# BEH Boson (CMS)

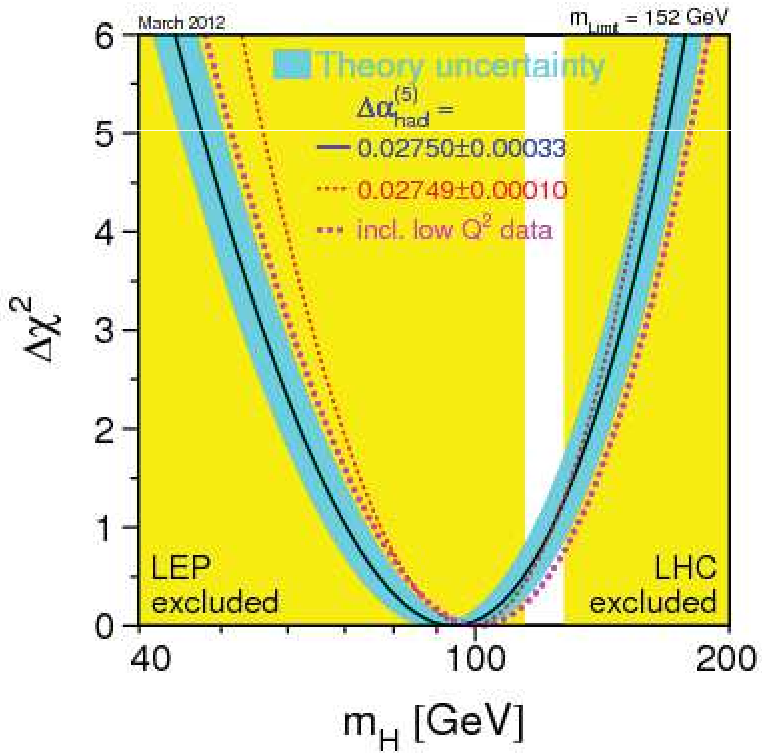
## From Discovery to precision measurements

### 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**

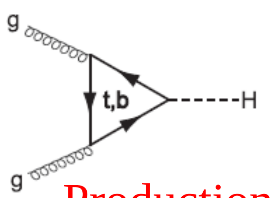


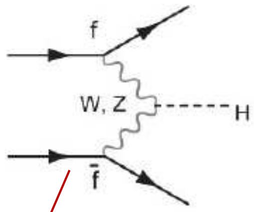

**Fits to SM precision measurements prefer a low mass value and exclusion regions are compatible with the fit**

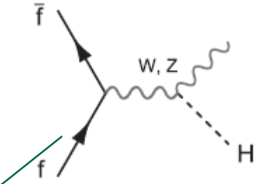
# Higgs properties after RUN I

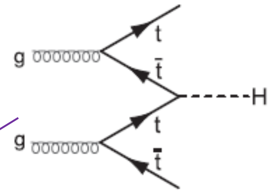
## The expectations at LHC

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

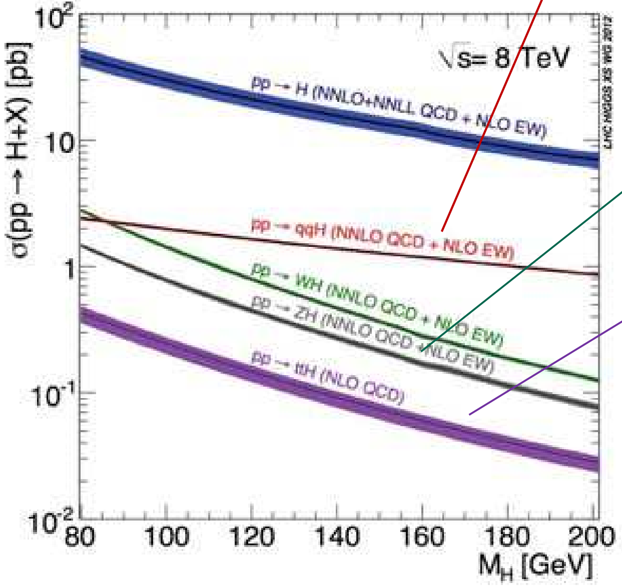


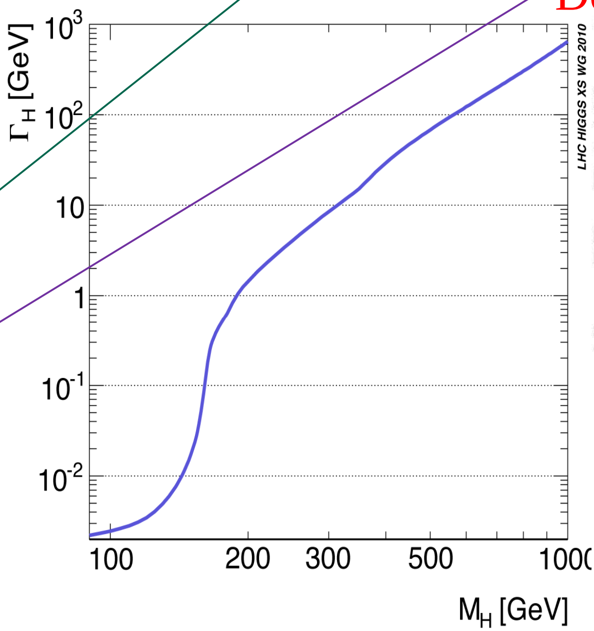



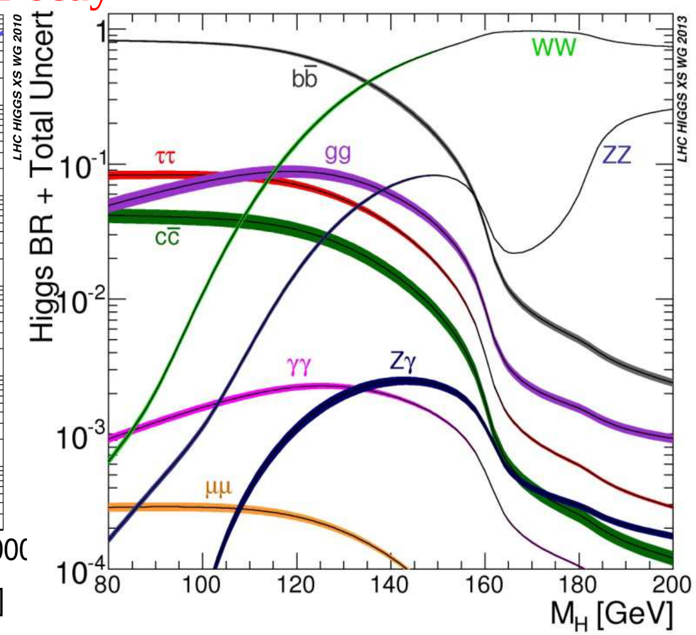




Production




Decay




**SM predictions of production/decay properties depend on the mass**

# Higgs properties after RUN I

## The mass

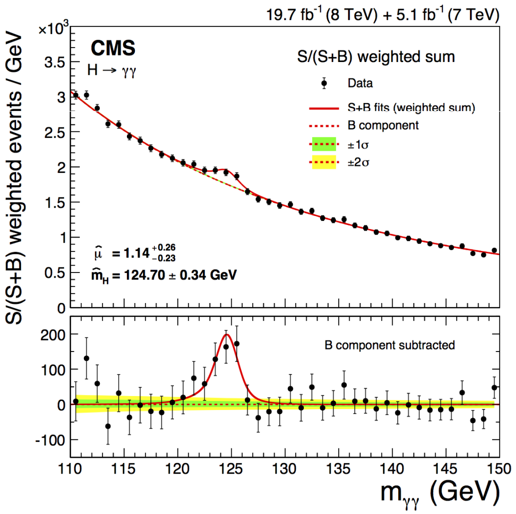
**Two final states with peaks: the same channels relevant for the discovery are giving a precise measurement of the mass.**

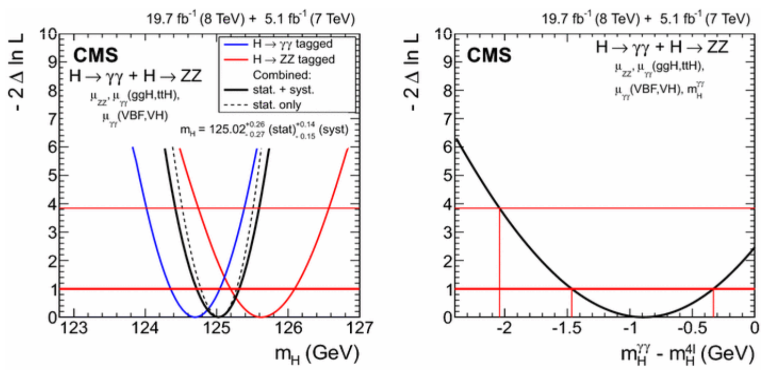
**$H\rightarrow\gamma\gamma$** EPCJ 74 (2014) 3076

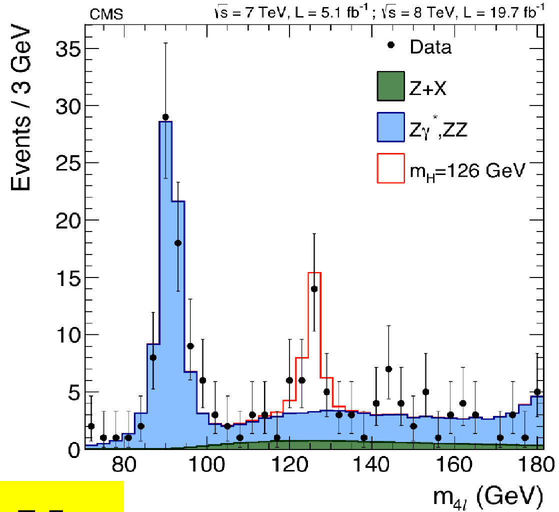
124.70±0.31(stat)±0.15(syst) GeV

**$H\rightarrow ZZ^*\rightarrow 4l$:** PRD 89 (2014) 092007

125.6±0.4(stat)±0.2(syst) GeV




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

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

NB2: difference within ~1.6 σ

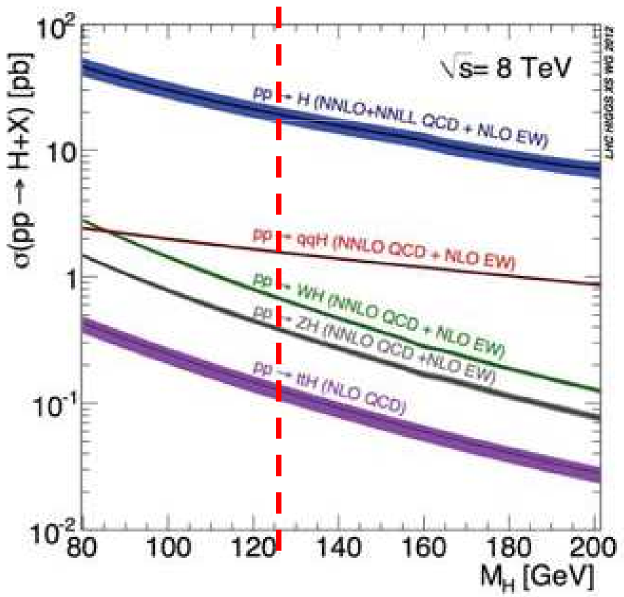
NB3:evaluations from other channels (less precise) compatible with this result .

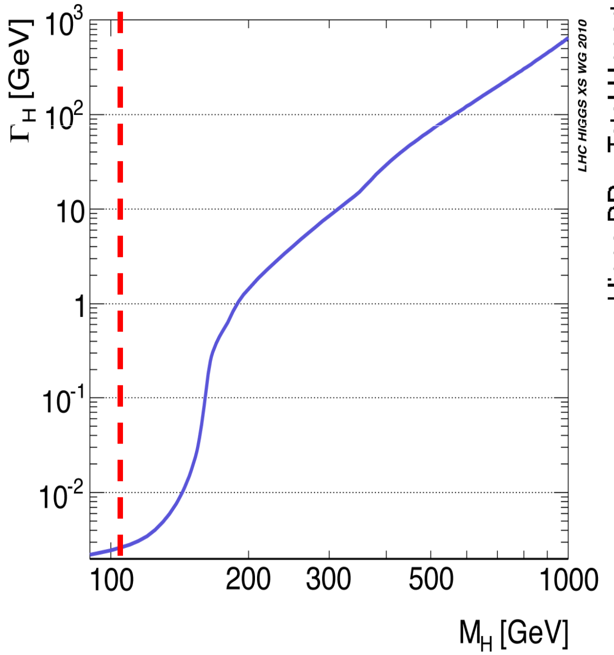
NB4: ATLAS+CMS PRL 114 191803 (2015) **$m_H$=125.09±0.24 (± 0.21±0.11)**

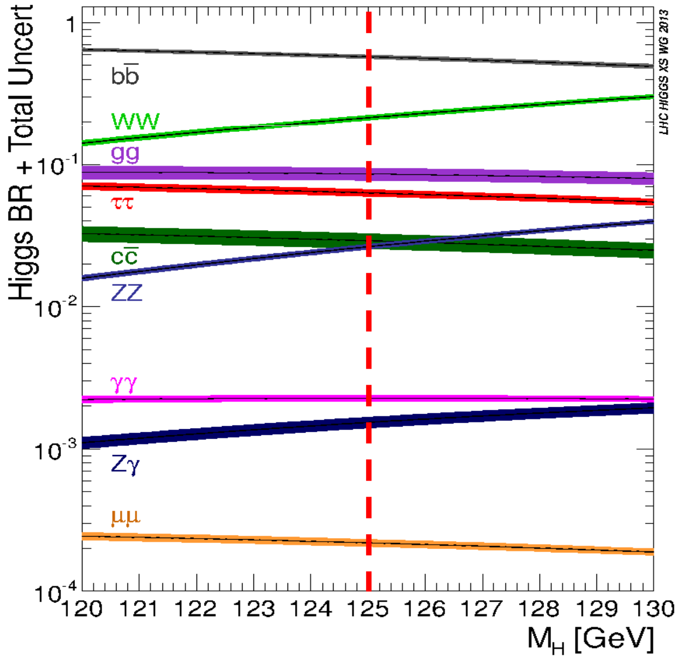
# Higgs properties after RUN I

## The mass

**Once mass is known SM predicts all production/decay properties**



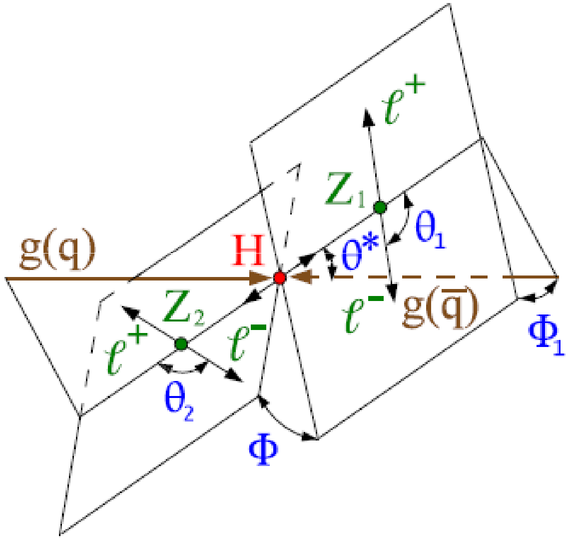
# Higgs properties after RUN I

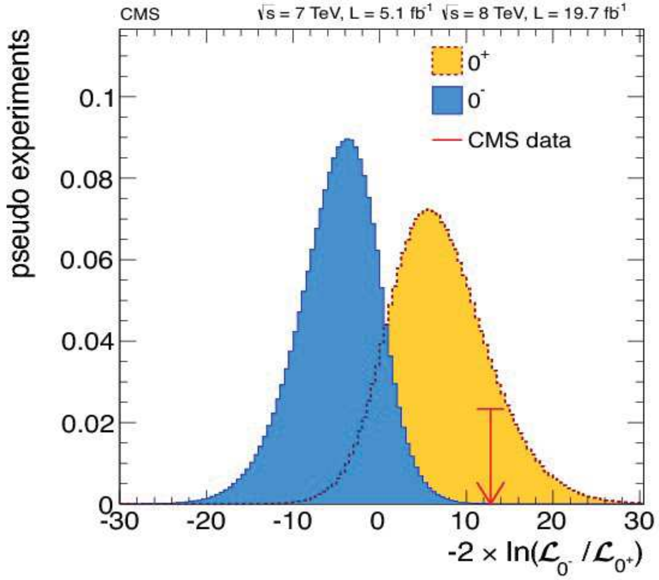
## Spin-parity

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: $\Phi$ $\theta_1\theta_2$**
**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**
$P_{J^P} = P(q > q_{obs} | J^P)$

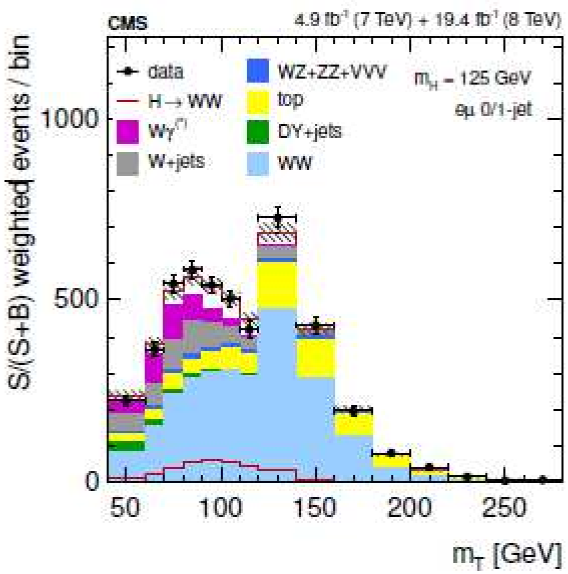
**the hypothesis $0^-$ is excluded at the 99.9% C. L.**

# Higgs properties after RUN I

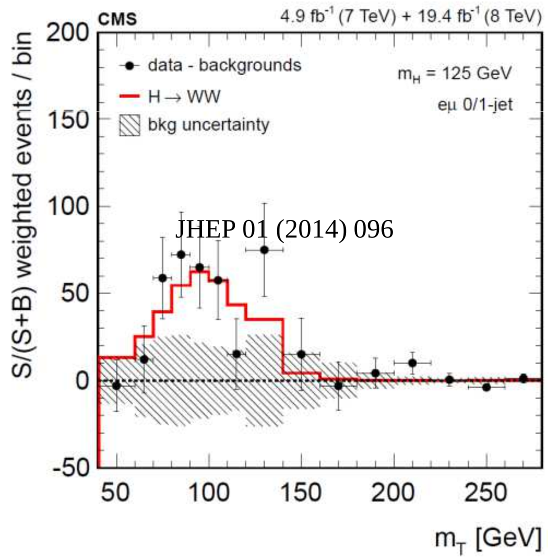
## Other Boson channel: WW

**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**

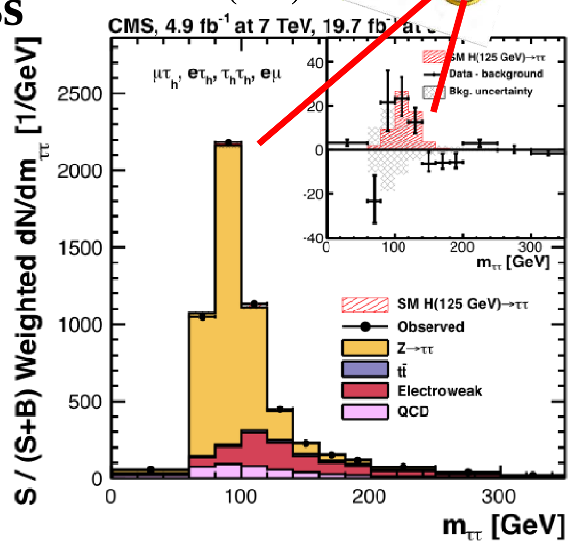



**Relevant to study VBF and VH production**

## The fermionic channels: H→ττ

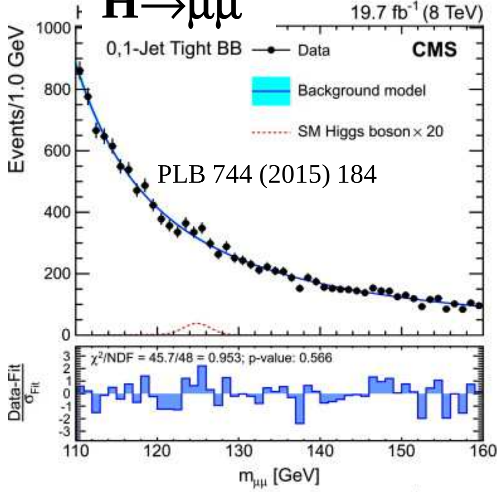
**Yukawa coupling with fermions proportional to their mass**
**⇒ for leptonic decay only H→ττ is visible at present****
**neutrino's in the final state:**
**peak reconstruction problematic**
**(with a much larger peak from Z→ττ )**

JHEP 05 (2014) 104




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

**H→μμ**




**** 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

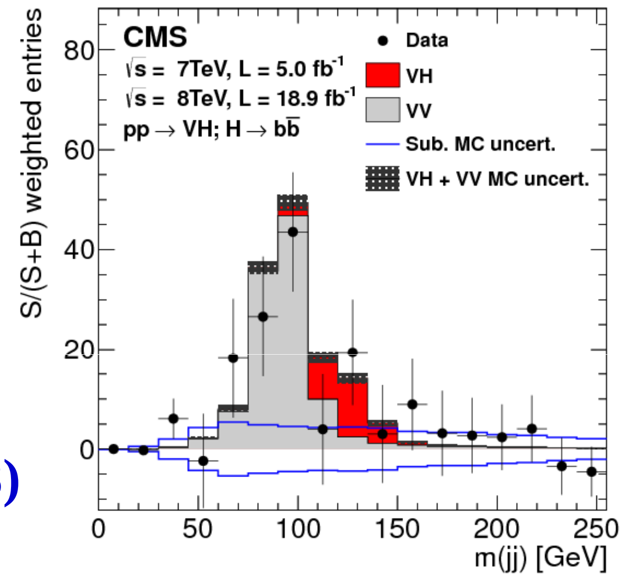
Phys. Rev. D 89 (2014) 012003, Nature Phys. 10 (2014) 557

**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)**

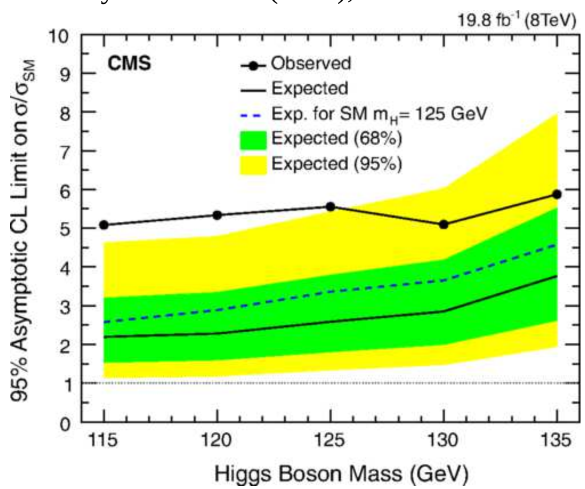
**NB combined with ττ 3.8 σ: evidence for fermionic coupling**

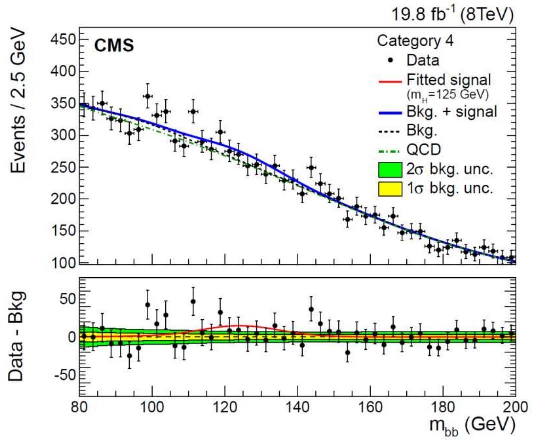



**And VBF**

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

Phys. Rev. D 92 (2015), 032008

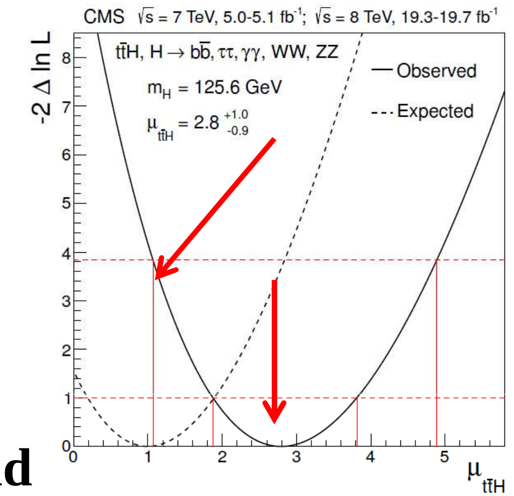


# Higgs properties after RUN I

## ttH production

JHEP 09 (2014) 087

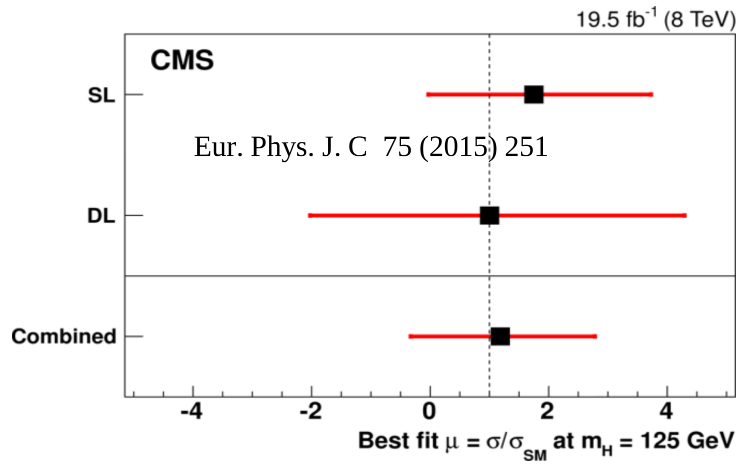



**Several cathegories depending on H decay (3: bb,γγ,multiLeptons) and t decay (3: sl,dl,h)**

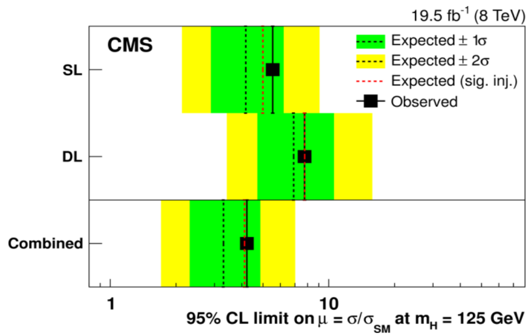
**Significance w.r.t. bckg only hyp.: 3.4 σ (1.2)**
**Higher than expected:**
**if SM signal is considered excess of ~2 σ**

**New: Matrix Element Method to improve signal/ background 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**




Eur. Phys. J. C 75 (2015) 251




**Limit: <4.2 $\sigma_{SM}$ (3.3) (4.1with H SM)**

# Couplings

## Some formalism

**A direct comparison with SM expectation is convenient:** arXiv:1307.1347

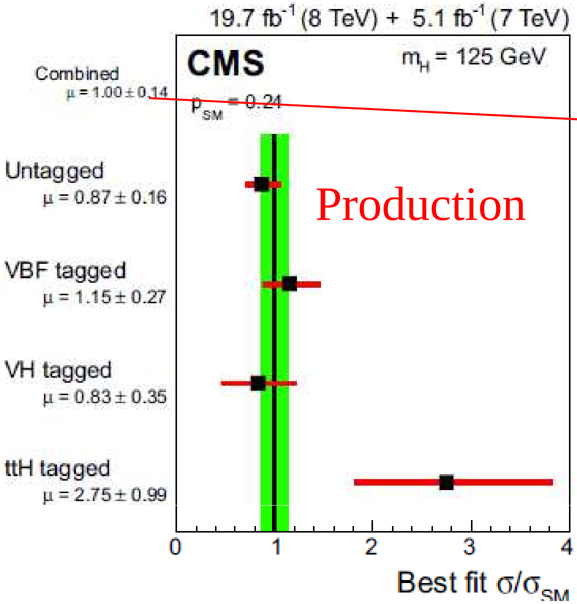
SM coupling to V bosons: $g_{HVV} = \frac{2m_V^2}{v}$

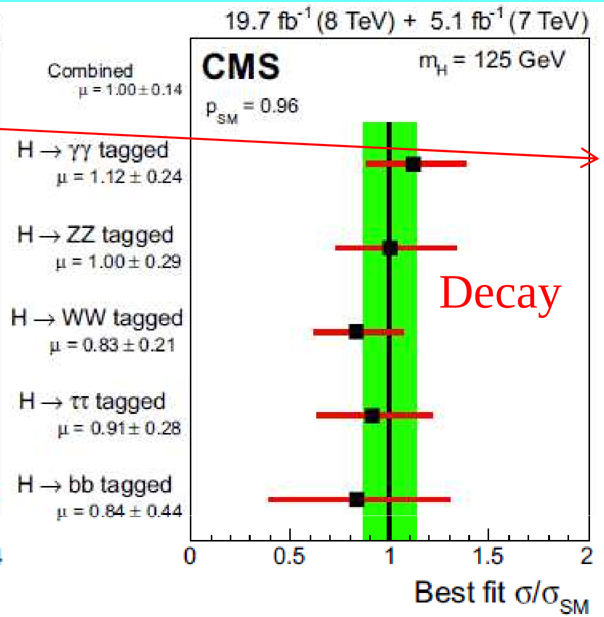
SM coupling to fermions: $g_{Hff} = \frac{m_f}{v}$

| Name | Meaning | Symbol |
|---|---|---|
| Signal strength | $\frac{\sigma(\mathrm{BR})}{\sigma^{\mathrm{SM}}(\mathrm{BR}^{\mathrm{SM}})}$ | $\mu$ |
| Coupling modifiers | $\frac{g_{HXX}}{g_{HXX}^{\mathrm{SM}}}$ | $\kappa_X$ |
| Total width modifier | $\frac{\Gamma_{\mathrm{tot}}}{\Gamma_{\mathrm{tot}}^{\mathrm{SM}}}$ | $\kappa_H^2$ |
| Ratio of coupling modifiers | $\frac{\kappa_X}{\kappa_Y}$ | $\lambda_{XY}$ |

**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

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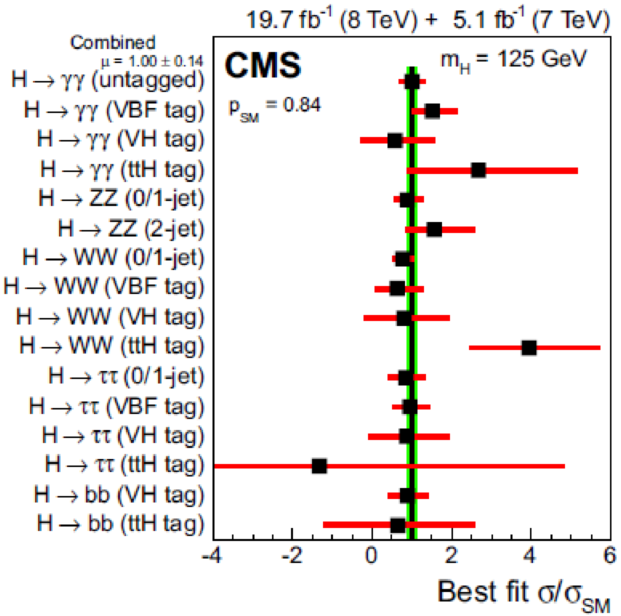
$\mu(\sigma/\sigma_{SM}) = 1.00 \pm 0.14$



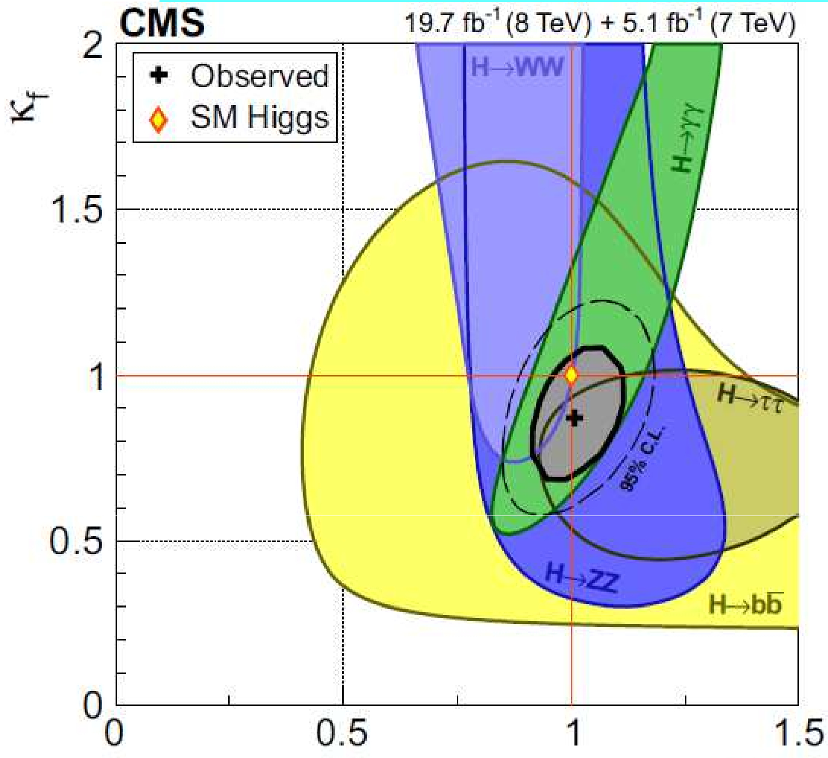

**Custodial symmetry: equal coupling modifiers for W and Z: $\lambda_{WZ} = \kappa_W/\kappa_Z = 1$**

**Since**

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

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

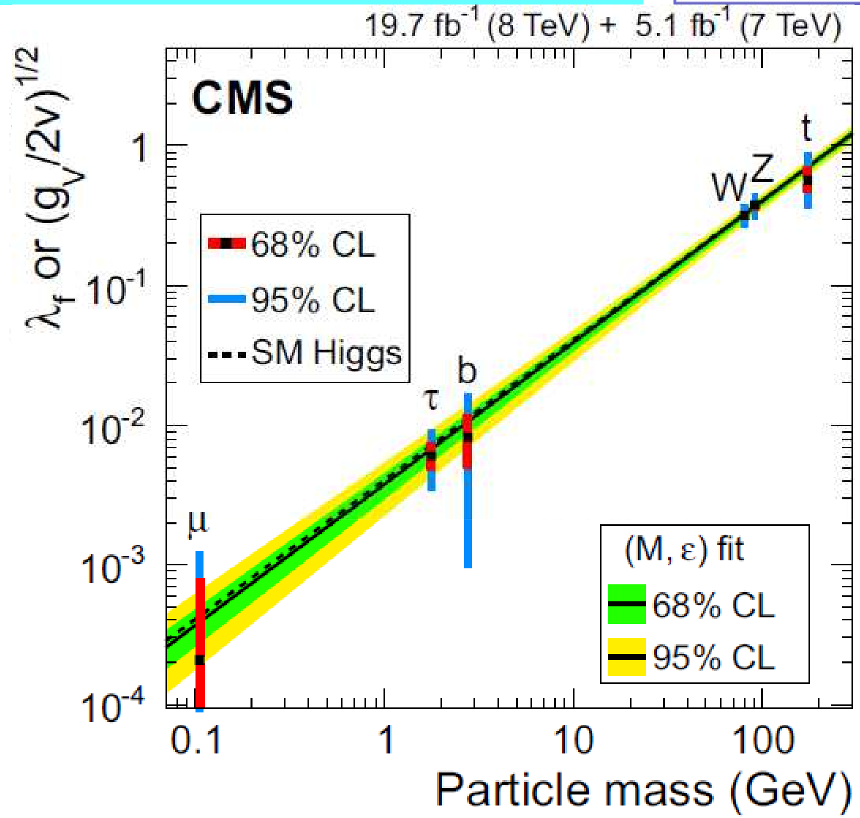
# Couplings




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

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

**Compatible with SM**
**(also the combination ATLAS-CMS)**




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

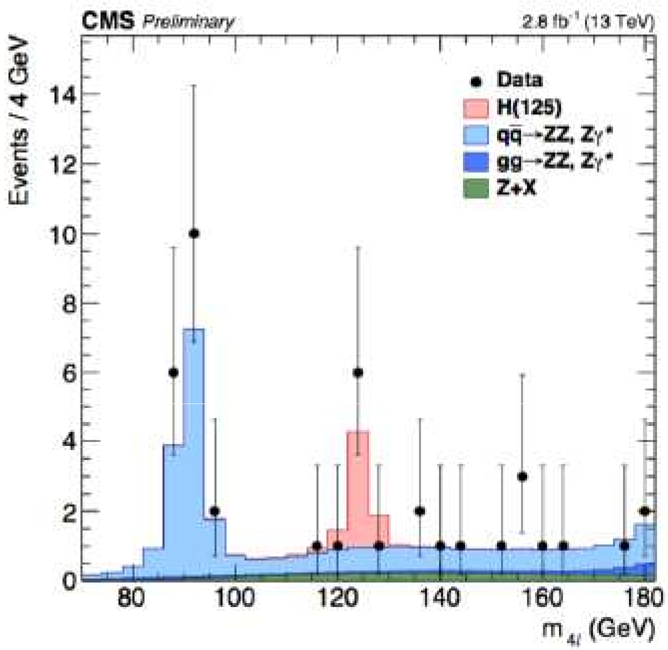
$v$ = **VEV ≈ 246 GeV**

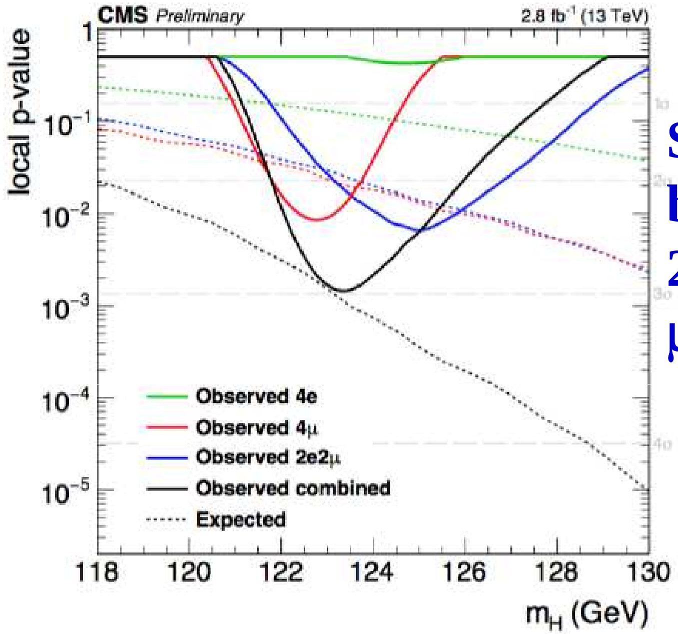
**several assumptions

# First Results at 13 TeV*

## H→ZZ*→4l:

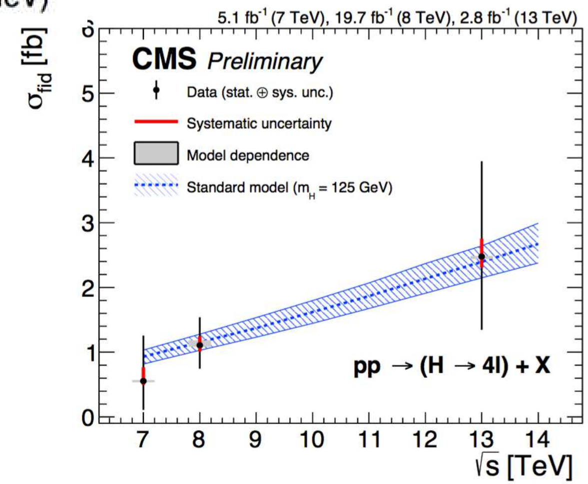
HIG-15-004




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

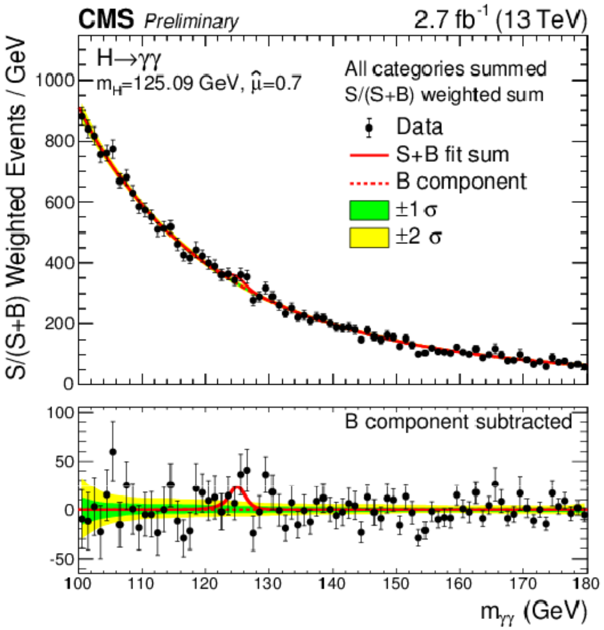
$\mu=\sigma/\sigma_{SM}= 0.82^{+0.57}_{-0.43}$




**Fiducial cross section compared with results at 7 and 8 TeV**

***Only 2015 data**

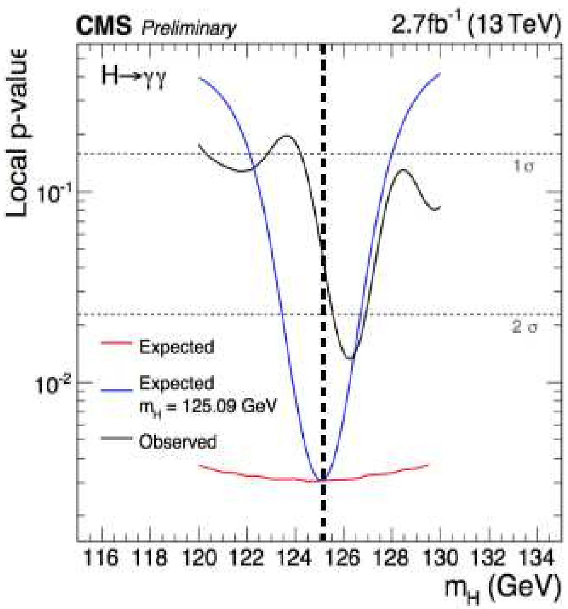
# First Results at 13 TeV

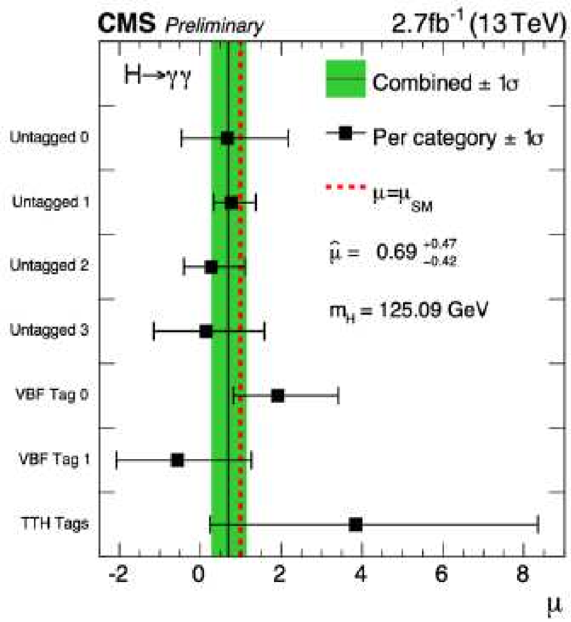



HIG-15-005

## H→γγ

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



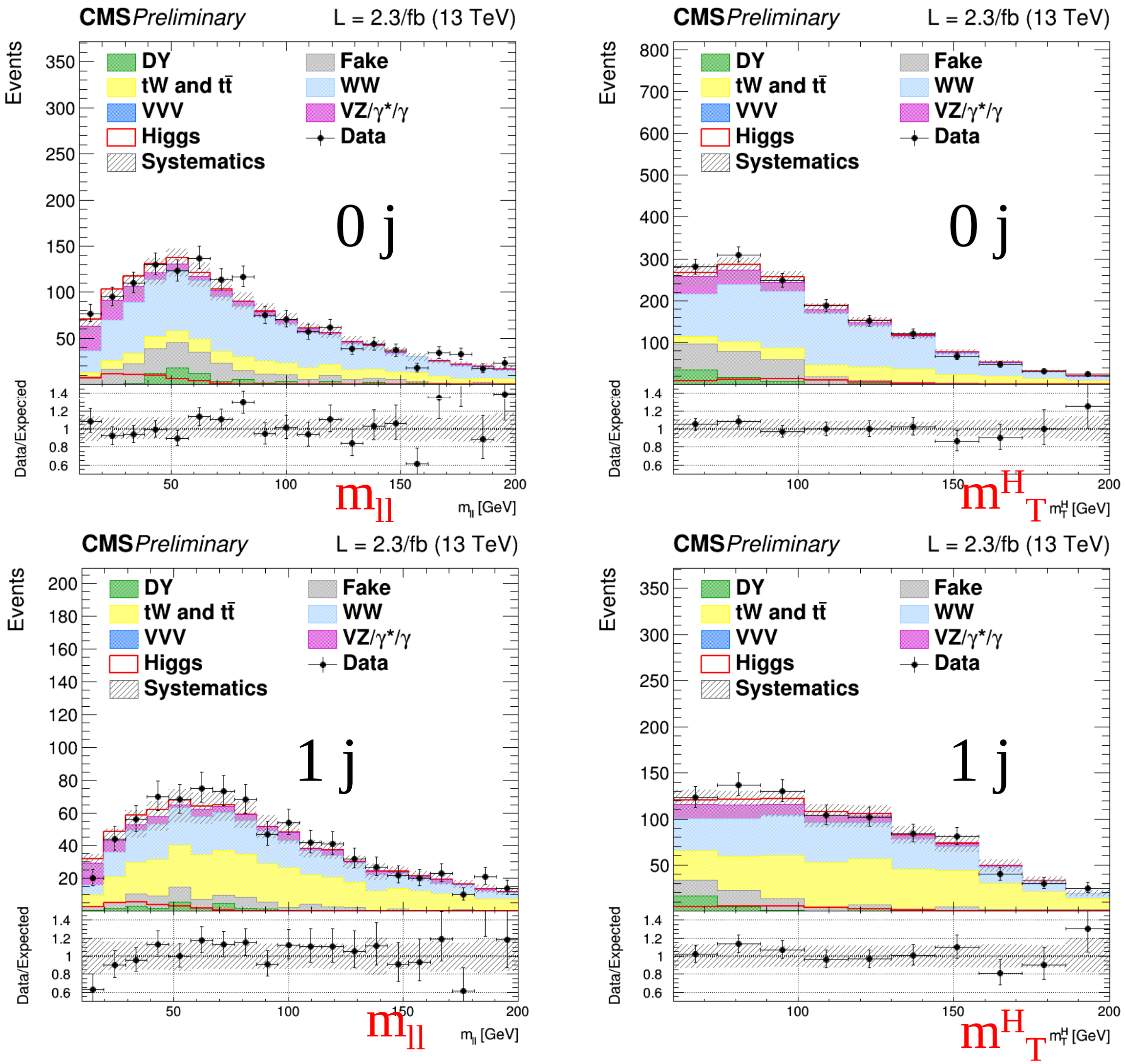



# First Results at 13 TeV

## 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)**

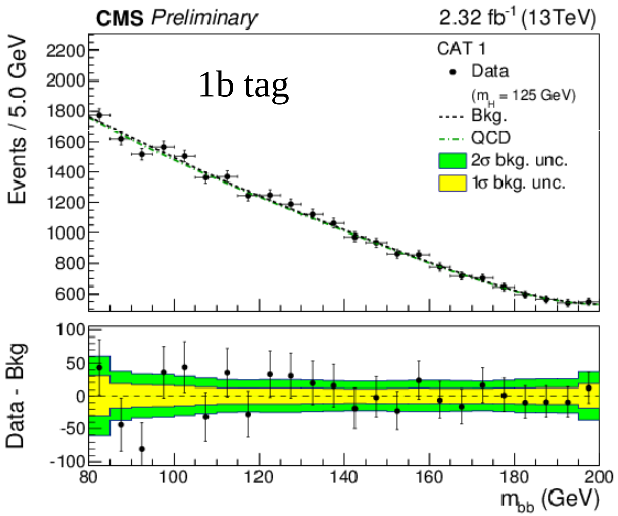
# First Results at 13 TeV

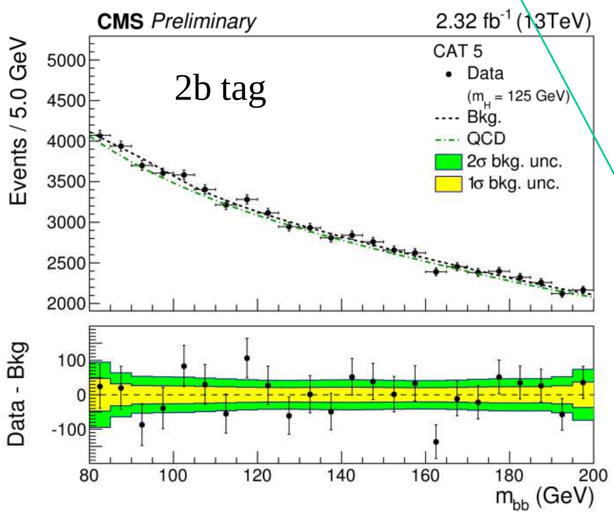
## VBF H→bb

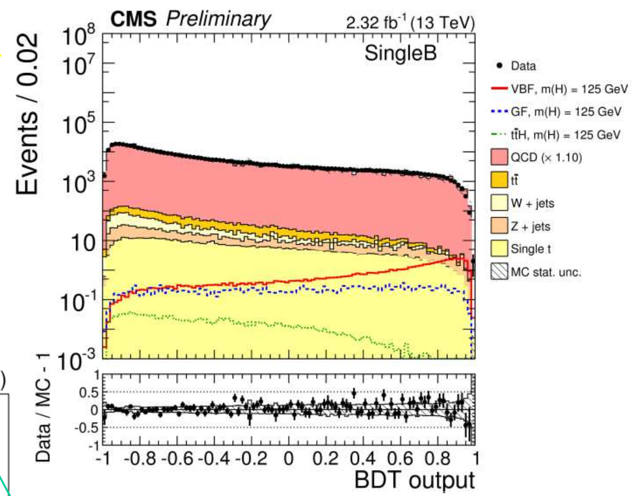
NEW

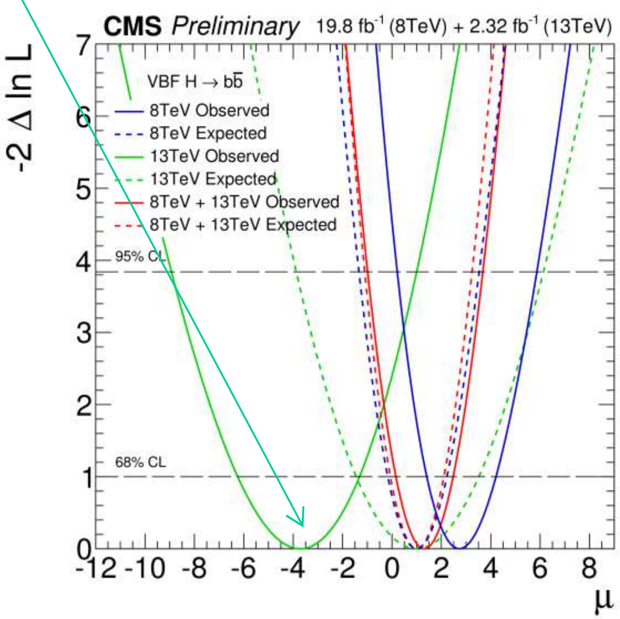
**VBF: events in 4 jets**
**1 or 2 b tag and BDT categorization**

HIG-16-003



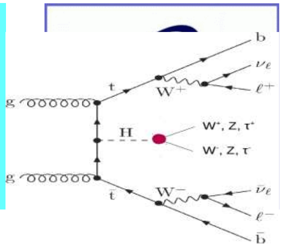




**No evidence yet @ 13 TeV**

**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

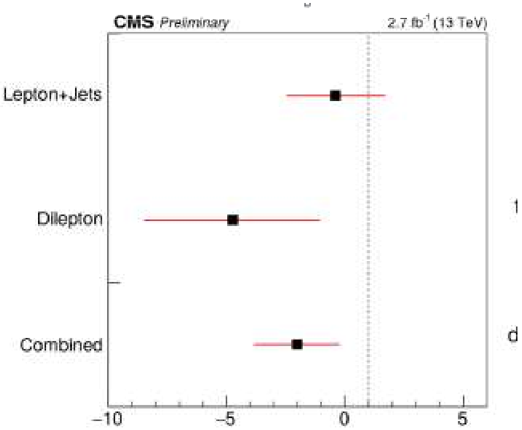


## ttH

### ttH(bb)

HIG-16-004

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

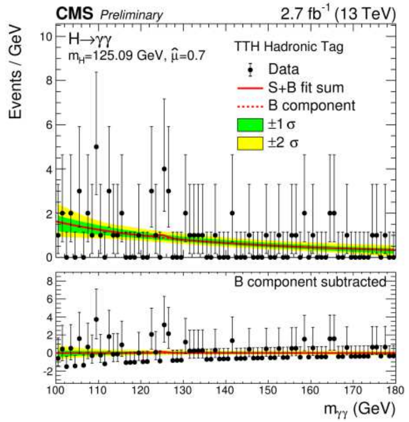



$\sigma/\sigma_{SM}<2.6$ (3.6)
$\mu=\sigma/\sigma_{SM}= -2.0\pm1.8$

### ttH(γγ)

HIG-15-005

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

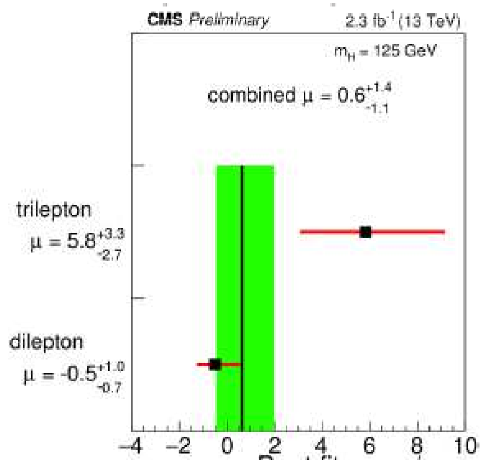



$\mu=\sigma/\sigma_{SM}= 3.8^{+4.5}_{-3.6}$

### ttH multileptons

HIG-15-008

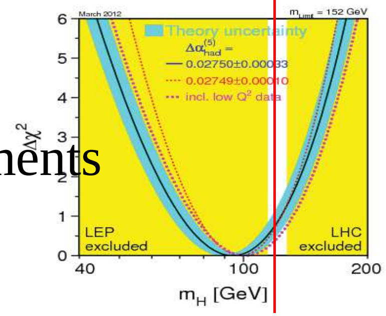
**ss dileptons or ≥3 l**
**≥ 4 j ≥5 j**
**≥1 b tag**
**and other cat.**




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

**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**

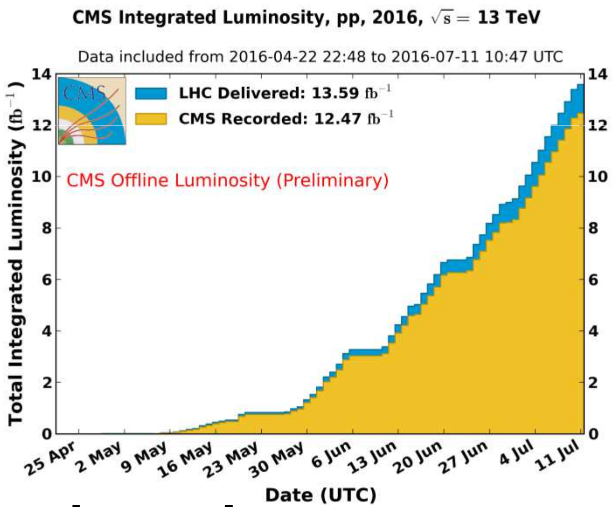
**The value $m_H$=125 GeV is within the SUSY-accepted range**

**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**

[optimistic, pessimistic]

| $\kappa_\gamma$ | $\kappa_W$ | $\kappa_Z$ | $\kappa_g$ | $\kappa_b$ | $\kappa_t$ | $\kappa_\tau$ | $\kappa_{Z\gamma}$ | $\kappa_\mu$ | |
|---|---|---|---|---|---|---|---|---|---|
| [ 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**

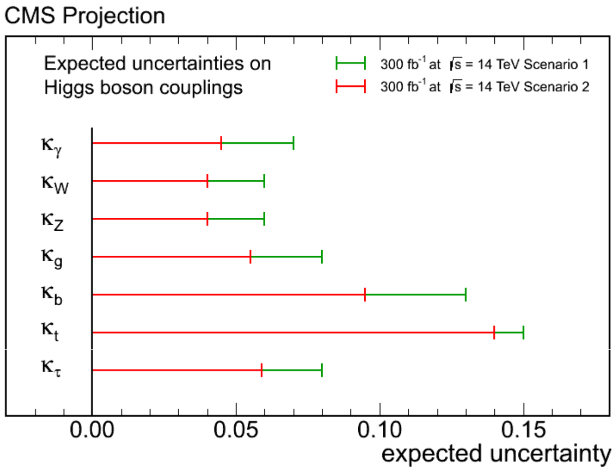
**The increase in E and Lumi gives an opportunity to observe heavy H states as foreseen by MSSM or to extend the excluded region in $m_A$-tan$\beta$ plane.**

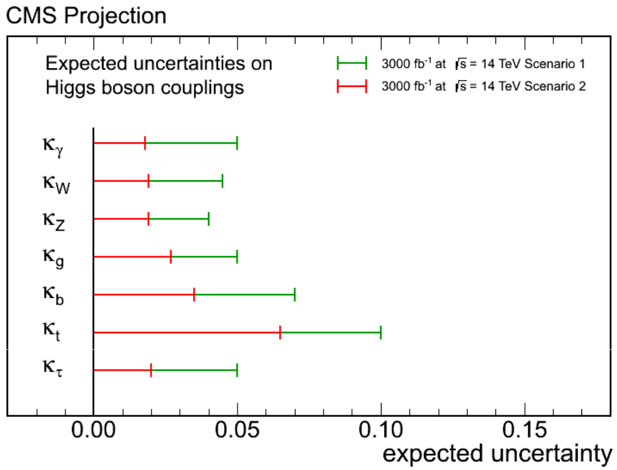
**If the discovered particle is the lightest CP-even state $h$ , $m_A$<230-260 excluded for all tan$\beta$ values**

# Perspectives

## long time scale

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

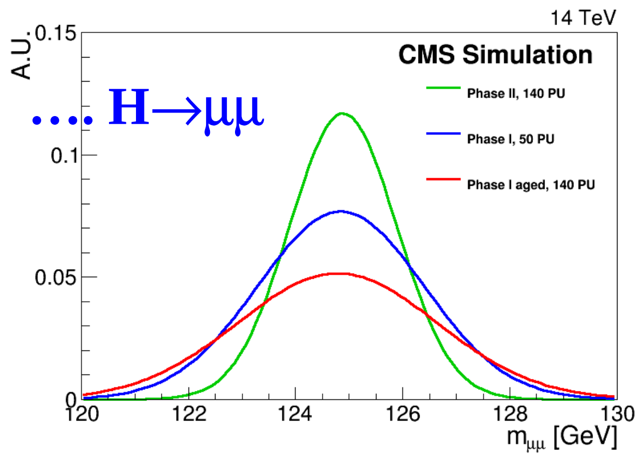


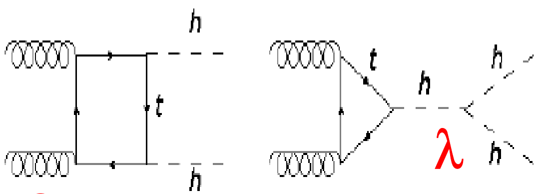

CERN-LHCC-2015-10

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

…. $H \to \mu\mu$




- 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 $H \rightarrow ZZ^* \rightarrow 4\ell$**

**as in the past the parity of $\pi^0$ 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

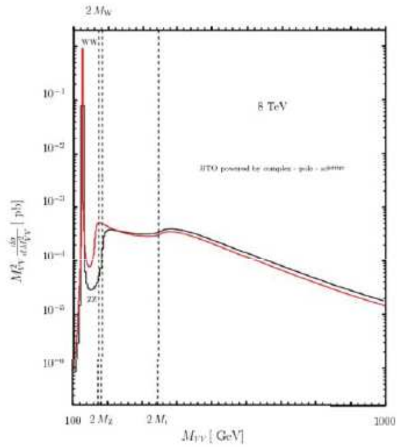
# Higgs properties after RUN I

## 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 $\Gamma_H/\Gamma_H^{SM}$, 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

**$\Gamma_H$< 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 ($\sigma$) | |
|---|---|---|---|
| | | 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* $\kappa_g$ *depends*
only on the fermion contribution without additional
contributions

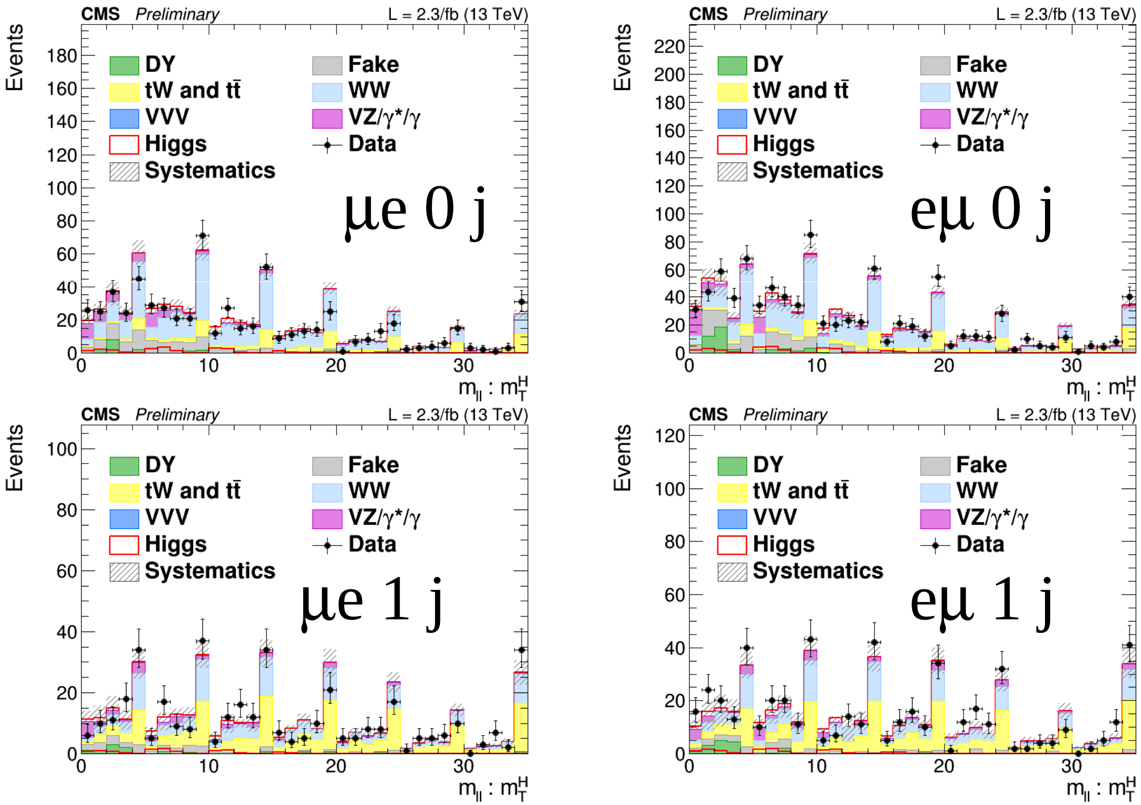
| Model parameters | Table in Ref. [171] | Parameter | Best-fit result 68 % CL | 95 % CL | Comment |
|---|---|---|---|---|---|
| $\kappa_Z, \lambda_{WZ}$ ($\kappa_f = 1$) | – | $\lambda_{WZ}$ | $0.94^{+0.22}_{-0.18}$ | [0.61, 1.45] | $\lambda_{WZ} = \kappa_W/\kappa_Z$ from ZZ and 0/1-jet WW channels |
| $\kappa_Z, \lambda_{WZ}, \kappa_f$ | 44 (top) | $\lambda_{WZ}$ | $0.92^{+0.14}_{-0.12}$ | [0.71, 1.24] | $\lambda_{WZ} = \kappa_W/\kappa_Z$ from full combination |
| $\kappa_V, \kappa_f$ | 43 (top) | $\kappa_V$ | $1.01^{+0.07}_{-0.07}$ | [0.87, 1.14] | $\kappa_V$ scales couplings to W and Z bosons |
| | | $\kappa_f$ | $0.87^{+0.14}_{-0.13}$ | [0.63, 1.15] | $\kappa_f$ scales couplings to all fermions |
| $\kappa_V, \lambda_{du}, \kappa_u$ | 46 (top) | $\lambda_{du}$ | $0.99^{+0.19}_{-0.18}$ | [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 | $\kappa_W$ | $0.95^{+0.14}_{-0.13}$ | [0.68, 1.23] | |
| | | $\kappa_Z$ | $1.05^{+0.16}_{-0.16}$ | [0.72, 1.35] | |
| | | $\kappa_t$ | $0.81^{+0.19}_{-0.15}$ | [0.53, 1.20] | Up-type quarks (via t) |
| | | $\kappa_b$ | $0.74^{+0.33}_{-0.29}$ | [0.09, 1.44] | Down-type quarks (via b) |
| | | $\kappa_\tau$ | $0.84^{+0.19}_{-0.18}$ | [0.50, 1.24] | $\kappa_\tau$ scales the coupling to tau leptons |
| | | $\kappa_\mu$ | $0.49^{+1.38}_{-0.49}$ | [0.00, 2.77] | $\kappa_\mu$ scales the coupling to muons |
| $M, \epsilon$ | Ref. [206] | $M$ (GeV) | $245 \pm 15$ | [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) |
| | | $\epsilon$ | $0.014^{+0.041}_{-0.036}$ | [−0.054, 0.100] | |
| $\kappa_g, \kappa_\gamma$ | 48 (top) | $\kappa_g$ | $0.89^{+0.11}_{-0.10}$ | [0.69, 1.11] | Effective couplings to gluons (g) and photons ($\gamma$) |
| | | $\kappa_\gamma$ | $1.14^{+0.12}_{-0.13}$ | [0.89, 1.40] | |
| $\kappa_g, \kappa_\gamma, BR_{BSM}$ | 48 (middle) | $BR_{BSM}$ | $\leq 0.14$ | [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) | $\kappa_{gZ}$ | $0.98^{+0.14}_{-0.13}$ | [0.73, 1.27] | $\kappa_{gZ} = \kappa_g\kappa_Z/\kappa_H$, i.e. floating $\kappa_H$ |
| | | $\lambda_{WZ}$ | $0.87^{+0.15}_{-0.13}$ | [0.63, 1.19] | $\lambda_{WZ} = \kappa_W/\kappa_Z$ |
| | | $\lambda_{Zg}$ | $1.39^{+0.36}_{-0.28}$ | [0.87, 2.18] | $\lambda_{Zg} = \kappa_Z/\kappa_g$ |
| | | $\lambda_{bZ}$ | $0.59^{+0.22}_{-0.23}$ | $\leq 1.07$ | $\lambda_{bZ} = \kappa_b/\kappa_Z$ |
| | | $\lambda_{\gamma Z}$ | $0.93^{+0.17}_{-0.14}$ | [0.67, 1.31] | $\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$ |
| | | $\lambda_{\tau Z}$ | $0.79^{+0.19}_{-0.17}$ | [0.47, 1.20] | $\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$ |
| | | $\lambda_{tg}$ | $2.18^{+0.54}_{-0.46}$ | [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