Recent mass, width and CP results from ATLAS and CMS

F. Errico,
INFN Roma

on behalf of ATLAS/CMS Collaborations

20th Workshop of the LHC Higgs Working Group

13/11/2023

Overview

Higgs boson discovery was announced on the 4th of July 2012.

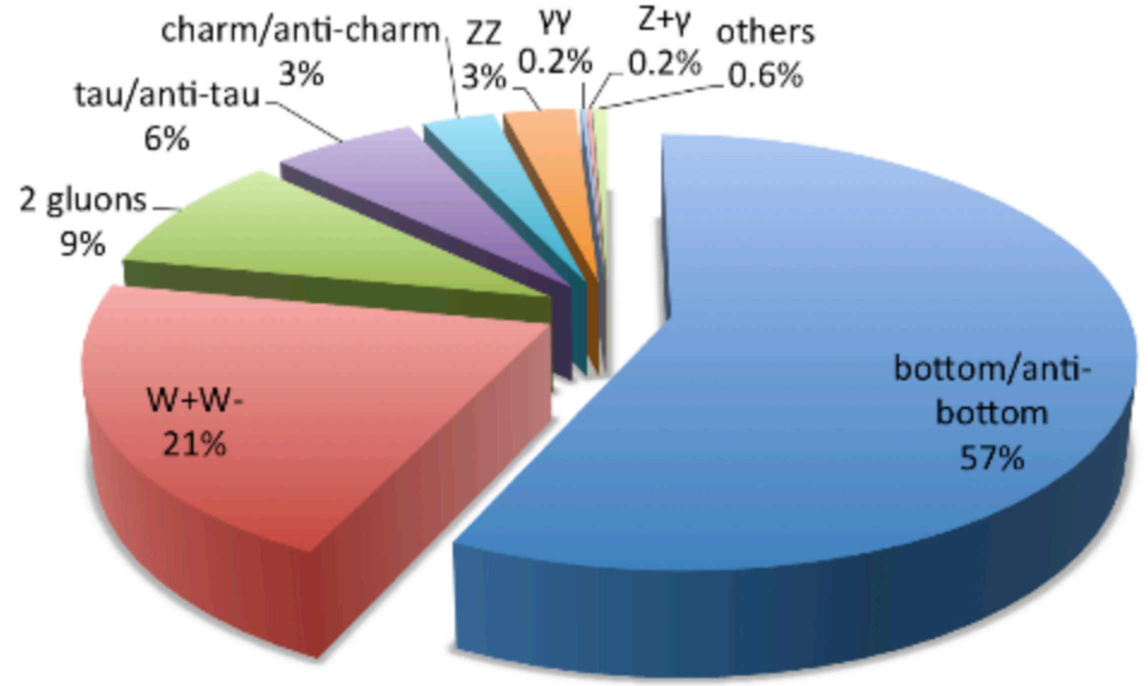
Since then, much effort has been put into determining its properties

XS @ m_H = 125 GeV

$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125$ GeV					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$16.9^{+5.5\%}_{-7.6\%}$	$1.24^{+2.2\%}_{-2.2\%}$	$0.58^{+2.2\%}_{-2.3\%}$	$0.34^{+3.1\%}_{-3.0\%}$	$0.09^{+5.6\%}_{-10.2\%}$	19.1
8	$21.4^{+5.4\%}_{-7.6\%}$	$1.60^{+2.1\%}_{-2.1\%}$	$0.70^{+2.1\%}_{-2.2\%}$	$0.42^{+3.4\%}_{-2.9\%}$	$0.13^{+5.9\%}_{-10.1\%}$	24.2
13	$48.6^{+5.6\%}_{-7.4\%}$	$3.78^{+2.1\%}_{-2.1\%}$	$1.37^{+2.0\%}_{-2.0\%}$	$0.88^{+4.1\%}_{-3.5\%}$	$0.50^{+6.8\%}_{-9.9\%}$	55.1
14	$54.7^{+5.6\%}_{-7.4\%}$	$4.28^{+2.1\%}_{-2.1\%}$	$1.51^{+1.8\%}_{-1.9\%}$	$0.99^{+4.1\%}_{-3.7\%}$	$0.61^{+6.9\%}_{-9.8\%}$	62.1

R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022)

H_{BR} @ m_H = 125 GeV



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H_{BR} @ m_H = 125 GeV

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	2.1%
$H \to ZZ$	2.62×10^{-2}	$\pm 1.5\%$
$H \to W^+W^-$	2.14×10^{-1}	$\pm 1.5\%$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$\pm 1.6\%$
[illegible]	[illegible]	[illegible]
$H \to c\bar{c}$	2.89×10^{-2}	$^{+5.5\%}_{-2.0\%}$
$H \to Z\gamma$	1.53×10^{-3}	$\pm 5.8\%$
[illegible]	[illegible]	[illegible]

The Higgs boson mass is one of the most important free parameters of the Standard Model.

It is crucial to properly determine its value since it could be used to put constraint on all the others Higgs boson properties (e.g cross section, branching ratio)

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Phys. Rev. Lett. 114 (2015) 191803

m_H = 125.09 GeV ± 0.24 GeV

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$H \to c\bar{c}$		$^{+5.5\%}_{-2.0\%}$
$H \to Z\gamma$		$\pm 5.8\%$
$H \to \mu^+\mu^-$		$\pm 1.7\%$

Best fit value from Run 1

1. Higgs boson mass

Higgs boson mass measurement is performed using **$H \to ZZ^* \to 4\ell$** and **$H \to \gamma\gamma$**, thanks to their mass resolution (1-2%) and complete reconstruction of the final state.

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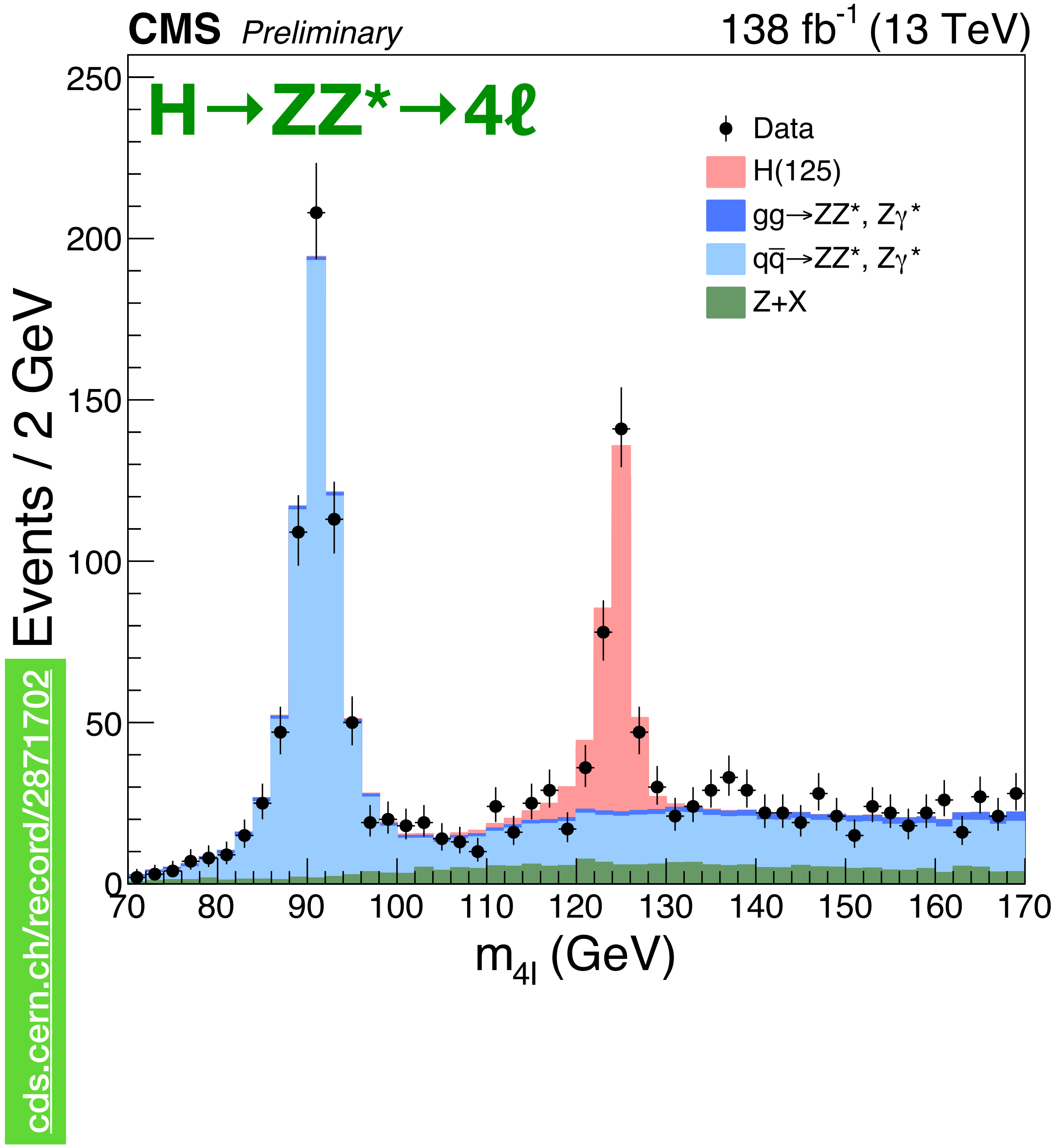
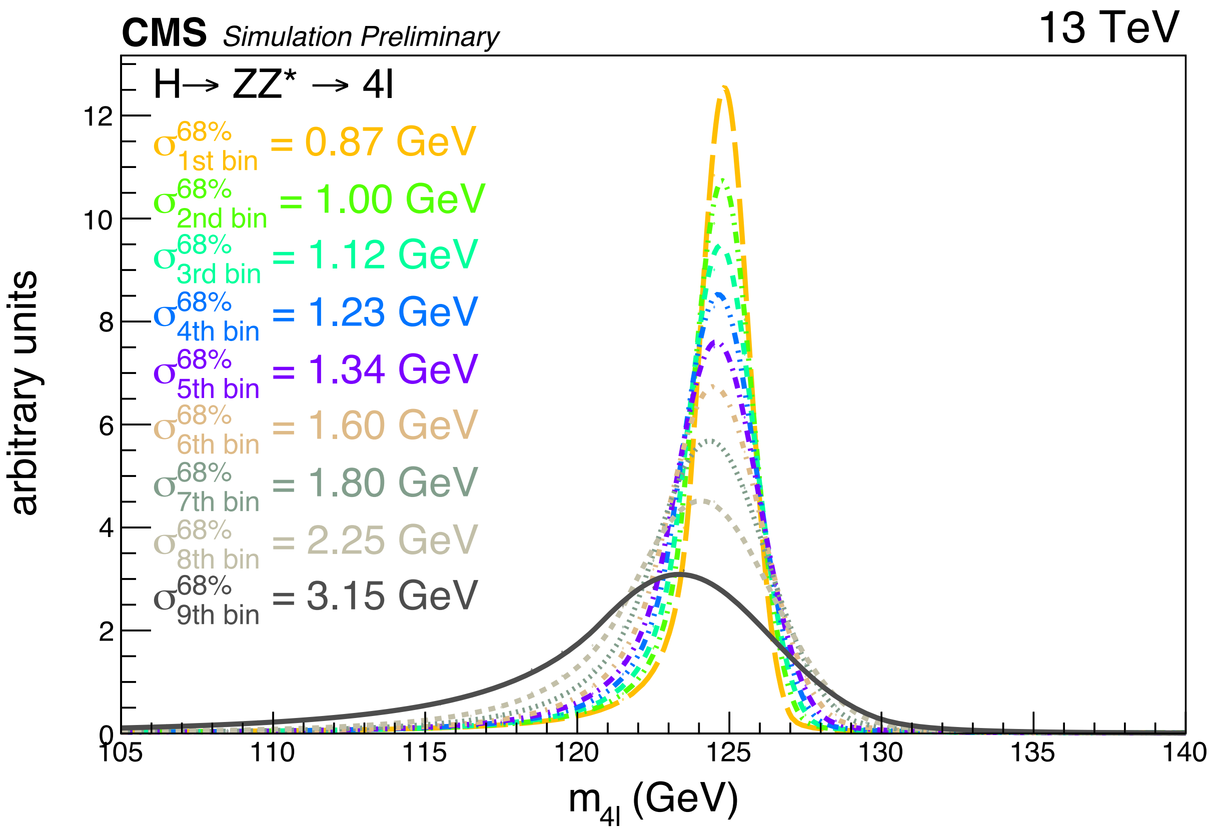


- Implemented beam spot constraint to improve muon reconstruction
- Per-event mass resolution used to categorise events into 9 mutually exclusive bins



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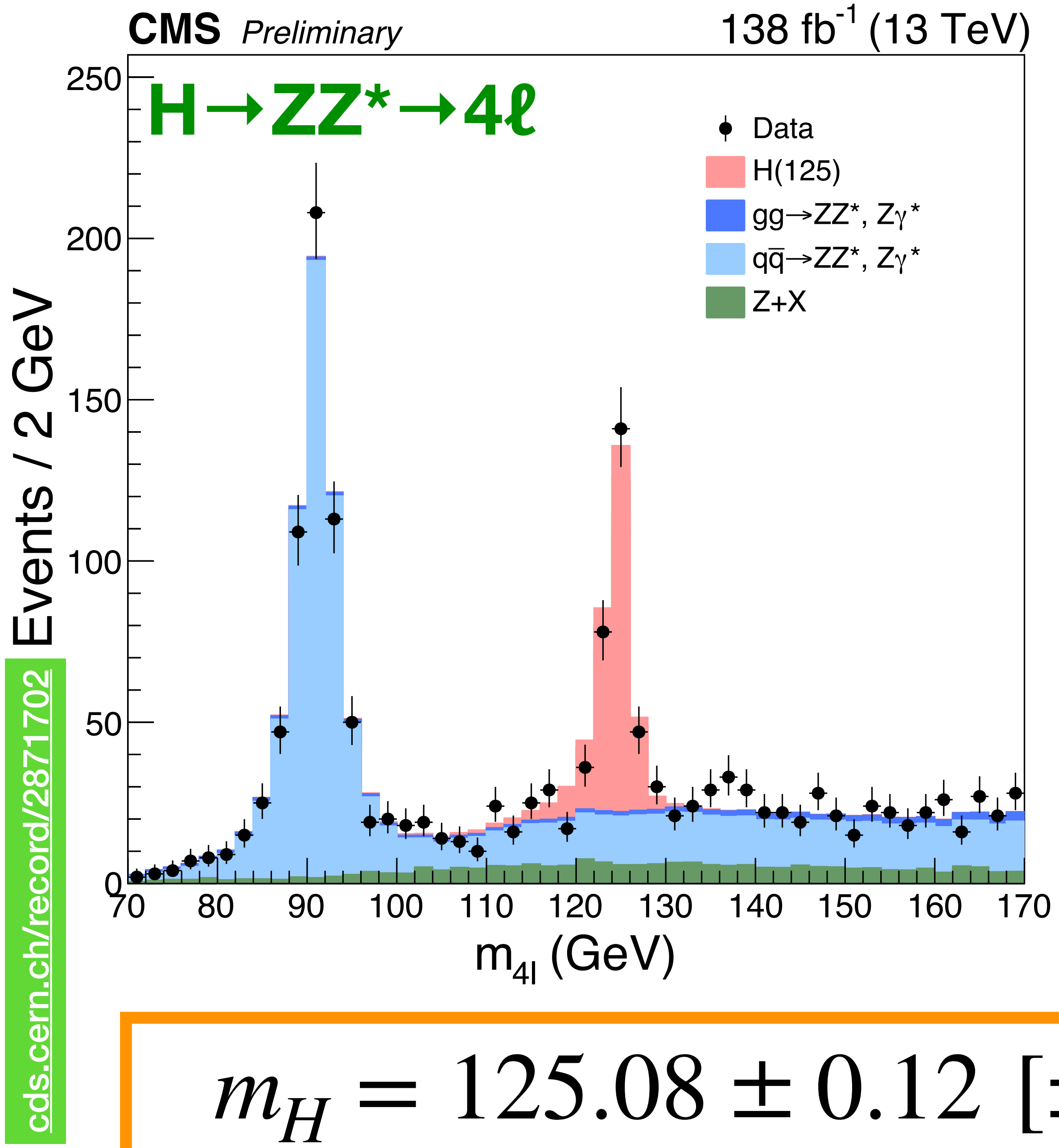

- Implemented beam spot constraint to improve muon reconstruction
- Per-event mass resolution used to categorise events into 9 mutually exclusive bins
- **m_H single channel best measurement**

$$m_H = 125.08 \pm 0.12\ [\pm 0.10(stat) \pm 0.05(syst)]\ GeV$$

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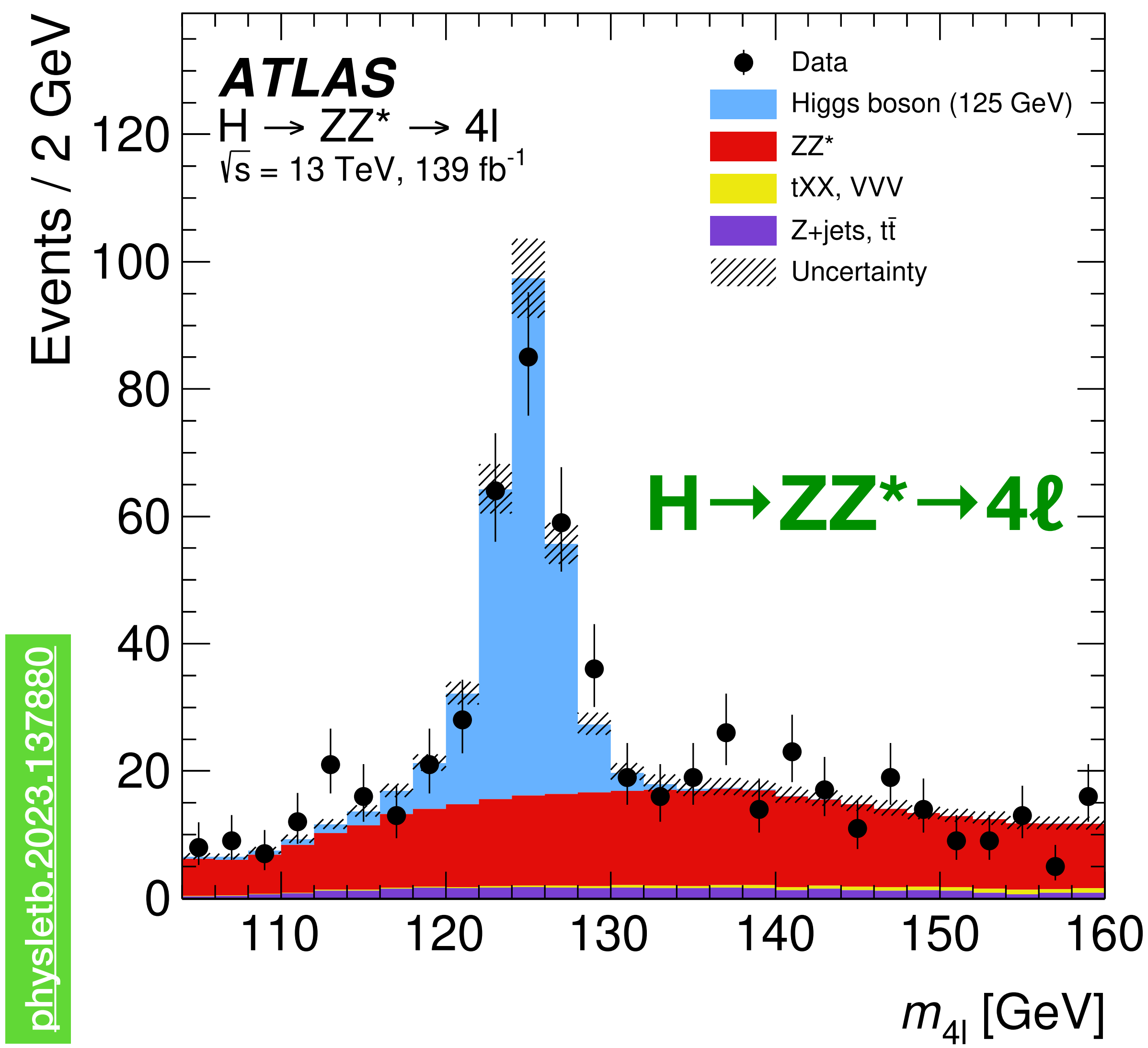
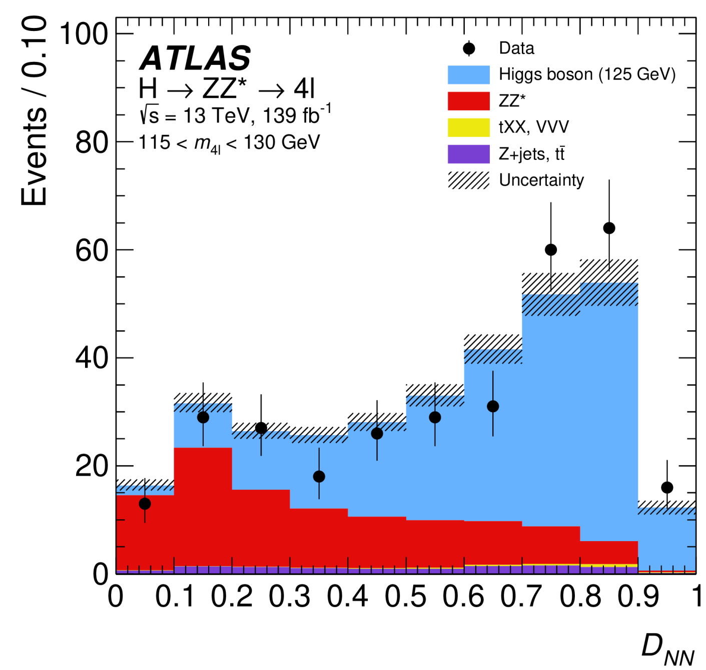
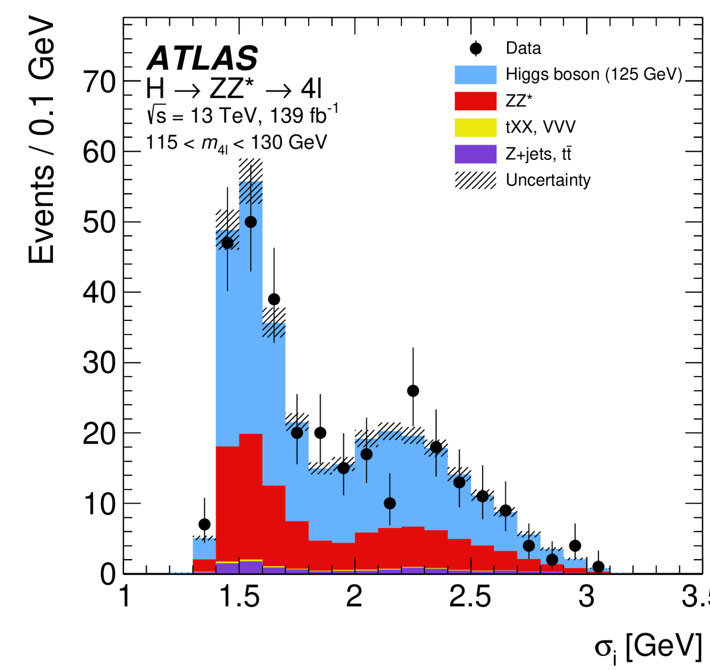


physletb.2023.137880

- ME discriminant combined with p_T and η of the 4-lepton system in a DNN discriminant
- Per-event mass resolution estimated by using a quantile regression neural network





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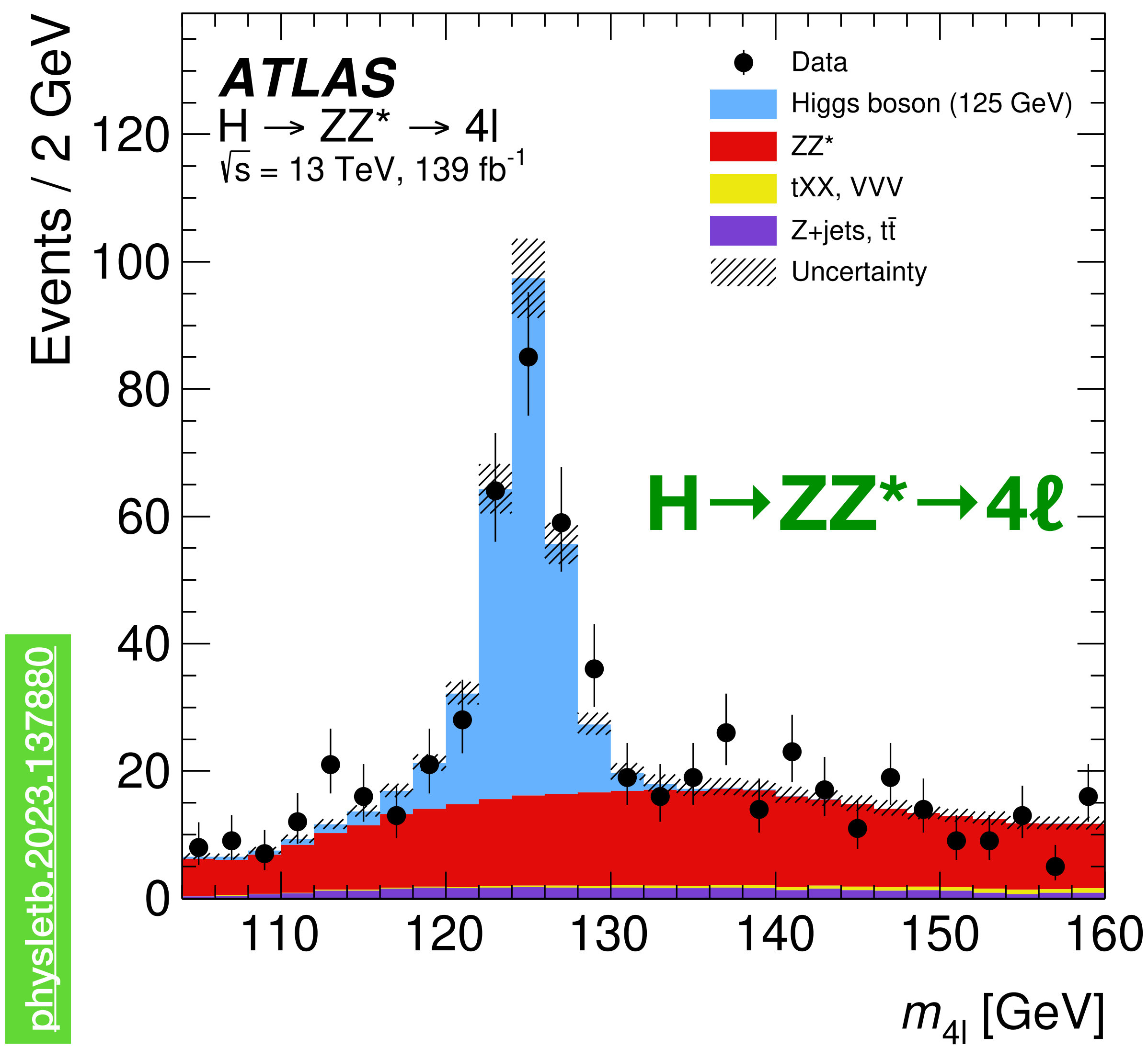

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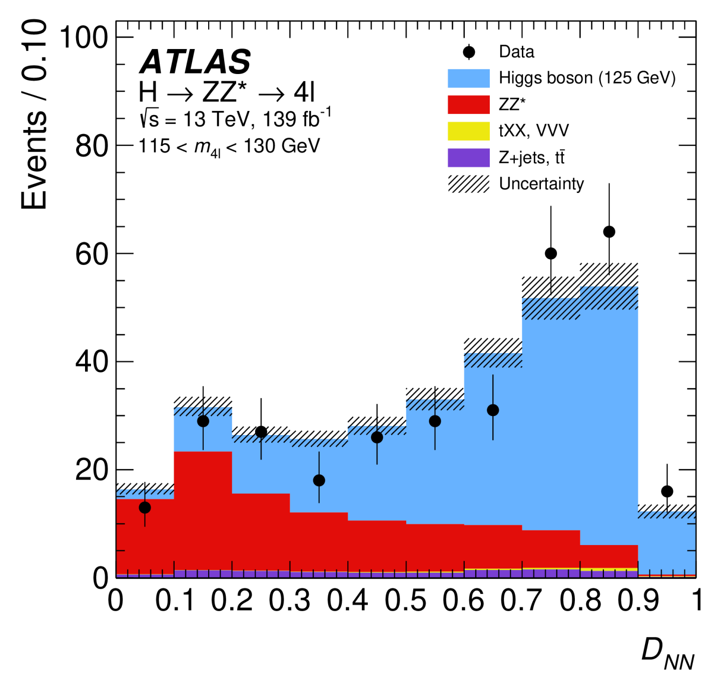

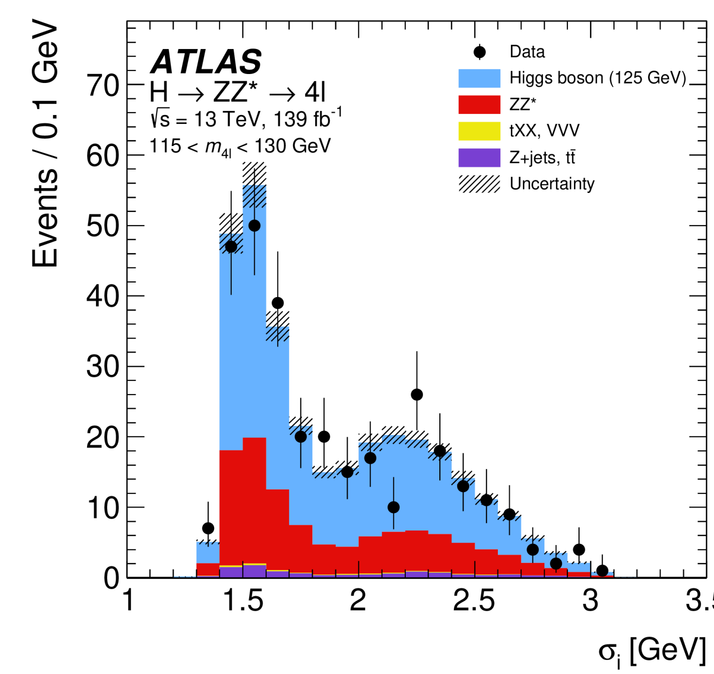

$$m_H = 124.94 \pm 0.18\ [\pm 0.17(stat) \pm 0.03(syst)]\ GeV$$

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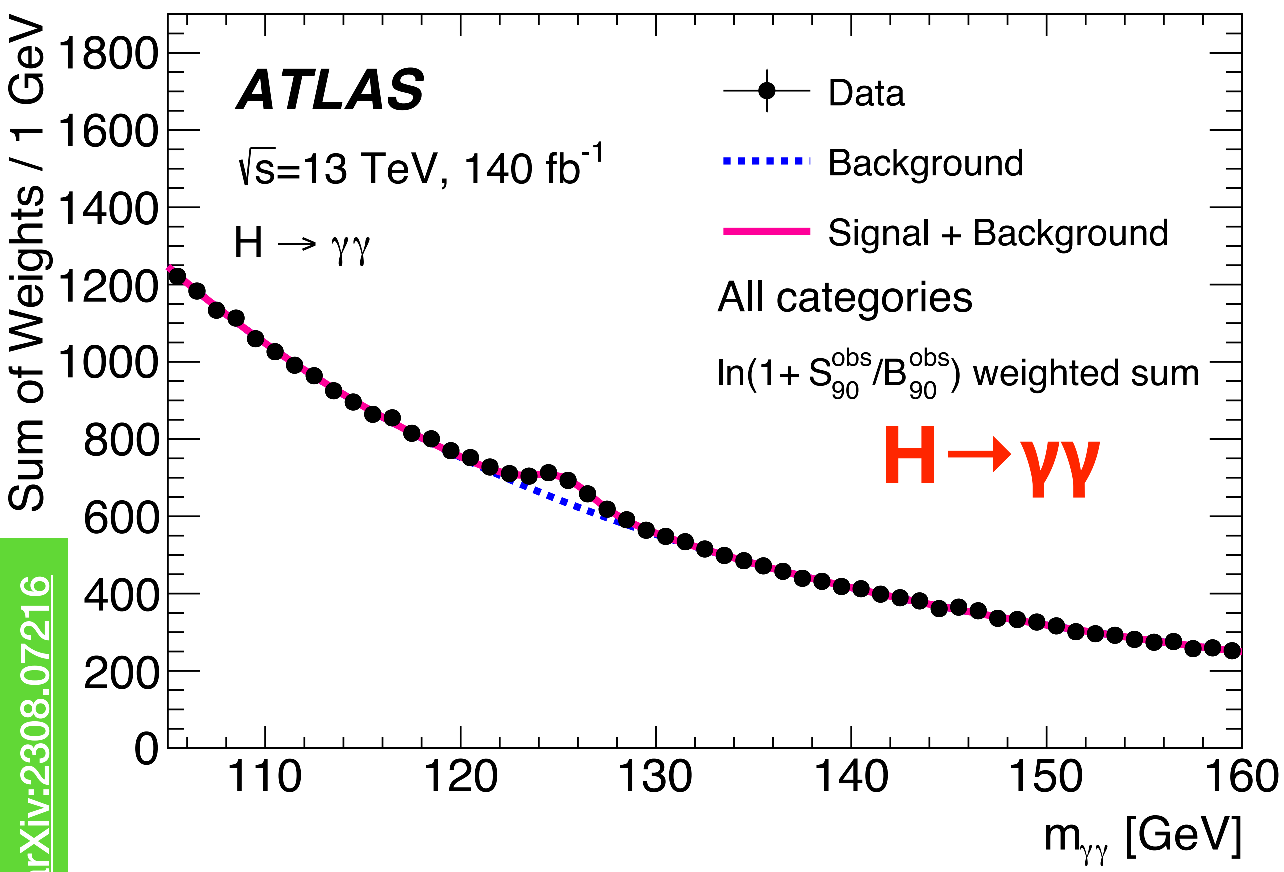

arXiv:2308.07216

Improved photon energy scale adding correction as a function of E_T

Source	Impact [MeV]
Photon energy scale	83
$Z \rightarrow e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^\pm \rightarrow \gamma$ 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

$$m_H = 125.22 \pm 0.14\ [\pm 0.11(stat) \pm 0.09(syst)]\ GeV$$

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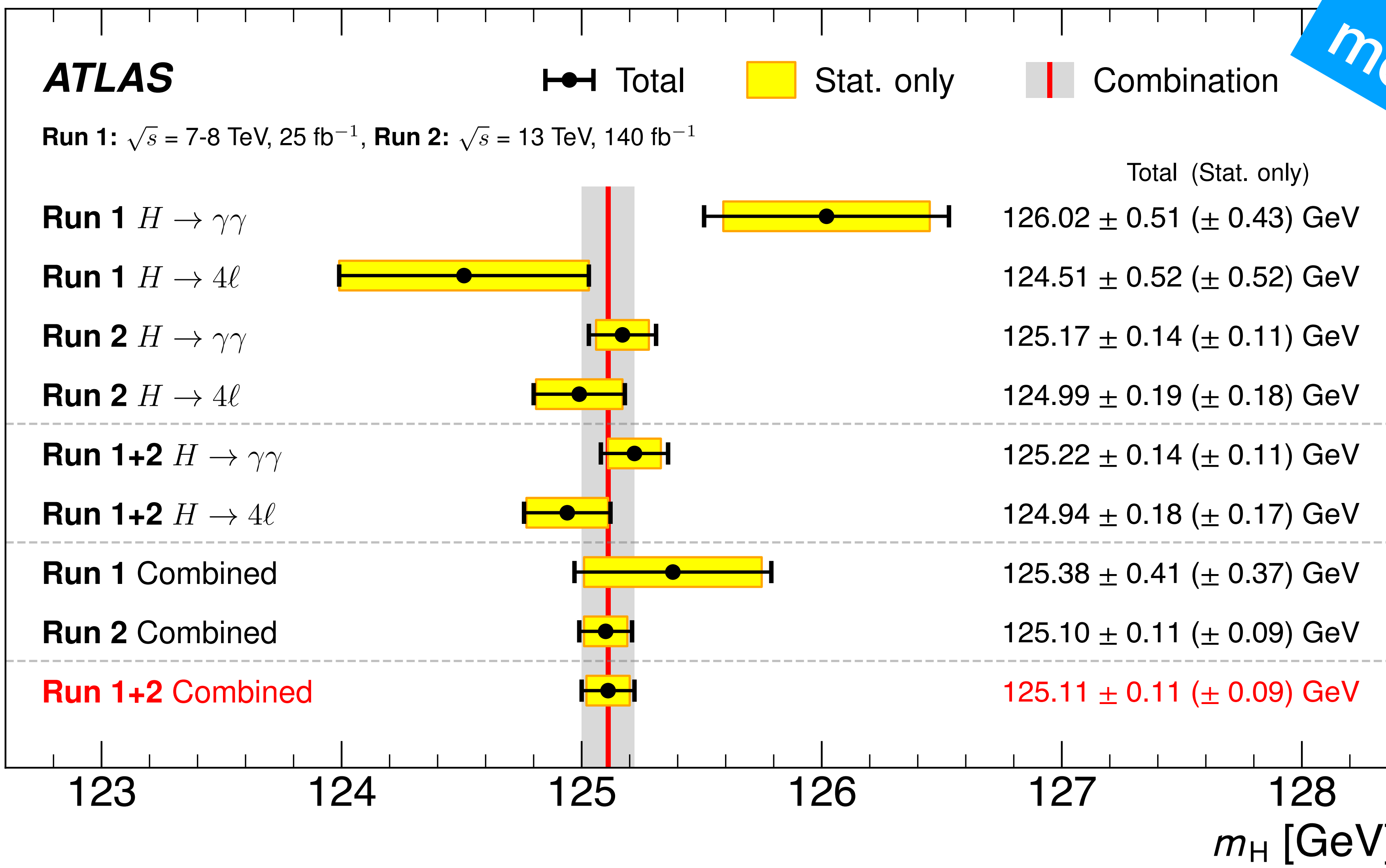
Current best measurement

arXiv:2308.07216



$$m_H = 125.11 \pm 0.11\ [\pm 0.09(stat) \pm 0.06(syst)]\ GeV$$

F. Errico, 20th Workshop of the LHC Higgs Working Group

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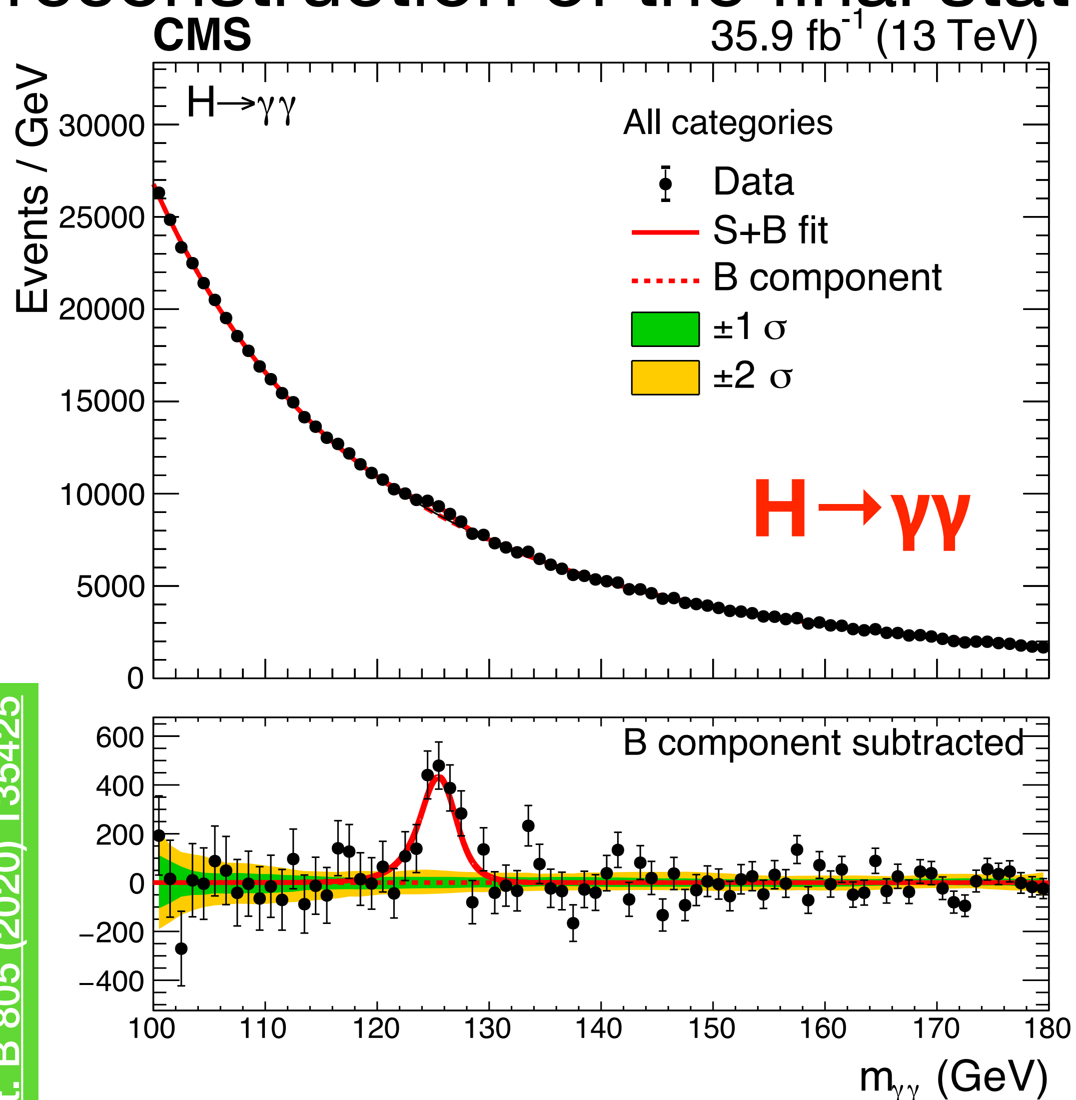

Phys. Lett. B 805 (2020) 135425

Most **CMS** recent result on Higgs mass [**36 fb^{-1}**]

Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_{T} dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

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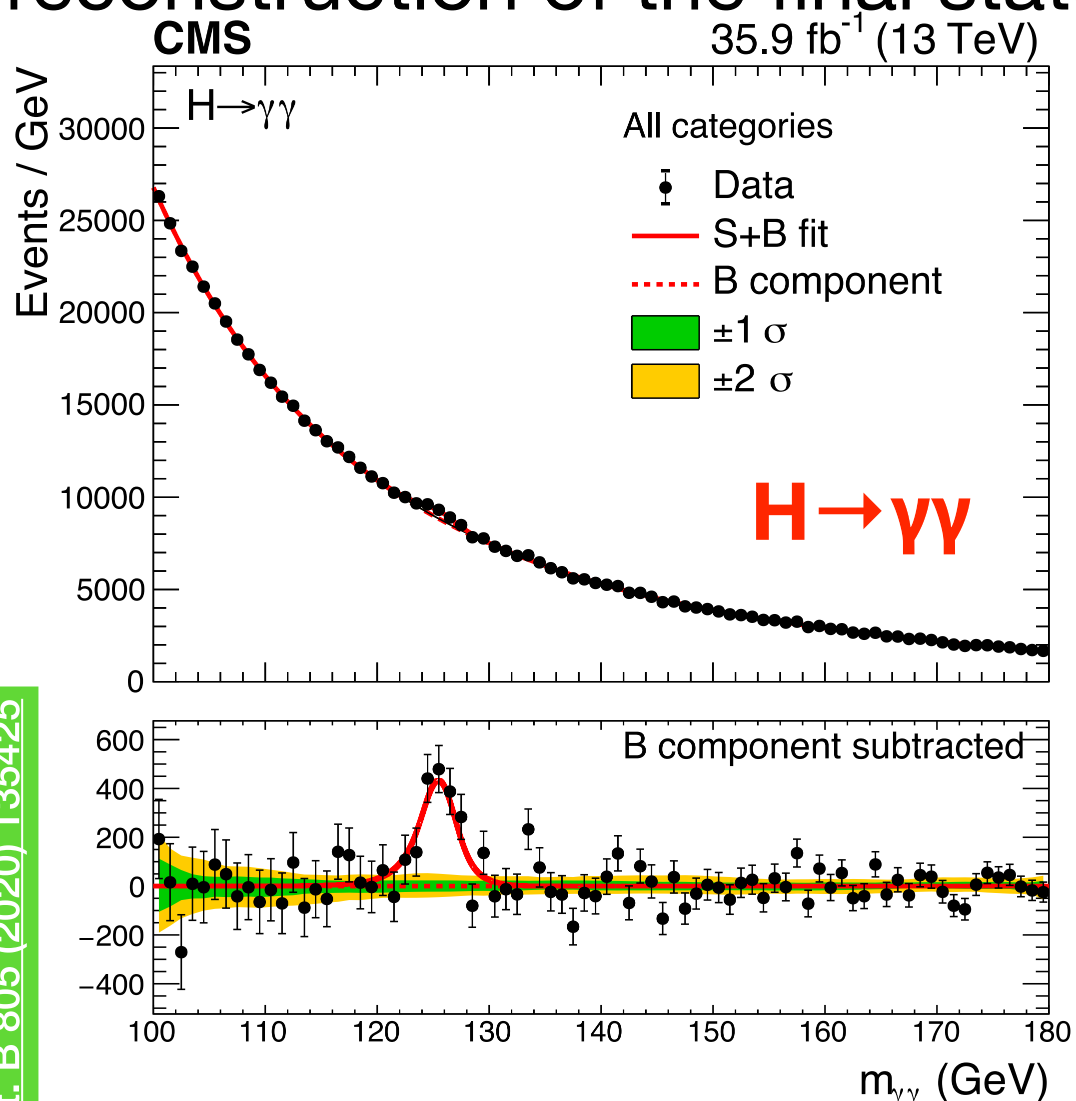

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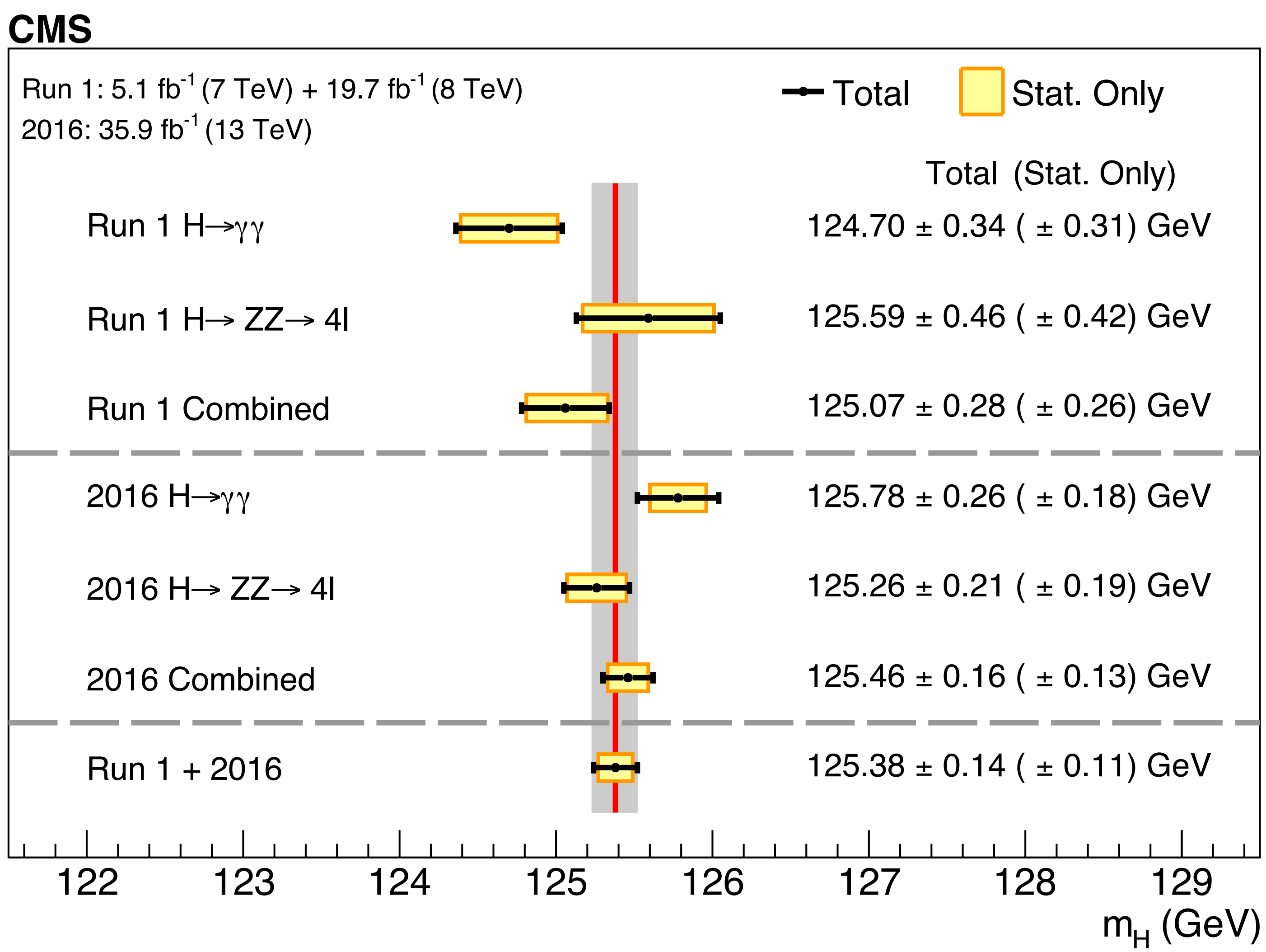


Phys. Lett. B 805 (2020) 135425

$$m_H = 125.38 \pm 0.14\ [\pm 0.11(stat) \pm 0.08(syst)]\ GeV$$

2. Higgs boson width

Predicted precisely within the SM: 4.07 MeV*

Differences with this value could be hints of modifications of the H boson couplings to the SM particles and/or a test for invisible decays

Due to its small value, difficulties in directly measuring it.

Measured in the **H→ZZ** channel, full Run 2 data, comparing on-shell and off-shell production, in different decay channels

$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$

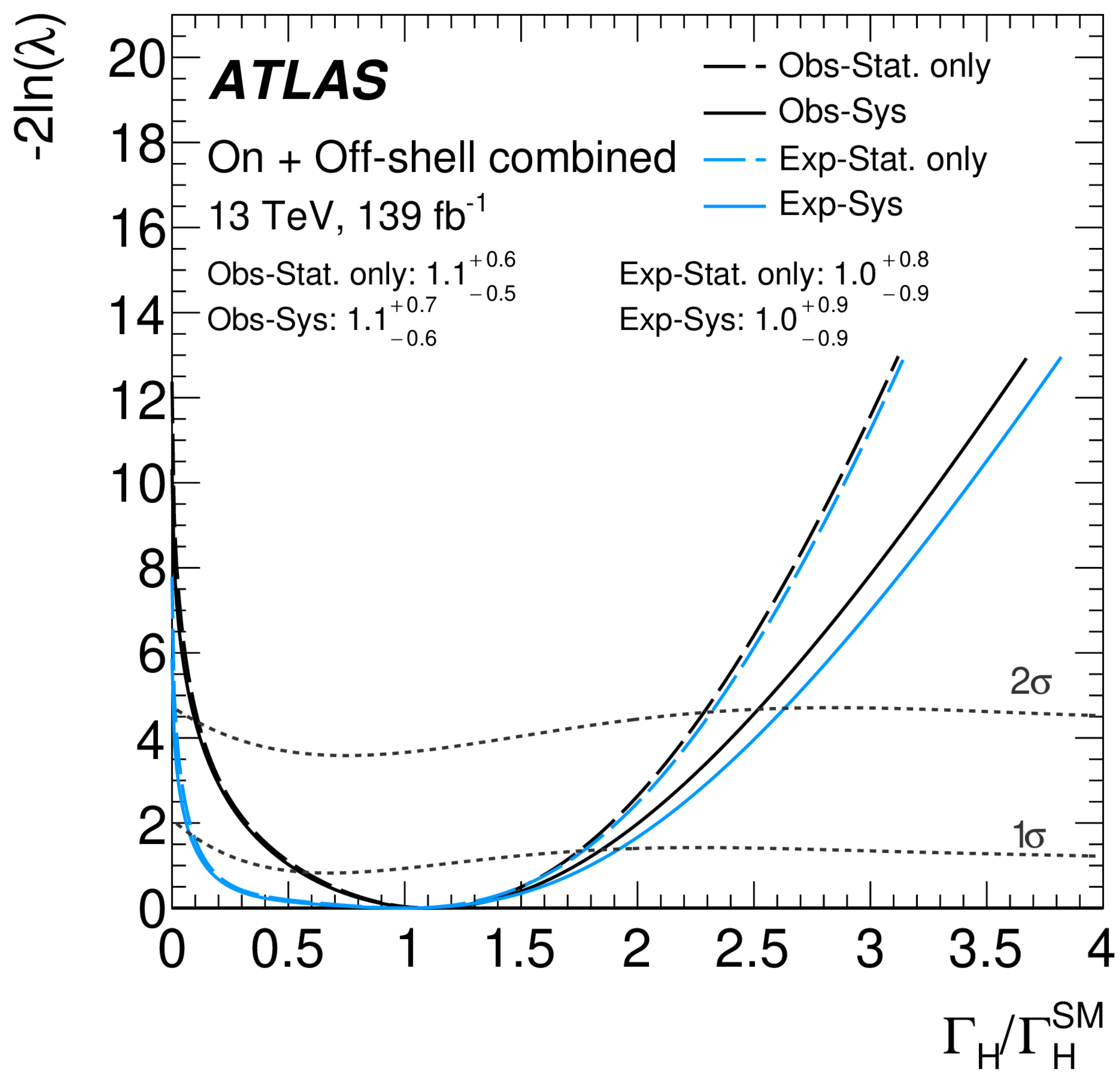
*R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022)

2. Higgs boson width

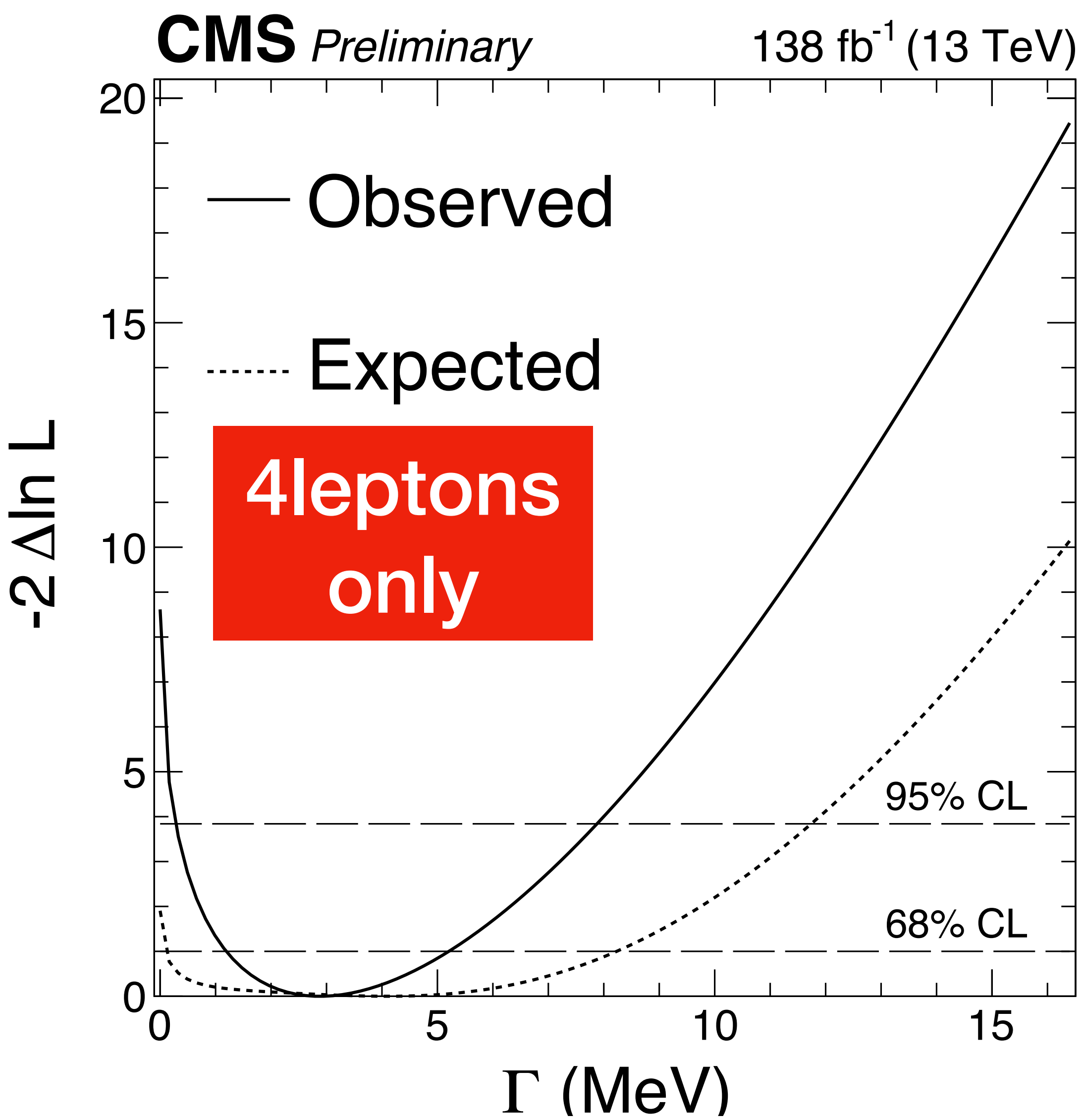
Difficulties in directly measuring the width (4.07 MeV*) due to detector resolution.

Measured in the **H→ZZ** channel, full Run 2 data, comparing on-shell and off-shell production, in different decay channels

physletb.2023.138223



3 categories: ggF, VBF and mixed [multi-class NN (4l) + m_T (2l2v)]



cds.cern.ch/record/2871702

3 categories: VBF, VH, untagged [mass+kinematic discriminant]

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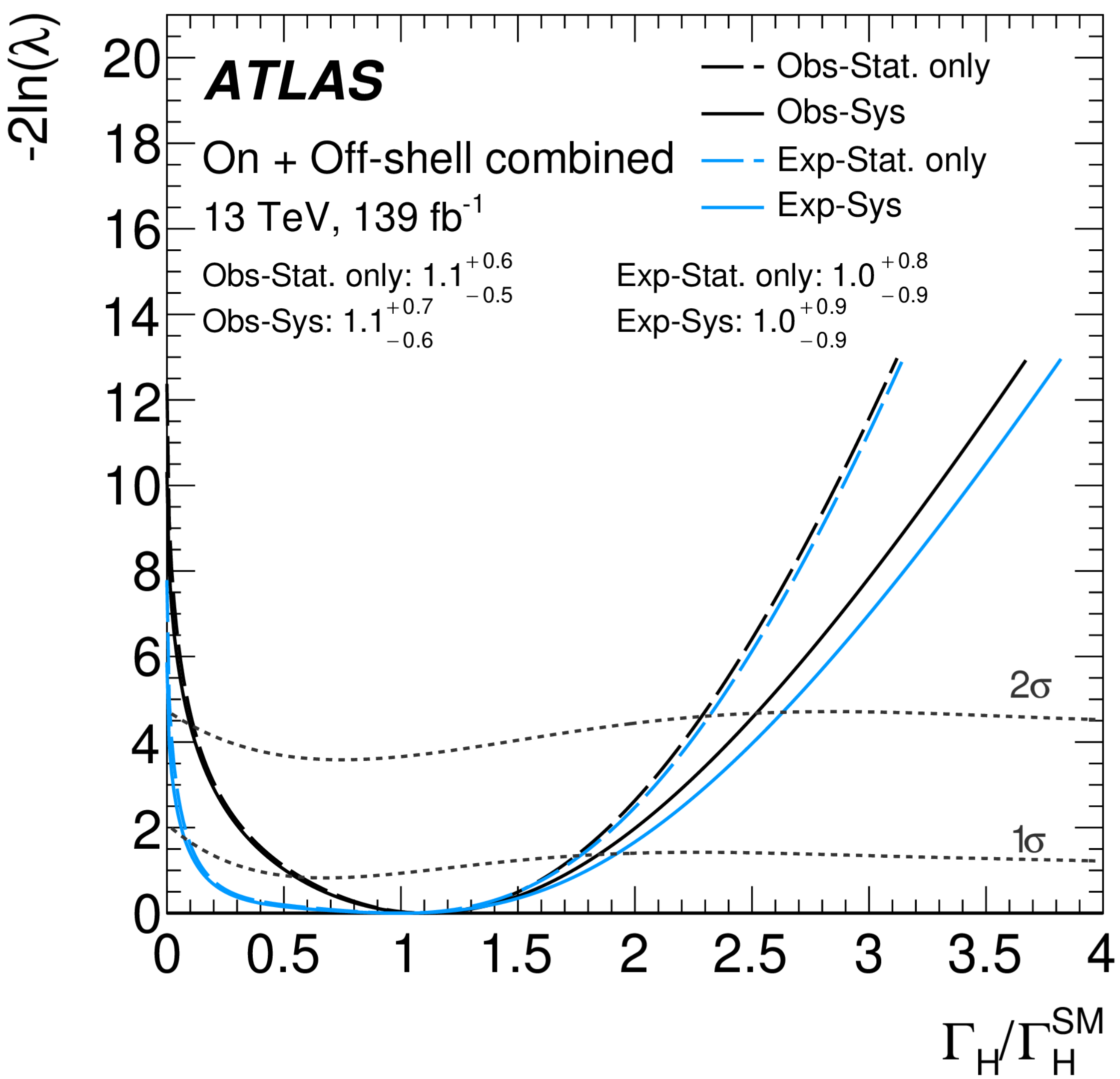
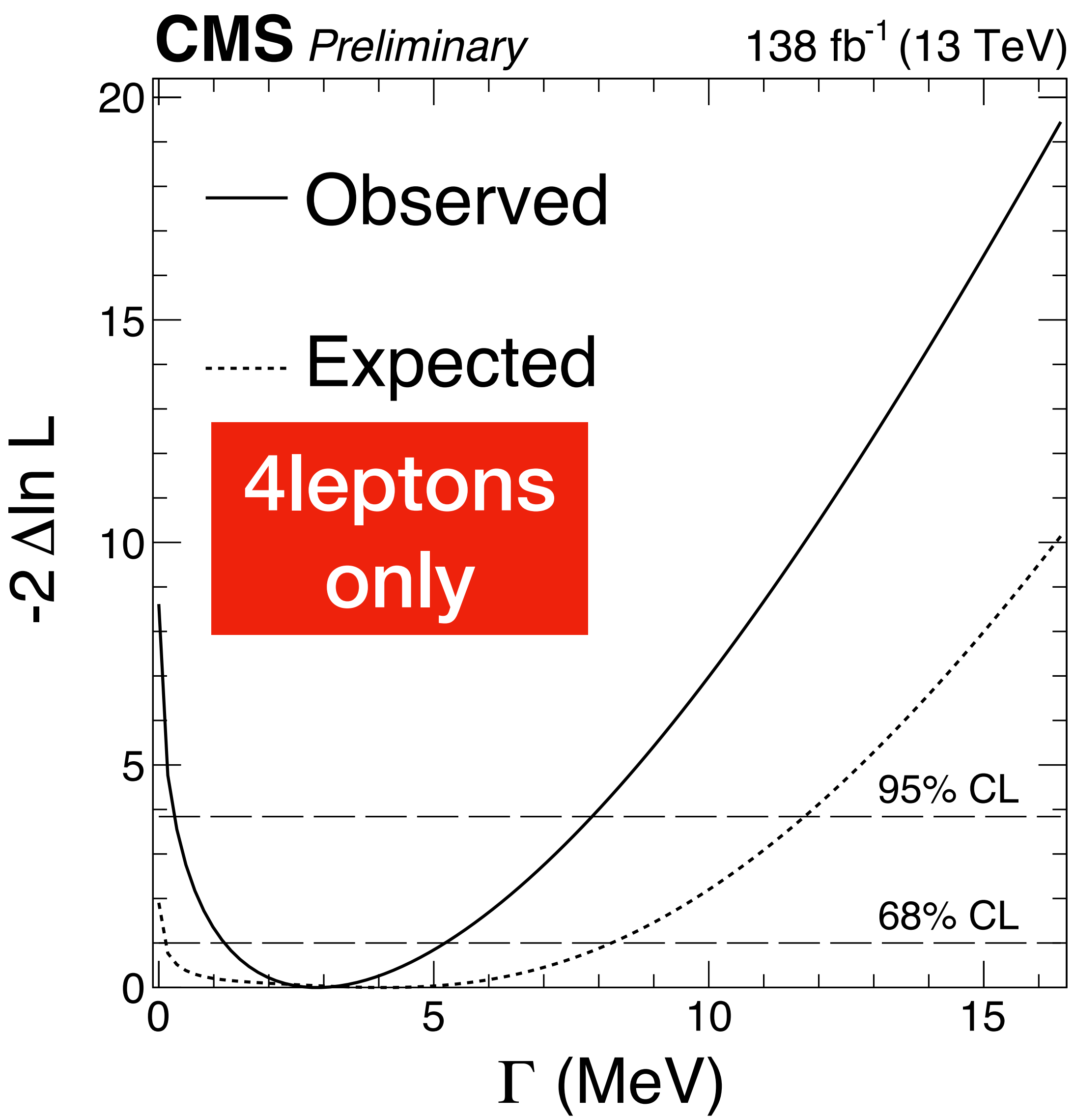
physletb.2023.138223





cds.cern.ch/record/2871702

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

$$\Gamma_H = 2.9^{+2.3}_{-1.7}\ MeV$$

3. Higgs boson CP

Looking for anomalous Higgs boson couplings to **vector bosons**

$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

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SM coupling
(the only no-zero term)

CP odd - AC

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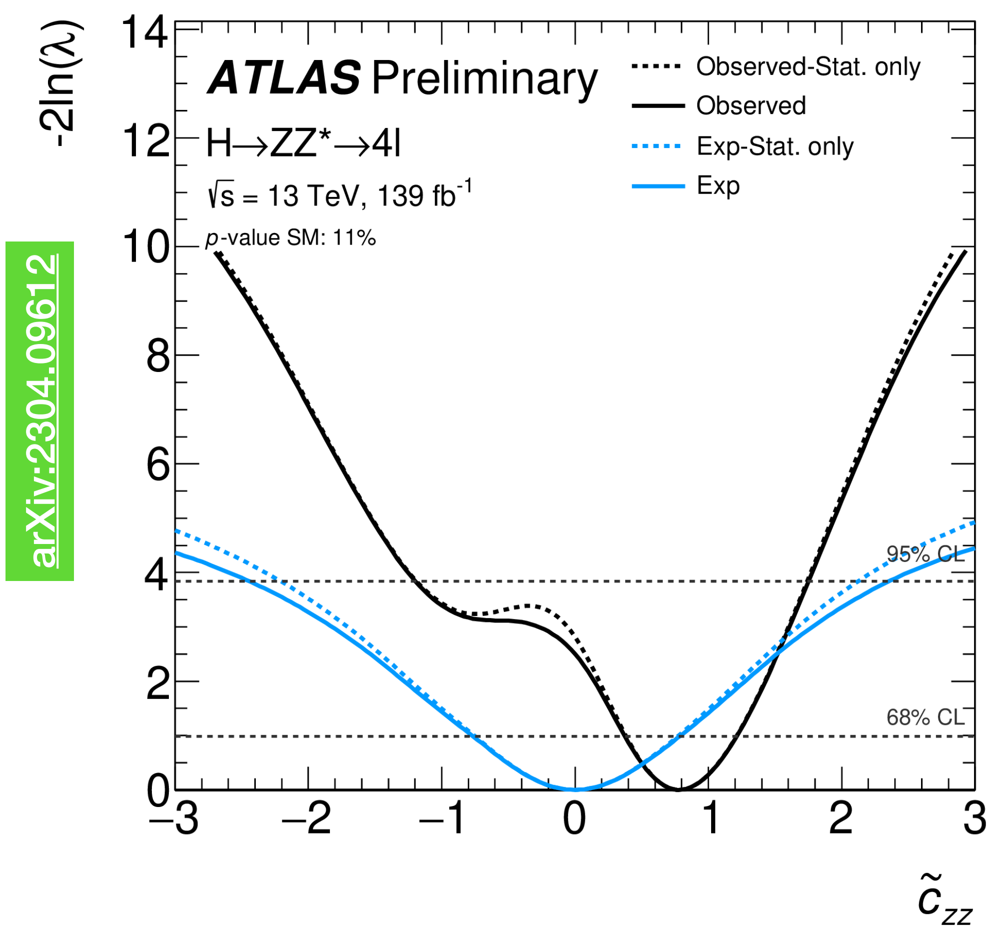
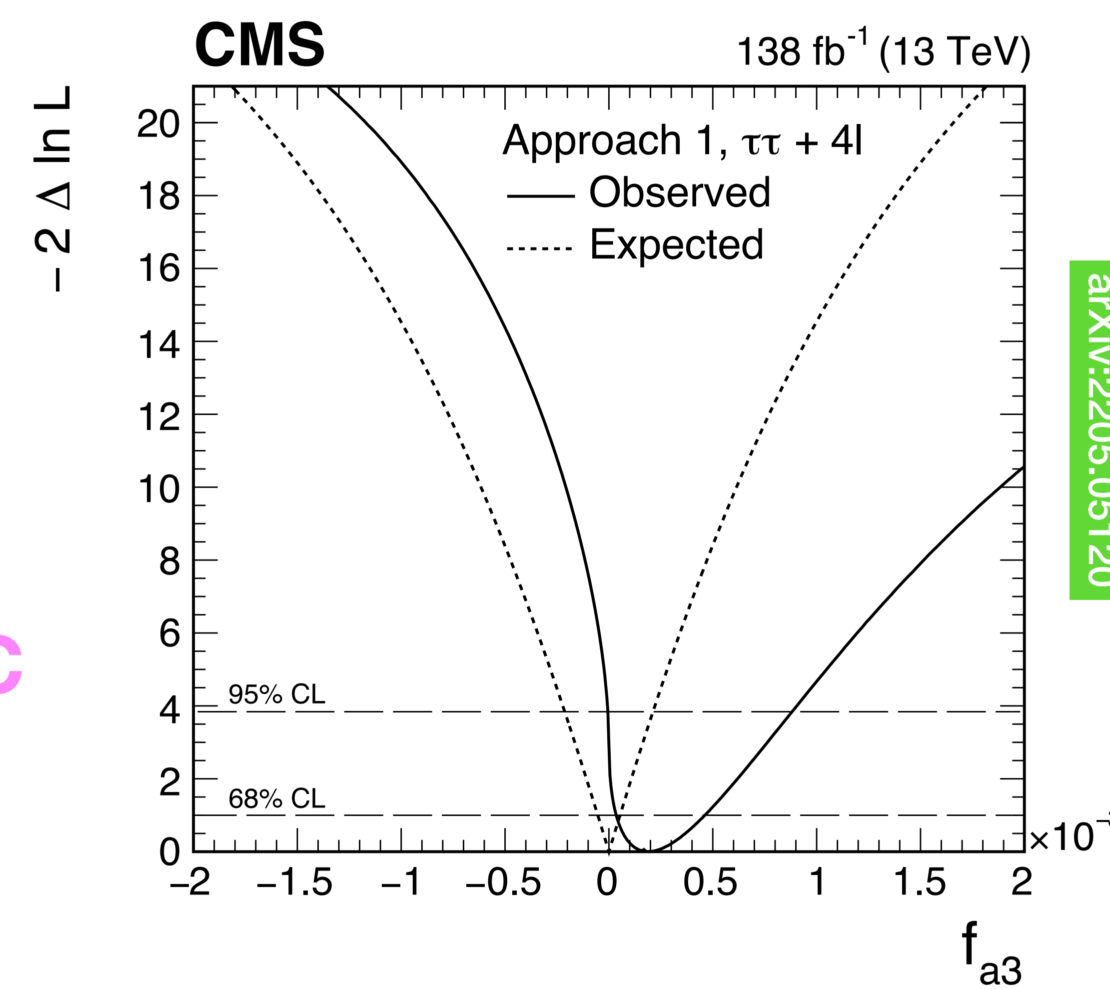
arXiv:2304.09612



$H \to ZZ$

ME observable used to constrain AC



arXiv:2205.05120

$H \to ZZ + H \to \tau\tau$

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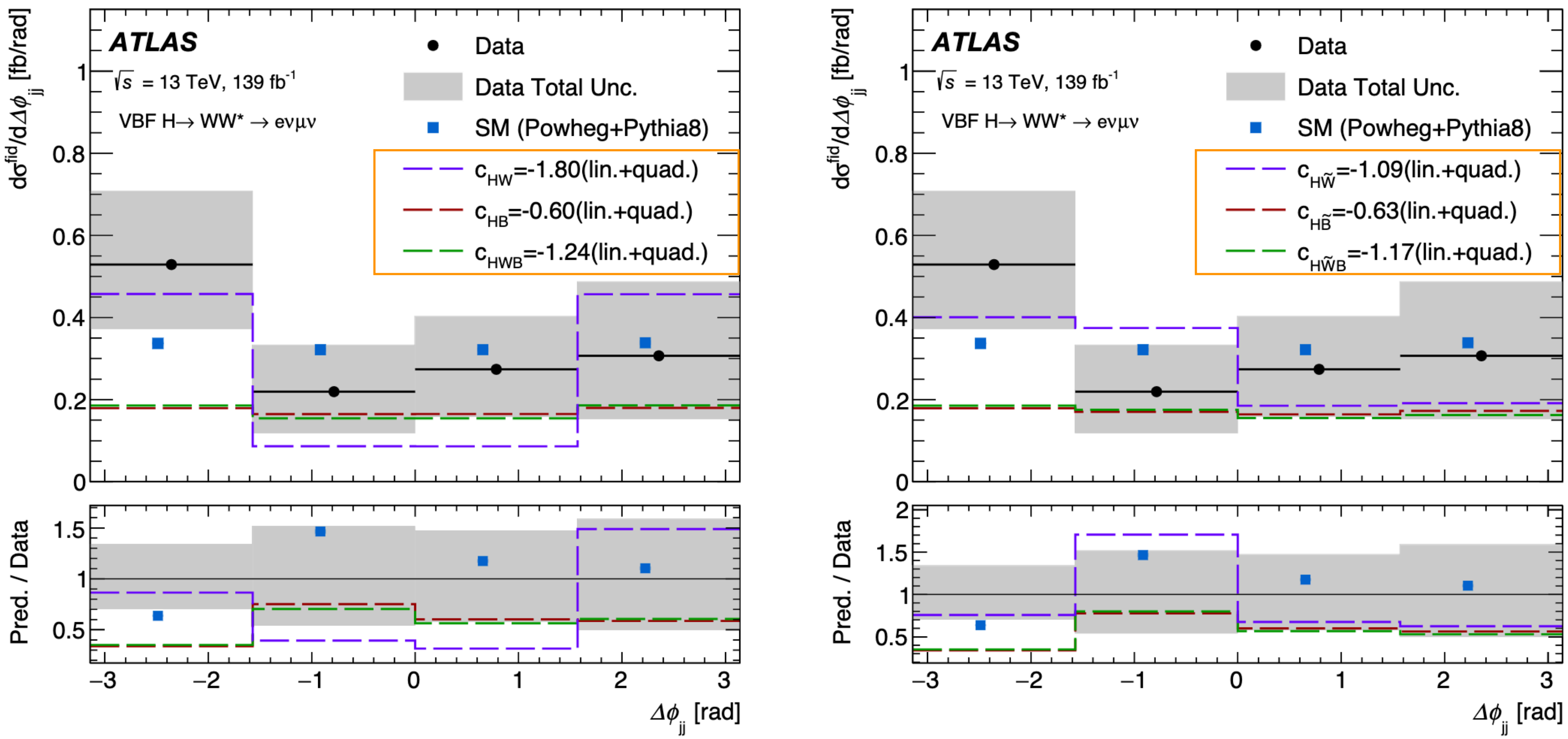
PhysRevD.108.072003



SM vs EFT model

Δφjj sensitive to anomalous couplings between H and V

VBF $H \rightarrow WW$

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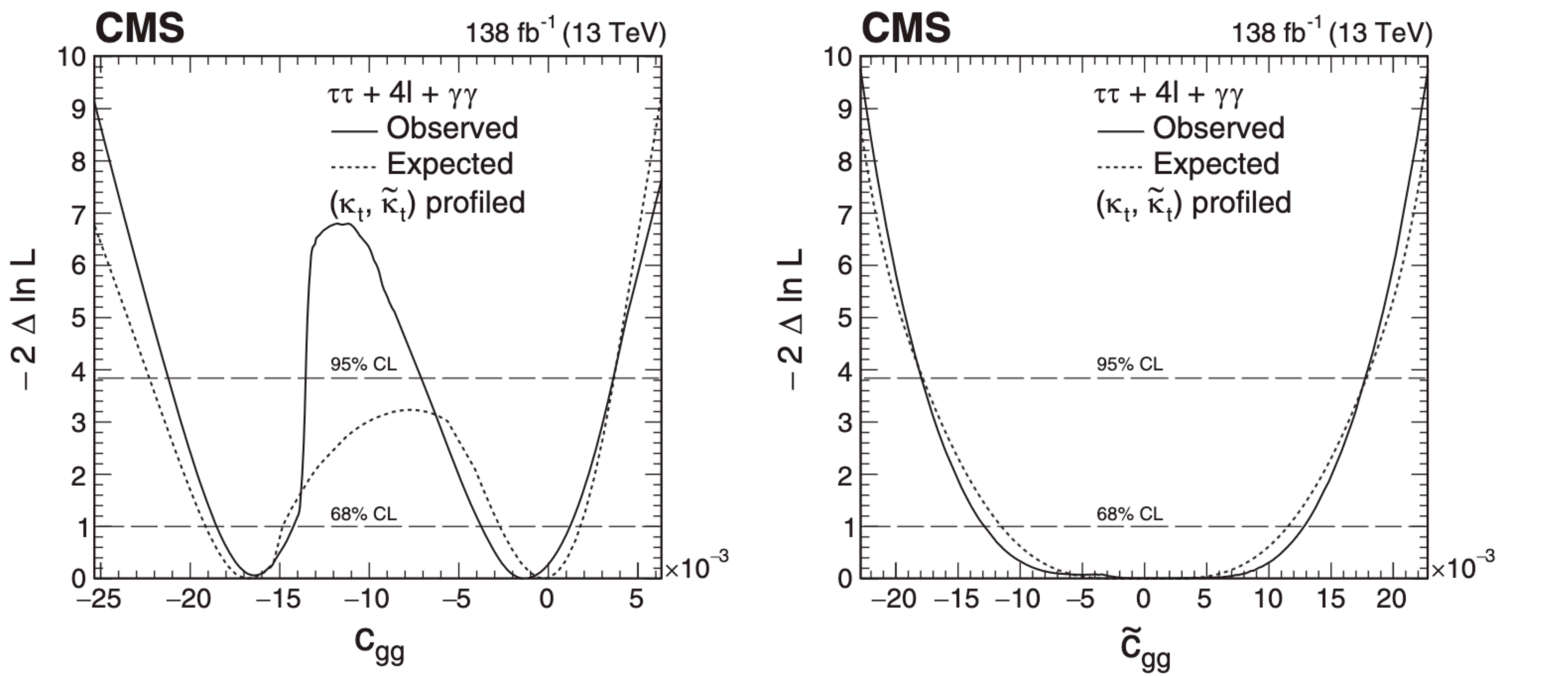


arXiv:2205.05120

$$H \to ZZ + H \to \tau\tau + H \to \gamma\gamma$$

INFN ROMA Istituto Nazionale di Fisica Nucleare Sezione di Roma ATLAS EXPERIMENT CMS

3. Higgs boson CP

Looking for anomalous Higgs boson couplings to **fermions**

$$\mathcal{L}_{\mathrm{t\bar{t}H}} = \frac{m_{\mathrm{t}}}{v}\bar{\psi}_{\mathrm{t}}(\kappa_{\mathrm{t}} + i\gamma_5\widetilde{\kappa}_{\mathrm{t}})\psi_{\mathrm{t}}\mathrm{H}$$

3. Higgs boson CP

Looking for anomalous Higgs boson couplings to **fermions**

$$\mathcal{L}_{t\bar{t}H} = \frac{m_t}{v}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H$$

CP even Yukawa Coupling (SM)

CP odd Yukawa Coupling

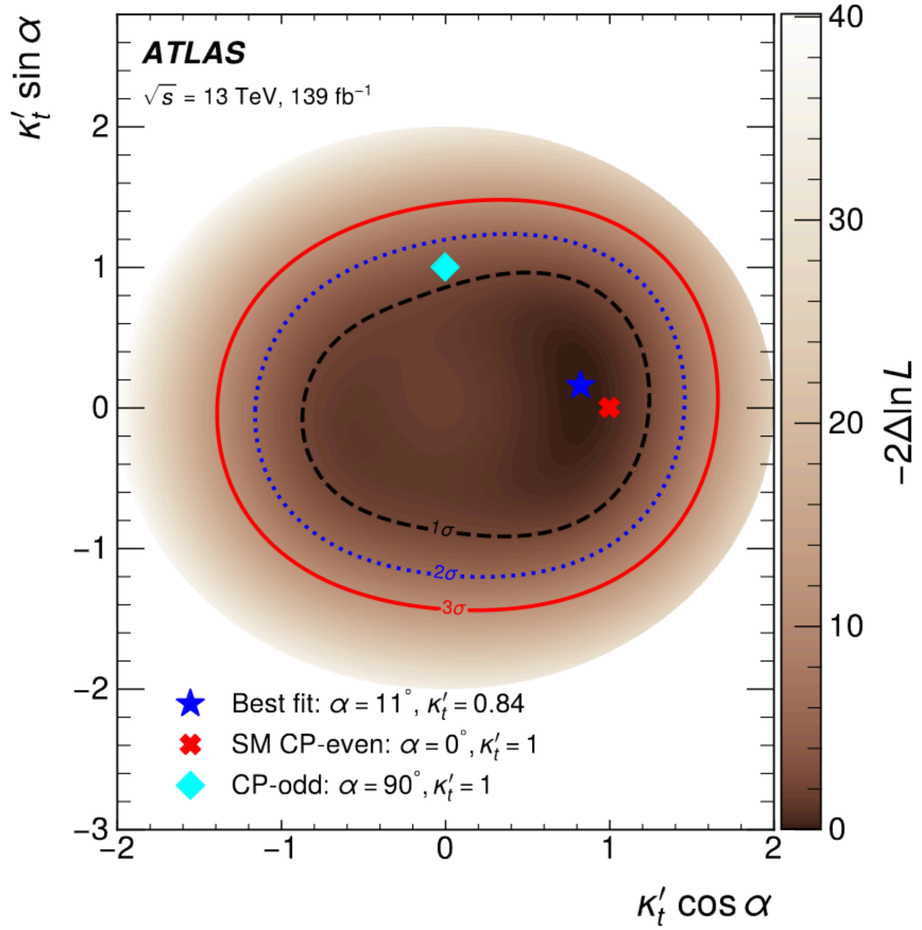
3. Higgs boson CP

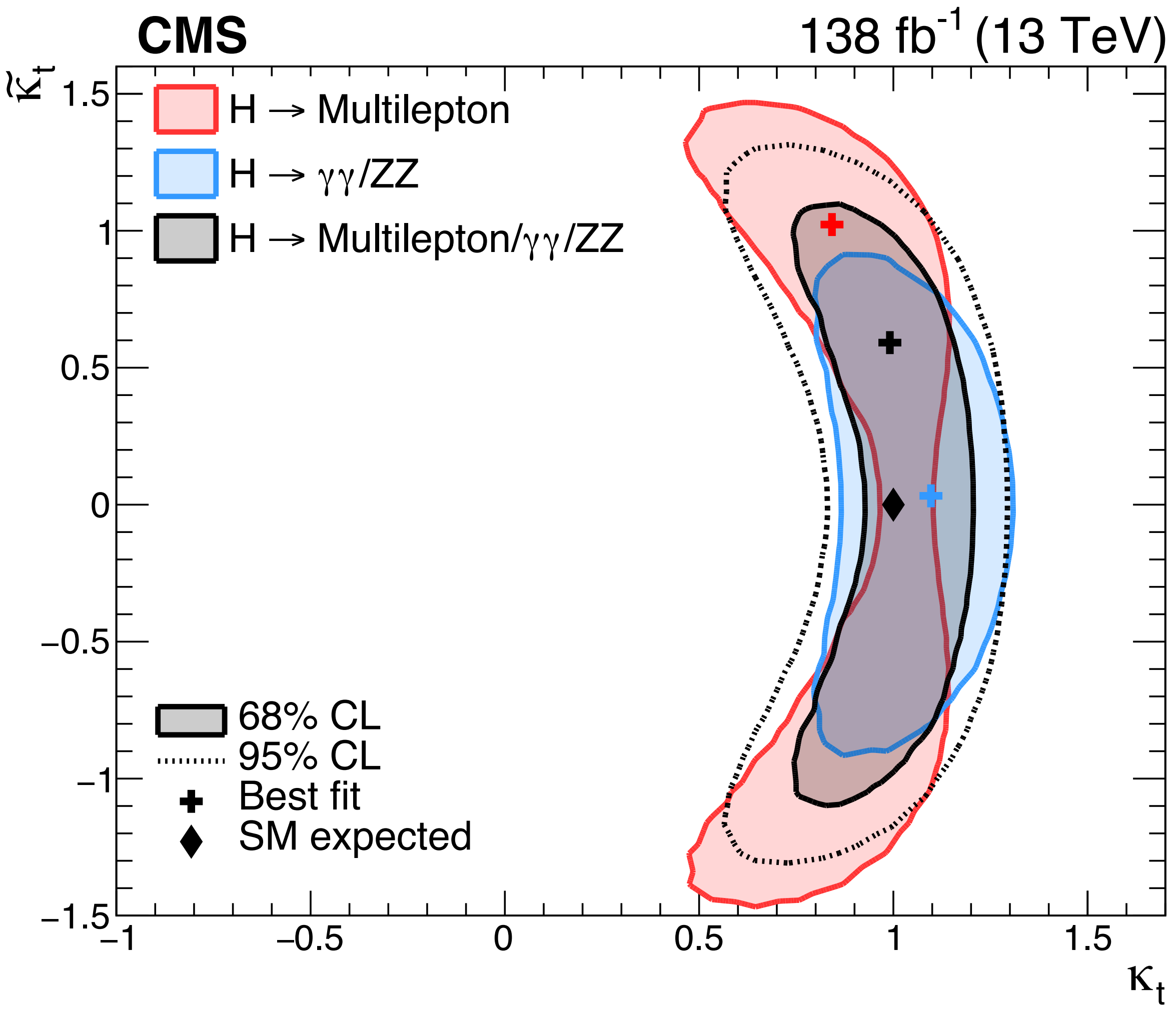
Looking for anomalous Higgs boson couplings to **fermions**

$$\mathcal{L}_{t\bar{t}H} = \frac{m_t}{v}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H$$

$H \to bb$

arXiv.2303.05974





JHEP07(2023)092

ML & momentum based variables used to constrain AC

ME + ML variables used to constrain AC

Conclusion

Higgs boson properties, measured by the ATLAS and CMS collaborations have been presented.

The Higgs boson mass, free parameter of the SM, is known with a precision of the order to 0.1%

- ATLAS best results (from full Run 2 combination): m_H = 125.11±0.11 MeV
- CMS best results (from HZZ full Run 2): m_H = 125.08±0.12 MeV

The best width measurement is extracted comparing on-shell with off-shell decay region:

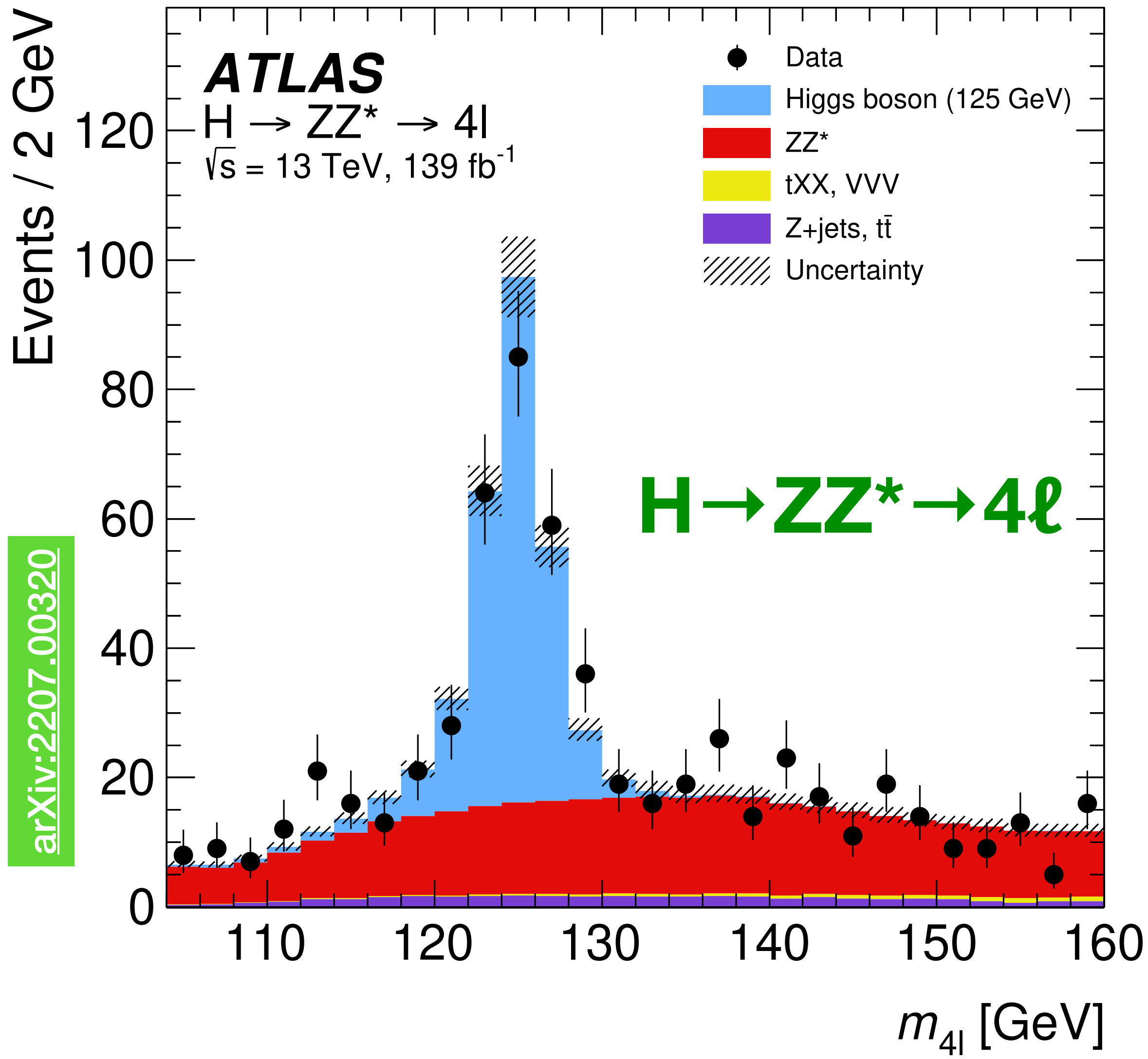
- ATLAS (4L +2L2v): $\Gamma_H = 4.5^{+3.3}_{-2.5}\ MeV$
- CMS (4L only): $\Gamma_H = 2.9^{+2.3}_{-1.7}\ MeV$

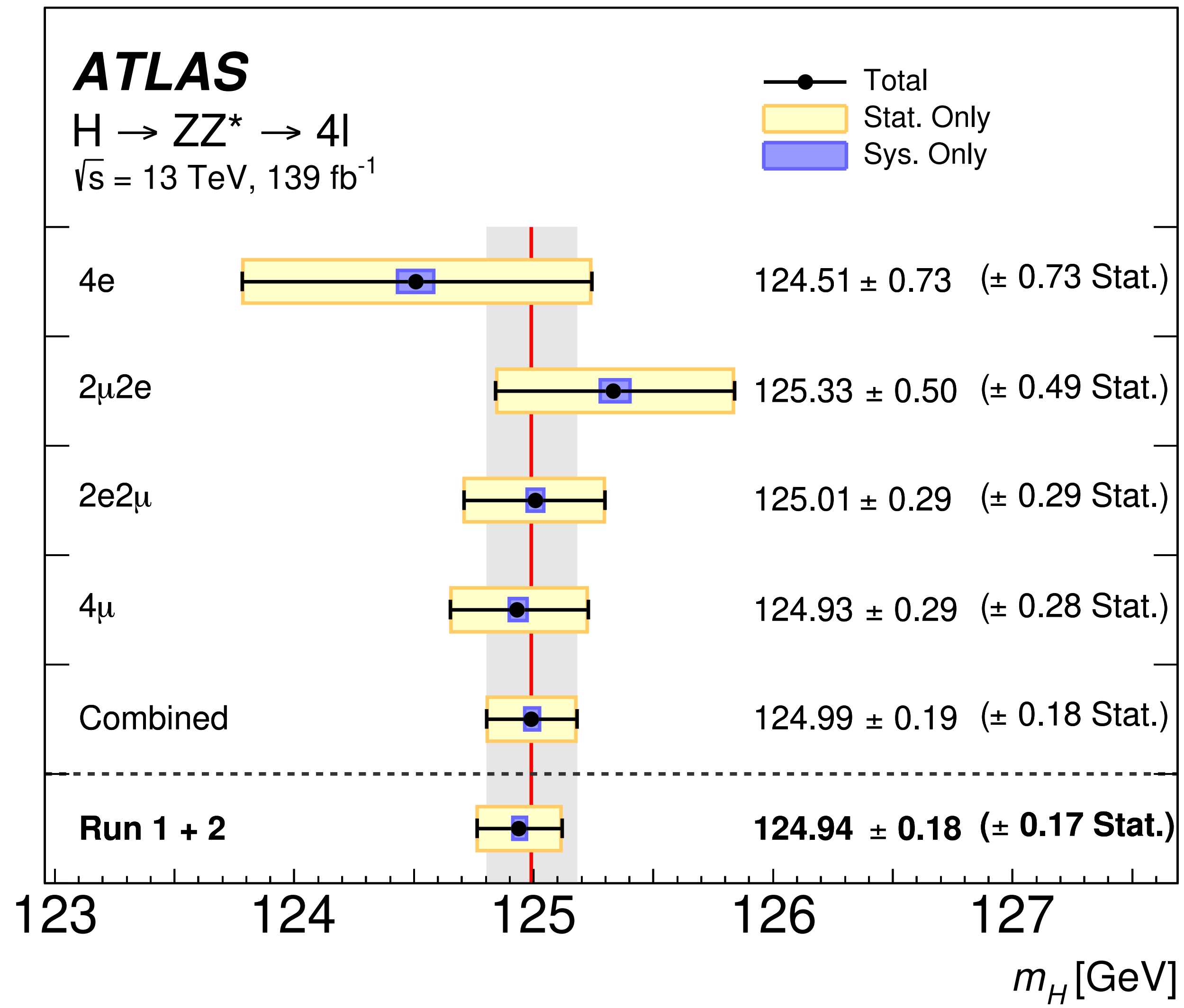
No indication of anomalous couplings with fermions or vector bosons.

Backup

1. Higgs boson mass

Higgs boson mass measurement is performed using **H→ZZ*→4ℓ** and **H→γγ**, thanks to their mass resolution (1-2%) and complete reconstruction of the final state.





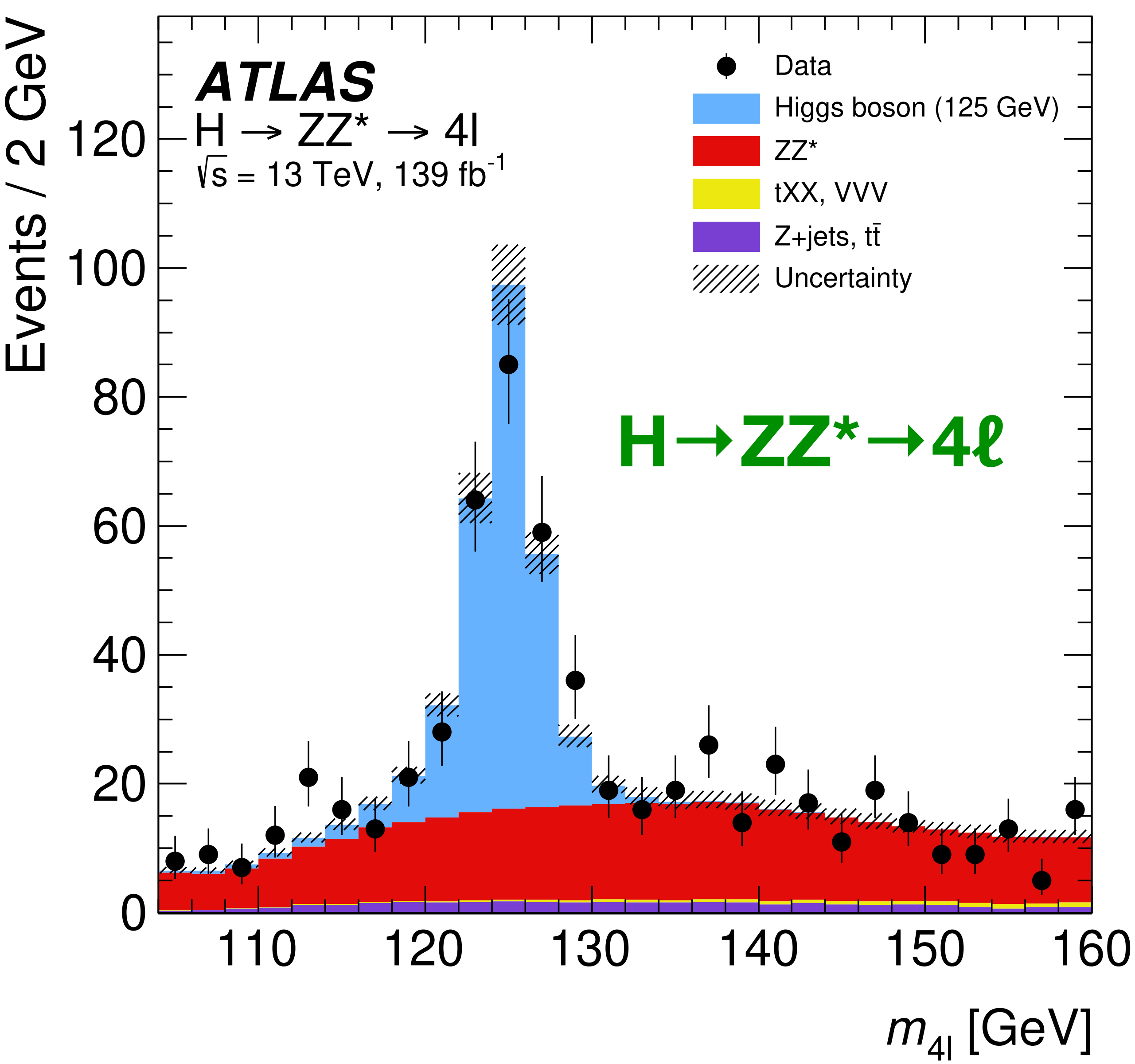
$$m_H = 124.94 \pm 0.18\ [\pm 0.17(stat) \pm 0.03(syst)]\ GeV$$

1. Higgs boson mass

Higgs boson mass measurement is performed using **$H \to ZZ^* \to 4\ell$** and **$H \to \gamma\gamma$**, thanks to their mass resolution (1-2%) and complete reconstruction of the final state.

Most **ATLAS** recent result on Higgs mass [**139 fb^{-1}**]

- Signal-background discrimination enhanced employing a NN (D_{NN})
- Event-level m_{4l} resolution estimated using a QRNN
- Signal parametrisation improved profits of the new discriminant D_{NN}



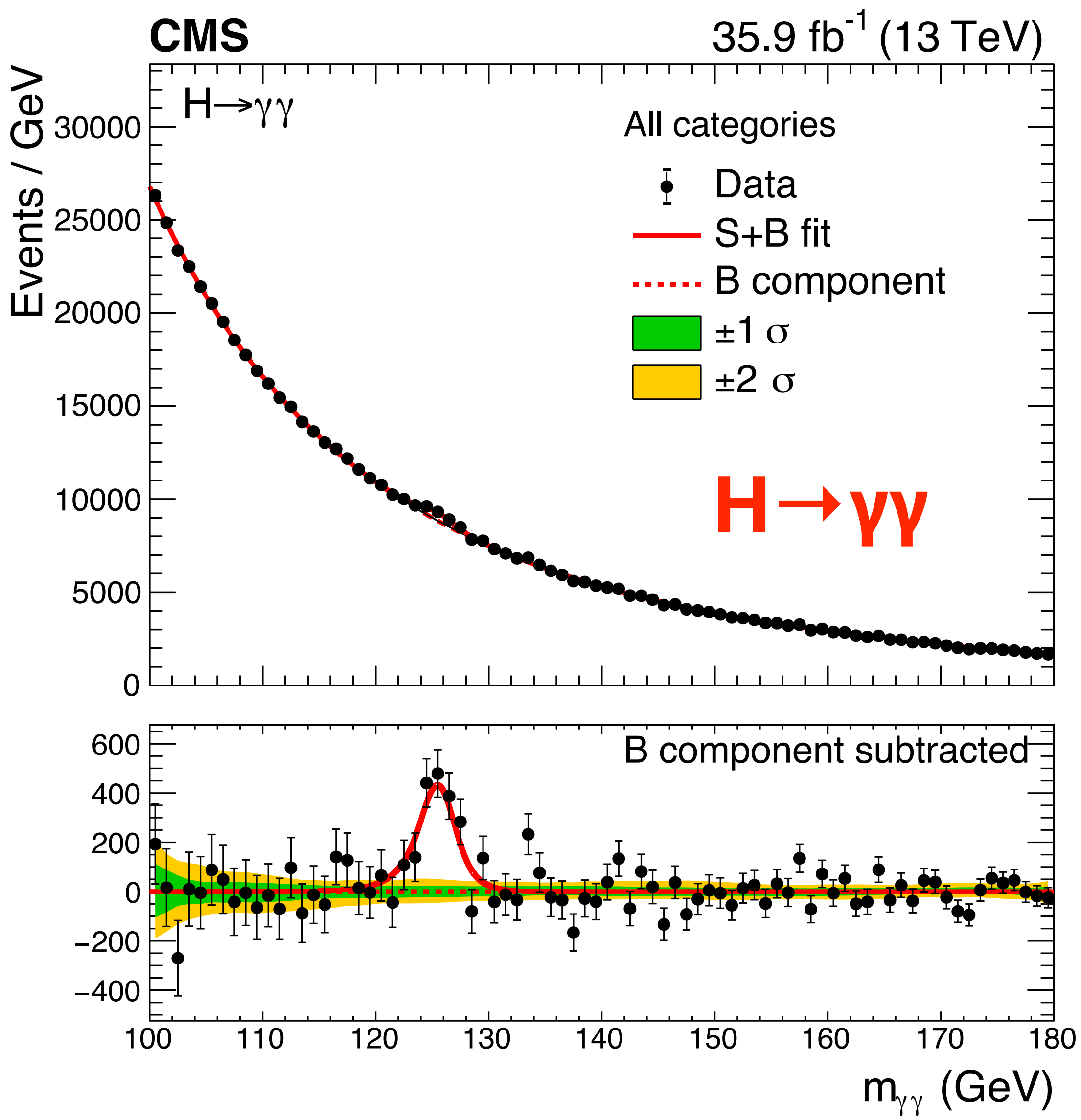
arXiv:2207.00320

$$m_H = 124.99 \pm 0.19\ [\pm 0.18(stat) \pm 0.04(syst)]\ GeV$$

1. Higgs boson mass

Higgs boson mass measurement is performed using **H→ZZ*→4ℓ** and **H→γγ**, thanks to their mass resolution (1-2%) and complete reconstruction of the final state.

Phys. Lett. B 805 (2020) 135425



Most **CMS** recent result on Higgs mass [**36 fb^{-1}**]

- Energy calibration profits of multivariate regression technique
- Residual differences between data and MC corrected with an ad-hoc multi-step method
- Event classification performed according to the production mode, mass resolution and the predicted signal-to-background ratio

$$m_H = 125.78 \pm 0.26\ [\pm 0.18(stat) \pm 0.18(syst)]\ GeV$$

1. Main systematic uncertainties

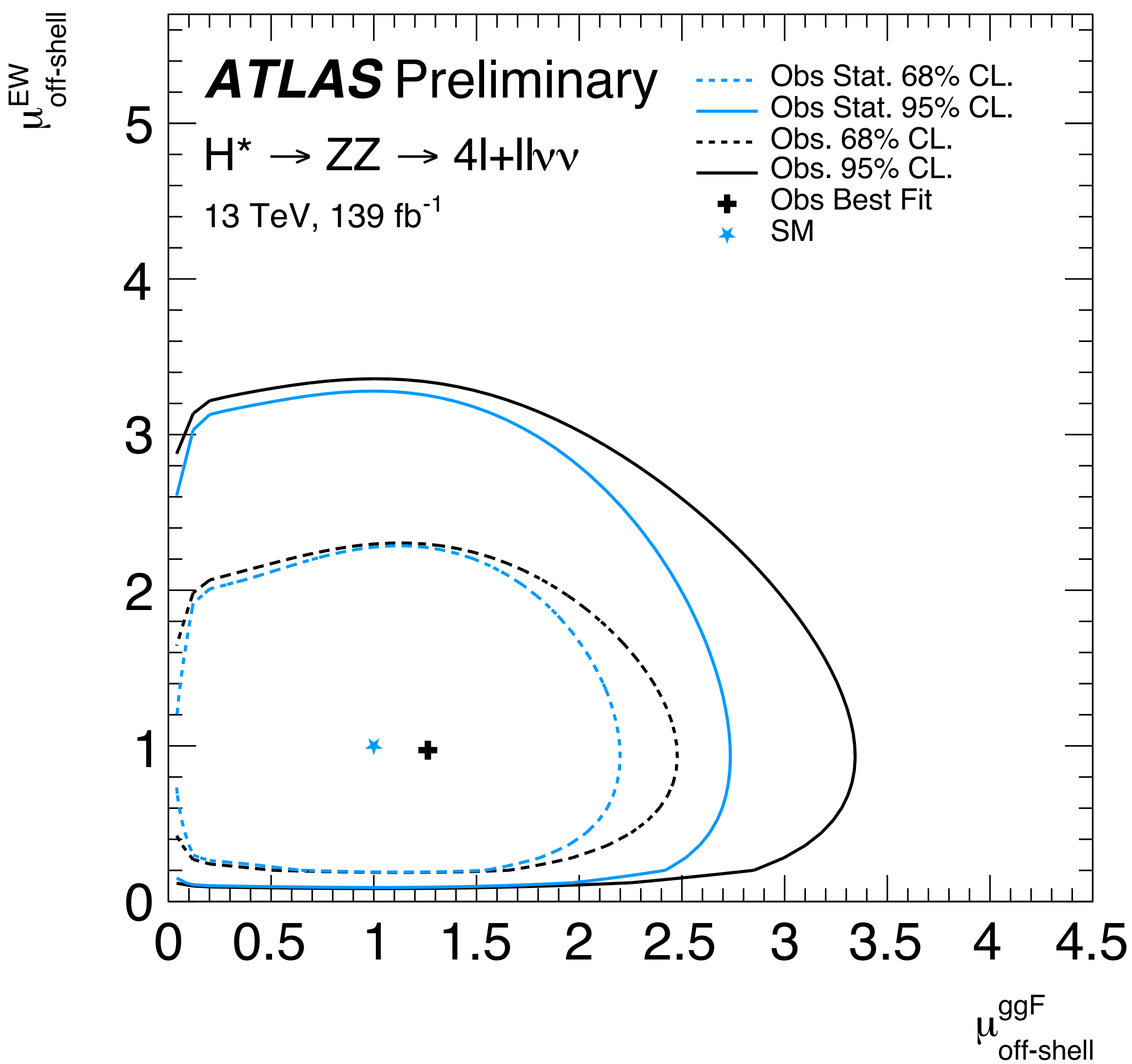
	ATLAS	CMS
$H \to \gamma\gamma$	• Zee calibration: 59 MeV • E_T correction: 44 MeV • Non-uniformity of the light collection: 30 MeV	• Electron energy scale and resolution 0.05 - 0.3% —> 100 MeV • Residual pT dependence of the energy scale correction 0.075 - 0.15% —> 110 MeV • Non-uniformity of the light collection 0.16-0.45% —> 110 MeV
$H \to ZZ^* \to 4\ell$	• muon momentum scale 28 MeV • electron energy scale 19 MeV	• 4-lepton mass scale 0.03 - 0.15% (different for different final state) • 4-lepton mass resolution 3-10%

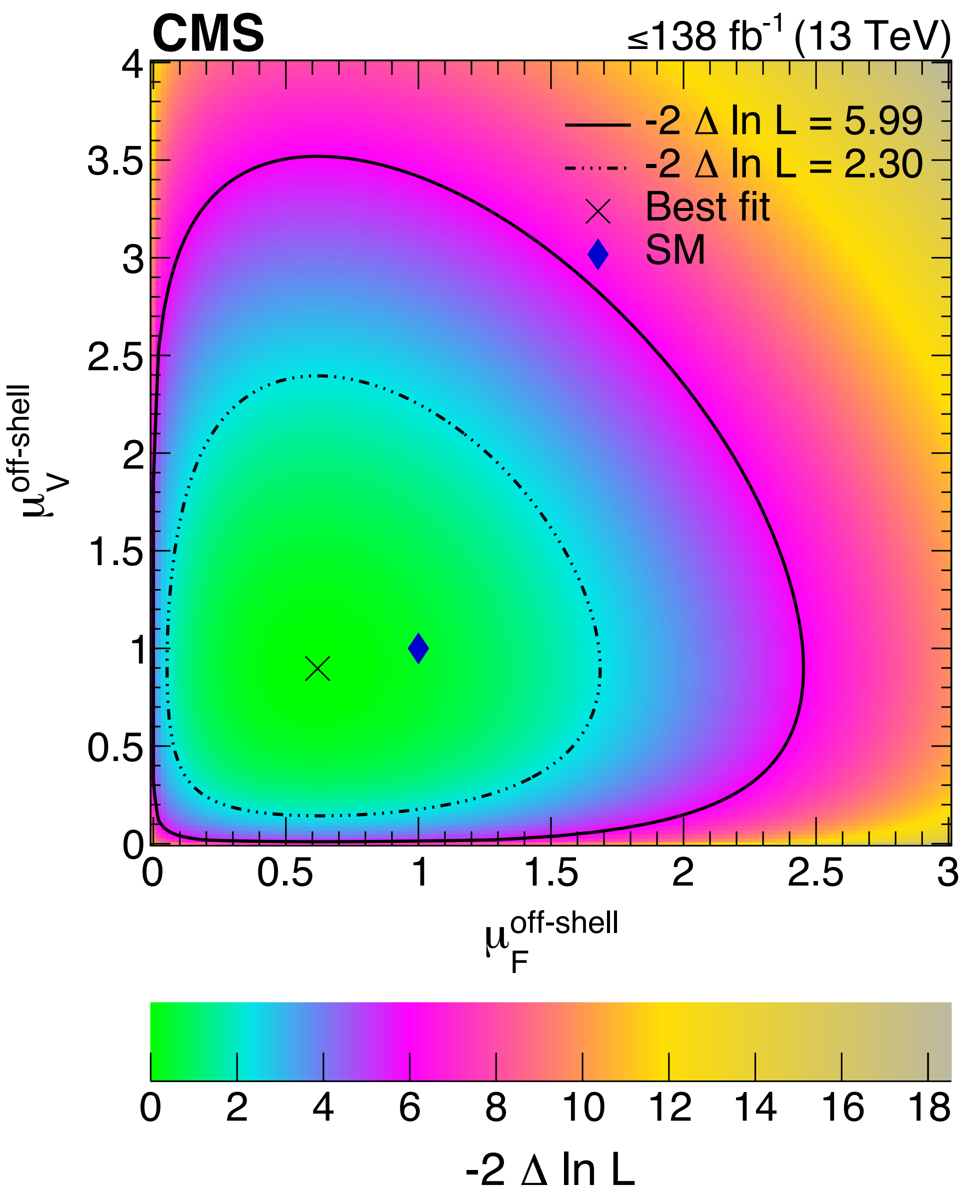
2. Higgs boson width

Difficulties in directly measuring the width (4.07 MeV*) due to detector resolution.

Measured in the **H→ZZ** channel, full Run 2 data, comparing on-shell and off-shell production, in different decay channels

ATLAS-CONF-2022-068





Nat. Phys. 18 (2022) 1329

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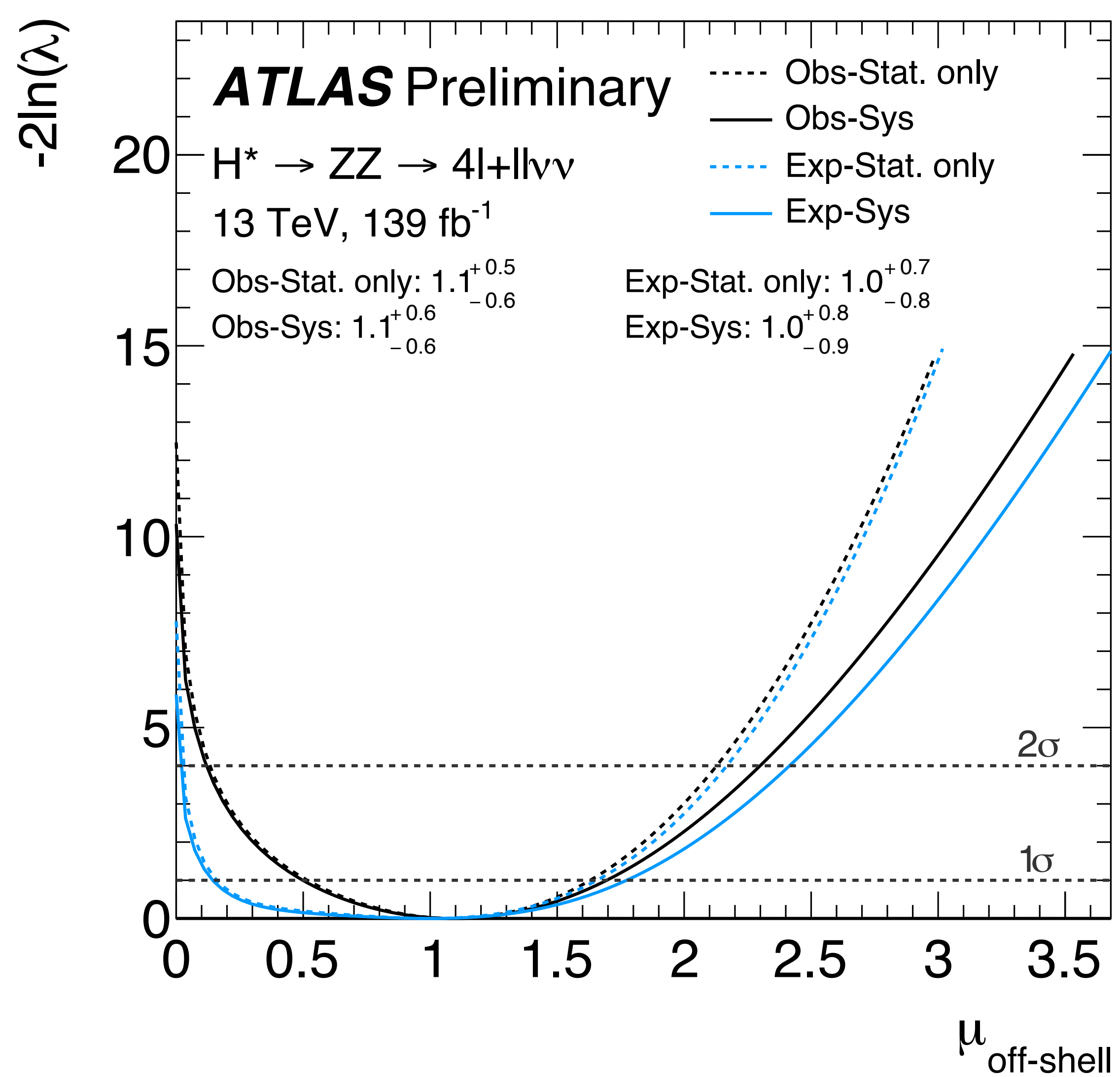
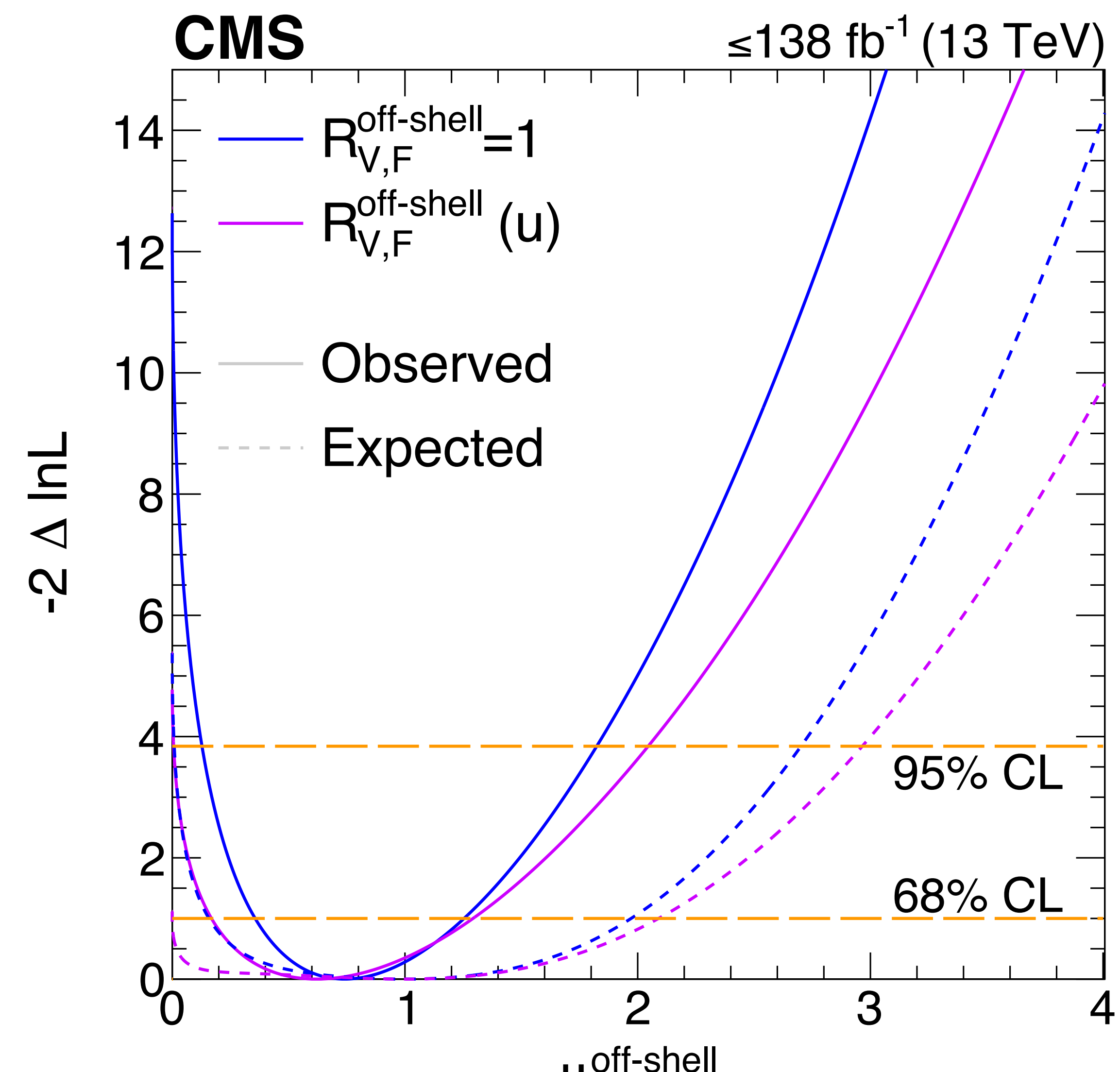
ATLAS-CONF-2022-068

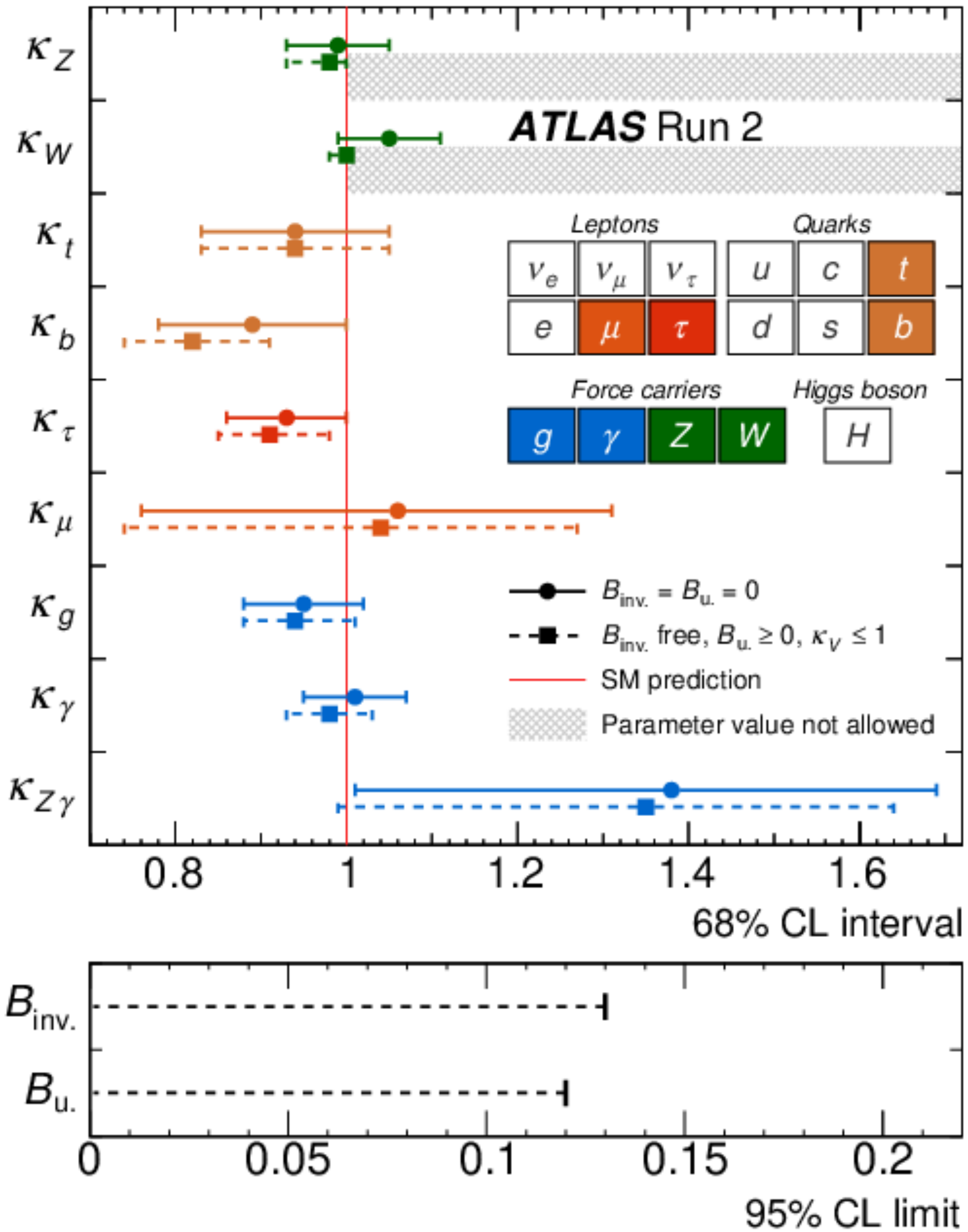




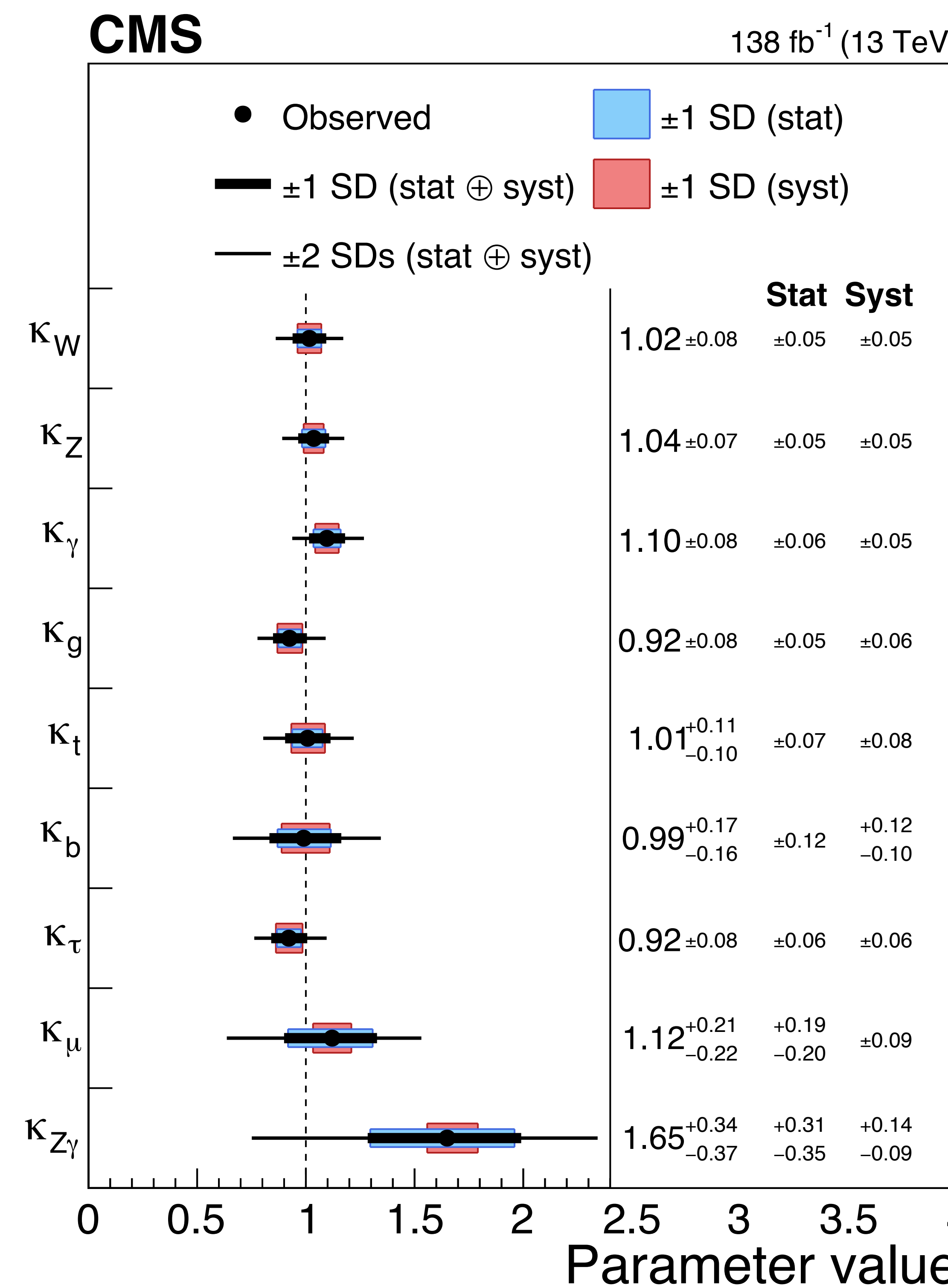
$$R_{V,F}^{off-shell} = \mu_V^{off-shell} \;/\; \mu_F^{off-shell}$$

Nat. Phys. 18 (2022) 1329

Higgs boson couplings



Nature 607, pages 52-59 (2022)



Nature 607 (2022) 60-68

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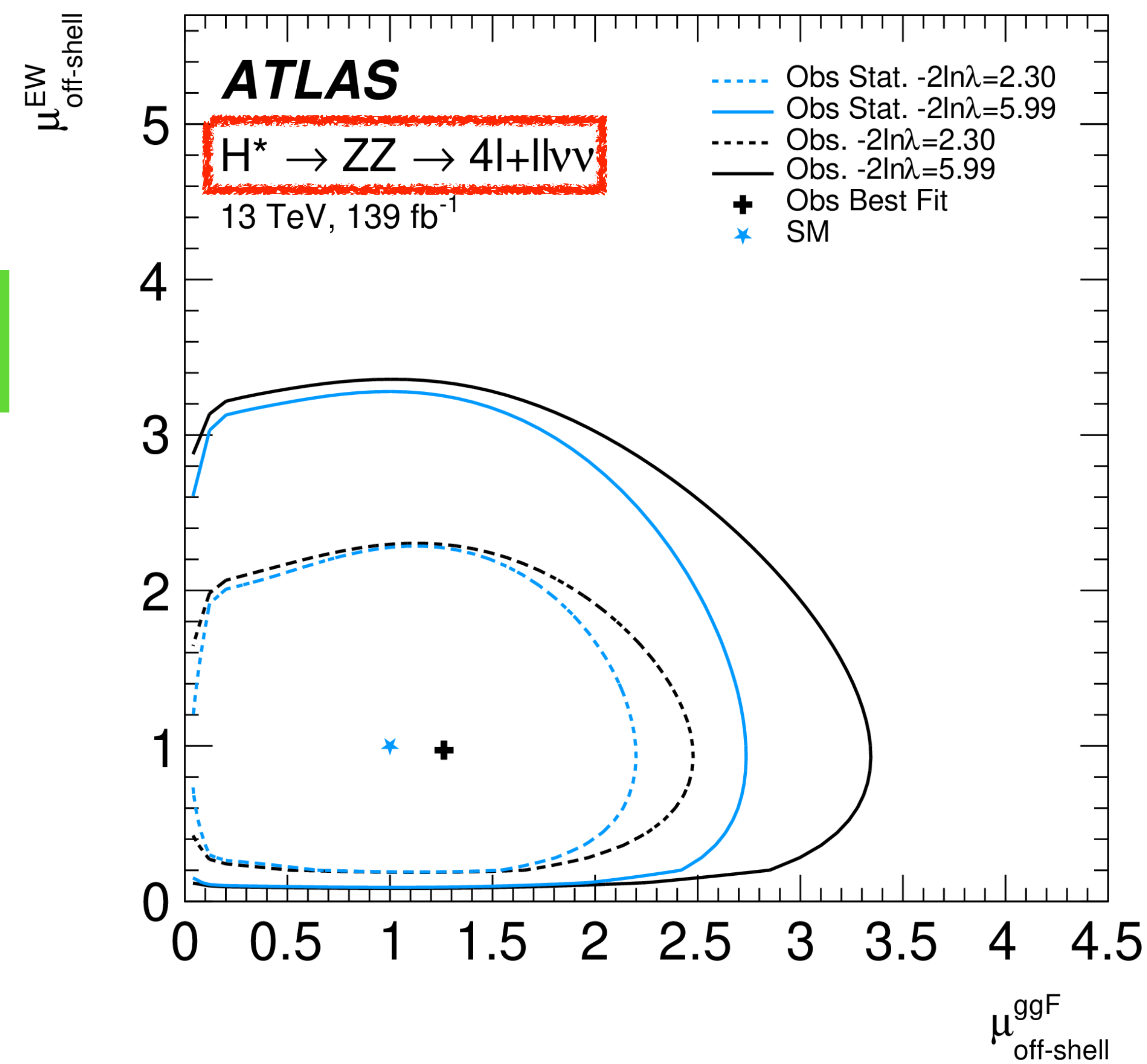
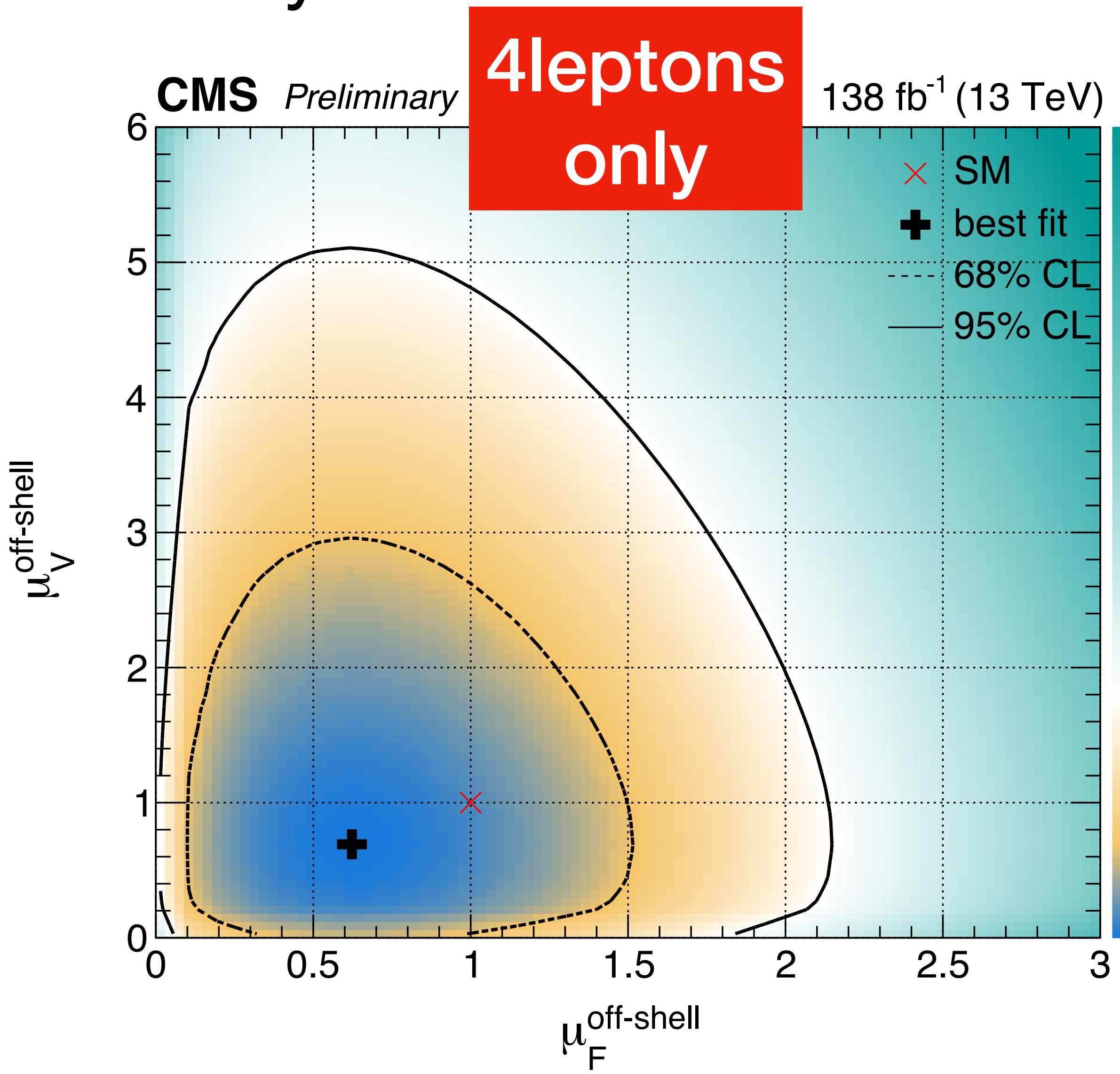
Measured in the **H→ZZ** channel, full Run 2 data, comparing on-shell and off-shell production, in different decay channels

LINK





LINK

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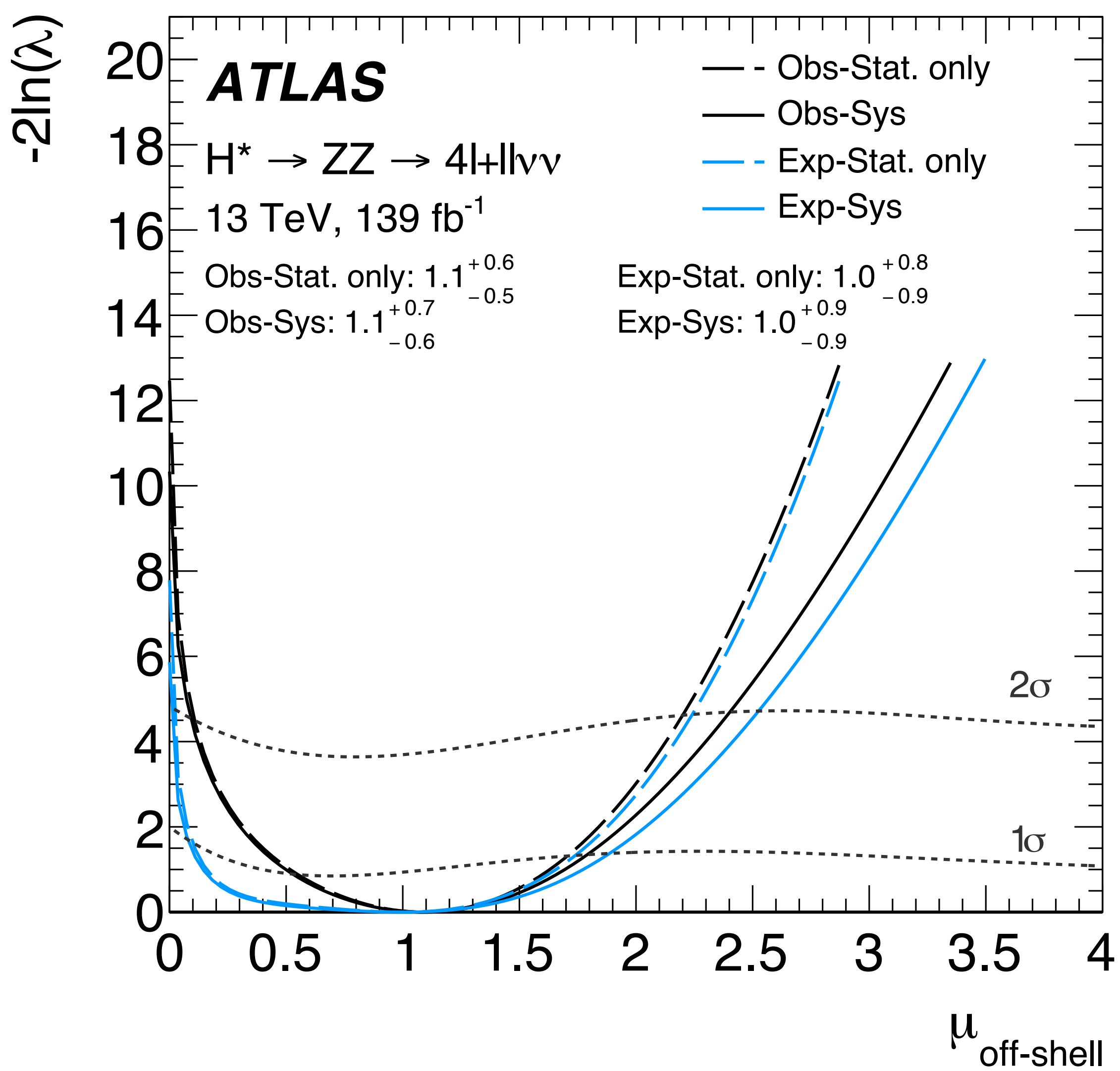
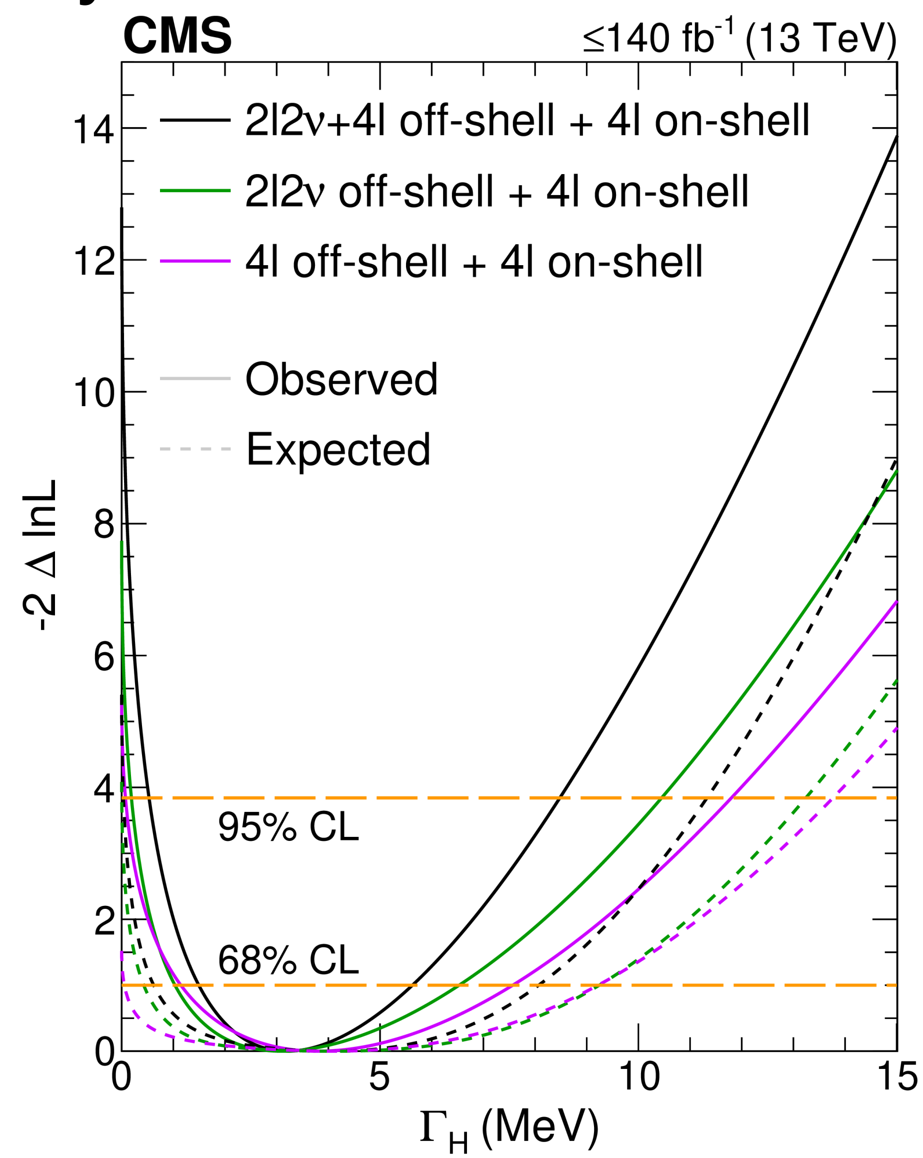
ATLAS-CONF-2022-068



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

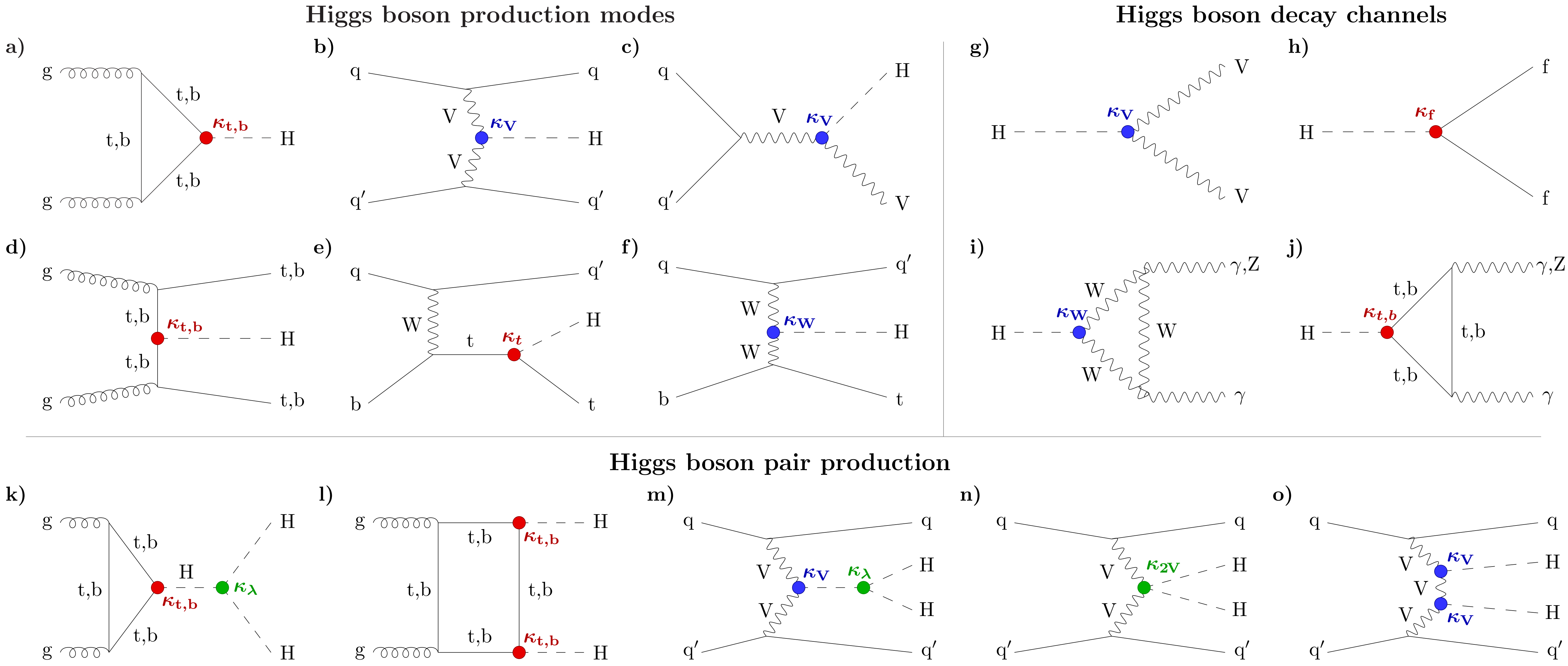


Nat. Phys. 18 (2022) 1329

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

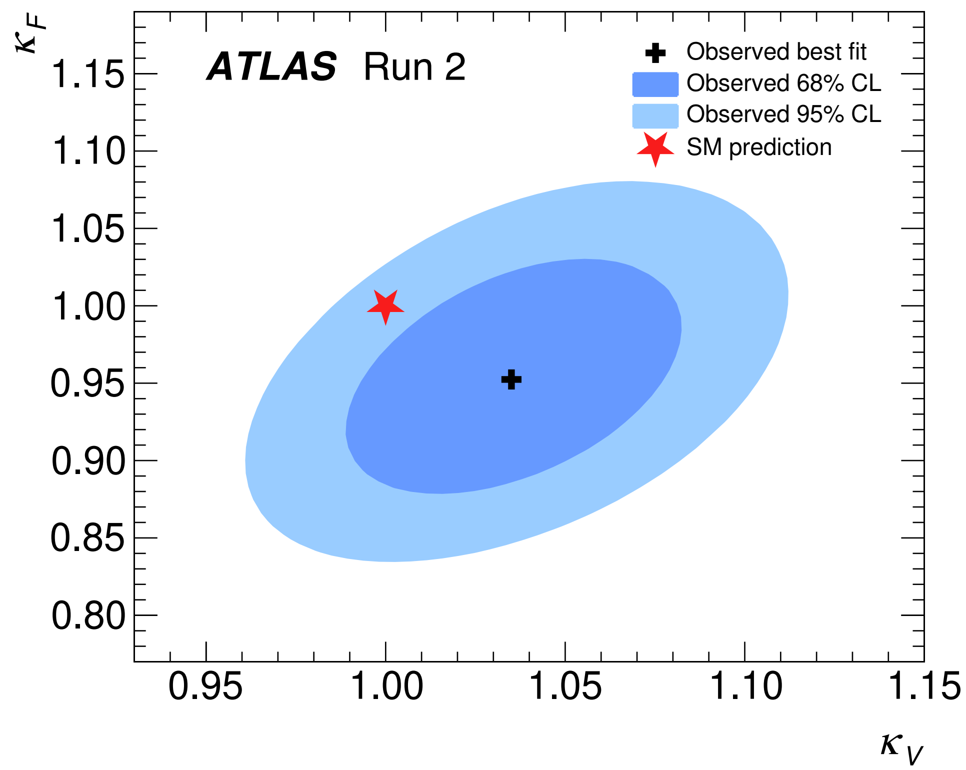
Higgs boson couplings

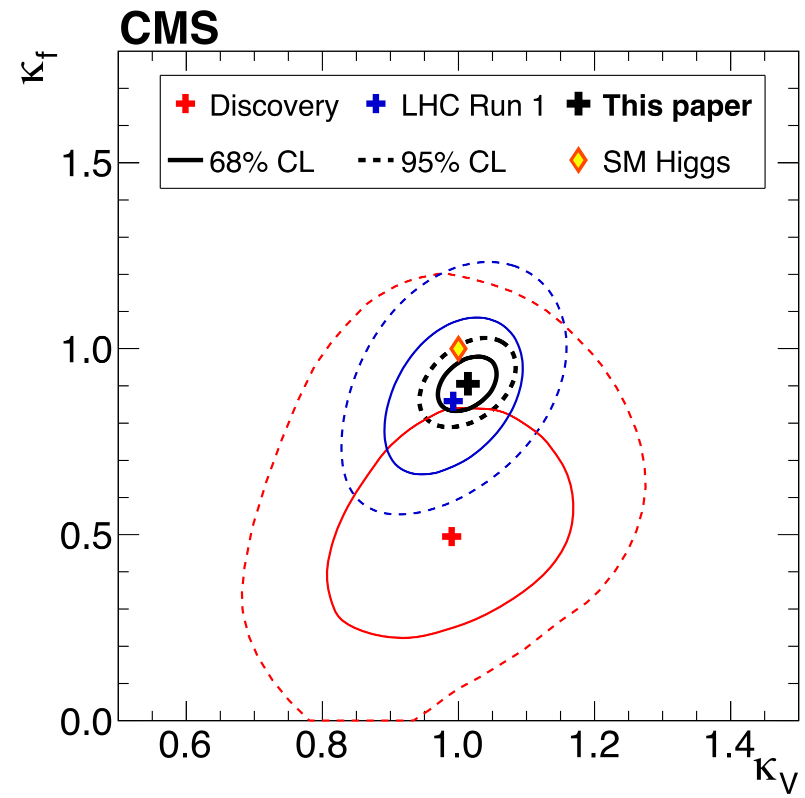
Nature 607 (2022) 60-68



Higgs boson couplings

Nature 607, pages 52-59 (2022)

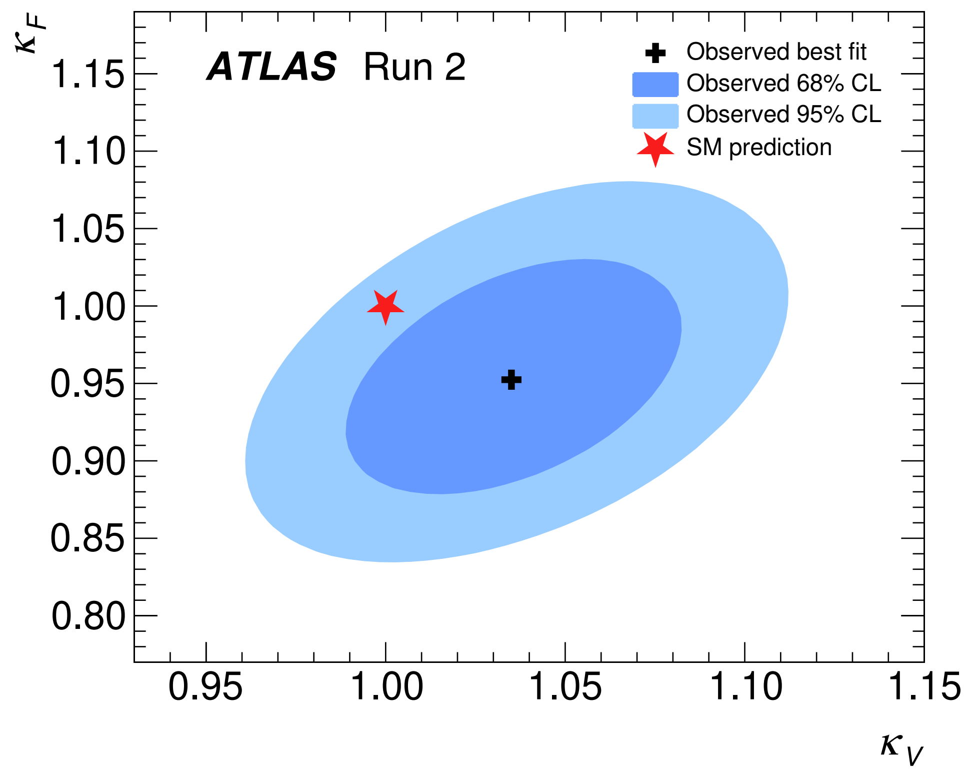




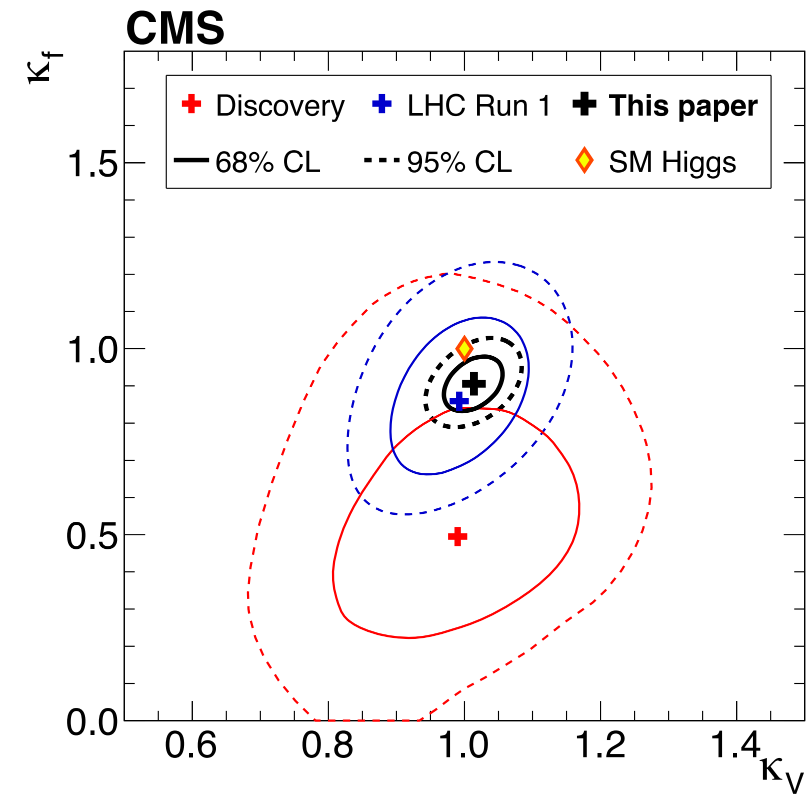
Nature 607 (2022) 60-68

Higgs boson couplings

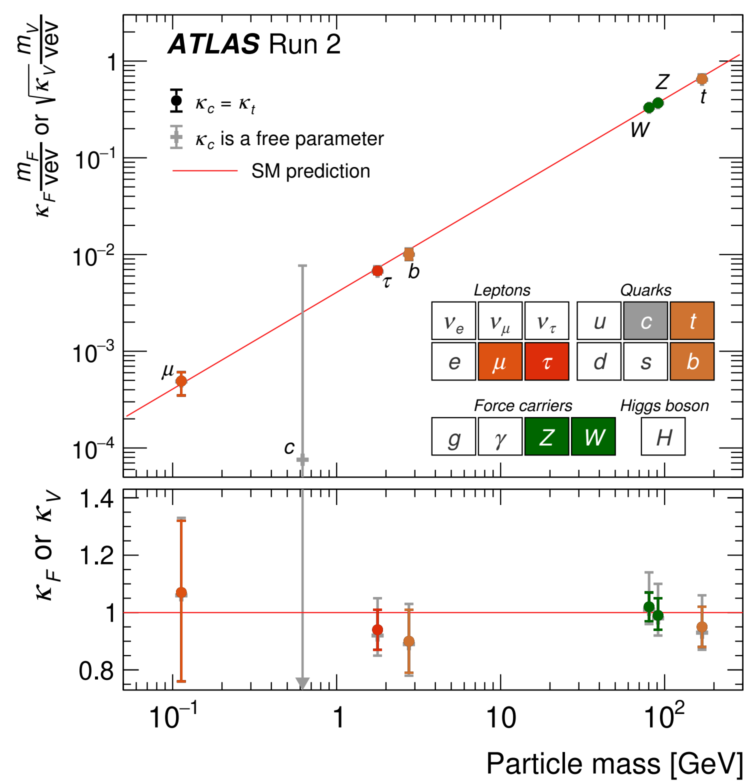
Nature 607, pages 52-59 (2022)



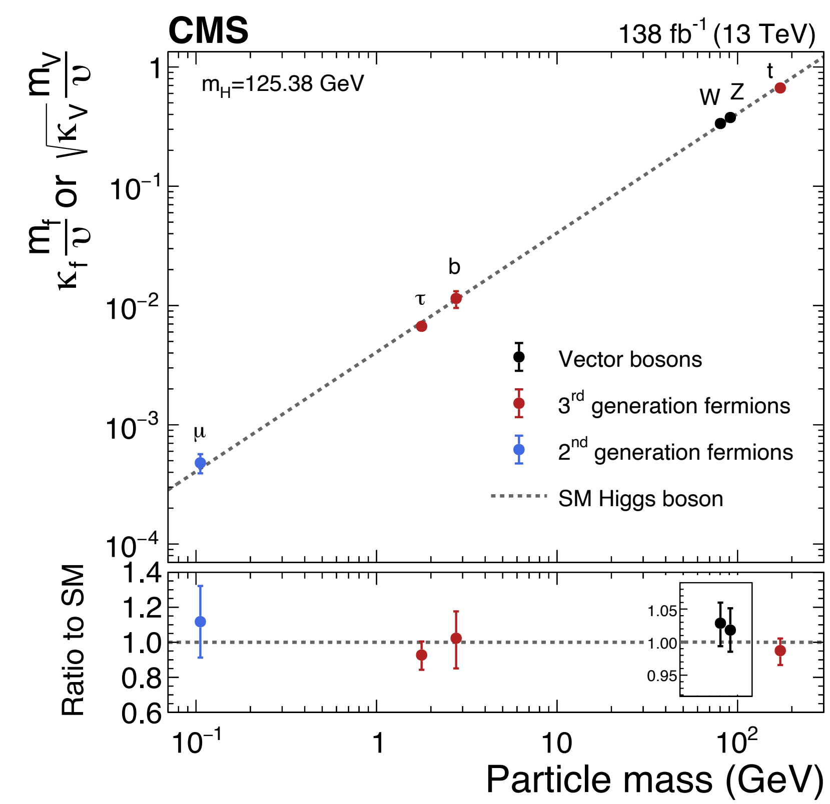
Nature 607 (2022) 60-68



Nature 607, pages 52-59 (2022)



Nature 607 (2022) 60-68



Higgs boson couplings

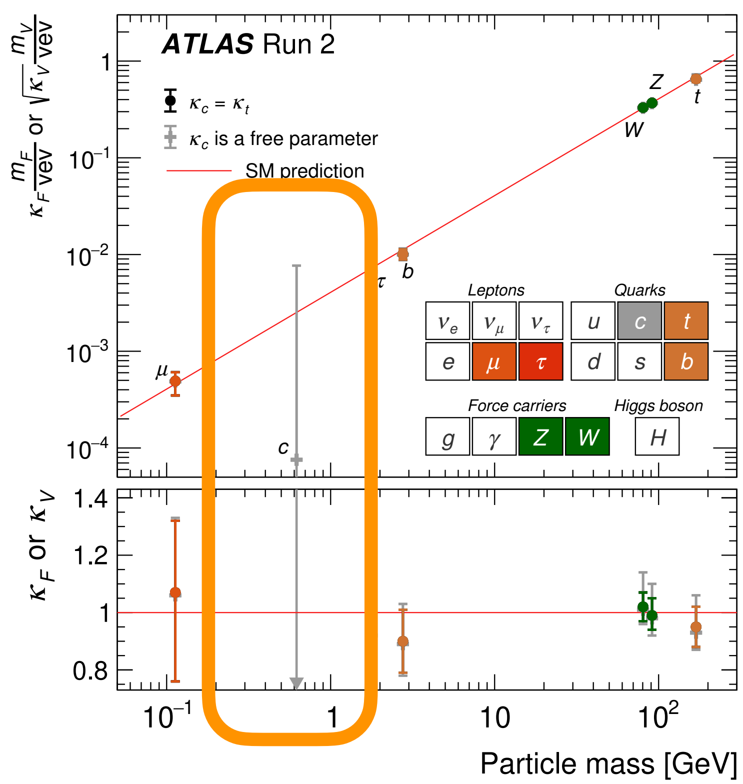
$\kappa_c < 5.7$ @95 CL

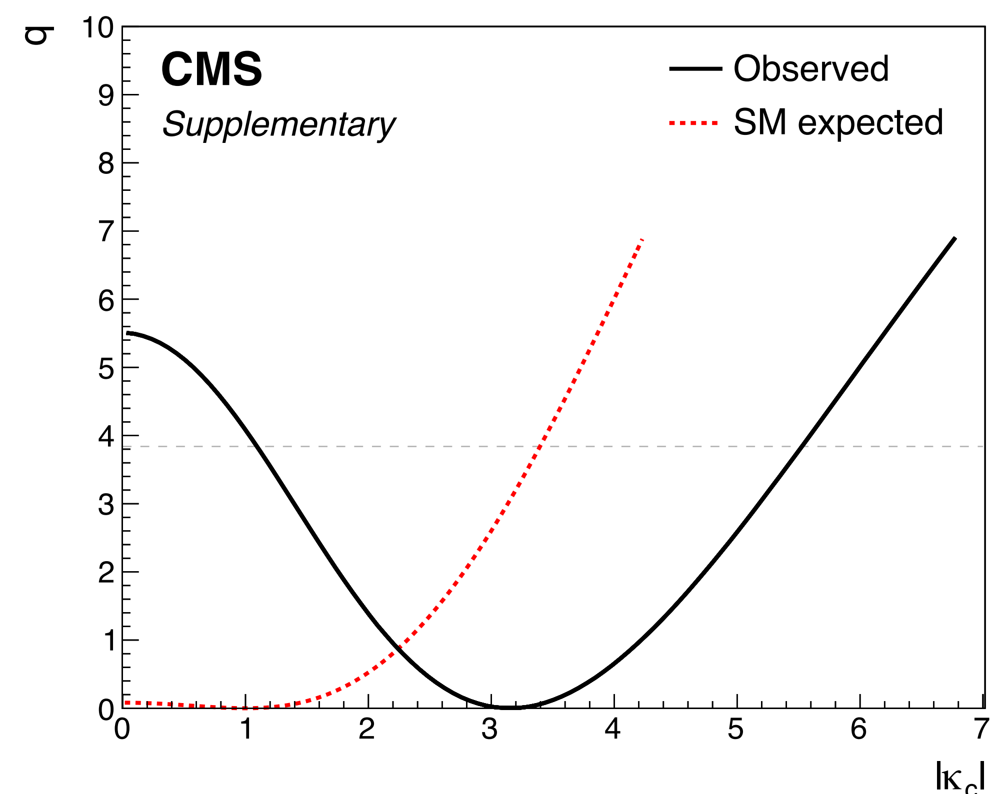
$(\kappa_c < 7.6$ @95 CL)

$1.1 < |\kappa_c| < 5.5$ @95 CL

$(|\kappa_c| < 3.4$ @95 CL)

Nature 607, pages 52-59 (2022)



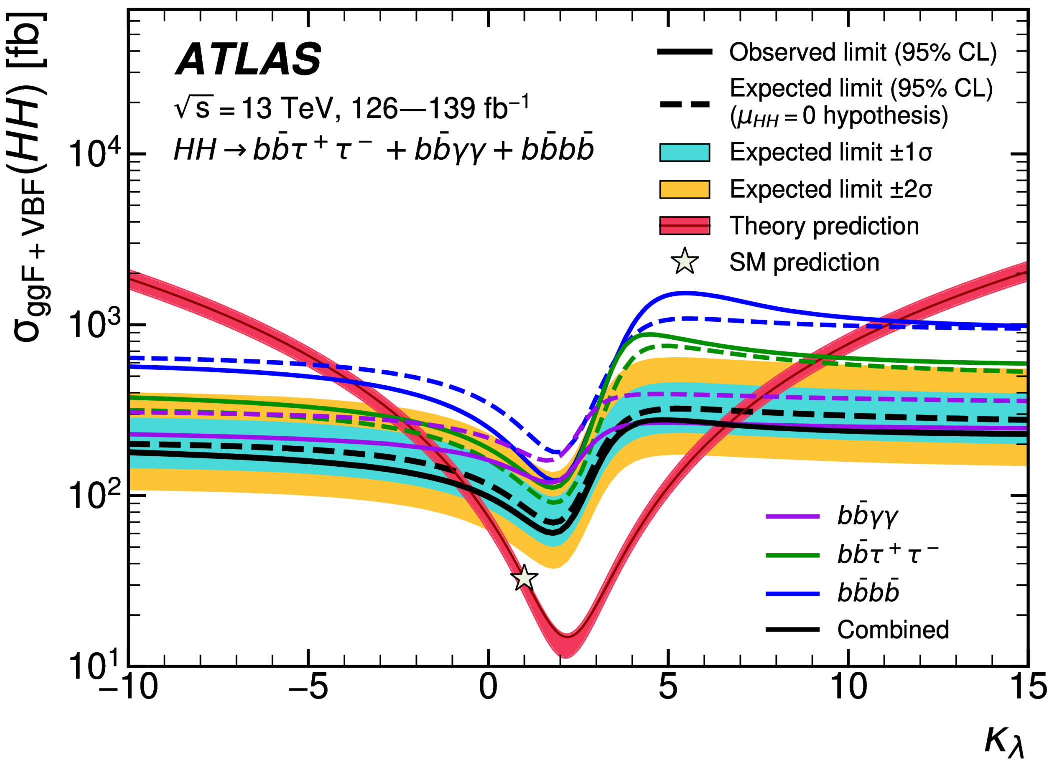


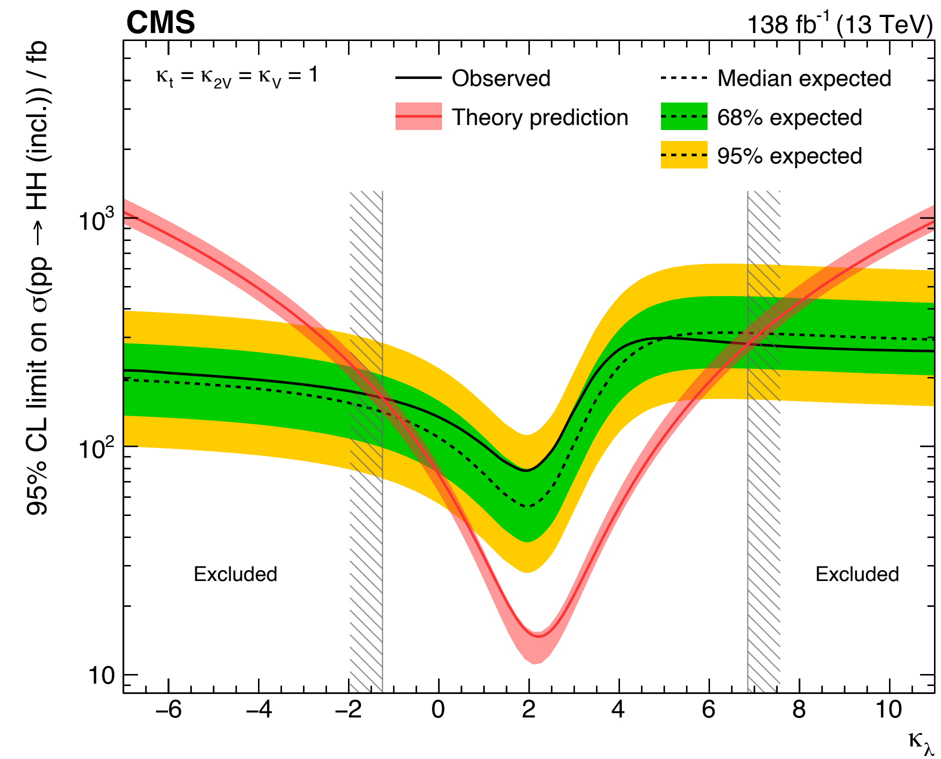
arXiv:2205.05550

Coupling with c quark

Higgs boson couplings

arXiv:2211.01216





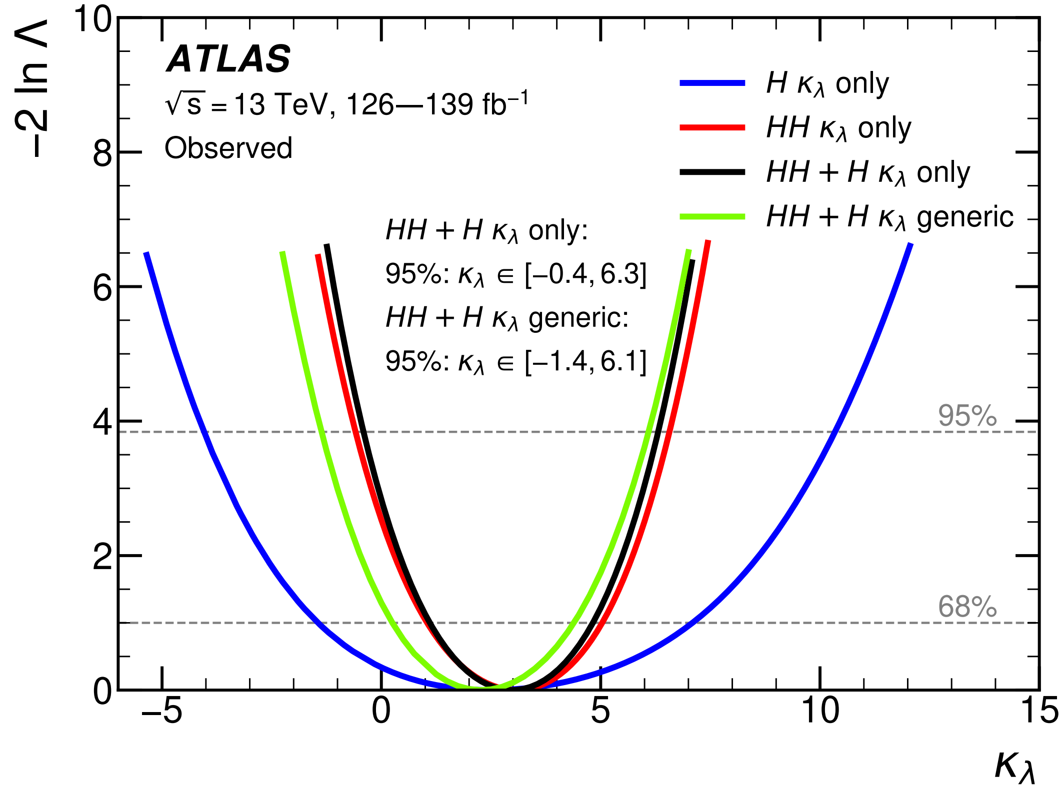
Nature 607 (2022) 60-68

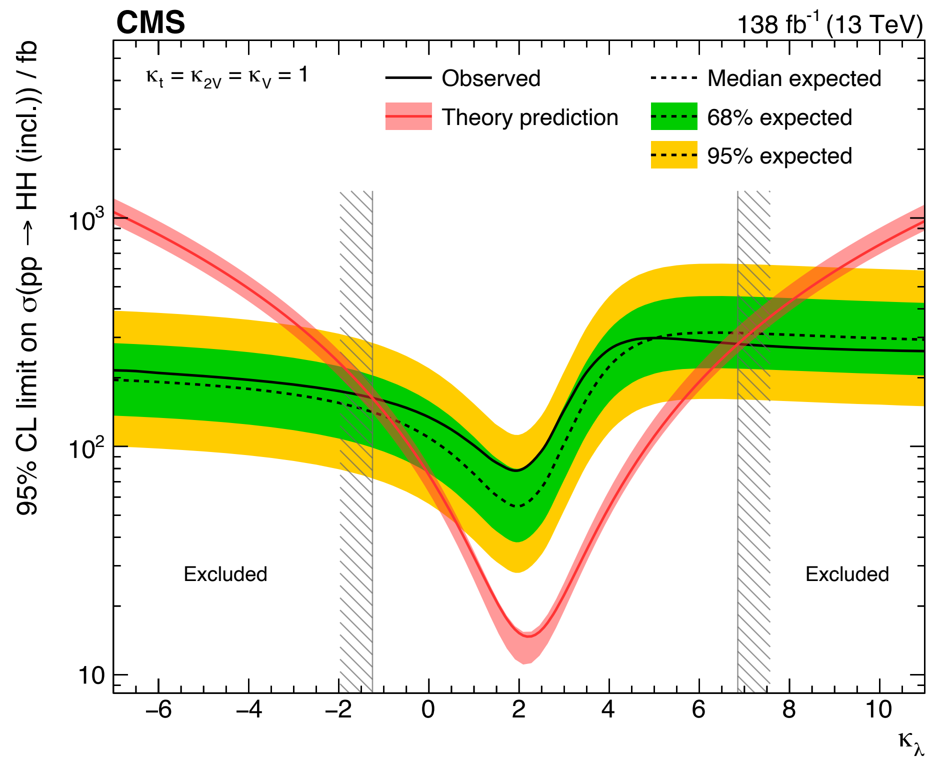
$-0.6 < \kappa_\lambda < 6.6$

$-1.24 < \kappa_\lambda < 6.49$

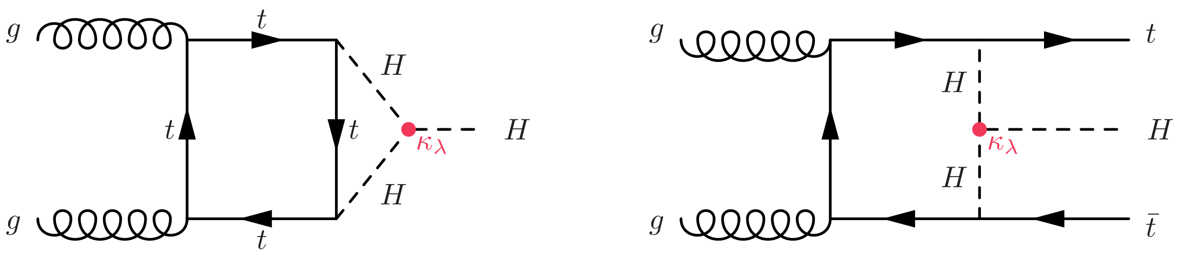
Higgs boson couplings

arXiv:2211.01216





Nature 607 (2022) 60-68

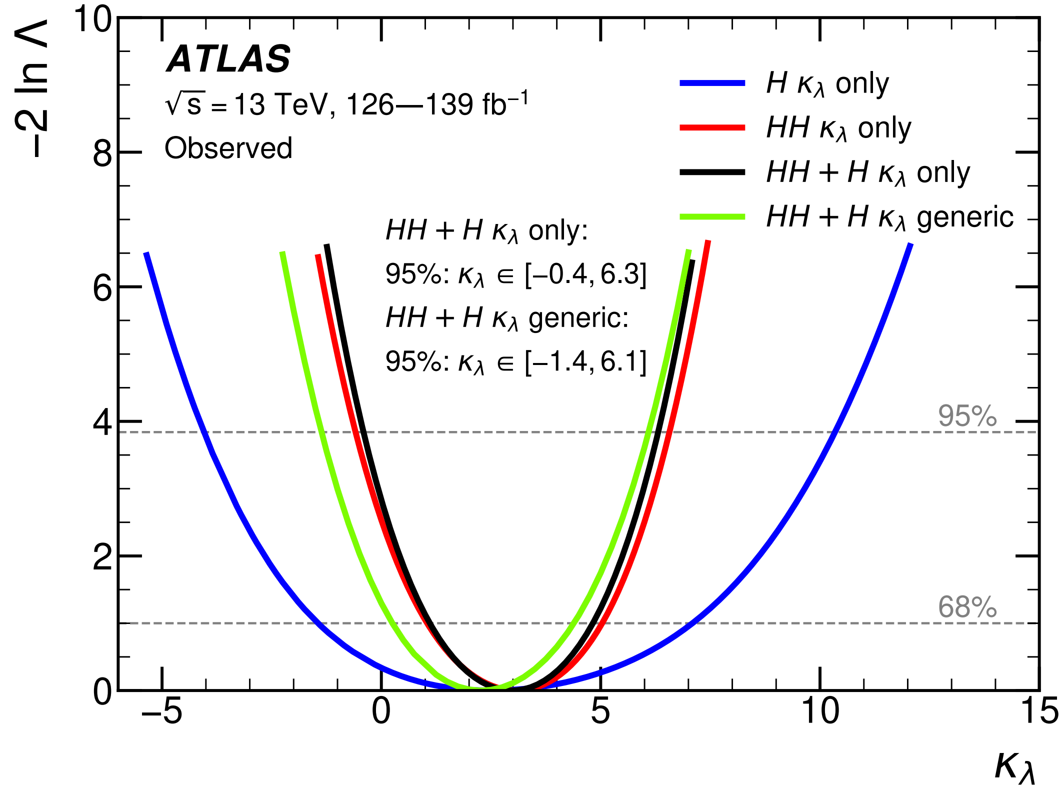


$$-1.24 < \kappa_\lambda < 6.49$$

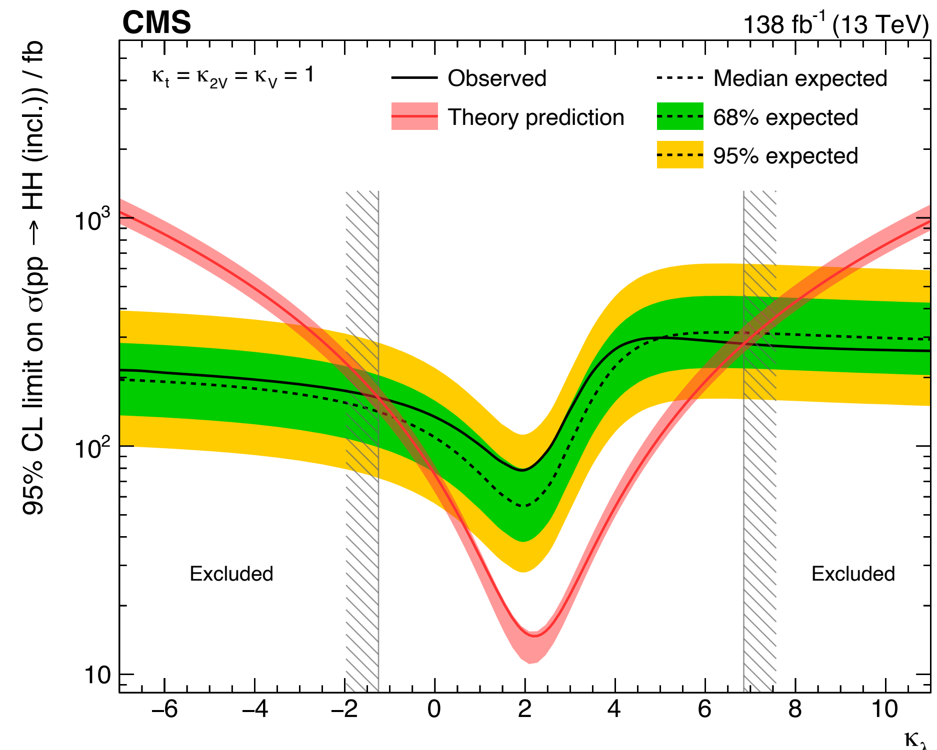
$$-0.4 < \kappa_\lambda < 6.3$$

Higgs boson couplings

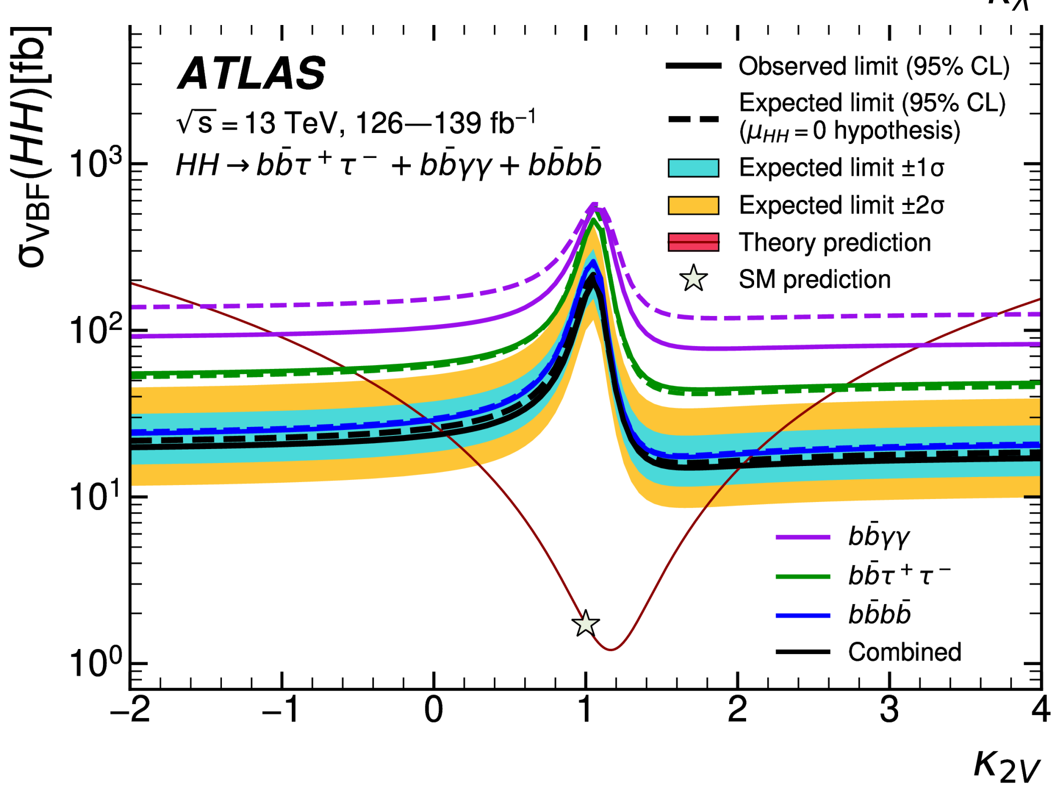
arXiv:2211.01216



Nature 607 (2022) 60-68

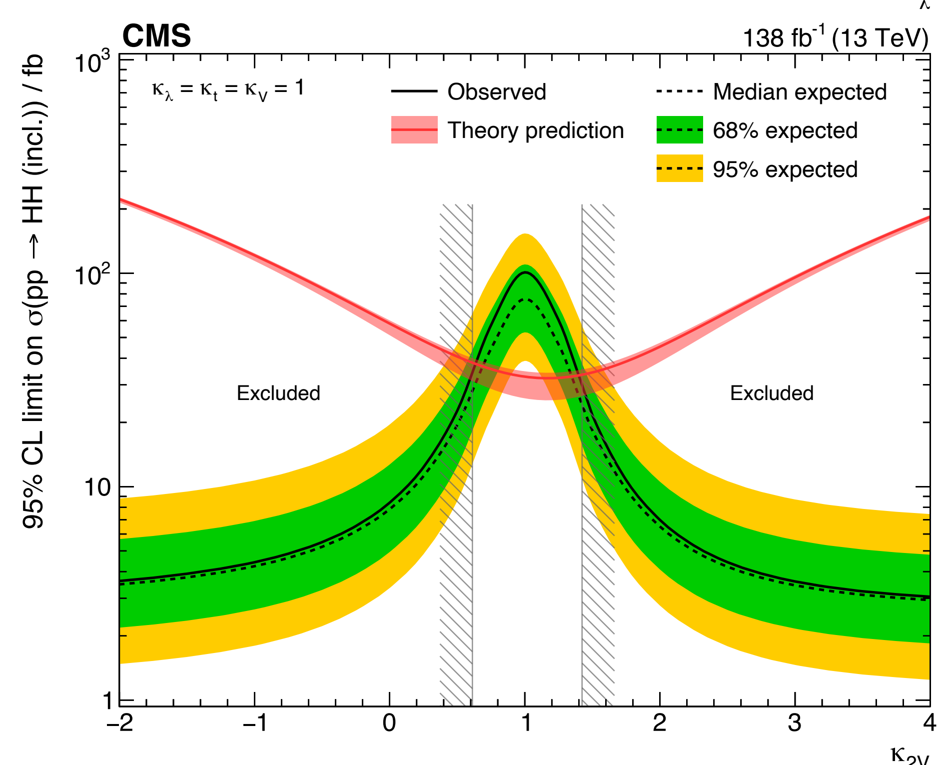


arXiv:2211.01216



$0.1 < \kappa_{2V} < 2.0$

Nature 607 (2022) 60-68

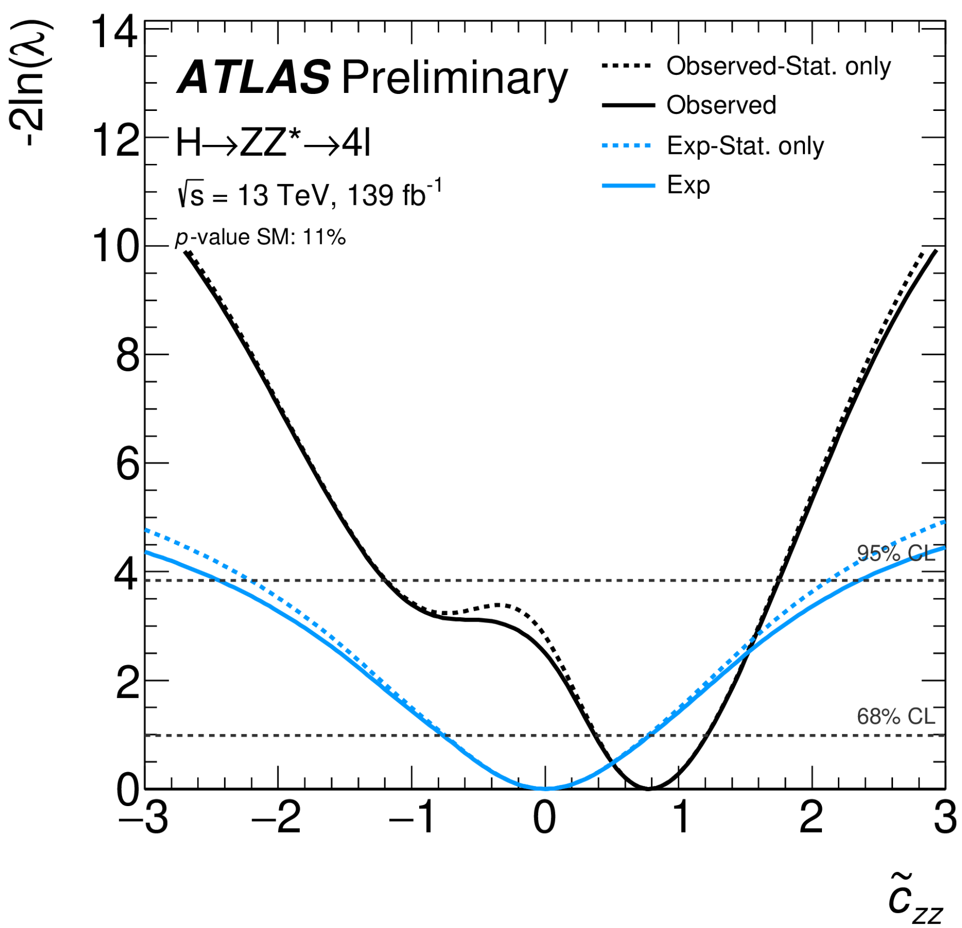


$0.67 < \kappa_{2V} < 1.38$

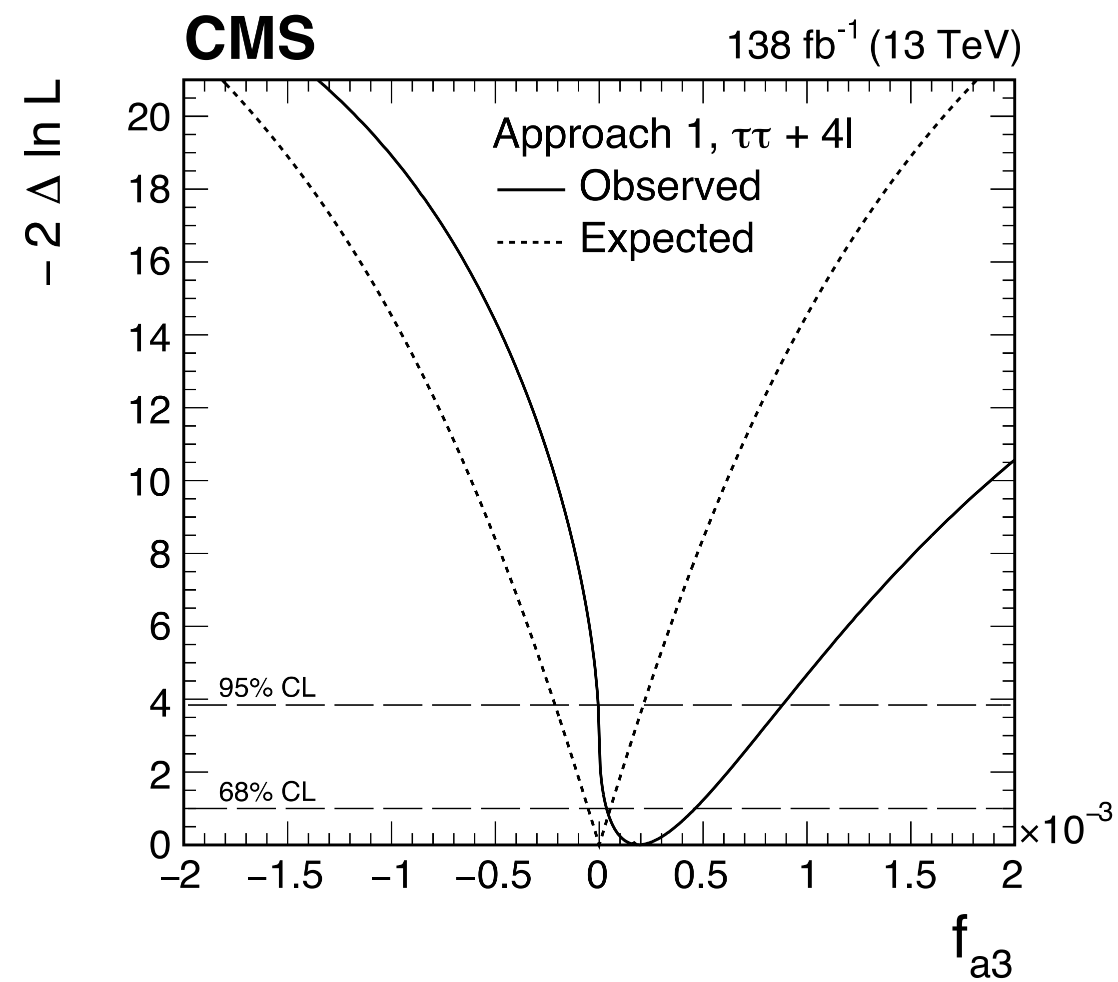
3. Higgs boson CP

$$\tilde{c}_{zz} = -\frac{s_W^2 c_W^2}{2\pi\alpha} a_3.$$

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2\sigma_{\Lambda 1}^{Z\gamma}} \operatorname{sgn}\left(\frac{a_3}{a_1}\right),$$



$H \to ZZ$ only



$H \to ZZ + H \to \tau\tau$

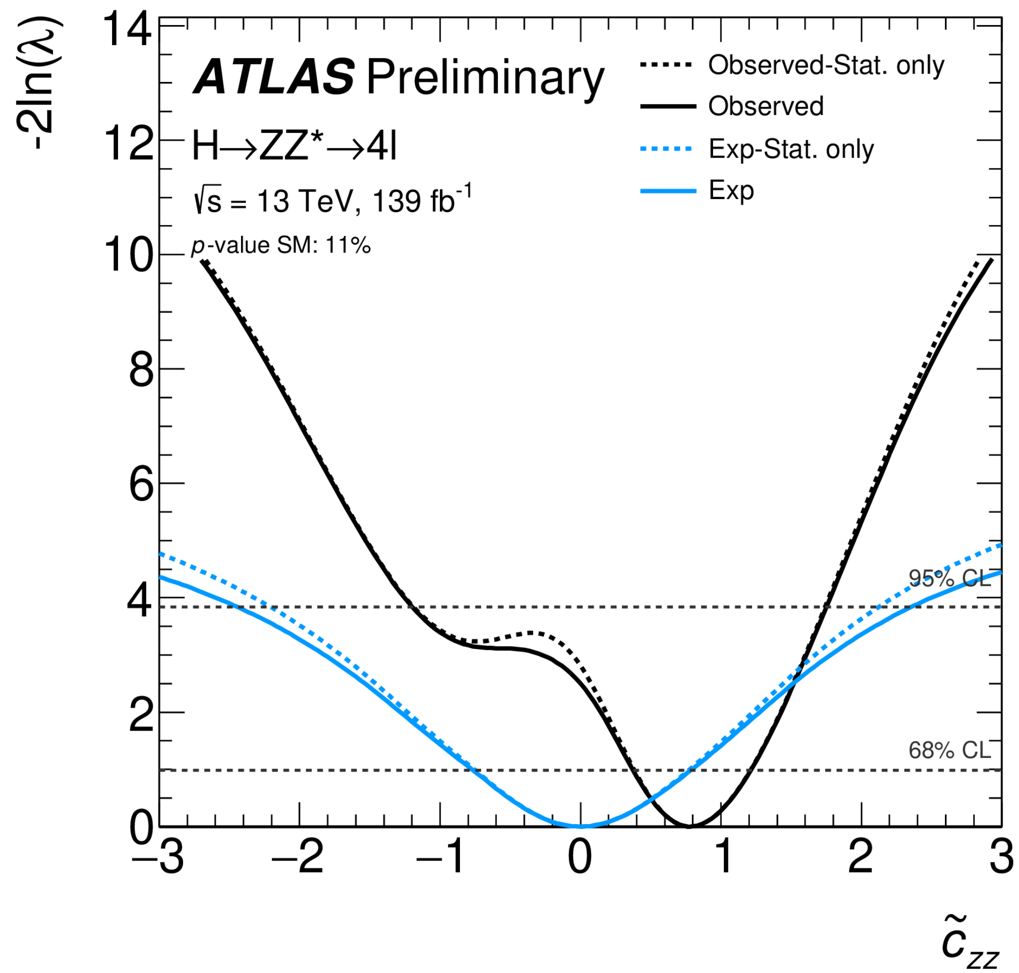
arXiv:2205.05120

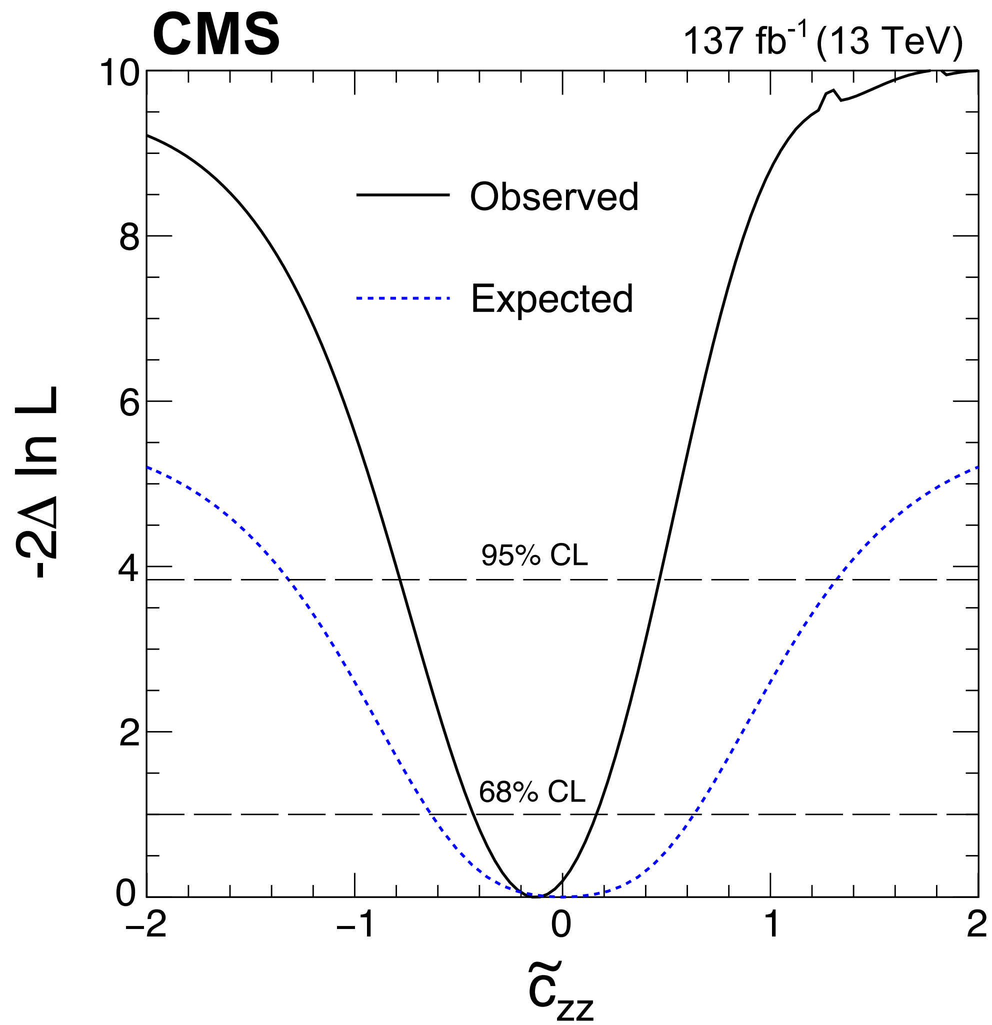
3. Higgs boson CP

Looking for anomalous Higgs boson couplings to **vector bosons**

$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

CP odd - AC





Phys. Rev. D 104 (2021) 052004

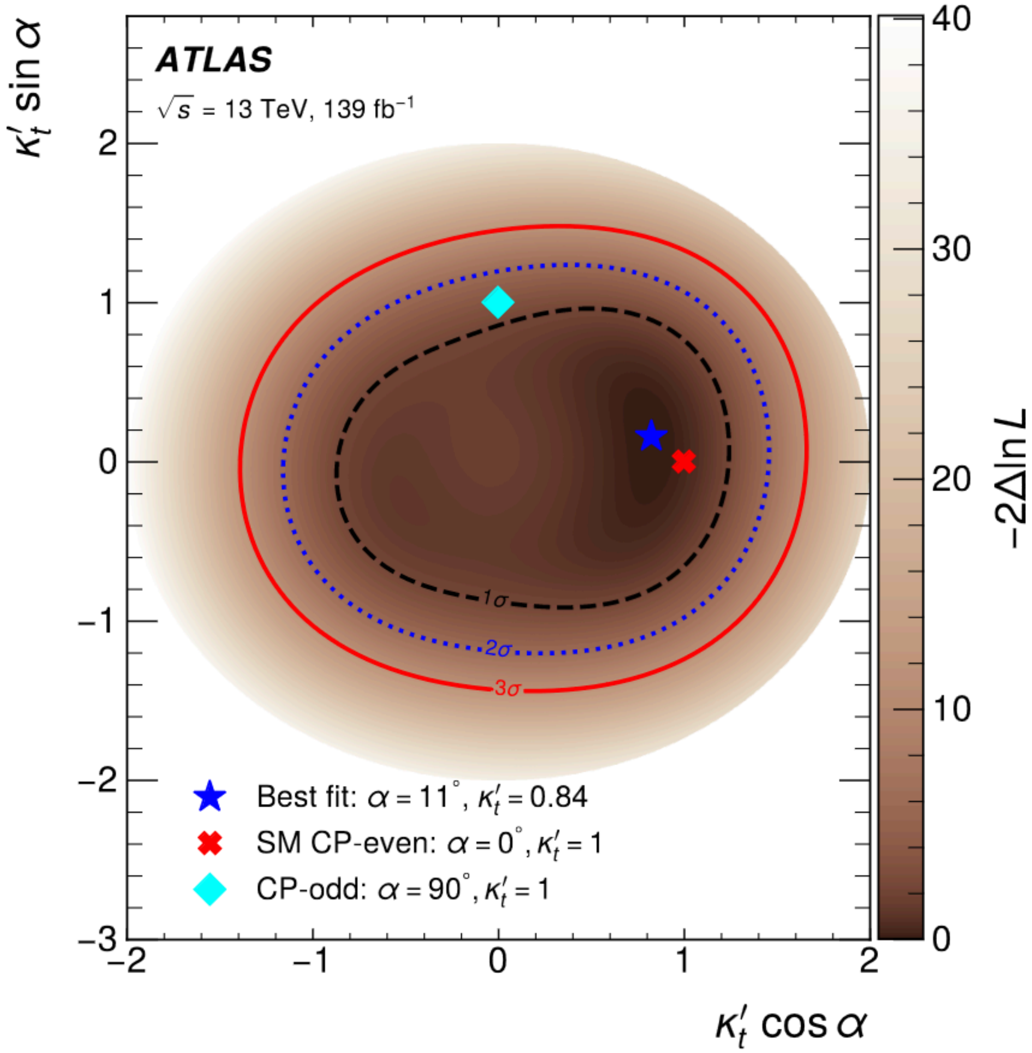
H → ZZ only

3. Higgs boson CP

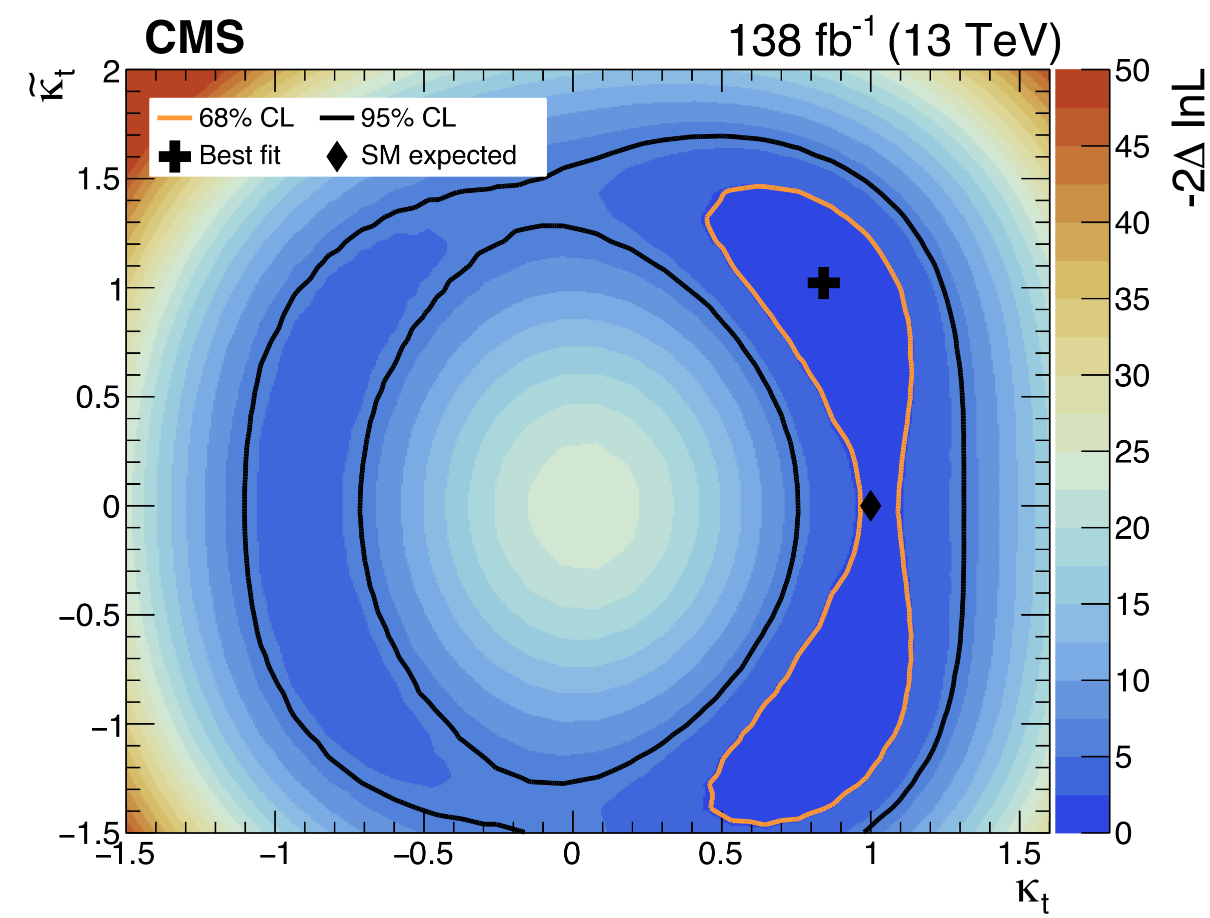
Looking for anomalous Higgs boson couplings to **fermions**

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

arXiv:2303.05974



$H \to bb$



arXiv:2208.02686

$H \to WW + H \to \tau\tau$