SM measurements in the Higgs sector in ATLAS experiment

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On behalf of ATLAS Collaborations

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Outline and analyses overview

- Higgs Boson's key properties using the full dataset of proton-proton collisions at $\sqrt{s}$ = 13 TeV and 13.6 TeV (Run 2 and Run 3)
- Recent projections for the HL-LHC

Analyses:

- Run 3
  - $H \rightarrow ZZ^* \rightarrow 4\ell$ ATLAS-CONF-2025-002
- Run 2+3
  - $H \rightarrow \mu\mu$ HIGP-2024-11 - arXiv:2507.03595
- Run 2 Legacy
  - ggF+VBF H→WW couplings HIGP-2024-07 - arXiv:2504.07686

The Higgs boson

The Higgs boson is the linchpin holding the Standard Model together
Many pathways to new physics begin with BSM physics in the Higgs sector

Couplings to Gauge bosons

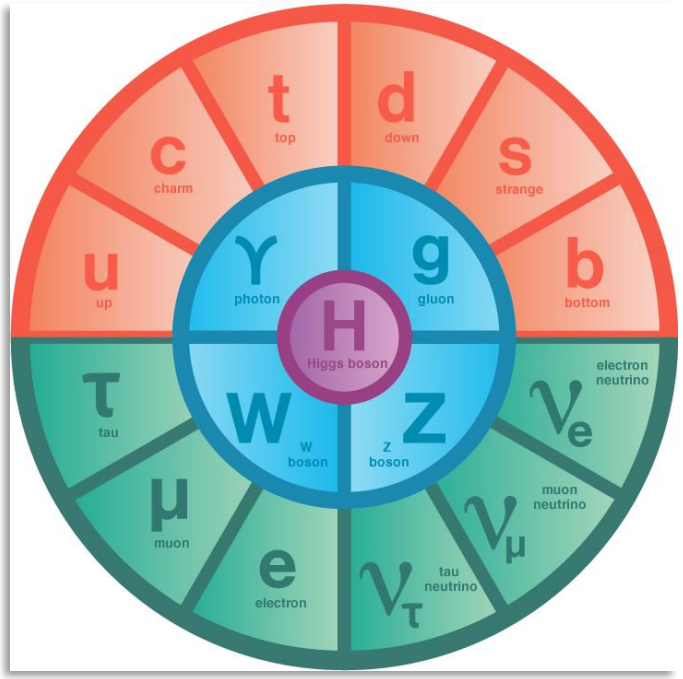
- Exactly predicted by EWSB
- Anomalous couplings imply modified EW unification
- Measured to ~5% precision

Yukawa couplings

- 9 free parameters fixed by m_f
- Connections to the origin of flavor and the CKM matrix
- Measured to ~10% or worse

Higgs potential

- Shape ultimately drives EWSB
- Implications for cosmology
- Accessed via self-coupling, no experimental sensitivity yet



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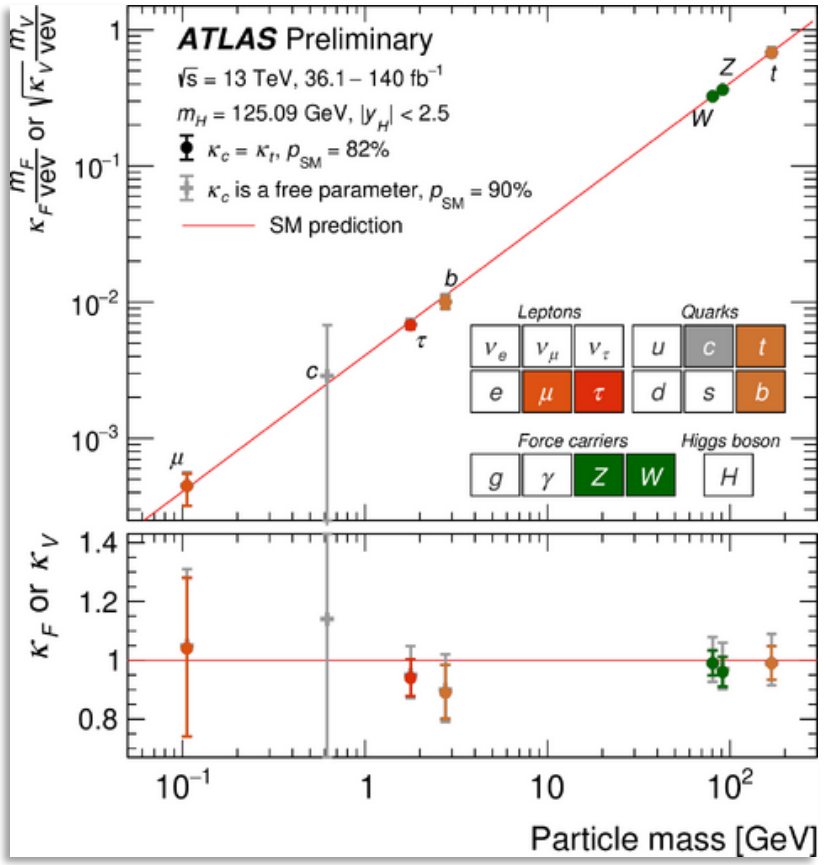


Many Beyond-the-Standard-Model scenarios predict small modifications to Higgs couplings, or possible CP-violating effects — things we can systematically test through the Effective Field Theory, or EFT framework

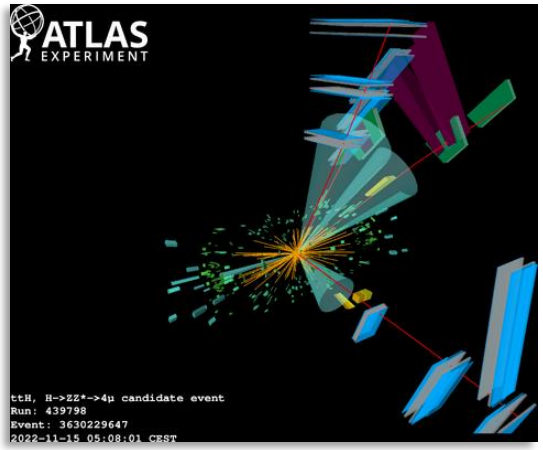
ATLAS measurements of the Higgs couplings line up with the particle masses, showing the expected linear relationship.
The agreement with the Standard Model remains striking, but the precision is now reaching the level where new physics could subtly appear

$H \rightarrow ZZ^* \rightarrow 4\ell$ (Run 3)

Golden channel:

- fully reconstructed final state
- excellent lepton momentum resolution
- very low background contamination

$H \rightarrow ZZ^* \rightarrow 4\ell$ (Run 3)



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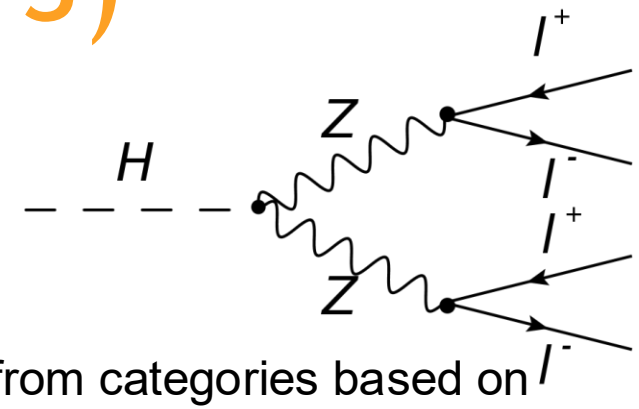
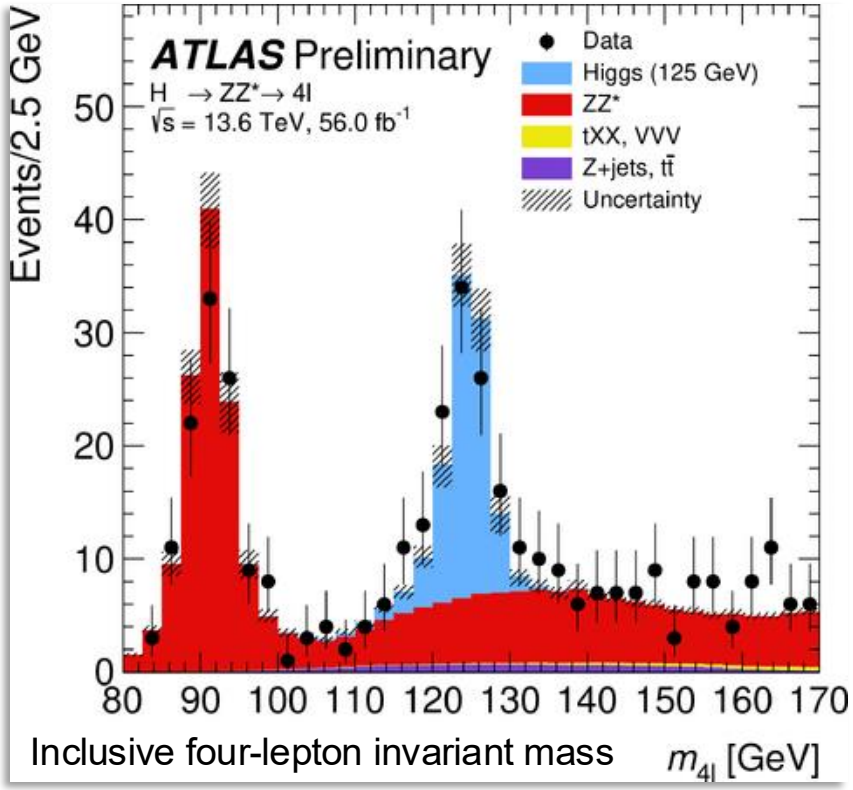


A golden channel for discovery

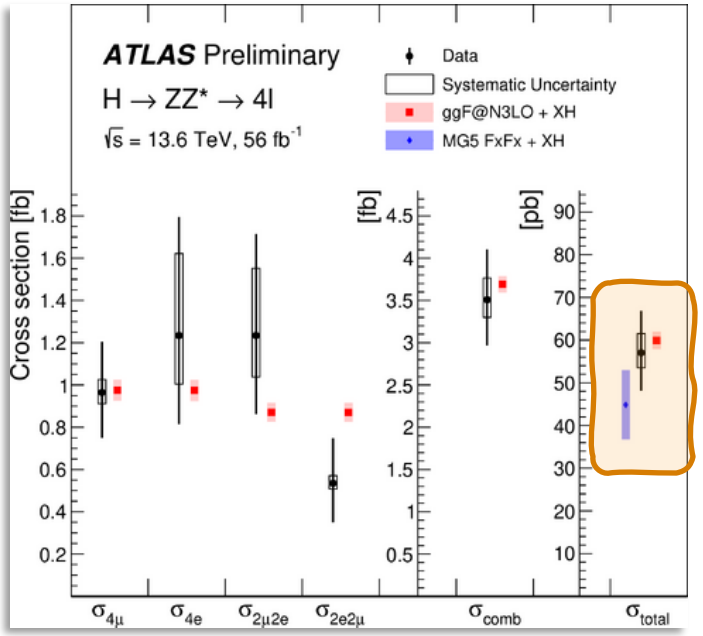
- Measures Higgs mass down to 0.1%!
- Uses 56 fb-1 data from Run 3
- Combined with Run 2 analysis (140 fb^{-1})
- measurement of main production modes from categories based on properties of the particle produced in association

Inclusive cross sections

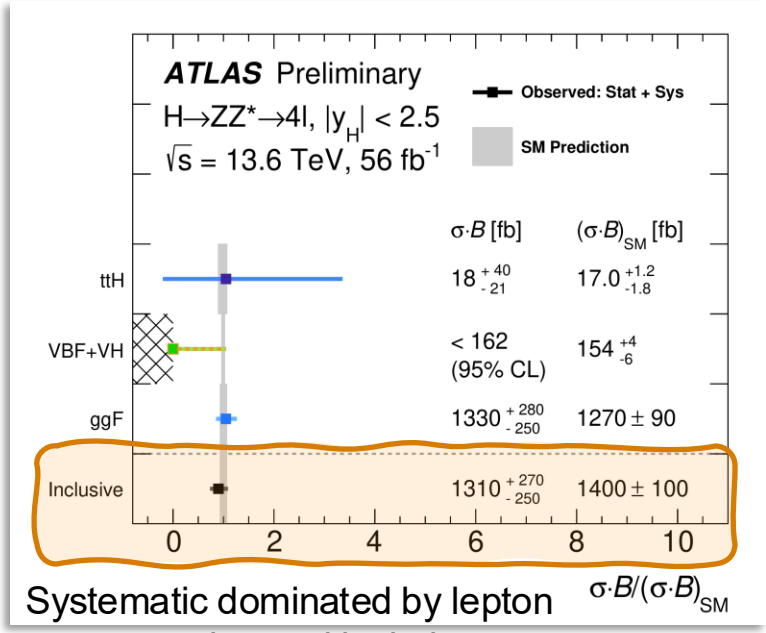
Need precision theory inputs to match experimental reach



Inclusive four-lepton invariant mass



total cross section accounting BR(H->4l) and fiducial acceptance from simulated SM sample



Systematic dominated by lepton reconstruction and isolation

H → ZZ* → 4ℓ (Run 3): Differential cross sections

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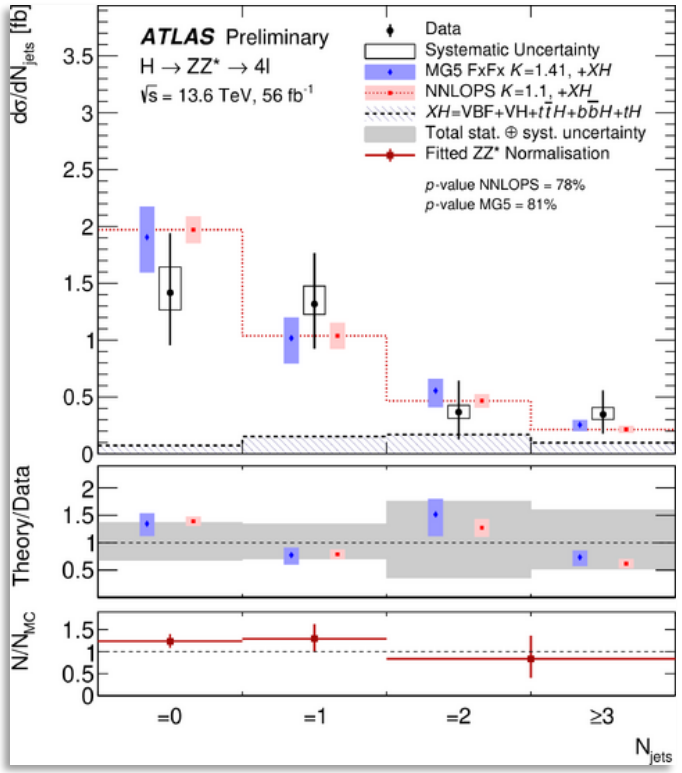
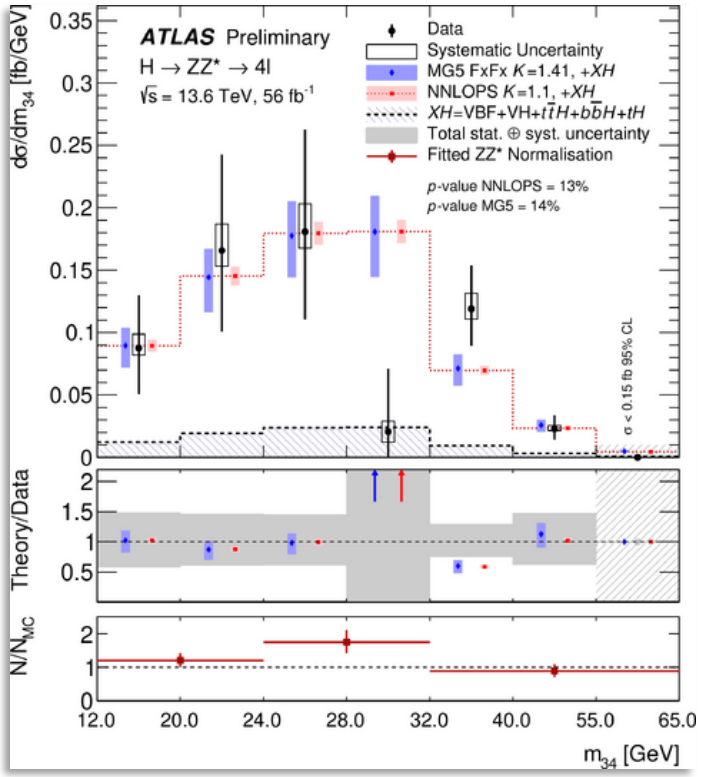
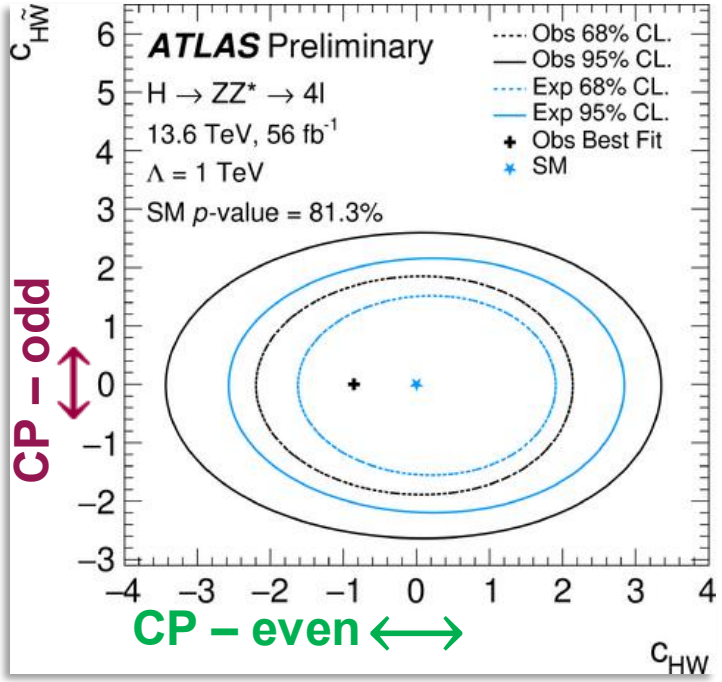
Constrain CP-violation using effective field theory







✚ maximum likelihood coupling values

★ SM

An EFT validity scale of Λ = 1 TeV is assumed. Except for the two fitted Wilson coefficients, all others are set to zero.

Observables sensitive to EW corrections and angular effects

- **The differential fiducial cross sections** as a function of jet multiplicity and the invariant mass of the subleading lepton pair, m_{34}.
- The shape of the m_{34} spectrum is particularly interesting: it's sensitive to the spin-parity structure of the Higgs, and any deviation from the Standard Model could indicate anomalous couplings or even a non-scalar nature.

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)} \quad \text{for } d > 4$$

$H \rightarrow ZZ^* \rightarrow 4\ell$

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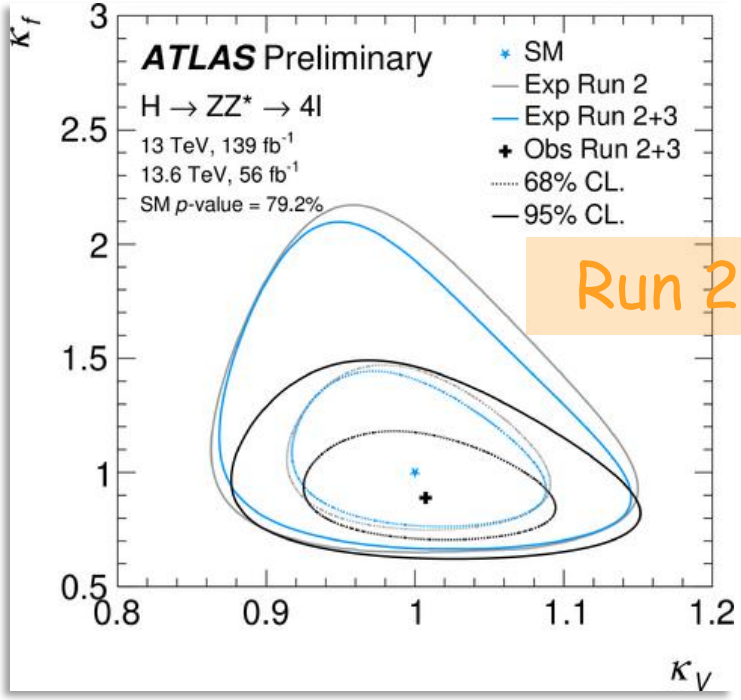
Interpret as universal modifiers to boson and fermion couplings



$$\sigma \cdot \mathcal{B}\,(i \rightarrow H \rightarrow f) = \kappa_i^2 \cdot \kappa_f^2 \cdot \sigma_i^{\mathrm{SM}} \cdot \frac{\Gamma_f^{\mathrm{SM}}}{\Gamma_H(\vec{\kappa})} \qquad \kappa_i^2 = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \quad \text{and} \quad \kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{\mathrm{SM}}}$$

Universal coupling-strength modifiers κ_f for fermions and κ_V for heavy vector bosons are defined as:

$$\kappa_V = \kappa_W = \kappa_Z \text{ and } \kappa_f = \kappa_t = \kappa_b = \kappa_c = \kappa_\tau = \kappa_\mu$$

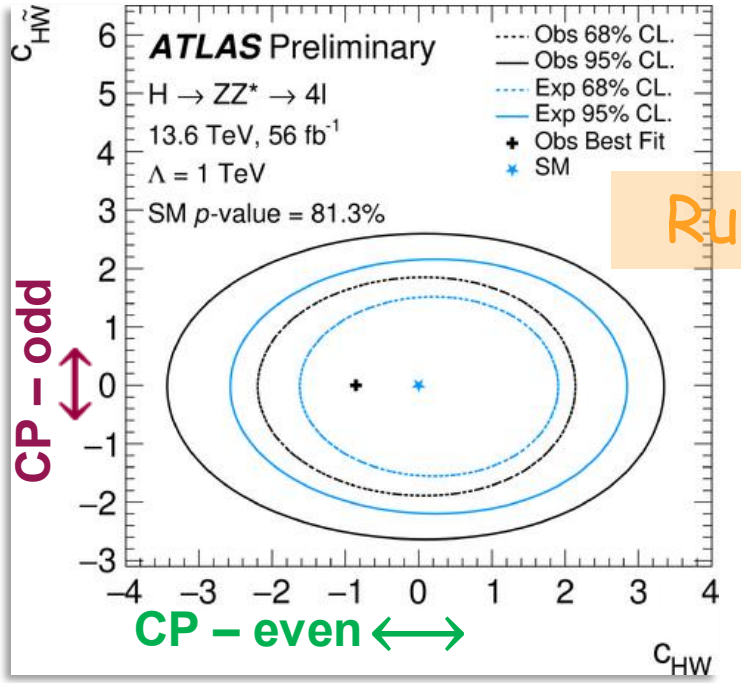
Constrain CP-violation using effective field theory

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}$$

$C_i^{(d)}$ **Wilson coefficients**: They specify the strength of new interactions and Λ is the scale of new physics

$$c_i = C_i^{(d=6)} / \Lambda^2$$

For energies below the scale Λ, only the ratio can be constrained by the data.



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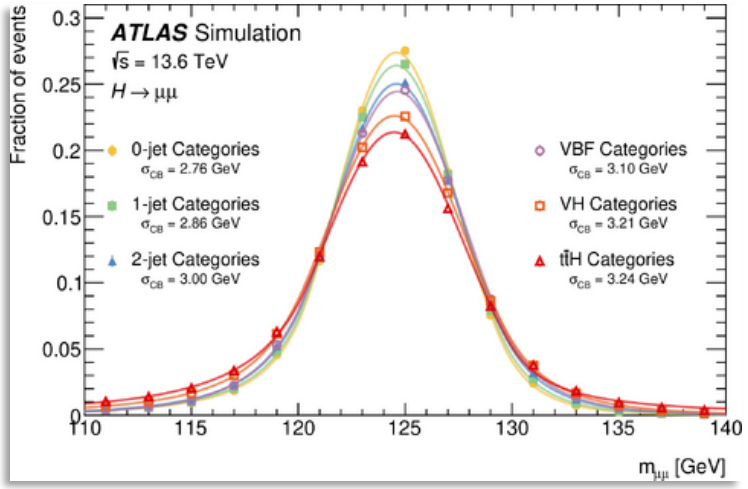
Evidence of $H \rightarrow \mu\mu$ (Run 2+3)

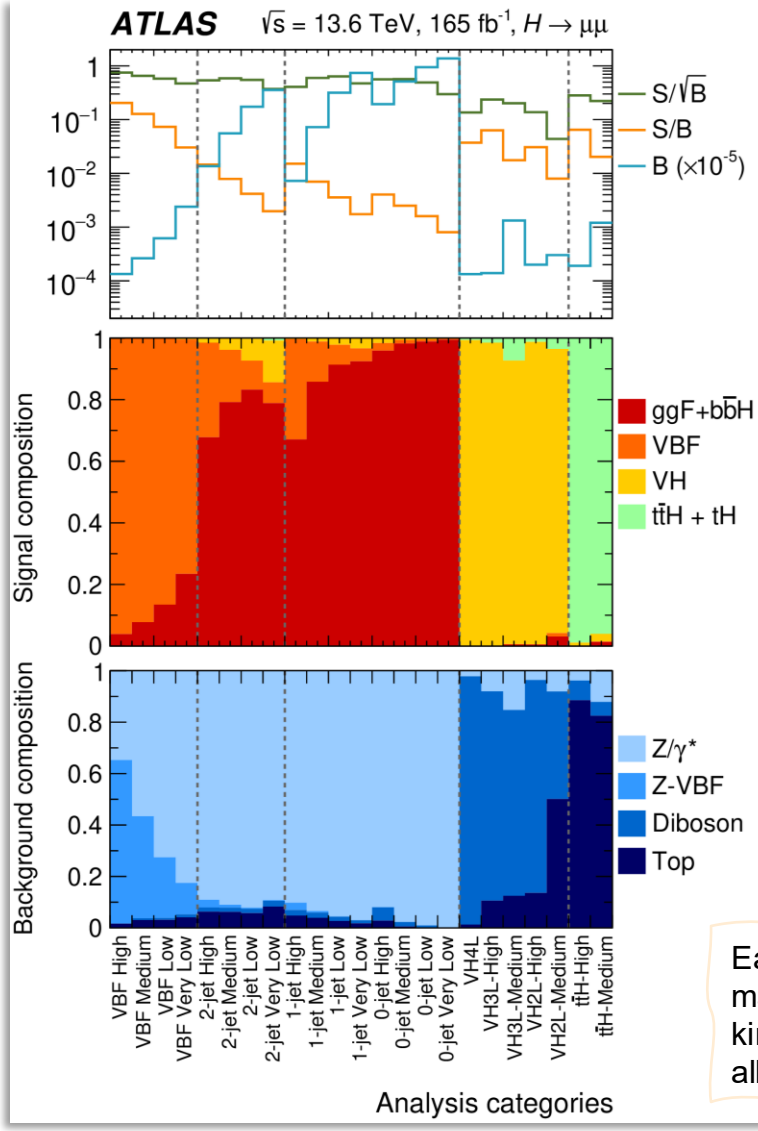
- Probes the Higgs coupling to second generation fermions
- Tiny BR
- Big Background from Drell-Yan
- Highly optimized categorization, using ML classifiers (BDT/DNN)

Evidence of H → μμ (Run 2+3)

- Search for decays of H→μμ decays → direct measurement of Higgs coupling to second generation fermions
- Very small S/B: Categorization based on Higgs production mode and kinematic observables (BDT/NN)
- Main improvements compared Run 2 analysis:
  - Additional 2022-2024 dataset (165 fb^{-1})
  - High statistics Drell-Yan samples for background modelling studies
  - Additional a 2-lpton VH category and ttH-hadronic categories



Signal and Background composition in the 23 analysis categories in the mass region $m_{\mu\mu}$ =120-130GeV



S/√B = significance
S/B = expected signal-to-background ratio
B x 10^{-5} = number of background events multiplied by a factor of 10^{-5}

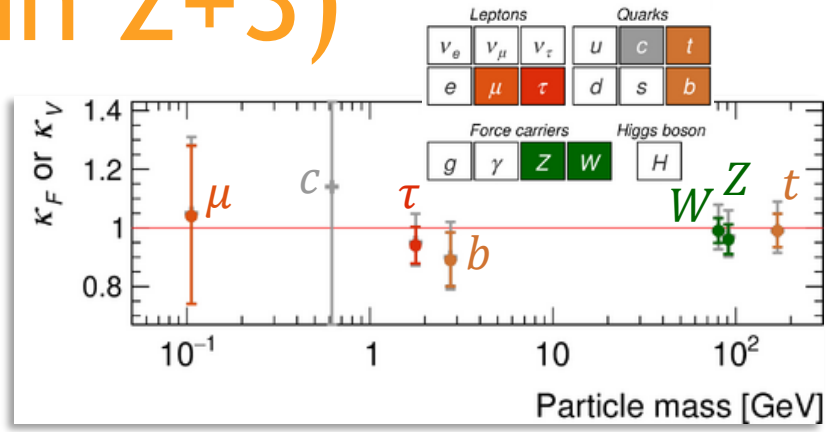
Expected contributions of different Higgs-boson production modes to the total signal in each category

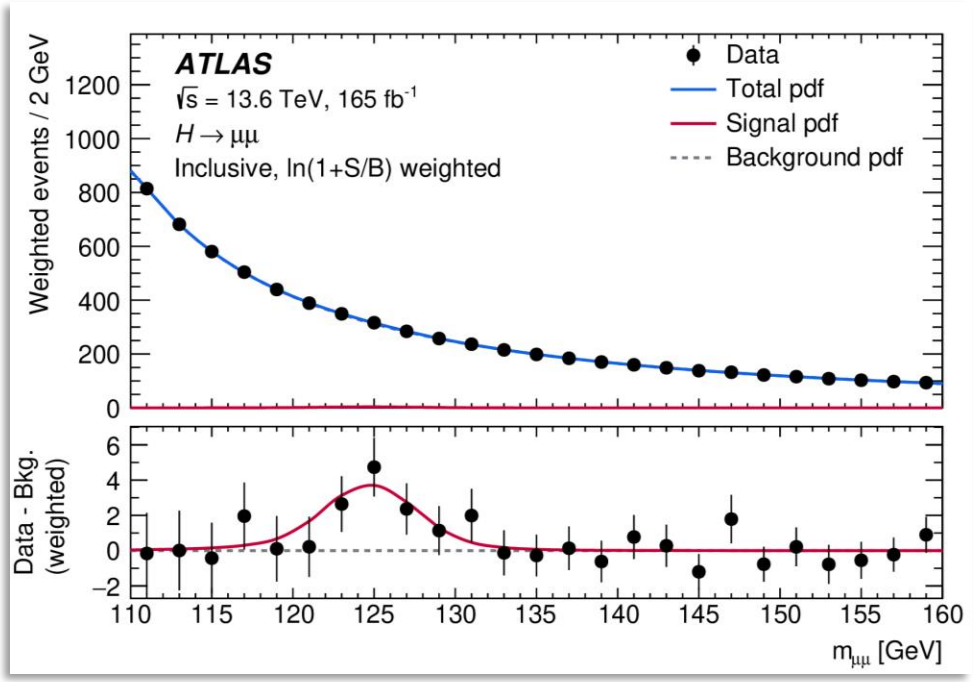
Background composition from Drell–Yan, diboson and top-quark processes in simulation.

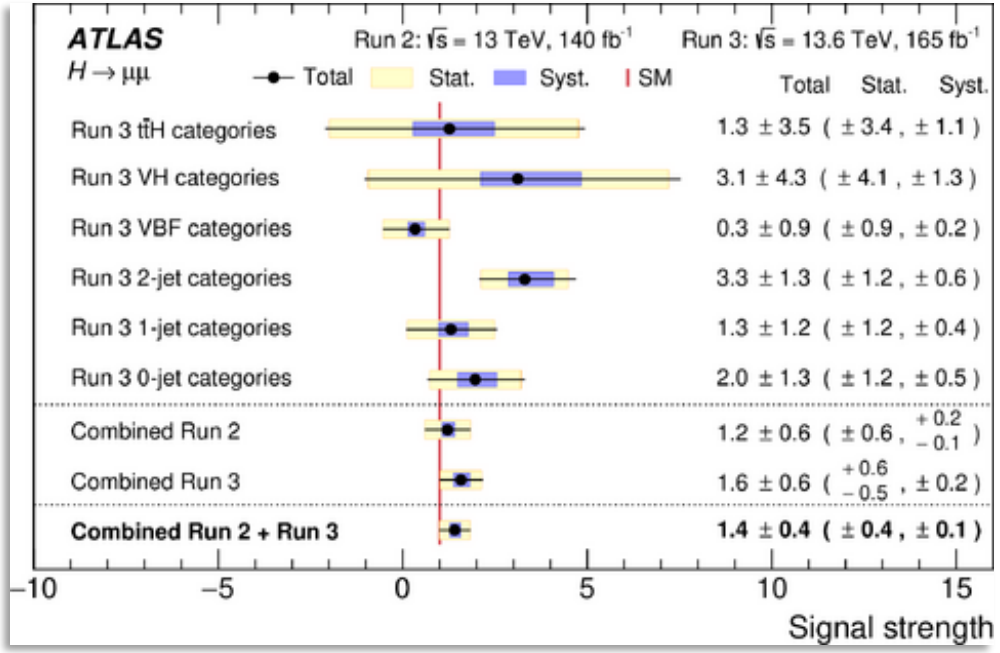
Each category is carefully designed to maximize sensitivity while decorrelating kinematic variables from dimuon mass, allowing precise fit to signal peak

Evidence of H → μμ (Run 2+3)

- Primary probe of 2nd gen. Yukawa coupling at LHC
- Small signal over enormous Drell-Yan background
- This analysis uses 165 fb^{-1} of data collected in 2022-2024
- Boost $m_{\mu\mu}$ resolution
- Maximize significance using multivariate analysis







- Run 3 result: $\mu_{H\to\mu\mu} = 1.6 \pm 0.6$ → 2.8σ (1.8σ) observed (expected) significance
- **Run 2+ Run 3 result: $\mu_{H\to\mu\mu} = 1.4 \pm 0.4$ → 3.4σ (2.5σ) observed (expected) significance**

→ Clear **evidence for H→μμ** in agreement with the SM

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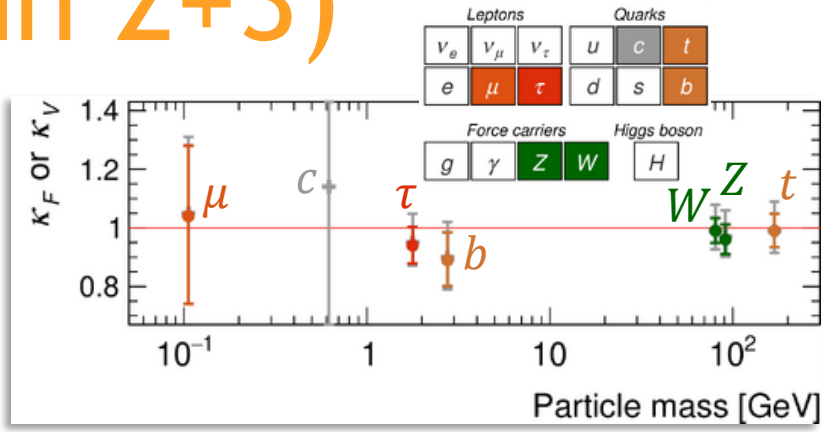

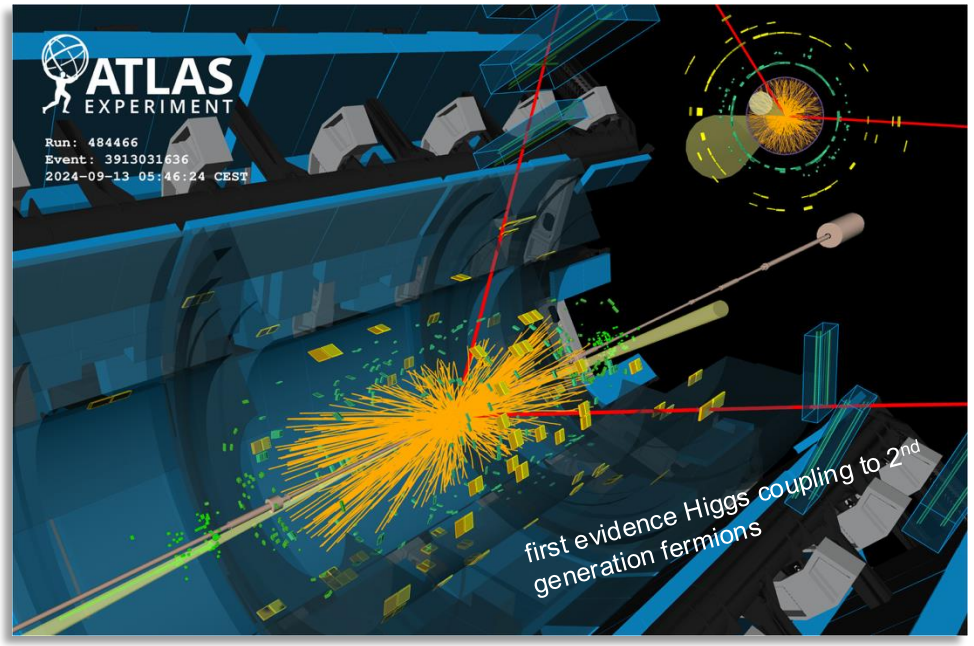

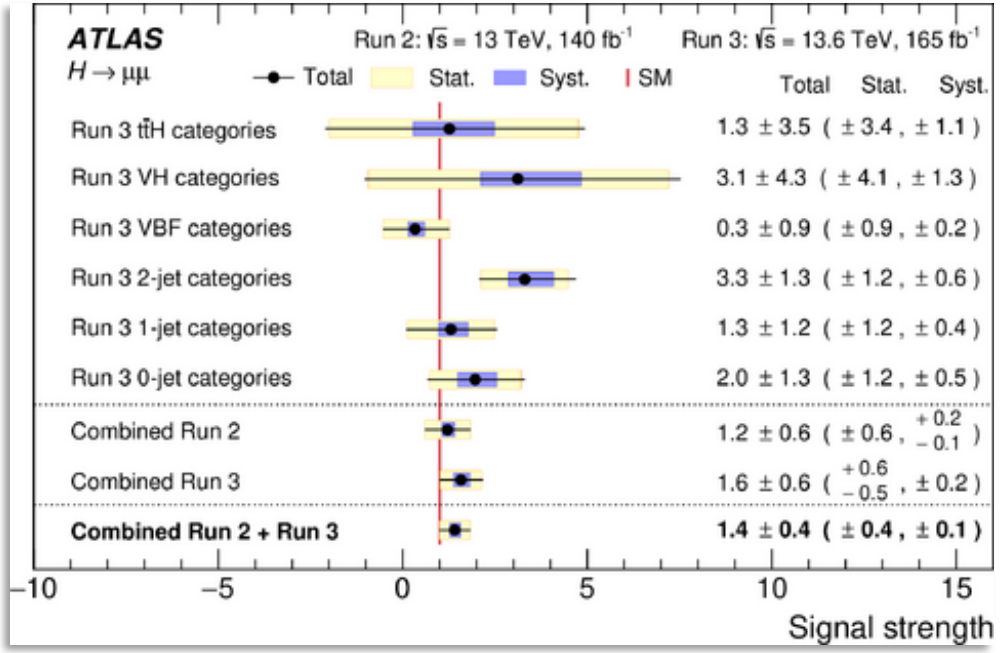

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→ Clear **evidence for H→μμ** in agreement with the SM

ggF+VBF H→WW couplings

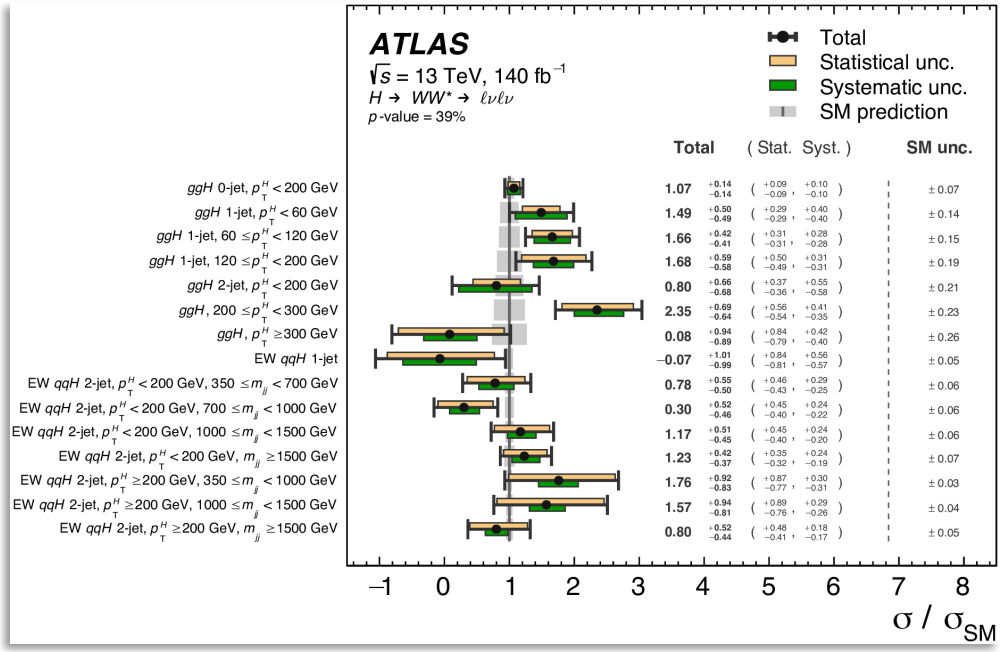
- Channel with higher statistics
- More complex backgrounds: from continuum WW and top production
- We use both opposite and same flavour dilepton final state to maximize sensitivity

ggF+VBF H→WW couplings

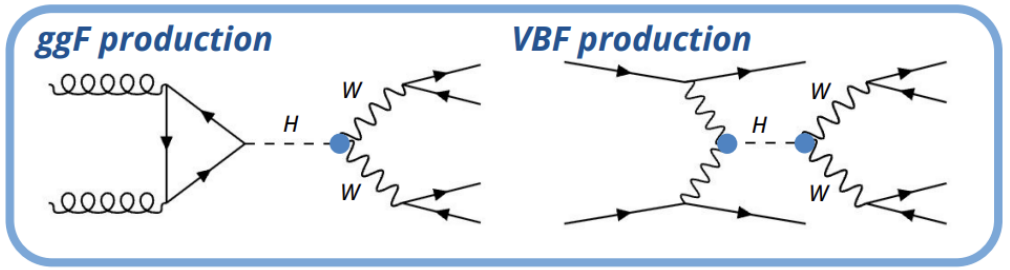
arXiv: 2504.07686

Measurement of H→WW→ℓνℓν decays in the ggF and VBF production modes

- Run 2 “legacy” analysis, improving on previous iteration through:
  - Addition of same flavour channel
  - Improvements to neural net analysis discriminants & usage in all categories
  - Dedicated CP-sensitive Simplified Template Cross-Section (STXS) scheme and Effective Field Theory (EFT) interpretation



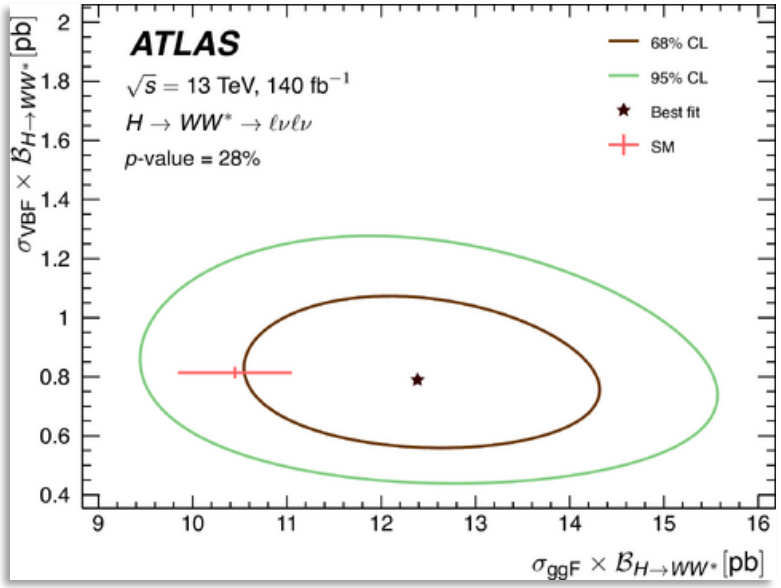
cross section measured in each of the STXS categories, normalised to SM predictions



Best-fit cross-sections:

- $\sigma_{ggF} \times BR_{H\to WW} = 12.4\ ^{+1.3}_{-1.2}$ pb
- $\sigma_{VBF} \times BR_{H\to WW} = 0.79\ ^{+0.18}_{-0.16}$ pb

→ 10-30% improvement in sensitivity compared to previous iteration



ggF+VBF H→WW couplings

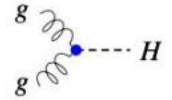
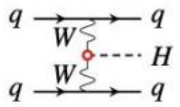
arXiv: 2504.07686

Measurement of H→WW→ℓνℓν decays in the ggF and VBF production modes

- Measurement of cross-sections in the STXS CP scheme compatible with SM with a p-value of 91%
- EFT interpretation in CP-conserving and CP-violating scenarios

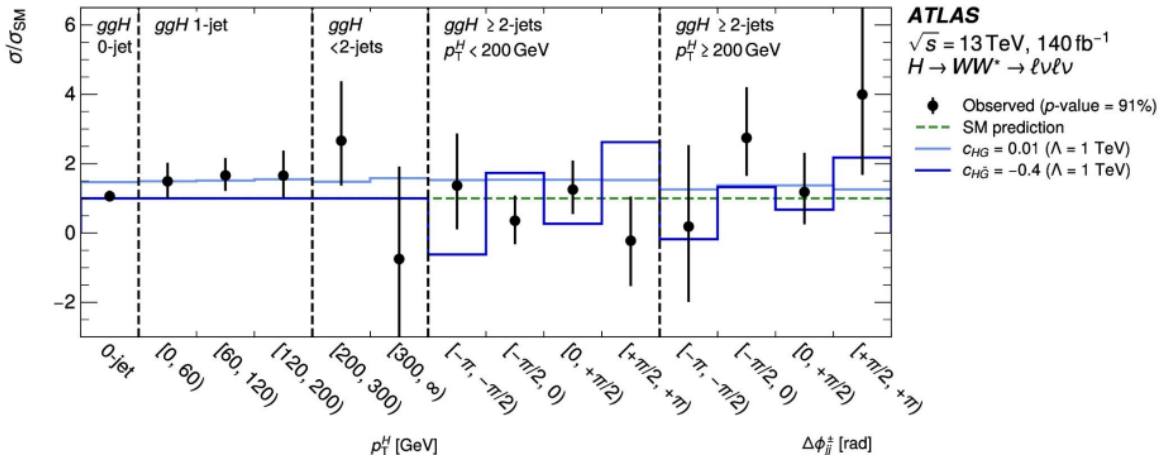
→ Best-fit Wilson coefficients show good agreement with SM expectations

SMEFT Lagrangian $\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_i \frac{c_i O_i^{(d)}}{\Lambda^{(d-4)}}$

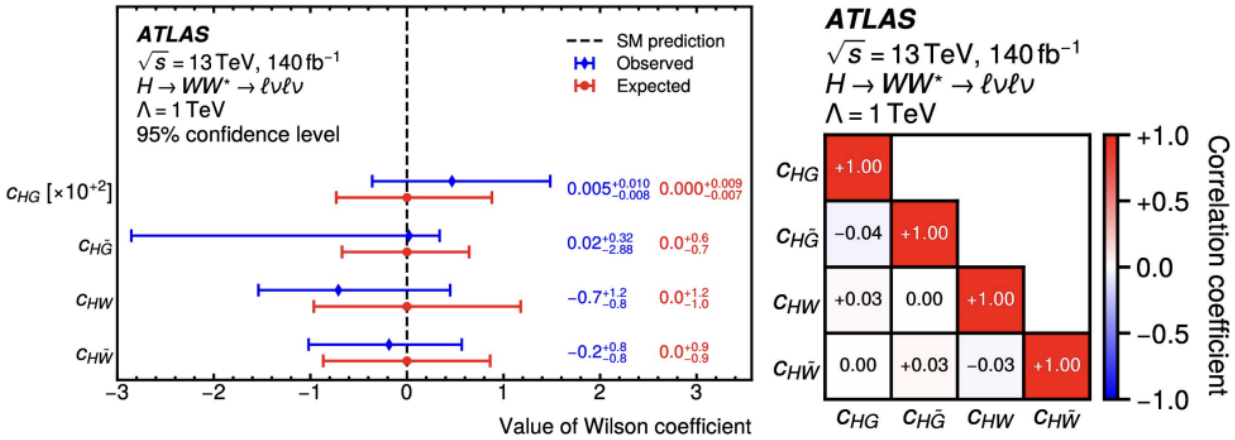
Wilson coefficient	Operator	Effect or affected diagram
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	

CP-even Wilson coefficients & relevant vertices

Best fit signal strengths in the ggF STXS$_{CP}$ categories



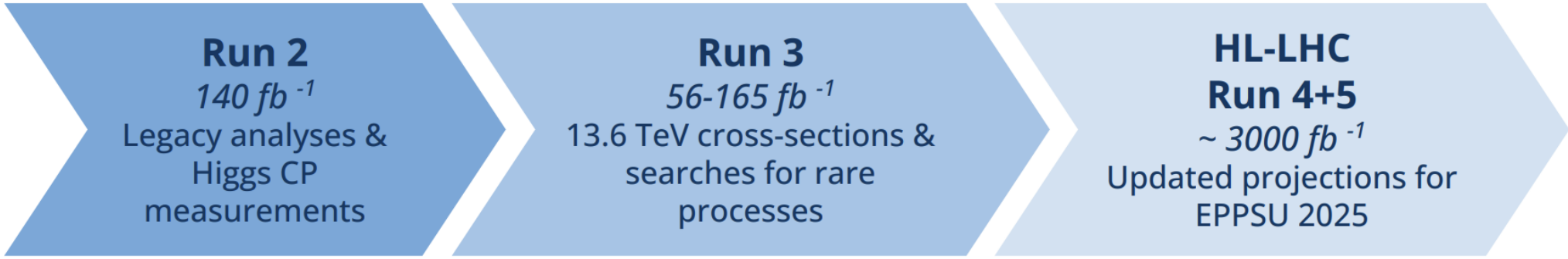
Best fit Wilson coefficients for CP violating scenario



- EFT framework allow us to interpret the results in a broader context; combining CP-sensitive observables and EFT fits, are essential preparation for the H—LHC, where we expect to reach percent-level precision on many of these parameters

Summary & Conclusions

In this talk, overview of recent recent **ATLAS** results on **Higgs boson measurements** were presented:



- The $H \longrightarrow ZZ^* \longrightarrow 4l$ channel provides per mille precision on the Higgs mass an differential cross section
- The $H \longrightarrow \mu\mu$ analysis gives first evidence of the muon Yukawa coupling
- The $H \longrightarrow WW$ results refine our EFT and CP-violation tests, establishing strong groundwork for future studies

All these results are fully consistent with the Standard Model, yet the precision we are reaching is such that even small deviations, if any, could soon become visible.

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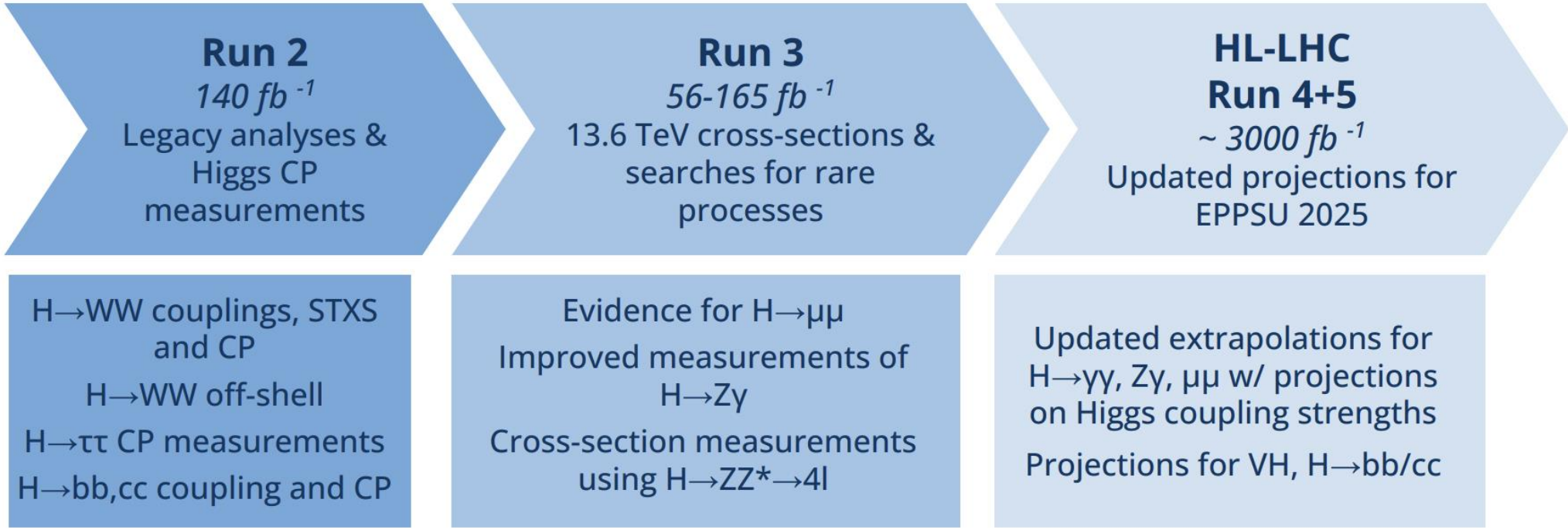

Broad Higgs measurement program in ATLAS with Higgs precision measurements and searches → aiming to make the most of the available and future datasets!

Thank you