Higgs Boson Property Measurements
Status and Prospect

Introduction
Main decay channels
Rare productions and decays
Mass, width and Spin
Coupling fits

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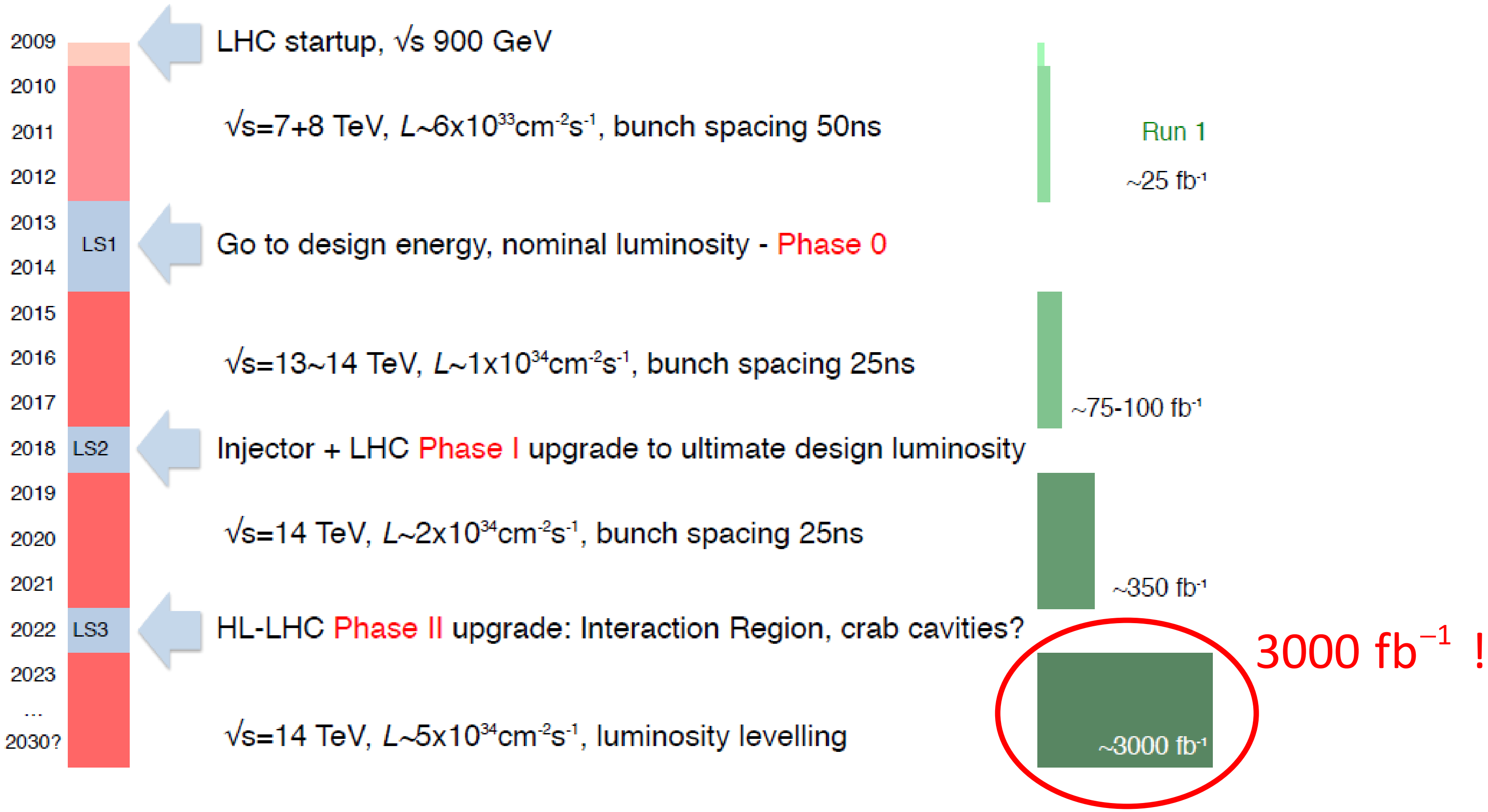
Lattice Meets Experiment 2013: Beyond the Standard Model
Brookhaven National Laboratory, December 5-6, 2013

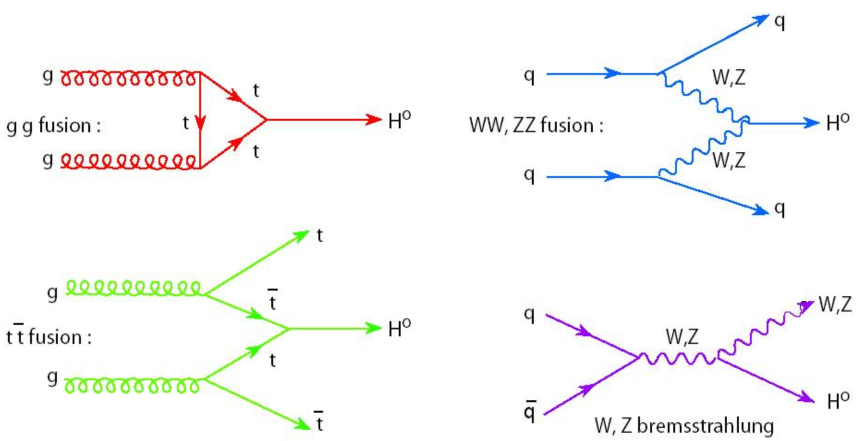
LHC – High Luminosity Upgrade

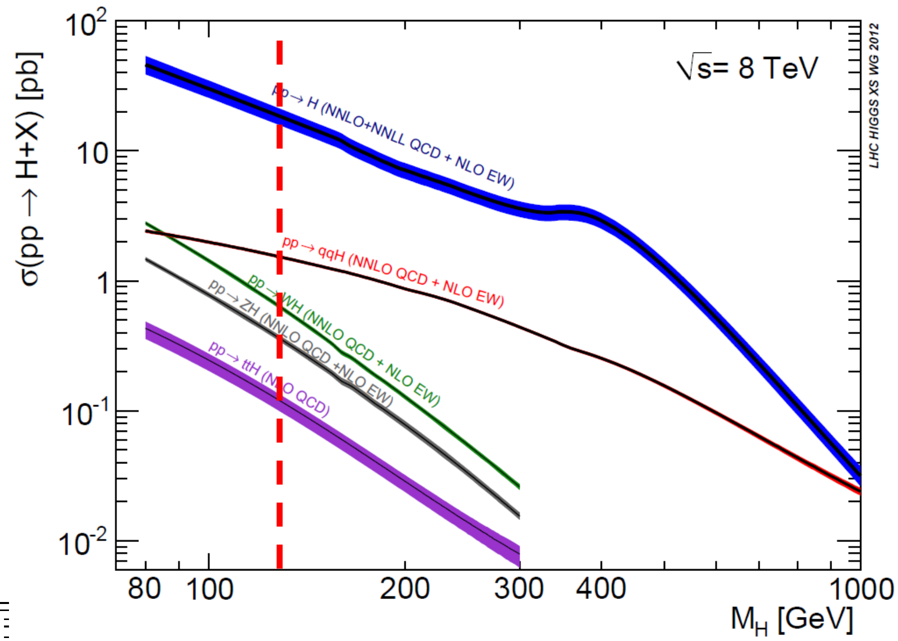
Update of European Strategy for Particle Physics:

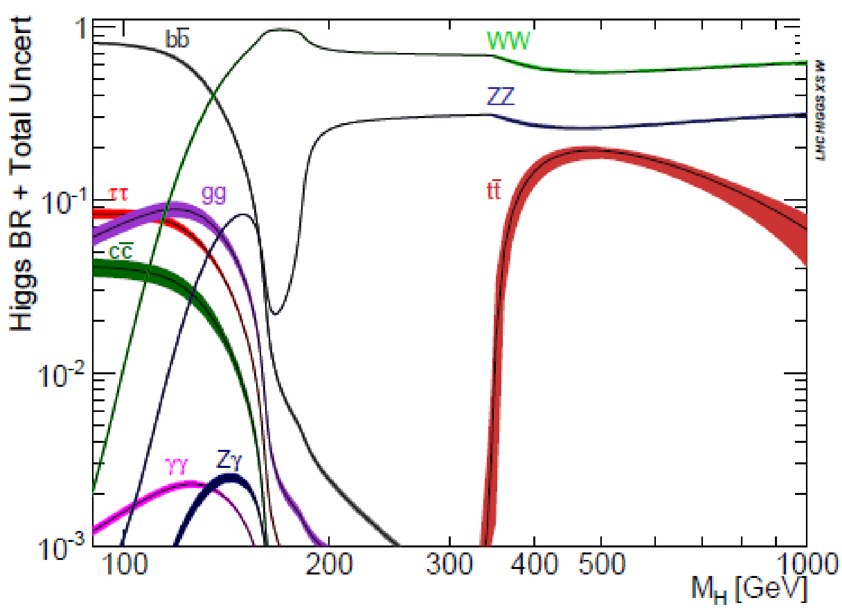
"Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030."



Higgs Productions & Decays





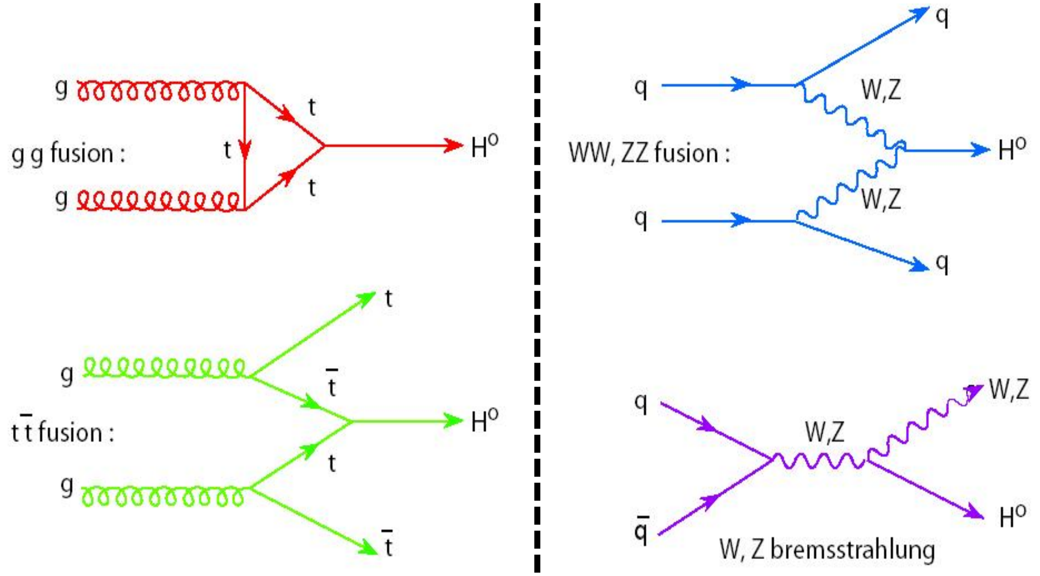


$$m_H = 125 \text{ GeV} \quad \sigma_H = 22.3 \text{ pb}$$

Branching ratio	
$H \to b\bar{b}$	57.7%
$H \to WW^*$	21.5%
$H \to \tau\tau$	6.32%
$H \to ZZ^*$	2.64%
$H \to \gamma\gamma$	0.23%
$H \to \mu\mu$	0.02%

Disentangle Production Processes – Why?

Production processes naturally fall into two groups



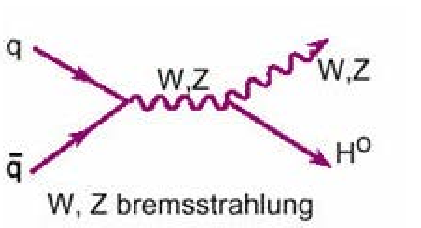
Strong Production
Fermion Coupling

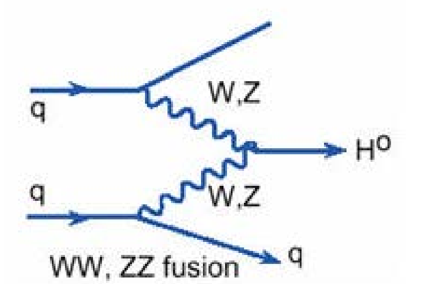
Electroweak Production,
Vector Boson Coupling

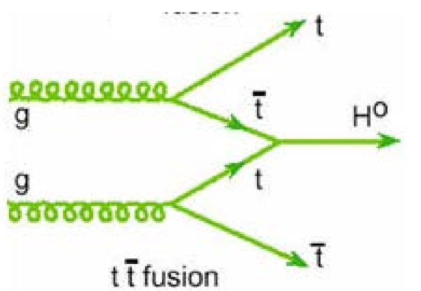
Higgs candidate events are selected from their decay signatures, independent of production.

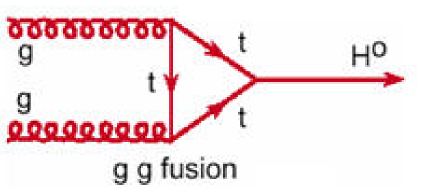
Need to disentangle the production processes using the production signatures (independent of decay) to study couplings.

Disentangle Production Processes – How?









VH

Leptons, missing ET or low-mass dijets from W or Z decays

VBF

Two high pT jets with high-mass and large Pseudorapidity separation

ttH

Two top quarks: leptons, missing ET, multijets or b-tagged jets

ggF

the rest

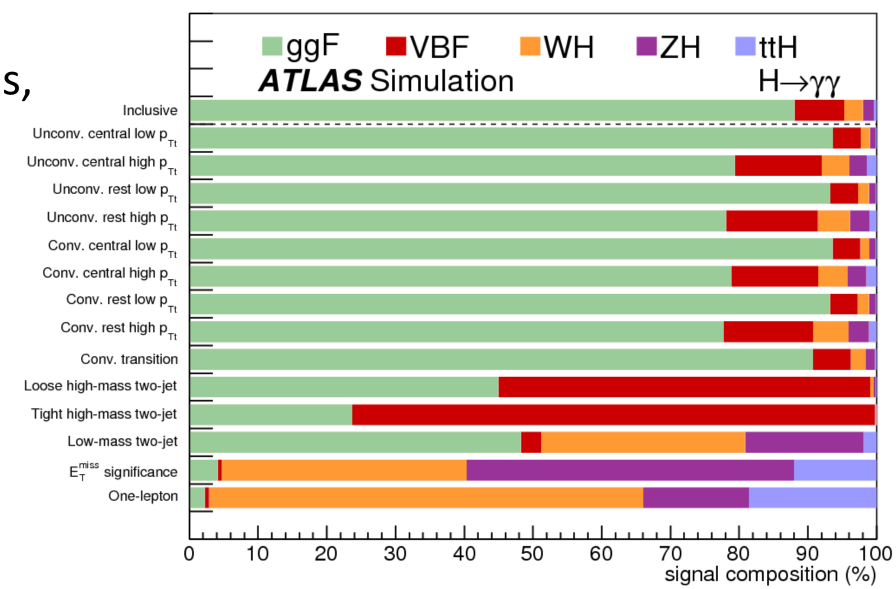
Analyses are generally done in categories based on additional activities, Higgs p_T or detector performance:

VBF (forward jets);

boosted Higgs (large p_T^H);

additional leptons, ...

to improve S/B ratios and to isolate different production processes.



Theoretical Uncertainties

$\Delta\sigma/\sigma$ for pp at8 TeV

Process	QCD scale	PDF+α_s	Total (linear sum)
ggF	$\pm 8\%$	$\pm 8\%$	$\pm 15\%$
$t\bar{t}$H	$\pm 7\%$	$\pm 8\%$	$\pm 15\%$
VBF	$\pm 1\%$	$\pm 4\%$	$\pm 5\%$
VH	$\pm 1\%$	$\pm 4\%$	$\pm 5\%$

LHC cross section working group

The uncertainties in the ggF process are starting to limit the precision of the coupling measurements.

ΔBR/BR at $M_H = 125$ GeV

decay	theory	parameters	total (linear sum)
$H \to bb$	$\pm 1.3\%$	$\pm 1.5\%$	$\pm 2.8\%$
$H \to \tau\tau$	$\pm 3.6\%$	$\pm 2.5\%$	$\pm 6.1\%$
$H \to \mu\mu$	$\pm 3.9\%$	$\pm 2.5\%$	$\pm 6.4\%$
$H \to WW^*$	$\pm 2.2\%$	$\pm 2.5\%$	$\pm 4.8\%$
$H \to ZZ^*$	$\pm 2.2\%$	$\pm 2.5\%$	$\pm 4.8\%$
$H \to \gamma\gamma$	$\pm 2.9\%$	$\pm 2.5\%$	$\pm 5.4\%$

A. Denner et al., arXiv:1107.5909

$\Gamma_{b\bar{b}} \approx 0.57\Gamma_H \Rightarrow \Delta m_b$ has a large impact on parametric uncertainties

Snowmass Report arXiv:1310.8361

	Higgs X-section Working Group [15]	PDG [19]	non-lattice	Lattice (2013)	Lattice (2018)
$\Delta\alpha_s$	0.002	0.0007	0.0012 [19]	0.0006 [20]	0.0004
Δm_c (GeV)	0.03	0.025	0.013 [21]	0.006 [20]	0.004
Δm_b (GeV)	0.06	0.03	0.016 [21]	0.023 [20]	0.011

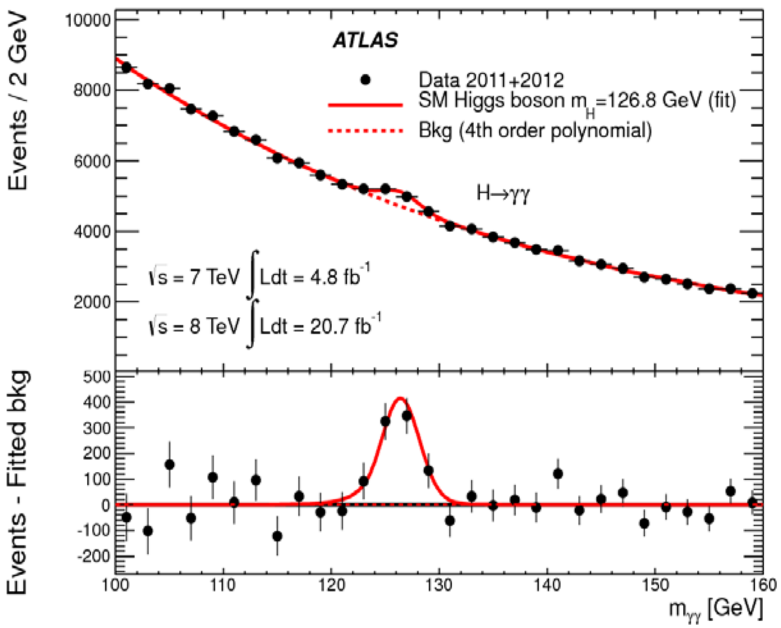
H→γγ Analysis

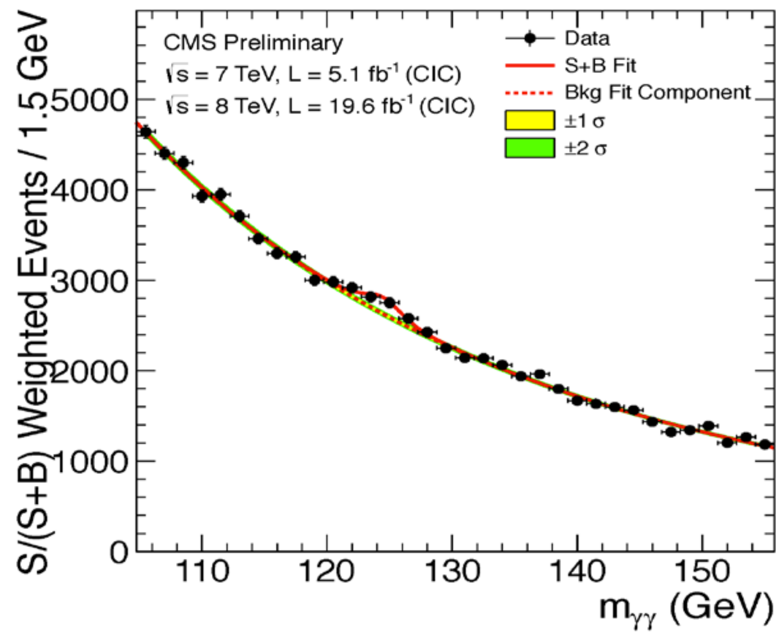
Simple topology: narrow diphoton resonance over a continuum background

- Determine background from data side-band;
- Typical mass resolution 1-2%;
- Categorized analysis to improve S/B ratio

Signal strength: $\mu = \dfrac{\sigma \times BR}{(\sigma \times BR)_{SM}}$

arXiv:1307.1427





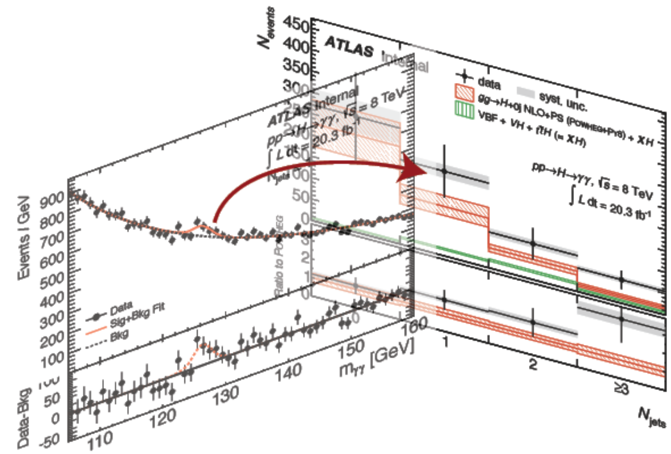
CMS-PAS-HIG-13-001

	ATLAS	CMS
Peak mass	126.8 GeV	125.4 GeV
Excess significance	7.4σ (4.3σ expected)	3.2σ (4.2σ expected)
Signal strength	$1.57 \pm 0.24(\mathrm{stat}) \pm 0.22(\mathrm{syst})$	0.78 ± 0.27

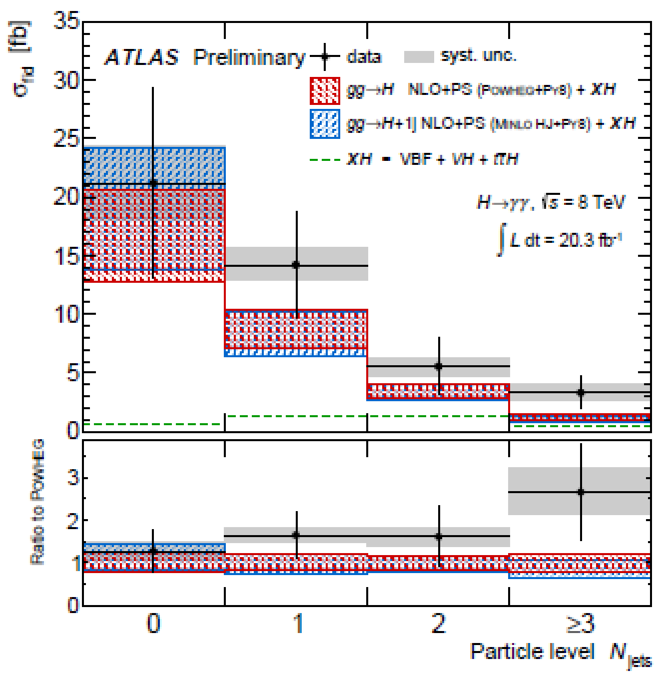
H→γγ: Differential Distributions

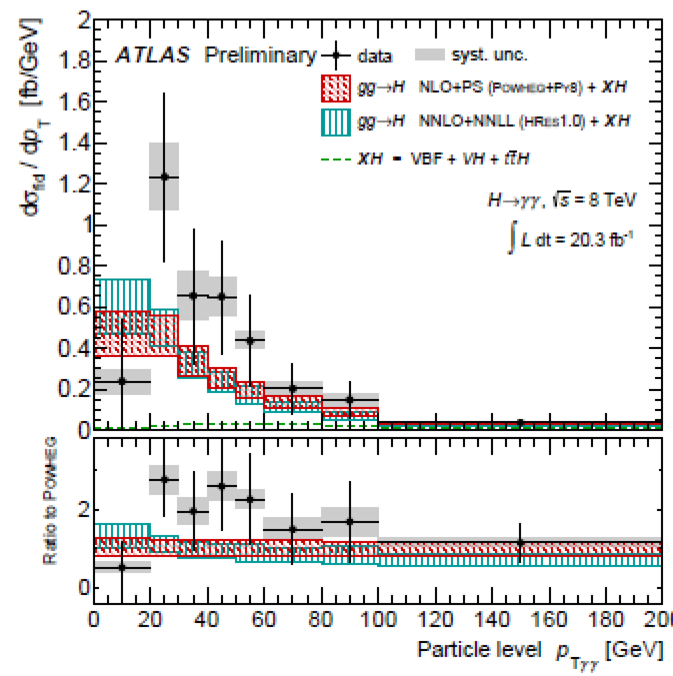
Study kinematics of candidate events:

- 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



ATLAS-CONF-2013-072





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

H→ZZ*→4ℓ Analysis

Clean signature, very little background mainly irreducible SM ZZ contribution

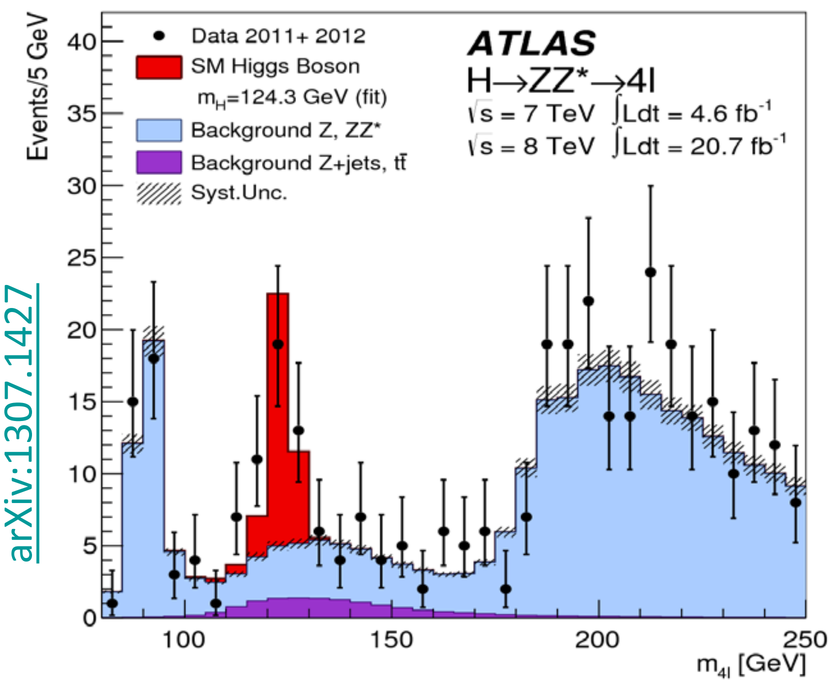
Narrow resonance and good mass resolution:

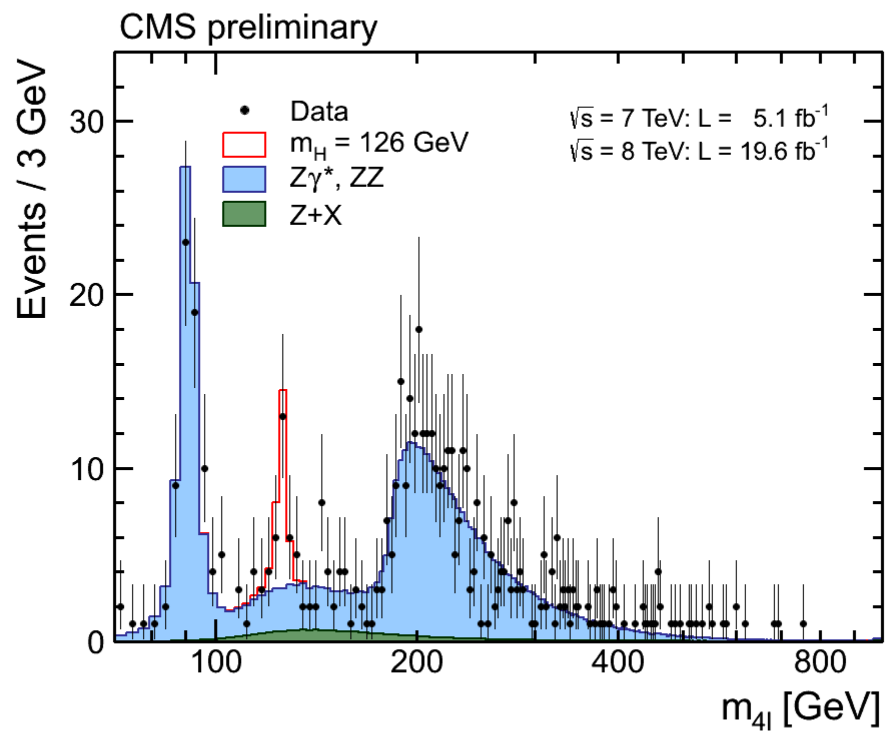
1-2% similar to H→γγ

High signal-background ratio

	ATLAS	CMS
Peak mass	124.3 GeV	125.7 GeV
Excess significance	6.6σ (4.4σ)	6.7σ (7.1σ)
Signal strength	$1.7 \pm 0.5 \pm 0.4$	0.92 ± 0.28

arXiv:1307.1427





CMS-PAS-HIG-13-002

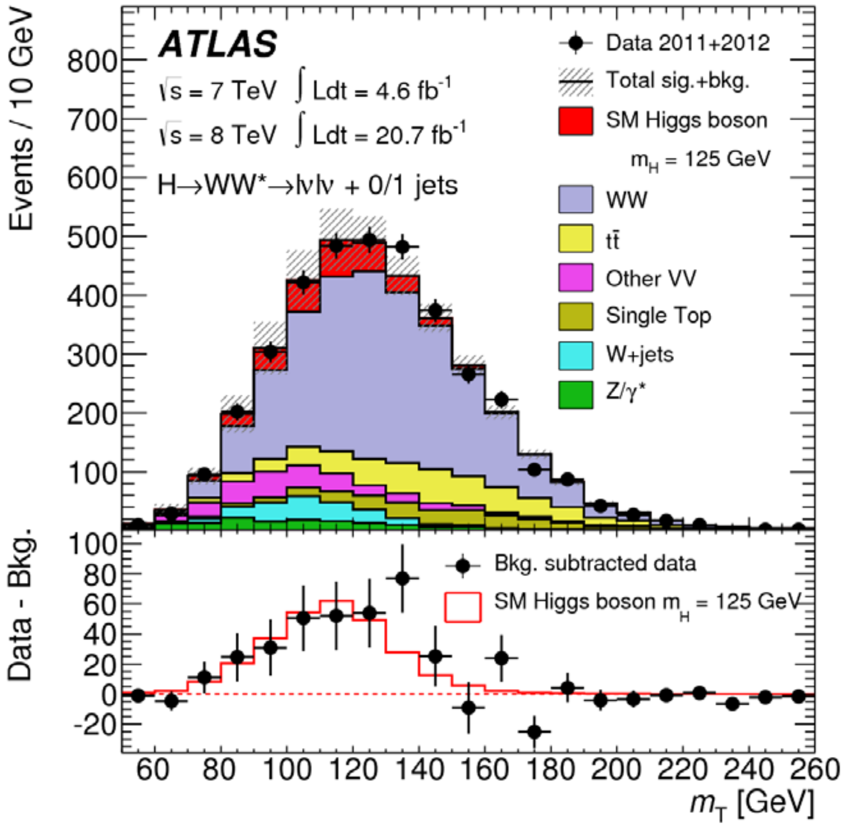
H→WW*→ℓνℓν Analysis

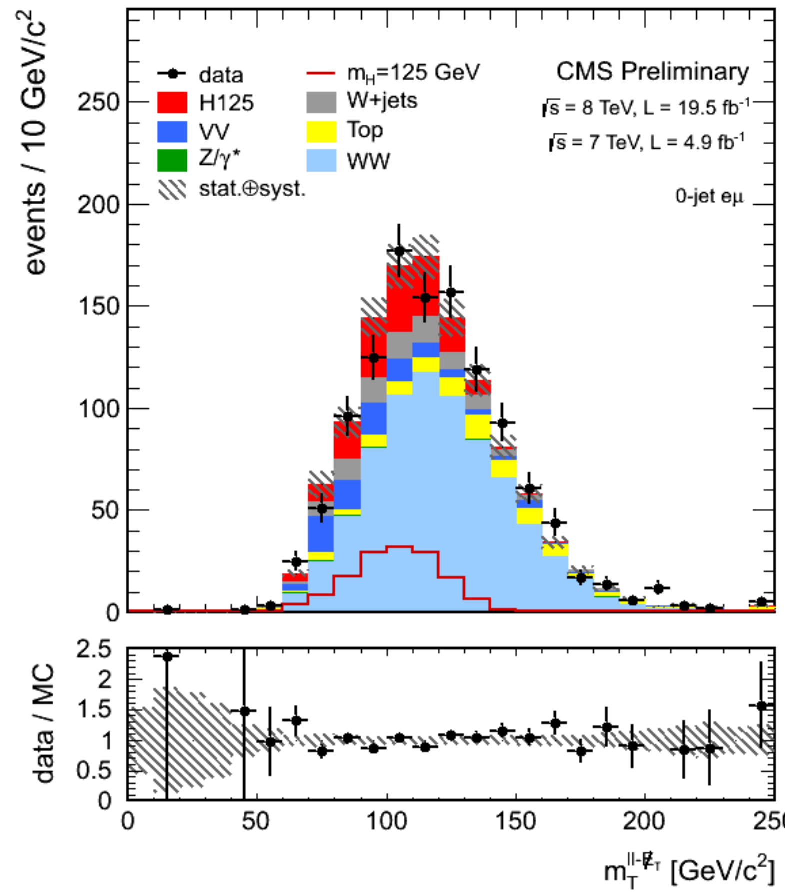
No full Higgs decay reconstruction, transverse mass as the discriminant

Backgrounds are strongly jet multiplicity dependent => analysis in jet bins

S/B ratio ~ 10-20% in 0/1 jet bin

	ATLAS	CMS
Excess significance	3.8σ (3.8σ)	4.0σ (5.1σ)
Signal strength	$0.99^{+0.31}_{-0.28}$	0.76 ± 0.21



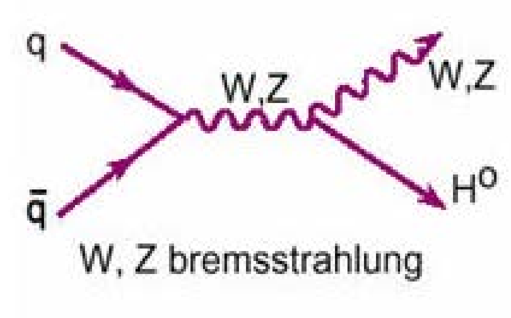


CMS-PAS-HIG-13-003

arXiv:1307.1427

H→bb from VH Production

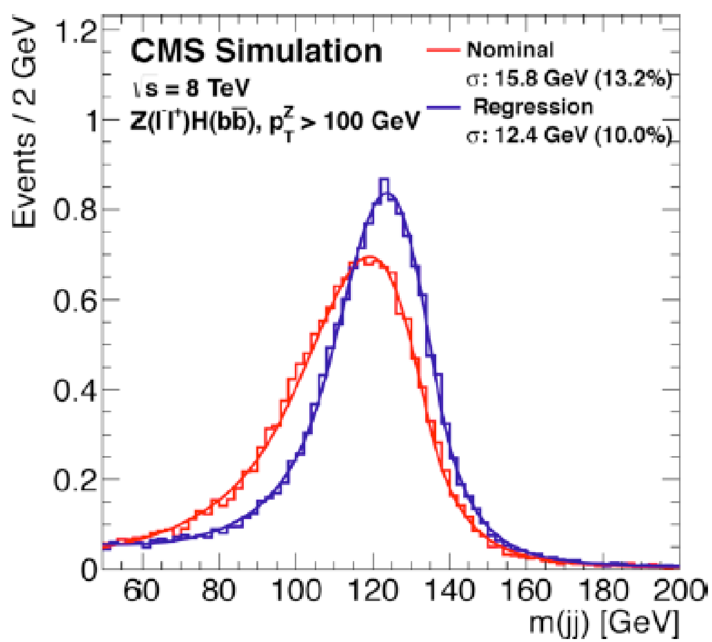
No triggering on leptons or photons from Higgs decays, rely on associated objects such as V $(W \text{ or } Z)$ in the VH production.



Three distinct final states:

0-lepton: $\nu\nu b\bar{b}\ (ZH)$;
1-lepton: $\ell\nu b\bar{b}\ (WH)$;
2-leptons: $\ell\ell b\bar{b}\ (ZH)$

CMS-PAS-HIG-13-012



Full reconstruction of the $H \to b\bar{b}$ decay, but poor mass resolution $\sim 10-20\%$. Coupled with the relative low VH cross section $\Rightarrow$ large backgrounds.

b-jet tagging to reduce light-flavor W+jets and Z+jets background.

Explore event kinematics to further separate signal from Vbb background:

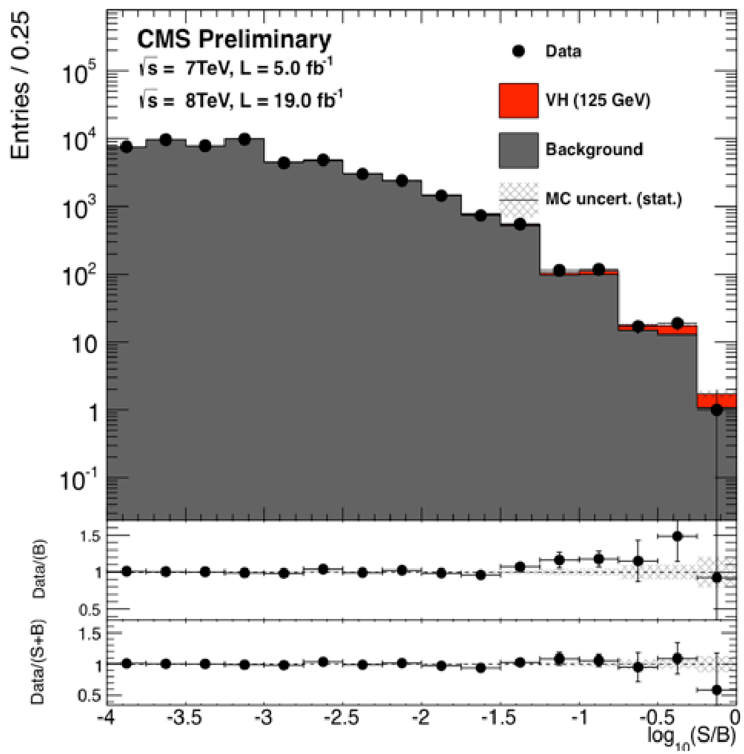
categorize in p_T^V bins to take advantage of different S/B ratios

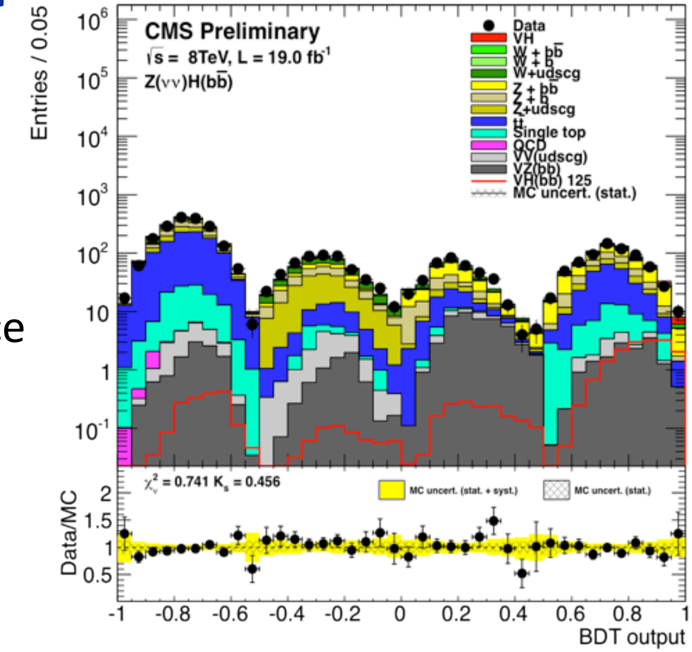
H→bb from VH Production

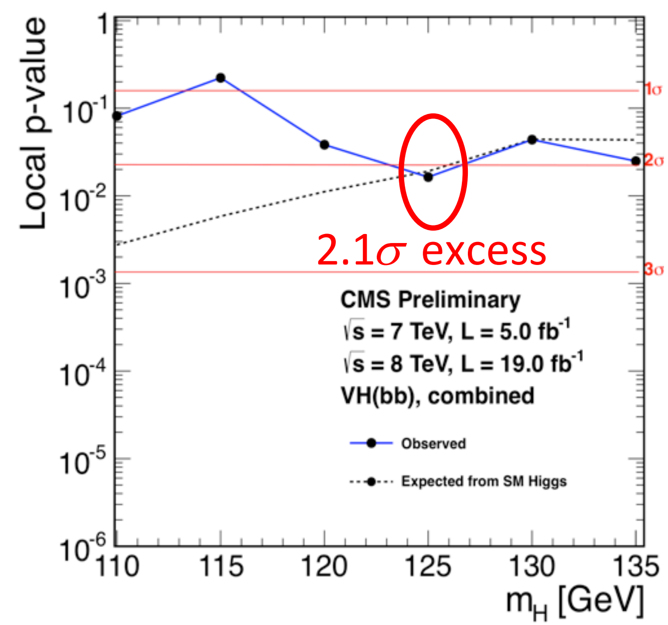
While ATLAS relies on the cut-based analysis, CMS applies advanced techniques extensively in its analysis:

- Separate BDTs for each signal final state;
- Separate BDT for each major background source

CMS-PAS-HIG-13-012







Observed signal strength at 125 GeV

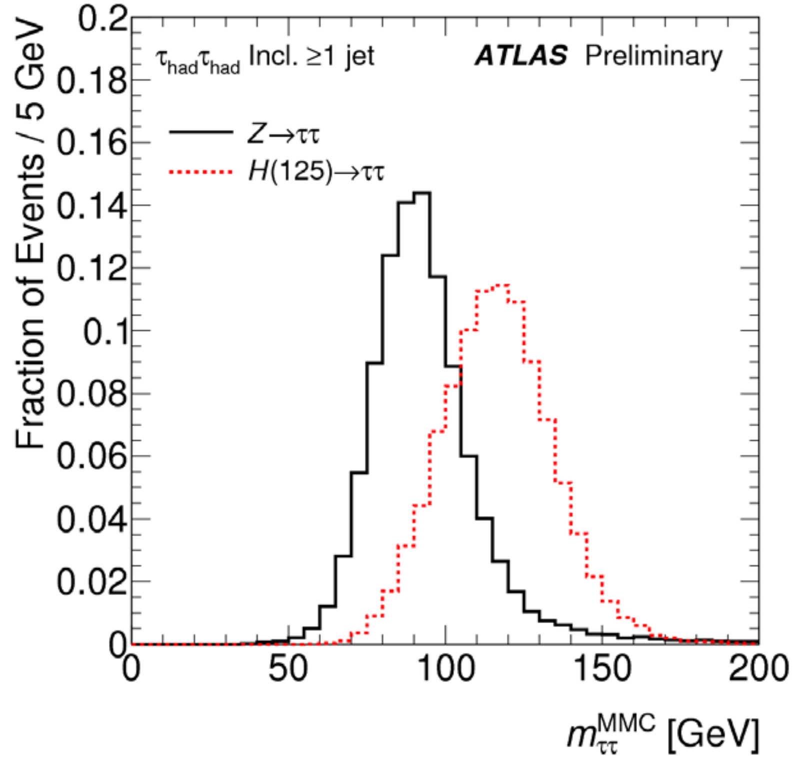
$$\mu = 1.0 \pm 0.5 \ (\text{CMS})$$

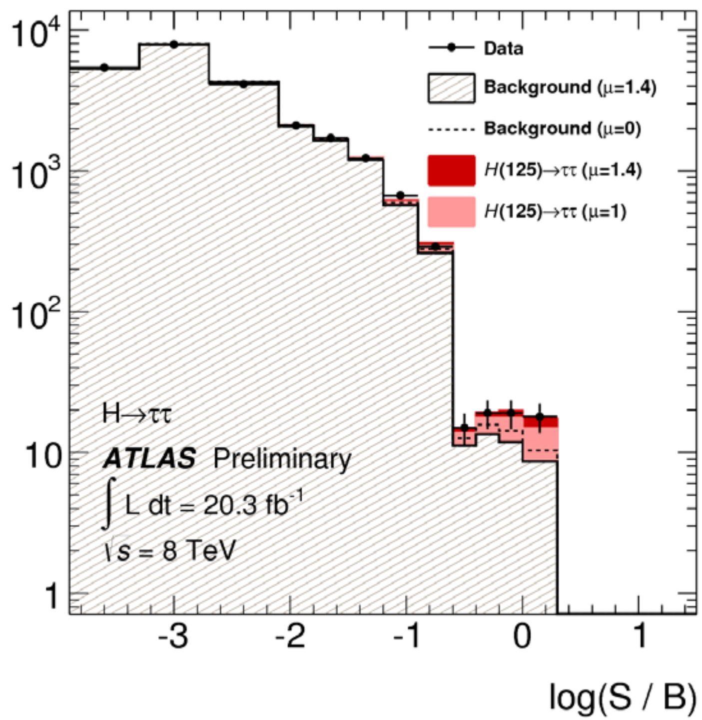
H→ττ Analysis

Analyzed all three final states of the $\tau\tau$ decays:

- lep-lep channel: $\mathrm{H}\to\tau\tau\to2\ell+4\nu$ (12.4%)
- lep-had channel: $\mathrm{H}\to\tau\tau\to\ell+\tau_{had}+3\nu$ (45.6%)
- had-had channel: $\mathrm{H}\to\tau\tau\to2\tau_{had}+2\nu$ (42%)

Reconstruct $\tau\tau$ mass using the Missing Mass Calculator (MMC) with a resolution $\sim$15%.





ATLAS-CONF-2013-108

Major backgrounds: $\mathrm{Z}\to\tau\tau$, fake τ's. Estimate $\mathrm{Z}\to\tau\tau$ background using "embedding":

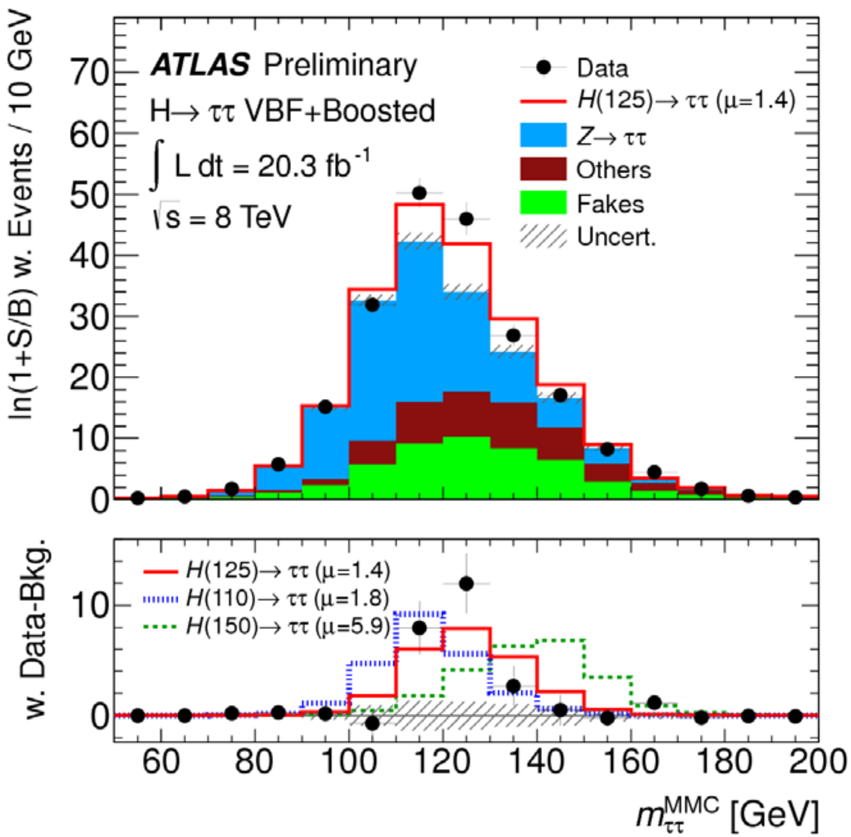
Taking data $\mathrm{Z}\to\mu\mu$ events, replace the "μ" with the simulated τ.

Two major categories: VBF and boosted
Employing MVA after basic selection.

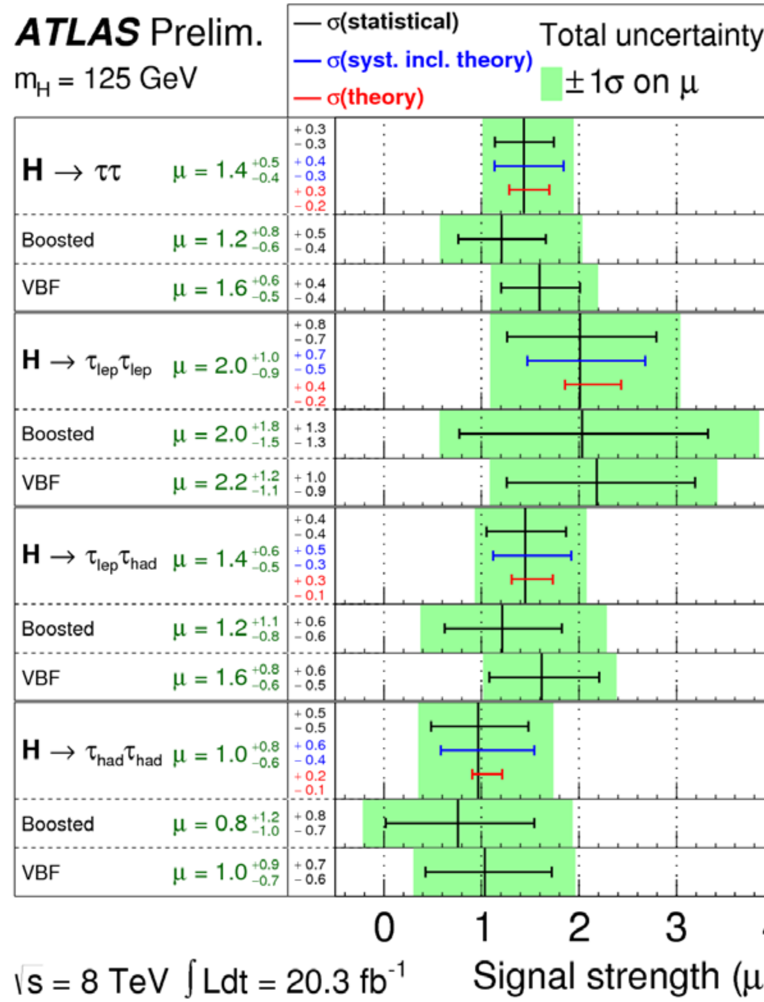
H→ττ Analysis

Excesses observed in all three channels with an observed (expected) combined significance of 4.1σ (3.2σ) at 125 GeV.

ATLAS-CONF-2013-108



The excess is consistent with a SM Higgs boson at 125 GeV.

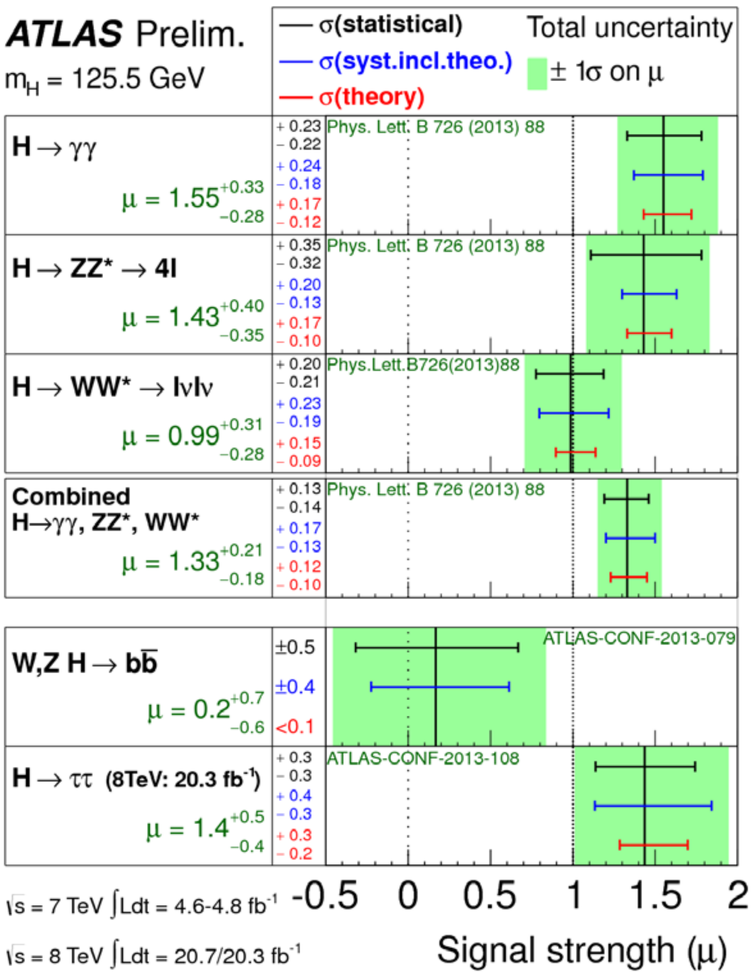


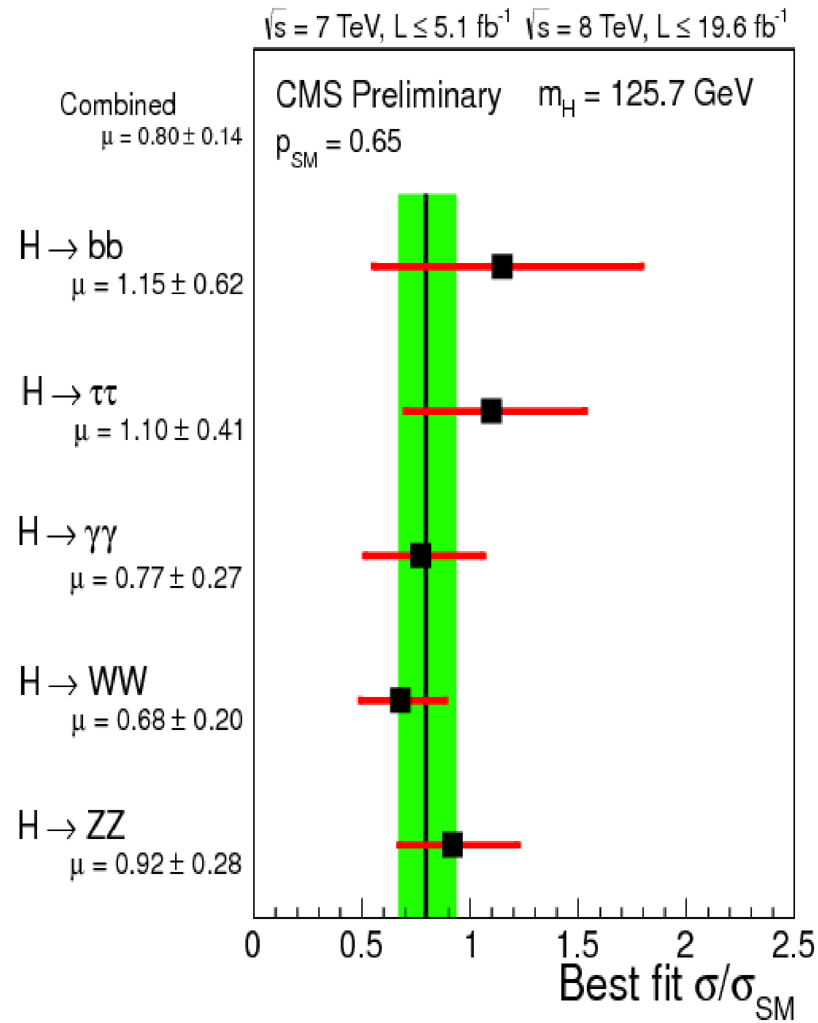
Observed signal strength at 125 GeV

$$\mu = 1.4 \pm 0.3(stat)^{+0.4}_{-0.3}(syst)$$

Summary of Signal Strengths

ATLAS-CONF-2013-108



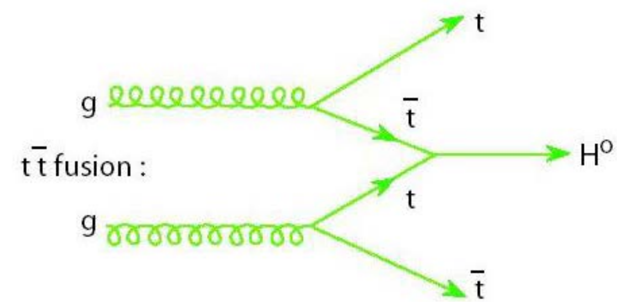


CMS-PAS-HIG-13-005

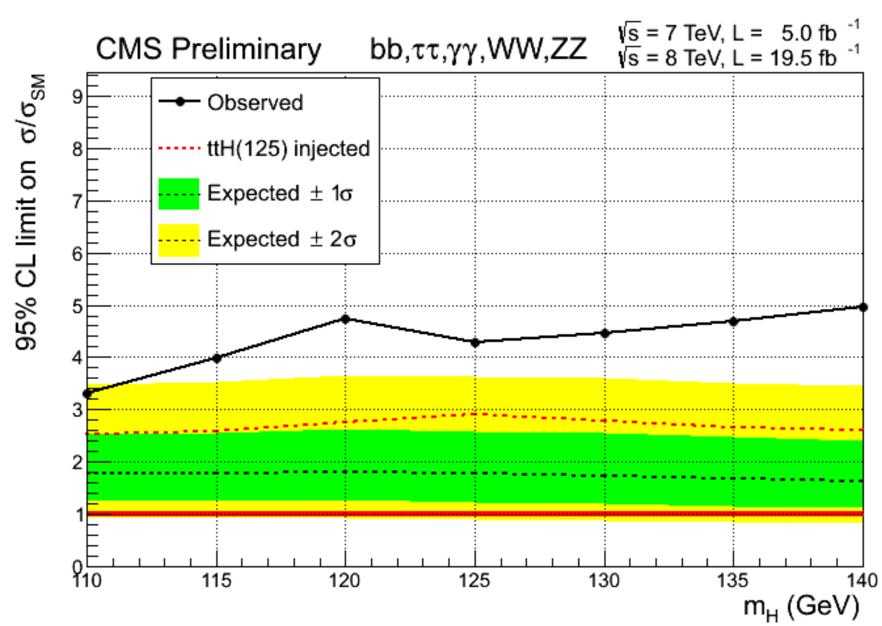
Combining ATLAS and CMS, there is little doubt that the Higgs boson has been observed in both fermion and boson final states

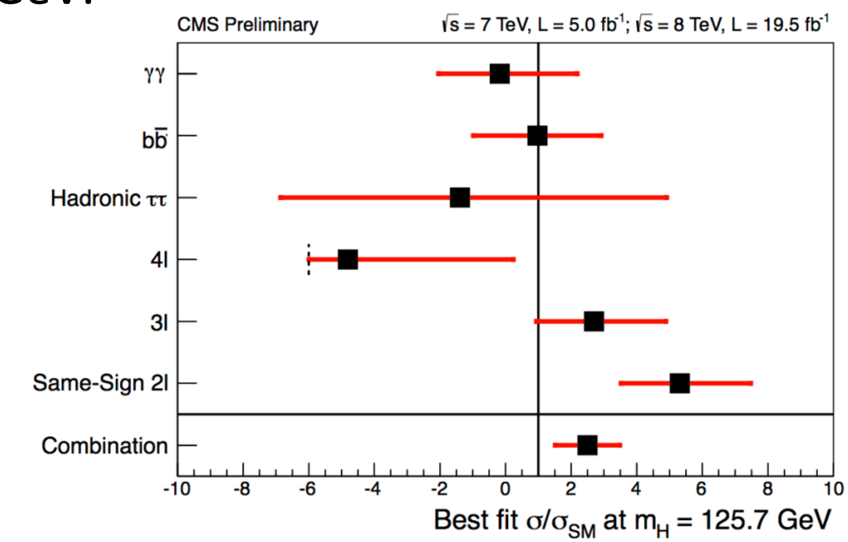
ttH Production

Searches for additional Higgs boson in $t\bar{t}$ events
$\Rightarrow$ allow direct study of top-Higgs Yukawa couplings, but large backgrounds from SM $t\bar{t}$ production.



Combining searches in $\gamma\gamma$, bb, $\tau\tau$ and multi-lepton final states, CMS sets an upper limit on the signal strength of 4.3 (2.9) at 125 GeV.





The measured signal strength

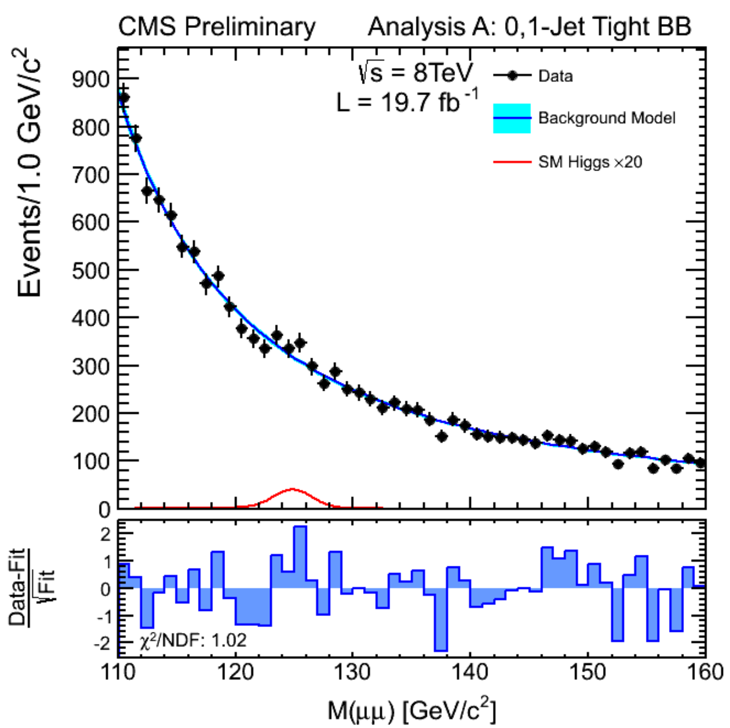
$$\mu = 2.5^{+1.1}_{-1.0}$$

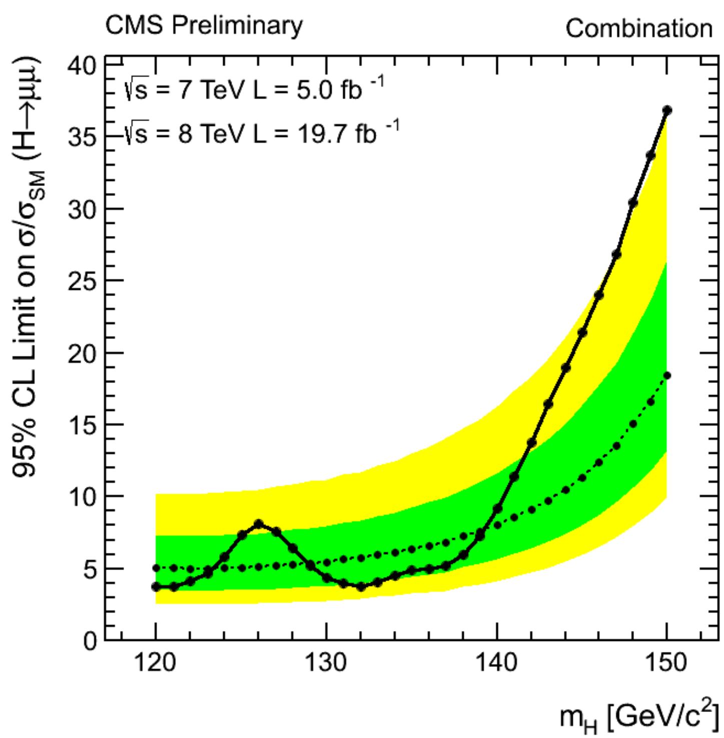
Direct hint of the Higgs coupling to the top quark.

H→μμ Decay

Small $BR(H \to \mu\mu) = 2.2 \times 10^{-4}$ @ 125 GeV, good mass resolution ~ 2 GeV, 10 times smaller than $BR(H \to \gamma\gamma)$ with a larger background

A broad excess $(\sim 2.3\sigma)$ is observed for the mass above 140 GeV.
At 125 GeV, upper limit on the signal strength: 7.4 (5.1)observed (expected).





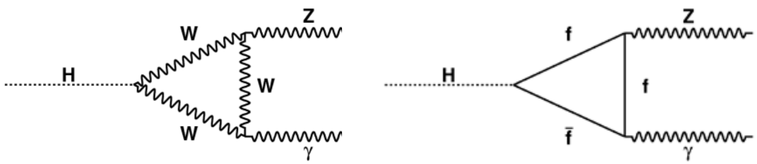
CMS-PAS-HIG-13-007

At $m_H = 125.7$ GeV (CMS value), the measured signal strength is $2.9^{+2.8}_{-2.7}$.

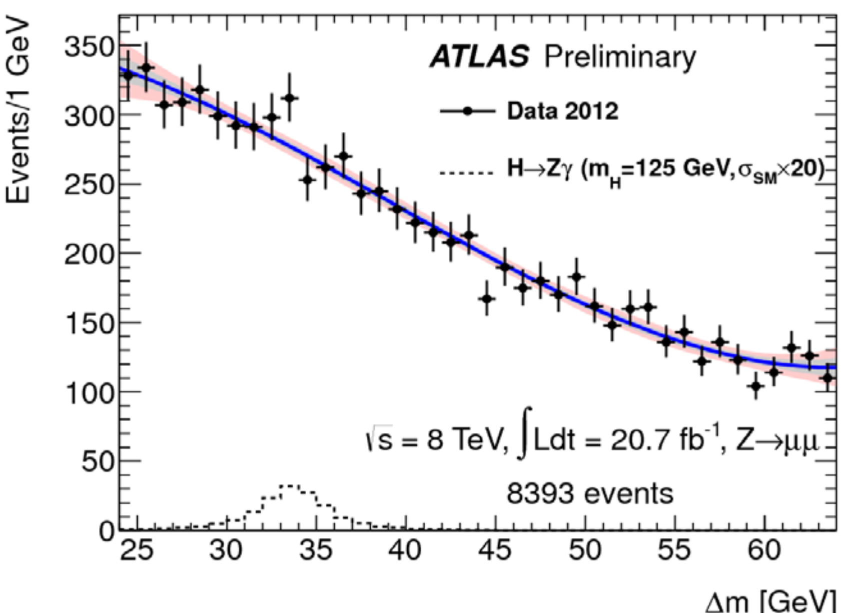
H→Zγ→ℓℓγ

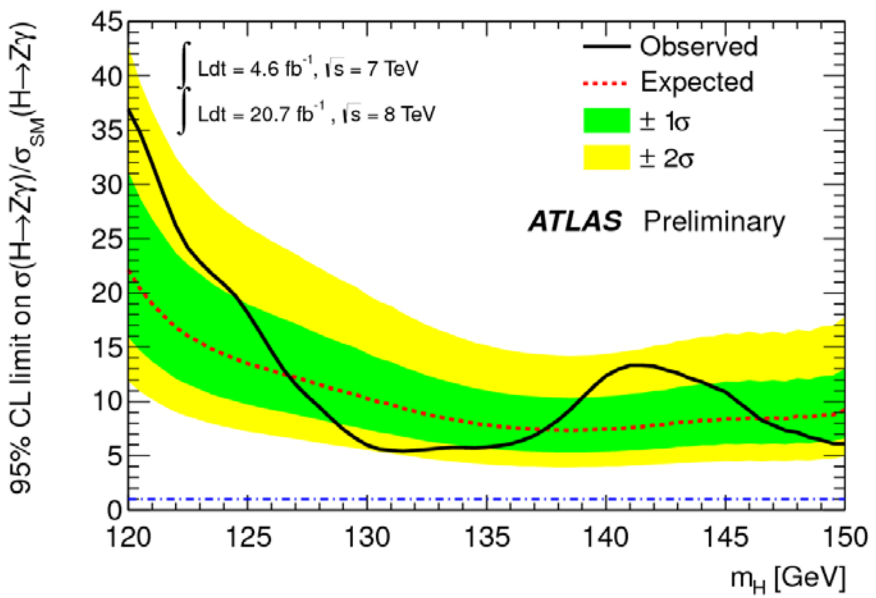
Small $BR(H \to Z\gamma) = 1.5\times10^{-3}$ @ 125 GeV, good mass resolution ~2 GeV, comparable to $BR(H \to \gamma\gamma)$, but suffer from small $\mathrm{BR}(Z \to \ell\ell)$.

Typical selection efficiency $\sim 30\%$,
Main background: SM $Z\gamma$ production



The upper limit on the signal strength at 125 GeV: 18.2 (13.5) observed (expected), Not yet sensitive to the SM production.

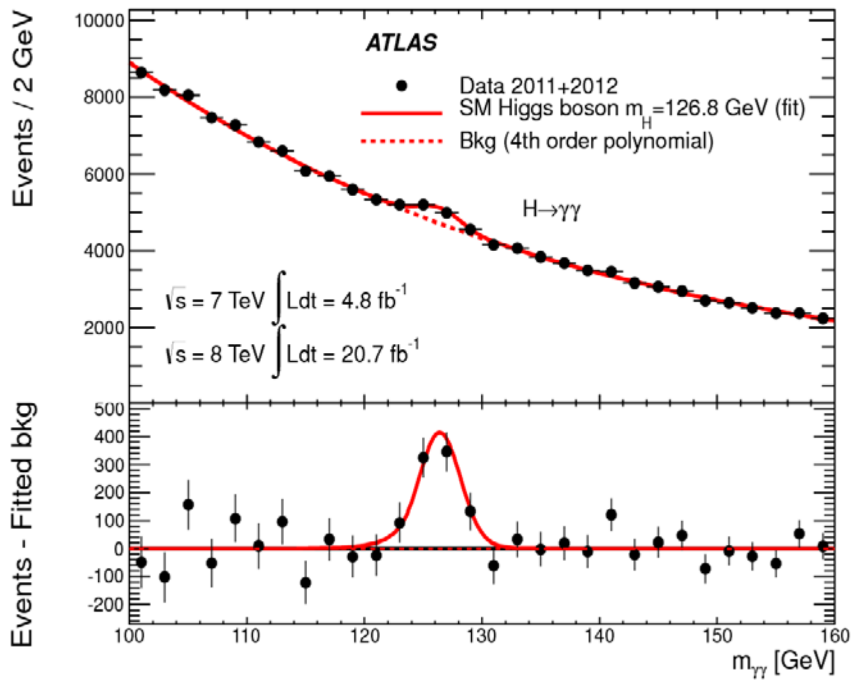


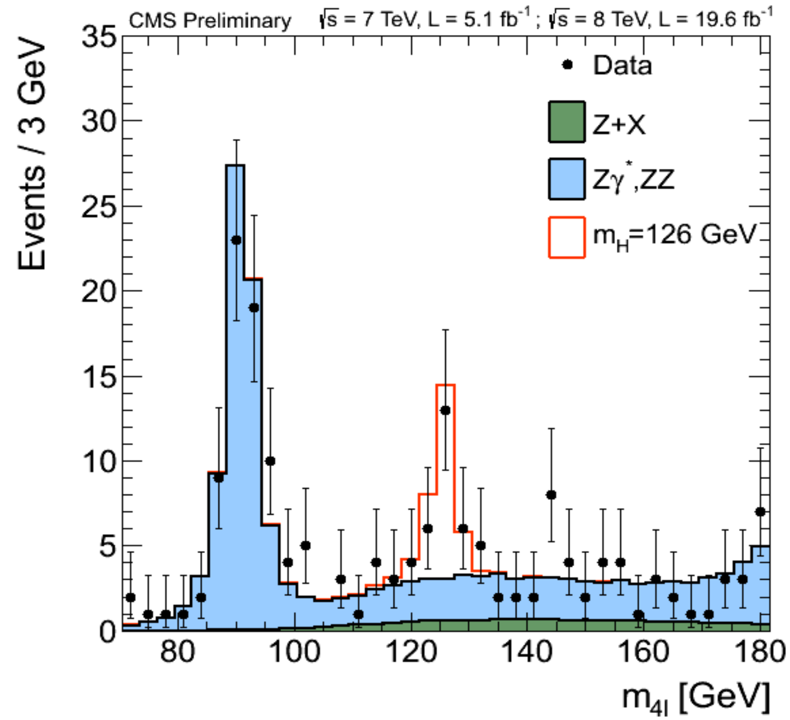


ATLAS-CONF-2013-009

Higgs Boson Mass

can be precisely measured from the $m_{\gamma\gamma}$ and $m_{4\ell}$ distributions of the high resolution channels: $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$.





$$\text{ATLAS: } m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{syst}) \text{ GeV}$$
$$\text{CMS: } m_H = 125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{syst}) \text{ GeV}$$

The two measurements agree well, but…

ATLAS arXiv:1307.1427 CMS-PAS-HIG-13-005

Higgs Boson Mass

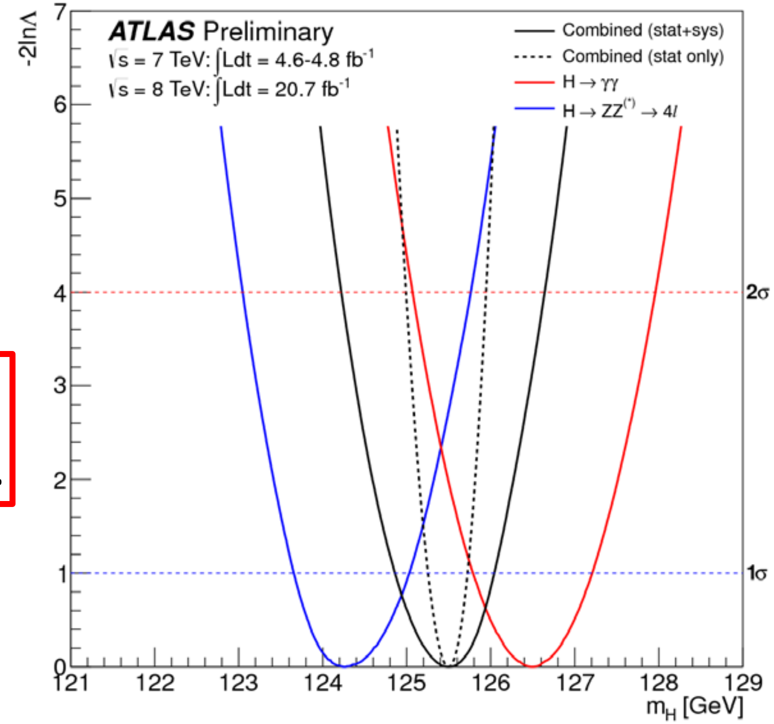
ATLAS:

$$m_H^{\gamma\gamma} = 126.8 \pm 0.2(stat) \pm 0.7(syst)\ \text{GeV}$$

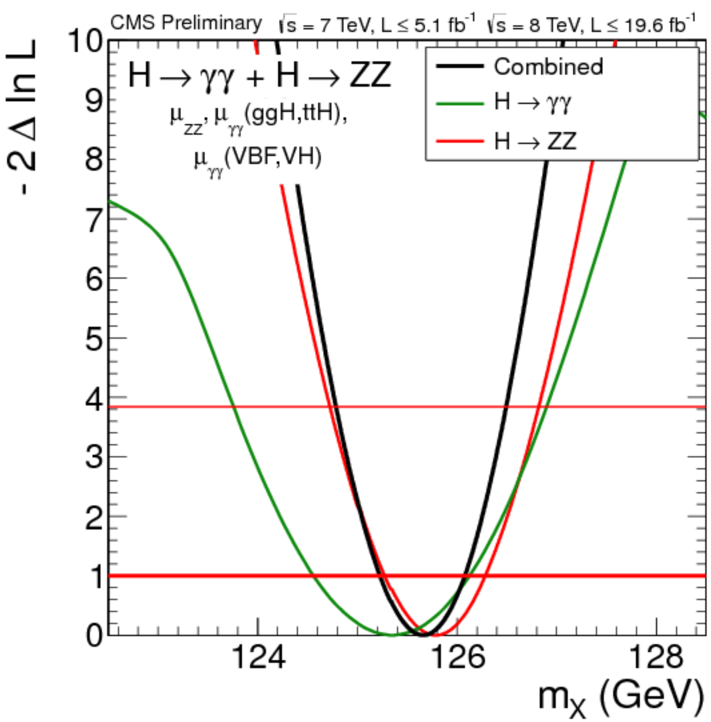
$$m_H^{4\ell} = 124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(syst)\ \text{GeV}$$

$$\boxed{\Rightarrow \Delta m_H = 2.3^{+0.6}_{-0.7}(stat) \pm 0.6(syst)\ \text{GeV}}$$

a 2.4σ difference, not likely but possible…



ATLAS-CONF-2013-014



No discrepancy is observed in CMS:

$$m_H^{\gamma\gamma} = 125.4 \pm 0.5(stat) \pm 0.6(syst)\ \text{GeV}$$

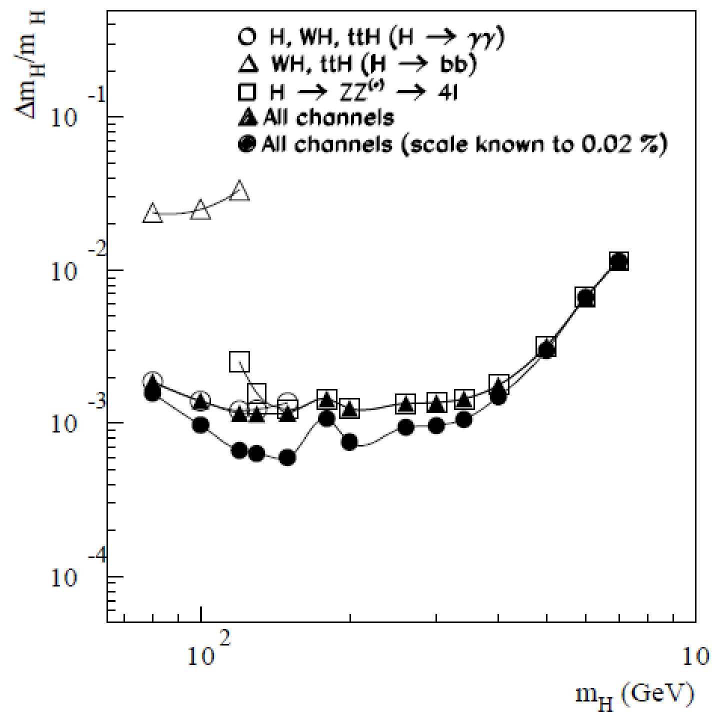
$$m_H^{4\ell} = 125.8 \pm 0.5(stat) \pm 0.2(syst)\ \text{GeV}$$

Systematics or statistics? Interesting to see updates…

Higgs Boson Mass

With 300 fb^{-1}, ATLAS estimates a precision of 0.07% @ 125 GeV $\Rightarrow \Delta m_H \approx 90$ MeV.

ATLAS TDR: CERN-LHCC-1999-15

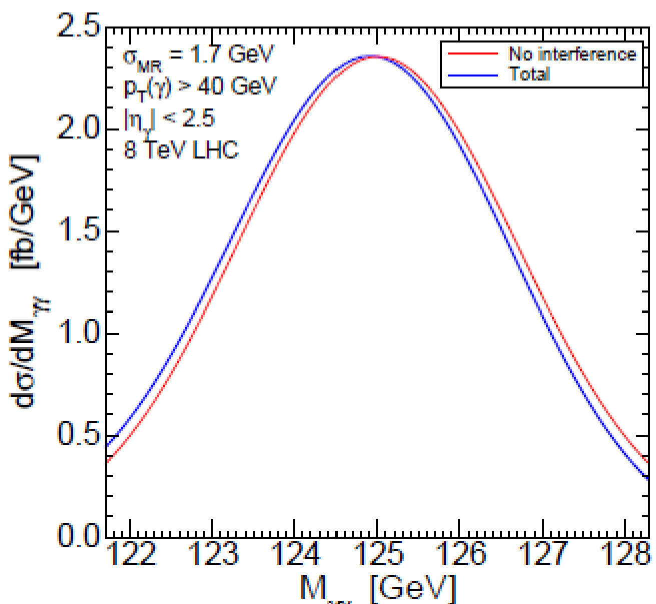


Precision in MeV on m_H

	Δ(stat)	Δ(syst)	Δ(total)
Present	250	450	520
300 fb^{-1}	50	80	100
3000 fb^{-1}	15	25	30

Assuming $\Delta \propto 1/\sqrt{\mathcal{L}}$.

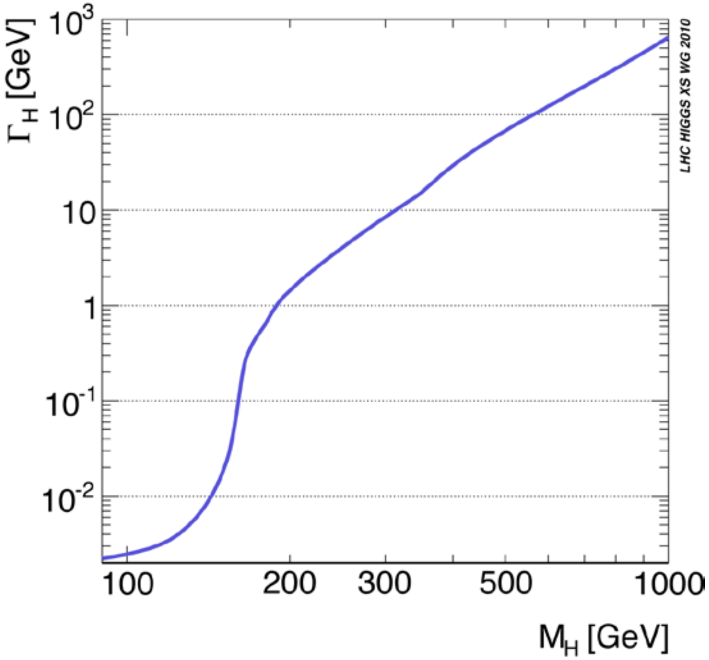
Martin, arXiv:1303.3342



For $H \to \gamma\gamma$, precision measurement will need to take into account the interference with the continuum.

$\Delta m_H \sim 100\ (50)$ MeV for $300\ (3000)\ \text{fb}^{-1}$ should be achievable at the LHC.

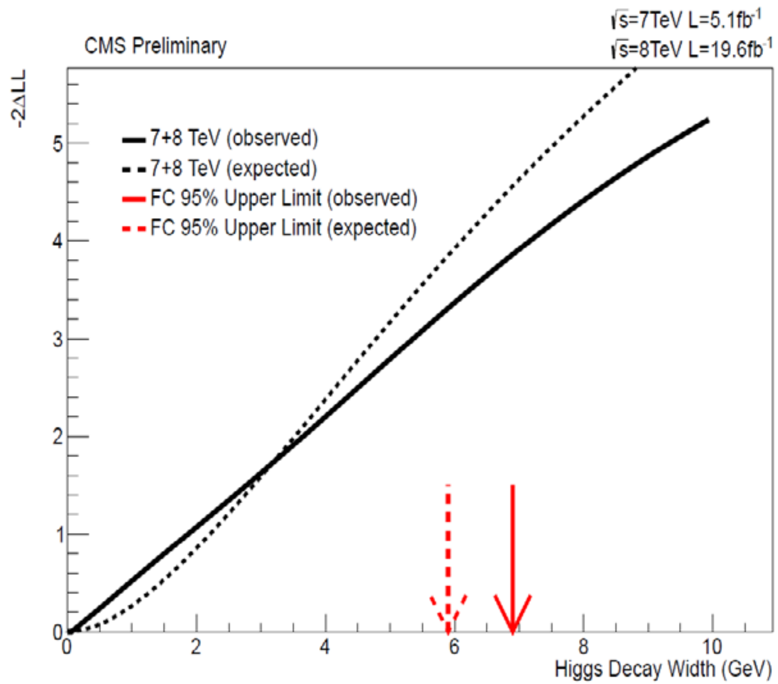
Higgs Boson Total Width



In the SM, the Higgs boson has a very narrow width below 200 GeV:

$$\Gamma_H = 4.1 \text{ MeV at } m_H = 125 \text{ GeV}$$

beyond the reach of direct measurements at the LHC: $\Gamma_H \ll \sigma_m$



From the $m_{\gamma\gamma}$ distribution of the 7+8 TeV dataset, CMS observed (expected) an upper limit $\Gamma_H < 6.9\ (5.9)$ GeV @ 95% CL.

Assuming it scales with luminosity, an upper limit of ~ 300 MeV or $\sim 80 \times \Gamma_H^{SM}$ with 3000 fb^{-1}.

CMS-PAS-HIG-13-016

Higgs Boson Total Width

Diffcult to extract from the rate measurements without some assumptions on couplings:

$\sigma \cdot \mathrm{BR}\left(i \to H \to f\right) \propto \dfrac{g_i^2 \cdot g_f^2}{\Gamma_H}$ Examples: only SM decays or weaker assumptions $g_{HVV} \le g_{HVV}^{SM}$...

In these scenarios, the sensitivity $\sim \Gamma_H^{SM}$.

Off-shell $gg \to H^* \to ZZ$ production:

$$\frac{d\sigma}{dm_{4\ell}^2} \sim \frac{g_g^2 \cdot g_Z^2}{\left(m_{4\ell}^2 - m_H^2\right)^2 + m_H^2\Gamma_H^2} \approx \frac{g_g^2 \cdot g_Z^2}{\left(m_{4\ell}^2 - m_H^2\right)^2}$$

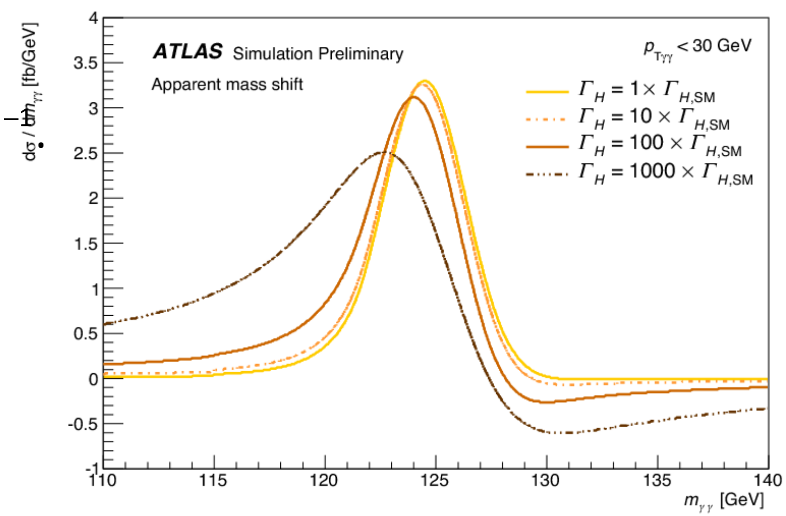
Off-shell: determine $g_g^2 \cdot g_Z^2$ independent of Γ_H. Expected sensitivity: $\Gamma_H <\sim 10 \times \Gamma_H^{SM}$

(Caola & Melnikov, arXiv:1307.4935)

Signal-background interference leads to shift in resonance mass: $\Delta m_H \equiv m_H^{\gamma\gamma} - m_H^{4\ell} \propto \sqrt{\Gamma_H}$

Potentially sensitive to $\Gamma_H <\sim 2 \times \Gamma_H^{SM}$ with 3000 fb^{-1}.

(Dixon & Li, arXiv:1305.3854)



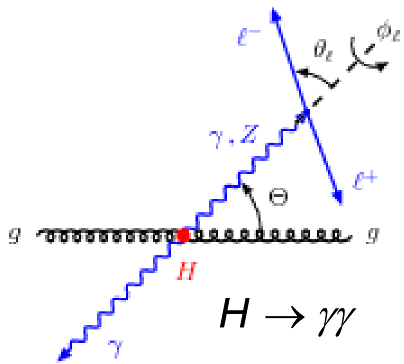
Or alternatively, study the mass difference of different kinematic phase space. ATLAS studied

$$\Delta m_H = m_H\left(p_T^{\gamma\gamma} < 30\ \mathrm{GeV}\right) - m_H\left(p_T^{\gamma\gamma} > 30\ \mathrm{GeV}\right)$$

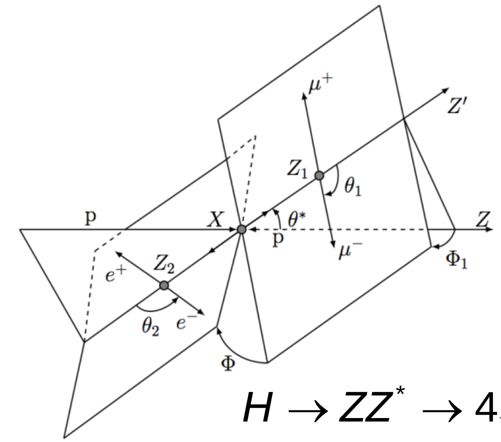
and expects a sensitivity $\Gamma_H \sim 50 \times \Gamma_H^{SM}$ at HL-LHC.

Spin Determination

Higgs decay kinematics depends on its properties of spin and parity. $\mathrm{H} \rightarrow \gamma\gamma$, $\mathrm{H} \rightarrow ZZ^* \rightarrow 4\ell$ and $\mathrm{H} \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ final states have been analyzed to determine these properties.

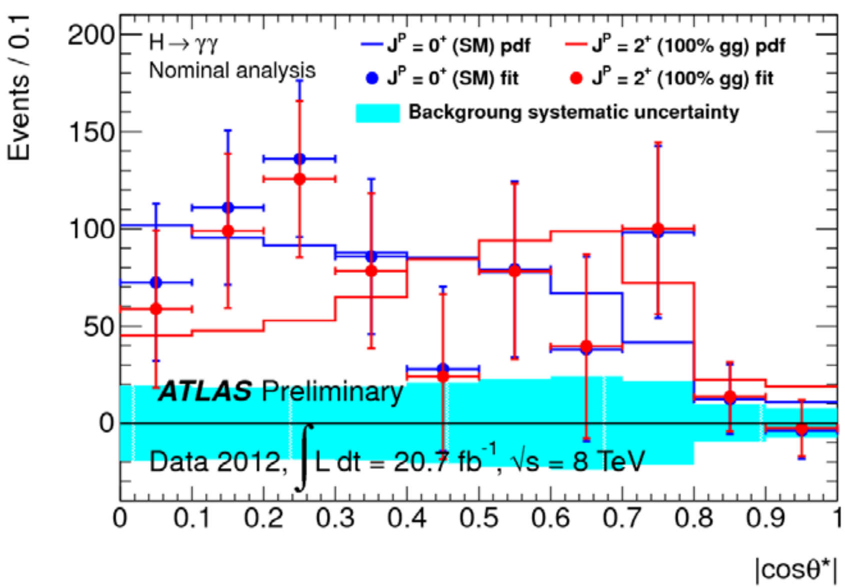


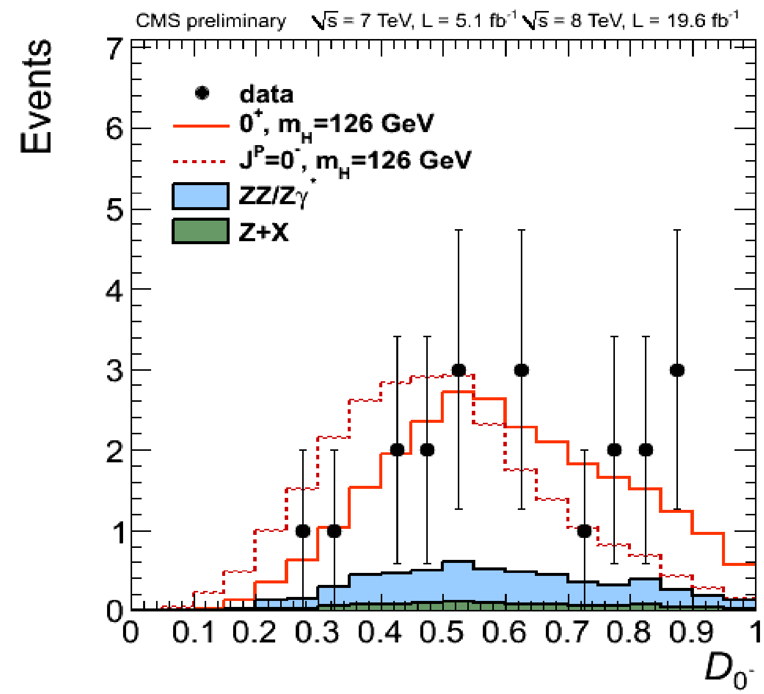
$H \rightarrow \gamma\gamma$



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

ATLAS-CONF-2013-029





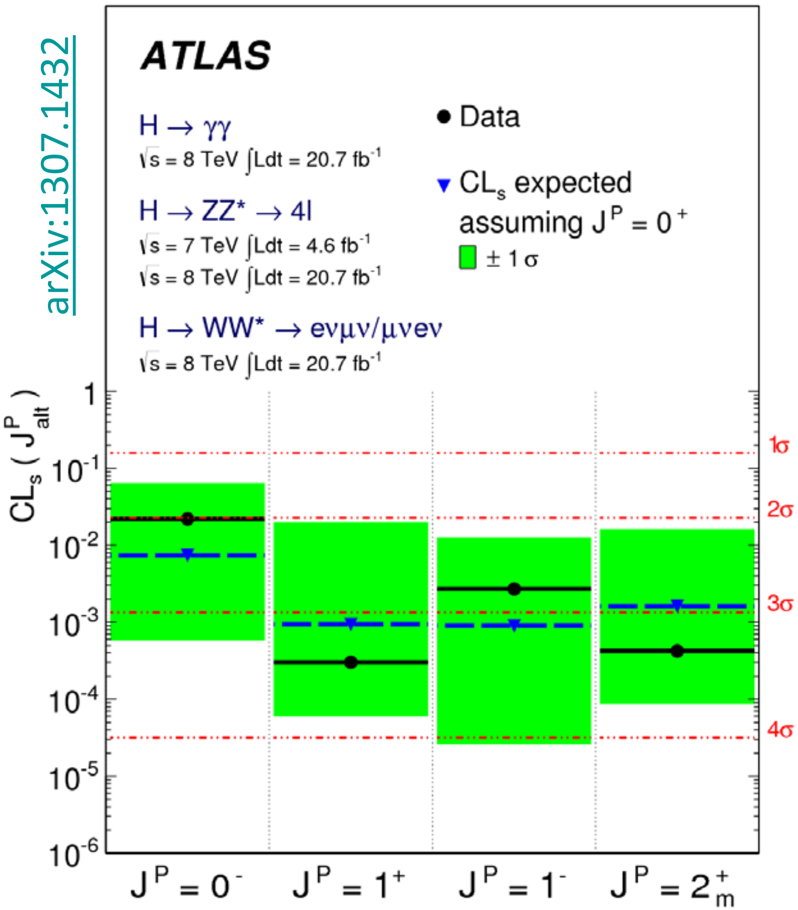
CMS-PAS-HIG-13-002

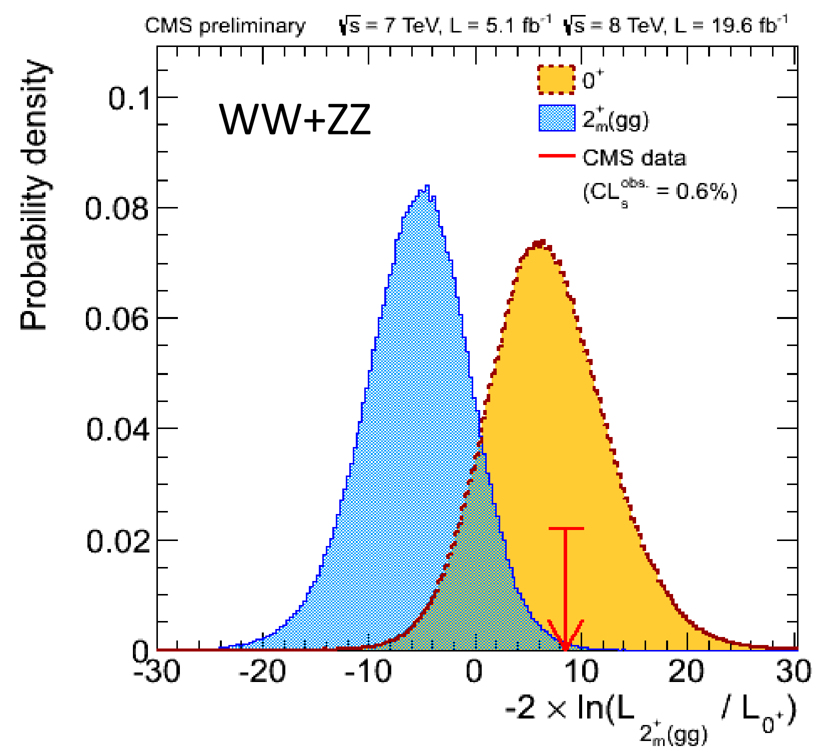
Spin Determination

SM prediction of $J^P = 0^+$ is strongly favored, most alternatives are excluded at 95% CL or higher.

The spin of the 125 GeV boson is already tightly constrained. Limited parameter space of spin-2 hypothesis remains.

arXiv:1307.1432





CMS-PAS-HIG-13-005

CP Admixture

H→VV coupling:

$$A_{VV} \propto a_1 m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

a_1 : tree-level coupling to WW and ZZ;
a_2 : loop-induced processes such as $\gamma\gamma$, $Z\gamma$ and gg;
a_3 : pseudoscalar coupling

Scalar couples to VV at tree-level, pseudoscalar couples to VV at loop-level $\Rightarrow$ strong suppression of CP admixture effect.

H→ff coupling:

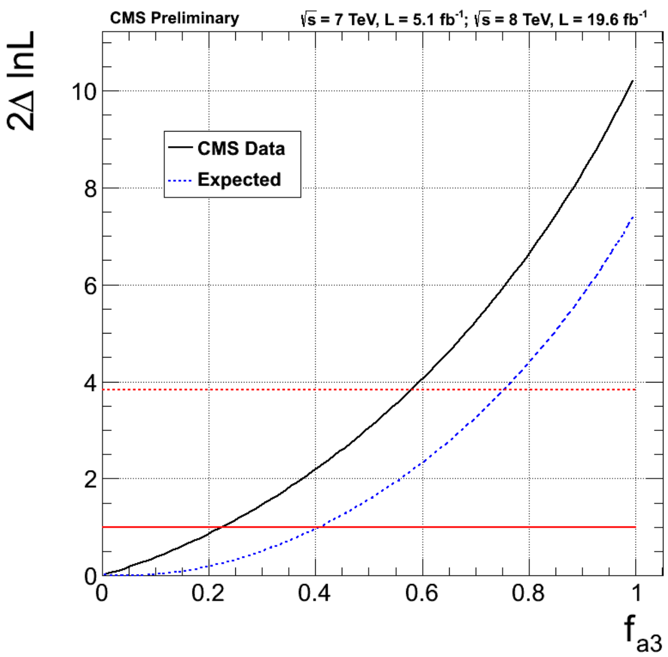
$$A_{f\bar{f}} \propto \frac{m_f}{v} \bar{u}_2 \left(\rho_1 + \rho_2 \gamma_5\right) v_1$$

No loop-suppression for pseudoscalar coupling to fermions. Can be studied in Higgs decays such as H→ττ as well as in the Higgs production of the ttH process.

CP Admixture

Parametrizing CP admixture using the CP-odd fraction: $f_{CP} = \frac{|a_3|^2 \sigma_3}{\sum |a_i|^2 \sigma_i}$

CMS has measured f_{CP} by analyzing kinematics of $H \to ZZ^* \to 4\ell$ candidates of the current dataset: $f_{CP} = 0.00^{+0.23}_{-0.00}$ or $f_{CP} < 0.58$ @ 95% CL



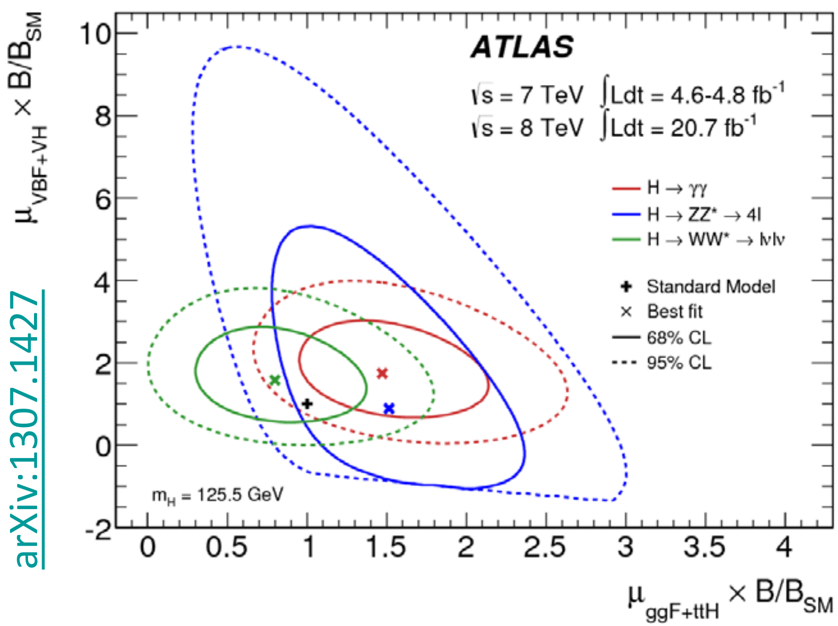
The expected uncertainty is 0.4 which projects to

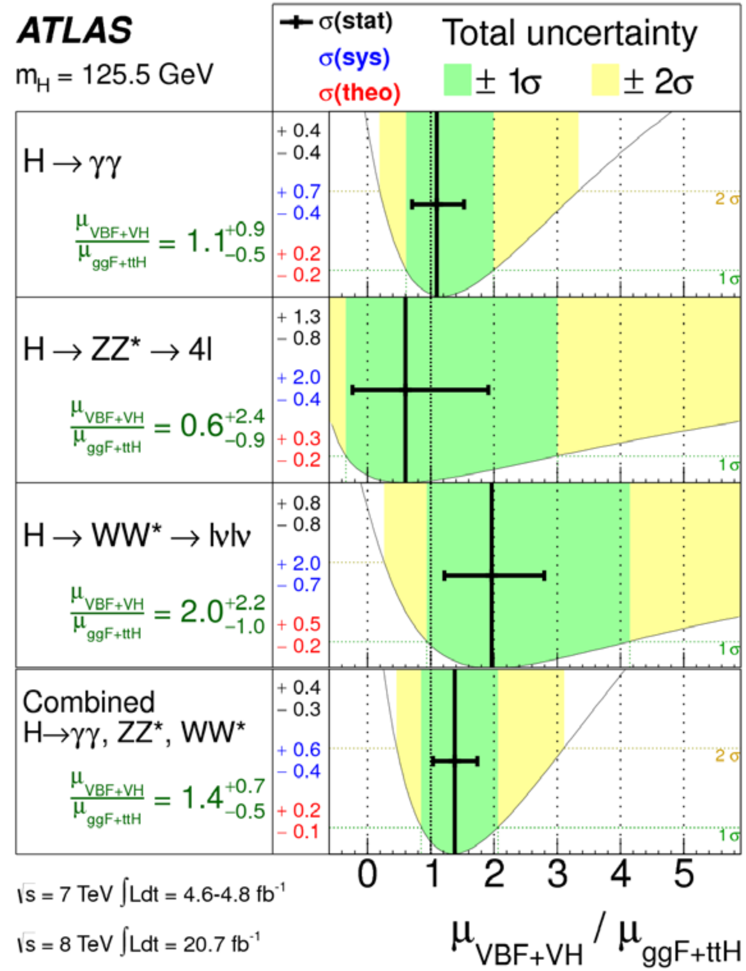
$$\Delta f_{CP} = \pm 0.07 \text{ at } 300 \text{ fb}^{-1}$$
$$\Delta f_{CP} = \pm 0.02 \text{ at } 3000 \text{ fb}^{-1}$$

However, f_{CP} in $H \to VV$ decay is expected to be small due loop-suppression. A ~10% CP admixture will lead to $f_{CP} < 10^{-5}$.

Probing the Production…

Strong vs electroweak
(fermion vs vector boson)





The ratio $\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$ probes production only

(BRs cancel out for each final state)

The combination is independent of potential new physics in different decay final states.

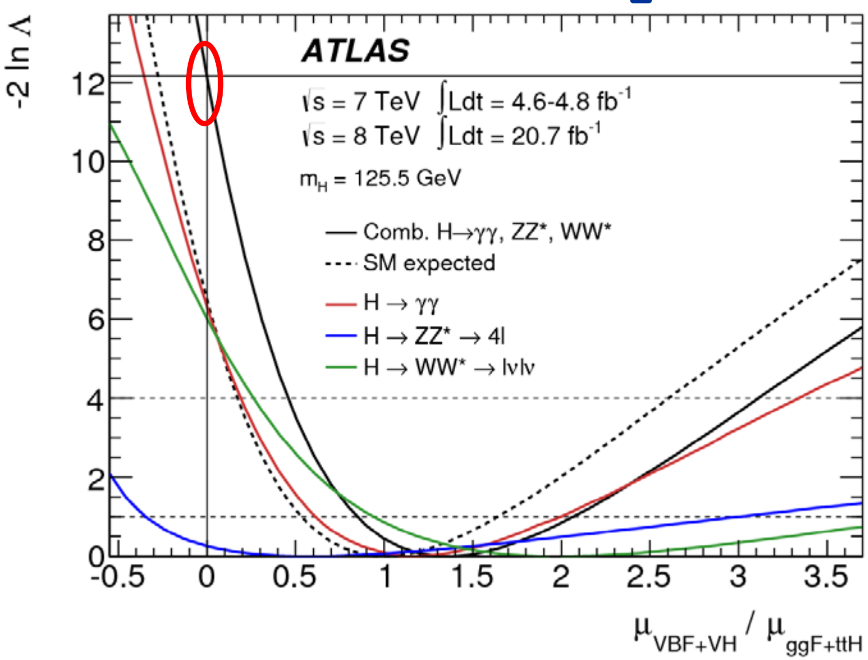
$$\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}} = 1.4^{+0.4}_{-0.3}\,(\text{stat})^{+0.6}_{-0.4}\,(\text{syst})$$

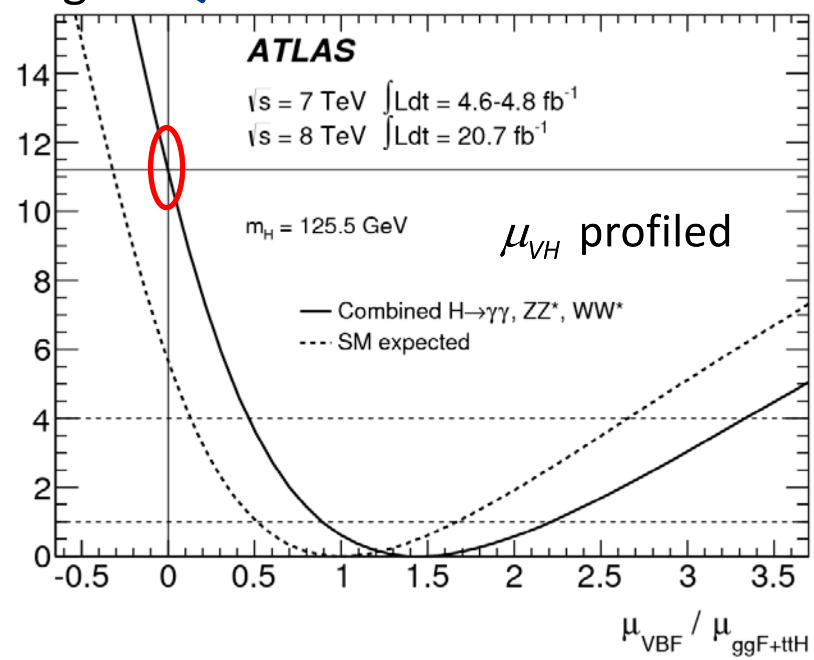
Evidence for the VBF Production

The signal strength of the VBF process can be extracted by profiling (factor out) the contribution from VH $\Rightarrow$ little effect from the profiling:

$$\boxed{\frac{\mu_{VBF}}{\mu_{ggF+ttH}} = 1.4^{+0.4}_{-0.3}(\text{stat})^{+0.6}_{-0.4}(\text{syst})} \quad \left(\approx \frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}\right)$$

Profiling





arXiv:1307.1427

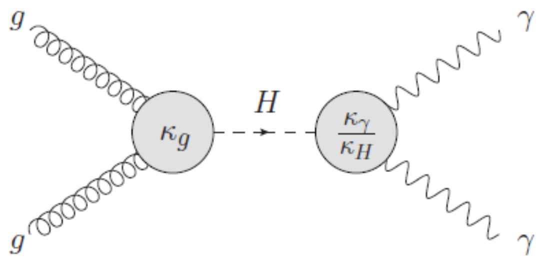
$$p\left(\mu_{VBF}/\mu_{ggF+ttH}=0\right)=0.04\% \Rightarrow$$ a 3.3σ evidence for the VBF production.

Coupling Scale Parameters

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.

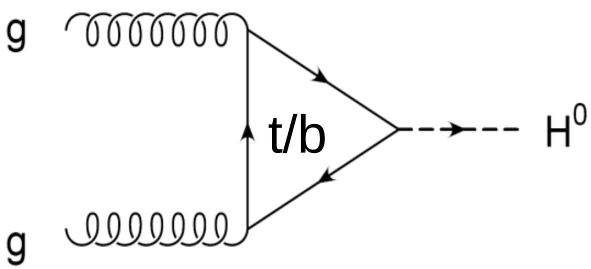
κ_H^2 is the scale factor to the total Higgs decay width

$$\kappa_H^2 = \sum_x \kappa_x^2 \cdot BR(H \to xx) \xrightarrow{\text{No BSM decays}} \kappa_H^2 = \sum_x \kappa_x^2 \cdot BR_{SM}(H \to xx)$$

$$\xrightarrow{\text{With BSM decays}} \kappa_H^2 = \sum \kappa_x^2 \cdot \frac{BR_{SM}(H \to xx)}{1 - BR_{BSM}}$$

Benchmark models with different assumptions. Most models assume no BSM decays $\left(BR_{BSM} = 0\right)$.

Decomposing Loops…



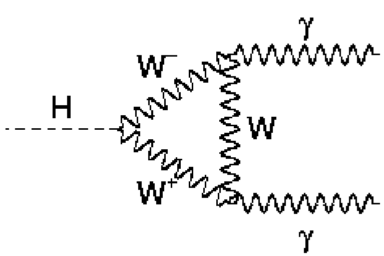
In SM, the $gg \to H$ cross section can be broken into three pieces: $\sigma_{SM} = \sigma_{tt} + \sigma_{bb} + \sigma_{tb}$

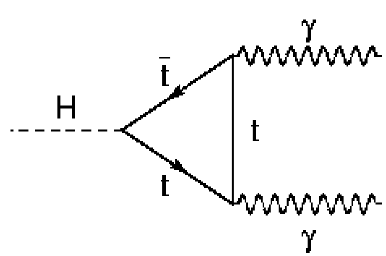
With coupling modifications, the cross section becomes $\Rightarrow \sigma = \kappa_t^2 \sigma_{tt} + \kappa_b^2 \sigma_{bb} + \kappa_t \kappa_b \sigma_{tb}$

The effective *Hgg* coupling scale parameter is

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

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





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

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

* $m_H = 125.5$ GeV

Benchmark Models

Current statistics not sufficient to fit the most general model, reducing number of parameters through benchmark models.

A few selected models following the prescriptions of arXiv:1209.0040

Model	Probed couplings	Parameters of interest	Functional assumptions				
			κ_V	κ_F	κ_g	κ_γ	κ_H
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-
3	Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	√	√	√	-
4		$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$	-	√	√	-	-
5	Vertex loops	κ_g, κ_γ	=1	=1	-	-	√

All models assume no BSM productions and decays

Parameter definitions: $\kappa =$ coupling scale parameter

$$\lambda_{ij} = \frac{\kappa_i}{\kappa_j} \text{ and } \kappa_{ii} = \frac{\kappa_i^2}{\kappa_H^2}$$

Fermion and Boson Couplings

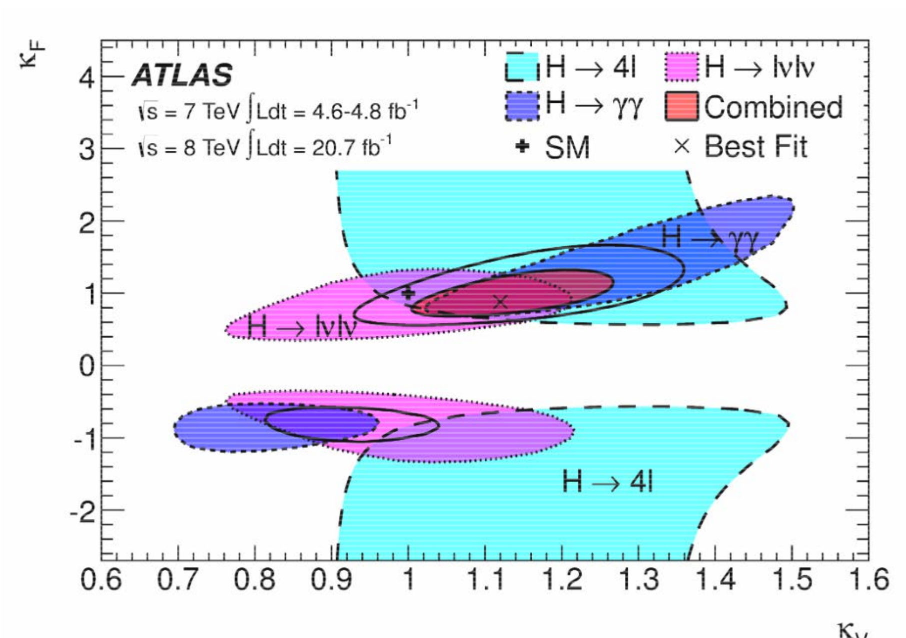
$\boxed{\kappa_F\,,\ \kappa_V}$

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

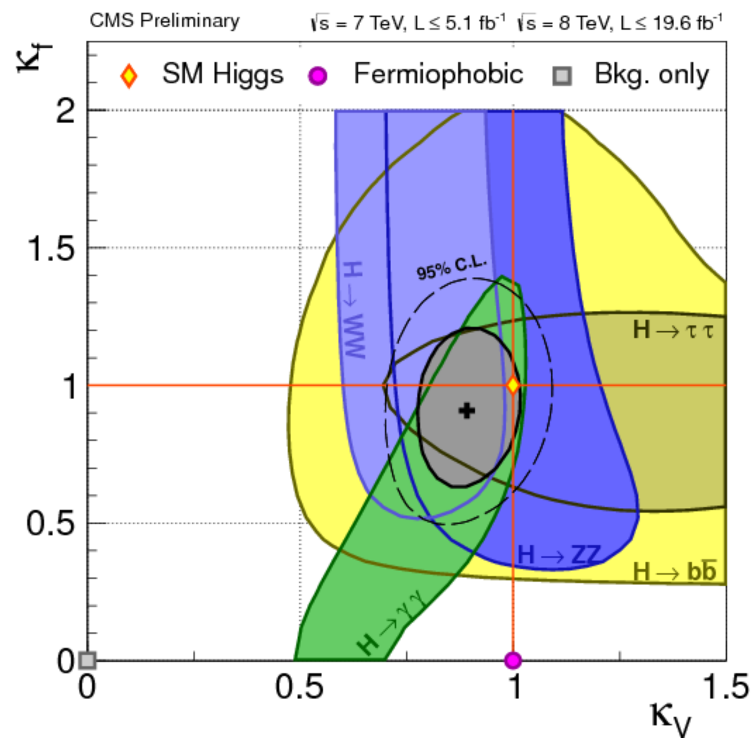
κ_V : for all vector bosons $\left(\kappa_V \equiv \kappa_W = \kappa_Z\right)$

κ_g and κ_γ are decomposed to their tree-level couplings

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



arXiv:1307.1427



CMS-PAS-HIG-13-005

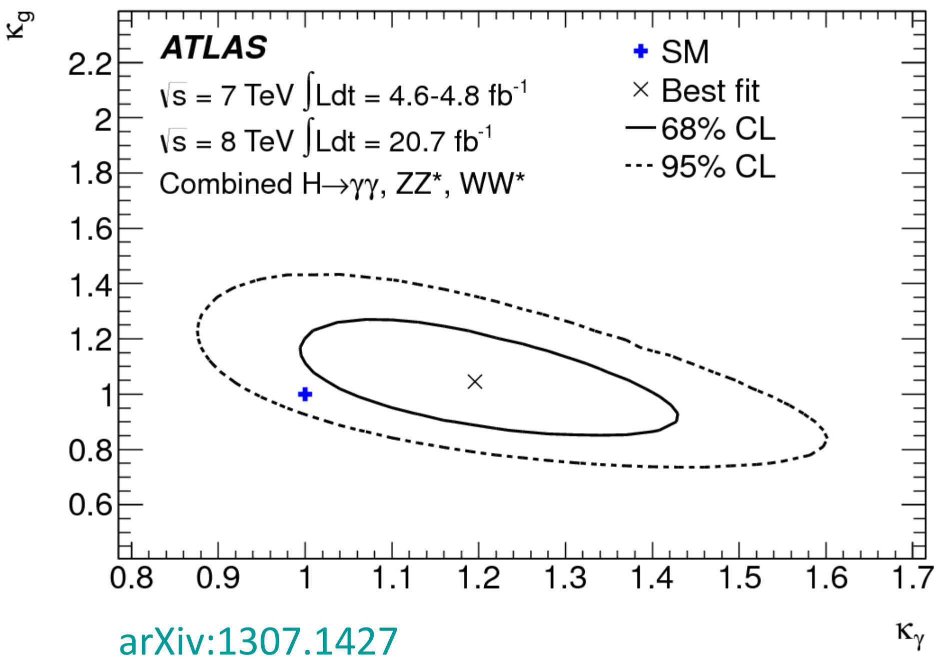
Probing Vertex Loops…

$\boxed{\kappa_g\,,\ \kappa_\gamma}$

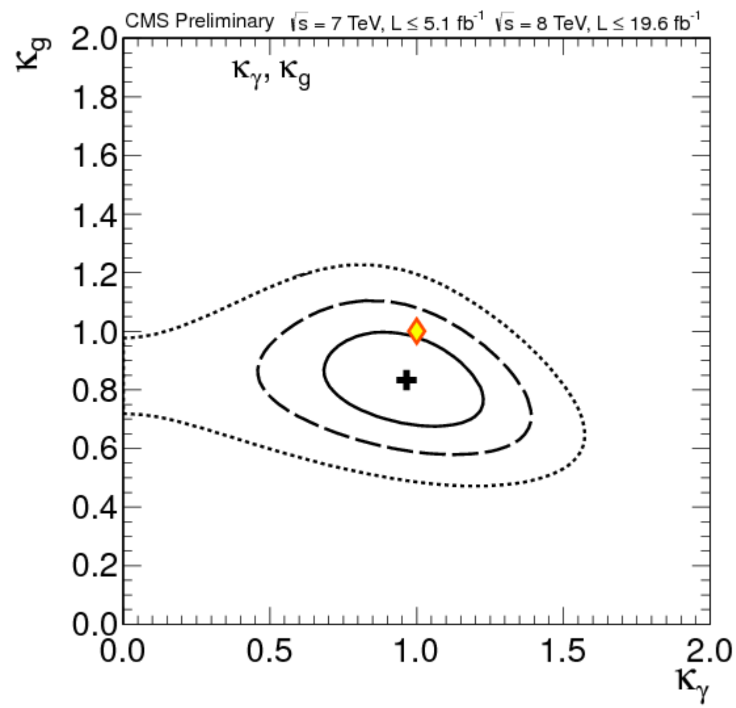
- κ_g and κ_γ for $gg \to$ H and H$\to\gamma\gamma$ couplings;
- All other tree-level scale parameters $\kappa_i = 1$.

$$\Rightarrow \kappa_H^2 \approx 0.91 + 0.085\kappa_g^2 + 0.0023\kappa_\gamma^2$$

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



arXiv:1307.1427



CMS-PAS-HIG-13-005

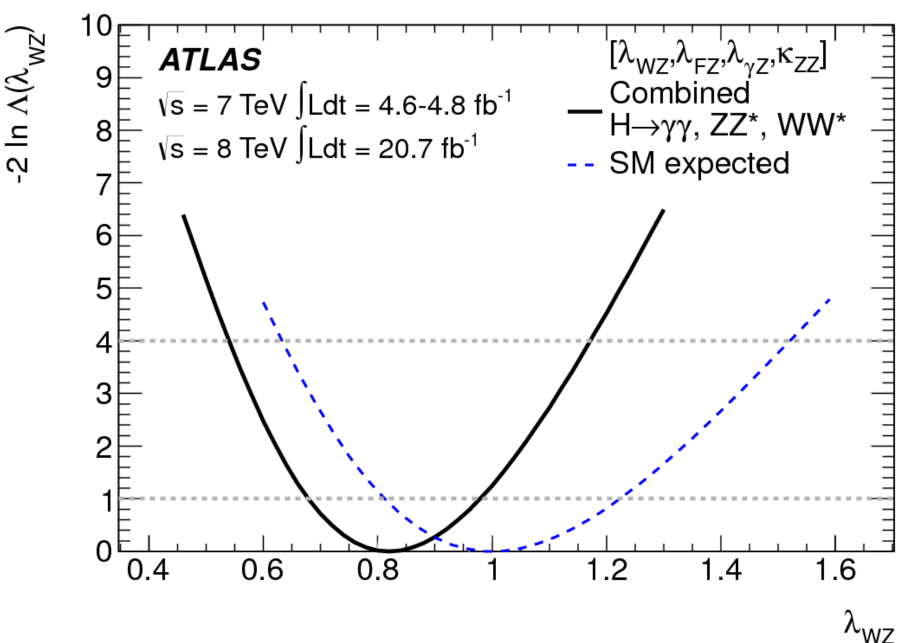
Custodial Symmetry

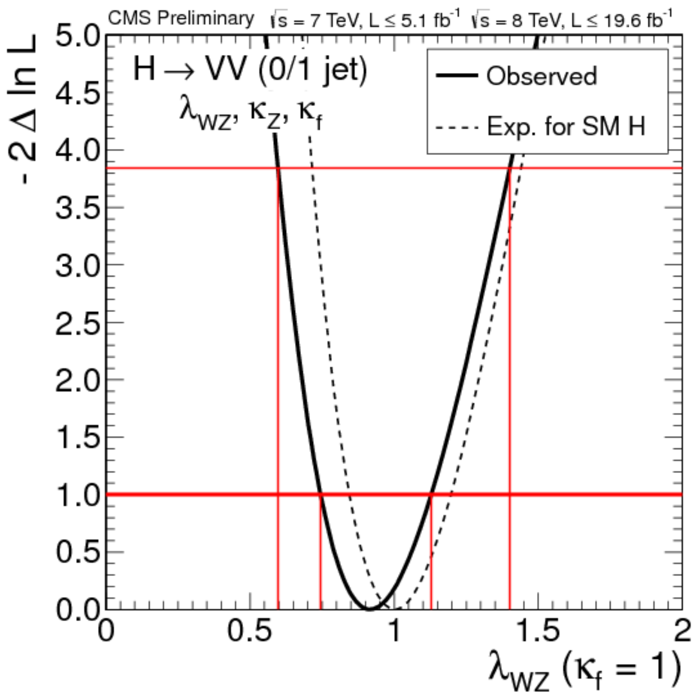
is required by the SM and imposes $\kappa_W = \kappa_Z \Rightarrow \lambda_{WZ} = 1$, can be tested from the measured rates (mostly from decays).

$$\boxed{\lambda_{WZ},\ \lambda_{FZ},\ \left(\lambda_{\gamma Z}\right),\ \kappa_{ZZ}}$$

All κ's are normalized to κ_Z;
Universal fermion scale parameter.

Potential new physics in the $\mathrm{H} \to \gamma\gamma$ decay loops may result in apparent λ_{WZ} deviation from unity.





arXiv:1307.1427

CMS-PAS-HIG-13-005

Five-Parameter Model

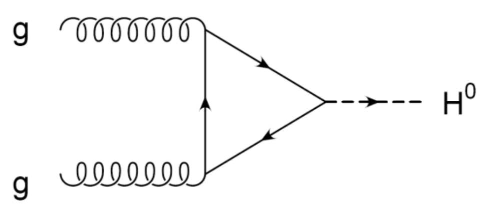
$$\boxed{\kappa_W,\ \kappa_Z,\ \kappa_t,\ \kappa_b,\ \kappa_\tau}$$

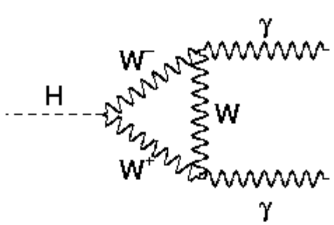
$$\kappa_H^2 = 0.577\kappa_b^2 + 0.215\kappa_W^2 + 0.086\kappa_g^2 + 0.063\kappa_\tau^2 + 0.029\kappa_c^2 + 2.63\times10^{-2}\kappa_Z^2 + 2.28\times10^{-3}\kappa_\gamma^2 + \ldots$$

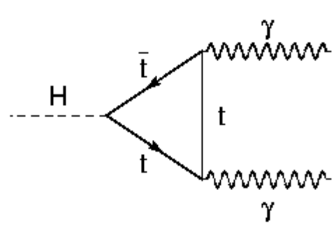
up-quarks: $\kappa_c^2 = \kappa_t^2$; down-quarks: $\kappa_s^2 = \kappa_b^2$

Decompose loop diagrams:

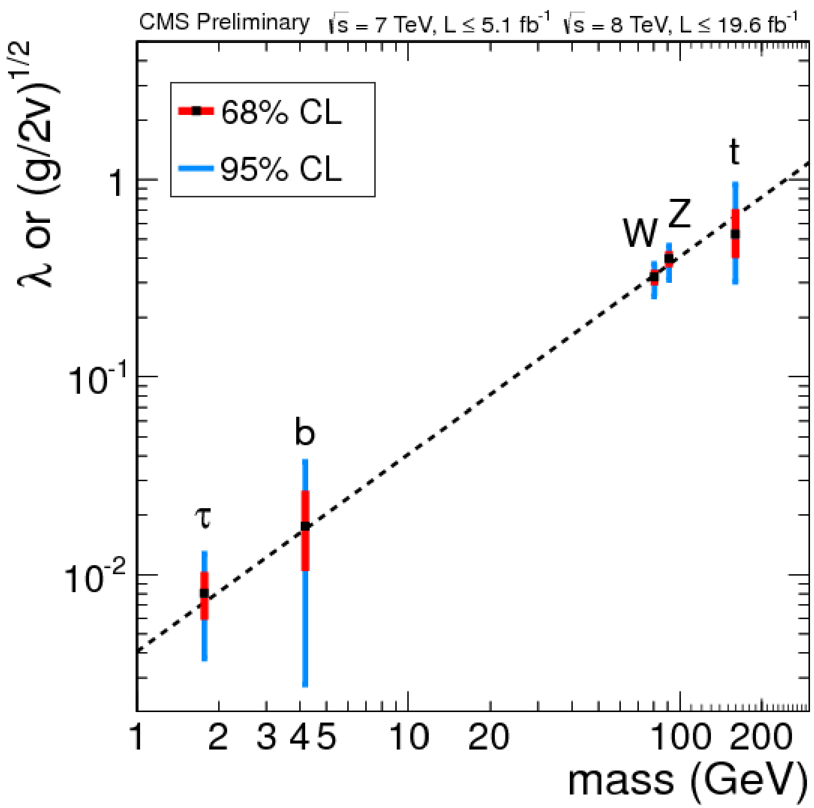
$$\kappa_g^2 \approx \kappa_t^2$$







$$\kappa_\gamma^2 \approx \left|1.26\kappa_W - 0.26\kappa_t\right|^2$$



CMS-PAS-HIG-13-005

Good agreement with SM expectation ⇒ SM-like Higgs boson

Non-SM Decays

Higgs could have decays that are not accounted for in SM. The decays do not have to be invisible. They could be decays not detectable at LHC.
$\Rightarrow$ modified total Higgs decay width and therefore decay branching ratios.

A model allows for potential new physics in vertex loops and additional decays

$$\boxed{\kappa_\gamma\,,\ \kappa_g\,,\ BR_{\text{inv,undet.}}}$$

$$\Gamma_H = \Gamma_H^{SM} \times \kappa_H^2 \quad \text{with}$$

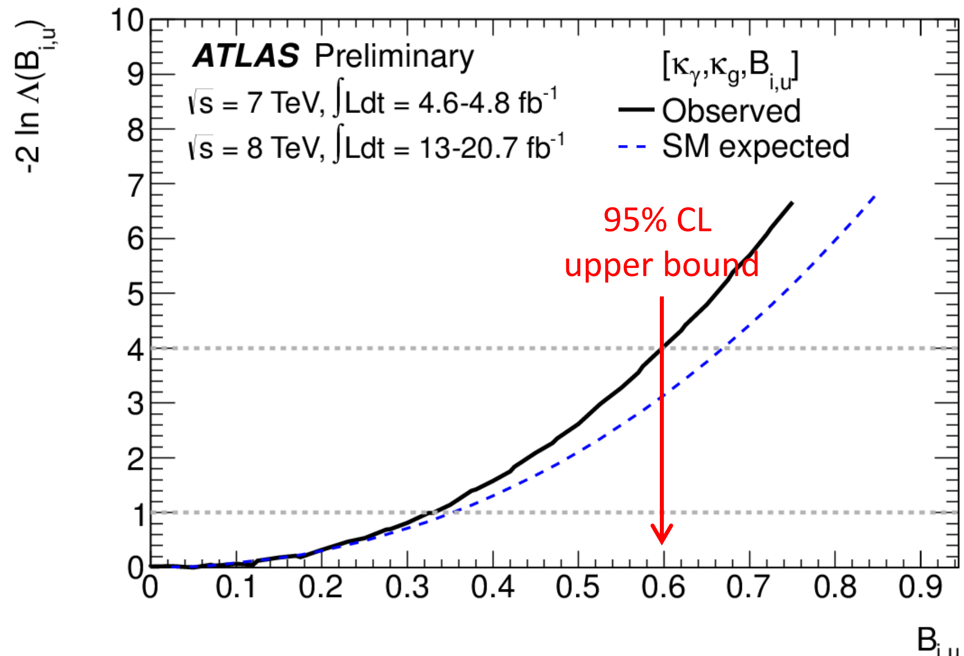
$$\kappa_H^2 = \frac{0.91 + 0.085\kappa_g^2 + 0.0023\kappa_\gamma^2}{1 - BR_{inv,undet.}}$$

Constraints can be derived from the coupling fit:

$$\kappa_g = 1.08^{+0.32}_{-0.14}$$

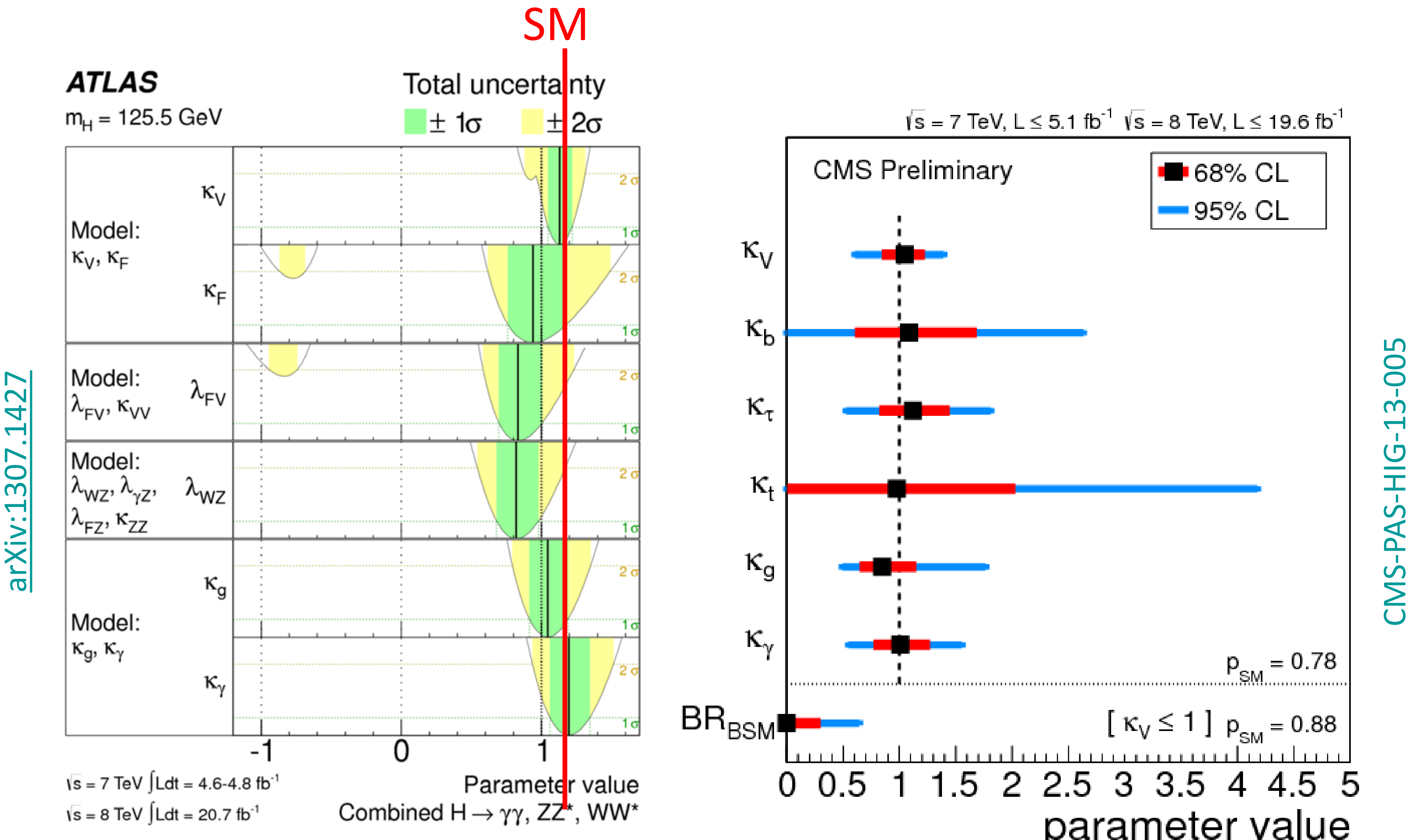
$$\kappa_\gamma = 1.24^{+0.16}_{-0.14}$$

$$BR_{\text{inv,undet.}} < 0.6\ @\ 95\%\ \text{CL}$$



ATLAS-CONF-2013-011

Summary of Coupling Fits



The couplings are consistent with the SM expectations…

Expected Coupling Deviations

Typical effect on coupling from heavy state (or new physics scale) M:

$$\Delta \sim \left(\frac{\upsilon}{M}\right)^2 \sim 5\% \text{ @ M} \sim 1 \text{ TeV}$$

(Han et al., hep-ph/0302188, Gupta et al. arXiv:1206.3560, …)

Snowmass Higgs report

Typical sizes of coupling modification from some selected BSM models

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

To be sensitive to a deviation Δ, the measurement precision needs to be much better than Δ, at least $\Delta/3$! Challenging to measure absolute couplings at the LHC, better precisions can be achieved for some ratios of couplings.

Projections of Coupling Precisions

Luminosity	$300\ \text{fb}^{-1}$	$3000\ \text{fb}^{-1}$
Coupling parameter	7-parameter fit	
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_u	$14-15\%$	$7-10\%$
κ_d	$10-13\%$	$4-7\%$
κ_ℓ	$6-8\%$	$2-5\%$
Γ_H	$12-15\%$	
	additional p	
$\kappa_{Z\gamma}$	$41-41\%$	
κ_μ	$23-23\%$	
BR_{BSM}	$<14-18\%$	

HL-LHC can achieve precisions of a few percent,
Sub-percent precisions will need lepton colliders.

TLEP offers the best prospect.

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500[‡]	10000	+2600
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%
κ_μ	91%	91%	16%	10%	6.4%	6.2%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%
κ_t	–	14%	3.2%	2.0%	–	13%
BR_{inv}	0.9%	$<0.9\%$	$<0.9\%$	0.4%	0.19%	$<0.19\%$

Snowmass Report
arXiv:1310.8361

Analyses not covered here…

Several ongoing analyses that are either searching for H $\rightarrow$ invisible decay directly or can be interpreted as such decays:

$ZH \rightarrow \ell\ell\not{E}_T$;

$qq' \rightarrow qq'H \rightarrow qq'\not{E}_T$;

$jet + \not{E}_T$,...

Exotic productions and decays such as through FCNC top decays: t $\rightarrow$ Hc, ...

2HDM or MSSM motivated searches

Charged Higgs bosons;

Heavy neutral Higgs bosons;

Higgs to higgs decays $\left(A \rightarrow Zh,\ \mathrm{H} \rightarrow \mathrm{hh},\ \ldots\right)$

NMSSM motivated searches

$gg \rightarrow a$; $\mathrm{h} \rightarrow 2\mathrm{a}$; $\mathrm{H}^{\pm} \rightarrow a_1 W^{\pm}$

Summary

- The discovery of the 125 GeV Higgs boson is the beginning of a new era in particle physics.

- The major couplings of the Higgs boson have been measured at ~10% precision, consistent with the SM expectation.

- But the question whether the discovered particle is the only source of electroweak symmetry breaking remains to be answered.

- A wealthy program to explore BSM physics in the Higgs sector:
  - Precision measurements of the 125 GeV Higgs boson;
  - Direct searches of exotic Higgs productions or decays;
  - Direct searches for new Higgs bosons.