



CMS Higgs Coupling Measurements

BSM@LPC-2014: BSM Higgs Workshop

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November 3-5 2014





Introduction

Higgs boson a well established player at the LHC...

All 5 major channels now published using full Run-1 dataset, $19.7(5.1)fb^{-1}$ at 8(7)TeV.

This talk covers their combination:

- ▶ Mass
- ▶ Rates
- ▶ Couplings
- ▶ BSM considerations

See detailed talks this week for J^{CP} , Γ_H (Direct constraints), $H \rightarrow Inv$ and BSM Higgs searches.

PHYSICAL REVIEW D **89**, 012003 (2014)

Search for the standard model Higgs boson produced in association with a W or a Z boson and decaying to bottom quarks

S. Chatrchyan *et al.**
(CMS Collaboration)

(Received 14 October 2013; published 21 January 2014)

A search for the standard model Higgs boson (H) decaying to $b\bar{b}$ when produced in association with a

HEP

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: January 08, 2014
REVISION: April 13, 2014
ACCEPTED: April 13, 2014
PUBLISHED: May 23, 2014

Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons

PHYSICAL REVIEW D **89**, 092007 (2014)

Measurement of the properties of a Higgs boson in the four-lepton final state

S. Chatrchyan *et al.**
(CMS Collaboration)

(Received 18 December 2013; published 14 May 2014)

The properties of a Higgs boson produced in association with a W boson and decaying to e^+e^- or $\mu^+\mu^-$ using data from pp collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV

HEP

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: December 18, 2013
ACCEPTED: December 18, 2013
PUBLISHED: January 23, 2014

Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states

Eur. Phys. J. C (2014) 74:3076
DOI 10.1140/epjc/s10052-014-3076-z

Regular Article - Experimental Physics

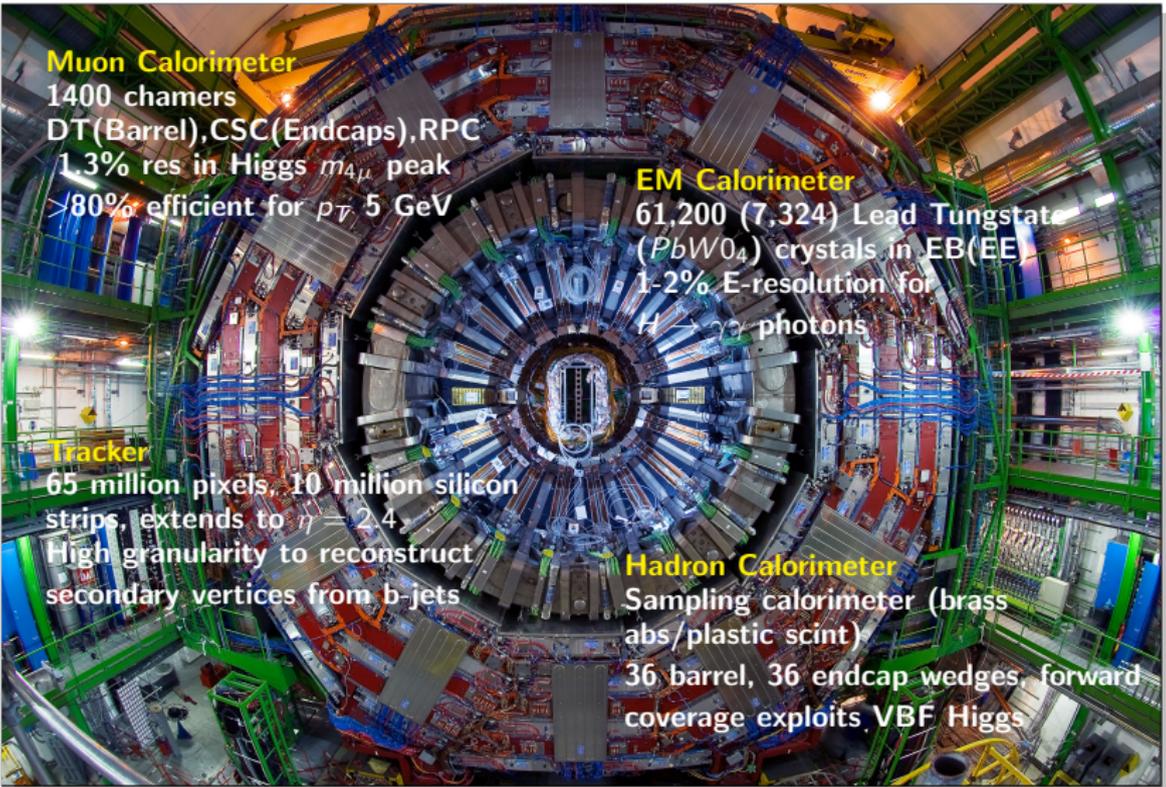
THE EUROPEAN PHYSICAL JOURNAL C

Observation of the diphoton decay of the Higgs boson and measurement of its properties

The CMS Collaboration*
CERN, 1211 Geneva 23, Switzerland

Received: 2 July 2014 / Accepted: 12 September 2014
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The CMS Detector



Muon Calorimeter

1400 chambers
DT(Barrel), CSC(Endcaps), RPC
1.3% res in Higgs $m_{4\mu}$ peak
>80% efficient for $p_T > 5$ GeV

EM Calorimeter

61,200 (7,324) Lead Tungstate
($PbWO_4$) crystals in EB(EE)
1-2% E-resolution for
 $H \rightarrow \gamma\gamma$ photons

Tracker

65 million pixels, 10 million silicon
strips, extends to $|\eta| = 2.4$
High granularity to reconstruct
secondary vertices from b-jets

Hadron Calorimeter

Sampling calorimeter (brass
abs/plastic scint)
36 barrel, 36 endcap wedges, forward
coverage exploits VBF Higgs



Higgs Signatures

Wide coverage of Higgs production/decay channels at CMS

	Incl.(ggH)	VBF-tag	VH-tag	ttH-tag*
$H \rightarrow ZZ$	✓	✓		✓
$H \rightarrow \gamma\gamma$	✓	✓	✓	✓
$H \rightarrow WW$	✓	✓	✓	✓
$H \rightarrow \tau\tau$	✓	✓	✓	✓
$H \rightarrow bb$		✓	✓	✓
$H \rightarrow Z\gamma$	✓	✓		
$H \rightarrow \mu\mu/ee$	✓	✓		

PhysRevD.89.092007

EPJ C 74(2014) 3076

JHEP01(2014)096

JHEP05(2014)104

PhysRevD.89.012003

PLB 726(2013)587

arXiv:1406.7663 (Sub PLB)

✓ Included in couplings combination

CMS-PAS-HIG-14-009

- ▶ >200 sub-channels
- ▶ >2500 nuisance parameters

*[JHEP 09(2014)087]

Rare production searches: $tHq(\gamma\gamma, bb)$
[HIG-14-001, HIG-14-015]

See dedicated talks covering the many **BSM** scenarios studied (J. Steggemann, A. de Oliveira, C. Vernieri, S. Padhi, D. Wood, C. Jessop)





Mass Measurement



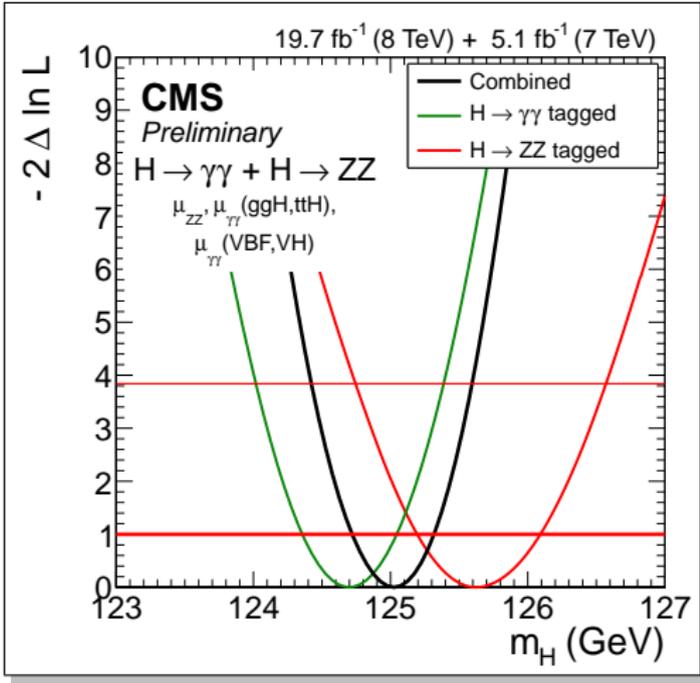
Higgs properties extracted at the best fit mass:

$125.03^{+0.26}_{-0.27}$ (stat) $^{+0.13}_{-0.15}$ (syst) GeV

- ▶ Combine high resolution channels, $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$.
- ▶ Reduce model dependence in fit by independently floating 3 signal modifiers...

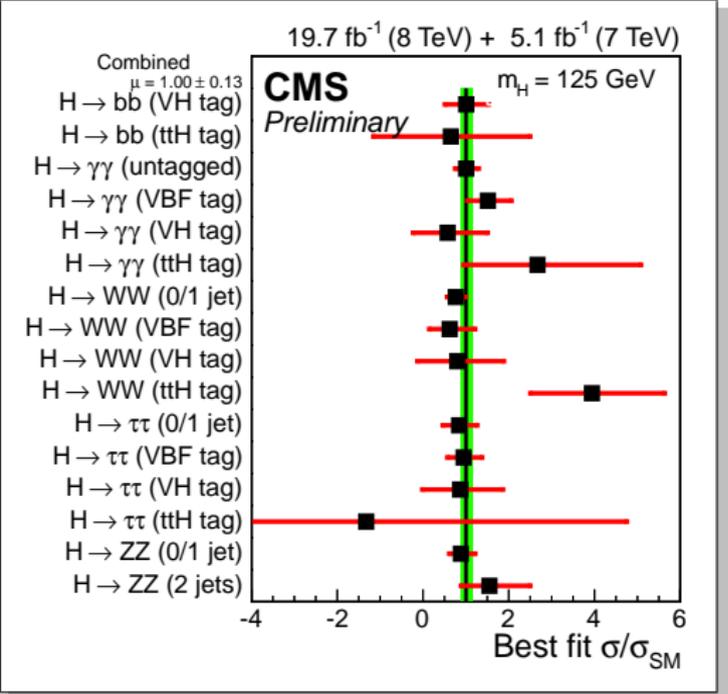
$\mu_{ggH, ttH} (H \rightarrow \gamma\gamma),$
 $\mu_{VBF, VH} (H \rightarrow \gamma\gamma),$
 $\mu (H \rightarrow ZZ^* \rightarrow 4l)$

$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ measurements compatible within 1.6σ .





Signal Strengths by Topology



Sub-combinations of production tagging and decay modes:

- ▶ $\chi^2/ndf = 10.5/16$
- ▶ p-value = 0.84 (wrt SM)

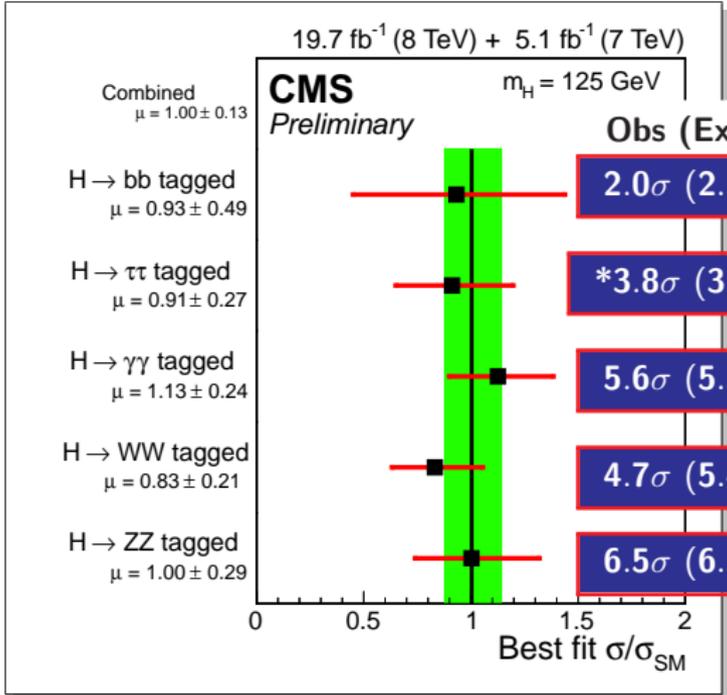
Combined best fit:

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

- ▶ Theory uncertainty includes QCD scales, α_s +PDF, BR, UE-PS.
- ▶ "Syst" includes all experimental uncertainties.



Signal Strengths by Decay



Sub-combinations by decay tags:

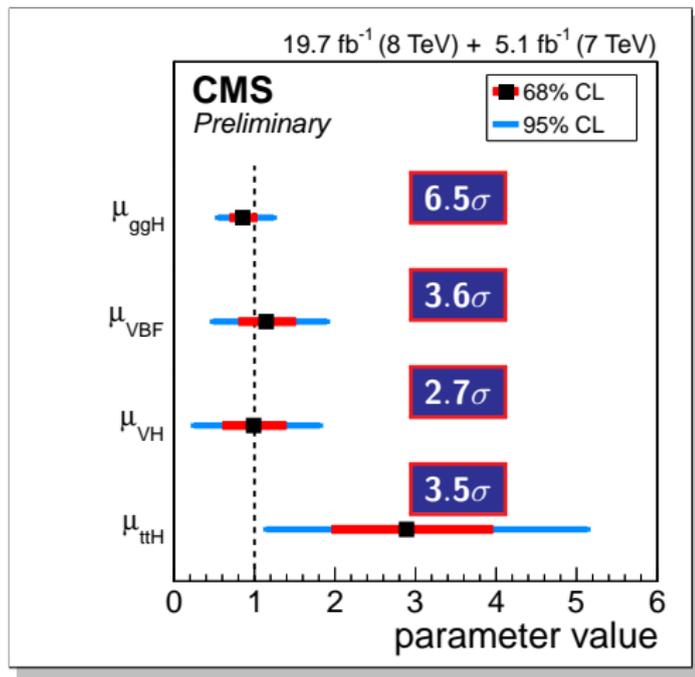
- ▶ $\chi^2/ndf = 0.9/5$
- ▶ p-value = 0.97

Signal well established in main boson decay modes. Evidence for Higgs decays to fermions.

* $H \rightarrow WW$ included as signal for $H \rightarrow \tau\tau$ result.

Fits of production XS:

- ▶ Assume SM values for all BRs (uncertainties included).
- ▶ Simultaneous fit for four production cross-section normalized to SM.
- ▶ Deviation from SM in μ_{ttH} at 2.1σ , driven by excesses in ttH tagged $H \rightarrow WW$ and $H \rightarrow \gamma\gamma$ analyses (see talk by P. Onyisi).

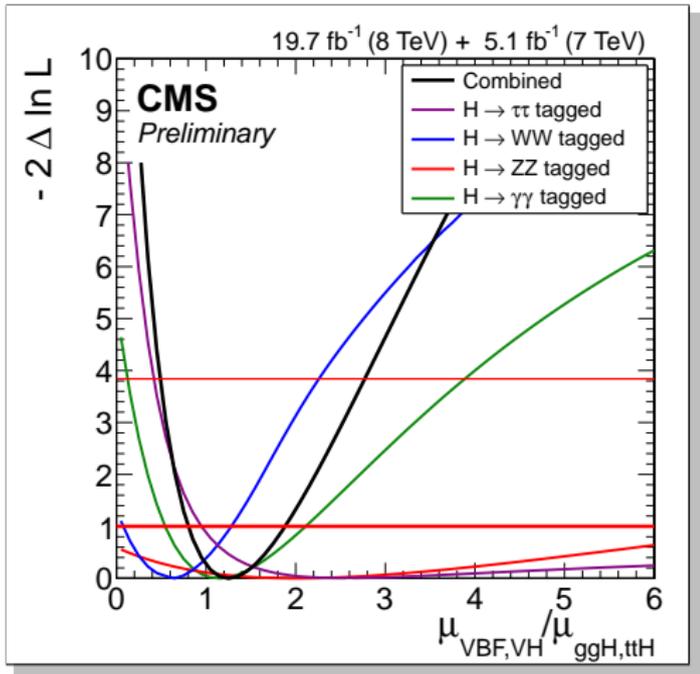


Ratio of V-boson to fermion modes:

- ▶ Group vector boson and fermion related production processes.
- ▶ BR uncertainties cancel in ratio of $\mu_{ggH,ttH}$ to $\mu_{ggH,ttH}$.

Observed (expected) Combined Ratio:

$$1.25^{+0.63}_{-0.45} \quad (1.00^{+0.49}_{-0.35})$$

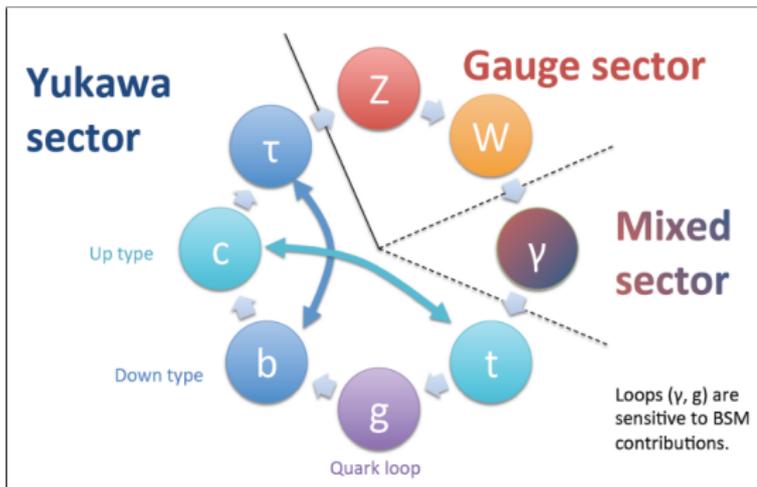


Unfold the signal rates per-production/per-decay back to underlying coupling modifiers

Framework appropriate for testing deviations from SM.

Assumptions:

- ▶ Single resonance at $m_X = 125.03$ GeV.
- ▶ Zero width (factorize prod x-sec and decay BR)
- ▶ Tensor structure $J^P = 0^+$



Based on recommendations from the LHC HXSWG (input from theorists and experimentalists) [arXiv:1307.1347]

Couplings

Total of eight independent parameters (7 partial and 1 total width) used to describe relevant production and decay mechanisms:

$$N(ii \rightarrow H \rightarrow ff) \approx \sigma(ii \rightarrow H) \cdot BR(H \rightarrow ff) \approx \frac{\Gamma_{ii} \Gamma_{ff}}{\Gamma_{tot}}$$

- ▶ Define scaling factors κ_i for couplings which map to partial widths:

$$\kappa_W, \kappa_Z, \kappa_b, \kappa_t, \kappa_\tau, \kappa_g, \kappa_\gamma$$

Loop couplings κ_γ and κ_g treated as effective couplings in some models.

NB: $\Gamma_{ii} = \kappa_i^2 \times \Gamma_{ii}^{SM}$ only for non-loop induced processes



Coupling vs Mass

Test compatibility of tree-level couplings with SM

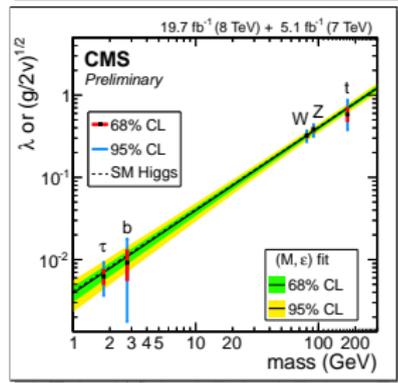
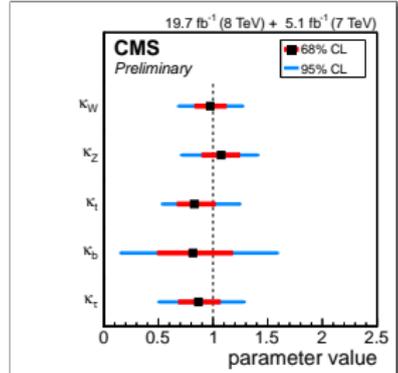
- ▶ One parameter per tree-level coupling.
- ▶ Assume SM structure for loops.
- ▶ Resolve VBF into W/Z, ggH into top/bottom contributions etc...

Parameterize couple modifiers in terms of v_{ev} parameter (M) and power relation of coupling with mass (ϵ)*

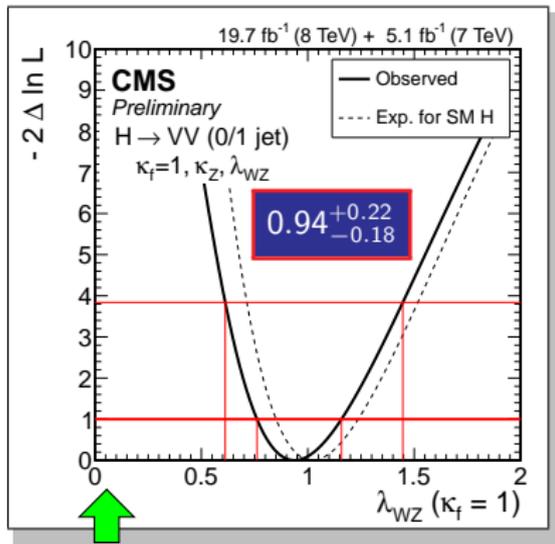
- ▶ $\kappa_{W,Z} : v_{ev} \times \frac{m_V^{2\epsilon}}{M^{1+2\epsilon}}$
- ▶ $\kappa_{t,b,\tau} : v_{ev} \times \frac{m_f^\epsilon}{M^{1+\epsilon}}$

SM recovered for $M = v_{ev} = 246.22 \text{ GeV}$,
 $\epsilon = 0 \implies \kappa_{W,Z,t,b,\tau} = 1$.

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



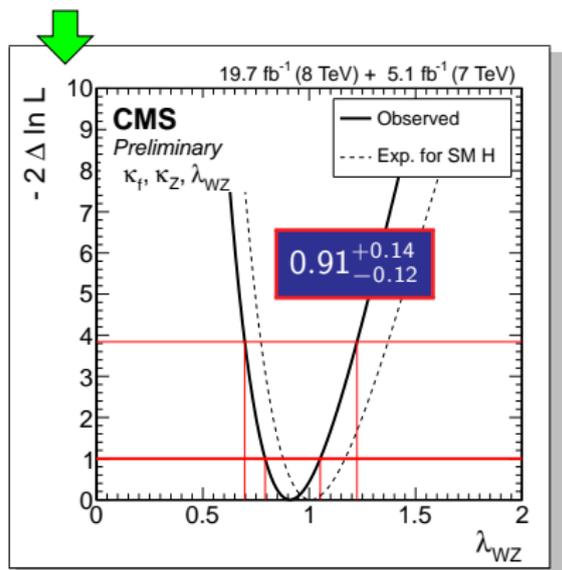
Custodial Symmetry



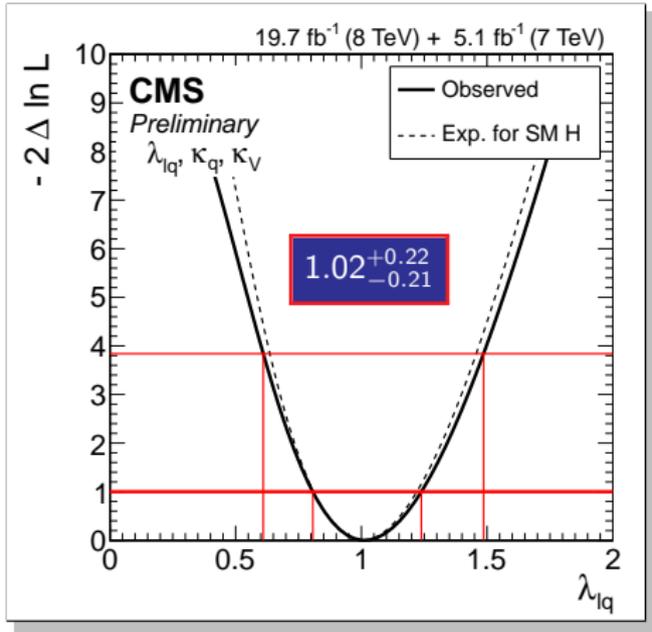
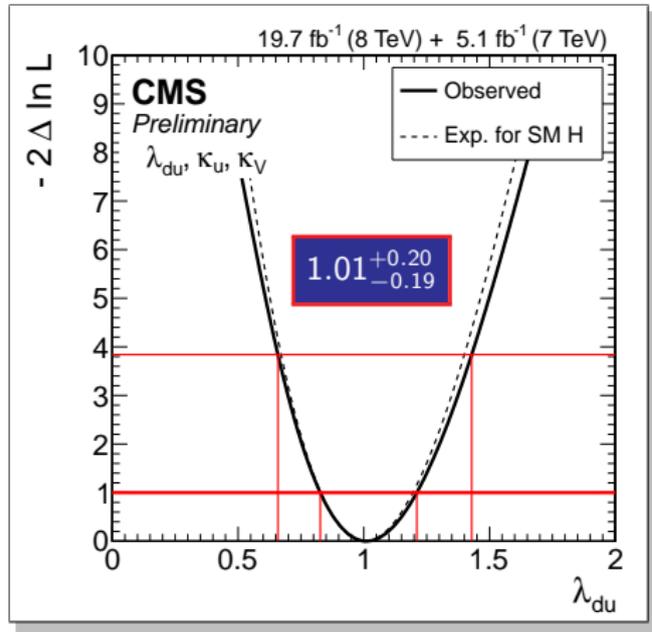
- ▶ **Direct contribution from WW and ZZ 0/1-jet channels (Fix κ_f = κ_t = κ_b = κ_τ = 1)**

Fit for λ_{WZ} = κ_W/κ_Z. In the SM, the ratio of W to Z couplings is nearly unaffected by loop corrections

- ▶ **Full combination (profile κ_f)**



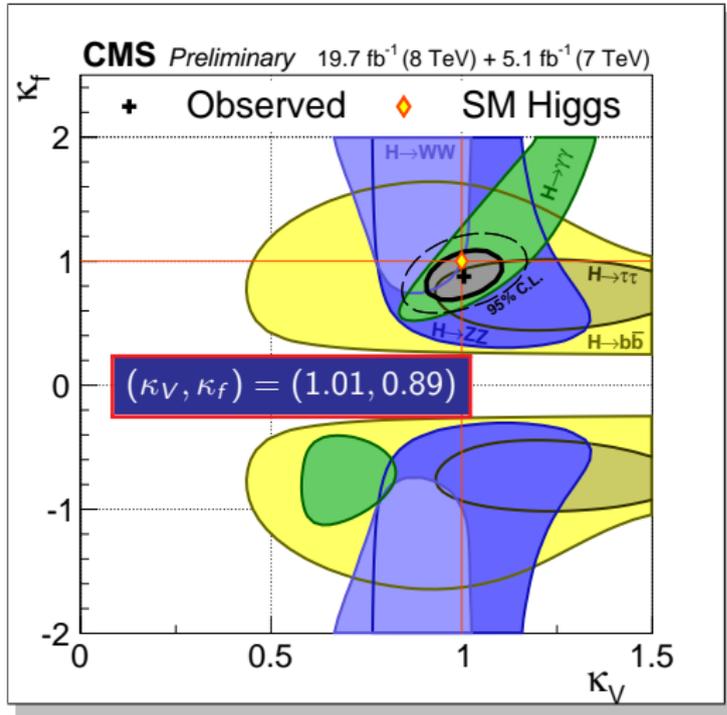
Couplings to fermions



λ_{du} = ratio between up to down type couplings.

λ_{lq} = ratio between lepton to quark couplings (lepton universality).

Vector bosons vs fermions



Collapse vector boson and fermion couplings into two modifiers:

- ▶ SM Corresponds to positive quadrant.
- ▶ $H \rightarrow \gamma\gamma$ decay loop sensitive to relative sign of top and W amplitudes.
- ▶ Interference impacts observed $H \rightarrow \gamma\gamma$ rate.

Combined 95% CI:

$$\kappa_V \in [0.88, 1.15]$$

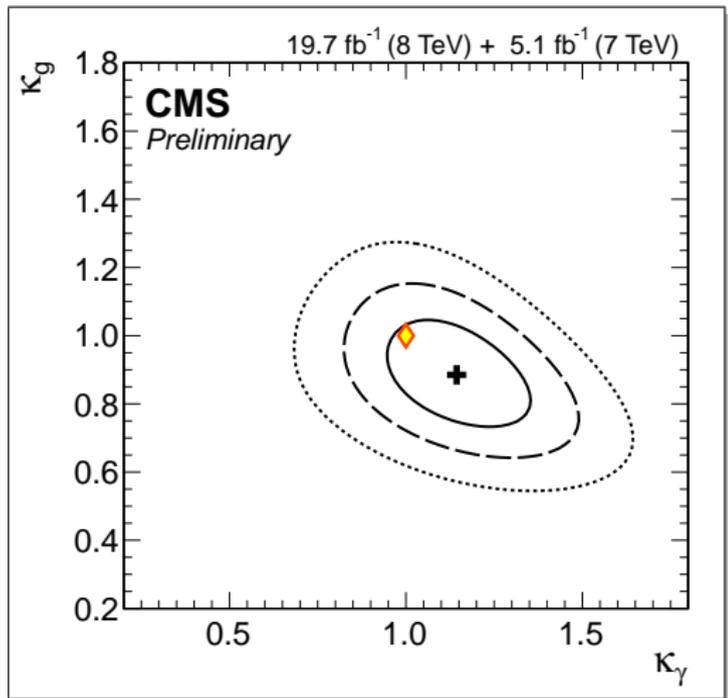
$$\kappa_f \in [0.64, 1.16]$$

New physics can show up in loop-mediated processes:

- ▶ Consider coupling to photons and gluons as effective couplings with modifiers κ_γ and κ_g .
- ▶ Fix all tree level couplings to SM values.
- ▶ Best fit parameters:

$$\kappa_g = 0.89 \pm 0.10$$

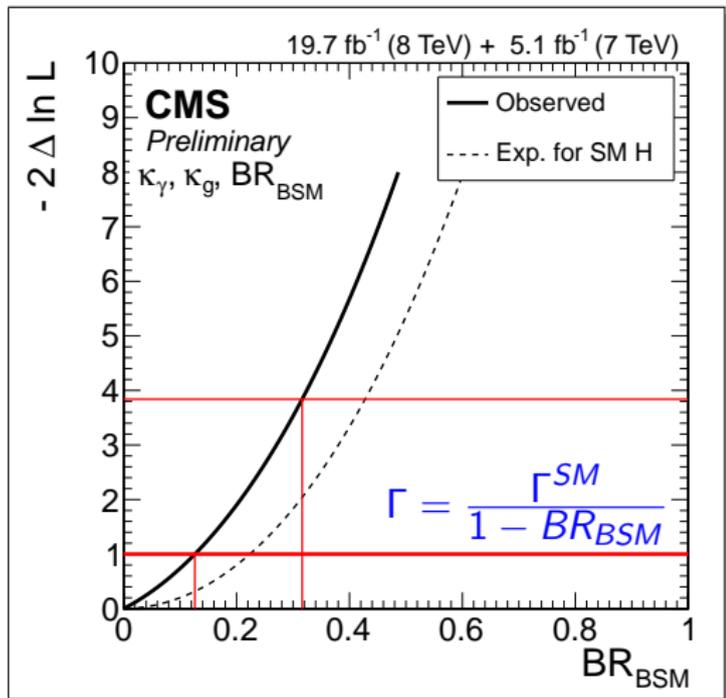
$$\kappa_\gamma = 0.15 \pm 0.13$$



New physics can show up in-loop mediated processes:

- ▶ Consider coupling to photons and gluons as effective couplings with modifiers κ_γ and κ_g .
- ▶ Fix all tree level couplings to SM values.
- ▶ Additionally allow for undetected decay width to new particles BR_{BSM} .

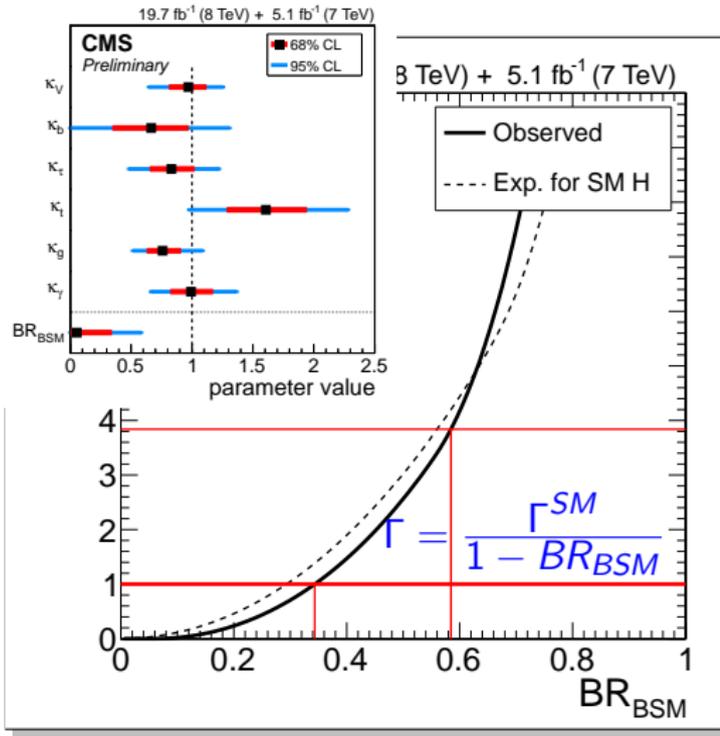
$$BR_{BSM} < 0.32 \text{ @95\% CL}$$



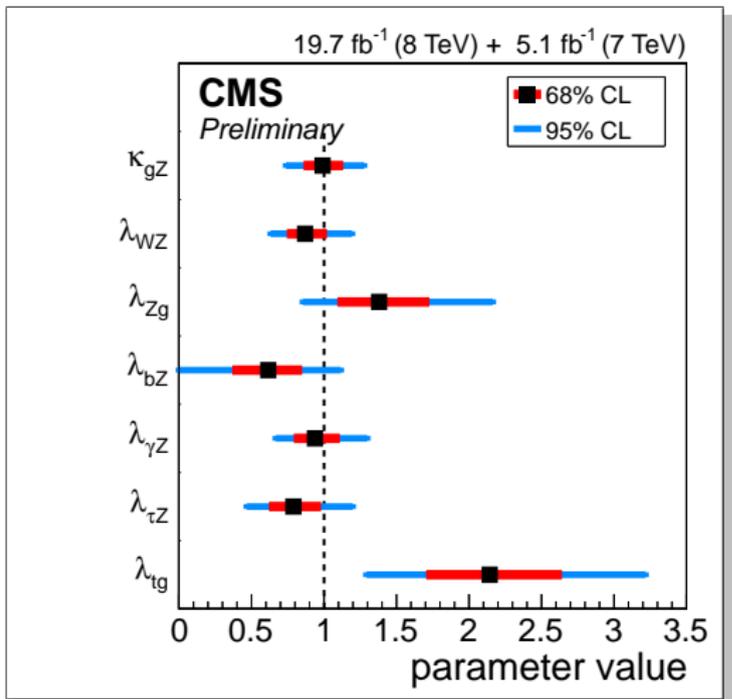
New physics can show up in loop-mediated processes:

- ▶ Consider coupling to photons and gluons as effective couplings with modifiers κ_γ and κ_g .
- ▶ **Float tree level couplings, restrict $k_V \leq 1$**
- ▶ Additionally allow for undetected decay width to new particles BR_{BSM} .

$BR_{BSM} < 0.58 \text{ @95\% CL}$



Generic modifier ratio model



Most general parameterization we have to test deviations from the SM:

- ▶ Take ratios of coupling modifiers, $\lambda_{ab} = \kappa_a / \kappa_b$.
- ▶ $\kappa_{gZ} = \kappa_g \times \kappa_Z / \kappa_H$.
- ▶ Allows for additional (invisible) widths from BSM physics with no additional assumptions.

Most significant deviation observed driven by excess in $t\bar{t}H$ channels since ggH coupling is effective in this model.



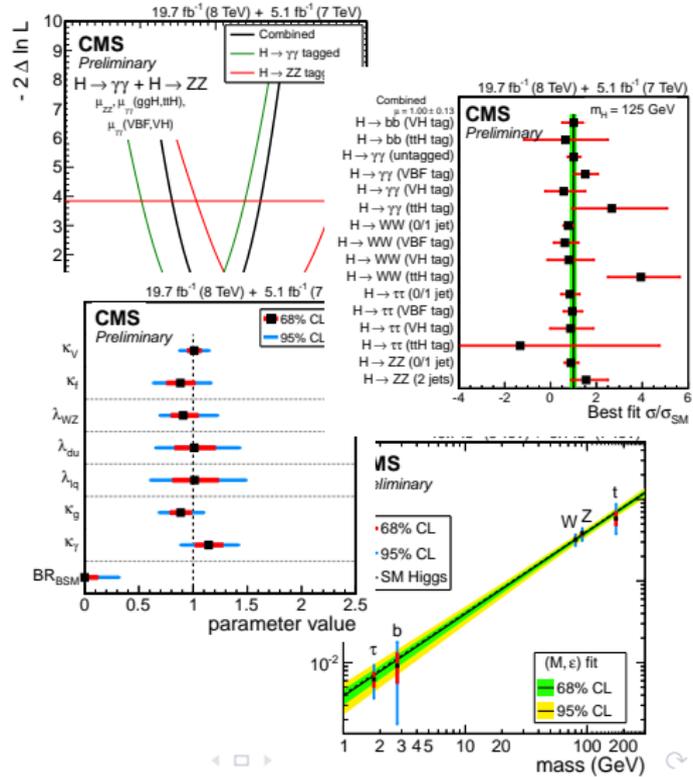
Summary



Higgs combination at CMS:

- ▶ Observation in decays to bosons
- ▶ Evidence for decays to fermions [Nat.Phys:10, 557-560 (2014)]
- ▶ $m_H = 125.03^{+0.26}_{-0.27}$ (stat) $^{+0.13}_{-0.15}$ (sys) GeV
 $\mu = 1.00 \pm 0.09$ (stat) $^{+0.08}_{-0.07}$ (theo) ± 0.07 (sys)
- ▶ Excess over SM seen in ttH largely from one channel.
- ▶ Several tests of compatibility show no significant deviations from the SM in Run-1.
- ▶ Still a long way from desired O(1%) uncertainties.

Many more talks on this Higgs boson and others which we haven't seen (yet?) this week...



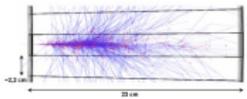


Thanks for your attention!

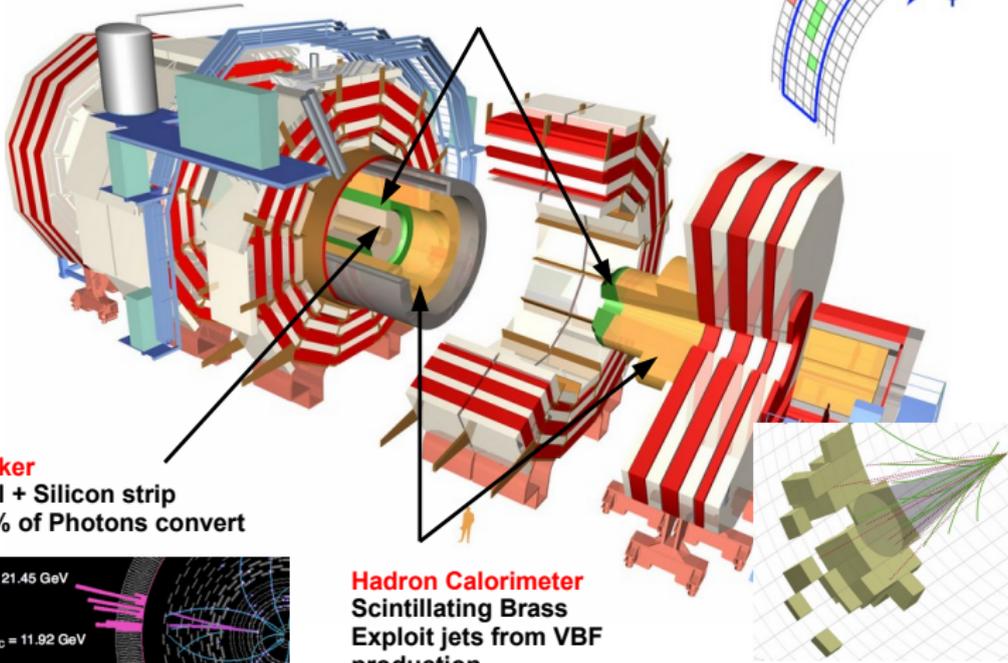
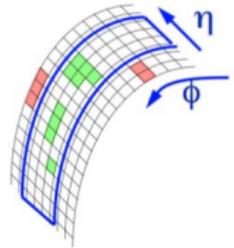


BACKUP SLIDES

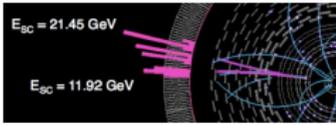
The CMS Detector



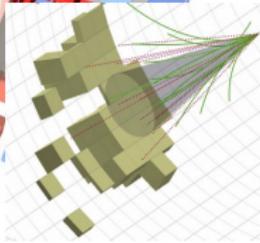
EM Calorimeter
Lead tungstate (PbWO₄) crystals
61 200 (EB) / 7 324 (EE)



Tracker
Pixel + Silicon strip
~50% of Photons convert

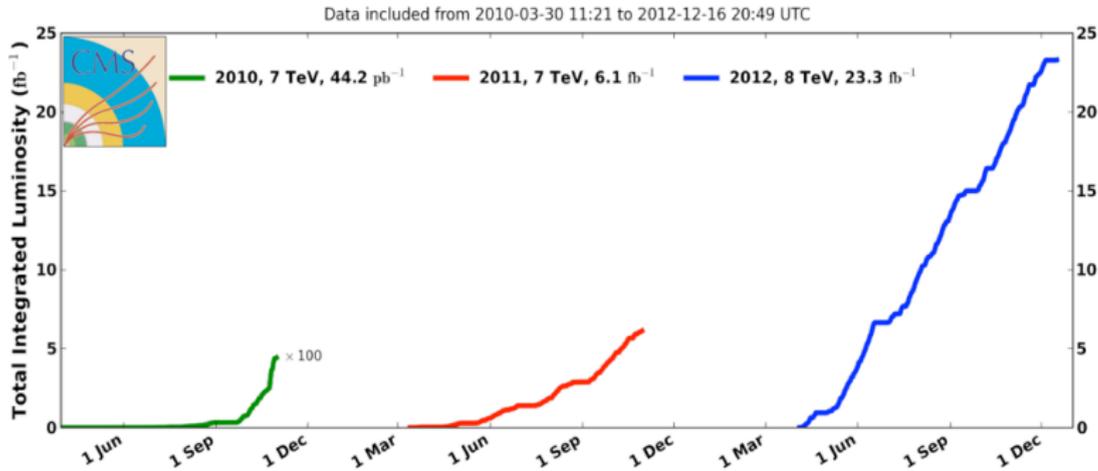


Hadron Calorimeter
Scintillating Brass
Exploit jets from VBF production





CMS Data Taking

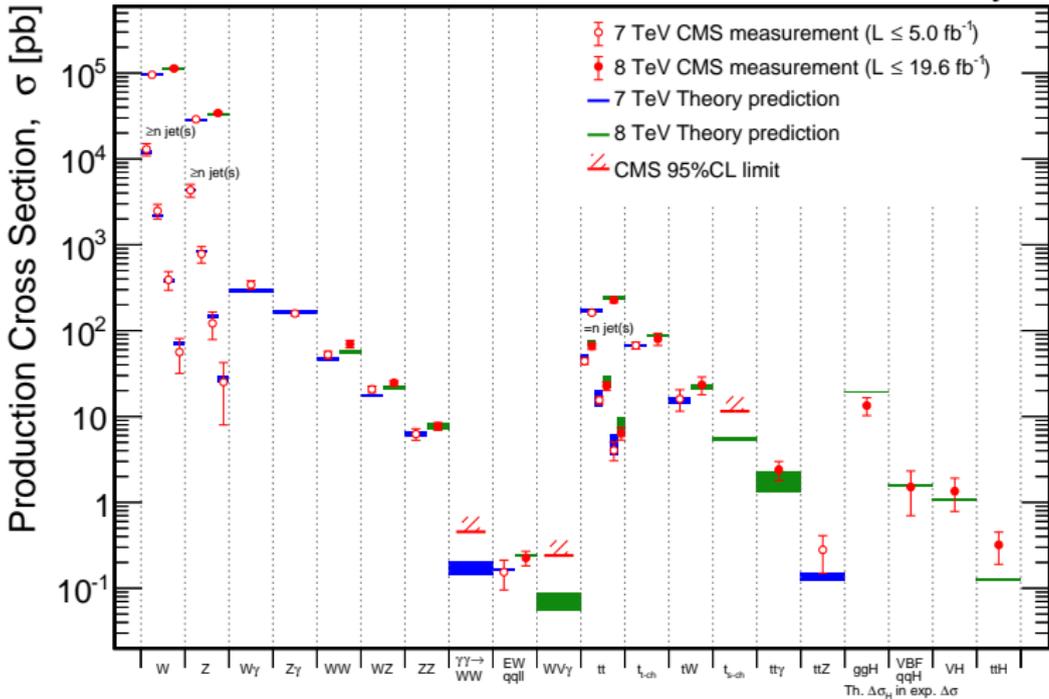




SM Production

Feb 2014

CMS Preliminary



Navigation icons: back, forward, search, etc.



Channels in the Combination



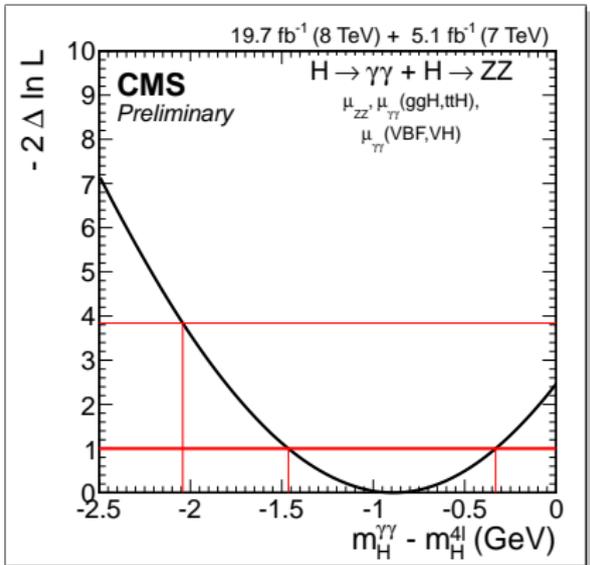
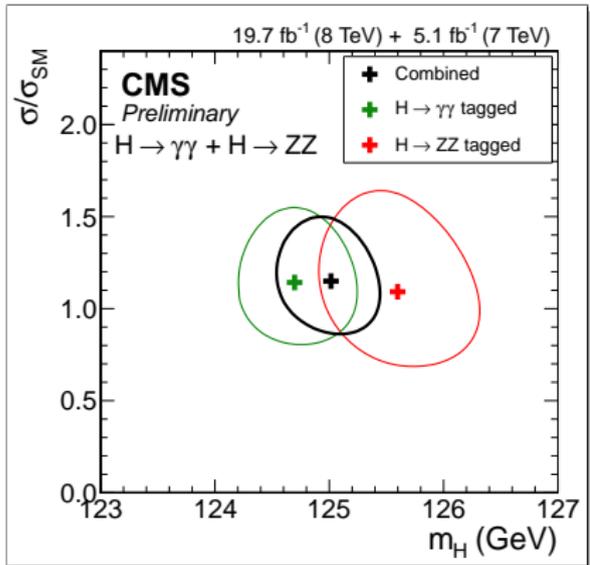
Decay tag and production tag		Expected signal composition	$\sigma_{sig}/m_{H^{\pm}}$	Luminosity (fb^{-1})	
				7TeV	8TeV
H $\rightarrow \gamma\gamma$ [20], Section 2.1				5.1	19.7
$\gamma\gamma$	Untagged	76-93% ggH	0.8-2.1%	4	5
	2-jet VBF	50-80% VBF	1.0-1.3%	2	3
	Leptonic VH	$\approx 95\%$ VH (WH/ZH ≈ 5)	1.3%	2	2
	E_T^{miss} VH	70-80% VH (WH/ZH ≈ 1)	1.3%	1	1
	2-jet VH	$\approx 65\%$ VH (WH/ZH ≈ 5)	1.0-1.3%	1	1
	Leptonic tH	$\approx 95\%$ tH	1.1%	1 [†]	1
Multijet tH	>90% tH	1.1%	1 [†]	1	
H $\rightarrow ZZ^{(*)} \rightarrow 4\ell$ [18], Section 2.2				5.1	19.7
4 μ , 2e2 μ , 4e	2-jet	42% VBF + VH		3	3
	Other	$\approx 90\%$ ggH	1.3, 1.8, 2.2% [†]	3	3
H $\rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$ [17], Section 2.3				4.9	19.4
ee + $\mu\mu$, $e\mu$	0-jet	96-98% ggH	ep: 16% [†]	2	2
	1-jet	82-84% ggH	ep: 17% [†]	2	2
	2-jet VBF	78-86% VBF		2	2
	2-jet VH	31-40% VH		2	2
3 ℓ 3 ν WH	SF-SS, SF-CS	$\approx 100\%$ WH, up to 20% $\tau\tau$		2	2
$\ell\ell + \ell'\nu$ ZH	eee, ee μ , $\mu\mu\mu$, $\mu\mu e$	$\approx 100\%$ ZH		4	4
H $\rightarrow \tau\tau$ [19], Section 2.4				4.9	19.7
$e\nu_e, \mu\nu_e$	0-jet	$\approx 98\%$ ggH	11-14%	4	4
	1-jet	70-80% ggH	12-16%	5	5
	2-jet VBF	75-83% VBF	13-16%	2	4
$\tau\nu_e$	1-jet	67-70% ggH	10-12%	-	2
	2-jet VBF	80% VBF	11%	-	1
$e\mu$	0-jet	$\approx 98\%$ ggH, 23-30% WW	16-20%	2	2
	1-jet	75-80% ggH, 31-38% WW	18-19%	2	2
	2-jet VBF	79-94% VBF, 37-43% WW	14-19%	1	2
ee, $\mu\mu$	0-jet	88-98% ggH		4	4
	1-jet	74-78% ggH, $\approx 17\%$ WW +		4	4
2-jet CJV	$\approx 50\%$ VBF, $\approx 45\%$ ggH, 17-24% WW +		2	2	
$\ell\ell + LL^* ZH$	LL = $\tau\nu_e, \tau\nu_e, \ell\nu_e, e\mu$	$\approx 15\%$ (70%) WW for LL = $\ell\nu_e$ (ep)		8	8
$\ell + \tau\nu_e, \tau\nu_e$ WH		$\approx 98\%$ VH, ZH/WH ≈ 0.1		2	2
$\ell + \ell'\nu_e, \tau\nu_e$ WH		ZH/WH $\approx 5\%$, 9-11% WW		2	4
VH with H \rightarrow bb [16], Section 2.5				5.1	18.9
W($\ell\nu$)bb	$p_T(V)$ bins	$\approx 100\%$ VH, 96-98% WH		4	6
W($\nu_e\nu_e$)bb		93% WH		-	1
Z($\ell\ell$)bb	$p_T(V)$ bins	$\approx 100\%$ ZH	$\approx 10\%$	4	4
Z($\nu\nu$)bb	$p_T(V)$ bins	$\approx 100\%$ VH, 62-76% ZH		2	3
tH with H \rightarrow hadrons [14, 28], Section 2.6				5.0	19.3
H \rightarrow bb	t \bar{t} lepton+jets	$\approx 90\%$ bb but $\approx 24\%$ WW in $\geq 6j + 2b$		7	7
	t \bar{t} dilepton	45-85% bb, 8-35% WW, 4-14% $\tau\tau$		2	3
H $\rightarrow \tau\nu_e, \tau\nu_e$	t \bar{t} lepton+jets	68-80% $\tau\tau$, 13-22% WW, 5-13% bb		-	6
tH with H \rightarrow leptons [29], Section 2.6				-	19.6
2 ℓ -SS		WW/ $\tau\tau \approx 3$		-	6
3 ℓ		WW/ $\tau\tau \approx 3$		-	2
4 ℓ		WW : $\tau\tau$: ZZ $\approx 3 : 2 : 1$		-	1

[†] Events fulfilling the requirements of either selection are combined into one category.
^{††} Values for analyses dedicated to the measurement of the mass that do not use the same categories and/or observables.
^{†††} Composition in the regions for which the ratio between signal and background $s/(s+b) \approx 0.05$.

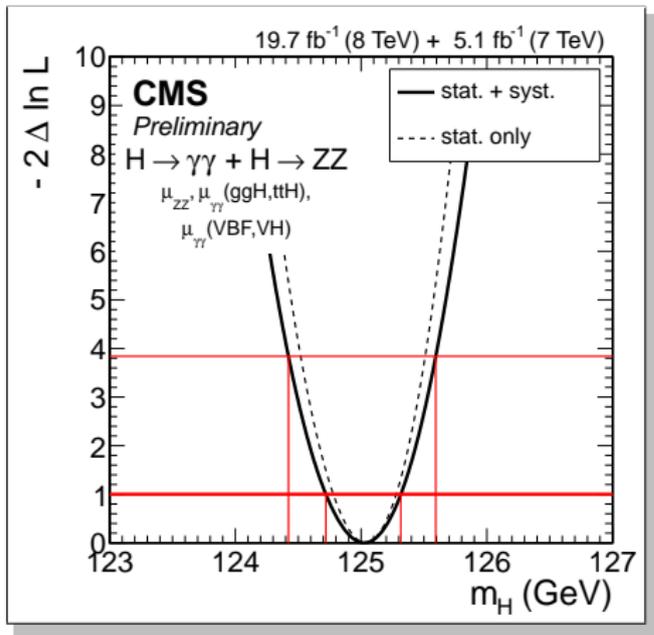




$H \rightarrow \gamma\gamma - H \rightarrow ZZ$ m_H Compatibility

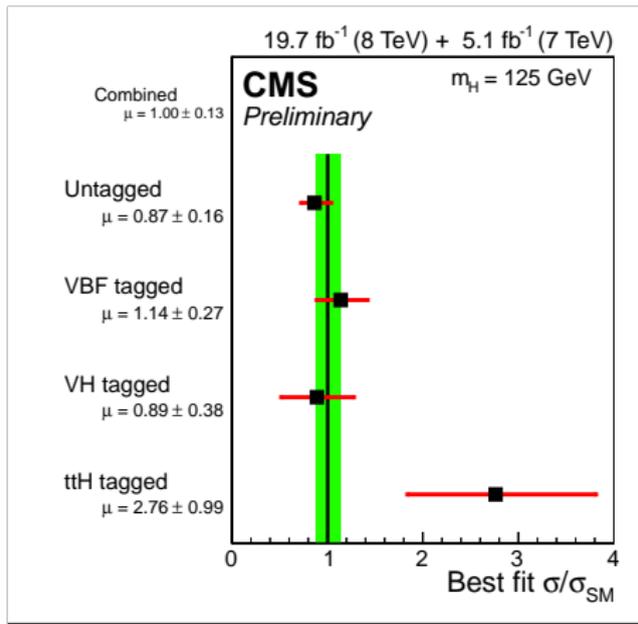


m_H Measurement Systematics/Statistics



- ▶ $m^{H \rightarrow \gamma\gamma} = 124.7 \pm 0.31$ (stat) ± 0.15 (sys) GeV
- ▶ $m^{H \rightarrow ZZ} = 125.6 \pm 0.4$ (stat) ± 0.2 (sys) GeV
- ▶ $m_H = 125.03^{+0.26}_{-0.27}$ (stat) $^{+0.13}_{-0.15}$ (sys) GeV

- ▶ Higgs production by Tags
- ▶ Tags are not 100% pure in production process
- ▶ ttH here is not the same as in separate ttH combination [JHEP 09(2014)087]



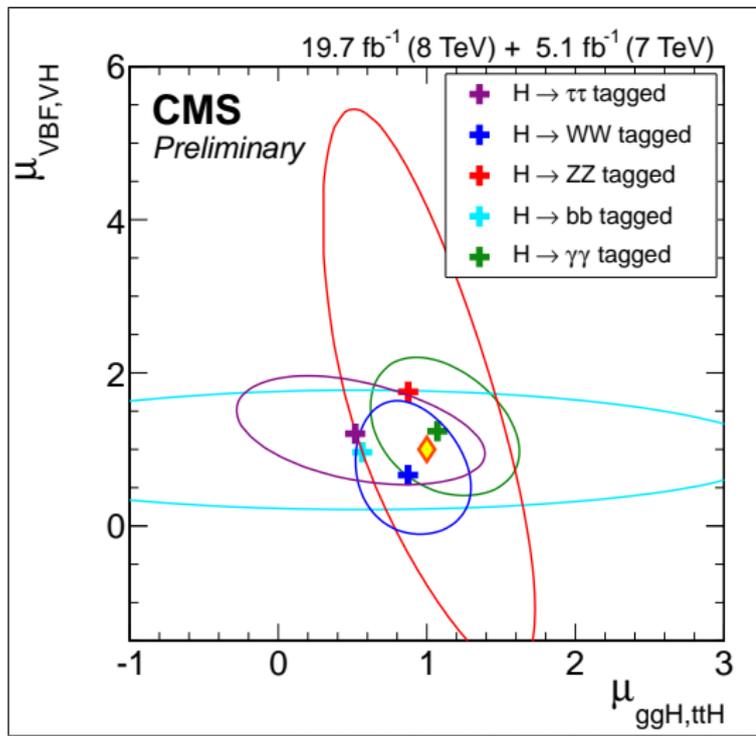
Vector Boson vs Gluon Fusion Production



Compare fermion and vector boson based production modes

- ▶ Tagged sub-channels provide separation of these modes
- ▶ Combine fermion ($\mu_F = \mu_{ggH, ttH}$) and vector boson ($\mu_V = \mu_{VBF, VH}$)

SM inside 1σ contours

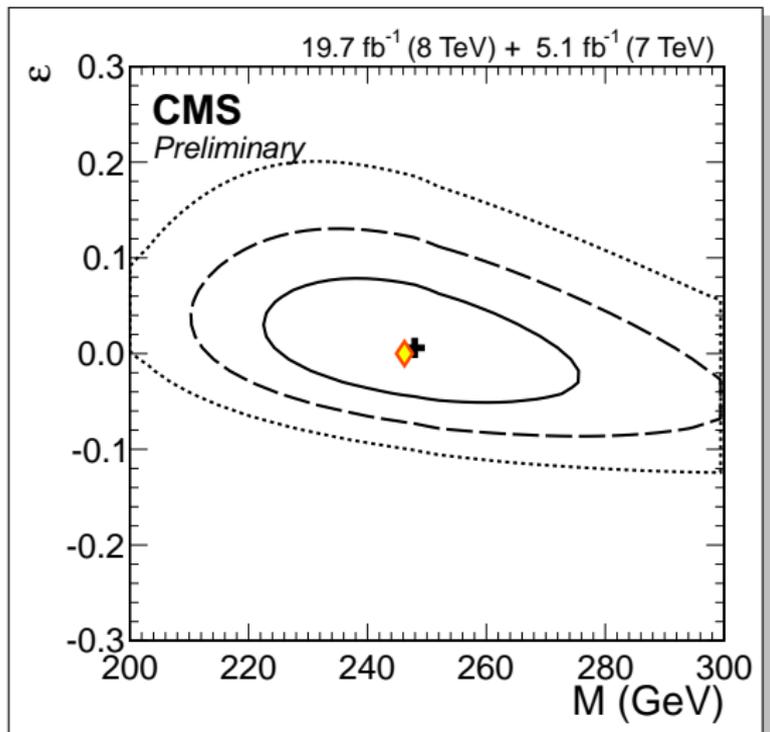


Numerical values

The best-fit results for independent signal strengths corresponding to the four main production processes, ggH, VBF, VH, and ttH; the expected sensitivities and observed significances with respect to background-only hypothesis ($\mu = 0$), and the pull of the observation with respect to the SM hypothesis ($\mu = 1$). These results assume that the relative values of the branching fractions are those predicted by the SM.

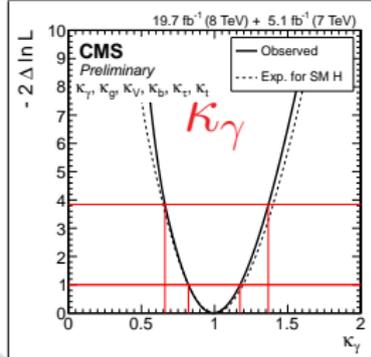
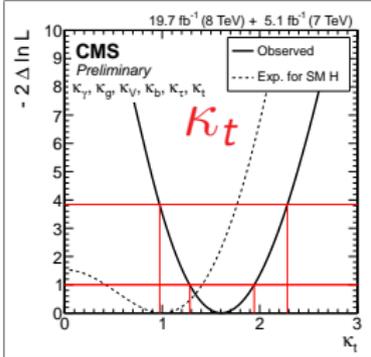
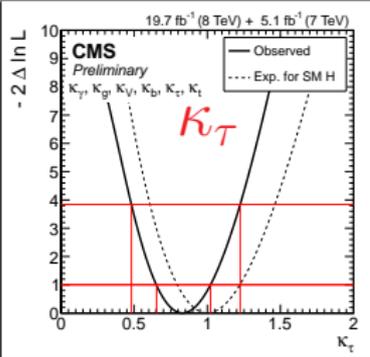
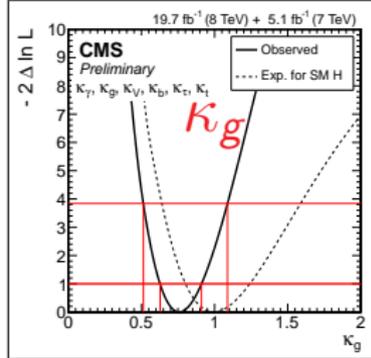
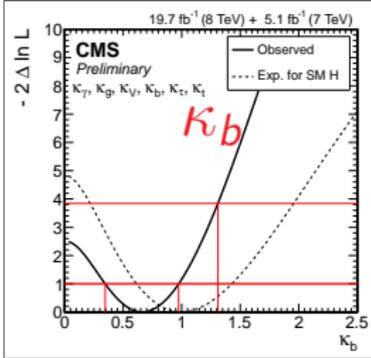
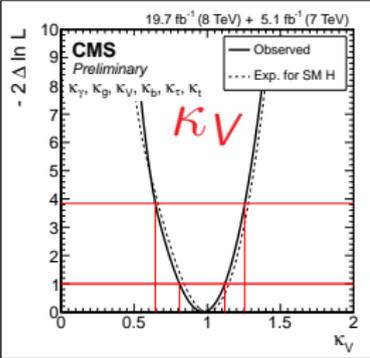
Parameter	Best fit result (68% CL) for full combination	Observed significance (σ)	Expected sensitivity (σ)	Pull to SM hypothesis (σ)
μ_{ggH}	$0.85^{+0.19}_{-0.17}$	6.5	7.5	-0.8
μ_{VBF}	$1.15^{+0.37}_{-0.35}$	3.6	3.3	0.4
μ_{VH}	$1.00^{+0.40}_{-0.40}$	2.7	2.7	0.0
μ_{ttH}	$2.93^{+1.04}_{-0.97}$	3.5	1.2	2.1

5 Parameter (M, ϵ) fit

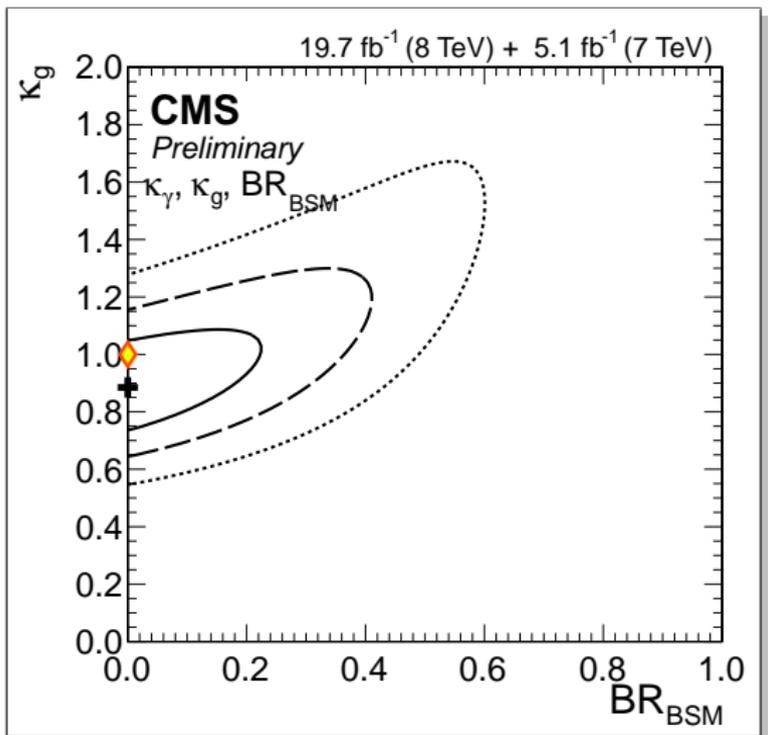




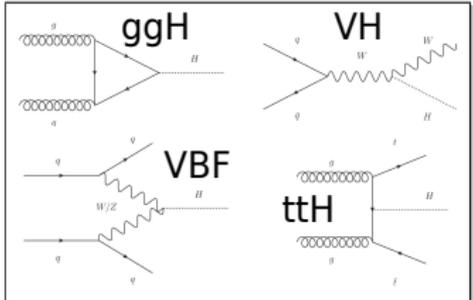
Generic Search for Deviations



New Physics in Loops

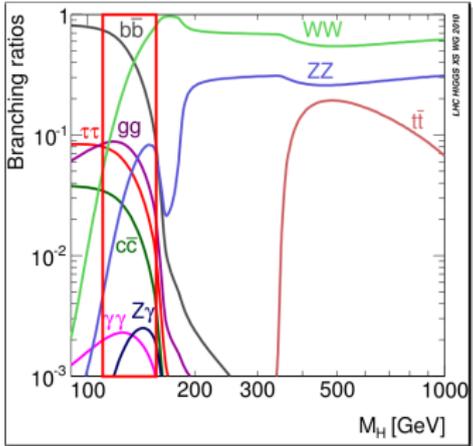


Measurements



A low mass Higgs boson provides a rich environment for measuring properties.

- ▶ Uniform statistical treatment for all higgs-channels.
- ▶ Test-statistic for measurements is ratio of profiled likelihoods



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

- ▶ 68% confidence intervals interpreted from $\{a : q(a) \leq 1\}$



Couplings Summary



Model		Best-fit result			Comment
Parameters	Table in Ref. [27]	Parameter	68% CL	95% CL	
$\kappa_Z, \lambda_{WZ} (\kappa_f=1)$	-	λ_{WZ}	$0.94^{+0.22}_{-0.18}$	[0.61,1.45]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ using ZZ and 0/1-jet WW channels.
$\kappa_Z, \lambda_{WZ}, \kappa_f$	44 (top)	λ_{WZ}	$0.91^{+0.14}_{-0.12}$	[0.70,1.22]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from full combination.
κ_V, κ_f	43 (top)	κ_V	$1.01^{+0.07}_{-0.07}$	[0.88,1.15]	κ_V scales couplings to W and Z bosons.
		κ_f	$0.89^{+0.14}_{-0.13}$	[0.64,1.16]	κ_f scales couplings to all fermions.
κ_g, κ_γ	48 (top)	κ_g	$0.89^{+0.10}_{-0.10}$	[0.69,1.10]	Effective couplings to gluons (g) and photons (γ).
		κ_γ	$1.15^{+0.13}_{-0.13}$	[0.89,1.42]	
$\kappa_g, \kappa_\gamma, BR_{BSM}$	48 (middle)	BR_{BSM}	≤ 0.13	[0.00,0.32]	Branching fraction for BSM decays.
$\kappa_V, \lambda_{du}, \kappa_u$	46 (top)	λ_{du}	$1.01^{+0.20}_{-0.19}$	[0.66,1.43]	$\lambda_{du} = \kappa_u/\kappa_d$, relating up-type and down-type fermions.
$\kappa_V, \lambda_{\ell q}, \kappa_q$	47 (top)	$\lambda_{\ell q}$	$1.02^{+0.22}_{-0.21}$	[0.61,1.49]	$\lambda_{\ell q} = \kappa_\ell/\kappa_q$, relating leptons and quarks.
$\kappa_g, \kappa_\gamma, \kappa_V, \kappa_b, \kappa_\tau, \kappa_t$	Similar to 50 (top)	κ_g	$0.76^{+0.15}_{-0.13}$	[0.51,1.09]	Down-type quarks (via b). Charged leptons (via τ). Up-type quarks (via t).
		κ_γ	$0.99^{+0.18}_{-0.17}$	[0.66,1.37]	
		κ_V	$0.97^{+0.15}_{-0.16}$	[0.64,1.26]	
		κ_b	$0.67^{+0.31}_{-0.32}$	[0.00,1.31]	
		κ_τ	$0.83^{+0.19}_{-0.18}$	[0.48,1.22]	
κ_t	$1.61^{+0.33}_{-0.32}$	[0.97,2.28]			
as above plus BR_{BSM} and $\kappa_V \leq 1$	-	BR_{BSM}	≤ 0.34	[0.00,0.58]	

