text{all})}{\Gamma(h_1 \rightarrow \text{all})}$$

- Modified mainly through the universal h_1 coupling rescaling from $\cos \theta_{13}$.

New charged particles in the loop

For $XY = \gamma\gamma, Z\gamma$,

$$\mu_{XY} = \cos^4 \theta_{13} |1 + \zeta_{XY}|^2 \frac{\Gamma(h^{\text{SM}} \rightarrow \text{all})}{\Gamma(h_1 \rightarrow \text{all})}$$

where ζ_{XY} parametrizes the additional charged-particle loop amplitude from $H^\pm$ and the vector-like lepton χ , relative to the mixing-rescaled SM amplitude.

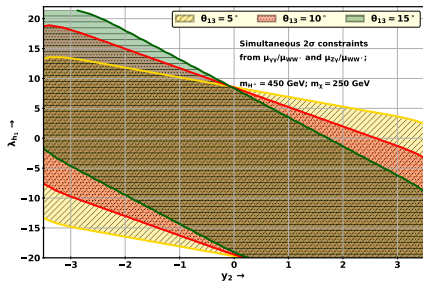
- Probe the additional charged sector of the model

KEY PARAMETERS

$$\mu_{\gamma\gamma}, \mu_{Z\gamma} \longleftarrow \theta_{13}, m_{H^\pm}, m_\chi, \lambda_{h_1 H^+ H^-}, y_2$$

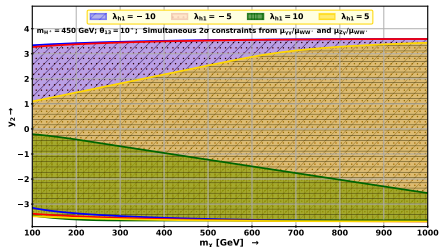
COMBINED HIGGS SIGNAL-STRENGTH CONSTRAINTS

$(y_2, \lambda_{h_1 H^+ H^-})$ plane.

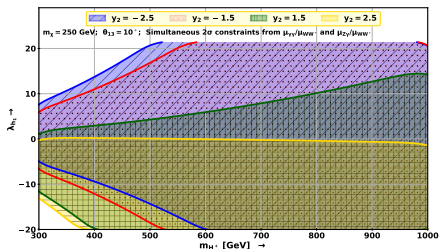


Combined Higgs constraints select correlated regions of $y_2, \lambda_{h_1 H^+ H^-}, m_\chi$ and $m_{H^\pm}$, with appreciable dependence on θ_{13} .

(y_2, m_χ) plane



$(m_{H^\pm}, \lambda_{h_1 H^+ H^-})$ plane



COMPLEMENTARY EXPERIMENTAL CONSTRAINTS

Besides the Higgs signal strengths, the parameter space is constrained by complementary precision measurements.

LEP II	Muon-pair production	$\sigma(e^+e^- \rightarrow \mu^+\mu^-) = 3.072 \pm 0.108 \pm 0.018 \text{ pb}$
EW Precision	Oblique parameters	$\Delta S = 0.008 \pm 0.071, \quad \Delta T = 0.021 \pm 0.055$ $\rho_{ST} = 0.92$
Muon $g-2$	Anomalous magnetic moment	$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (0.38 \pm 0.64) \times 10^{-9}$

GLOBAL PARAMETER SCAN

Scan parameter Space

$$\theta = \{m_{A^0}, m_{P^0}, m_{h_2}, m_{h_3}, m_{H^\pm}, m_\chi, \theta_{13}, \theta_{23}, y_1, y_2, y_3, \lambda_{h_1 H^+ H^-}, \lambda_{h_3 H^+ H^-}\}$$

Imposing Physical scan ranges and Theoretical-consistency conditions.



Evaluate observables for each retained parameter point

$$(g-2)_\mu, \sigma_{\text{LEP}}, \Delta S, \Delta T, \mu_{\gamma\gamma}, \mu_{Z\gamma}, \mu_{WW}, \mu_{ZZ}$$



Compute Total χ^2

$$\chi_{\text{tot}}^2 = \chi_{\text{LEP}}^2 + \chi_{(g-2)_\mu}^2 + \chi_{ST}^2 + \chi_{\text{Higgs}}^2$$

The correlated $S-T$ constraint is included through its covariance matrix.



$$\theta_{\text{bf}} = \arg \min_{\theta} \chi_{\text{tot}}^2(\theta)$$

BEST FIT AND MCMC EXPLORATION

Starting from the global minimum of the combined likelihood, we explore the surrounding parameter space with MCMC.

MCMC sampling

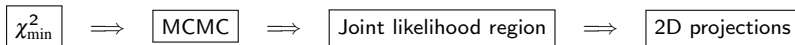
The posterior is sampled according to

$$P(\theta|D) \propto \pi(\theta) \exp\left[-\frac{1}{2}\chi_{\text{tot}}^2(\theta)\right].$$

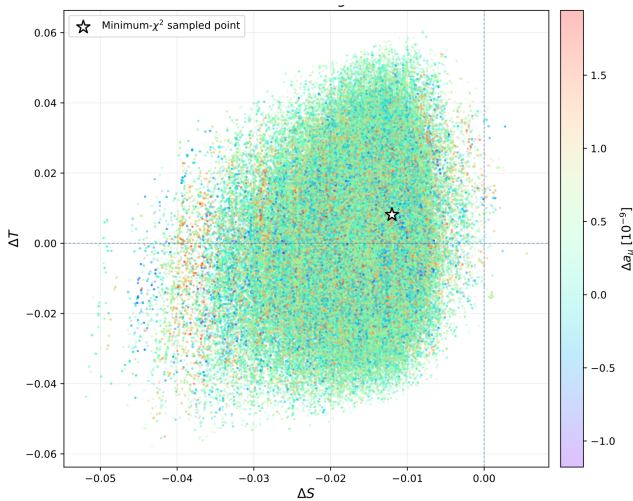
- Flat priors within the adopted scan ranges.
- The exact model calculation is used at each sampled point.
- The chain explores correlated directions beyond the best-fit point.

What do we extract?

- Preferred regions of the multidimensional parameter space.
- Correlations among masses, mixing angles and couplings.
- Predicted distributions of the constrained observables.
- Two-dimensional projections of the joint likelihood-selected region.



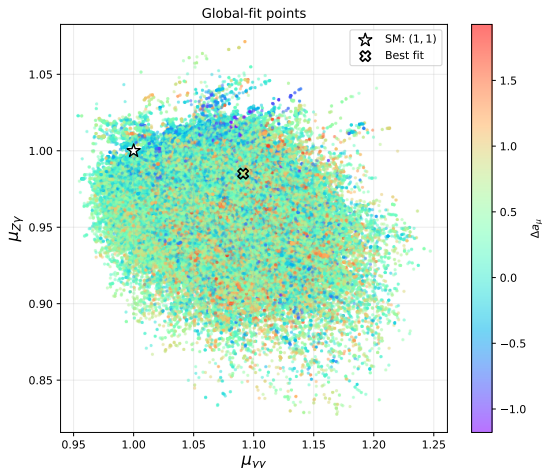
ELECTROWEAK PRECISION CONSTRAINTS



Projection of the joint 95.45% global-fit region onto the $(\Delta S, \Delta T)$ observable plane.

HIGGS SIGNAL STRENGTHS

Projection of the global fit points in the $(\mu_{\gamma\gamma}, \mu_{Z\gamma})$ Plane



Projection of the joint 95.45% global-fit region onto the $(\mu_{\gamma\gamma}, \mu_{Z\gamma})$ observable plane.

Correlated predictions for the two loop-induced Higgs decay channels.

SUMMARY OF OUR ANALYSIS

- ▶ The extended scalar + vector-like lepton sector is tested **simultaneously** against Higgs signal strengths, electroweak precision observables, $(g-2)_\mu$, and LEP constraints.
- ▶ The global analysis selects **correlated regions of the full 13-dimensional parameter space**; the different observables therefore cannot, in general, be interpreted independently.
- ▶ The present data remain compatible with the SM, while still allowing **non-SM predictions across multiple precision observables**.
- ▶ The observable-space projections illustrate how **different precision measurements probe complementary directions of the same underlying parameter space**.

ONGOING WORK

Refining the Analysis, Extending the global analysis to additional observables and their experimental correlations, and studying how improved precision further restricts the viable parameter space.

OUTLOOK

- **Precision is a discovery tool.** Small, correlated deviations across several observables can probe new-physics scales and structures beyond the direct kinematic reach.
- **The next gain is not only more data, but more precision.** The HL-LHC will substantially improve Higgs, electroweak and rare-process measurements, turning presently weak constraints into increasingly restrictive tests of new physics.
- **Global interpretation becomes increasingly important.** As more decay channels and precision observables enter the fits, their correlations can break parameter degeneracies and progressively narrow the viable BSM parameter space.
- **Precision measurements help define the next questions.** The pattern—or absence—of deviations at the HL-LHC will provide important guidance for the physics priorities and capabilities required of future colliders.

Precision turns measurements into a roadmap for new physics.

Thank You

Questions & Discussion

*Precision tests remain powerful windows
to new physics.*

Backup slides follow