Higgs couplings and properties

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Outline

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  - Mass
  - Cross section measurements
  - Couplings
  - Width
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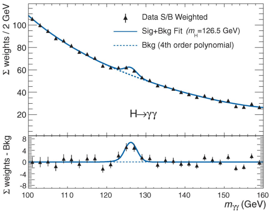
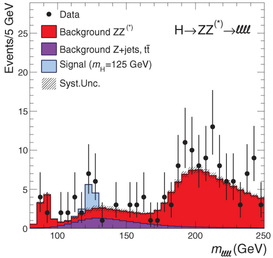
Introduction

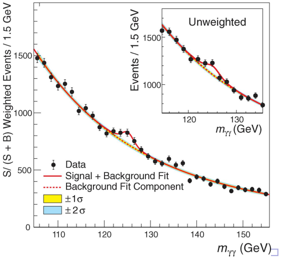
- After the discovery of the Higgs boson in 2012, ATLAS and CMS have been working on various topics to explore the Higgs properties and use the Higgs boson as a probe to explore the possibility of BSM physics.
- We can characterize the Higgs boson by studying:
  - **Production cross sections**, **differential and fiducial cross sections**, **couplings**, **mass**, **width**, **rare decays**, and else.
- Two Nature papers from ATLAS (Nature 607, 52 (2022)) and CMS (Nature 607 (2022) 60-68) give an overview of the Higgs boson ten years after discovery.

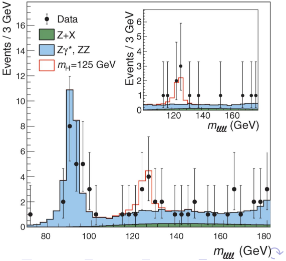
Science 338 (2012) 1576-1582





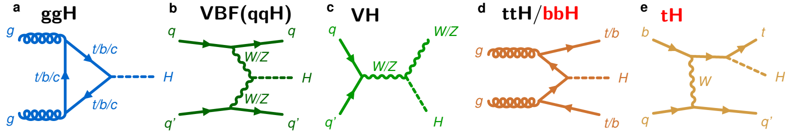
Science 338 (2012) 1569-1575





Single Higgs production

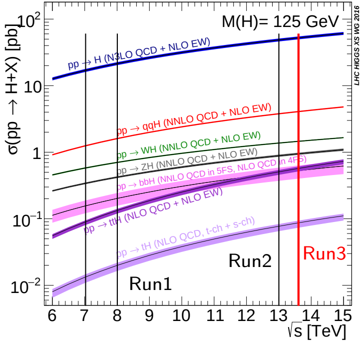
Nature 607, 52 (2022)



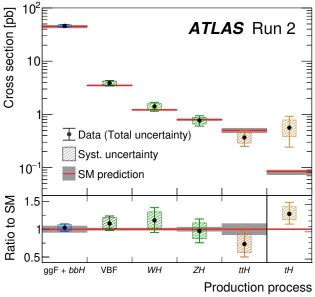
- Global signal strength:
  - $\mu = 1.05 \pm 0.06$ (ATLAS)
  - $\mu = 1.002 \pm 0.057$ (CMS)

- **bbH** and **tH** are not yet discovered.

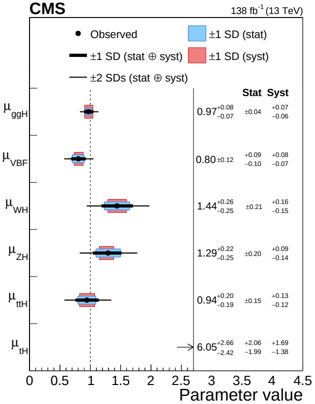
CERN Yellow Report 4



Nature 607, 52 (2022)



Nature 607 (2022) 60-68

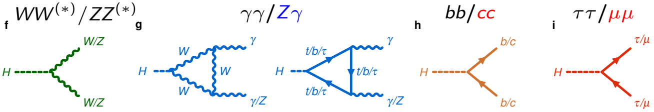


$$\mu_i = \frac{\sigma_{obs}}{\sigma_{\rm SM}}$$

Higgs decay

- cc and $\mu\mu$ are still under searching.
- $Z\gamma$ is above 3σ in the combination of ATLAS and CMS.

Nature 607, 52 (2022)



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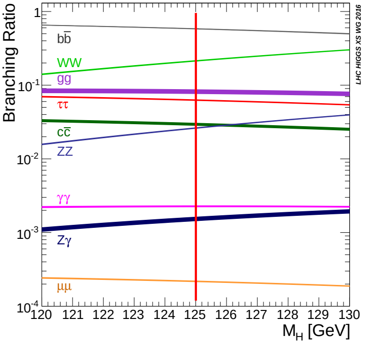

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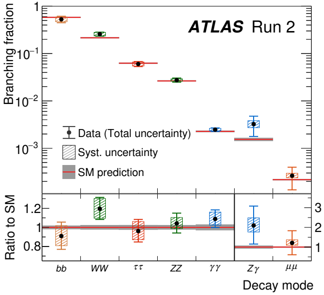
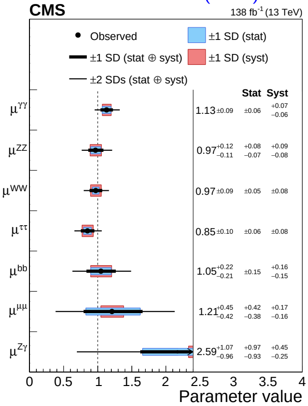


Nature 607 (2022) 60-68



$$\mu_i = \frac{\mathcal{B}_{obs}}{\mathcal{B}_{\rm SM}}$$

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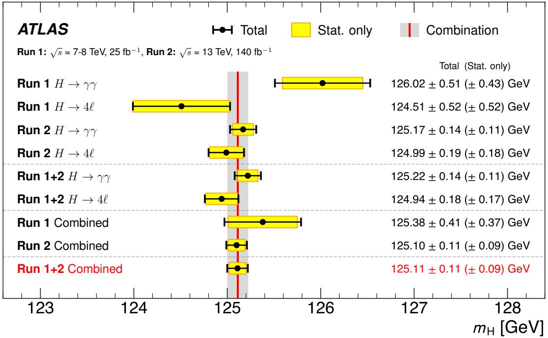
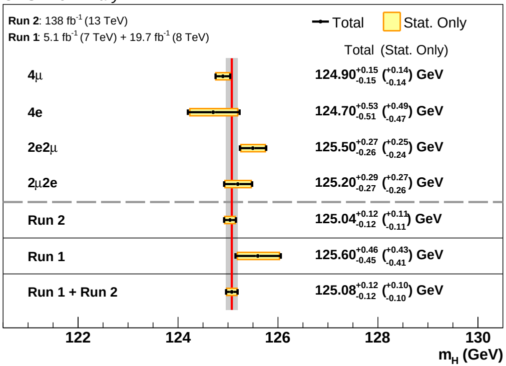
Higgs mass

- ATLAS and CMS measured the Higgs mass with full Run2 data combined with the Run1 results, achieving an accuracy of less than 0.1%.
  - 125.11±0.09 (stat.)±0.06(syst.) = **125.11±0.11** GeV (ATLAS).
  - 125.08±0.10 (stat.)±0.07(syst.) = **125.08±0.12** GeV (CMS).

Phys. Rev. Lett. 131 (2023) 251802



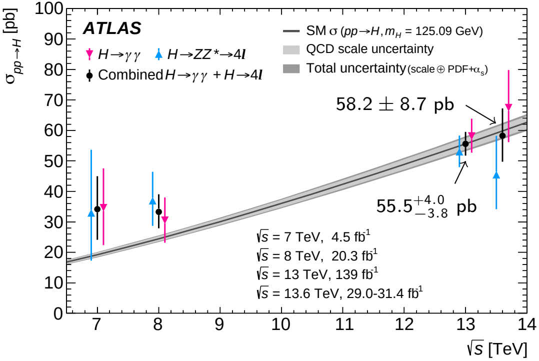
CMS-PAS-HIG-21-019



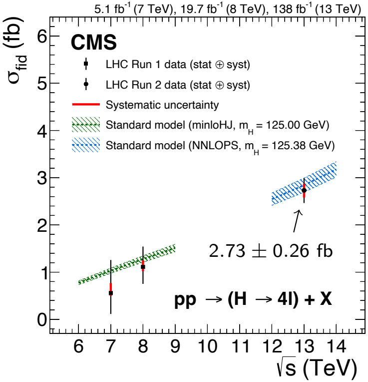
Inclusive cross section measurement

- ATLAS published the measurements of the total cross section in $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ with Run1, Run2 and Run3 (2022) data.
  - Relative uncertainties: $\sim$**7 % for Run2**, $\sim$**15 % for Run3**.
- CMS has the results in $H \to ZZ^* \to 4\ell$ with Run1 and Run2 datasets.
  - $\sigma_{\mathrm{fid}} = 73.4^{+5.4}_{-5.3}(\mathrm{stat})^{+2.4}_{-2.2}(\mathrm{syst})$ fb in agreement with 75 ± 4.1 fb in $H \to \gamma\gamma$ with Run2 data.

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



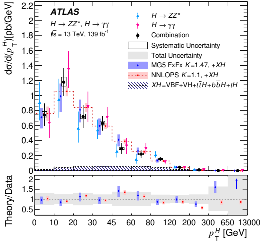
JHEP 08 (2023) 040

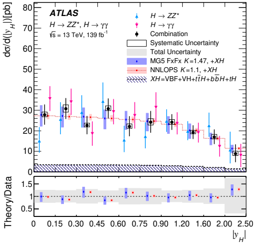


Differential cross sections

- $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ show comparable results of Higgs kinematics with full Run2 data.
- ATLAS further combined the Run2 results of two channels.
- There are $H \to WW^*$ results from ATLAS and CMS and $H \to \tau\tau$ results from CMS.

JHEP 05 (2023) 028





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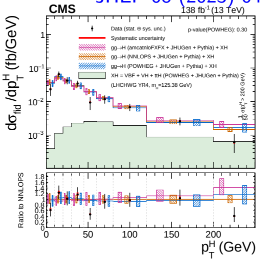
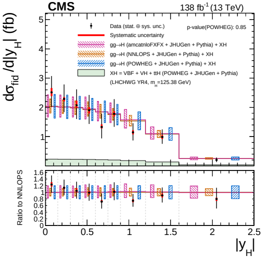
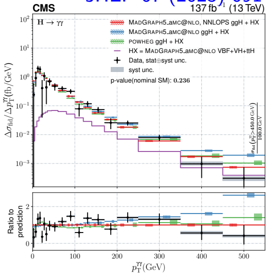
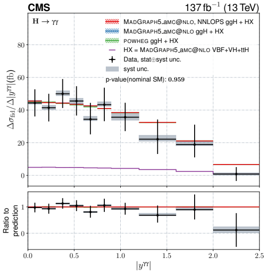




JHEP 07 (2023) 091

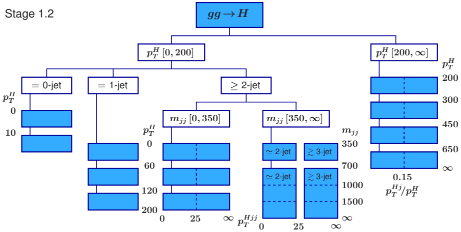


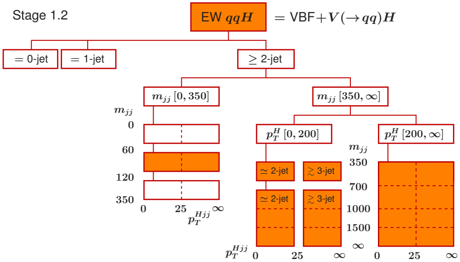


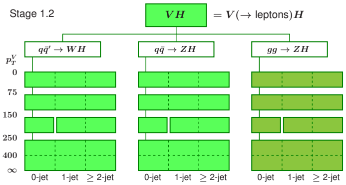
Simplified template cross sections (STXS)

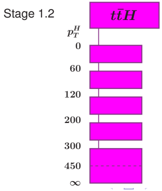
- STXS reveals the kinematic properties of Higgs production processes with associated jets to maximize the experimental sensitivities while at the same time minimizing their theory dependence.

LHCHXSWG





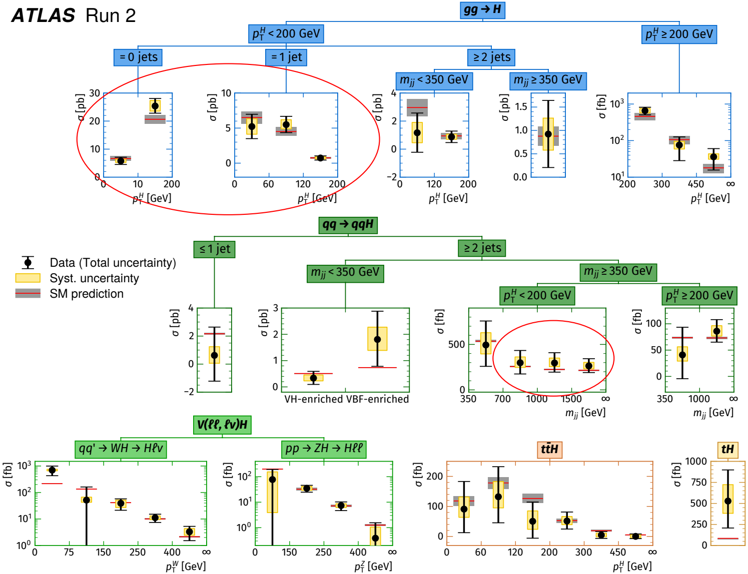




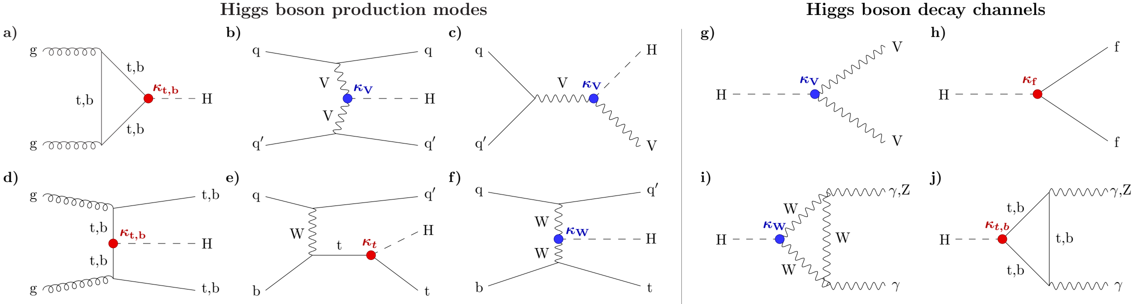
Recent results of STXS

Nature 607, 52 (2022)

- ggH with the low jet multiplicity and qqH with high m_{jj} and lower p_T^H show the better precision measurements.
- No significant deviation is found.



Higgs coupling in the κ-framework



Nature 607 (2022) 60-68

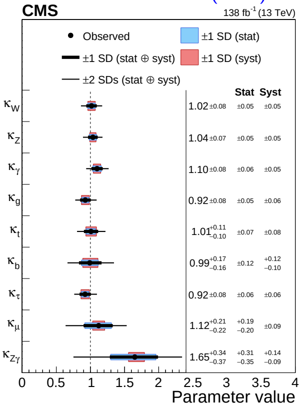
- The κ-framework is used to parametrize all the deviations from SM predictions of Higgs boson couplings to SM bosons and fermions with a set of coupling modifiers $\vec{\kappa}$.
- Any BSM process modifying the coupling strengths can be observed by this framework.

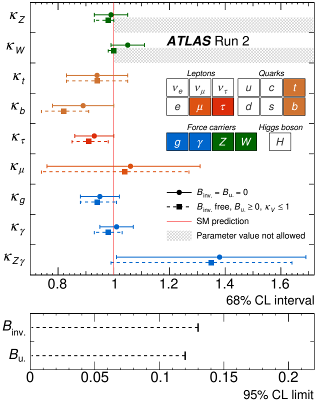
$$\sigma \cdot \mathcal{B}(i \to H \to f) = \kappa_i^2 \cdot \kappa_f^2 \cdot \sigma^{\mathrm{SM}} \cdot \frac{\Gamma_f^{\mathrm{SM}}}{\Gamma_{(\kappa_i^2, \kappa_f^2)}}, \quad \kappa_i^2 = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}}, \quad \kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{\mathrm{SM}}}$$

Higgs coupling

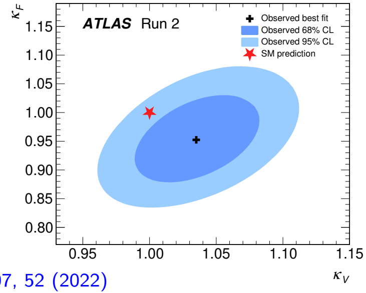
- The loop-induced processes are treated using effective coupling strength modifiers (κ_g, κ_γ and $\kappa_{Z\gamma}$).
- $\mathcal{B}_{inv}$ and $\mathcal{B}_u$ are the branching ratios of invisible particles and other decay which are undetected owing to a large background, respectively.

Nature 607 (2022) 60-68





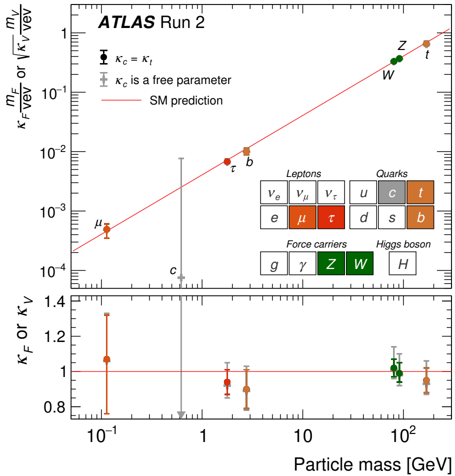
- ATLAS and CMS checked κ_F vs. κ_V with $\kappa_V = \kappa_Z = \kappa_W$ and κ_F for all fermions.



Nature 607, 52 (2022)

Higgs coupling strength

Nature 607, 52 (2022)



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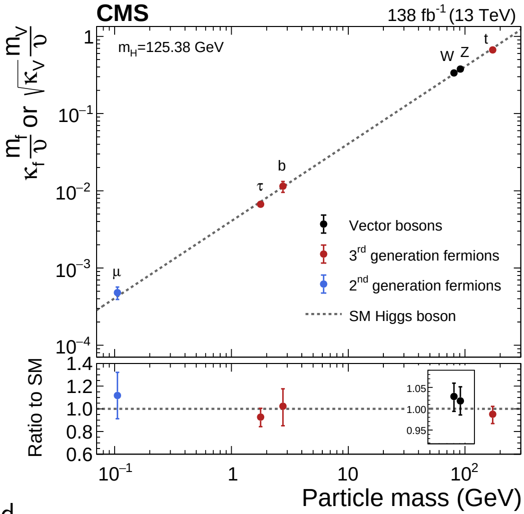


- κ_c is obtained from the fit with floating κ_c and fixed the other κ parameters.

Higgs width

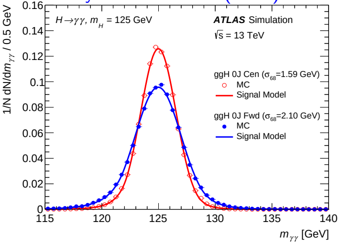
- The SM prediction of total Higgs width is 4.1 MeV, which is inaccessible from direct measurements.
- The total width can be extracted from the ratios of yields of on-shell and off-shell Higgs boson events.
- $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV (ATLAS) and $3.2^{+2.4}_{-1.7}$ MeV (CMS)

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

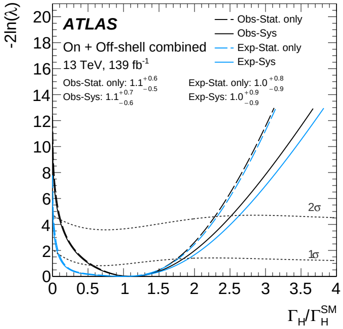
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggF}g^2_{HZZ}}{m^2_{ZZ}}$$

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

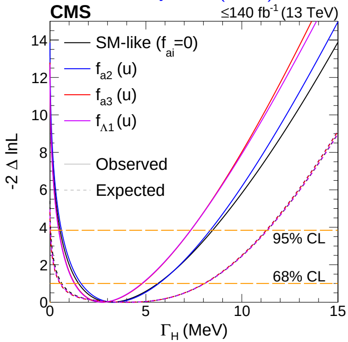
Phys. Lett. B 784 (2018) 345



Phys. Lett. B 846 (2023) 138223



Nat. Phys. 18 (2022) 1329



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Standard Model Effective Field Theory (SMEFT)

JHEP10(2010)085

- SMEFT is an expansion of SM implemented with non-SM interactions as perturbative terms:

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(d)}}{\Lambda^{(d-4)}} \mathcal{O}_i^{(d)} \quad \text{for } d > 4.$$

  where the parameters $C_i^{(d)}$ describe the strength of new interactions and are known as the Wilson coefficients, and Λ is the scale of new physics.

- $C_i^{(6)}$ are usually considered in the experiment since operators with d=5 and d=7 violate lepton and/or baryon number conservation and higher order terms are suppressed by the cutoff scale Λ.

- Measuring the cross sections can constrain the Wilson coefficients.

$$\sigma \propto \left|\mathcal{M}_{\mathsf{SMEFT}}\right|^2 = \left|\mathcal{M}_{\mathsf{SM}} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{M}_{\mathsf{BSM},i}\right|^2 =$$

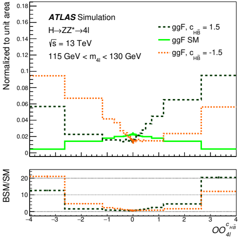
$$\left|\mathcal{M}_{\mathrm{SM}}\right|^2 + \sum_i 2\Re\left(\mathcal{M}_{\mathrm{SM}}^{*}\mathcal{M}_{\mathsf{BSM},i}\right)\frac{C_i}{\Lambda^2} + \sum_{ij} 2\Re\left(\mathcal{M}_{\mathsf{BSM},i}^{*}\mathcal{M}_{\mathsf{BSM},j}\right)\frac{C_i C_j}{\Lambda^4}$$

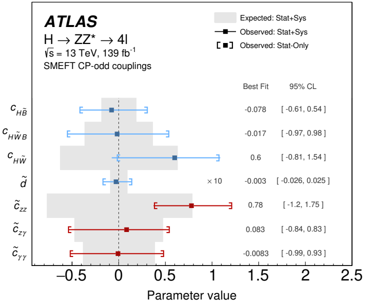
Test of CP-invariance in $H \to ZZ^* \to 4\ell$

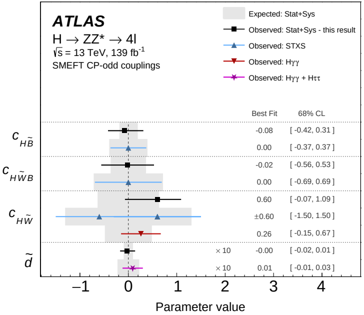
arXiv:2304.09612

- CP-odd HVV couplings in Warsaw and Higgs basis were tested in this study.
  - $c_{H\widetilde{W}}$, $c_{H\widetilde{B}}$, $c_{H\widetilde{W}B}$, $\widetilde{c}_{zz}$, $\widetilde{c}_{z\gamma}$ and $\widetilde{c}_{\gamma\gamma}$.
- Optimal Observables ($\mathcal{OO}$) are sensitive to CP-odd couplings and are defined as:

$$\mathcal{OO}_i = \frac{2\Re(\mathcal{M}^*_{\rm SM}\mathcal{M}_{\rm BSM,i})}{|\mathcal{M}_{\rm SM}|^2}$$



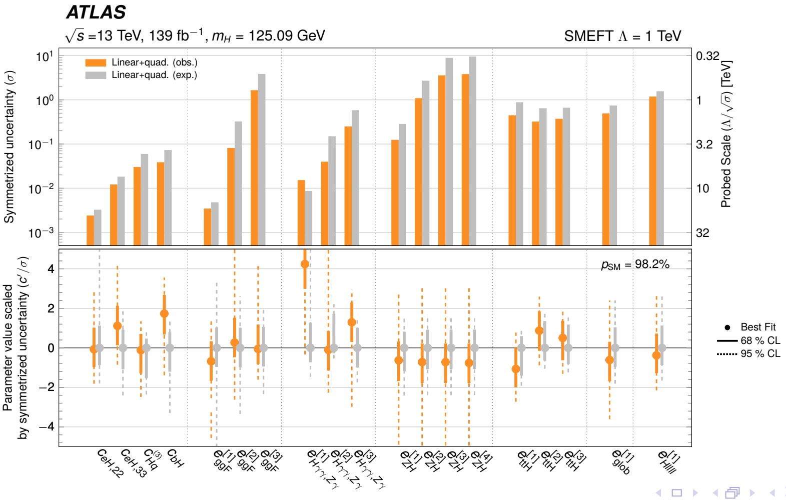




STXS analysis with SMEFT interpretations

arXiv:2402.05742

- 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.



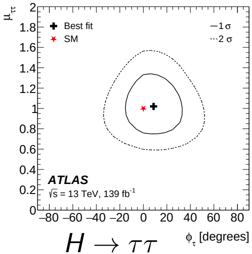
Anomalous couplings of *Hff*

- The spin-parity quantum numbers of the Higgs boson are consistent with $J^{PC} = 0^{++}$.
- The anonmalous effects of Hff can be parameterized with the amplitude as:

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

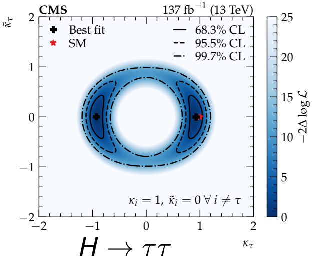
- No deviation from SM has been found.

Eur. Phys. J. C 83 (2023) 563



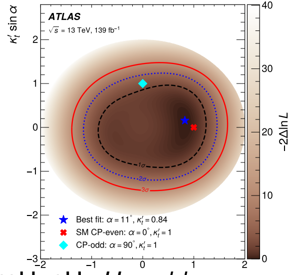
$H \to \tau\tau$

JHEP 06 (2022) 012



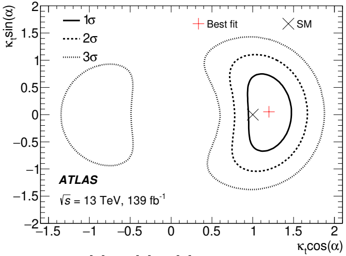
$H \to \tau\tau$

Phys. Lett. B 849 (2024) 138469



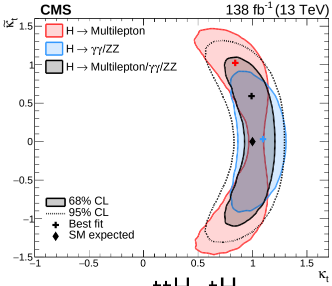
ttH, tH, $H \to bb$

Phys. Rev. Lett. 125 (2020) 061802



ttH, tH, $H \to \gamma\gamma$

JHEP 07 (2023) 092



ttH, tH

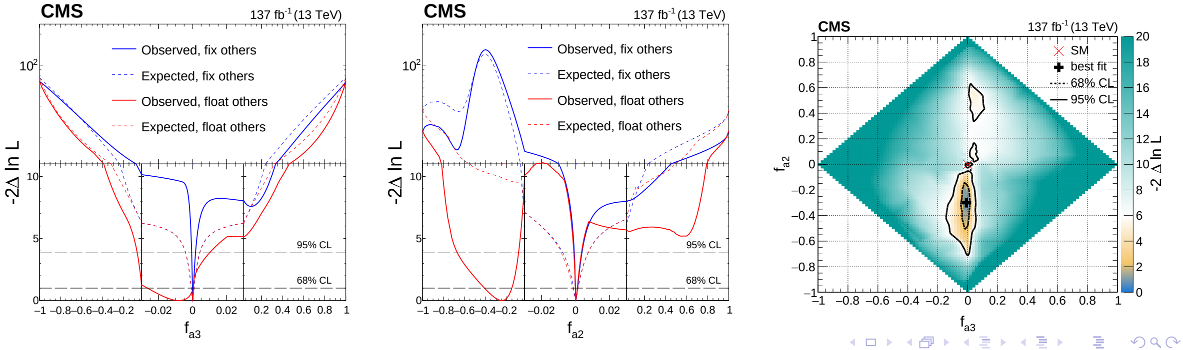
Anomalous couplings of *HVV*

PRD 104 (2021) 052004

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

$$A(HVV) = \frac{1}{v}[a_1^{VV} + F_1(\kappa_1^{VV}, \kappa_2^{VV}, \kappa_3^{VV})] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^* + \frac{1}{v} F_2(a_2^{VV}) + \frac{1}{v} F_3(a_3^{VV})$$

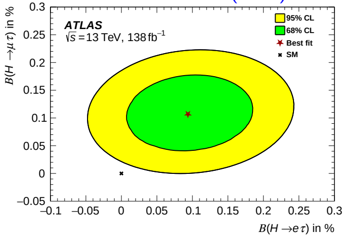
- Except for a_1^{VV}, the rest of the couplings are considered to be anomalous contributions.
- Only a_3^{VV} are the CP-odd couplings. Others are CP-even.
- f_{a2} and f_{a3} are the cross section fractions with the dependence of a_2 and a_3, respectively.



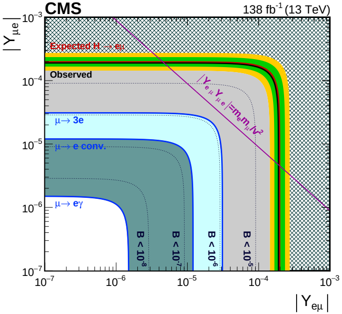
Search for lepton flavor violation

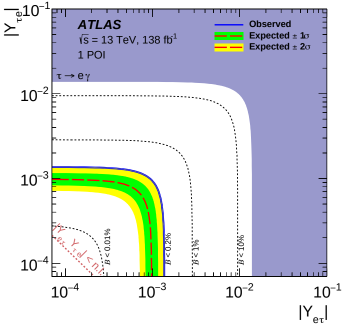
- ATLAS and CMS performed the search for $H \to e\tau$ and $H \to \mu\tau$.
  - ATLAS found 2.1σ of the deviation for the 2D scan of $\mathcal{B}(H \to e\tau)$ and $\mathcal{B}(H \to \mu\tau)$ and 2.5σ for the symmetry method of $\mathcal{B}(H \to \mu\tau) - \mathcal{B}(H \to e\tau)$.
- CMS performed $H \to e\mu$ with the observed limit of 4.4×10^{-5}. (6.2×10^{-5} for ATLAS)

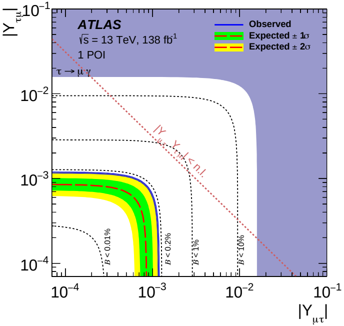
JHEP 07 (2023) 166



Phys. Rev. D 108 (2023) 072004



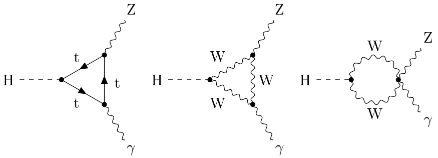


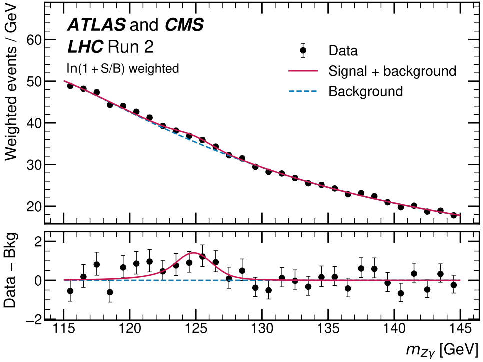


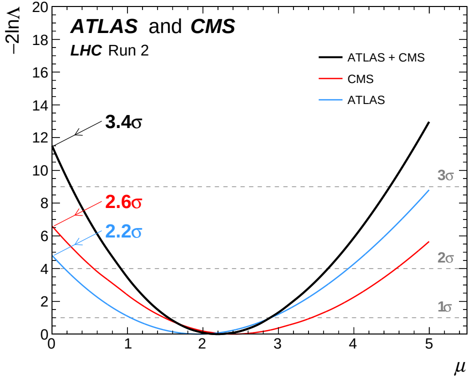
$H \to Z\gamma$

Phys. Rev. Lett. 132 (2024) 021803

- The first evidence with a statistical significance of 3.4σ is presented by the combination of ATLAS and CMS results.
- The signal strength is 2.2 ± 0.7 within 1.9σ of the deviations from the SM prediction.





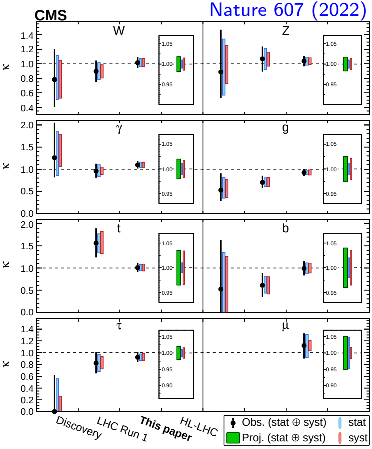


Summary

- The new results with Run3 data in the channels of $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ at ATLAS are available.
- The first evidence of $H \to Z\gamma$ is presented in the combination of ATLAS and CMS.

- High precision measurements of Higgs mass (0.1% accuracy) is achieved.
- Comprehensive measurements of inclusive/differential fiducial cross sections and STXS bins in the discovered channels are performed.
  - More new public results can complement the combination. (ex. VH $H \to WW$ and VH $H \to \tau\tau$ in ATLAS)
  - BSM interpretations are also taken into account.
- More results from ATLAS and CMS with Run3 data are coming out.

Nature 607 (2022) 60-68



Back up

More results of anomalous couplings for Hff

- The measurement is also done in a four-top process via an off-shell Higgs boson.

ATL-PHYS-PUB-2023-013