

Where Will the Higgs Boson Take Us?

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A celebration of curiosity-driven science

Nobel Prize in Physics 2026

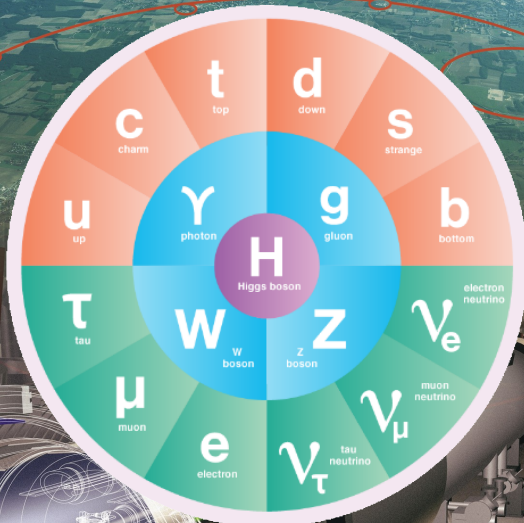
Francis Halzen

“for decisive contributions to the IceCube Neutrino Observatory and the discovery of high-energy neutrinos of astrophysical origin”



Ill. Niklas Elmehed © Nobel Prize Outreach

Source: nobelprize.org



● QUARKS ● LEPTONS ● BOSONS ● HIGGS BOSON

The Higgs boson

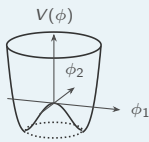
1. The puzzle (1960s)

The symmetry of the weak force ($SU(2)$ gauge symmetry) demands **massless** force carriers, like the photon

But the W and Z bosons are **heavy**: about 100 times the proton mass

2. The Higgs mechanism

A new field, the **Higgs field**, with this potential:



It **breaks** the electroweak symmetry and gives the W and Z their **masses**

Brout, Englert, Higgs et al. (1964)



3. Mass and interaction

For every particle, a **mass term** and an **interaction** with the Higgs boson

$$-m \bar{f} f \left(\underbrace{1}_{\text{mass}} + \underbrace{H/v}_{\text{interaction}} \right)$$

Quarks, leptons, W and Z alike

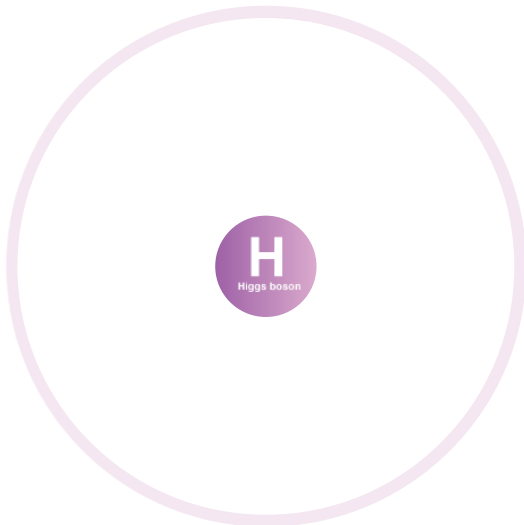
4. Unique: self-interaction

The Higgs potential predicts that the Higgs boson **interacts with itself**



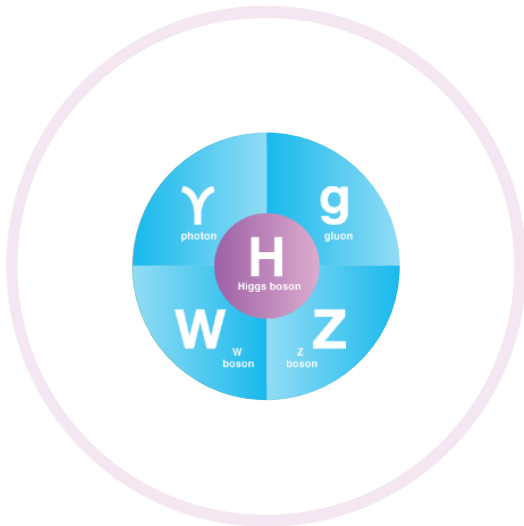
Higgs interactions: what we have seen

- ▶ **2012:**
discovery of
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boson



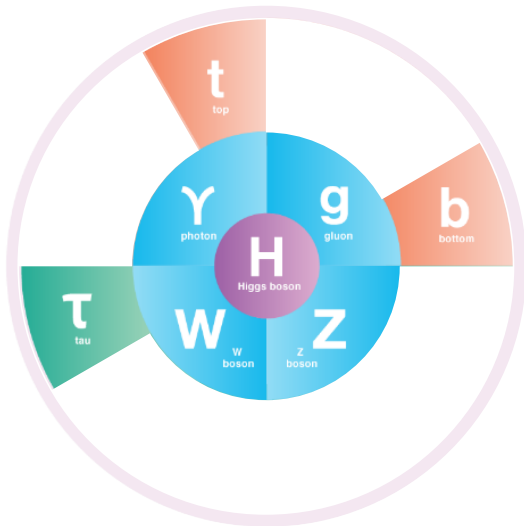
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- ▶ **2012:**
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Higgs interactions: what we have seen

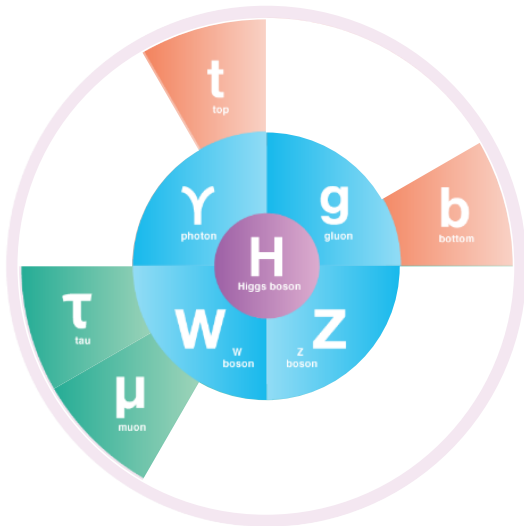
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- Direct evidence for its interactions with the W and Z bosons; **effective** interactions with **gluons** and **photons**



- Established: interactions with the **top** and **bottom** quarks and the τ lepton

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- **2012:** discovery of the Higgs boson
- Direct evidence for its interactions with the W and Z bosons; **effective** interactions with **gluons** and **photons**



- Established: interactions with the **top** and **bottom** quarks and the τ lepton
- Evidence: interaction with the **muon**

The Higgs boson is connected to our current big questions

Hierarchy problem

$$(\text{Higgs mass})^2 = (\text{Higgs bare mass})^2 \\ + \text{quantum corrections (top quark, new physics scale)}$$

The corrections are **much larger** than $(\text{Higgs mass})^2$. Why?



The Higgs boson is connected to our current big questions

Solutions to the hierarchy problem require **new physics** at a **lower energy scale**, and/or **new particles** that interact with the Higgs boson and **reduce** the large corrections



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Matter–antimatter

The universe is made of **matter**, not equal amounts of matter and antimatter

This requires interactions that violate **CP**, the symmetry between matter and antimatter

The **weak interaction** does, but may not be enough

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Can Higgs interactions break CP symmetry?

The Higgs boson brings **new types of interactions**: with gauge bosons, fermions, and itself

Can its interactions, in particular with **fermions**, break CP?

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Dark matter

85% of the matter in the universe: **massive**, but no electromagnetic interaction

Can we find it with **colliders**?

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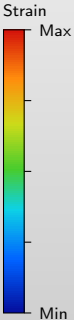
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Higgs as a portal to the dark sector?

If the dark sector has its own **particles** and **force carriers**, can the Higgs boson **decay** to them?

Can they **interact** with the Higgs boson?

Stress test the Higgs sector


$$\mathcal{L} \supset \sum_V g_{HVV} H V V - \frac{m_t}{v} H \bar{t} t$$
$$- \sum_{f \neq t} \frac{m_f}{v} H \bar{f} f - \lambda v H^3$$

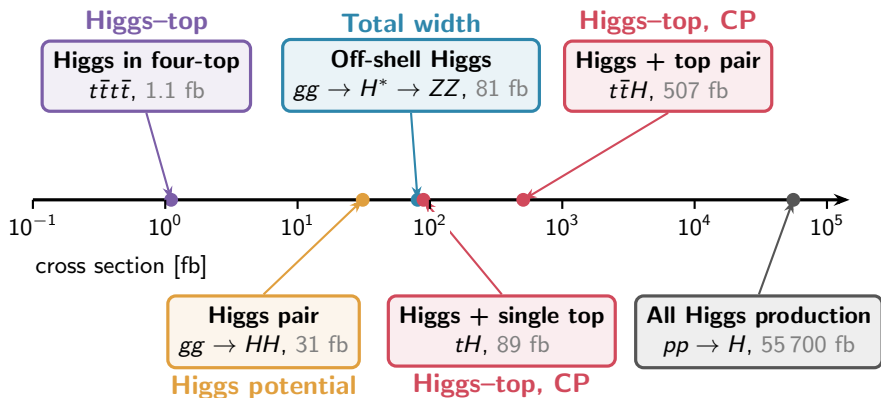
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+ new physics terms

Stress test the Higgs sector at the most **brittle points**:

- ▶ **Higgs–top interaction** (the strongest interaction)
- ▶ **Higgs decay total width** (a probe to unknown decays)

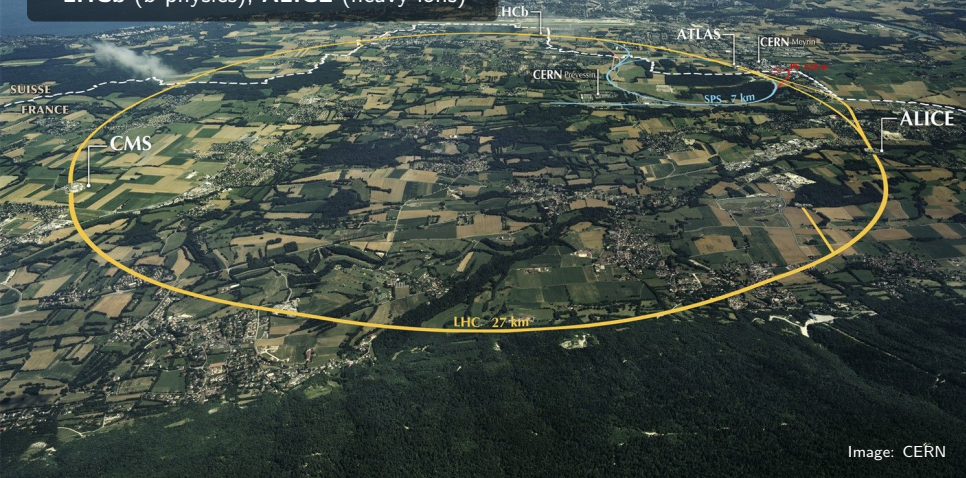
Higgs physics across many orders of magnitude



Stress testing the Higgs sector needs a lot of Higgs bosons!

The Large Hadron Collider

- Proton–proton collider at **CERN**, Geneva
- About 100 m underground
- Four interaction points, four detectors:
ATLAS, **CMS**: general purpose
LHCb (*b* physics), **ALICE** (heavy ions)



The LHC timeline

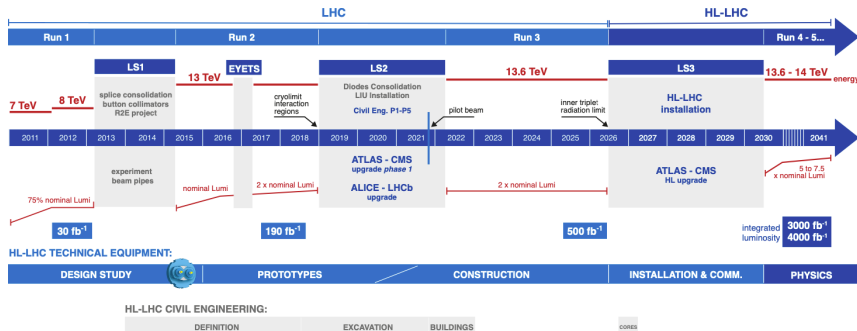
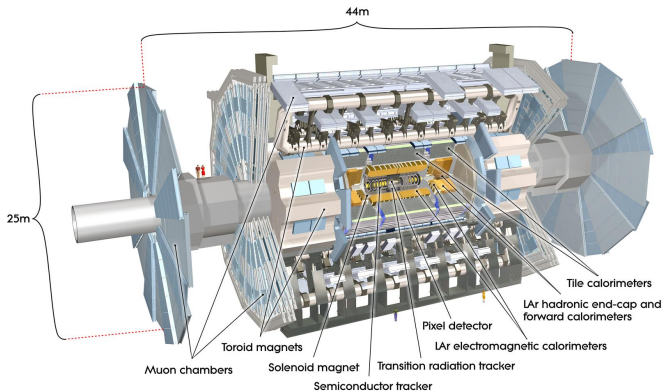


Image: CERN

	Energy	Data	Higgs bosons
Run 1, 2009–12 2012: Higgs discovery	7–8 TeV	$\sim 10 \text{ fb}^{-1}$	$\sim 200\,000$
Run 2 + 3, 2015–26	13–13.6 TeV	$> 450 \text{ fb}^{-1}$	$\sim 25 \text{ million}$
HL-LHC, from 2030 runs 10–12 years		$\sim 3000 \text{ fb}^{-1}$	

Now, Long Shutdown 3: accelerator upgrade (magnets in the interaction regions); ATLAS and CMS build new all-silicon inner trackers

LHC detectors: ATLAS as an example



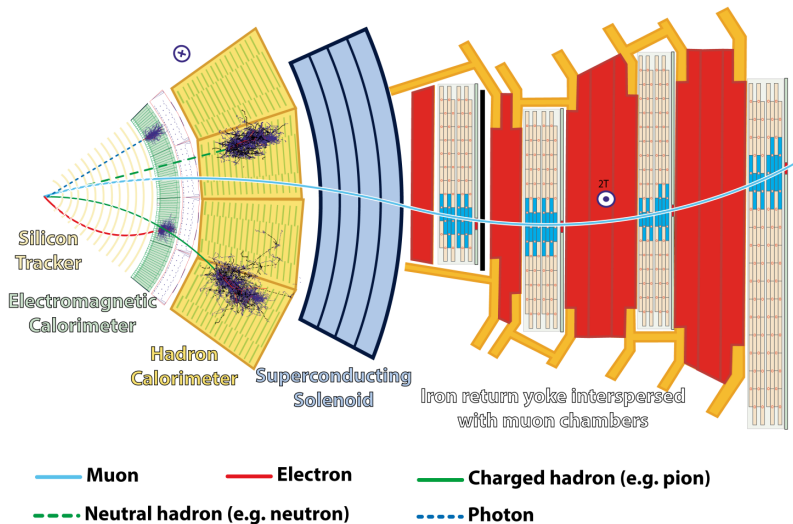
ATLAS detector. Image: CERN

Built like an **onion**
around the collision point

- ▶ **Tracking detector:** trajectories of charged particles
- ▶ **Calorimeters:** particle energies
- ▶ **Muon detectors:** muons penetrate the whole detector

What ATLAS and CMS measure: CMS as the example

Determine each particle's **identity**; measure its **energy** and **momentum**

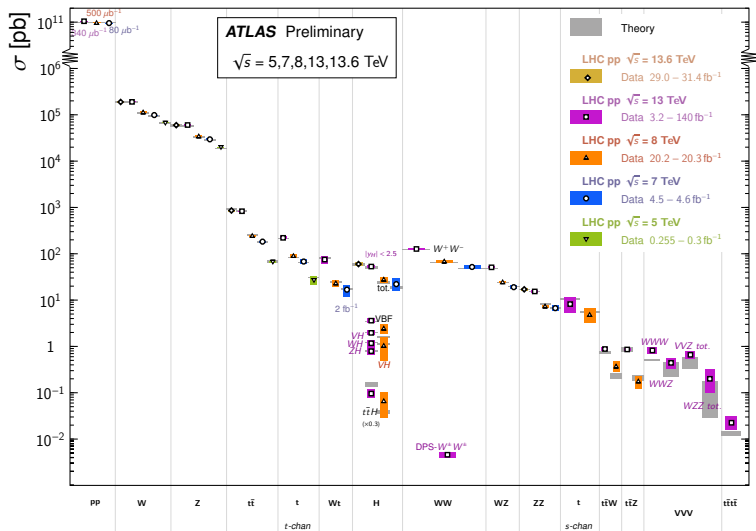


CMS detector slice. Image: CMS Collaboration/CERN

The LHC: a program of thousands of experiments

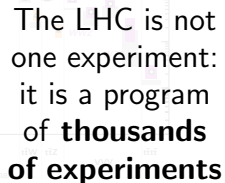
Standard Model Production Cross Section Measurements

Status: July 2026



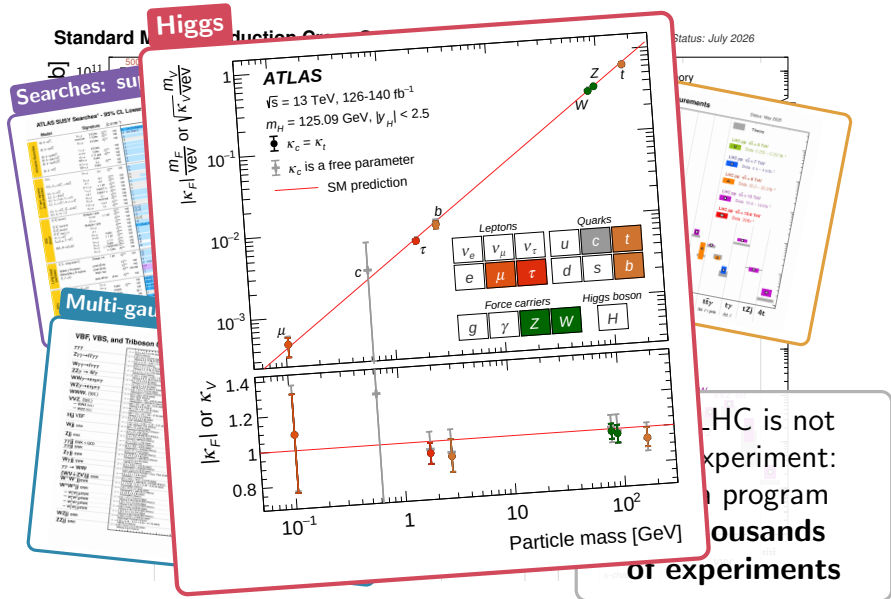
ATLAS: ATL-PHYS-PUB-2026-017 Figs. 1a, 19; ATL-PHYS-PUB-2026-003 Fig. 14;
 ATL-PHYS-PUB-2026-009 Fig. 1; arXiv:2608.07332 Fig. 7

Status: July 2026



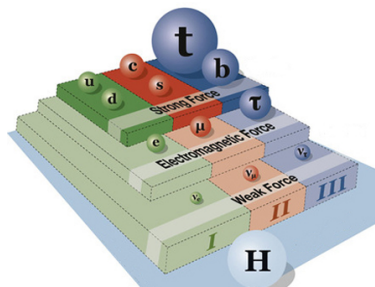
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The LHC: a program of thousands of experiments



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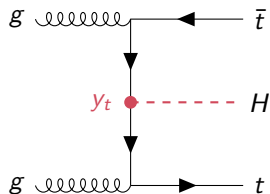
The Higgs-top interaction



- ▶ The top quark is by far the **heaviest**: a Higgs coupling of **order one**
- ▶ A critical player in **electroweak symmetry breaking**
- ▶ Many models connect the top quark and the Higgs boson to **dark matter**, **CP violation** and the **hierarchy problem**

Experimentally: characterize the **structure** of the interaction

$t\bar{t}H$: the direct probe



- ▶ The top quark is the only particle the Higgs boson **cannot decay to**: the interaction must be measured in Higgs **production**
- ▶ Two outgoing **top quarks**: unambiguous evidence for the **Higgs–top vertex**
- ▶ **Observed in 2018** with part of the Run 2 data

Since then: the **CP structure** of the Higgs–top interaction

CP symmetry, and a process we have not yet seen

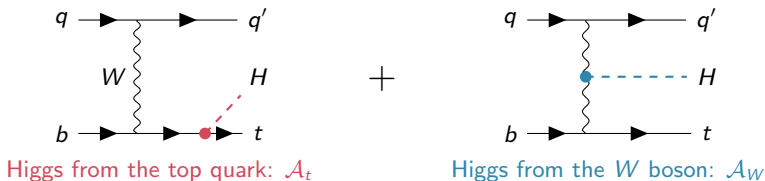
CP symmetry says that when particles are replaced by their **antiparticles** (charge conjugation) and their spatial coordinates are **reversed** (parity operation), the physical system is **unchanged**

- In the Standard Model the Higgs–top interaction is **CP-even**; a **CP-odd** part would violate CP

$$\mathcal{L}_{Ht\bar{t}} = -\frac{y_t}{\sqrt{2}} \kappa_t \bar{t} \left(\underbrace{\cos \alpha}_{\text{CP-even}} + \underbrace{i\gamma_5 \sin \alpha}_{\text{CP-odd}} \right) t H$$

A process we have **not yet observed** tells us a lot about it:
a **single top quark** produced with a Higgs boson, tH

tH : strong destructive interference



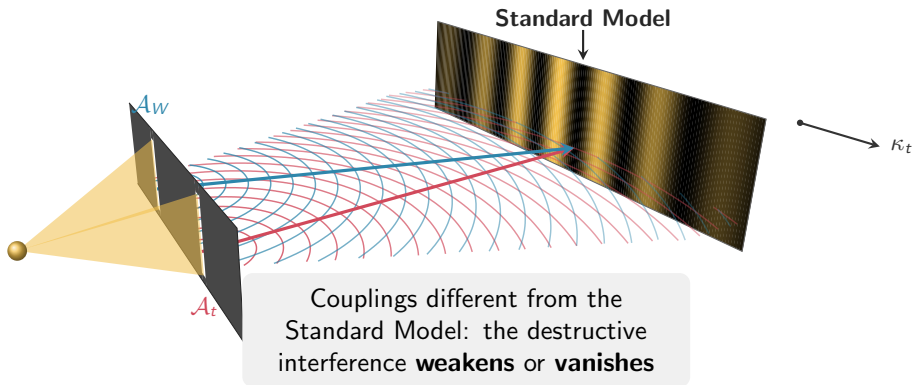
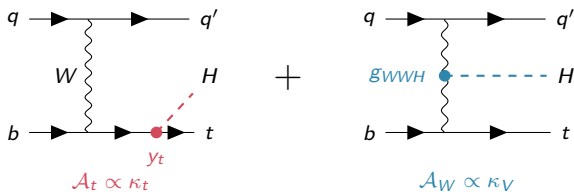
- ▶ Same initial state, same final state: quantum mechanics says the two paths **interfere**

$$|\mathcal{A}_t + \mathcal{A}_W|^2 = |\mathcal{A}_t|^2 + 2\text{Re}(\mathcal{A}_t \mathcal{A}_W^*) + |\mathcal{A}_W|^2$$

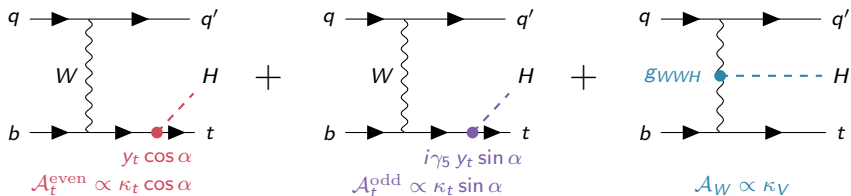
In the Standard Model the two paths interfere **destructively**:
they nearly cancel

- ▶ tH is only $\sim 20\%$ of $t\bar{t}H$, despite its lighter final state

tH production is a double slit



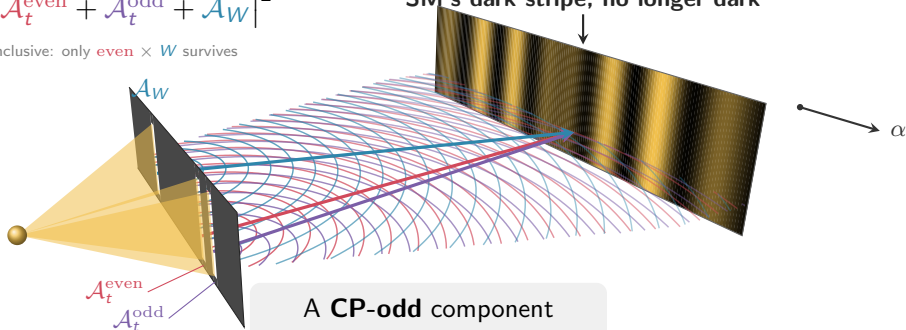
A CP-odd top coupling adds a third slit



$$|\mathcal{A}_t^{\text{even}} + \mathcal{A}_t^{\text{odd}} + \mathcal{A}_W|^2$$

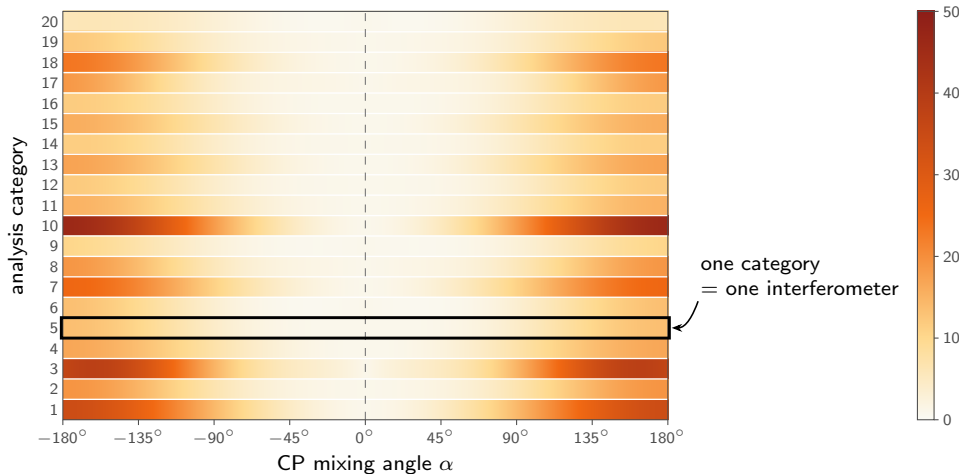
inclusive: only **even** $\times$ W survives

SM's dark stripe, no longer dark



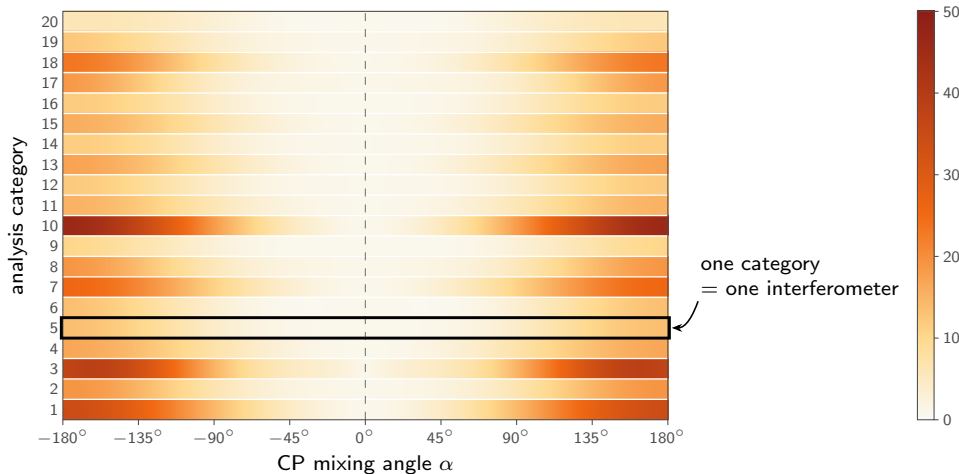
A **CP-odd** component
does exactly that

Every category is an interferometer



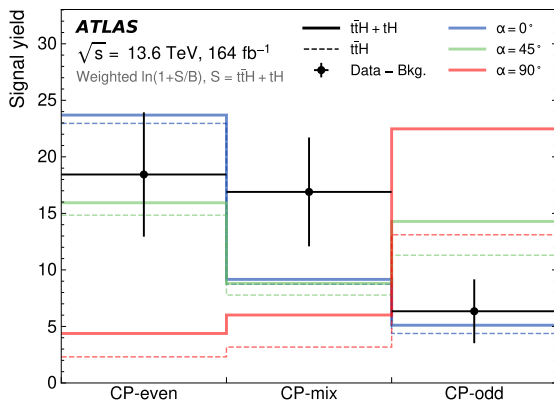
tHjb rows, $\kappa_t = \kappa_W = 1$; Run-2 parameterization, J. E. Dickinson, CERN-THESIS-2020

Every category is an interferometer



*tHj*b rows, $\kappa_t = \kappa_W = 1$; Run-2 parameterization, J. E. Dickinson, CERN-THESIS-2020

Latest result on Higgs-top CP



ATLAS, arXiv:2606.04855, Fig. 6

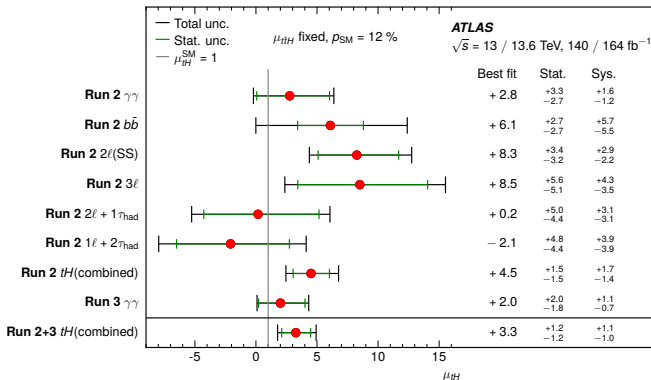
164 fb⁻¹ at 13.6 TeV with Run 2 (140 fb⁻¹)

Graph neural networks and a pre-trained model

ATLAS, Phys. Rev. Lett. (2026), doi:10.1103/r1hx-gymf (Editors' Suggestion)

- ▶ **Half of Run 3** and **all Run 2** data; just published in Phys. Rev. Lett. (Editors' Suggestion)
- ▶ $|\alpha| < 38^\circ$ at 95% CL
- ▶ Purely **CP-odd** excluded at **5.8 σ**

tH across Higgs decay channels



ATLAS, arXiv:2607.27708, Fig. 10

- ▶ **ATLAS:**
 $\mu_{tH} = 3.3^{+1.7}_{-1.5} (2.3\sigma)$
- ▶ **CMS Run 2: 2.2σ excess** (Rep. Prog. Phys. 89 (2026) 087801)
- ▶ New physics $\Rightarrow$ weaker cancellation $\Rightarrow$ **more tH**
- ▶ Not exciting yet: a **brittle point** to keep pressing

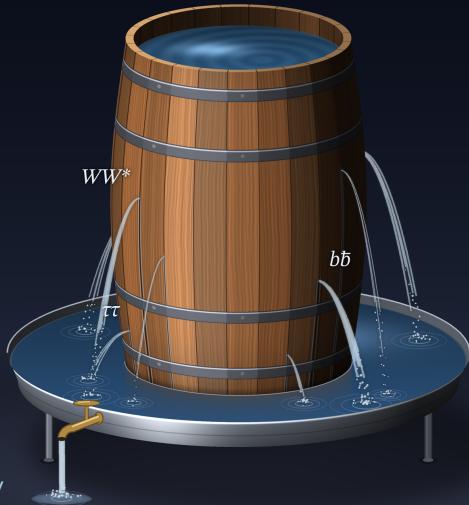
A second brittle point: the Higgs total width

The total width receives contributions from **every** decay channel

$$\Gamma_H = \underbrace{\sum_f \Gamma(H \rightarrow f)}_{\text{SM: 4.1 MeV}} + \underbrace{\Gamma_{\text{BSM}}}_{\text{BSM?}}$$

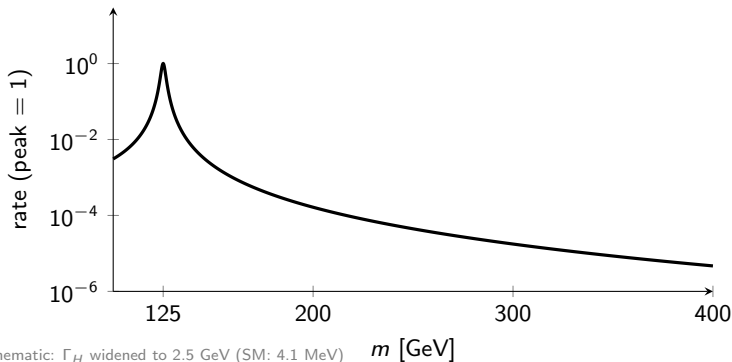
Measuring the total width probes whether **BSM** contributes to Higgs decays, **even if we do not see the BSM channel directly**

Too narrow to see directly: 4.1 MeV against a mass resolution of 1–2 GeV



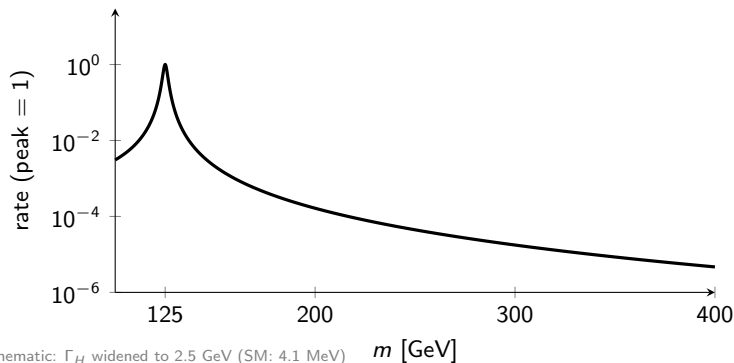
Constraining the total width

Breit-Wigner $\frac{d\sigma}{dm^2} \propto \frac{g_i^2 g_f^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$



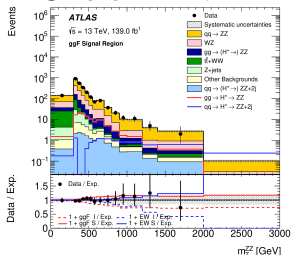
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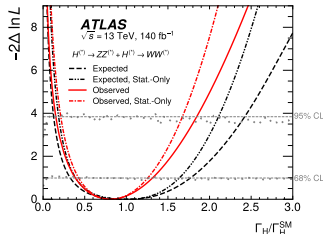
The Higgs width: ATLAS combination

Off-shell: $H^* \rightarrow ZZ$



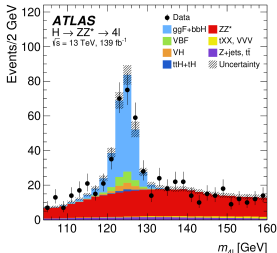
ATLAS, arXiv:2304.01532, Fig. 4a

Combination



ATLAS, arXiv:2608.07332, Fig. 12a

On-shell: $H \rightarrow ZZ^* \rightarrow 4\ell$



ATLAS, arXiv:2004.03447, Fig. 5

$$\Gamma_H = 3.6_{-1.6}^{+2.1} \text{ MeV}$$

Standard Model: 4.1 MeV

What comes next?

- ▶ Wrap up **Run-3** analysis: calibration and analysis of the data
 - ▶ Expect updates of the tH and **total width** measurements discussed here, and many more
- ▶ **HL-LHC** starts in 2030, with a new **all-silicon inner tracker**, extended coverage in the **forward regions**, new **trigger and readout**, and many more

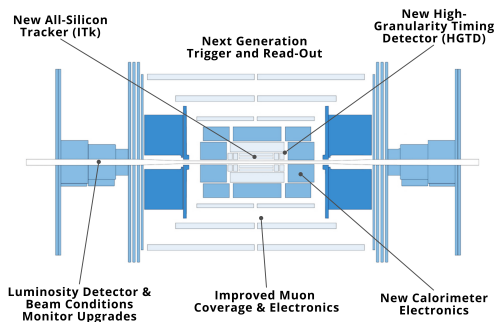


Image: ATLAS Collaboration/CERN

The future

HL-LHC

About **3000 fb⁻¹** of data: **~350 million**
Higgs bosons (ATLAS + CMS)

- ▶ **Total width:** $4.1^{+0.7}_{-0.8}$ MeV, **<20%** uncertainty, dominated by theory
- ▶ ***tH*:** at least a **5 σ** discovery with ATLAS + CMS if exactly as in the Standard Model; likely earlier thanks to analysis optimization
- ▶ **Higgs pairs:** about **7 σ** with ATLAS + CMS, a first glance at the **Higgs potential**
- ▶ **Higgs couplings, electroweak symmetry breaking, and exhaustive searches** for new physics

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FCC-ee

- ▶ **Total width**
- ▶ **First- and second-generation** couplings
- ▶ **Precision** couplings
- ▶ Programs at the Z , WW and $t\bar{t}$ energies

FCC-hh and muon colliders

- ▶ Parton-level center-of-mass energy of **10 TeV**
- ▶ Higgs **self-interaction**

Summary

- ▶ An exciting time for particle physics: the LHC has delivered **over 50 million** Higgs bosons (ATLAS + CMS), about **125×** the discovery sample
- ▶ Two novel approaches to the big open questions:
 - ▶ **Higgs total width** from on- and off-shell production:
 $\Gamma_H = 3.6^{+2.1}_{-1.6}$ MeV, once thought impossible at a hadron collider
 - ▶ **CP structure of the Higgs-top interaction**: pure CP-odd excluded at 5.8σ ; mixing angle $|\alpha| < 38^\circ$

The stress test has **just started**: the HL-LHC (from 2030) brings **5–6×** more data than today

Acknowledgements

Postdocs



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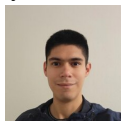
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Deutscher-Bishop
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