BEH Boson (CMS)

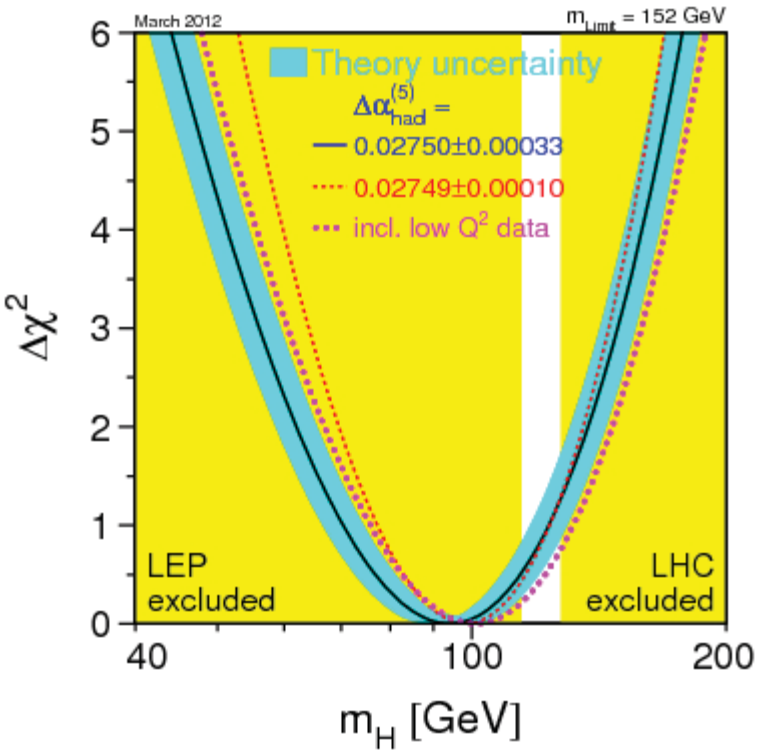
From Discovery to precision measurements

Outline

- Ἐν ἀρχῇ ἦν ὁ ...., **a bit of history: ..**
- **..Higgs properties after Run I**
- **First results at 13 TeV**
- **Implications**
- **Future perspectives**

History: a long hunt since 1969

The legacy of LEP, SLC, Tevatron, first LHC searches on SM BEH state

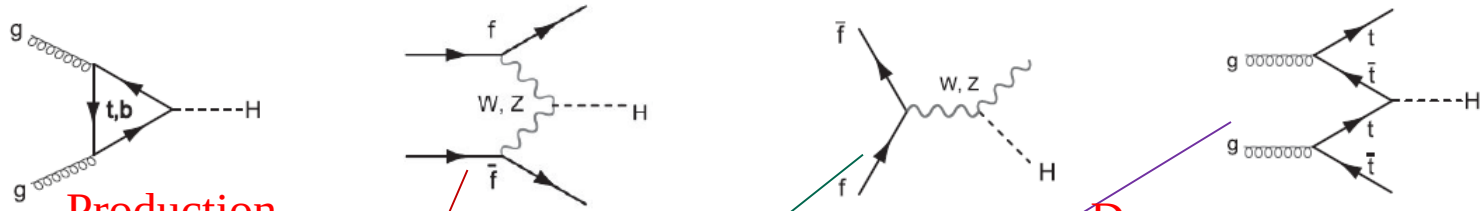


Fits to SM precision measurements prefer a low mass value and exclusion regions are compatible with the fit

Higgs properties after RUN I

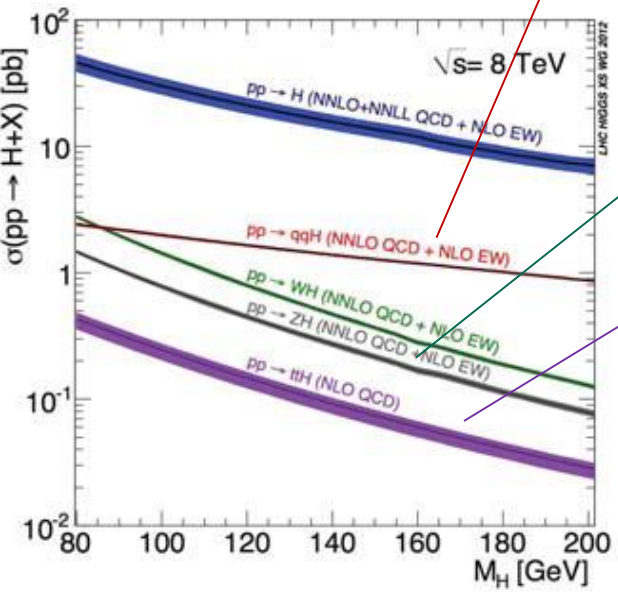
The expectations at LHC

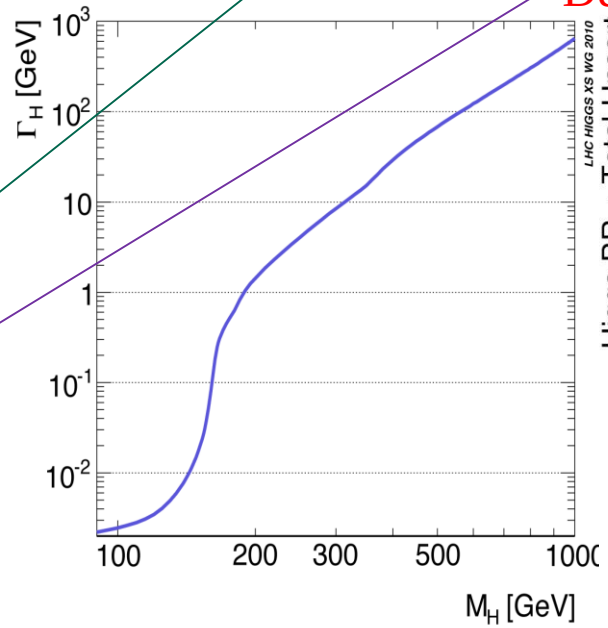
gluon**g**luon**F**usion **V**ector **B**oson **F**usion **VH** (Higgs-strahlung) **ttH**

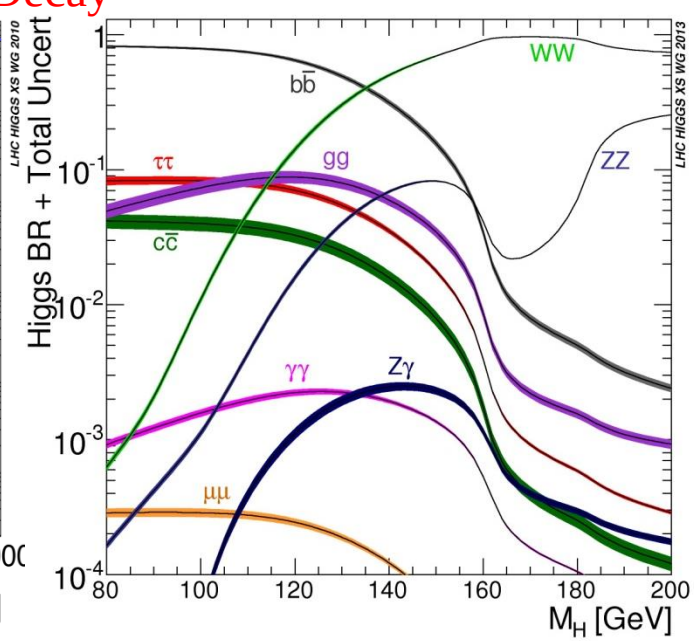


Production

Decay







SM predictions of production/decay properties depend on the mass

Higgs properties after RUN I

The mass

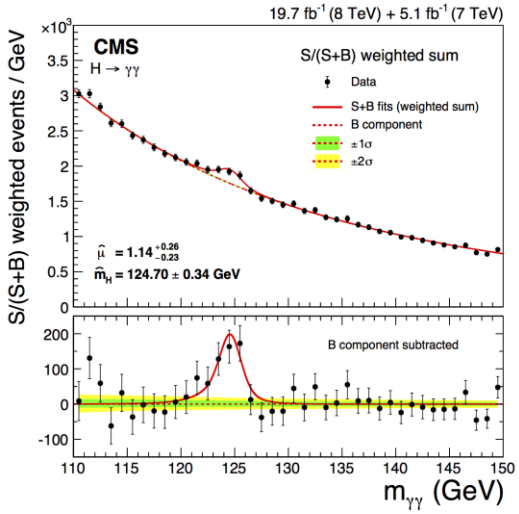
Two final states with peaks: the same channels relevant for the discovery are giving a precise measurement of the mass.

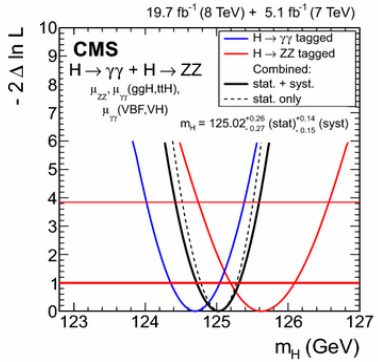
H→γγ EPCJ 74 (2014) 3076

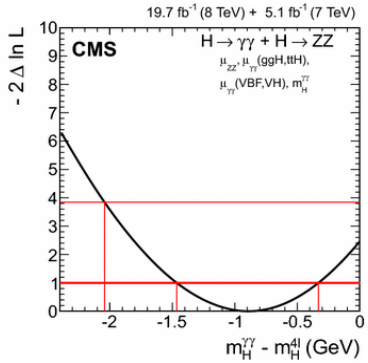
124.70±0.31(stat)±0.15(syst) GeV

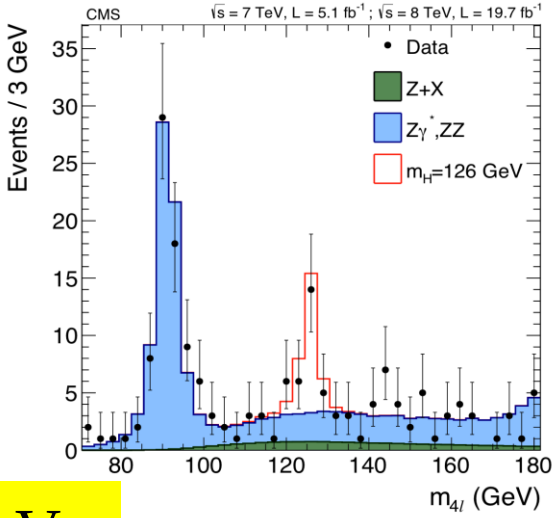
H→ZZ*→4l: PRD 89 (2014) 092007

125.6±0.4(stat)±0.2(syst) GeV









$125.02\ ^{+0.26}_{-0.27}$ (stat) $^{+0.14}_{-0.15}$(syst) GeV

NB1: dominated by stat. errors; systematic from detector calibr. (Energy/momentum scale)

NB2: difference within ~1.6 σ

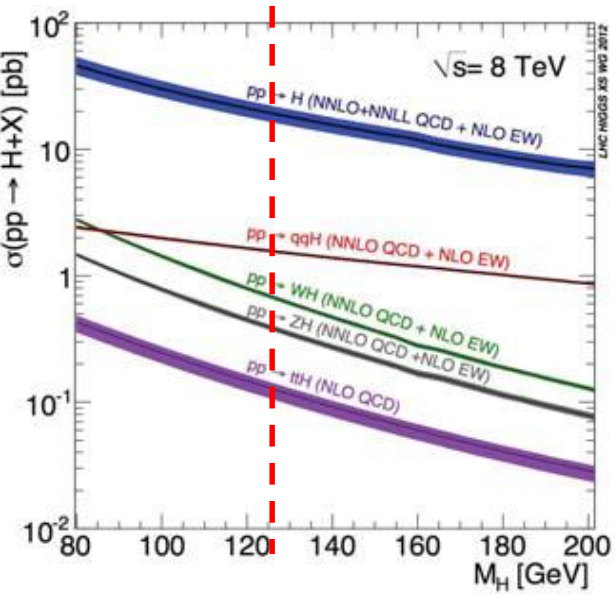
NB3:evaluations from other channels (less precise) compatible with this result .

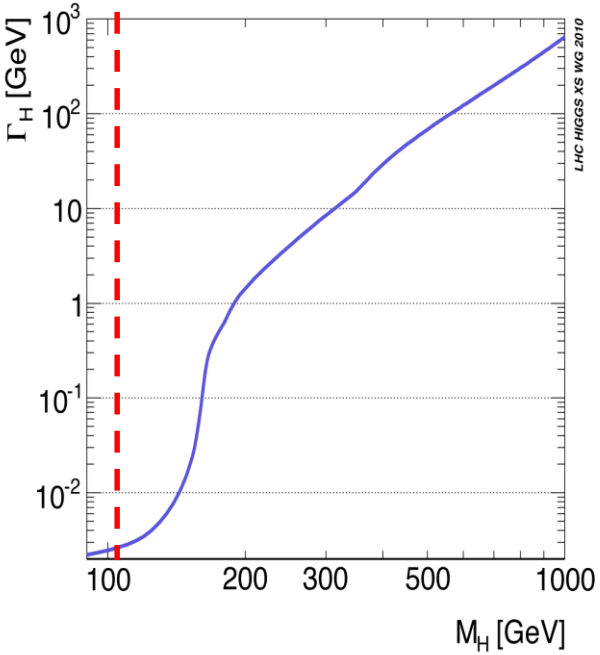
NB4: ATLAS+CMS PRL 114 191803 (2015) **m_H=125.09±0.24 (± 0.21±0.11)**

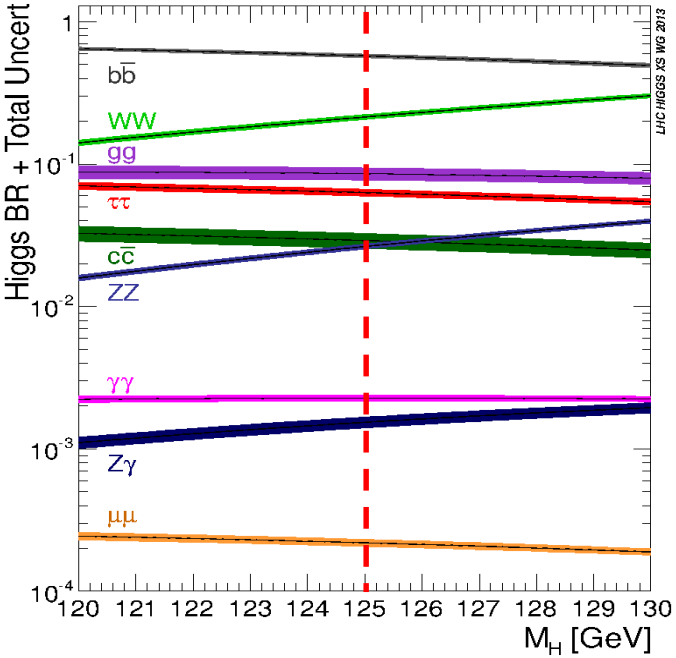
Higgs properties after RUN I

The mass

Once mass is known SM predicts all production/decay properties







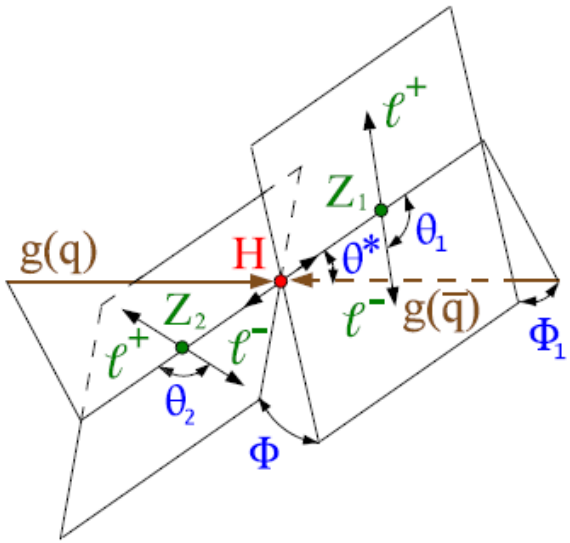
Higgs properties after RUN I

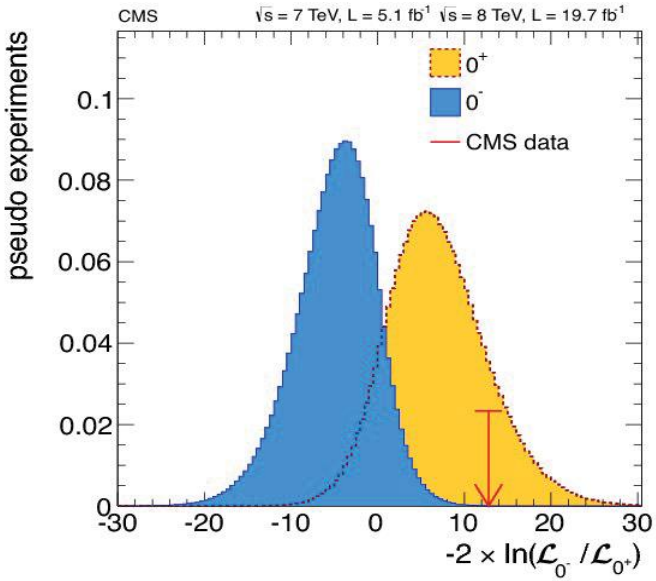
Spin-parity

PRD 89 (2014) 092007

Crucial to determine the nature of the particle:
it is a BEH boson if it is a scalar : is $J^P=0^+$ hypothesis the most probable?

Variables used to discriminate: Φ $\theta_1\theta_2$
Combining all the discriminant observables, define the signal plus background likelihood functions $\mathcal{L}_{J^P}$ for a given J^P hypothesis.
Test statistics to compare that hypothesis with the SM one (0^+) is q= -ln ($\mathcal{L}_{J^P}$ / $\mathcal{L}_{0+}$)





The expected distributions of q for both hypotheses are obtained with Monte Carlo pseudo-experiments. From the ratio of cumulative probabilities
$P_{J^P} = P(q > q_{obs}|J^P)$

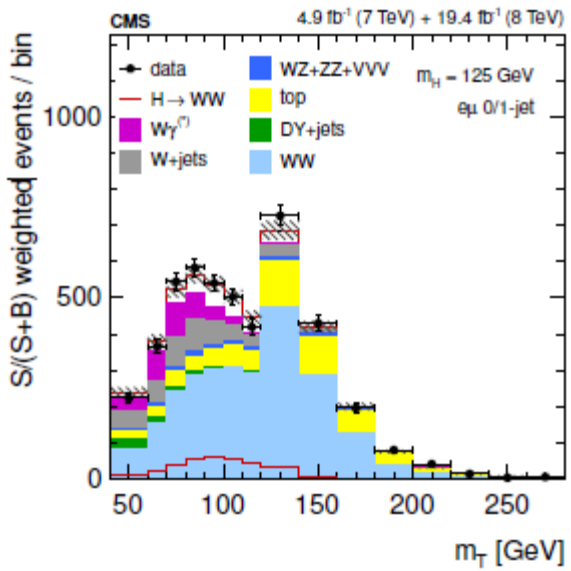
the hypothesis 0^- is excluded at the 99.9% C. L.

Higgs properties after RUN I

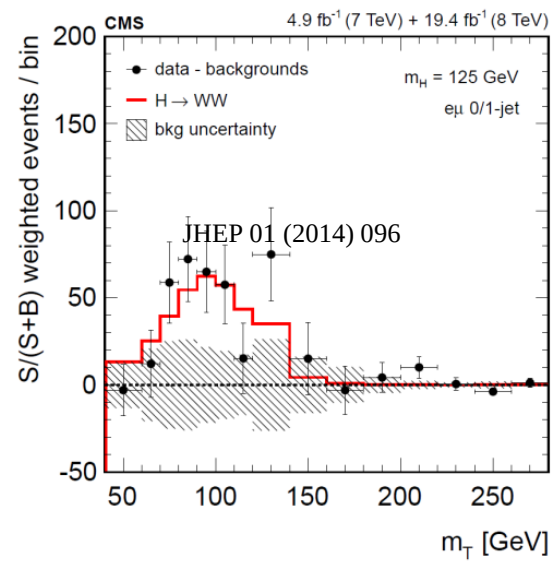
Other Boson channel: WW

For m_h= 125 GeV : WW 2nd largest SM Branching Ratio
Due to background ⇒ only H →WW →lν lν (no invariant mass) : m_{ll} and

$$m_T = \sqrt{2 p_T^{ll} E_T^{miss} (1 - \cos \Delta\phi_{ll, E_T^{miss}})}$$



Observed (expected) Significance w.r.t. bckg only hypothesis: 4.3 σ (5.8) @ 125.6



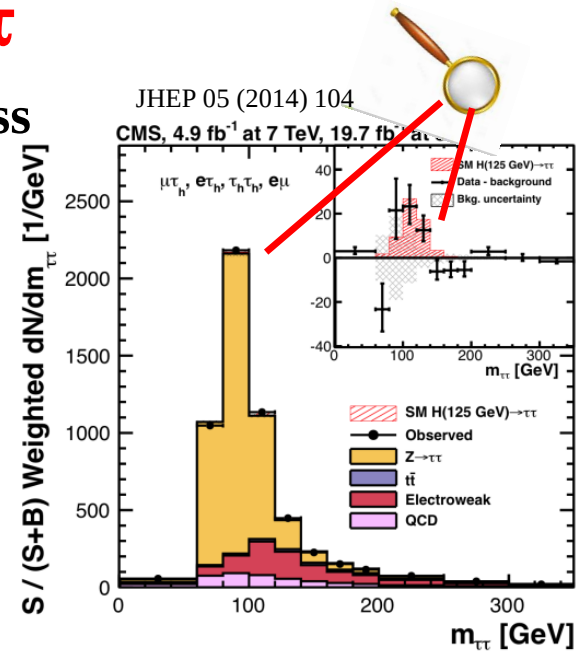
Relevant to study VBF and VH production

Higgs properties after RUN I

The fermionic channels: H→ττ

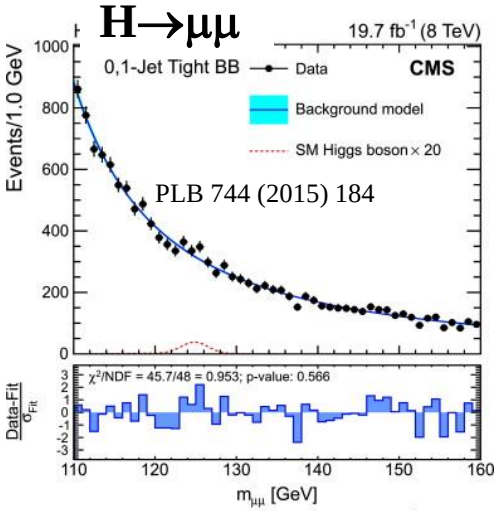
Yukawa coupling with fermions proportional to their mass
⇒ for leptonic decay only H→ττ is visible at present**
neutrino's in the final state:
peak reconstruction problematic
(with a much larger peak from Z→ττ)

JHEP 05 (2014) 104



Significance w.r.t. bckg only hyp.: 3.2 σ (3.7)

H→μμ



PLB 744 (2015) 184

** **only limits for H→μμ (end ee)**

Evidence: no flavor universality for leptons in the BEH decay

Higgs properties after RUN I

The fermionic channels: H→bb

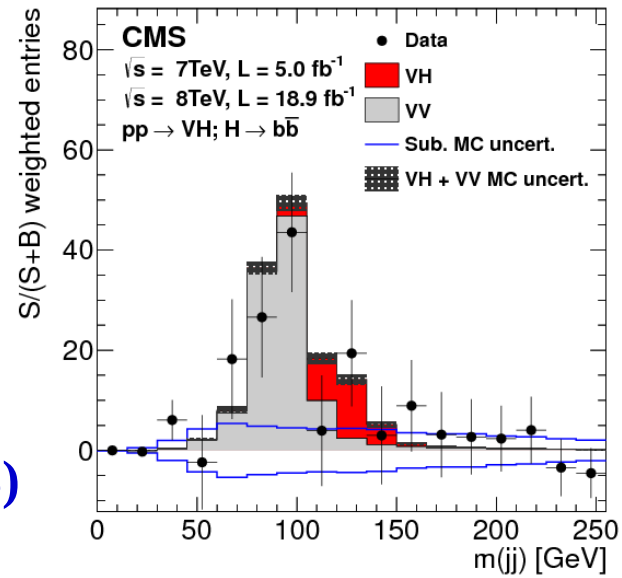
Phys. Rev. D 89 (2014) 012003, Nature Phys. 10 (2014) 557

The most copious decay channel is embedded in a huge QCD bb background.

Limit the analysis to associated production (VH)

Significance w.r.t. bckg only hyp.: 2.1 σ (2.1)

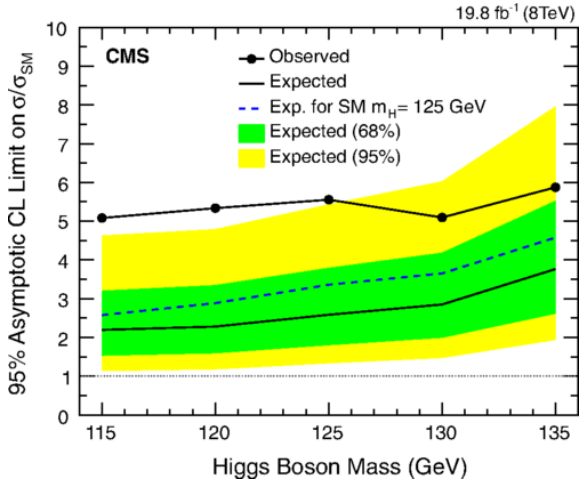
NB combined with ττ 3.8 σ: evidence for fermionic coupling

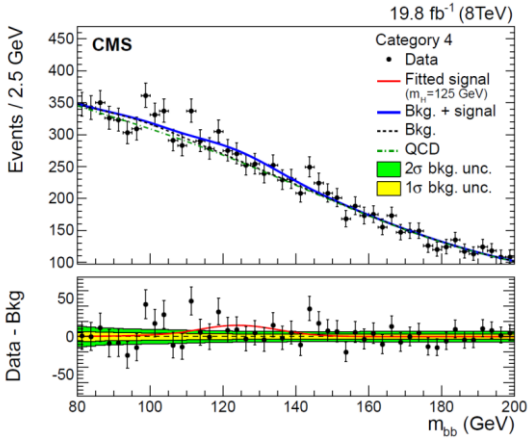


And VBF

Significance w.r.t. bckg only hyp.: 2.2 σ (0.8)

Phys. Rev. D 92 (2015), 032008

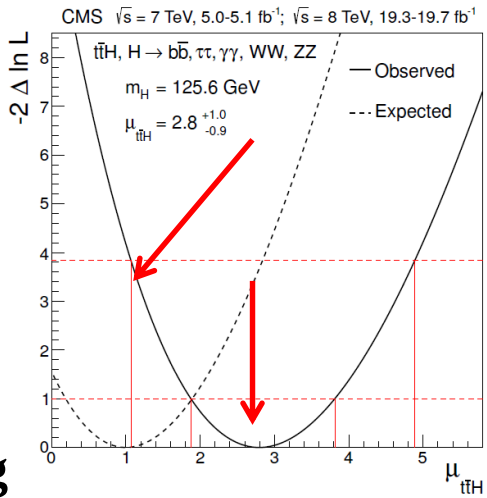




Higgs properties after RUN I

ttH production

JHEP 09 (2014) 087

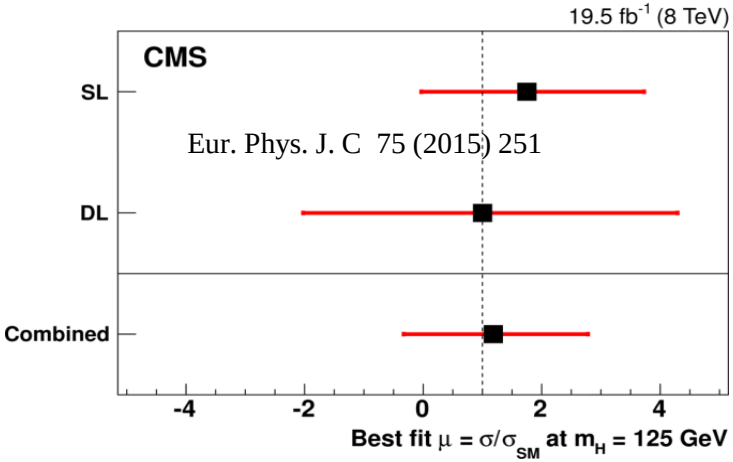


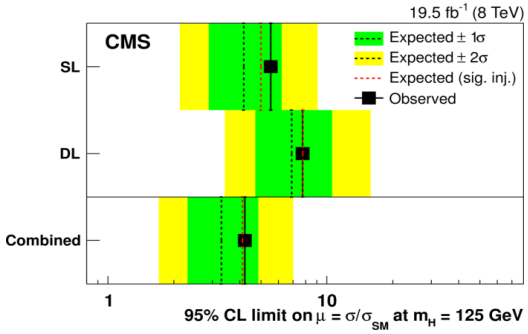
Several cathegories depending on H decay (3: bb,γγ,multiLeptons) and t decay (3: sl,dl,h)

Significance w.r.t. bckg only hyp.: 3.4 σ (1.2)
Higher than expected:
if SM signal is considered excess of ~2 σ

New: Matrix Element Method to improve signal/ backgroung separation: each event is assigned a p.d.f. based on theoretical differential cross section

Single lepton and double lepton for t
only H→bb





Limit: <4.2 σ_{SM} (3.3)
(4.1with H SM)

Couplings

Some formalism

A direct comparison with SM expectation is convenient:

arXiv:1307.1347

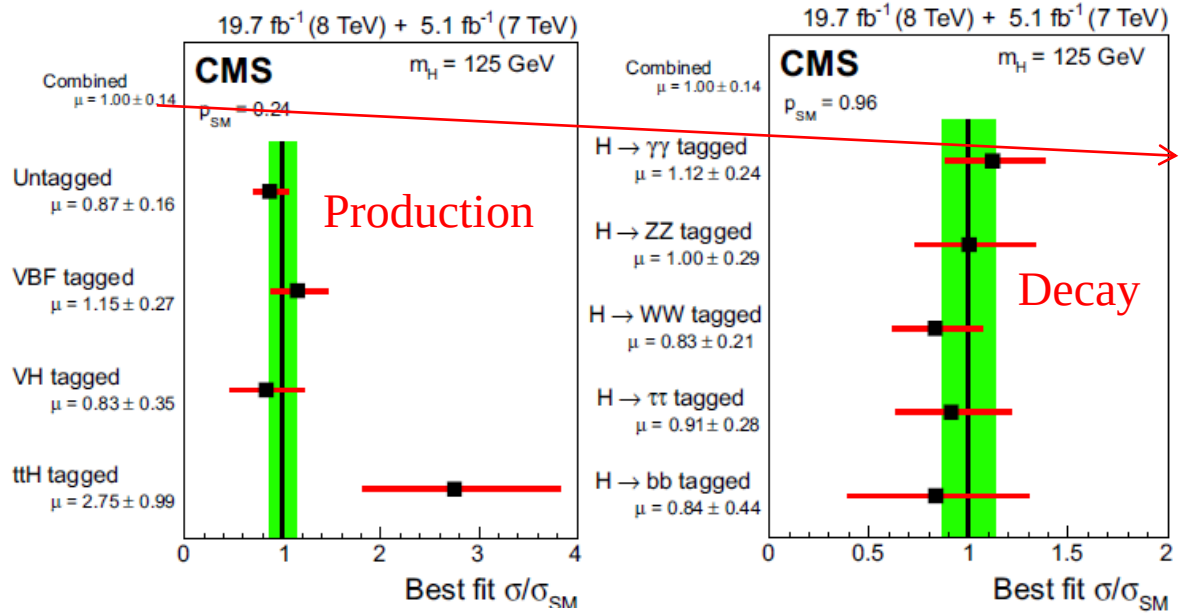
SM coupling to V bosons: $g_{HVV} = \frac{2m_V^2}{v}$

SM coupling to fermions: $g_{Hff} = \frac{m_f}{v}$

Name	Meaning	Symbol
Signal strength	$\frac{\sigma(\mathrm{BR})}{\sigma^{\mathrm{SM}}(\mathrm{BR}^{\mathrm{SM}})}$	μ
Coupling modifiers	$\frac{g_{HXX}}{g_{HXX}^{\mathrm{SM}}}$	κ_X
Total width modifier	$\frac{\Gamma_{\mathrm{tot}}}{\Gamma_{\mathrm{tot}}^{\mathrm{SM}}}$	κ_H^2
Ratio of coupling modifiers	$\frac{\kappa_X}{\kappa_Y}$	λ_{XY}

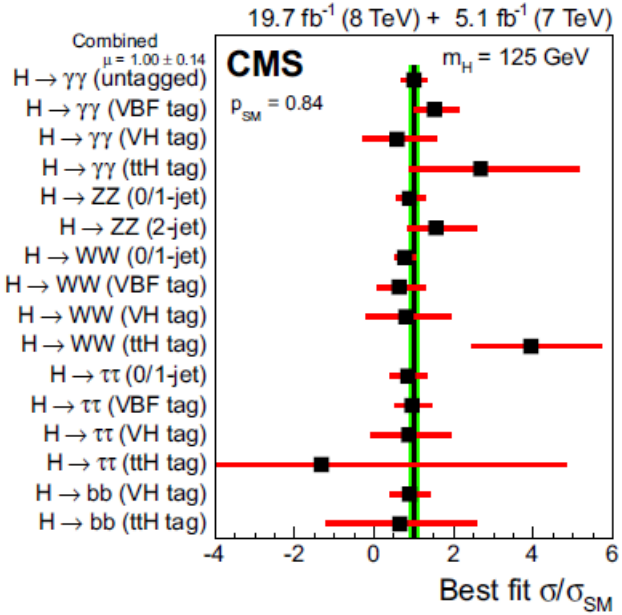
When the coupling is not direct (e.g. in gluon fusion production or $\gamma\gamma$ decay) : calculated in terms of direct parameters: $\kappa_g = \kappa_g(\kappa_b, \kappa_t, m_H)$ $\kappa_\gamma = \kappa_\gamma(\kappa_b, \kappa_t, \kappa_W, m_H)$

Couplings



Eur. Phys. J. C 75 (2015) 212

$\mu(\sigma/\sigma_{SM}) = 1.00 \pm 0.14$



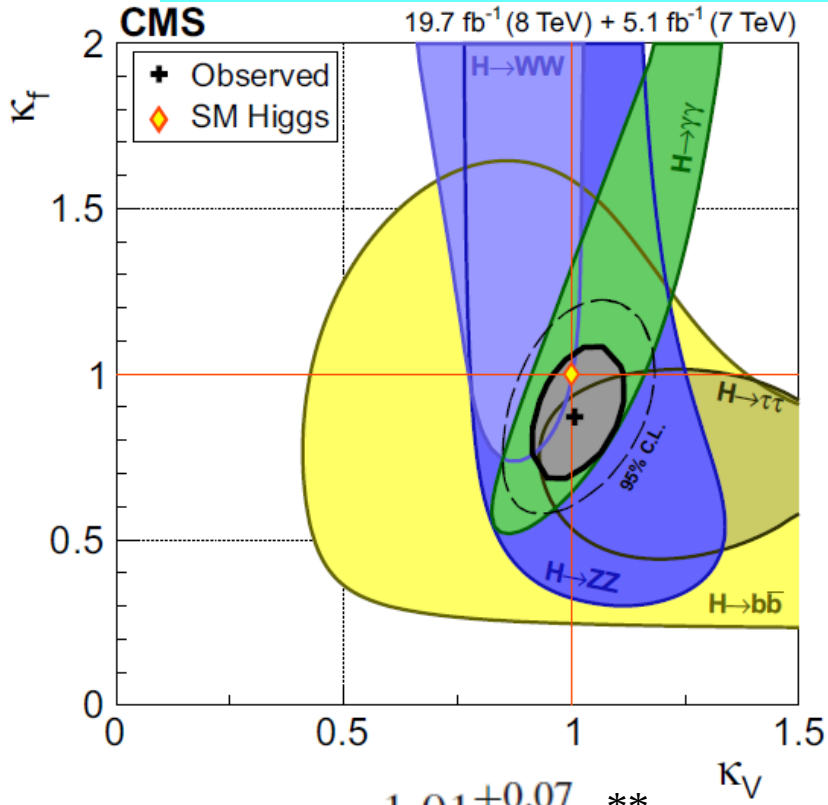
Custodial symmetry: equal coupling modifiers for W and Z: $\lambda_{WZ} = \kappa_W/\kappa_Z = 1$

Since

$$\lambda_{WZ} = 0.92^{+0.14}_{-0.12}$$

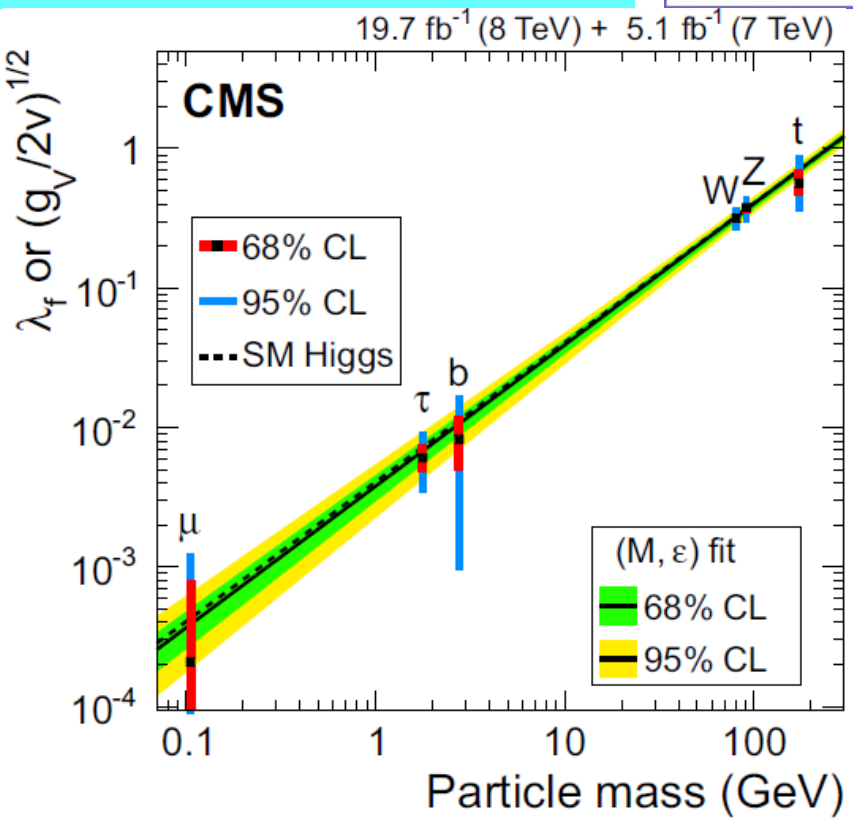
Assumed to be valid: $\kappa_W = \kappa_Z \equiv \kappa_V$

Couplings



$$\kappa_V = 1.01^{+0.07}_{-0.07} \quad **$$

$$\kappa_f = 0.87^{+0.14}_{-0.13}$$



to have all couplings in the same plot:
$\lambda_f \sim \kappa_f m_f/v$; $[g_V/(2v)]^{1/2} \sim (\kappa_V)^{1/2}\, m_V/v$

v= VEV ≈ 246 GeV

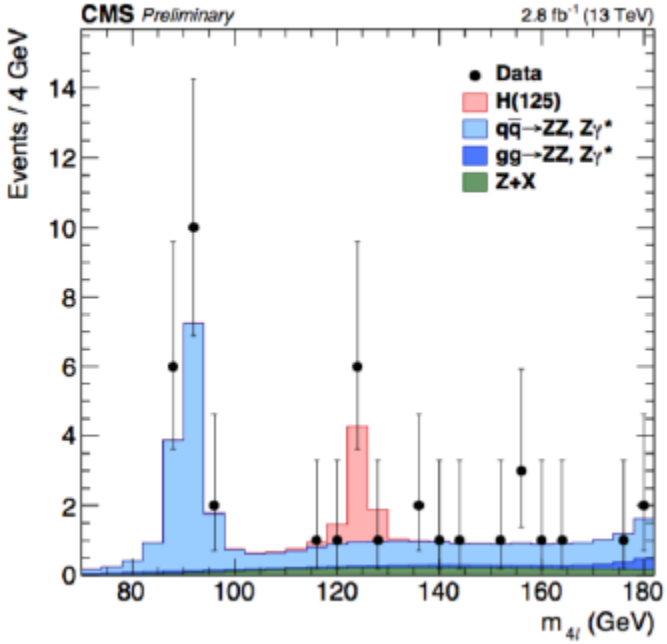
Compatible with SM
(also the combination ATLAS-CMS)

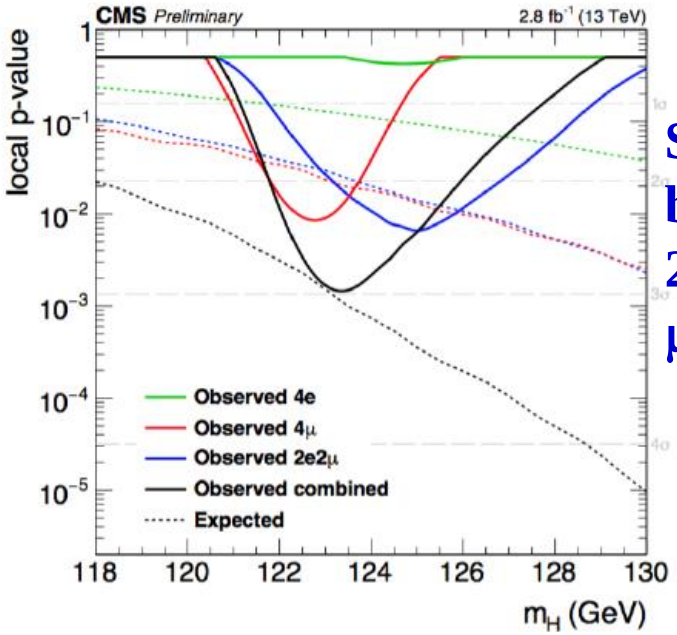
**several assumptions

First Results at 13 TeV*

H→ZZ*→4l:

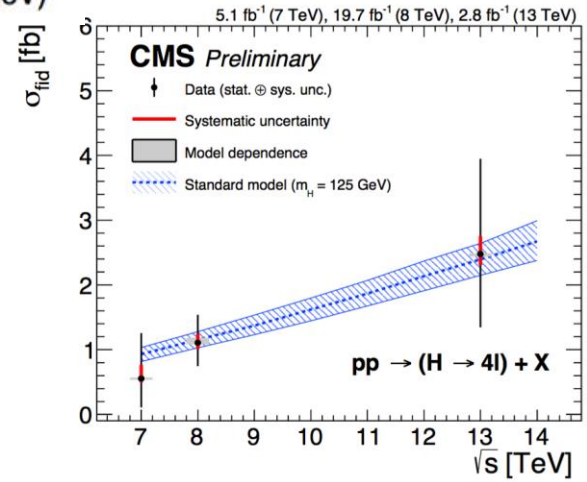
HIG-15-004





Significance w.r.t. bckg only hyp.: 2.5 σ (3.4)

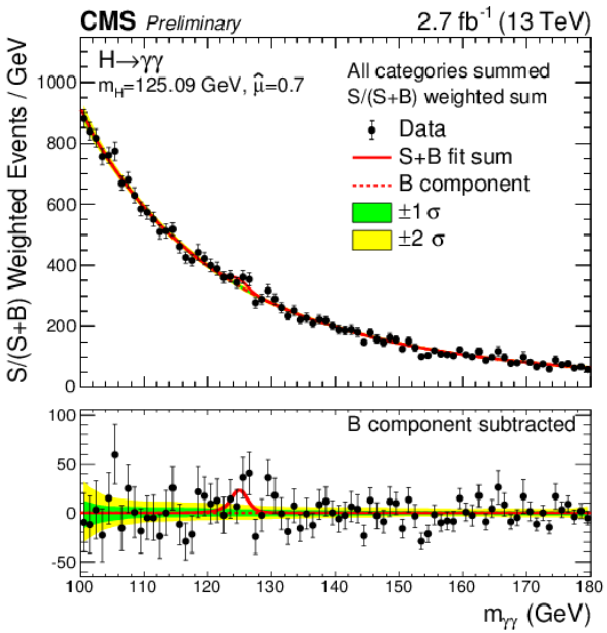
$\mu=\sigma/\sigma_{SM}=$ $0.82^{+0.57}_{-0.43}$



Fiducial cross section compared with results at 7 and 8 TeV

***Only 2015 data**

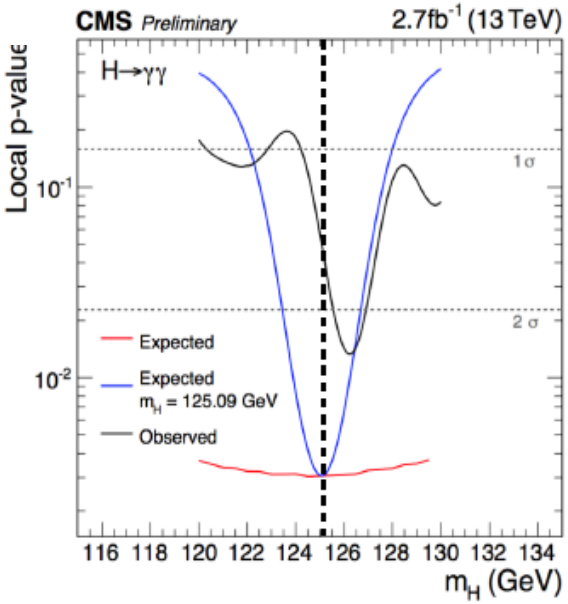
First Results at 13 TeV

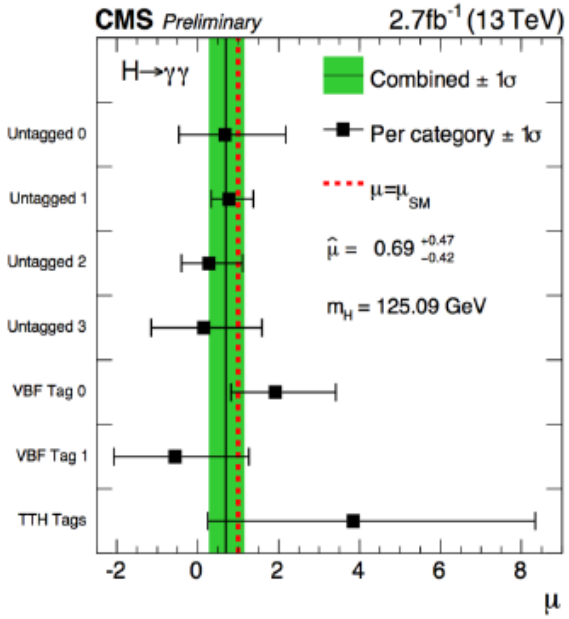


HIG-15-005

H→γγ

Several categories
Significance w.r.t. bckg only hyp.: 1.7 σ (2.7)
$\mu=\sigma/\sigma_{SM}$= $0.69^{+0.47}_{-0.42}$



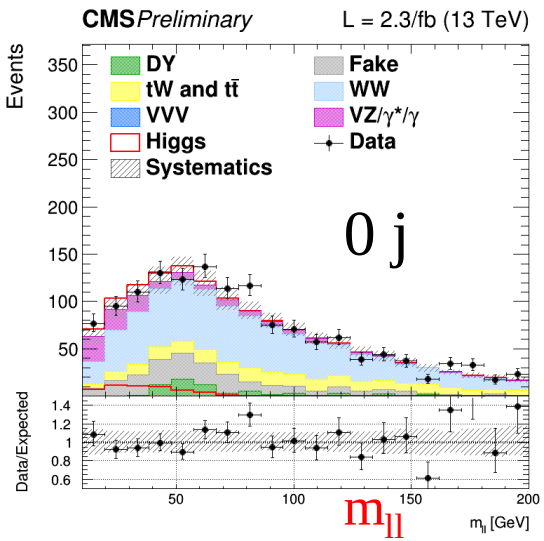


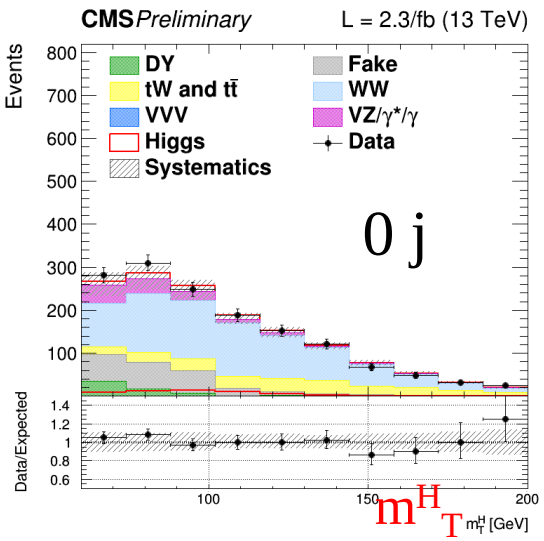
First Results at 13 TeV

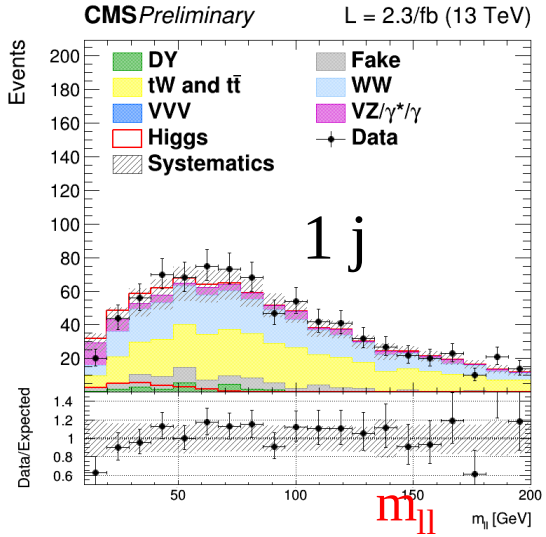
H→WW WW→eμ 0/1 jet

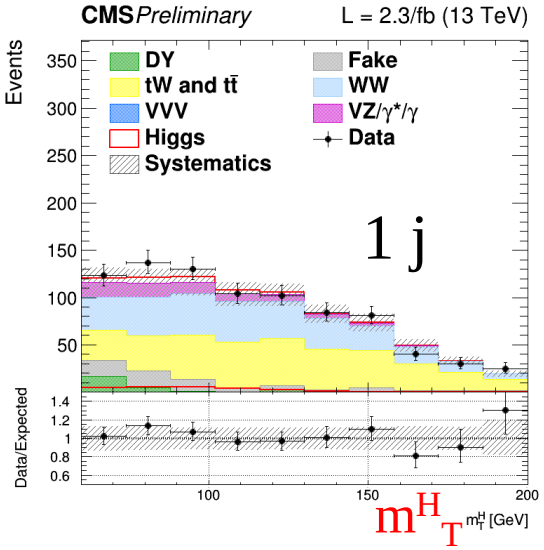
NEW

HIG-15-003









Signal/bckg as function of m_{ll} and m^H_T

events divided in 4 categories:
μe, eμ (leading p_t)
0j , 1j

Two dimensional plot (m_{ll},m_T)

Significance w.r.t. bckg only hyp.: 0.7 σ (2.0)

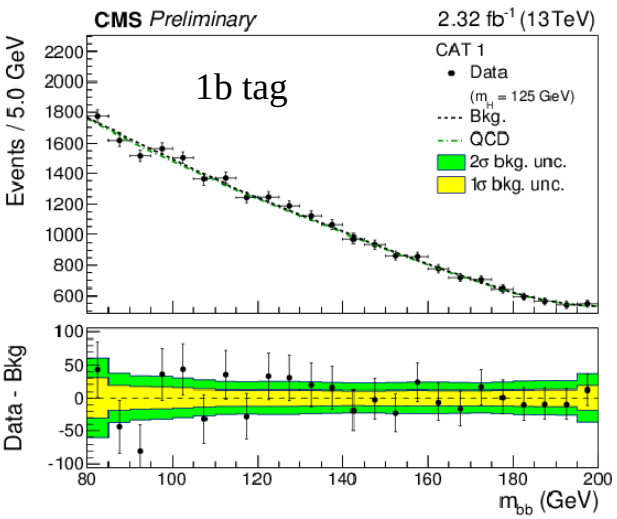
First Results at 13 TeV

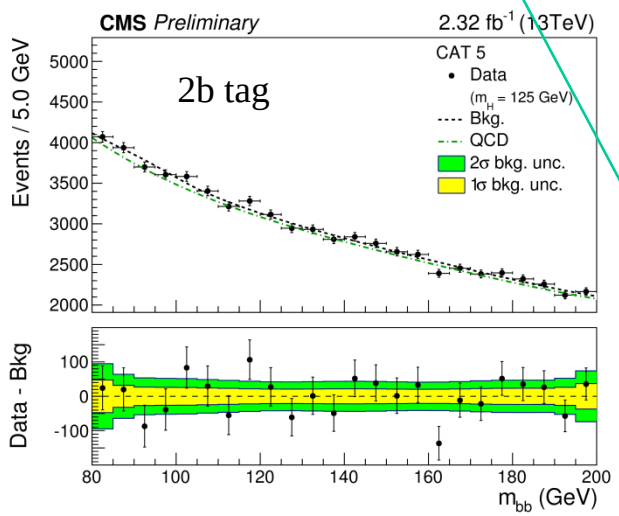
VBF H→bb

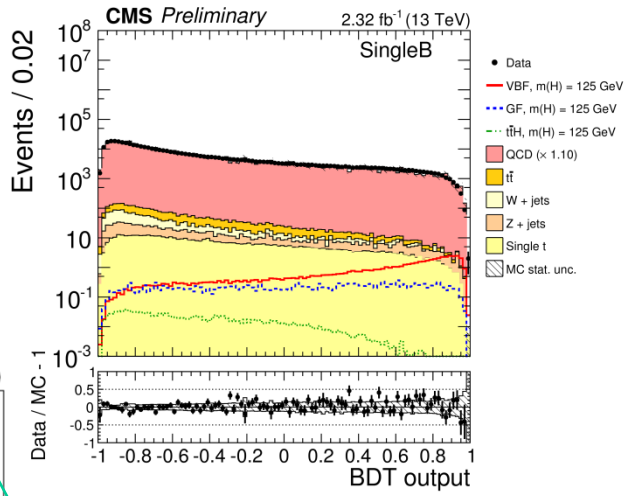
NEW

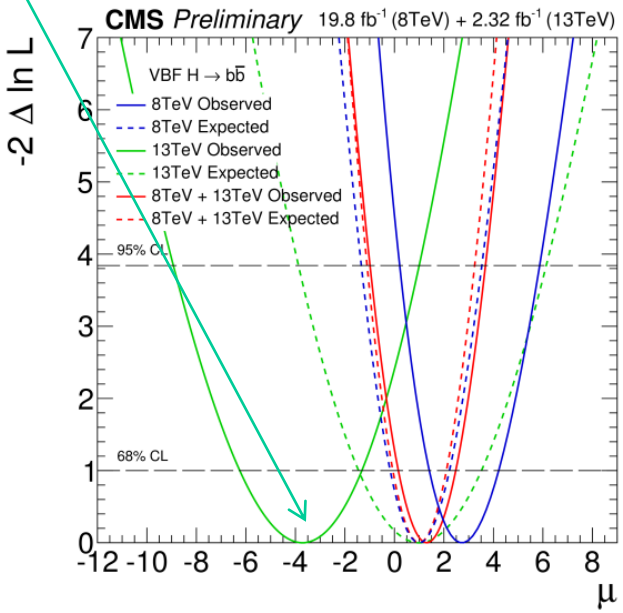
VBF: events in 4 jets
1 or 2 b tag and BDT categorization

HIG-16-003





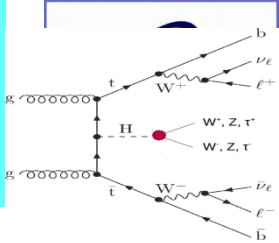




No evidence yet @ 13 TeV

Combined with RUN I:
significance w.r.t. bckg only hyp.: 1.2 σ
$\mu=\sigma/\sigma_{SM}=1.3^{+1.2}_{-1.1}$

First Results at 13 TeV

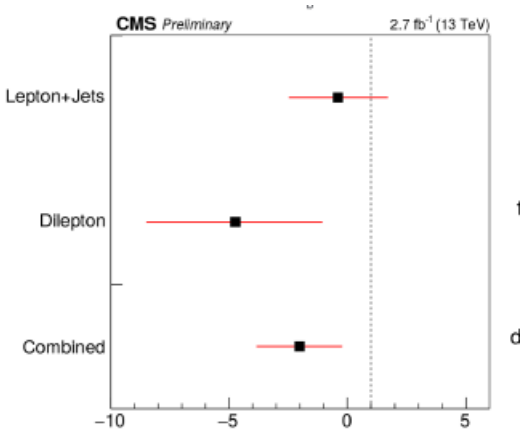


ttH

ttH(bb)

HIG-16-004

dileptons and l+j
≥2 b tag and other categorizations

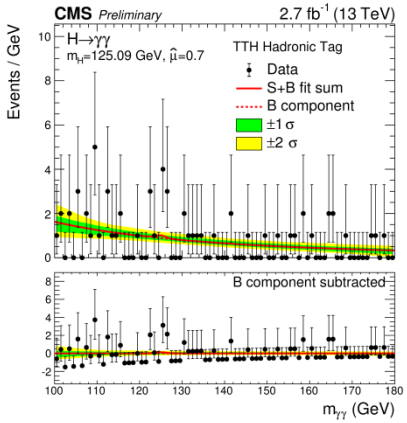


σ/σ_{SM}<2.6 (3.6)
$\mu=\sigma/\sigma_{SM}$= - 2.0±1.8

ttH(γγ)

HIG-15-005

Leptonic or hadronic tt
≥ 2 j ≥5 j
≥1 b tag
and other γγ BDT cat.

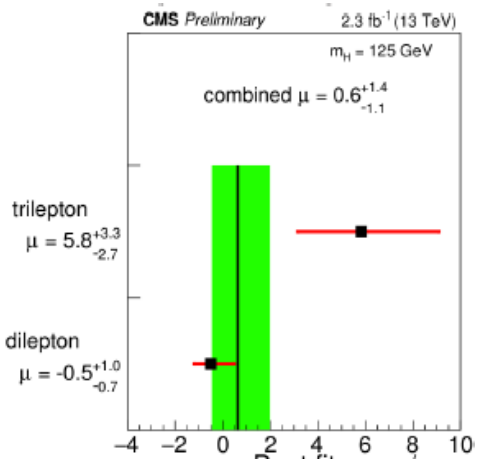


$\mu=\sigma/\sigma_{SM}= 3.8^{+4.5}_{-3.6}$

ttH multileptons

HIG-15-008

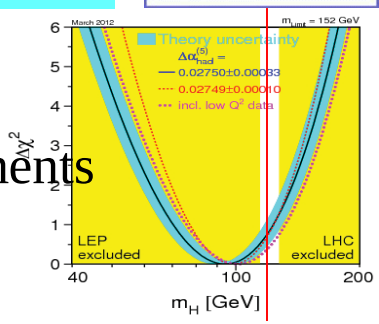
ss dileptons or ≥3 l
≥ 4 j ≥5 j
≥1 b tag
and other cat.



$\mu=\sigma/\sigma_{SM}= 0.6^{+1.4}_{-1.1}$

Combined $\mu= 0.15^{+0.95}_{-0.81}$ ($1.00^{+0.96}_{-0.85}$) @ 13 TeV

Implications



- The 125 GeV particle is in the range of fits to SM precision measurements
- It is a SCALAR so it is a BEH-like boson
- at that mass several accessible final states according to SM
- coupled to bosons and fermions
- all the measured production/decay products compatible with SM @that mass
- couplings do not show deviations from SM predictions
- no other states from additional H doublets have been found despite…
- No other signals of new physics discovered (yet)

The above does not prove this is the SM BEH boson:
Lightest states of more complex H sectors may have similar properties

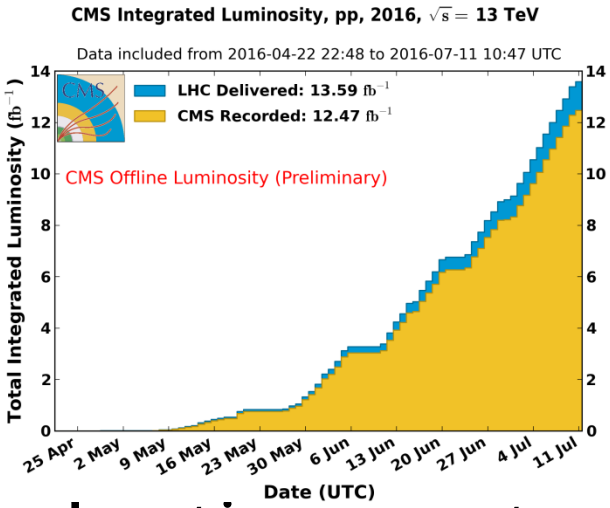
The value m_H=125 GeV is within the SUSY-accepted range

More precise measures are necessary

Perspectives

Short time scale

- The 2016 LHC run is going to confirm (exceed?) the expectations
- CMS is taking data with a good efficiency
- ggF production increased by ~2.2 @ 13 TeV w.r.t. 8 TeV (but ~ 3.9 for ttH)
- "rediscovery" with the same RUN I accuracy possible with half lumi



Done!…
and any day a
better figure

- results coming soon
- likely at the end of 2016 a relevant improvement on the measured values
- A factor 2 reduction on uncertainties (?)

Perspectives

middle time scale

- **Following plans LHC should deliver 300-350 /fb (@ 13 and/or 14 TeV)**

Expected CMS precisions with integrated lumi of 300/fb @ 14 TeV

κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
[optimistic, pessimistic]								
[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]

($\Delta\kappa/\kappa$ %)

- **theory uncertainties begin to play a role**

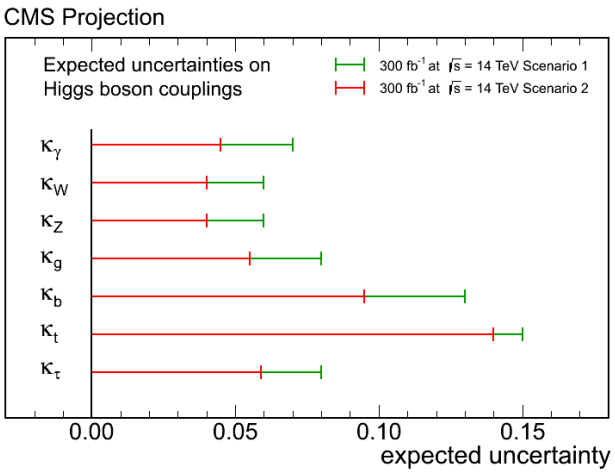
The increase in E and Lumi gives an opportunity to observe heavy H states as foreseen by MSSM or to extend the excluded region in m_A-tanβ plane.

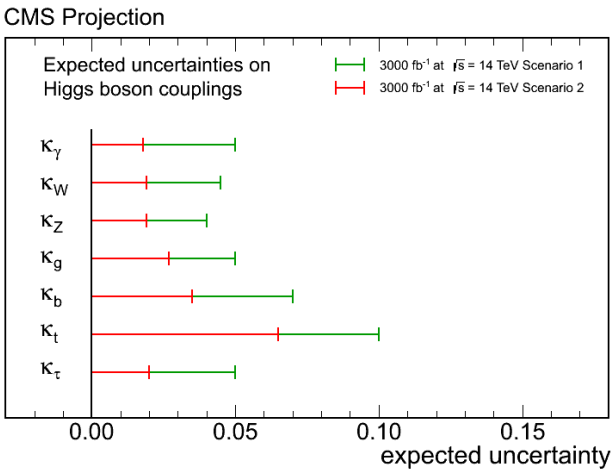
If the discovered particle is the lightest CP-even state h , m_A<230-260 excluded for all tanβ values

Perspectives

long time scale

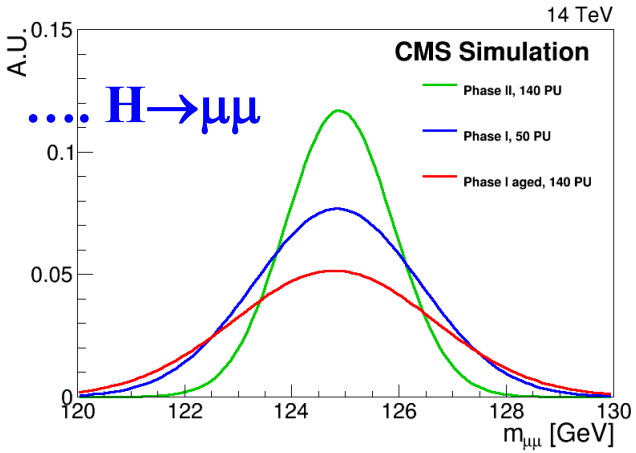
- **HL LHC recently officially approved! 3000/fb (@ 14 TeV)**





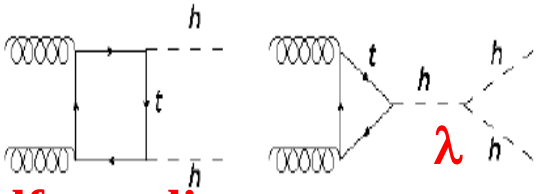
CERN-LHCC-2015-10

- **theory uncertainties play a crucial role**
- **rare signals as ….**



…. H→μμ

- **pair production**



to measure the self coupling parameter

Conclusions

The discovery of the BEH particle has been not only one of the most important results in particle Physics but also one of the most relevant scientific achievements

The discovery requires several further actions that will engage the HEP community for several years. In particular try to give an answer to:

- **is the new particle really the SM BEH Boson?**
- **is it an elementary particle? or…**
- **is it a composite particle?**
- **is it natural**
- **are there other Higgs fields?**
- **is it really responsible for the mass of all elementary particles?**

and also

- **is it at the origin of the matter-antimatter asymmetry?**
- **does it have a role in the inflationary expansion of the Universe?**

Frascati Phys. Ser. 60 (2015) pp. 1-291

More and more precise measures are necessary


ευχαριστώ

MORE Slides

Higgs properties after RUN I

Spin-parity

Crucial to determine the nature of the particle:
it is a BEH boson if it is a scalar : is $J^P=0^+$ hypothesis the most probable?

- **Spin 1 ~ ruled out by the two photon final state (..and by measurements)**
- **Several models for spin-2 are disfavored or excluded by kinematic properties of final states**
- **Can we distinguish between 0^+ and 0^- ?**

Yes:

Mainly from $H \rightarrow ZZ^* \rightarrow 4\ l$

as in the past the parity of π^0 was determined from $\pi^0 \rightarrow \gamma^*\gamma^* \rightarrow e^+e^-e^+e^-$:

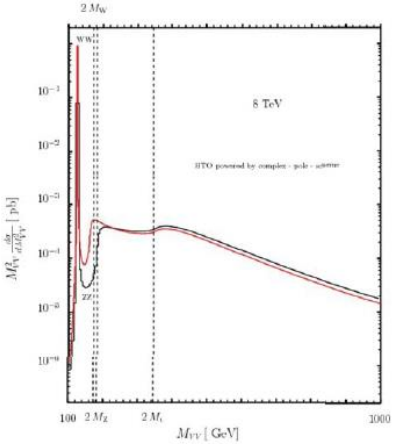
R. Plano, A. Prodell, N. Samios, M. Schwartz and J. Steinberger, *Phys. Rev. Lett.***3, 525 (1959), doi:10.1103/PhysRevLett.3.525**
N. P. Samios, R. Plano, A. Prodell, M. Schwartz and J. Steinberger, *Phys. Rev.* ***126,***1844 (1962), doi:10.1103/PhysRev.126.1844
E. Abouzaid *et al., Phys. Rev. Lett.* ***100, 182001 (2008),***doi:10.1103/PhysRevLett.100.182001

Higgs properties after RUN I

The width

The expected width @ 125 GeV is ~4 MeV.
Too large…. and too narrow…. to be measured.

Direct measurement of peak width dominated by experimental resolution $\mathcal{O}$(GeV)



But * for VV final states the off-shell contribution is relevant:

$$\sigma^{\text{on-shell}}_{gg\to H\to 4ZZ} \sim \frac{g^2_{Hgg}g^2_{HZZ}}{\Gamma_H m_H} \quad \text{and} \quad \sigma^{\text{off-shell}}_{gg\to H\to 4ZZ} \sim \frac{g^2_{Hgg}g^2_{HZZ}}{(2m_Z)^2}$$

Positive off- shell signal compared to on-shell prop to Γ_H/Γ_H^{SM}, considering negative interference with *gg→ZZ* bckg ($\sqrt{\Gamma_H/\Gamma_H^{SM}}$)

Including information from WW final state and VBF process arXiv:1605.02329

Γ_H< 13 (26) MeV @ 95% CL

•N.Kauer, G. Passarino
Phy. Rev. D 88 054024(2013)

Higgs properties after RUN I

Observed and expected excesses at 125 GeV Eur. Phys. J. C 75 (2015) 212

Channel grouping		Significance (σ)	
		Observed	Expected
$H \to ZZ$ tagged		6.5	6.3
$H \to \gamma\gamma$ tagged		5.6	5.3
$H \to WW$ tagged		4.7	5.4
Grouped as in Ref.	JHEP 01 (2014) 096	*4.3*	*5.4*
$H \to \tau\tau$ tagged		3.8	3.9
Grouped as in Ref.	JHEP 05 (2014) 104	*3.9*	*3.9*
$H \to bb$ tagged		2.0	2.6
Grouped as in Ref.	Phys. Rev. D 89 (2014) 012003)	*2.1*	*2.5*
$H \to \mu\mu$ tagged		<0.1	0.4

Couplings

Fit assumptions

•the signals on different channels are supposed to come from the same resonance with a well defined mass

•the width is supposed to be narrow so that the zero-width approximation can be used

•SM tensor structure of the Lagrangian is assumed while the couplings are free to vary

$\kappa_W = \kappa_Z = \kappa_V$

$\kappa_t = \kappa_b = \kappa_\tau = \kappa_g = \kappa_f$

with the further assumption that κ_g *depends* only on the fermion contribution without additional contributions

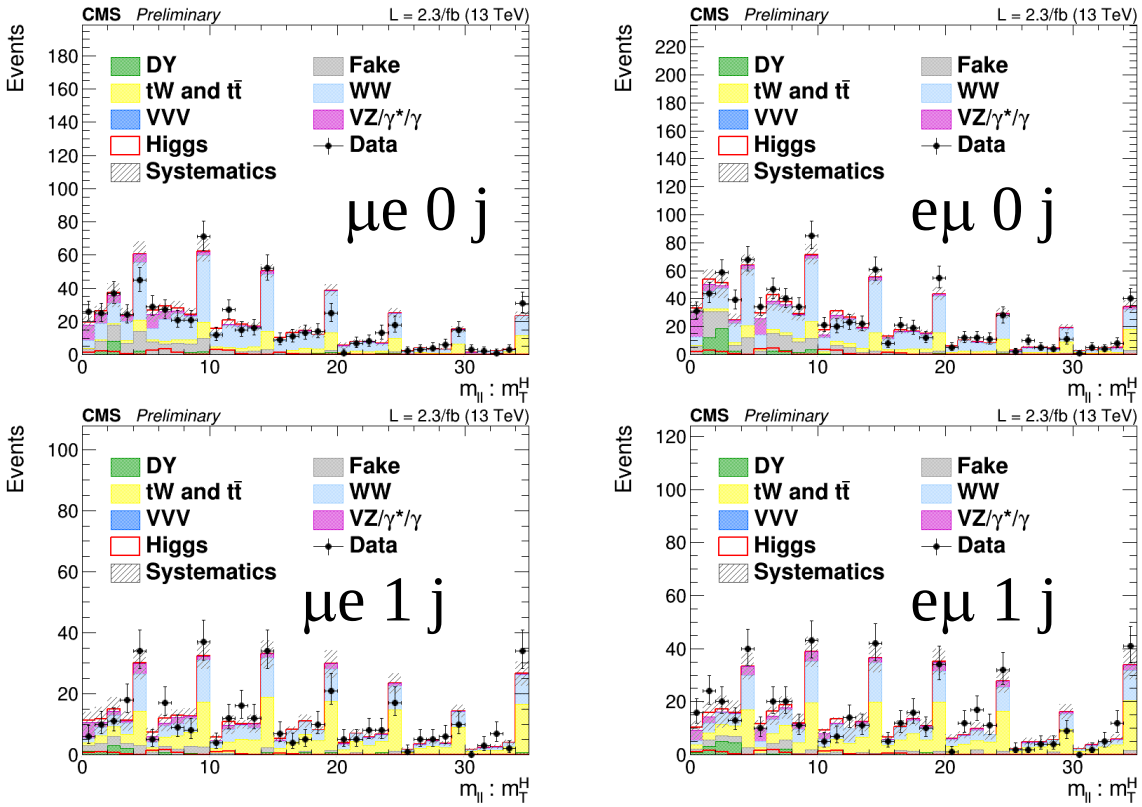
Model parameters	Table in Ref. [171]	Parameter	Best-fit result 68 % CL	Best-fit result 95 % CL	Comment
κ_Z, λ_{WZ} ($\kappa_f = 1$)	–	λ_{WZ}	$0.94^{+0.22}_{-0.18}$	[0.61, 1.45]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from ZZ and 0/1-jet WW channels
$\kappa_Z, \lambda_{WZ}, \kappa_f$	44 (top)	λ_{WZ}	$0.92^{+0.14}_{-0.12}$	[0.71, 1.24]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from full combination
κ_V, κ_f	43 (top)	κ_V	$1.01^{+0.07}_{-0.07}$	[0.87, 1.14]	κ_V scales couplings to W and Z bosons
		κ_f	$0.87^{+0.14}_{-0.13}$	[0.63, 1.15]	κ_f scales couplings to all fermions
$\kappa_V, \lambda_{du}, \kappa_u$	46 (top)	λ_{du}	$0.99^{+0.19}_{-0.18}$	[0.65, 1.39]	$\lambda_{du} = \kappa_u/\kappa_d$, relates up-type and down-type fermions
$\kappa_V, \lambda_{\ell q}, \kappa_q$	47 (top)	$\lambda_{\ell q}$	$1.03^{+0.23}_{-0.21}$	[0.62, 1.50]	$\lambda_{\ell q} = \kappa_\ell/\kappa_q$, relates leptons and quarks
$\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$	Extends 51	κ_W	$0.95^{+0.14}_{-0.13}$	[0.68, 1.23]	
		κ_Z	$1.05^{+0.16}_{-0.16}$	[0.72, 1.35]	
		κ_t	$0.81^{+0.19}_{-0.15}$	[0.53, 1.20]	Up-type quarks (via t)
		κ_b	$0.74^{+0.33}_{-0.29}$	[0.09, 1.44]	Down-type quarks (via b)
		κ_τ	$0.84^{+0.19}_{-0.18}$	[0.50, 1.24]	κ_τ scales the coupling to tau leptons
		κ_μ	$0.49^{+1.38}_{-0.49}$	[0.00, 2.77]	κ_μ scales the coupling to muons
M, ϵ	Ref. [206]	M (GeV)	245 ± 15	[217, 279]	$\kappa_f = v\frac{m_f^\epsilon}{M^{1+\epsilon}}$ and $\kappa_V = v\frac{m_V^{2\epsilon}}{M^{1+2\epsilon}}$ (Sect. 7.4)
		ϵ	$0.014^{+0.041}_{-0.036}$	[−0.054, 0.100]	
κ_g, κ_γ	48 (top)	κ_g	$0.89^{+0.11}_{-0.10}$	[0.69, 1.11]	Effective couplings to gluons (g) and photons (γ)
		κ_γ	$1.14^{+0.12}_{-0.13}$	[0.89, 1.40]	
κ_g, κ_γ, BR_{BSM}	48 (middle)	BR_{BSM}	≤ 0.14	[0.00, 0.32]	Allows for BSM decays
With H(inv) searches	–	BR_{inv}	$0.03^{+0.15}_{-0.03}$	[0.00, 0.32]	H(inv) use implies BR_{undet} =0
With H(inv) and $\kappa_i = 1$	–	BR_{inv}	$0.06^{+0.11}_{-0.06}$	[0.00, 0.27]	Assumes $\kappa_i = 1$ and uses H(inv)
$\kappa_{gZ}, \lambda_{WZ}, \lambda_{Zg}, \lambda_{bZ}, \lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{tg}$	50 (bottom)	κ_{gZ}	$0.98^{+0.14}_{-0.13}$	[0.73, 1.27]	$\kappa_{gZ} = \kappa_g\kappa_Z/\kappa_H$, i.e. floating κ_H
		λ_{WZ}	$0.87^{+0.15}_{-0.13}$	[0.63, 1.19]	$\lambda_{WZ} = \kappa_W/\kappa_Z$
		λ_{Zg}	$1.39^{+0.36}_{-0.28}$	[0.87, 2.18]	$\lambda_{Zg} = \kappa_Z/\kappa_g$
		λ_{bZ}	$0.59^{+0.22}_{-0.23}$	$\leq$1.07	$\lambda_{bZ} = \kappa_b/\kappa_Z$
		$\lambda_{\gamma Z}$	$0.93^{+0.17}_{-0.14}$	[0.67, 1.31]	$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$
		$\lambda_{\tau Z}$	$0.79^{+0.19}_{-0.17}$	[0.47, 1.20]	$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$
		λ_{tg}	$2.18^{+0.54}_{-0.46}$	[1.30, 3.35]	$\lambda_{tg} = \kappa_t/\kappa_g$

First Results at 13 TeV

H→WW WW→eμ 0/1 jet

NEW

HIG-15-003



events divided in 4 categories:
μe, eμ (leading p_t)
0j , 1j

Two dimensional plot

Significance w.r.t. bckg only: 0.7 σ (2.0)

First Results at 13 TeV