Measurements of Higgs boson properties with the ATLAS experiment

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On behalf of the ATLAS Collaboration
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Introduction and Outline

Since its discovery in 2012, the Higgs boson has been one of the focus at the ATLAS

- test the Standard Model (SM) prediction,
- any deviation could indicate Beyond Standard Model (BSM) physics

Higgs boson is fundamental and the only known scalar particle

We need knowledge on its properties

With **LHC Run 2 data (and early Run 3)**, ATLAS has measured

Higgs boson mass,

width,

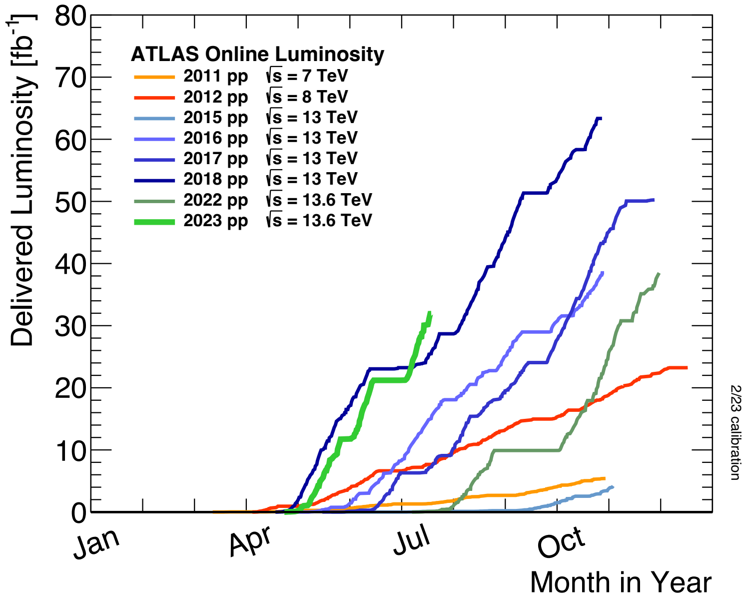
production cross-sections,

couplings,

CP structure,

Self-couplings

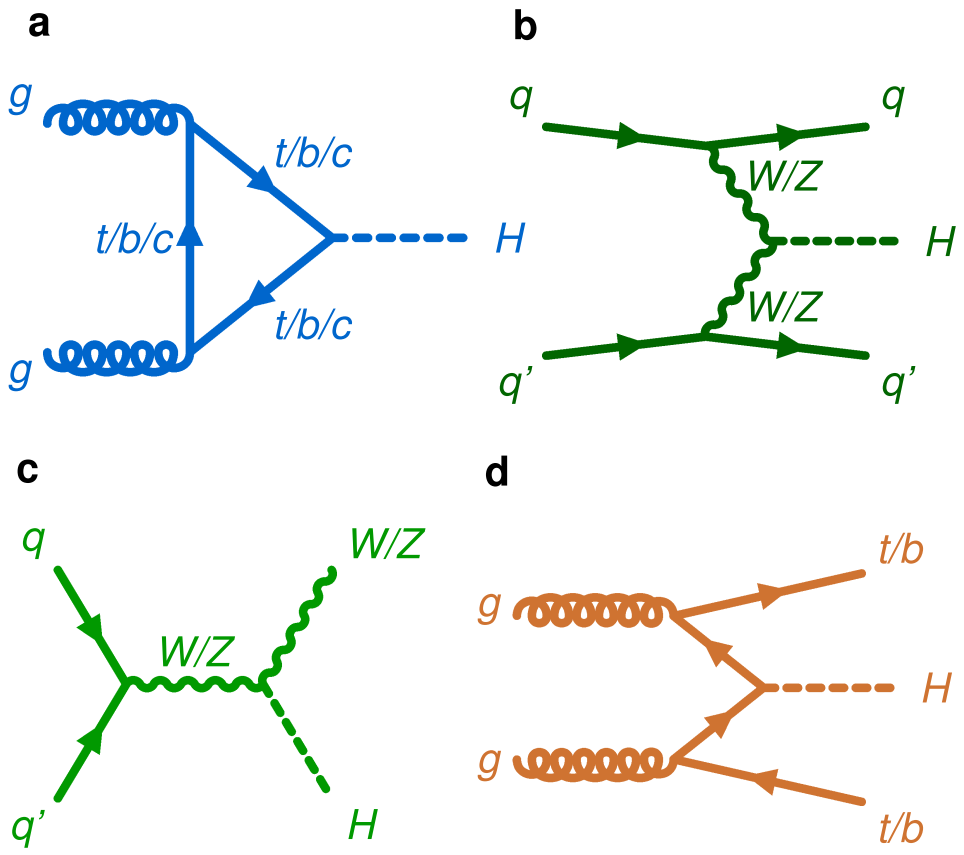
ATLAS Luminosity



The Higgs Boson at LHC

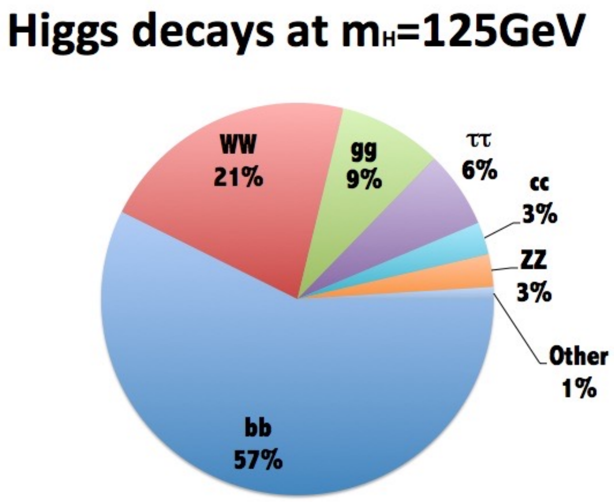
Higgs Production mechanisms:

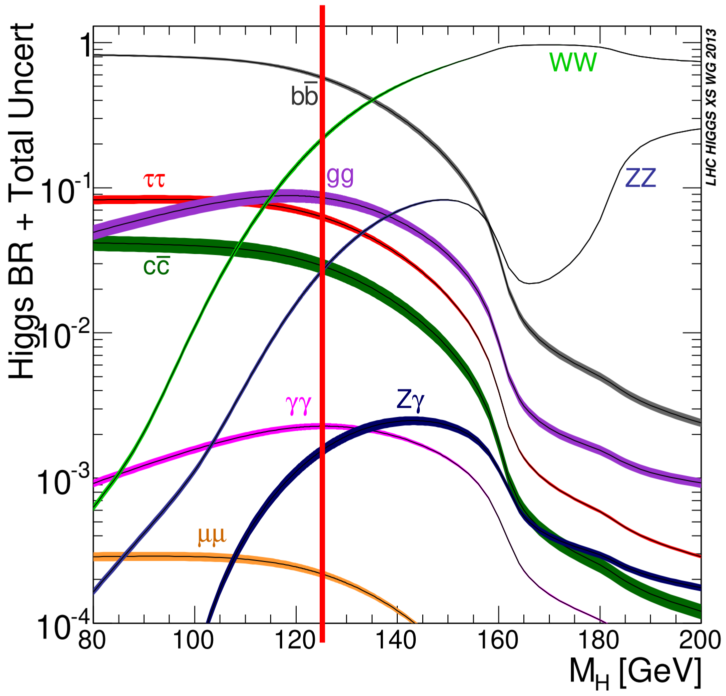
- Gluon-gluon fusion (ggF)
- Vector Boson fusion (VBF)
- Associated production with a vector boson (VH)
- Associated production with top quark pair (ttH)



Decay channels:

- $H \rightarrow ZZ^*$: low BR, good S/B ratio, high mass resolution
- $H \rightarrow \gamma\gamma$: low BR, large background, high mass resolutions
- $H \rightarrow WW^*$: high BR, low mass resolution
- $H \rightarrow b\bar{b}$ and $H \rightarrow \tau^+\tau^-$: high BR, large background, low mass resolution
- $H \rightarrow \mu^+\mu^-$ and $H \rightarrow Z\gamma$: very low BR





Higgs Mass Measurement

[Phys. Lett. B 847 (2023) 138315](#)

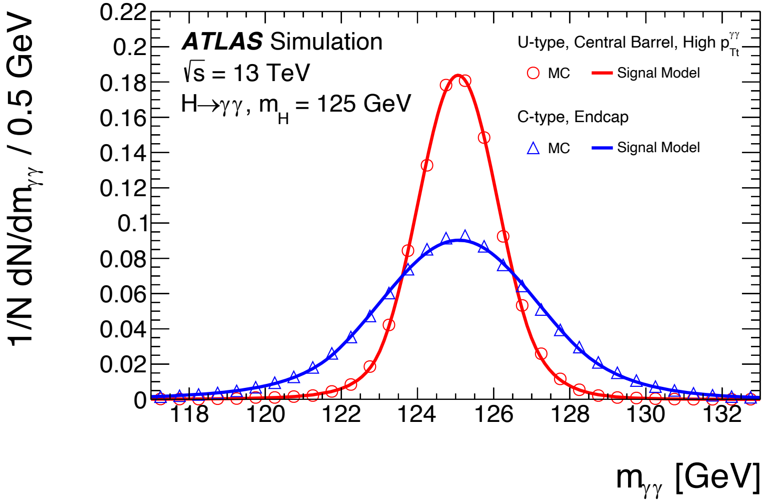
[arXiv:2309.05471](#)

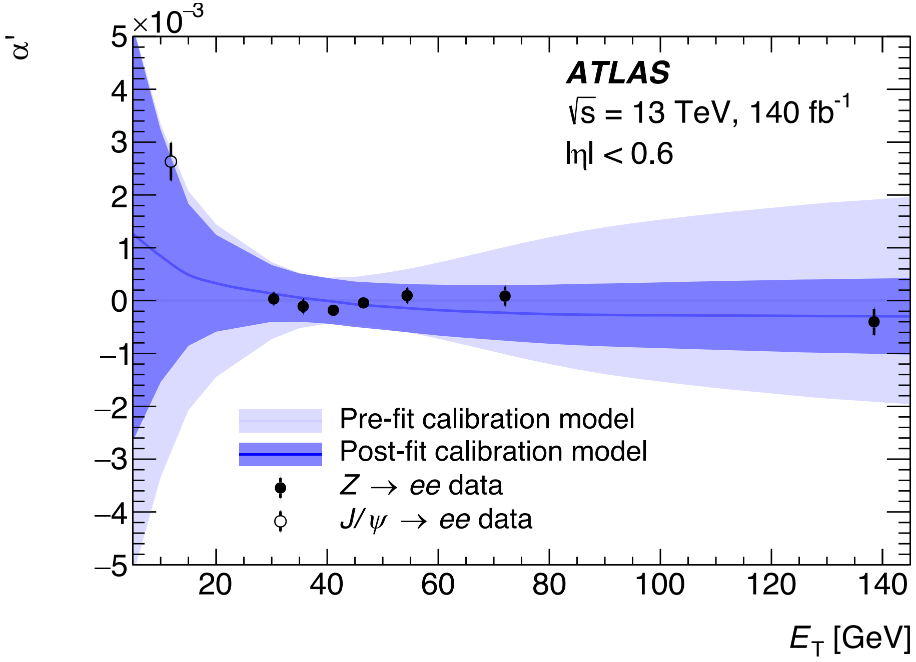
The latest ATLAS $H \rightarrow \gamma\gamma$

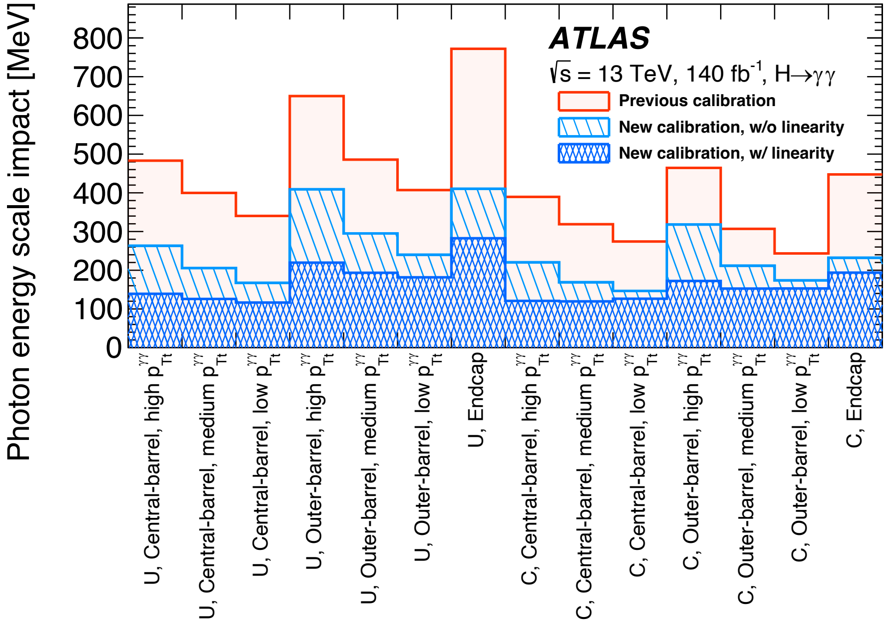
- ➢ Full Run 2 dataset (140 fb^{-1})

- ❖ Categorization by detector region, γ conversion type, and $p_{Tt}^{\gamma\gamma}$ improves the expected statistical and photon energy scale systematic uncertainties by **17%** compared with inclusive case
- ❖ Reduction of systematic uncertainty by factor of **4** compared with previous iteration based on partial Run 2 data (36 fb^{-1})
  - ➢ Improved photon energy scale calibration and resolution

    Total expected systematic uncertainty 340 MeV → 90 MeV







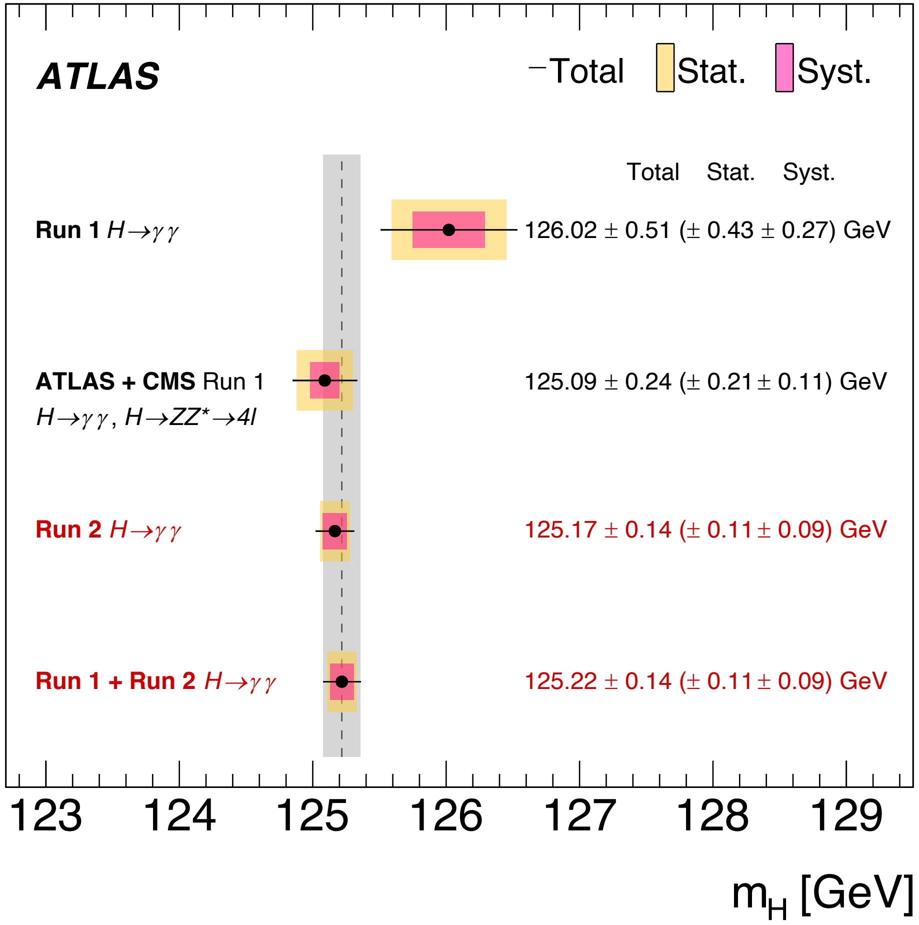
Higgs Mass Measurement

[Phys. Lett. B 847 (2023) 138315]

The latest ATLAS $H \to \gamma\gamma$

Full Run 2 result: m_H = 125.17 ± 0.11 (stat.) ± 0.09 (syst.) = 125.17 ± 0.14 GeV

Run 1 + Run 2 result: m_H = 125.22 ± 0.11 (stat.) ± 0.09 (syst.) = 125.22 ± 0.14 GeV



0.1% precision from a single channel!

Source	Impact [MeV]
Photon energy scale	83
$Z \to e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^\pm \to \gamma$ extrapolation	30
Conversion modelling	24
Signal–background interference	26
Resolution	15
Background model	14
Selection of the diphoton production vertex	5
Signal model	1
Total	90

Higgs Mass Measurement

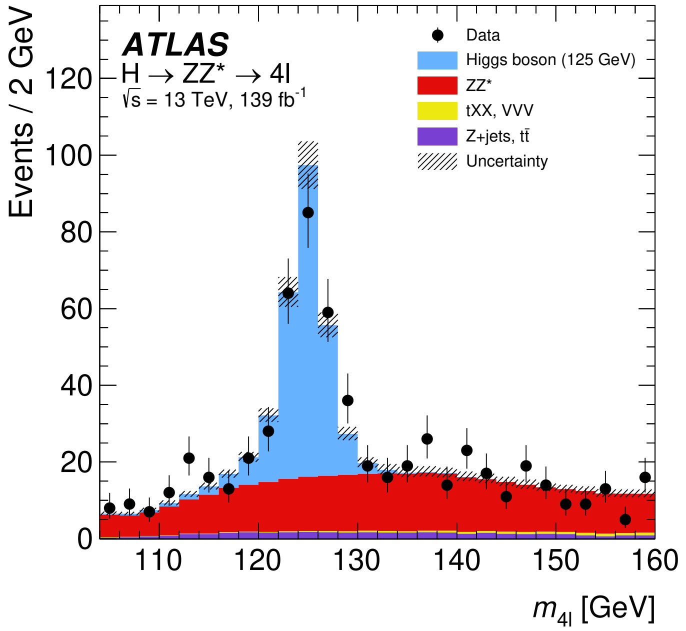
Phys. Lett. B 843 (2023) 137880

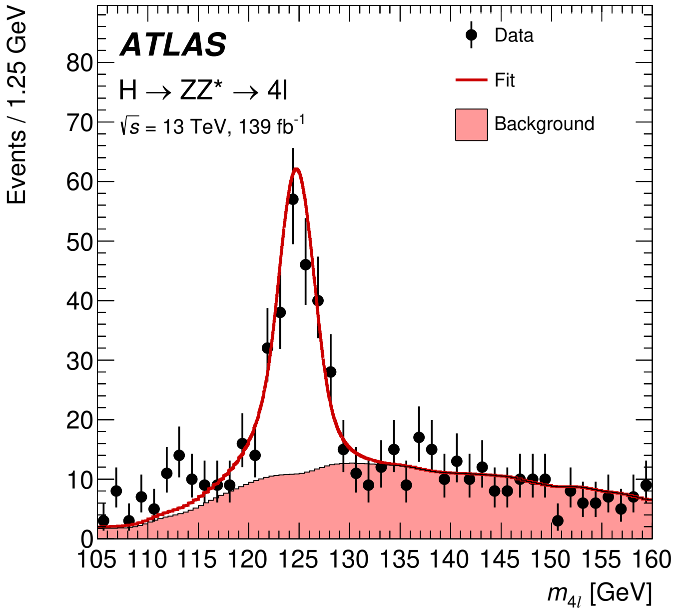
The latest ATLAS $H \to ZZ^* \to 4\ell$ ($\ell = e, \mu$)

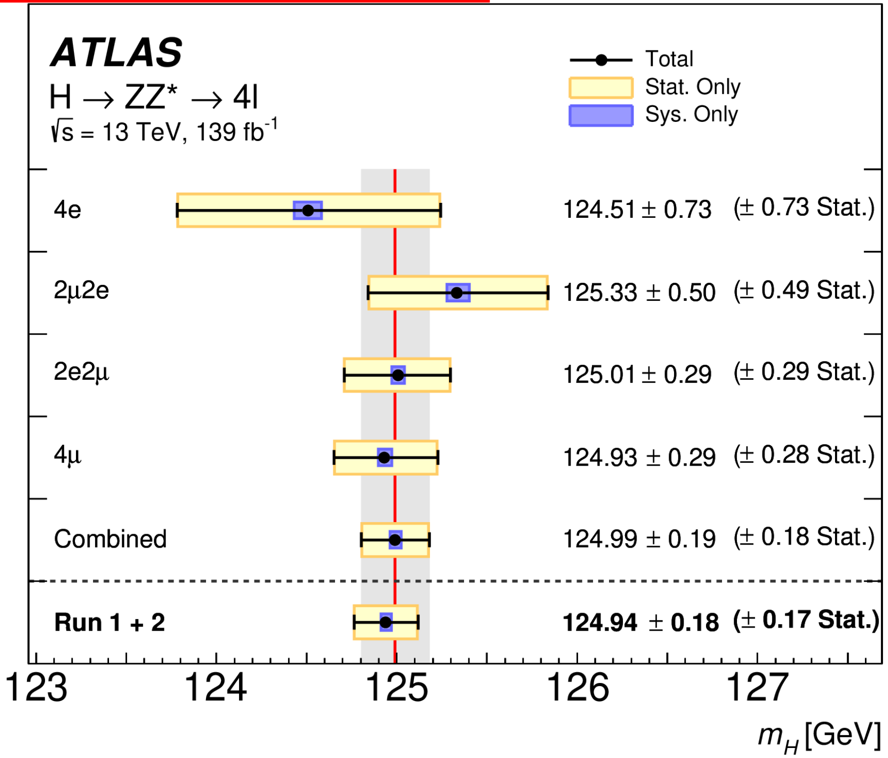
- Full Run 2 dataset (139 fb^{-1})

Full Run 2 result: m_H = 124.99 ± 0.18 (stat.) ± 0.04 (syst.) = 124.99 ± 0.19 GeV

Run 1 + Run 2 result: m_H = 124.94 ± 0.17 (stat.) ± 0.03 (syst.) = 124.94 ± 0.18 GeV







Higgs Mass Measurement

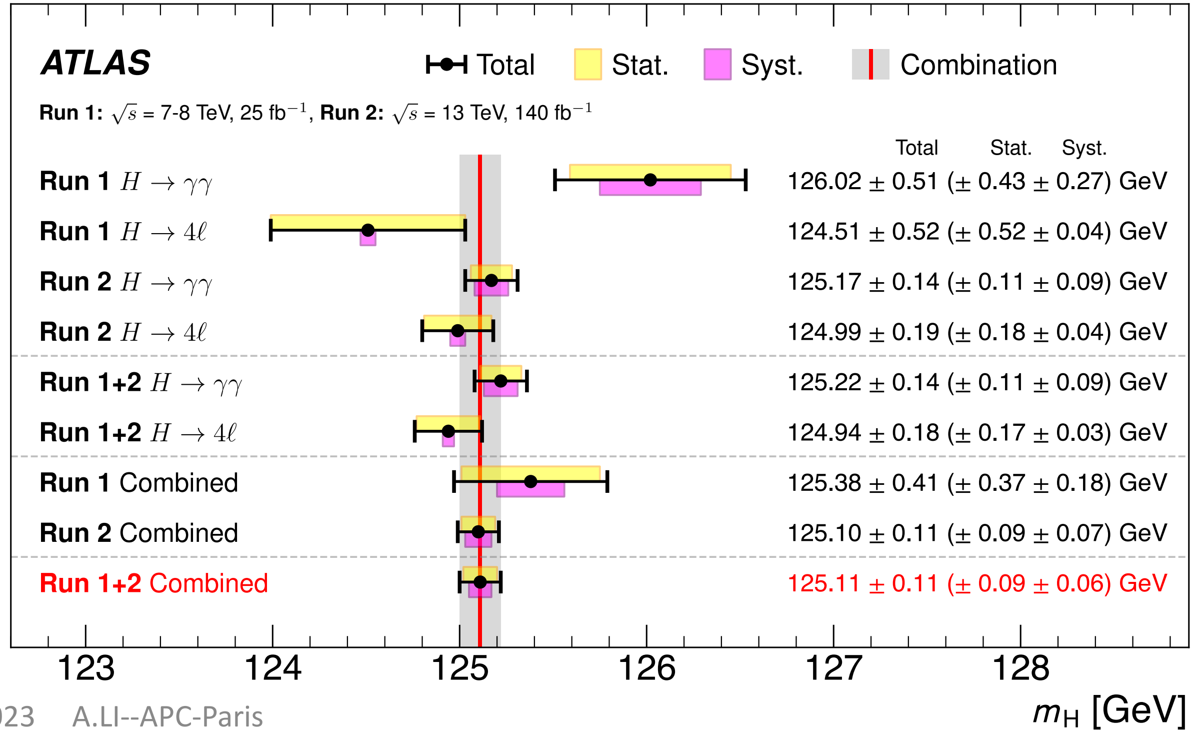
arXiv:2308.04775

ATLAS Combined $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$

- Full Run 2 dataset (140 fb^{-1})
- 18% compatibility among input measurements
- The most precise m_H measurement to date
- ATLAS+CMS combination under preparation

Full Run 2 result: m_H = 125.10 ± 0.09 (stat.) ± 0.07 (syst.) = 125.10 ± 0.11 GeV

Run 1 + Run 2 result: m_H = 125.11 ± 0.09 (stat.) ± 0.06 (syst.) = 125.11 ± 0.11 GeV



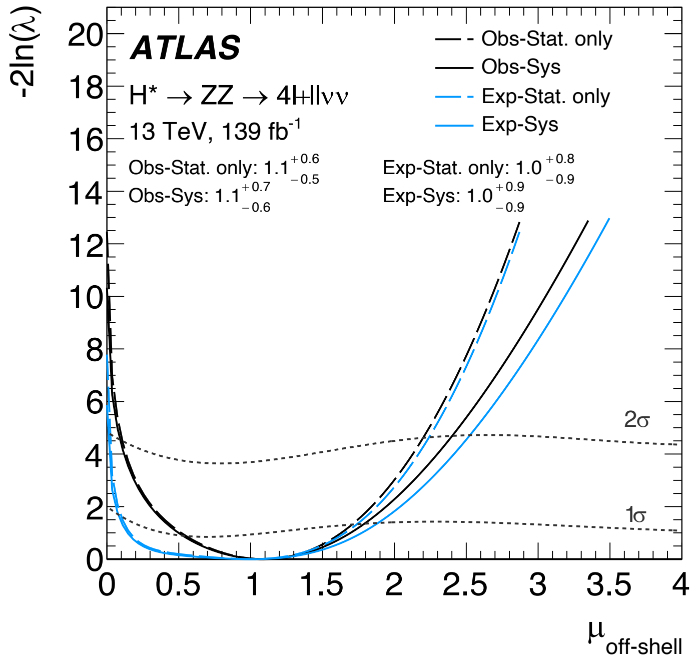
Source	Systematic uncertainty on m_H [MeV]
e/γ E_T-independent $Z \to ee$ calibration	44
e/γ E_T-dependent electron energy scale	28
$H \to \gamma\gamma$ interference bias	17
e/γ photon lateral shower shape	16
e/γ photon conversion reconstruction	15
e/γ energy resolution	11
$H \to \gamma\gamma$ background modelling	10
Muon momentum scale	8
All other systematic uncertainties	7

Higgs Boson Width Measurement

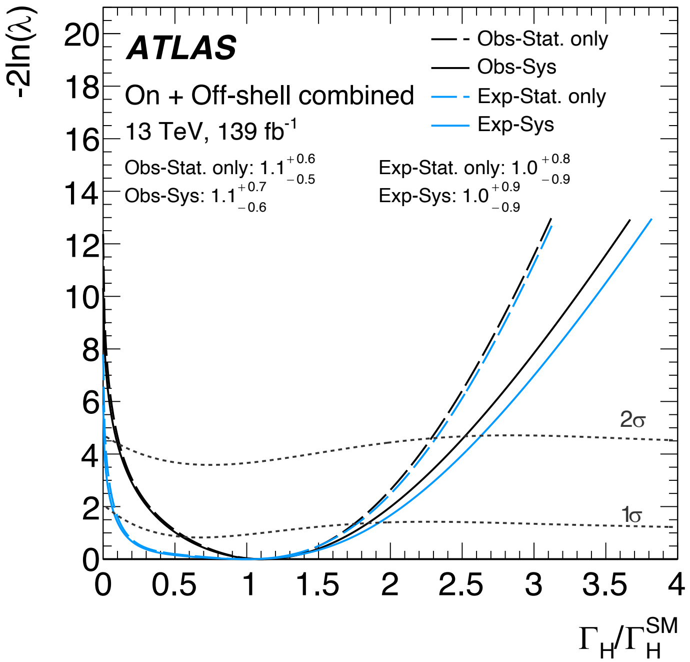
Phys. Lett. B 846 (2023) 138223

- SM Theoretical prediction Higgs width of 4.1 MeV is much smaller than the detector resolution (GeV level)
- Indirect measurement from the ratio of the off-shell/on-shell Higgs boson production
- $\mathrm{H} \rightarrow ZZ^{*} \rightarrow 4\ell$ and $2\ell 2\nu$, full Run 2

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



- $\mu_{\text{off-shell}} = 1.1^{+0.7}_{-0.6}$
- 3.3σ obs. (2.2σ exp.) exclusion of $\mu_{\text{off-shell}} = 0$
- First evidence for off-shell Higgs boson production!



68% C.L.

$\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

95%CL limit Obs.(Exp.):

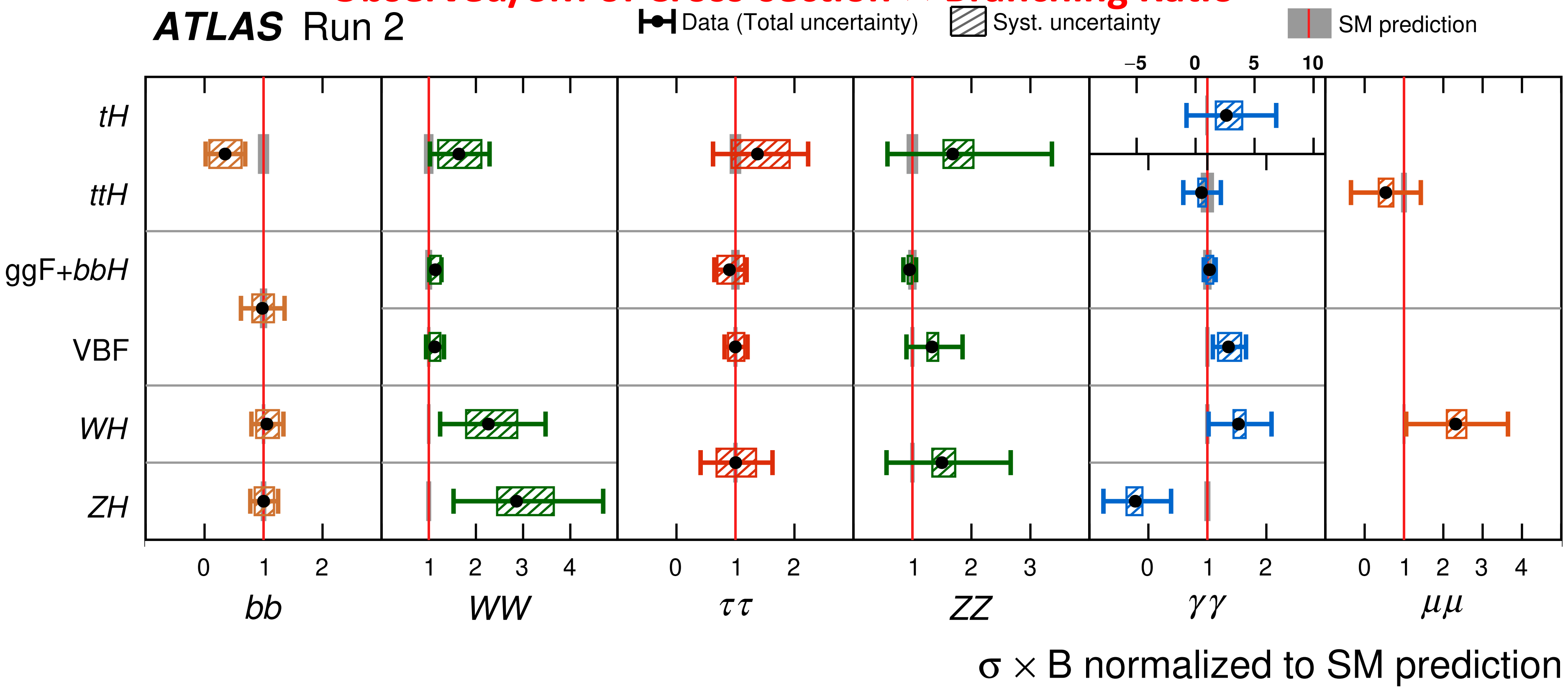
0.5 (0.1)< Γ_H <10.5 (10.9) MeV

The Higgs boson cross-section and couplings

Nature 607, 52 (2022)

- Production cross-sections 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, ATLAS provided the combined measurements of its couplings

Observed/SM of Cross-section × Branching Ratio



The p-value for compatibility of the measurement and the SM prediction is 72%

Analysis enter the combination:

Decay mode	Targeted production processes
$H \to \gamma\gamma$	ggF, VBF, WH, ZH, $t\bar{t}H$, tH
$H \to ZZ$	ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$ $t\bar{t}H + tH$ (multilepton)
$H \to WW$	ggF, VBF WH, ZH $t\bar{t}H + tH$ (multilepton)
$H \to Z\gamma$	inclusive
$H \to b\bar{b}$	WH, ZH VBF $t\bar{t}H + tH$ inclusive
$H \to \tau\tau$	ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$ $t\bar{t}H + tH$ (multilepton)
$H \to \mu\mu$	ggF + $t\bar{t}H + tH$, VBF + $WH + ZH$
$H \to c\bar{c}$	$WH + ZH$
$H \to$ invisible	VBF ZH

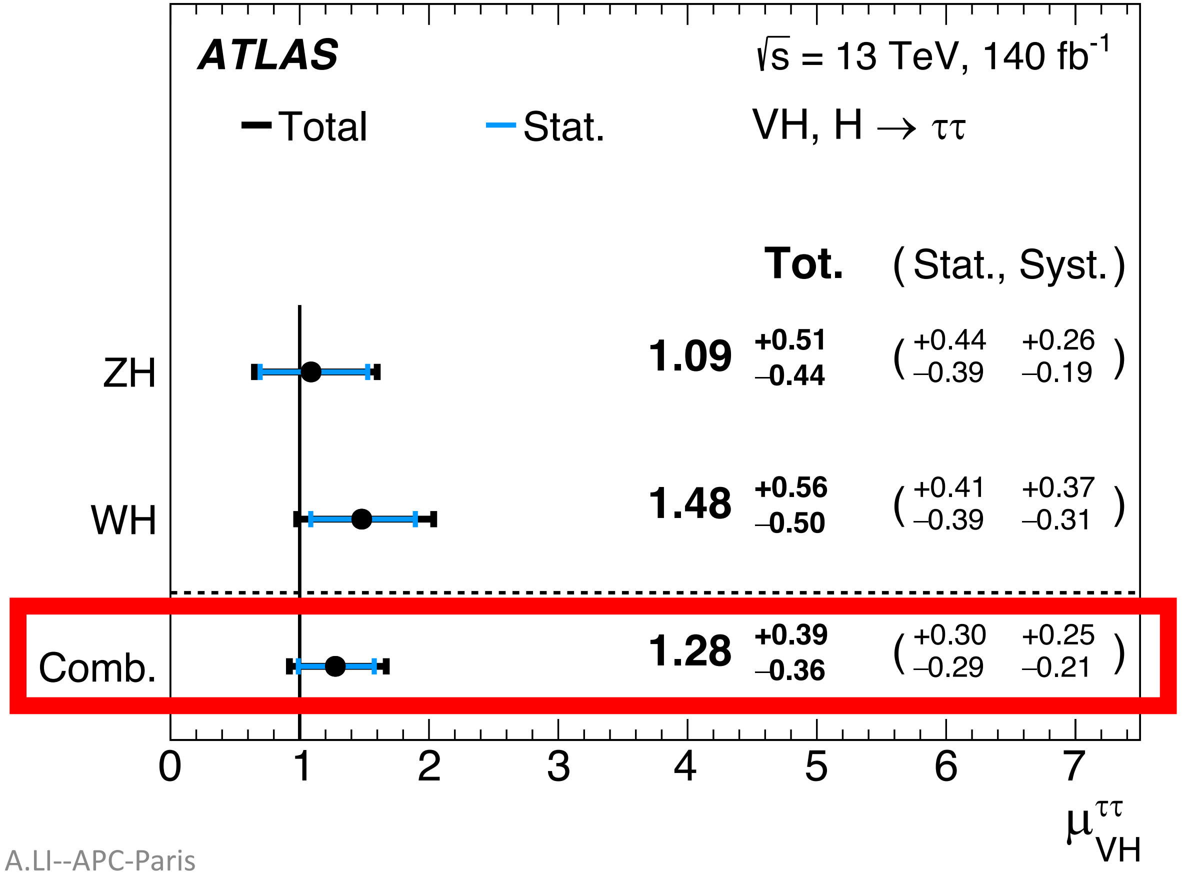
Evidence of VH, $H \to \tau^+\tau^-$

VH final states: HIGG-2018-20

- $H \to \tau^+\tau^-$ at least one τ decaying hadronically ($\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$, at least one τ decaying hadronically)
- $W \to \ell\nu$, $Z \to \ell\ell$, V decaying leptonically (with $\ell = e, \mu$)

Results extracted from a simultaneous fit of the NN score in all final states

- Observed (expected) significance of 4.2 (3.6) σ: evidence of $VH, H \to \tau^+\tau^-$ process
- Measured signal strength $\mu_{VH} = 1.28^{+0.39}_{-0.36}$ (Corresponding cross-section $8.5^{+2.6}_{-2.4}\ fb$, SM prediction $6.59 \pm 0.03\ fb$)



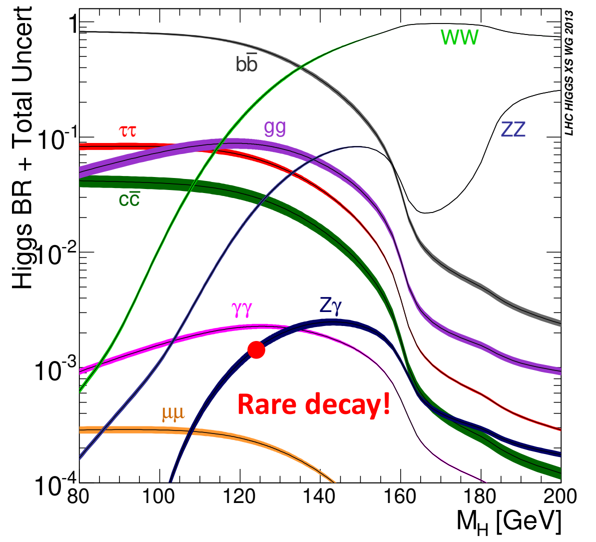
	Significance exp	Significance obs
WH	2.2	3.3
ZH	2.9	2.8
Combined	3.6	4.2

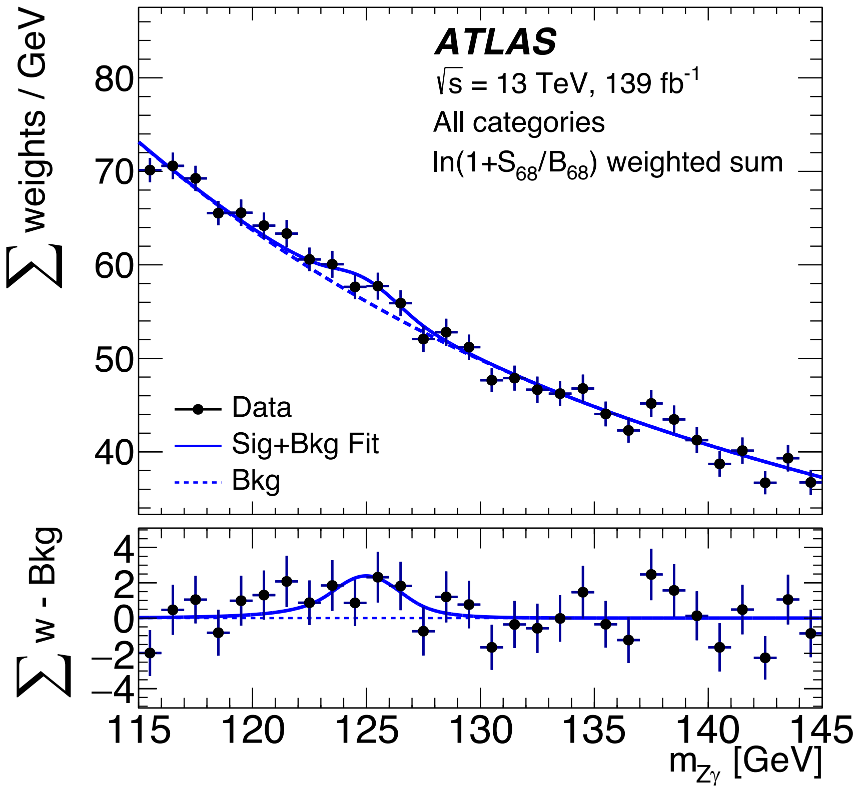
Evidence of $VH, H \to \tau^+\tau^-$ process

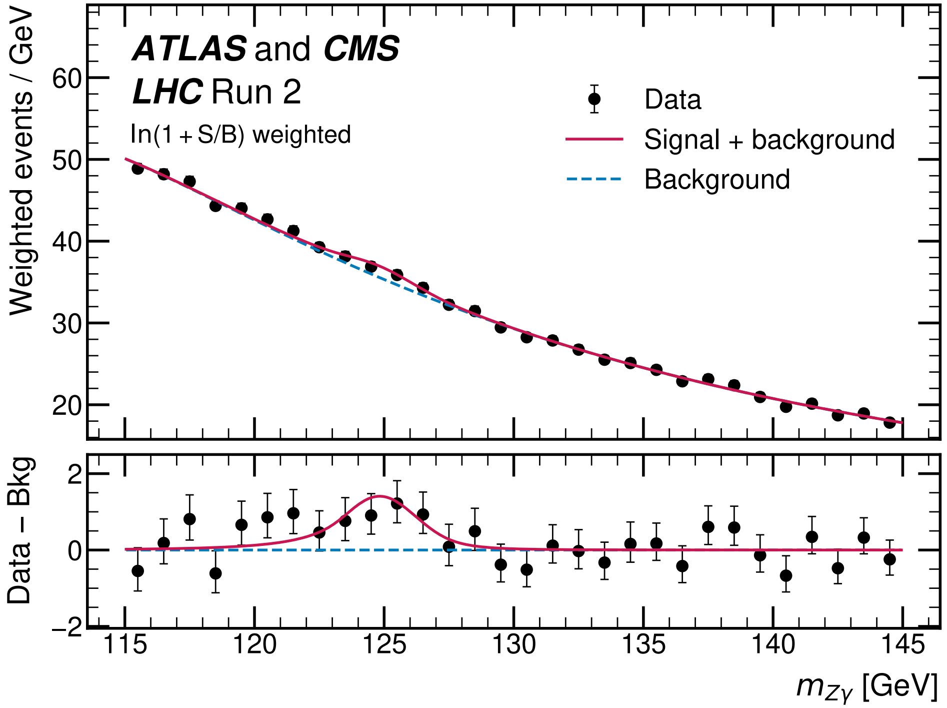
Higgs Rare decay: $H \to Z\gamma$

[Phys. Lett. B 809 (2020) 135754](#)
[arXiv:2309.03501](#)

- **$H \to Z\gamma$ Rare decay**
- **Probing the Higgs properties and for validating SM/BSM theories**
- **Using full Run 2 data, observed an excess**
  - Z reconstructed from $\ell^+\ell^-$ ($\ell = e$ or μ) decay
  - Photon well isolated
  - Sensitivity enhanced studying the S/B in different categories to exploit different production modes







ATLAS:

- $\mu_{sig.} = 2.0^{+1.0}_{-0.9}$
- Local significance $2.2(1.2)\sigma$

When combined with CMS

- Observed 3.4σ (1.6σ)

Higgs decay to invisible

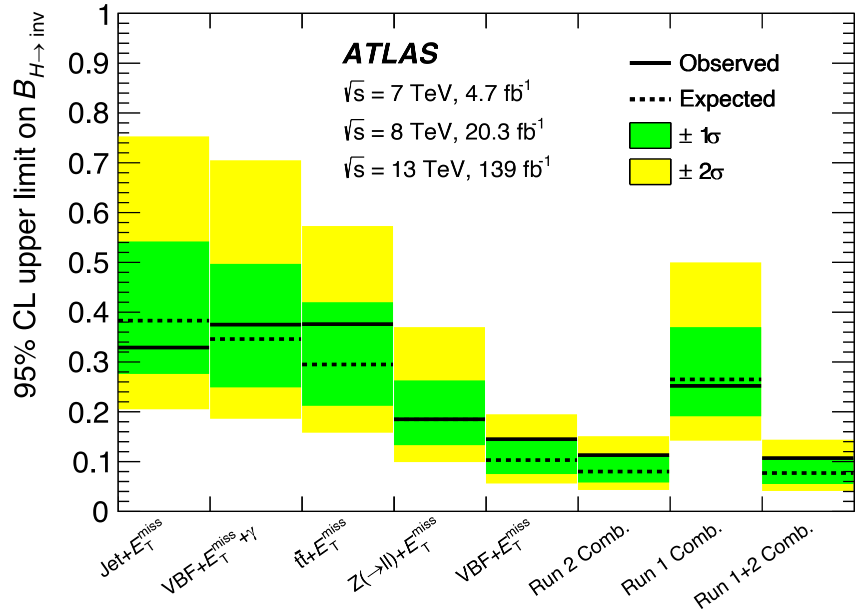
[Phys. Lett. B 842 (2023) 137963](#)

- **Probe possible Higgs decay to WIMPs (Higgs portal dark matters)**
- **Missing transverse momentum (E_T^{miss}) in the interaction**
- **Run 1 + 2 Combination**

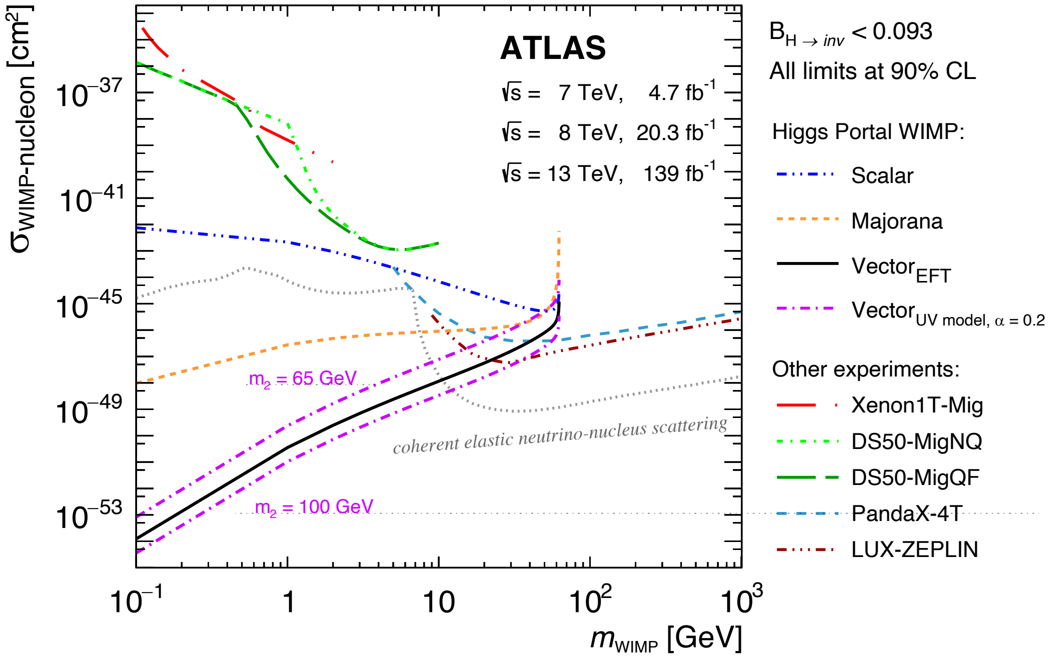
At 95% CL:

$BR(H \rightarrow \text{inv.}) < 0.107$ (0.077 expected)

SM: $BR(H \rightarrow \text{inv.}) = 0.1\%$



Constraints on Higgs portal WIMP cross-section as function of the WIMP candidate mass

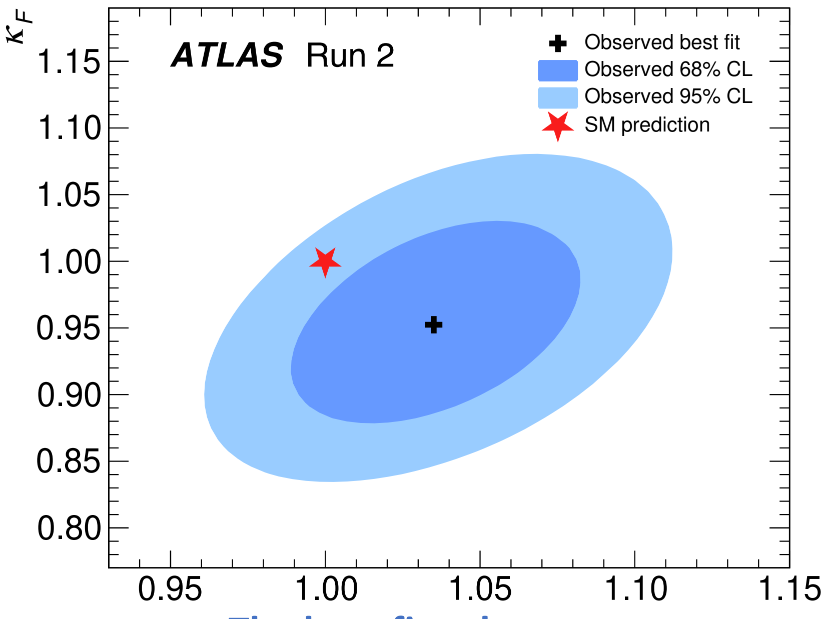


The Higgs boson couplings

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

[Nature 607, 52 (2022)](#)

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



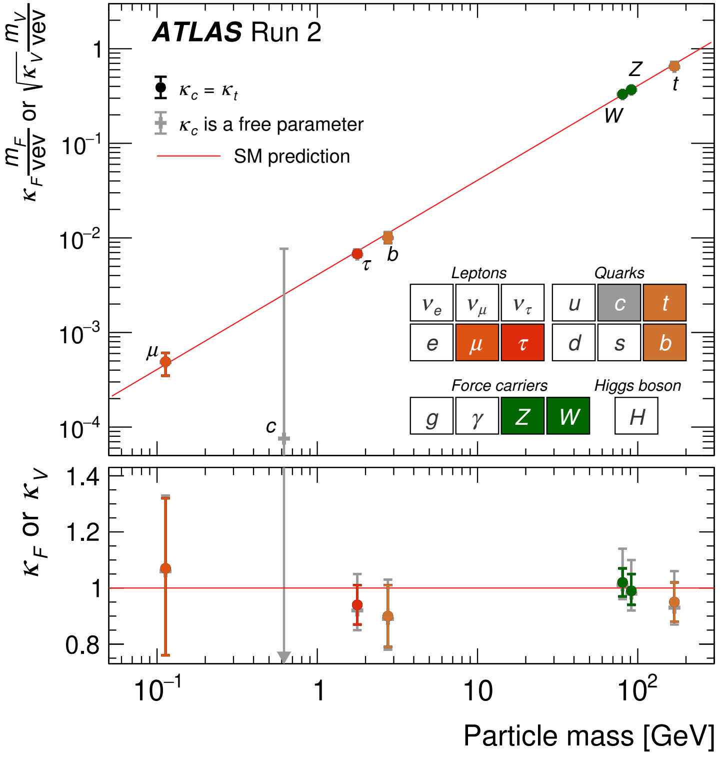
The best-fit values:

➢ $\kappa_V = 1.035 \pm 0.031$

➢ $\kappa_F = 0.95 \pm 0.05$

The p-value for compatibility of the combined measurement and the SM prediction is 14%

The coupling strength modifiers for W, Z, t, b, c, τ and μ are treated independently

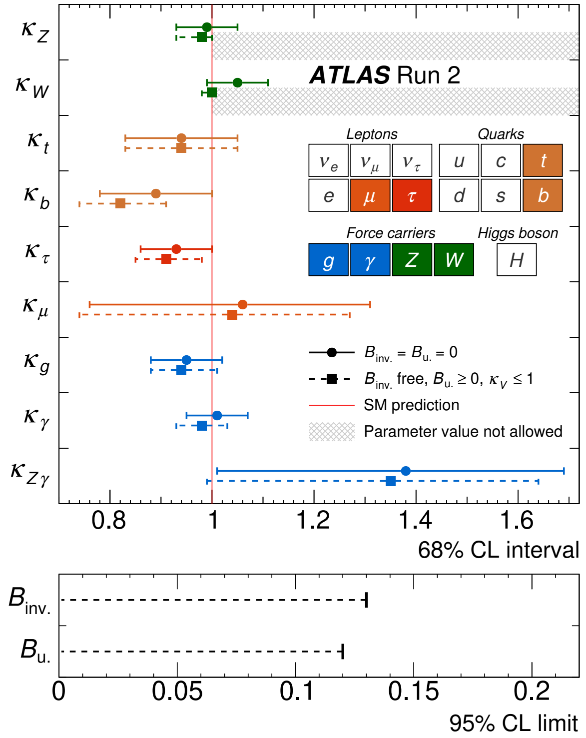


Compatible with their SM prediction

Coupling with charm quark:

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

Allows for the presence of non-standard model particles in the loop-induced processes

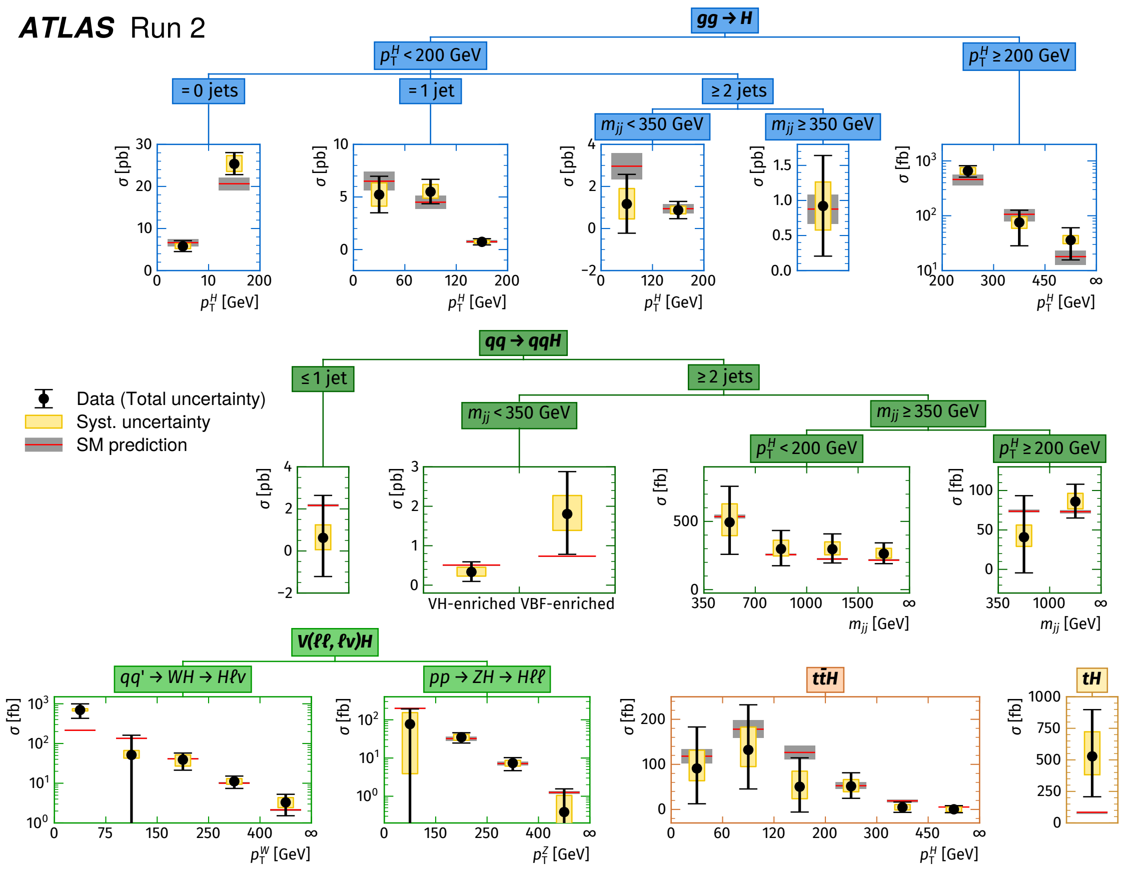


The p-value for compatibility with the SM is 61%

The Higgs boson Simplified Template Cross Section

Nature 607, 52 (2022)

- **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 produced in association**
  - Minimizing the dependence on theoretical uncertainties
  - Maximizing experimental sensitivity also to possible BSM effects



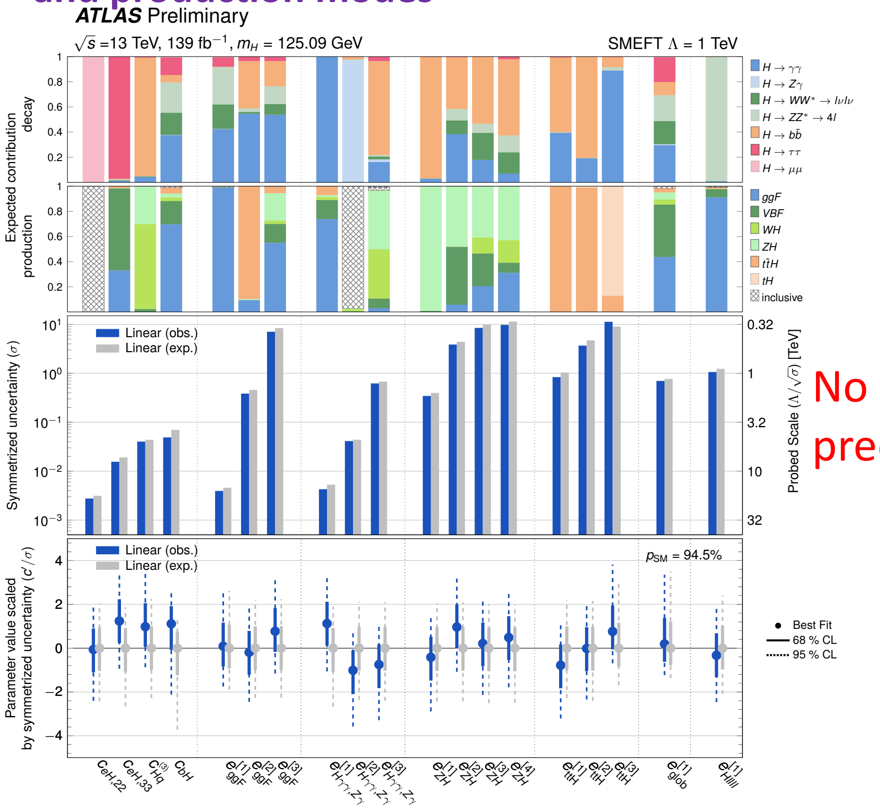
- Simultaneous measurement in 36 kinematic regions
- Combining the results in the 5 observed decay channels
- All measurements are consistent with the standard model predictions, p-value 94%

BSM/EFT

ATLAS-CONF-2023-052

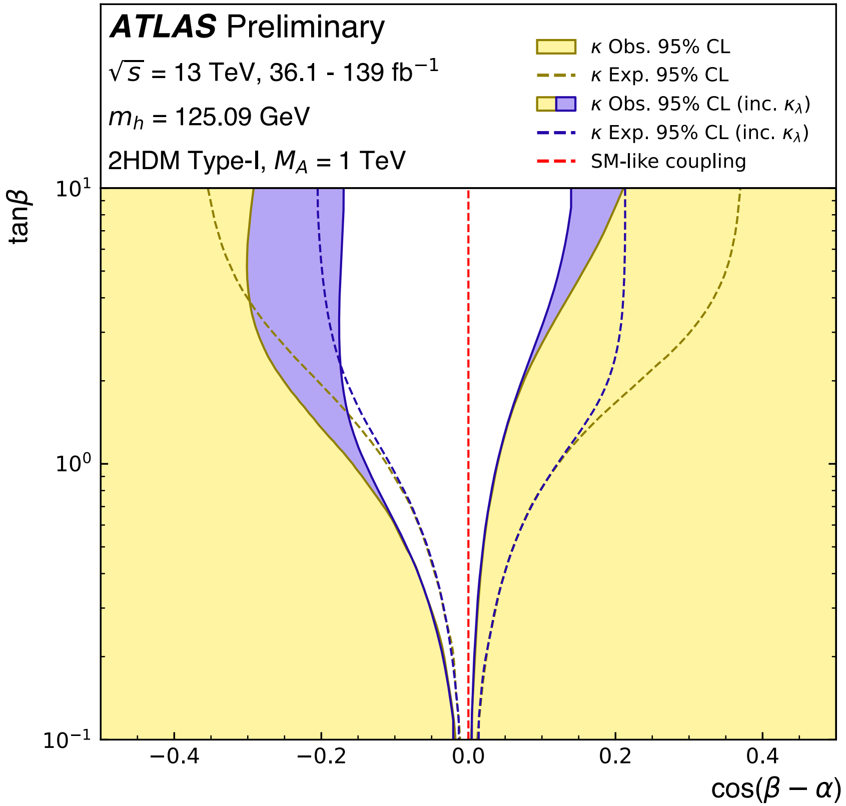
- **The STXS measurements and differential cross sections are interpreted**
  Effective Field Theory (EFT)
- **The production cross section and decay branching ratio measurements are interpreted**
  BSM scenarios: Two-Higgs-Doublet Model (2HDM) or Minimal Supersymmetric Extension of the SM (MSSM)

Linear SMEFT model result: Constraining power from the Higgs decay and production modes



No deviations from the SM predictions p-value (94.5%)

2HDM interpretation: Plane of excluded regions at 95%CL for Type-I model (all fermions couple to same Higgs doublet)



The Higgs boson Fiducial Cross-sections

[Eur. Phys. J. C 83 (2023) 774](#)

[Phys. Rev. D 108, 072003](#)

[arXiv:2304.09612](#)

- **Fiducial phase space definition based on detector acceptance to minimize the model dependency**

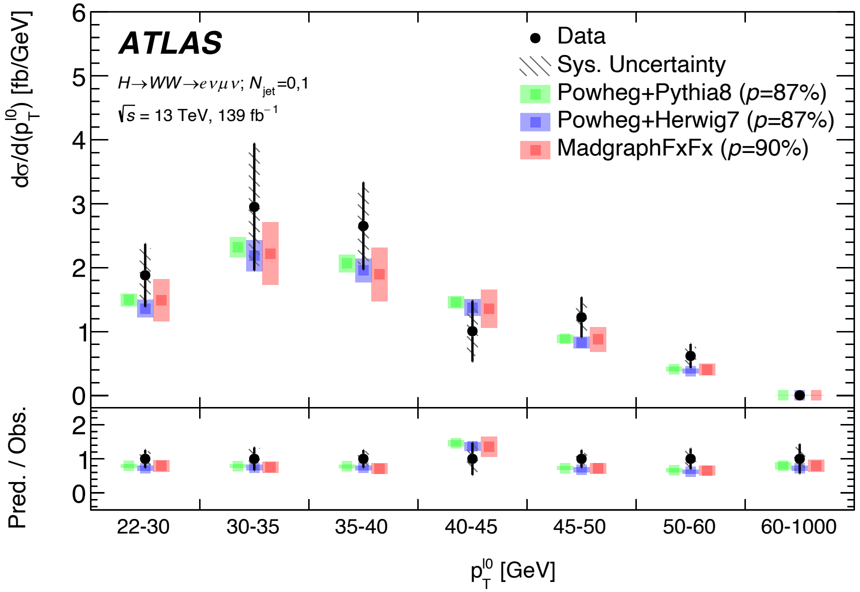
  Different phase space definition to target different production modes

$$\sigma^{\text{fid}} = \frac{N^{\text{SR}}_{\text{data}} - N^{\text{SR}}_{\text{bkg}}}{C \times \mathcal{L}}$$

C: accounts for detector inefficiencies

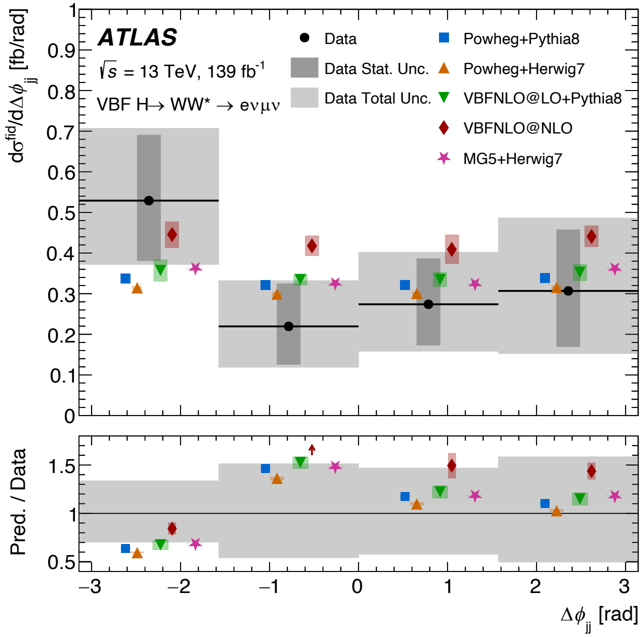
- **gluon-gluon Fusion (ggF) Fiducial Cross-sections**

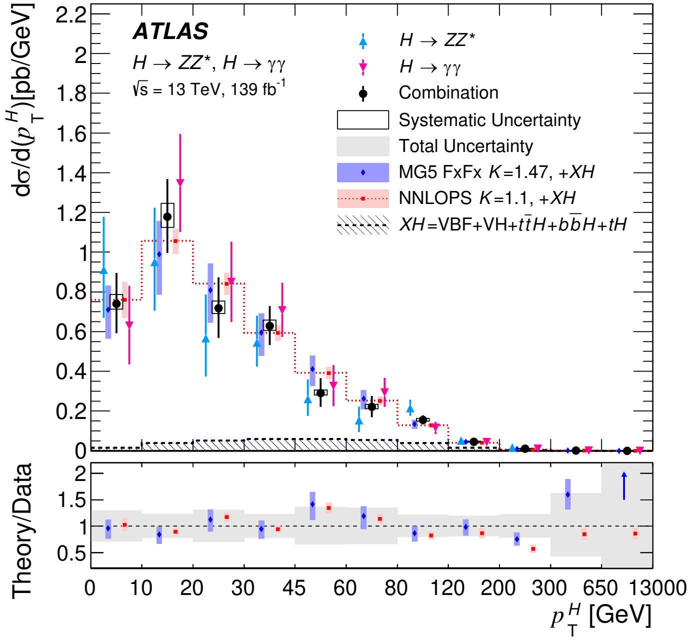
  $H \rightarrow WW^{*} \rightarrow e\nu\mu\nu$



- **Vector Boson Fusion (VBF) Fiducial Cross-sections**

  $H \rightarrow WW^{*} \rightarrow e\nu\mu\nu$ and $H \rightarrow ZZ^{*} \rightarrow 4\ell + H \rightarrow \gamma\gamma$





The Higgs boson Cross-sections at 13.6 TeV

[arXiv:2306.11379](https://arxiv.org/abs/2306.11379)

Measurements at 13.6 TeV, early Run 3

$H \to \gamma\gamma$ channel:

Luminosity 31.4 fb^{-1}

Fiducial cross-section $\sigma_{\mathrm{fid},\gamma\gamma} = 76^{+14}_{-13}\ fb$

$H \to ZZ^* \to 4\ell$ channel:

Luminosity 29.0 fb^{-1}

Fiducial cross-section $\sigma_{\mathrm{fid},4\ell} = 2.80 \pm 0.74\ fb$

Assuming SM acceptances and branching fractions

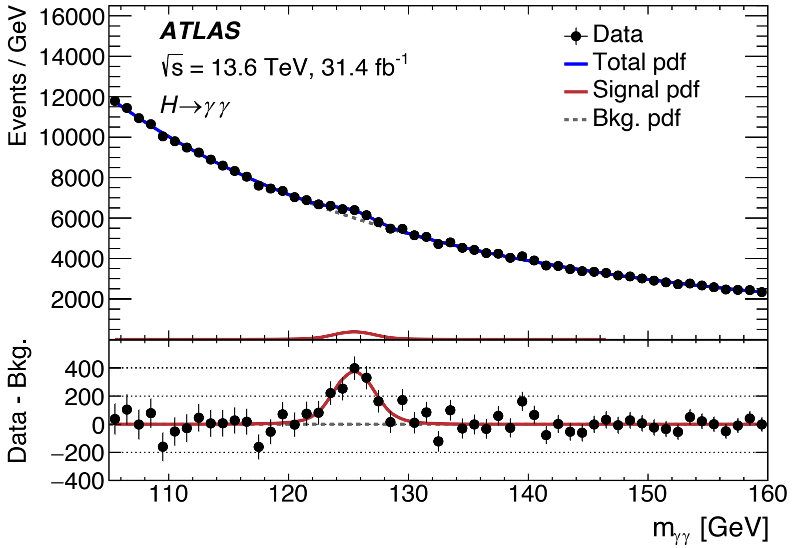
Total cross-sections $\sigma(pp \to H) = 67^{+12}_{-11}\ pb$

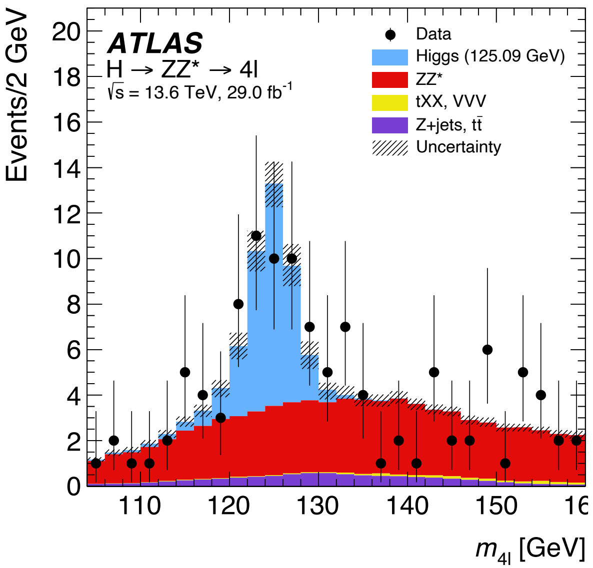
Total cross-sections $\sigma(pp \to H) = 46 \pm 12\ pb$

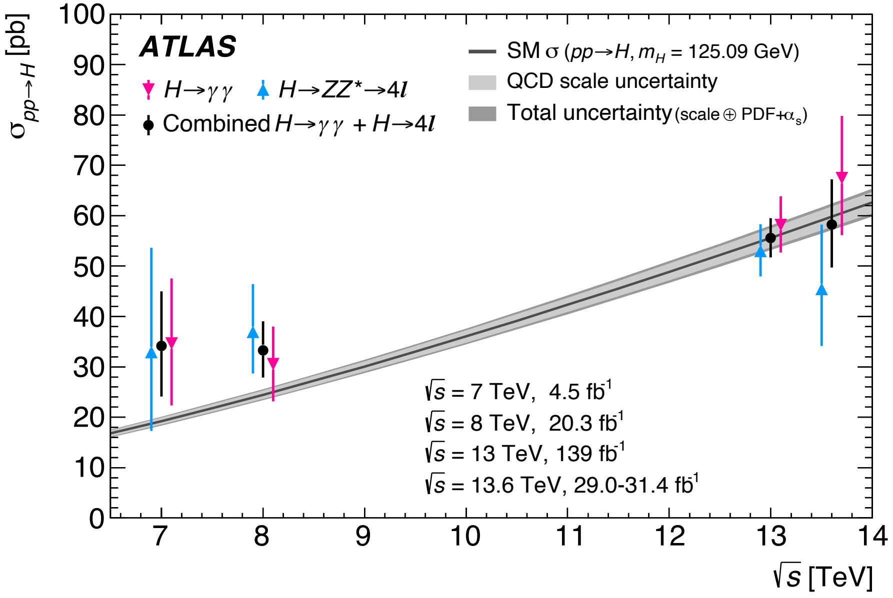
Combined total cross-section: $\sigma(pp \to H) = 58.2 \pm 8.7\ pb$

Standard Model prediction: $\sigma(pp \to H)_{SM} = 59.9 \pm 2.6\ pb$

Measurement in agreement with the SM prediction!!!







The Higgs boson CP Structure: Higgs-Vector Boson

Phys. Rev. Lett. 131 (2023) 061802
arXiv:2304.09612

- **Looking for signs of CP-violation in the Higgs sector**
  - SM Higgs boson is a CP-even scalar particle
  - Look for possible CP-odd couplings
  - Study the coupling with vector bosons (HVV) and fermions (Hff)
  - Use of Effective Field Theory to discriminate different CP hypothesis

Warsaw basis

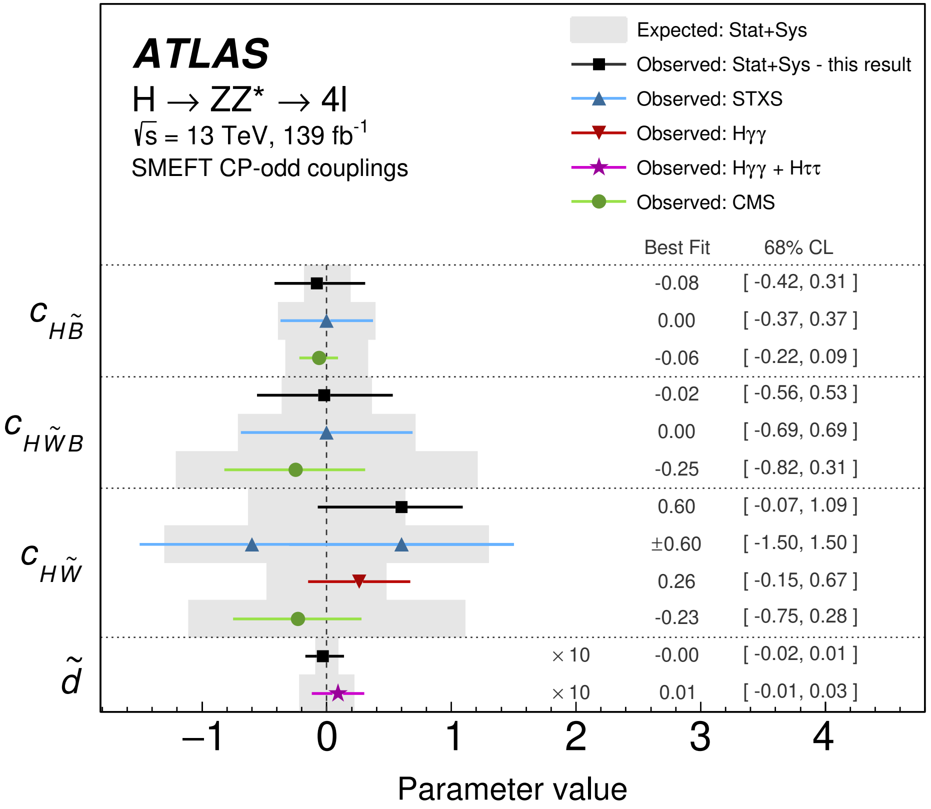
Operator	Structure	Coupling
$\mathcal{O}_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^{I}_{\mu\nu}W^{\mu\nu\,I}$	$C_{H\tilde{W}}$
$\mathcal{O}_{\Phi\tilde{W}B}$	$\Phi^\dagger\Phi\tilde{W}^{I}_{\mu\nu}B^{\mu\nu}$	$C_{H\tilde{W}B}$
$\mathcal{O}_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$C_{H\tilde{B}}$

A simplified assumption: HISZ basis

$$C_{H\tilde{W}} = C_{H\tilde{B}} = \frac{\Lambda^2}{v^2}\tilde{d},\ C_{H\tilde{W}B} = 0$$

$\tilde{d}$ is the only CP violation parameter

HVV vertex in the VBF production



Higgs decay modes

- $H \to \gamma\gamma$
- $H \to \tau^+\tau^-$
- $H \to ZZ^* \to 4\ell$

- Consistent with the SM expectation
- No significant CP-odd component is observed

Hff vertex studies in the $H \rightarrow \tau^+\tau^-$ decay

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

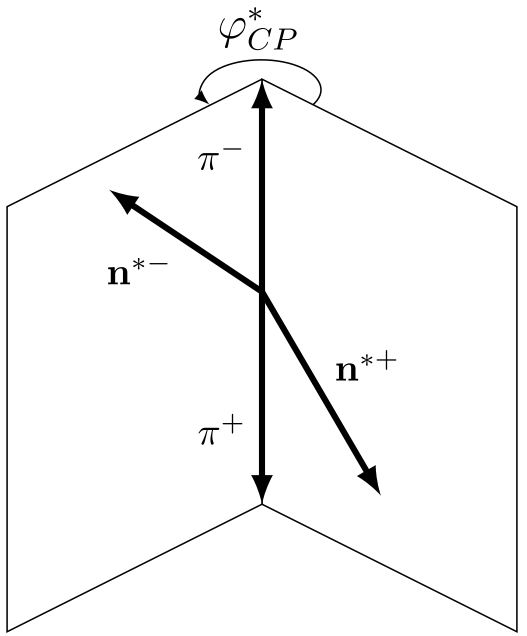
- The CP-mixing angle ϕ_τ is reflected in τ decay kinematics
- Rejection of the CP-odd hypothesis at 3.4σ (2.1σ expected)

$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\underbrace{\cos\phi_\tau\bar{\tau}\tau}_{\text{CP-even}} + \underbrace{\sin\phi_\tau\bar{\tau}i\gamma_5\tau}_{\text{CP-odd}})H$$

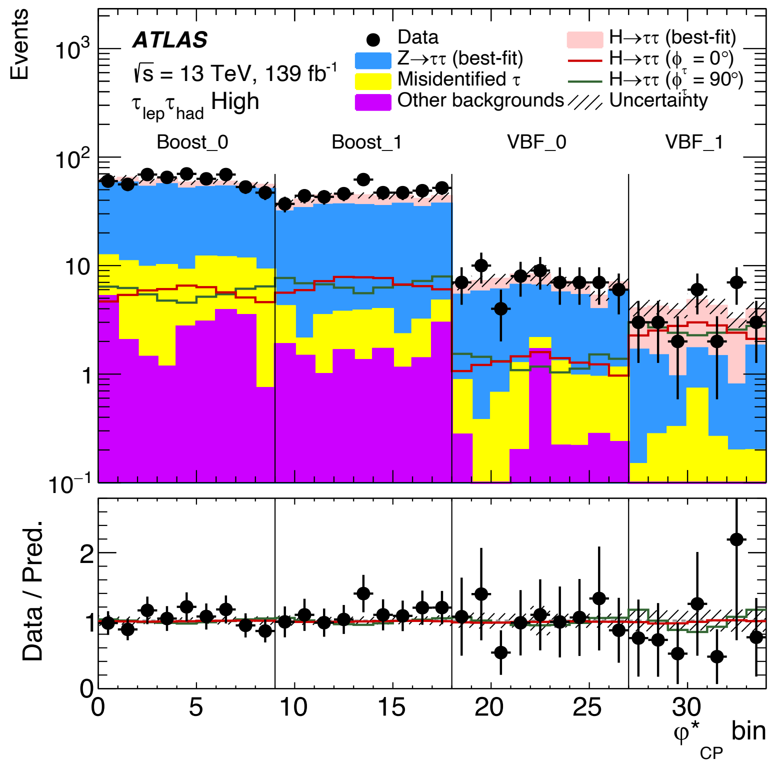
Observed: $\phi_\tau^{\text{obs.}} = 9 \pm 16°$

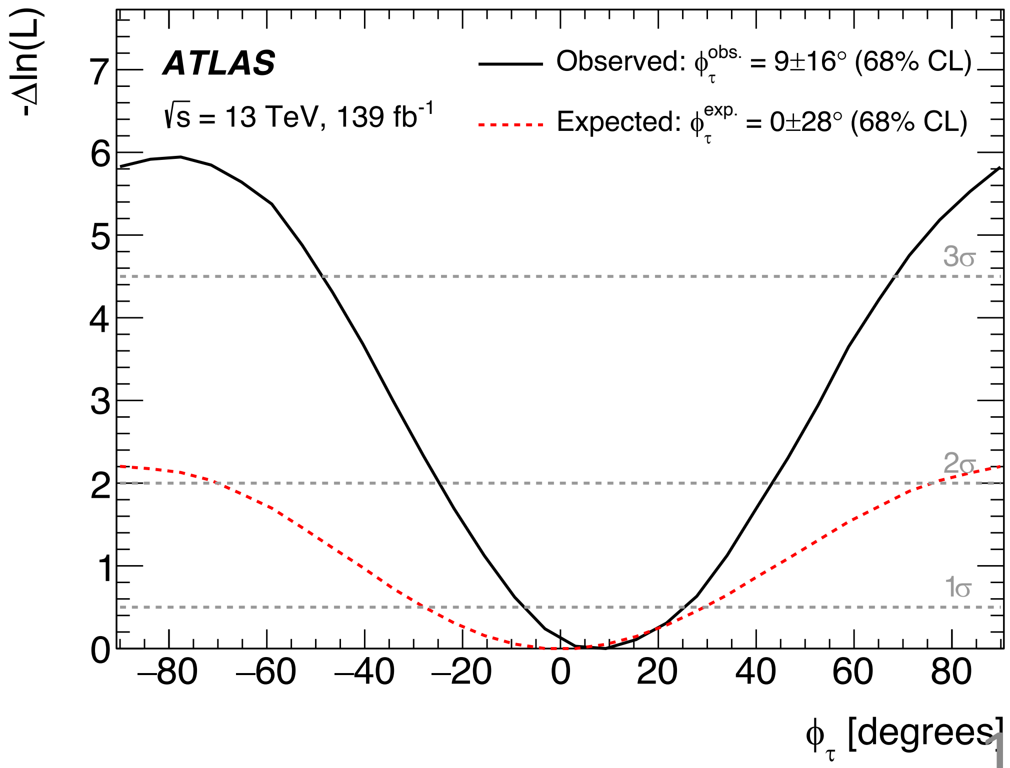
Expected: $\phi_\tau^{\text{exp.}} = 0 \pm 28°$

SM: $\phi_\tau = 0$



$$H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^- + 2\nu$$





The Higgs boson CP Structure: Higgs-top quark

Hff vertex studies in the ttH/tH production

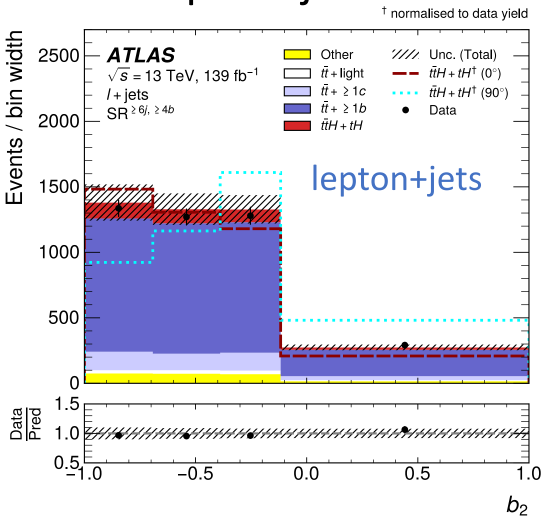
arXiv:2303.05974

- Measure the CP structure of H-top interaction in ttH and tH production using $H \to b\bar{b}$ decays ($H \to \gamma\gamma$ done in *Phys. Rev. Lett. 125 (2020) 061802*)
- Uses lepton+jets and di-lepton channels

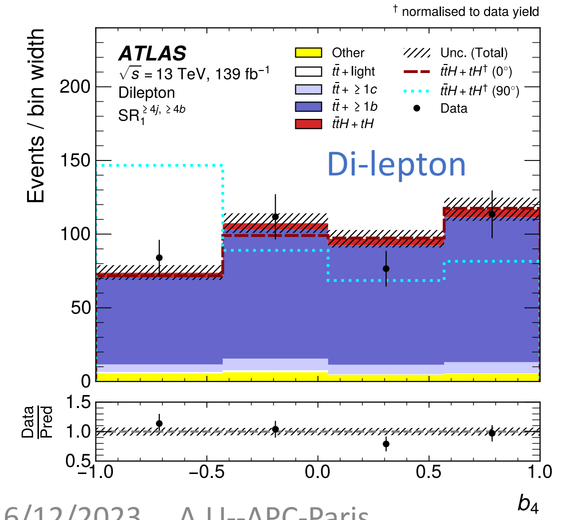
$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

CP-even CP-odd

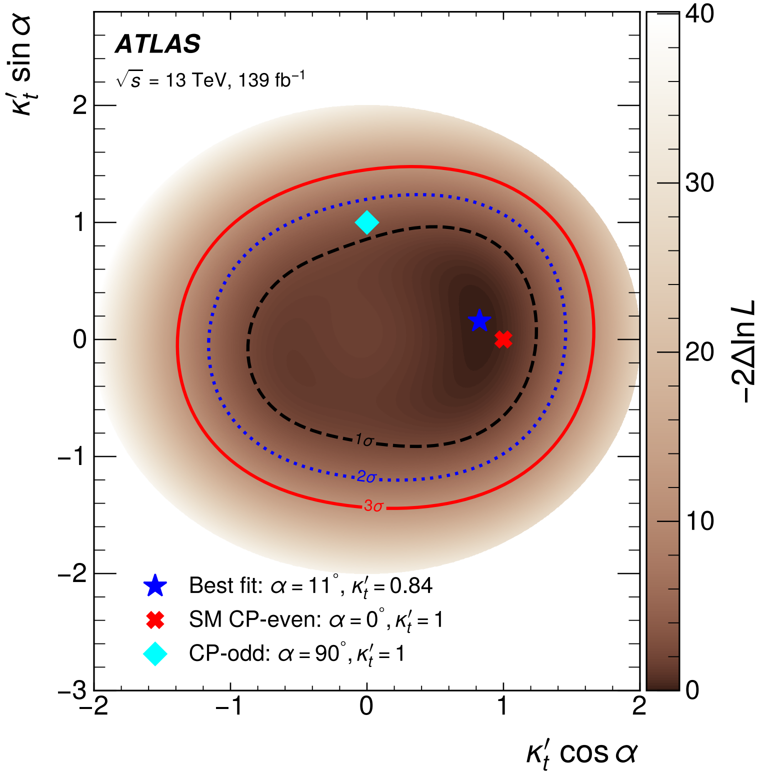
SM: $k_t' = 1$ and $\alpha = 0$



$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$



$$b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$



Best fit value:

- $\alpha = 11^{\circ}{}^{+56^{\circ}}_{-77^{\circ}}$
- $k_t' = 0.84^{+0.30}_{-0.46}$

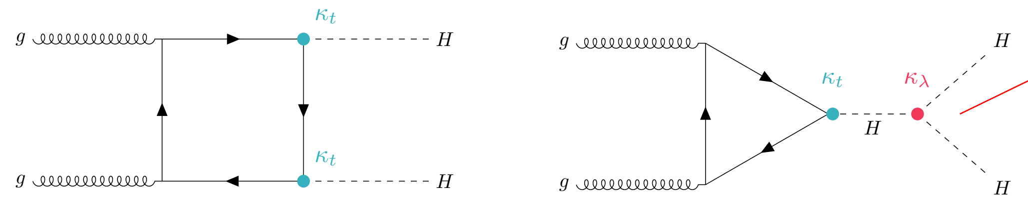
The data disfavour the pure CP-odd hypothesis with a 1.2 σ significance

The Higgs boson Self-couplings

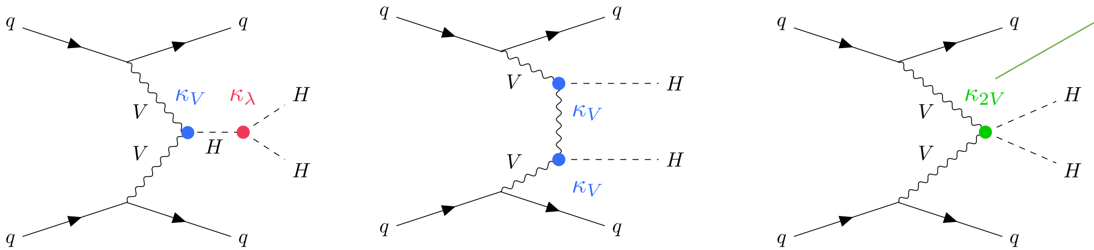
[Phys. Lett. B 843 (2023) 137745]

Double Higgs direct measurement:

gluon-gluon Fusion (ggF) $\sigma_{ggF} = 31\ fb$ (SM)



Vector Boson Fusion (VBF) $\sigma_{VBF} = 1.7\ fb$ (SM)



Higgs boson self-coupling (κ_λ)

$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$

VVHH coupling (κ_{2V})

$$\kappa_{2V} = \frac{\lambda_{VVHH}}{\lambda_{VVHH}^{SM}}$$

Signal Strength $\mu_{HH} = \frac{\sigma_{HH}}{\sigma_{HH}^{SM}}$

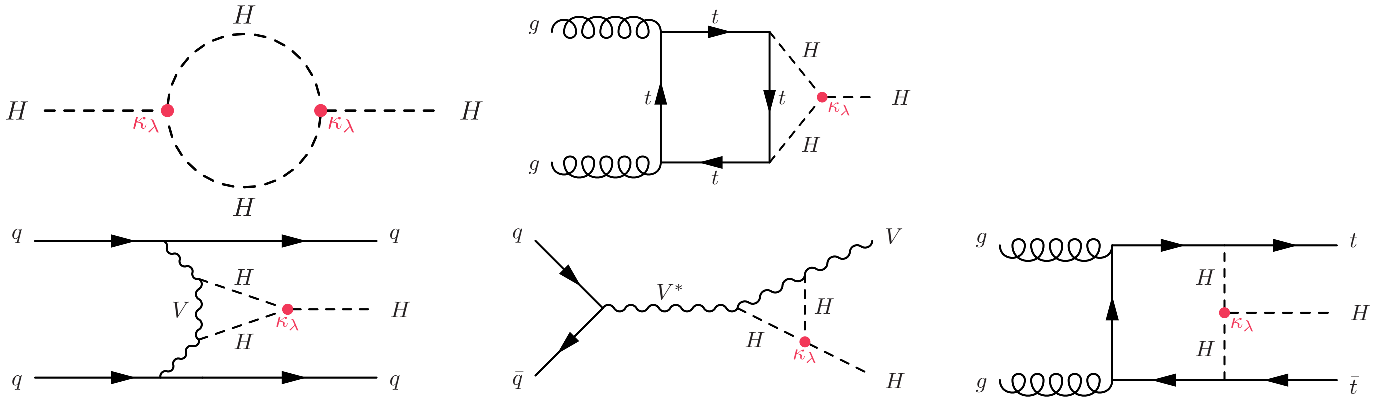
SM prediction:

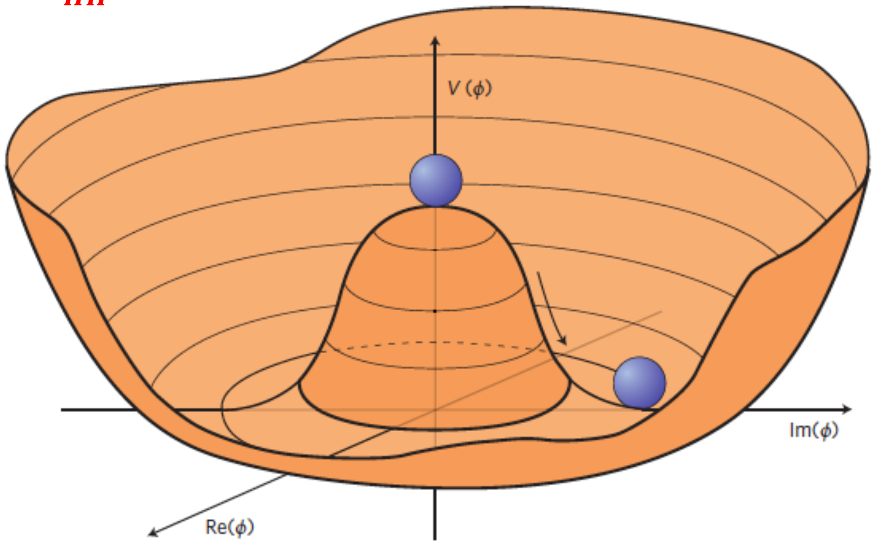
Higgs mass

$$\lambda_3^{SM} = \frac{m_H^2}{2v}$$

Vacuum Expectation Value

Single Higgs indirect measurement from NLO:



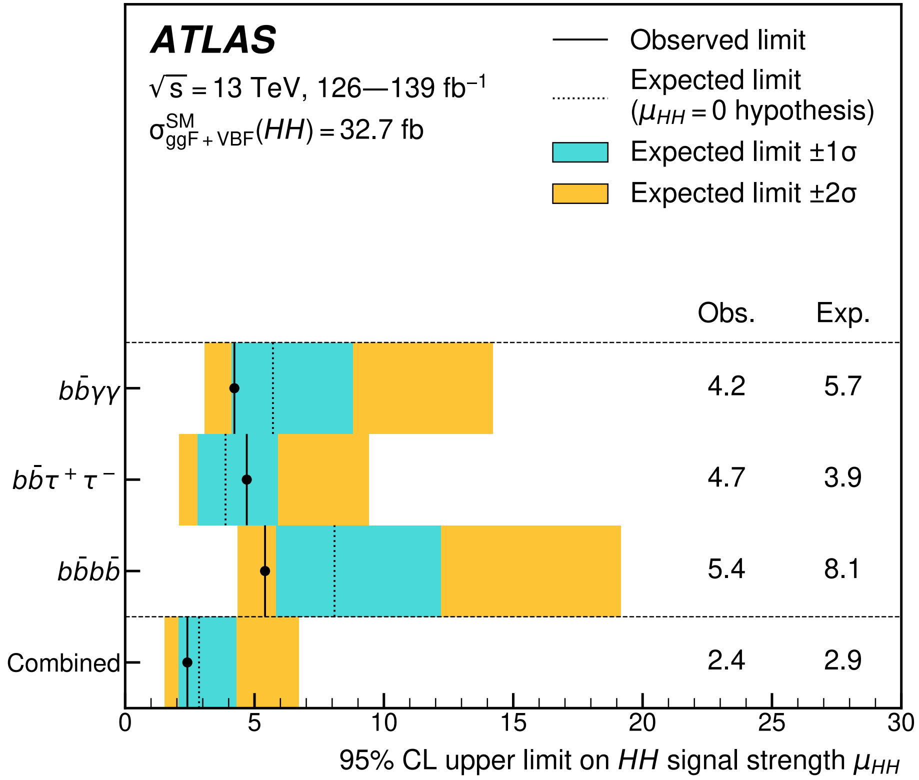


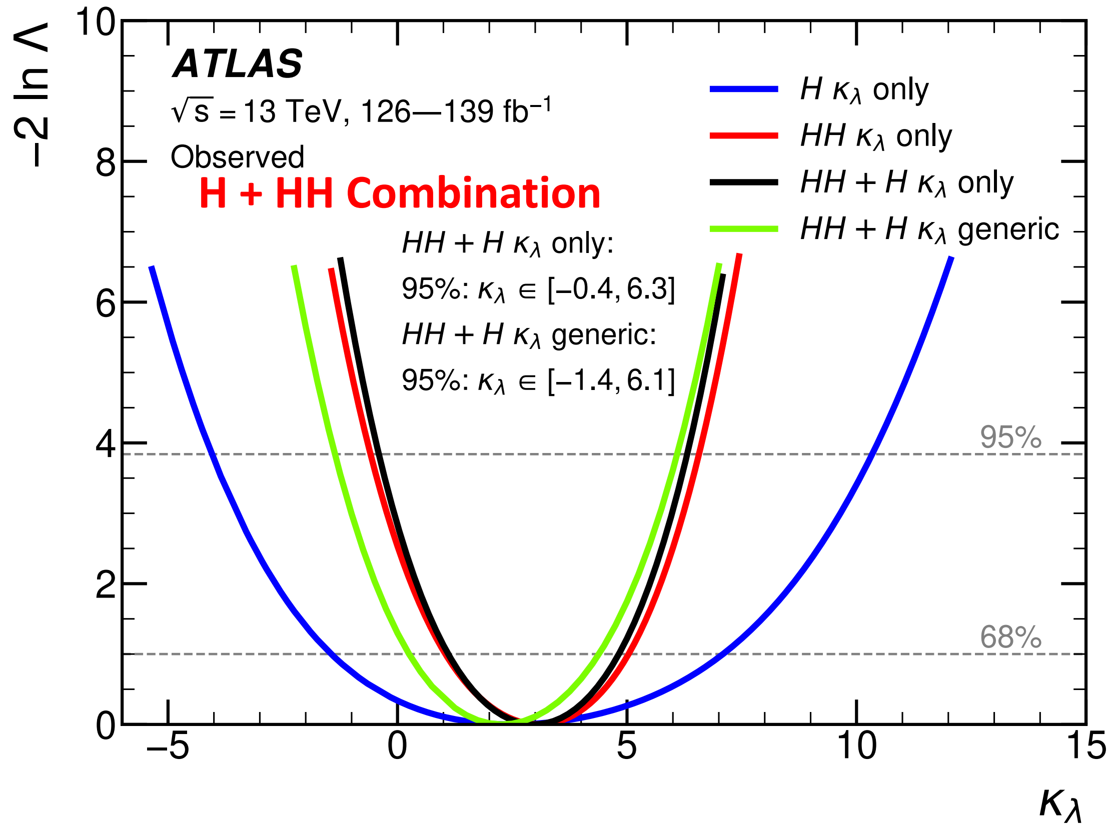
arXiv:1312.5672

The Higgs boson Self-couplings

$b\bar{b}\gamma\gamma, b\bar{b}\tau^+\tau^-, b\bar{b}b\bar{b}$

Phys. Lett. B 843 (2023) 137745





Higgs boson self-coupling λ_3 is a fundamental parameter of the SM

- Combined results from di-Higgs searches
- Constraint on σ_{HH} and κ_λ

  $\mu_{HH} < 2.4$ @ 95 % C.L.

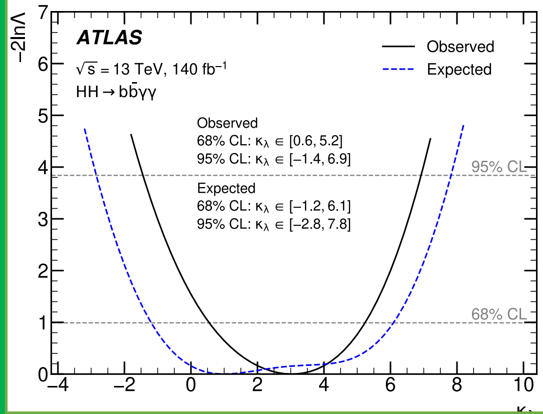
  $-0.4 < \kappa_\lambda < 6.3$ @ 95 % C.I.

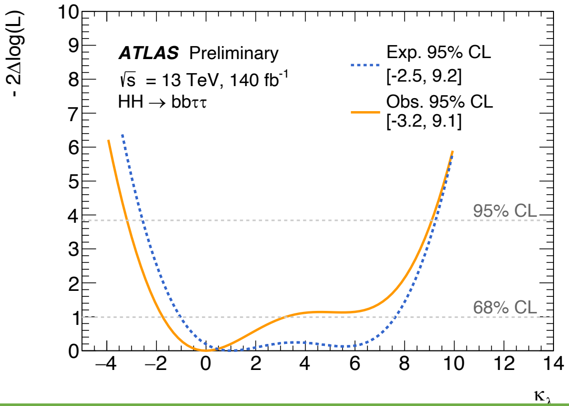
The Higgs boson Self-couplings, Updates

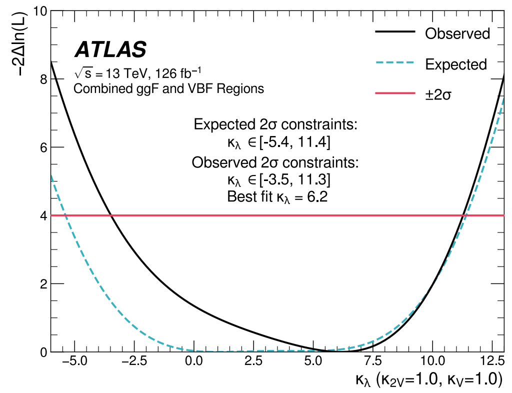
Introduce VBF signal region to further constraint κ_{2V}

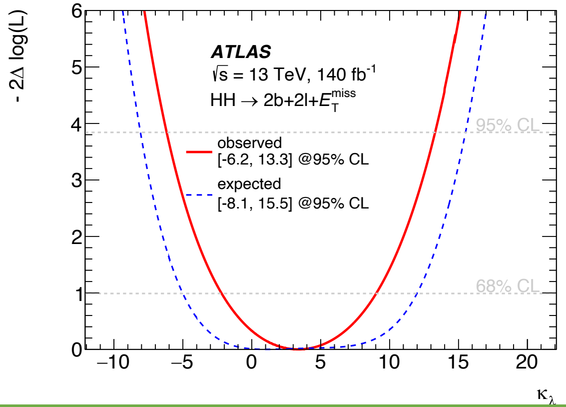
κ_λ **Observed 95 C.I.**		κ_{2V} **Observed 95 C.I.**	
$b\bar{b}\gamma\gamma$:	$\kappa_\lambda \in [-1.4, 6.9]$ ★	$b\bar{b}\gamma\gamma$:	$\kappa_{2V} \in [-0.5, 2.7]$
$b\bar{b}\tau^+\tau^-$:	$\kappa_\lambda \in [-3.2, 9.1]$	$b\bar{b}\tau^+\tau^-$:	$\kappa_{2V} \in [-0.4, 2.6]$
$b\bar{b}b\bar{b}$:	$\kappa_\lambda \in [-3.5, 11.3]$	$b\bar{b}b\bar{b}$:	$\kappa_{2V} \in [-0.0, 2.1]$ ★
$b\bar{b}\ell\ell$:	$\kappa_\lambda \in [-6.2, 13.3]$	$b\bar{b}\ell\ell$:	$\kappa_{2V} \in [-0.2, 2.4]$

κ_λ

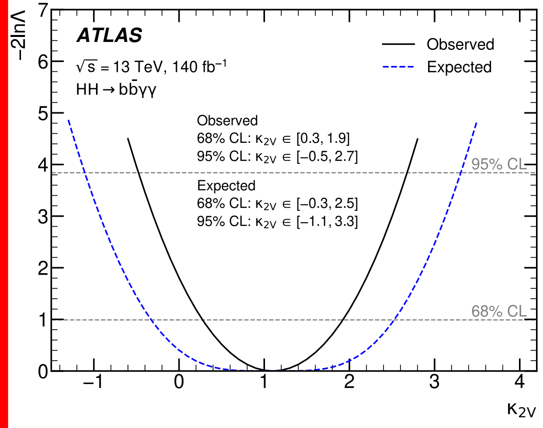


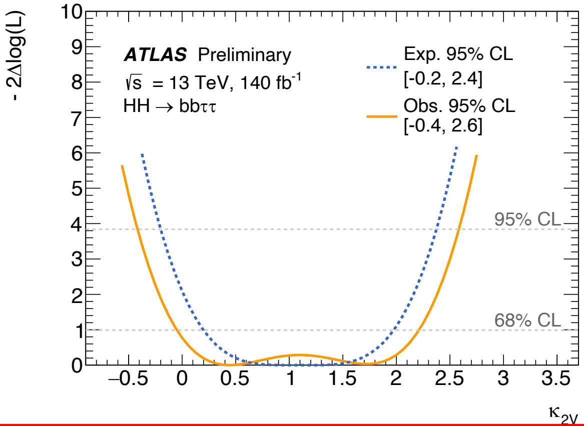


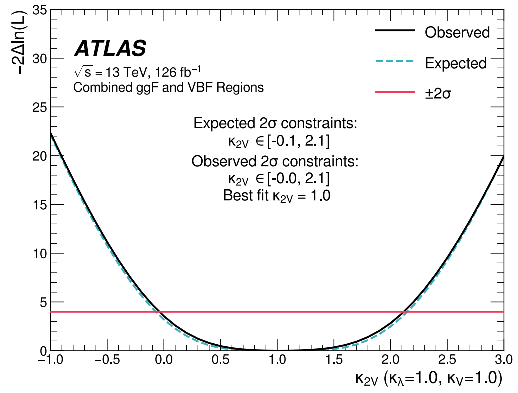


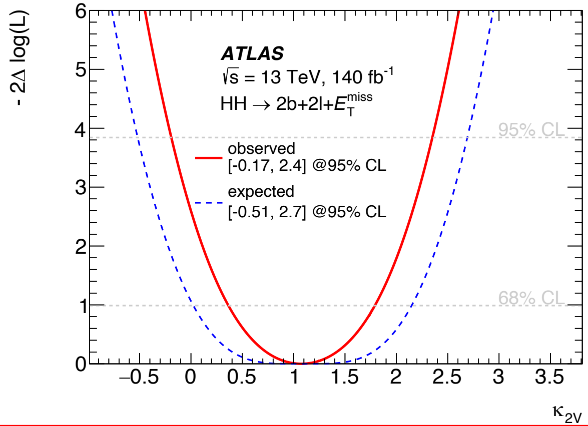


κ_{2V}









$bb\gamma\gamma$	$bb\tau^+\tau^-$	$bbbb$	$bb\ell\ell$
arXiv:2310.12301	ATLAS-CONF-2023-071	*Phys. Rev. D 108 (2023) 052003*	arXiv:2310.11286

Conclusion

- Using $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$, the Run 1 + 2, combined Higgs mass results is:

  m_H = 125.11 ± 0.09 (stat.) ± 0.06 (syst.) = 125.11 ± 0.11 GeV
- Evidence of off-shell Higgs boson production
- The Higgs boson width is measured to be: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV
- Higgs cross-section first measurement at 13.6 TeV
- First constraint on Higgs coupling with charm quark
- CP properties of the Higgs boson found to be consistent with the Standard Model (CP-even)
- Higgs Self-couplings constrained

Run 3 data at 13.6 TeV has started, more precise results are coming!

Thank you for your attention

The Higgs boson Cross-sections at 13 TeV

Eur. Phys. J. C 80 (2020) 942
JHEP 08 (2022) 027
JHEP 05 (2023) 028

Measurements at 13 TeV

$H \rightarrow \gamma\gamma$ channel:

Fiducial cross-section $\sigma_{\text{fid},\gamma\gamma} = 67 \pm 6\ fb$

SM prediction $\sigma^{\text{SM}}_{\text{fid},\gamma\gamma} = 64 \pm 4\ fb$

Total cross-sections $\sigma(pp \rightarrow H) = 58.1^{+5.7}_{-5.4}\ pb$

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

Fiducial cross-section $\sigma_{\text{fid},4\ell} = 3.28 \pm 0.32\ fb$

SM prediction $\sigma^{\text{SM}}_{\text{fid},4\ell} = 3.41 \pm 0.18\ fb$

Total cross-sections $\sigma(pp \rightarrow H) = 53.0^{+5.3}_{-5.1}\ pb$

Combined total cross-section: $\sigma(pp \rightarrow H) = 55.5^{+4.0}_{-3.8} pb$

Standard Model prediction: $\sigma(pp \rightarrow H)_{SM} = 55.6 \pm 2.5\ pb$