Lecture 2

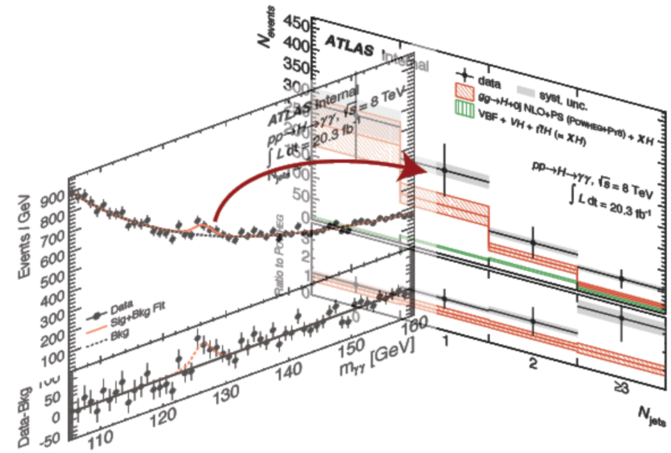
Properties of the Higgs Boson

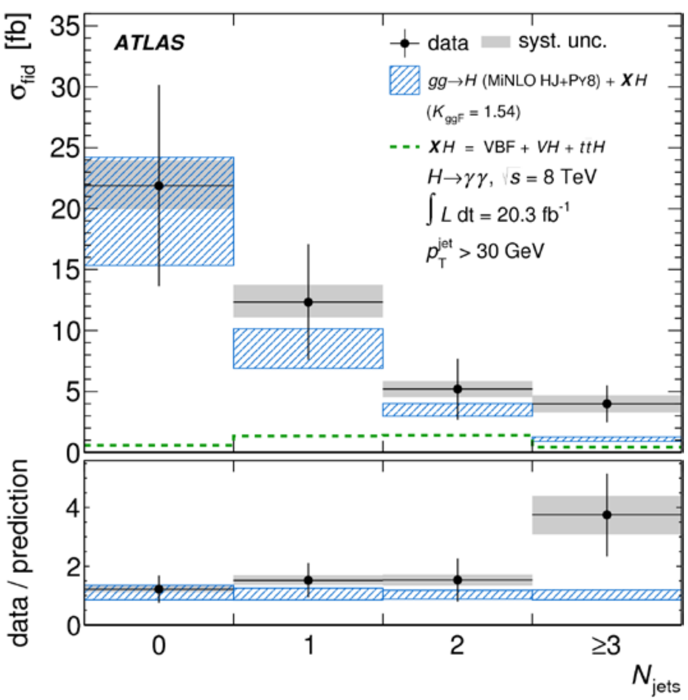
H→γγ: Differential Distributions

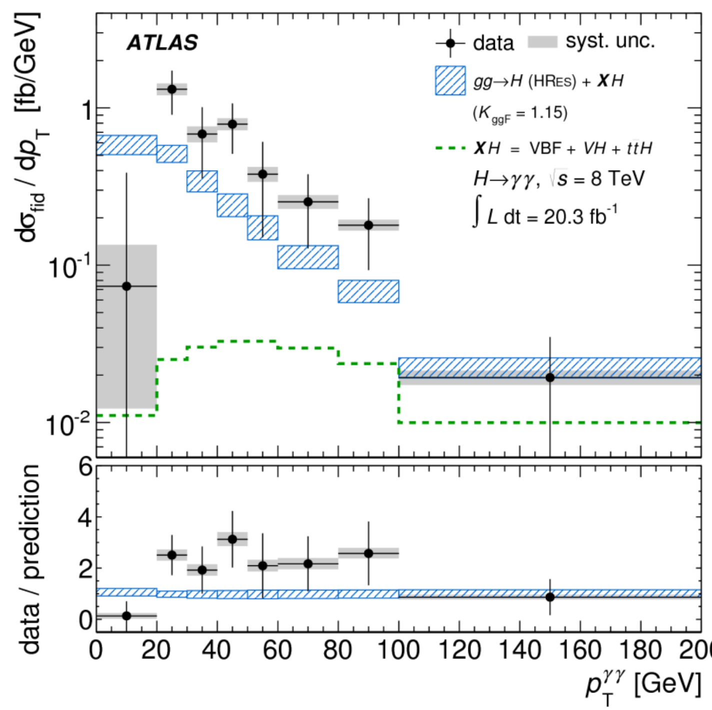
Study kinematics of candidate events:

- fit $m_{\gamma\gamma}$ distributions into bins of kinematic variables such as N_{jet} and $p_T^{\gamma\gamma}$,

- unfold to particle-level cross sections



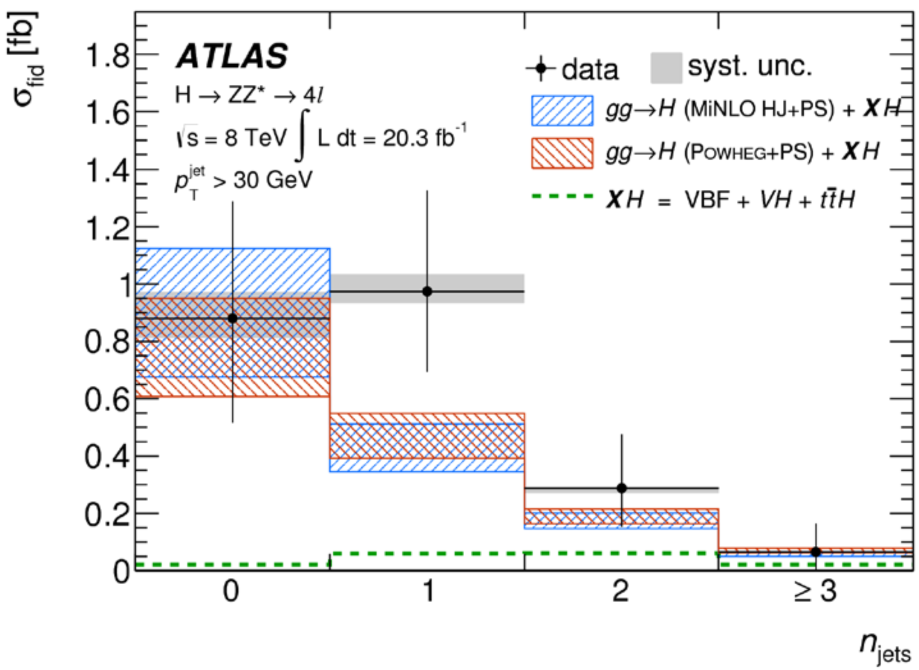


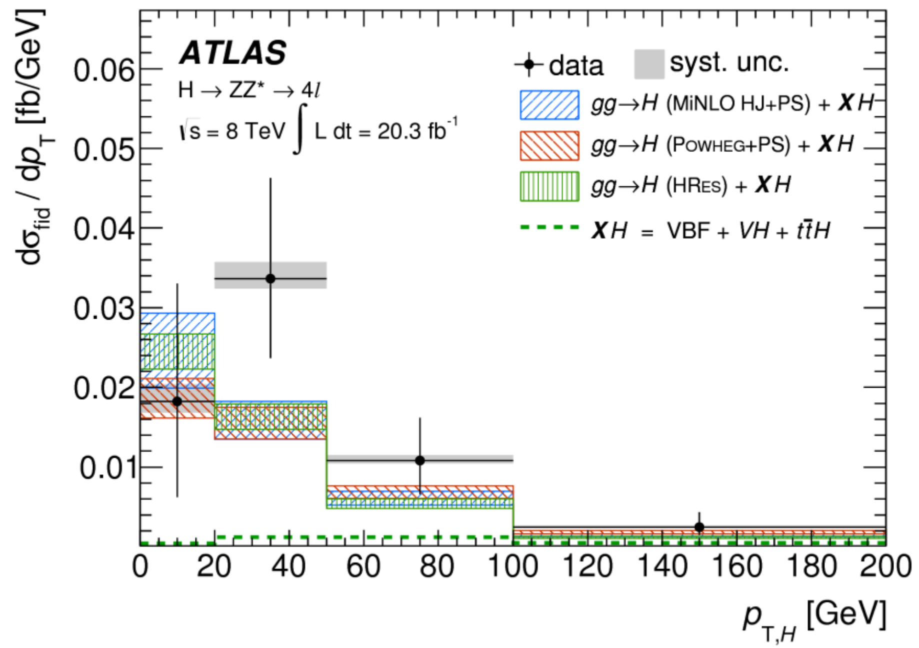


Good agreements between data and the SM expectations (within statistics)

H→ZZ*→4ℓ Differential Distributions

Similar measurements from $H \rightarrow ZZ^* \rightarrow 4\ell$ with slightly different fiducial volume and much low statistics.

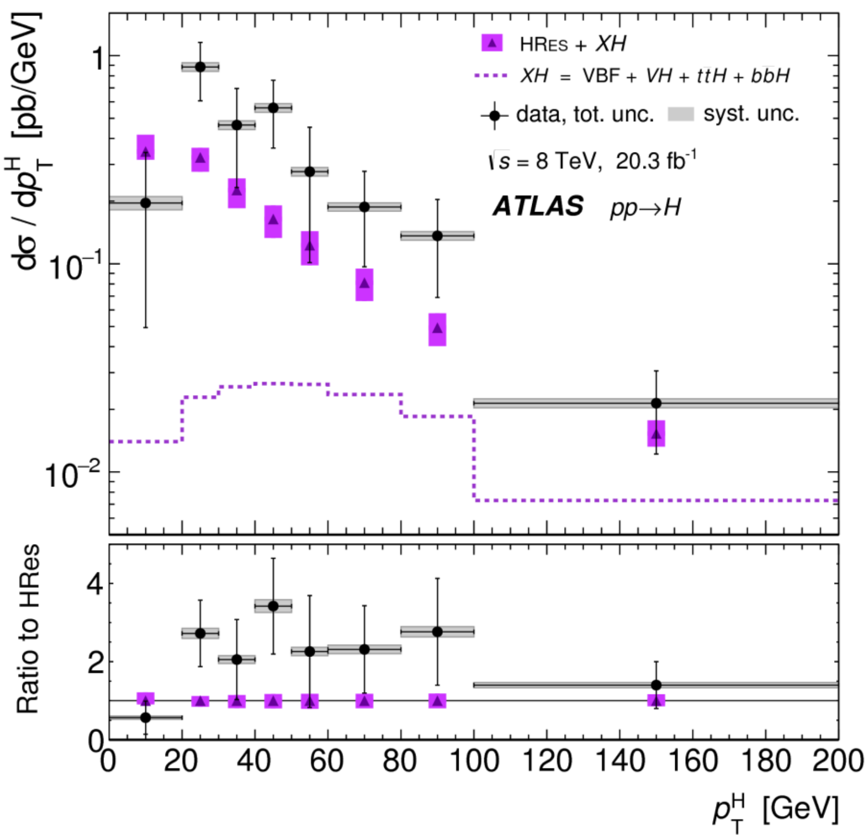




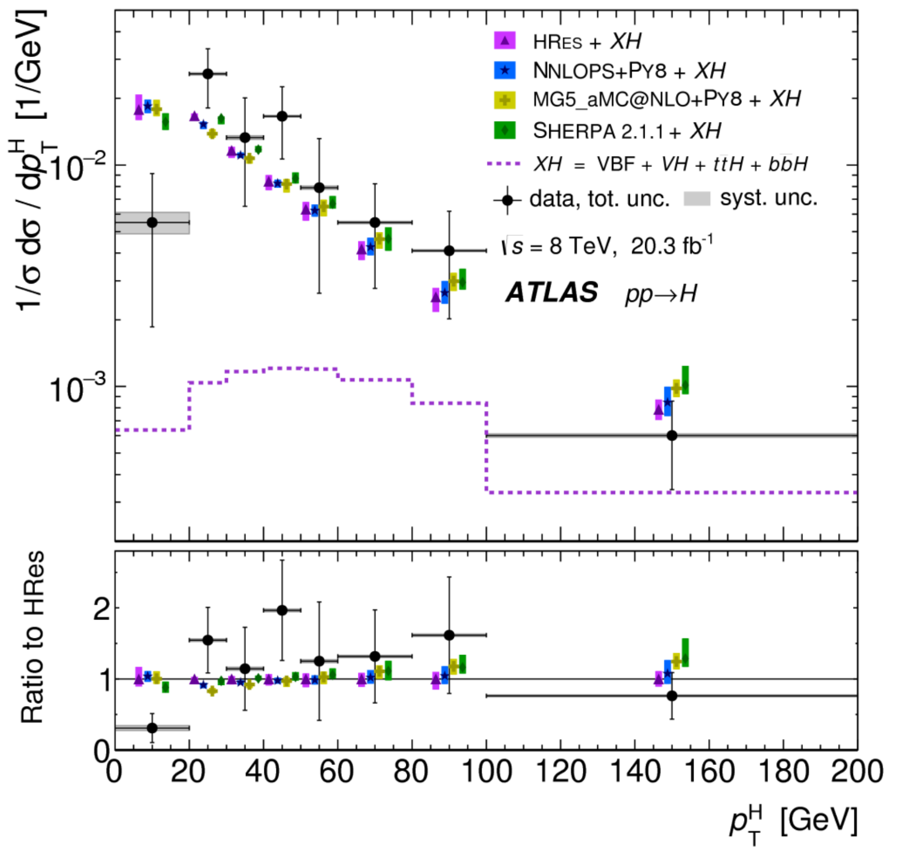
$\gamma\gamma$ and 4ℓ Combination

Combination after correction to the full acceptance.
High overall rate, but good agreement in shape

absolute



normalized



Higgs boson mass measurements

$H \rightarrow \gamma\gamma$: m_H Measurement

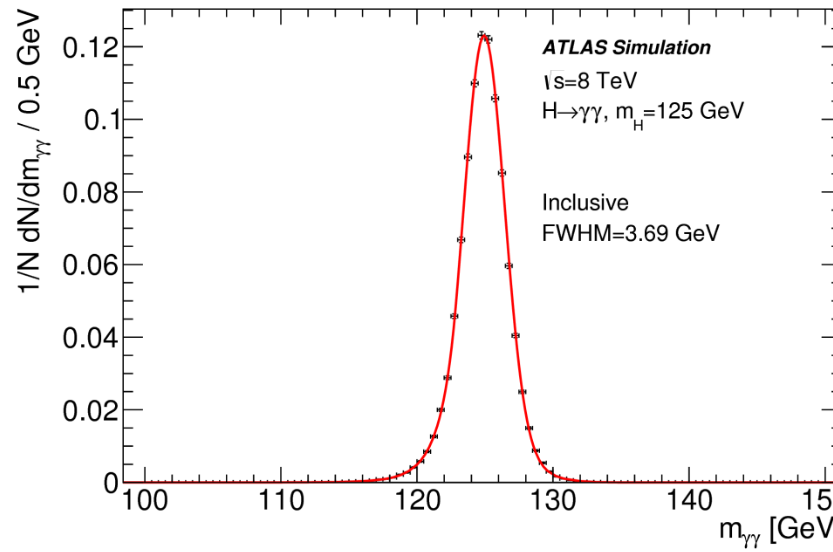
arXiv:14070558 (CMS)

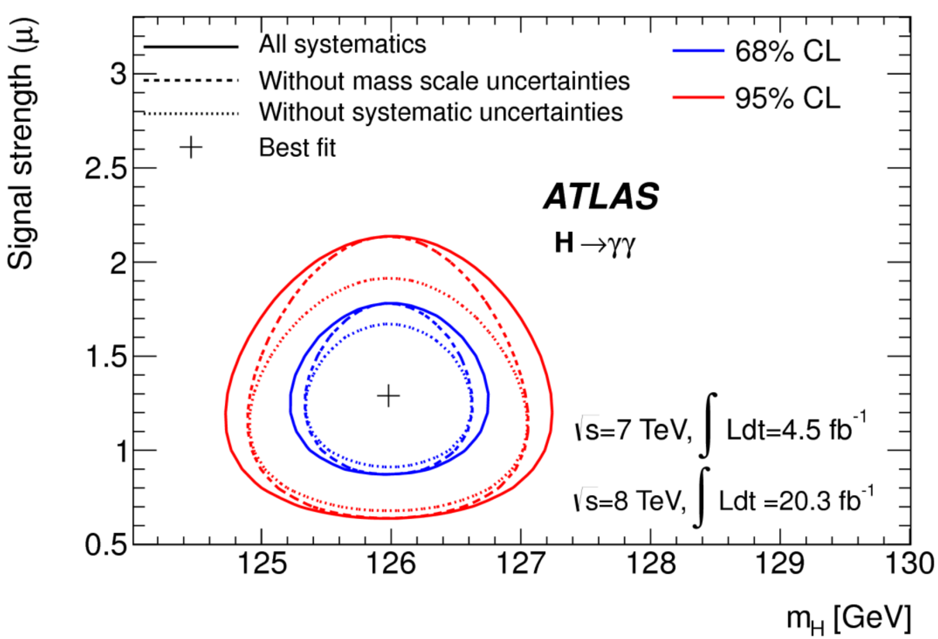
arXiv:1406.3827 (ATLAS)

Full $H \rightarrow \gamma\gamma$ decay reconstruction, excellent mass resulution $\sigma \sim 1.5$ GeV

Systematic uncertainties dominated by those of photon energy calibration.

Largely independent of signal strength





ATLAS:
$$m_H = 125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst})\ \text{GeV}$$

CMS:
$$m_H = 124.70 \pm 0.31(\text{stat}) \pm 0.15(\text{syst})\ \text{GeV}$$

Note a 1.3 GeV ($\sim 2\sigma$) difference between the two measurements

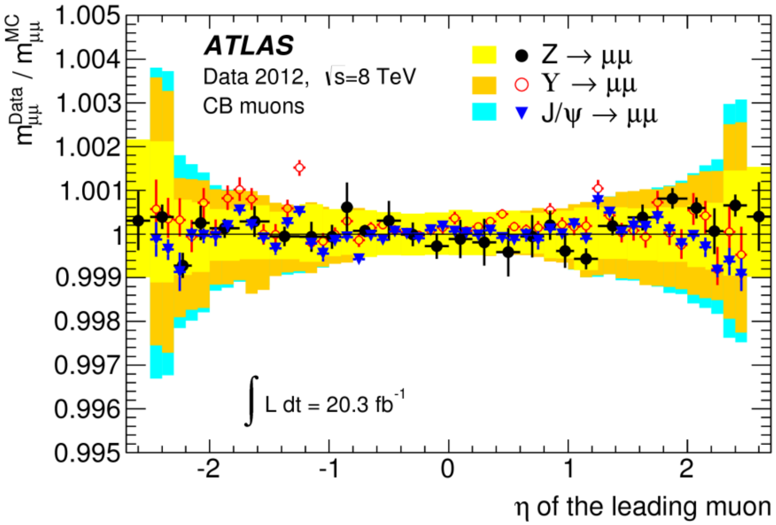
H→ZZ*→4ℓ: m_H Measurement

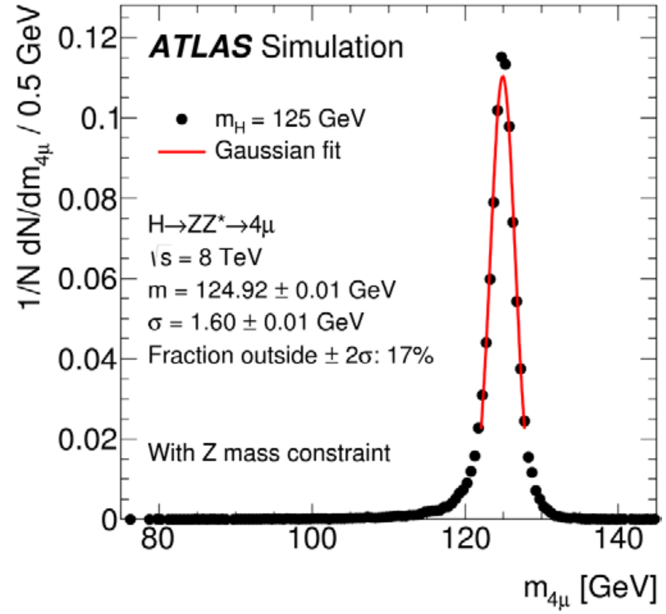
Full $H \to ZZ^* \to 4\ell$ reconstruction, excellent $m_{4\ell}$ mass resolution

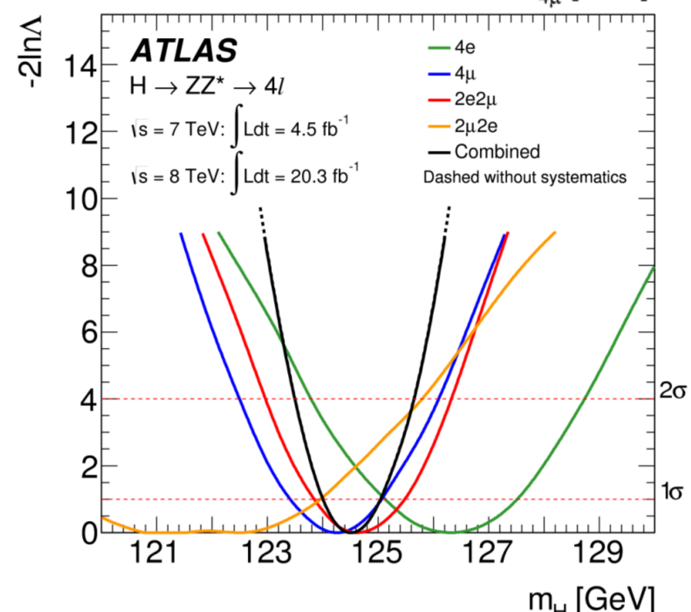
Energy/momentum calibration from data of "Standard candle" events

arXiv:1406.3827 (ATLAS)

arXiv:1312.5353 (CMS)







ATLAS:

$$m_H = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst})\ \text{GeV}$$

CMS:

$$m_H = 125.6 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})\ \text{GeV}$$

Good agreements between the two measurements

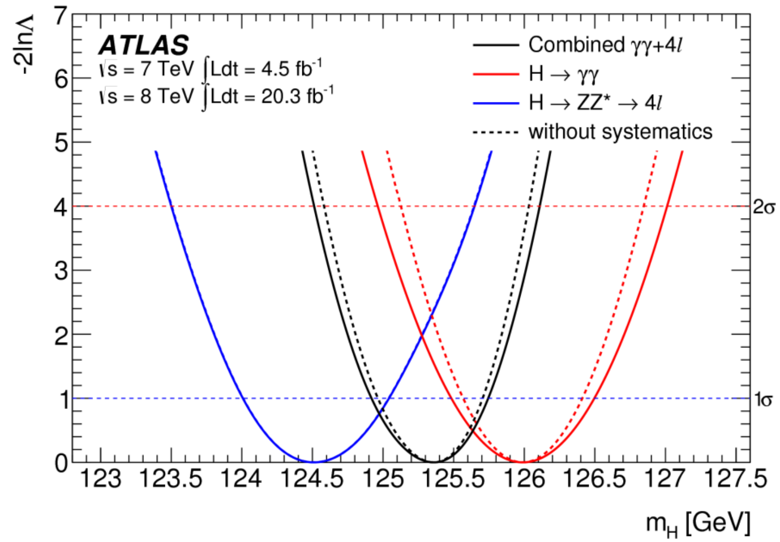
Individual Experiment Combination

ATLAS:

$$m_H^{\gamma\gamma} = 125.98 \pm 0.42(stat) \pm 0.28(syst)\ \text{GeV}$$

$$m_H^{4\ell} = 124.51 \pm 0.52(stat) \pm 0.06(syst)\ \text{GeV}$$

a 2.0σ difference between $m_H^{\gamma\gamma}$ and $m_H^{4\ell}$



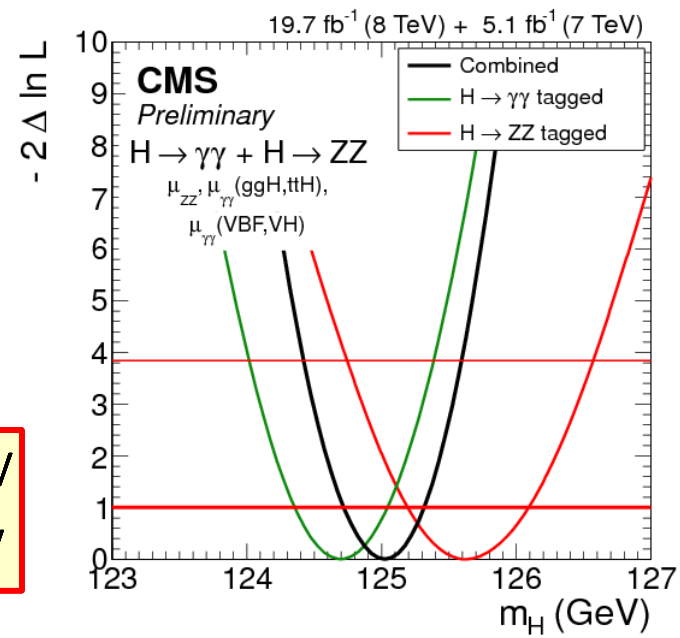
arXiv:1406.3827 (ATLAS)

CMS:

$$m_H^{\gamma\gamma} = 124.70 \pm 0.31(stat) \pm 0.15(syst)\ \text{GeV}$$

$$m_H^{4\ell} = 125.6 \pm 0.4(stat) \pm 0.2(syst)\ \text{GeV}$$

$\sim 1^{+}\sigma$ difference in the other direction



CMS-PAS-HIG-14-009

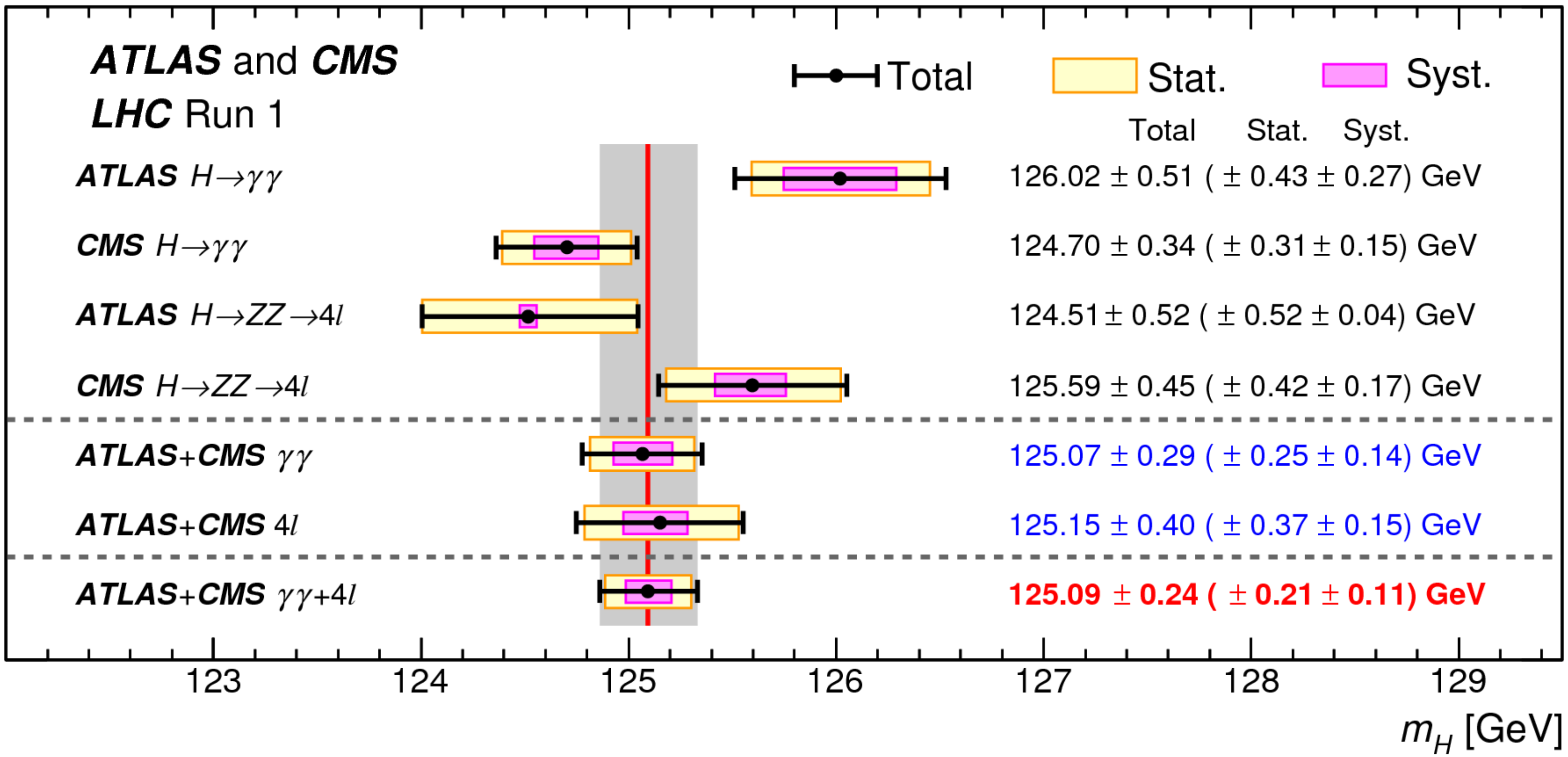
Combined:

$$m_H^{ATLAS} = 125.36 \pm 0.37(stat) \pm 0.18(syst)\ \text{GeV}$$

$$m_H^{CMS} = 125.03 \pm 0.27(stat) \pm 0.14(syst)\ \text{GeV}$$

ATLAS and CMS Combination

Combining measurements in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ taking into account correlations of uncertainties

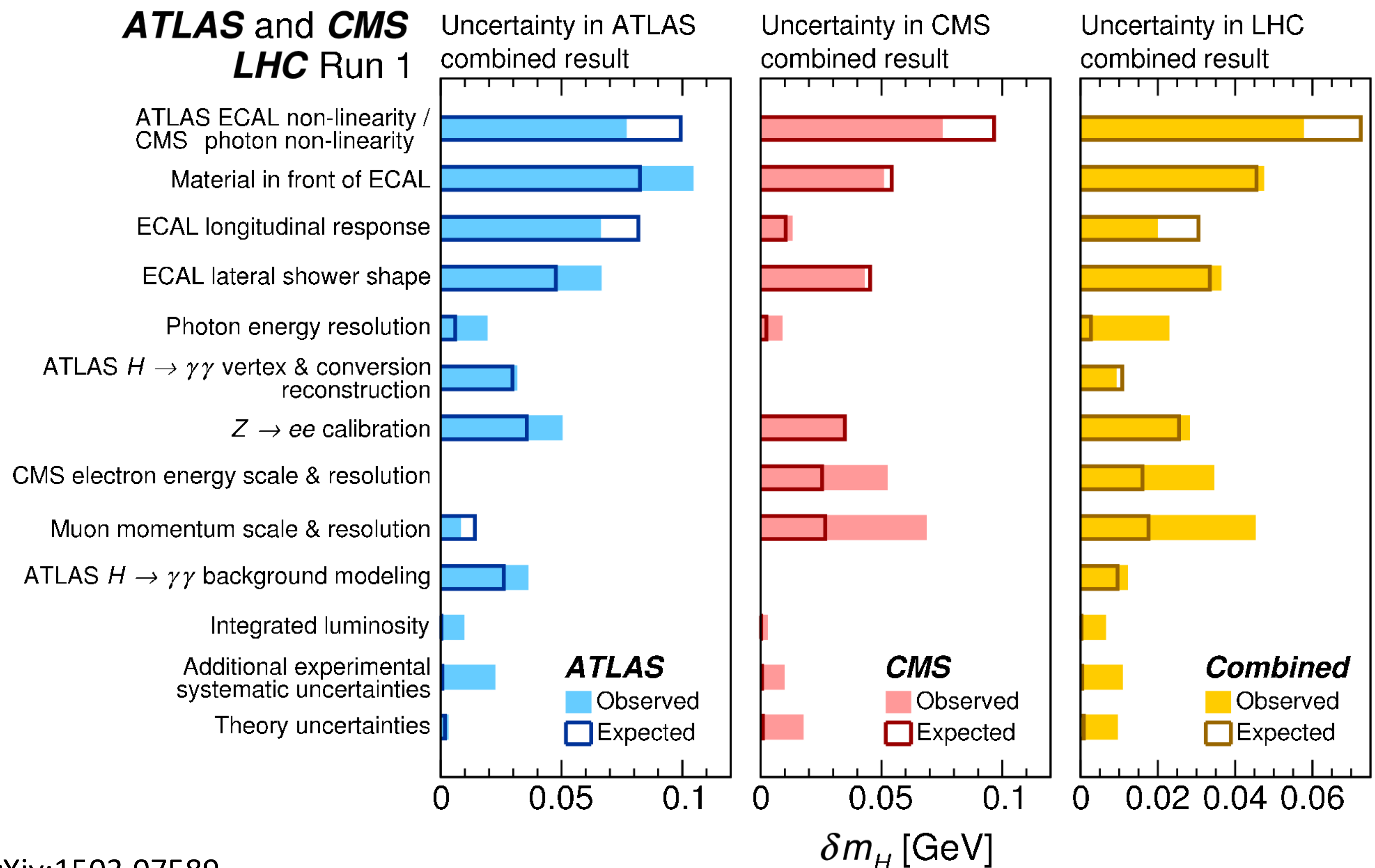


$$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) = 125.09 \pm 0.24 \text{ GeV}$$

arXiv:1503.07589

ATLAS and CMS Combination

Leading systematic uncertainties



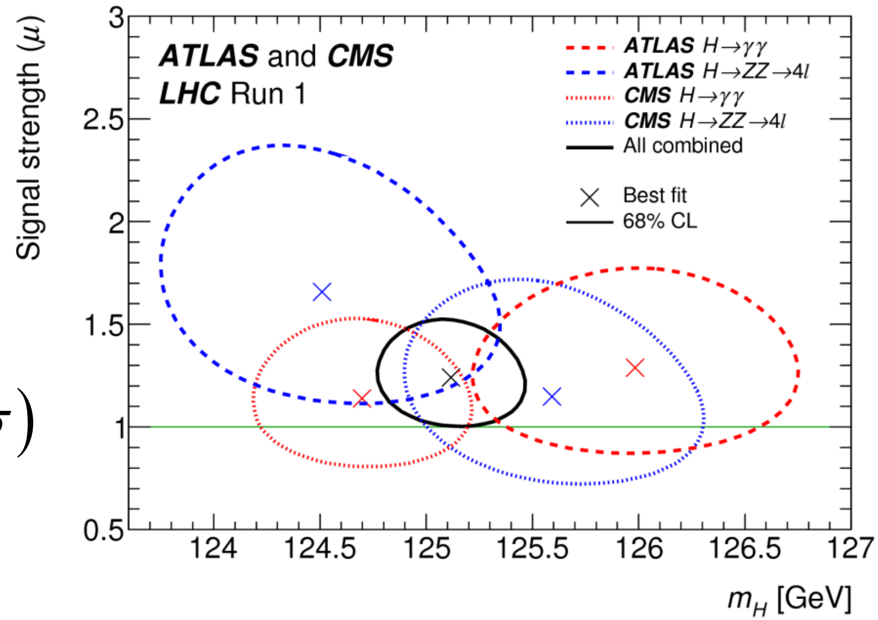
arXiv:1503.07589

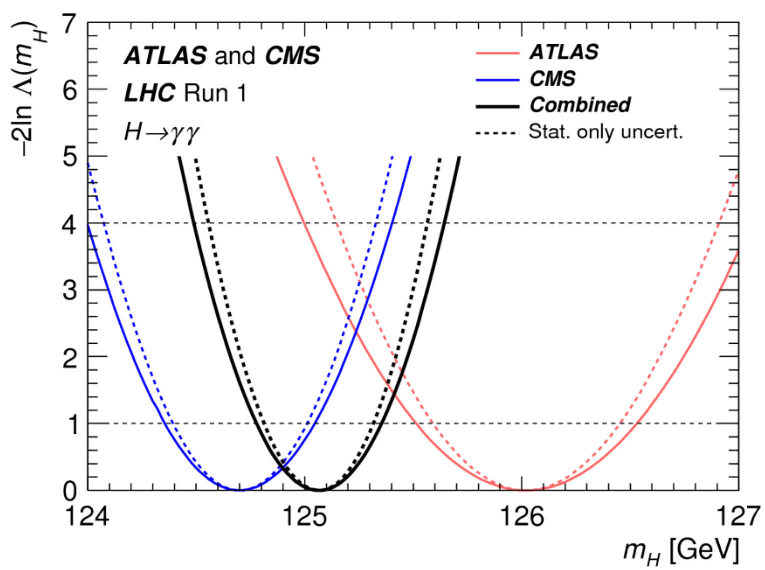
ATLAS and CMS Combination

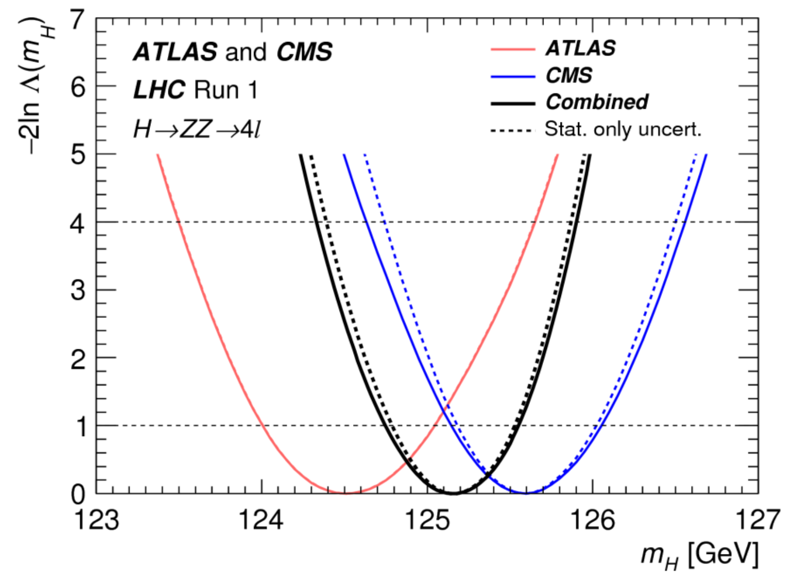
Some tension between ATLAS and CMS individual measurements

$$m_{\gamma\gamma}^{ATLAS} - m_{\gamma\gamma}^{CMS} = 1.3 \pm 0.6 \text{ GeV } (2.1\sigma)$$
$$m_{4\ell}^{ATLAS} - m_{4\ell}^{CMS} = -0.9 \pm 0.7 \text{ GeV } (1.3\sigma)$$

Statistics? Calibration?





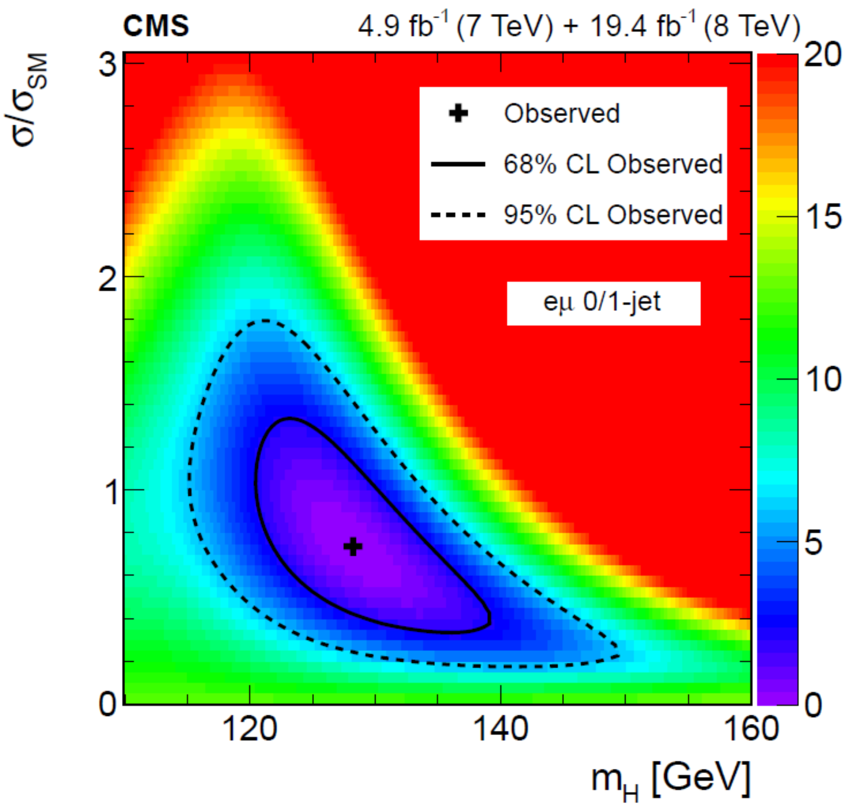


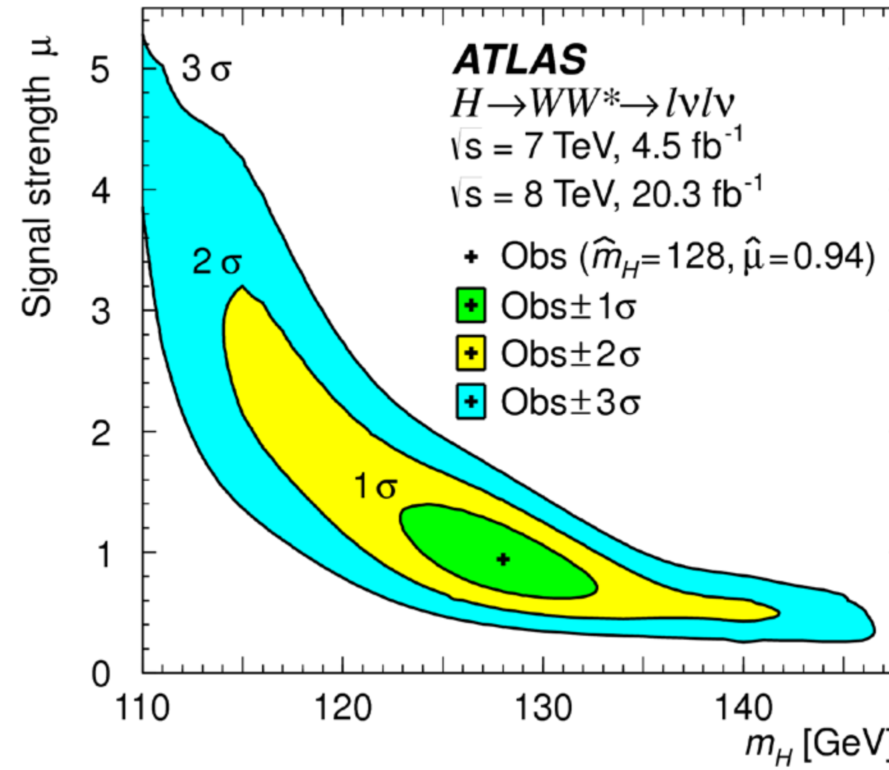
arXiv:1503.07589

H→WW*→ℓνℓν: Mass Estimator

No full reconstruction, but still sensitive to the Higgs boson mass,

(~15% resolution at 125 GeV)





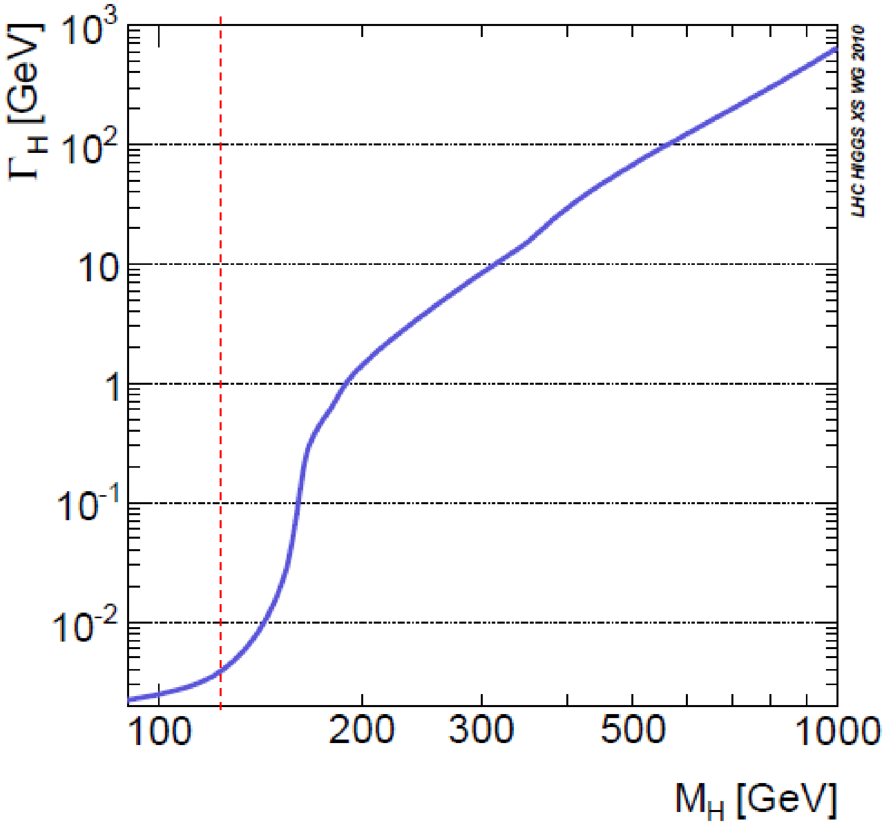
CMS: $m_H = 125.5^{+3.6}_{-3.8}$ GeV assuming SM rate.

If were not for $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$, $H \to WW^* \to \ell\nu\ell\nu$ would be the main final state for the mass measurement (think about top quark!).

Higgs boson width measurements

Higgs Boson Width

SM @ 125 GeV: $\Gamma_h \approx 4.07$ MeV $\ll$ smaller than the experimental resolutions of direct measurements



For measurements: 

hard to measure experimentally though indirect measurements can significantly improve the precision

For searches: 

Even a small contribution to the width from potential new physics can lead to a sizable decay BR

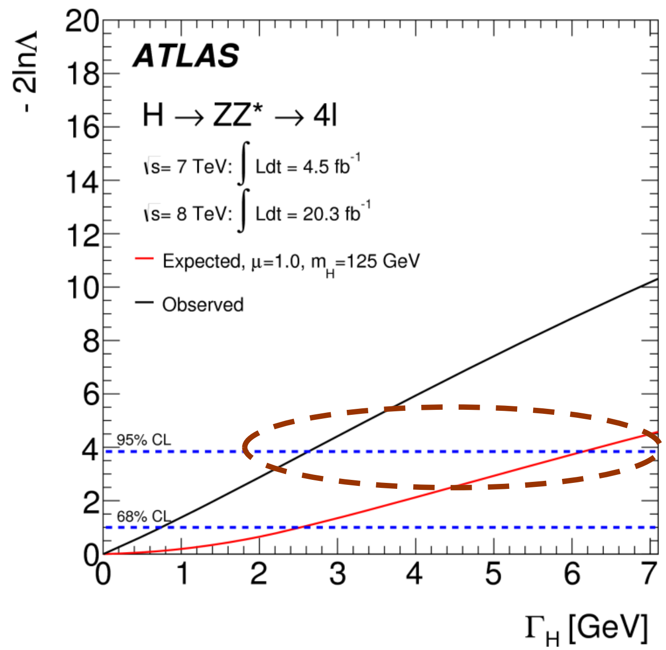
Direct Width Measurement

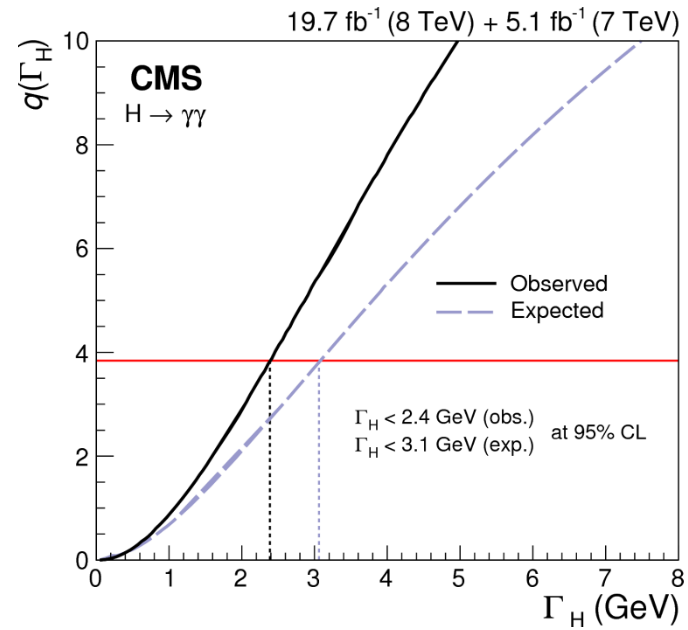
The Higgs width can be in principle extracted from the $m_{\gamma\gamma}$ or $m_{4\ell}$ distributions with the signal lineshape

$$\text{Breit-Wigner}(m, \Gamma_H) \otimes \text{Resultion}(\sigma)$$

Limited by detector mass resolution, statistics and backgrounds

arXiv:1406.3827 (ATLAS)





arXiv:1407.0558 (CMS)

The observed high μ value plays an important role in the difference between the observation and the expectation.

Observed (expected) upper limit on Γ_H in GeV

Final state	$H \to \gamma\gamma$	$H \to ZZ^* \to 4\ell$
ATLAS	5.0 (6.2)	2.6 (6.2)
CMS	2.4 (3.1)	3.4 (2.8)

x2 difference in sensitivity between ATLAS and CMS?

Indirect Width Measurement

$$\text{Process } i \to H \to f: \quad \frac{d\sigma}{dm^2} \sim \frac{g_i^2 g_f^2}{\left(m^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2}$$

$$\text{On-peak:} \quad \frac{d\sigma}{dm^2} \sim \frac{\boxed{g_i^2 g_f^2}}{m_H^2 \boxed{\Gamma_H^2}}$$

$$\text{Off-peak:} \quad \frac{d\sigma}{dm^2} \sim \frac{\boxed{g_i^2 g_f^2}}{\left(m^2 - m_H^2\right)^2}$$

on-shell measures $\left(g_i g_f / \Gamma_H\right)^2$,

off-shell measures $\left(g_i g_f\right)^2$

Extract Γ_H by comparing the on-shell and off-shell signal strength measurements assuming

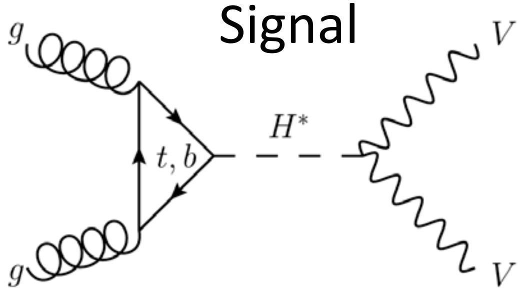
- No BSM contribution in the loops;
- the couplings are the same on- and off-shell

(thanks to the large off-shell contribution)

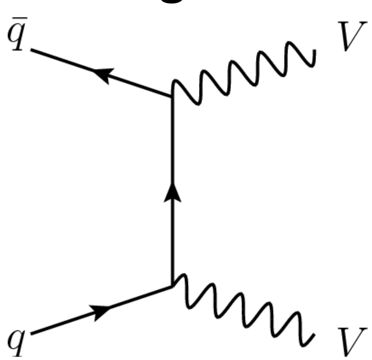
Indirect Width Measurement

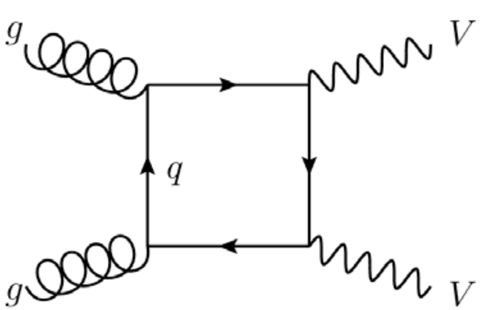
Caola & Melnikov, arXiv:1307.4935
Campbell & Ellis, arXiv:1311.3589

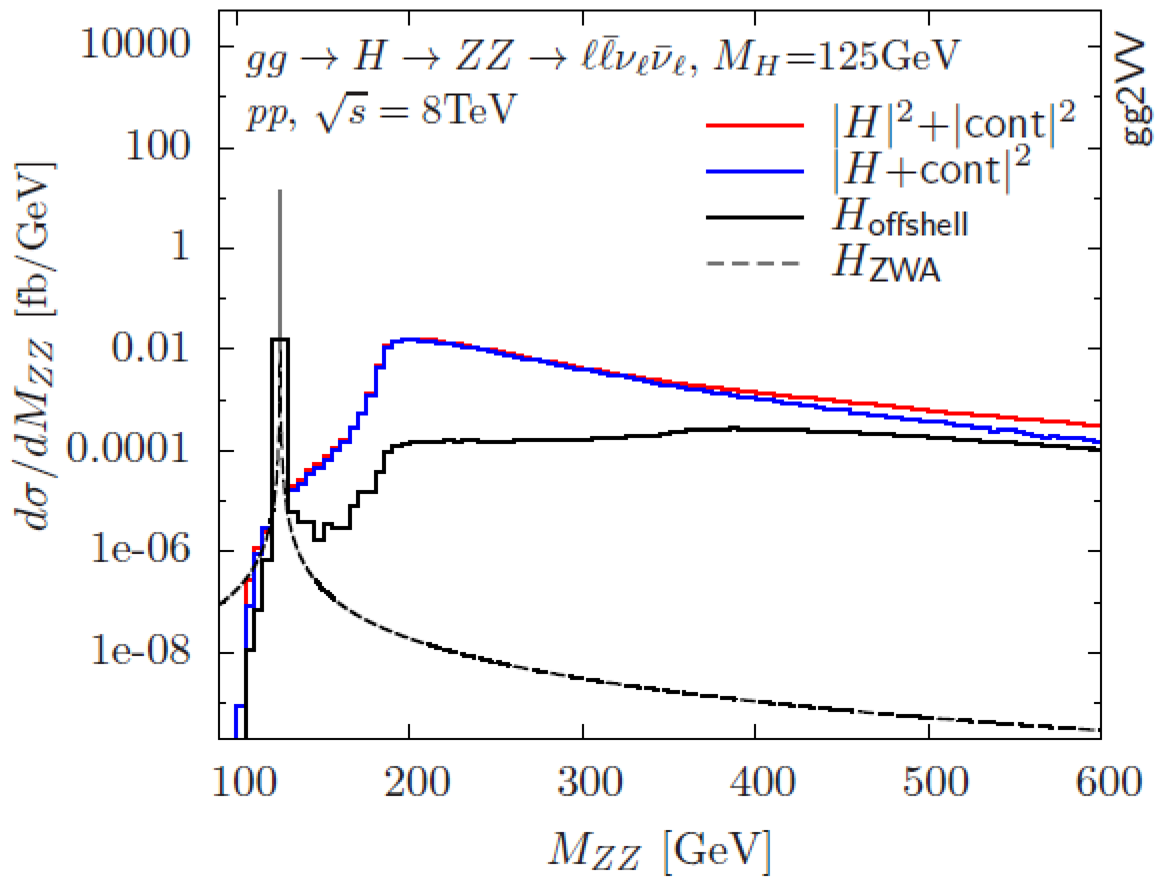
Signal



Background

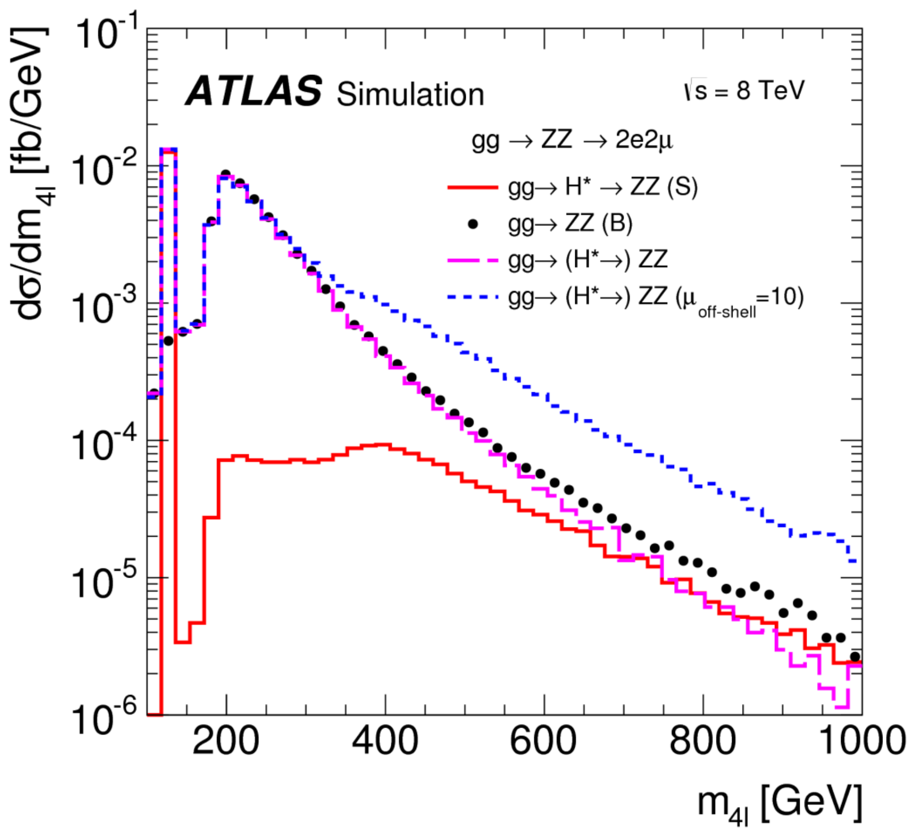


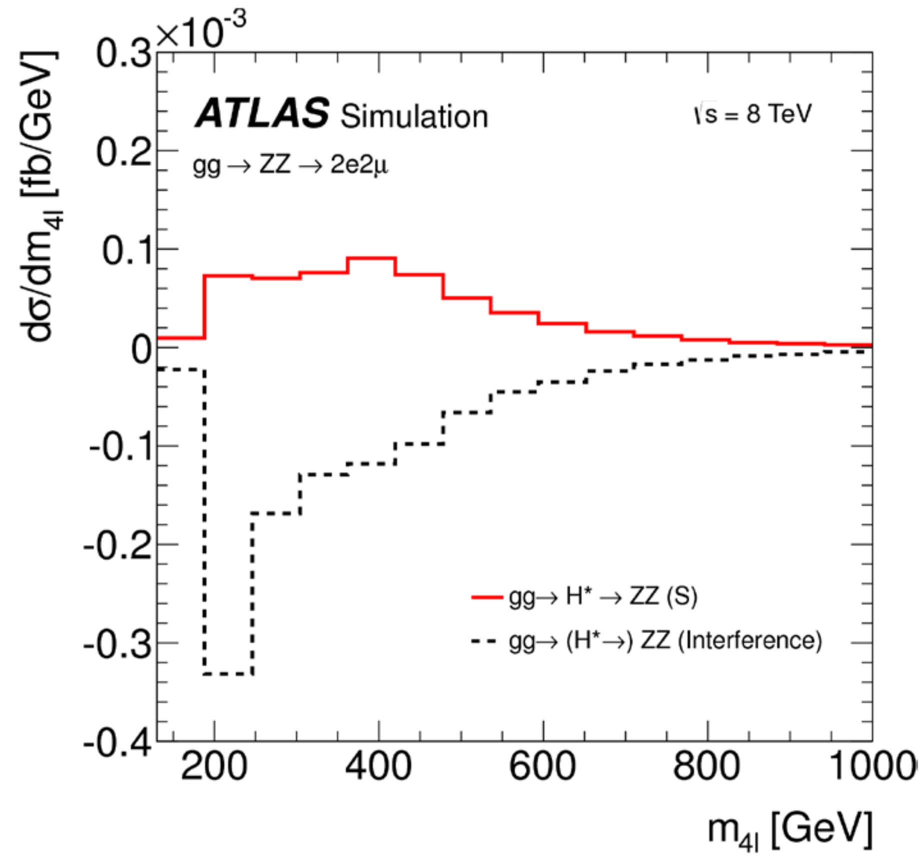




	Tot[pb]	$M_{ZZ} > 2\,M_Z$[pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

Indirect Width Measurement





Large $gg \to H^* \to ZZ$ off-shell Higgs boson production in SM already, significant enhancement for a larger

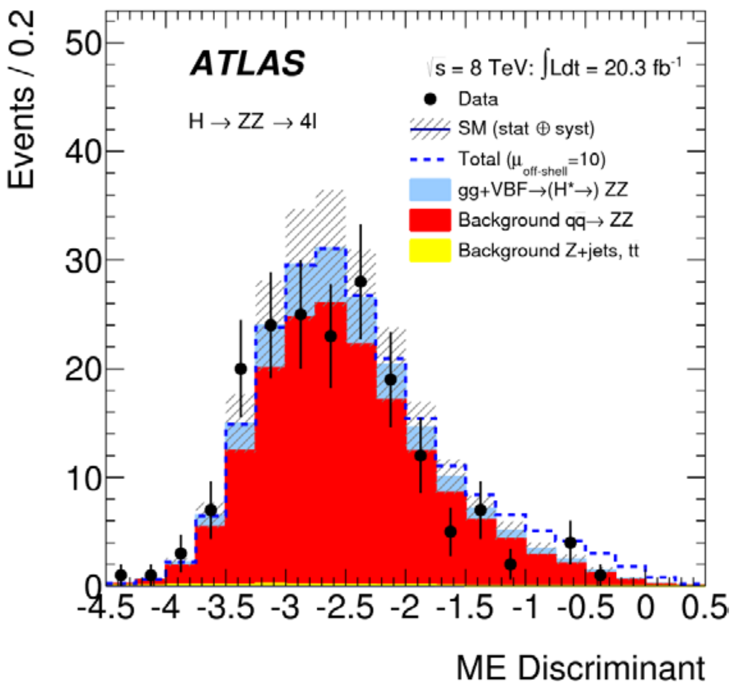
Destructive interference between the $gg \to H^* \to ZZ$ signal and the $gg \to ZZ$ background

Indirect Width Measurement

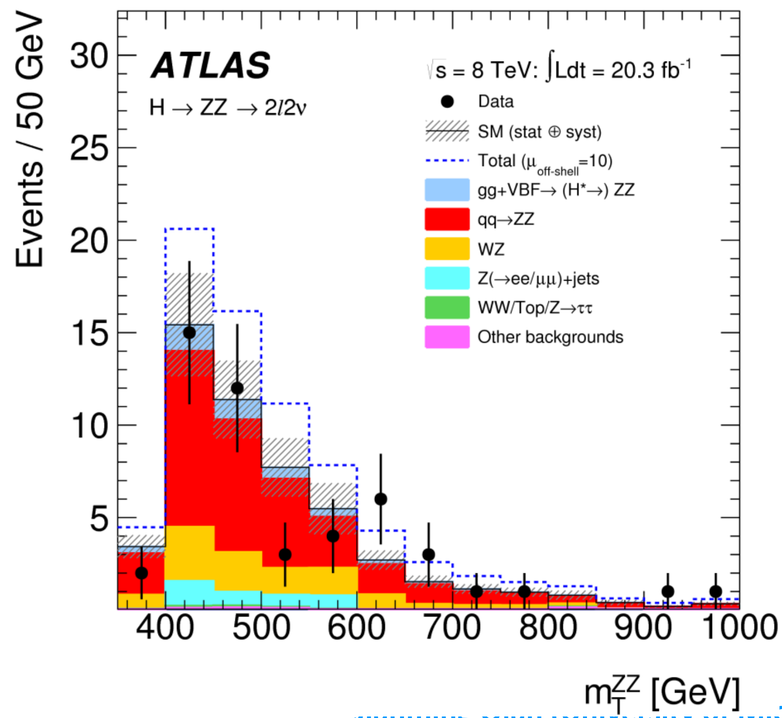
The key is to isolate off-shell Higgs signal from the continuum background, such as $q\bar{q}/gg \rightarrow WW, ZZ$ for the case of $H \rightarrow WW, ZZ$. Exploring kinematic difference for the separation of the signal and background.

ATLAS analyzed $ZZ \rightarrow 4\ell$, $2\ell 2\nu$ and $WW \rightarrow \ell\nu\ell\nu$ final states.

4ℓ: $m_{4\ell} > 220\ GeV$



$2\ell 2\nu$: $E_T^{miss} > 180$ GeV, $m_T^{ZZ} > 380$ GeV



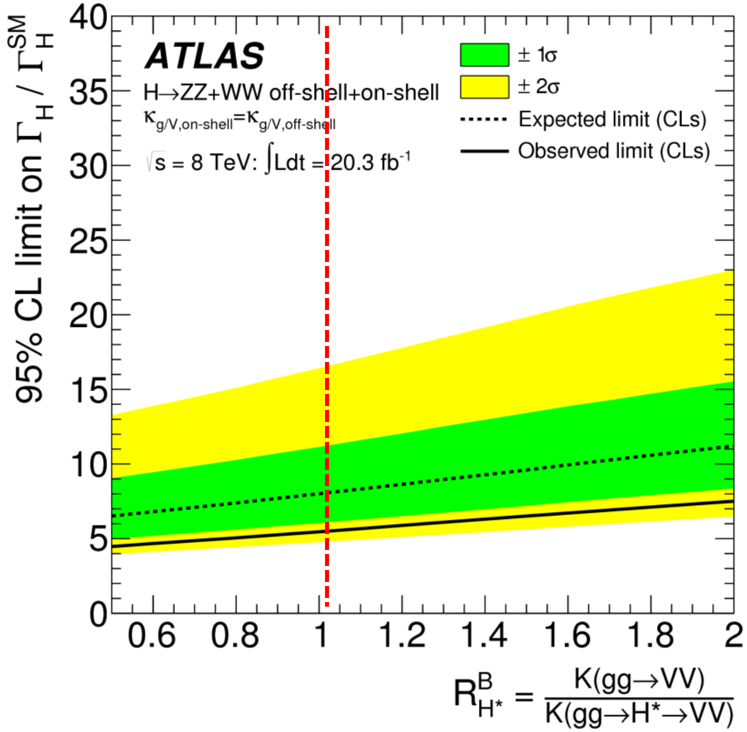
Indirect Width Measurement

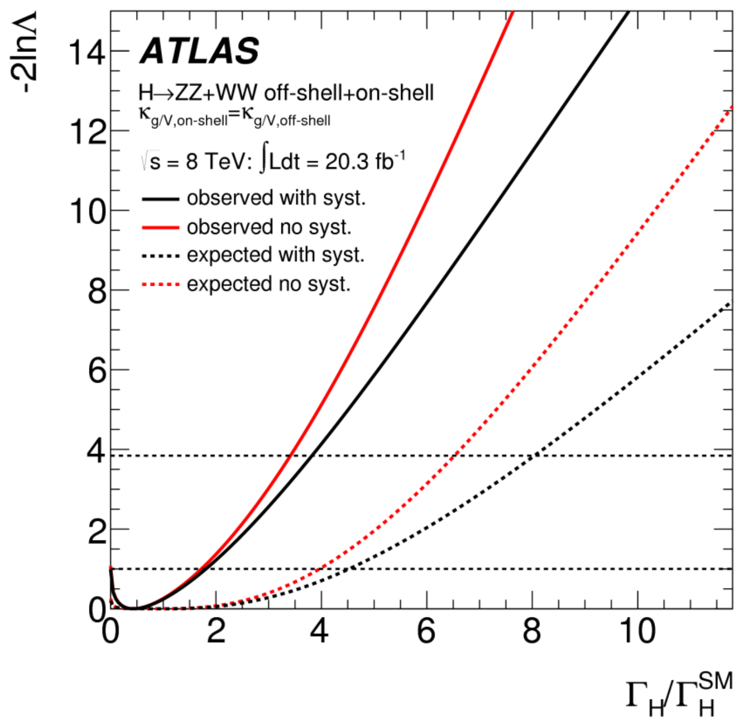
The $q\bar{q} \to ZZ$ process is reasonably wellunderstood theoretically, but the $gg \to ZZ$ process is not, calculation available only at LO

Unknown K-factor of the background $gg \to ZZ$ production:

$$R^B_{H^*} = \frac{K(gg \to ZZ)}{K(gg \to H^* \to ZZ)}$$

$\Gamma_H < 22.7\ (33.0)$ MeV at 95% CL for $R^B_{H^*} = 1.0$

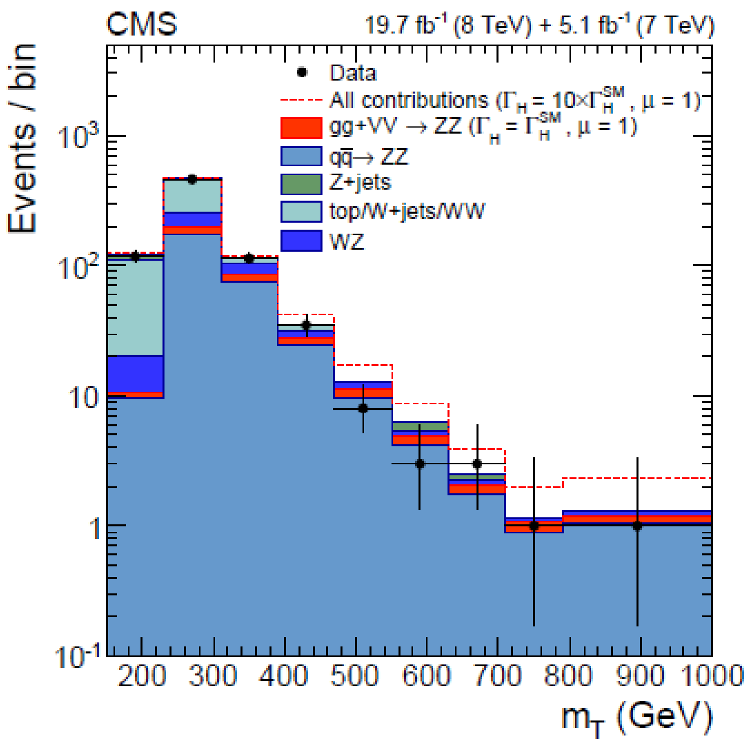


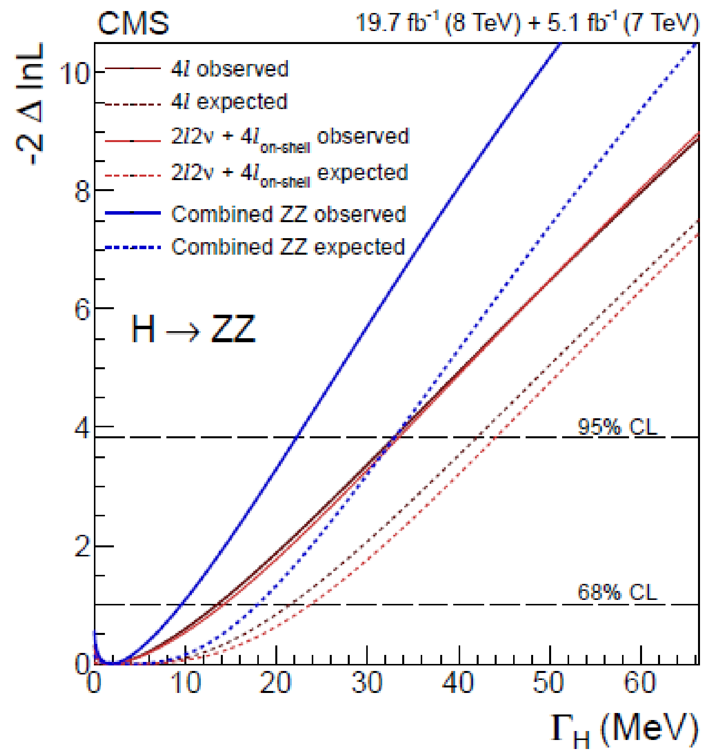


Indirect Width Measurement

The key is to isolate off-shell Higgs signal from the continuum background, such as $q\bar{q}/gg \rightarrow WW, ZZ$ for the case of $H \rightarrow WW, ZZ$

arXiv:1405.3455 (CMS)





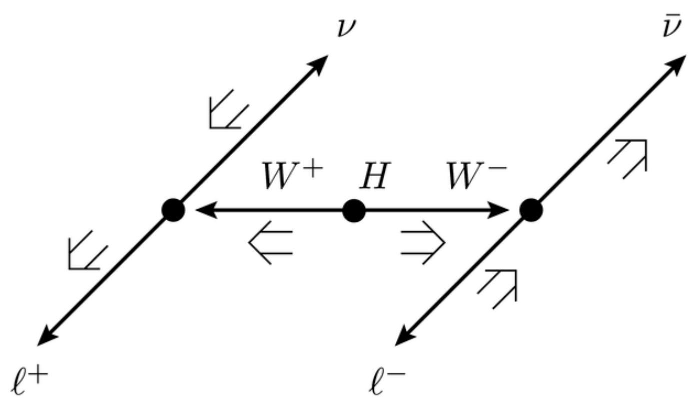
CMS has studied $H \rightarrow ZZ^{*} \rightarrow 4\ell, \ell\ell\nu\nu$ with the combined observed (expected) limit: $\Gamma_H < 22(33)$ MeV or $5.4(8.0) \times \Gamma_H^{SM}$ @ 95% CL

Or as a measurement $\Gamma_H = 1.8^{+7.7}_{-1.8}$ MeV

Spin parity tests

Spin Parity Property

The Higgs boson has the quantum numbers $J^{CP} = 0^{++}$ in the SM, this information is encoded in its decay products and has been exploited by the event selection, e.g. the $H \rightarrow WW^{*} \rightarrow \ell \nu \ell \nu$ analysis:



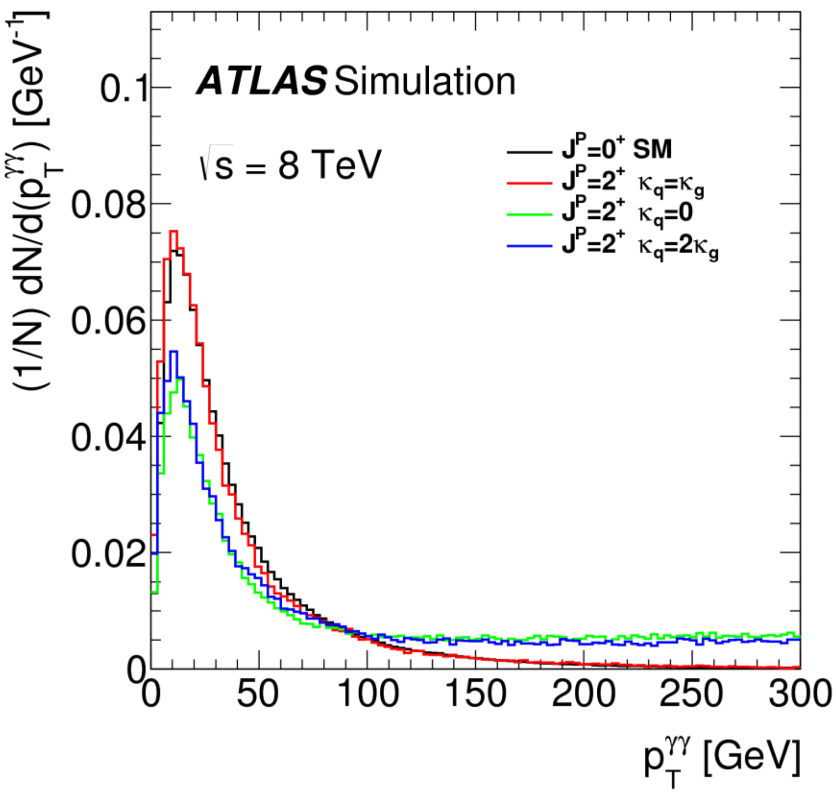
The spin/CP properties of the Higgs boson have been tested in diboson decays. Construct statistic to test alternative spin/CP hypothese against the SM prediction.

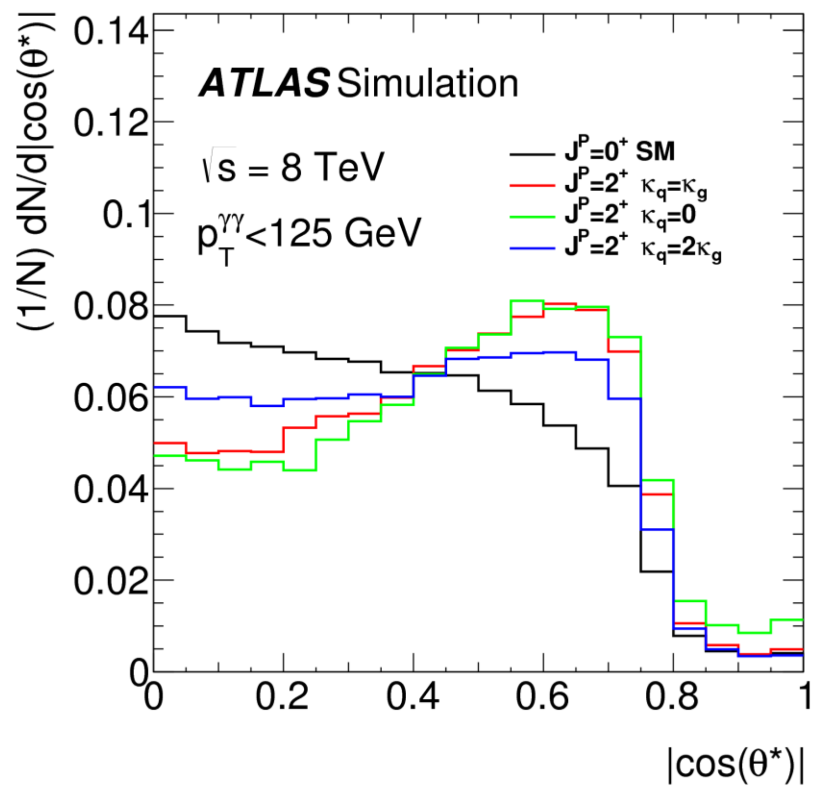
$H \to \gamma\gamma$

$H \to \gamma\gamma$ decay is forbidden for the spin-1 particle by the Landau-Yang theorem. Test spin-2 hypothesis of both $q\bar{q} \to X$ and $gg \to X$ production.

$\kappa_q = \kappa_g$ example:

similar $p_T^{\gamma\gamma}$ distribution, but very different $\cos\theta^*$ distribution.

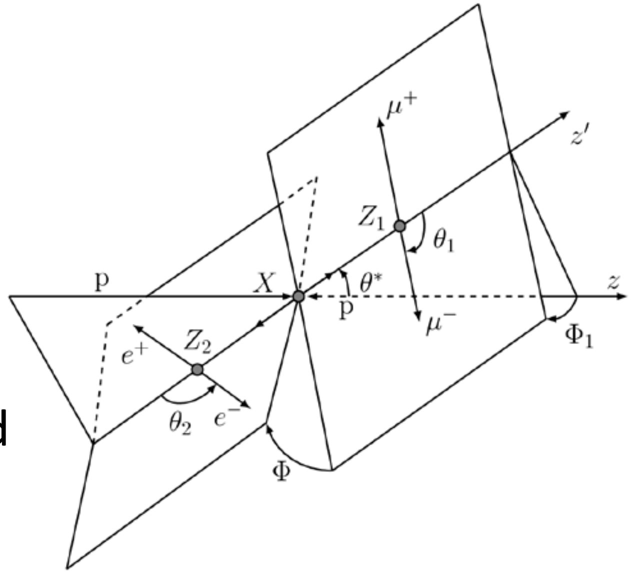




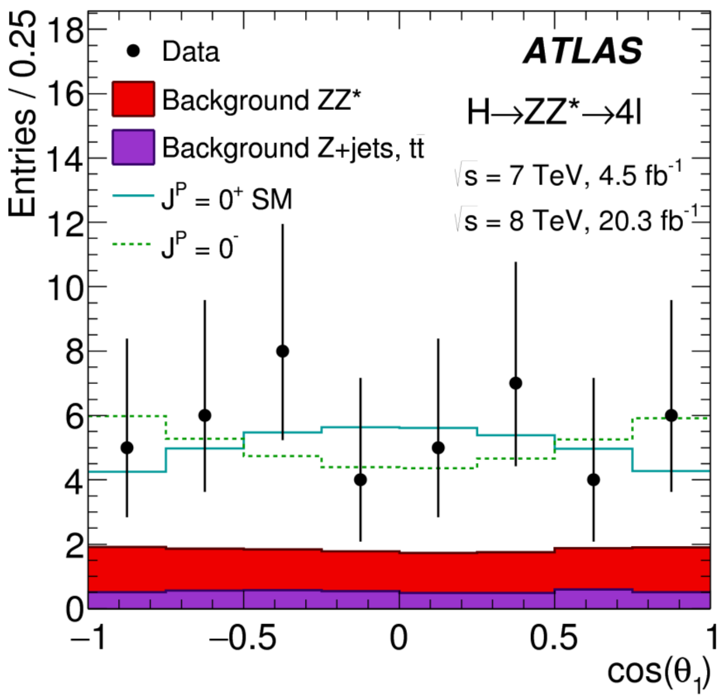
H→ZZ*→4ℓ

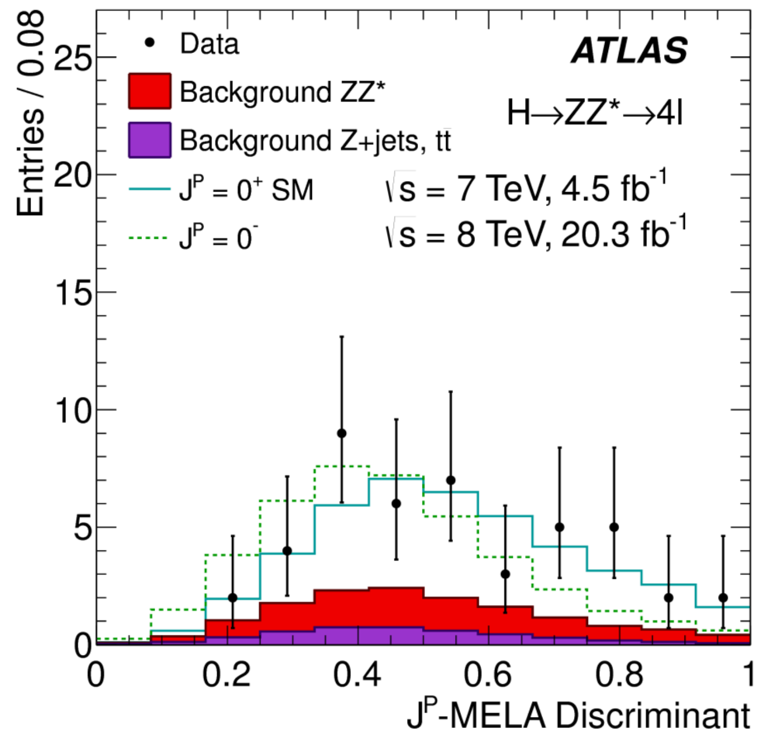
Small differences in many observables between the SM and alternative hypotheses.

Use MVA techniques to characterize these differences and to discriminate against background



Test scalar vs pseudoscalar



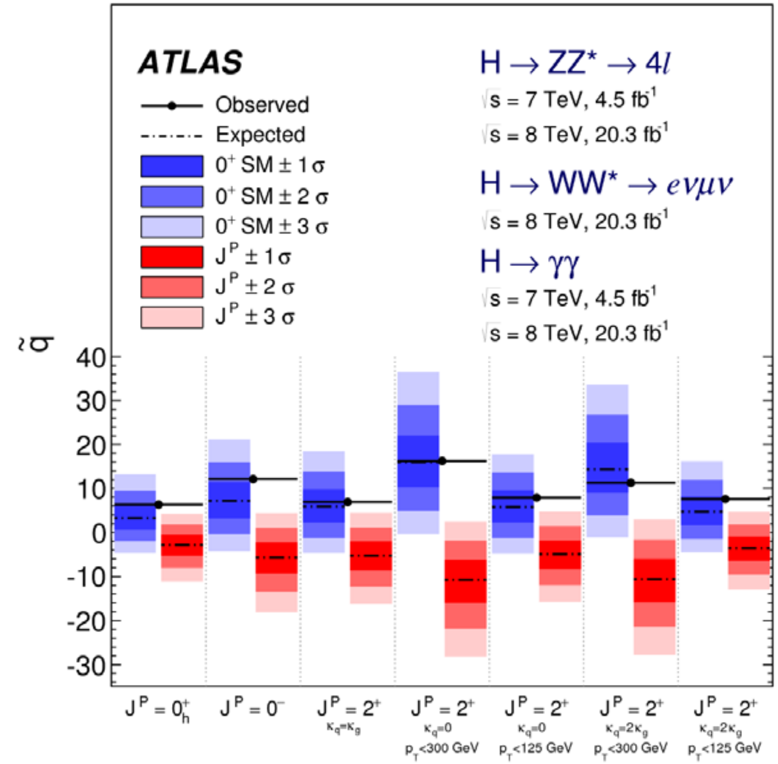


Spin/CP Combination

Combining test statistics from contributing final states

$$\tilde{q} = \log \frac{\mathcal{L}(J^P_{\rm SM}, \hat{\hat{\mu}}_{J^P_{\rm SM}}, \hat{\hat{\theta}}_{J^P_{\rm SM}})}{\mathcal{L}(J^P_{\rm alt}, \hat{\hat{\mu}}_{J^P_{\rm alt}}, \hat{\hat{\theta}}_{J^P_{\rm alt}})}$$

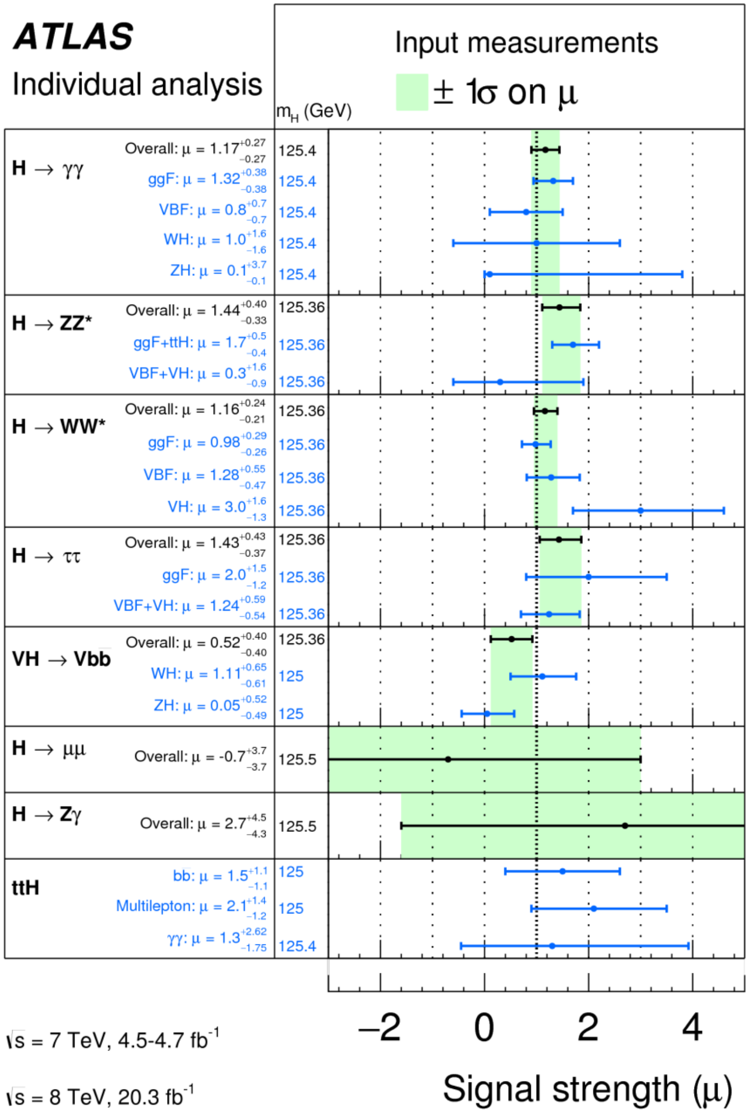
All alternative hypotheses studied are excluded at > 95% CL

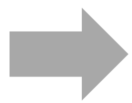


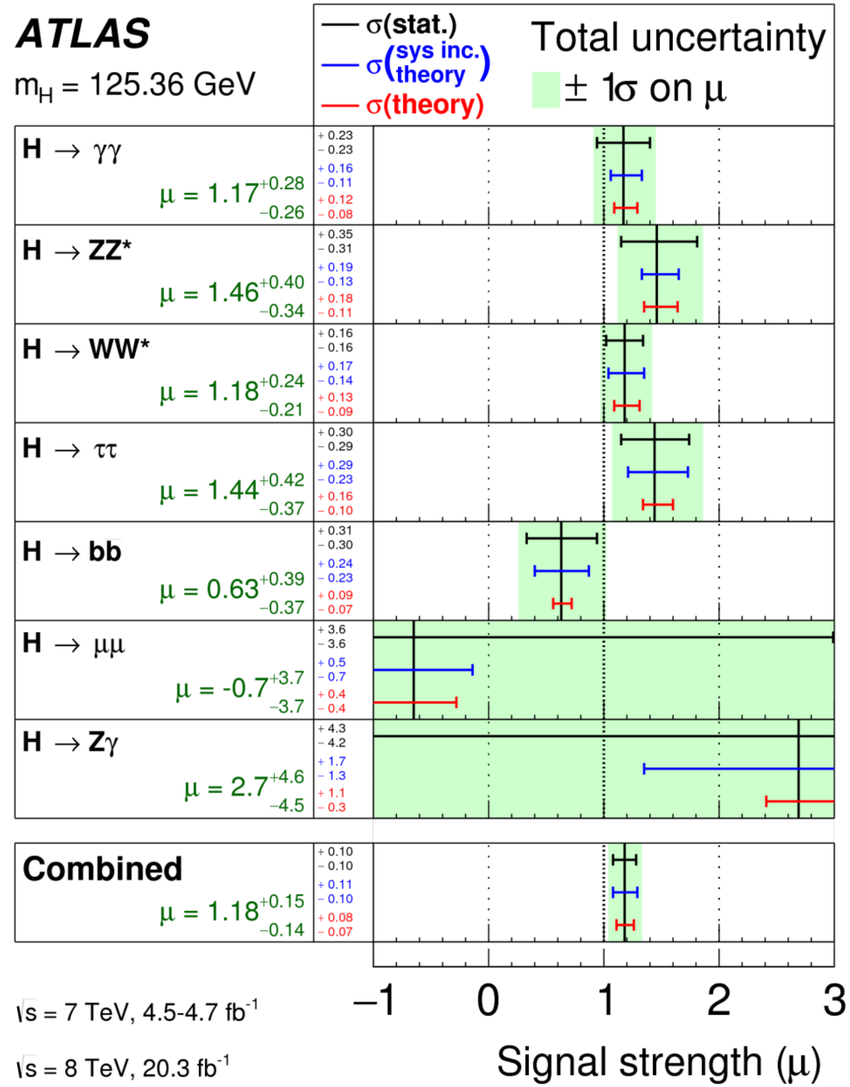
Tested Hypothesis	$p^{\rm alt}_{{\rm exp},\mu=1}$	$p^{\rm alt}_{{\rm exp},\mu=\hat{\mu}}$	$p^{\rm SM}_{\rm obs}$	$p^{\rm alt}_{\rm obs}$	Obs. CL$_s$ (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
$2^+(\kappa_q = \kappa_g)$	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_{\rm T} < 300$ GeV)	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_{\rm T} < 125$ GeV)	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_{\rm T} < 300$ GeV)	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_{\rm T} < 125$ GeV)	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

Signal strength and coupling fits

Input to the Coupling Fits







Signal Rate Characterization

At the LHC, only the products $\sigma \cdot \text{BR}$ are measured, there is no model-independent way to determine the cross section and the branching ratio separately.

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{\sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f\right\},$$
$$= \mathcal{L}(k) \times \sum_i \sum_f \mu_i \mu^f \left\{\sigma_i^{\text{SM}} \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}_{\text{SM}}^f\right\}$$

Signal strengths:

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \quad \text{and} \quad \mu^f = \frac{\text{BR}^f}{\text{BR}_{\text{SM}}^f}.$$

$$\mu_i^f \equiv \frac{\sigma_i \cdot \text{BR}^f}{(\sigma_i \cdot \text{BR}^f)_{\text{SM}}} = \mu_i \times \mu^f$$

Only μ_i^f are determined from the Higgs signal rate measurements.

Global Signal Strength

Assuming all signal rates are modified by a global signal strength μ:

$$\mu = 1.18^{+0.15}_{-0.14}$$

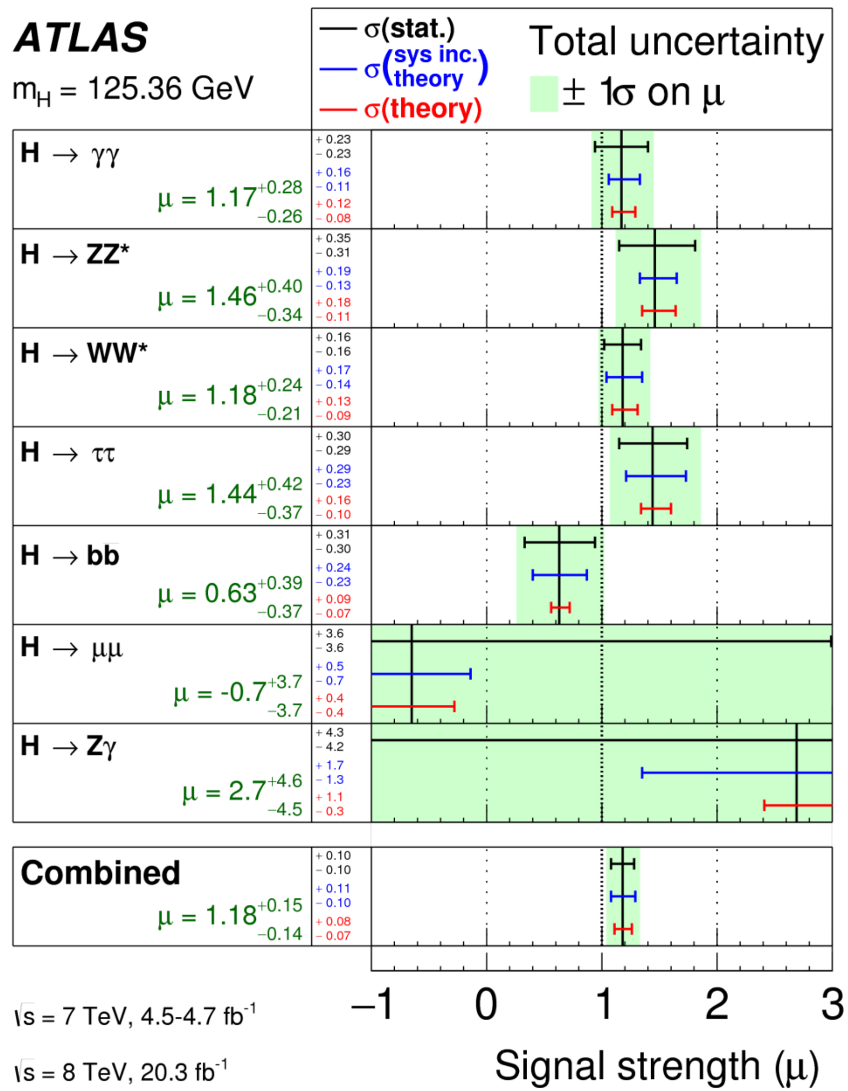
Consistency p-values:

76% with μ=1.18

18% with μ=1.0 (SM)

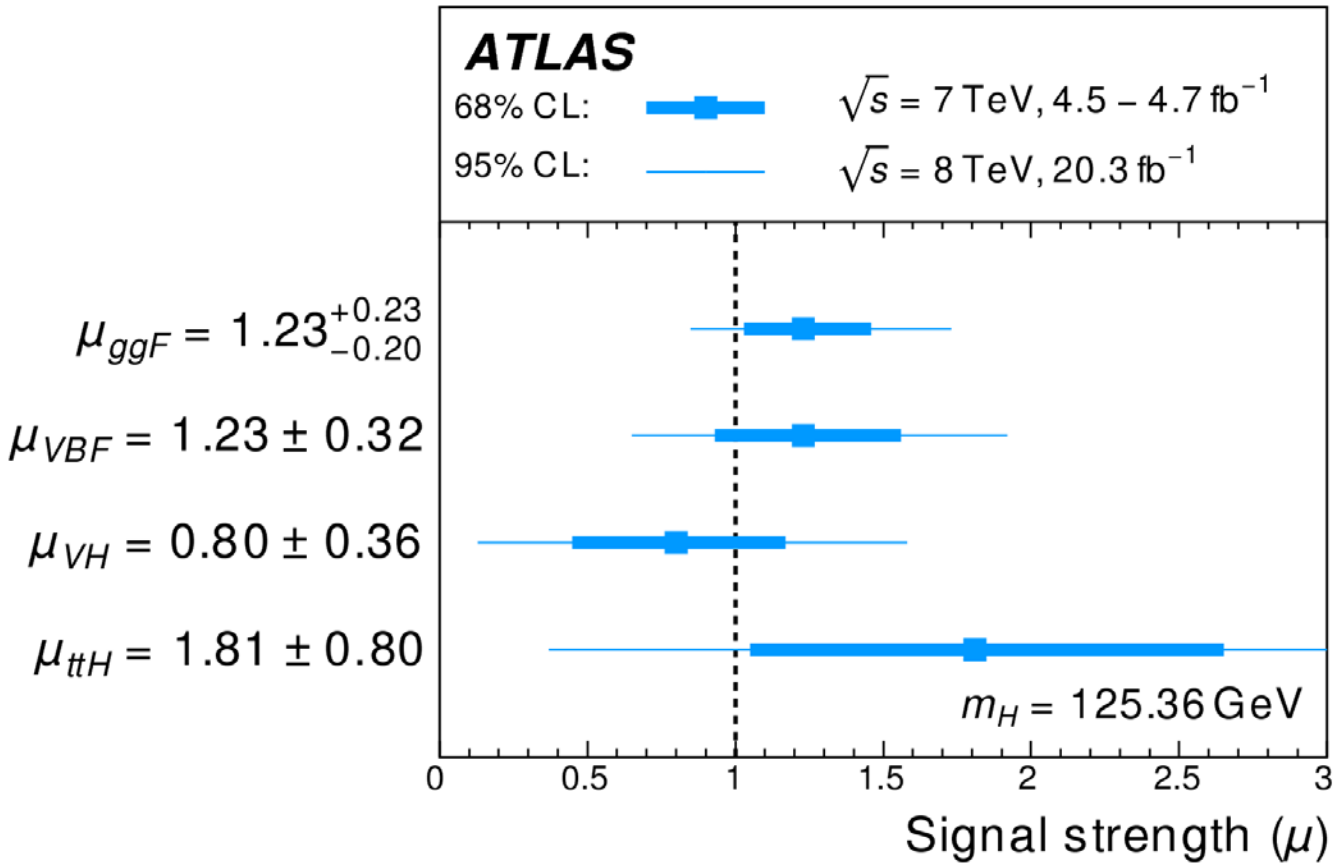
Systematic uncertainty:

roughly equal experimental and theoretical contribution.



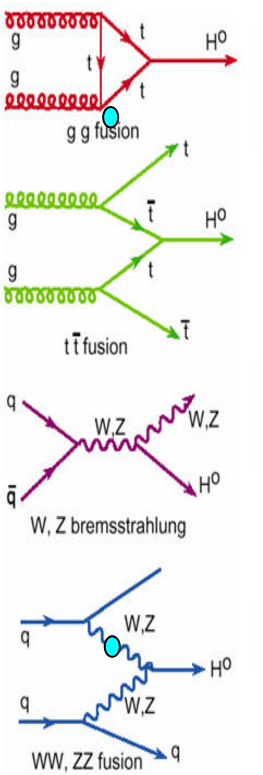
Probe Production

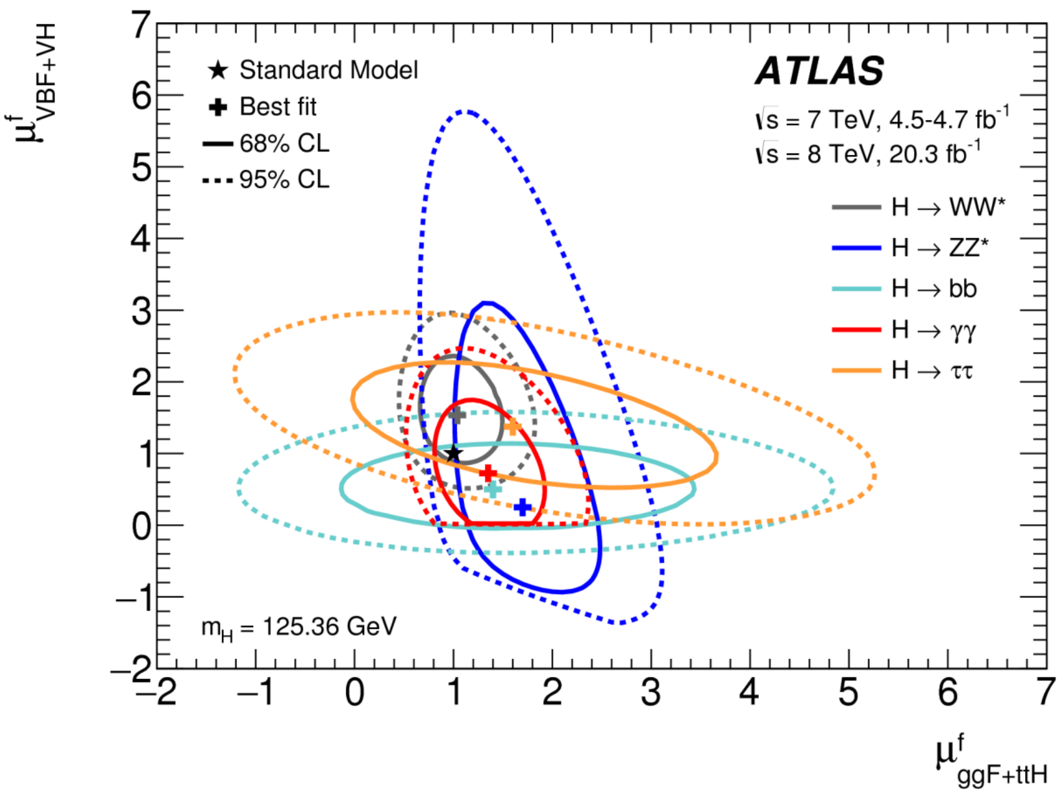
One signal strength for each production process assuming SM decay branching ratios



Probe Production Groups

Vector boson mediation vs fermion mediation: $\mu_{\mathrm{VBF+VH}}$ vs $\mu_{\mathrm{ggF+}ttH}$





Branching ratios cancel in the ratio $\mu_{\mathrm{VBF+VH}}/\mu_{\mathrm{ggF+}ttH}$, thus it is independent of potential new physics in decays.

$$\left(\mu_{\mathrm{VBF+VH}}/\mu_{\mathrm{ggF+}ttH}\right)_{\mathrm{Combined}} = 0.96^{+0.43}_{-0.31}$$

Parametrization using Ratios

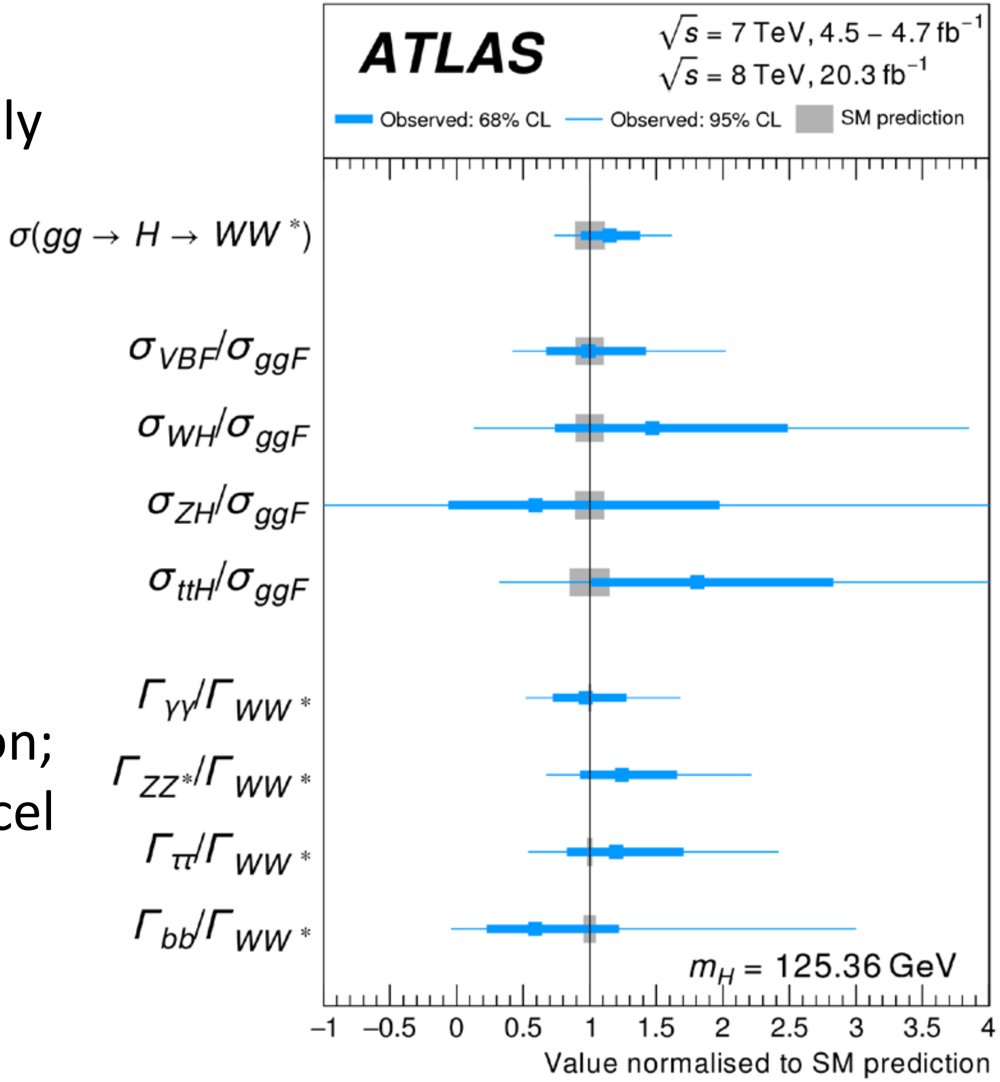
$$\sigma_i \cdot \mathrm{BR}_f = \sigma(gg \to H \to WW^*) \times \left(\frac{\sigma_i}{\sigma_{\mathrm{ggF}}}\right) \times \left(\frac{\Gamma_f}{\Gamma_{WW^*}}\right)$$

$gg \to H \to WW$ is chosen for the normalization because it is relatively well measured.

One ratio of cross sections per process other than ggF

One ratio of branching ratios per decay mode other than WW.

Model-independent parametrization; Many systematic uncertainties cancel in the ratio .

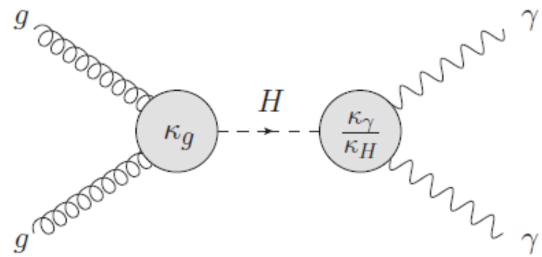


Coupling Parametrization

Parametrizing deviations from SM using scale parameters: κ $\left(\text{SM: } \kappa = 1\right)$

$$g_{Hff} = \frac{\sqrt{2}m_f}{\upsilon}, \qquad g_{HVV} = \frac{2m_V^2}{\upsilon} \quad \Rightarrow$$

$$g_{Hff} = \boxed{\kappa_f} \cdot \frac{\sqrt{2}m_f}{\upsilon}, \quad g_{HVV} = \boxed{\kappa_V} \cdot \frac{2m_V^2}{\upsilon}$$



For example: $(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \left[\sigma(gg \to H) \cdot BR(H \to \gamma\gamma)\right]_{SM} \times \boxed{\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}}$

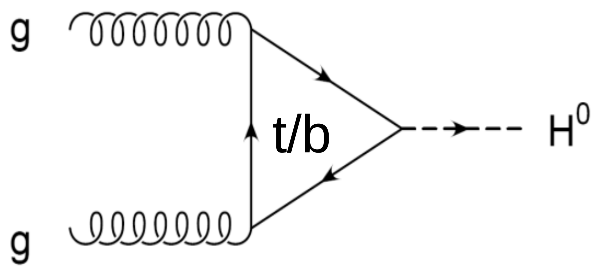
assuming there is no new production processes and decay modes.

κ_H^2 is the scale factor to the total Higgs decay width: $\kappa_H^2 = \sum_x \kappa_x^2 \cdot BR_{SM}(h \to xx)$

If there are new decays with a total branching ratio BR_{NEW}, then

$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \left[\sigma(gg \to H) \cdot BR(H \to \gamma\gamma)\right]_{SM} \times \boxed{\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2} \bullet (1 - BR_{NEW})}$$

Decomposing Loops…



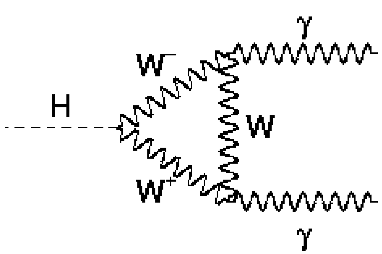
In SM, the $gg \rightarrow H$ cross section can be broken into three pieces: $\sigma_{SM} = \sigma_{tt} + \sigma_{bb} + \sigma_{tb}$

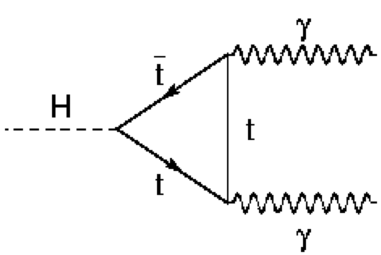
With coupling modifications, the cross section becomes $\Rightarrow \sigma = \kappa_t^2 \sigma_{tt} + \kappa_b^2 \sigma_{bb} + \kappa_t \kappa_b \sigma_{tb}$

The effective *Hgg* coupling scale parameter is

$$\kappa_g^2 = \frac{\sigma}{\sigma_{SM}} = \frac{\kappa_t^2 \sigma_{tt} + \kappa_b^2 \sigma_{bb} + \kappa_t \kappa_b \sigma_{tb}}{\sigma_{tt} + \sigma_{bb} + \sigma_{tb}}$$

$$\approx 1.058\kappa_t^2 + 0.007\kappa_b^2 - 0.065\kappa_t \kappa_b \;^*$$





$$\kappa_\gamma^2 = \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \frac{\kappa_t^2 \Gamma_{\gamma\gamma}^{tt} + \kappa_W^2 \Gamma_{\gamma\gamma}^{WW} + \kappa_t \kappa_W \Gamma_{\gamma\gamma}^{tW}}{\Gamma_{\gamma\gamma}^{tt} + \Gamma_{\gamma\gamma}^{WW} + \Gamma_{\gamma\gamma}^{tW}}$$

$$\approx 0.07\kappa_t^2 + 1.59\kappa_W^2 - 0.66\kappa_t \kappa_W \;^*$$

* $m_H = 125.5$ GeV

Coupling dependences

Production	Loops	Interference	Multiplicative factor
$\sigma(\text{ggF})$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(q\bar{q} \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq')$	–	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
Partial decay width			
$\Gamma_{b\bar{b}}$	–	–	$\sim \kappa_b^2$
Γ_{WW}	–	–	$\sim \kappa_W^2$
Γ_{ZZ}	–	–	$\sim \kappa_Z^2$
$\Gamma_{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
Total width for $\text{BR}_{\text{BSM}} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Higgs Boson Width Constraint

The Higgs rate measurements alone are insufficient to constrain the Higgs boson width. For process $i \rightarrow H \rightarrow f$, the rate

$$\sigma_i \cdot BR_f = \sigma_i \cdot \frac{\Gamma_f}{\Gamma_H} \quad \text{with} \quad \Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{NEW}}$$

If both Γ_H and Γ_f are scaled by the same factor, the rate is unchanged.

Three assumptions are considered:

1) No beyond SM decay, $\mathrm{BR}_{NEW}\left(\mathrm{BR}_{i.u.}\right) = 0$;
2) constraint from the off-shell measurement;
3) $\kappa_V \leq 1$ (motivated by the unitarity requirement in VV scattering)

Fermion and Boson Couplings

$$\kappa_F\,,\ \kappa_V \qquad \Rightarrow \kappa_H^2 \approx 0.75\kappa_F^2 + 0.25\kappa_V^2$$

κ_F : for all fermions $\left(\kappa_F \equiv \kappa_t = \kappa_b = \kappa_\tau = \ldots\right)$

κ_V : for all vector bosons $\left(\kappa_V \equiv \kappa_W = \kappa_Z\right)$

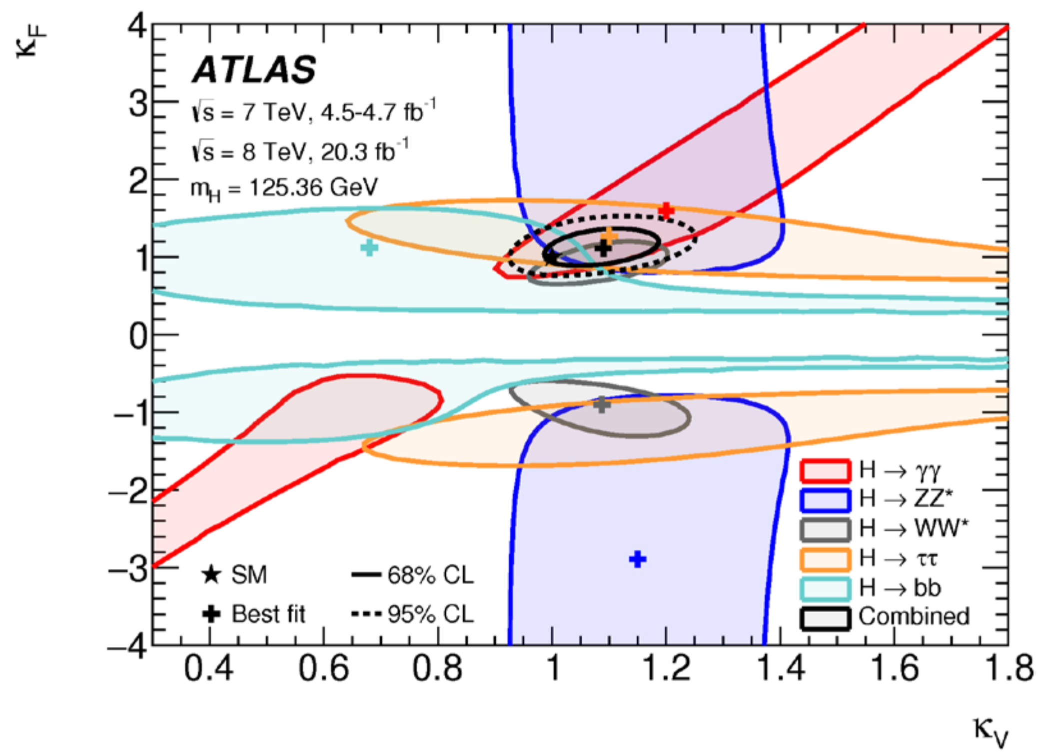
κ_g and κ_γ are decomposed to their tree-level couplings

No beyond SM decays

$$\kappa_F = 1.11 \pm 0.16$$
$$\kappa_V = 1.09 \pm 0.07$$

$VH \to Vb\bar{b}$ analysis:

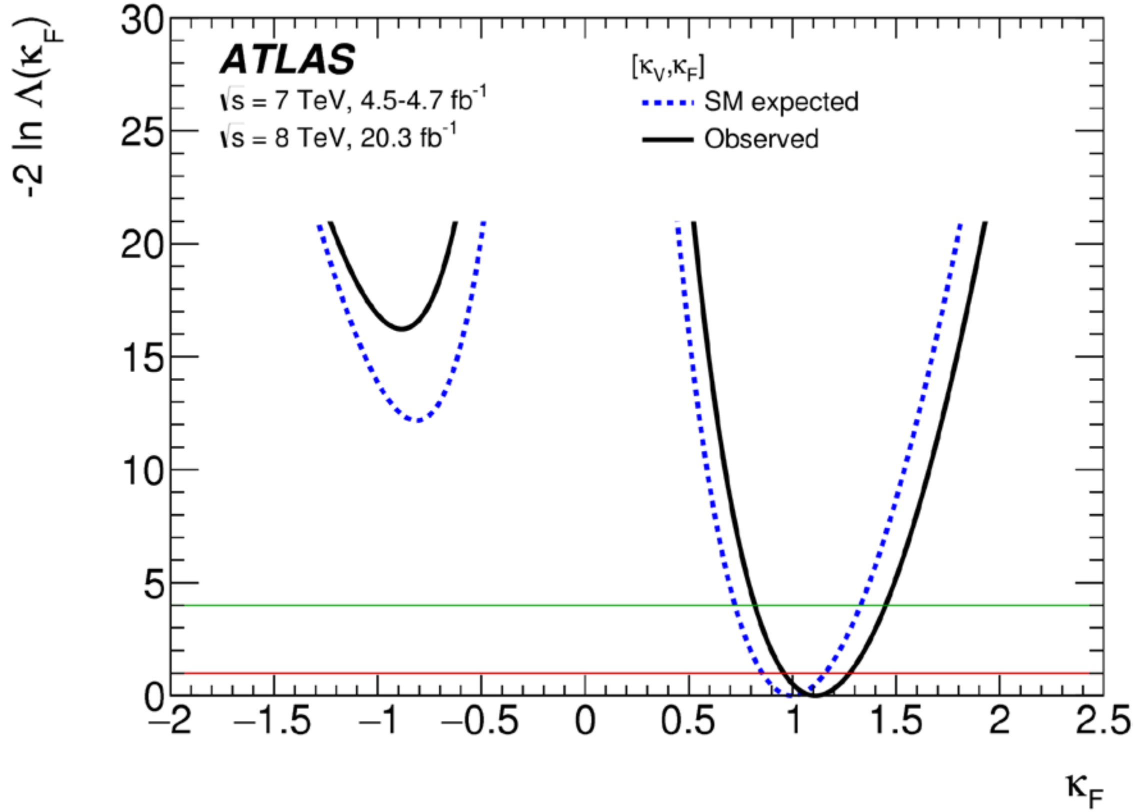
$$\sigma \cdot BR \sim \kappa_V^2 \cdot \frac{\kappa_F^2}{\kappa_H^2} \xrightarrow{\kappa_V \to \infty} \kappa_F^2$$

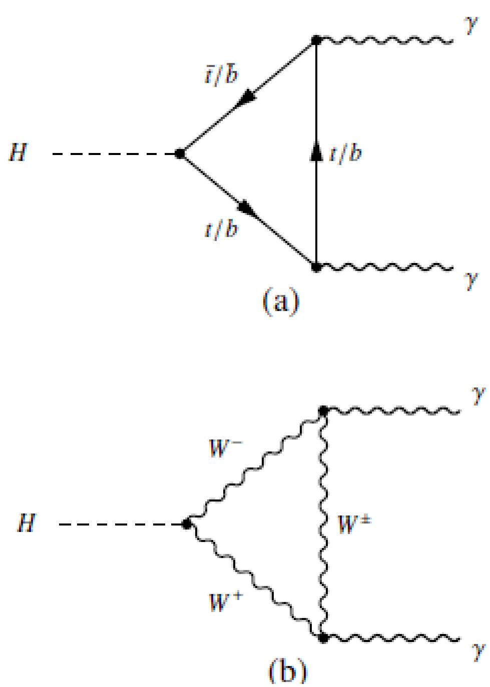


arXiv:1507.04548 (ATLAS)

Probe Coupling Sign

The interference effects (mostly from the H→γγ decay) are sensitive to the sign of fermion and vector boson couplings.





$\kappa_F < 0$ disfavored by 4.0σ

arXiv:1507.04548 (ATLAS)

Probe New Decays

$\kappa_F , \kappa_V , BR_{i.u.}$

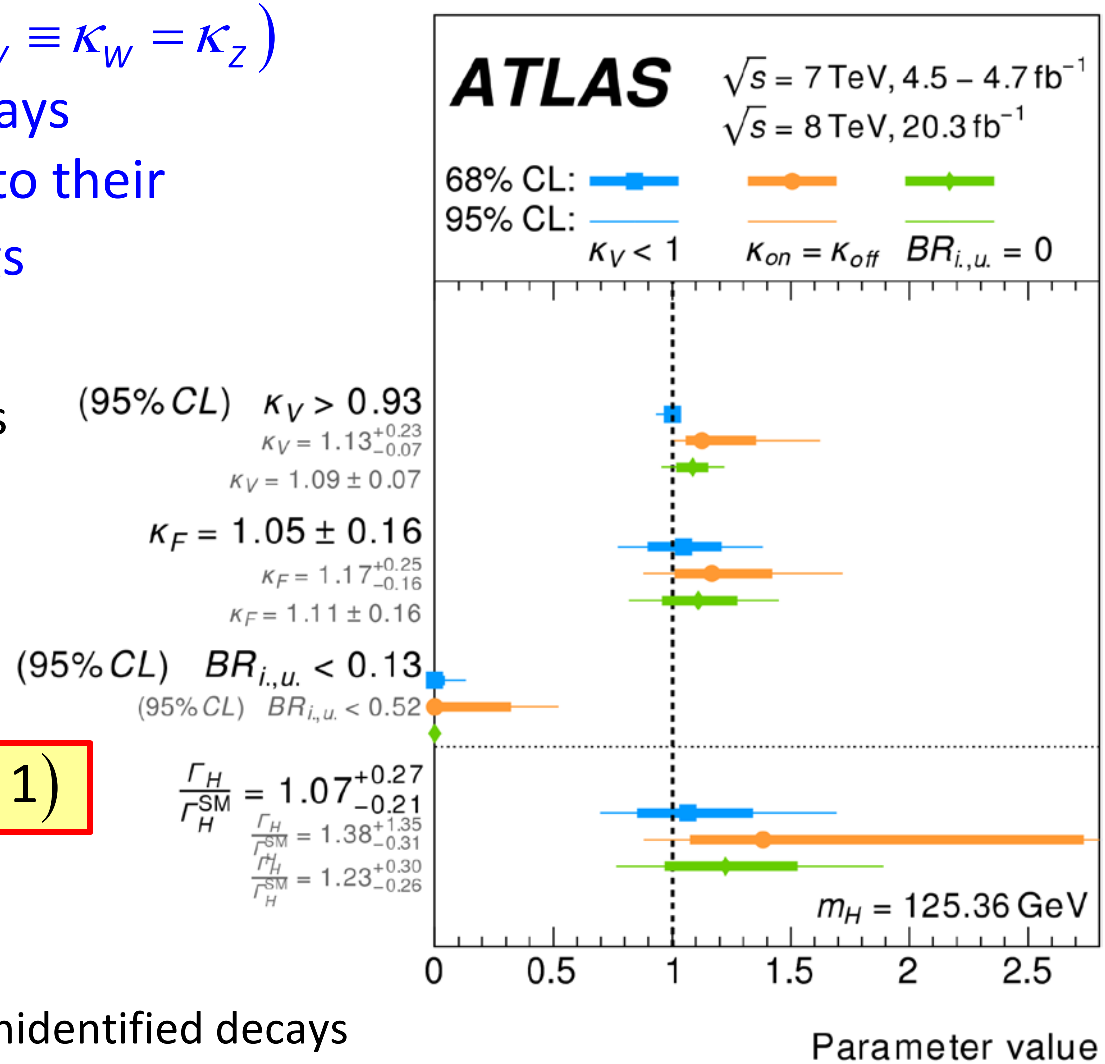
κ_F : for all fermions $(\kappa_F \equiv \kappa_t = \kappa_b = \kappa_\tau = ...)$

κ_V : for all vector bosons $(\kappa_V \equiv \kappa_W = \kappa_Z)$

$BR_{i.u.}$: allow beyond SM decays

κ_g and κ_γ are decomposed to their tree-level couplings

Consider 3 different constraints of the Higgs boson width



$BR_{i.u.} < 13\%$ at 95% CL $(\kappa_V < 1)$

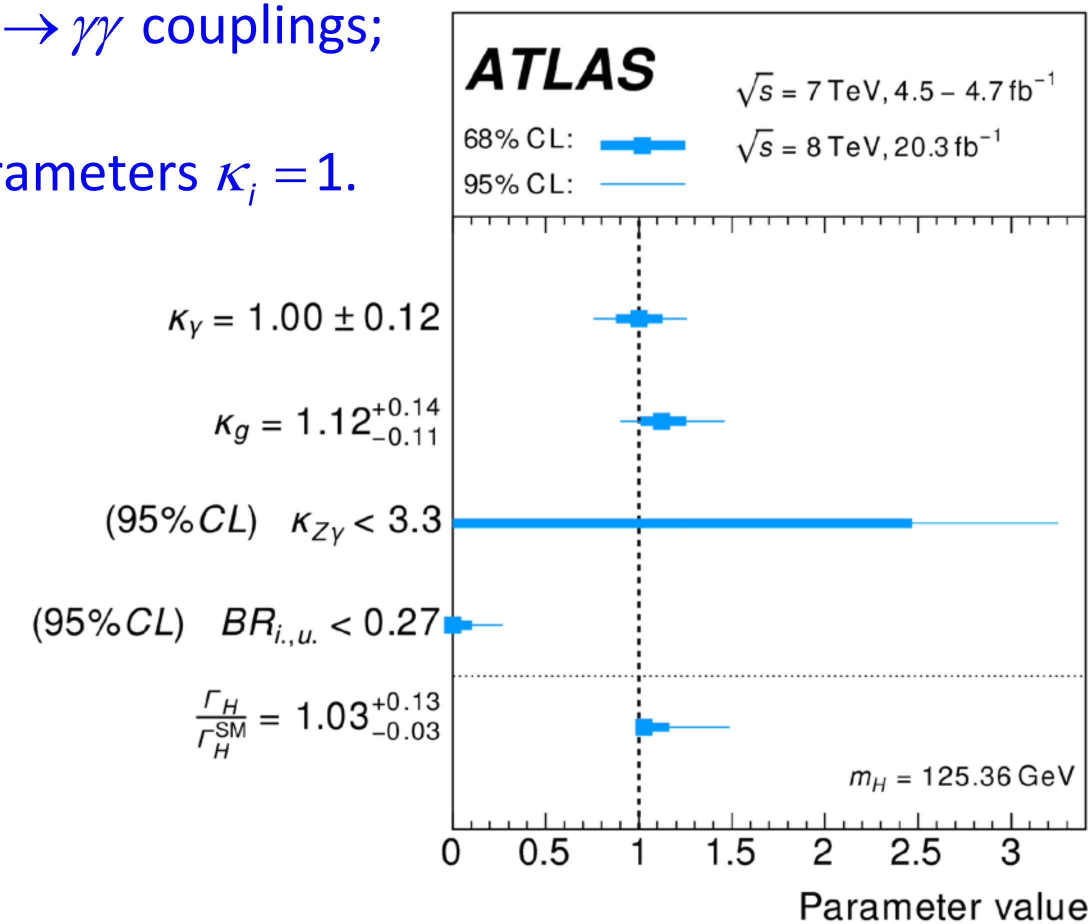
Note: $BR_{i.u.} \equiv BR_{NEW}$, $i.u.$ = invisible, unidentified decays

Probe Vertex Loops

$\kappa_g\,,\ \kappa_\gamma\,,\ BR_{i.u.}$ $\Rightarrow \kappa_H^2 \approx 0.91 + 0.085\kappa_g^2 + 0.0023\kappa_\gamma^2$

- κ_g and κ_γ for $gg \to$ H and H $\to \gamma\gamma$ couplings;
- Allow BSM decays;
- All other tree-level scale parameters $\kappa_i = 1$.

Probe $gg \to H$ production and $H \to \gamma\gamma$ decay loops, sensitive to potential new physics in the loops.

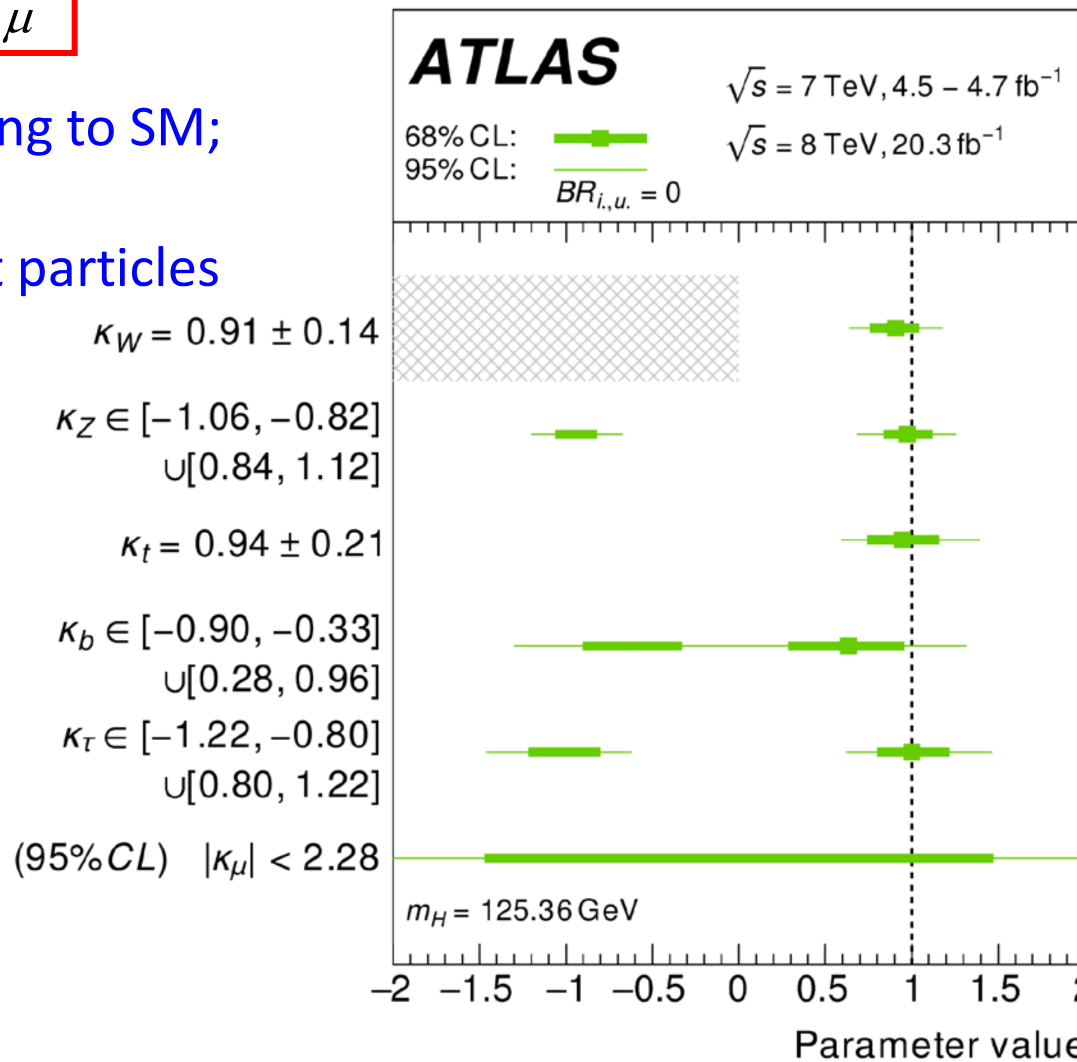


Test SM Consistency

$$\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$$

- Decompose all loops according to SM;
- No beyond SM decays;
- One scale factor per relevant particles

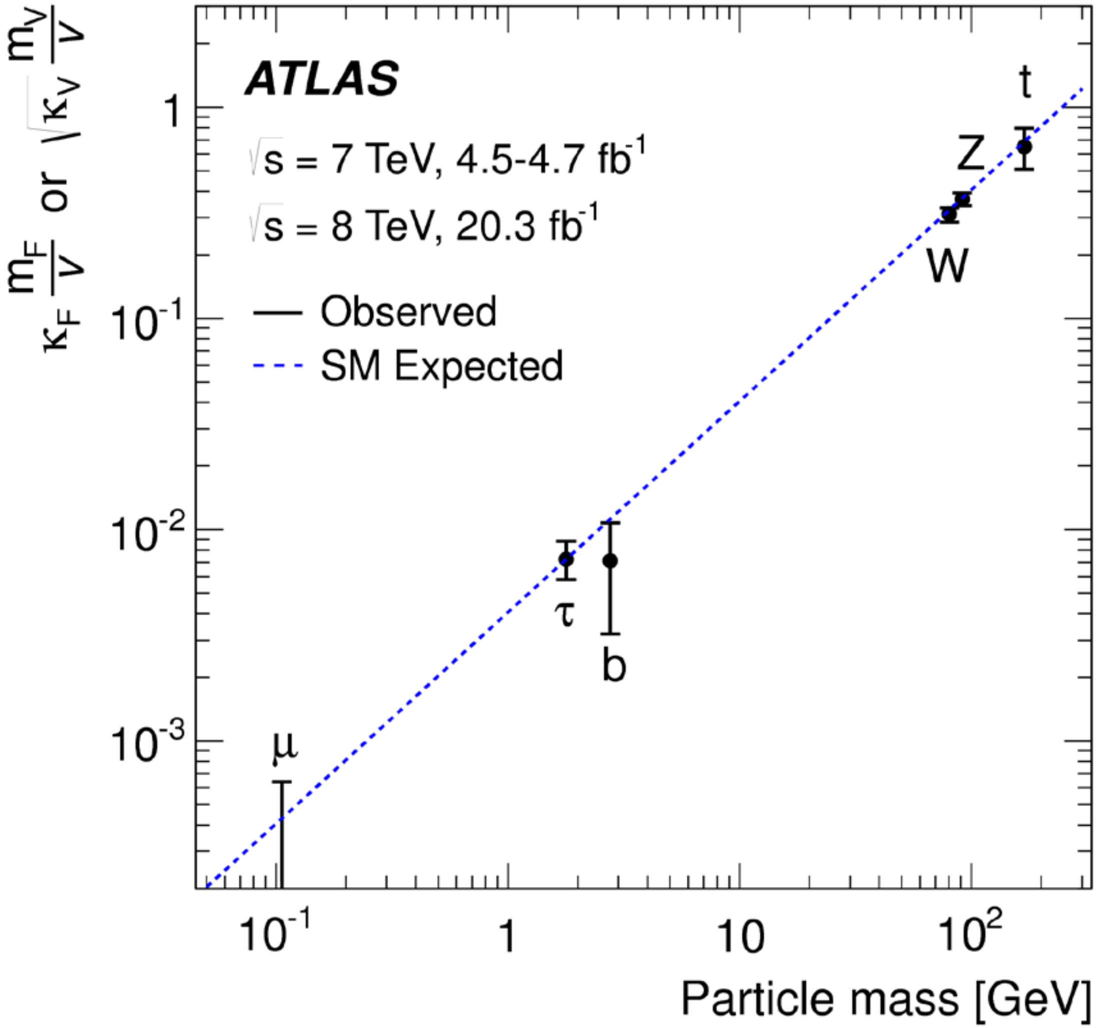
$$(\kappa_c = \kappa_t, \ \kappa_s = \kappa_b)$$



Mass Dependence

SM: $\lambda \propto m$ (fermions)

$g \propto m^2$ (bosons)



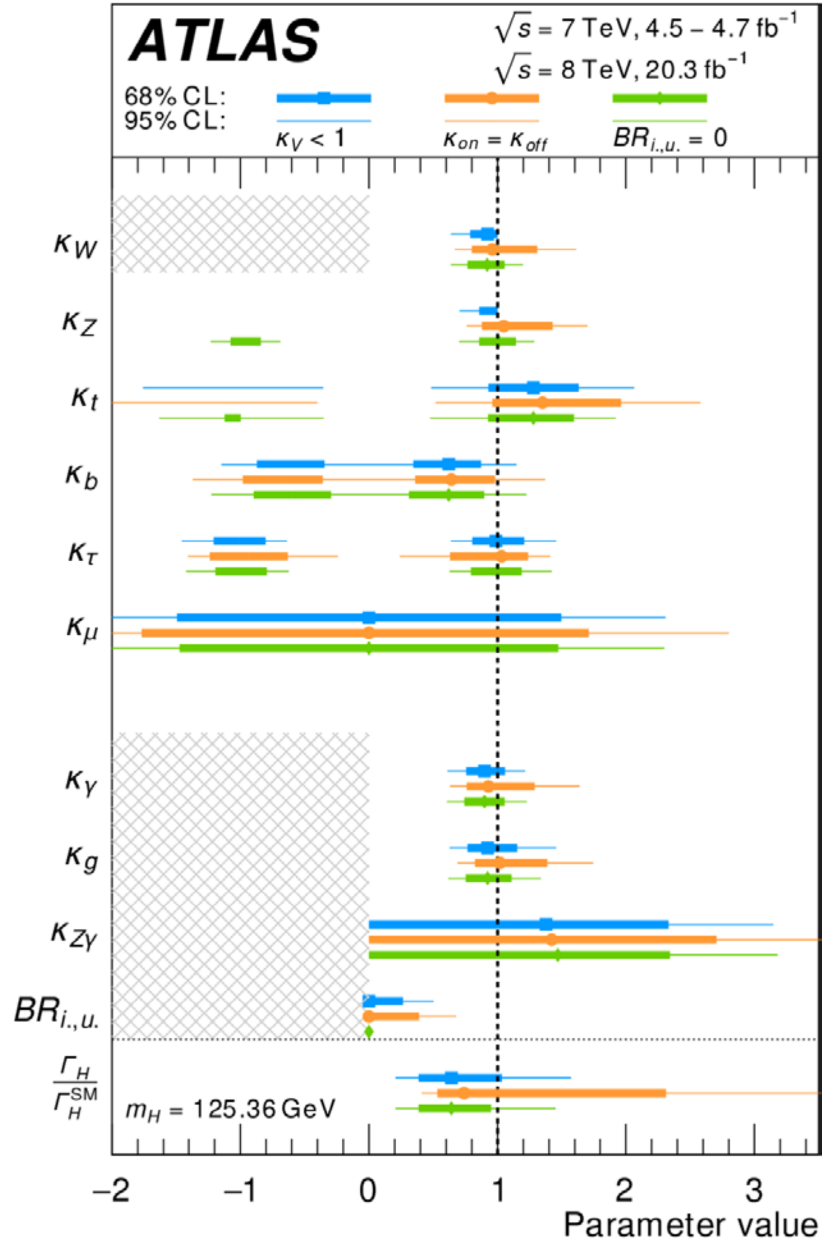
Measured couplings are very Standard Model like

General Parametrization

$\kappa_W,\ \kappa_Z,\ \kappa_t,\ \kappa_b,\ \kappa_\tau,\ \kappa_\mu,$
$\kappa_g,\ \kappa_\gamma,\ \kappa_{Z\gamma},\ BR_{i.u.}$

- one κ per relevant particle or loop;
- allow beyond SM decays

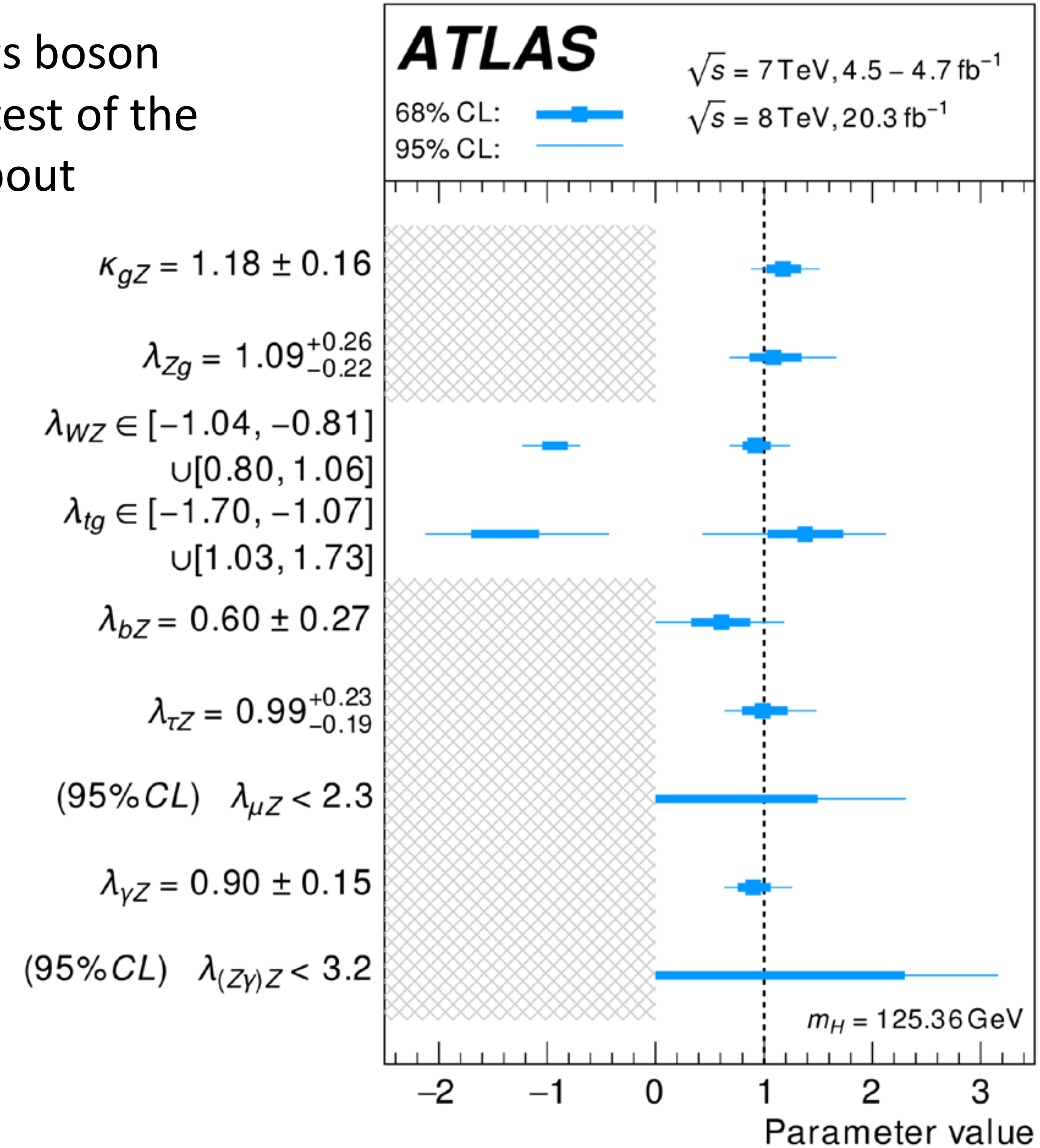
Parameter		$\kappa_V < 1$
κ_W		> 0.64 (95% CL)
κ_Z		> 0.71 (95% CL)
κ_t		$= 1.28^{+0.32}_{-0.35}$
$\lvert\kappa_b\rvert$	=	0.62 ± 0.28
$\lvert\kappa_\tau\rvert$	=	$0.99^{+0.22}_{-0.18}$
$\lvert\kappa_\mu\rvert$	<	2.3 (95% CL)
κ_γ	=	$0.90^{+0.16}_{-0.14}$
κ_g	=	$0.92^{+0.23}_{-0.16}$
$\kappa_{Z\gamma}$	<	3.15 (95% CL)
$BR_{i.,u.}$	<	0.49 (95% CL)
Γ_H/Γ_H^{SM}	=	$0.64^{+0.40}_{-0.25}$



Ratios of Couplings

When expressed in ratios, Higgs boson width cancels out ⇒ allowing test of the SM without any assumption about the Higgs boson width

$$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$$
$$\lambda_{Zg} = \kappa_Z / \kappa_g$$
$$\lambda_{WZ} = \kappa_W / \kappa_Z$$
$$\lambda_{tg} = \kappa_t / \kappa_g$$
$$\lambda_{bZ} = \kappa_b / \kappa_Z$$
$$\lambda_{\tau Z} = \kappa_\tau / \kappa_Z$$
$$\lambda_{\mu Z} = \kappa_\mu / \kappa_Z$$
$$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$$
$$\lambda_{(Z\gamma)Z} = \kappa_{Z\gamma} / \kappa_Z$$



Coupling fits to BSM models

SM + Singlet

The simplest extension of the standard model Higgs sector is the addition of a singlet S:

$$V(\phi,S)=\left\{\mu^2\phi^\dagger\phi+\lambda\left(\phi^\dagger\phi\right)^2\right\}+\left\{m_S^2S^2+\rho S^4\right\}+\kappa\left(\phi^\dagger\phi\right)S^2$$

Interesting phenomenology depends on whether $\langle S\rangle=0$.

If $\langle S\rangle\neq 0$, in general the singlet scalar and the "SM" Higgs boson can mix to form two mass eigenstates: $(h,\ H)$ assuming $h=h(125)$:

$$\begin{pmatrix} h \\ H \end{pmatrix}=\begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix}\begin{pmatrix} H_{SM} \\ S \end{pmatrix}$$

and new decay $H\to hh$ opens up if kinematically allowed.

If $\langle S\rangle=0$, there will be no mixing and the physical scalar s can be stable and is therefore a dark matter candidate.

Constraints on the Heavy Higgs

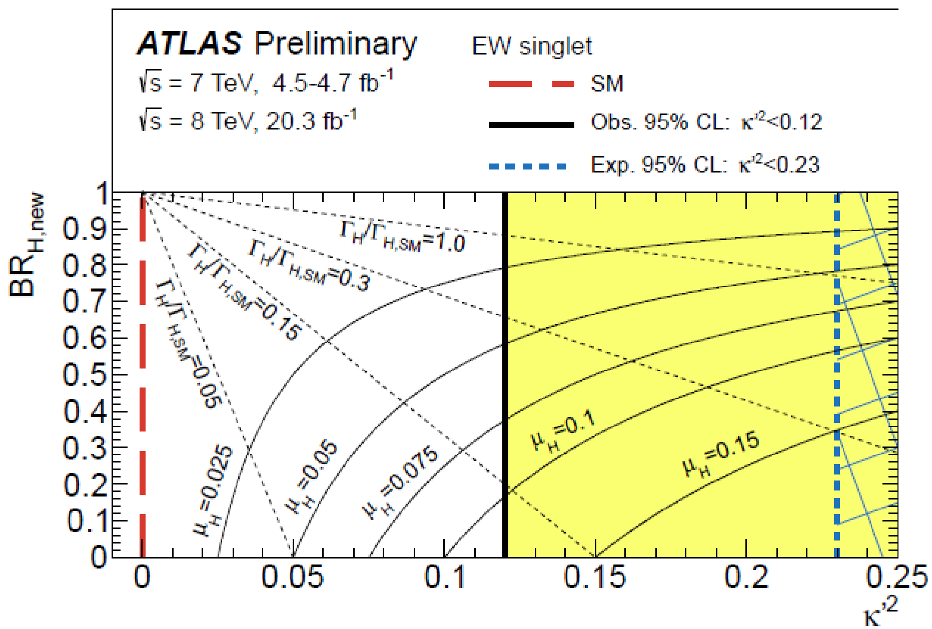
The mixing of H_{SM} and S leads to the modifications $\left(\kappa^2 = \cos^2\theta \text{ and } \kappa'^2 = \sin^2\theta\right)$

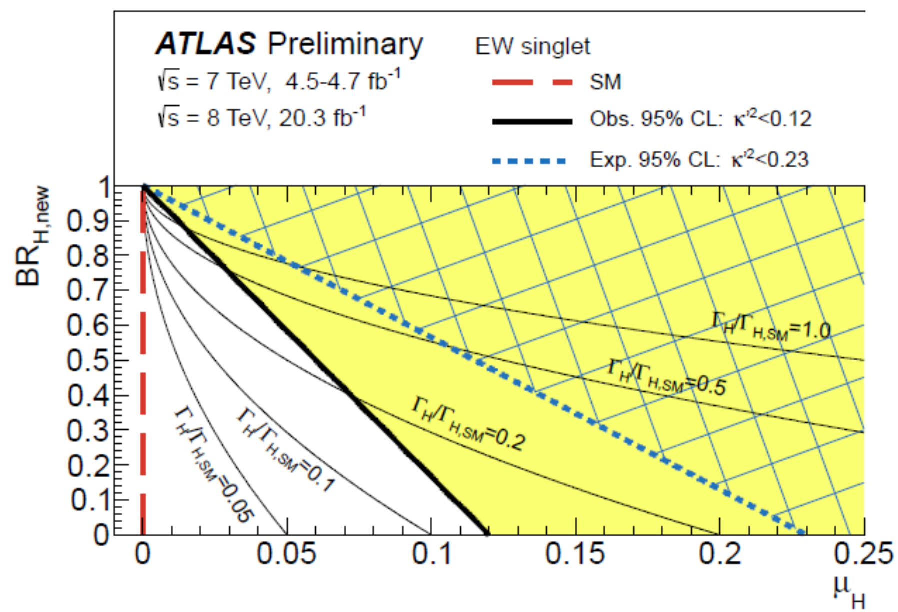
$$\sigma_h = \kappa^2 \times \sigma_h^{SM}, \qquad \Gamma_h = \kappa^2 \times \Gamma_h^{SM}, \qquad \text{BR}_h = BR_h^{SM},$$

$$\sigma_H = \kappa'^2 \times \sigma_H^{SM}, \qquad \Gamma_H = \frac{\kappa'^2}{1 - BR_{new}} \times \Gamma_H^{SM}, \qquad \text{BR}_H = \left(1 - BR_{new}\right) \times BR_H^{SM}$$

The measurement of the light Higgs boson can constrain the heavy Higgs boson:

$$\mu_h = \frac{(\sigma \times BR)_h}{(\sigma \times BR)_h^{SM}} = \kappa^2 \quad \Rightarrow \quad \mu_H = \frac{(\sigma \times BR)_H}{(\sigma \times BR)_H^{SM}} = \kappa'^2\left(1 - BR_{new}\right) = \left(1 - \mu_h\right)\left(1 - BR_{new}\right)$$





independent of the mass of the heavy Higgs boson m_H.

2 Higgs Doublet Models (2HDM)

These models result in 5 Higgs bosons after the symmetry breaking:

- two neutral CP-even scalars: h and H;
- one neutral CP-odd pseudoscalar: A;
- two charged H^+ and H^- scalars.

and are described by 8 free parameters (2 in SM), often chosen to be

5 mass parameters: m_h, m_H, m_A, $m_{H^\pm}$ and m_{12}^2

2 angular parameters: α and $\tan\beta$

(One more parameter is fixed by W boson mass: $\upsilon = 246$ GeV)

α: mixing parameter of two CP-even Higgs scalars;

$\tan\beta = \frac{\upsilon_2}{\upsilon_1}$: ratio of V.E.V. of the two Higgs doublets

2HDMs are classified into 4 types according to Higgs-Fermion couplings

Type	I	II	III	IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2
Also known as	"Fermiophobic"	MSSM-like	Lepton-specific	Flipped

Decoupling and Alignment Limits

Typically, the neutral Higgs bosons of 2HDMs have very different properties compared with the SM Higgs boson. However, SM-like Higgs boson can arise from 2HDMs in two ways

Decoupling limit

All but the lightest Higgs boson are heavy: $m_h \ll m_H, m_A, m_{H^\pm} \Rightarrow$ $h \approx H_{SM}$

Integrating out the heavy states yields an effective 1 Higgs doublet theory.

Alignment limit

$$\sin(\beta - \alpha) \to 1$$
$$\cos(\beta - \alpha) \to 0$$
$$\Downarrow$$
$$h \approx H_{SM}$$

Vertex	Type II tree-level coupling factor	
$h\ VV$	$\sin(\beta - \alpha)$	$\longrightarrow 1$
$h\ tt$	$\cos\alpha / \sin\beta = \sin(\beta - \alpha) + \cot\beta\cos(\beta - \alpha)$	$\longrightarrow 1$
$h\ bb$	$-\sin\alpha / \cos\beta = \sin(\beta - \alpha) - \tan\beta\cos(\beta - \alpha)$	$\longrightarrow 1$
$h\ \tau\tau$	$-\sin\alpha / \cos\beta = \sin(\beta - \alpha) - \tan\beta\cos(\beta - \alpha)$	$\longrightarrow 1$

These relations hold true for all 2HDM types

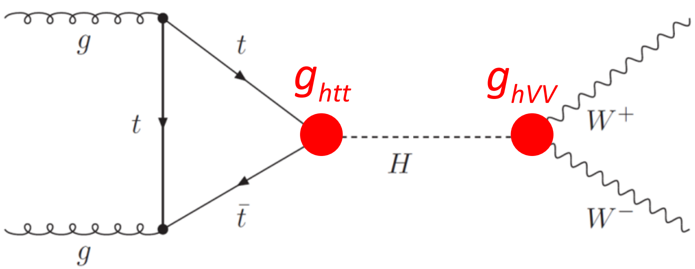
$$g_{hVV} \Rightarrow g_{H_{SM}VV},\quad g_{htt} \Rightarrow g_{H_{SM}tt},\quad g_{hbb} \Rightarrow g_{H_{SM}bb},\quad g_{h\tau\tau} \Rightarrow g_{H_{SM}\tau\tau}$$

Indirect Constraints from Coupling Fits

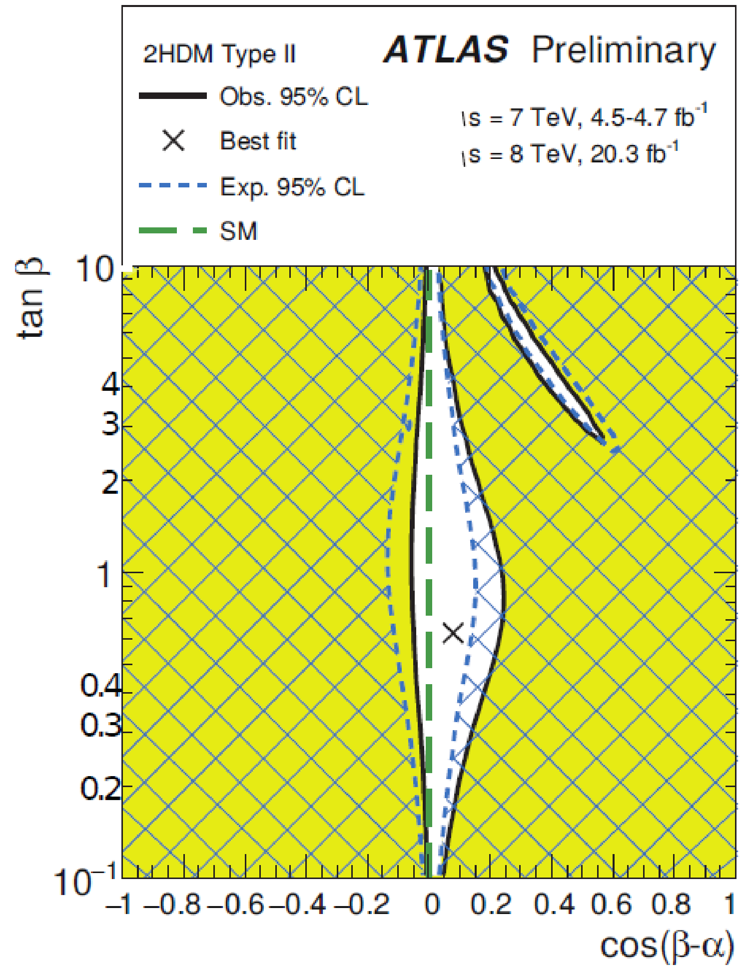
Assuming no change in Higgs decay kinematics and no new production process, the measured rates of h(125) can be turned into constraints on the two 2HDM parameters: α and β

Parametrized using $\tan\beta$ and $\sin(\beta-\alpha)$

Vertex	Type II tree-level coupling factor
$h\,VV$	$\sin(\beta-\alpha)$
$h\,tt$	$\cos\alpha/\sin\beta = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$
$h\,bb$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$
$h\,\tau\tau$	$-\sin\alpha/\cos\beta = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$

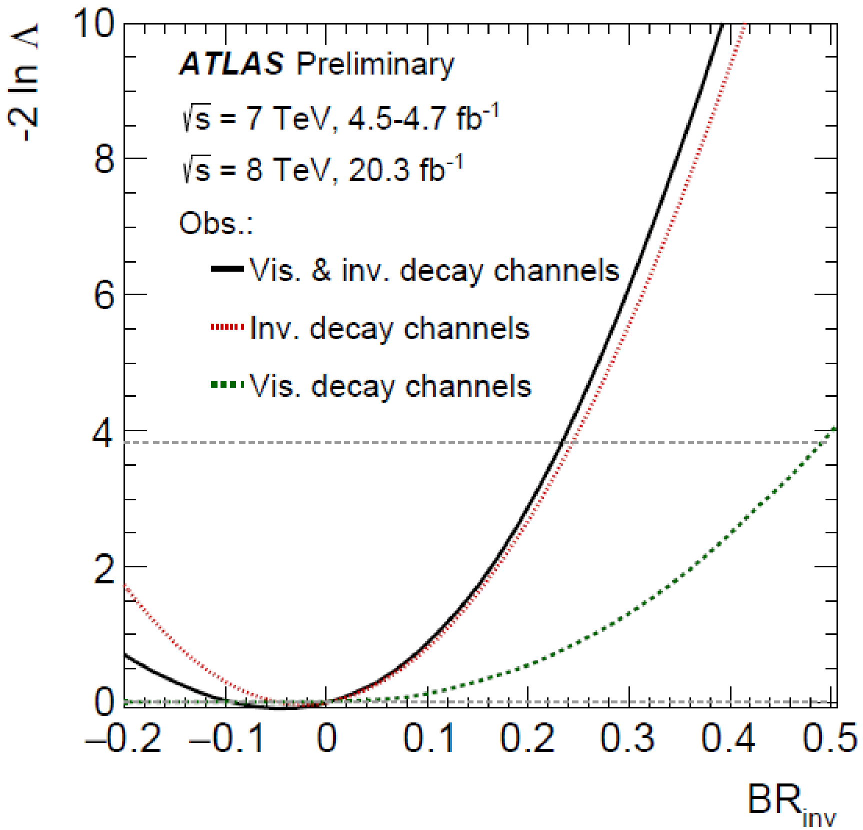


$$\frac{(\sigma\cdot BR)(gg\to h\to WW)}{\left[\sigma(gg\to h)\cdot BR(h\to WW)\right]_{SM}} \approx \left(\frac{g_{htt}}{g_{htt}^{SM}}\right)^2 \times \left(\frac{g_{hVV}}{g_{hVV}^{SM}}\right)^2$$



BR_{inv} from direct and indirect constraints

Assuming $BR_{NEW} = BR_{inv}$, i.e., all new decays are invisible decays,
constraints from: - the rate measurements: $BR_{inv} < 0.49$ for $\kappa_V \leq 1$;
- the direct searches: $BR_{inv} < 0.25$



Combining the direct searches with the indirect (rate measurements) in the most general model: κ_W, κ_Z, κ_t, κ_b, κ_τ, κ_μ, κ_g, κ_γ, $\kappa_{Z\gamma}$, BR_{inv} with

The total Higgs boson width

$$\Gamma_h = \frac{\kappa_h^2 \cdot \Gamma_h^{SM}}{1 - BR_{inv}}$$

$BR_{inv} < 23\%$ at 95% CL

Dark Matter Interpretation

The constraints on $\mathrm{BR}(h \to inv)$ can be turned into constraint on Γ_{inv}

$$\Gamma_{inv} = \frac{BR(h \to inv)}{1 - BR(h \to inv)} \Gamma_h^{SM}$$

$\Rightarrow$ constrain dark-matter and nucleon interactions

$$BR(h \to inv) < 23\%$$

$$\Gamma^{\text{inv}}(h \to SS) = \lambda_{hSS}^2 \frac{v^2 \beta_S}{128 \pi m_h}$$

$$\Gamma^{\text{inv}}(h \to ff) = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{v^2 \beta_f^3 m_h}{64 \pi}$$

$$\Gamma^{\text{inv}}(h \to VV) = \lambda_{hVV}^2 \frac{v^2 \beta_V m_h^3}{512 \pi m_V^4} \left(1 - 4\frac{m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right).$$

$$\sigma_{S-N} = \lambda_{hSS}^2 \frac{m_N^4 f_N^2}{16 \pi m_h^4 (m_S + m_N)^2}$$

$$\sigma_{f-N} = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{m_N^4 f_N^2 m_f^2}{4 \pi m_h^4 (m_f + m_N)^2}$$

$$\sigma_{V-N} = \lambda_{hVV}^2 \frac{m_N^4 f_N^2}{16 \pi m_h^4 (m_V + m_N)^2},$$