SM Higgs boson properties by CMS and ATLAS

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on behalf of ATLAS and CMS collaboration

The University of Tokyo

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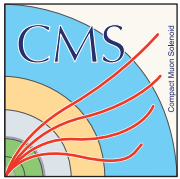

Outline

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  - Decay modes
  - Mass
  - Cross section measurements
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- SMEFT interpretations
- Anomalous couplings of Hff
- Spin correlation in HZZ
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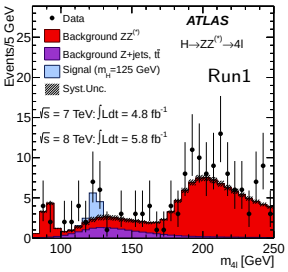
Introduction

- After the discovery of the Higgs boson in 2012, ATLAS and CMS have been working on various topics to explore the Higgs properties and use the Higgs boson as a probe to explore the possibility of BSM physics.
- We can characterize the Higgs boson by studying:
  - **Production cross sections**, **differential and fiducial cross sections**, **couplings**, **mass**, **width**, **rare decays**, and else.
- ATLAS and CMS updated the combination of Higgs results published with the Run2 dataset (and partial Run3 for ATLAS) after the Nature papers published in 2022.

Phys. Lett. B 716 (2012) 1



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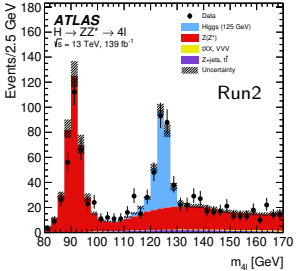

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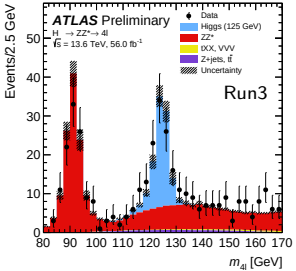

Single Higgs production

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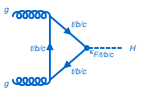
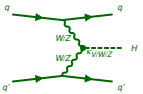
ggH

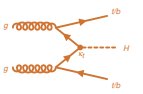


VBF(qqH)

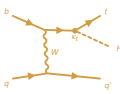


VH

ttH/bbH



tH



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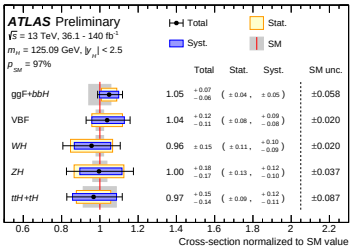
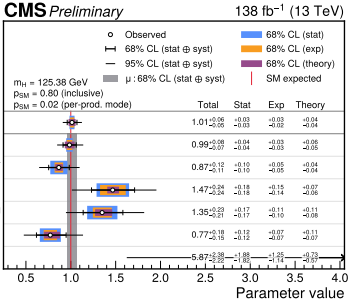


CMS-PAS-HIG-21-018



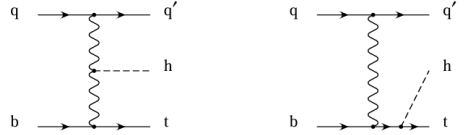
- **bbH** and **tH** are not yet discovered.
- Compared to the publications in the Nature papers[1,2], the inclusion of the new analysis improves the uncertainties of the cross section measurements.
  - $H \to bb$ for VH and ttH in both ATLAS and CMS, and VBF in CMS.
- Global signal strength:
  - $\mu = 1.023^{+0.056}_{-0.053}$ (ATLAS)
  - $\mu = 1.014^{+0.055}_{-0.053}$ (CMS)

1 CMS Collaboration, "A portrait of the Higgs boson by the CMS experiment ten years after the discovery.", Nature 607 (2022) 60.

2 ATLAS Collaboration, "A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery", Nature 607 (2022) 52.

Search for tH production mode

JHEP 10 (2025) 093 (ATLAS)
JHEP 02 (2025) 097 (CMS)



- Sensitive to the sign of the y_t.
  - $\kappa_t = y_t / y_t^{SM}$, positive κ_t causes the destructive interference to W boson, suppressing the cross section.
- Targeting various Higgs decay modes:
  - H $\to$ bb, H $\to$ WW, H $\to$ ZZ, H $\to$ $\tau\tau$.
  - only H $\to$ bb in CMS.
- Upper limit at 95% CL ($\kappa_t = 1$):
  - $\mu_{tHq+tWH} < 14.6$ (CMS) and 13.6 (ATLAS).
- Inverted top-quark Yukawa coupling (ITC) (κ_t = -1)
  - $\mu_{tHq+tWH} < 2.4$ (ATLAS).

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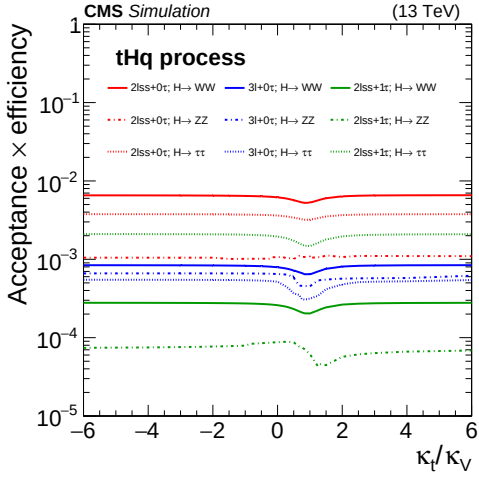

Higgs decay

- Final states include
  - vector bosons $WW^{(*)}/ZZ^{(*)}$
  - $\gamma\gamma/Z\gamma$ via one loop
  - quarks bb/cc
  - leptons $\tau\tau/\mu\mu$
  - etc.
- cc is not yet observed.
- Both of ATLAS and CMS achieved 3σ for $\mu\mu$.
- $Z\gamma$ is above 3σ in the combination of ATLAS and CMS.

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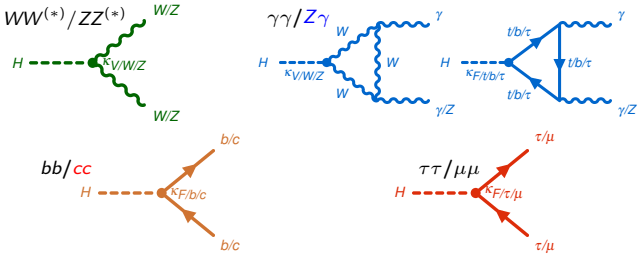

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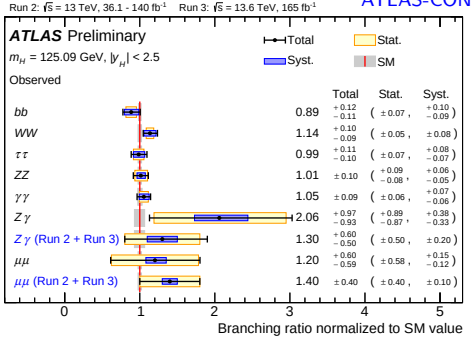
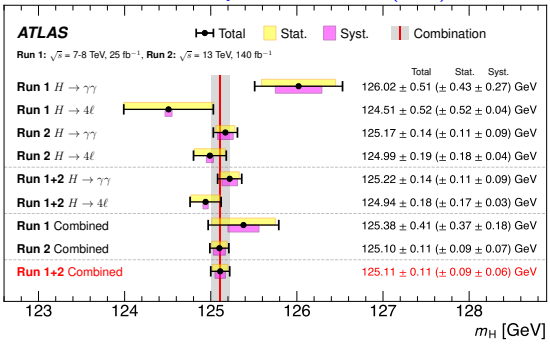


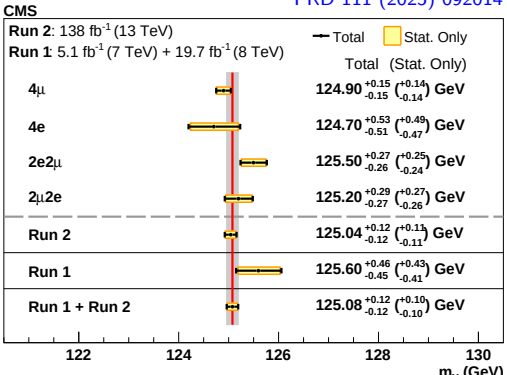
Higgs mass

- ATLAS and CMS measured the Higgs mass with full Run2 data combined with the Run1 results, achieving the precision of less than 0.1%.
  - 125.11±0.09 (stat.)±0.06(syst.) = **125.11±0.11** GeV (ATLAS). (H4ℓ+H$\gamma\gamma$)
  - 125.08±0.10 (stat.)±0.07(syst.) = **125.08±0.12** GeV (CMS). (H4ℓ only)

Phys. Rev. Lett. 131 (2023) 251802



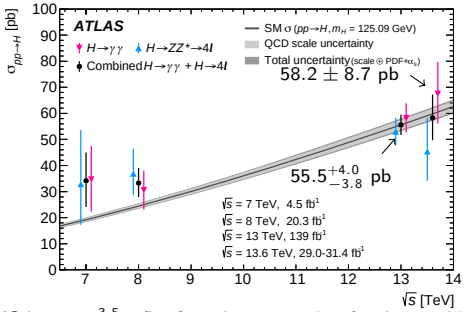
PRD 111 (2025) 092014



Inclusive cross section measurement with Run3 dataset

- ATLAS reported the total cross section for $H4\ell$ and $H\gamma\gamma$.
  - 58.2±8.7 pb in combination of $H4\ell$ and $H\gamma\gamma$ with Run3 (2022) (∼**15%** of rel. uncert.)
  - 57^{+10}_{-9} pb in $H4\ell$ with 56 fb^{-1}of Run3 data (2022+2023). (∼**17%**) (ATLAS-CONF-2025-002)
- CMS reported fiducial cross section for $H4\ell$ and $H\gamma\gamma$ with 2022 data. (JHEP 09 (2025) 070)
  - $\sigma_{\rm fid} = 74 \pm 11({\rm stat})^{+5}_{-4}({\rm syst})$ for and $H\gamma\gamma$ with changed fiducial phase space in Run3 measurement. (∼**16%**)
  - $\sigma_{\rm fid} = 2.89 \pm^{+0.53}_{-0.49}({\rm stat})^{+0.29}_{-0.21}({\rm syst})$ for $H4\ell$. (∼**21%**)

Eur. Phys. J. C 84 (2024) 78



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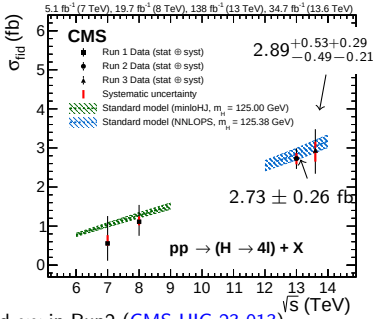
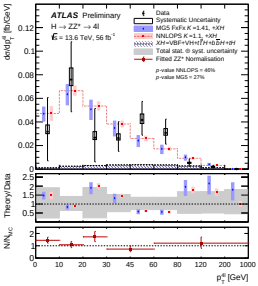


Note: CMS has $53.4^{3.5}_{-3.4}$ fb of total cross section for the combiniation of ZZ and $\gamma\gamma$ in Run2 (CMS-HIG-23-013)

Differential cross sections

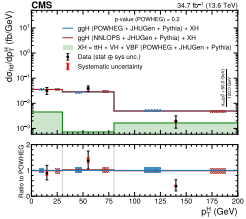
- p_T^H and y^H with Run3 dataset are available for $H \to ZZ^* \to 4\ell$ (ATLAS, CMS) and $H \to \gamma\gamma$ (CMS).
- CMS combined the Run2 results of $\gamma\gamma$, ZZ^*, WW^*, and $\tau\tau$.
- No significant deviation is confirmed.

ATLAS-CONF-2025-002



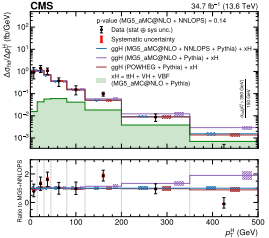
$H \to 4\ell$

JHEP 05 (2025) 079



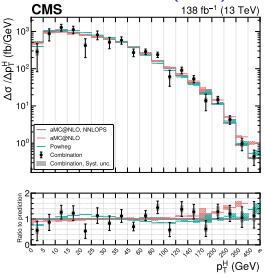
$H \to 4\ell$

JHEP 09 (2025) 070



$H \to \gamma\gamma$

JHEP 07 (2023) 091

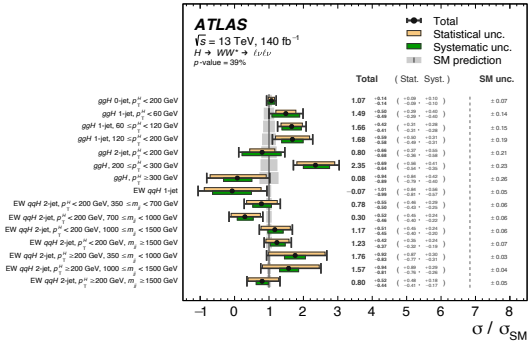


Combination

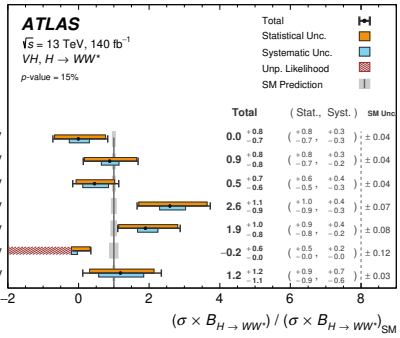
Simplified template cross sections (STXS)

- STXS: LHC-wide framework, prescribes differential bins that maximize sensitivity and reduce theory dependence.
- ggF categories shows the best limits and deviations are still considered as data fluctuations.
- STXS Stage 1.3 is available with finer binnings in Higgs pT and additional bins in $\Delta\phi_{jj}$ in the VBF phase space.

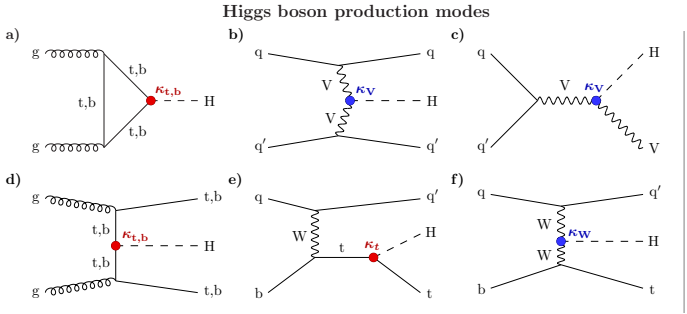
Eur. Phys. J. C 85 (2025) 1403



JHEP 08 (2025) 034



Higgs coupling in the κ-framework



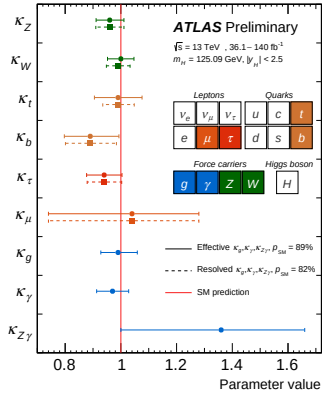
Nature 607 (2022) 60-68

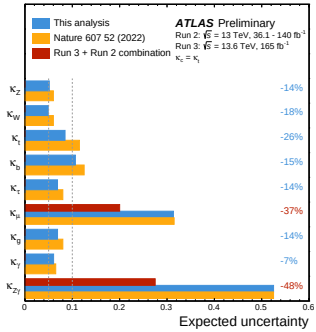
- The κ-framework is used to parametrize all the deviations from SM predictions of Higgs boson couplings to SM bosons and fermions with a set of coupling modifiers $\vec{\kappa}$.
- Any BSM process modifying the coupling strengths can be observed by this framework.

$$\sigma \cdot \mathcal{B}(i \to H \to f) = \kappa_i^2 \cdot \kappa_f^2 \cdot \sigma^{\mathrm{SM}} \cdot \frac{\Gamma_f^{\mathrm{SM}}}{\Gamma_{(\kappa_i^2,\kappa_f^2)}}, \quad \kappa_i^2 = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}}, \quad \kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{\mathrm{SM}}}$$

Higgs coupling

- The loop-induced processes are treated either using effective coupling strength modifiers (κ_g, κ_γ and $\kappa_{Z\gamma}$) or using the resolved parametrization.
- κ_F vs. κ_V with $\kappa_V = \kappa_Z = \kappa_W$ and κ_F for all fermions is also measured.





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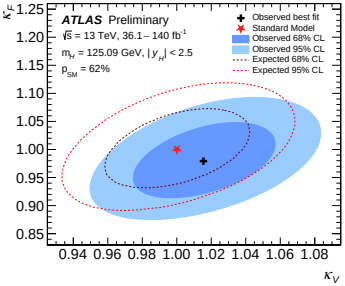

Higgs coupling strength

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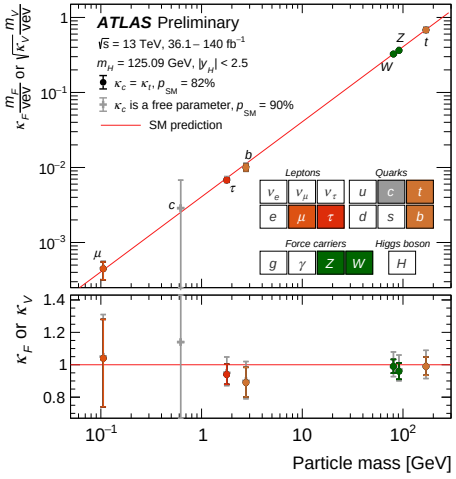

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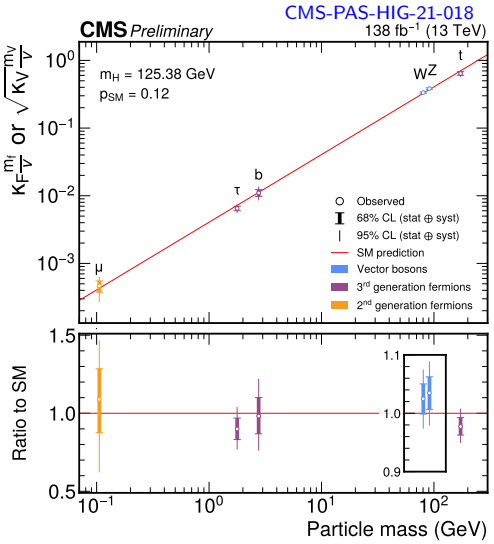
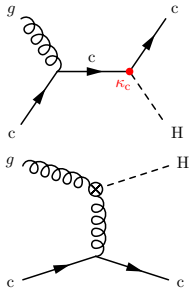


Higgs coupling to c-quark

- Low efficiency of the c-tagging makes the search difficult.
- **Decay side approach**: H→ cc, VH (ATLAS/CMS), VBF (ATLAS) or ttH (CMS). See Austin's talk and Lisa's talk.
  - c-quark from the decay of the vector boson is the main background.
- **Production side approach** (CMS): y_c-sensitive c+H , $H \to \gamma\gamma$ and WW
  - Very low cross section: 0.028 pb.
  - ATLAS has inclusive c+H measurements.



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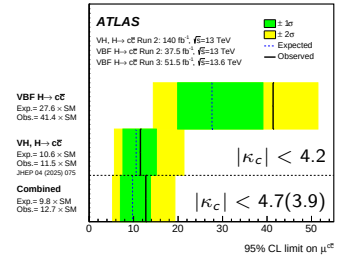
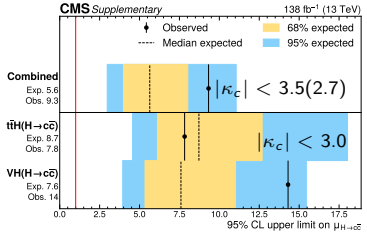


Phys. Rev. Lett. 136 (2026) 011801



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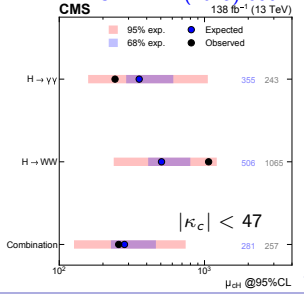


Higgs width

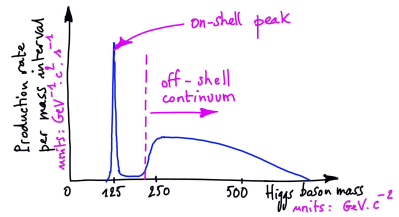
- The total width can be extracted from the ratios of yields of on-shell and off-shell Higgs boson events.
  - Total Higgs width is 4.1 MeV in SM prediction. It is too small to be measured directly.
- Total decay width measurements:
  - $4.3^{+2.7}_{-1.9}$ MeV (ATLAS H→ZZ re-analyzed)
  - $3.2^{+2.4}_{-1.7}$ MeV (CMS H→ZZ)
  - $\Gamma_H < 13.1$ MeV at 95 CL. (ATLAS H→WW), $3.9^{+2.7}_{-2.2}$ MeV (CMS H→WW)
  - $\Gamma_H < 92$ MeV at 95 CL. (CMS H→ $\gamma\gamma$)

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggF} g^2_{HZZ}}{m_H \Gamma_H}.$$

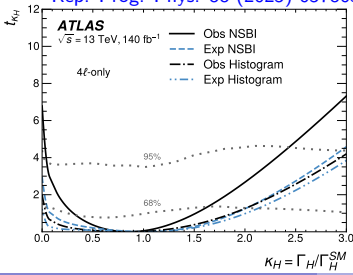
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggF} g^2_{HZZ}}{m^2_{ZZ}}$$

$$\Gamma_H = \frac{\sigma^{\text{off-shell}}_{gg\to H\to ZZ}}{\sigma^{\text{on-shell}}_{gg\to H\to ZZ}}$$

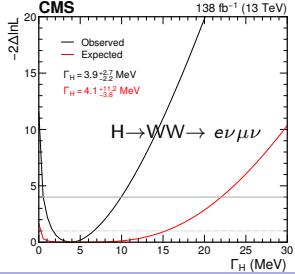
Life of the Higgs boson



Rep. Prog. Phys. 88 (2025) 057803



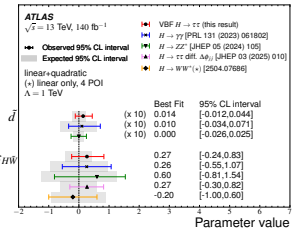
CMS-HIG-24-011



SMEFT interpretations

- A new result of H $\to \tau\tau$ (VBF production) using optimal observables is published by ATLAS.
- CMS performed the combination of $\gamma\gamma$, ZZ^*, WW^*, $\tau\tau$ with p_T^H and $\Delta\phi_{jj}$.
- ATLAS performed the STXS analysis including $\gamma\gamma$, ZZ^*, WW^*, $\tau\tau$, bb, $Z\gamma$ and $\mu\mu$ channels.
- Wilson coefficients are rotated to a new fit basis to maximize the sensitivities.

JHEP 10 (2025) 92



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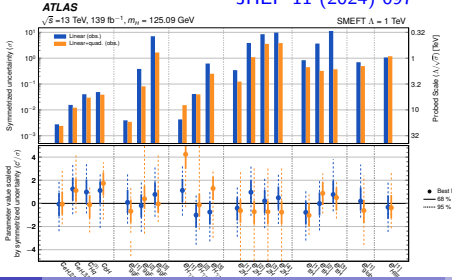
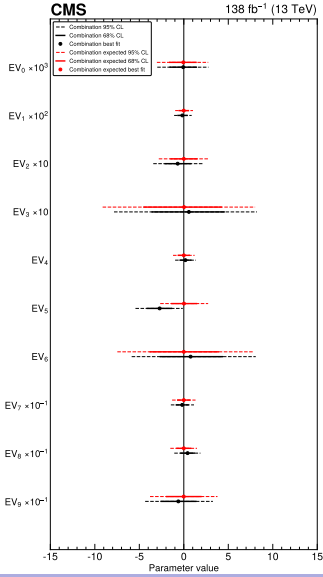


CMS-HIG-23-013



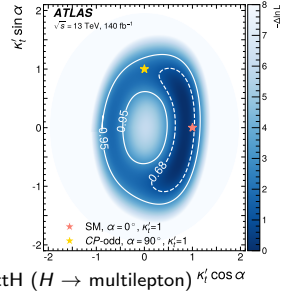
Anomalous couplings of *Hff*

- The anonmalous effects of Hff can be parameterized with the amplitude as:

$$A(Hff) = -\frac{m_f}{v}\bar{\psi}(\kappa_f + i\tilde{\kappa}_f\gamma_5)\psi$$

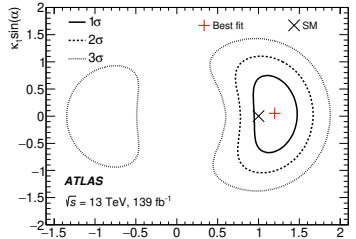
- ttH (H $\rightarrow$ multilepton) is available in ATLAS.
  - Six Categories are defined in the N. of τ_{had} and the N. of light leptons.
  - BDT discriminants are used for all categories except for 4ℓ (DNN is used).
- No deviation from SM has been found.

ATLAS HIGP-2024-08



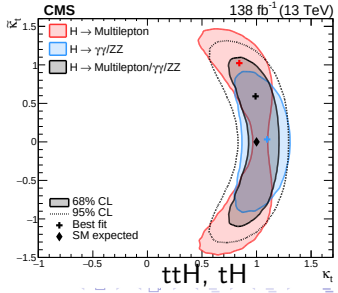
ttH ($H \rightarrow$ multilepton)

Phys. Rev. Lett. 125 (2020) 061802



ttH, tH, $H \rightarrow \gamma\gamma$

JHEP 07 (2023) 092



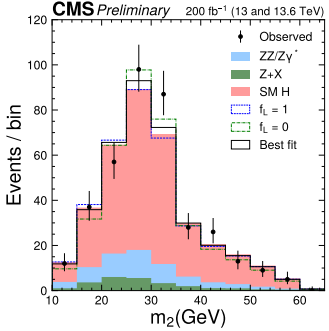
ttH, tH

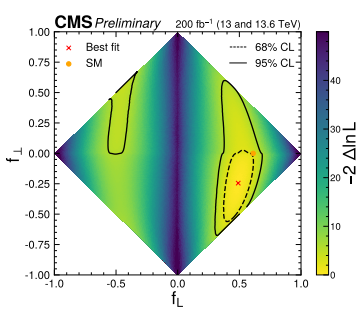
Spin correlations in H $\to ZZ \to 4\ell$

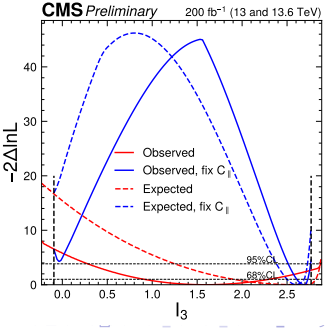
CMS-PAS-HIG-25-011

- CMS provided the results with Run2 + partial Run3 (22-23) dataset.
- f_L and $f_\perp$ are average fractions of longitudinal polarization and CP-odd transverse polarization states. $C_\parallel$ is a coherent parameter.
- Results match to the SM prediction.

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & (1-f_L)/2 & 0 & -C_\parallel\sqrt{f_L(1-f_L)/2} & 0 & (1-f_L)/2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -C_\parallel\sqrt{f_L(1-f_L)/2} & 0 & f_L & 0 & -C_\parallel\sqrt{f_L(1-f_L)/2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & (1-f_L)/2 & 0 & -C_\parallel\sqrt{f_L(1-f_L)/2} & 0 & (1-f_L)/2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$



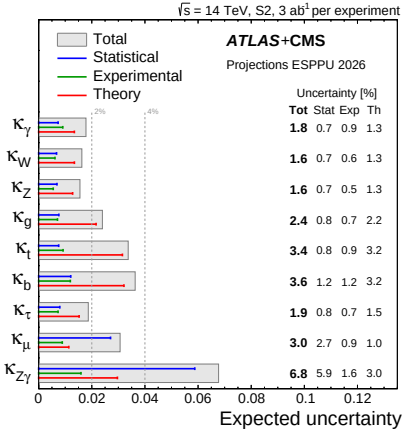




Summary

- The results with partial Run3 data in the channels of $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ are available at ATLAS and CMS.

ATL-PHYS-PUB-2025-018



- The first evidence of $H \to \mu\mu$ at ATLAS is published with paritial Run3 and Run2 dataset.
- High precision measurements of Higgs mass (0.1% accuracy) is achieved with Run2 dataset.
- Combination of Run2 results among the production modes and final states achieved higher precision.
- Production mode (tH) and decay modes ($\mu\mu$, cc, $Z\gamma$) with low rates are getting more attention.
- More results with partial Run3 dataset are working in process.

Back up

New measurements in Run3

- ATLAS reported the new measurements for $H \to \mu\mu$ and $H \to Z\gamma$ with partial Run3 dataset (2022-2024).
- In the combination of the Run2 results:
  - $H \to \mu\mu$: observed significance 2.0σ (1.7σ) (Run2) $\to$ 3.4σ (2.5σ) (Run2+Run3).
  - $H \to Z\gamma$: observed significance 2.2σ (1.1σ) (Run2) $\to$ 2.5σ (1.9σ) (Run2+Run3).

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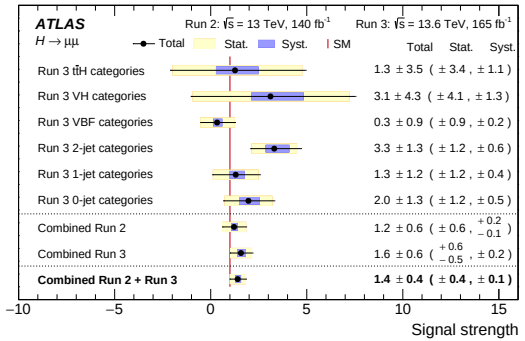

HIGP-2024-19