



# Combination of couplings and mass in ATLAS and CMS

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- Higgs couplings and mass are important SM parameters
  - The mass was the last missing ingredient to the EWK fit
- Both ATLAS and CMS released updated results with the full run I statistics
- The LHC-HCG is taking care of combining the results of the 2 experiments
  - The combined results for the mass are ready ✓
  - Couplings combination is to be released soon (it also depends on the mass!)
- The full SM Higgs picture will be completed by the results on **spin/parity (K. Liu)** and **width (M. Calandri)**



# Higgs mass measurement

Precise mass determination possible in 2 channels:

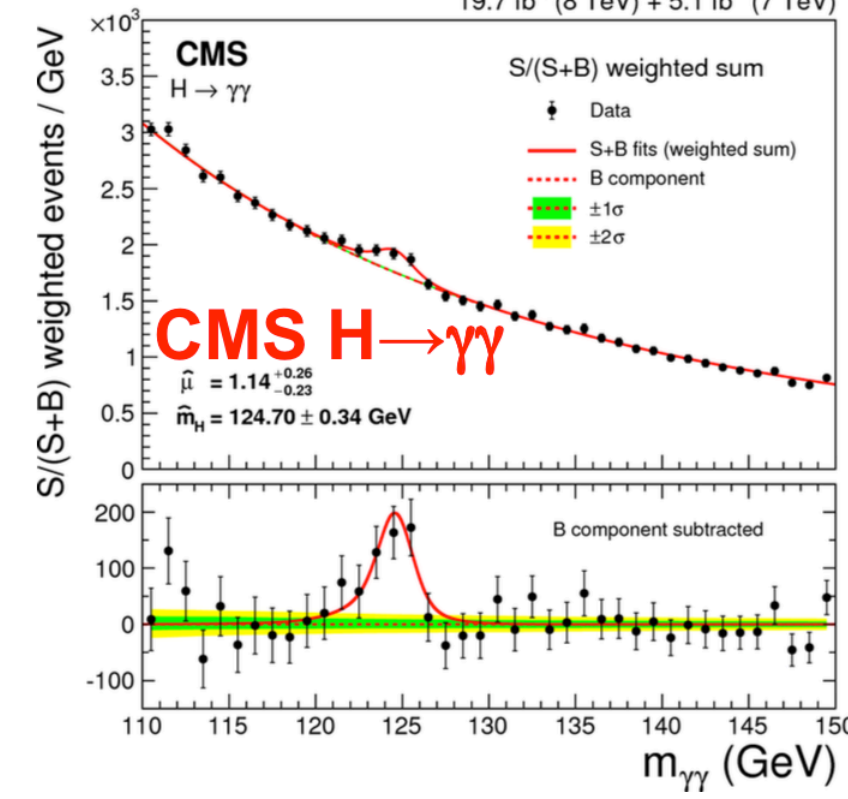
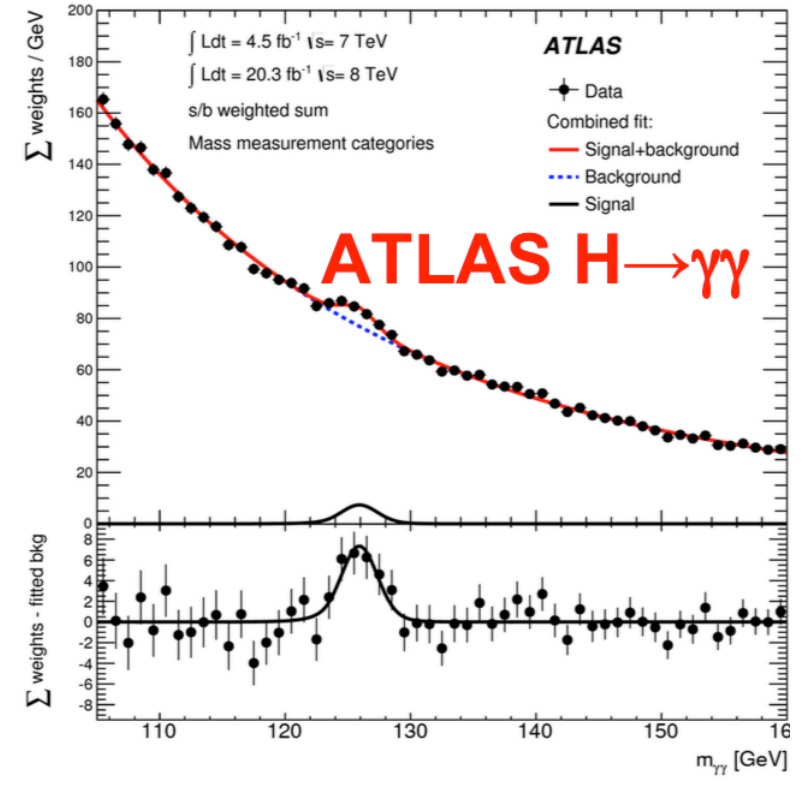
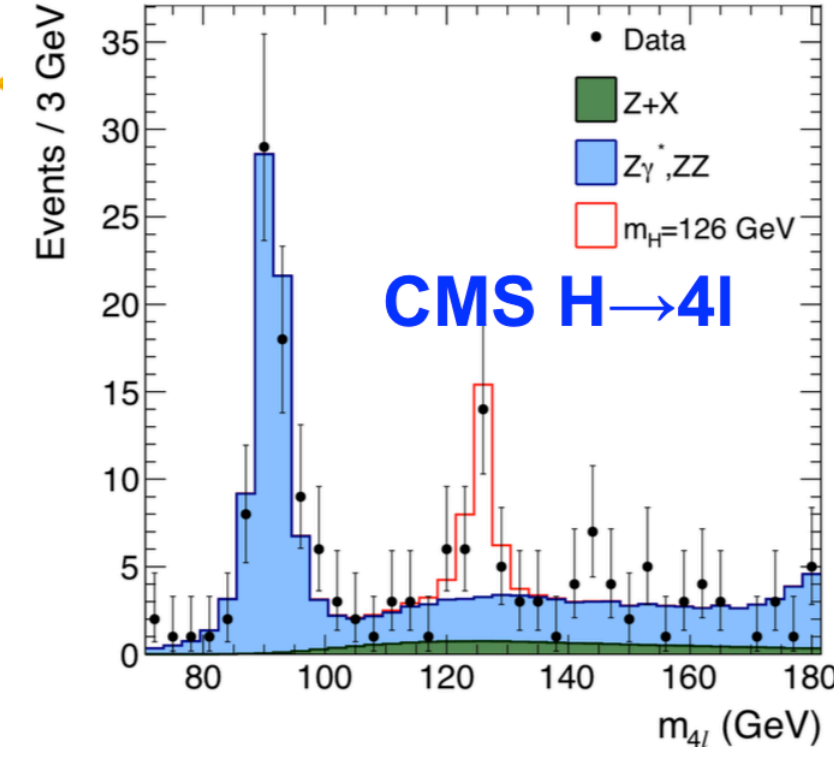
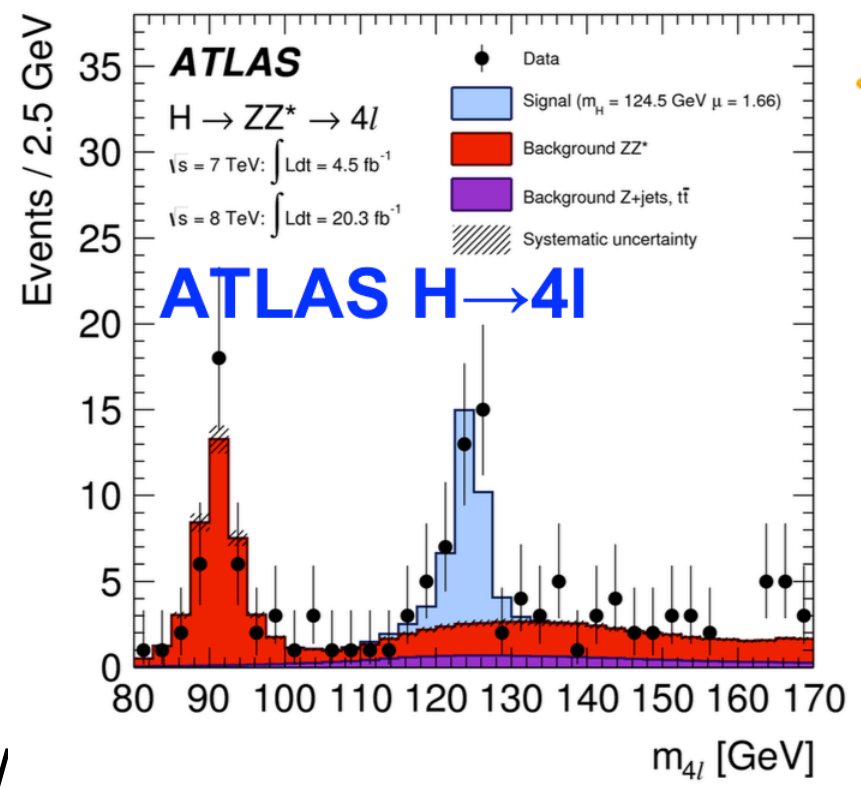
- $4l$  and  $\gamma\gamma$
- All other channels have  $V$  or hadrons in final state

Comparable results among the experiments

Lot of work to properly assess/correlate/quantify all the systematics in the 2 experiments in order to combine properly the likelihoods.

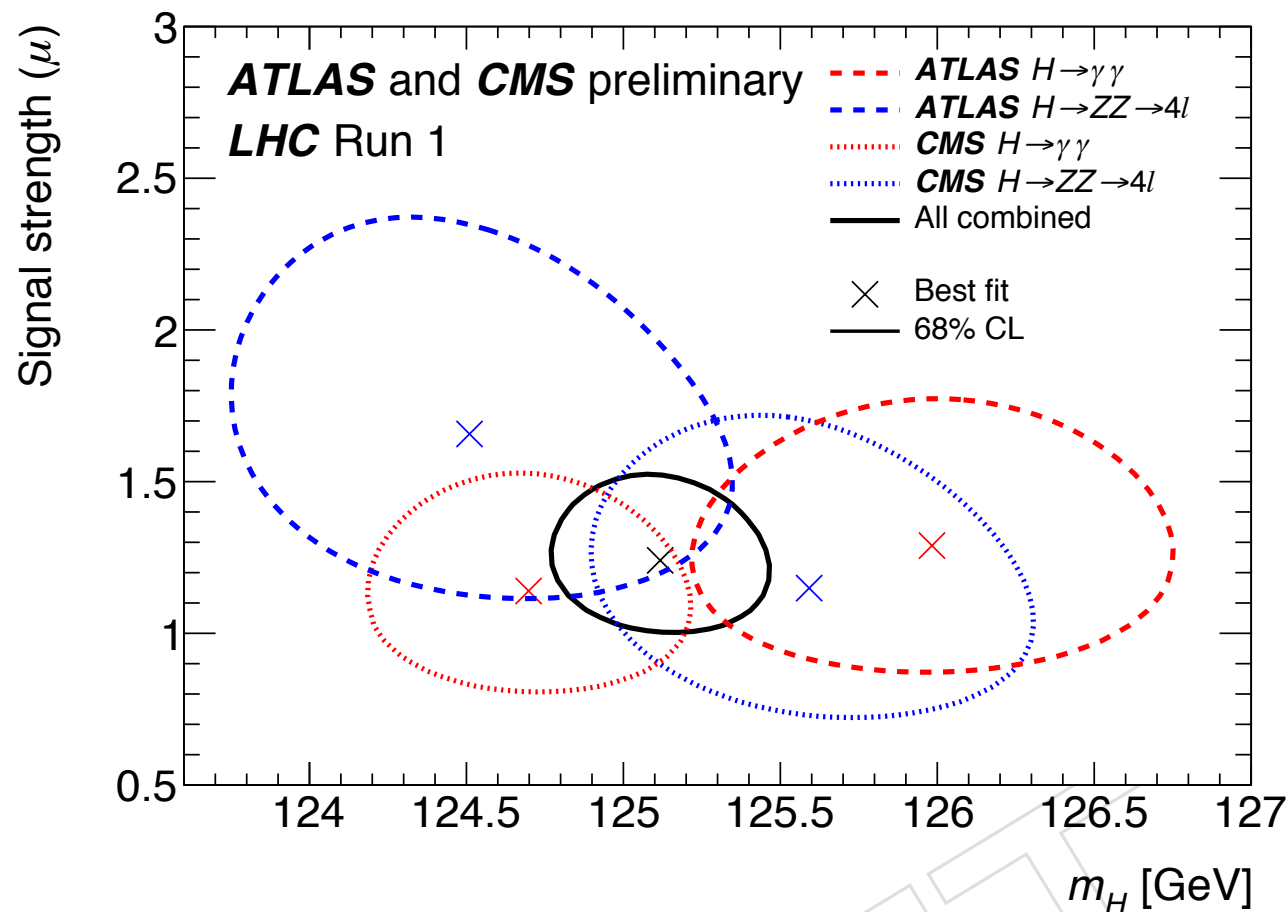
Individual results:

- ATLAS: Phys. Rev. D. 90, 052004 (2014)
- CMS: arXiv: 1412.8662



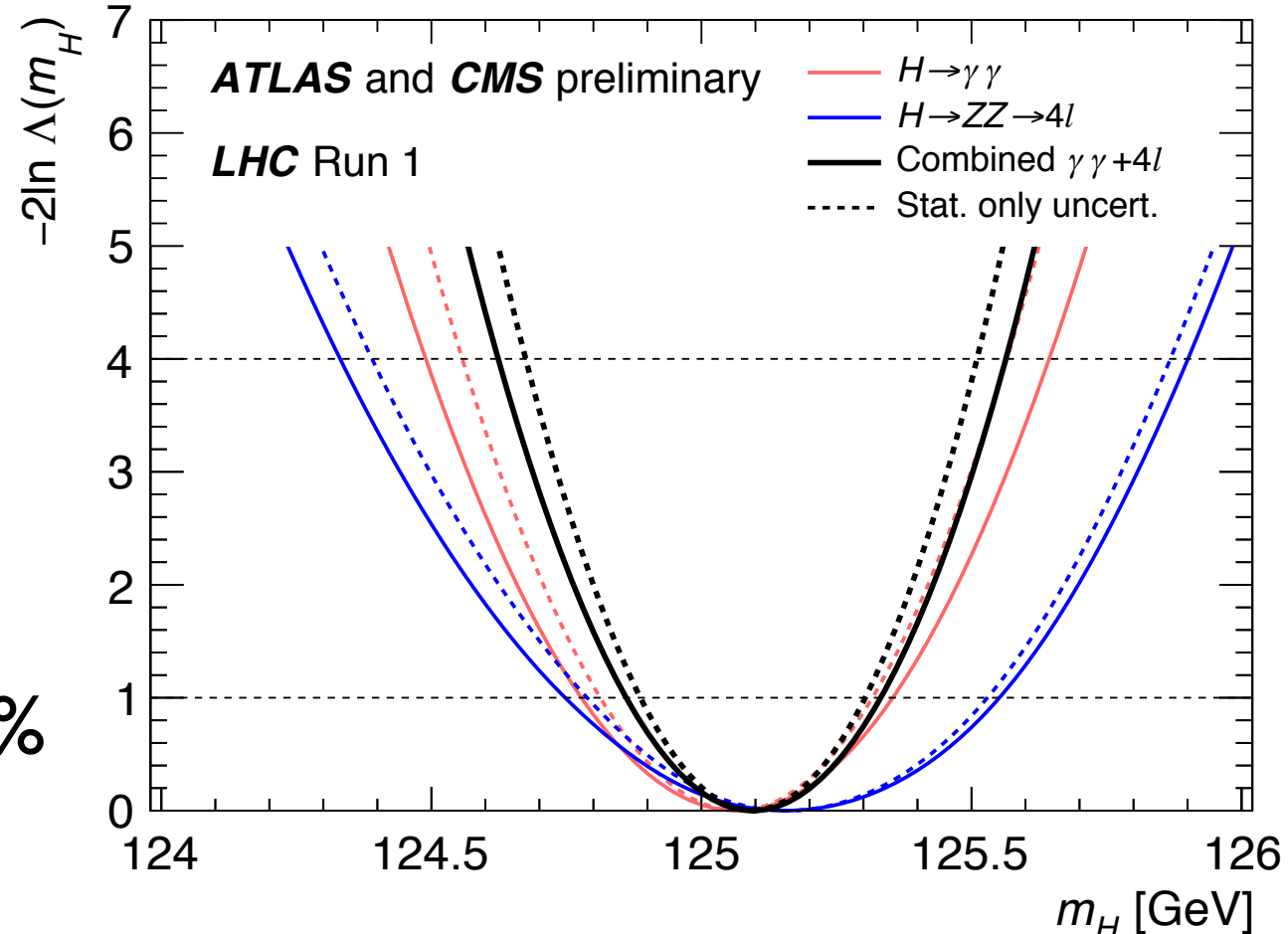
Combination results available at [arXiv:1503.07589](https://arxiv.org/abs/1503.07589)

# Results from the experiments



- Good agreement between the combined  $\gamma\gamma$  and  $4l$  results
- CMS  $\gamma\gamma$  weight  $\sim 40\%$ , CMS  $4l$   $\sim 23\%$ , ATLAS  $\gamma\gamma$  and  $4l$   $\sim 18-19\%$

- To avoid assumptions, three signal strengths are introduced in the fit as free parameters when combining
- $\mu_{ggF+ttH}$ ,  $\mu_{VBF+VH}$  for  $\gamma\gamma$  and  $\mu^{4l}$  for  $4l$  (the same in ATLAS and CMS)
- Interference is neglected (expect a few MeV mass shift)



$$m_{\gamma\gamma} = 125.07 \pm 0.25(\text{stat}) \pm 0.14(\text{syst}) \quad m_{4l} = 125.15 \pm 0.37(\text{stat}) \pm 0.15(\text{syst})$$

# Compatibility checks



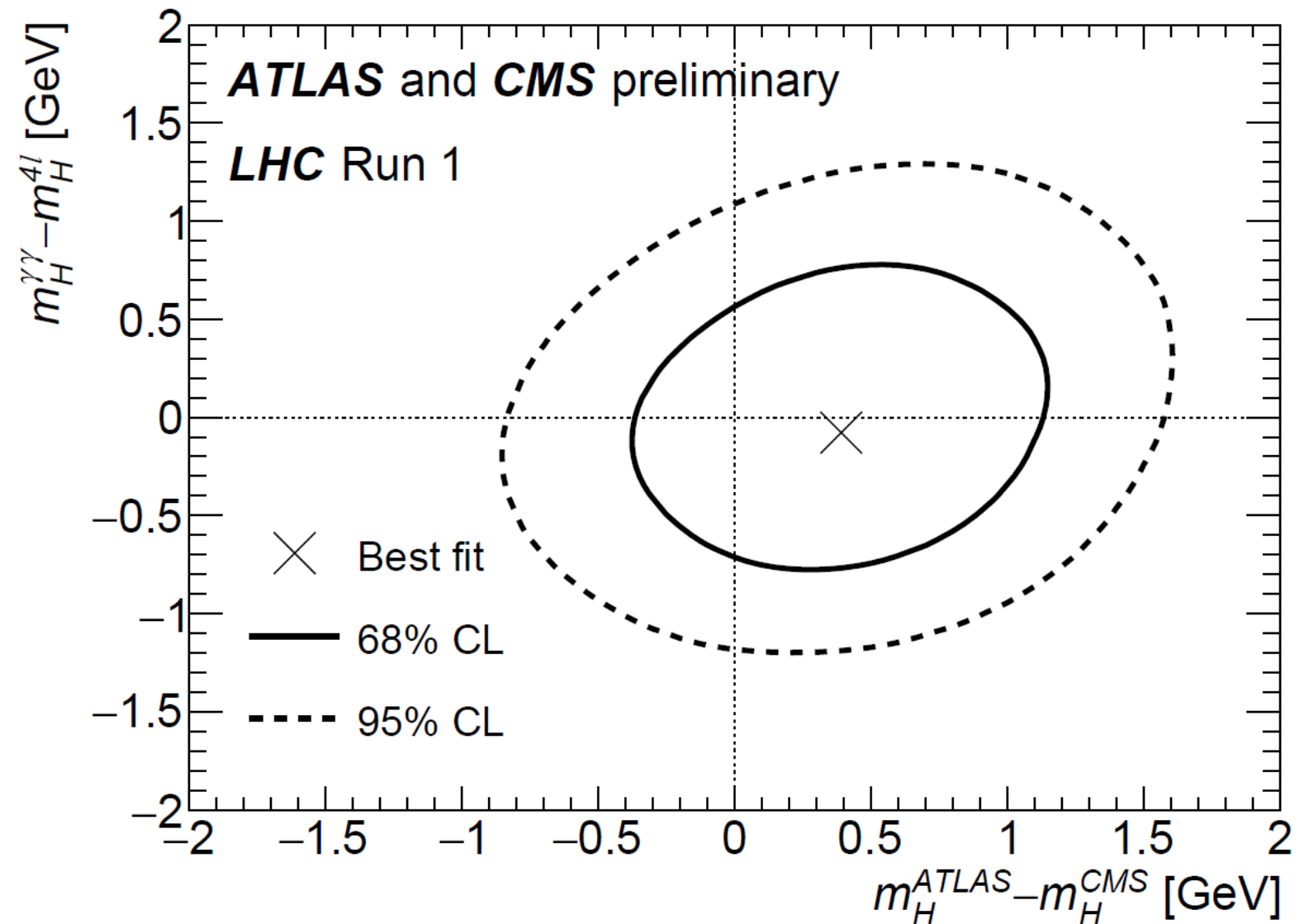
- All the signal strength factors are compatible with 1

- $\mu_{ggF+ttH} = 1.15^{+0.28}_{-0.25}$

- $\mu_{VBF+VH} = 1.17^{+0.58}_{-0.53}$

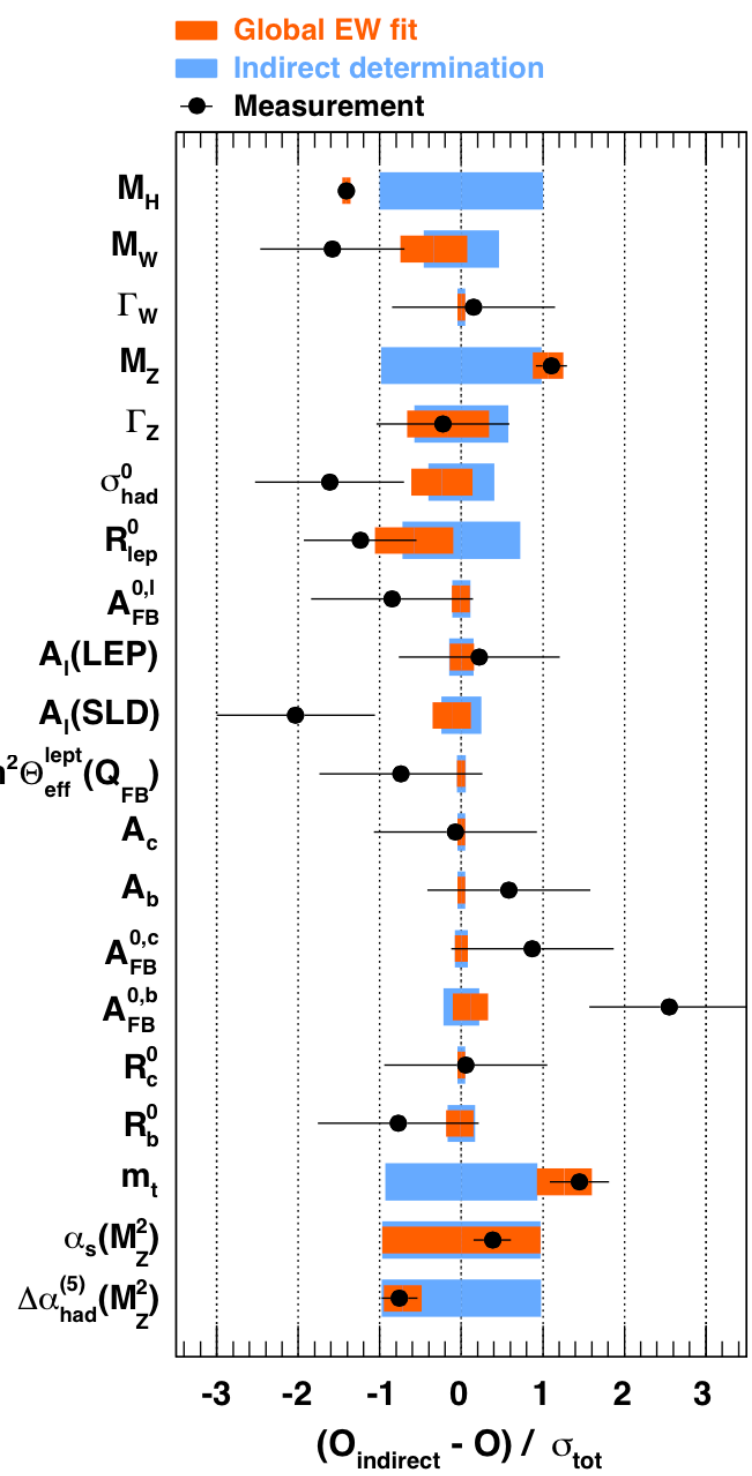
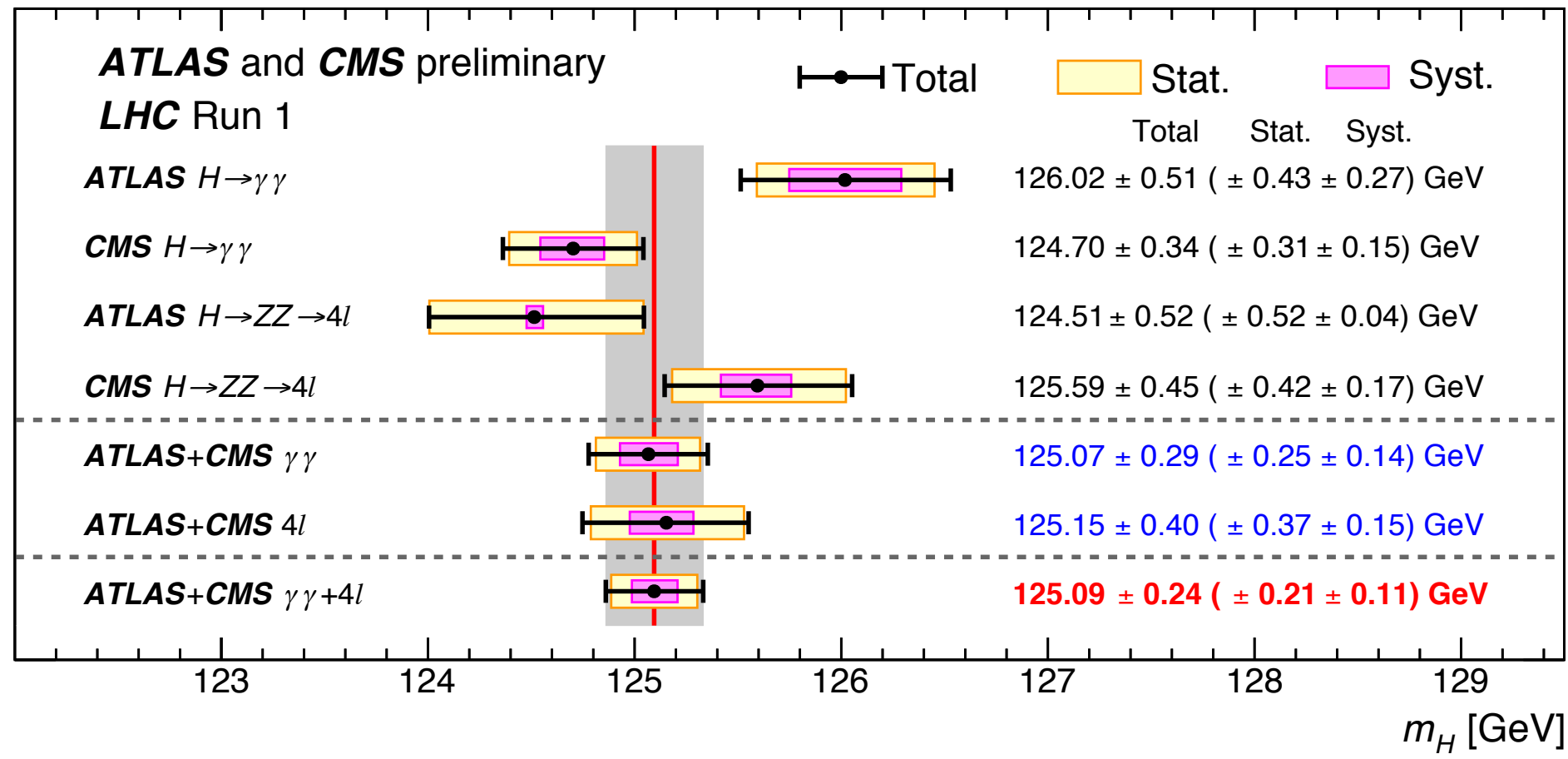
- $\mu_{4l} = 1.40^{+0.30}_{-0.25}$

- $\mu = 1.24^{+0.18}_{-0.16}$



- $m_{\gamma\gamma}$  and  $m_{4l}$  almost on top of each other
- Small difference between the experiments, **well below  $1\sigma$** 
  - ATLAS:  $125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst})$  CMS:  $125.02 \pm 0.27(\text{stat}) \pm 0.15(\text{syst})$

# Combined results



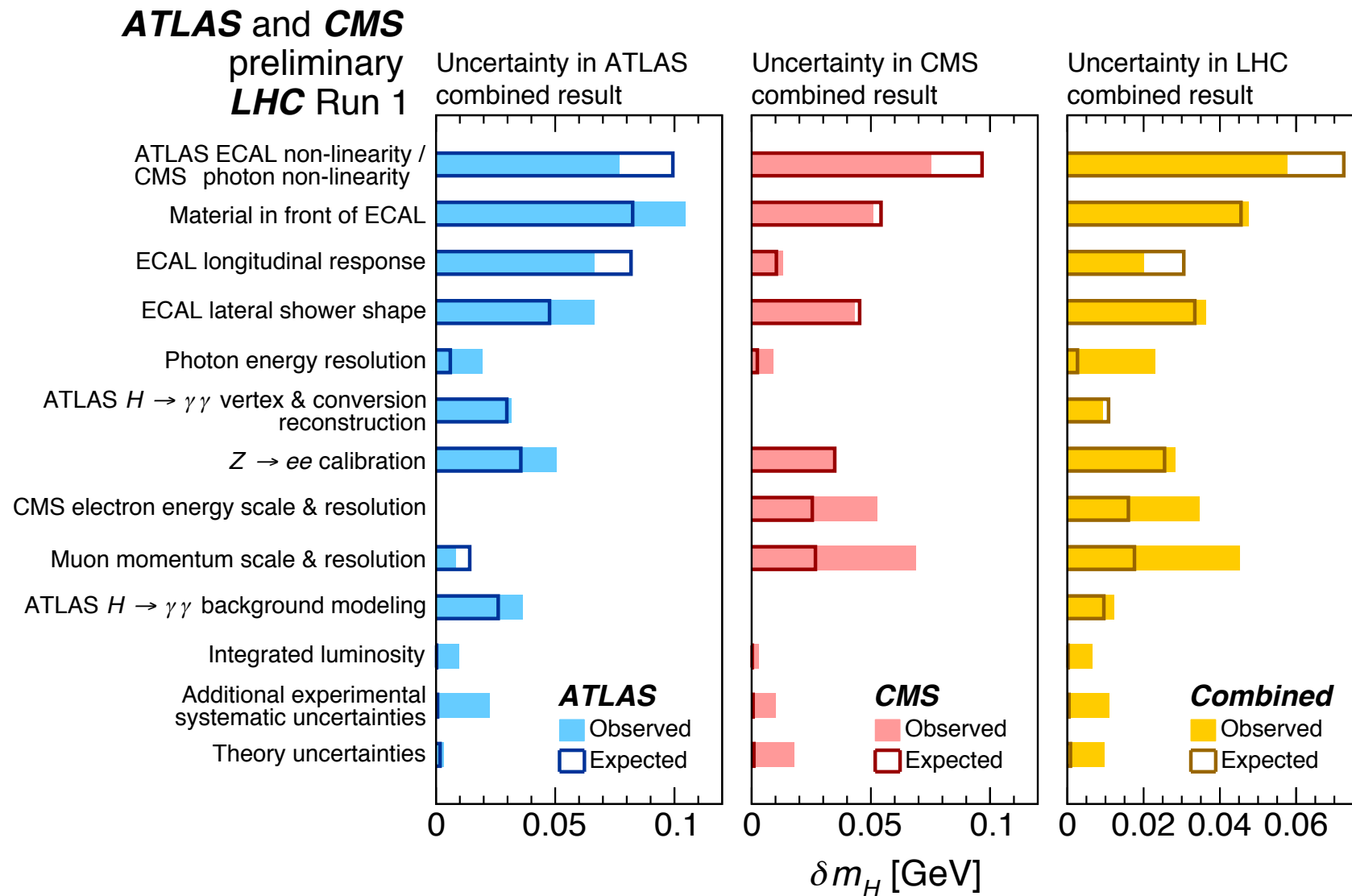
- $m_H = 125.09 \pm 0.21$  (stat)  $\pm 0.11$  (syst) GeV
- 0.19% precision!
- Among the most precise parameters of the EWK fit
- Mostly statistical uncertainties
- Tensions mostly within experiments, no indications of channel dependencies



# Systematic uncertainties



$$m_H = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (scale)} \pm 0.02 \text{ (other)} \pm 0.01 \text{ (th)} \text{ GeV}$$



- Measurement dominated by statistical uncertainties
- Systematics dominated by energy/momentum scale corrections (dominated by the available statistics)

# Measure of the signal strength



- Measure of the ratio  $\mu$  between the observed/predicted event rate
- SM kinematics for production and decay
- Disentangle for production mechanism and decay mode in different channels

	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ$	$H \rightarrow WW$	$H \rightarrow \tau\tau$	$H \rightarrow bb$	$H \rightarrow Z\gamma$	$H \rightarrow \mu\mu$
ggH	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS		ATLAS CMS	ATLAS CMS
VBF	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS		ATLAS CMS	ATLAS CMS
VH	ATLAS CMS	ATLAS CMS	ATLAS CMS	CMS	ATLAS CMS	ATLAS CMS	CMS
ttH	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS		

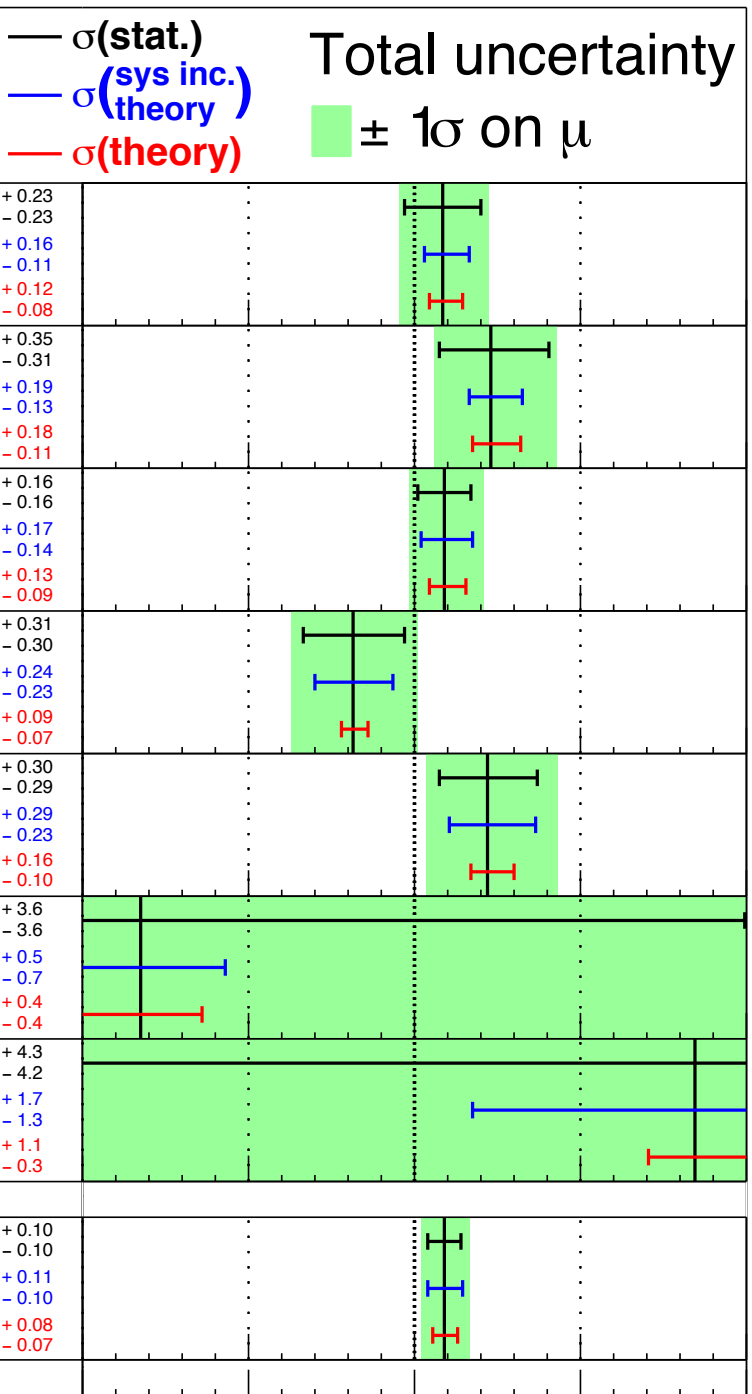


# Signal strength by decay channel



ATLAS-CONF-2015-007

ATLAS Preliminary  
 $m_H = 125.36 \text{ GeV}$

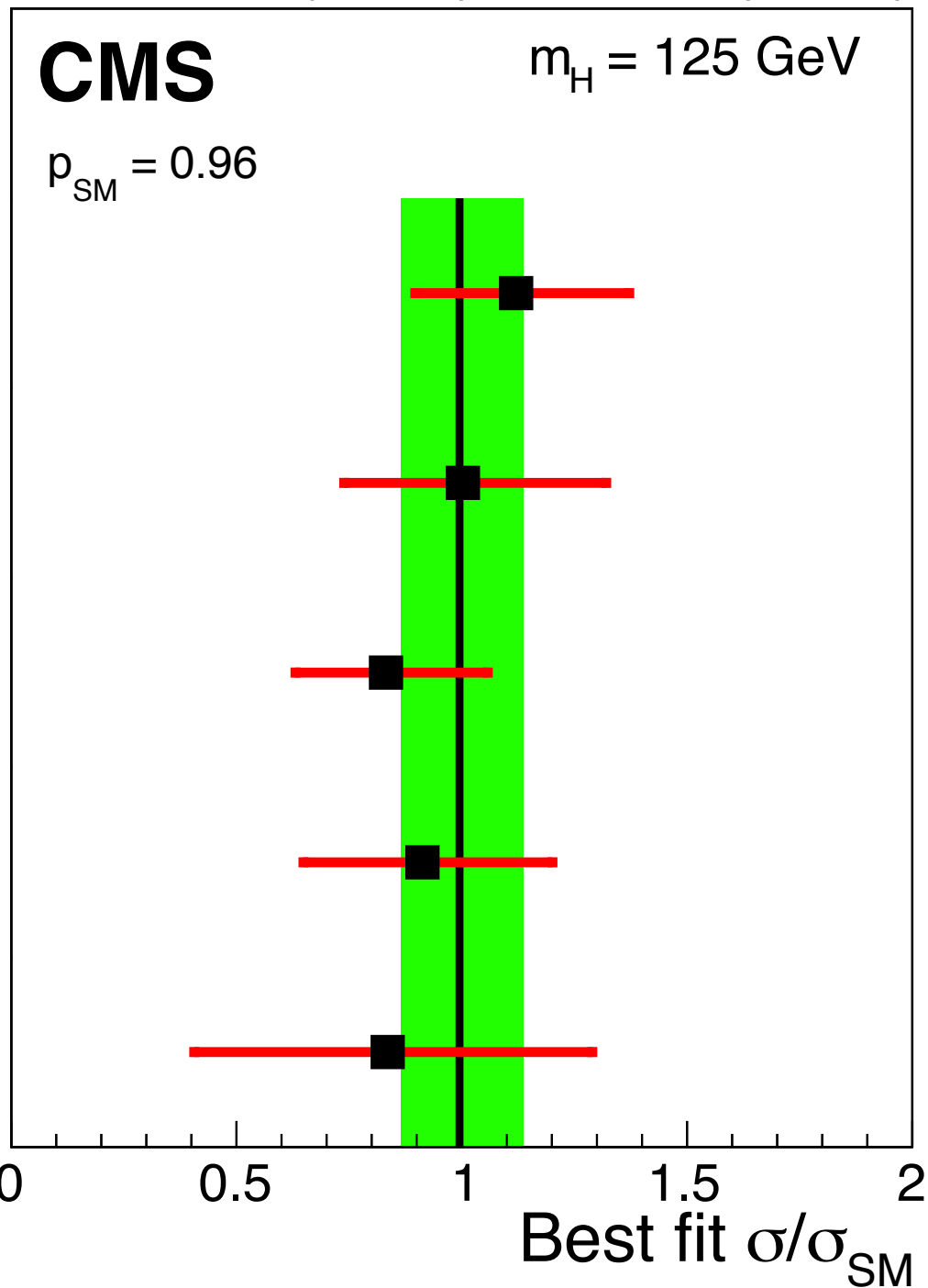


$\sqrt{s} = 7 \text{ TeV}, 4.5\text{-}4.7 \text{ fb}^{-1}$   
 $\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$

Signal strength ( $\mu$ )

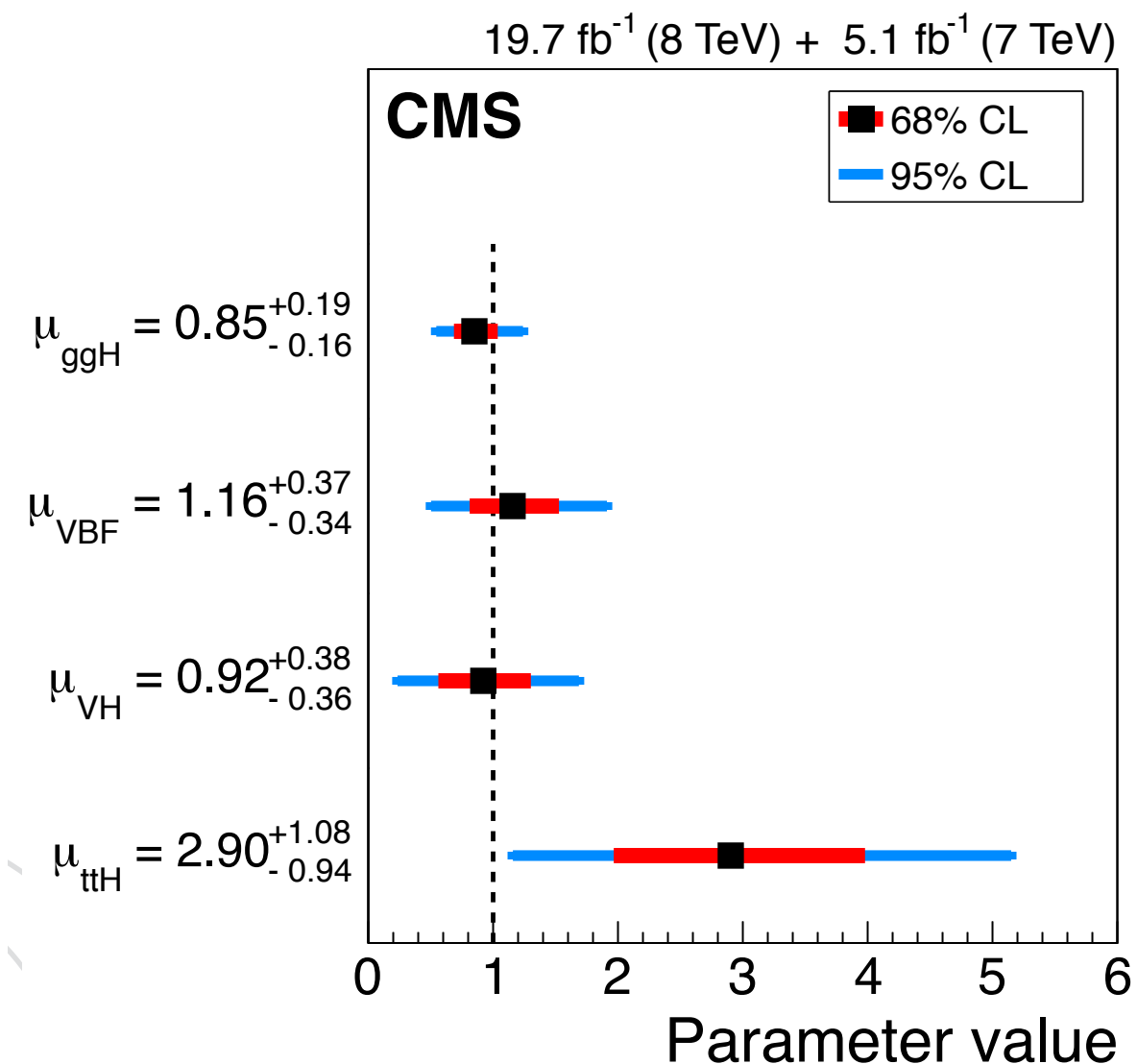
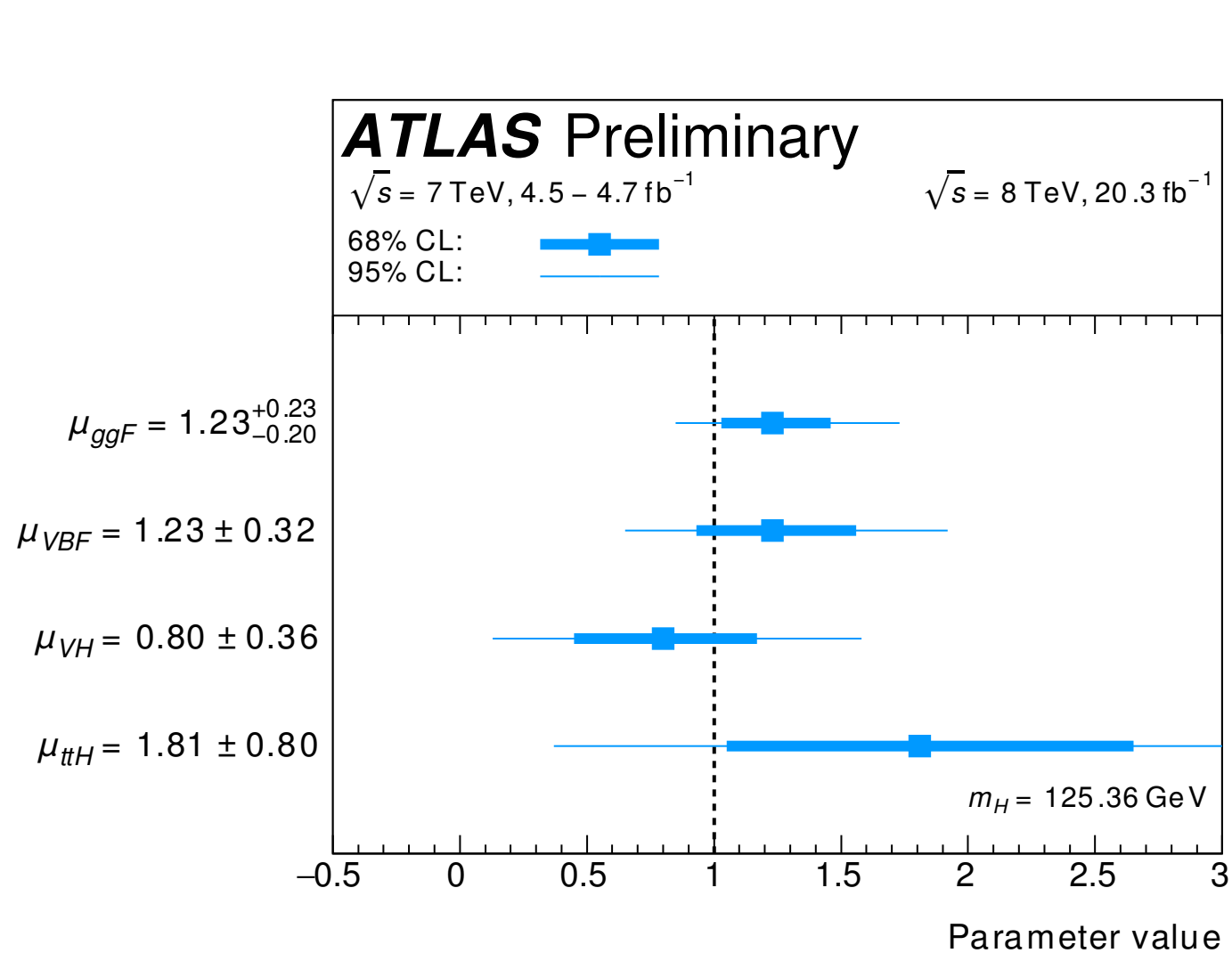
arXiv: 1412.8662  
 $19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 5.1 \text{ fb}^{-1} (7 \text{ TeV})$

- Combined  $\mu = 1.00 \pm 0.14$
- $H \rightarrow \gamma\gamma$  tagged  $\mu = 1.12 \pm 0.24$
- $H \rightarrow ZZ$  tagged  $\mu = 1.00 \pm 0.29$
- $H \rightarrow WW$  tagged  $\mu = 0.83 \pm 0.21$
- $H \rightarrow \tau\tau$  tagged  $\mu = 0.91 \pm 0.28$
- $H \rightarrow b\bar{b}$  tagged  $\mu = 0.84 \pm 0.44$



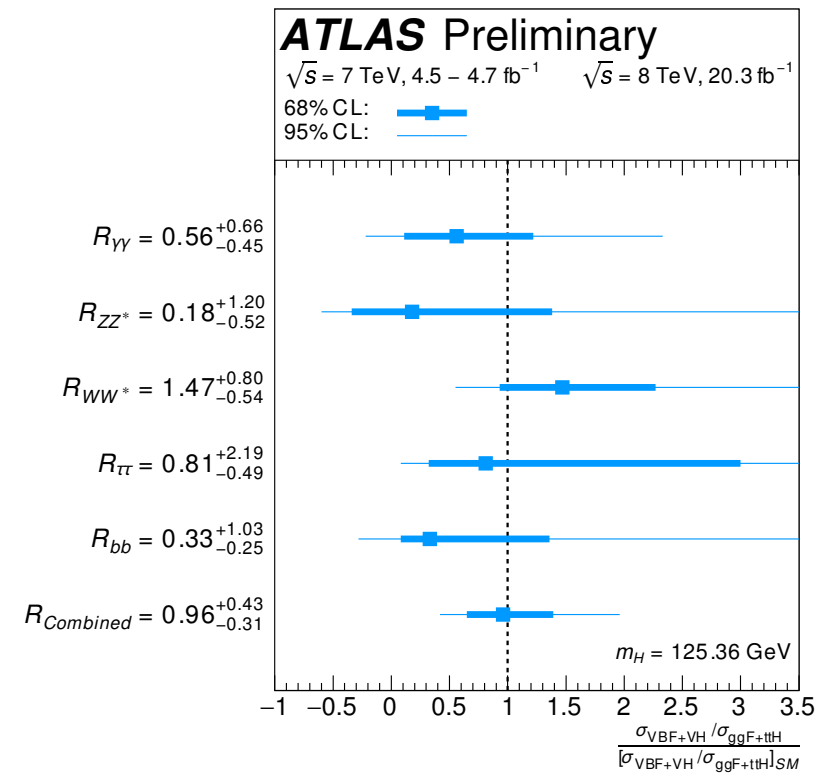
● No deviations from the SM

# Signal strength by production



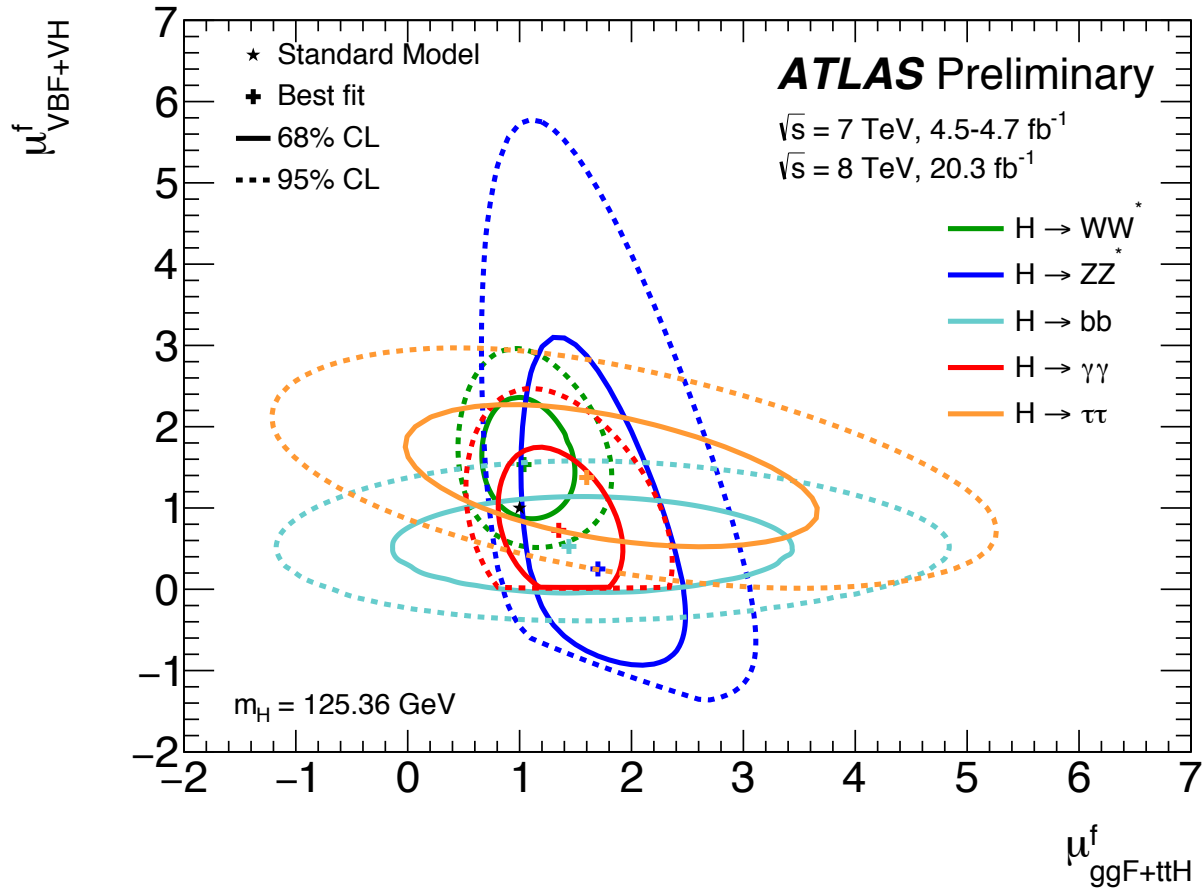
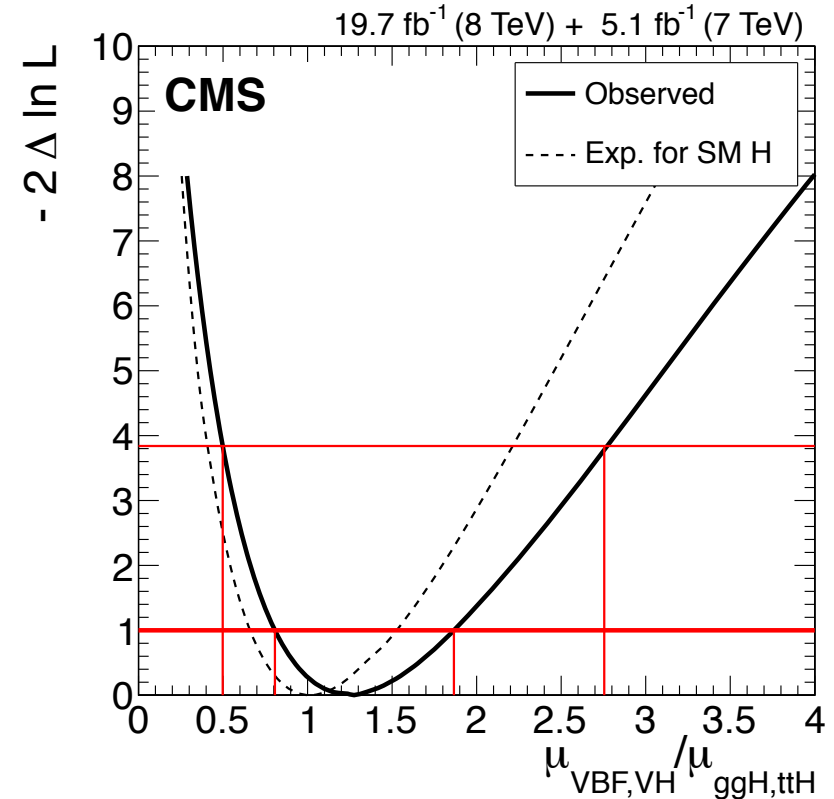
- Assume SM values for ratios between different branching fractions
- Small 1-2 $\sigma$  excess in ttH, consistent among the 2 experiments
  - Compatible with SM

# Comparison between ggH and VBF

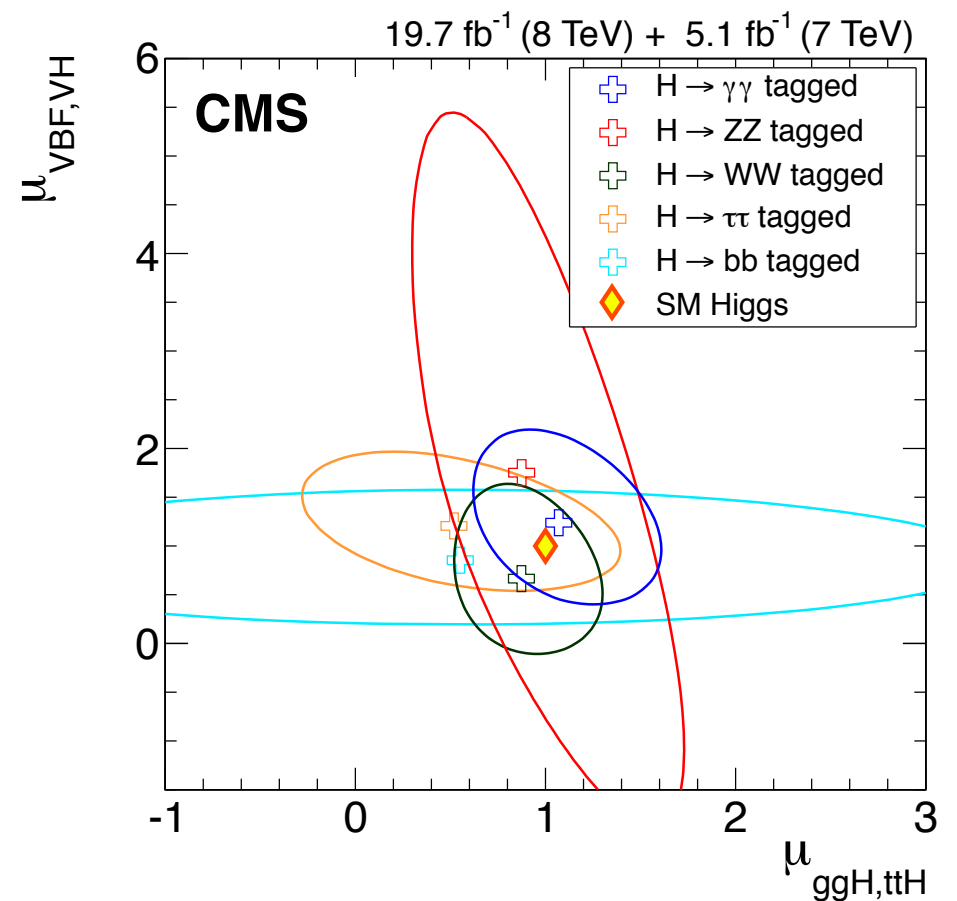


Remove assumptions on decay BR

- Separate ggH(+ttH) from VBF (+VH) production
- BR(H → ff) cancels in the ratio



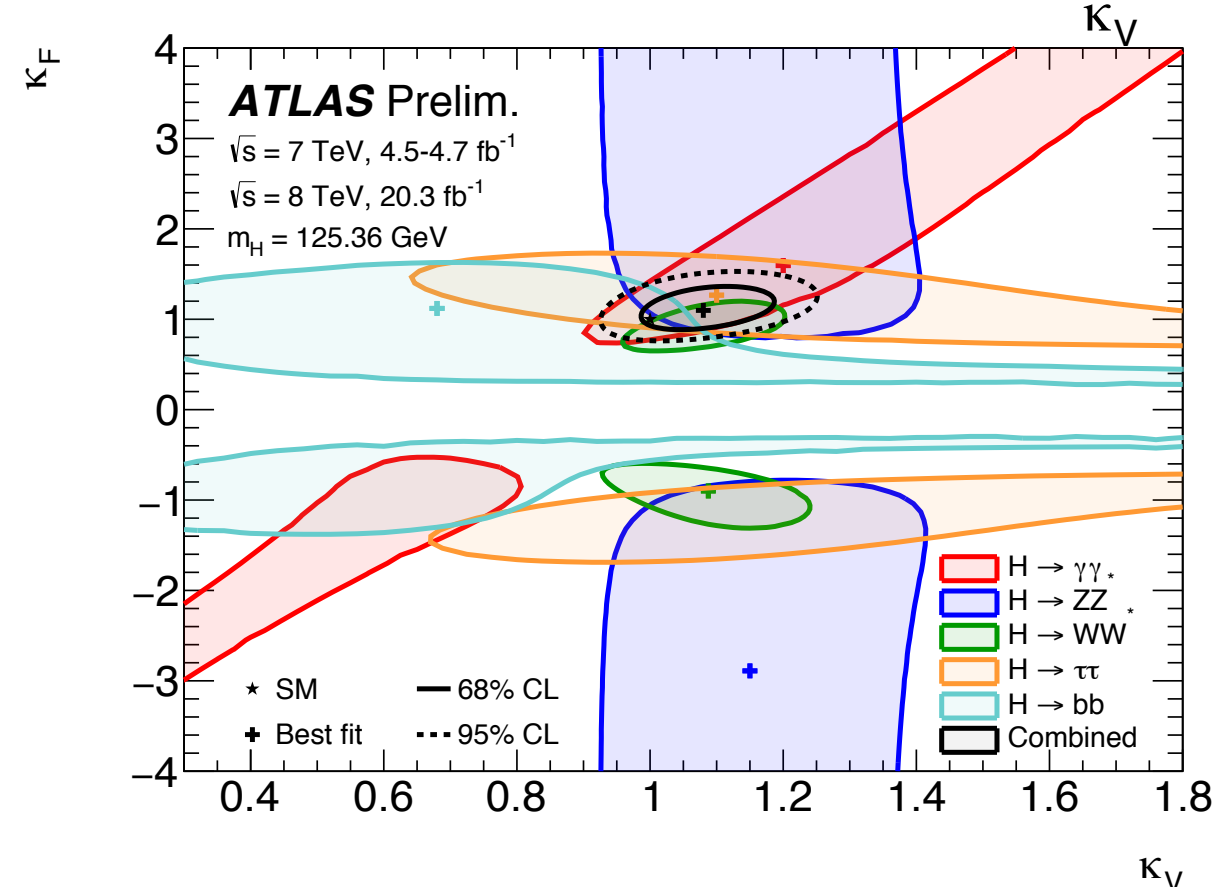
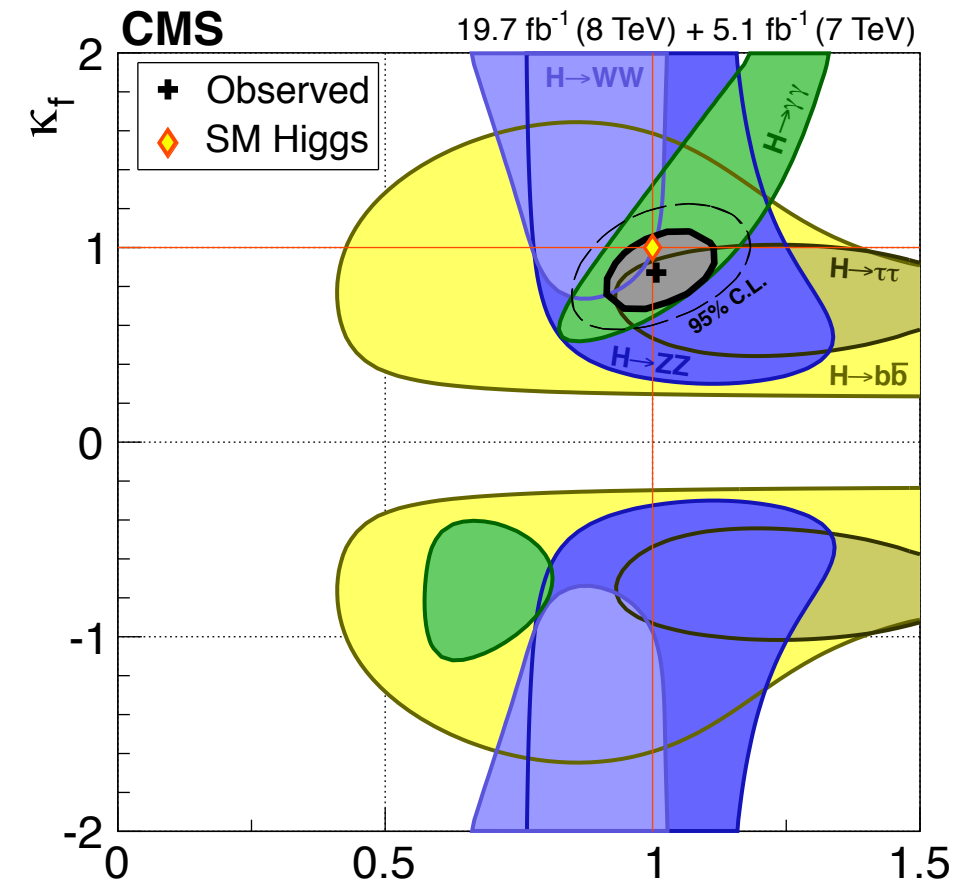
Good agreement with SM



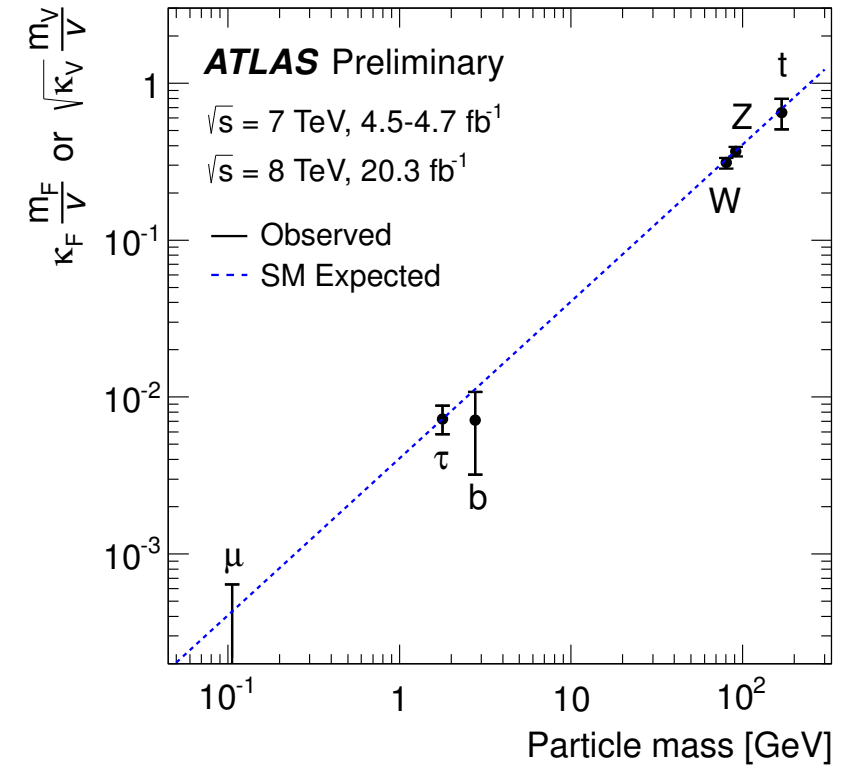
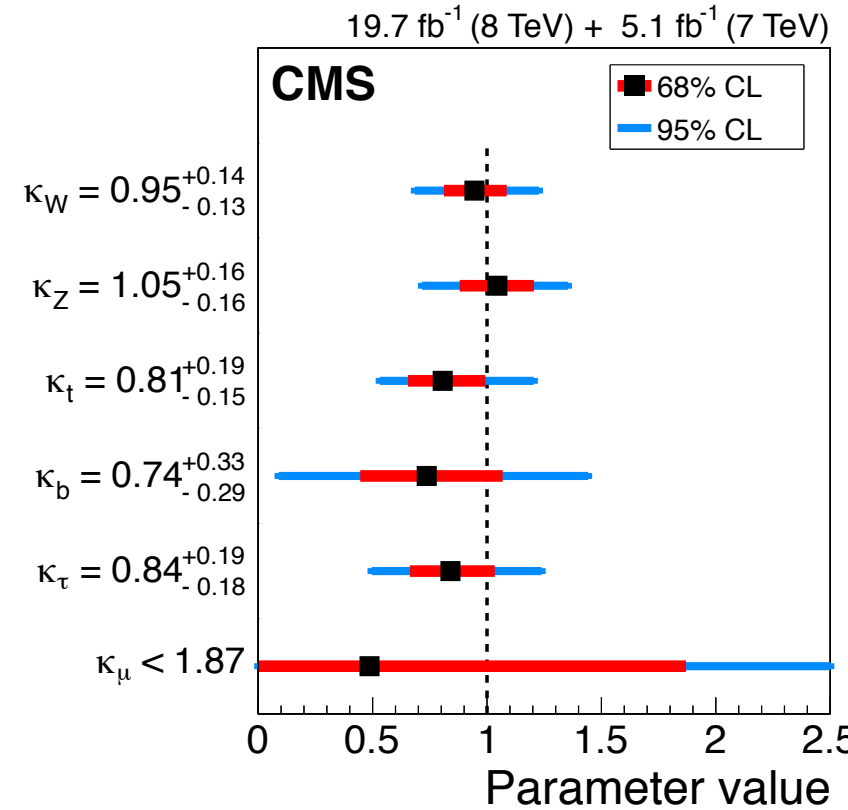
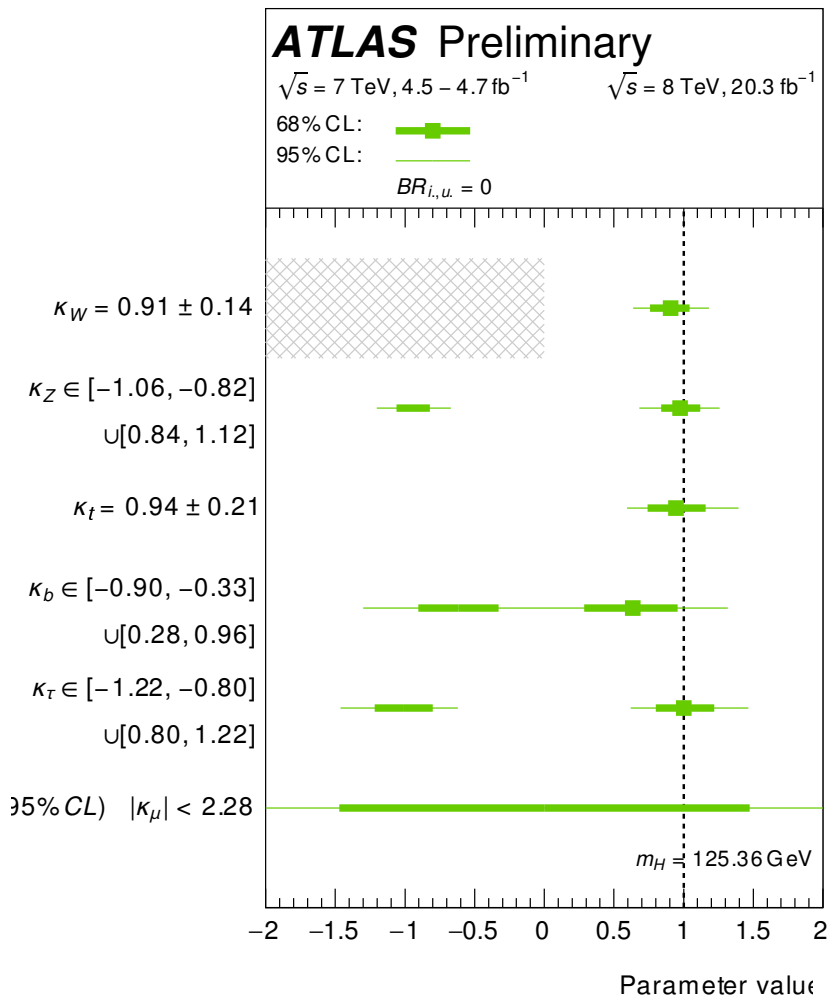
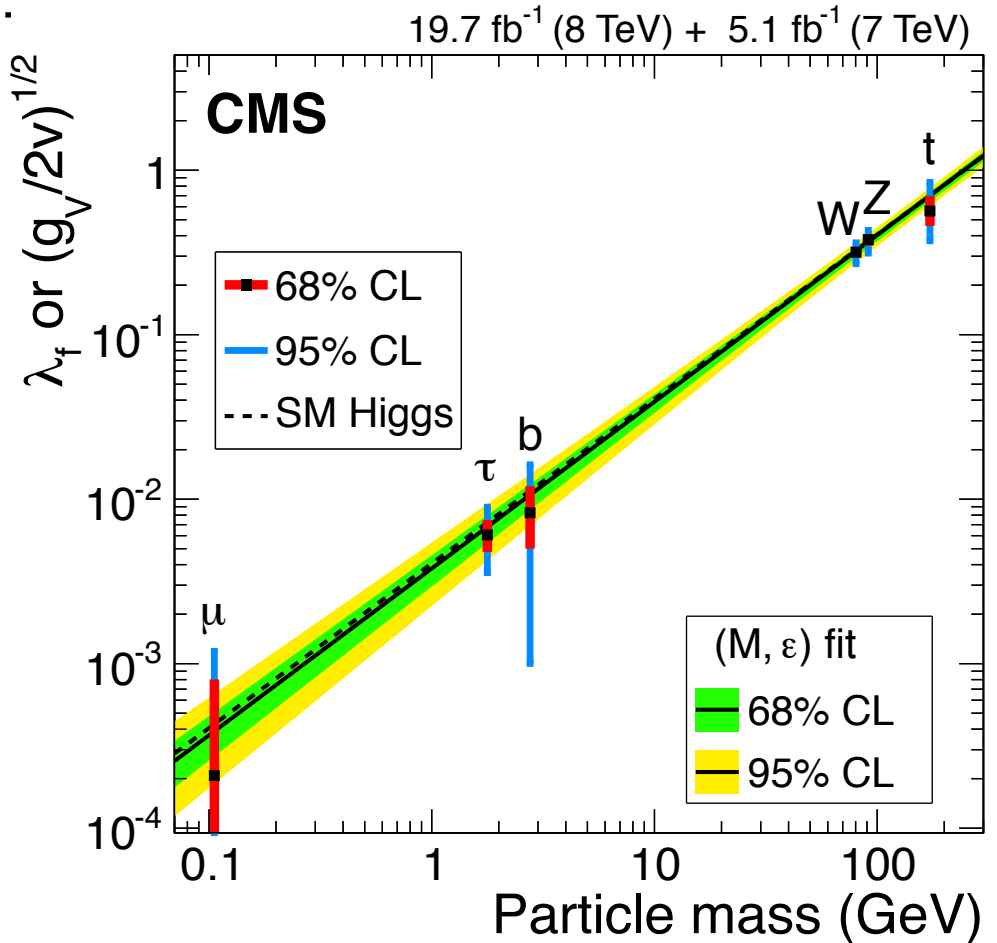
# Couplings to fermions and gauge



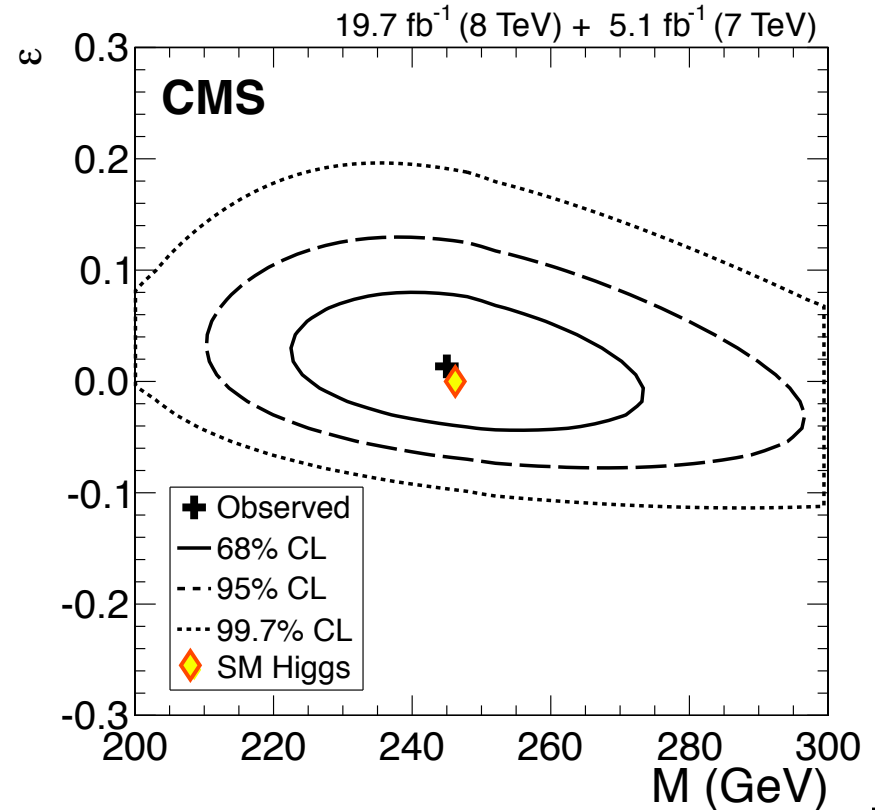
- For each coupling, introduce a scale factor  $k$  that accounts for deviations from SM (by definition  $k_i=1$  is SM)
- Explore differences between Yukawa and gauge couplings by introducing 2  $k$  factors  $k_f$  and  $k_v$
- Assume SM  $H$  width and no additional effects in the loops
- Sign ambiguity resolved by interference in  $\gamma\gamma, tH$  decays
- **Good agreement with the SM**



# Absolute couplings

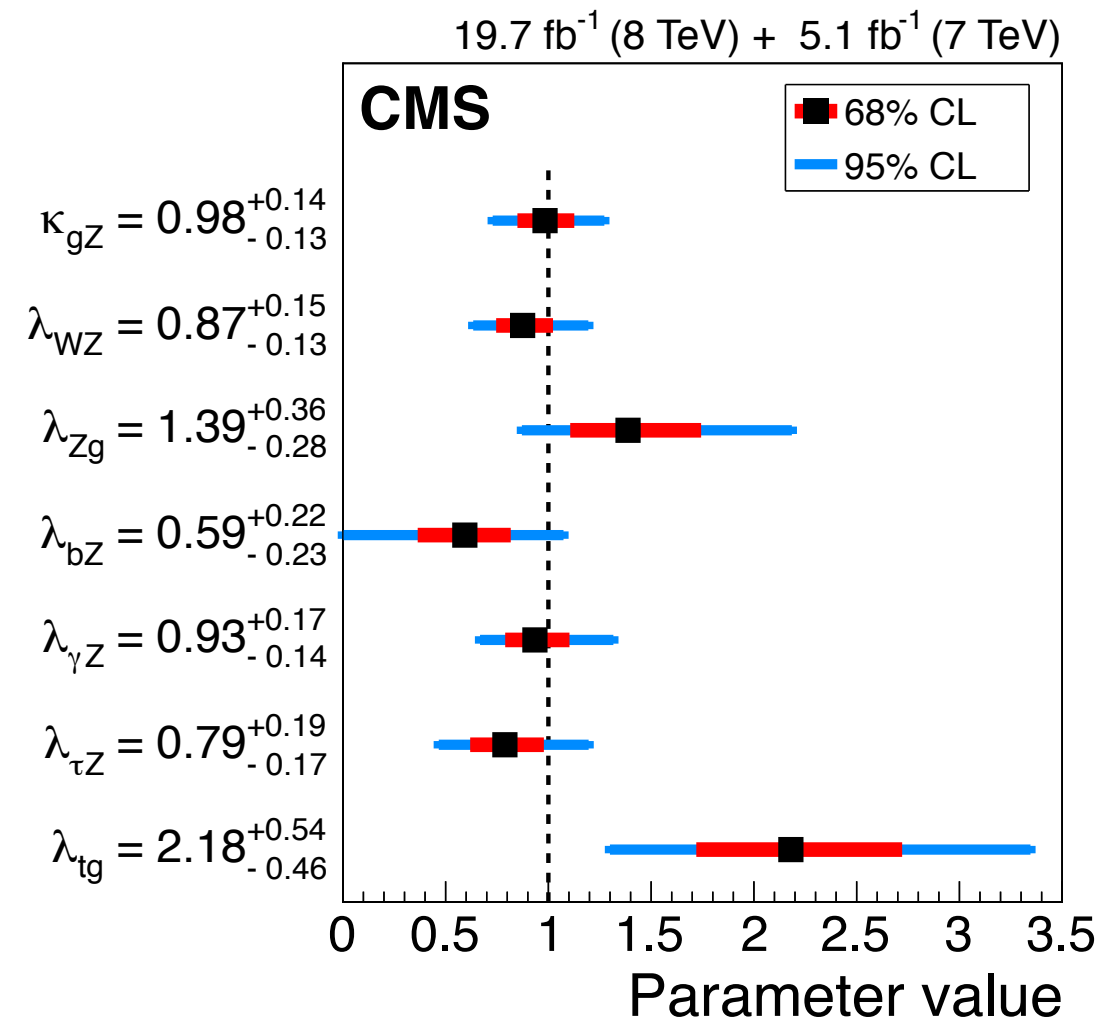
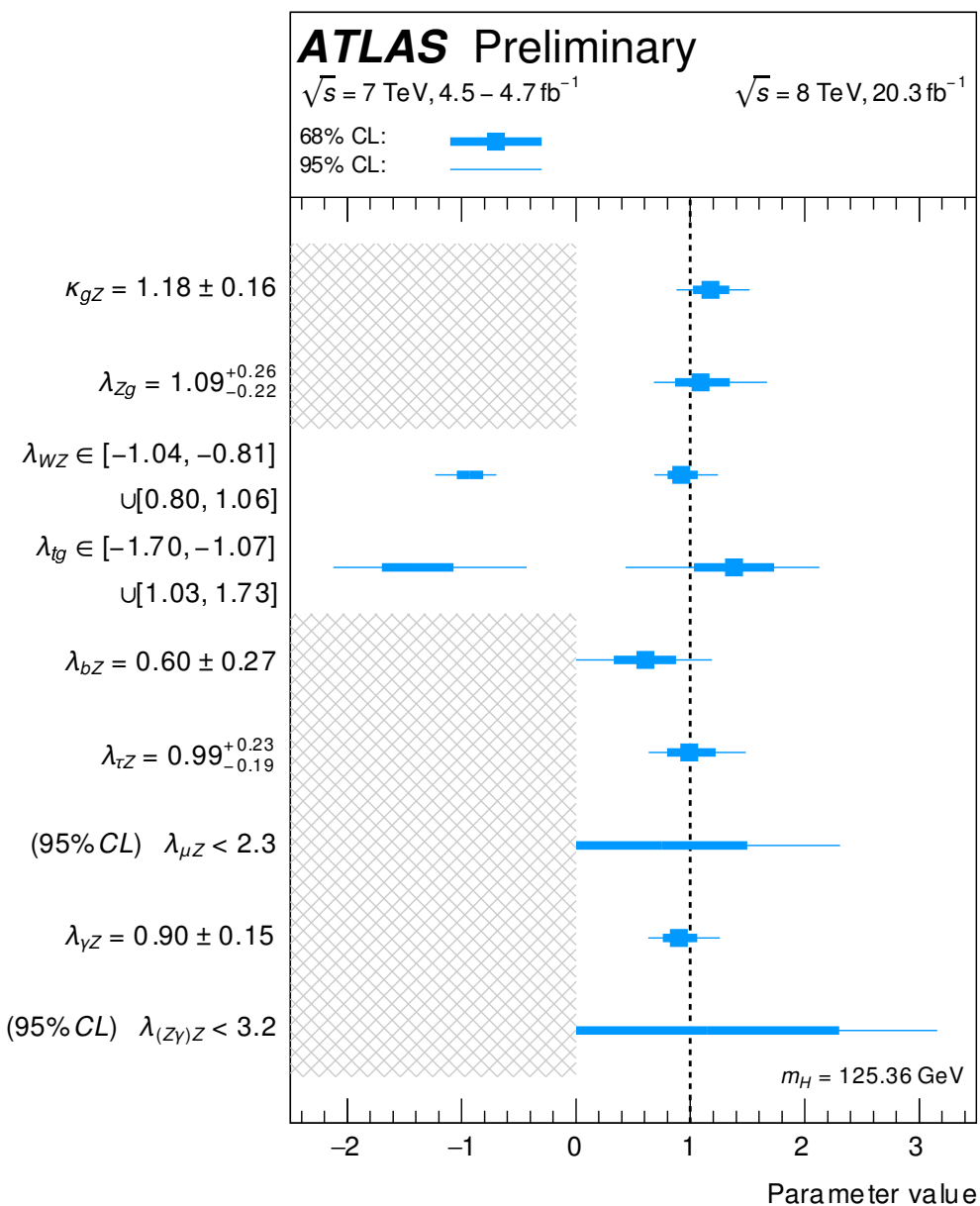


- Assume only SM particles in loops, no invisible decays
- All results compatible with the SM



# Higgs coupling ratios

Fit ratio of couplings  $\lambda_{ij} = k_i/k_j$  in order to avoid assumptions on ratios of production mechanisms and branching fractions

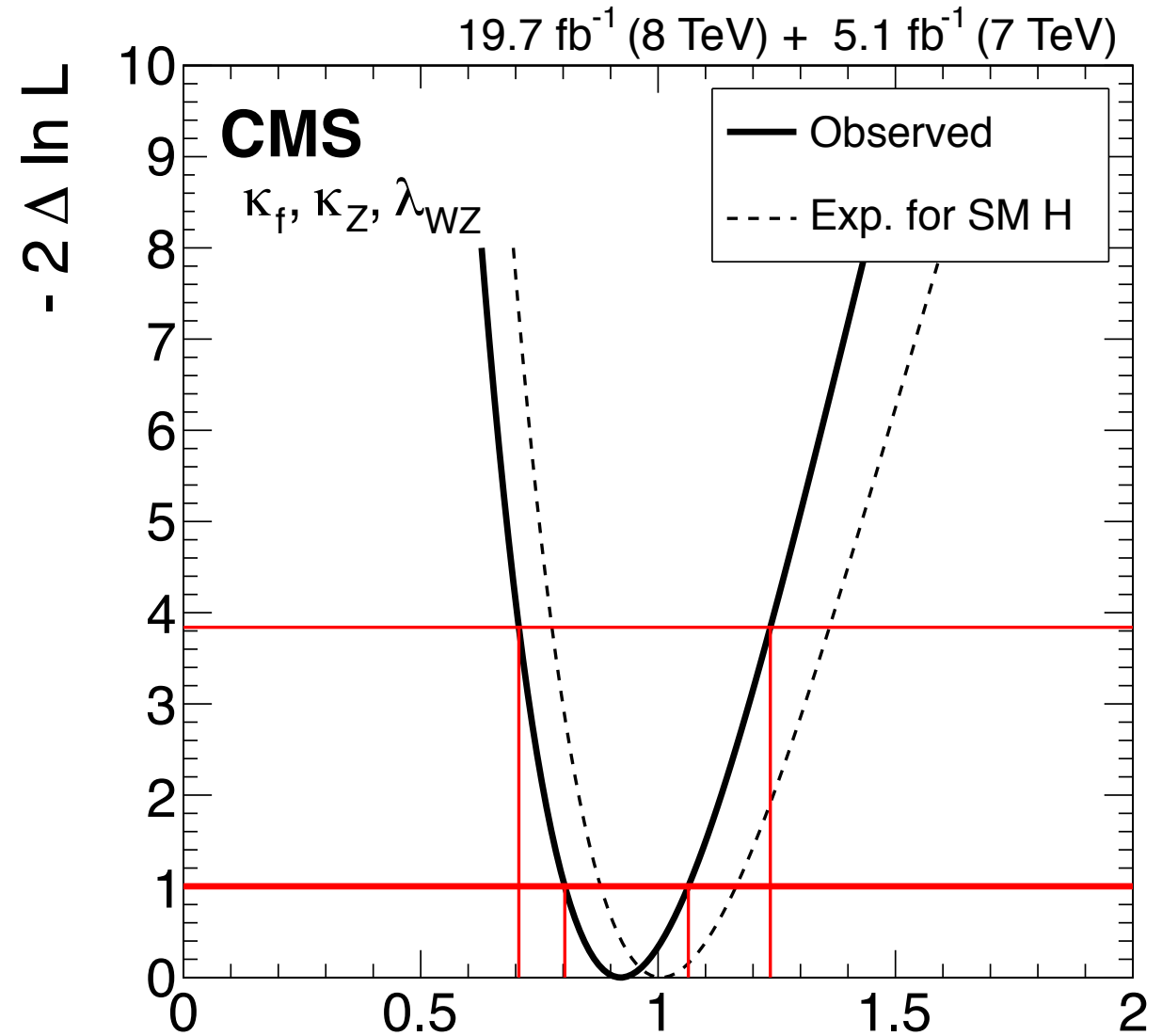
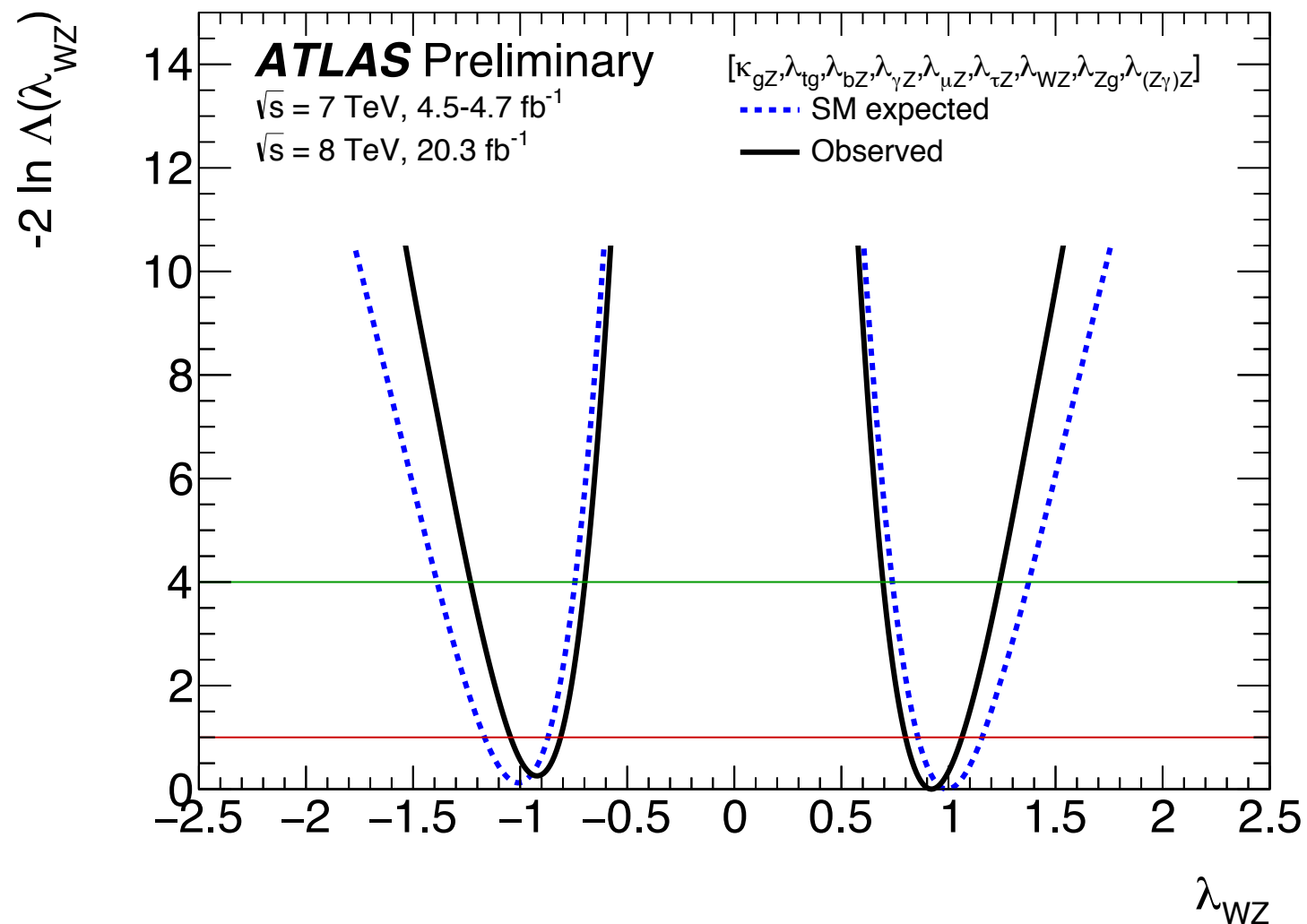


- Most general measurement possible within the k framework
- We will do better in run2
- No assumptions on particle content in loops
- No assumptions on BSM decay modes or  $\Gamma_H$



# Custodial symmetry

- In the SM custodial symmetry prevents deviations from  $\lambda_{WZ}=1$
- No assumptions on other couplings



- CMS:  $\lambda_{WZ} = 0.94^{+0.22}_{-0.18}$
- ATLAS:  $\lambda_{WZ} = 0.92^{+0.14}_{-0.12}$
- Negative solutions slightly disfavoured thanks to tH and ZH productions

- ATLAS and CMS combined results produced an amazingly precise Higgs mass measurement  $m_H = 125.09 \pm 0.24$  GeV
- Result dominated by statistical uncertainties, will improve in run2
- Measurement of the Higgs boson coupling to the SM particles show very good agreement with SM expectations within the current uncertainties
- Only deviation observed so far in ttH production, between 1 and  $2\sigma$
- Combination of couplings (ongoing) will provide a better picture
- No more room for large deviations from the SM. The study of the couplings in “rare” production/decays channel is a priority for run2

BACKUP

# Absolute couplings



- Relaxing the assumptions, e.g. allowing for the BR to invisible to float and for the presence of non-SM particles in loops or only keeping the total Higgs width unmodified does not have a huge impact on the measured couplings
- Couplings values are quite stable (within these uncertainties)

