



# Combined results of the 125 GeV Higgs boson couplings using all decay channels measured by the CMS detector



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On behalf of CMS Collaboration





# Higgs signatures explored at CMS

Decay tag	incl.(ggH)	VBF tag	VH tag	ttH tag
$H \rightarrow ZZ$	✓	✓		
$H \rightarrow \gamma\gamma$	✓	✓	✓	✓
$H \rightarrow WW$	✓	✓	✓	✓
$H \rightarrow \tau\tau$	✓	✓	✓	✓
$H \rightarrow bb$		✓	✓	✓
$H \rightarrow Z\gamma$	✓	✓		
$H \rightarrow \mu\mu$	✓	✓		
$H \rightarrow \text{inv.}$		✓	✓	

✓ Used in the NEW combination

[CMS-PAS-HIG-14-009](#)

207 (sub-)categories, 2519 nuisance parameters

NOTE: tags are never 100% pure

(e.g. VBF-tagged events are expected to contain 20-50%  $gg \rightarrow H$ , depending on the analysis and sub-category)



# Higgs signatures explored at CMS

$m_H$  fixed at **125.0** GeV

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$H \rightarrow ZZ$	✓	✓			→	6.5	6.3
$H \rightarrow \gamma\gamma$	✓	✓	✓	✓	→	5.6	5.3
$H \rightarrow WW$	✓	✓	✓	✓	→	4.7	5.4
$H \rightarrow \tau\tau$	✓	✓	✓	✓	→	3.8	3.9
$H \rightarrow bb$		✓	✓	✓	→	2.0	2.3
$H \rightarrow Z\gamma$	✓	✓					
$H \rightarrow \mu\mu$	✓	✓					
$H \rightarrow \text{inv.}$		✓	✓				

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	Obs.	Exp.
→	6.5	6.3
→	5.6	5.3
→	4.7	5.4
→	3.8	3.9
→	2.0	2.3

## References

Reference	Analyses	Talk given by
<a href="#">PhysRevD.89.092007</a>	H $\rightarrow$ ZZ	A. Vartak M. Sani
<a href="#">arXiv:1407.0558</a>	H $\rightarrow$ $\gamma\gamma$	M. Kenzie
<a href="#">JHEP01(2014)096</a>	H $\rightarrow$ WW	P. Govoni
<a href="#">JHEP05(2014)104</a>	H $\rightarrow$ $\tau\tau$	J. Steggemann
<a href="#">PhysRevD.89.012003</a>	H $\rightarrow$ bb	C. Vernieri
<a href="#">CMS-PAS-HIG-13-019</a> <a href="#">CMS-PAS-HIG-13-020</a>	ttH $\rightarrow$ $\tau\tau, bb$ ttH $\rightarrow$ leptons	L. Bianchini

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207 (sub-)categories, 2519 nuisance parameters

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# Global signal strength

- Overall signal strength

$$1.00 \pm 0.13$$

$1.00 \pm 0.09 \text{ (stat.)} {}^{+0.08}_{-0.07} \text{ (theo.)} \pm 0.07 \text{ (syst.)}$

- “theo.” includes QCD scales, PDF+ $\alpha_s$ , UEPS, and BR

# Global signal strength and break down

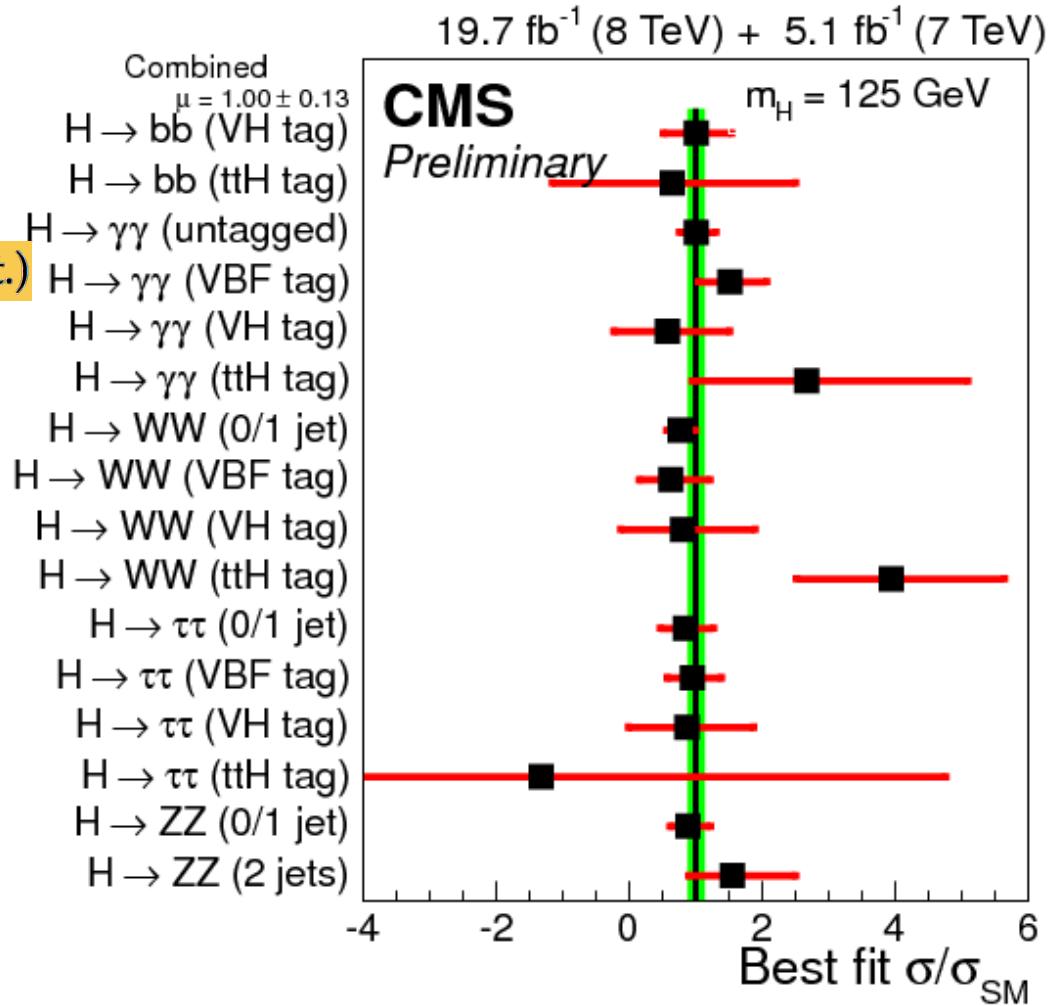


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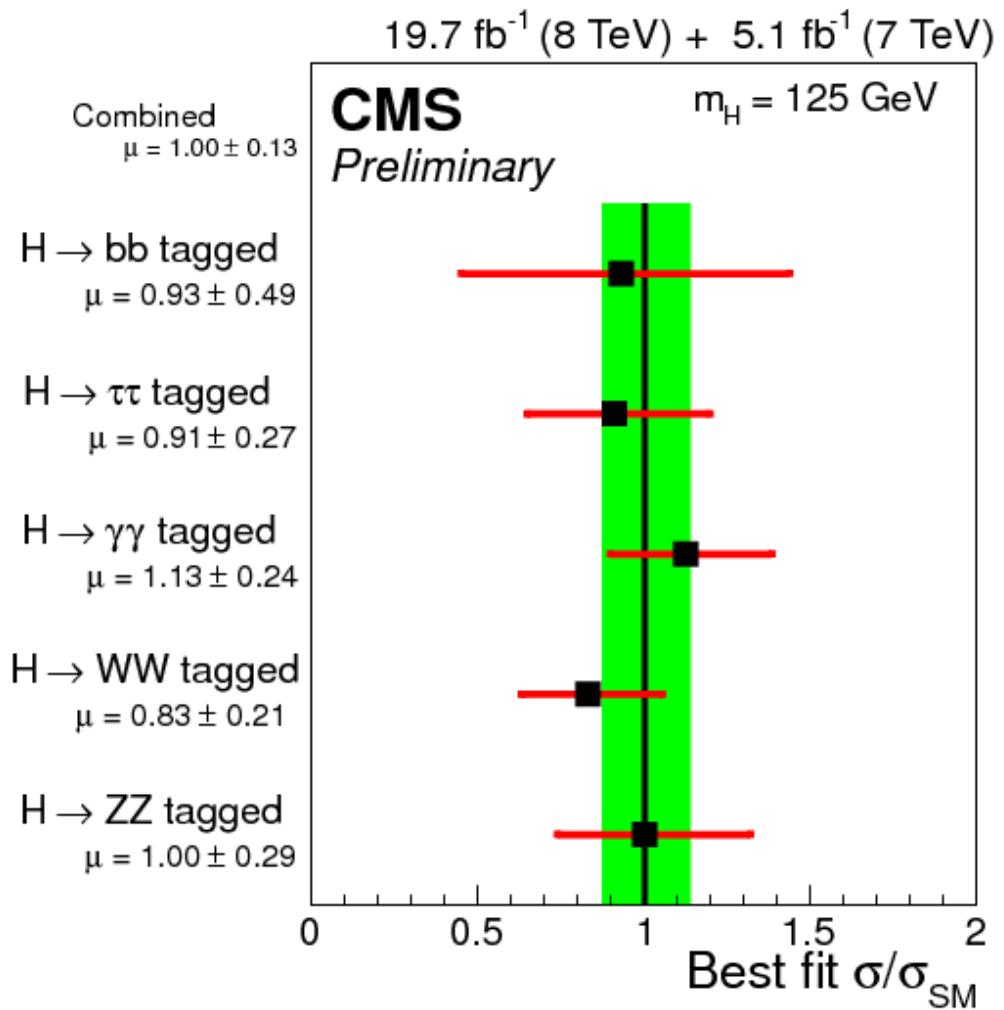
- “theo.” includes QCD scales, PDF+ $\alpha_s$ , UEPS, and BR
- Per production and decay tag:
  - $\chi^2/\text{dof} = 10.5/16$
  - p-value = 0.84 (asymptotic)





# Signal strength per decay group

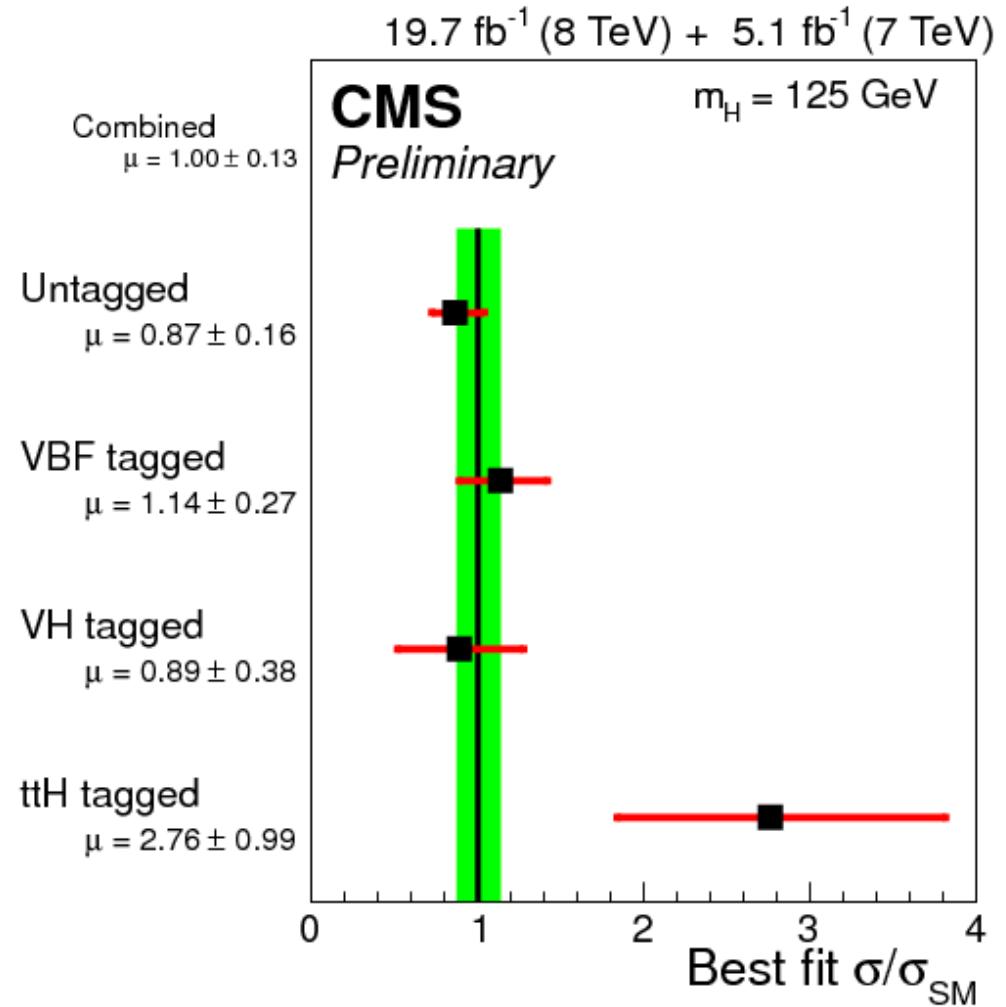
- Per decay tag:
  - $\chi^2/\text{dof} = 0.9/5$
  - p-value = 0.97 (asymptotic)





# Signal strength per production tag

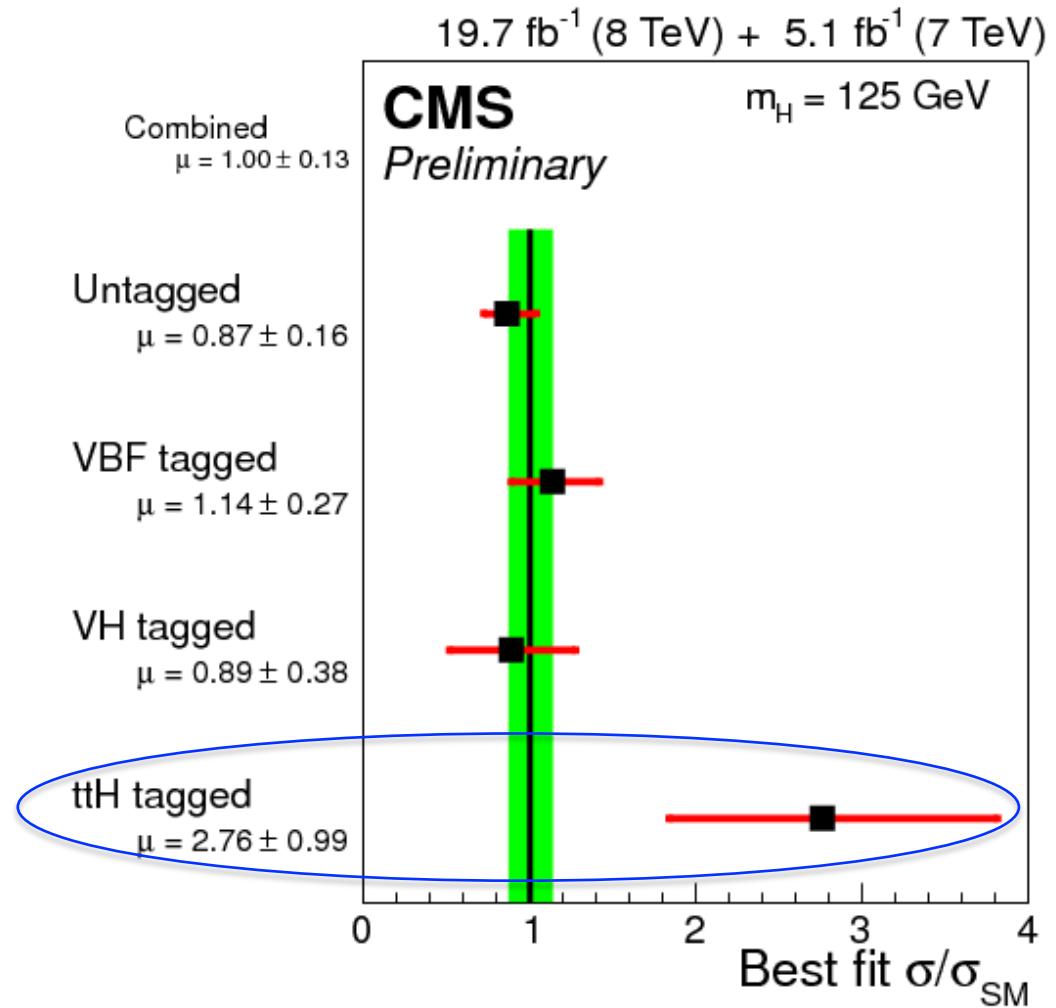
- Per production tag:
  - $\chi^2/\text{dof} = 5.3/4$
  - p-value = 0.26 (asymptotic)





# Signal strength per production tag

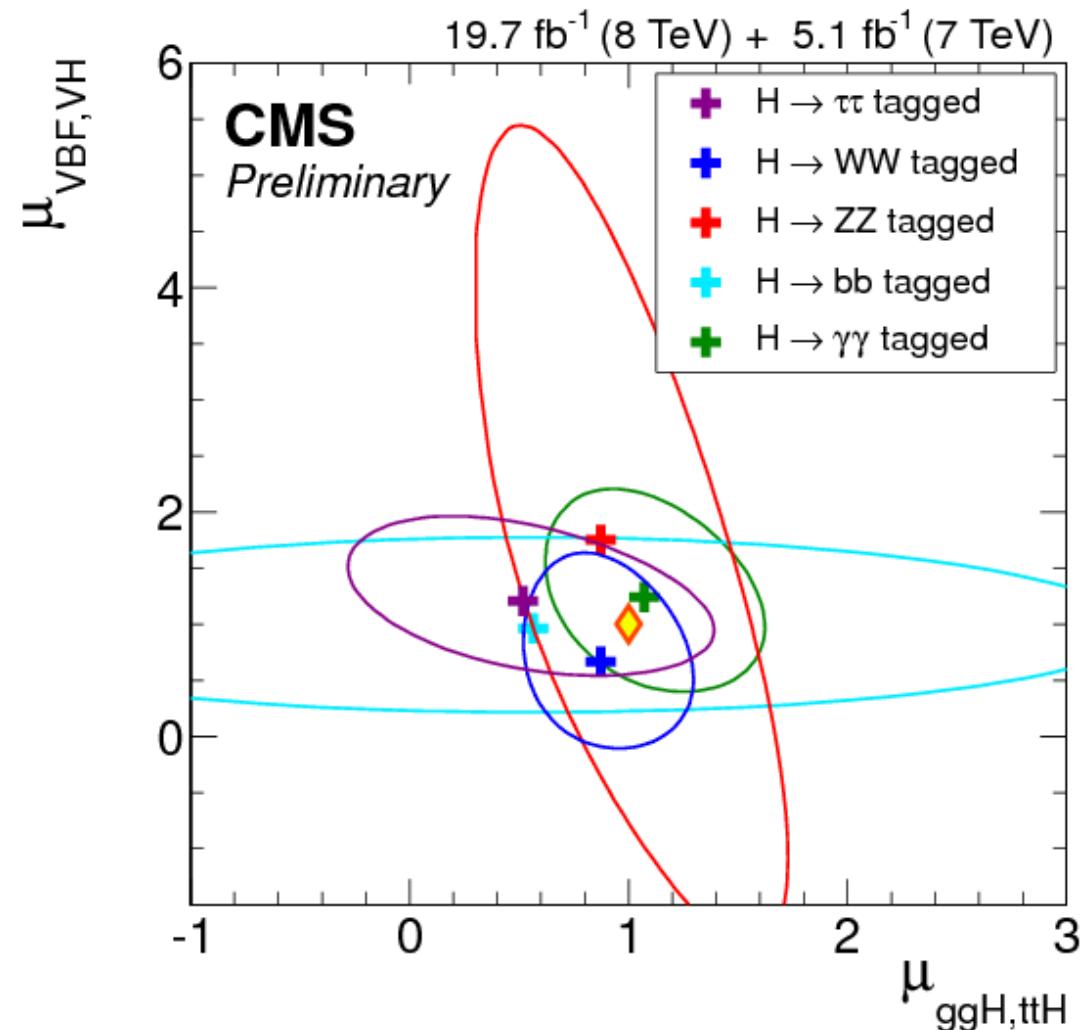
- Per production tag:
  - $\chi^2/\text{dof} = 5.3/4$
  - p-value = 0.26 (asymptotic)
  - driven by the excess seen in ttH analyses, where the deviation from SM is at  $2.0\sigma$  level





# Production modes

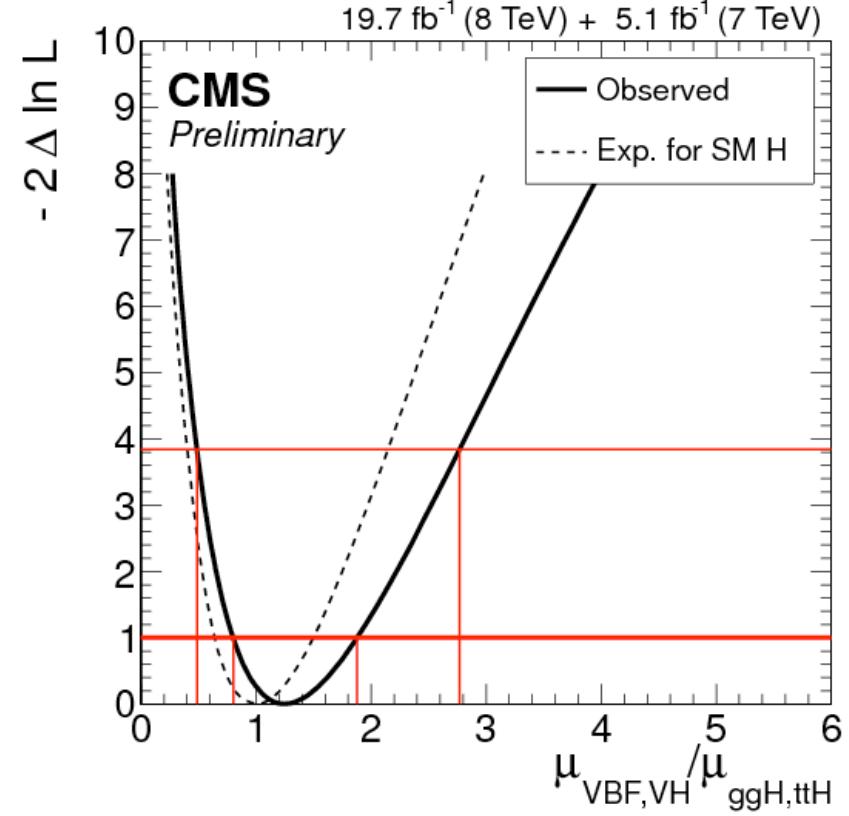
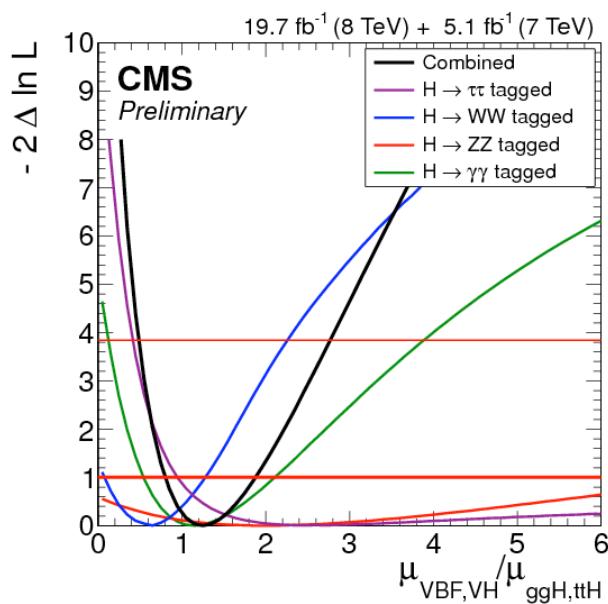
- Group fermion-related and vector-boson-related production processes
- Properly accounts for composition in the tagged categories and its uncertainty



# Production mode ratio



- BR uncertainties cancel out in ratio of  $\mu_{\text{VBF,VH}}$  and  $\mu_{\text{ggH,ttH}}$
- Can combine all ratios

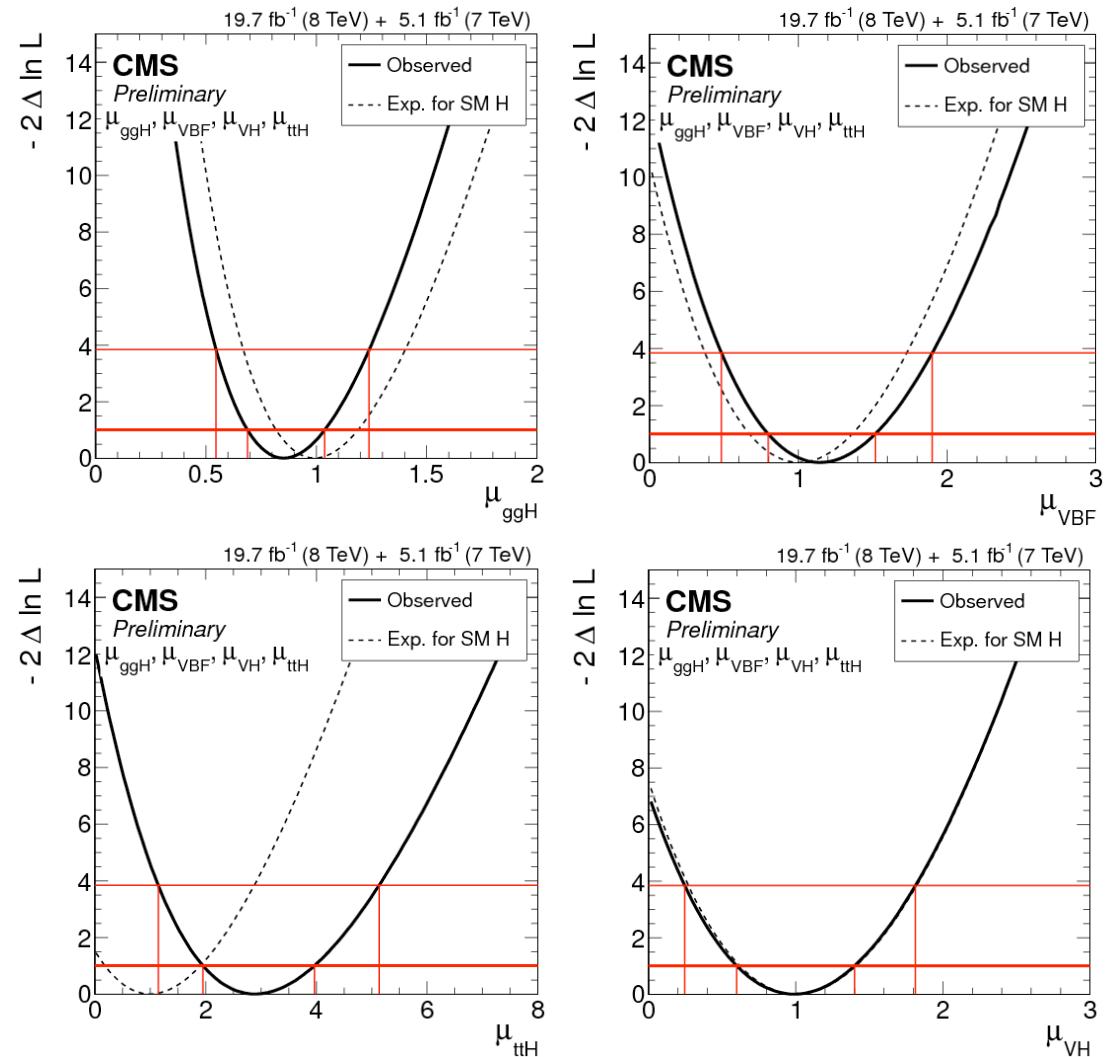


Combined best fit  $\mu_{\text{VBF,VH}} / \mu_{\text{ggH,ttH}}$   
 Observed (expected)  
 $1.25^{+0.63}_{-0.45} (1.00^{+0.49}_{-0.35})$

# Individual production modes



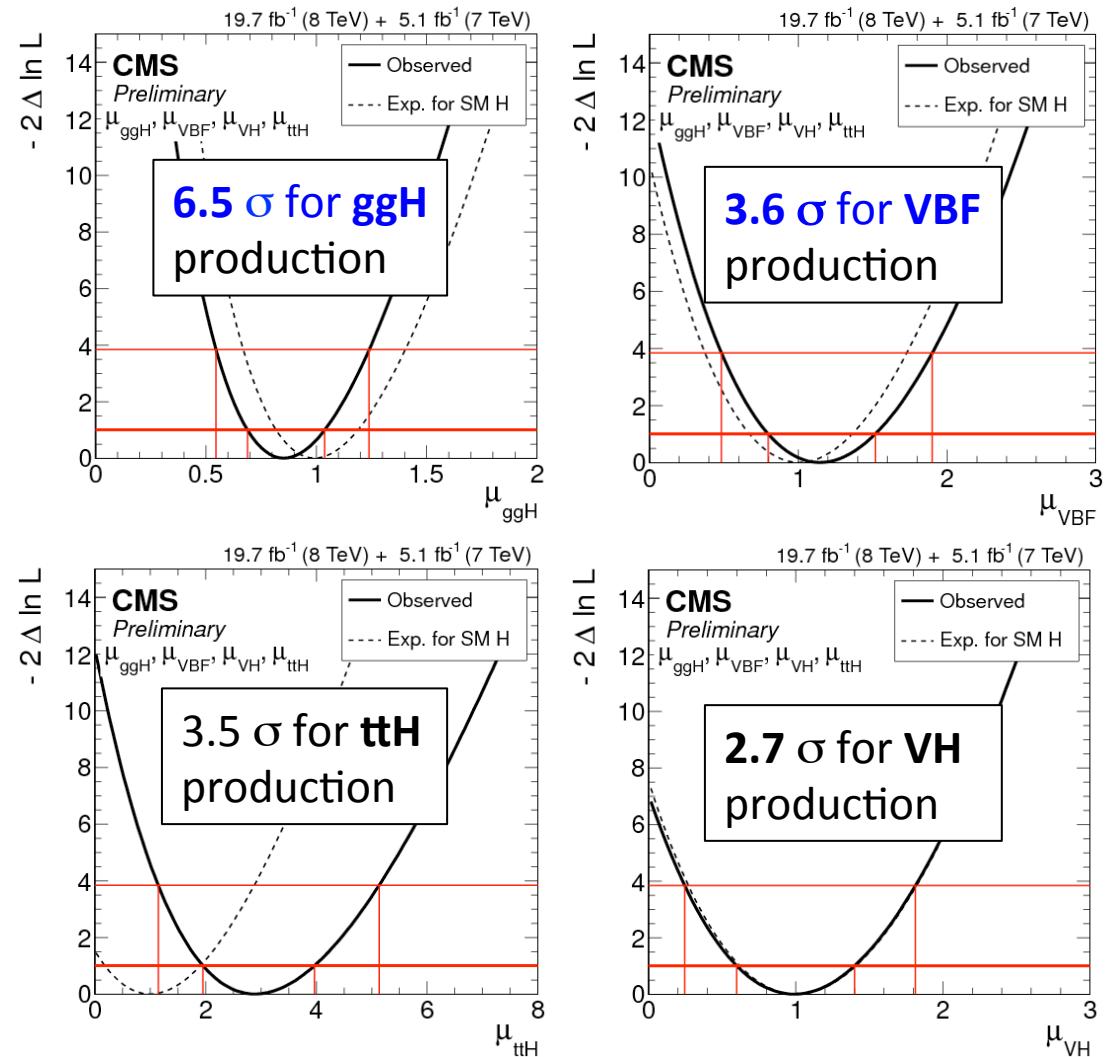
- Simultaneous fit for 4 production cross sections, normalized to SM
- Decay BR's assumed to be the SM ones.



# Individual production modes



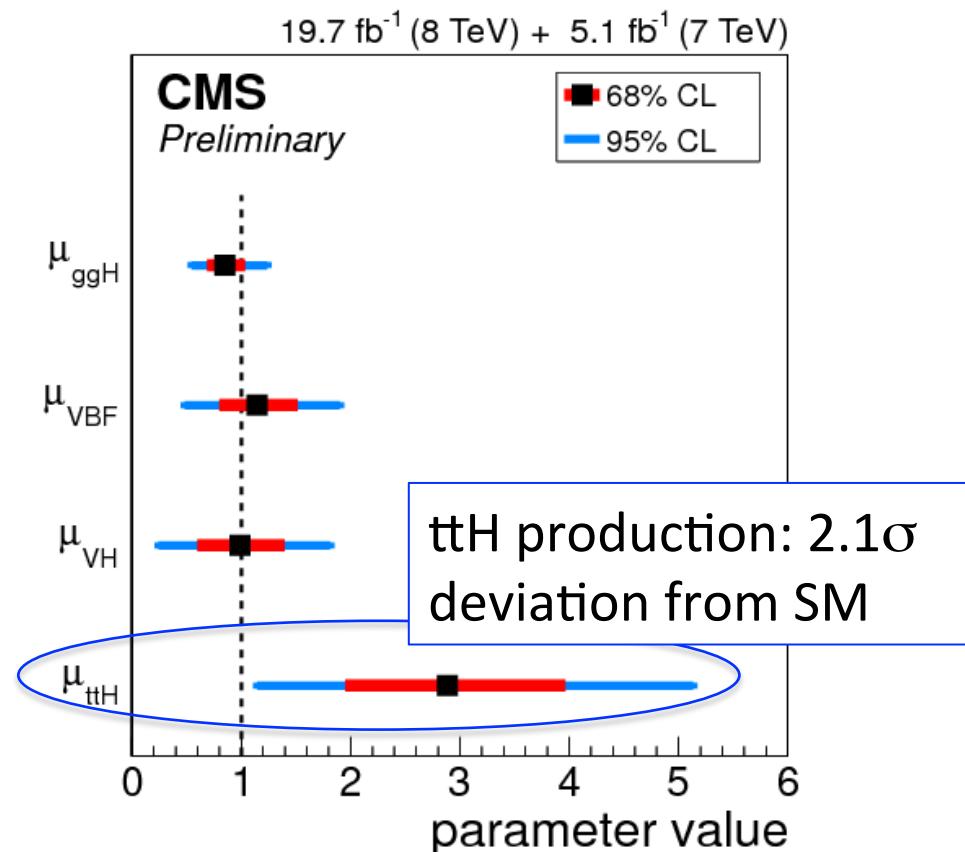
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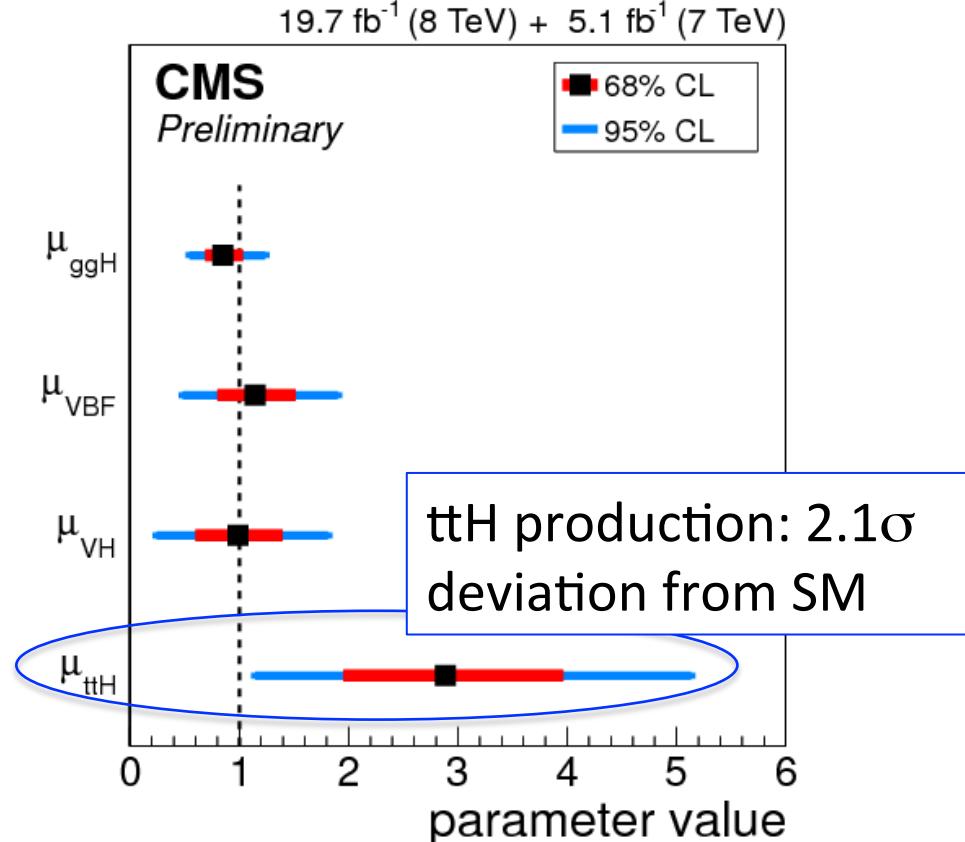




# Individual production modes

- Simultaneous fit for 4 production cross sections, normalized to SM
- Decay BR's assumed to be the SM ones.
- Break down  $\mu_{ggH}$  uncertainty:

$$0.85^{+0.11}_{-0.09} \text{ (stat.)} \quad {}^{+0.11}_{-0.08} \text{ (theo.)} \quad {}^{+0.10}_{-0.09} \text{ (syst.)}$$





# Tests of Higgs couplings

## Follow the prescription from LHCHXSWG

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} : \text{ see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

Total width

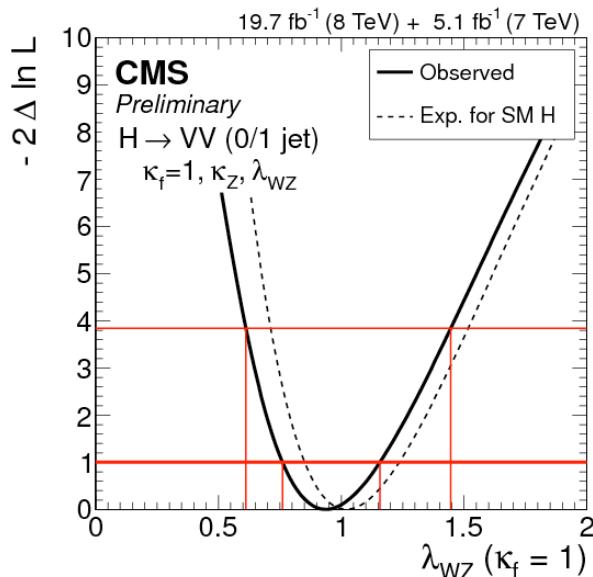
$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

- Assume single resonance
- Zero-width approximation:  $(\sigma \cdot BR)(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$
- SM tensor structure

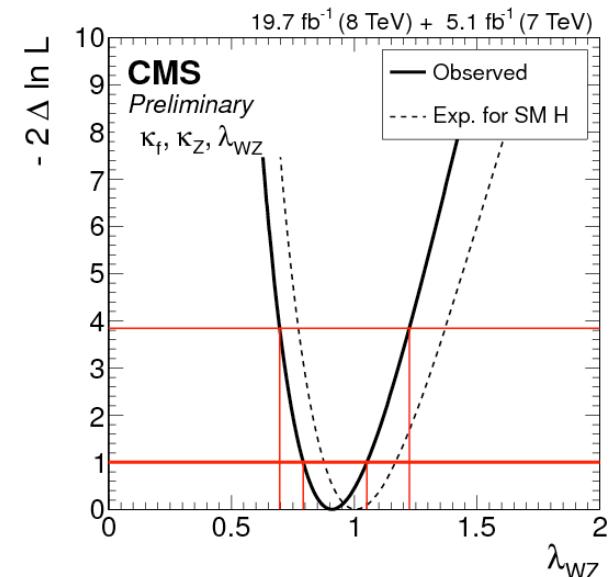
# Custodial symmetry



- Use only WW and ZZ  
0/1 jet categories
- Full combination



$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = 0.94^{+0.22}_{-0.18}$$



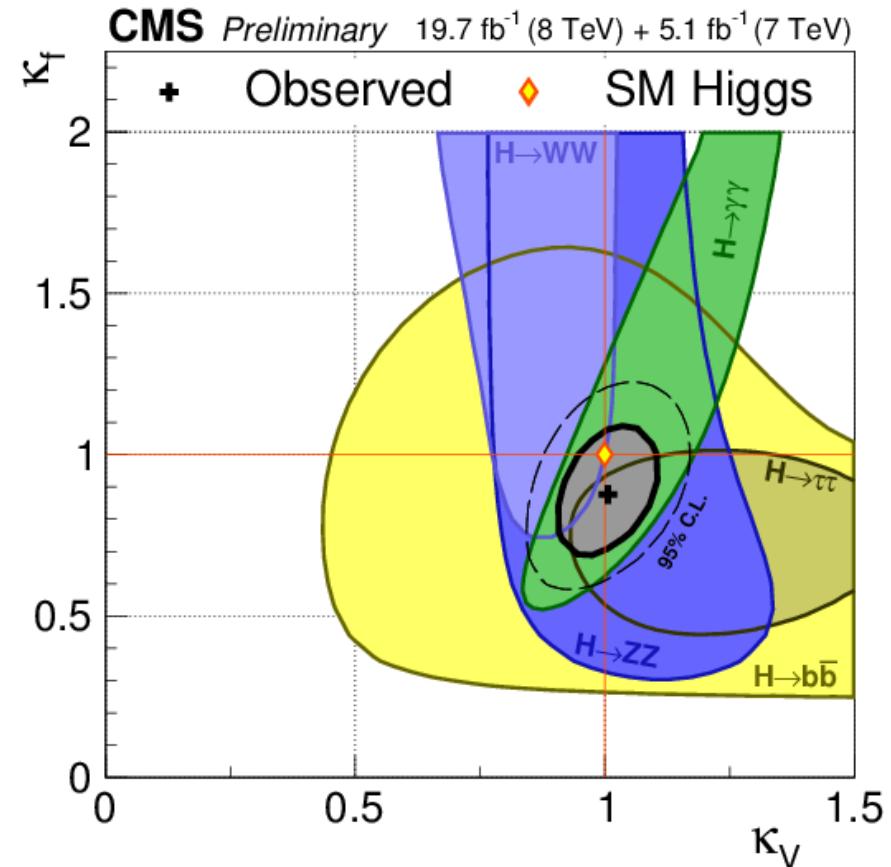
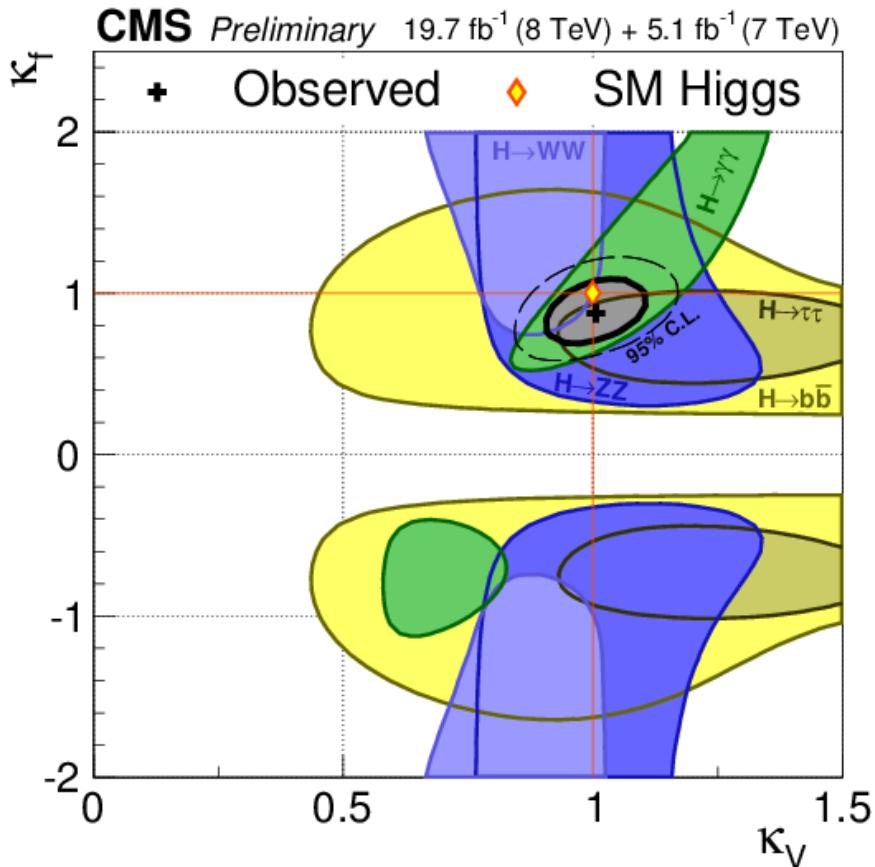
$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = 0.91^{+0.14}_{-0.12}$$

- No deviations → treat Z and W together as V

# Couplings to vector bosons and fermions



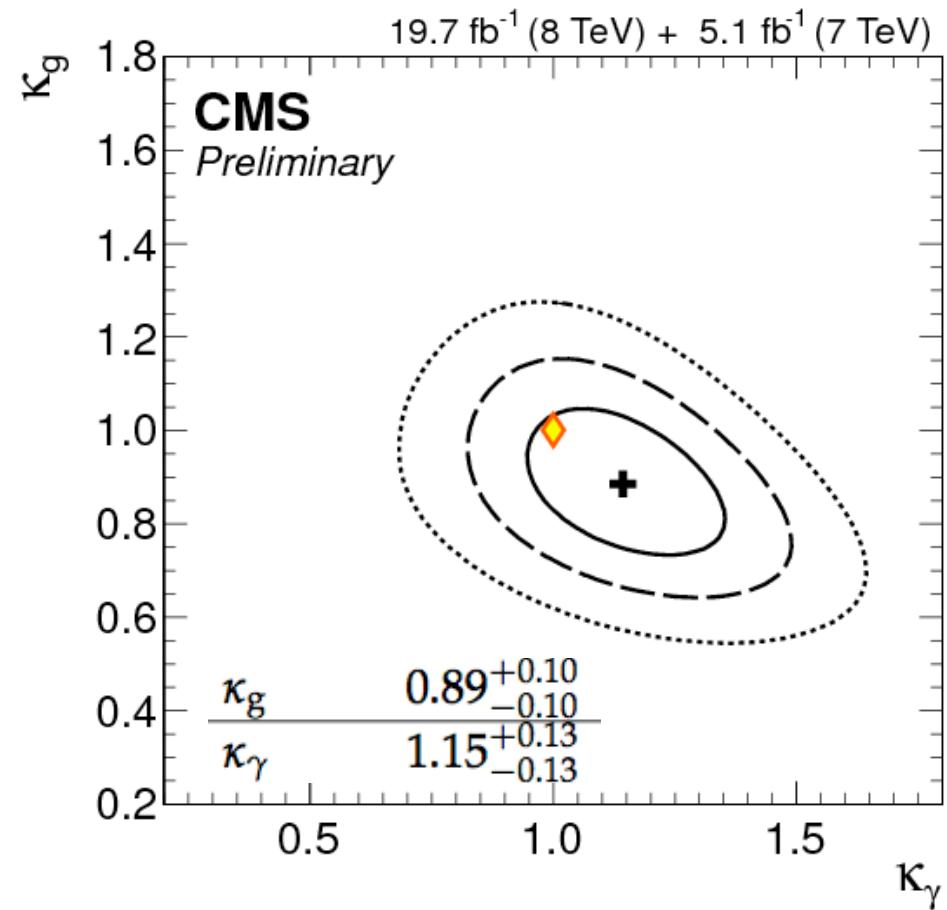
- Map vector-boson and fermionic couplings into  $\kappa_V$  and  $\kappa_f$
- two-quadrant ↘ and one-quadrant ↘





# Search for new physics in Loops

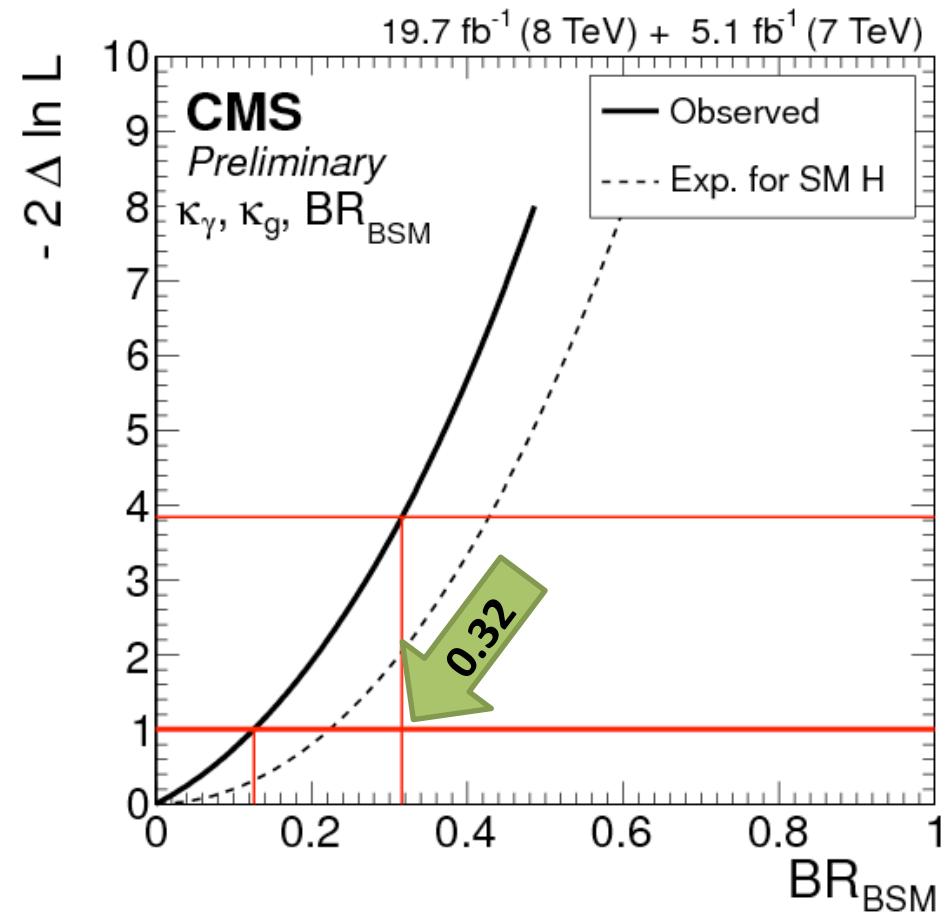
- New particles can hide in the loop-mediated couplings
- Treat photons and gluons as tree-level effective coupling



# Search for new physics in Loops



- New particles can hide in the loop-mediated couplings
- New particles can contribute to the total width
- Treat photons and gluons as tree-level effective coupling
- Allow total width to scale as  $1/(1-\text{BR}_{\text{BSM}})$



# Asymmetry of couplings to fermions

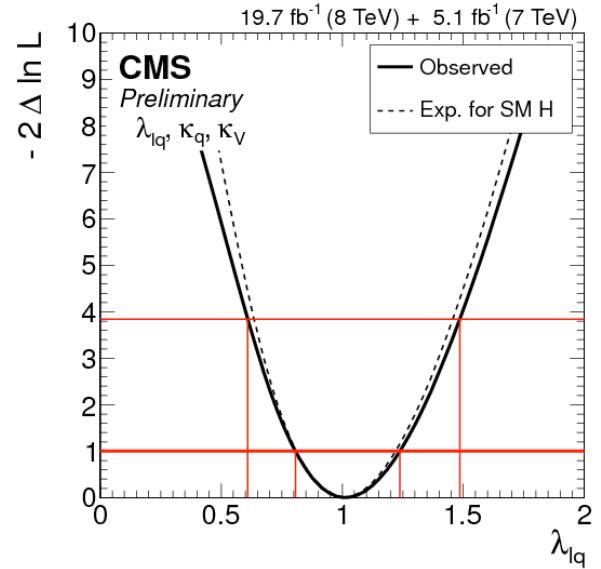
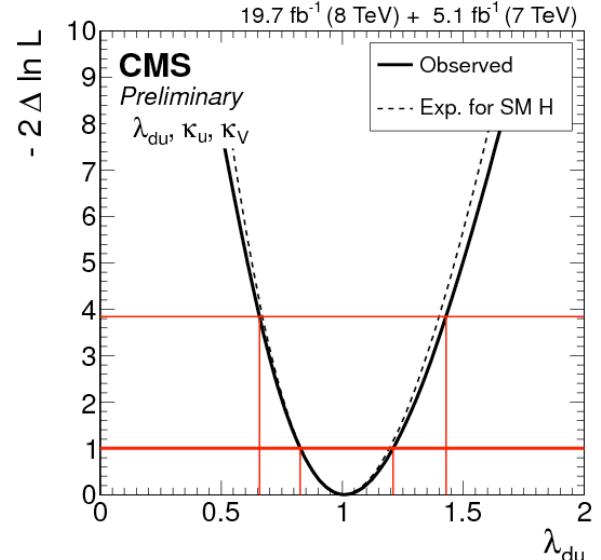


- In some BSM models, e.g. 2HDM, relative couplings to fermions can be altered
  - Up-type quarks vs down-type quarks

$$\lambda_{du} = \frac{K_d}{K_u} = 1.01^{+0.20}_{-0.19}$$

- Leptons vs quarks

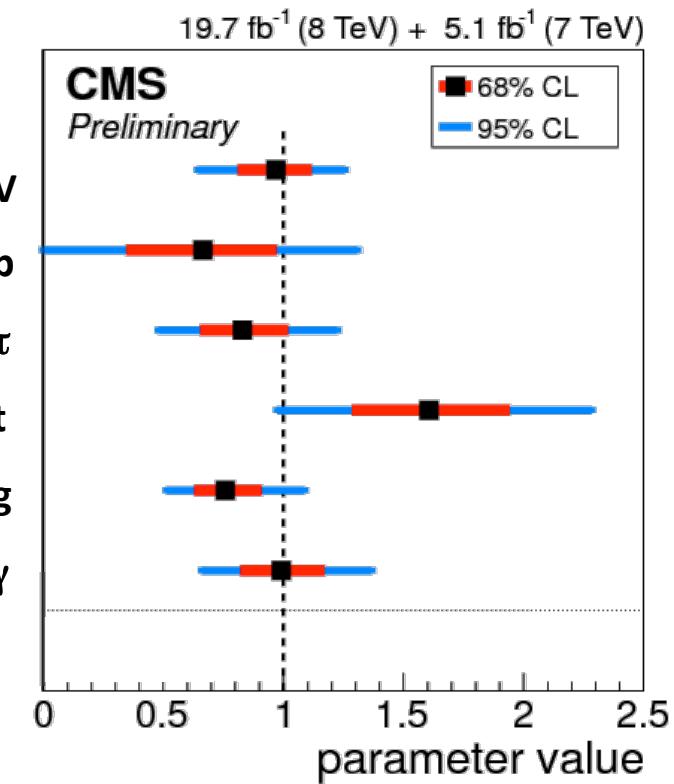
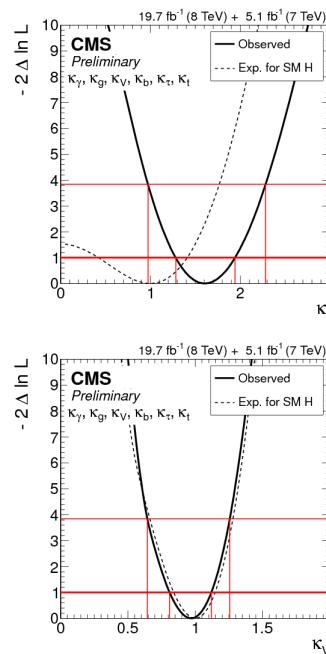
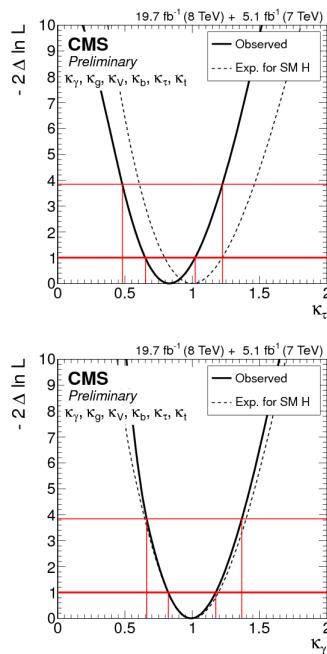
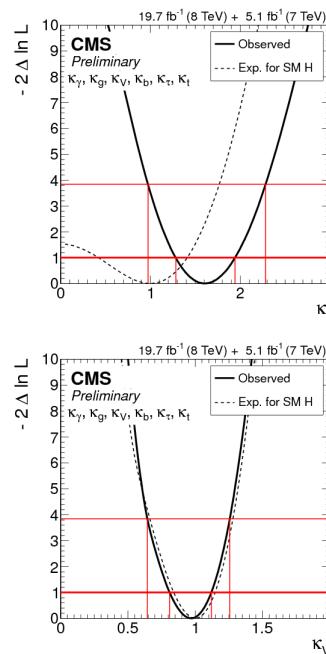
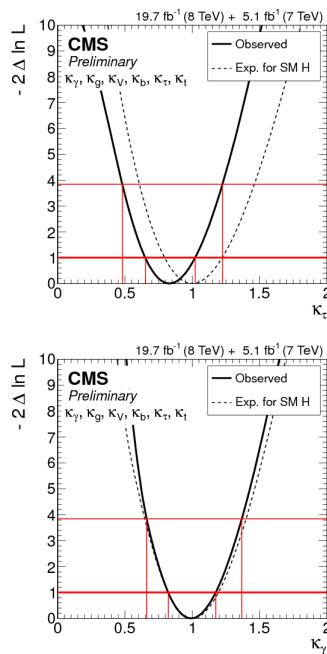
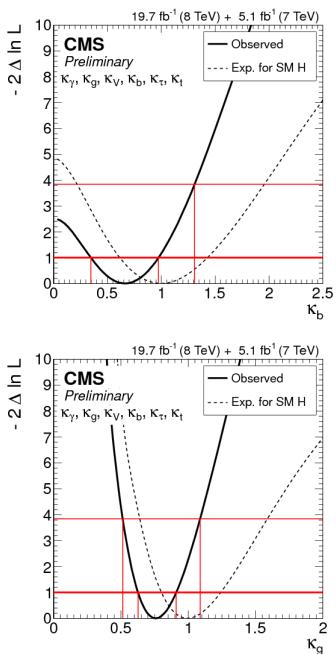
$$\lambda_{lq} = \frac{K_l}{K_q} = 1.02^{+0.22}_{-0.21}$$



# Six-parameter model



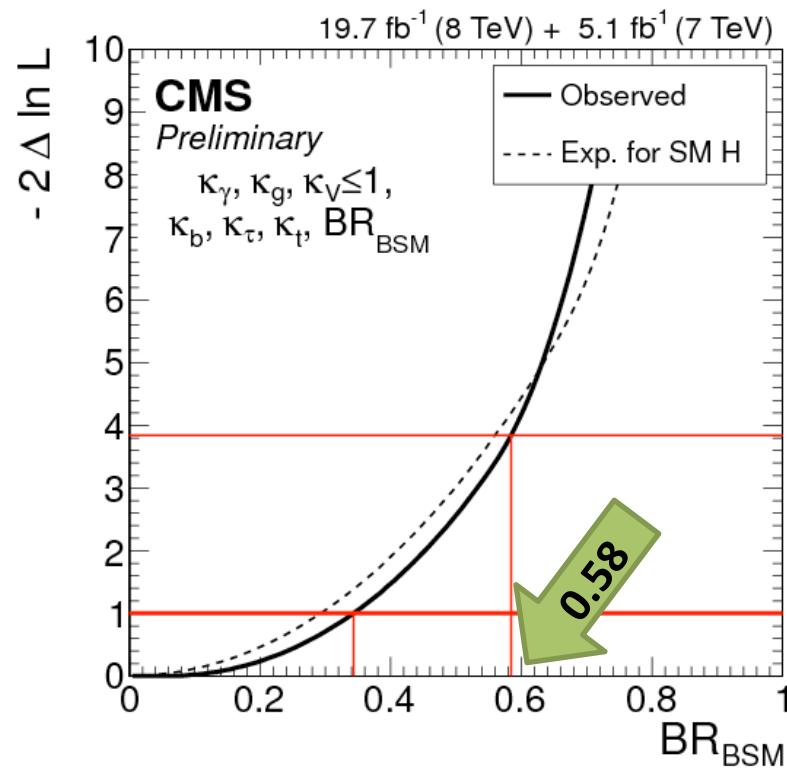
- Tree-level couplings (effective for gluon and photon):





# Six-parameter model + free width

- Tree-level couplings (effective for gluon and photon) + **free width** and  $\kappa_V \leq 1$ :

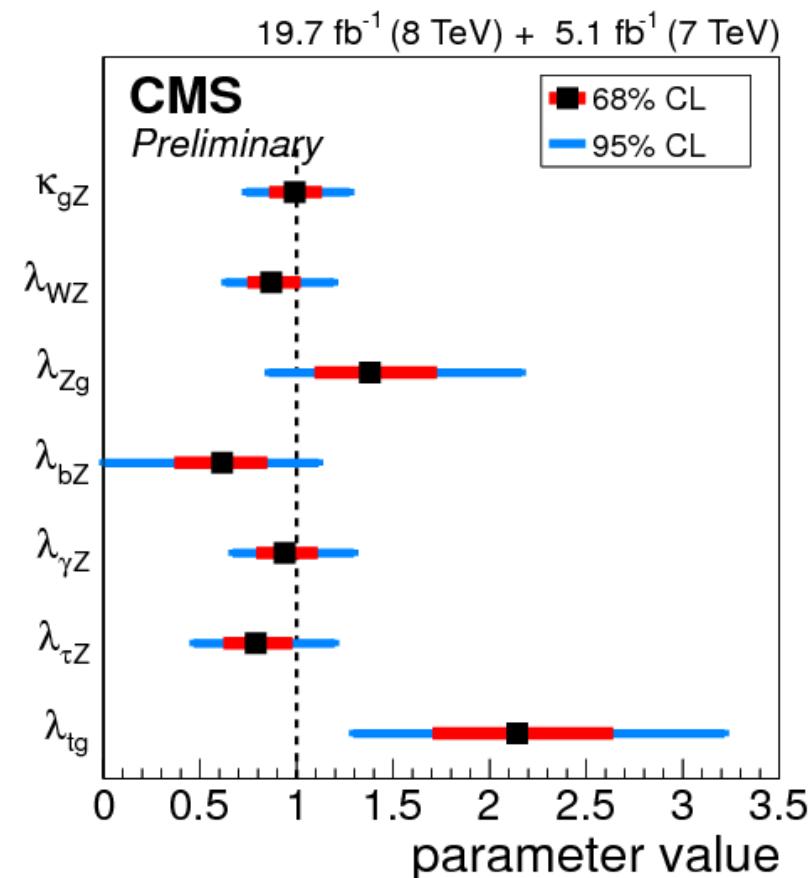
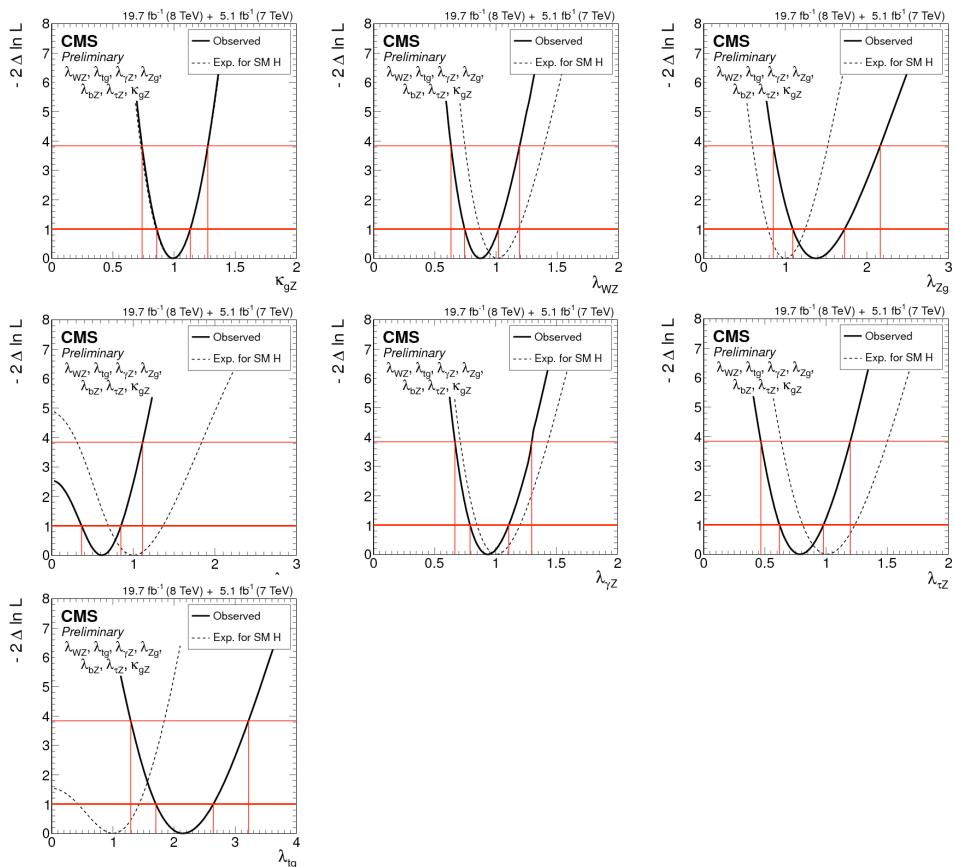




# Generic model of coupling ratios

**General parameterization allowing all gauge and third generation fermion couplings to float allowing for invisible or undetectable widths**

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

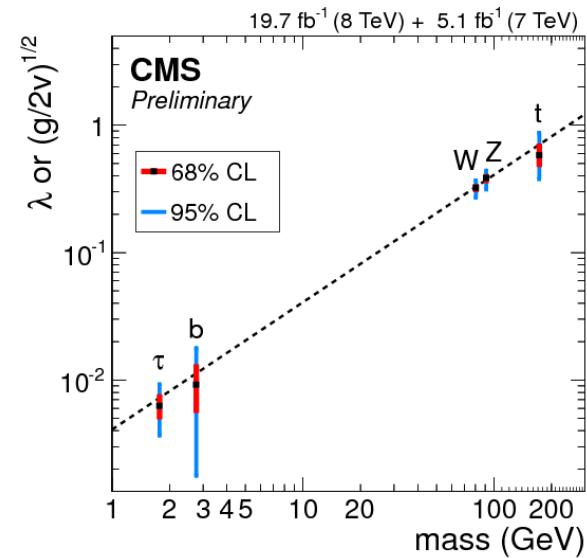
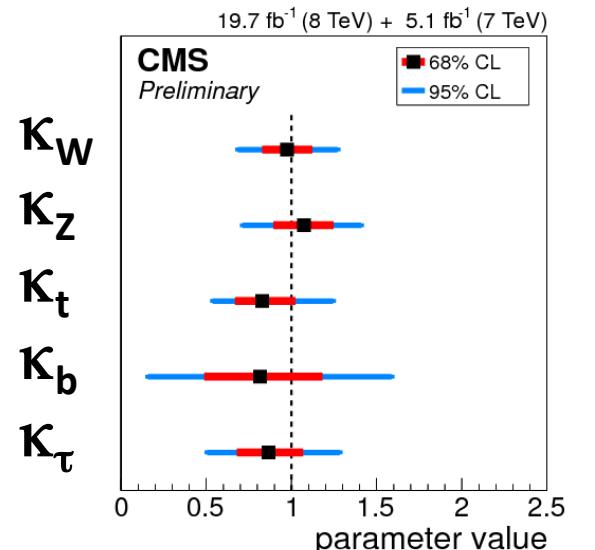


# Coupling vs. particle mass



- Test of generic model, **assuming SM structure for loops**
  - i.e., VBF is resolved into W and Z, ggH is resolved into top and bottom, etc

- One parameter per tree-level coupling:
  - $\kappa_W, \kappa_Z$ :  $\left(\frac{g_V}{2\bar{v}ev}\right)^{1/2} = \kappa_V^{1/2} \frac{m_V}{\bar{v}ev}$
  - $\kappa_t, \kappa_b, \kappa_\tau$ :  $\lambda = \kappa_f \frac{m_f}{\bar{v}ev}$





# M and $\epsilon$

- Parameterize coupling scale factors in terms of  $v\bar{v}v$  modifier (**M**) and power of coupling to mass ( $\epsilon$ )

[J. Ellis and T. You, arXiv:1207.1693]:

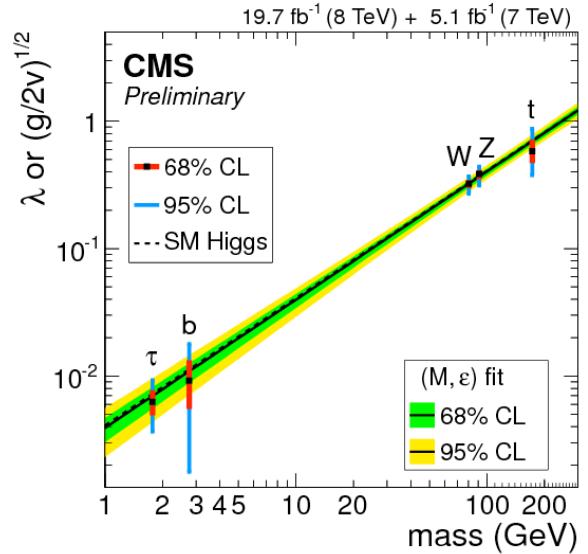
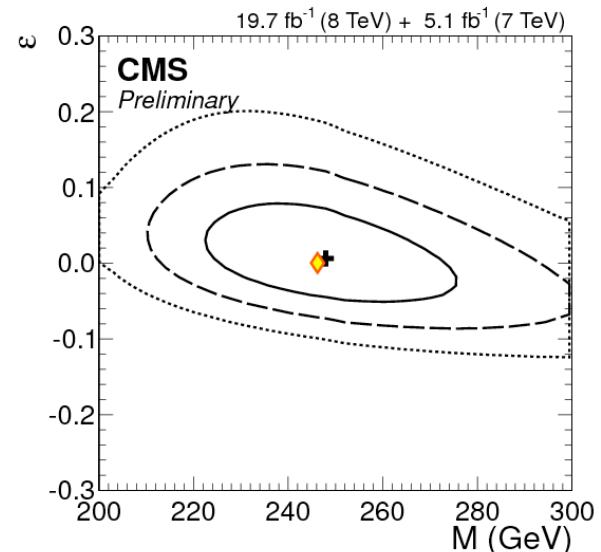
- Gauge bosons:

$$K_V = v\bar{v}v \times m_V^{-2\epsilon} / M^{1+2\epsilon}$$

- Fermions:

$$K_f = v\bar{v}v \times m_f^{-\epsilon} / M^{1+\epsilon}$$

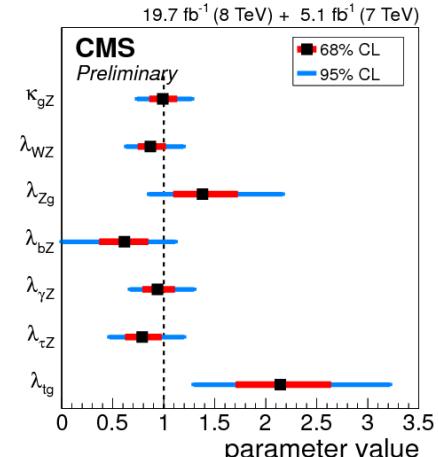
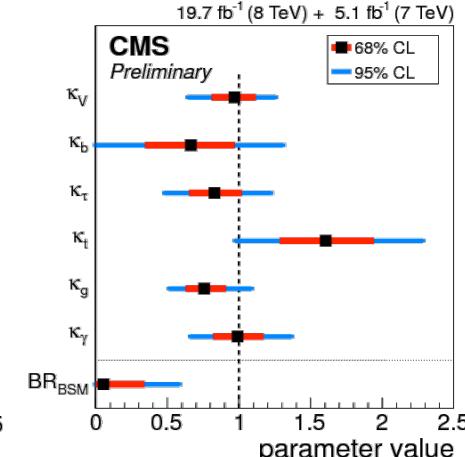
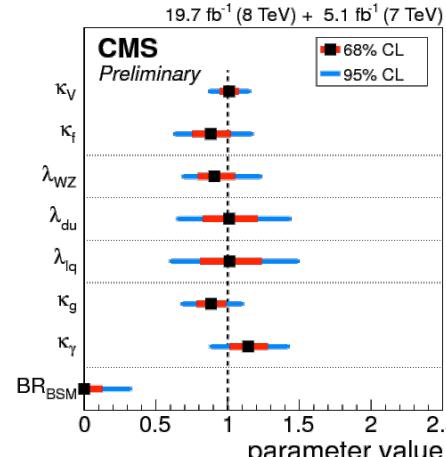
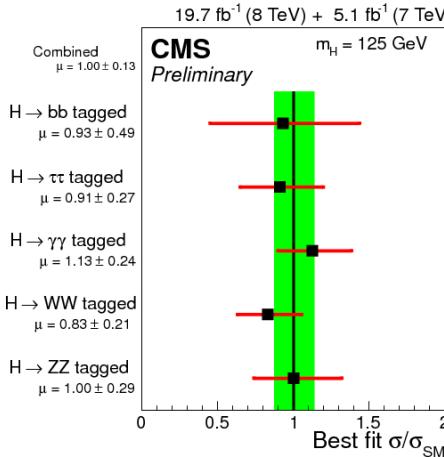
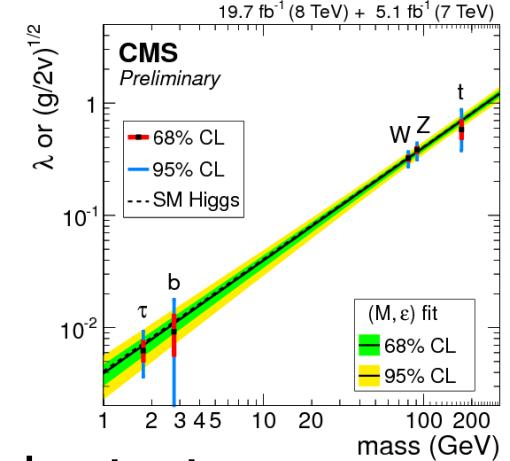
- For SMH,  $M = v\bar{v}v = 246.22$  GeV and  $\epsilon = 0$ .



# Summary



- Evidence @ CMS
  - $3.8\sigma$  for direct fermionic decays ([Nature Physics](#))
  - $3.6\sigma$  for VBF production
  - +  $2.7\sigma$  for VH production
- $2\sigma$  excess over SM in ttH searches
- Compatibility tests show no significant deviation from SM expectation
  - Continues to be very SM-like





# Additional materials



# Individual production modes

Parameter	Best fit result (68% CL) for full combination	Observed significance ( $\sigma$ ) w.r.t. $\mu=0$	Expected sensitivity ( $\sigma$ ) w.r.t. $\mu=0$	Deviation ( $\sigma$ ) from SM hypothesis
$\mu_{ggH}$	$0.85^{+0.19}_{-0.17}$	6.5	7.5	-0.8
$\mu_{VBF}$	$1.15^{+0.37}_{-0.35}$	3.6	3.3	0.4
$\mu_{VH}$	$1.00^{+0.40}_{-0.40}$	2.7	2.7	0
$\mu_{ttH}$	$2.93^{+1.04}_{-0.97}$	3.5	1.2	2.1



# Caveats: Combination $\neq \sum$ inputs

- Expanded notion of “production tags” also to “decay tag groups”:
  - H  $\rightarrow \gamma\gamma$  tagged** includes only categories from the **H  $\rightarrow \gamma\gamma$  analysis** of Ref. [19].
  - H  $\rightarrow ZZ$  tagged** includes only categories from the **H  $\rightarrow ZZ$  analysis** of Ref. [17].
  - H  $\rightarrow WW$  tagged** includes all the channels from the **H  $\rightarrow WW$  analysis** of Ref. [16] and the channels from the analysis of **tH with H  $\rightarrow$  leptons** of Ref. [28].
  - H  $\rightarrow \tau\tau$  tagged** includes all the channels from the **H  $\rightarrow \tau\tau$  analysis** of Ref. [18] and the channels from the analysis of **tH targeting H  $\rightarrow \tau_h \tau_h$**  of Ref. [27].
  - H  $\rightarrow bb$  tagged** includes all the channels of the analysis of **VH with H  $\rightarrow bb$**  of Ref. [15] and the channels from the analysis of **tH targeting H  $\rightarrow bb$**  of Refs. [13, 27].
- Some differences between the individual publications and the combination:
  - **Different  $m_H$  value than used in H $\rightarrow ZZ$  and H $\rightarrow WW$  publications.**
  - **H $\rightarrow WW$  treated as signal in H $\rightarrow \tau\tau$  analysis.**



# Combination methodology

## 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:

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

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,  $q_0^{\text{data}}$ :

$$p_0 = P(q_0 \geq q_0^{\text{data}} | b). \quad (2)$$

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

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

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 methodology

## 3.2 Extracting signal model parameters

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

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

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.



# Scale factors for loops

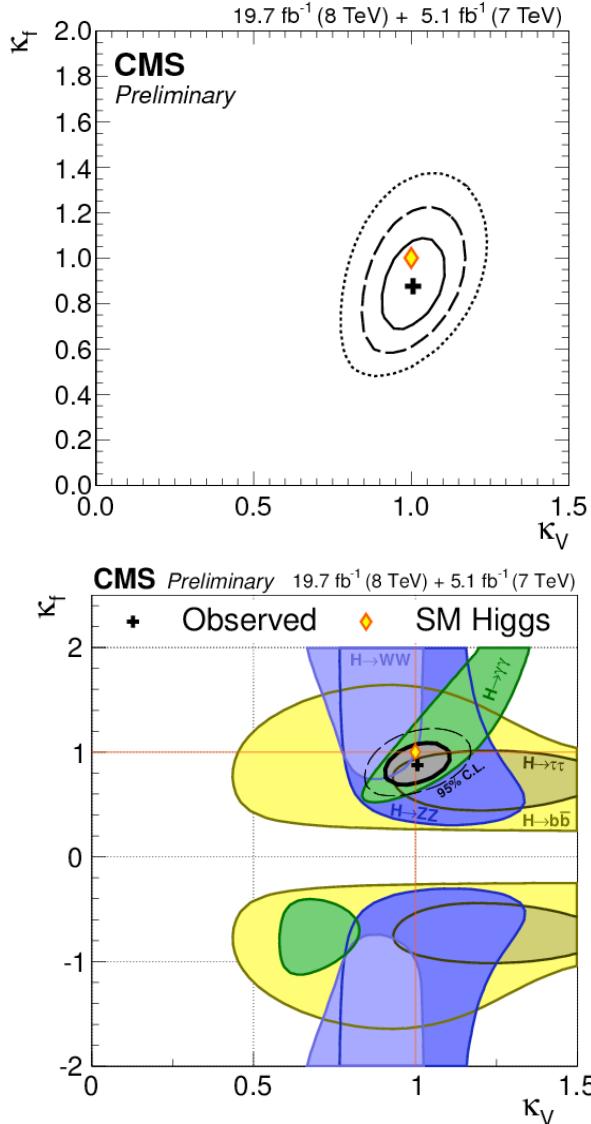
- In the case of coupling via loops scale factors are functions of the other scale factors
- Example: the gluon fusion cross section scaling:

$$\kappa_g^2(\kappa_t, \kappa_b, M_H) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt} + \kappa_b^2 \cdot \sigma_{ggH}^{bb} + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$

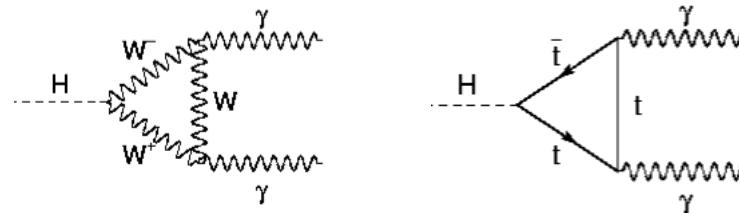
- Where  $\sigma_{ggH}^{tt,bb}$  is the square of the top and bottom contributions and  $\sigma_{ggH}^{tb}$  is the square of the interference terms
  - Interference term is negative for  $M_H < 200$  GeV
- Similar expressions implemented for other loops ( $\gamma\gamma$ ,  $Z\gamma$ )
  - VBF is also expressed as combination of  $\kappa_w$  and  $\kappa_z$
- Alternatively the dependency on other scale factors can be discarded and treat the loop scale factor as additional free parameter



# Two parameters: $\kappa_V$ and $\kappa_F$



- Map vectorial and fermionic couplings into two scale factors,  $\kappa_V$  and  $\kappa_F$
- $H \rightarrow (W \text{ and } t \text{ loops}) \rightarrow \gamma\gamma$



- sensitive to relative sign of couplings to W and top
- relative sign of W and top loop amplitudes is negative
- interference between W and top loops plays a role

# Benchmarks



**Table 43:** A benchmark parameterization where custodial symmetry is assumed and vector boson couplings are scaled together ( $\kappa_V$ ) and fermions are assumed to scale with a single parameter ( $\kappa_f$ ).

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## Boson and fermion scaling assuming no invisible or undetectable widths

Free parameters:  $\kappa_V (= \kappa_W = \kappa_Z)$ ,  $\kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$

Dependent parameters:  $\kappa_\gamma = \kappa_\gamma(\kappa_f, \kappa_f, \kappa_f, \kappa_V)$ ,  $\kappa_g = \kappa_f$ ,  $\kappa_H = \kappa_H(\kappa_i)$ .

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^-\tau^+$
ggH	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_f^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$
tH					
VBF					
WH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$
ZH					

# Benchmarks



**Table 44:** A benchmark parameterization where custodial symmetry is probed through the  $\lambda_{WZ}$  parameter.

## Probing custodial symmetry assuming no invisible or undetectable widths

Free parameters:  $\kappa_Z, \lambda_{WZ} (= \kappa_W / \kappa_Z), \kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$ .

Dependent parameters:  $\kappa_\gamma = \kappa_\gamma(\kappa_f, \kappa_f, \kappa_f, \kappa_Z \lambda_{WZ}), \kappa_g = \kappa_f, \kappa_H = \kappa_H(\kappa_i)$ .

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^-\tau^+$
ggH	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2 (\kappa_f, \kappa_f, \kappa_f, \kappa_Z \lambda_{WZ})}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_Z^2}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_f^2 \cdot (\kappa_Z \lambda_{WZ})^2}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_f^2}{\kappa_H^2 (\kappa_i)}$	
tH					
VBF	$\frac{\kappa_{VBF}^2 (\kappa_Z, \kappa_Z \lambda_{WZ}) \cdot \kappa_\gamma^2 (\kappa_f, \kappa_f, \kappa_f, \kappa_Z \lambda_{WZ})}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_{VBF}^2 (\kappa_Z, \kappa_Z \lambda_{WZ}) \cdot \kappa_Z^2}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_{VBF}^2 (\kappa_Z, \kappa_Z \lambda_{WZ}) \cdot (\kappa_Z \lambda_{WZ})^2}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_{VBF}^2 (\kappa_Z, \kappa_Z \lambda_{WZ}) \cdot \kappa_f^2}{\kappa_H^2 (\kappa_i)}$	
WH	$\frac{(\kappa_Z \lambda_{WZ})^2 \cdot \kappa_\gamma^2 (\kappa_f, \kappa_f, \kappa_f, \kappa_Z \lambda_{WZ})}{\kappa_H^2 (\kappa_i)}$	$\frac{(\kappa_Z \lambda_{WZ})^2 \cdot \kappa_Z^2}{\kappa_H^2 (\kappa_i)}$	$\frac{(\kappa_Z \lambda_{WZ})^2 \cdot (\kappa_Z \lambda_{WZ})^2}{\kappa_H^2 (\kappa_i)}$	$\frac{(\kappa_Z \lambda_{WZ})^2 \cdot \kappa_f^2}{\kappa_H^2 (\kappa_i)}$	
ZH	$\frac{\kappa_Z^2 \cdot \kappa_\gamma^2 (\kappa_f, \kappa_f, \kappa_f, \kappa_Z \lambda_{WZ})}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_Z^2}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_Z^2 \cdot (\kappa_Z \lambda_{WZ})^2}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_f^2}{\kappa_H^2 (\kappa_i)}$	

# Benchmarks



**Table 46:** A benchmark parameterization where the up-type and down-type symmetry of fermions is probed through the  $\lambda_{du}$  parameter.

## Probing up-type and down-type fermion symmetry assuming no invisible or undetectable widths

Free parameters:  $\kappa_V (= \kappa_Z = \kappa_W)$ ,  $\lambda_{du} (= \kappa_d / \kappa_u)$ ,  $\kappa_u (= \kappa_t)$ .

Dependent parameters:  $\kappa_\gamma = \kappa_\gamma(\kappa_u \lambda_{du}, \kappa_u, \kappa_u \lambda_{du}, \kappa_V)$ ,  $\kappa_g = \kappa_g(\kappa_u \lambda_{du}, \kappa_u)$ ,  $\kappa_H = \kappa_H(\kappa_i)$ .

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^-\tau^+$
ggH	$\frac{\kappa_g^2(\kappa_u \lambda_{du}, \kappa_u) \cdot \kappa_\gamma^2(\kappa_u \lambda_{du}, \kappa_u, \kappa_u \lambda_{du}, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2(\kappa_u \lambda_{du}, \kappa_u) \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_g^2(\kappa_u \lambda_{du}, \kappa_u) \cdot (\kappa_u \lambda_{du})^2}{\kappa_H^2(\kappa_i)}$	
t $\bar{t}$ H	$\frac{\kappa_u^2 \cdot \kappa_\gamma^2(\kappa_u \lambda_{du}, \kappa_u, \kappa_u \lambda_{du}, \kappa_V)}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_u^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_u^2 \cdot (\kappa_u \lambda_{du})^2}{\kappa_H^2(\kappa_i)}$
VBF					
WH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_u \lambda_{du}, \kappa_u, \kappa_u \lambda_{du}, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$			$\frac{\kappa_V^2 \cdot (\kappa_u \lambda_{du})^2}{\kappa_H^2(\kappa_i)}$
ZH					

# Benchmarks



**Table 47:** A benchmark parameterization where the quark and lepton symmetry of fermions is probed through the  $\lambda_{lq}$  parameter.

## Probing quark and lepton fermion symmetry assuming no invisible or undetectable widths

Free parameters:  $\kappa_V (= \kappa_Z = \kappa_W)$ ,  $\lambda_{lq} (= \kappa_l / \kappa_q)$ ,  $\kappa_q (= \kappa_t = \kappa_b)$ .

Dependent parameters:  $\kappa_\gamma = \kappa_\gamma (\kappa_q, \kappa_q, \kappa_q \lambda_{lq}, \kappa_V)$ ,  $\kappa_g = \kappa_q$ ,  $\kappa_H = \kappa_H (\kappa_i)$ .

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^-\tau^+$
ggH	$\frac{\kappa_q^2 \cdot \kappa_\gamma^2 (\kappa_q, \kappa_q, \kappa_q \lambda_{lq}, \kappa_V)}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_q^2 \cdot \kappa_V^2}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_q^2 \cdot \kappa_q^2}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_q^2 \cdot (\kappa_q \lambda_{lq})^2}{\kappa_H^2 (\kappa_i)}$	
t̄tH					
VBF					
WH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2 (\kappa_q, \kappa_q, \kappa_q \lambda_{lq}, \kappa_V)}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_q^2}{\kappa_H^2 (\kappa_i)}$	$\frac{\kappa_V^2 \cdot (\kappa_q \lambda_{lq})^2}{\kappa_H^2 (\kappa_i)}$	
ZH					

# Benchmarks



**Table 48:** A benchmark parameterization where effective vertex couplings are allowed to float through the  $\kappa_g$  and  $\kappa_\gamma$  parameters. Instead of absorbing  $\kappa_H$ , explicit allowance is made for a contribution from invisible or undetectable widths via the  $BR_{inv.,undet.}$  or  $BR_{inv.}$  and  $BR_{undet.}$  parameters.

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### Probing loop structure assuming no invisible or undetectable widths

Free parameters:  $\kappa_g, \kappa_\gamma$ .

Dependent parameters:  $\kappa_H = \kappa_H(\kappa_i)$ . Fixed parameters  $\kappa_Z = \kappa_W = \kappa_\tau = \kappa_b = \kappa_t = 1$ .

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$			$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)}$	
tH					
VBF					$\frac{1}{\kappa_H^2(\kappa_i)}$
WH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$				
ZH					

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### Probing loop structure allowing for invisible or undetectable widths

Free parameters:  $\kappa_g, \kappa_\gamma, BR_{inv.,undet.}$ .

Dependent parameters:  $\kappa_H = \kappa_H(\kappa_i)$ . Fixed parameters  $\kappa_Z = \kappa_W = \kappa_\tau = \kappa_b = \kappa_t = 1$ .

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$		$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$		
tH					
VBF					$\frac{1}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$
WH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$				
ZH					

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# Benchmarks



**Table 50:** A benchmark parameterization without further assumptions and maximum degrees of freedom.

## General parameterization allowing all gauge and third generation fermion couplings to float assuming no invisible or undetectable widths

Free parameters:  $\kappa_g, \kappa_\gamma, \kappa_W, \kappa_Z, \kappa_b, \kappa_t, \kappa_\tau$ .

Dependent parameters:  $\kappa_H = \kappa_H(\kappa_i)$ .

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2 \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2 \cdot \kappa_W^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2 \cdot \kappa_b^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2 \cdot \kappa_\tau^2}{\kappa_H^2(\kappa_i)}$
t̄tH	$\frac{\kappa_t^2 \cdot \kappa_b^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_t^2 \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_t^2 \cdot \kappa_W^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_t^2 \cdot \kappa_b^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_t^2 \cdot \kappa_\tau^2}{\kappa_H^2(\kappa_i)}$
VBF	$\frac{\kappa_{VBF}^2(\kappa_Z, \kappa_W) \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z, \kappa_W) \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z, \kappa_W) \cdot \kappa_W^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z, \kappa_W) \cdot \kappa_b^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z, \kappa_W) \cdot \kappa_\tau^2}{\kappa_H^2(\kappa_i)}$
WH	$\frac{\kappa_W^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_W^2 \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_W^2 \cdot \kappa_W^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_W^2 \cdot \kappa_b^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_W^2 \cdot \kappa_\tau^2}{\kappa_H^2(\kappa_i)}$
ZH	$\frac{\kappa_Z^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_W^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_b^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_\tau^2}{\kappa_H^2(\kappa_i)}$

## General parametrization allowing other couplings to float

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

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^-\tau^+$
ggH	$\kappa_{gZ}^2 \quad 1 \quad \lambda_{\gamma Z}^2$	$\kappa_{gZ}^2 \quad 1 \quad 1$	$\kappa_{gZ}^2 \quad 1 \quad \lambda_{WZ}^2$	$\kappa_{gZ}^2 \quad 1 \quad \lambda_{bZ}^2$	$\kappa_{gZ}^2 \quad 1 \quad \lambda_{\tau Z}^2$
t̄tH	$\kappa_{gZ}^2 \quad \lambda_{tg}^2 \quad \lambda_{\gamma Z}^2$	$\kappa_{gZ}^2 \quad \lambda_{tg}^2 \quad 1$	$\kappa_{gZ}^2 \quad \lambda_{tg}^2 \quad \lambda_{WZ}^2$	$\kappa_{gZ}^2 \quad \lambda_{tg}^2 \quad \lambda_{bZ}^2$	$\kappa_{gZ}^2 \quad \lambda_{tg}^2 \quad \lambda_{\tau Z}^2$
VBF	$\kappa_{gZ}^2 \lambda_{Zg}^2 \kappa_{VBF}^2(1, \lambda_{WZ}) \lambda_{\gamma Z}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \kappa_{VBF}^2(1, \lambda_{WZ}) 1$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \kappa_{VBF}^2(1, \lambda_{WZ}) \lambda_{WZ}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \kappa_{VBF}^2(1, \lambda_{WZ}) \lambda_{bZ}^2$	$\kappa_{gZ}^2 \lambda_{Zg}^2 \kappa_{VBF}^2(1, \lambda_{WZ}) \lambda_{\tau Z}^2$
WH	$\kappa_{gZ}^2 \quad \lambda_{Zg}^2 \lambda_{WZ}^2 \quad \lambda_{\gamma Z}^2$	$\kappa_{gZ}^2 \quad \lambda_{Zg}^2 \lambda_{WZ}^2 \quad 1$	$\kappa_{gZ}^2 \quad \lambda_{Zg}^2 \lambda_{WZ}^2 \quad \lambda_{WZ}^2$	$\kappa_{gZ}^2 \quad \lambda_{Zg}^2 \lambda_{bZ}^2 \quad \lambda_{bZ}^2$	$\kappa_{gZ}^2 \quad \lambda_{Zg}^2 \lambda_{WZ}^2 \quad \lambda_{\tau Z}^2$
ZH	$\kappa_{gZ}^2 \quad \lambda_{Zg}^2 \quad \lambda_{\gamma Z}^2$	$\kappa_{gZ}^2 \quad \lambda_{Zg}^2 \quad 1$	$\kappa_{gZ}^2 \quad \lambda_{Zg}^2 \quad \lambda_{WZ}^2$	$\kappa_{gZ}^2 \quad \lambda_{Zg}^2 \quad \lambda_{bZ}^2$	$\kappa_{gZ}^2 \quad \lambda_{Zg}^2 \quad \lambda_{\tau Z}^2$

$$\kappa_i^2 = \Gamma_{ii} / \Gamma_{ii}^{\text{SM}}$$

**Table A.1:** A benchmark parametrization without further assumptions and maximum degrees of freedom. The colors denote the common factor (black) and the factors related to the production (blue) and decay modes (red). Ones are used to denote the trivial factor.

# Benchmarks



**Table 51:** A benchmark parameterization expressing all processes in terms of the SM gauge- and Yukawa-coupling scale factors, assuming no beyond SM particle contributions.

## General parameterization assuming no beyond SM particles

Free parameters:  $\kappa_W, \kappa_Z, \kappa_b, \kappa_t, \kappa_\tau$ .

Dependent parameters:  $\kappa_g = \kappa_g(\kappa_b, \kappa_t), \kappa_\gamma = \kappa_\gamma(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W), \kappa_H = \kappa_H(\kappa_i)$ .

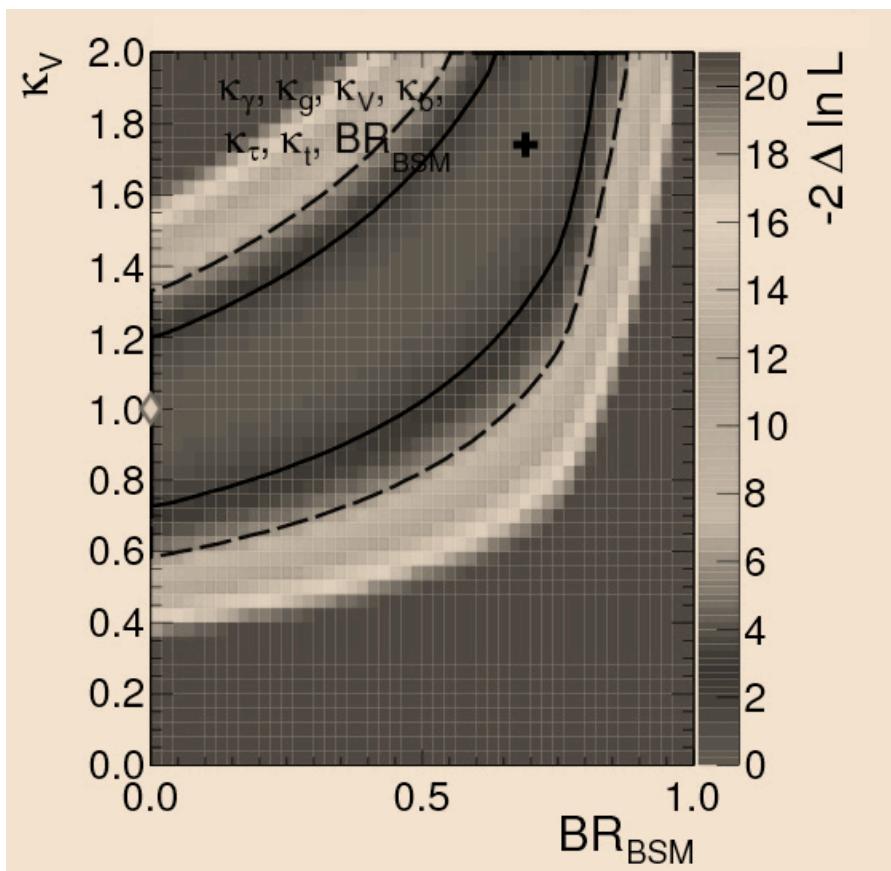
	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^-\tau^+$
ggH	$\frac{\kappa_g^2(\kappa_b, \kappa_t) \cdot \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2(\kappa_b, \kappa_t) \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2(\kappa_b, \kappa_t) \cdot \kappa_W^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2(\kappa_b, \kappa_t) \cdot \kappa_b^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2(\kappa_b, \kappa_t) \cdot \kappa_\tau^2}{\kappa_H^2(\kappa_i)}$
t <bar>t&gt;H</bar>	$\frac{\kappa_t^2 \cdot \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_t^2 \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_t^2 \cdot \kappa_W^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_t^2 \cdot \kappa_b^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_t^2 \cdot \kappa_\tau^2}{\kappa_H^2(\kappa_i)}$
VBF	$\frac{\kappa_{VBF}^2(\kappa_Z, \kappa_W) \cdot \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z, \kappa_W) \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z, \kappa_W) \cdot \kappa_W^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z, \kappa_W) \cdot \kappa_b^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z, \kappa_W) \cdot \kappa_\tau^2}{\kappa_H^2(\kappa_i)}$
WH	$\frac{\kappa_W^2 \cdot \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_W^2 \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_W^2 \cdot \kappa_W^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_W^2 \cdot \kappa_b^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_W^2 \cdot \kappa_\tau^2}{\kappa_H^2(\kappa_i)}$
ZH	$\frac{\kappa_Z^2 \cdot \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_W^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_b^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_\tau^2}{\kappa_H^2(\kappa_i)}$

$$\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{\text{SM}}$$



# C6+BR<sub>BSM</sub>

- If no assumption is made, all couplings are degenerate with the total width:
  - All  $\sigma \cdot BR$  scale as  $\kappa^4 / (\kappa^2 \Gamma_{SM} + \Gamma_{BSM})$



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