University of Sheffield

MEASUREMENTS OF HIGGS BOSON PROPERTIES WITH THE ATLAS DETECTOR AT CERN

THE LAKE LOUISE WINTER INSTITUTE 2023 CONFERENCE | CHATEAU LAKE LOUISE - CANADA

KAMAL SAOUCHA | ON BEHALF OF THE ATLAS COLLABORATION

CERN

ATLAS EXPERIMENT

Why measure the Higgs boson properties?

~~*Why measure the Higgs boson properties?*~~

The right question to ask is …

Did we find "THE" Higgs boson?

i.e. the Standard Model (SM) Higgs Boson

~~*Why measure the Higgs boson*~~ *properties*~~*?*~~

The right question to ask is …

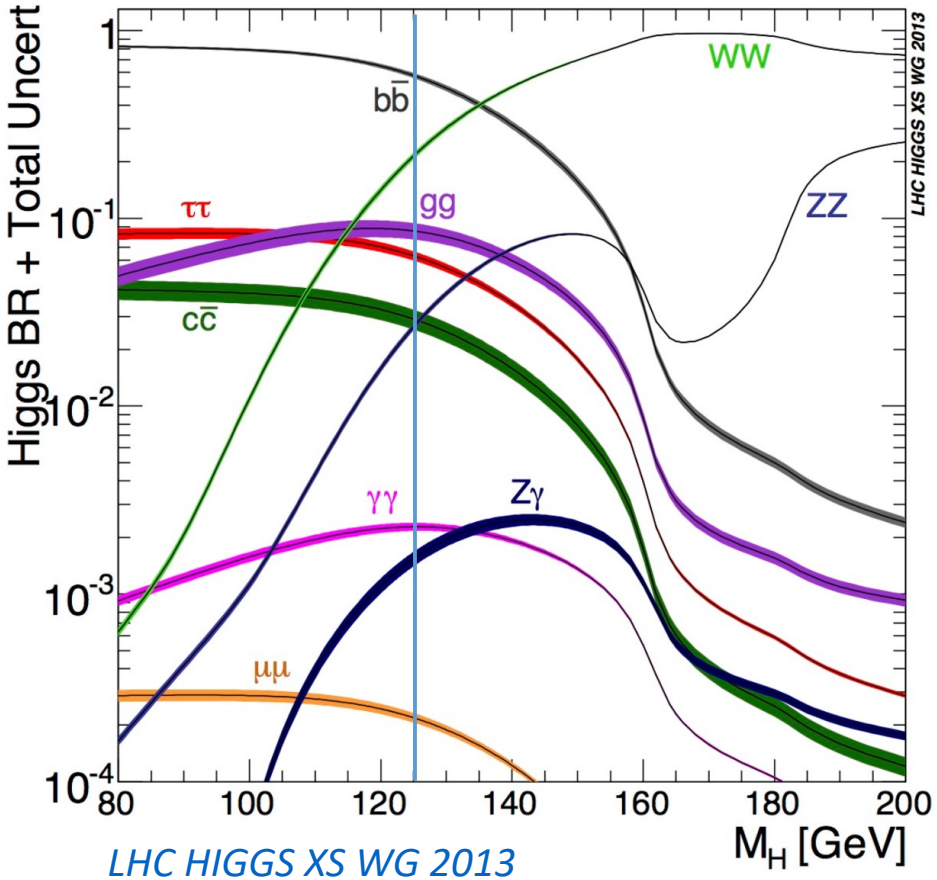
Did we find "THE" Higgs boson?

i.e. the Standard Model (SM) Higgs Boson

The Higgs boson mass

The Higgs mass is a free parameter of the SM

… has to be measured empirically



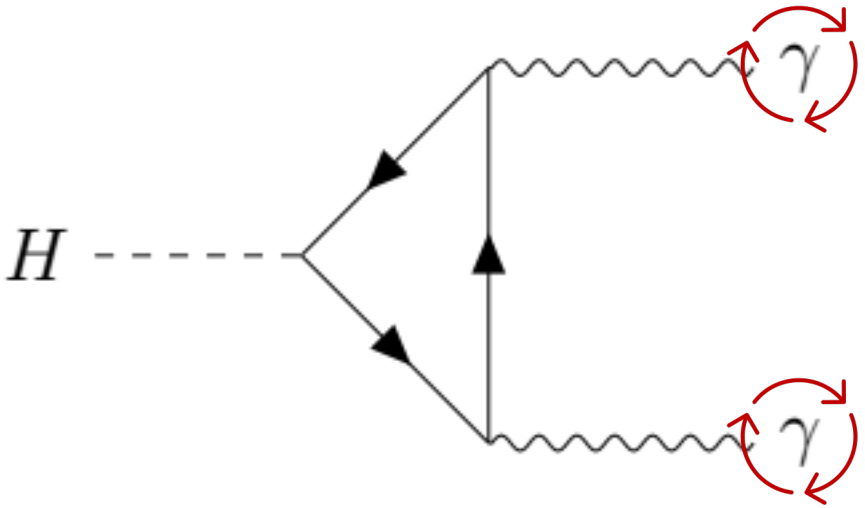
LHC HIGGS XS WG 2013

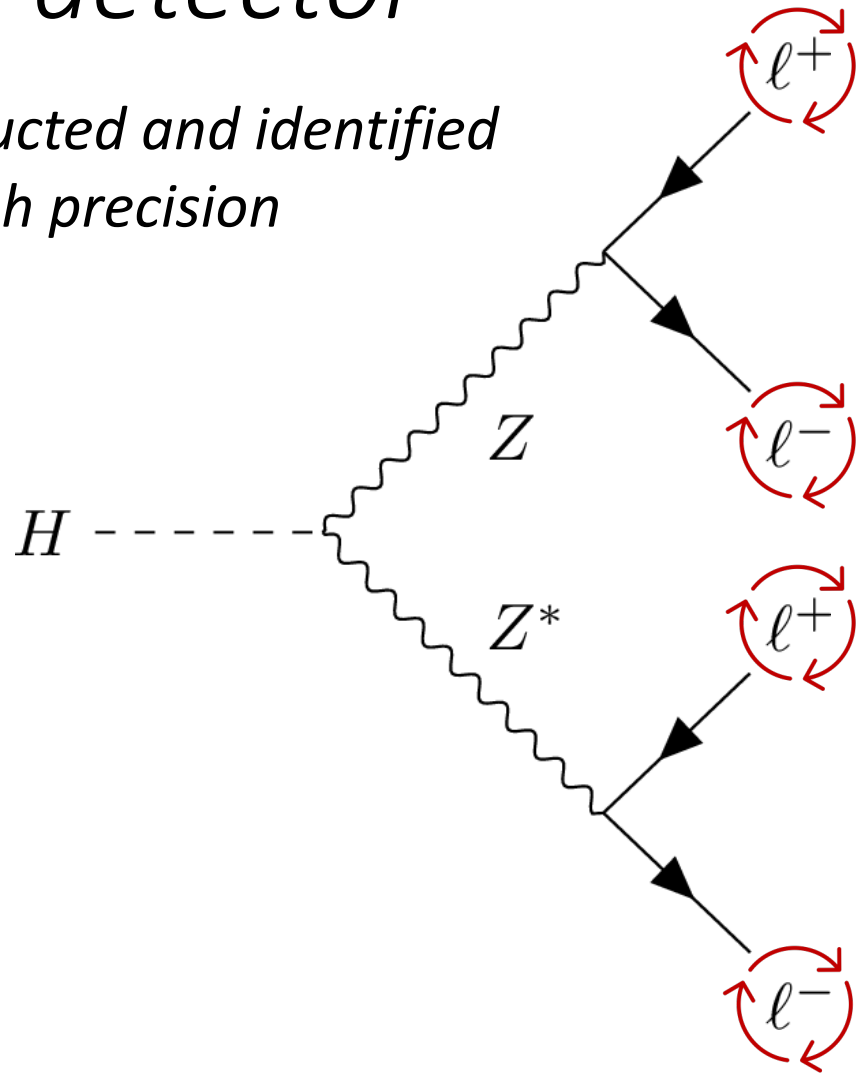
Given the Higgs boson mass, the SM can make precise predictions of the Higgs properties

=> Precise measurement of m_H important for testing the SM predictions!

Fully reconstructed Higgs boson decay channels using the ATLAS detector

In ATLAS, photons, electrons and muons reconstructed and identified with high efficiency, as well as measured with high precision





$H \rightarrow \gamma\gamma$: mass estimator = $m_{\gamma\gamma}$

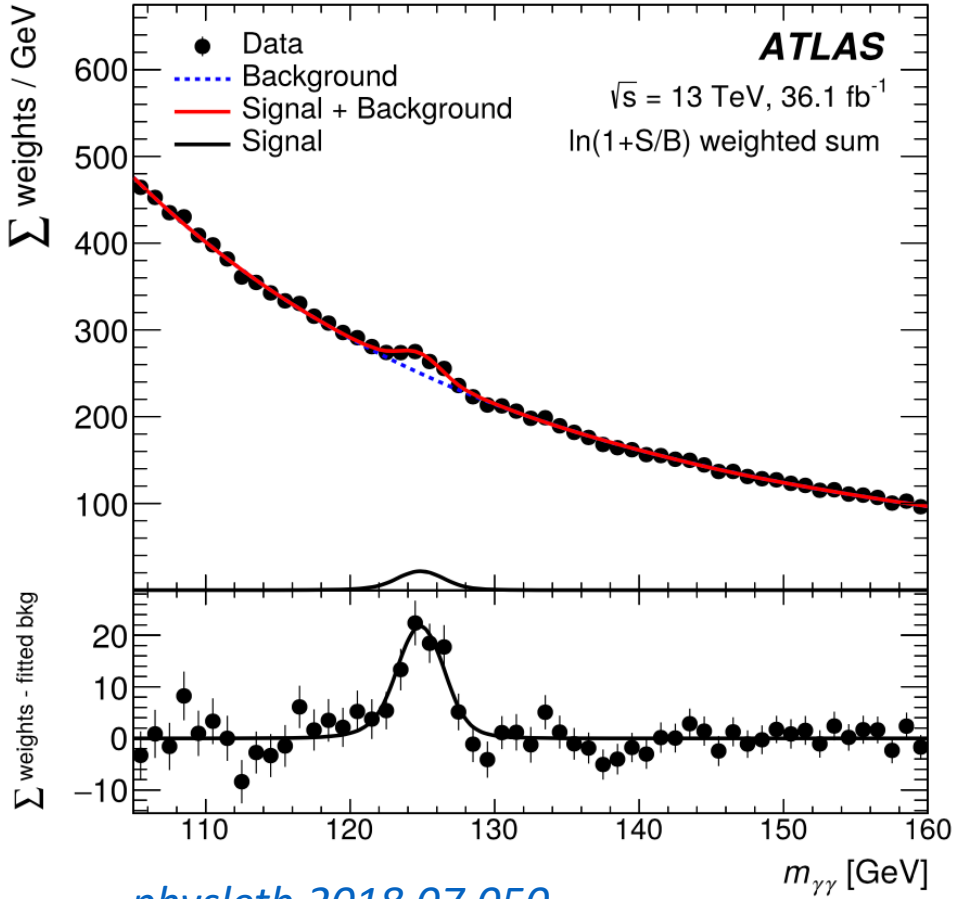
$H \rightarrow ZZ \rightarrow 4l^{\pm}$: mass estimator = m_{4l}

m = invariant mass of the decay products

ℓ = electron or muon

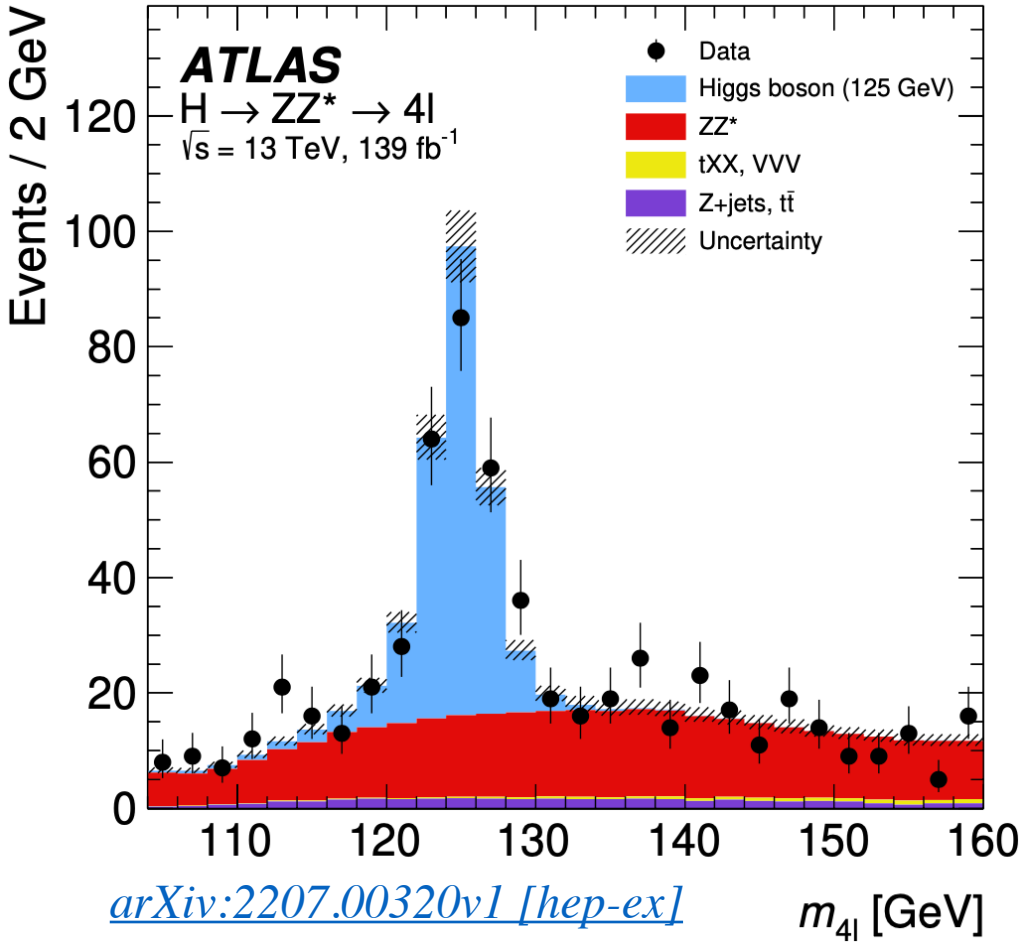
Higgs mass measurement in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l^{\pm}$

Very good invariant mass resolution



physletb.2018.07.050

High signal over background ratio



arXiv:2207.00320v1 [hep-ex]

The latest ATLAS Higgs mass measurements

$H \rightarrow \gamma\gamma$

Latest measurement using fraction of Run 2 data (36 fb^{-1})

$m_{\gamma\gamma} = 124.93 \pm 0.21\,(stat) \pm 0.34\,(syst)\ GeV$

(systematics dominated, lead by calibration uncertainty)

$m_{\gamma\gamma} = 124.93 \pm 0.40\ GeV$

Combined with Run 1 measurement

$m_{\gamma\gamma} = 125.32 \pm 0.35\ GeV$

(Full Run 2 measurement coming soon!)

$H \rightarrow ZZ \rightarrow 4l^{\pm}$

Latest measurement using full Run 2 data (139 fb^{-1})

$m_{4l} = 124.99 \pm 0.18\,(stat) \pm 0.04\,(syst)\ GeV$

(dominated by statistical uncertainty)

$m_{4l} = 124.99 \pm 0.19\ GeV$

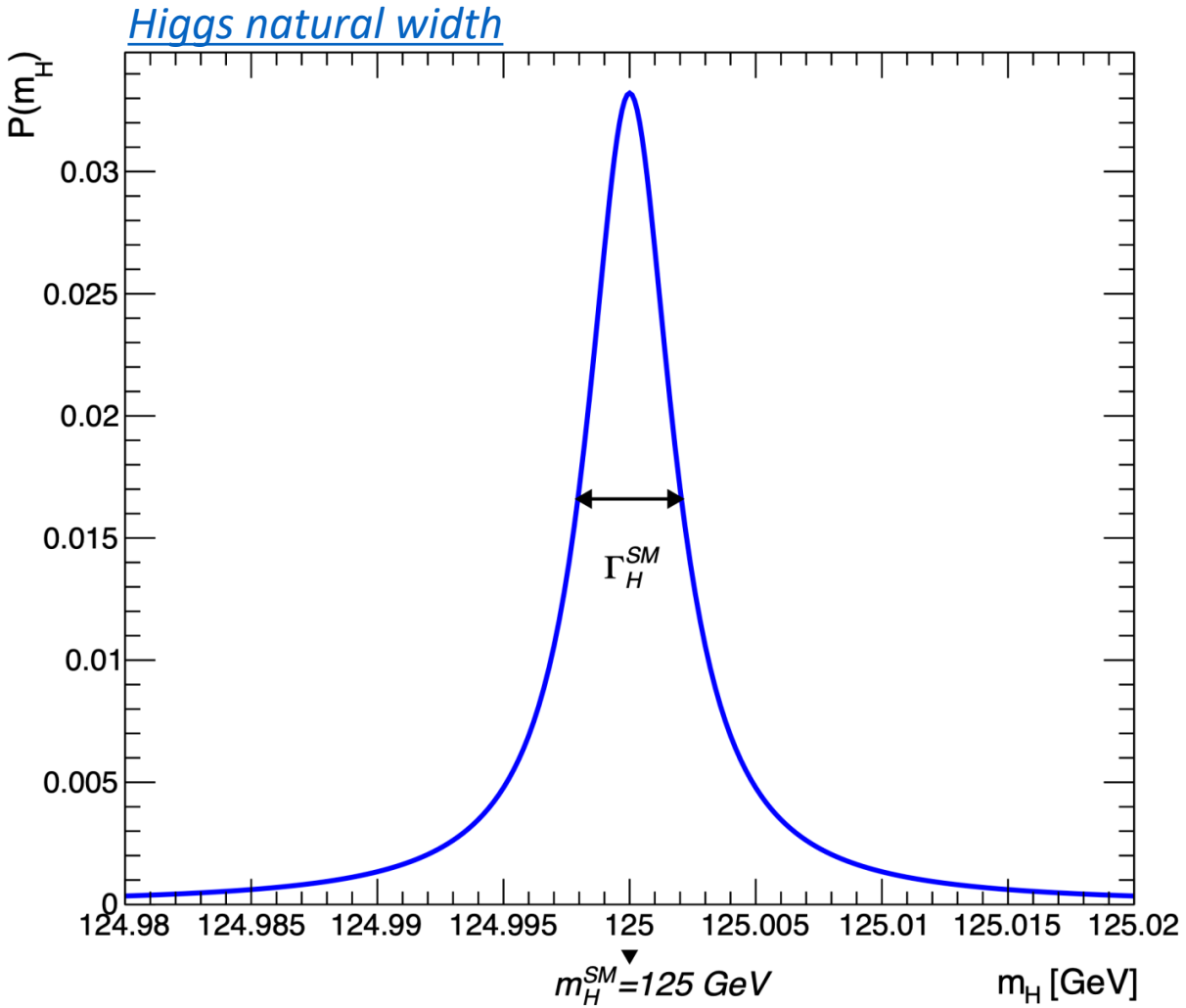
Combined with Run 1 measurement

$m_{4l} = 124.94 \pm 0.18\ GeV$

(Best measurement so far!)

The Higgs boson natural width

The Higgs boson natural width Γ_H

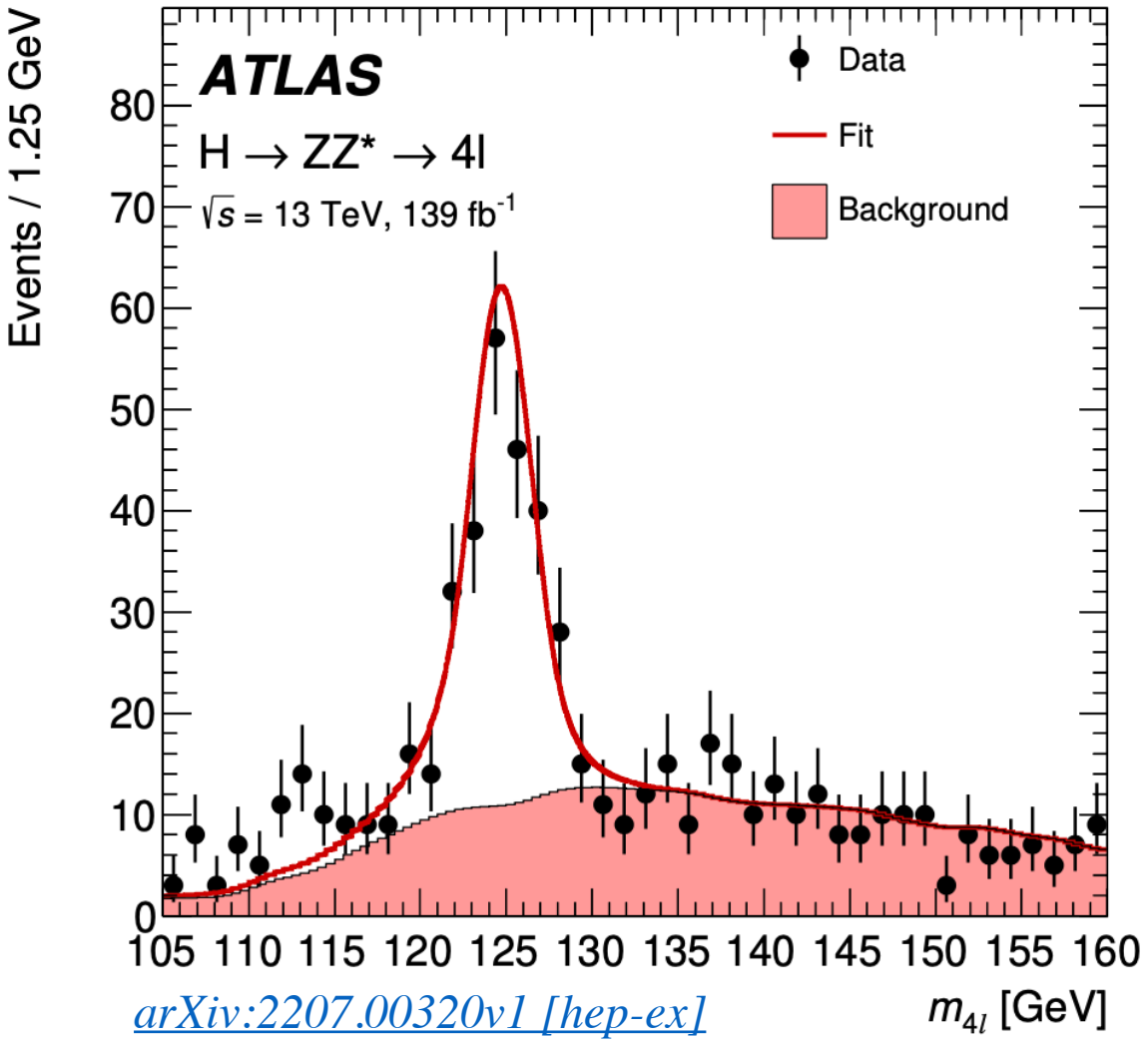


The width of the Higgs boson depends on its couplings to SM particles …

Important parameter for sensitivity for Beyond SM contributions!

Predicted to be 4.1 MeV for $m_H = 125$ *GeV*

The Higgs boson natural width Γ_H

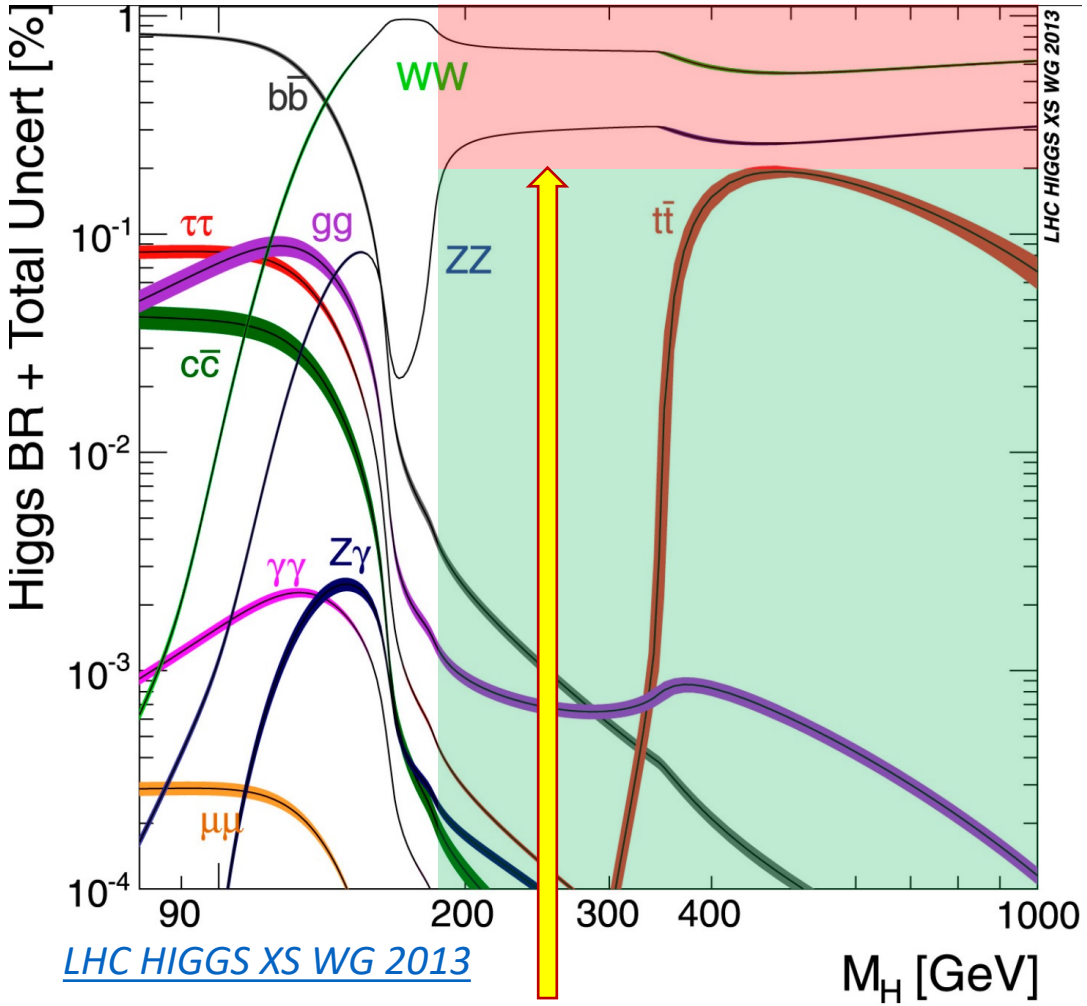


[arXiv:2207.00320v1 [hep-ex]](arXiv:2207.00320v1 [hep-ex])

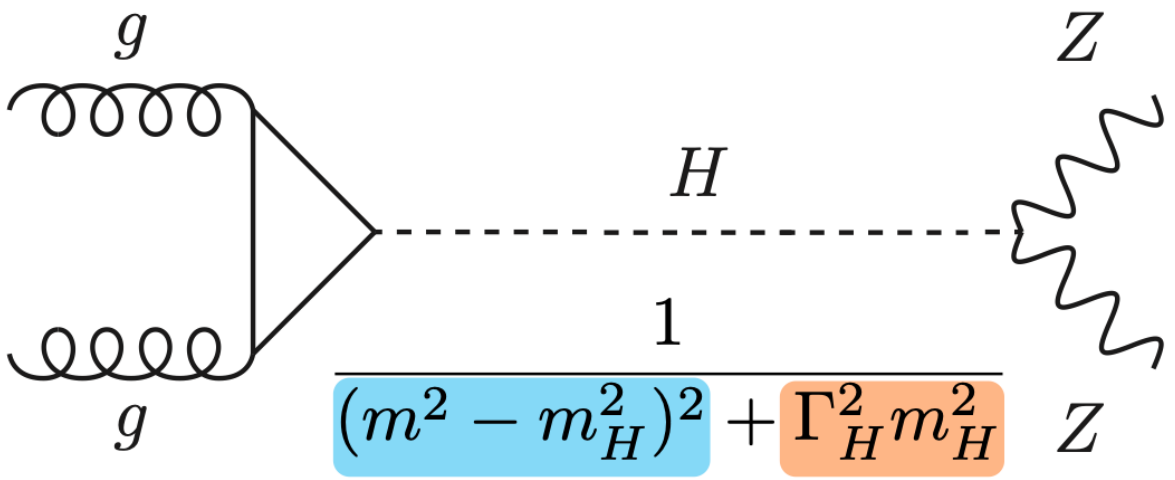
Typical experimental resolution of the order $\mathcal{O}(GeV)$ *…*

⇒ Direct measurement from invariant mass peak not possible!

Indirect measurement of Γ_H using the off-shell Higgs production



HVV production enhanced in the off-shell high mass region



On-shell region

$m^2 \sim m_H^2$

Cross section with dependence on Γ_H

Off-shell region

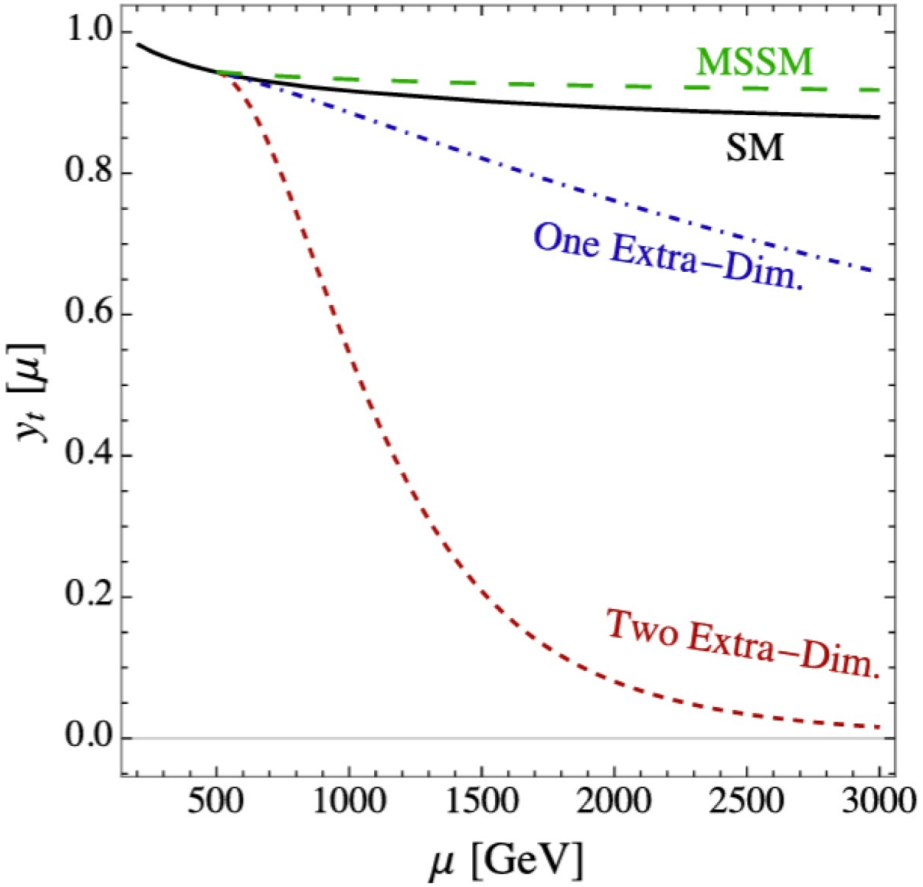
$m^2 > m_H^2$

Cross section independent of Γ_H

Assuming a negligible on- and off-shell coupling difference, evolving SM like …

i.e. assuming no contribution from new physics!

PHYSICAL REVIEW D 98, 015023 (2018)

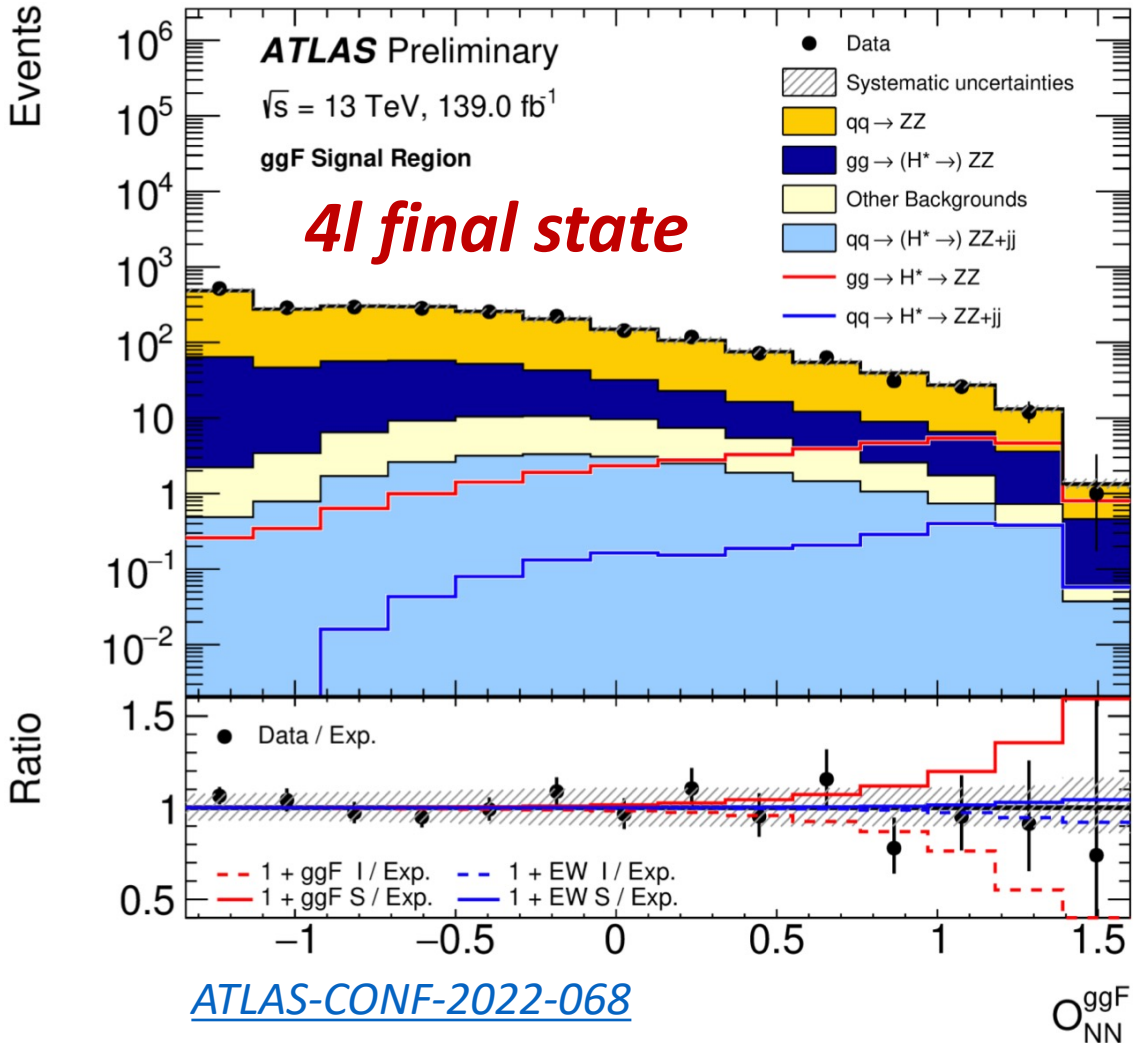


$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma_H}{\Gamma_H^{SM}}$$

μ the signal strength

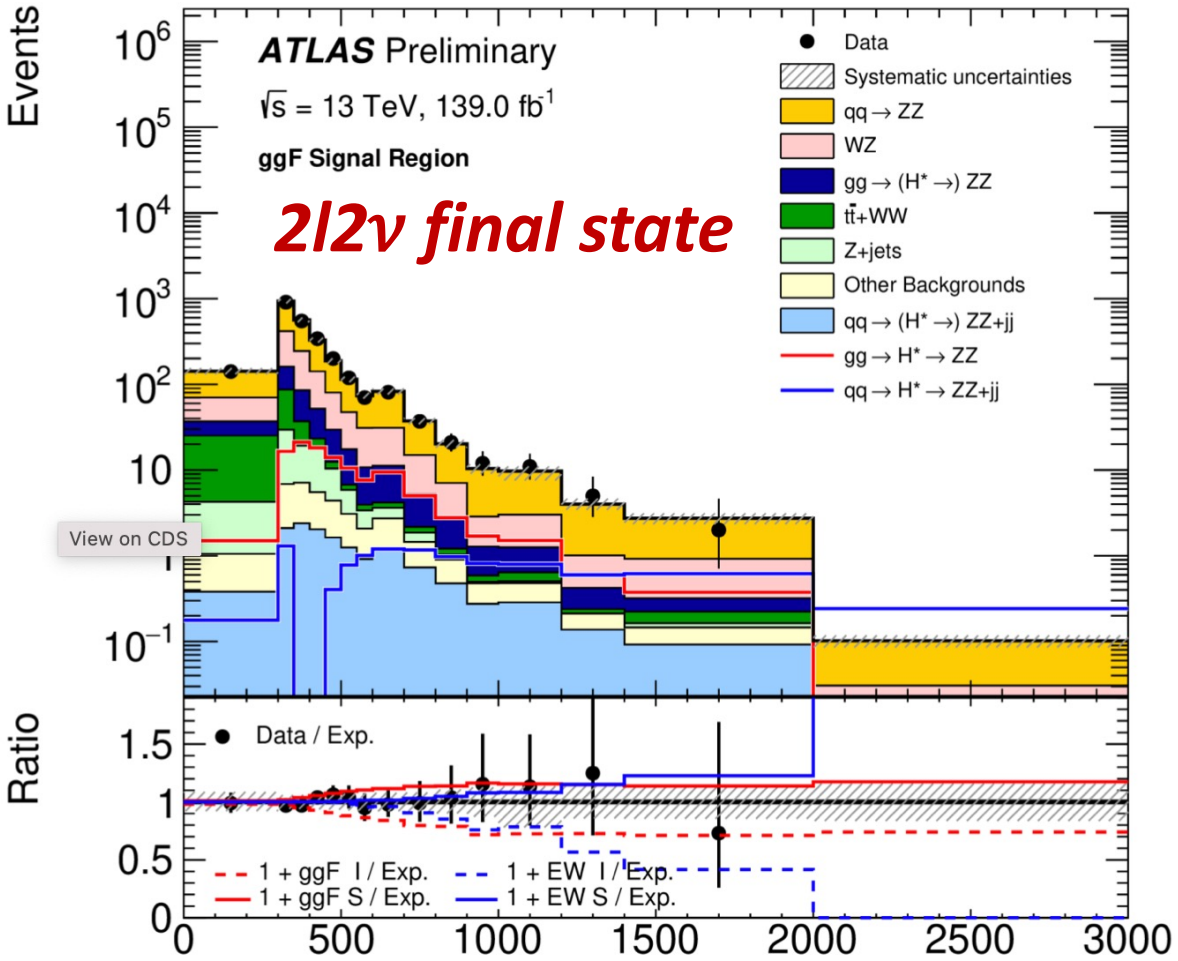
Higgs width measurement in 4l and 2l2ν finale states

Observable: neural network discriminant



[ATLAS-CONF-2022-068]

Observable: transverse ZZ mass

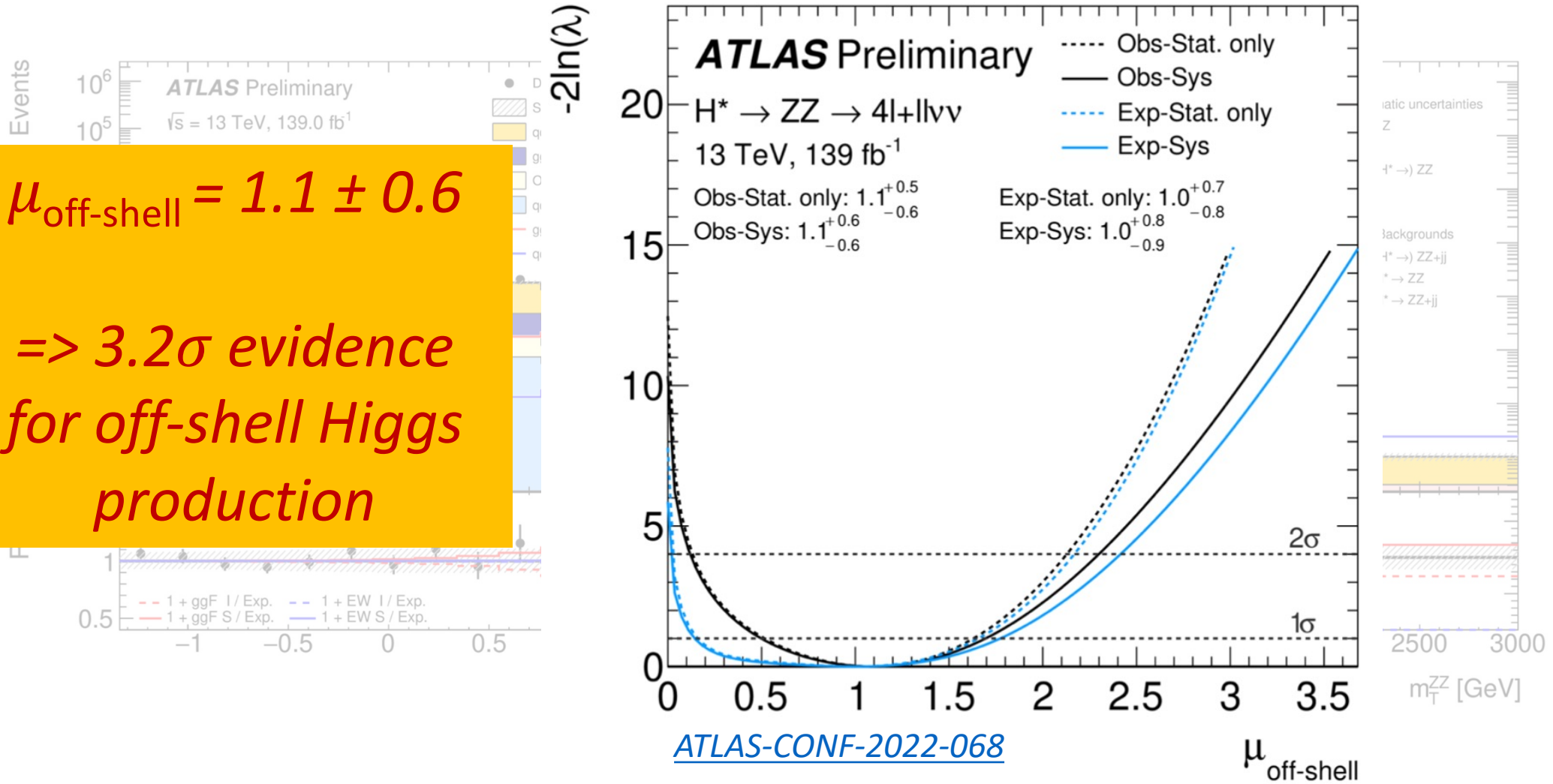


[ATLAS-CONF-2022-068]

Higgs width measurement in 4l and 2l2ν finale states

$\mu_{\text{off-shell}} = 1.1 \pm 0.6$

=> 3.2σ evidence for off-shell Higgs production



[ATLAS-CONF-2022-068]

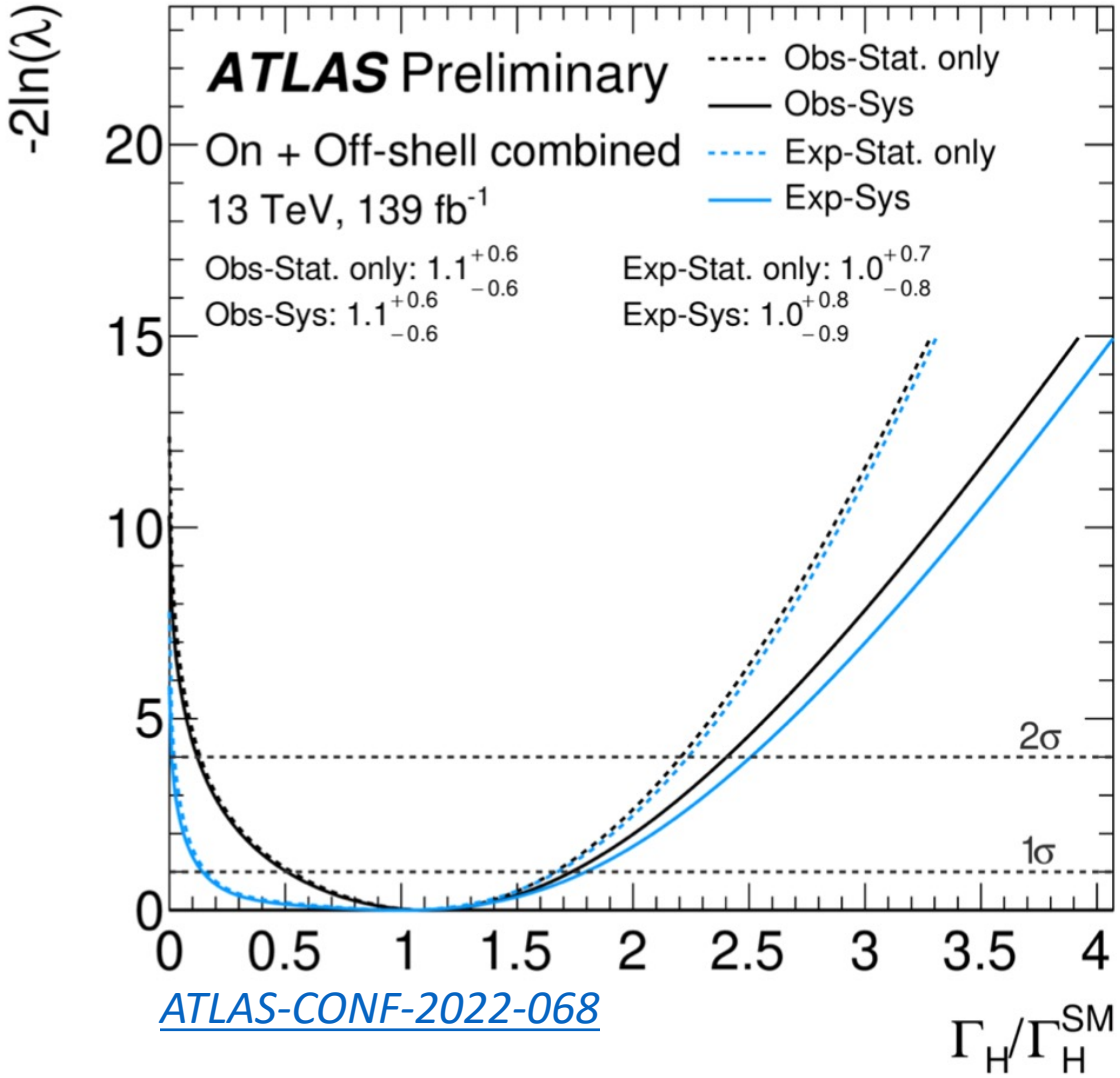
Indirect measurement of Γ_H from off-shell Higgs

$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma_H}{\Gamma_H^{SM}}$$

Combined with the previous on-shell result (Eur.Phys.J.C 80(2020)10, 957)

$$\Gamma_H = 4.6^{+2.6}_{-2.5}\ \text{MeV}$$

Upper limit on Γ_H of 9.7 MeV at 95% CL

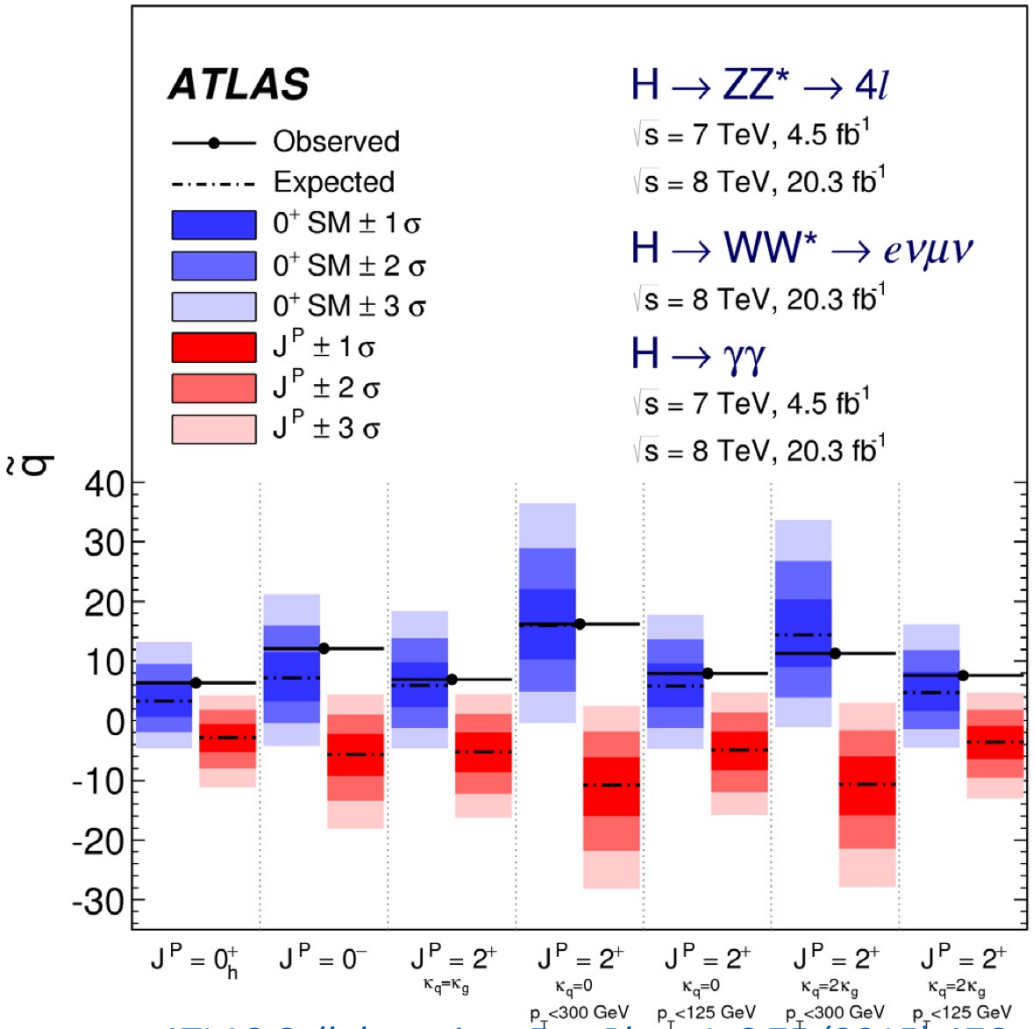


ATLAS-CONF-2022-068

The Higgs boson spin and CP properties

The Higgs boson spin-parity

The SM Higgs boson has spin 0 and positive parity (CP even)



Using measurements of H →γγ, H → ZZ and H → WW in Run 1

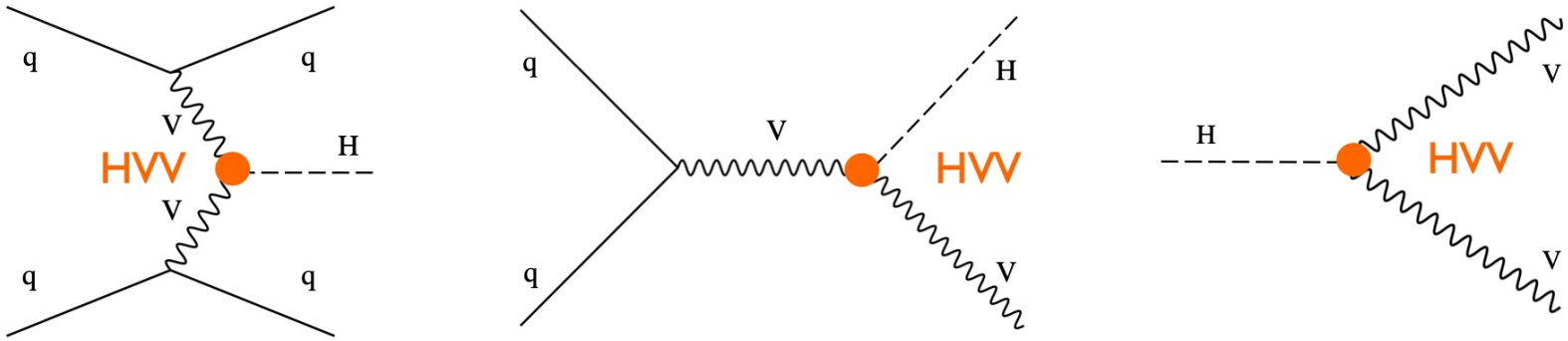
=> Spin 1 and spin 2 hypotheses have been excluded with a confidence level larger than 99.9%

ATLAS Collaboration, Eur. Phys. J. C 75 (2015) 476

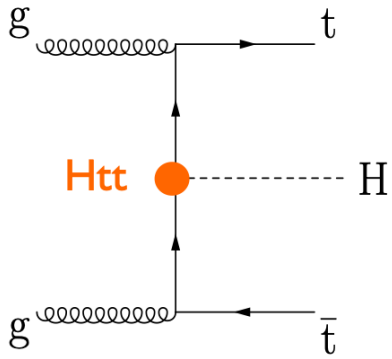
The Higgs boson CP properties

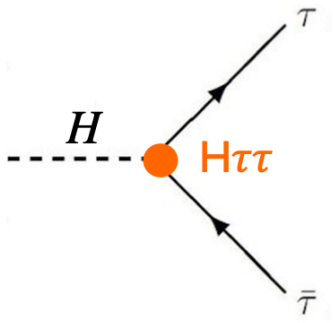
Higgs purely CP-even? possible CP-violation in the Higgs sector?

coupling to EW vector bosons

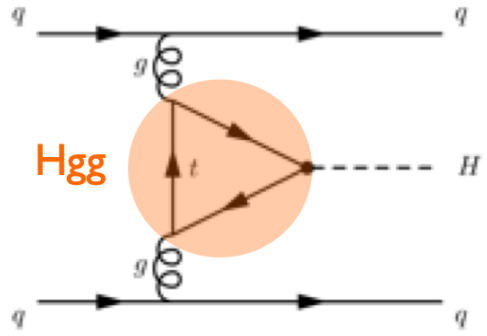


coupling to fermions



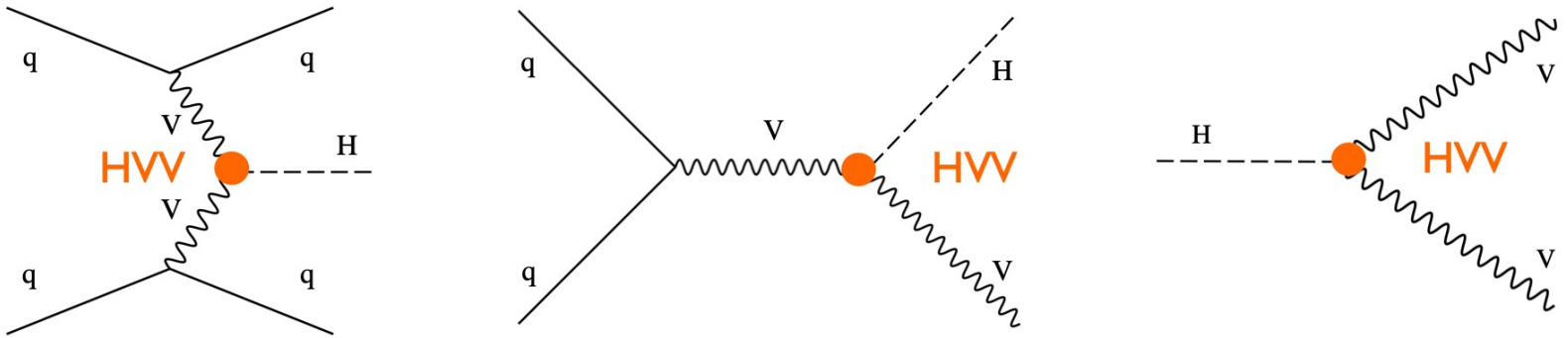


coupling to gluons



The Higgs boson CP properties

coupling to EW vector bosons



CP-odd components in HVV couplings forbidden in SM at tree level …

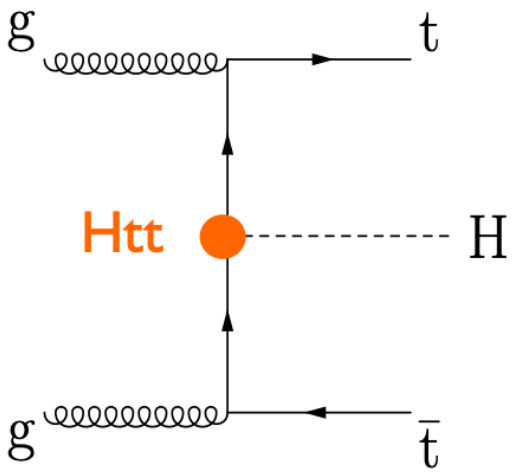
Typically described in higher order terms in an effective field expansion

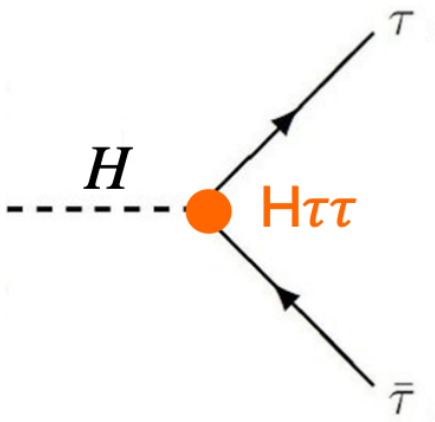
The Higgs boson CP properties

CP-odd components of Higgs-fermion couplings at tree level allowed!

Important to constrain CP-odd Higgs-fermion couplings

coupling to fermions





CP properties of Higgs-top coupling using t(t)H

Effective Yukawa interaction between Higgs boson and top quark

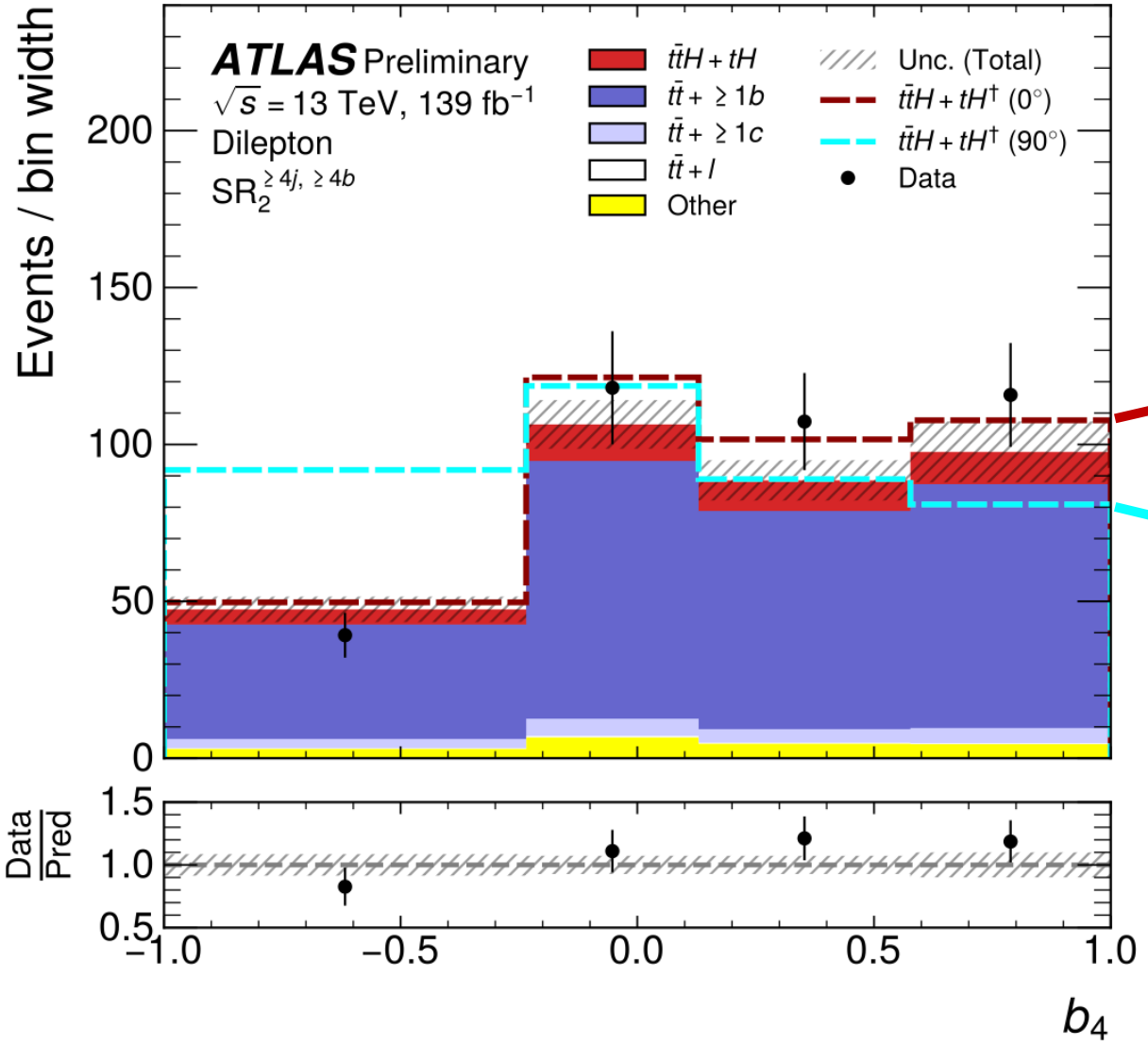
$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

y_t = *SM top Yukawa coupling*
κ_t' = *coupling modifier*
α = *CP-mixing angle*

CP-even (SM-like)

CP-odd (BSM-like)

CP properties of Higgs-top coupling using t(t)H



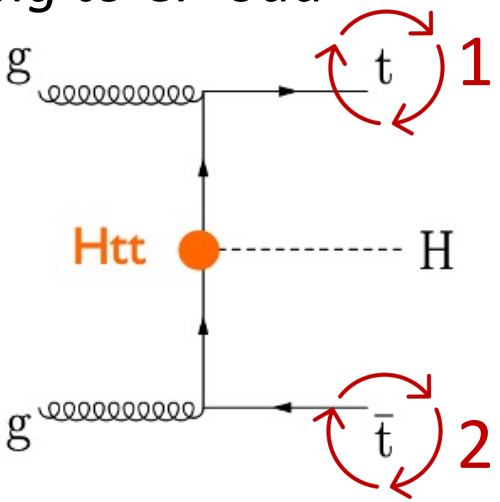
ttH + tH production in the
H → bb decay channel

α = 0° corresponding to CP-even

α = 90° corresponding to CP-odd

CP sensitive variable

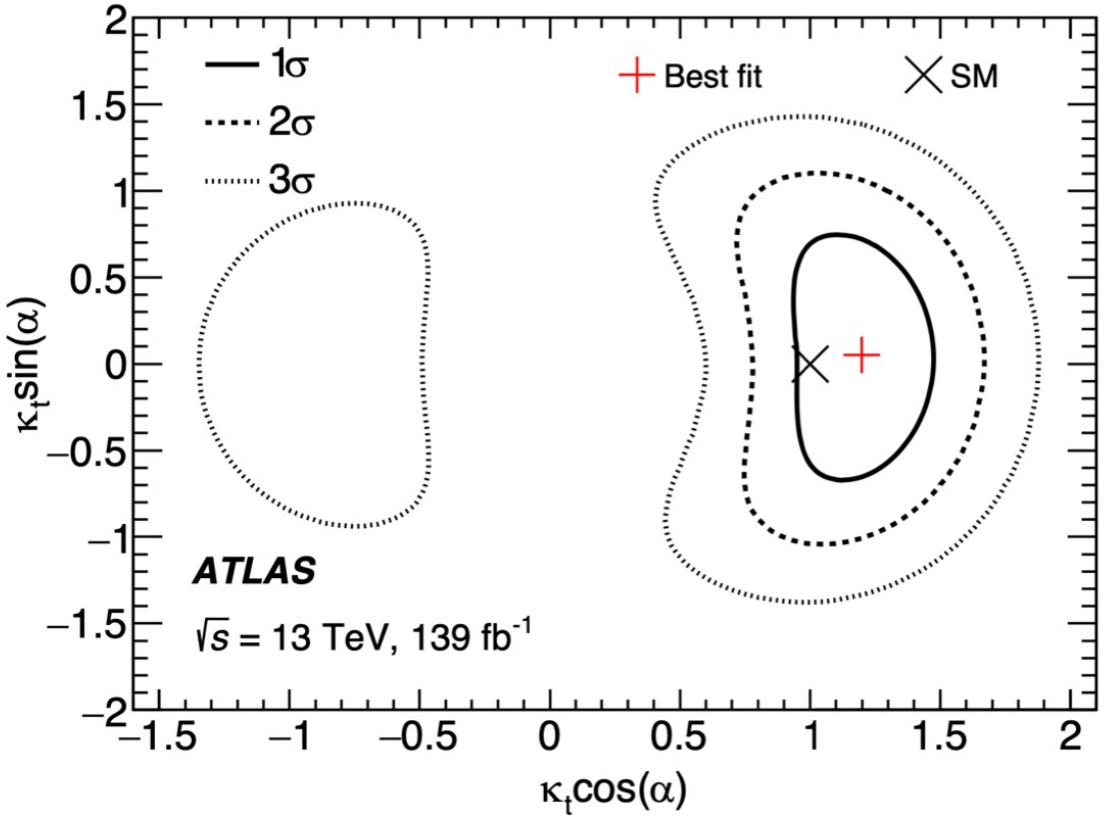
$$b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|},$$



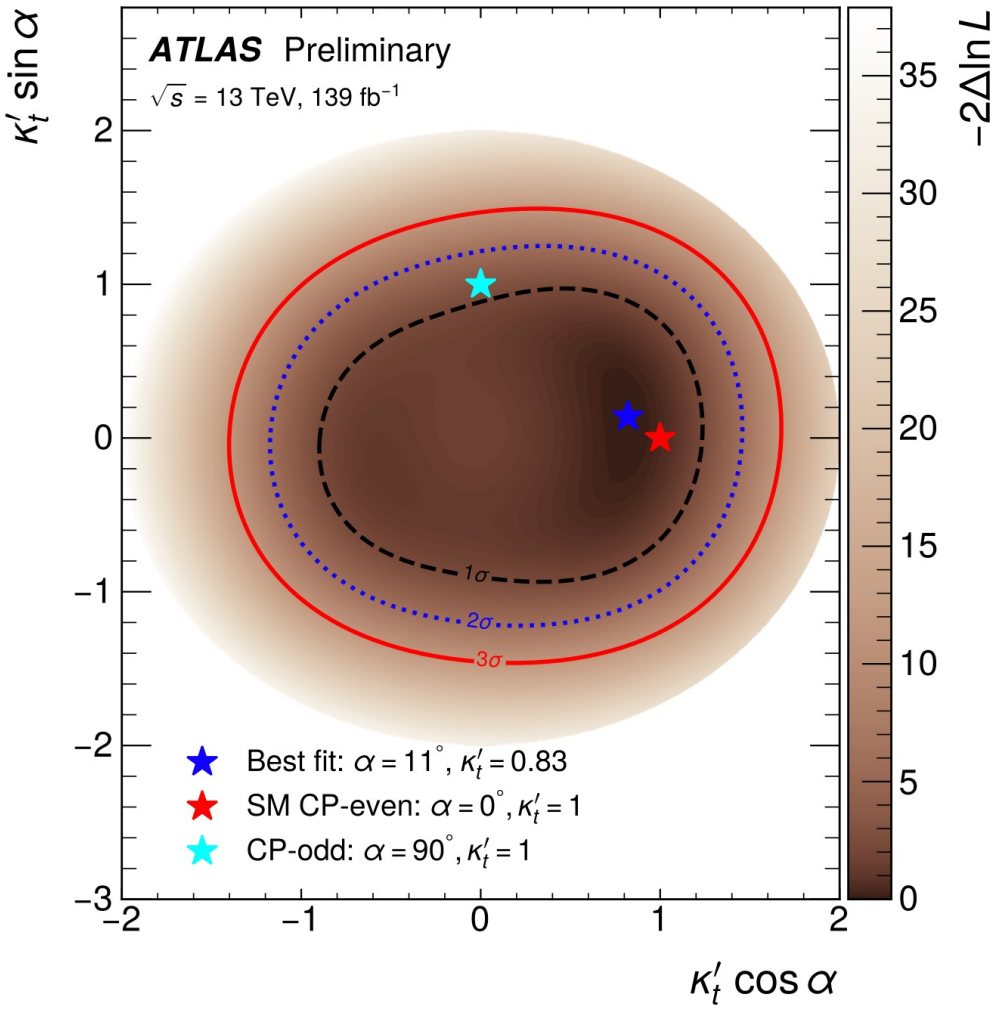
CP properties of Higgs-top coupling using t(t)H

CP-mixing angle and coupling modifier extracted from a profile likelihood fit

$H \rightarrow \gamma\gamma$

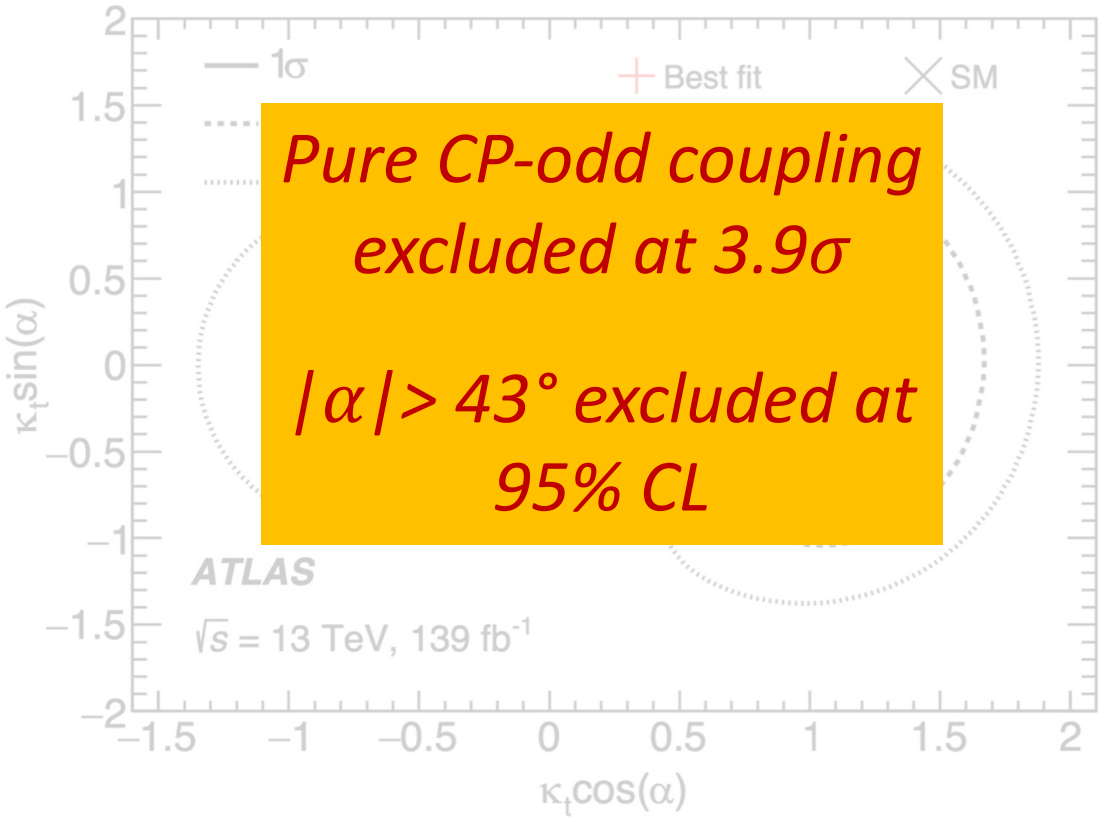


$H \rightarrow bb$



CP properties of Higgs-top coupling using ttH

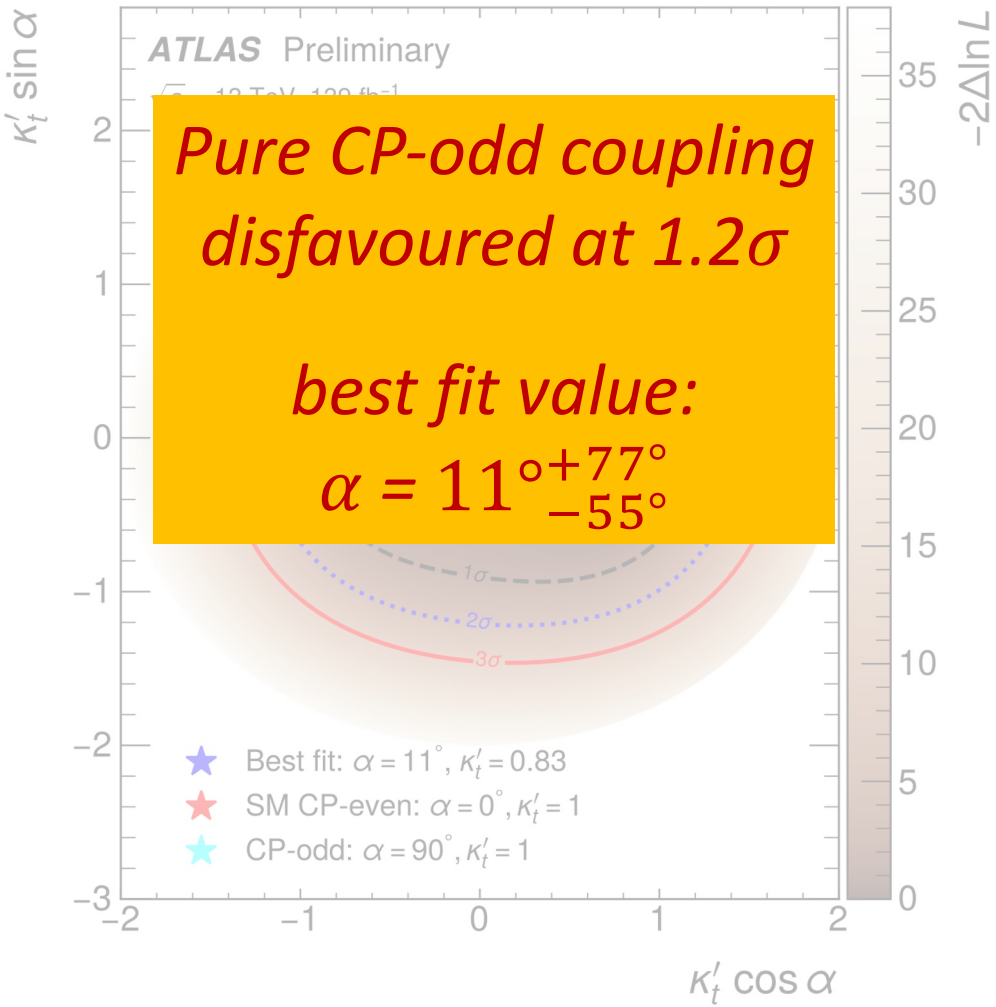
$H \rightarrow \gamma\gamma$



Pure CP-odd coupling excluded at 3.9σ

$|\alpha| > 43°$ excluded at 95% CL

$H \rightarrow bb$



Pure CP-odd coupling disfavoured at 1.2σ

best fit value:

$\alpha = 11°^{+77°}_{-55°}$

CP properties of Higgs-τ coupling using in $H \rightarrow \tau\tau$

Effective Yukawa interaction between Higgs boson and τ-lepton

$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{\nu}\kappa_\tau \left(\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i\gamma_5 \tau\right) H$$

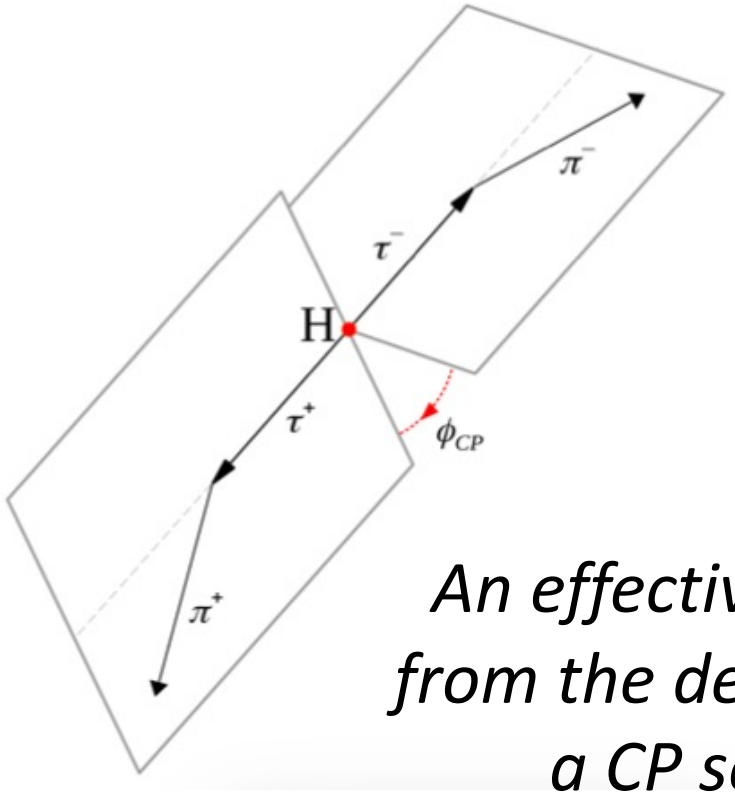
CP-even (SM-like)

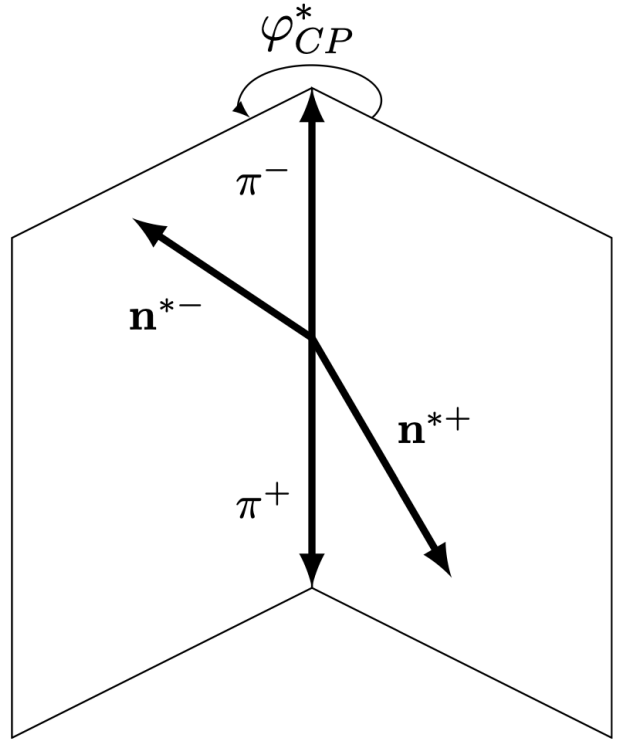
CP-odd (BSM-like)

m_τ = τ-lepton mass
κ_τ = reduced Yukawa coupling
v = vacuum expectation value of the Higgs field
ϕ_τ = CP-mixing angle

CP properties of Higgs-τ coupling using in H → ττ

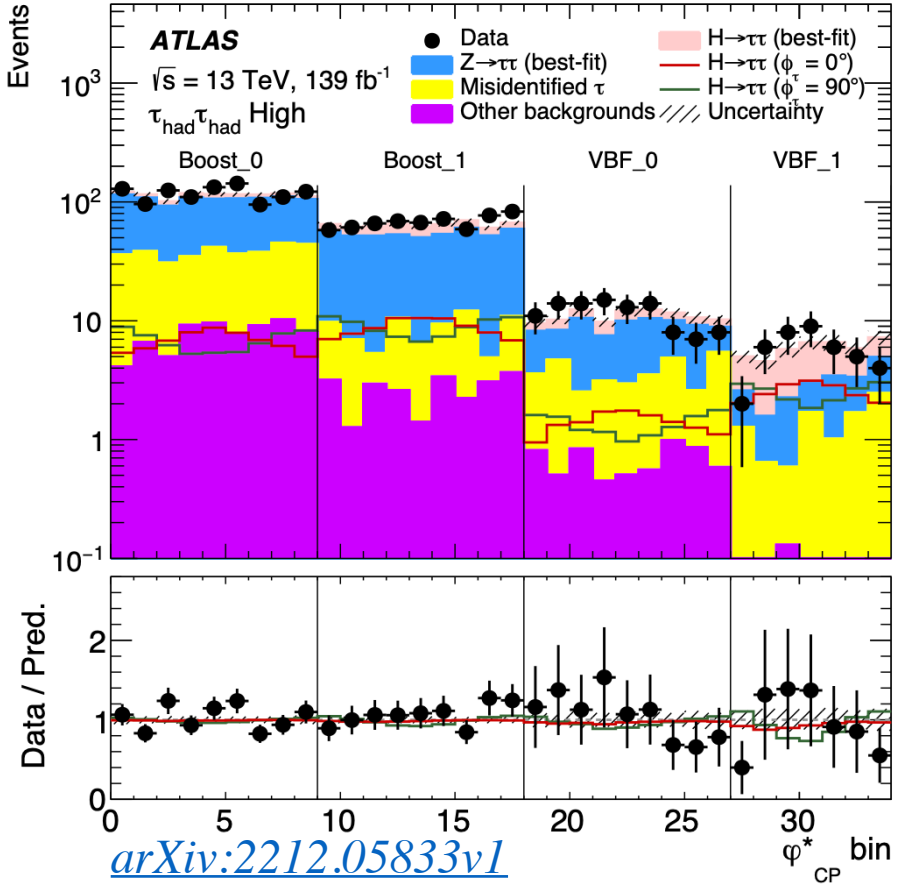
The τ-lepton is reconstructed from its decay products …



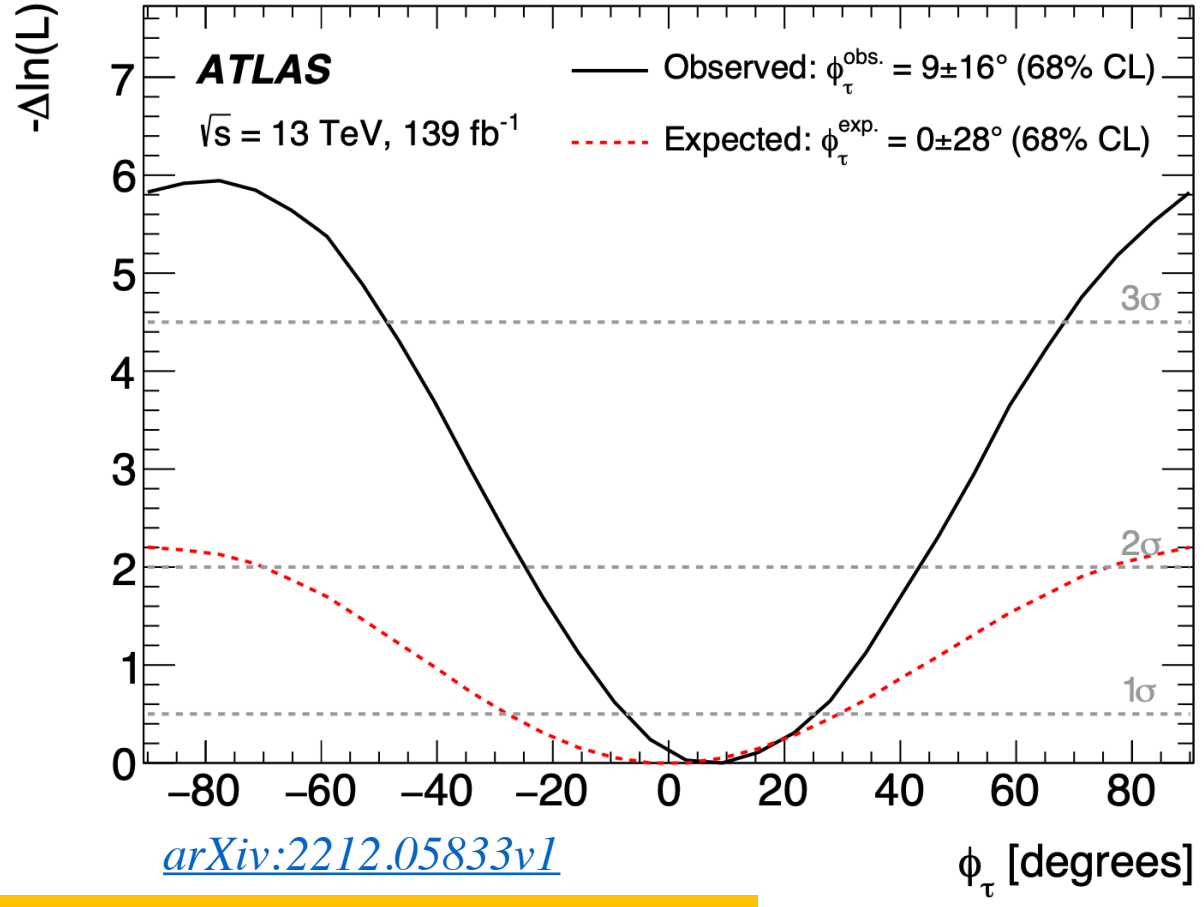


An effective angle is extracted from the decay products to build a CP sensitive variable

CP properties of Higgs-τ coupling using in H → ττ



arXiv:2212.05833v1



arXiv:2212.05833v1

Pure CP-odd coupling excluded at 3.4σ

best fit value: ϕ_τ = 9° ± 16°

After ten years since the discovery …

Great progress in measuring the Higgs boson properties

The Higgs boson mass known to 0.11% with the full Run 2 $H \rightarrow \gamma\gamma$ mass measurement to come, and more combined results

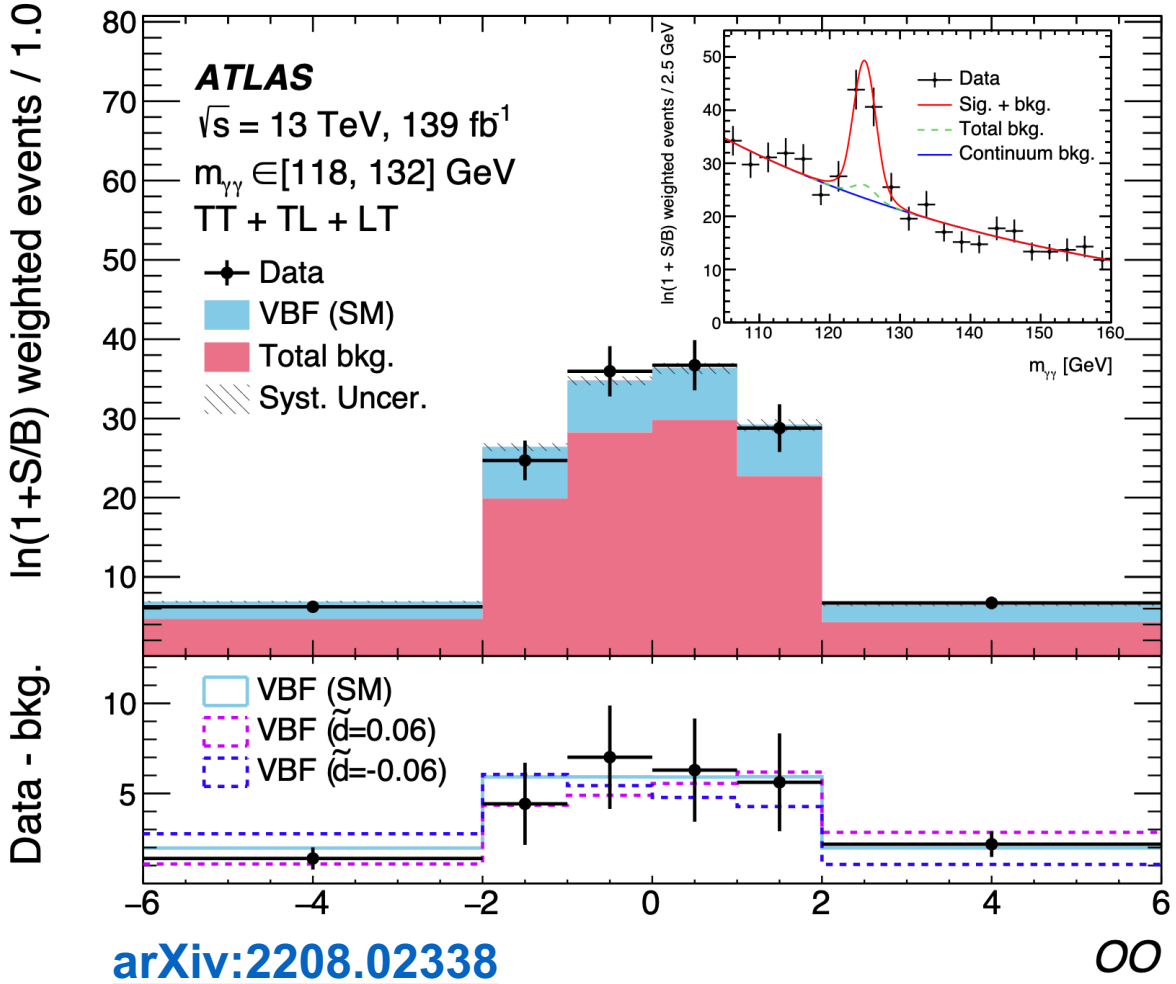
The Higgs boson natural width measured at MeV level + evidence of off-shell Higgs boson production (more measurements and combined results to come)

CP structure of different Higgs couplings probed: pure CP-odd coupling excluded at > 3σ in several measurements (with more results to come)

Stay tuned for more Run 2, combined and Run 3 results!

Extra slides

CP properties of HVV coupling with VBF Higgs to diphoton



arXiv:2208.02338

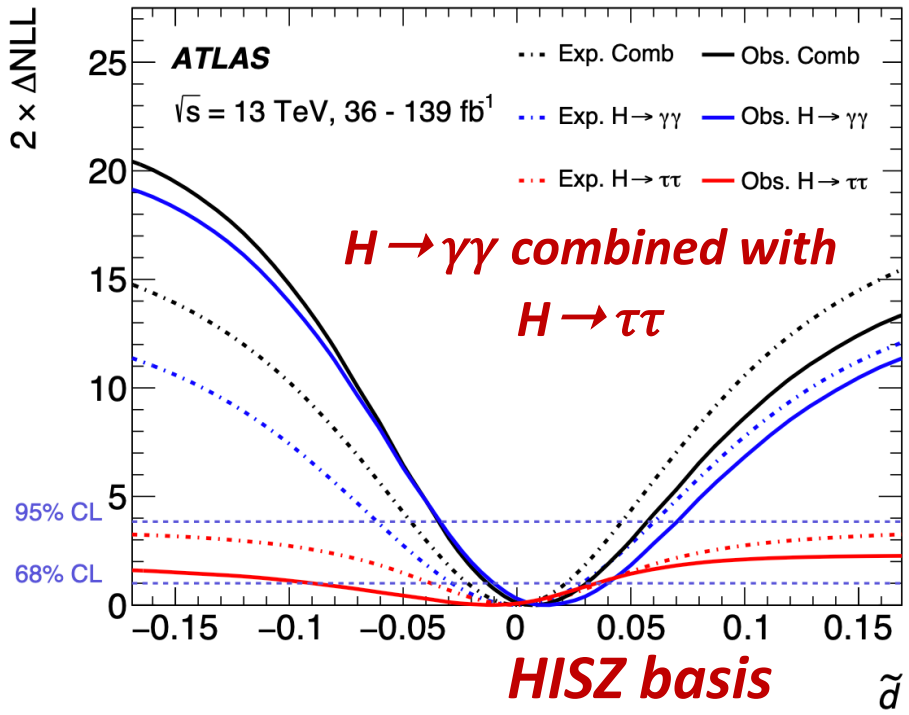
CP-odd component can be described by adding dimension-6 operators to the SM Lagrangian (EFT approach)

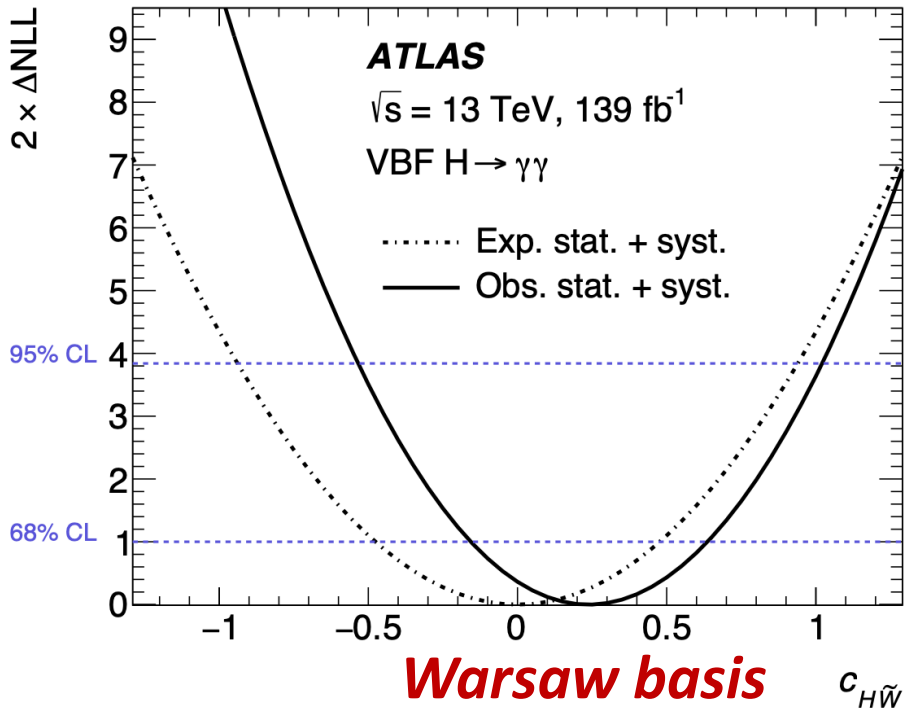
$$|\mathscr{M}|^2 = |\mathscr{M}_{\mathrm{SM}}|^2 + 2 \cdot c_i \cdot \mathrm{Re}(\mathscr{M}^*_{\mathrm{SM}} \mathscr{M}_{\text{CP-odd}}) + c_i^2 \cdot |\mathscr{M}_{\text{CP-odd}}|^2.$$

The optimal observable:

$$OO = 2 \cdot \mathrm{Re}(\mathscr{M}^*_{\mathrm{SM}} \cdot \mathscr{M}_{\mathrm{CP-odd}}) / |\mathscr{M}_{\mathrm{SM}}|^2$$

CP properties of HVV coupling with VBF Higgs to diphoton





	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
$\tilde{d}$ (inter. only)	[−0.027, 0.027]	[−0.055, 0.055]	[−0.011, 0.036]	[−0.032, 0.059]
$\tilde{d}$ (inter.+quad.)	[−0.028, 0.028]	[−0.061, 0.060]	[−0.010, 0.040]	[−0.034, 0.071]
$\tilde{d}$ from $H \to \tau\tau$	[−0.038, 0.036]	–	[−0.090, 0.035]	-
Combined $\tilde{d}$	[−0.022, 0.021]	[−0.046, 0.045]	[−0.012, 0.030]	[−0.034, 0.057]
$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]	[−0.15, 0.67]	[−0.55, 1.07]

Most stringent constraints on CP-properties of HVV coupling to date

arXiv:2208.02338

CP properties of Higgs-gluon coupling with ggF+VBF

Measured in the H → WW → lvlv

Found consistent with the CP-even SM hypothesis