COUPLINGS AND PROPERTIES OF THE HIGGS-LIKE PARTICLE AT CMS

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on behalf of the CMS collaboration

Les Rencontres de Physique de la Vallée d'Aoste
Friday, March 1, 2013

Outline

- Introduction
- Input analysis and data samples
  - unfortunately no update with full 2012 8TeV pp data samples
- the signal mass
- the signal strength
- tests of SM couplings
- spin/parity in ZZ→4l

Introduction

- Observation of a narrow bosonic resonance around 125 GeV in the contest of the searches for the Higgs particle : July 4^{th} 2012. The background only hypothesis is excluded at about 5 standard deviations by both CMS & ATLAS
- Now collected a quite larger integrated luminosity at $\sqrt{s}$=8TeV
  - L(8TeV) = 20 fb^{-1}, L(7TeV)=5 fb^{-1}
  - Results from individual analyses presented by Nicolas yesterday
- The interest now is on the boson properties
  - What is the precise mass and quantum numbers (spin and CP)?
  - What are the coupling widths to individual particles ?
  - how well is this signal compatible with a SM Higgs boson ?

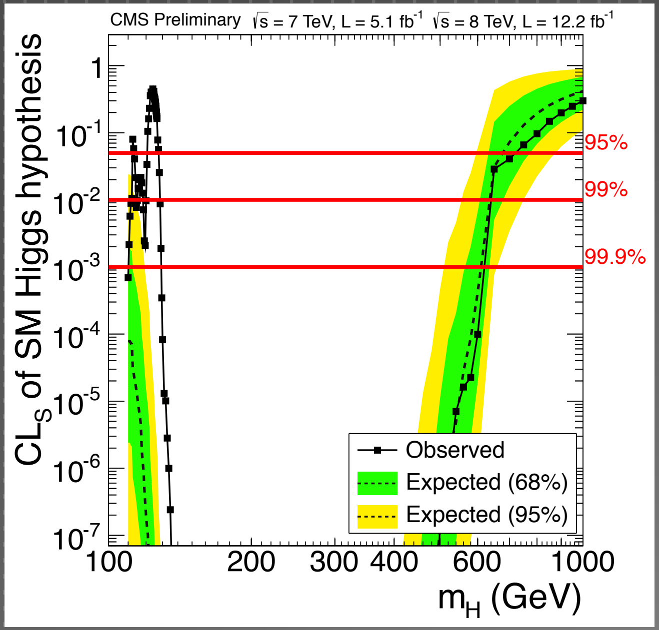
Analysis channels

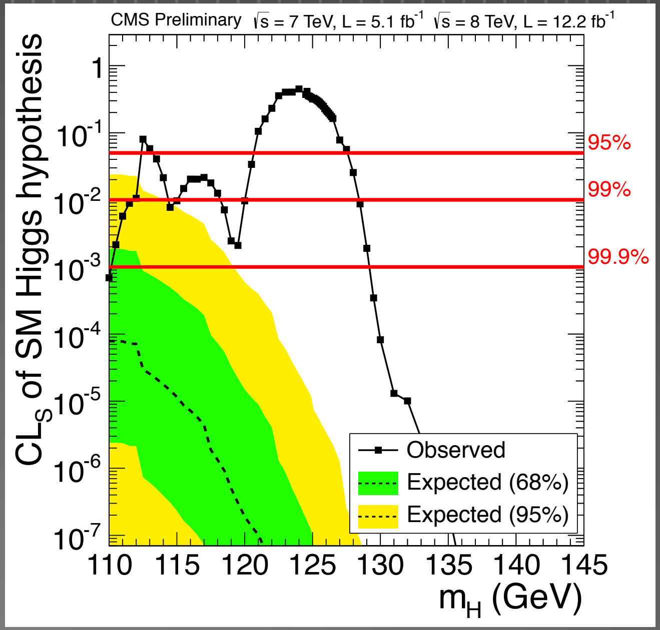
analyzed data samples luminosities (@7TeV + @8TeV)

	gg	VBF	VH	ttH
H→ZZ	4.9+12.1 fb^{-1}			
H→γγ	5.1+5.3 fb^{-1}	5.1+5.3 fb^{-1}		
H→WW	4.9+12.1 fb^{-1}	4.9+12.1 fb^{-1}	4.9+0.0 fb^{-1}	
H→ττ	4.9+12.1 fb^{-1}	4.9+12.1 fb^{-1}	5.0+12.0 fb^{-1}	
H→bb			5.0+12.1 fb^{-1}	5.0+0.0 fb^{-1}

see yesterday's presentation by Nicolas Chanon

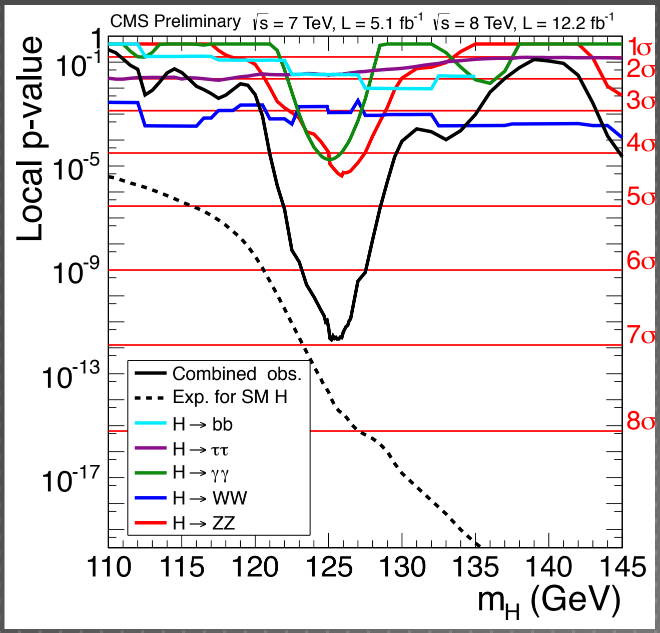
expected and observed CLs





minimal SM Higgs with $113<m_H<121$ or $128<m_H<700$ excluded @95%CL

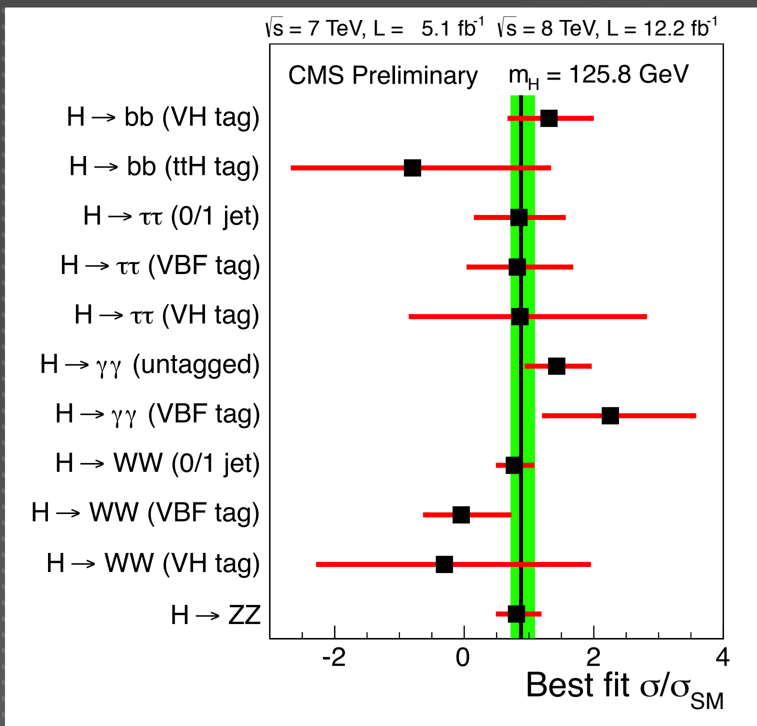
Signal strength

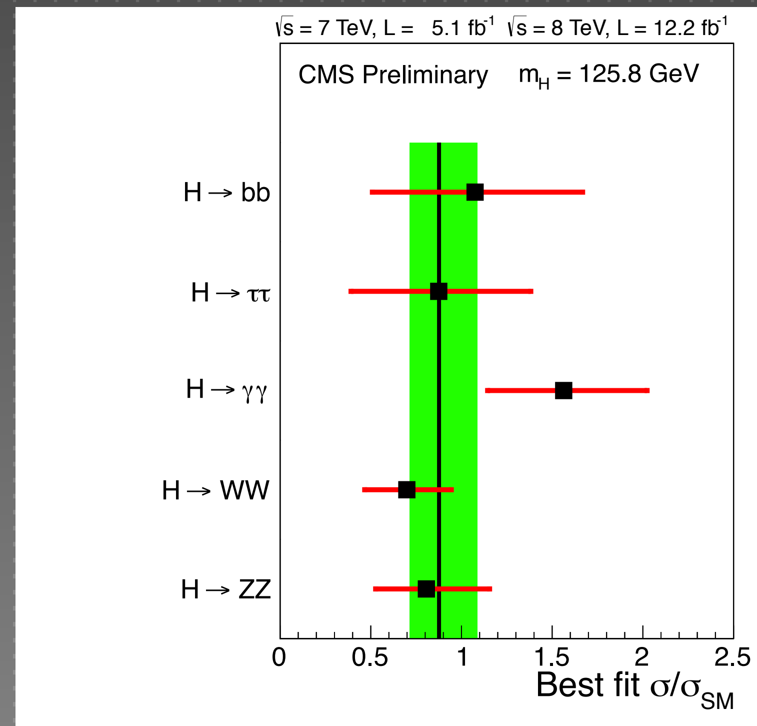


background-only (in)-compatibility

Decay mode or combination	Expected (σ)	Observed (σ)
ZZ	5.0	4.4
$\gamma\gamma$	2.8	4.0
WW	4.3	3.0
bb	2.2	1.8
$\tau\tau$	2.1	1.8
$\gamma\gamma$ + ZZ	5.7	5.8
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	7.8	6.9

Strengths in channels

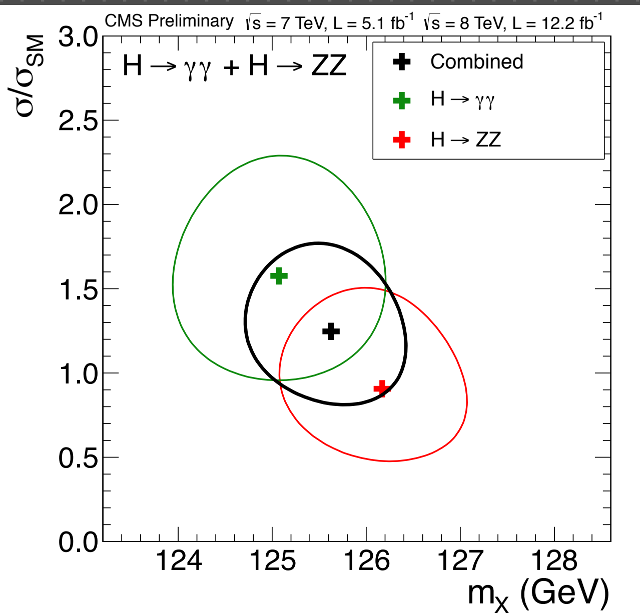


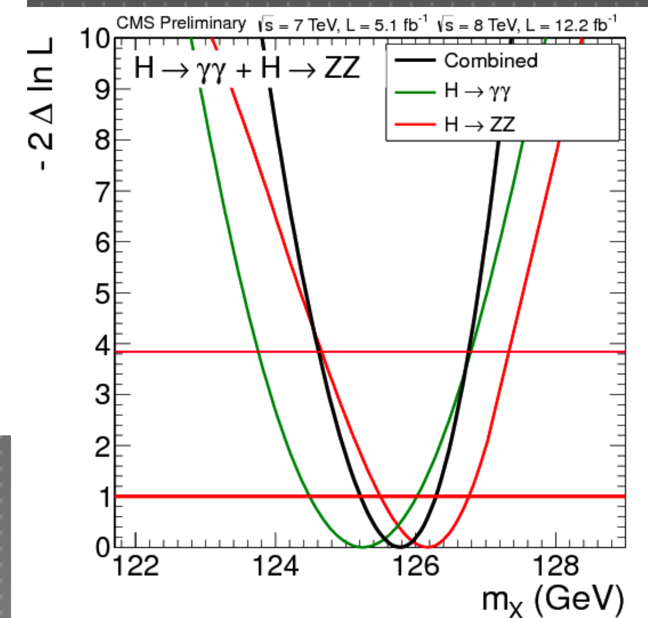


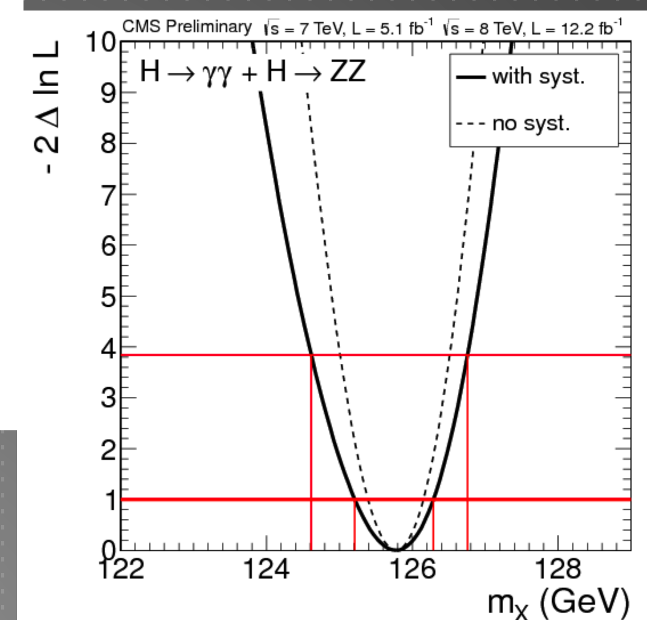
combined σ/σ_{SM}=0.88±0.21
for m_H=125.8

Signal mass

$m_X(ZZ) = 126.2 \pm 0.6 \pm 0.2$ GeV
$m_X(\gamma\gamma) = 125.2 \pm 0.8$ GeV







$m_X = 125.8 \pm 0.4 \pm 0.4$ GeV

signal couplings

coupling measurements

- LHC working group prescription (arXiv:1209.0040):
  - test the overall compatibility of the data with the SM
  - Assumptions: single resonance, zero-width, no modification of the tensor structure (0+)
- Set of fit models mapping the measured rates to multipliers (κ) of the SM cross sections and BRs:

$$(\sigma \cdot BR)(ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H} = \sigma_{SM} \cdot BR_{SM} \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

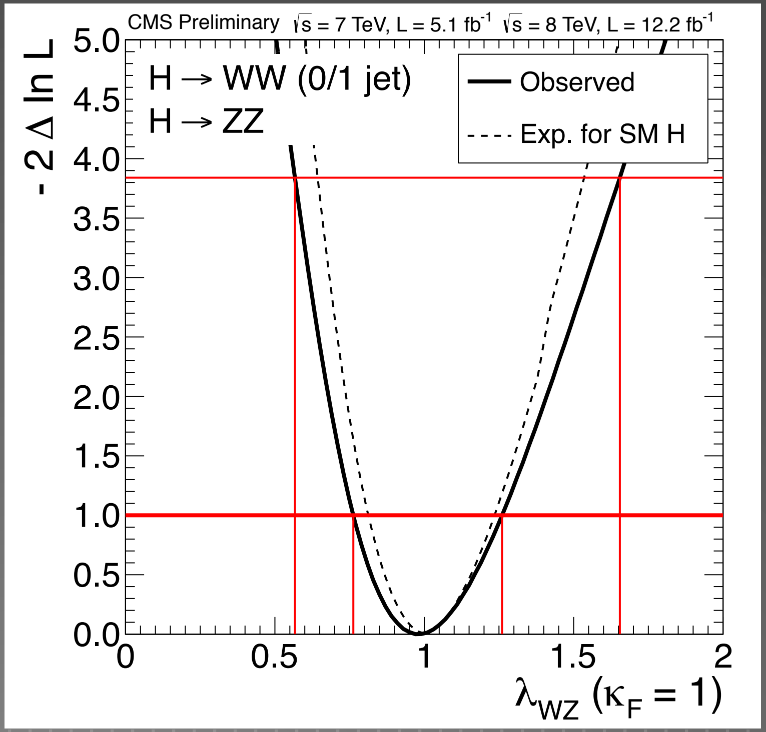
- Scaling for couplings through loops defined as additional free parameters
  - or as function of scale factors for the fields in the loop (with NLO accuracy)
- Total width taken as the sum of the partial widths
  - In special case allow also for invisible contributions
- Need to limit the degrees of freedom with the current data

W/Z SU2 custodial symmetry

$\lambda_{WZ}=\kappa_W/\kappa_Z$

In the SM the tree-level
W and Z masses relations are protected
against large radiative corrections

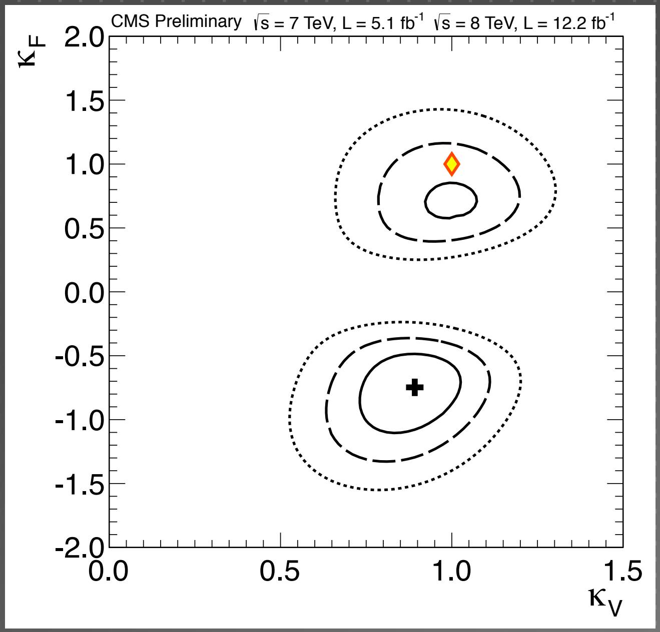
λ_{WZ} is essentially given by the measured ratio of untagged WW and ZZ yields.

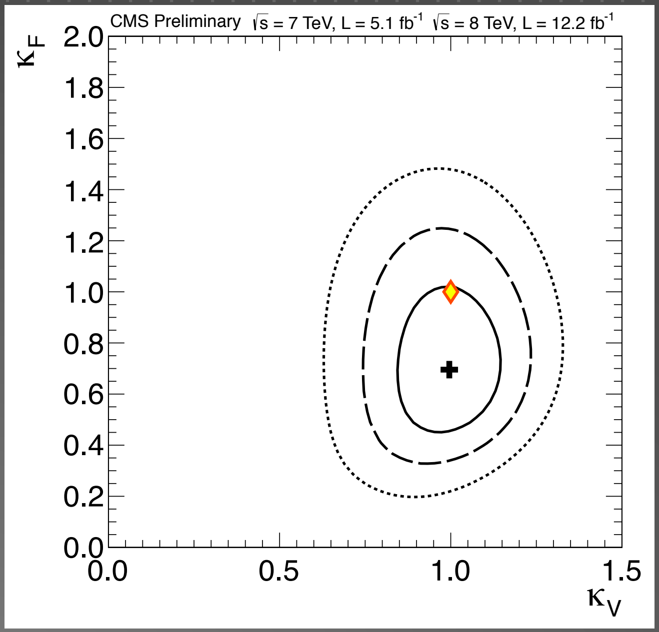


The 95% CL interval for λ_{WZ} is [0.67,1.55]

further we assume λ_{WZ}= 1

boson and fermion couplings





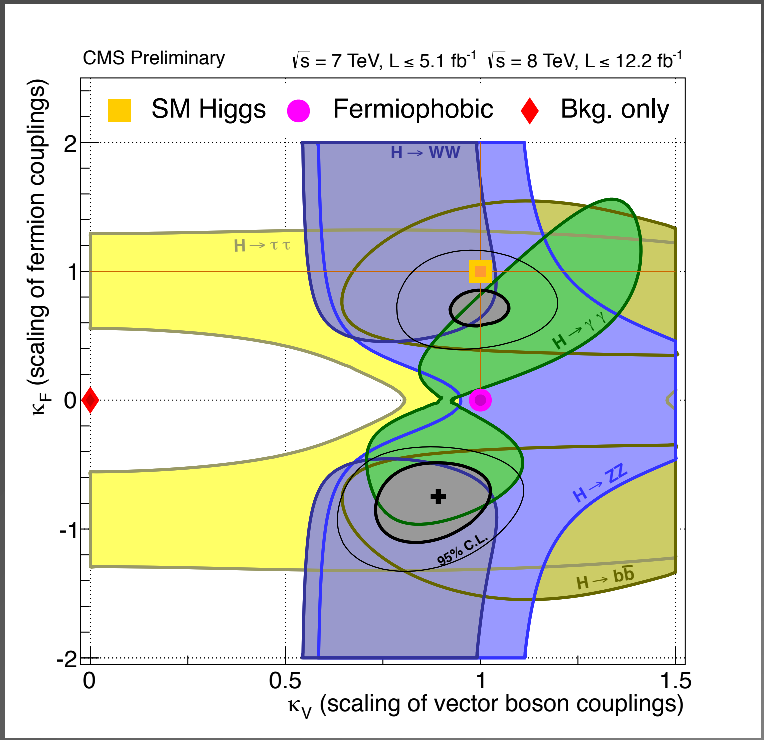
global minimum in (+,—) quadrant driven by the $\gamma\gamma$ excess: positive W-top loops interferences

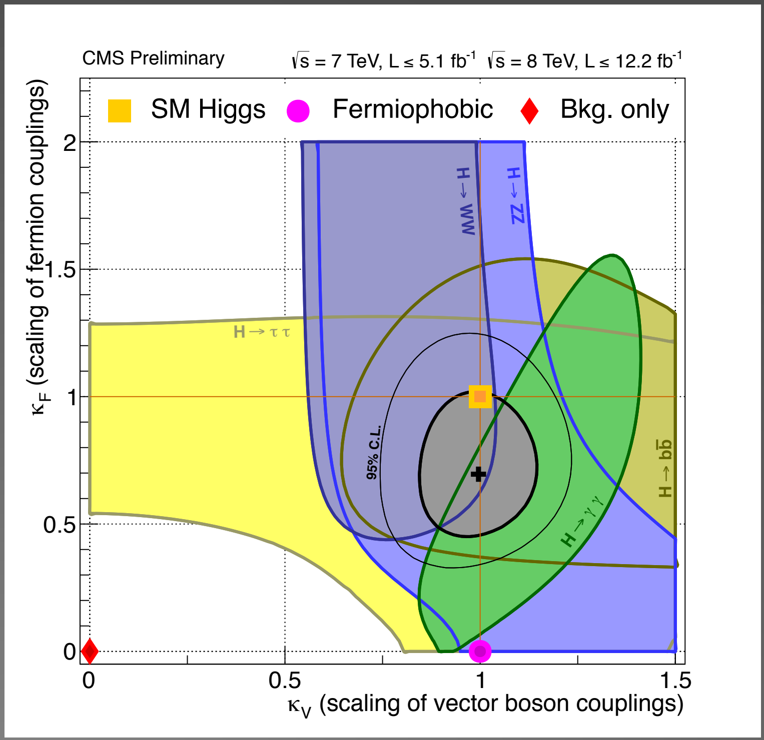
1-dim 95% CL intervals

κ_V [0.78,1.19] and κ_F [0.40,1.12]

where the other parameter is fixed to unity

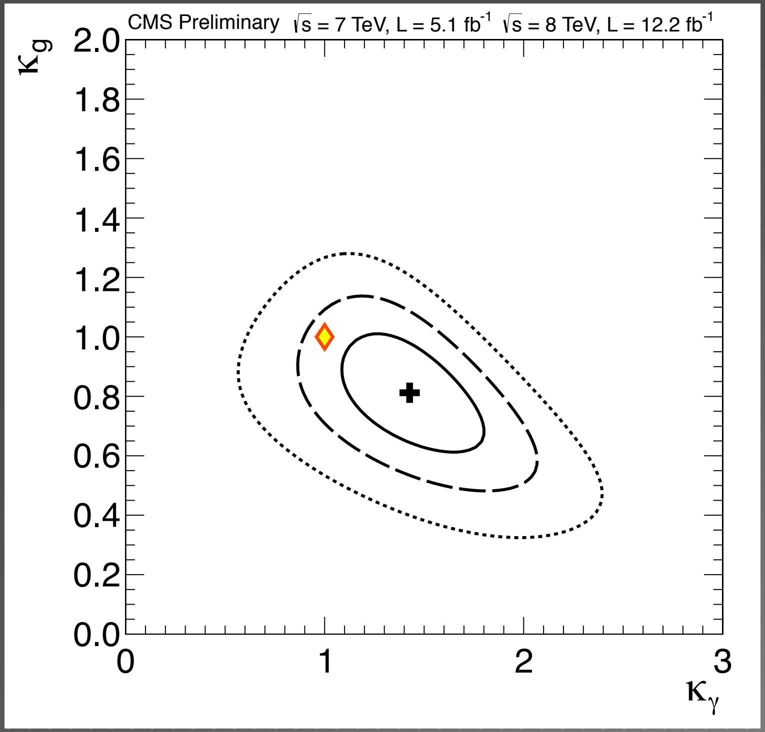
κ_F / κ_V from individual channels





fermiophobic scenario excluded with >4 σ

κ_g / κ_γ : hidden loop contributions



best-fit value (κ_γ, κ_g) = (1.43, 0.81)

test of the presence of BSM particles in H gg & $\gamma\gamma$ production & decay loops

assuming Γ(BSM) = 0

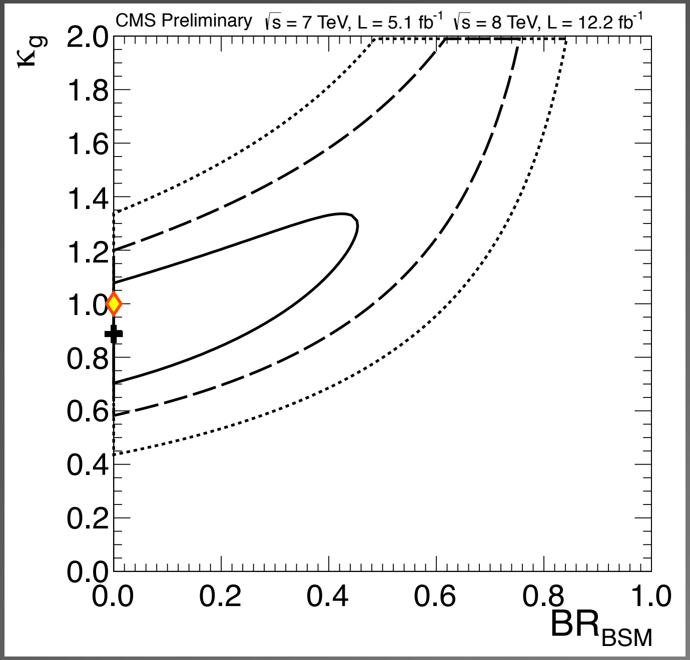
1-dim 95% CL intervals

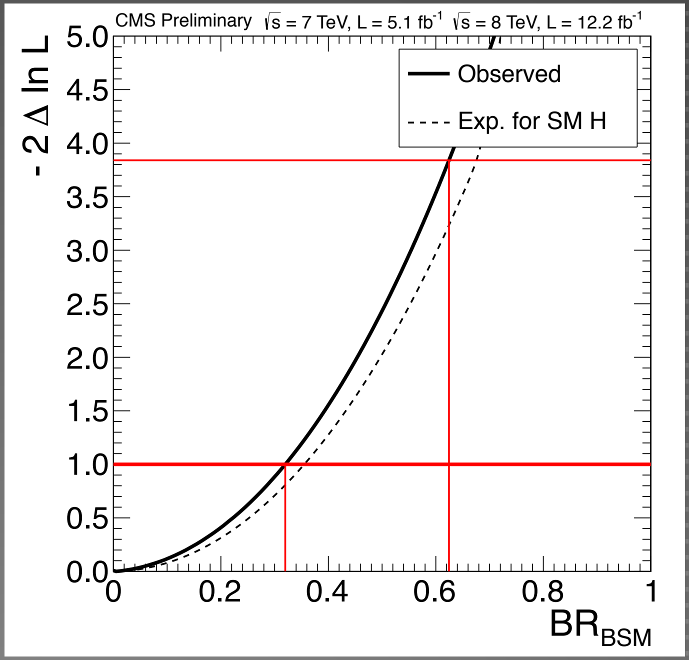
κ_γ [0.98,1.92] and κ_g= [0.55,1.07]

where the other parameter is fixed to unity

BSM invisible width

total width scales as $1/(1\text{-}BR_{Inv})$

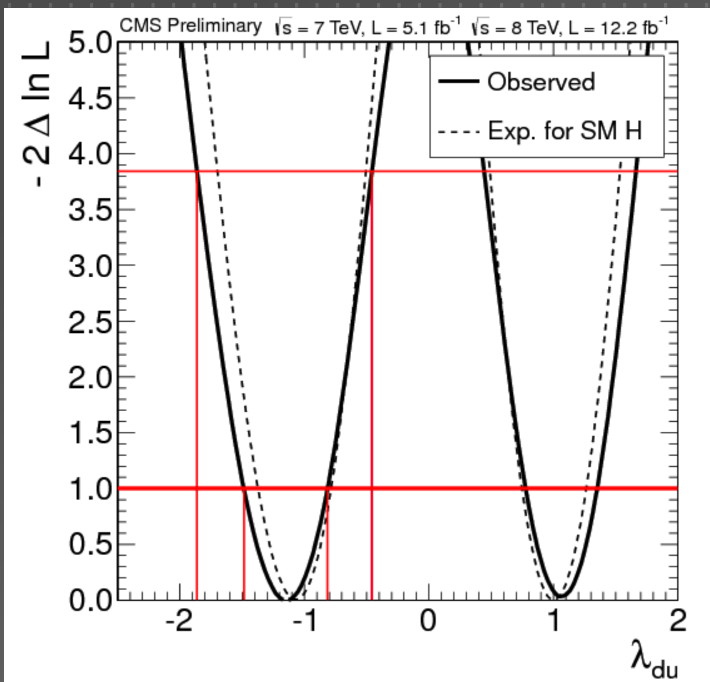


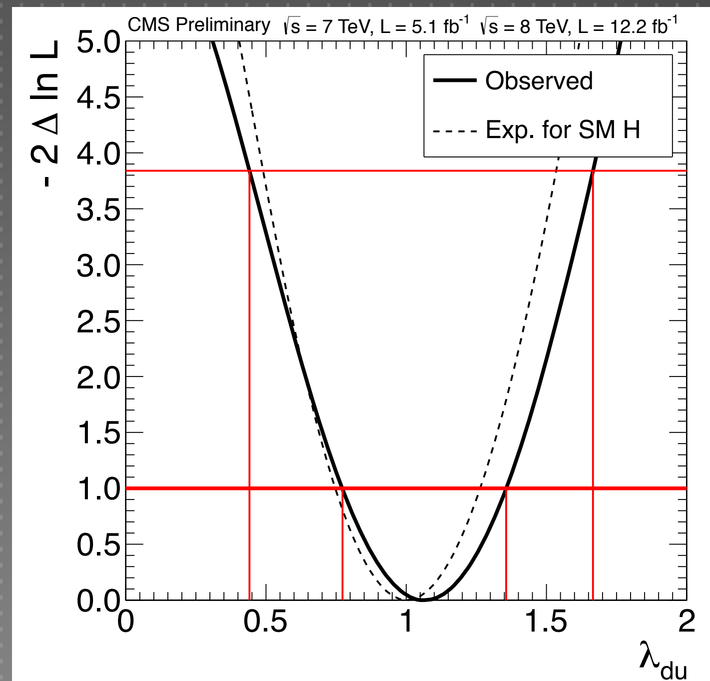


invisible BR(BSM) is in the interval [0.00,0.62] at 95% CL

κ_u / κ_d : up vs down couplings

test of the presence of additional Higgs fields (doublets)

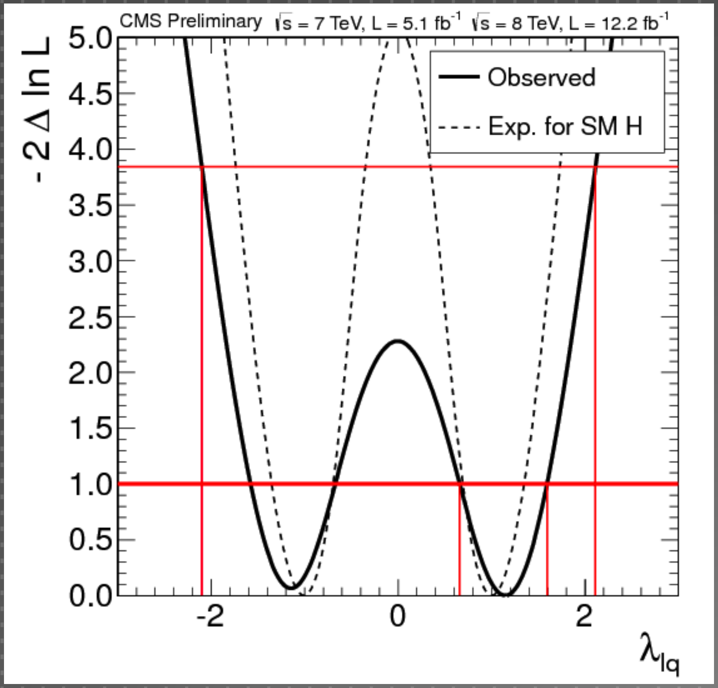


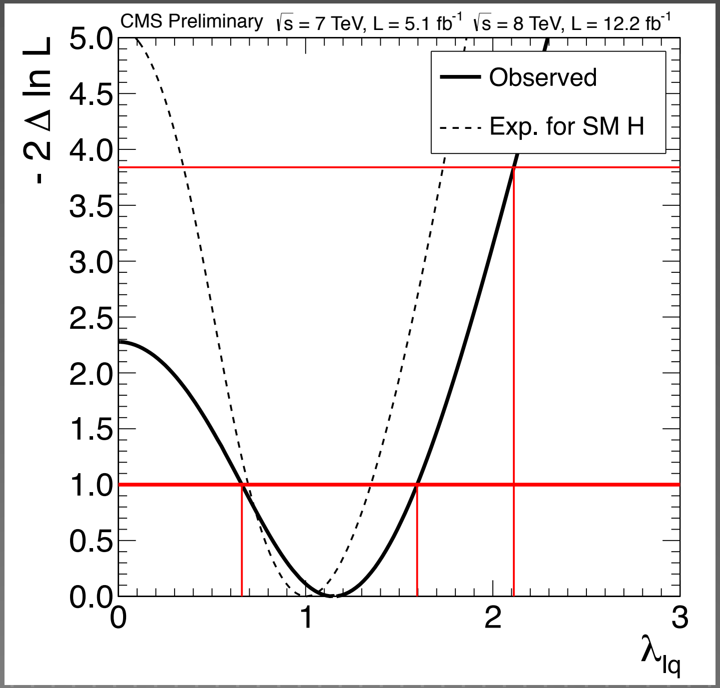


$d = b, \tau$
$u = t$

$\lambda_{du} = \kappa_d / \kappa_u$ 95% CL interval [0.45,1.66]

κ_l / κ_q : lepton vs quark couplings





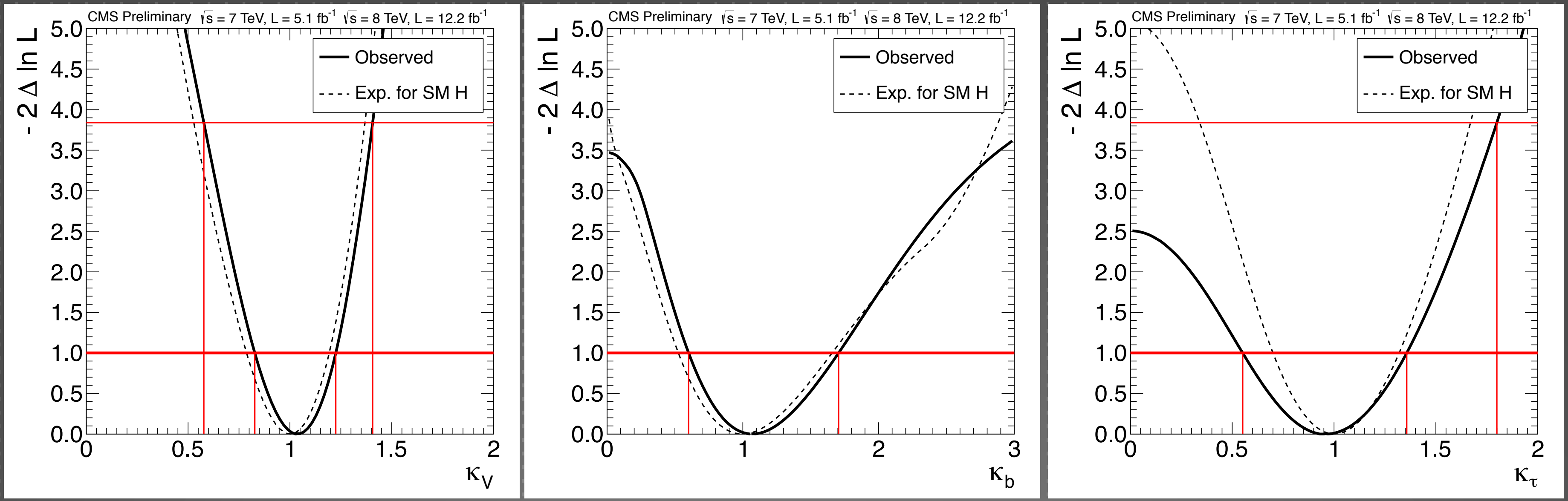
l = τ
q = t, b

$\lambda_{lq} = \kappa_l / \kappa_q$ 95% CL interval [0.00,2.11]

Individual couplings

- Assess individual couplings assuming only custodial symmetry and without resolving the loops structure.
- No BSM decays
- Study 6 scale factors:
  - κ_V, κ_t, κ_b, κ_τ, κ_g, κ_γ
- Fit individually each of those, while profiling the others

Individual couplings

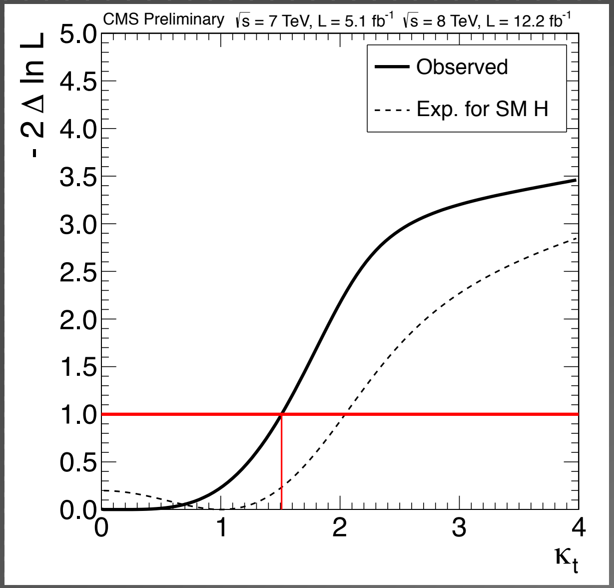


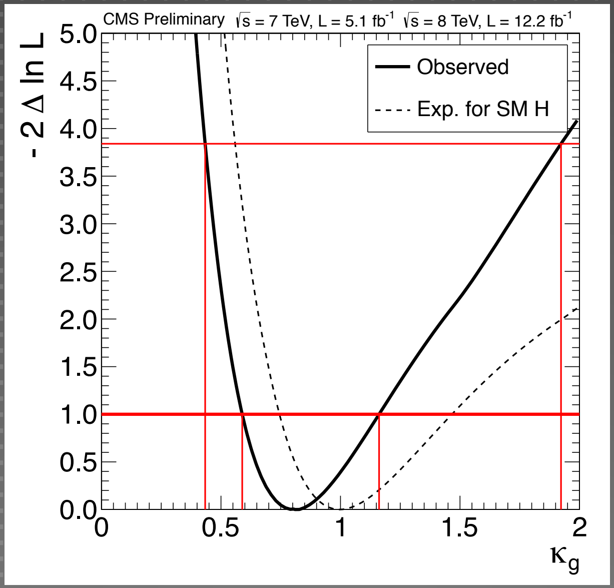
κ_V: 30% accuracy

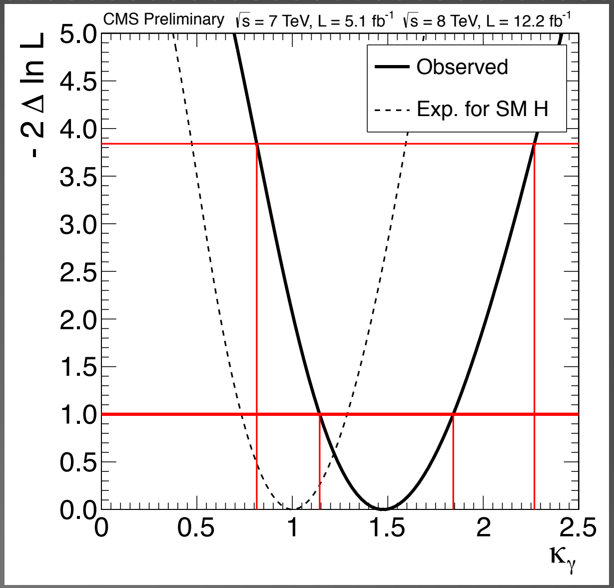
κ_b: 50% accuracy

κ_τ: 40% accuracy

Individual couplings





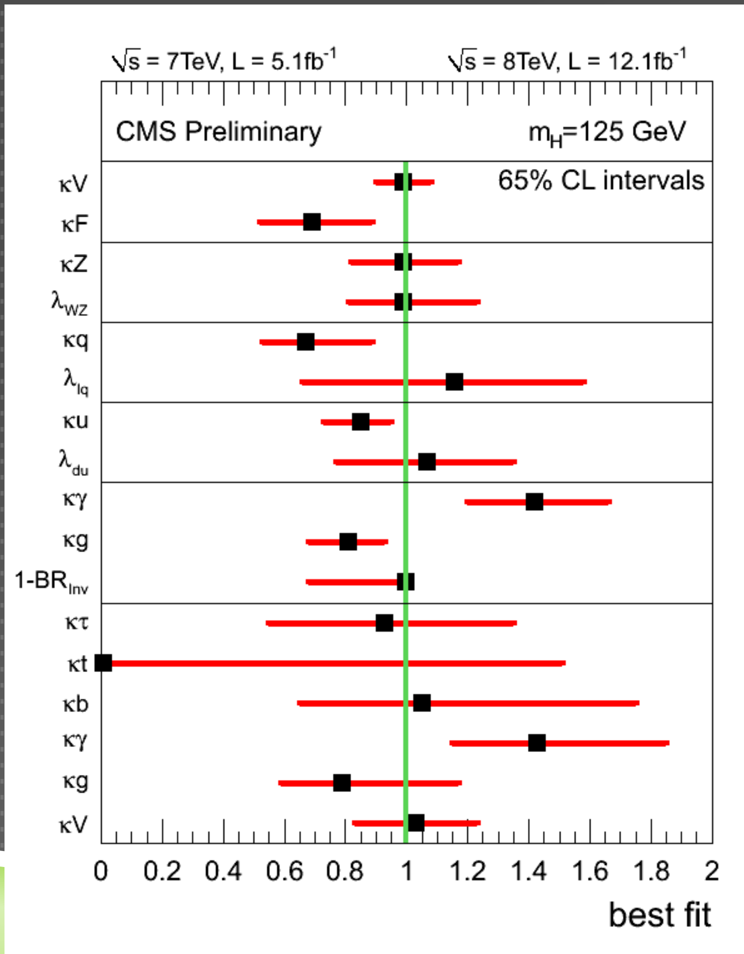


κ_t: 80% accuracy

κ_g: 30% accuracy

κ_γ: 35% accuracy

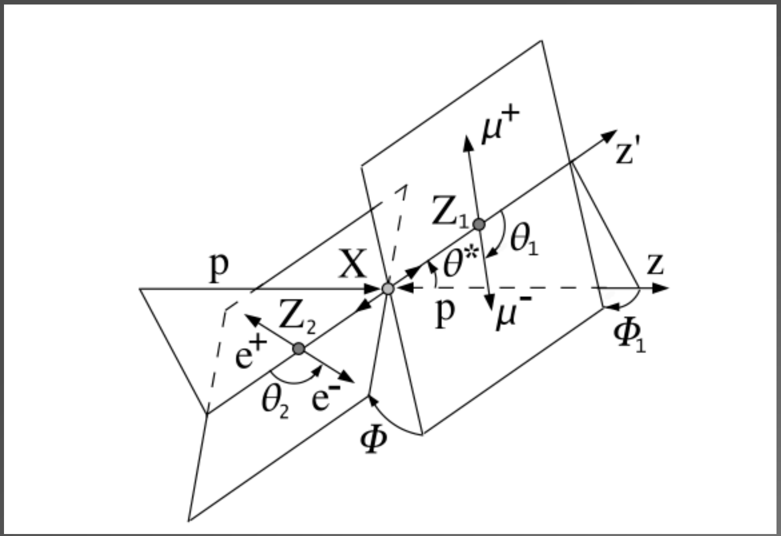
Summary of individual couplings



Model parameters	Assessed scaling factors (95% CL intervals)	
λ_{wz}, κ_z	λ_{wz}	[0.57,1.65]
$\lambda_{wz}, \kappa_z, \kappa_f$	λ_{wz}	[0.67,1.55]
κ_v	κ_v	[0.78,1.19]
κ_f	κ_f	[0.40,1.12]
κ_γ, κ_g	κ_γ	[0.98,1.92]
	κ_g	[0.55,1.07]
$\mathcal{B}(H \to BSM), \kappa_\gamma, \kappa_g$	$\mathcal{B}(H \to BSM)$	[0.00,0.62]
$\lambda_{du}, \kappa_v, \kappa_u$	λ_{du}	[0.45,1.66]
$\lambda_{\ell q}, \kappa_v, \kappa_q$	$\lambda_{\ell q}$	[0.00,2.11]
$\kappa_v, \kappa_b, \kappa_\tau, \kappa_t, \kappa_g, \kappa_\gamma$	κ_v	[0.58,1.41]
	κ_b	not constrained
	κ_τ	[0.00,1.80]
	κ_t	not constrained
	κ_g	[0.43,1.92]
	κ_γ	[0.81,2.27]

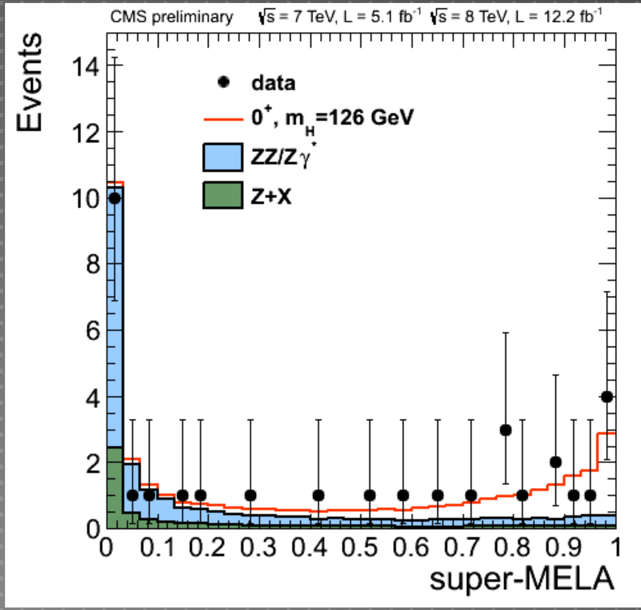
spin-parity determination

spin-parity in ZZ→ 4l



$$K_D \equiv \frac{\mathcal{P}_{\rm sig}}{\mathcal{P}_{\rm sig} + \mathcal{P}_{\rm bkg}} = \left[1 + \frac{\mathcal{P}_{\rm bkg}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm sig}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

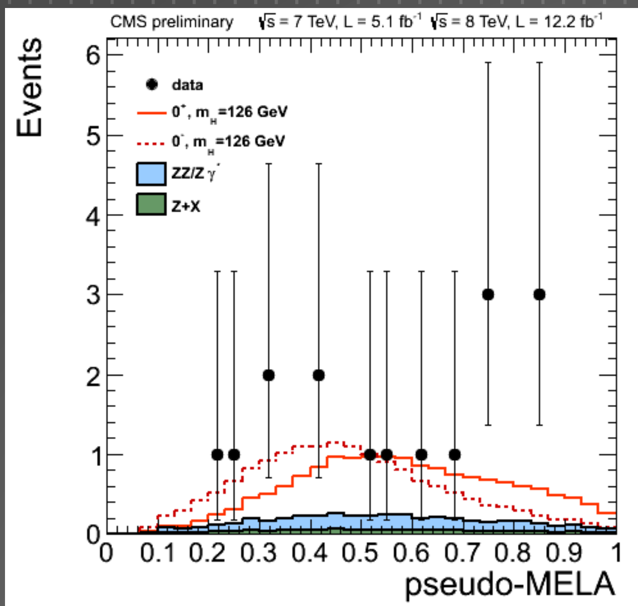
Matrix Element Likelihood approach with the two dilepton masses m_{Z1} and m_{Z2} and five angular variables Ω, here also with the m_{4l} with assumed 126 GeV signal mass (super-MELA or D_{SB})

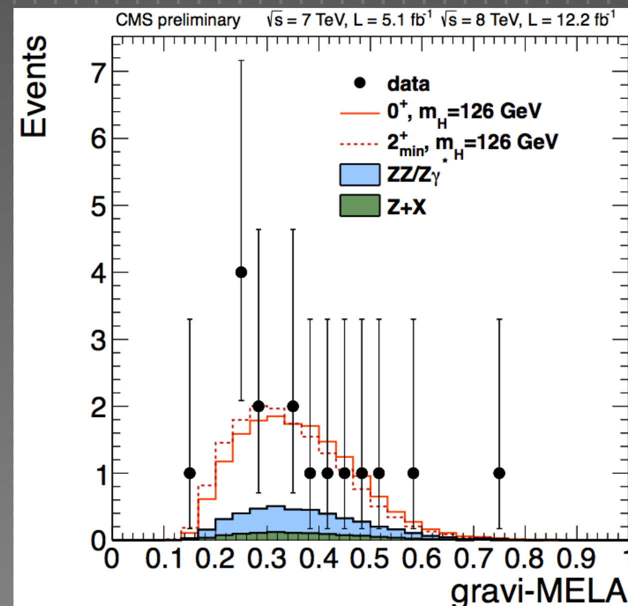


$106 < m_{4l} < 141$ GeV

spin-parity in ZZ→ 4l

build additional probability densities $D_{12}=P_1/(P_1+P_2)$ with two different spin-parity signal hypothesis : **D_{PS}** (pseudo-MELA) for 0-/0+ and **D_{GS}** (gravi-MELA) for 2+/0+

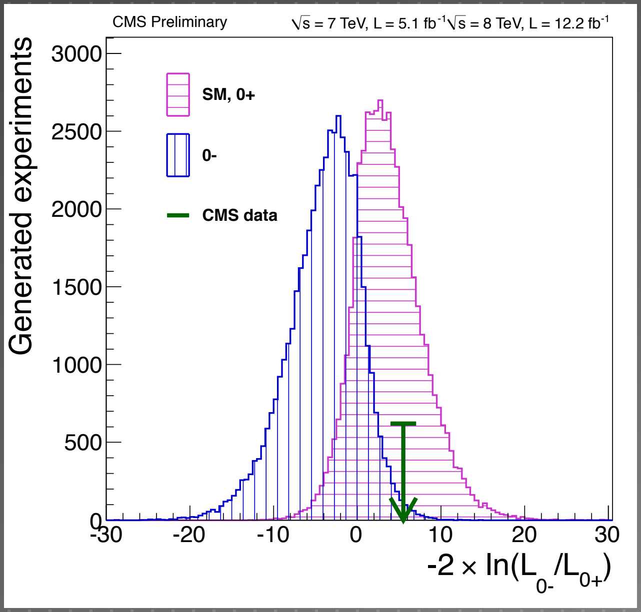




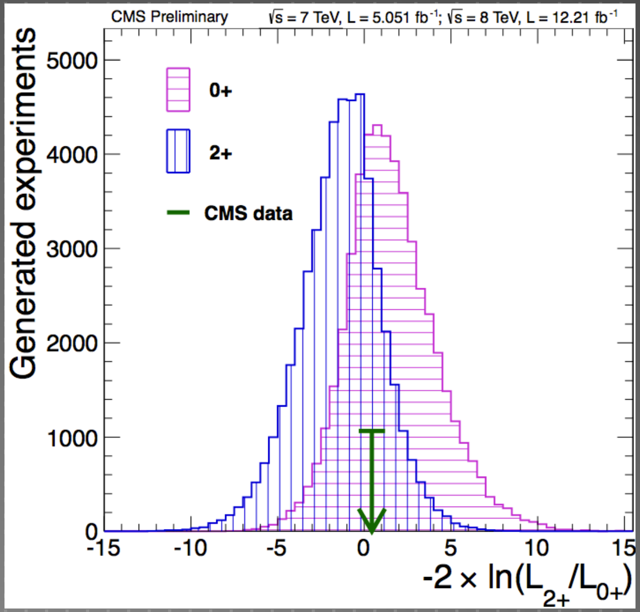
$D_{SB}>0.5$

spin-parity in ZZ→ 4l

fit the data in the DSB vs D_{PS} or D_{GS} plane to obtain likelihoods of the two signal hypothesis
compare the observed likelihood ratio with (50k) pseudo-experiments



2.4% pseudoscalar 0- hypothesis CLs



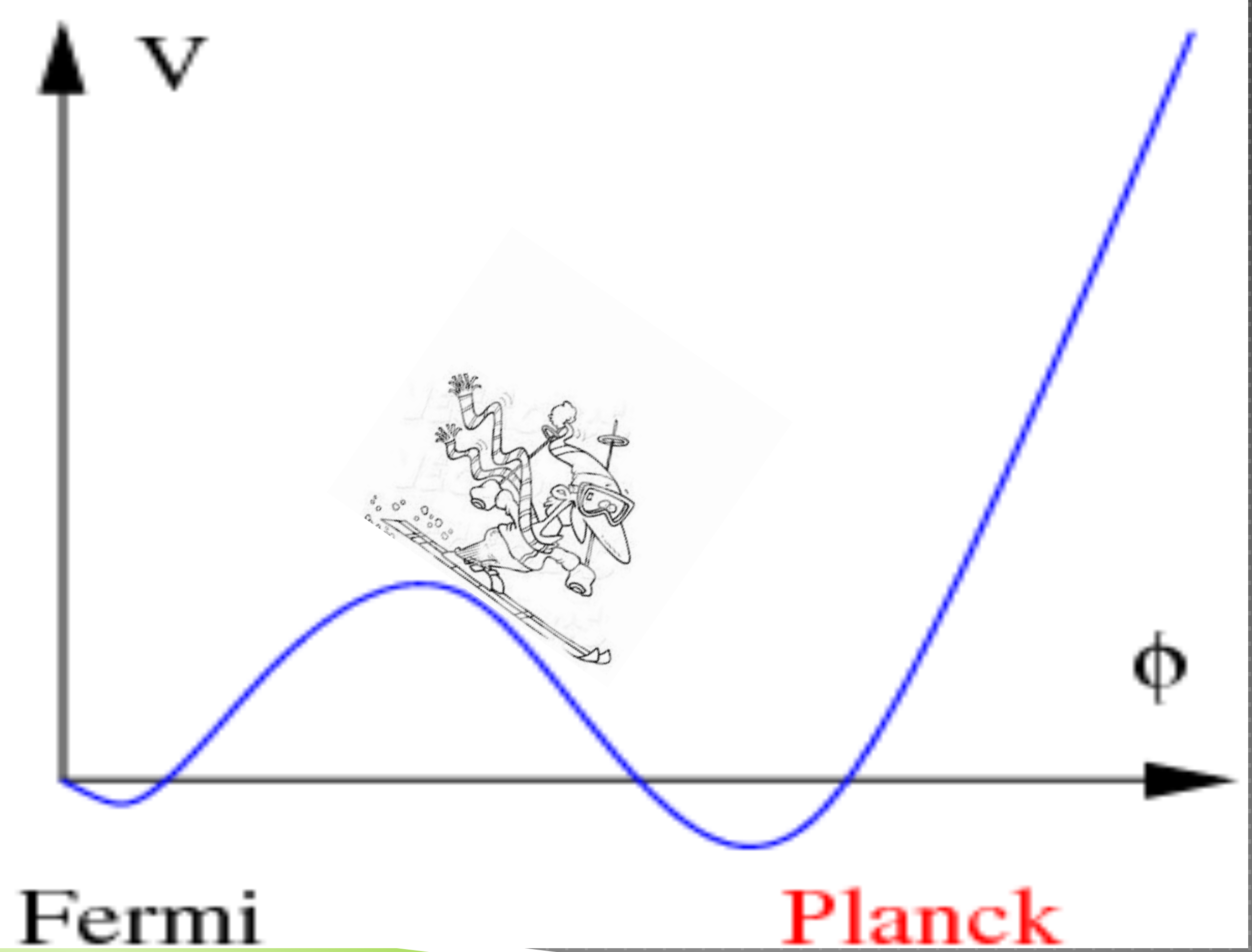
no indication yet between scalar and tensor

Conclusions

- The presence of a new bosonic state announced on July 4th 2012 is confirmed with the new 2012 data with larger significance (6.9σ).
- The production yield is σ/σ_{SM}=0.88±0.21
- The mass is measured m_X=125.8 ±0.4 ± 0.4 GeV (in ZZ and γγ)
- The coupling structure is in good agreement with minimal SM predictions.
  - no stringent results yet
- Pseudoscalar hypothesis excluded at 2.5σ level

- need to wait here @Moriond for probable new combined results with full CMS 2012 20/fb@8TeV data samples …

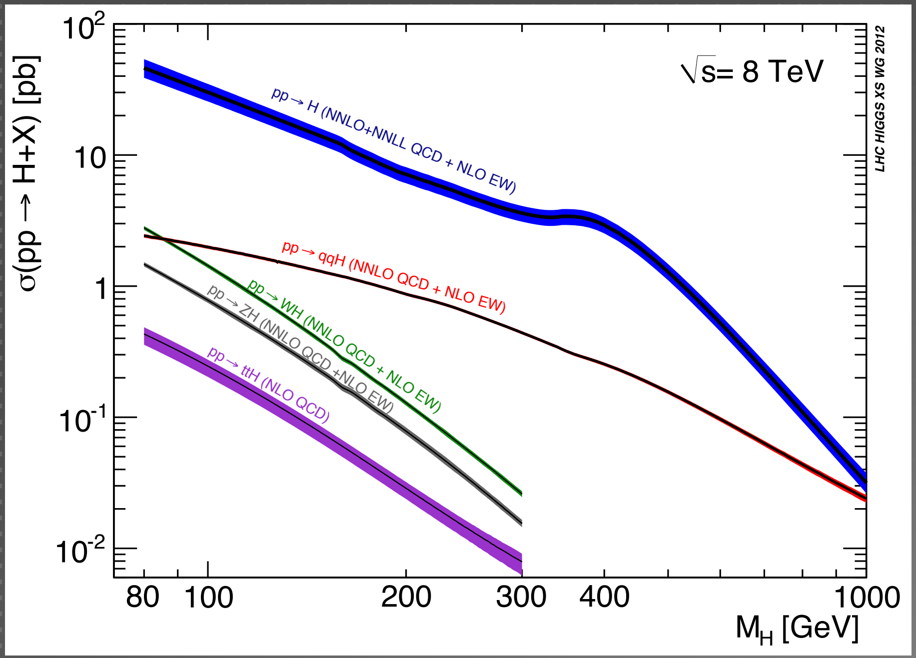
in the meanwhile …

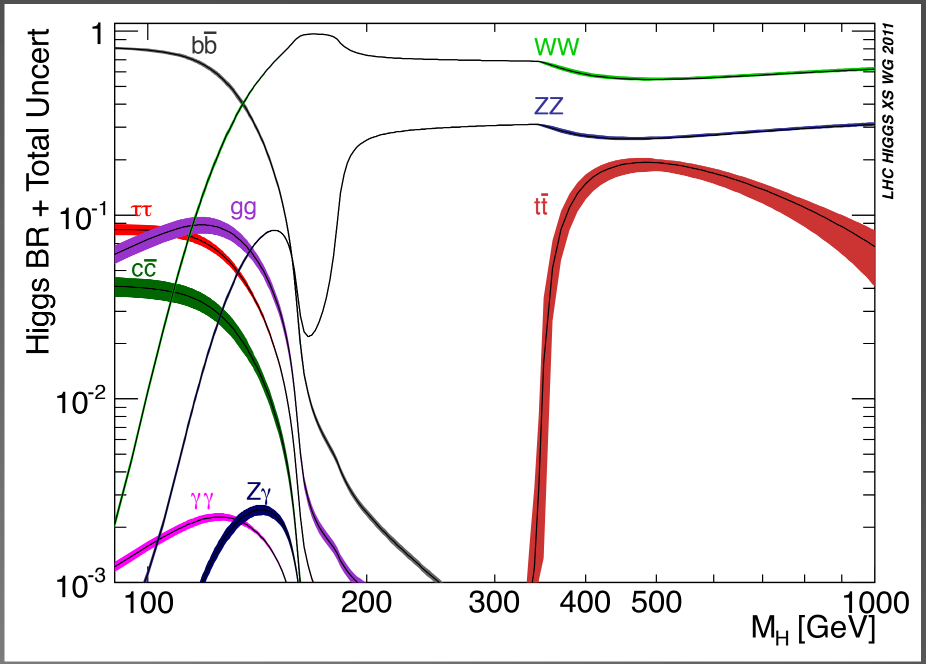


enjoy
the
slopes

Backup

SM Higgs: theo σ & BR



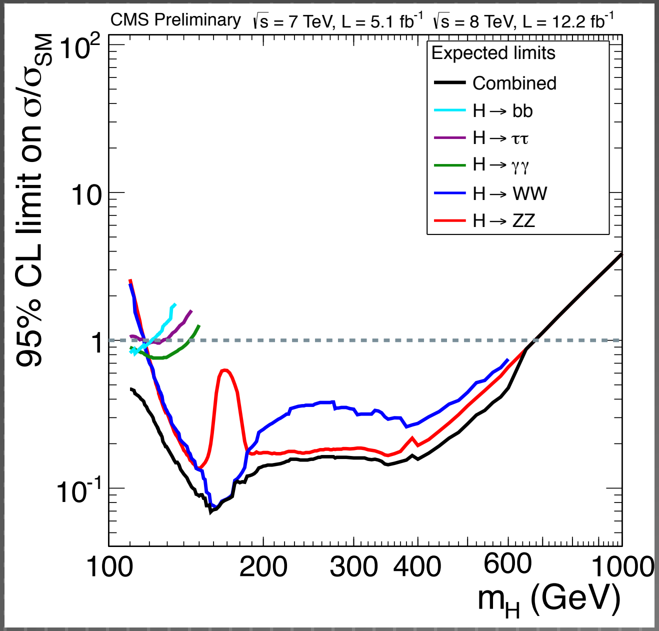


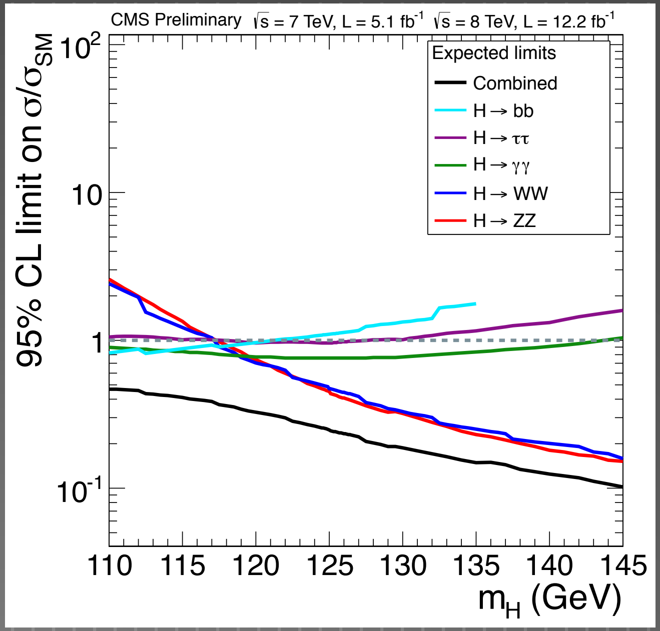
Backup

H decay	H prod	Analyses: Exclusive final states	No. of channels	m_H range (GeV)	m_H resolution	Lumi (fb^{-1}) 7 TeV	Lumi (fb^{-1}) 8 TeV
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	110–150	1-2%	5.1	5.3
	VBF-tag	$\gamma\gamma + (jj)_{VBF}$ (low or high m_{jj} for 8 TeV)	1 or 2	110–150	1-2%	5.1	5.3
bb	VH-tag	($\nu\nu$, ee, $\mu\mu$, $e\nu$, $\mu\nu$ with 2 b-jets) $\times$ (low or high p_T^V or loose b-tag)	10 or 13	110–135	10%	5.0	12.1
	ttH-tag	(ℓ with 4,5,$\geq$6 jets) $\times$ (3,$\geq$4 b-tags); (ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-tagged jets)	9	110–140		5.0	-
$H \to \tau\tau$	1-jet	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$) $\times$ (low or high p_T^τ) and $\tau_h\tau_h$	9	110–145	20%	4.9	12.1
	VBF-tag	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$) $+ (jj)_{VBF}$	5	110–145	20%	4.9	12.1
	ZH-tag	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	110–160		5.0	-
	WH-tag	$\tau_h ee$, $\tau_h\mu\mu$, $\tau_h e\mu$	3	110–140		4.9	-
$WW \to \ell\nu qq$	untagged	($e\nu$, $\mu\nu$) $\times$ ($(jj)_W$ with 0 or 1 jets)	4	170–600		5.0	12.1
$WW \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\times$ (0 or 1 jets)	4	110–600	20%	4.9	12.1
$WW \to \ell\nu\ell\nu$	VBF-tag	$\ell\nu\ell\nu + (jj)_{VBF}$ (DF or SF dileptons for 8 TeV)	1 or 2	110–600	20%	4.9	12.1
$WW \to \ell\nu\ell\nu$	WH-tag	$3\ell 3\nu$	1	110–200		4.9	5.1
$ZZ \to 4\ell$	inclusive	$4e$, 4μ, $2e2\mu$	3	110–1000	1-2%	5.0	12.2
$ZZ \to 2\ell 2\tau$	inclusive	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	180–1000	10-15%	5.0	12.2

Summary of analyses included in the CMS combinations

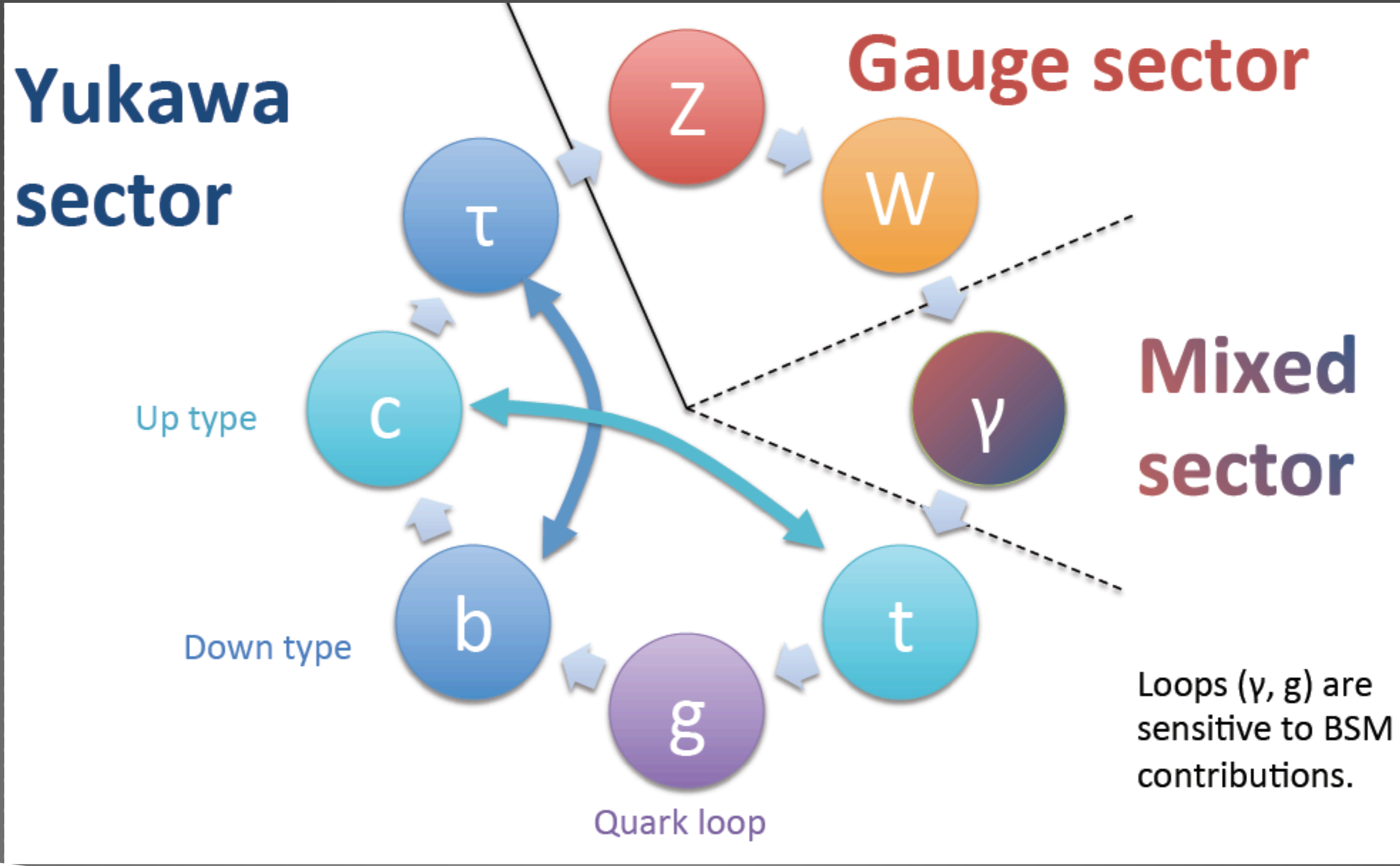
individual channels expected 95%CL limits



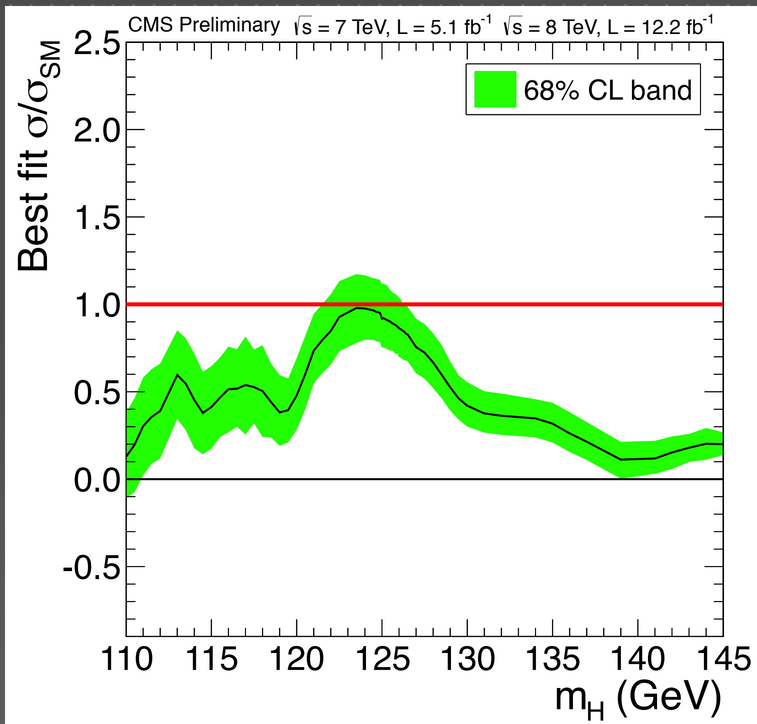


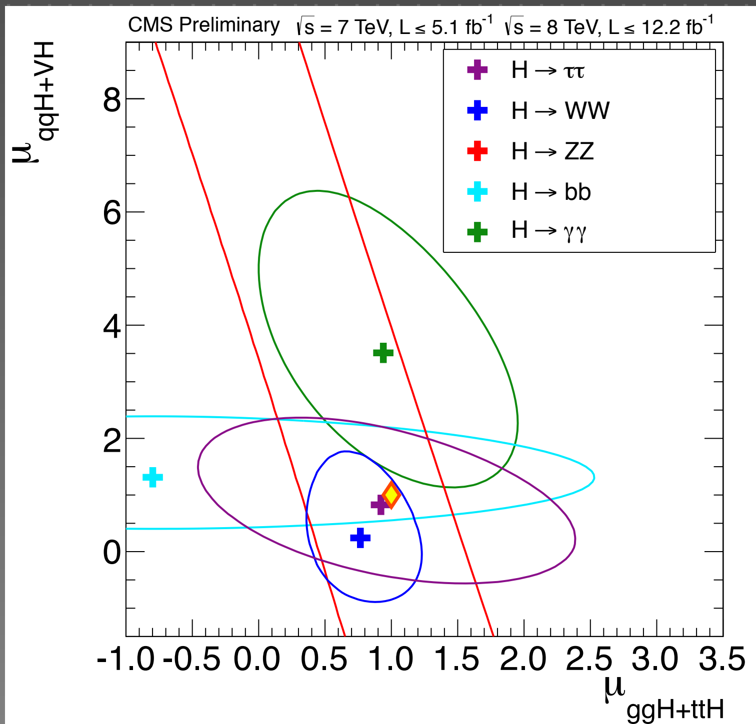
with 5.1/fb @7TeV + 12.2/fb @8TeV
the combined CMS analysis expect to exclude the full
110-700 GeV SM Higgs mass range

Backup


Yukawa sector
Gauge sector
Mixed sector
Z
W
τ
γ
c
Up type
b
Down type
t
g
Quark loop
Loops (γ, g) are sensitive to BSM contributions.

Signal strength vs m_H and ggH+ttH vs VBF+VH





Backup

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ggH}}} = \begin{cases} \kappa^2_{\mathrm{g}}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa^2_{\mathrm{g}} \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma^{\mathrm{SM}}_{\mathrm{VBF}}} = \kappa^2_{\mathrm{VBF}}(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}})$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma^{\mathrm{SM}}_{\mathrm{WH}}} = \kappa^2_{\mathrm{W}}$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ZH}}} = \kappa^2_{\mathrm{Z}}$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}H}}} = \kappa^2_{\mathrm{t}}$$

Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{WW}^{(*)}}} = \kappa^2_{\mathrm{W}}$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{ZZ}^{(*)}}} = \kappa^2_{\mathrm{Z}}$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{b\bar{b}}}} = \kappa^2_{\mathrm{b}}$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{\mathrm{SM}}_{\tau^-\tau^+}} = \kappa^2_{\tau}$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{\gamma\gamma}} = \begin{cases} \kappa^2_{\gamma}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa^2_{\gamma} \end{cases}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma^{\mathrm{SM}}_{\mathrm{Z}\gamma}} = \begin{cases} \kappa^2_{(\mathrm{Z}\gamma)}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa^2_{(\mathrm{Z}\gamma)} \end{cases}$$

Undetectable decay modes

$$\frac{\Gamma_{\mathrm{t\bar{t}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{t\bar{t}}}} = \kappa^2_{\mathrm{t}}$$

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

$$\frac{\Gamma_{\mathrm{c\bar{c}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{c\bar{c}}}} = \kappa^2_{\mathrm{t}}$$

$$\frac{\Gamma_{\mathrm{s\bar{s}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{s\bar{s}}}} = \kappa^2_{\mathrm{b}}$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{\mathrm{SM}}_{\mu^-\mu^+}} = \kappa^2_{\tau}$$

Backup

- 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 σ_{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 κ_W and κ_Z
- Alternatively the dependency on other scale factors can be discarded and treat the loop scale factor as additional free parameter

Backup

Scaling of the VBF cross section

$$\kappa^2_{\rm VBF}(\kappa_{\rm W},\kappa_{\rm Z},m_{\rm H}) \quad = \quad \frac{\kappa^2_{\rm W}\cdot\sigma_{WF}(m_{\rm H})+\kappa^2_{\rm Z}\cdot\sigma_{ZF}(m_{\rm H})}{\sigma_{WF}(m_{\rm H})+\sigma_{ZF}(m_{\rm H})}$$

Scaling of the gluon fusion cross section and of the H → gg ***decay vertex***

$$\kappa^2_{\rm g}(\kappa_{\rm b},\kappa_{\rm t},m_{\rm H}) \quad = \quad \frac{\kappa^2_{\rm t}\cdot\sigma^{\rm tt}_{\rm ggH}(m_{\rm H})+\kappa^2_{\rm b}\cdot\sigma^{\rm bb}_{\rm ggH}(m_{\rm H})+\kappa_{\rm t}\kappa_{\rm b}\cdot\sigma^{\rm tb}_{\rm ggH}(m_{\rm H})}{\sigma^{\rm tt}_{\rm ggH}(m_{\rm H})+\sigma^{\rm bb}_{\rm ggH}(m_{\rm H})+\sigma^{\rm tb}_{\rm ggH}(m_{\rm H})}$$

$$\frac{\Gamma_{\rm gg}}{\Gamma^{\rm SM}_{\rm gg}(m_{\rm H})} = \frac{\kappa^2_{\rm t}\cdot\Gamma^{\rm tt}_{\rm gg}(m_{\rm H})+\kappa^2_{\rm b}\cdot\Gamma^{\rm bb}_{\rm gg}(m_{\rm H})+\kappa_{\rm t}\kappa_{\rm b}\cdot\Gamma^{\rm tb}_{\rm gg}(m_{\rm H})}{\Gamma^{\rm tt}_{\rm gg}(m_{\rm H})+\Gamma^{\rm bb}_{\rm gg}(m_{\rm H})+\Gamma^{\rm tb}_{\rm gg}(m_{\rm H})}$$

Backup

Scaling of the H → $\gamma\,\gamma$ ***partial decay width***

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}(m_H)}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}(m_H)}$$

Backup: custodial λ_{WZ}

Probing custodial symmetry assuming no invisible or undetectable widths

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

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

Probing custodial symmetry without assumptions on the total width

Free parameters: $\kappa_{ZZ}(=\kappa_Z\cdot\kappa_Z/\kappa_H), \lambda_{WZ}(=\kappa_W/\kappa_Z), \lambda_{FZ}(=\kappa_f/\kappa_Z)$.

	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH $t\bar{t}$H	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\lambda_{FZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\lambda_{FZ}^2$	
VBF	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)\cdot\lambda_{FZ}^2$	
WH	$\kappa_{ZZ}^2\lambda_{WZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{WZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{WZ}^2\cdot\lambda_{FZ}^2$	
ZH	$\kappa_{ZZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	κ_{ZZ}^2	$\kappa_{ZZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\cdot\lambda_{FZ}^2$	

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

Table 5: A benchmark parametrization where custodial symmetry is probed through the λ_{WZ} parameter.

Backup: κ_V / κ_F

Boson and fermion scaling assuming no invisible or undetectable widths

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

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

Boson and fermion scaling without assumptions on the total width

Free parameters: $\kappa_{VV} (= \kappa_V \cdot \kappa_V / \kappa_H), \lambda_{fV} (= \kappa_f / \kappa_V)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}$H	$\kappa_{VV}^2 \cdot \lambda_{fV}^2 \cdot \kappa_\gamma^2(\lambda_{fV}, \lambda_{fV}, \lambda_{fV}, 1)$	$\kappa_{VV}^2 \cdot \lambda_{fV}^2$		$\kappa_{VV}^2 \cdot \lambda_{fV}^2 \cdot \lambda_{fV}^2$	
VBF WH ZH	$\kappa_{VV}^2 \cdot \kappa_\gamma^2(\lambda_{fV}, \lambda_{fV}, \lambda_{fV}, 1)$	κ_{VV}^2		$\kappa_{VV}^2 \cdot \lambda_{fV}^2$	

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

Table 4: A benchmark parametrization where custodial symmetry is assumed and vector boson couplings are scaled together (κ_V) and fermions are assumed to scale with a single parameter (κ_f).

Backup: $\lambda_{du} = \kappa_d / \kappa_u$

Probing up-type and down-type fermion symmetry assuming no invisible or undetectable widths Free parameters: $\kappa_V (= \kappa_Z = \kappa_W), \lambda_{du} (= \kappa_d/\kappa_u), \kappa_u (= \kappa_t)$.			
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$ / $H \to WW^{(*)}$	$H \to b\bar{b}$ / $H \to \tau^-\tau^+$
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 ZH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_u\lambda_{du}, \kappa_u, \kappa_u\lambda_{du}, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot (\kappa_u\lambda_{du})^2}{\kappa_H^2(\kappa_i)}$

Probing up-type and down-type fermion symmetry without assumptions on the total width Free parameters: $\kappa_{uu} (= \kappa_u \cdot \kappa_u/\kappa_H), \lambda_{du} (= \kappa_d/\kappa_u), \lambda_{Vu} (= \kappa_V/\kappa_u)$.			
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$ / $H \to WW^{(*)}$	$H \to b\bar{b}$ / $H \to \tau^-\tau^+$
ggH	$\kappa_{uu}^2 \kappa_g^2(\lambda_{du}, 1) \cdot \kappa_\gamma^2(\lambda_{du}, 1, \lambda_{du}, \lambda_{Vu})$	$\kappa_{uu}^2 \kappa_g^2(\lambda_{du}, 1) \cdot \lambda_{Vu}^2$	$\kappa_{uu}^2 \kappa_g^2(\lambda_{du}, 1) \cdot \lambda_{du}^2$
$t\bar{t}H$	$\kappa_{uu}^2 \cdot \kappa_\gamma^2(\lambda_{du}, 1, \lambda_{du}, \lambda_{Vu})$	$\kappa_{uu}^2 \cdot \lambda_{Vu}^2$	$\kappa_{uu}^2 \cdot \lambda_{du}^2$
VBF WH ZH	$\kappa_{uu}^2 \lambda_{Vu}^2 \cdot \kappa_\gamma^2(\lambda_{du}, 1, \lambda_{du}, \lambda_{Vu})$	$\kappa_{uu}^2 \lambda_{Vu}^2 \cdot \lambda_{Vu}^2$	$\kappa_{uu}^2 \lambda_{Vu}^2 \cdot \lambda_{du}^2$

$$\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{SM}, \kappa_d = \kappa_b = \kappa_\tau$$

Table 6: A benchmark parametrization where the up-type and down-type symmetry of fermions is probed through the λ_{du} parameter.

Backup: $\lambda_{lq} = \kappa_l / \kappa_q$

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

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

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

Probing quark and lepton fermion symmetry without assumptions on the total width

Free parameters: $\kappa_{qq}(=\kappa_q\cdot\kappa_q/\kappa_H)$, $\lambda_{lq}(=\kappa_l/\kappa_q)$, $\lambda_{Vq}(=\kappa_V/\kappa_q)$.

	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH $t\bar{t}$H	$\kappa_{qq}^2\cdot\kappa_\gamma^2(1,1,\lambda_{lq},\lambda_{Vq})$	$\kappa_{qq}^2\cdot\lambda_{Vq}^2$		κ_{qq}^2	$\kappa_{qq}^2\cdot\lambda_{lq}^2$
VBF WH ZH	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\kappa_\gamma^2(1,1,\lambda_{lq},\lambda_{Vq})$	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\lambda_{Vq}^2$		$\kappa_{qq}^2\cdot\lambda_{Vq}^2$	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\lambda_{lq}^2$

$\kappa_i^2=\Gamma_{ii}/\Gamma_{ii}^{SM}$, $\kappa_l=\kappa_\tau$

Table 7: A benchmark parametrization where the quark and lepton symmetry of fermions is probed through the λ_{lq} parameter.

Backup: invisible BSM decays

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
Probing loop structure assuming no invisible or undetectable widths Free parameters: κ_g, κ_γ.					
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)}$			
$t\bar{t}H$ VBF WH ZH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{1}{\kappa_H^2(\kappa_i)}$			
Probing loop structure allowing for invisible or undetectable widths Free parameters: $\kappa_g, \kappa_\gamma, BR_{inv.,undet.}$.					
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$	$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$			
$t\bar{t}H$ VBF WH ZH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$	$\frac{1}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$			

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

Table 8: A benchmark parametrization where effective vertex couplings are allowed to float through the κ_g and κ_γ parameters. Instead of absorbing κ_H, explicit allowance is made for a contribution from invisible or undetectable widths via the $BR_{inv.,undet.}$ parameter.

Backup

Backup