Combination of SM Higgs boson results and Properties Measurements at CMS

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CMS

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SUSY2014

THE 22ND INTERNATIONAL CONFERENCE ON SUPERSYMMETRY AND UNIFICATION OF FUNDAMENTAL INTERACTIONS

Higgs boson signature studied by CMS Collaboration

- CMS explored a large set of accessible signatures:
  - Strong evidence in bosonic & fermionic channels!

  Details on individual bosonic and fermionic decays in talks by
  S. Stoynet & Y. Takahashi (Higgs 4 & 5)
  Higgs overview talk by A. Nikitenko (SM Higgs plenary)

- Significant set of explored signatures used for combined measurements

NEW combination: CMS-PAS-HIG-14-009

Channels explored by CMS:

	ϒϒ	ZZ	WW	ττ	bb	Zϒ	μμ	Inv
gg	✓	✓	✓	✓		✓	✓	
VBF	✓	✓	✓	✓	✓	✓	✓	✓
VH	✓		✓	✓	✓			✓
ttH	✓		✓	✓	✓			

Signal significance (m_H=125 GeV)

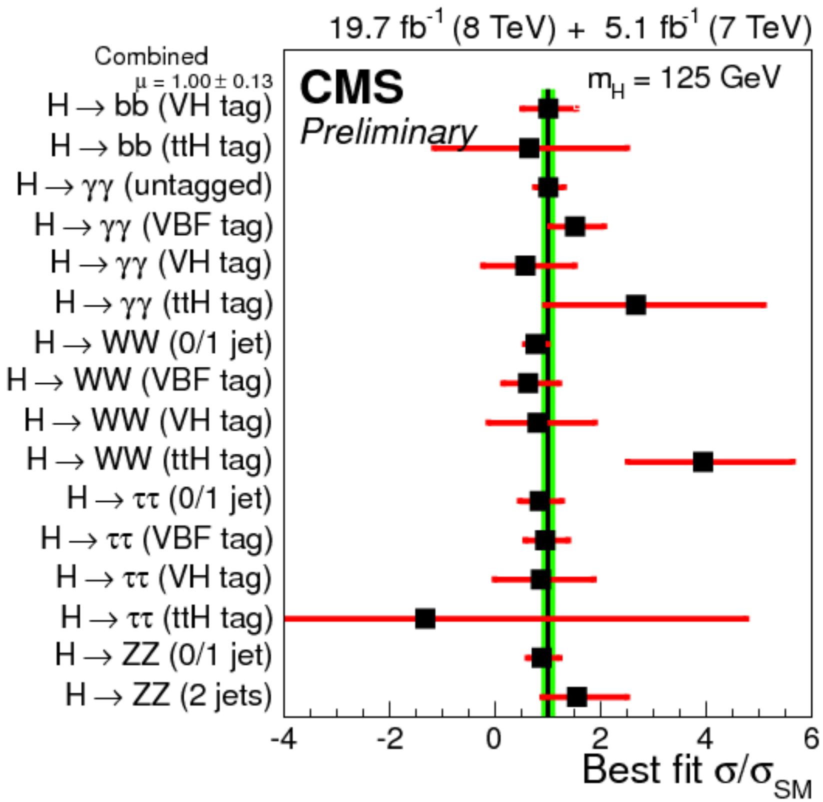
Exp.	5.6	6.5	4.7	3.9	2.0
Obs.	5.3	6.3	5.4	3.9	2.3

References

H→ZZ	PhysRevD.89.092007
H→YY	arXiv:1407.0558
H→WW	JHEP01(2014)096
H→ττ	JHEP05(2014)104
H→bb	PhysRevD.89.012003
ttH→bb,ττ	CMS-PAS-HIG-13-019
ttH→lept	CMS-PAS-HIG-13-020

Compatibility of the observed exess with the SM Higgs boson

Values of the best-fit σ/σ_{SM} for the combination



Fit per production and decay channel:

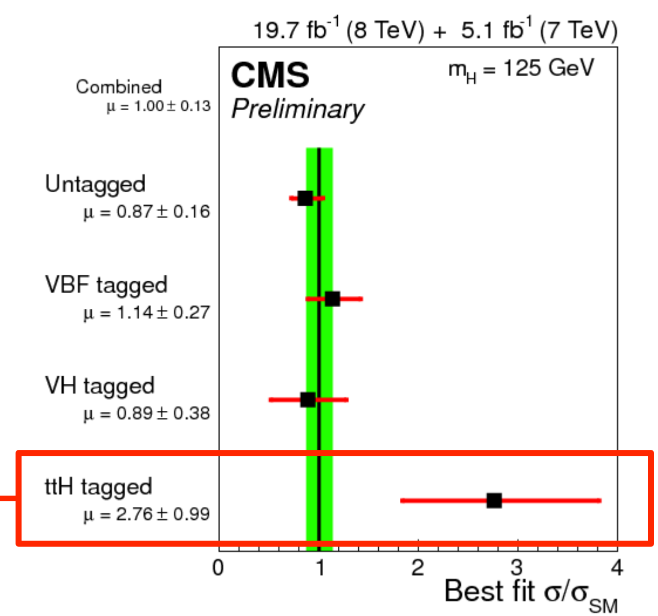
- χ^2/dof= 10.5/16
- p-value = 0.84 (asymptotic)

Overall signal strength:

$$\mathbf{1.00 \pm 0.09} \text{ stat. } {}^{+0.08}_{-0.07} \text{ th. } \pm \mathbf{0.07} \text{ syst.}$$

Per production mode:

- p-value = 0.26 (asymptotic)
- Driven by the excess seen in ttH analyses, where the deviation from SM is at 2.0 σ level



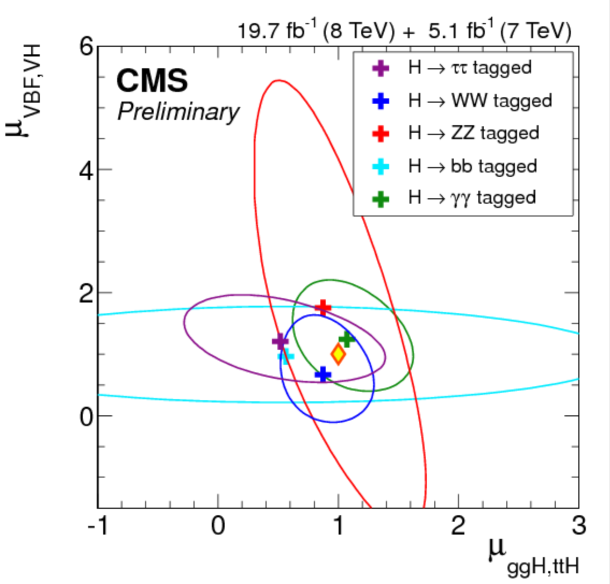
Deviation in Production mode

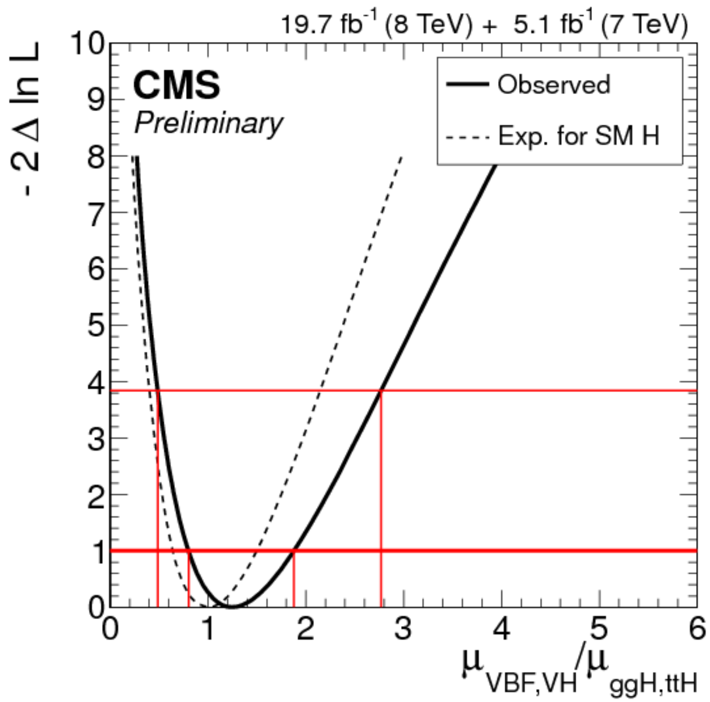
Signal strength (**μ**) results explored for various decay and production modes

- Results from individual modes compatible to SM Higgs predictions!

Four main Higgs boson production mechanisms associated with:

- fermion couplings (ggH and ttH)
- vector-boson couplings (VBF and VH)





Ratio of **μ**s in production modes with fermionic and bosonic couplings: $\mu_{VBF}, \mu_{VH}/\mu_{ggH}, \mu_{ttH}$

$$\text{Observed (expected): } \mathbf{1.25^{+0.63}_{-0.45}(1.00^{+0.49}_{-0.35})}$$

Deviation in the coupling

- Search for deviations from SM in the scalar couplings (LHC XS WG benchmarks) **[arXiv:1307.1347]**

It is assumed that:

- The observed signals is originates from a single narrow resonance
- Deviations can be parametrized only with couplings strengths modifiers $\{\boldsymbol{\kappa}_x\}$

Strategy

- Scale SM x-sections & SM partial widths as function of parameters $\{\boldsymbol{\kappa}x\}$.

$$(\sigma.\mathbf{BR})(\mathbf{x} \rightarrow \mathbf{H} \rightarrow \mathbf{ff}) = \frac{\sigma_{\mathbf{x}}.\boldsymbol{\Gamma}_{\mathbf{ff}}}{\boldsymbol{\Gamma}_{\mathrm{tot}}}$$

Example for H→γγ :

$$(\sigma.BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \rightarrow H).BR_{\mathrm{SM}}(H \rightarrow \gamma\gamma)\frac{\kappa_g^2.\kappa_\gamma^2}{\kappa_H^2}$$

Test of:

- Custodial symmetry
- Fermion and boson coupling
- Search for new physics in loop (production and decay)
- Simultaneous fit of the coupling modifiers

Deviation in the coupling

• Test of custodial symmetry

- m_W/m_Z, and their couplings to the Higgs boson, g_W/g_Z, are protected at tree-level: → **Custodial symmetry**.
- large violations of custodial symmetry are possible in new physics models

→ κ_W and κ_Z that modify the SM Higgs boson couplings to the W and Z.
Test consistency of $\lambda_{WZ} = \kappa_W/\kappa_Z$ with 1.

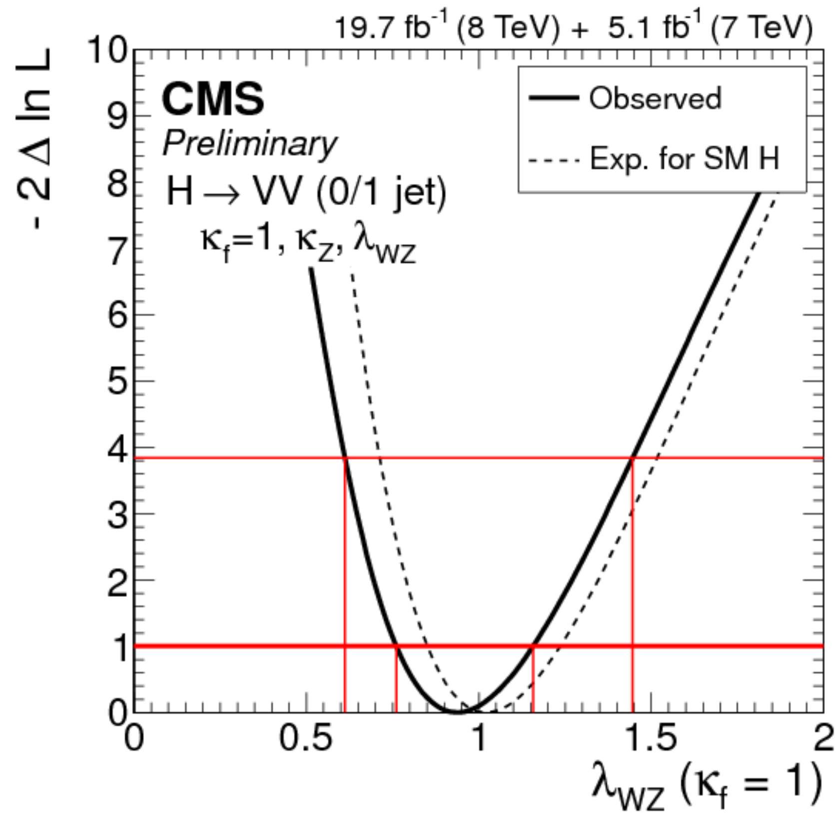
Using:
- H→WW
- H→ZZ→4l

$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = 0.94^{+0.22}_{-0.14}$$

Using full combination:

$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = 0.91^{+0.14}_{-0.12}$$

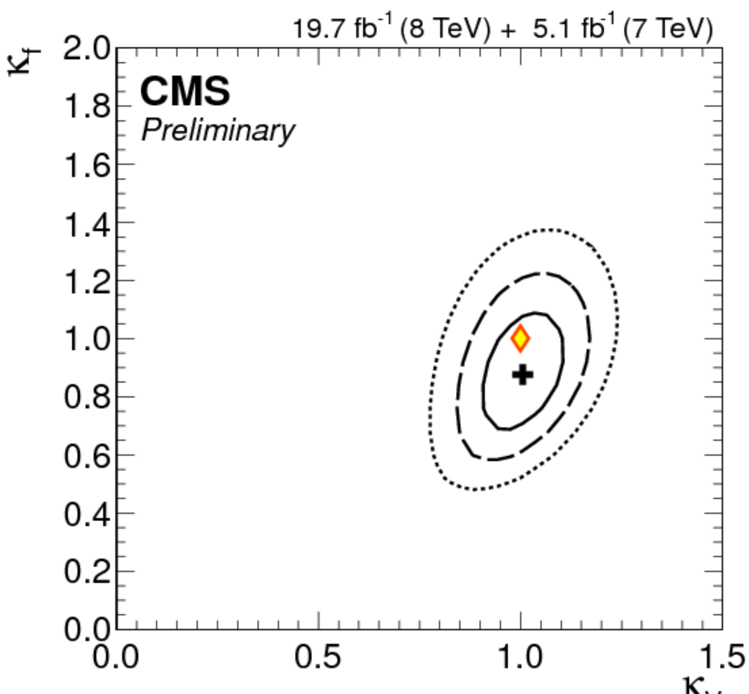
Data are consistent with the SM expectation

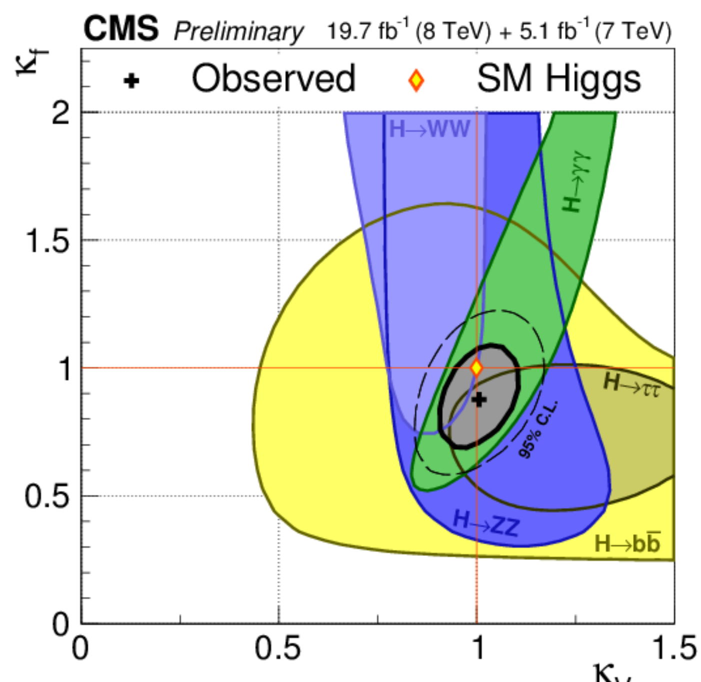


Deviation in the coupling

• Fermions – boson coupling

- Comparison of observation with SM expectation.
- Fit of κ_v, κ_f.
- Assuming no BSM





The 95% CL interval on κ_f and κ_V are respectively [0.64,1.16] and [0.88,1.15]

→ compatible with SM ($\kappa_f = \kappa_V$), clear preference for $\kappa_f > 0$

Deviation in the coupling

• Asymmetries in coupling to fermions

- In some BSM models,e.g. 2HDM,
- relative couplings to fermions can be altered.
- Two different ratios:
  - Down/up fermion type $\lambda_{\mathbf{du}} = \frac{\kappa_{\mathrm{d}}}{\kappa_{\mathrm{u}}}$

    $\mathbf{1.02^{+0.22}_{-0.21}}$
  - Lepton/quark coupling $\lambda_{\mathbf{lq}} = \frac{\kappa_{\mathrm{l}}}{\kappa_{\mathrm{q}}}$

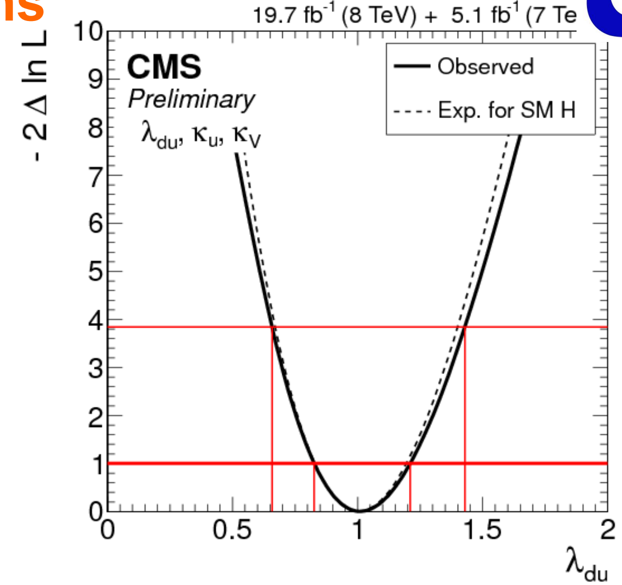
    $\mathbf{1.01^{+0.20}_{-0.19}}$

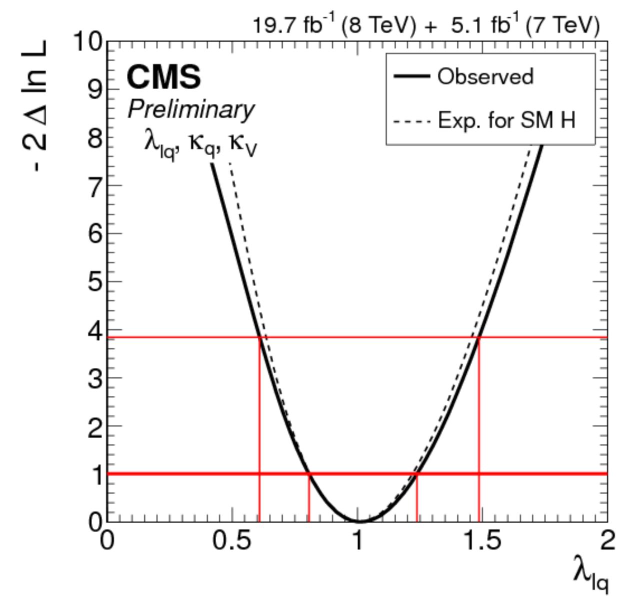
Likelihood scan allow to constraint:

$\lambda_{\mathbf{du}} : [\mathbf{0.66, 1.43}]$

$\lambda_{\mathbf{lq}} : [\mathbf{0.61, 1.49}]$

Both are compatible with **1**, in **agreement** with the SM.



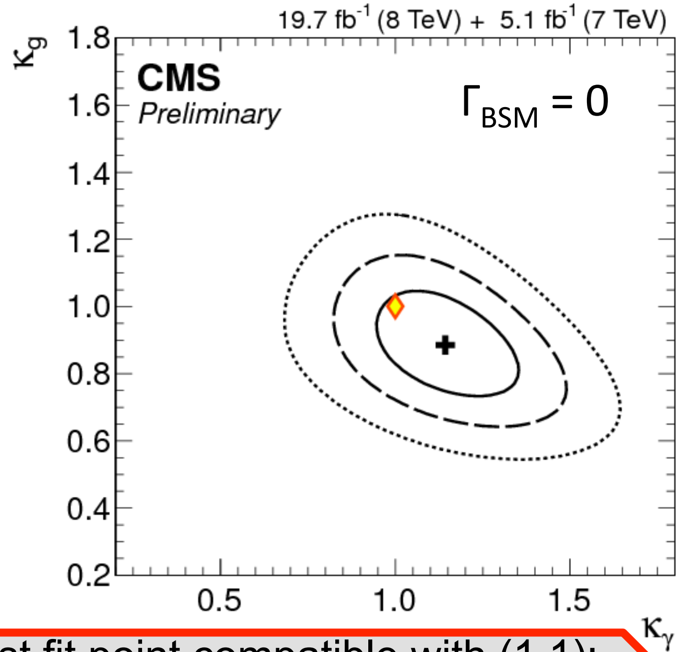


Deviation in the coupling

• New Physics in loop and decay

Processes induced by loop (gg→H, H→ γγ) susceptible to hide new particles

- combine data from gluon fusion production with data from photon decay.
- Fit of κ_γ and κ_g modifiers for theses processes.



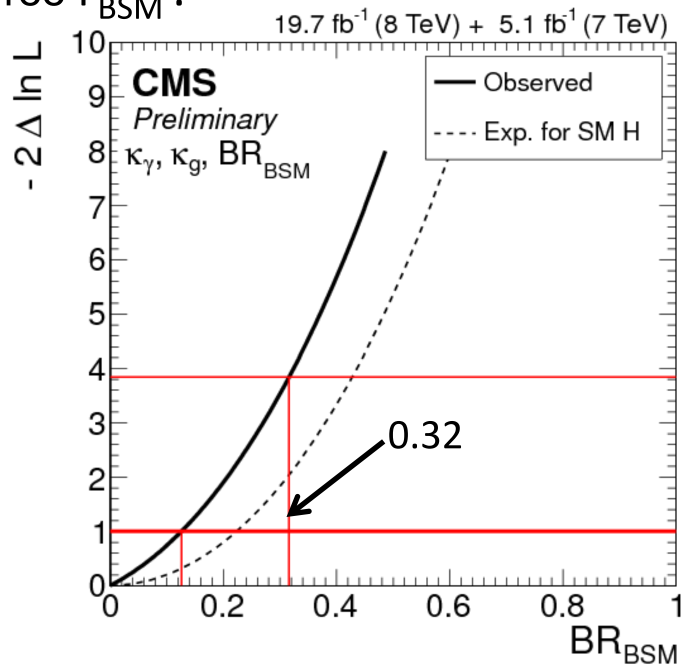
Best fit point compatible with (1,1):

$$(\kappa_\gamma, \kappa_g) = (1.14, 0.88)$$

$$@95\%\ \text{CL: } \kappa_\gamma : [0.89, 1.42]$$

$$@95\%\ \text{CL: } \kappa_g : [0.69, 1.10]$$

Letting free Γ_{BSM} :



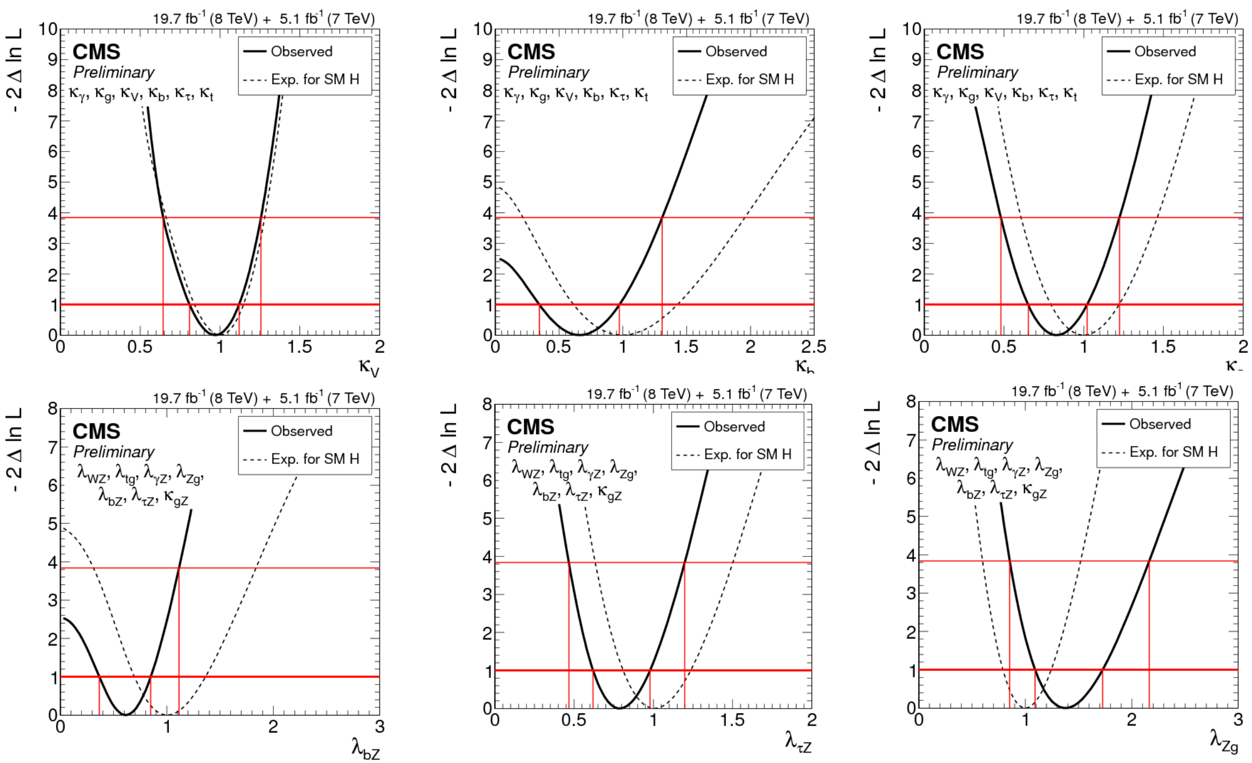
@ 95% CL: $BR_{BSM} = \frac{\Gamma_{BSM}}{\Gamma_{tot}} : [0.00, 0.32]$

Test of a model with 6 independant scaling factor

Simultaneous probe of 6 coupling:

- κ_V : assuming Z & W scaled by the same factor.
- $\kappa_t,\kappa_b,\kappa_\tau$: independent scaling for the third fermion generation.
- (modifiers factors assumed the same for first and second generation to those for third).
- κ_g, κ_γ : Factor for gluon and photon effective coupling assuned independent.
- Γ_{BSM} : partial Higgs width assumed to be 0.

Likelihood scan for these 6 parameters:



No significant deviations with respect to the Standard Model Higgs boson.

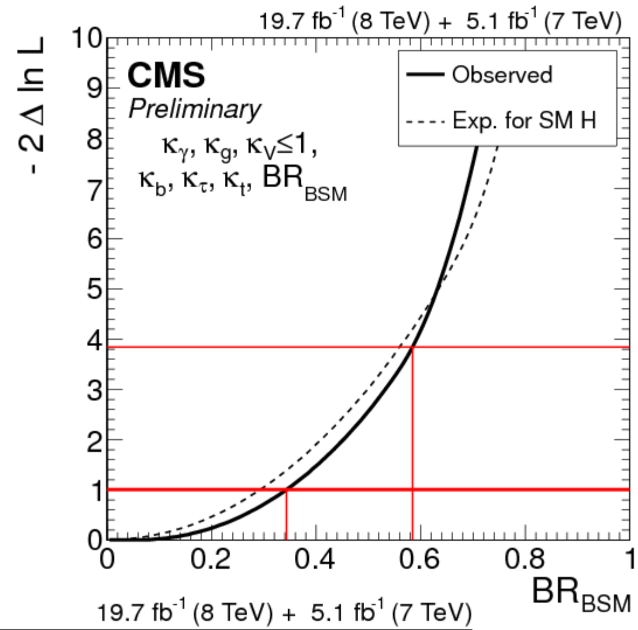
Test of a model with 6 independant scaling factor

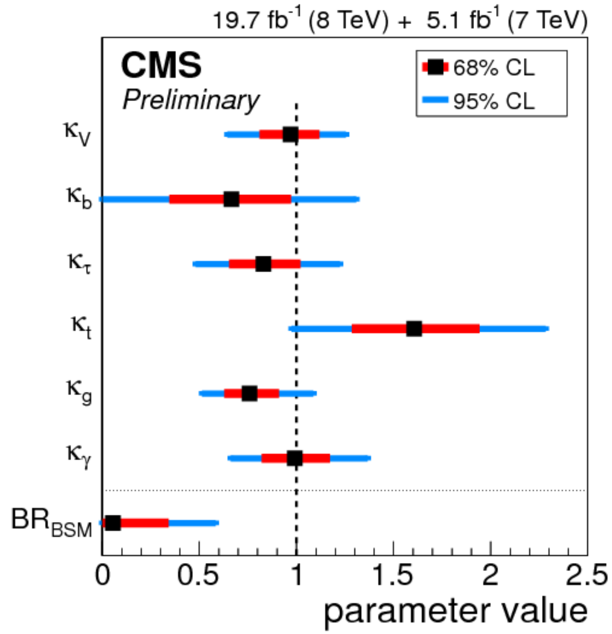
Simultaneous probe of 6 coupling + Γ_{BSM}:

- Fit of the 6 parameters extending the model to allow for beyond-SM decays while restricting the effective coupling to vector bosons to not exceed unity ($\kappa_V \leq 1.0$)

- Data allow to conclude at 95% of confidence level that:

$$BR_{BSM} = \frac{\Gamma_{BSM}}{\Gamma_{tot}} : [0.00, 0.58]$$





Mass Measurement

Mass measurement using **high resolution** channels:

- **H→ZZ→4l**

  Very good control of the leptons scale and resolution,
  exploits per-event mass uncertainties

H→ γγ (mass: fit $m_{\gamma\gamma}$ floating $\mu_{\gamma\gamma}$)

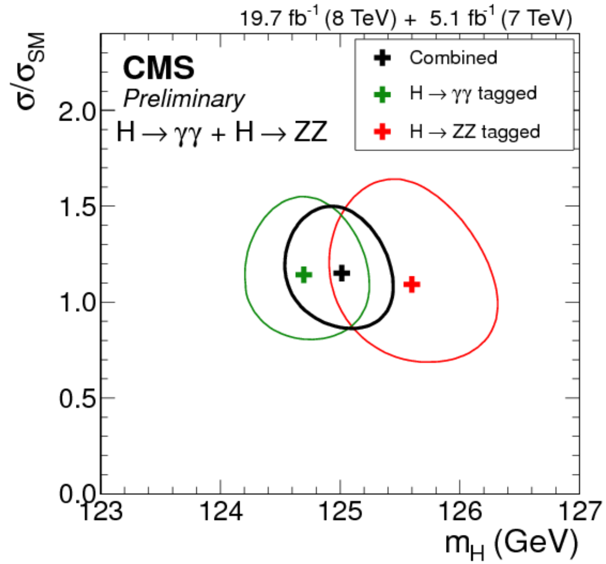
Good resolution, systematics on the extrapolation from the Z→ee to H→γγ

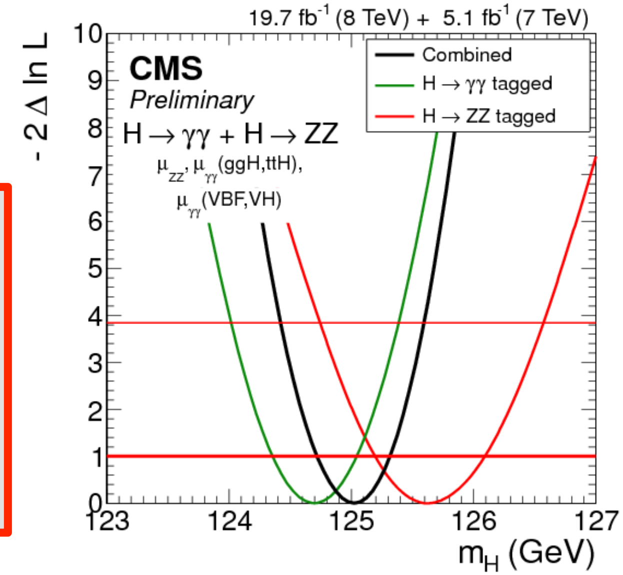
The mass is measured to be:

$$m_H = 125.04^{+0.26}_{-0.27}\ \text{stat.}\ ^{+0.13}_{-0.15}\ \text{syst.}\quad \text{GeV}$$

And the two measurement (ZZ, γγ) agree at

1.6 sigma: $m_H^{\gamma\gamma} - m_H^{4l} = -0.87^{+0.54}_{-0.59}$ GeV

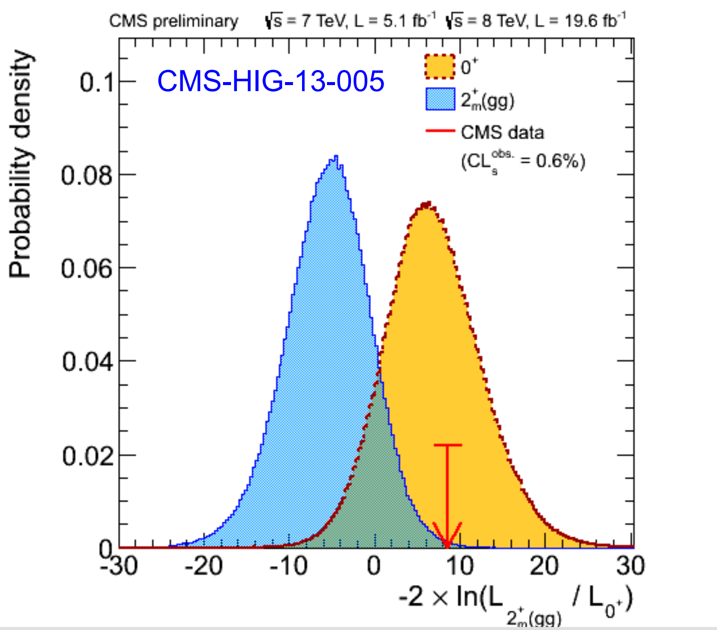




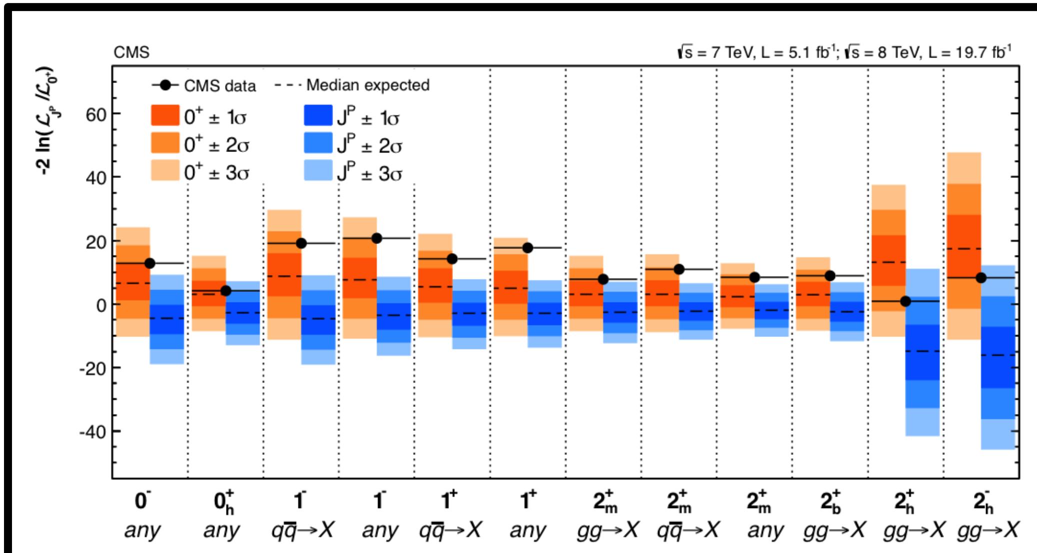
Spin-parity hypothesis testing

- compatibility of the new boson with alternative J^P hypotheses
- exploit shapes of kinematic observables (angles, inv. masses)
- Use of :
  - $H \rightarrow ZZ \rightarrow 4l$
  - $H \rightarrow WW$
  - $H \rightarrow \gamma\gamma$

- Combined test for hypothesis $gg \rightarrow 2_m^+$



- Hypothesis $gg \rightarrow 2_m^+$ is excluded at 99% CL



hypotheses excluded using the HZZ channel @99%C.L.

$J^P = 0^+$ strongly favoured by measurements

Spin 1 and spin 2 and Pseudoscalar boson hypotheses: Excluded

deviation on the mass scaling factor ε and vev

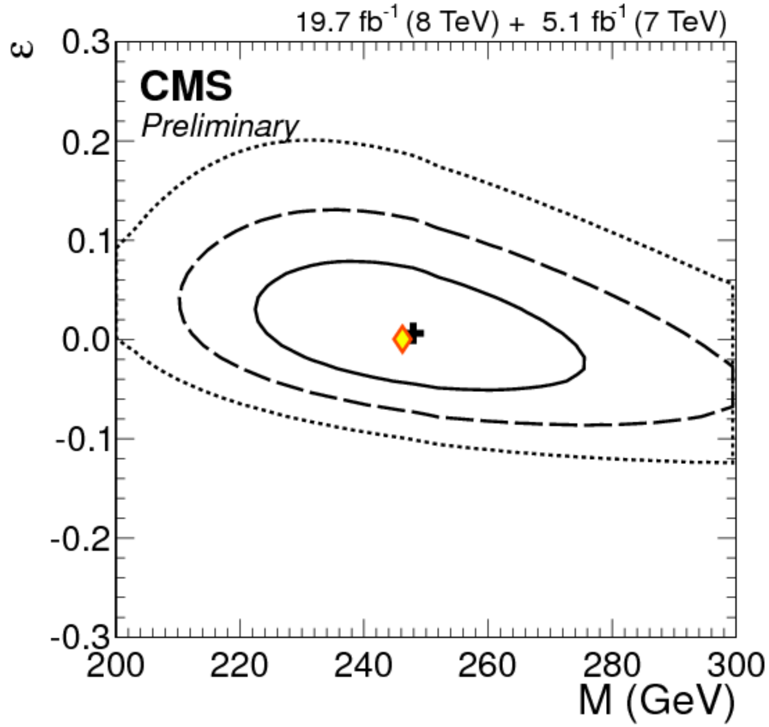
coupling scale factors to fermions and vector bosons are expressed in terms of:

- a mass scaling parameter: ϵ
- a "vacuum expectation value" parameter: M

- The coupling scale factors to fermions are: $\kappa_{f,i} = \nu . m_{f,i}^{\epsilon} / M^{1+\epsilon}$

- The coupling scale factors to vector bosons are: $\kappa_{V,j} = \nu . m_{V,j}^{2\epsilon} / M^{1+2\epsilon}$

- $v \approx 246$ GeV is the SM vacuum expectation value.
- $m_{f,l}$ are the fermion masses
- $m_{V,l}$ are the vector boson masses



The SM expectation of $\kappa_{f,l} = \kappa_{V,l} = 1$
is recovered in the double limit of $\epsilon = 0$ and $M = v$

Summary

SM Higgs boson evidences at CMS:

- 3.8 σ for direct fermionic decays
- 3.6 σ for VBF production
- 2.7 σ for VH production
- **+** 2 σ excess over SM in ttH searches

Wide range of test of Higgs coupling performed.

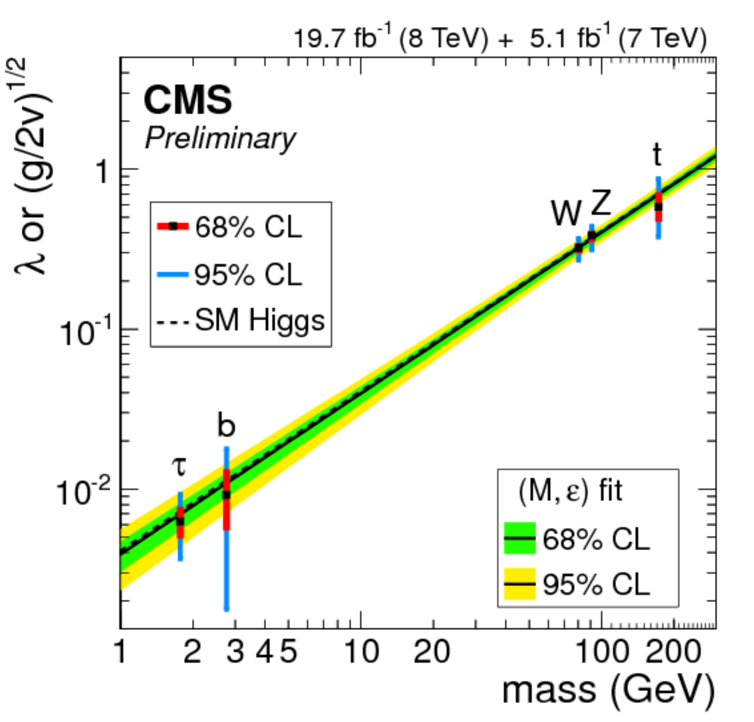
→ No deviations observed

Properties measurements:

- combining information from different channels:
- mass:

$$m_H = 125.04^{+0.26}_{-0.27}\ \text{stat.}\ ^{+0.13}_{-0.15}\ \text{syst.}\quad \text{GeV}$$

- spin-parity: compatible with $J^P = 0^+$



All measurements show that:
This particle is compatible with the SM Higgs boson!

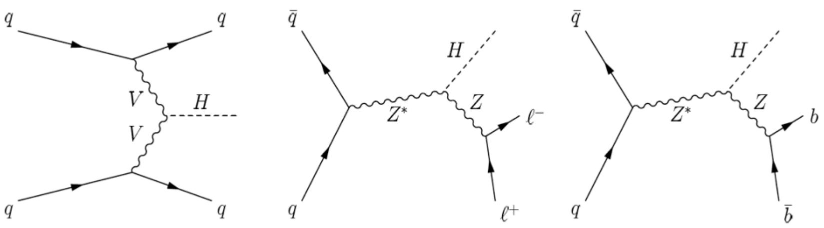
Thank you

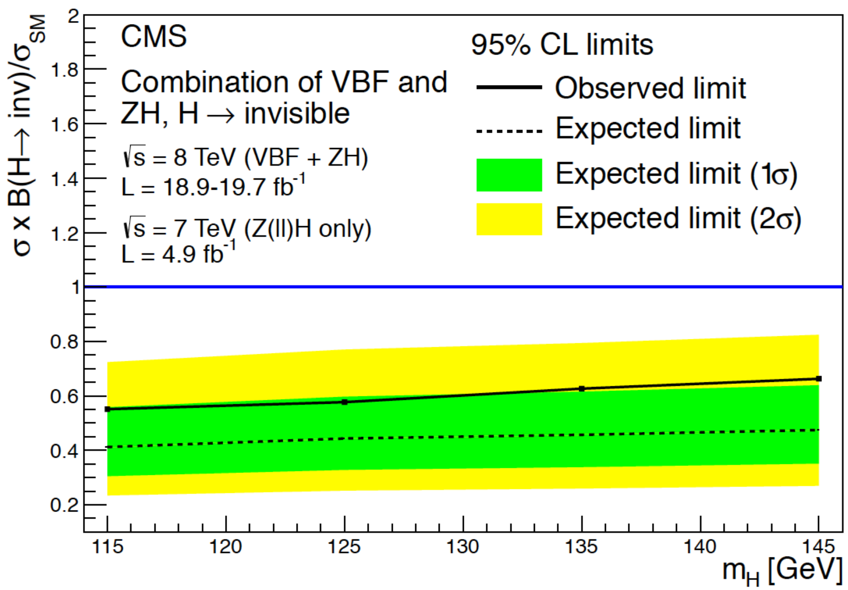
Next round with LHC run II …

Backup

Higgs Invisible

- Search performed using the VH (ZH) and the VBF production mode.
- Sensitive to non-SM invisible decay.
  sensitive to the presence of additionnal boson with similar production mode and larger invisile branching ratio.
- Combined VH and VBF:





the upper limit on the invisible branching fraction of a Higgs boson for **m**H = 125 GeV, is found to be 0.58, with an expected limit of 0.44, at 95% confidence level.

CMS-HIG-13-030

Combination technique

3.1 Characterizing an excess of events: p-values and significance

To quantify the presence of an excess of events over what is expected for the background, we use the test statistic where the likelihood appearing in the numerator corresponds to the background-only hypothesis:

$$q_0 = -2 \ln \frac{\mathcal{L}(\text{data} \mid b, \hat{\theta}_0)}{\mathcal{L}(\text{data} \mid \hat{\mu} \cdot s + b, \hat{\theta})}, \text{ with } \hat{\mu} > 0, \tag{1}$$

The quantity p_0, henceforth referred to as the local p-value, is defined as the probability, under the background-only (b) hypothesis, to obtain a value q_0 at least as large as that observed in data, q_0^{data}:

$$p_0 = \mathrm{P}\left(q_0 \geq q_0^{\text{data}} \,\middle|\, b\right). \tag{2}$$

The local significance z of a signal-like excess is then computed from the following equation, using the one-sided Gaussian tail convention:

$$p_0 = \int_z^{+\infty} \frac{1}{\sqrt{2\pi}} \exp(-x^2/2)\, dx. \tag{3}$$

Note that very small p-values should be interpreted with caution as the systematic biases and uncertainties in the underlying model are only known with finite precision.

Combination

$H \to \gamma\gamma$ tagged includes only categories from the $H \to \gamma\gamma$ analysis of Ref. [19].

$H \to ZZ$ tagged includes only categories from the $H \to ZZ$ analysis of Ref. [17].

$H \to WW$ tagged includes all the channels from the $H \to WW$ analysis of Ref. [16] and the channels from the analysis of $t\bar{t}H$ with $H \to$ leptons of Ref. [28].

$H \to \tau\tau$ tagged includes all the channels from the $H \to \tau\tau$ analysis of Ref. [18] and the channels from the analysis of $t\bar{t}H$ targeting $H \to \tau_h\tau_h$ of Ref. [27].

$H \to bb$ tagged includes all the channels of the analysis of VH with $H \to bb$ of Ref. [15] and the channels from the analysis of $t\bar{t}H$ targeting $H \to bb$ of Refs. [13, 27].

Combination technique

The combination of Higgs boson measurements requires the simultaneous analysis of the data selected by all individual analyses, accounting for all statistical uncertainties, systematic uncertainties, and their correlations.

3.2 Extracting signal model parameters

Signal model parameters a, such as the signal strength modifier μ, are evaluated from scans of the profile likelihood ratio $q(a)$:

$$q(a) = -2\,\Delta \ln \mathcal{L} = -2\,\ln \frac{\mathcal{L}(\text{data} \mid s(a) + b,\, \hat{\theta}_a)}{\mathcal{L}(\text{data} \mid s(\hat{a}) + b,\, \hat{\theta})}. \quad (4)$$

The parameters $\hat{a}$ and $\hat{\theta}$ correspond to the global maximum likelihood and are called the best-fit set.

The post-fit model, obtained after the signal-plus-background fit to the data, corresponds to the parametric bootstrap described in the statistics literature, includes information gained in the fit regarding the values of all parameters [36, 37], and is used when deriving expected quantities.

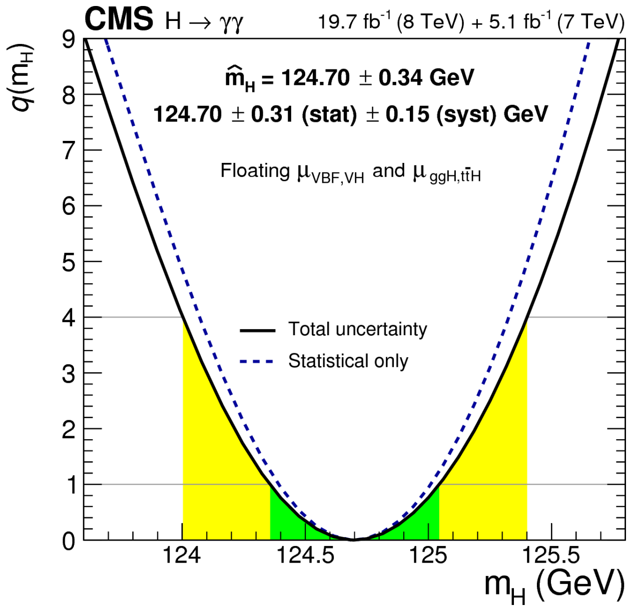
The 68% and 95% confidence level (CL) intervals for a given parameter of interest a_i are evaluated from $q(a_i) = 1.00$ and $q(a_i) = 3.84$ respectively, with all other unconstrained model parameters treated in the same way as the nuisance parameters. The two-dimensional (2D) 68% and 95% CL contours for pairs of parameters are derived from $q(a_i, a_j) = 2.30$ and $q(a_i, a_j) = 6.99$, respectively. One should keep in mind that boundaries of 2D confidence regions projected on either parameter axis are not identical to the one-dimensional (1D) confidence interval for that parameter.

All results are given using the chosen test statistic result in approximate CL intervals or regions.

Higgs boson mass measurement

$H \to \gamma\gamma$

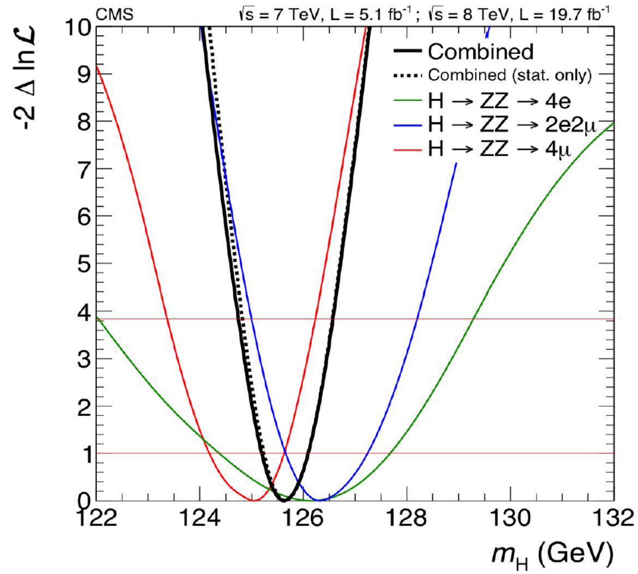
- The 4 main Higgs boson production mechanisms can be associated



- Scan of the likelihood ratio, as a function of the hypothesised mass.
  - µggH,ttH and µVBF, VH are allowed to vary independently

$H \to ZZ \to 4l$

Signal vs Background discrimination based on kinematic variables of decay product.

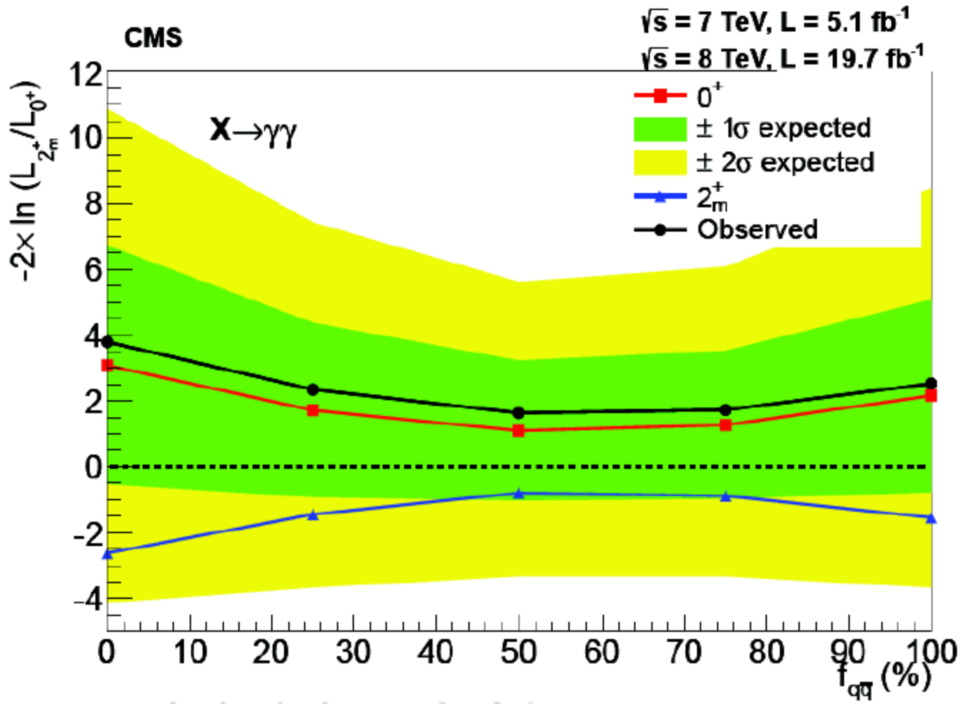


mass: fit with 3D likelihood

Spin parity measurement

spin/CP; CLS using 2D likelihood ratio

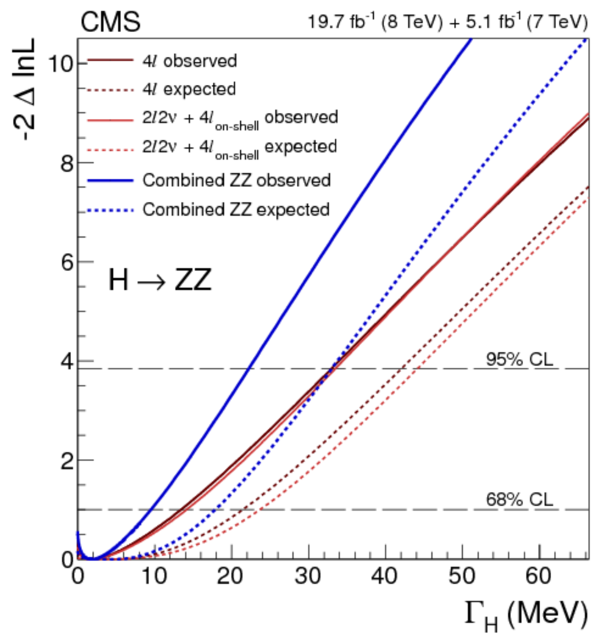
h→γγ: 0+ vs 2+



Higgs boson Width

- Experimental resolution strongly limits direct width (Γ_H) measurement to ~1GeV
  - SM Higgs decay width is 4.15 MeV at m_H = 125.6 GeV

- theoretical advances [*] :
- made possible to constrain the Higgs boson width
- using its off-shell production & decay away from the peak.



$$\sigma^{\text{on-peak}}_{gg\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma} \qquad \sigma^{\text{off-peak}}_{gg\to ZZ} \propto g^2_{ggH} g^2_{HZZ}$$

→ experimental constraints on the width Γ_H with mild model-dependence

Using:
- H→ZZ→4l
- H→ZZ→2l2ν

We measure:
Γ_H < 22 MeV @ 95% CL.

Analysis	Observed / Expected	95% CL limit on Γ_H (MeV)	95% CL limit on Γ_H/Γ_H^{SM}	Γ_H (MeV)	Γ_H/Γ_H^{SM}
4ℓ	Expected	42	10.1	$4.2^{+17.3}_{-4.2}$	$1.0^{+4.2}_{-1.0}$
	Expected (no syst.)	41	10.0	$4.2^{+17.1}_{-4.2}$	$1.0^{+4.1}_{-1.0}$
	Observed	33	8.0	$1.9^{+11.7}_{-1.9}$	$0.5^{+2.8}_{-0.5}$
$4\ell_{on-shell} + 2\ell 2\nu$	Expected	44	10.6	$4.2^{+19.3}_{-4.2}$	$1.0^{+4.7}_{-1.0}$
	Expected (no syst.)	34	8.3	$4.2^{+14.1}_{-4.2}$	$1.0^{+3.4}_{-1.0}$
	Observed	33	8.1	$1.8^{+12.4}_{-1.8}$	$0.4^{+3.0}_{-0.4}$
Combined	Expected	33	8.0	$4.2^{+13.5}_{-4.2}$	$1.0^{+3.2}_{-1.0}$
	Expected (no syst.)	28	6.8	$4.2^{+11.3}_{-4.2}$	$1.0^{+2.7}_{-1.0}$
	Observed	22	5.4	$1.8^{+7.7}_{-1.8}$	$0.4^{+1.8}_{-0.4}$