Measurement of Higgs boson production and properties

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Introduction

The 13 TeV Run 2 dataset enabled several new Higgs boson measurements in different decay channels and production modes, interpretation in various BSM frameworks

- Unprecedented precision levels of the Higgs boson properties
- New Physics phenomena investigated in several BSM frameworks
- Searches for rare decays lead to first evidences

Focus on the most updated measurements of the Higgs boson properties performed by the ATLAS and CMS experiments with Run 2 dataset…with a first look to new data at 13.6 TeV

Outline

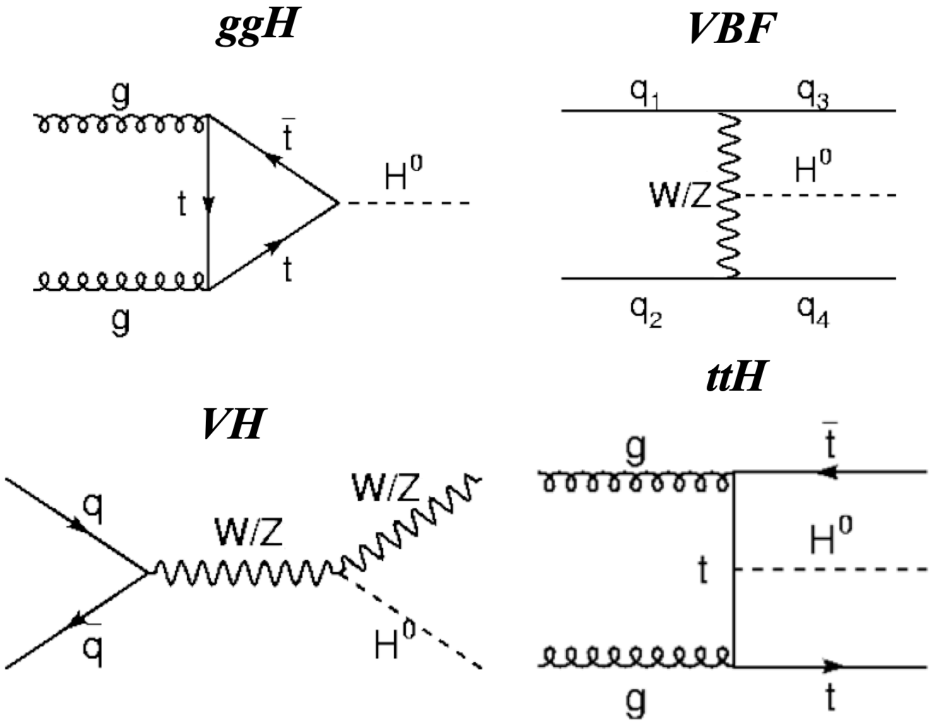
The Higgs boson …

- Mass
- CP structure
- Width
- Couplings
- Simplified Template Cross Section
- Fiducial and Total Cross Section
- $H \to Z\gamma$ decay
- Invisible decay
- Self-coupling

The Higgs Boson @ LHC

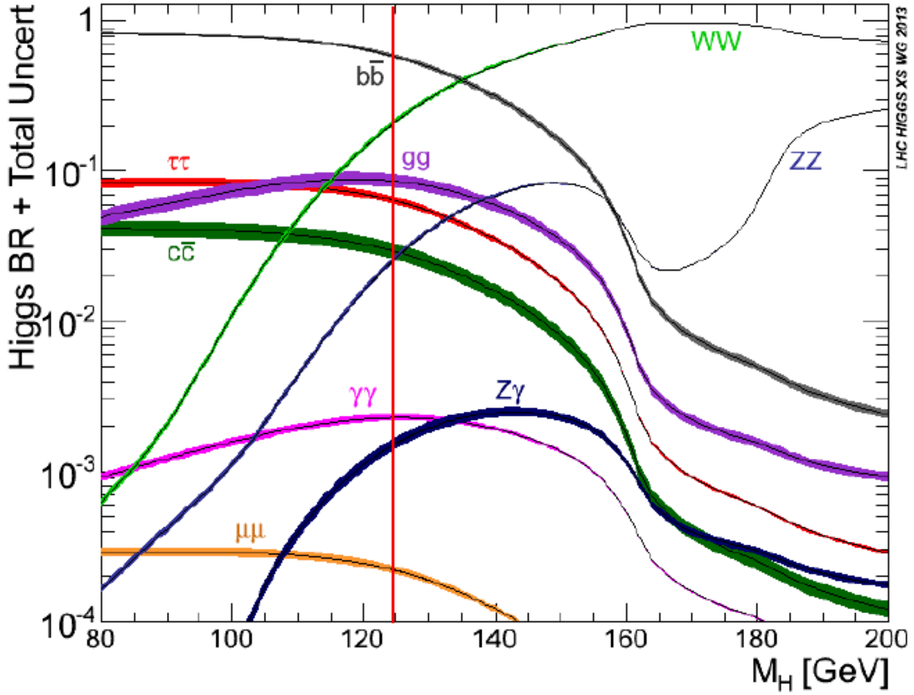
Production mechanisms

- Gluon-gluon fusion (ggF)
- Vector Boson fusion (VBF)
- Associated production with a vector boson (VH)
- Associated production with top quark pair (ttH)



Decay Channels

- $H \to ZZ^*$: low BR, very good S/B ratio, high mass resolution
- $H \to WW$: high BR, low mass resolution
- $H \to \gamma\gamma$: low BR, large background, high mass resolutions
- $H \to bb$ and $H \to \tau\tau$: high BR, large background, low mass resolution
- $H \to \mu\mu$ and $H \to Z\gamma$: very low BR



The evolution of the Higgs boson

Mass: Phys. Rev. Lett. 114, 191803 (2015)
CP: Eur. Phys. J. C75 (2015) 476, Phys. Rev. D 92, 012004 (2015)
Width: Eur. Phys. J. C (2015) 75:335, Phys. Lett. B 736 (2014) 64
Coupling: JHEP08(2016)045

Run 1

First Higgs boson property measurements

Mass ATLAS+CMS
125.09 ± 0.24
(± 0.21 ± 0.11) GeV

Spin/CP
Results consistent with a SM Higgs $J^{CP} = 0^{++}$

Width
ATLAS: $\Gamma_H < 22.7$ MeV @ 95% CL
CMS: $\Gamma_H < 22$ MeV @ 95% CL

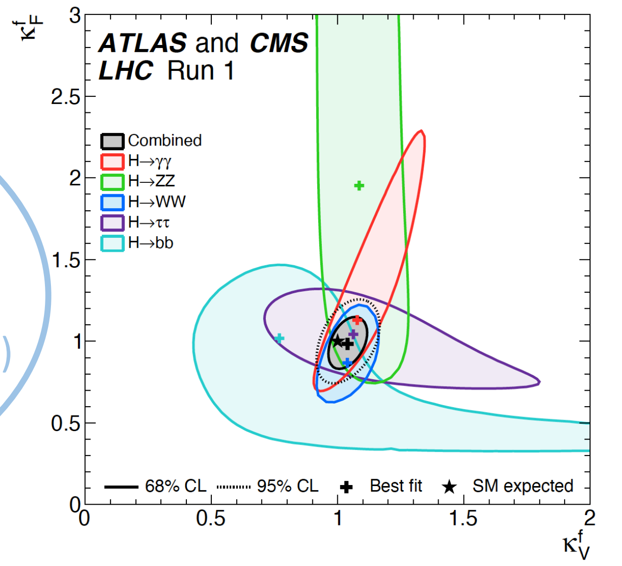
First **differential cross sections** as function of Higgs and jet kinematic variables

Couplings
Results interpreted in terms of

Signal Strength: $\mu = \frac{(\sigma \cdot BR)_{\text{obs}}}{(\sigma \cdot BR)_{\text{SM}}}$

Coupling modifiers (κ-framework)

$\kappa_j^2 = \frac{\sigma_j}{(\sigma_j)_{SM}} \quad \kappa_j^2 = \frac{\Gamma^j}{(\Gamma^j)_{SM}}$



Run 2

Beginning of *Precision Era*…

More precise measurements
of the Higgs mass, width, couplings and differential cross section

More stringent constraints on anomalous Higgs boson couplings with other SM particles
Interpretation of the results in different theoretical framework (EFT, PO, etc.)

Today's talk

Run 3

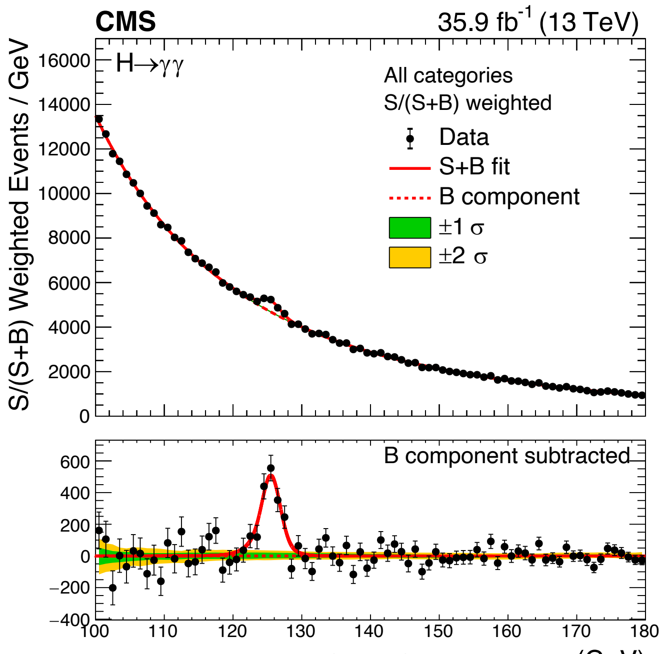
…walking towards higher energy and higher luminosity

looking to the first Higgs boson production cross section at 13.6 TeV!

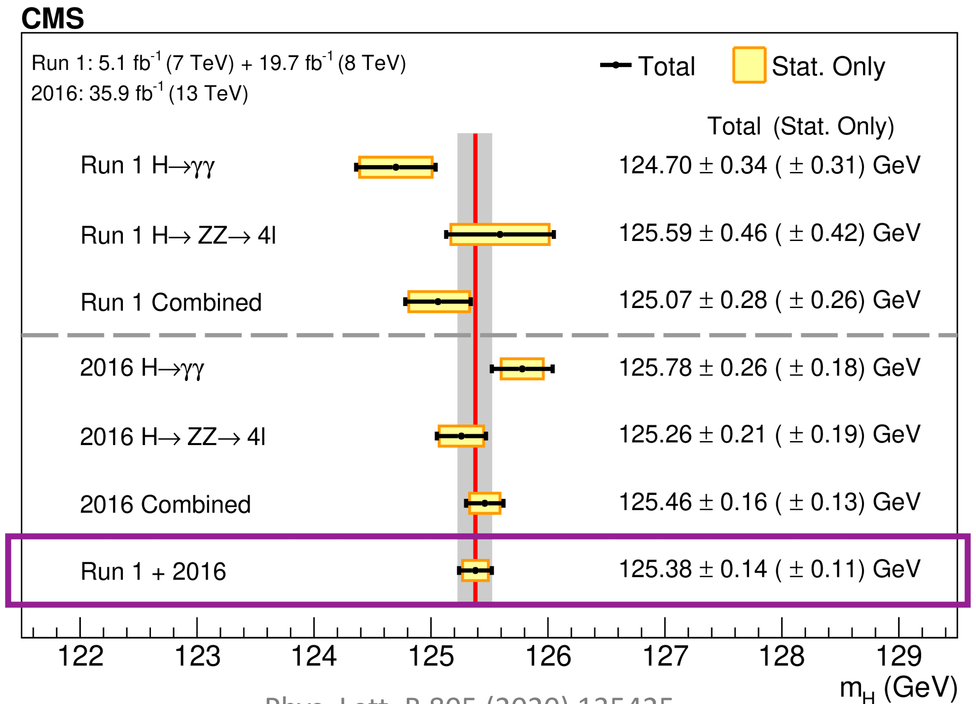
The Higgs boson Mass

H→ZZ*→4l and H→$\gamma\gamma$ are the most sensitive channels

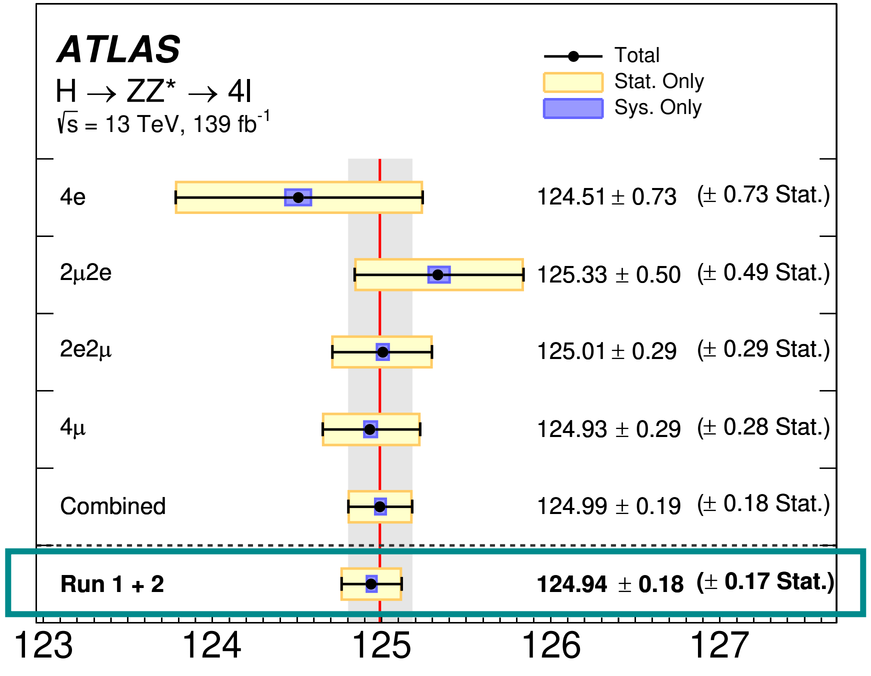
- Clear signature final states
- High mass resolution 1-2 %
- Main uncertainties: Electron/photon energy scale and muon momentum scale
- **ATLAS**: results @ 139 fb^{-1} in the H→ZZ*→4l channel (+Run1)
- **CMS**: results @ 35.9 fb^{-1} combined results H→ZZ* + H→$\gamma\gamma$ (+Run 1)



Phys. Lett. B 805 (2020) 135425



Phys. Lett. B 805 (2020) 135425



arXiv:2207.00320

ATLAS

(H→ZZ* Run1+Run2 @ 139 fb^{-1})

m_H = 124.94 ± 0.18 GeV

CMS

(H→ZZ*+H→$\gamma\gamma$ Run1+Run2 @ 35.9 fb^{-1})

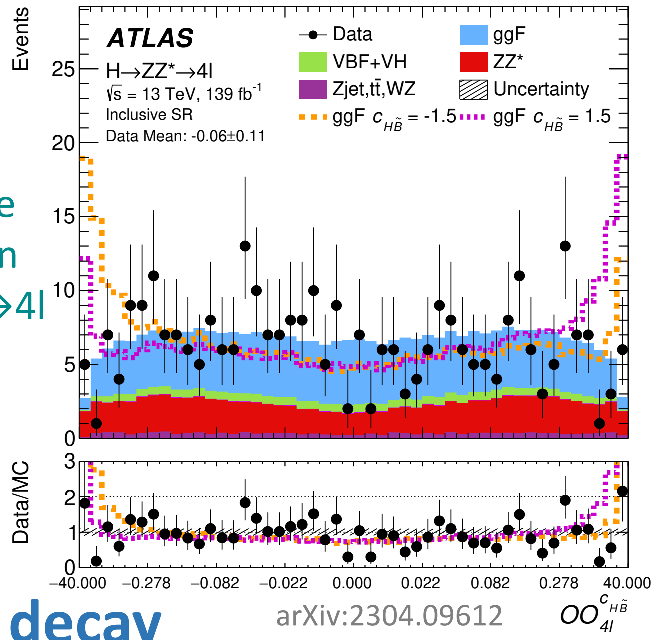
m_H = 125.38 ± 0.14 GeV

The Higgs boson CP structure

Looking for signs of CP-violation in the Higgs sector

- Study the coupling with vector bosons (*HVV*) and fermions (*Hff*)
- Use of observables optimized to discriminate different CP hypothesis
  - Rate cannot disentangle anomalous CP-even or CP-odd effects, observable shapes does
- Interpret the results in terms of anomalous Higgs boson couplings

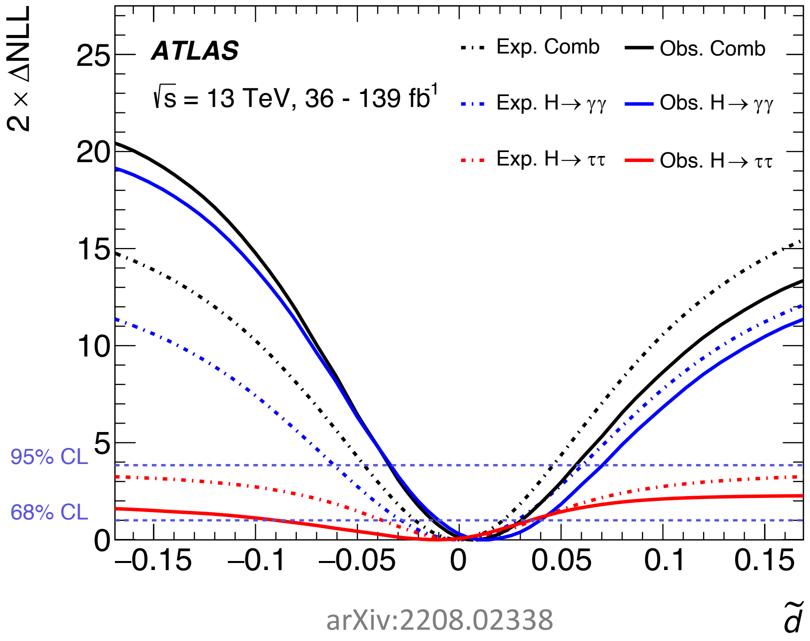
Optimal Observable distribution for H→ZZ*→4l



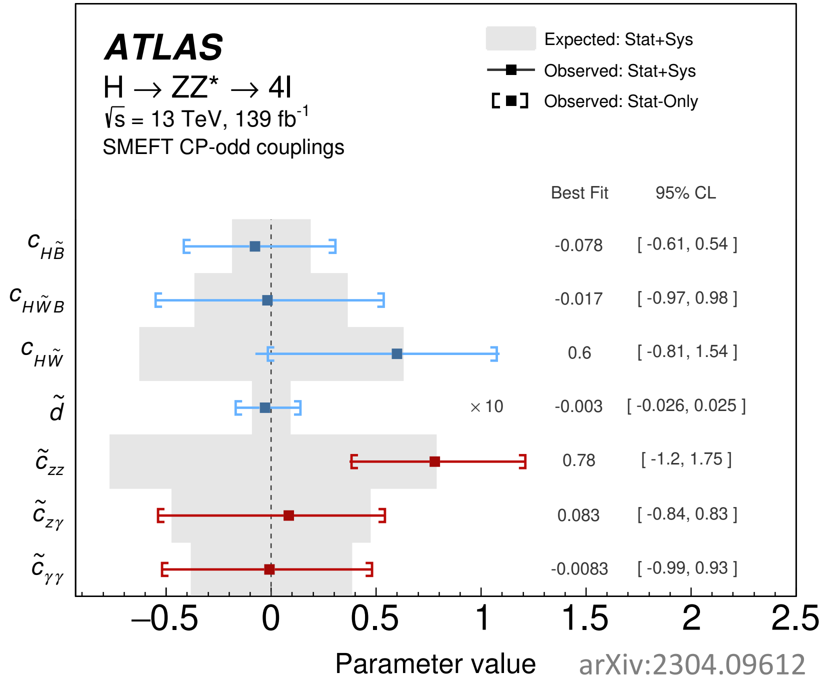
arXiv:2304.09612

HVV vertex studied in the VBF production and H→ZZ decay

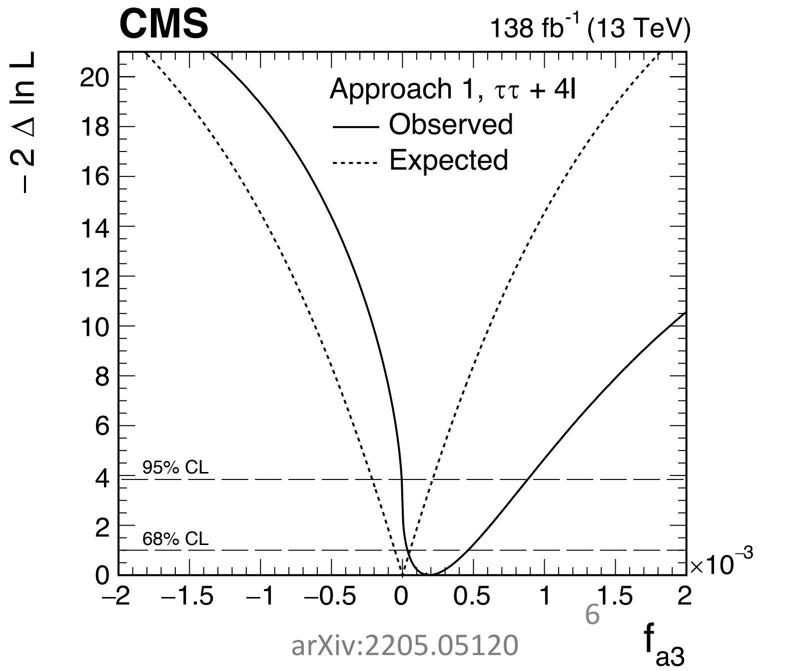
Limits from H→$\gamma\gamma$+H→$\tau\tau$ combination



Summary EFT coupling CP-odd constraint



Limits from H→ZZ*+H→$\tau\tau$ combination



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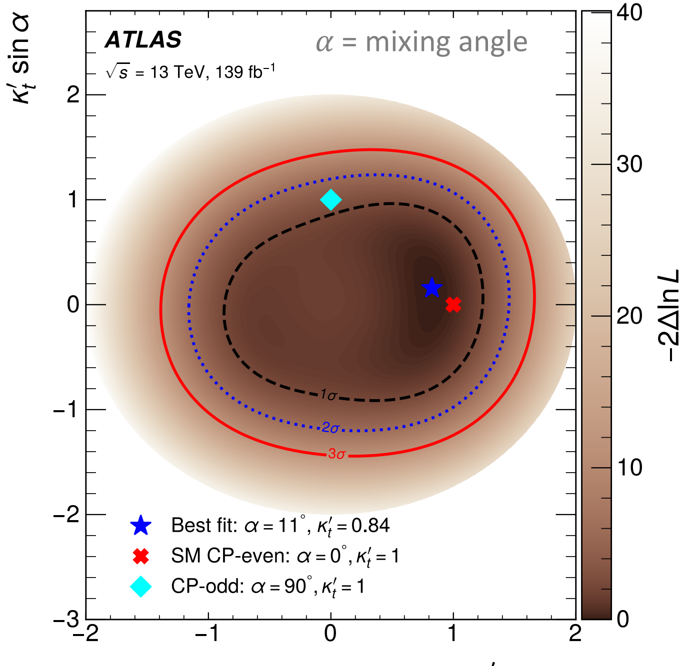
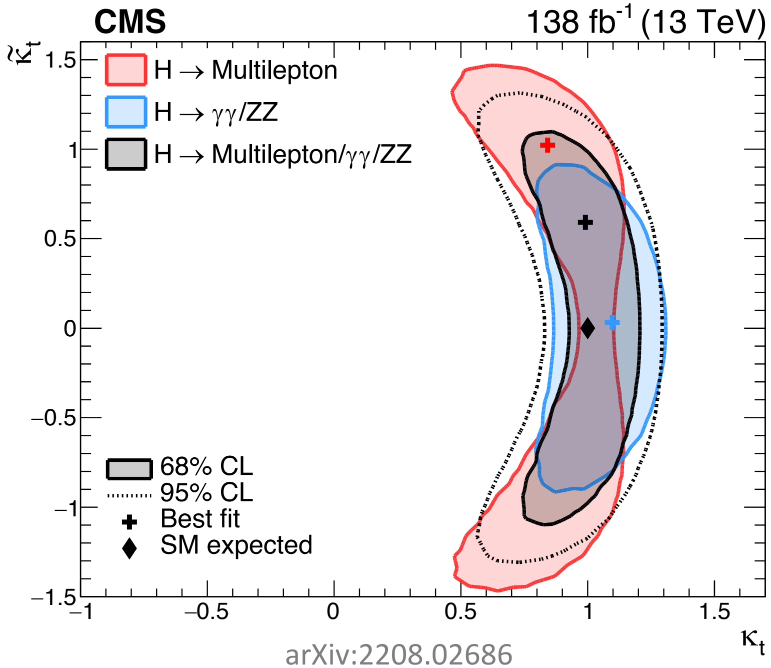
Hff **vertex studied in the ttH/tH production and H→$\tau\tau$ decay**

Exclusion plot ($\kappa_t$cosα, $\kappa_t$sinα) in H→bb



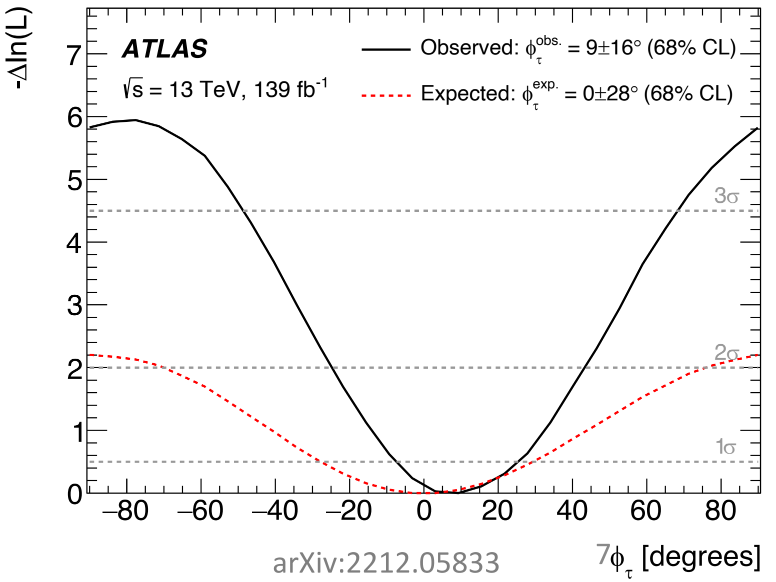
arXiv:2303.05974

Exclusion plot CP-even vs CP-odd H-top coupling



arXiv:2208.02686

Limits on CP mixing angle in H→$\tau\tau$ decay



arXiv:2212.05833

The Higgs boson Width

- SM Higgs width Γ_H=4.1 MeV → experimental resolution O(1-2 GeV) are too small to allow direct measurements
- Indirect measurement from the ratio of the on-shell/off-shell Higgs boson production

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m^2_{ZZ}} \Rightarrow \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} = \frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}}$$

H→ZZ*→ 4l and 2l2ν channels performed this measurements with full Run 2 dataset

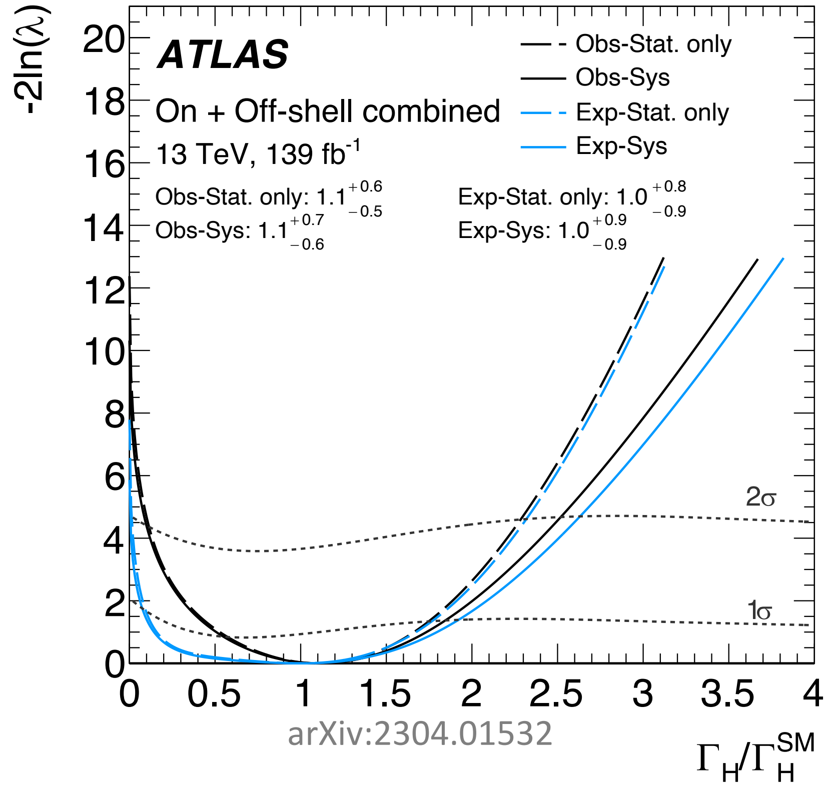
ATLAS: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV @68% C. L.

CMS: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV @68% C. L.

First evidence of **off-shell** Higgs boson production

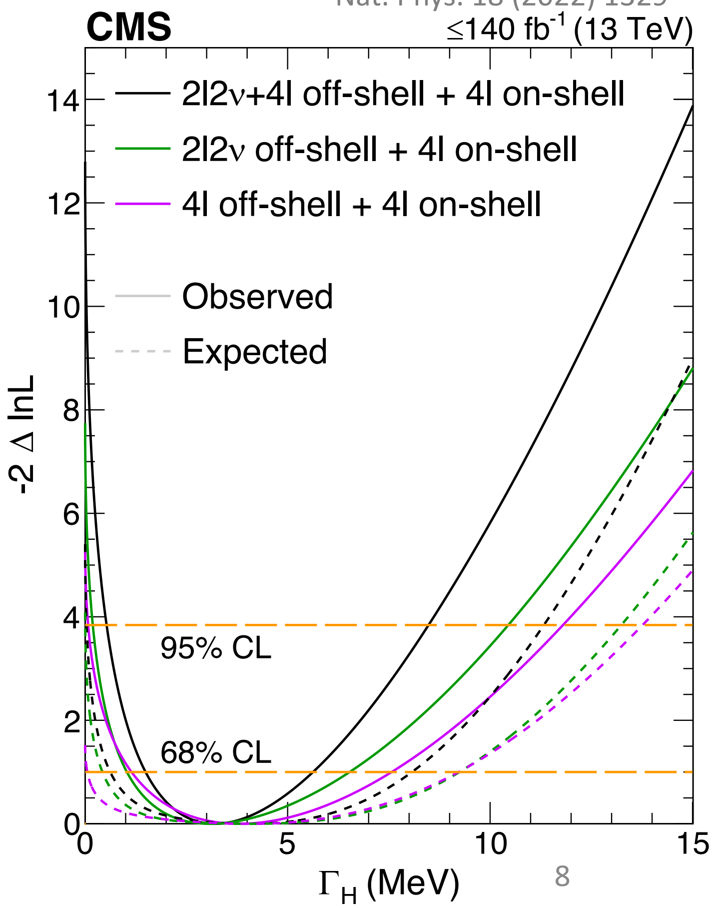
ATLAS: $\mu_{\text{off-shell}} = 1.1 \pm 0.6$ (3.3 σ)

CMS: $\mu_{\text{off-shell}} = 0.74^{+0.56}_{-0.38}$ (3.6 σ)



arXiv:2304.01532

Nat. Phys. 18 (2022) 1329

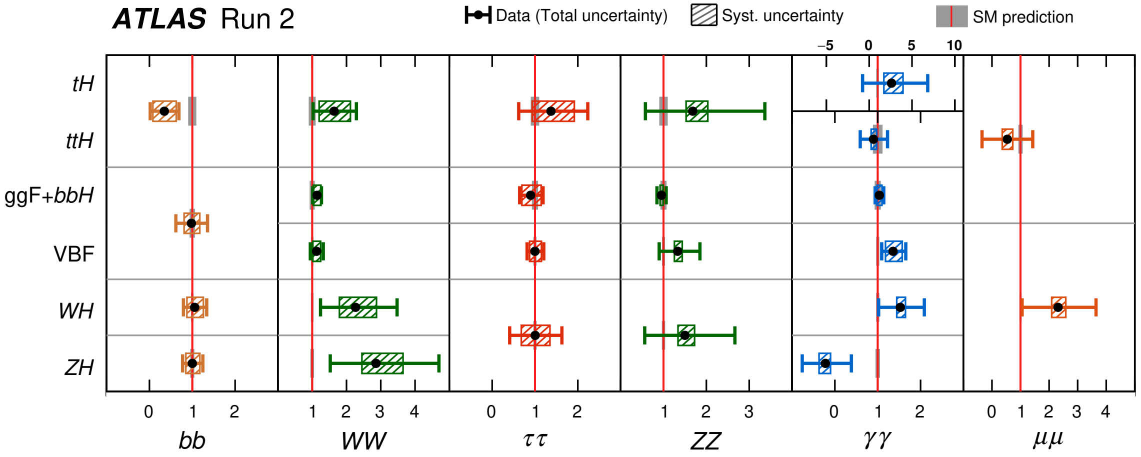


The Higgs boson Couplings

Production cross section and decay branching ratio are a way to probe the strength of the Higgs boson coupling with SM particles and possible BSM effects

After 10 years from the discovery both the experiments provided the combined measurements of its couplings

p-value = 72%

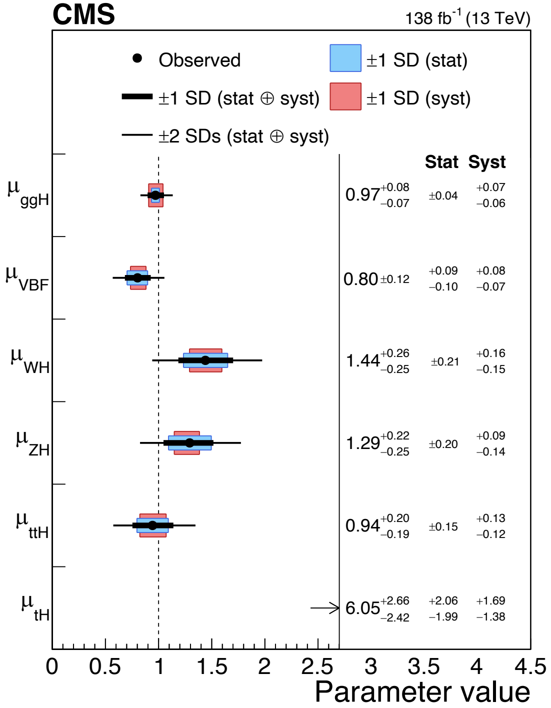


Nature 607, pages 52-59 (2022)

σ × B normalized to SM prediction

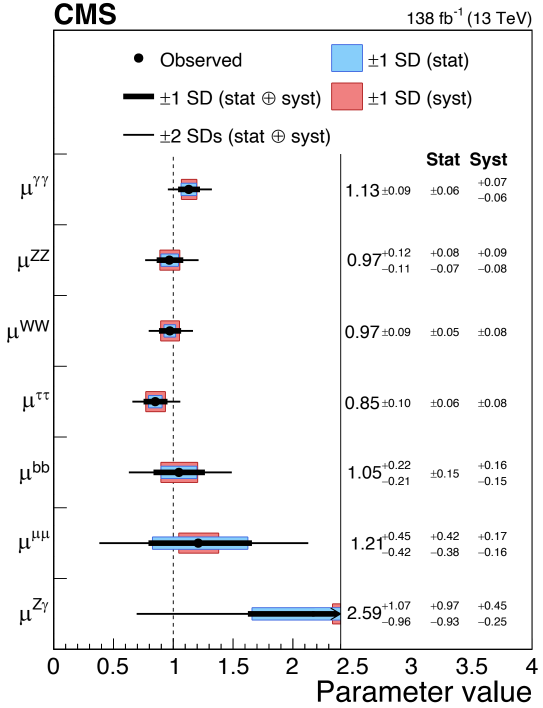
Cross section × Branching Ratio Observed/SM

p-value = 3.1%



Nature 607 (2022) 60-68

p-value = 30.1%



Signal Strength

A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

Nature 607, pages 52-59 (2022)

A portrait of the Higgs boson by the CMS experiment ten years after the discovery

Nature 607 (2022) 60-68

The Higgs boson Couplings

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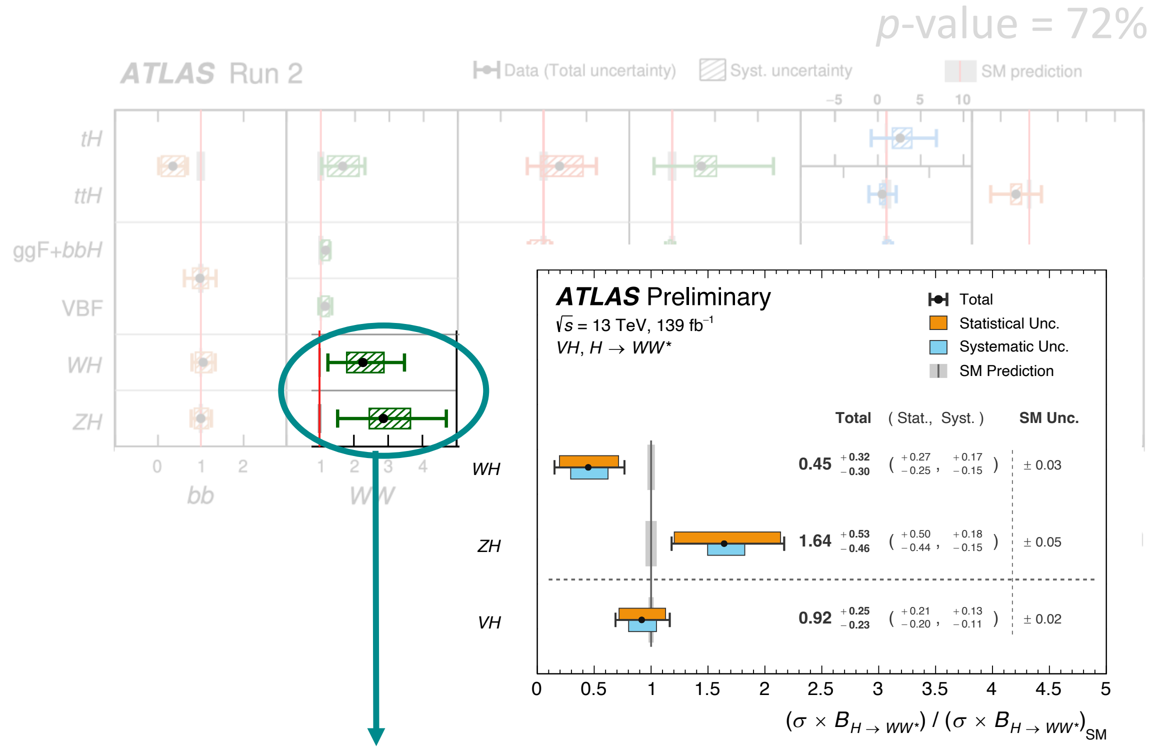
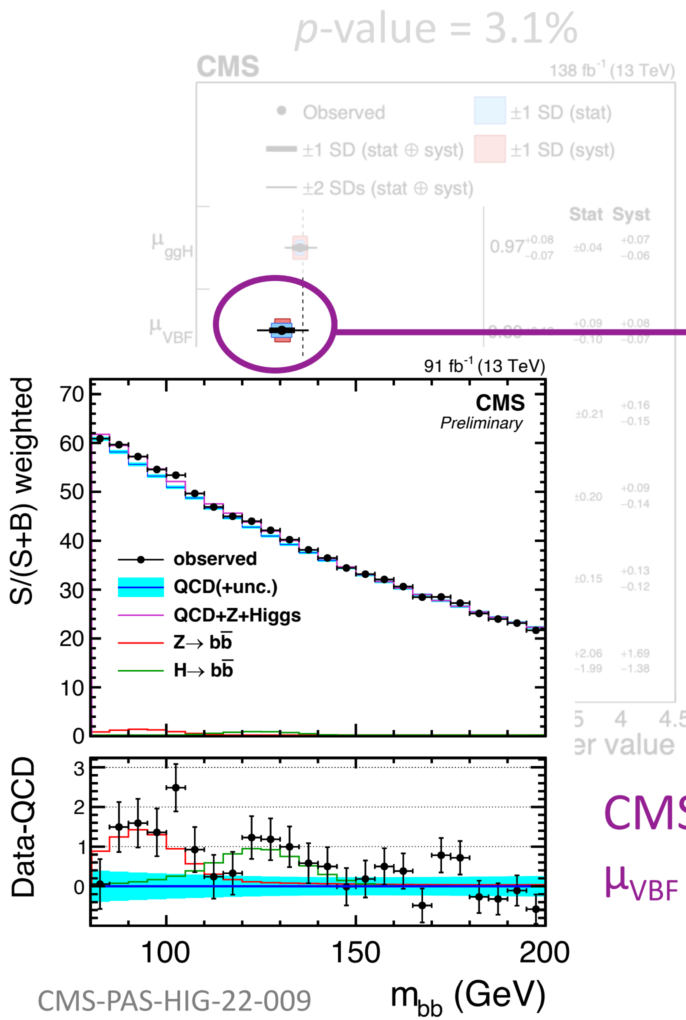


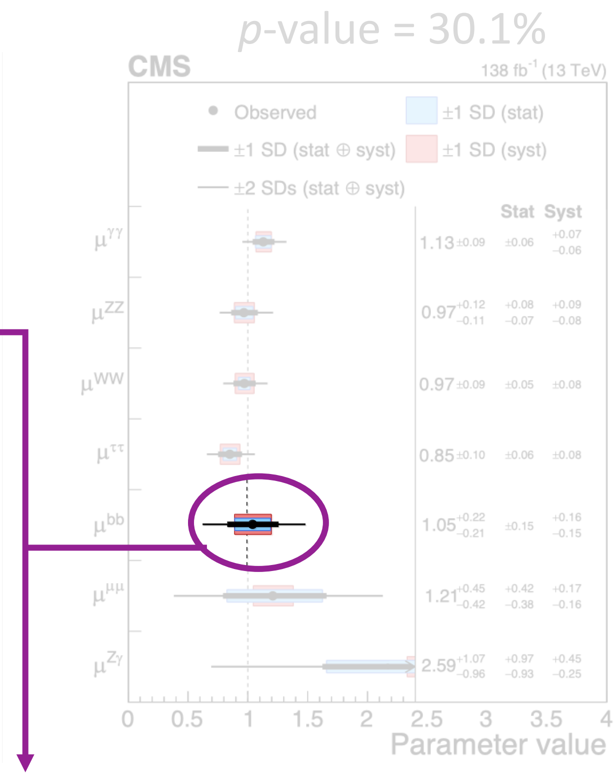
ATLAS **New results** on VH, H→WW*

$\sigma_{WH}\times B_{H\rightarrow WW^*} = 0.13^{+0.08}_{-0.07}$ (stat.) $^{+0.05}_{-0.04}$ (syst.) pb

$\sigma_{ZH}\times B_{H\rightarrow WW^*} = 0.31^{+0.09}_{-0.08}$ (stat.) ± 0.03 (syst.) pb

ATLAS-CONF-2022-067





CMS **New results** on VBF, H→bb

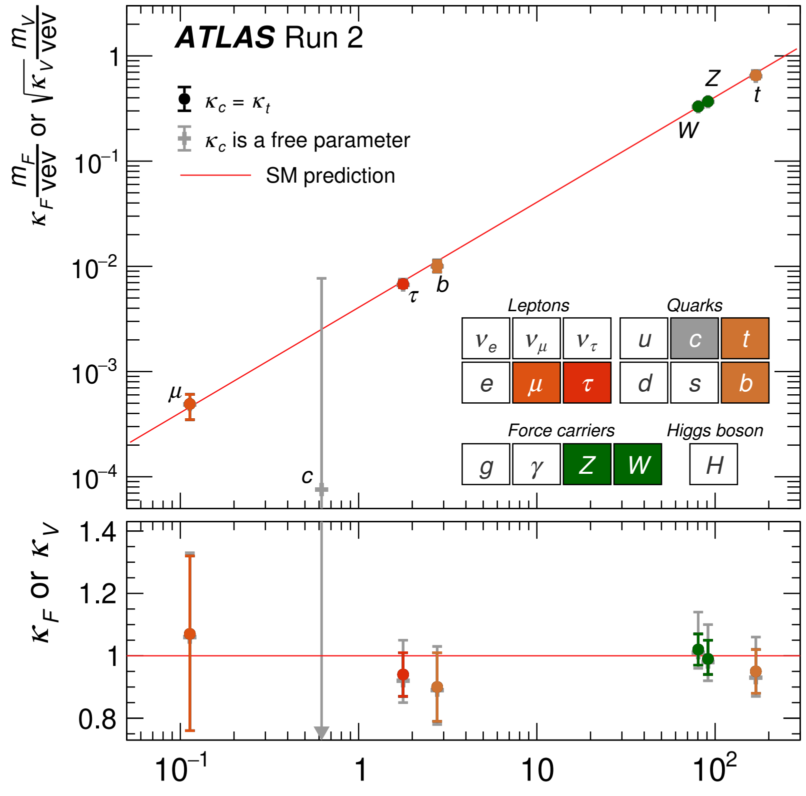
$\mu_{VBF} = 0.97^{+0.53}_{-0.45}$ (2.4 σ)

CMS-PAS-HIG-22-009

The Higgs boson Couplings

Results interpreted in terms of Higgs boson coupling strength multipliers κ in multiple scenarios

Generic parametrization with coupling strength modifiers for W, Z, t, b, c*, τ and μ treated independently



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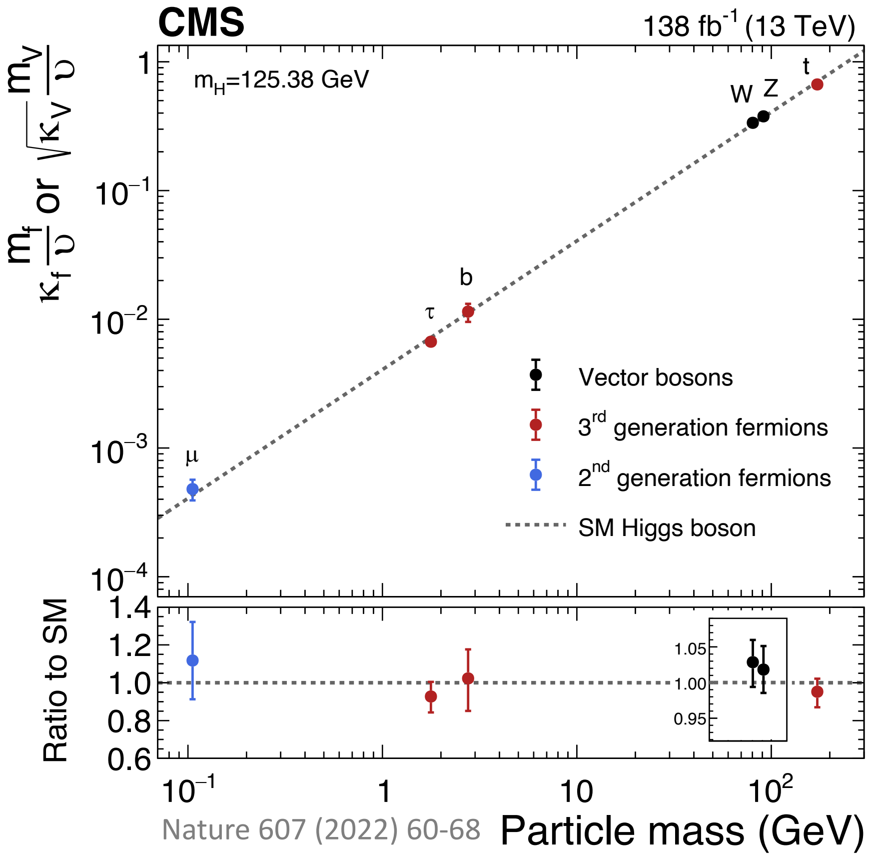

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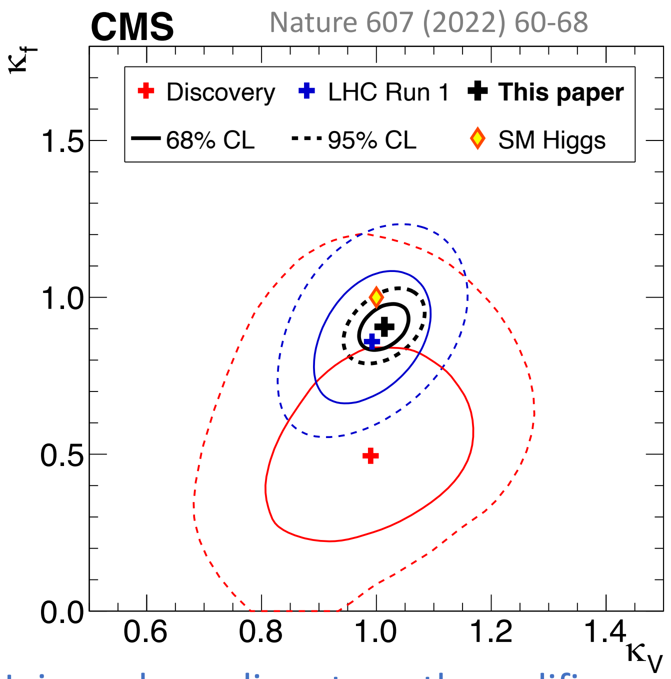
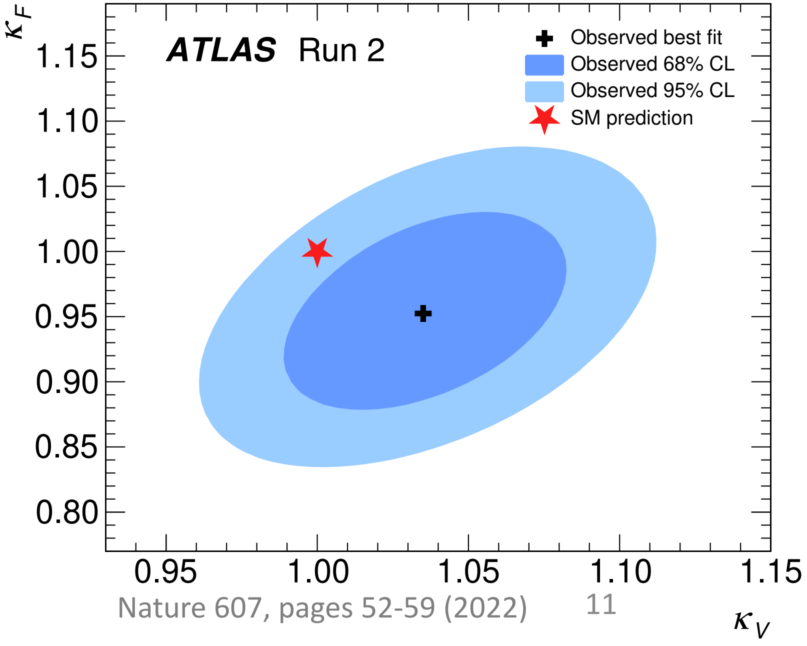


Universal coupling strength modifiers κ_V (vector bosons) and κ_F (fermions)



Nature 607, pages 52-59 (2022)

Coupling with quark charm

ATLAS: $\kappa_c < 5.7$ @ 95% C.L.

Coupling with quark charm arXiv:2205.05550

CMS: $1.1 < |\kappa_c| < 5.5$ @ 95% C.L.

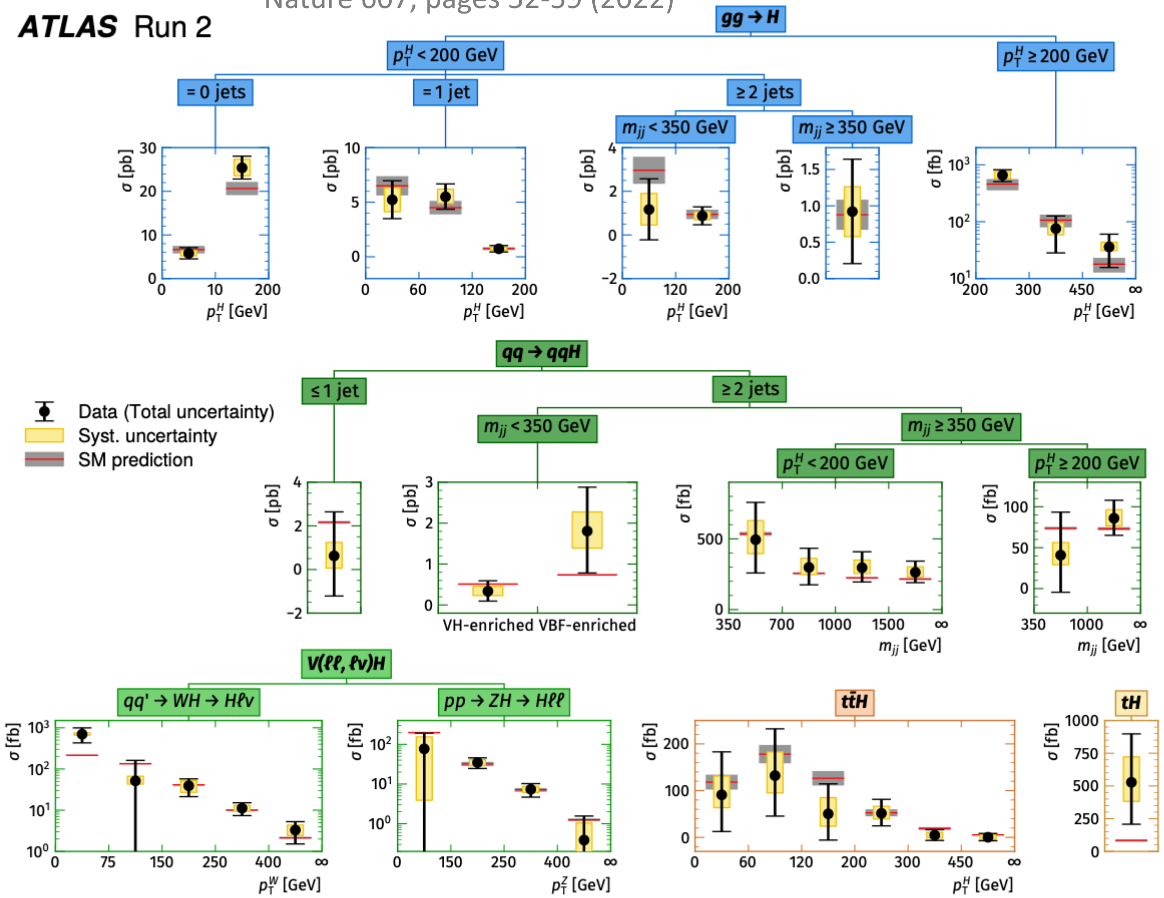
The Higgs boson Simplified Template Cross Section

STXS framework defines exclusive regions in the Higgs phase space of the Higgs production processes, based on the kinematics of the Higgs and of the particles/jets produced in association

- Minimizing the dependence on theoretical uncertainties
- Maximizing experimental sensitivity also to possible BSM effects

- Different STXS Stages definition, corresponding to increasingly fine granularity
- Not all the analyses are sensitive to all the STXS bins

Nature 607, pages 52-59 (2022)



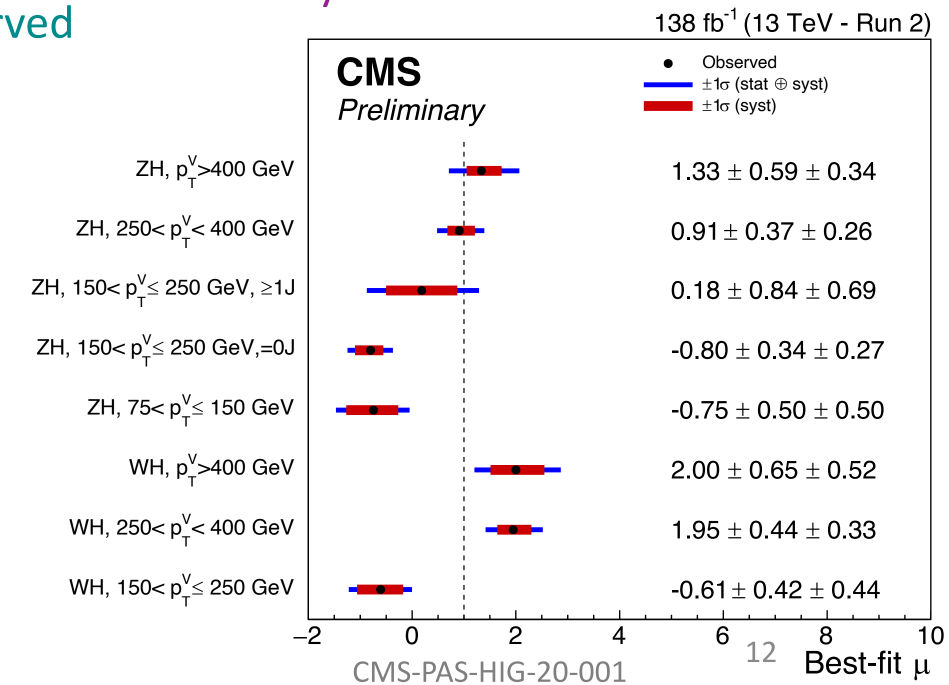
ATLAS

Joint measurement of 36 regions combining the results in the 5 observed decay channels.

Good agreement with SM p-value 94%

CMS

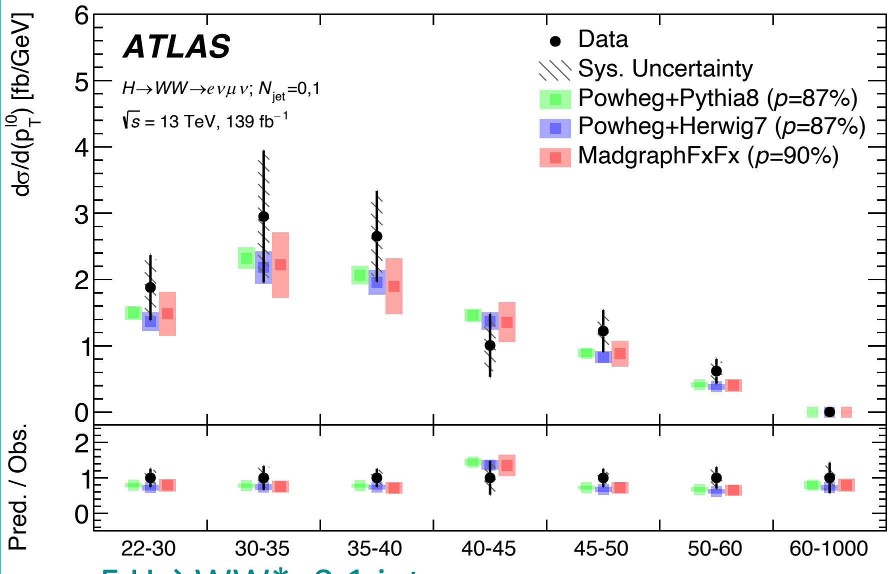
New recent results in VH, H→bb decay channel



CMS-PAS-HIG-20-001

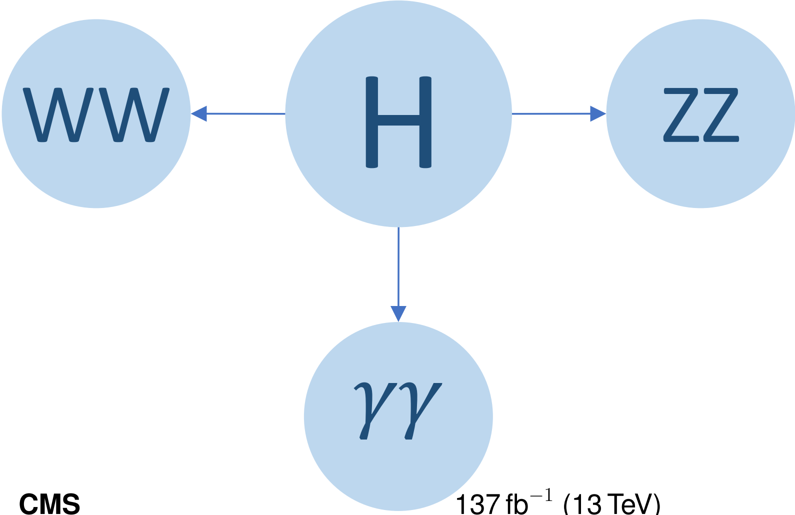
The Higgs boson Fiducial Cross Sections

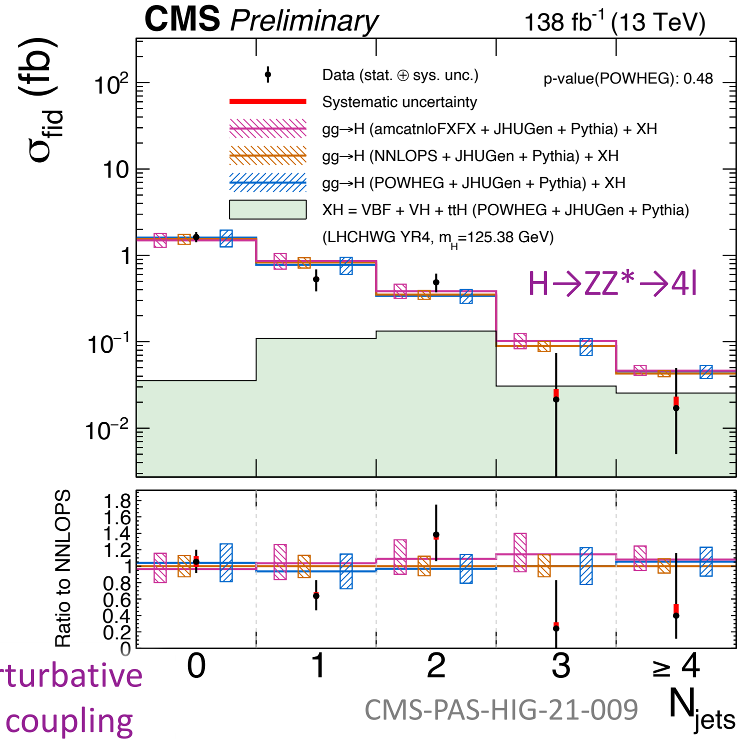
N_{jets} sensitive to different production mode



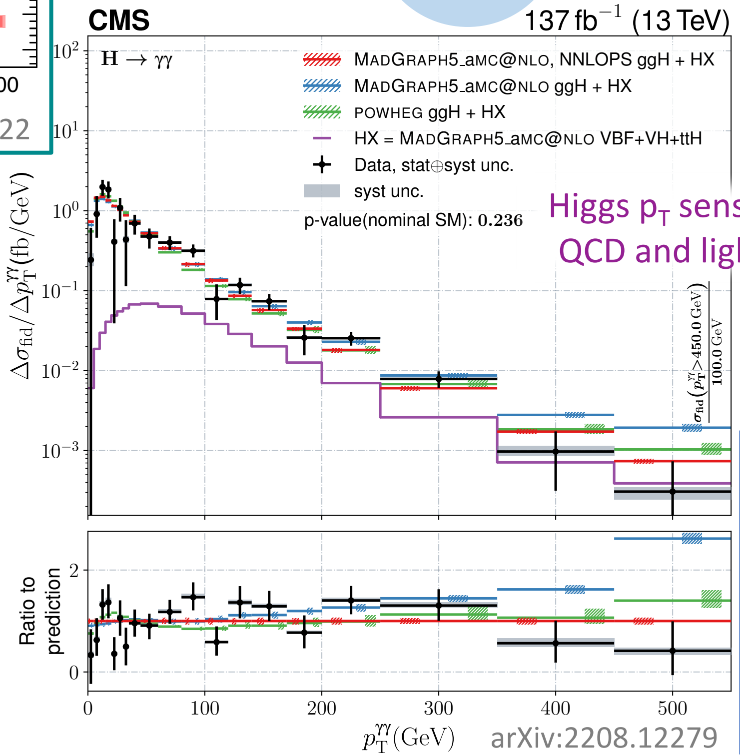
ggF H→WW*: 0,1 jets

arXiv:2301.06822





CMS-PAS-HIG-21-009



arXiv:2208.12279

Higgs p_T sensitive perturbative QCD and light quark coupling

- **Fiducial phase space** definition based on detector acceptance to minimize the model dependency
    - Different phase space definition to target different production modes
- **Unfolding** to correct for detector level effects, efficiency and resolutions

- **Variable sensitive to the Higgs boson properties** related to the Higgs kinematics or to the jets produced in association

Inclusive Fiducial Cross Sections in ZZ* and $\gamma\gamma$

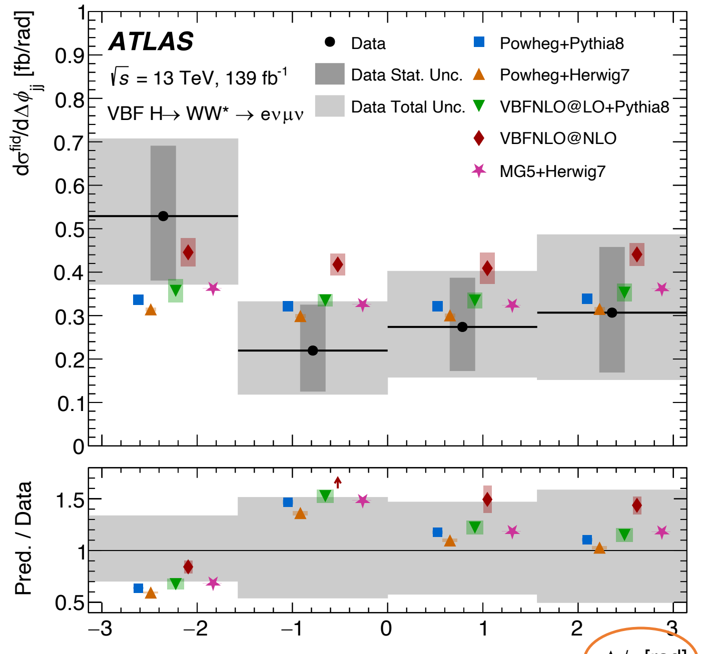
ATLAS: σ_{fid}^{4l} = 3.28 ± 0.32 fb (SM: 3.41 ± 0.18 fb)

CMS: σ_{fid}^{4l} = 2.73 ± 0.26 fb (SM: 2.86 ± 0.15 fb)

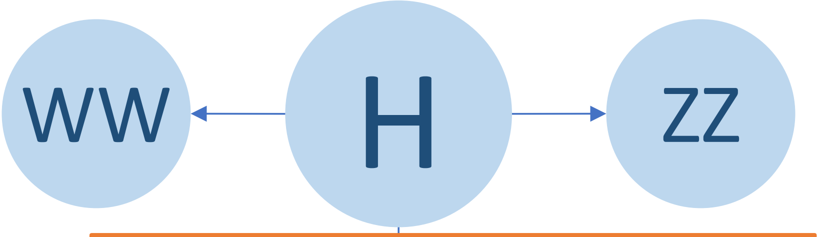
ATLAS: $\sigma_{fid}^{\gamma\gamma}$ = 67 ± 6 fb (SM: 64 ± 4 fb)

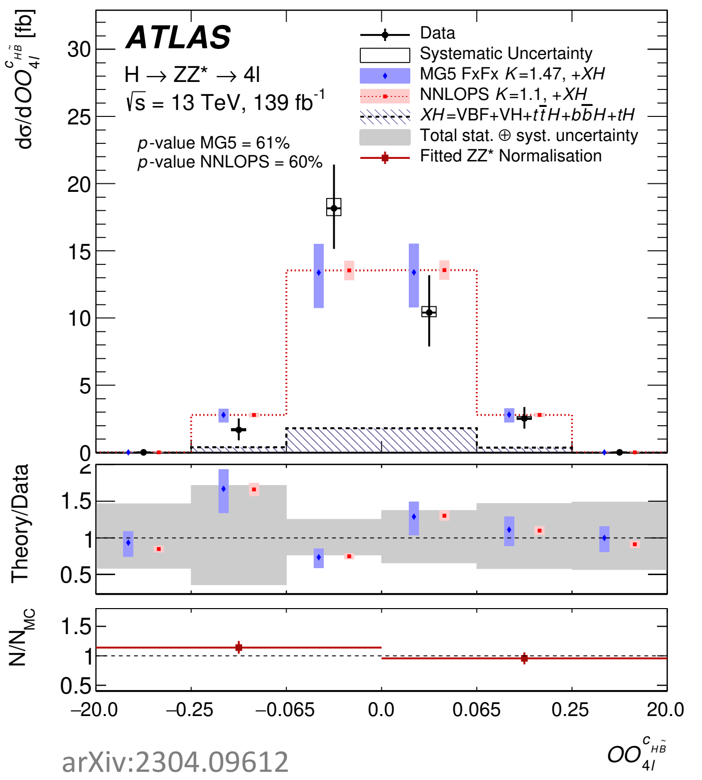
CMS: $\sigma_{fid}^{\gamma\gamma}$ = $73.4^{+5.4}_{-5.3}$ (stat) $^{+2.4}_{-2.2}$ (syst) (SM: 75.4 ± 4.1 fb)

The Higgs boson Fiducial Cross Sections

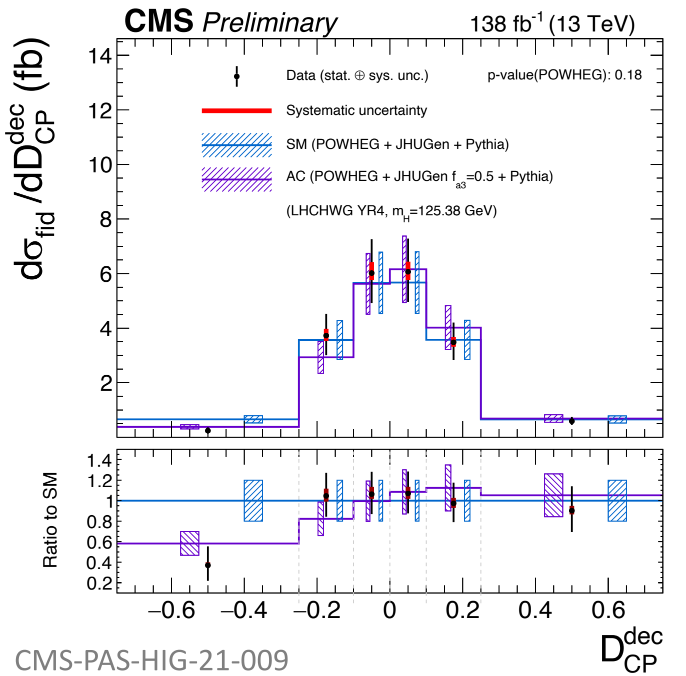


VBF H→WW*: ≥2jets
arXiv:2304.03053





arXiv:2304.09612



CMS-PAS-HIG-21-009

- **Fiducial phase space** definition based on detector acceptance to minimize the model dependency
  - Different phase space definition to target different production modes

ATLAS VBF in H→ZZ*→4l

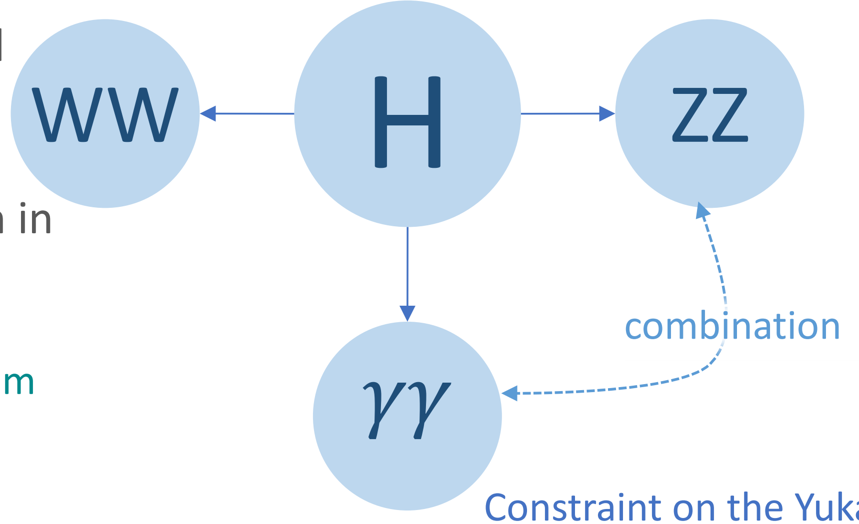
$\sigma^{VBF}_{fid} = 0.215^{+0.075}_{-0.063}(stat)\ ^{+0.016}_{-0.013}(syst)$ arXiv:2304.09612

Variable sensitive to the Higgs boson properties related to the Higgs kinematics or to the jets produced in association

- Variable sensitive to CP effects both at the decay as well as production vertex

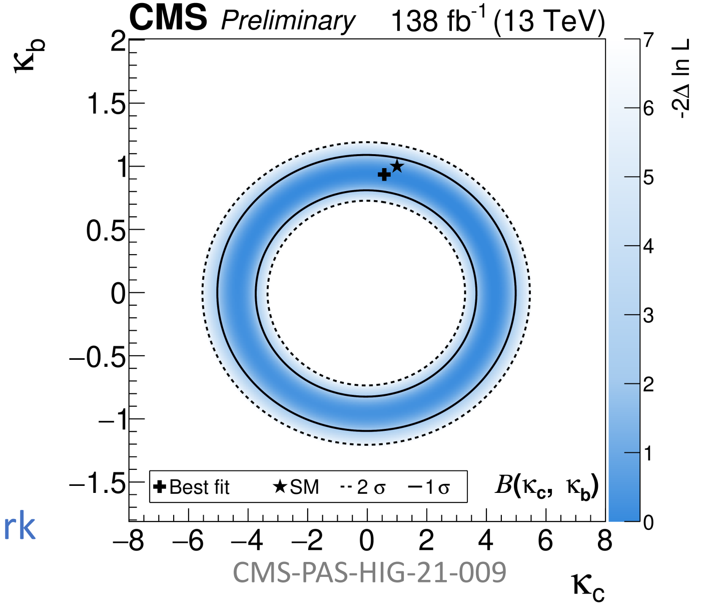
The Higgs boson Cross Sections and Interpretations

- **Combine the results** extrapolating to the full phase space (larger theory uncertainties)
→ sensible reduction of the statistical error
- **Interpretation** of the differential distribution in different framework



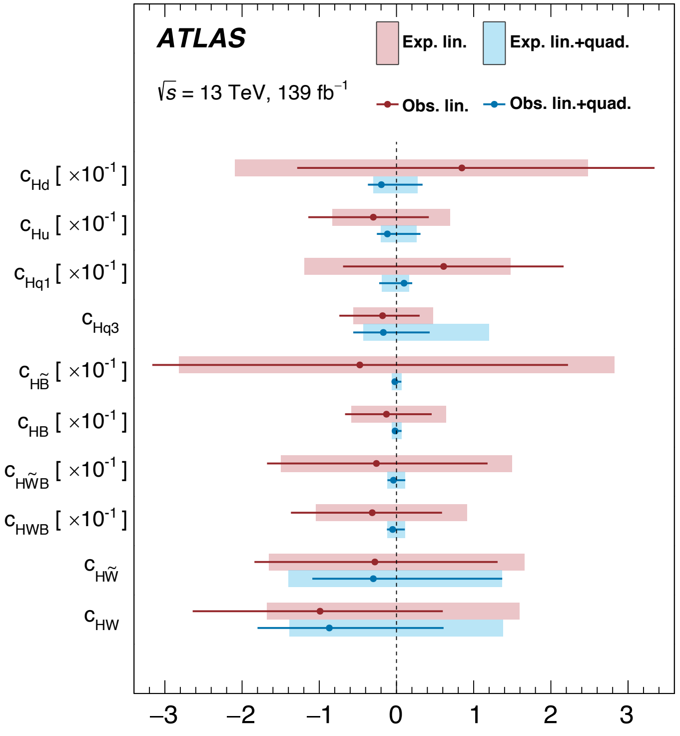
Constraint on the Yukawa coupling to the charm quark

from p_T^H in $H \to ZZ^* \to 4l$

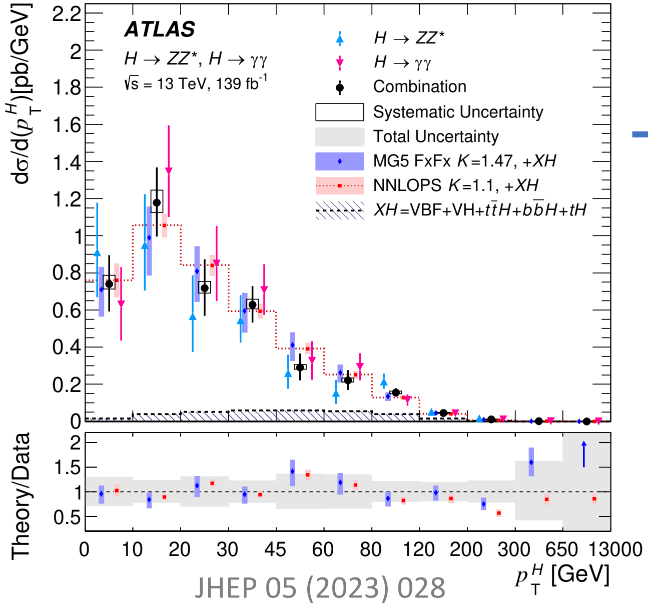


CMS-PAS-HIG-21-009

VBF, H→WW constrains EFT Wilson coefficient from CP-even and CP-odd operators using $\Delta\phi_{jj}$ and p_T^{j1}



arXiv:2304.03053



JHEP 05 (2023) 028

ZZ+$\gamma\gamma$

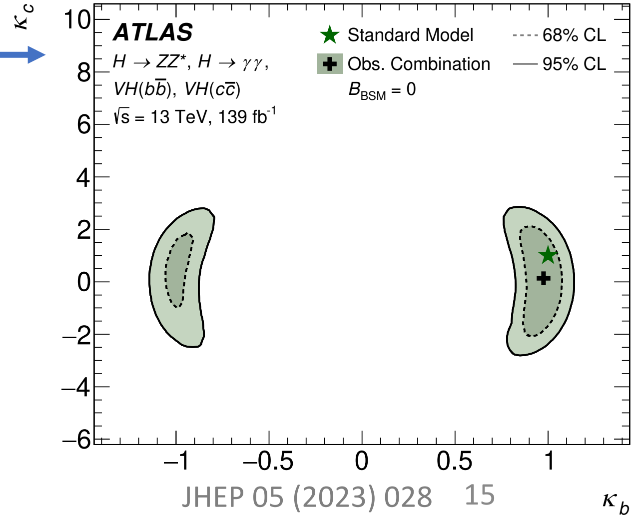
+ direct measurements VH(bb) and VH(cc)

ATLAS

$-2.47 < \kappa_c < 2.53$ @ 95% C.L.

CMS

$-5.3 < |\kappa_c| < 5.2$ @ 95% C.L.



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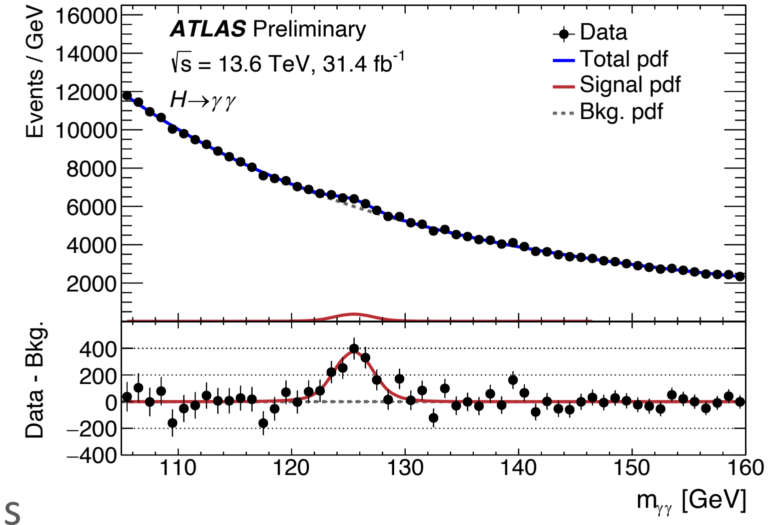
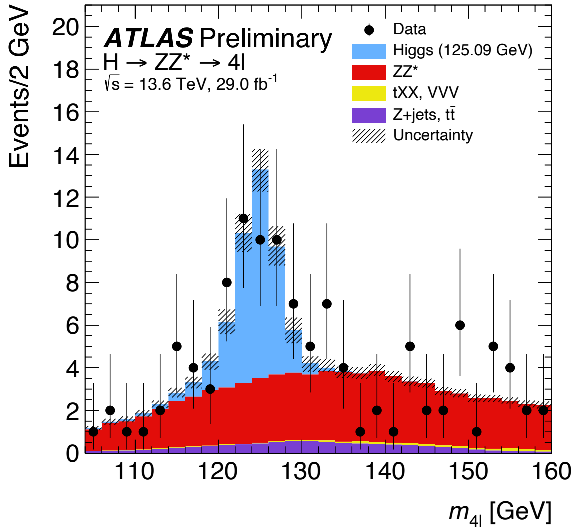
The Higgs boson Fiducial Cross Sections…@ 13.6 TeV

First measurement of the Higgs boson production cross section @ 13.6 TeV performed by ATLAS in $H\rightarrow ZZ^*\rightarrow 4l$ and $H\rightarrow\gamma\gamma$ decay channels and combined

- Collected luminosity of 31.4 fb^{-1} for $H\rightarrow\gamma\gamma$ and 29.0 fb^{-1} for $H\rightarrow ZZ^*\rightarrow 4l$ (only runs with muon triggers) in 2022
- Analysis strategy same as for Run 2 for both channels
  - $H\rightarrow\gamma\gamma$: reconstruction efficiency ~36% as for Run 2
  - $H\rightarrow ZZ^*$: different reco selection for muons wrt Run 2 ($|\eta|<2.5$)





Fiducial cross section results per channel extracted from fit of the invariant mass $m_{\gamma\gamma}$ or m_{4l} in the fiducial phase space, correcting for the fiducial efficiency

$$\sigma_{fid}^{\gamma\gamma} = 76^{+14}_{-13}\ \text{fb}$$

(SM: 67.6 ± 3.7 fb)

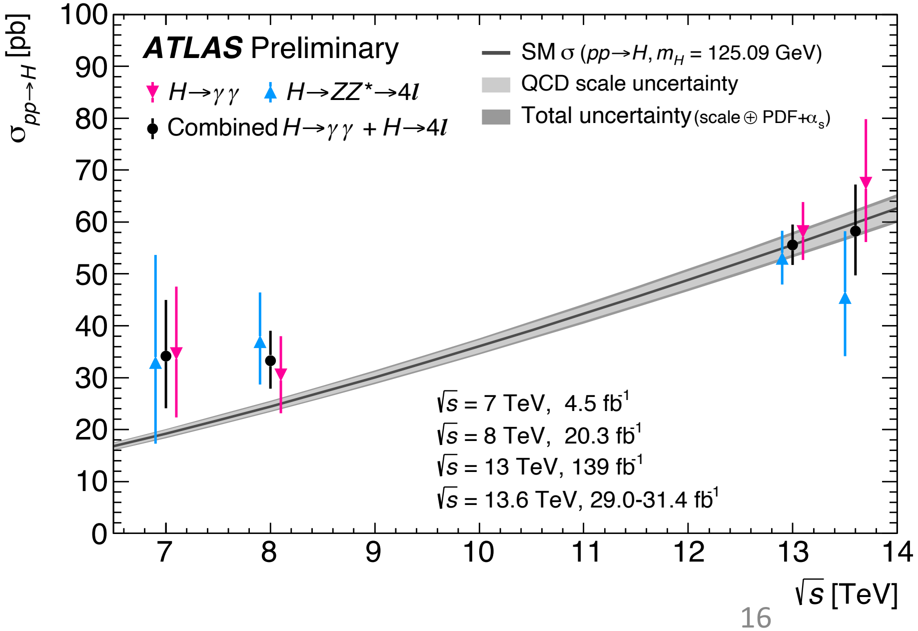
$$\sigma_{fid}^{4l} = 2.80 \pm 0.74\ \text{fb}$$

(SM: 3.67 ± 0.19 fb)

Combination of the total cross section

$$\sigma_{total} = 58.2 \pm 8.7\ \text{pb}$$

(SM: 59.9 ± 2.6 pb)



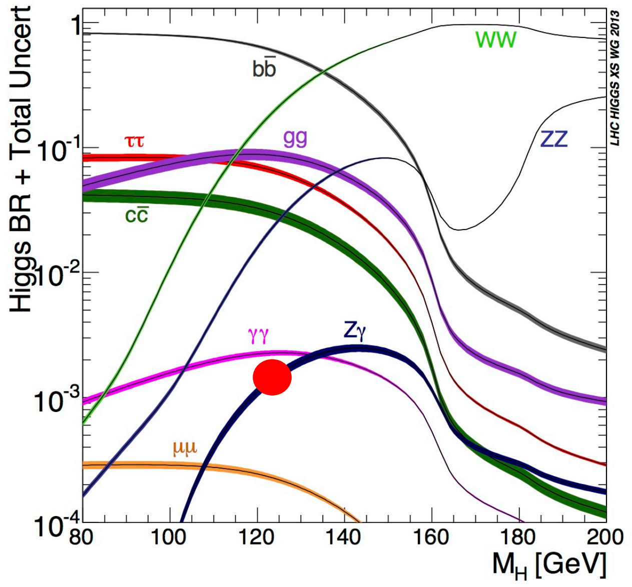
The Higgs boson rare decays: H→Zγ

Very rare decay! Important for probing the Higgs properties and for validating SM/BSM theories

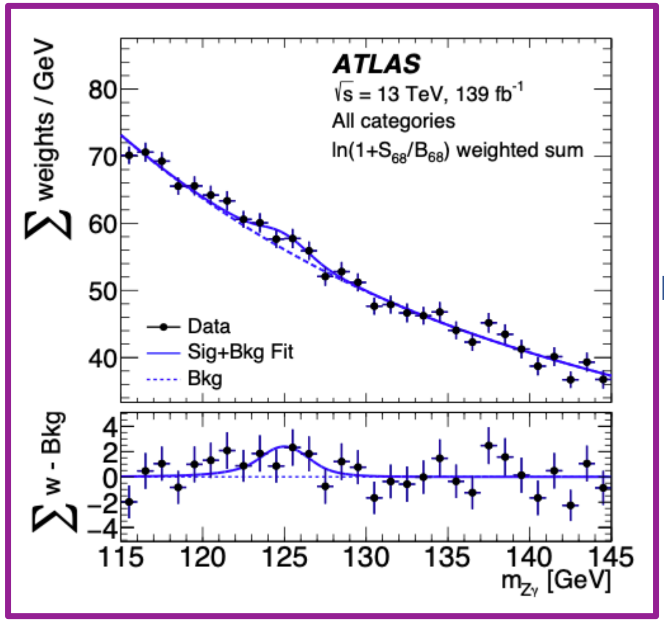
Not observed yet, but…using full Run2 data both experiments observed an **excess**

ATLAS: μ_{sig} = 2.0+1.0, local significance 2.2(1.2) σ Phys. Lett. B 809 (2020) 135754

CMS: μ_{sig} = 2.4 ± 0.9, local significance 2.7(1.2) σ arXiv:2204.12945



Combination effort between ATLAS and CMS



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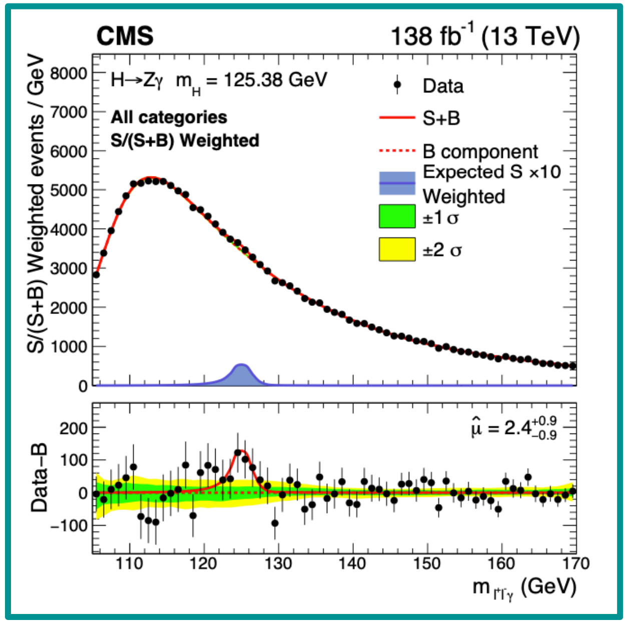

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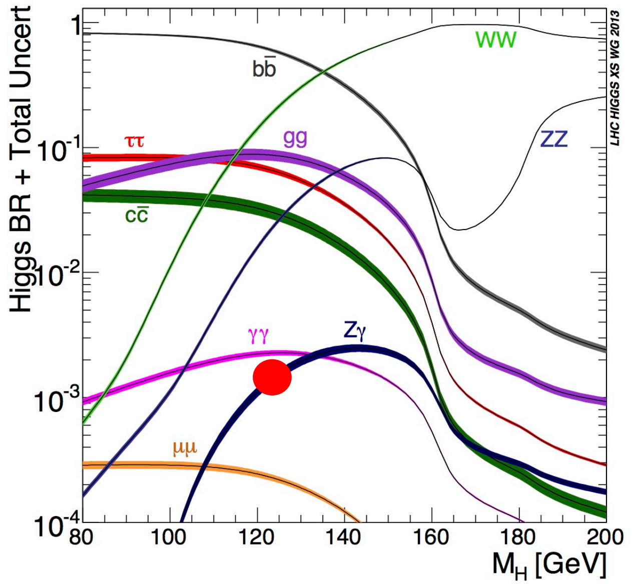
The Higgs boson rare decays: H→Zγ



Common strategy ATLAS and CMS

- Z reconstructed from l^+l^- (l=e or μ) decay
- Photon well isolated
- Sensitivity enhanced studying the S/B in different categories to exploit different production modes

Major differences ATLAS vs. CMS

- method to account for uncertainties on chosen background fit function
- Higgs mass: 125.09 GeV vs. 125.38 GeV

Combination

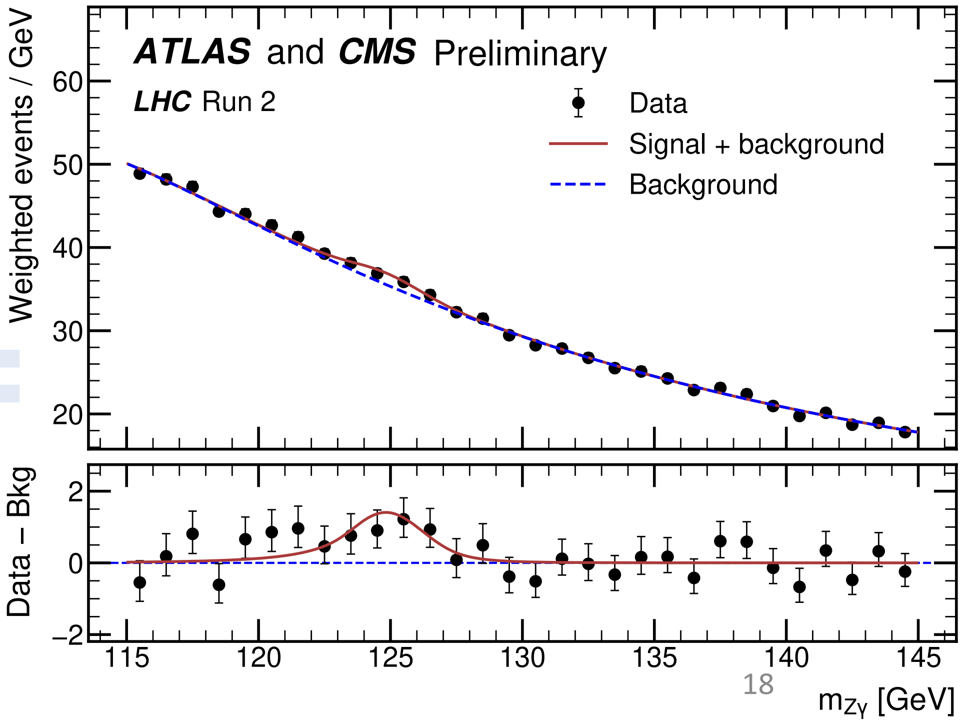
- Theory uncertainty on ggF cross section from higher order QCD corrections and BR uncertainties correlated (all other uncertainties uncorrelated)
  - The results holds for both Higgs mass assumption

The combined results between ATLAS and CMS claim the **first evidence** of this decay process!

μ_{sig} = 2.2 ± 0.7, **3.4σ**

SM compatibility: 1.9 σ

ATLAS-CONF-2023-025



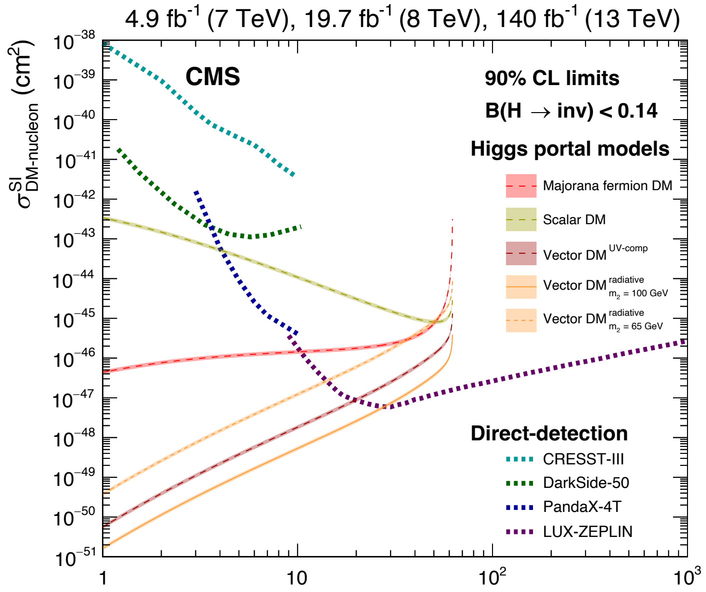
The Higgs boson invisible decays

- Probe possible Higgs decay in WIMPs (Dark Matter candidates)
  - Presence of missing transverse momentum (E_T^{miss}) in the interaction
- SM expectation BR(H→inv) = 0.1% (given by $ZZ^* \rightarrow 4\nu$)
- Combination between all the signature investigated in Run 2 (+Run 1)

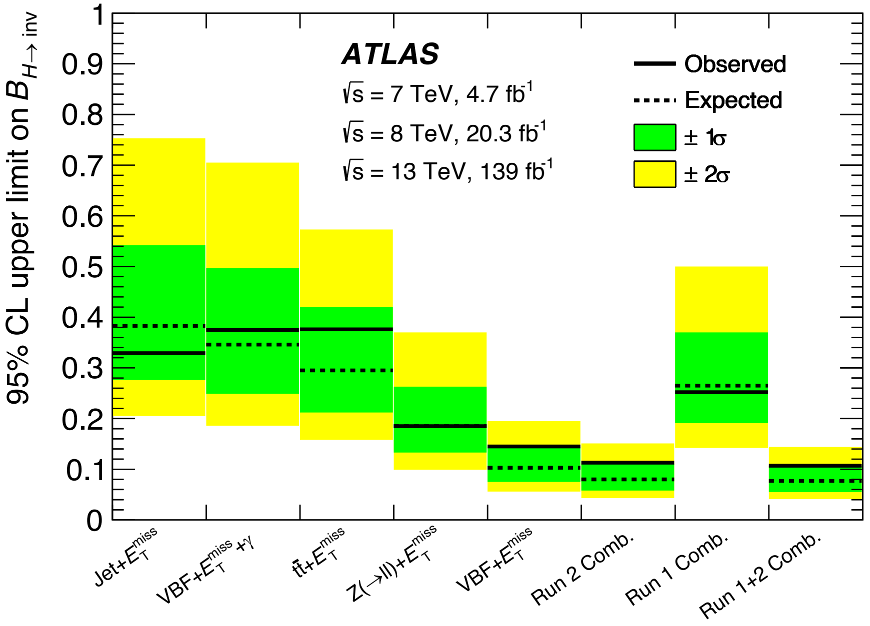
ATLAS: BR(H→inv)< 0.107 at 95% CL (0.077 expected) arXiv:2301.10731

CMS: BR(H→inv)< 0.15 at 95% CL (0.08 expected) arXiv:2303.01214

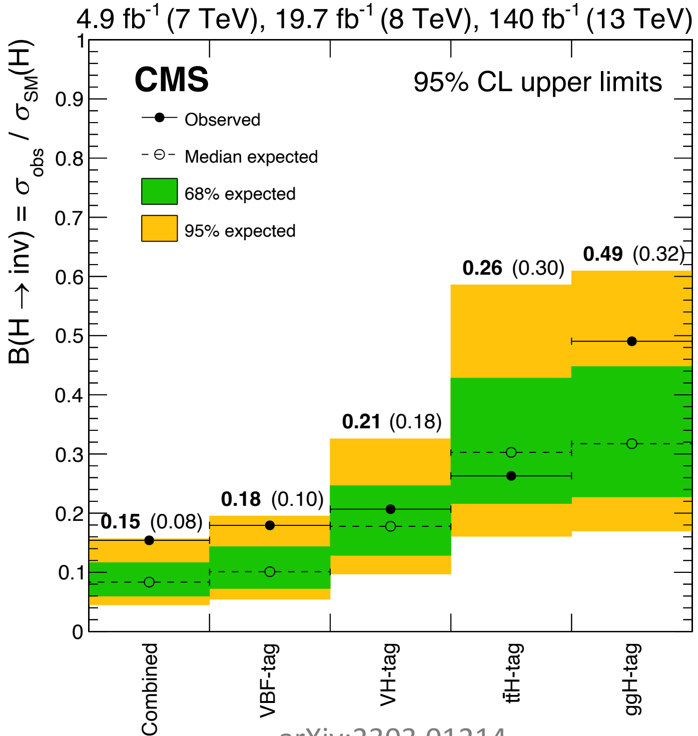
Constraints on WIMPs/DM nucleon scattering cross section as function of the WIMP/DM candidate mass



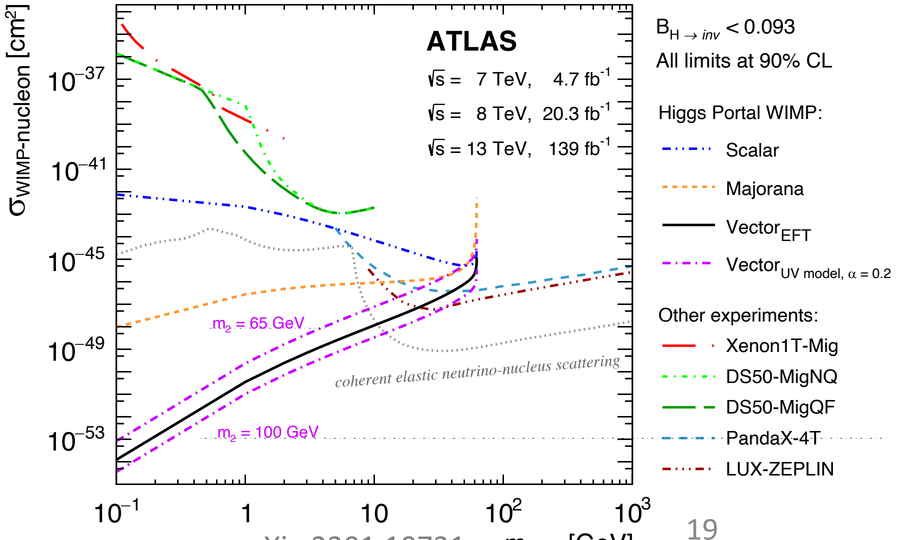
arXiv:2303.01214



arXiv:2301.10731



arXiv:2303.01214

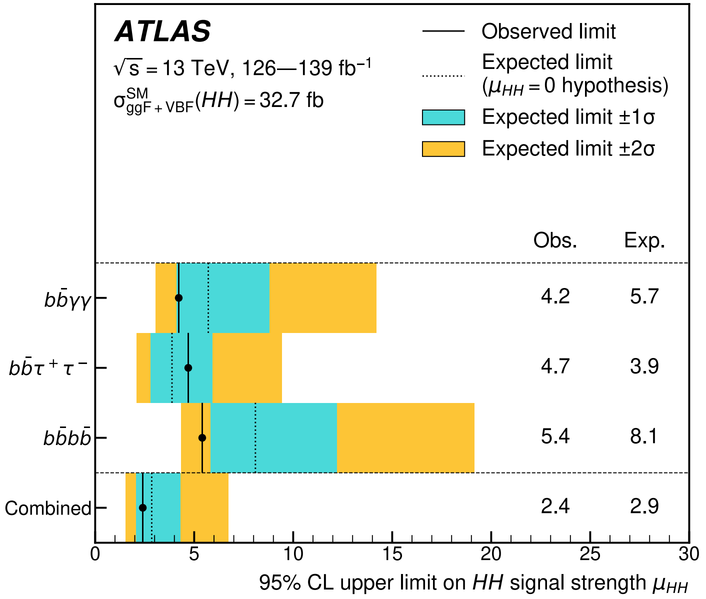


arXiv:2301.10731

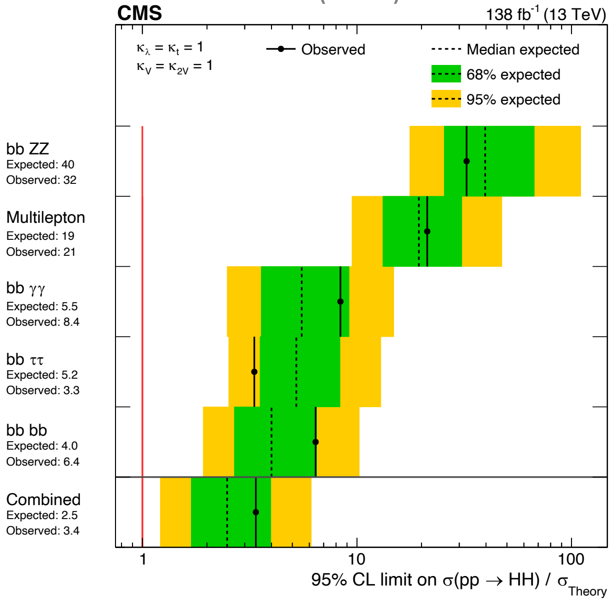
The Higgs boson self-coupling

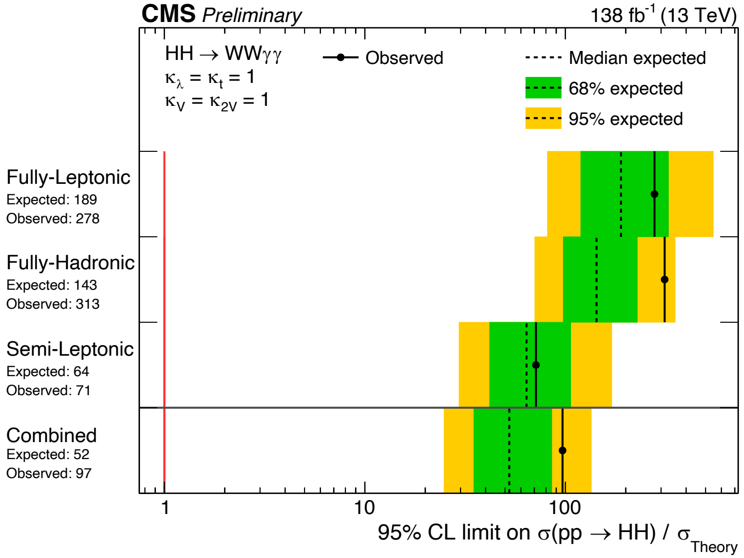
First study of the HH→WW$\gamma\gamma$ final state:
-25.8 < κ_λ < 24.1 @ 95 % C.L.

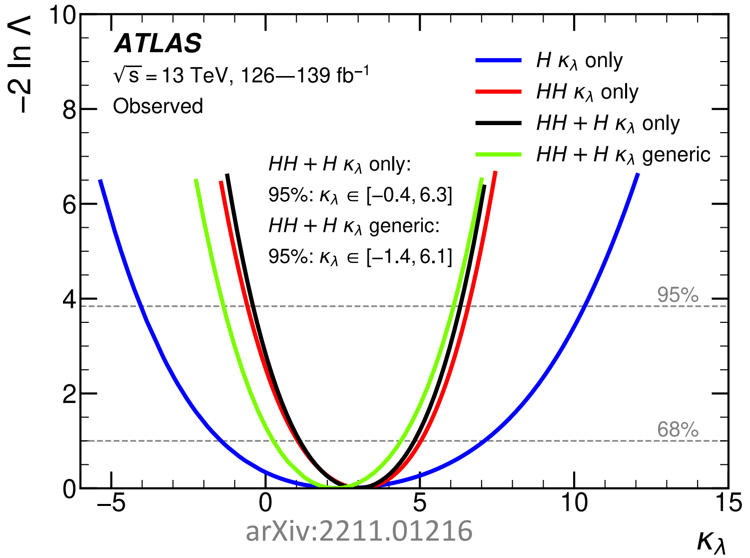
arXiv:2211.01216



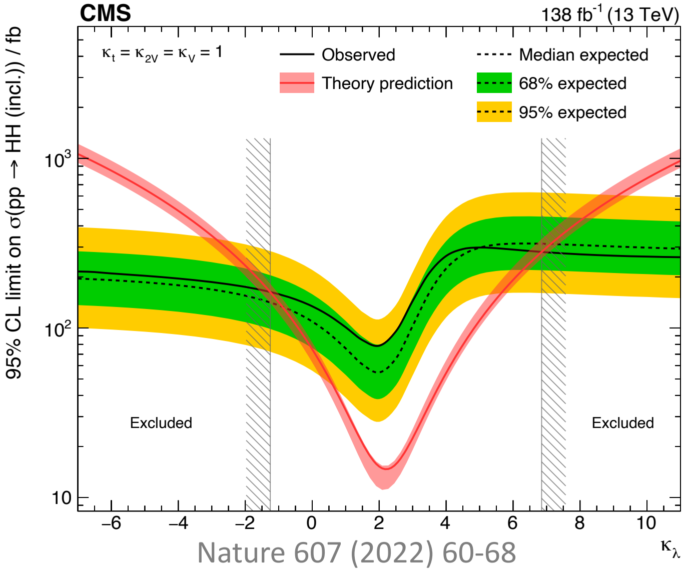
Nature 607 (2022) 60-68







arXiv:2211.01216



Nature 607 (2022) 60-68

Higgs boson self-coupling λ is a fundamental parameter of the SM

- Combined results from di-Higgs searches (bbbb, bb$\gamma\gamma$, bb$\tau\tau$, bbZZ)
- Constraint on $\sigma_{\rm HH}$ and κ_λ

ATLAS: combination HH+H
-0.4 < κ_λ < 6.3 @ 95 % C.L.

CMS combination HH
-1.24< κ_λ < 6.49@ 95 % C.L.

Conclusions

In LHC Run2 the enhancement of statistics allow to investigate Higgs boson properties, performing precision measurements and probing its couplings with SM particles and possible BSM effects

- All the measurements are in good agreement with SM expectations
- Higgs mass measured with a precision 140-180 MeV
- No hint of BSM effects or CP violation sign
- First evidence of off-shell Higgs boson production
- First evidence of $H \rightarrow Z\gamma$ decay
- First constraints on Higgs coupling with charm quark and on self-couplings
- …and first measurement @ 13.6 TeV!

Looking forward for new updated results with full Run 2 dataset and new coming data at 13.6 TeV