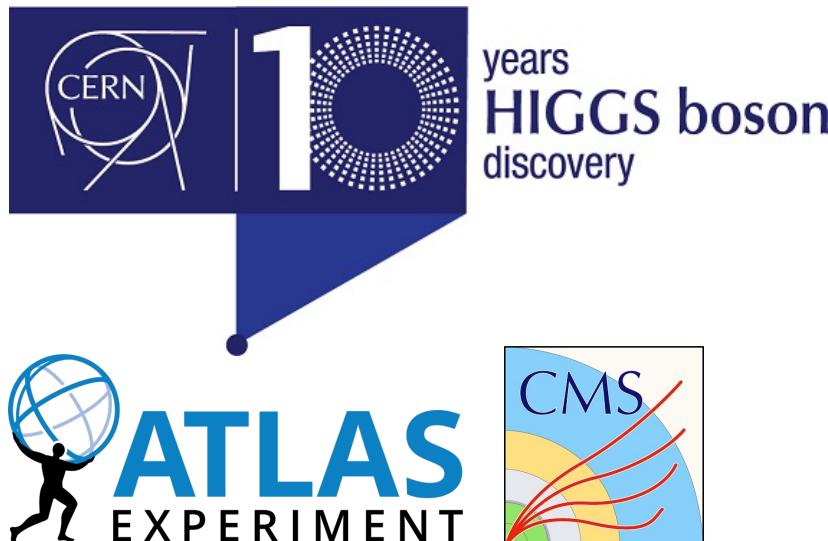


# Higgs boson properties: *mass, width, spin and CP*



Marco Delmastro  
*on behalf of the  
ATLAS and CMS Collaborations*



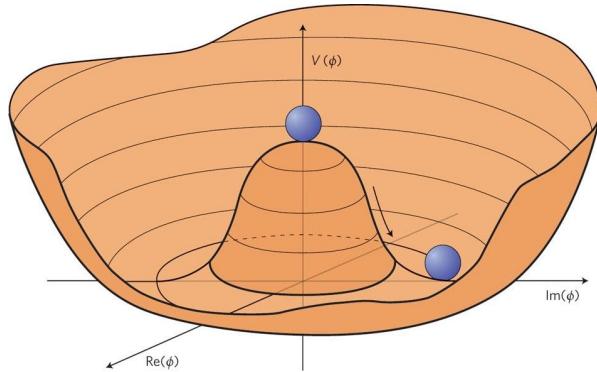
July 4<sup>th</sup> 2022

1.

# Higgs boson mass

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# An unknown of the Standard Model...



$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$V(\Phi) = V_0 + \frac{1}{2} m_H^2 H^2 + \lambda \nu H^3 + \frac{1}{4} \lambda H^4$$

$$m_H = \sqrt{2}\mu$$

Why do we want to measure  $m_H$ ?

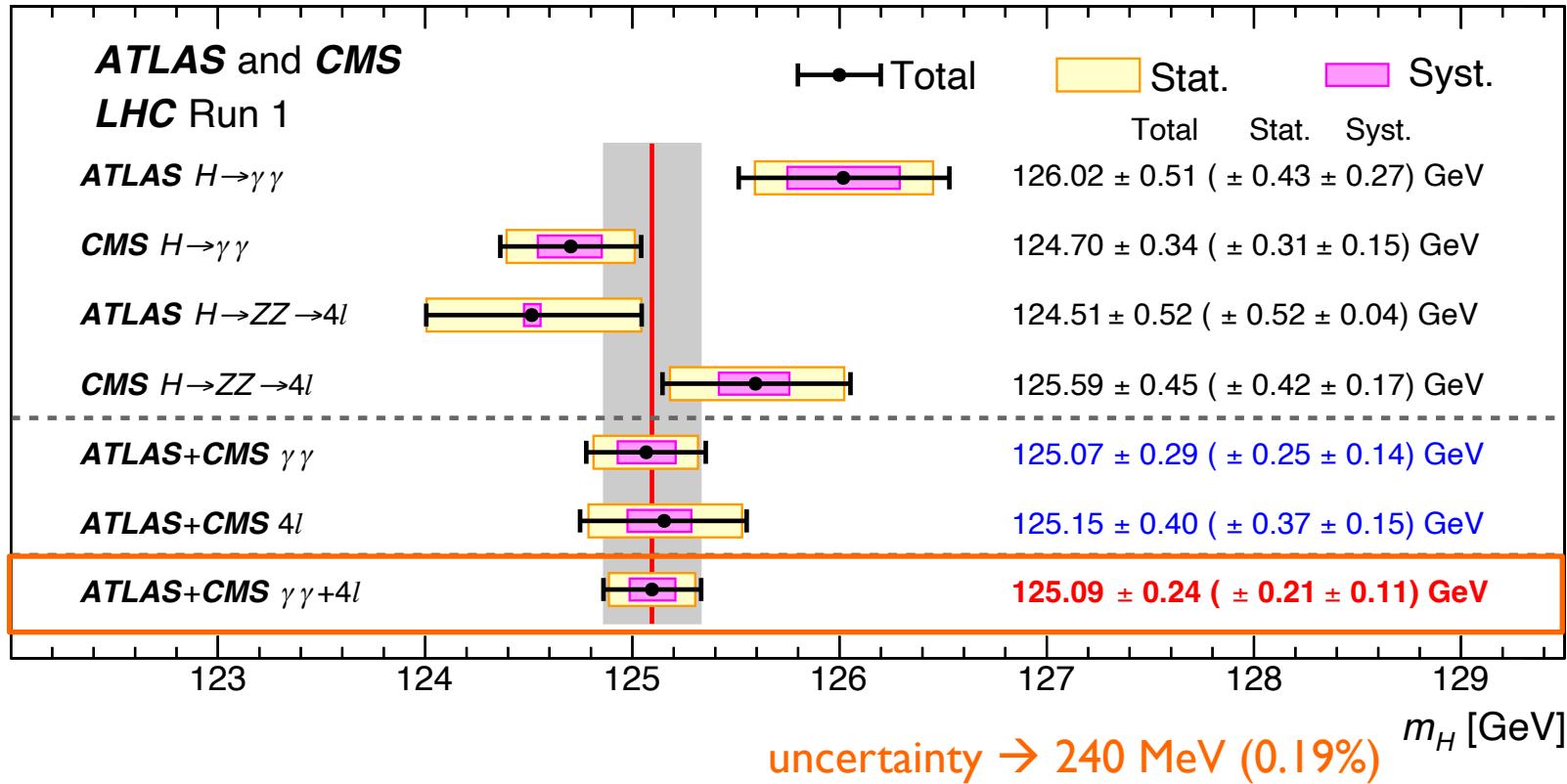
- $m_H$  not predicted by theory!
- Intimately related to Higgs potential
  - ✓ Higgs coupling defined by  $m_H$  value
  - ✓ Knowledge of  $m_H$  also have impact on precision of indirect measurements!

How do we want to measure  $m_H$ ?

- $m_H$  measured with  $H \rightarrow \gamma\gamma$  and  $H \rightarrow 4l$
- Precision dominated by statistics and experimental systematics
  - ✓ Precise calibration of photons, muons and electron energy and momentum scale crucial!

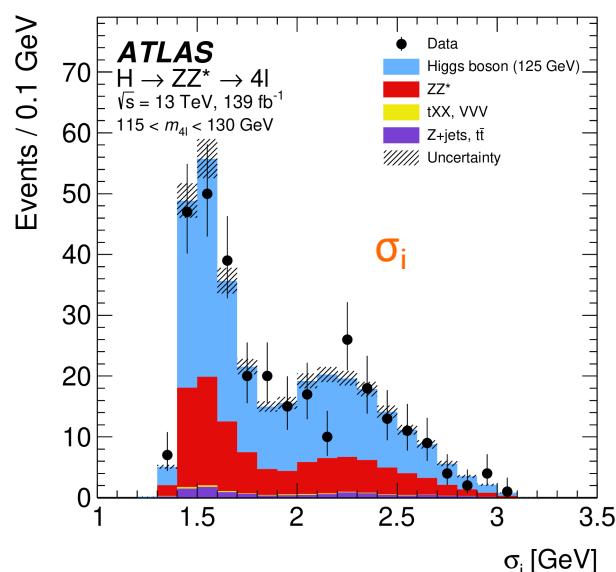
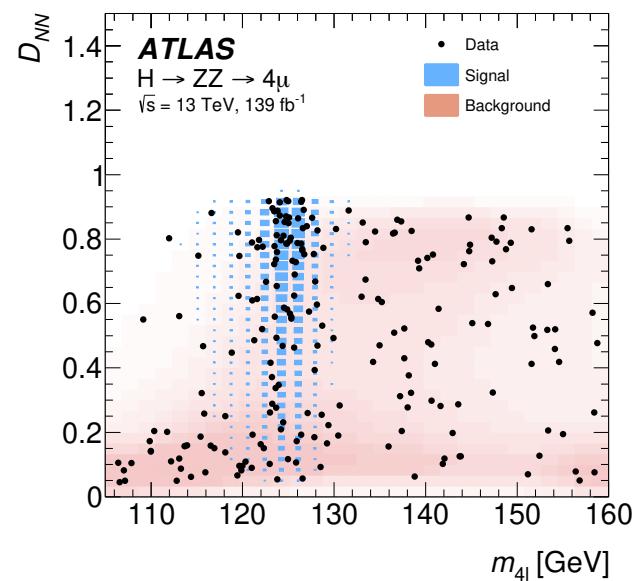
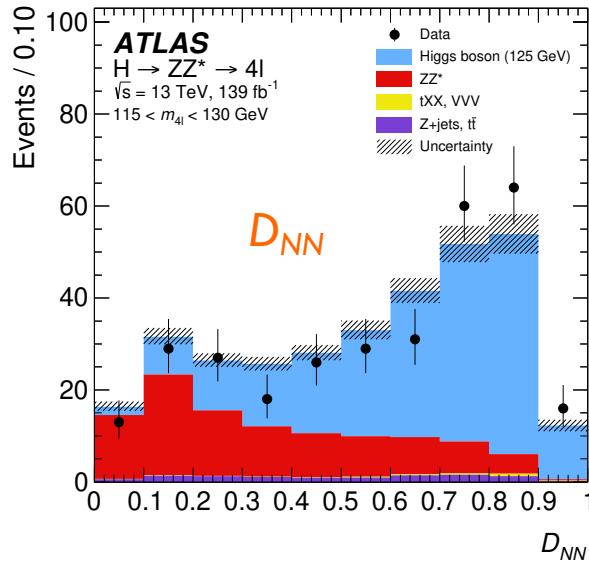
# The Higgs boson mass at the end of Run I

ATLAS+CMS RunI Combination [Phys. Rev. Lett. 114 \(2015\)](#)



# H $\rightarrow$ 4l mass: latest ATLAS result

**NEW**



- $D_{NN}$  • New DNN for S/B discrimination
- $\sigma_i$  • Per-event resolution estimate
- $p_T^\mu$  • Improved muon  $p_T$  calibration

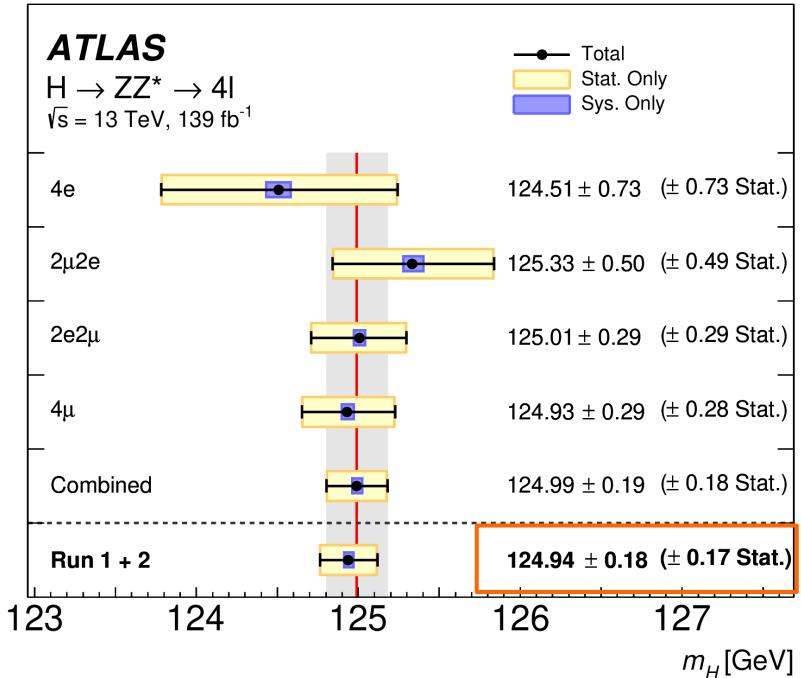
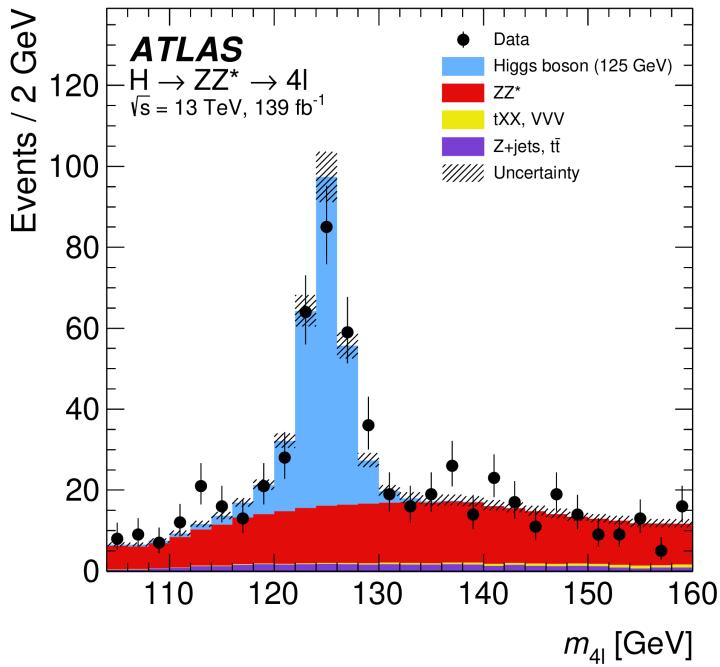
Systematic Uncertainty	Impact (MeV)
$p_T^\mu$ Muon momentum scale	±20
Electron energy scale	±16
Theory	±13

40 MeV  
in previous  
measurement!

arXiv:2207.00320

# H $\rightarrow$ 4l mass: latest ATLAS result

NEW

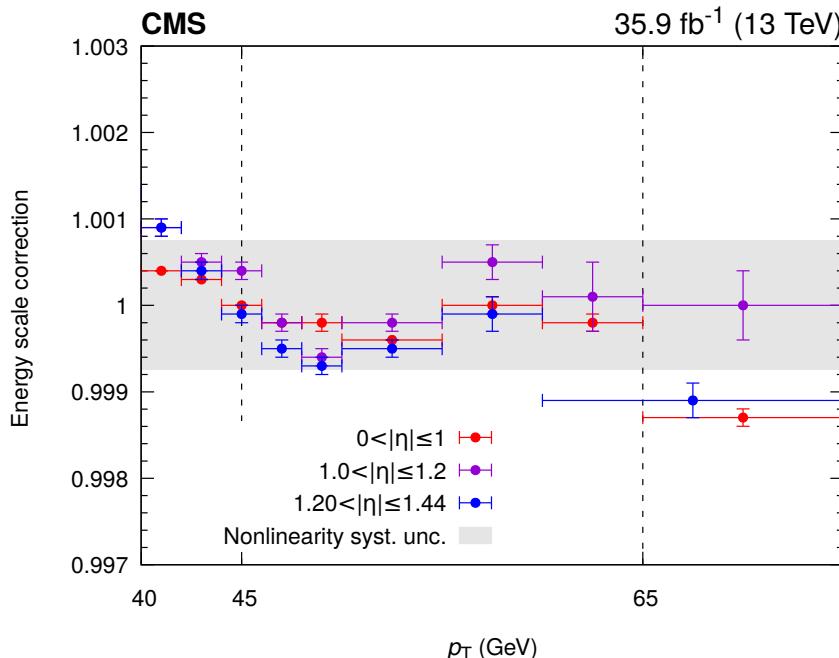


uncertainty → 180 MeV (0.14%)

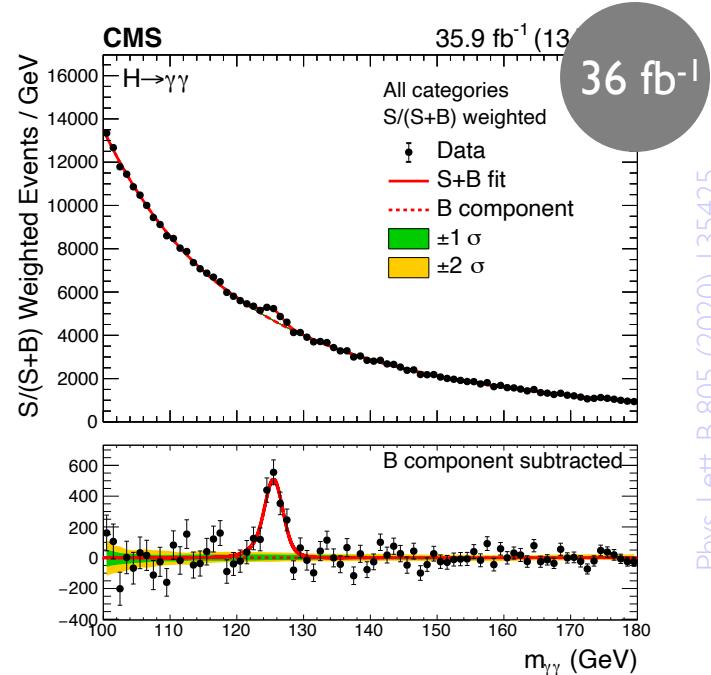
# H $\rightarrow\gamma\gamma$ mass: latest CMS measurement

- Photon energy scale and resolution calibration crucial!
  - ✓ MVA techniques + correction from detector knowledge and simulation imperfection + Z $\rightarrow ee$  in-situ calibration

$$m_H = 125.78 \pm 0.26 \text{ (0.18 stat} \pm 0.18 \text{ syst) GeV}$$



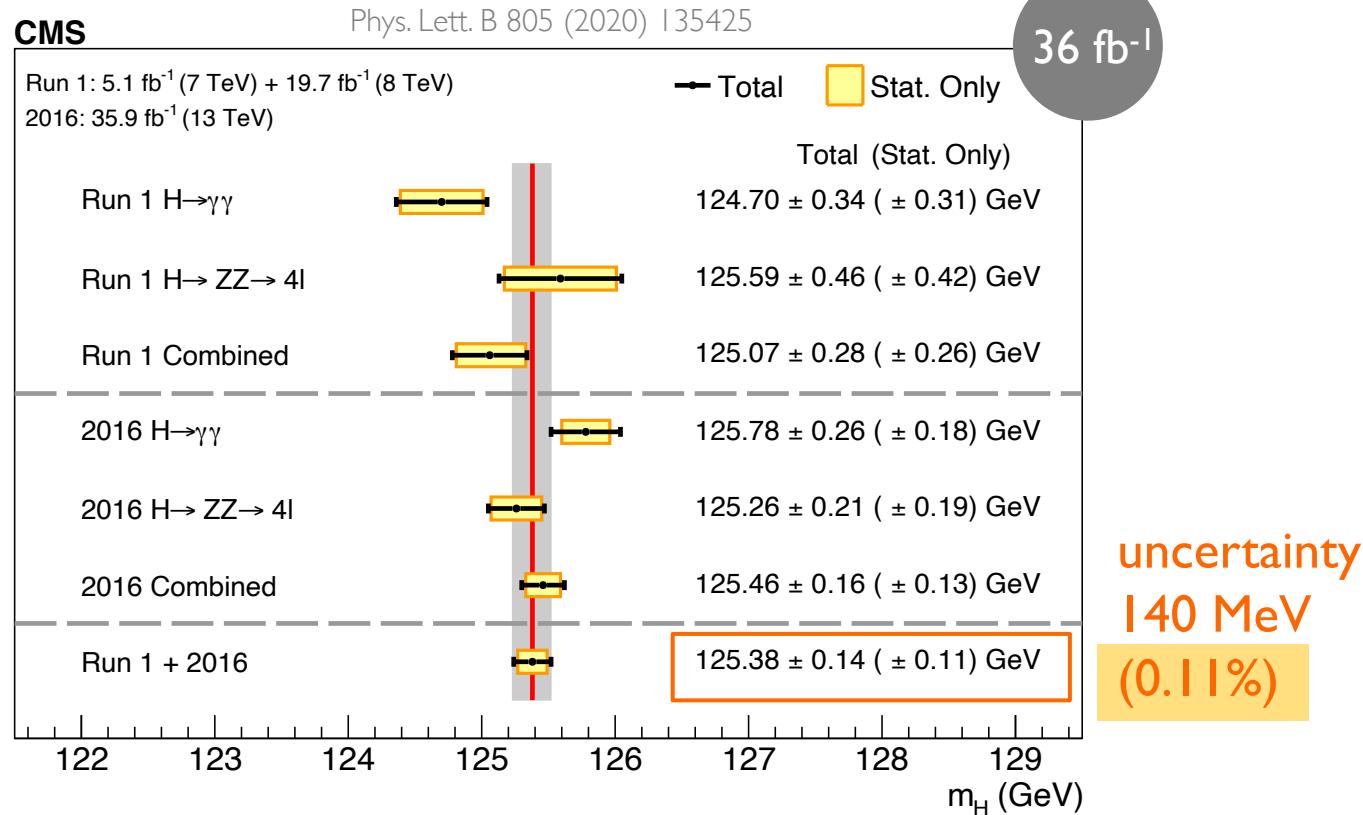
Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual $p_T$ dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26



# Higgs mass: best precision to date (and more to come)

Precision driven by **statistics**, but photon, electron and muon scale and resolution **systematics** will soon become limiting!

Some measurements still based on partial Run 2 datasets: **more improvements** to come, and **ATLAS+CMS** mass combination



2.

# Higgs boson width

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# Higgs width: a problem difficult to tackle directly!

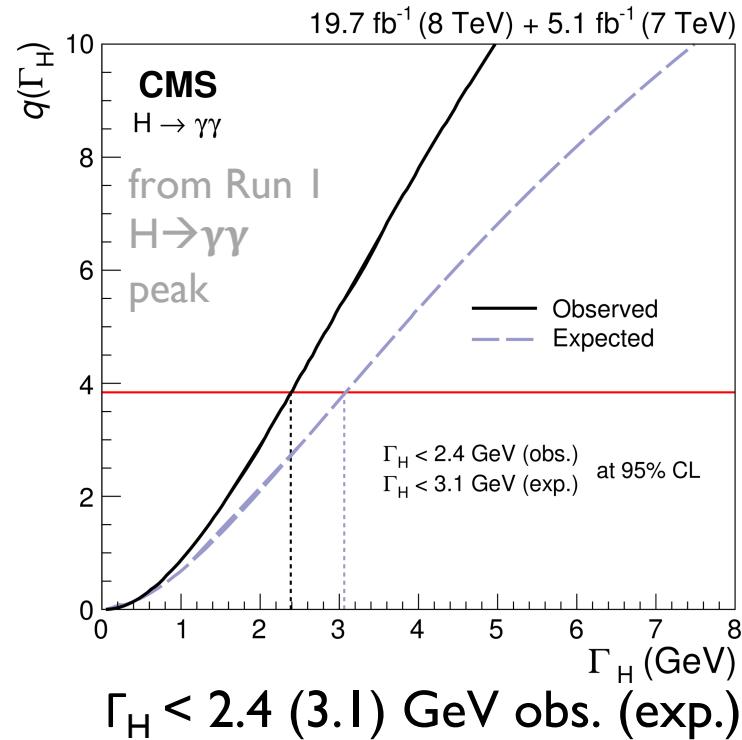
Total Higgs natural width in SM is **small**!

- ✓ Too small to be accessed experimentally at LHC from resonance line-shape in analysis where peak can be reconstructed...

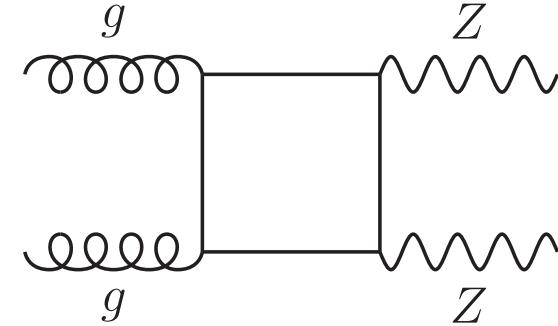
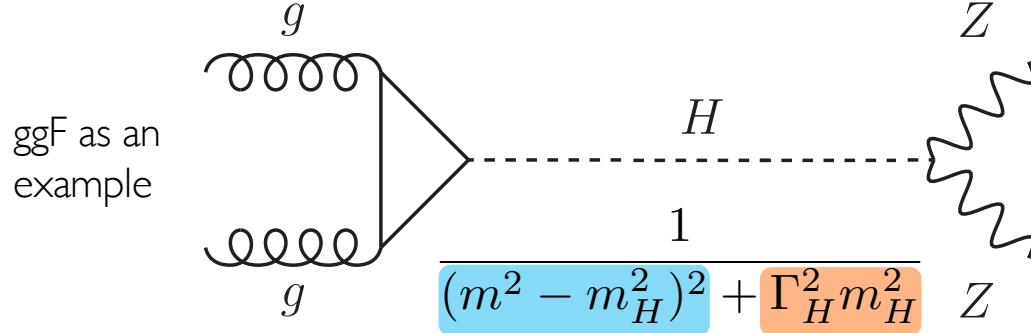
$$\Gamma_H^{\text{SM}} \text{ dominated by} \\ \Gamma(H \rightarrow b\bar{b}) \approx \frac{N_c g_w^2 m_b^2 m_H}{32\pi m_W^2}$$

$$\Gamma_H^{\text{SM}} = 4.07 \text{ MeV}$$

Direct measurement severely limited by detector resolution! One (old) example:



# The Higgs boson as propagator: width from off-shell Higgs



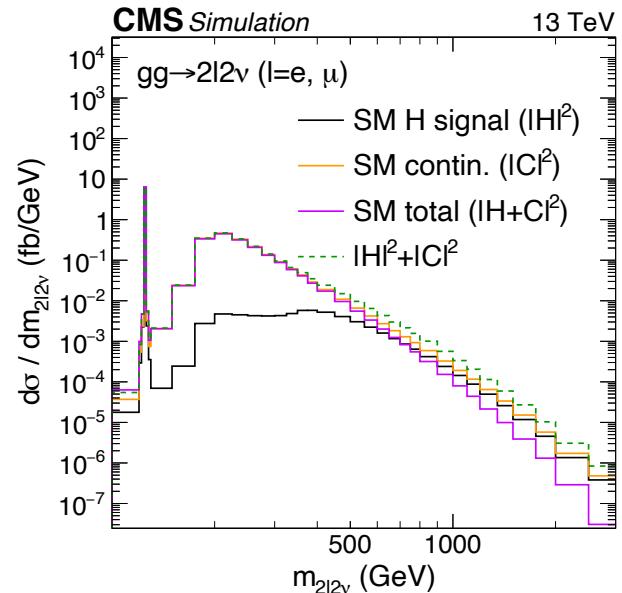
- Interference impacts both total cross section and  $m(VV)$  line-shape
- Assuming on-shell and off-shell couplings are equal:

$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma}{\Gamma_{\text{SM}}}$$

$$vv = gg$$

$$vv = WW, ZZ, Z\gamma, \gamma\gamma$$

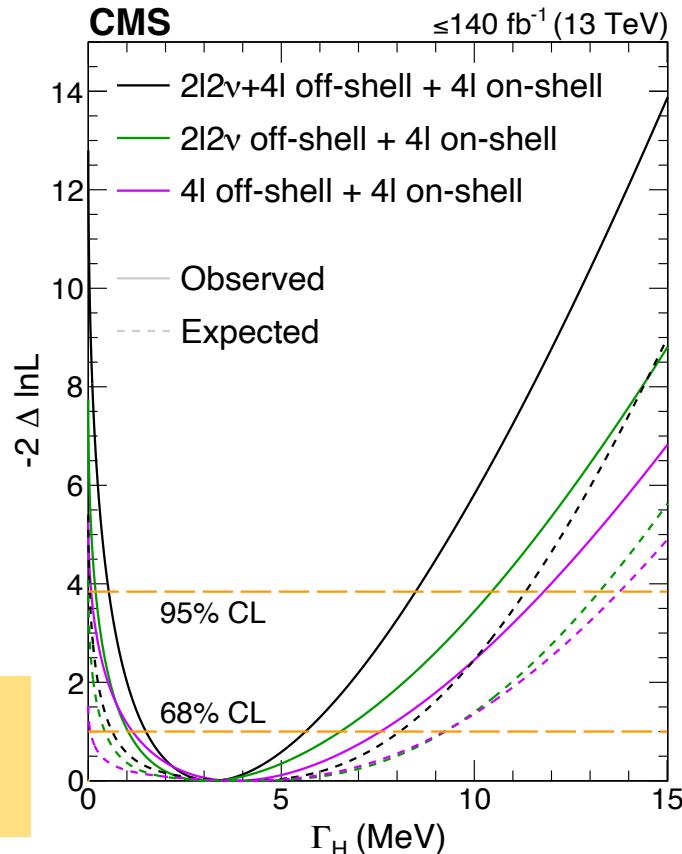
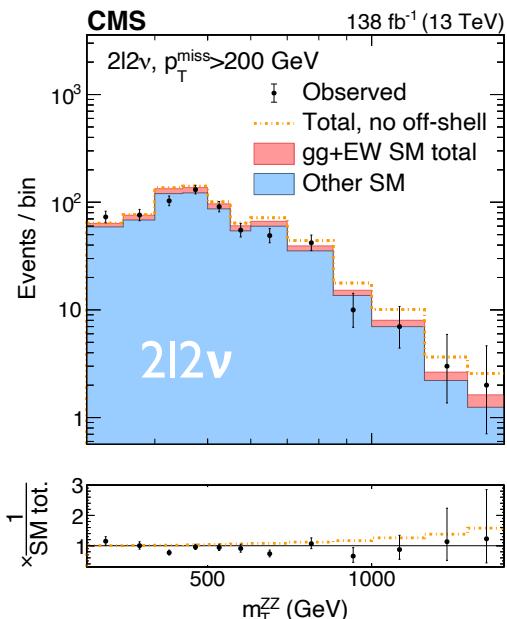
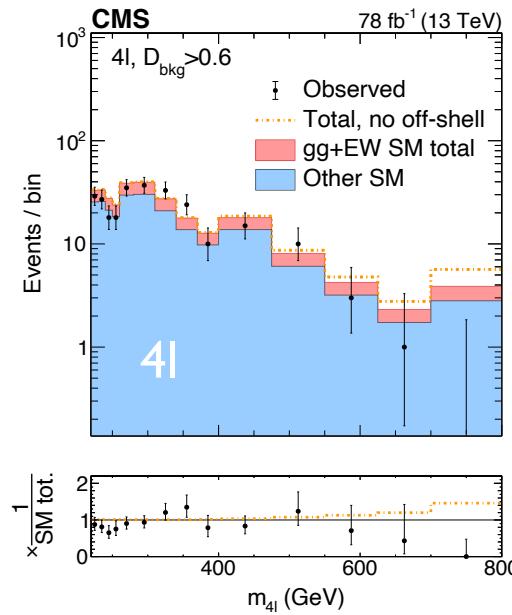
$$\sigma_{vv \rightarrow H \rightarrow 4\ell}^{\text{on-shell}} \propto \frac{g_{\text{gluon}}^2 g_V^2}{\Gamma_H} \quad \sigma_{vv \rightarrow H \rightarrow 4\ell}^{\text{off-shell}} \propto g_{\text{gluon}}^2 g_V^2$$



# Measurements of the Higgs width from off-shell production

Measurements in **4l** and **2l2v** final states and for different production modes (CMS: ttH, VH, VBF, ggH)

arXiv:2202.06923



$140 \text{ fb}^{-1}$  on-shell 4l  
 $78 \text{ fb}^{-1}$  off-shell 4l  
 $138 \text{ fb}^{-1}$  off-shell 2l2v

**3.6  $\sigma$  evidence for  
off-shell H production**

**CMS**  
 $\Gamma_H = 3.2^{+2.5}_{-1.7} \text{ MeV}$

# 3.

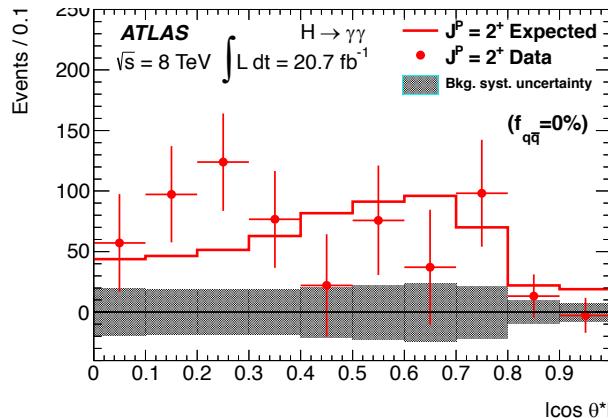
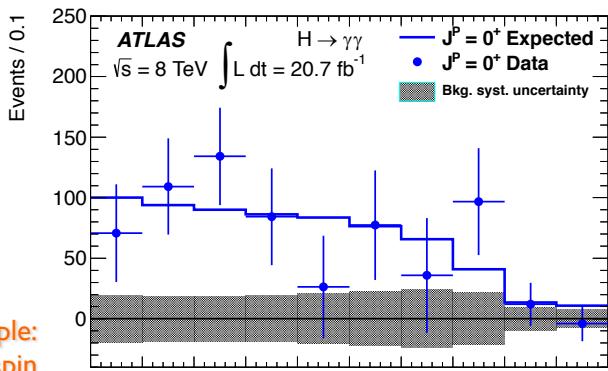
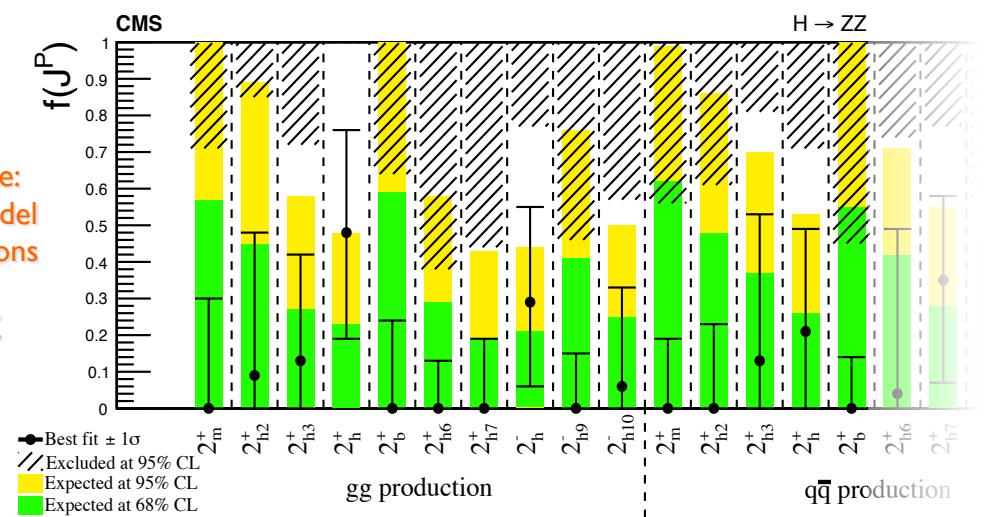
## Higgs spin & CP properties

---

# SM Higgs spin and CP properties

- SM Higgs has spin 0 and positive (even) parity ( $J^{CP} = 0^{++}$ )
- At the end of Run I we knew Higgs had spin 0...
  - ✓ Spin 1 and 2 hypotheses excluded at  $> 99.9\% \text{ CL}$  using  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow ZZ^*$  and  $H \rightarrow WW^*$

[Phys. Rev. D 92 \(2015\) 012004](https://arxiv.org/abs/1501.02004)



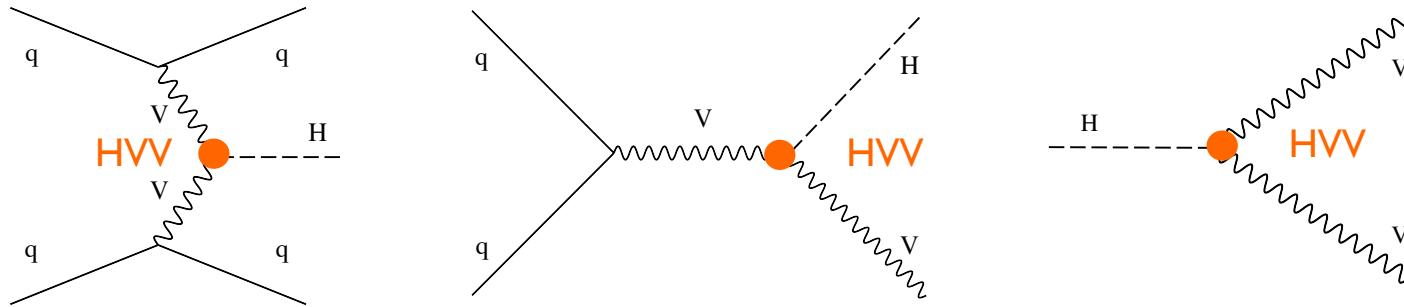
$$\cos \theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + (p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

$\gamma\gamma$  polar angle  $\theta^*$  with respect to Z-axis in Collins-Soper frame

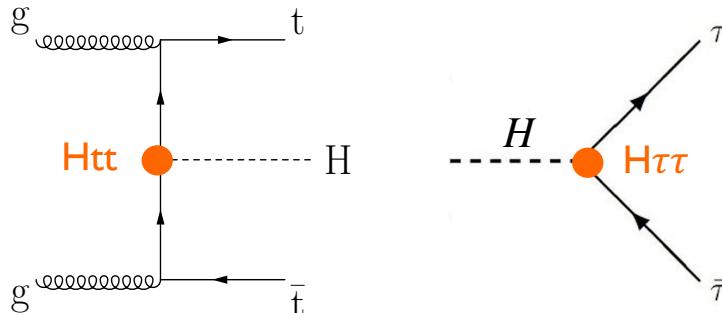
# Studies of the Higgs CP properties

Spin is property of the particle, CP of the coupling...

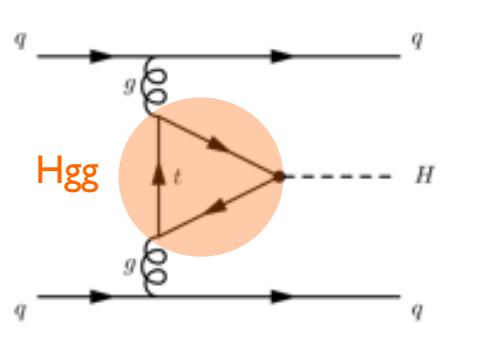
coupling to EW vector bosons



coupling to fermions



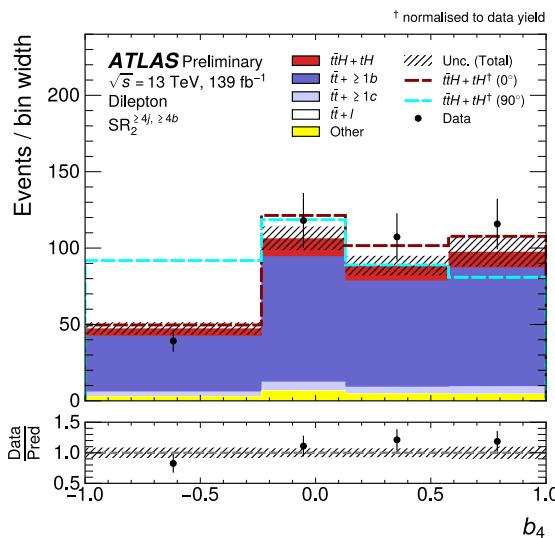
coupling to gluons



# CP properties of Higgs-top coupling with ttH

Effective Lagrangian for Yukawa coupling to top quarks parameterized by CP-Even and CP-odd components

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



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

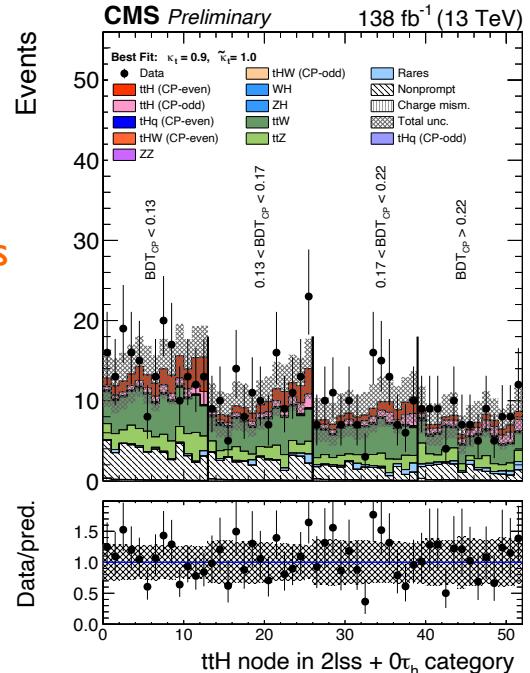
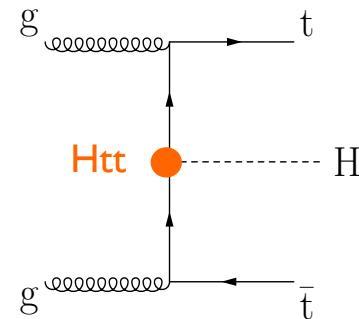
Two recent examples:

ttH+tH  
 $H \rightarrow bb$

ttH+tH  
 $H \rightarrow \text{MultiLeptons}$

Analyses use MVA discriminants  
and CP-sensitive observables

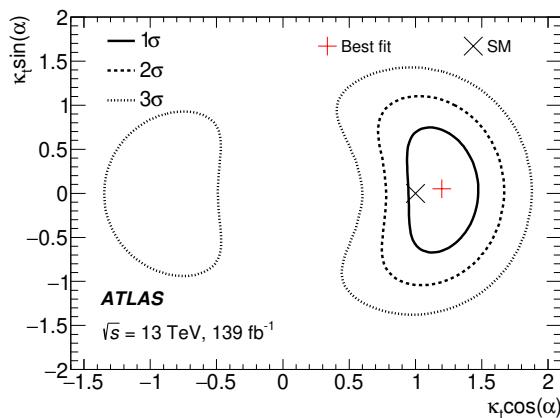
When possible, multiple decay  
channels can be combined...



# CP properties of Higgs-top coupling with ttH

## ATLAS ttH $H \rightarrow \gamma\gamma$

[Phys. Rev. Lett. 125 \(2020\) 061802](#)

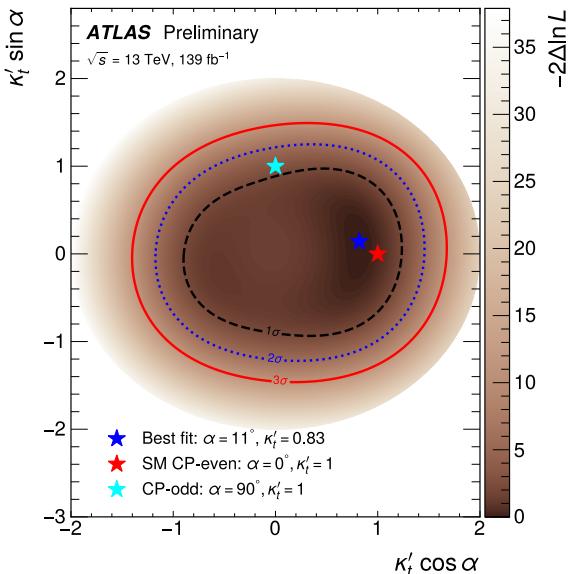


pure CP-odd coupling excluded at  $3.9\sigma$

$|\alpha| > 43$  deg excluded @ 95% CL.

## ATLAS ttH $H \rightarrow b\bar{b}$

[ATLAS-CONF-2022-016](#)

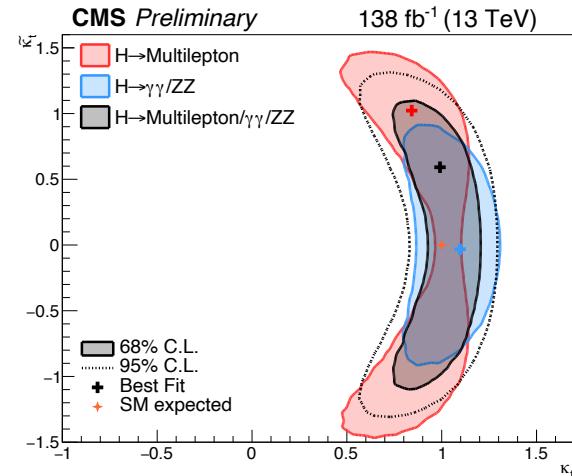


pure CP-odd coupling disfavoured at  $1.2\sigma$

$$\alpha = 11^\circ \begin{array}{l} + 55^\circ \\ - 77^\circ \end{array}$$

## CMS ttH $H \rightarrow \text{ML} + H \rightarrow \gamma\gamma + H \rightarrow ZZ$

[PAS HIG-21-006](#)



$$\mathcal{A}(Hff) = \frac{m_f}{v} \bar{\psi}_f (\kappa_t + i \tilde{\kappa}_t \gamma_5) \psi_f$$

pure CP-odd coupling excluded at  $3.7\sigma$

$$f_{CP}^{Htt} = \frac{\tilde{\kappa}_t^2}{\tilde{\kappa}_t^2 + \kappa_t^2}$$

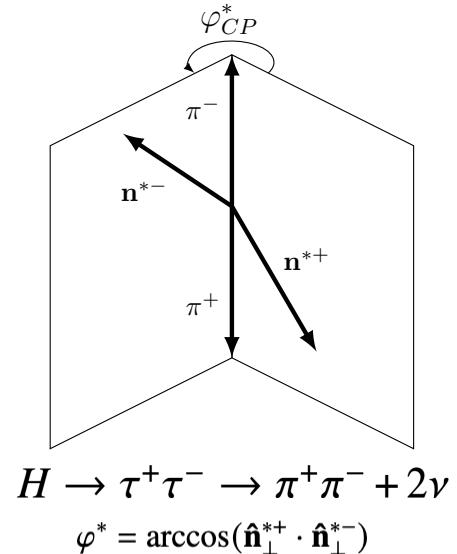
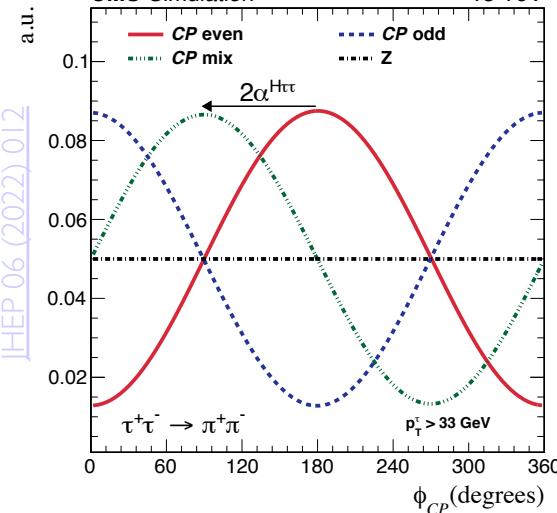
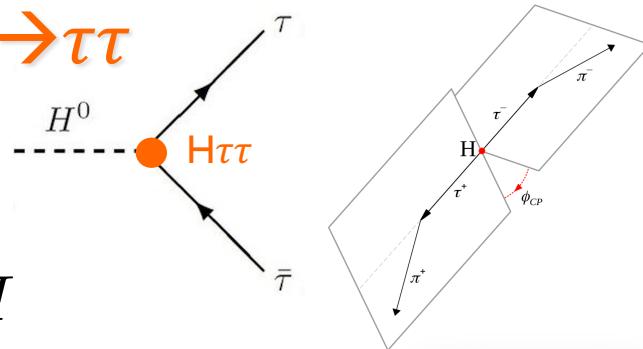
$$|f_{Htt}| = (\sin \alpha)^2$$

$$|f_{Htt}| = 0.28 \quad (< 0.55 \text{ at } 1\sigma)$$

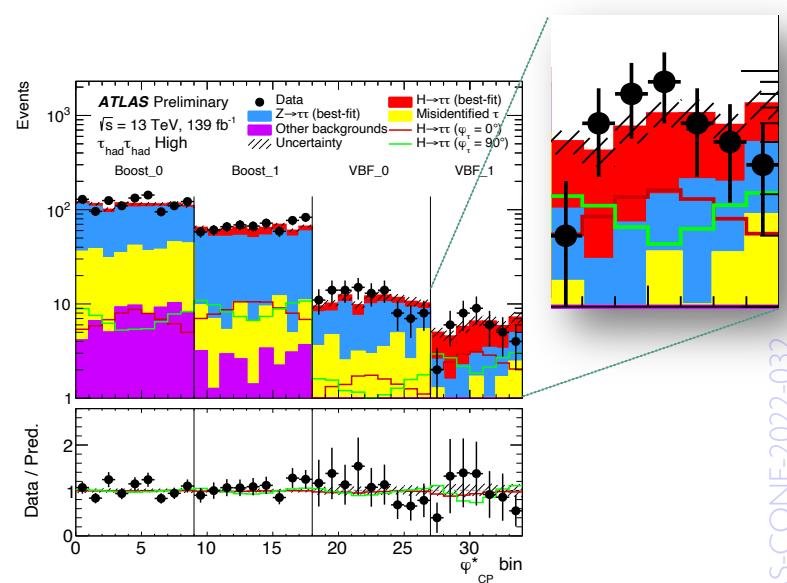
# CP properties of Higgs- $\tau$ coupling with $H \rightarrow \tau\tau$

Effective Lagrangian for Yukawa coupling to tau leptons parameterized by CP-Even and CP-odd components

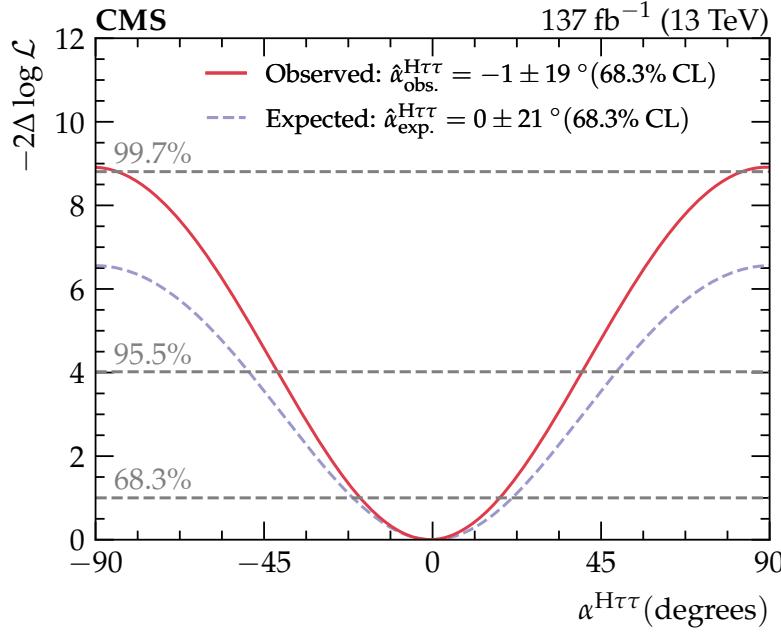
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{\nu} \kappa_\tau (\cos \phi_\tau \bar{\tau}\tau + \sin \phi_\tau \bar{\tau} i \gamma_5 \tau) H$$



Uses either the impact parameter direction for single-prong taus ( $\pi^\pm$ ) or  $\pi^0$  momentum for  $\tau \rightarrow \pi^\pm \pi^0 \rho \nu_\tau$  (also for 3-prong decays with  $\rho \rightarrow \pi^+ \pi^-$ )

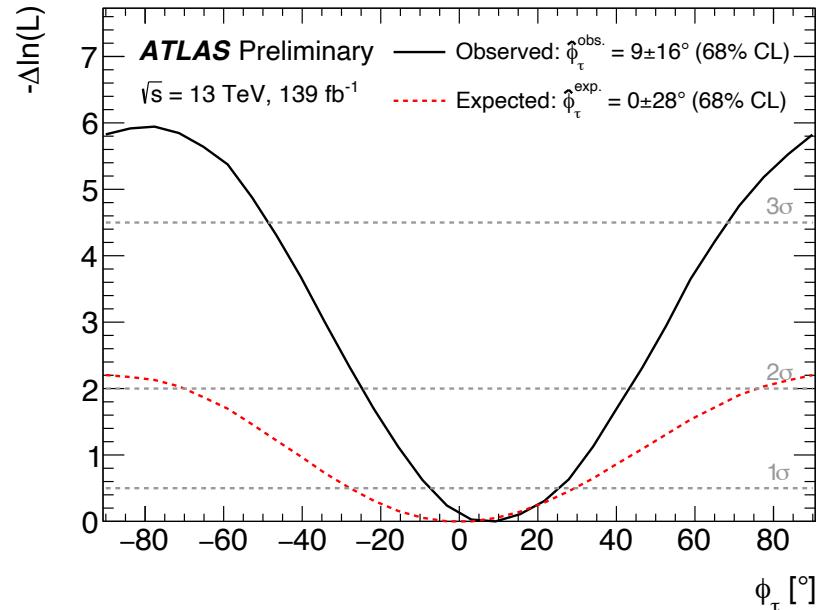


# CP properties of Higgs- $\tau$ coupling with $H \rightarrow \tau\tau$



$$\phi_\tau = -1 \pm 19^\circ \quad (21^\circ \text{ exp})$$

pure CP-odd coupling  
excluded at  $3\sigma$



$$\alpha^{\text{H}\tau\tau}(\text{CMS}) = \phi_\tau(\text{ATLAS})$$

$$\phi_\tau = 9 \pm 16^\circ \quad (28^\circ \text{ exp})$$

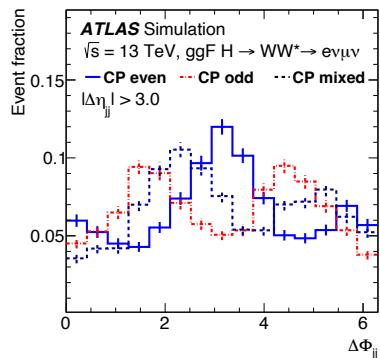
pure CP-odd coupling  
excluded at  $3.4\sigma$

# CP properties of Higgs-gluon coupling with ggF+VBF

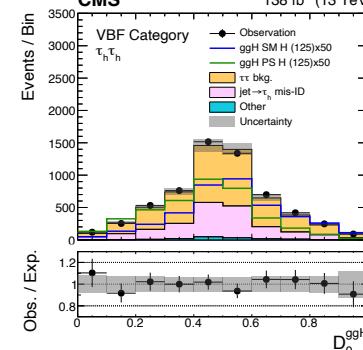
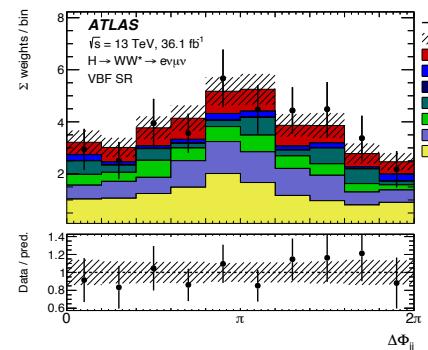
Study ggF+2 jets events: jet kinematics sensitive to Hgg coupling CP properties

arXiv2109.13808

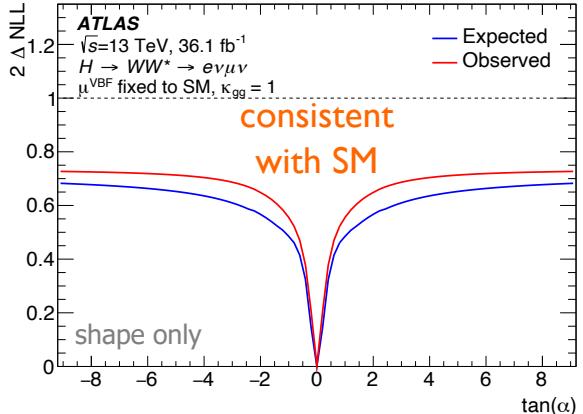
ATLAS:  $\Delta\Phi_{jj}$  ggF+VBF  $H \rightarrow WW^*$



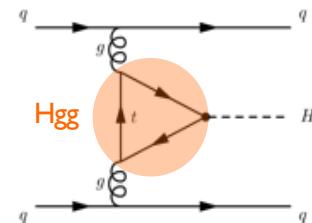
CMS:  $\Delta\Phi_{jj}$  or MELA discriminant ggF+VBF  $H \rightarrow \tau\tau$



$H \rightarrow WW^*$



$\alpha$  parameterizes CP-even/CP-odd mixture on Hgg coupling

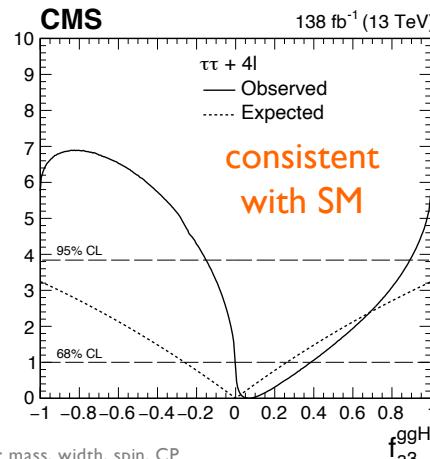


$$\mathcal{D}_{2\text{jet}}^{\text{VBF}} = \frac{\mathcal{P}_{\text{SM}}^{\text{ggH}} + \mathcal{P}_{0-}^{\text{ggH}}}{\mathcal{P}_{\text{SM}}^{\text{ggH}} + \mathcal{P}_{0-}^{\text{ggH}} + \mathcal{P}_{\text{SM}}^{\text{VBF}}} \quad \text{ggF vs VBF}$$

$$\mathcal{D}_{\text{CP}}^{\text{ggH}} = \frac{\mathcal{P}_{\text{SM}-0-}^{\text{ggH}}}{\mathcal{P}_{\text{SM}}^{\text{ggH}} + \mathcal{P}_{0-}^{\text{ggH}}} \quad \text{ggF CP-even vs ggF CP-odd}$$

$$\mathcal{D}_{0-}^{\text{ggH}} = \frac{\mathcal{P}_{\text{SM}}^{\text{ggH}}}{\mathcal{P}_{\text{SM}}^{\text{ggH}} + \mathcal{P}_{0-}^{\text{ggH}}} \quad \text{CP-even CP-odd interference}$$

$H \rightarrow \tau\tau$   
(combined with  $H \rightarrow 4l$ )



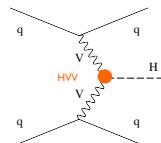
$f_{a3}^{\text{ggH}}$  parameterizes fraction of CP-odd BSM point-like Hgg coupling

# CP properties of HVV coupling (mult. prod. + H $\rightarrow$ 4l)

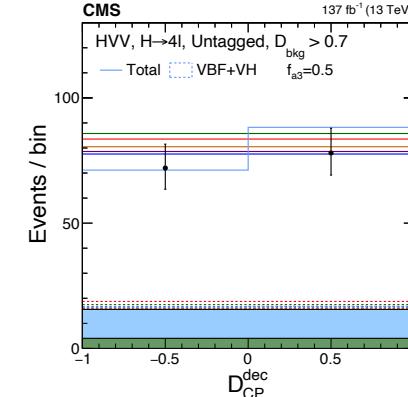
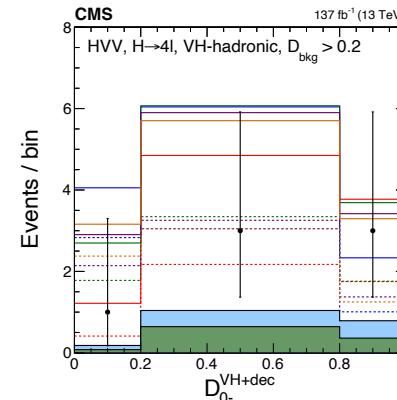
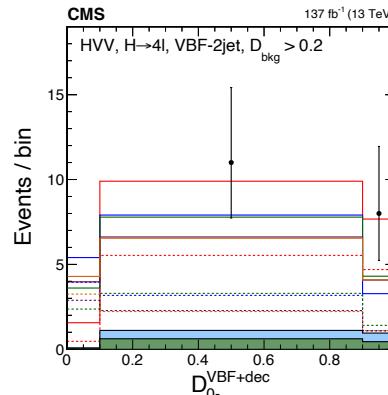
HVV couplings parameterized by tensor structures in scattering amplitude

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

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

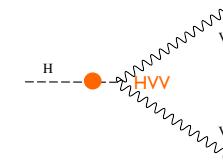


- data
- ZZ/Z $\gamma^*$
- Z+X
- Total VBF+VH
  - SM
  - $f_{a3}=1$
  - $f_{a2}=1$
  - $f_{a1}=1$
  - $f_{\Lambda 1}^{Z\gamma}=1$

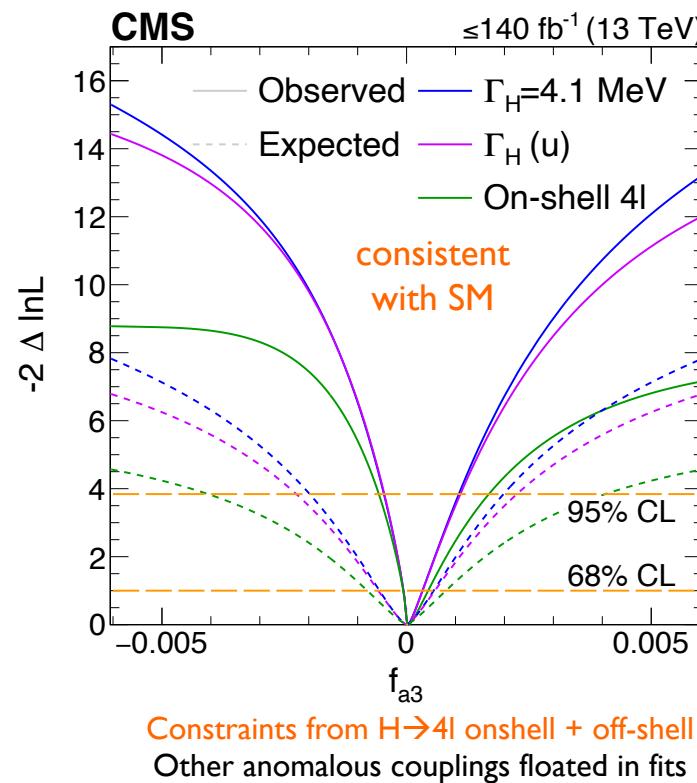
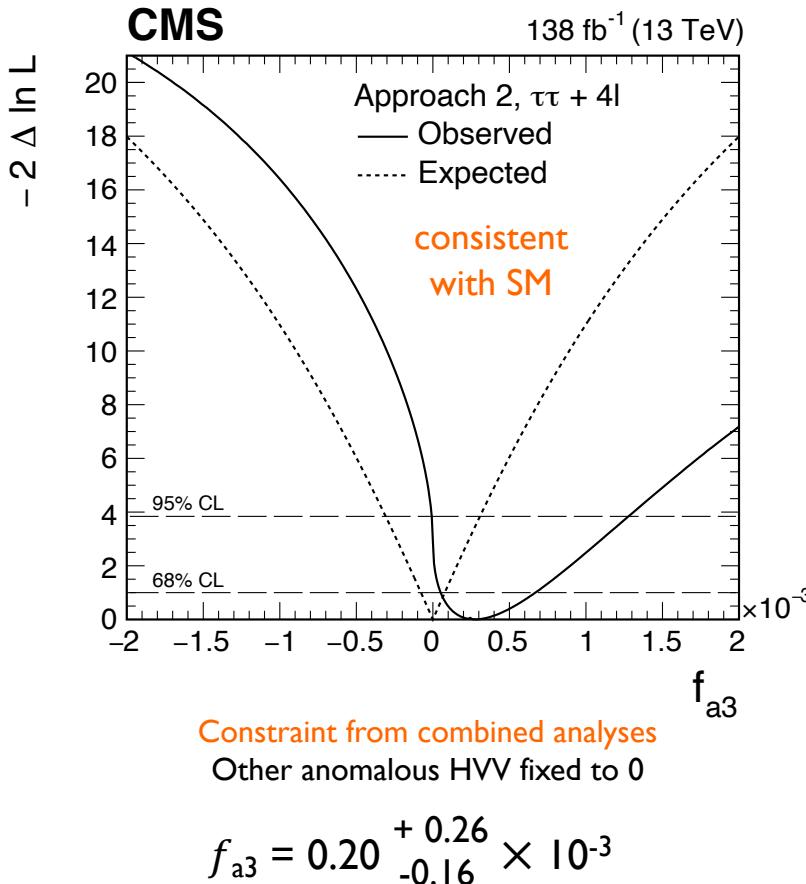


Multiple analyses constraining HVV couplings with ggH, VBF, VH, ttH, tH production and H $\rightarrow$ 4l, H $\rightarrow$ gg decay

$f_{a3}$  parameterizes fractional contribution of CP-odd HZZ coupling



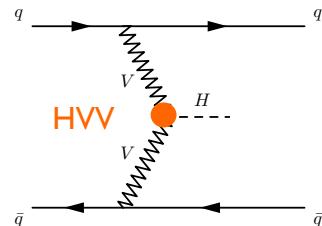
# CP properties of HVV coupling (mult. prod. + H $\rightarrow$ 4l; offshell)



$$f_{a3} = 0.024^{+0.32}_{-0.064} \times 10^{-3}$$

# CP properties of HVV coupling with VBF

SM Lagrangian augmented with CP-odd dim-6 operators involving Higgs and EW gauge fields in EFT formalism

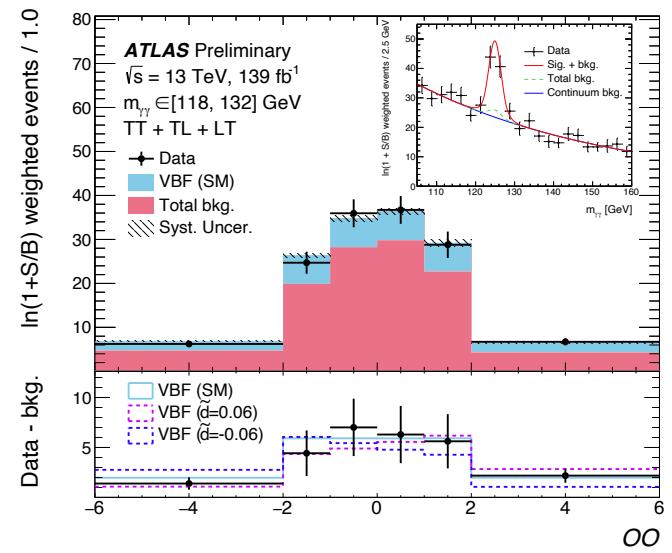
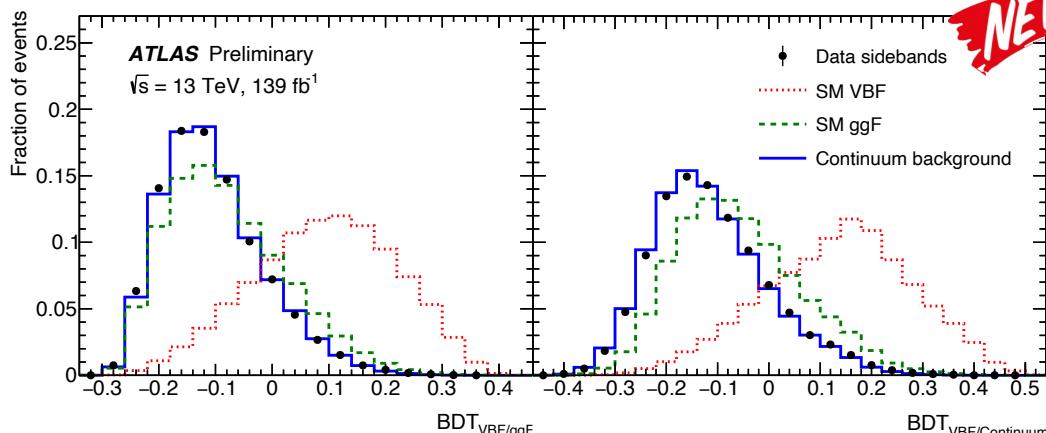


Approach pursued with various decay modes, here most recent ATLAS  $H \rightarrow \gamma\gamma$ , then combined with  $36 \text{ fb}^{-1} H \rightarrow \tau\tau$

$$c_{H\tilde{W}} = c_{H\tilde{B}} \\ c_{H\tilde{W}\tilde{B}} = 0$$

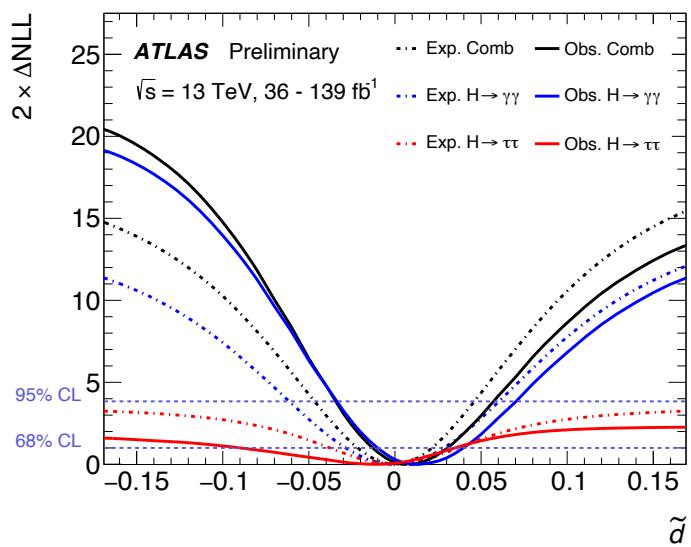
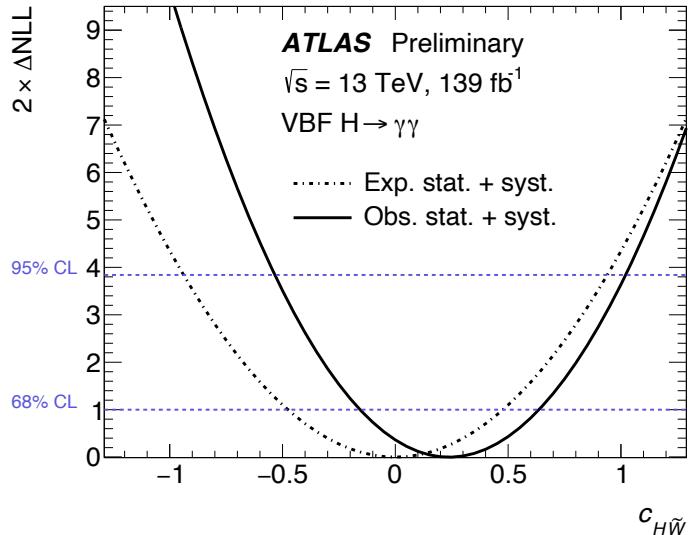
$$\tilde{d} = \frac{\nu^2}{\Lambda^2} c_{H\tilde{W}}$$

$$OO = \frac{2Re(\mathcal{M}_{SM}^* \mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$$



# CP properties of HVV coupling with VBF

**NEW**



$$\tilde{d} = \frac{\nu^2}{\Lambda^2} c_{H\tilde{W}}$$

	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 $H \rightarrow \tau\tau$	[-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

# Conclusions

Ten years after the Higgs boson discovery, we know its properties with impressive precision!

- Mass known to 0.11%
  - ✓ Only SM parameter unknown prior to LHC now one of the most precisely measured!
  - ✓ Was ~0.2% at end of Run I ATLAS+CMS
  - ✓ More measurements with full Run 2 dataset and ATLAS+CMS combination to come, precision will increase!
- Width measurements closing in on SM values →  $\Gamma_H = 3.2^{+2.5}_{-1.7}$  MeV
  - ✓ Evidence of Higgs off-shell production!
- Spin 0 already measured at Run I
  - ✓ Spin 1 and 2 hypotheses excluded at > 99.9% CL
- CP structure of various Higgs couplings probed for fermions ( $\text{top}, \tau$ ), gluons, EW vector bosons, with a variety of production and decay modes
  - ✓ Measurement globally in accord with SM CP-even hypothesis
  - ✓ Pure CP-odd  $\text{tH}$  coupling excluded  $3.9\sigma$
  - ✓ Pure CP-odd  $H\tau\tau$  coupling excluded  $3.4\sigma$

... some analyses still  
need to be finalized with full  
Run 2 dataset, and Run 3 is coming!

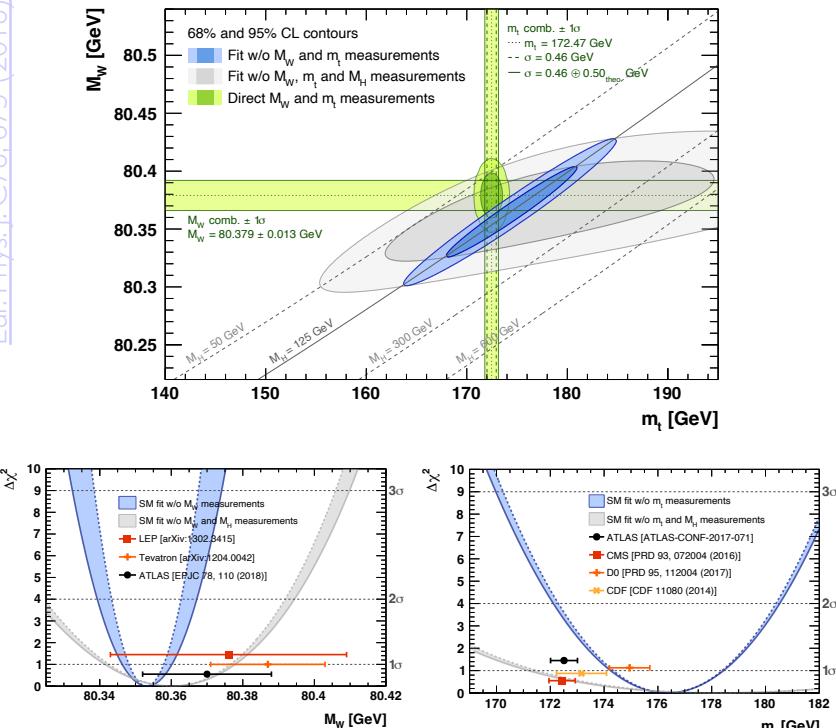
e<sup>iπ</sup>.

# More material

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# Knowing the Higgs mass values...

... allows to make precision predictions



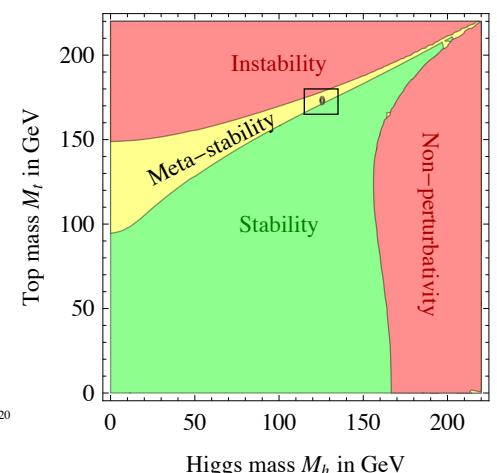
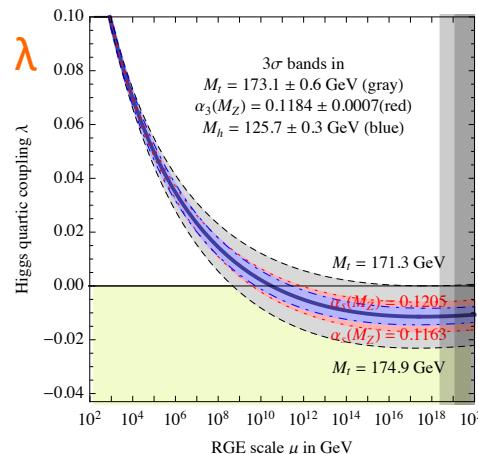
... but current  $m_H$  precision has little impact

... questions us on vacuum (meta) stability

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

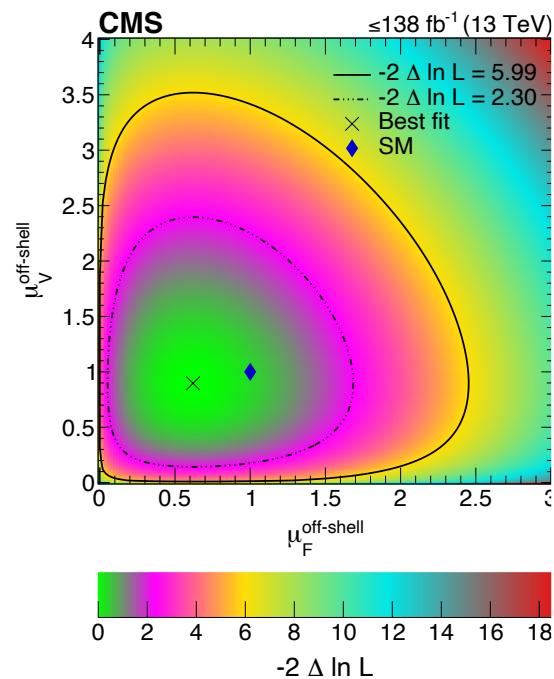
$$m_H = \sqrt{2\lambda}\nu$$

Running of the Higgs self coupling,  
assuming SM only at high scale

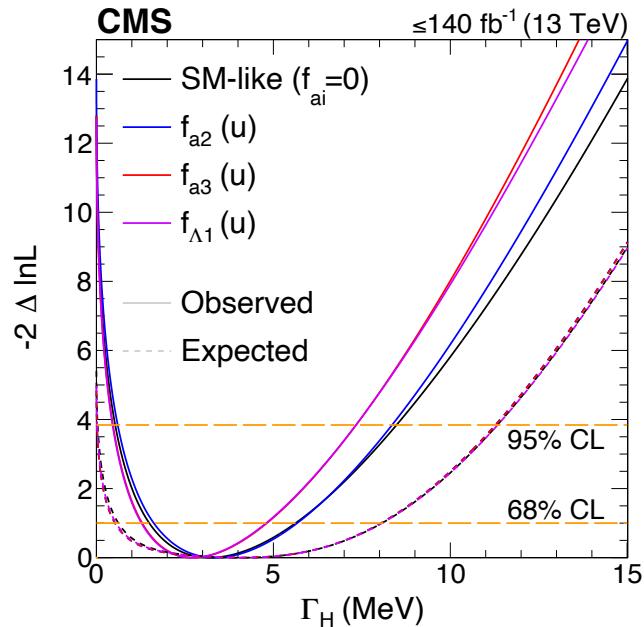
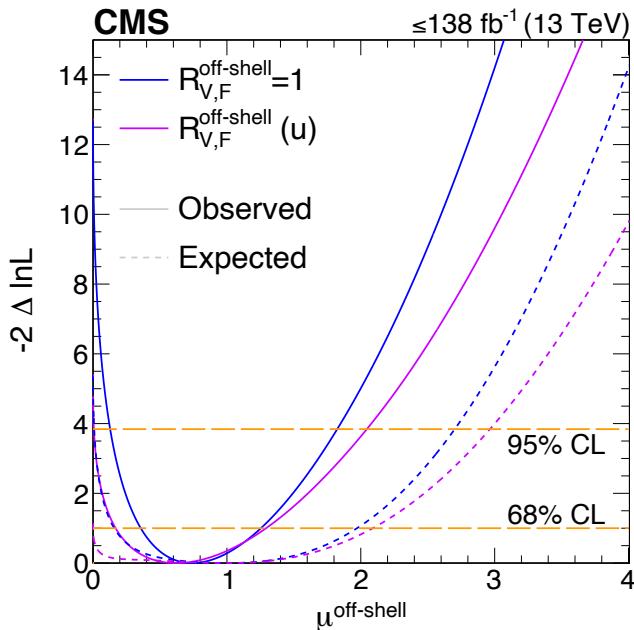


Vanishing quartic coupling at the Planck scale? Potential not bounded?  
... but interpretation more sensitive to precision on top quark mass

# More on Higgs width (also with anomalous HVV couplings)



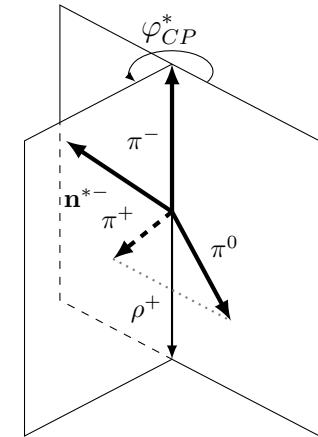
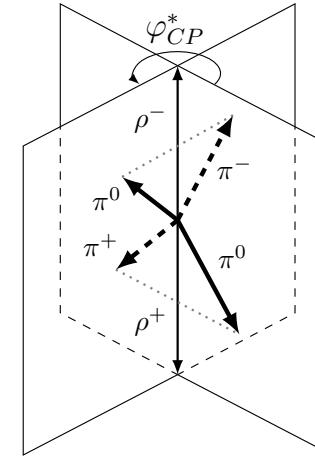
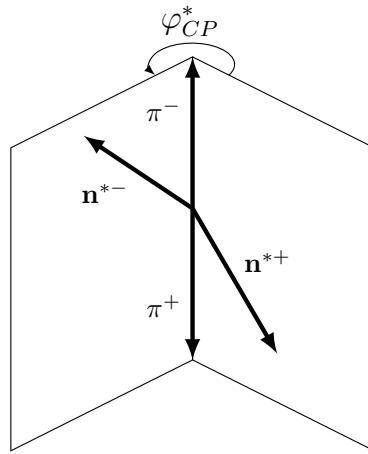
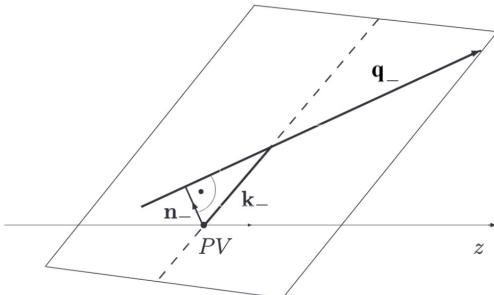
$\mu_F \rightarrow \text{gg mode}$   
 $\mu_V \rightarrow \text{EW mode}$



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

Param.	Cond.	Observed	Expected
		68%   95% CL	68%   95% CL
$\Gamma_H$	SM-like	$3.2^{+2.4}_{-1.7}   ^{+5.3}_{-2.7}$	$+4.0   ^{+7.2}_{-4.065}$
$\Gamma_H$	$f_{a2}(u)$	$3.4^{+2.3}_{-1.8}   ^{+5.0}_{-2.8}$	$+3.9   ^{+7.2}_{-4.085}$
$\Gamma_H$	$f_{a3}(u)$	$2.7^{+2.1}_{-1.4}   ^{+4.6}_{-2.2}$	$+3.9   ^{+7.2}_{-4.085}$
$\Gamma_H$	$f_{\Delta 1}(u)$	$2.7^{+2.1}_{-1.4}   ^{+4.5}_{-2.2}$	$+4.0   ^{+7.2}_{-4.081}$

# H $\rightarrow\tau\tau$ decay CP



Impact parameter

directional distance of closest approach of charged particle's track to reconstructed PV of the event

4-vectors boosted to the rest frame of visible di- $\tau$  Zero Momentum Frame (e.g. two decay charged particles)

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

impact parameter

$$\varphi^* = \arccos(\hat{\mathbf{n}}_{\perp}^{*+} \cdot \hat{\mathbf{n}}_{\perp}^{*-})$$

$$O_{CP}^* = \hat{\mathbf{q}}^{*-} \cdot (\hat{\mathbf{n}}_{\perp}^{*+} \times \hat{\mathbf{n}}_{\perp}^{*-})$$

$$\varphi_{CP}^* = \begin{cases} \varphi^* & \text{if } O_{CP}^* \geq 0 \\ 360^\circ - \varphi^* & \text{if } O_{CP}^* < 0 \end{cases}$$

$H \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^0\nu\pi^-\pi^0\nu$

$\rho$  decay plane

$$\varphi^* = \arccos(\hat{\mathbf{q}}_{\perp}^{*0+} \cdot \hat{\mathbf{q}}_{\perp}^{*0-})$$

$$O_{CP}^* = \hat{\mathbf{q}}^{*-} \cdot (\hat{\mathbf{q}}_{\perp}^{*0+} \times \hat{\mathbf{q}}_{\perp}^{*0-})$$

$$\varphi'^* = \begin{cases} \varphi^* & \text{if } O_{CP}^* \geq 0 \\ 360^\circ - \varphi^* & \text{if } O_{CP}^* < 0. \end{cases} \quad \varphi_{CP}^* = \begin{cases} \varphi'^* & \text{if } y_+^\rho y_-^\rho \geq 0 \\ \varphi'^* + 180^\circ & \text{if } y_+^\rho y_-^\rho < 0. \end{cases} \quad y_\pm^\rho = \frac{E_{\pi^\pm} - E_{\pi^0}}{E_{\pi^\pm} + E_{\pi^0}}$$