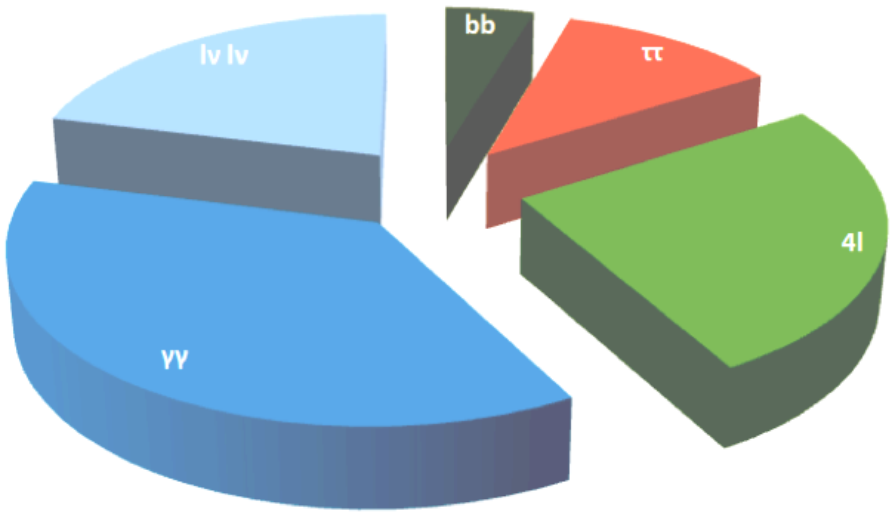
# Higgs Boson Mass and Couplings in ATLAS

Narei Lorenzo Martinez
Laboratoire de l'Accélérateur Linéaire (LAL-Orsay)

# Outline




$$w_i = \frac{(s_i/\sqrt{s_i+b_i})^2}{\sum(s_i/\sqrt{s_i+b_i})^2}$$

- **The following combined measurement will be reviewed**
  - **mass** using only the two channels with the better resolution (γγ and ZZ)
  - **signal strengths** using all channels
  - **couplings** using the three most sensitive channels: γγ, ZZ, and WW
    - **fermion vs boson mediated production modes**
    - **custodial symmetry**
    - **fermion vs gauge vectors couplings**
    - **beyond standard model contributions**

# Introduction



- In ATLAS, an update of the combined search for the Higgs boson is made using the 5 most sensitive channels in the low mass region given the LHC environment.

  ATLAS-CONF-2013-030, ATLAS-CONF-2013-012, ATLAS-CONF-2013-013, ATLAS-CONF-2012-161, ATLAS-CONF-2012-160, ATLAS-CONF-2013-034, ATLAS-CONF-2013-014

- **The observation of a Higgs-like particle is confirmed with this update**

- Some of these channels are now enough sensitive to distinguish various production modes, **through dedicated categories**

| Channel | $\int Ldt$ in fb$^{-1}$ (2011 +2012) | Tagged categories | Observed (expected) significance | Signal Strength | Mass (GeV) |
|---|---|---|---|---|---|
| $H \to \gamma\gamma$ | 4.6 + 20.7 | ggH, VBF, VH | $7.4\sigma$ ($4.1\sigma$) | $1.6 \pm 0.3$ | $126.8 \pm 0.2$ (stat) $\pm 0.7$ (syst) |
| $H \to ZZ \to 4l$ | 4.6 + 20.7 | ggH, VBF, VH | $6.6\sigma$ ($3.7\sigma$) | $1.5 \pm 0.4$ | $124.3\ ^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) |
| $H \to WW \to l\nu l\nu$ | 4.6 + 20.7 | ggH, VBF | $3.8\sigma$ ($3.7\sigma$) | $1.0 \pm 0.3$ | - |
| $H \to \tau\tau$ | 4.6 + 13 | ggH, VBF, VH | - | $0.8 \pm 0.7$ | - |
| $VH \to Vbb$ | 4.6 + 13 | VH | - | $-0.4 \pm 1.0$ | - |

- Combining these 5 channels, the different couplings to fermions and bosons can be probed.

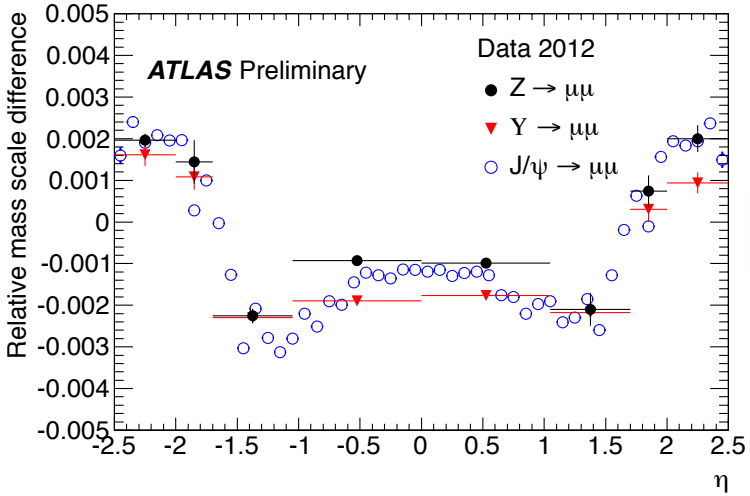
| | | | | |
|---|---|---|---|---|
| More details on | **-H->bb** | see | **N. Tannouri** | talk |
| | **-H->WW** | see | **Z.Zhang** | talk |
| | **-H->tt** | see | **A.Nayak** | talk |
| | **-H->gg** | see | **O.Davignon** | talk |
| | **-H->ZZ** | see | **T.Guillemin** | talk |

# Combined Mass Measurement

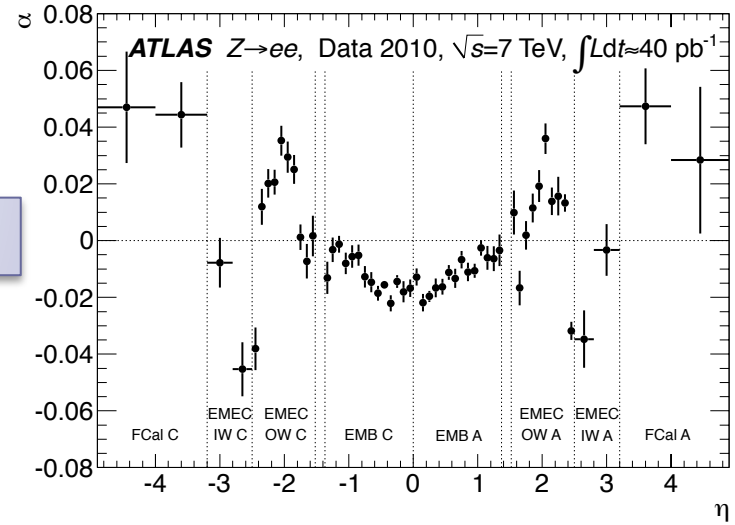
# The uncertainty on energy scale



- **Main uncertainty on the mass measurement**
- Two types of objects:
  - **Muons:** very low uncertainty on their energy scale (derived from J/ψ and Z->ee)
  - **Electrons and photons:** sizeable uncertainty on their energy scale (derived from J/ψ and Z->ee + validation with Zγ events →**see C.Rangel talk**)




$$E^{meas}=E^{true}(1+\alpha_i)$$




| | Source | $H \to \gamma\gamma$ | $H \to 4l$ |
|---|---|---|---|
| e/γ | Absolute Energy scale calibration from Z | ±0.3% | ±0.4% |
| | Upstream material simulation inaccuracies | ±0.3% | - |
| | Presampler energy scale | ±0.1% | - |
| | Energy scale calibration for low transverse energy electrons | - | ±0.2% |
| | Additional sources of uncertainties | ±0.35% | - |
| μ | Muon momentum scale | - | ±0.2% |
| | Total | ±0.6% | ±0.4% |

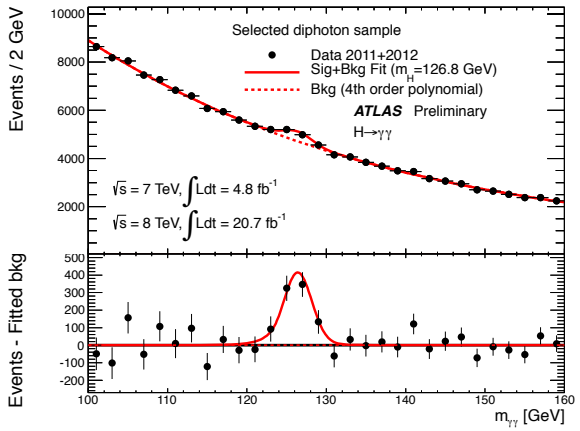
➢ Energy scale systematic correspond to the uncertainty coming from the computation of the energy scale factors

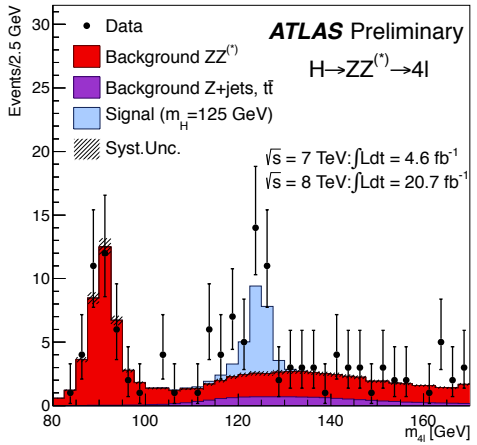
➢ Correlations between the two channels coming from absolute energy scale calibration from Z. The other sources of uncertainties are not correlated

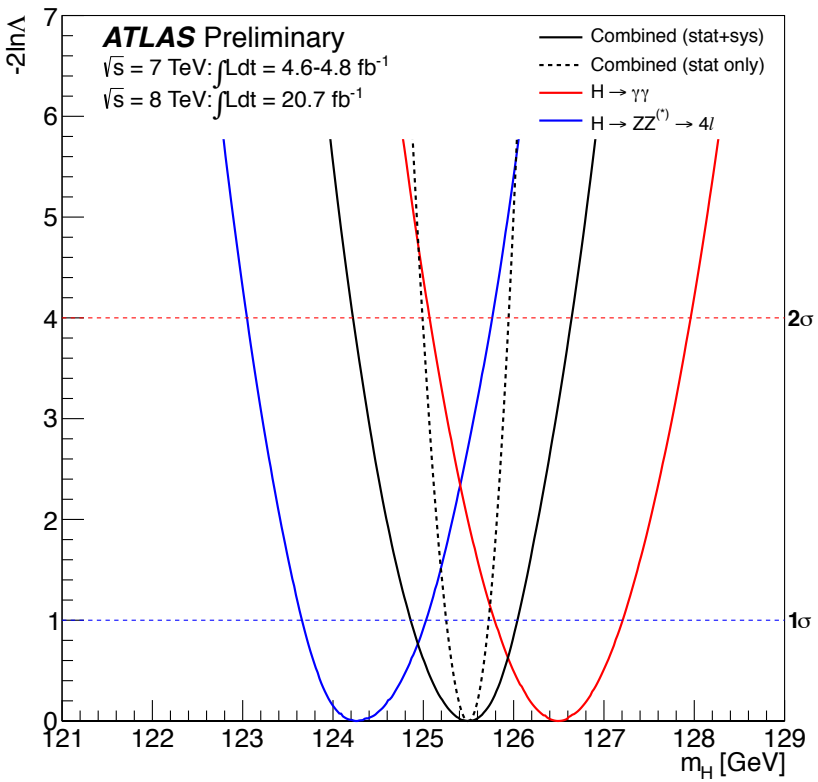
# Mass

- Combine the highest mass resolution channels γγ and ZZ
- Combined mass:

$$m_H = 125.5 \pm 0.2\,(\text{stat})\,^{+0.5}_{-0.6}\,(\text{sys})\ \text{GeV}$$




- Quantify the consistency between the two masses in γγ and ZZ channels
- Previous combination: compatibility = 2.7σ (p-value=0.8%)
- The mass difference is

$$\Delta\hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4\ell} = 2.3^{+0.6}_{-0.7}\,(\text{stat}) \pm 0.6\,(\text{sys})\ \text{GeV}$$

**The two masses are compatible within 2.5σ**
(p-value of 1.2% and up to 8% (<1.5σ) using more conservative treatment of the uncertainties)

# Signal strengths

- Most of the measurement are based on the number of signal observed:

category/channel detector acceptance decay final state

$$n^{k}_{\text{signal}} = \left( \sum_i \mu_i \sigma_{i,\text{SM}} \times A^{k}_{if} \times \varepsilon^{k}_{if} \right) \times \mu_f \times B_{f,\text{SM}} \times \mathcal{L}^{k}$$

production mode efficiency of reconstruction Luminosity

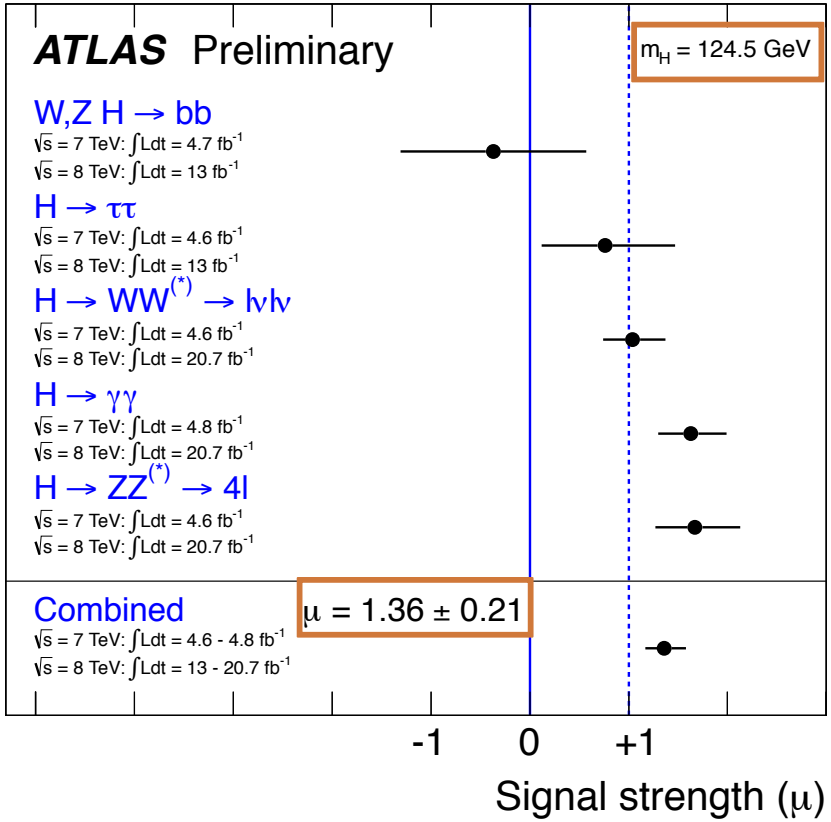
- The strength parameter is simply the comparison of the observed signal yield with the SM prediction

$$\left.\begin{aligned} \mu_i &= \sigma_i/\sigma_{i,\text{SM}} \\ \mu_f &= B_f/B_{f,\text{SM}} \end{aligned}\right\} \quad \boxed{\mu = \mu_i.\mu_f}$$

***global signal strength***

# Signal Strength

- Statistical procedure: measure the number of signal and parameterize it in the likelihood as a function of the cross section and the branching ratio




- **Combined value at 125.5 GeV :**

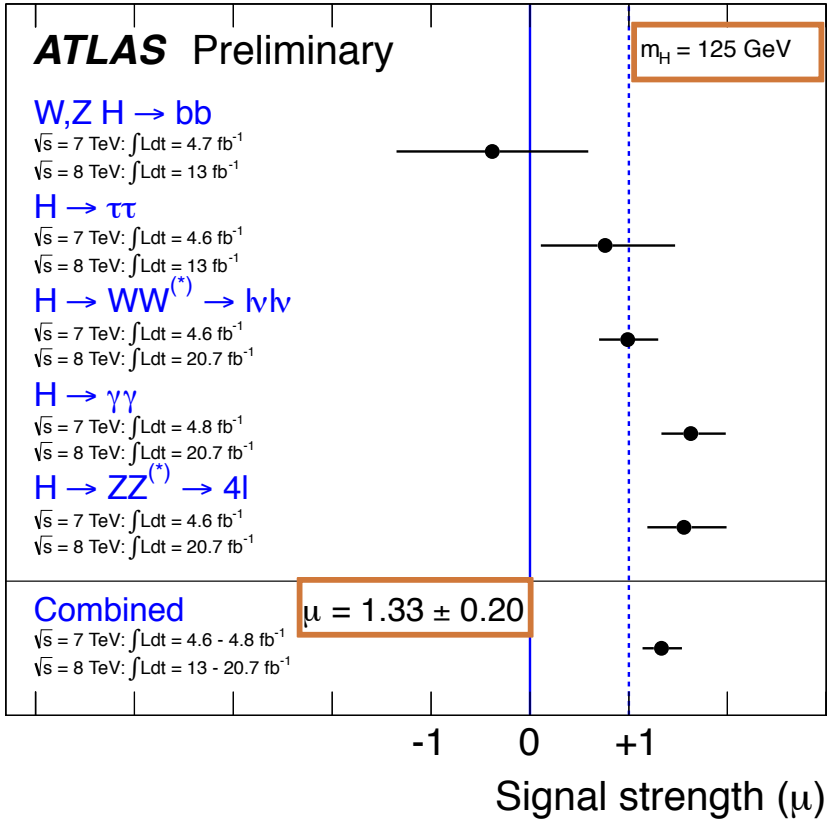
$$\hat{\mu} = 1.30 \pm 0.13\,(\text{stat}) \pm 0.14\,(\text{sys})$$

- **Consistent with SM hypothesis μ=1 within ~1.3σ** (p-value=0.09)

- Almost independent of the mass on which it is evaluated: changing the mass hypothesis from 124.5 to 126.5 changes μ by ~4%

# Signal Strength

- Statistical procedure: measure the number of signal and parameterize it in the likelihood as a function of the cross section and the branching ratio




- **Combined value at 125.5 GeV :**

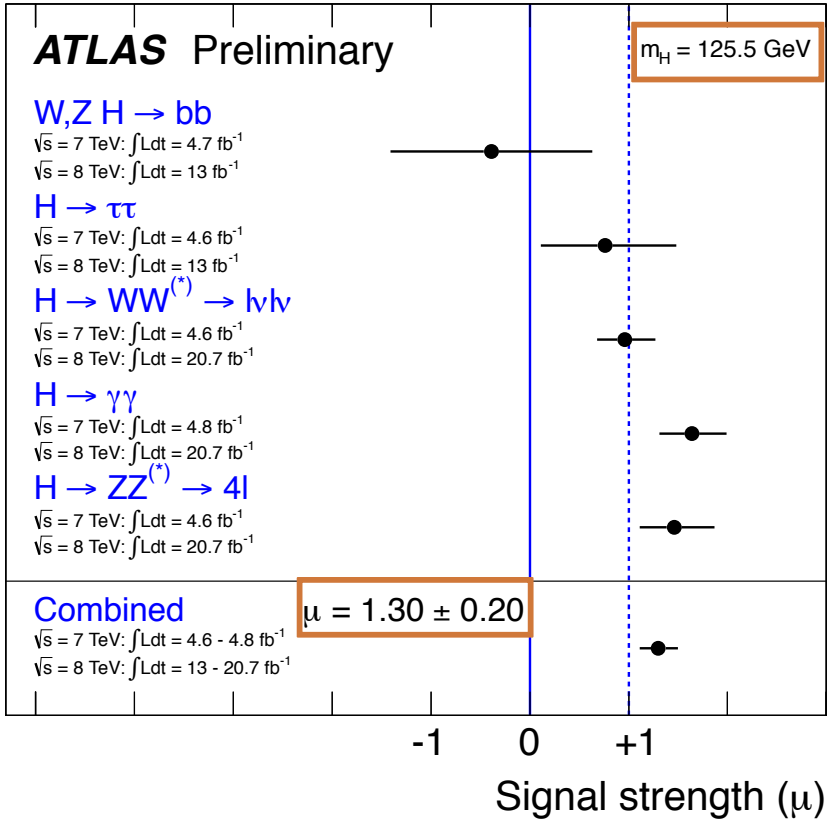
$$\hat{\mu} = 1.30 \pm 0.13\,(\text{stat}) \pm 0.14\,(\text{sys})$$

- **Consistent with SM hypothesis μ=1 within ~1.3σ** (p-value=0.09)

- Almost independent of the mass on which it is evaluated: changing the mass hypothesis from 124.5 to 126.5 changes μ by ~4%

# Signal Strength

- Statistical procedure: measure the number of signal and parameterize it in the likelihood as a function of the cross section and the branching ratio




- **Combined value at 125.5 GeV :**

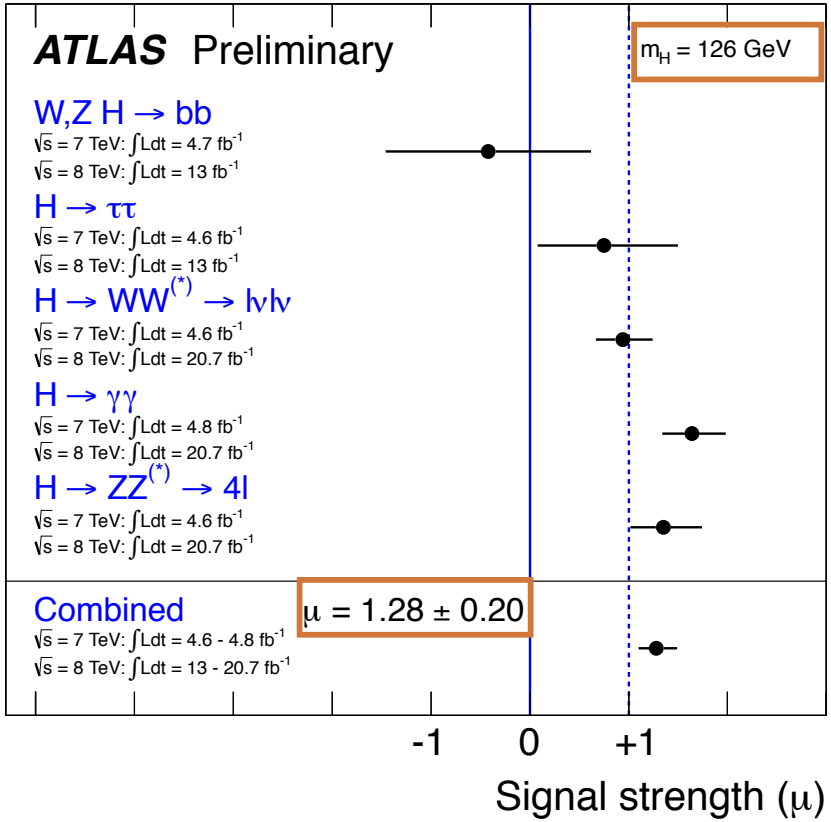
$$\hat{\mu} = 1.30 \pm 0.13\,(\text{stat}) \pm 0.14\,(\text{sys})$$

- **Consistent with SM hypothesis μ=1 within ~1.3σ** (p-value=0.09)

- Almost independent of the mass on which it is evaluated: changing the mass hypothesis from 124.5 to 126.5 changes μ by ~4%

# Signal Strength

- Statistical procedure: measure the number of signal and parameterize it in the likelihood as a function of the cross section and the branching ratio




- **Combined value at 125.5 GeV :**

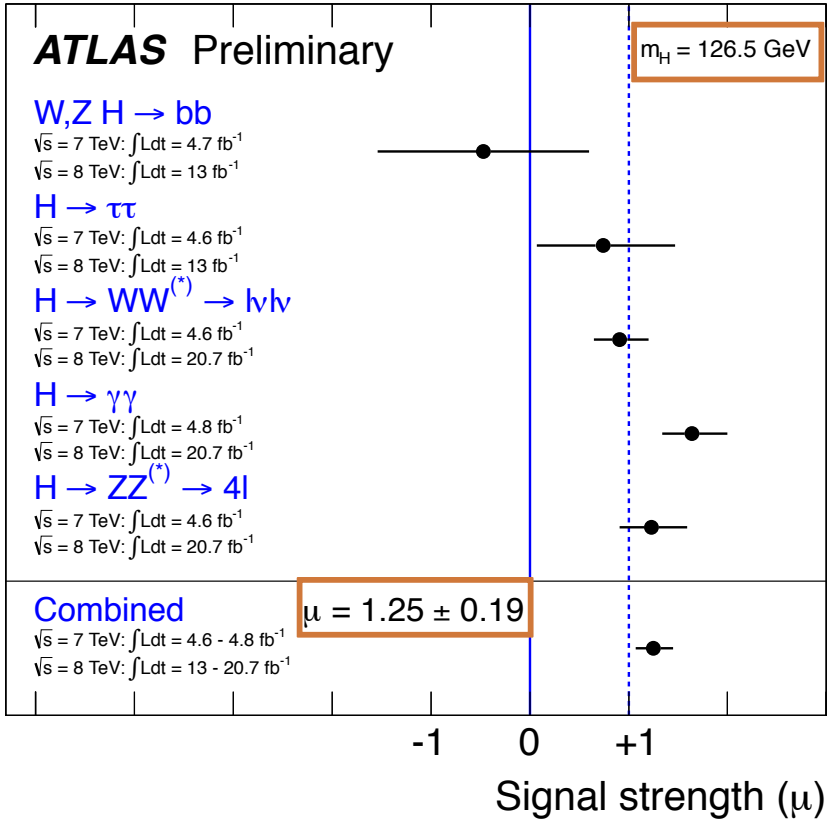
$$\hat{\mu} = 1.30 \pm 0.13\,(\text{stat}) \pm 0.14\,(\text{sys})$$

- **Consistent with SM hypothesis μ=1 within ~1.3σ** (p-value=0.09)

- Almost independent of the mass on which it is evaluated: changing the mass hypothesis from 124.5 to 126.5 changes μ by ~4%

# Signal Strength

- Statistical procedure: measure the number of signal and parameterize it in the likelihood as a function of the cross section and the branching ratio




- **Combined value at 125.5 GeV :**

$$\hat{\mu} = 1.30 \pm 0.13\,(\text{stat}) \pm 0.14\,(\text{sys})$$

- **Consistent with SM hypothesis μ=1 within ~1.3σ** (p-value=0.09)

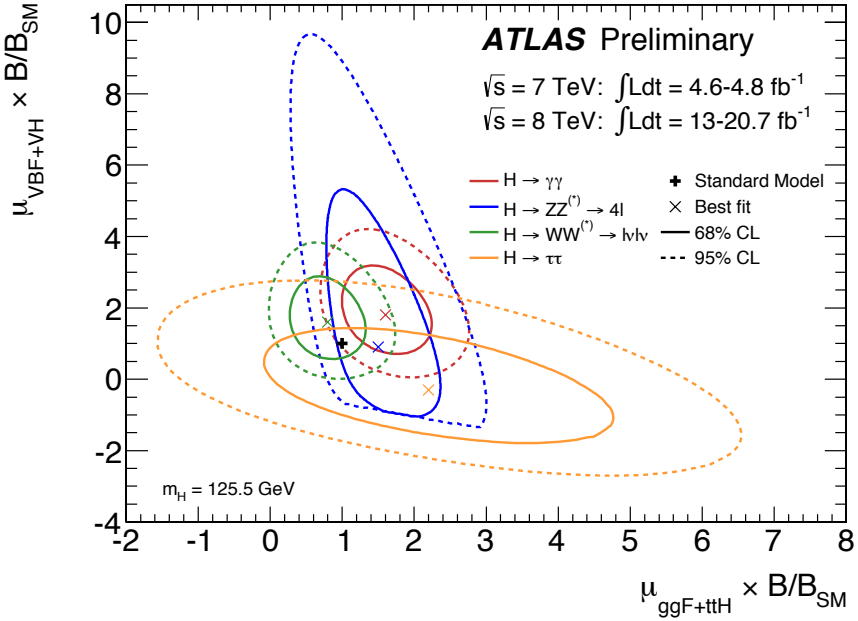
- Almost independent of the mass on which it is evaluated: changing the mass hypothesis from 124.5 to 126.5 changes μ by ~4%

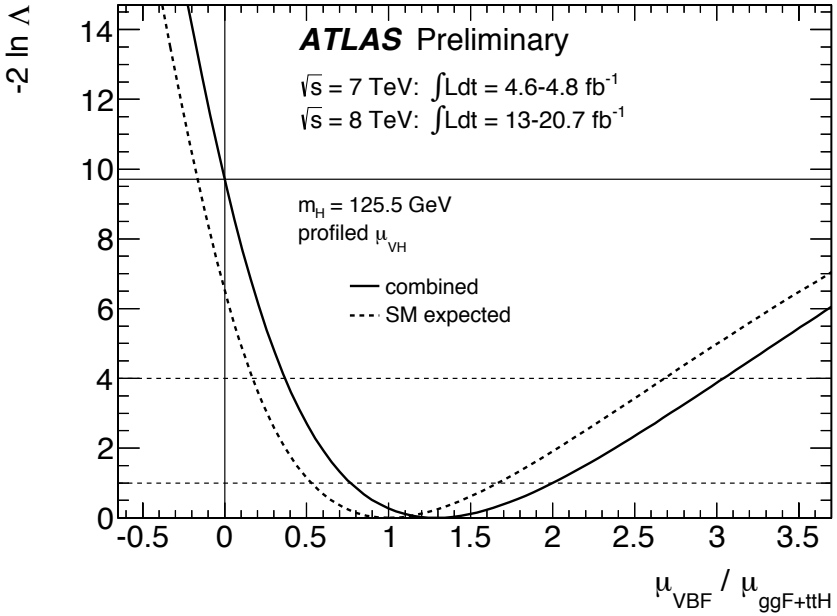
# Production modes: fermion vs boson mediated

- Test two kind of production:
  → fermion mediated (ggH and ttH processes) : $\mu_{ggH+ttH}$ *(too low cross section for ttH alone)*
  → boson mediated (VBF and VH processes) are grouped: $\mu_{VBF}$, $\mu_{VH}$, $\mu_{VBF+VH}$

- Measure the ratio $\mu_{VBF}/\mu_{ggF+ttH}$ to eliminate the different branching ratio:

$$\mu_{\mathrm{VBF}}/\mu_{\mathrm{ggF}+t\bar{t}H} = 1.2^{+0.7}_{-0.5}$$




→Compatible with SM expectation of unity.
**→3.1σ evidence for non-zero VBF production**

# Probing the couplings

- Fermion vs gauge vectors couplings
- Custodial symmetry
- Beyond standard model contributions

# Procedure



- Number of signal measured:

$$N(XX \to H \to YY) \sim \sigma(XX \to H).BR(H \to YY) \sim \frac{\Gamma_{XX}.\Gamma_{YY}}{\Gamma_{tot}}$$

- With:

$$\Gamma_{tot} = \sum \Gamma_i + \Gamma_{BSM}$$

- Define effective Higgs boson couplings

$$\kappa_i^2 \sim \frac{\Gamma_i}{\Gamma_{i(SM)}} \qquad \kappa_H^2 \sim \frac{\Gamma_{tot}}{\Gamma_{tot(SM)}} \quad \Rightarrow \quad n_{signal} \sim \frac{\overbrace{\kappa_{XX}^2}^{production} \cdot \overbrace{\kappa_{YY}^2}^{decay}}{\kappa_H^2}$$

- The relevant parameters for the current searches are:

$\kappa_f$, $\kappa_V$, $\kappa_W$, $\kappa_Z$, $\kappa_g$, $\kappa_\gamma$, $\Gamma_{BSM}$, $\kappa_d$, $\kappa_u$, $\kappa_l$, $\kappa_q$

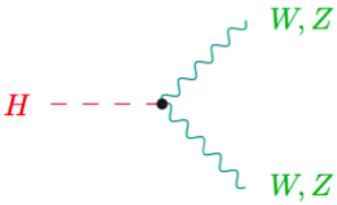
**ATLAS: General Framework for couplings, assume:**

- single narrow resonance
- Zero-width approximation
- tensors structure of the couplings same as in the SM

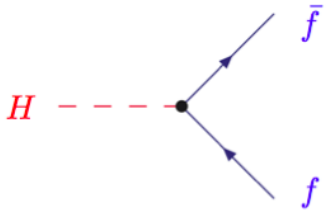
# Couplings: Fermion vs gauge vector

*(does the new state couple to vectors and fermions ?)*

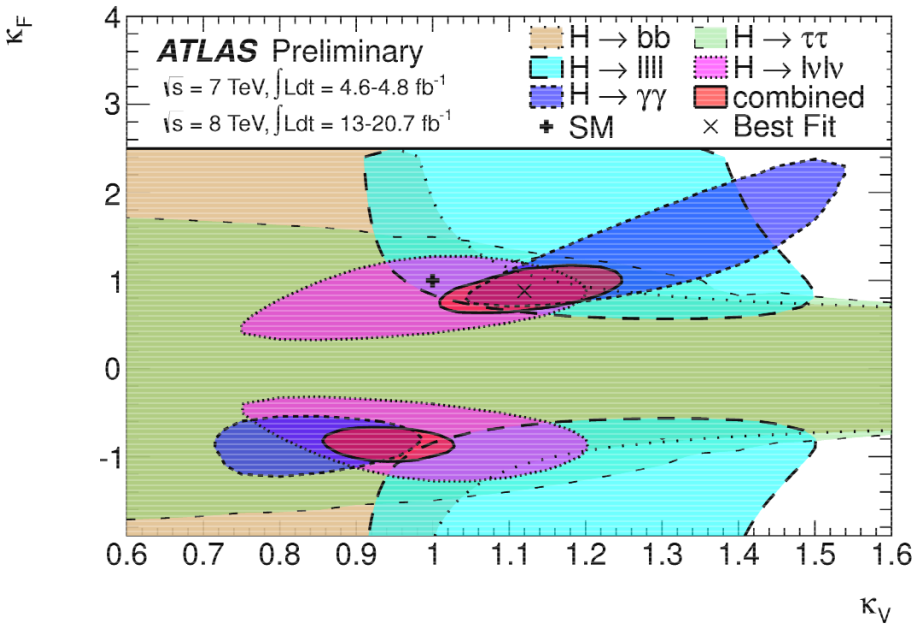
- Thanks to the various production and decays mode accessible at LHC, the couplings of fermions and gauge vector to the Higgs can be tested.




$\propto \kappa_V$



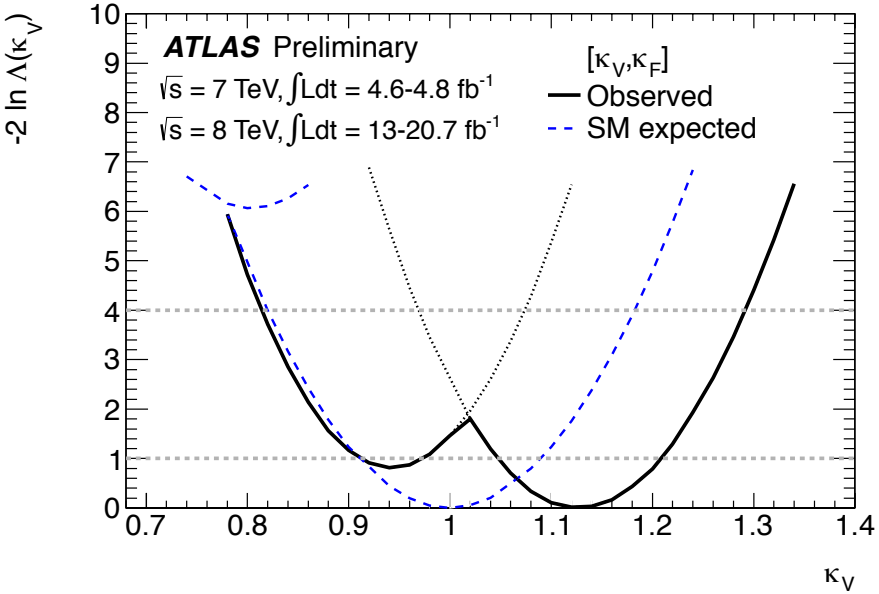

$\propto \kappa_F$

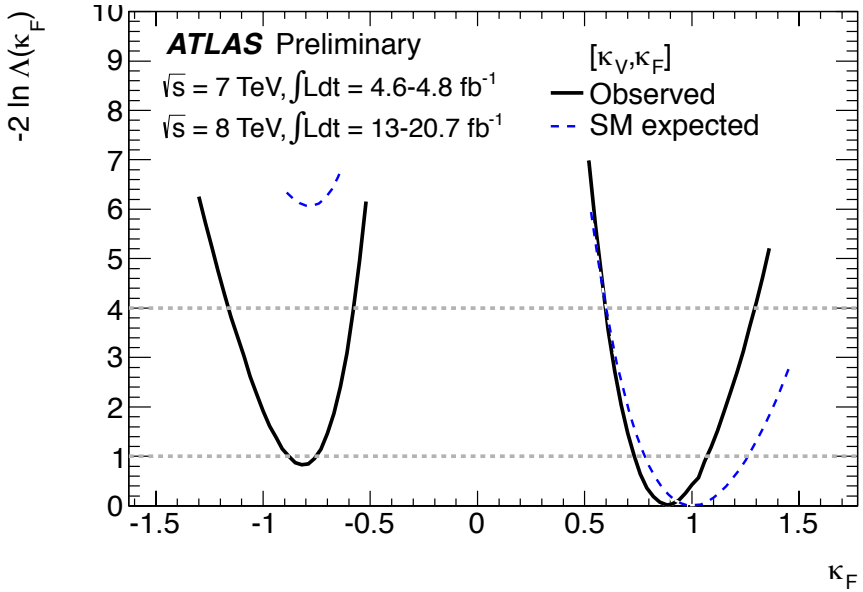



**Assume:**
- identical couplings within fermions
- identical couplings within vectors
- only SM particles contribute to the H→γγ and gg→H vertex loops.
- no contribution of BSM particles to total width

➢ 2D best fit point compatible with SM at 8%

# Couplings: Fermion vs gauge vector

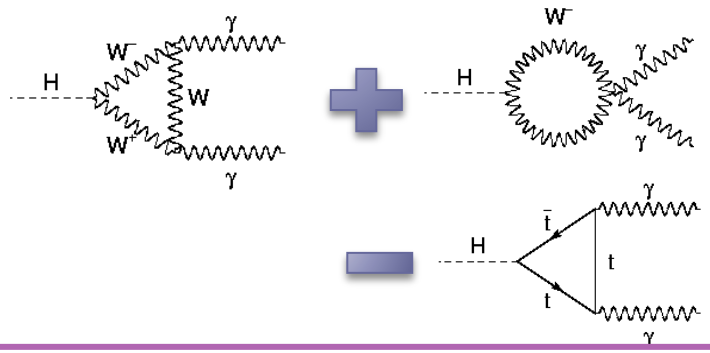



- In H->γγ decay, interference between W and top loop

➡ **H->γγ is the only channel sensitive to to the relative sign of $\kappa_V$ and $\kappa_F$**

$$1.59 \cdot \kappa_V^2 - 0.66 \cdot \kappa_V \kappa_F + 0.07 \cdot \kappa_F^2$$




*only relative sign between $\kappa_V$ and $\kappa_F$ is physical → assume $\kappa_V$>0*

- At 68% CL:
  - $\kappa_F \in [-0.88, -0.75] \cup [0.73, 1.07]$
  - $\kappa_V \in [0.91, 0.97] \cup [1.05, 1.21]$
- Compatible with SM
- Indirect evidence of couplings to fermions
- Already 2σ sensitivity to sign non degeneracy.

# Ratio of W/Z couplings (custodial symmetry)

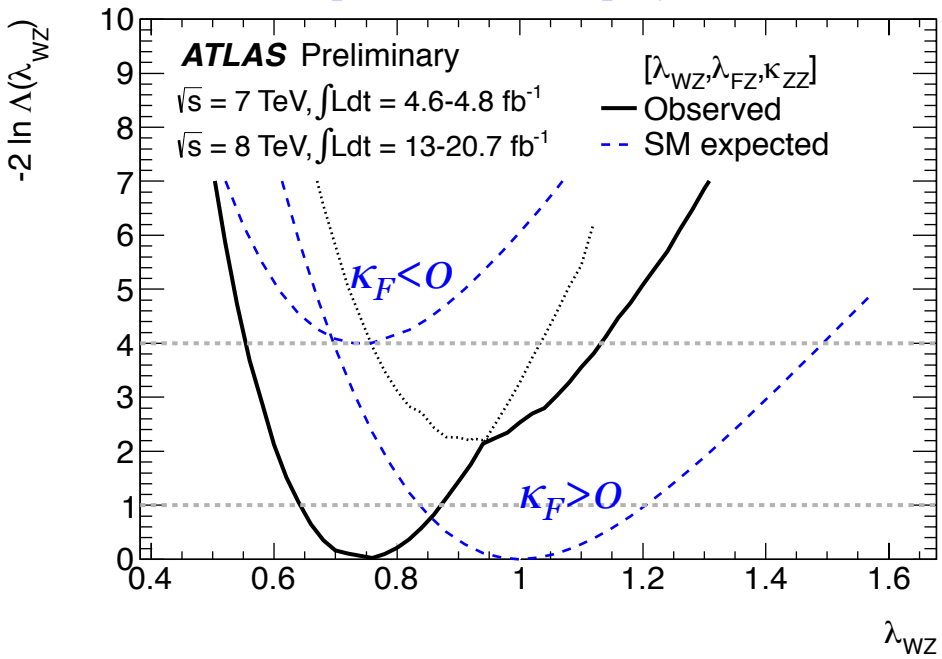
- Identical W and Z couplings scale factors are required from custodial symmetry and direct measurement of the ρ parameter at LEP
- Can test this constraint in the Higgs sector.

**Assume:**
➢ identical couplings within fermions

To avoid assumptions on total width need to parameterize the model with 3 free parameters:

$$\kappa_{ZZ} = \kappa_Z \cdot \kappa_Z/\kappa_H$$
$$\lambda_{WZ} = \kappa_W/\kappa_Z$$
$$\lambda_{FZ} = \kappa_F/\kappa_Z \quad .$$

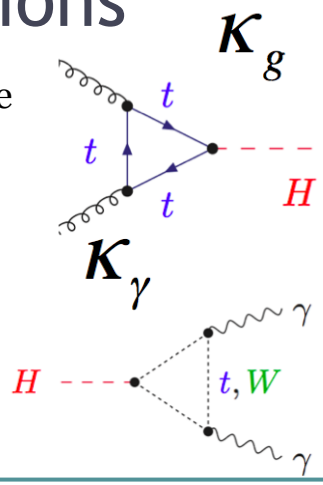
*$\lambda_{WZ}$ is scanned whereas the other parameters are profiled*




At 68% CL, find:
$\lambda_{WZ} \in$ **[0.64,0.87]**
→Fit prefers the non SM minimum, which is within **1.5σ** from the SM (p-value=5%)

# Couplings: Beyond Standard Model contributions

- Allow for extra contribution from new particles in the loops: H→γγ and gg→H and in the total width
- Two possibilities:
  - the non-SM particles have no sizeable contribution to the total width
  - the non-SM particles may contribute through invisible (i) or undetectable (u) final states → add a third free parameter: $BR_{i,u}$

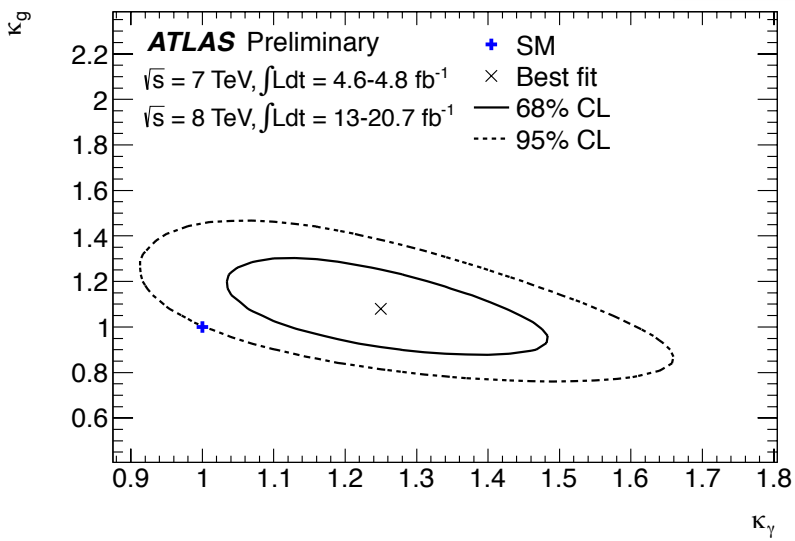


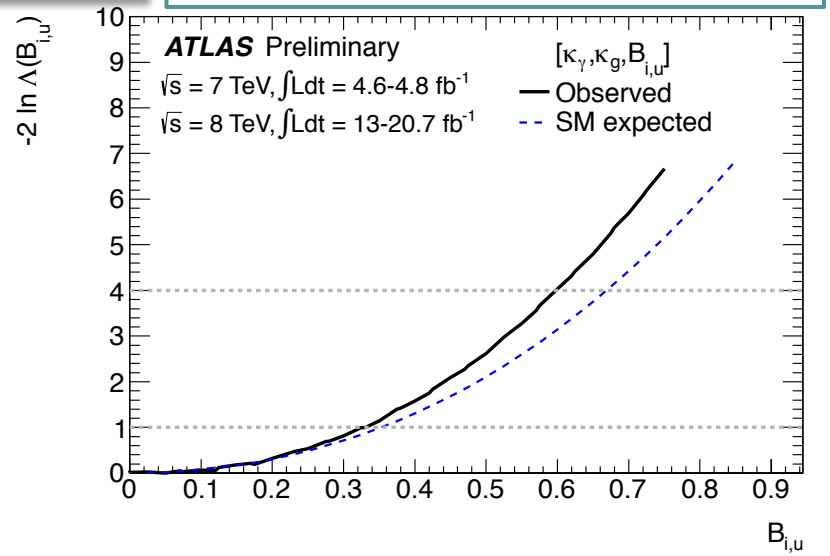

**Assume:**
➢all couplings but $\kappa_\gamma$ and $\kappa_g$ = 1 (SM)

At 68% CL level, find:

$$\kappa_g = 1.08^{+0.32}_{-0.14}$$
$$\kappa_\gamma = 1.24^{+0.16}_{-0.14}$$
$$BR_{inv.,undet.} < 0.33$$

➢ Similar result for kγ and kg with the two hypotheses
➢**Compatible with SM within ~1.2σ** (p-value: 10%)



# Conclusion

- The masses in the channels with the better resolution have been combined and give

$$m_H = 125.5 \pm 0.2\,(\text{stat})\,^{+0.5}_{-0.6}\,(\text{sys})\ \text{GeV}$$

→ the two masses are compatible within 2.5 σ

- The signal strength has been combined within the 5 channels currently analyzed in ATLAS.

$$\hat{\mu} = 1.30 \pm 0.13\,(\text{stat}) \pm 0.14\,(\text{sys})$$

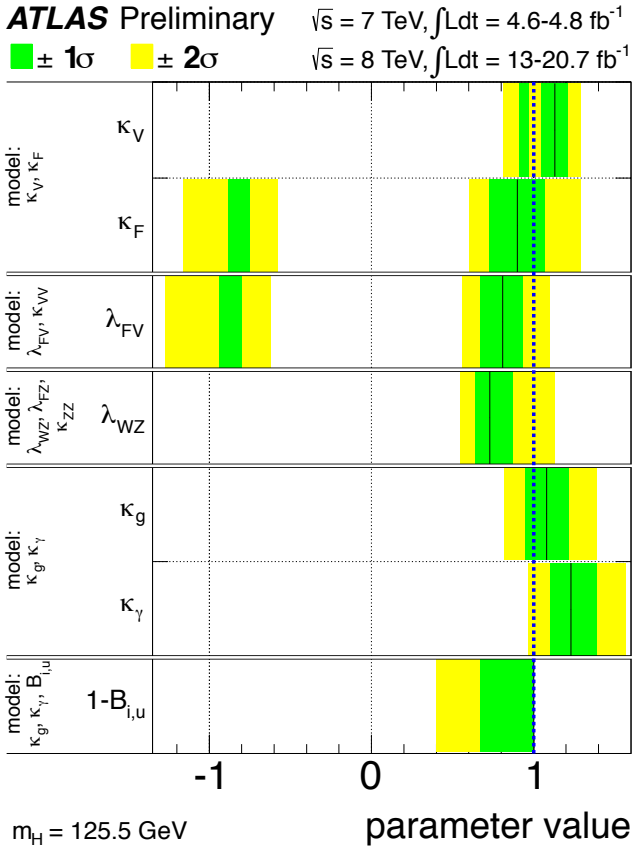
→ compatible with the SM at the 9% level

- Ratio of boson vs fermion mediated production modes is measured:

$$\mu_{\text{VBF}}/\mu_{\text{ggF}+t\bar{t}H} = 1.2^{+0.7}_{-0.5}$$

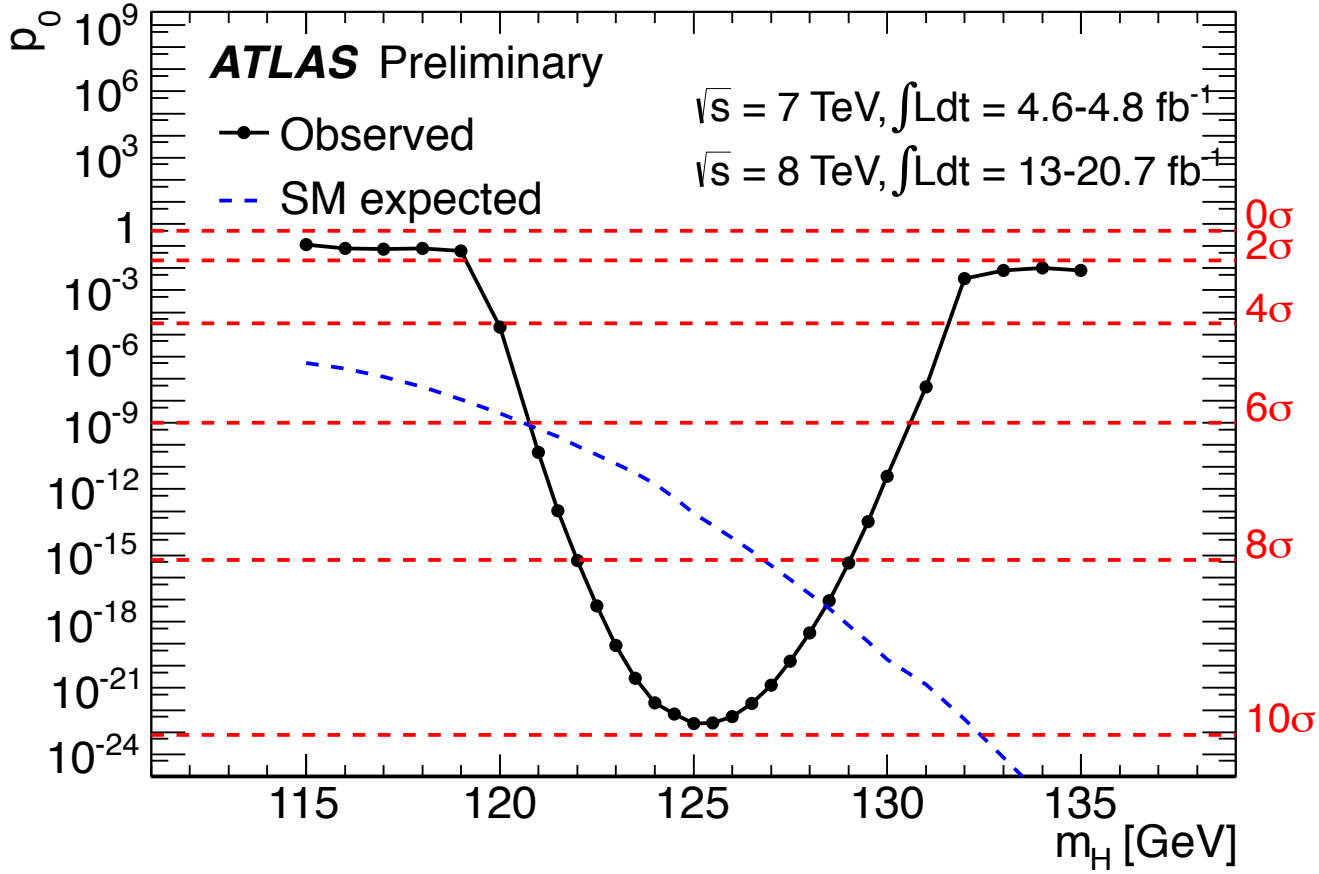
  - Compatible with the SM
  - 3.1 σ evidence for the VBF production

- The compatibility of the various couplings measurement with the SM hypothesis is within **~1.2σ-1.5σ** (p-value ~5-10% )
  - no significant deviation with respect to SM observed in the various fits
  - no sign of new physics in loops or decays



# Back-up

# Combined p0


ATLAS Preliminary
Observed
SM expected
√s = 7 TeV, ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV, ∫Ldt = 13-20.7 fb⁻¹
p0
10^9
10^6
10^3
1
10^-3
10^-6
10^-9
10^-12
10^-15
10^-18
10^-21
10^-24
0σ
2σ
4σ
6σ
8σ
10σ
115
120
125
130
135
mH [GeV]

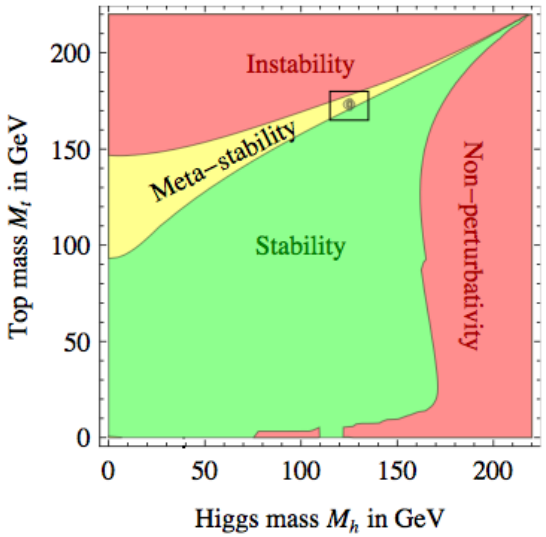
# Interest of the mass measurement

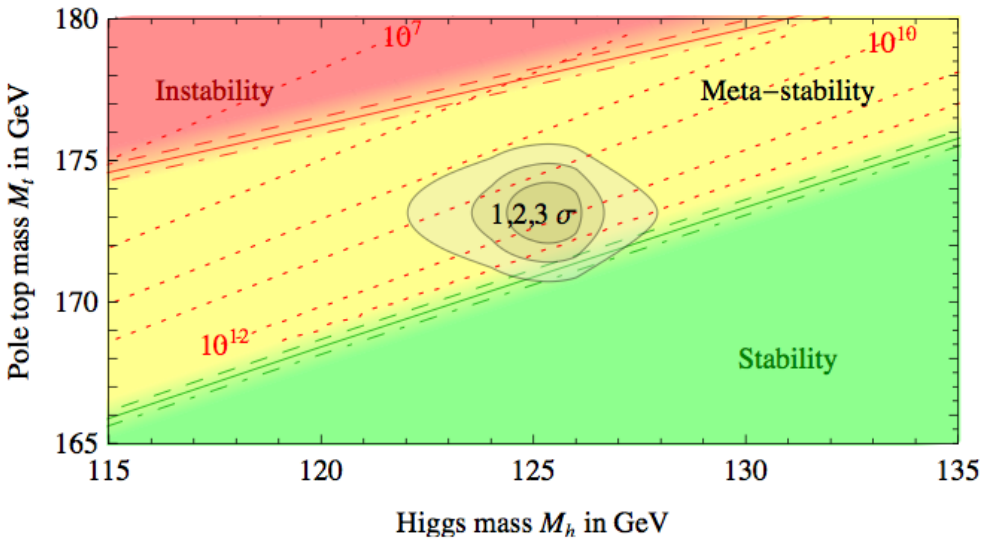


- Vacuum stability: equations from RGE (Renormalisation Group Equations) for the quartic coupling allow to link the evolution of this quartic coupling to the Higgs mass, and more particularly, for low values of the quartic coupling, it links the Higgs mass to the top Yukawa coupling. Asking for a coupling being stable until large scale allow to put a lower limit on the Higgs mass.

- MSSM and corrective radiations to the higgs mass : the MSSM predicts a mass for the lighter Higgs smaller than the one of the Z boson. From radiative corrections coming from scalar top sector, this limit can be passed. But there is an upper limit located around 130 GeV. A too important mass of the Higgs would invalidate these models.

- Correlations between mass and couplings



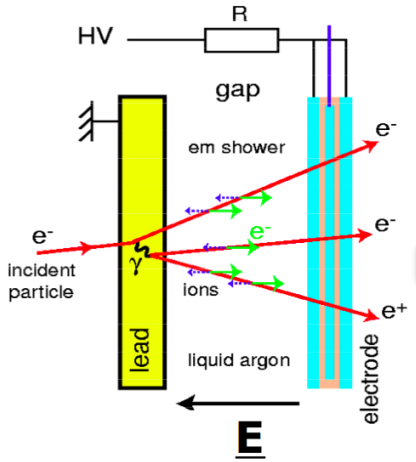
# The uncertainty on energy scale

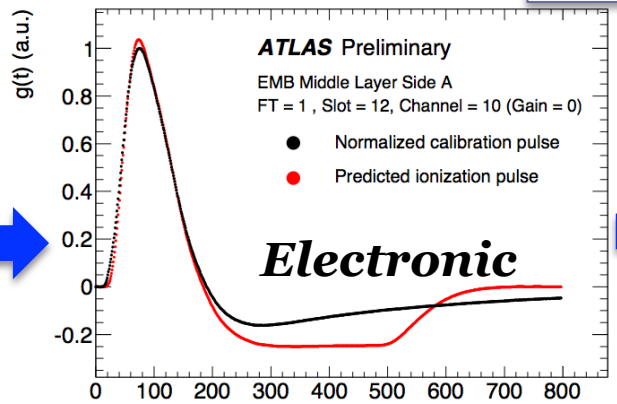


- **Main uncertainty on the mass measurement**
- Energy of electrons and photons are collected in the electromagnetic calorimeter
- From the electronic signal to the final energy, there are 3 main step of calibration:
  - electronic calibration
  - calibration with MC simulation
  - in situ calibration using Z→ee events

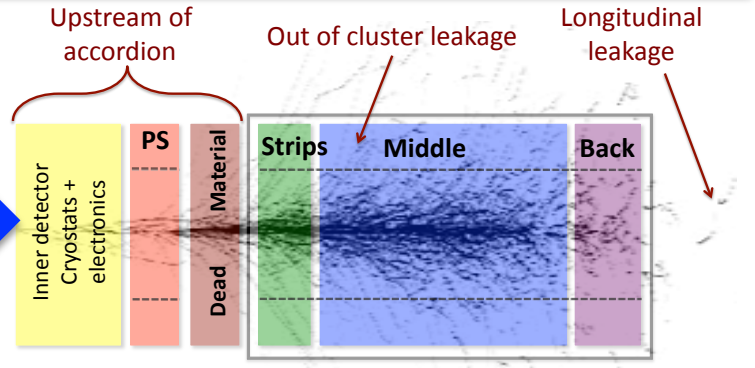
***Simulation***

$$E_{tot} = \alpha + \beta E_{PS} + \gamma(E_{strips} + E_{middle} + E_{back}) + \delta E_{back}$$



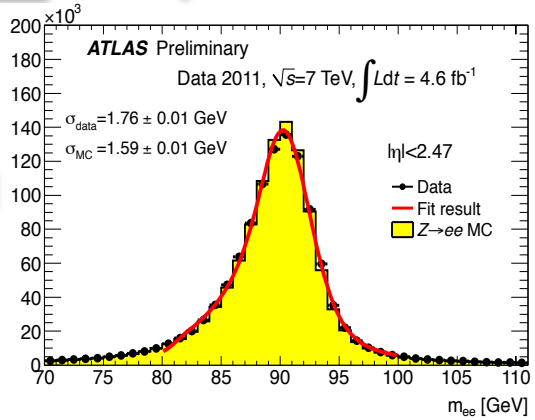



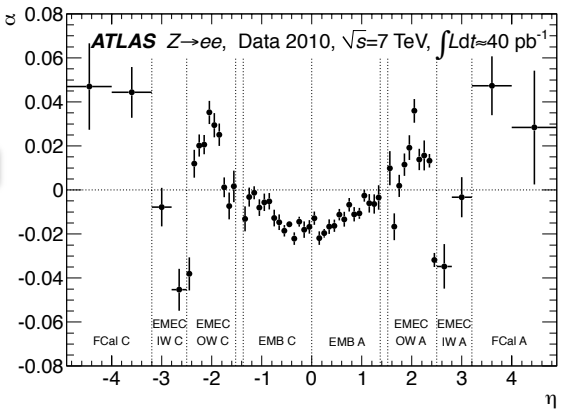

***Electronic***



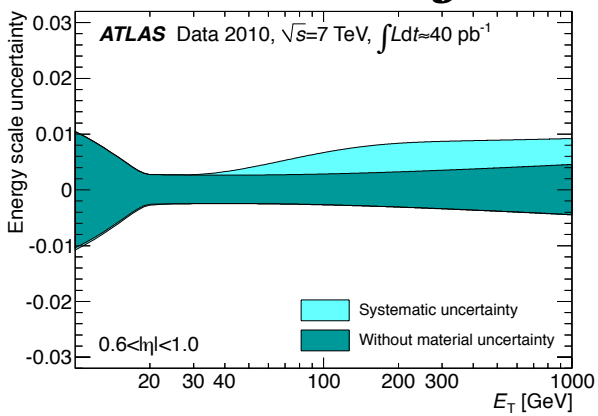

***"In-situ"***

$$E^{meas} = E^{true}(1+\alpha_i)$$




***Uncertainty***



# Uncertainty on Energy Scale for electrons



| | [0,0.6] | [0.6,1.0] | [1.0,1.37] | [1.52,1.8] | [1.8,2.5] | [2.5,3.2] | [3.2,4.5] |
|---|---|---|---|---|---|---|---|
| Statistical | ±0.1 | ±0.2 | ±0.2 | ±0.2 | ±0.2 | ±0.5 | ±1.0 |
| MC closure | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.2 | ±0.2 |
| Method comparison | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 |
| Background | ±0.1 | ±0.1 | ±0.1 | +0.3/-0.2 | +0.3/-0.2 | +1.2/-0.2 | +1.2/-0.6 |
| Pile-up | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 |
| Presampler energy scale | $p_T$-dependant from -1% to +1% for $\|\eta\|$ <1.8 (see Figure 16) | | | | | | |
| Front energy scale | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 |
| Detector condition | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | ±0.6 | ±0.8 |
| Electronic non-linearity | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 |
| Extra-material | $p_T$-dependant from -1.5% to +2% (see Figure 13) | | | | | | |

# Checks of the mass measurement



- Many checks have been performed:
  - Test the calibration of the method, using toys (calibration of the central value AND of the error)
  - Test the compatibility of the mass measurement in different production process: VBF/ggH categories
  - Test the compatibility of the mass measurement in photon type categories (converted, unconverted)
  - Test the compatibility of the mass measurement in different pT regimes of the diphoton system
  - Test the compatibility of the mass measurement in different regions of EM calorimeter
  - Test the compatibility of the mass measurement using different models for the background fit
  - Test the stability of the mass with respect to the time
  - Test the stability of the mass with respect to the pileup
  - Test the stability of the mass with respect to the choice of the primary vertex.

→ **All these checks give compatible results !**

# $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$ Mass Scale Systematic Uncertainties

H→gg

•Further investigation and extensive checks lead to find additional sources of systematic uncertainties :

- LAr Strips relative calibration (0.2%)
- Photon energy resolution (0.15%)
- Calibration of the high gain (0.15%)
- Mis-classification due to fake conversions (0.13%)
- Backgound modeling (0.1%)
- Lateral shower development simulation (0.1%)
- Effect of PV choice (0.03%)

H→4l

•Further investigation and extensive checks have not lead to additional substantial sources of systematic uncertainty :

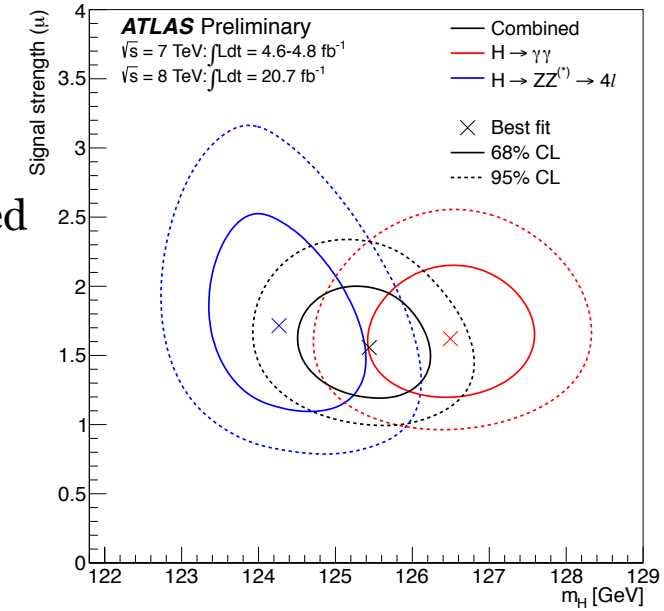
- Measurement with MS and ID alone
- Local detector biases checked event by event
- Local resolution effects checked using event- by-event error;
- kinematic distributions in agreement with expectation
- FSR simulation
- Different mass reconstruction using Z-mass constraint (+400 MeV shift)

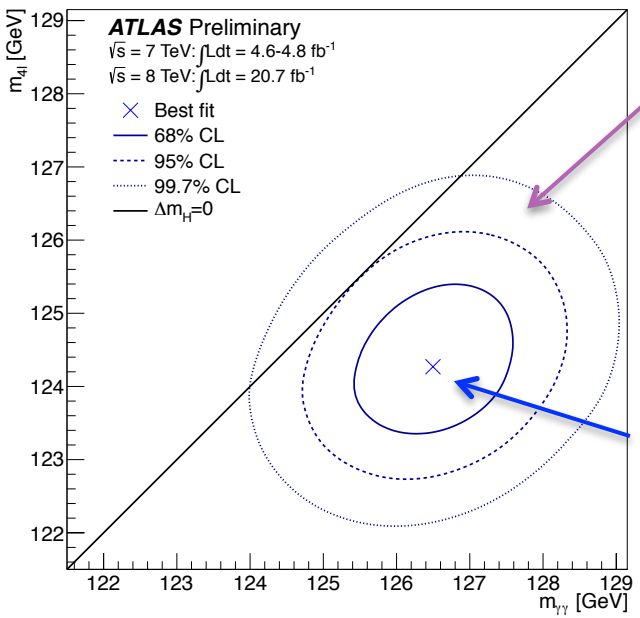
# Mass Difference

- Quantify the consistency between the two masses in γγ and ZZ channels
- Previous combination: compatibility = 0.8% = 2.7σ (deduced from a likelihood testing $\Delta m_H = m_{\gamma\gamma} - m_{4l} = 0$ )
- With the updated analysis, the mass difference is

$$\Delta\hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4\ell} = 2.3^{+0.6}_{-0.7}\,(\text{stat}) \pm 0.6\,(\text{sys})\ \text{GeV}$$

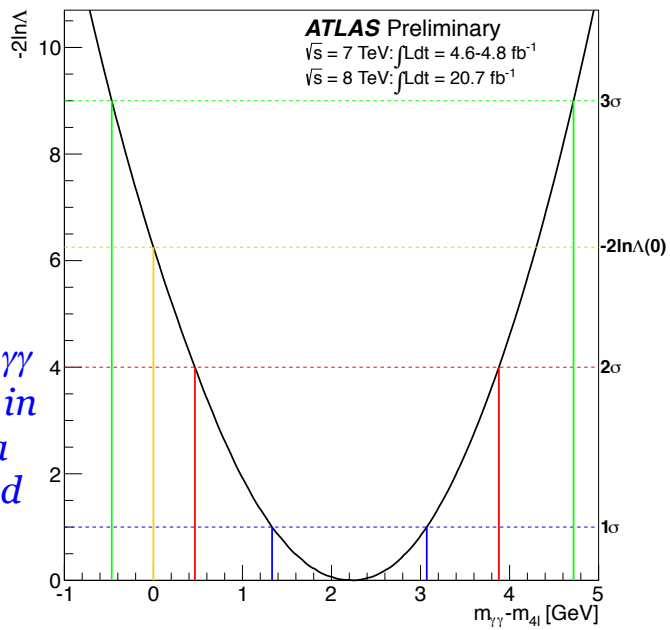
- Gives a compatibility of **1.2% (2.5σ)** and up to 8% using more conservative treatment of the uncertainties.



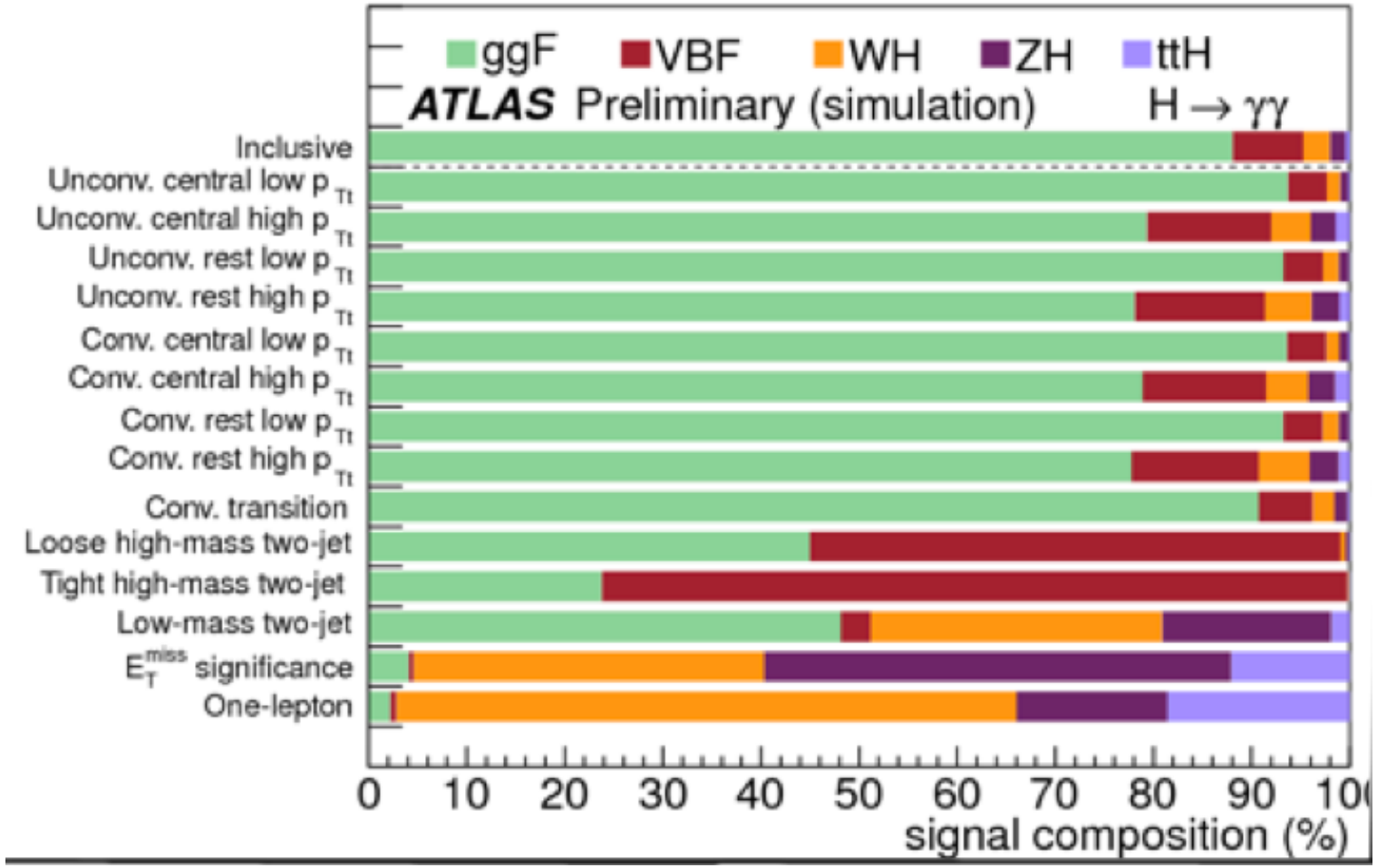

*correlation between $m_{4l}$ and $m_{\gamma\gamma}$ comes from the common e/γ energy scale uncertainty*

*~350 MeV downward shift of the γγ mass, due to the 0.8σ adjustment in the e/γ energy scale to provide a consistency between electrons and muons mass*



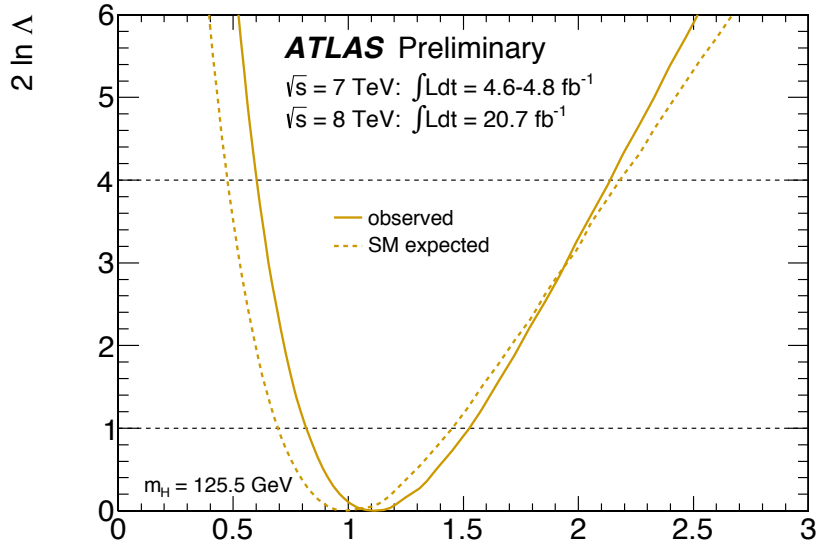
# Signal composition (H→γγ)

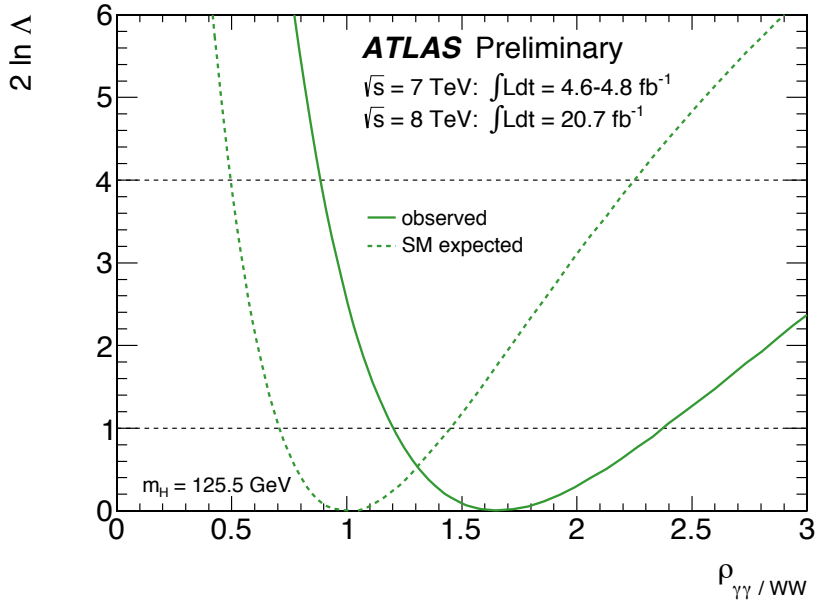


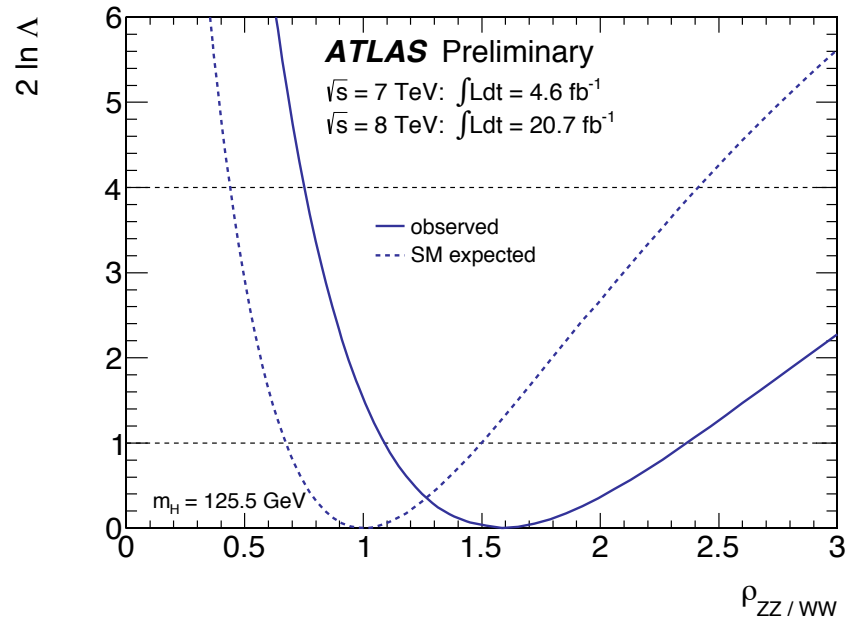


# Testing the Branching ratio





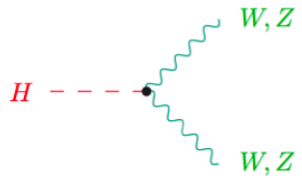

$$\rho_{XX/YY} = \frac{BR(H \to XX)}{BR(H \to YY)} \times \frac{BR_{SM}(H \to XX)}{BR_{SM}(H \to YY)}$$

# Couplings: Fermion vs gauge vector

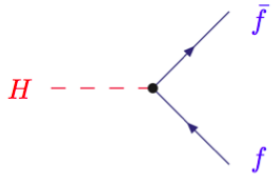
*(does the new state couple to vectors and fermions ?)*

- Thanks to the various production and decays mode accessible at LHC, the couplings of fermions and gauge vector to the Higgs can be tested.

$$\lambda_{FV} = \frac{\kappa_F}{\kappa_V}$$




$\propto \kappa_V$

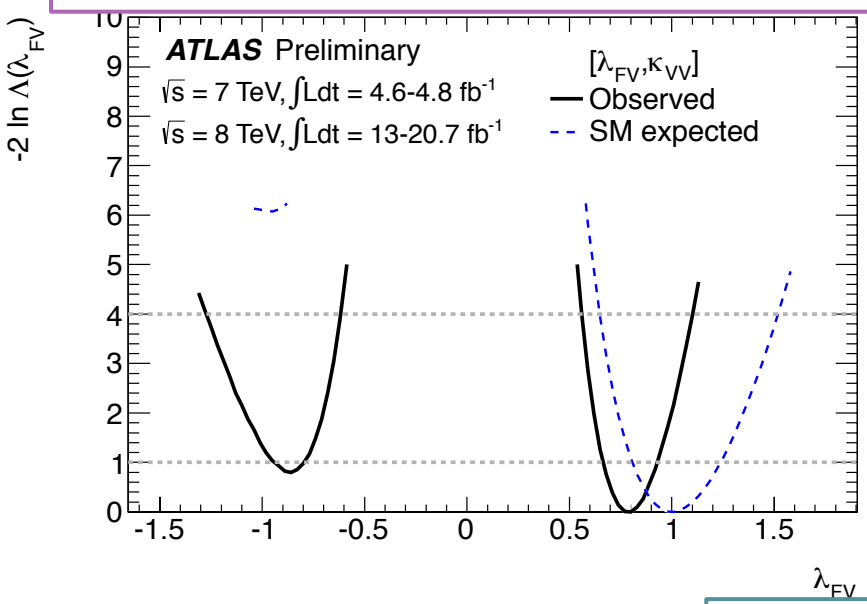



$\propto \kappa_F$

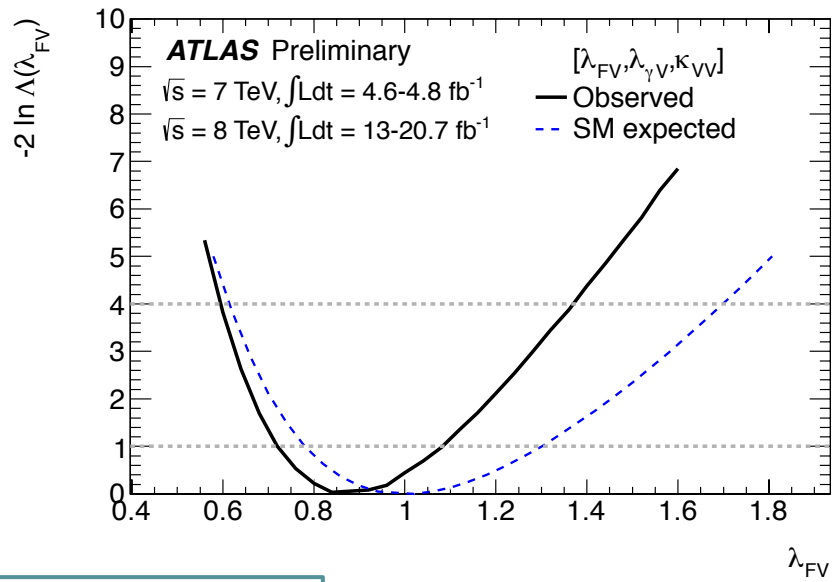
$$\kappa_{VV} = \kappa_V \cdot \frac{\kappa_V}{\kappa_H}$$

$$\lambda_{\gamma V} = \frac{\kappa_\gamma}{\kappa_V}$$

➢**Allows contribution of BSM particles to total width**

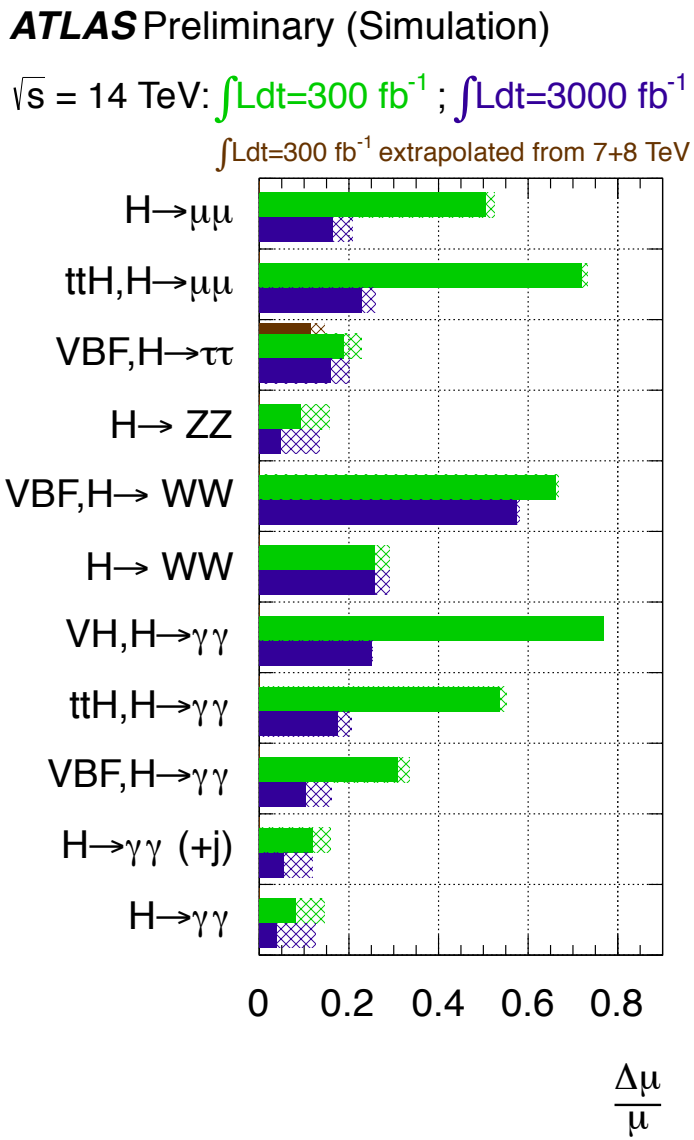


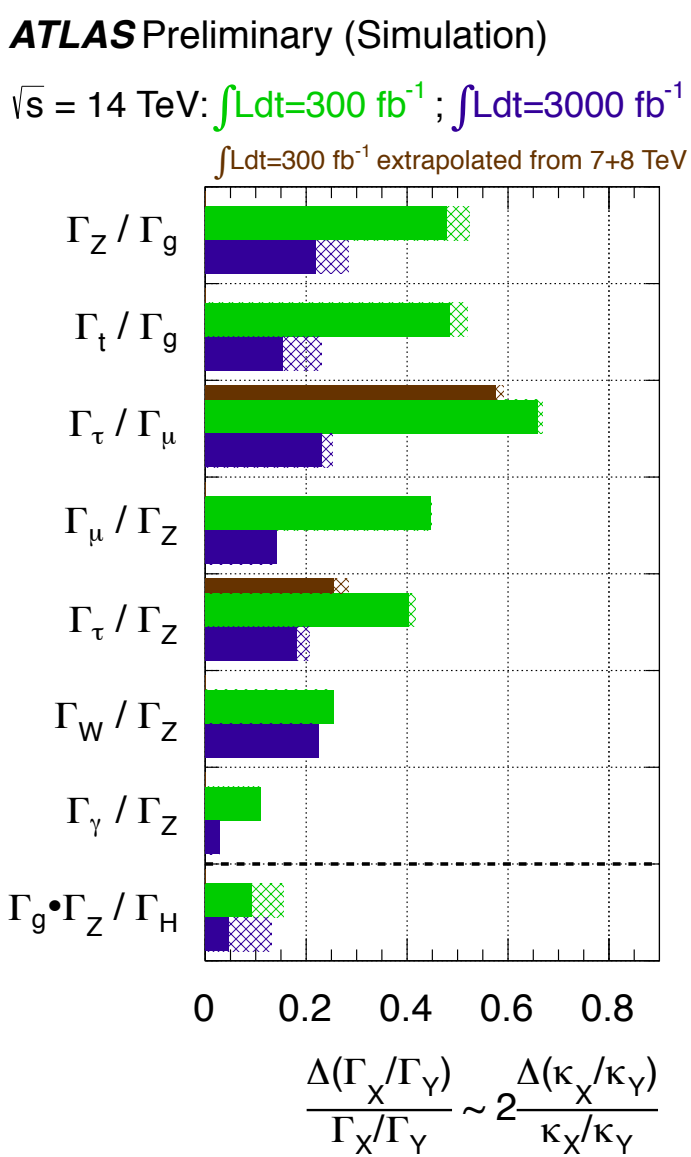

➢**Allows contribution of BSM particles in the loops.**




➢Well compatible with SM

# Prospects…

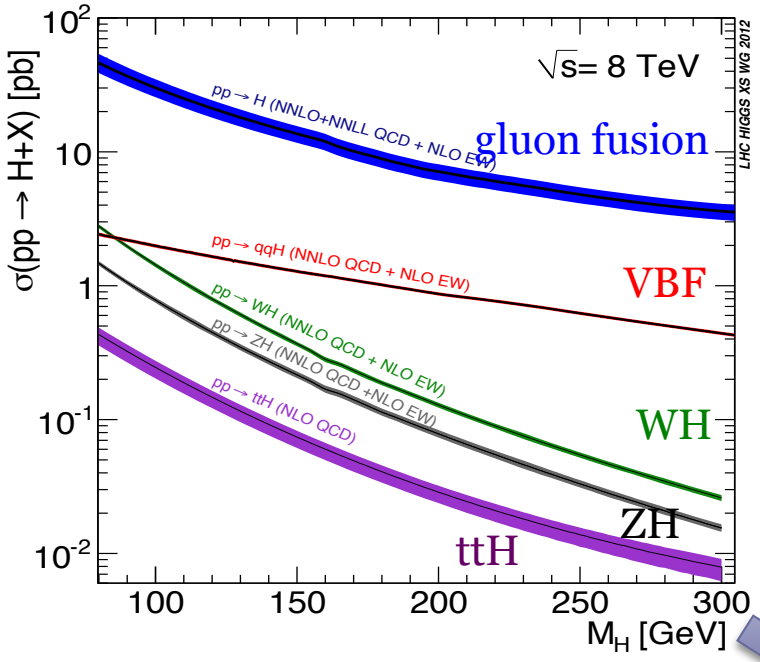


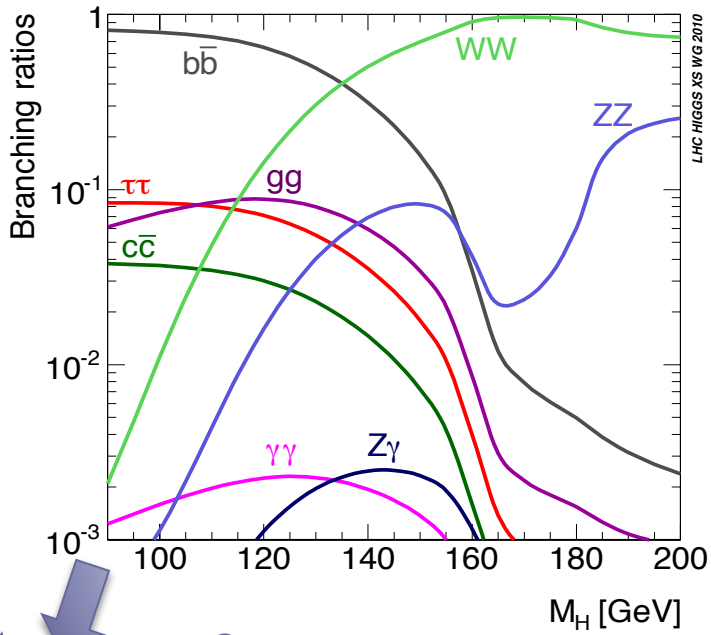




*Dashed areas include current theory uncertainties from QCD scale and PDF variations for luminosities of 300 fb-1 and 3000 fb-1*

→See A.Djouadi talk






$$\mu_i = \sigma_i/\sigma_{i,\mathrm{SM}}$$

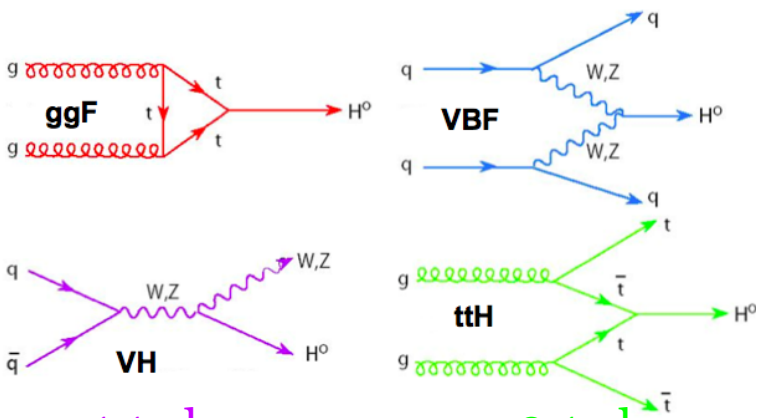
$$\mu_f = B_f/B_{f,\mathrm{SM}}$$

$$\boxed{\mu = \mu_i.\mu_f}$$

*global signal strength*

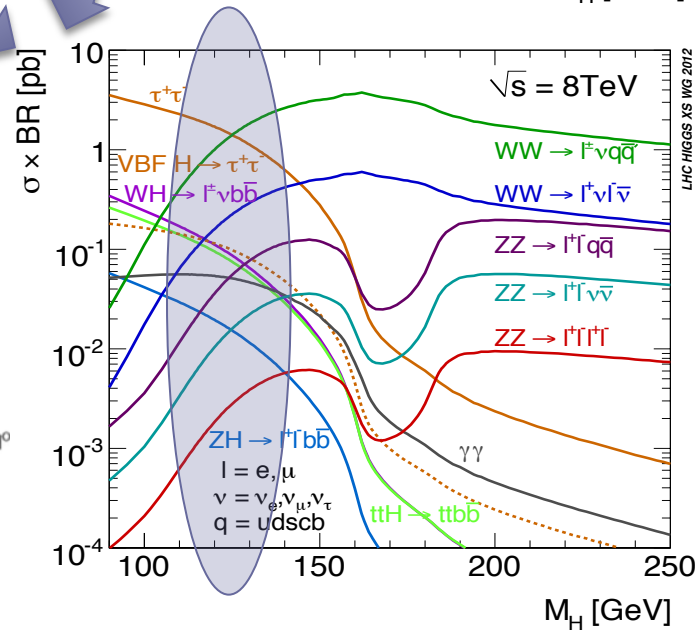
19.5 pb

1.6 pb



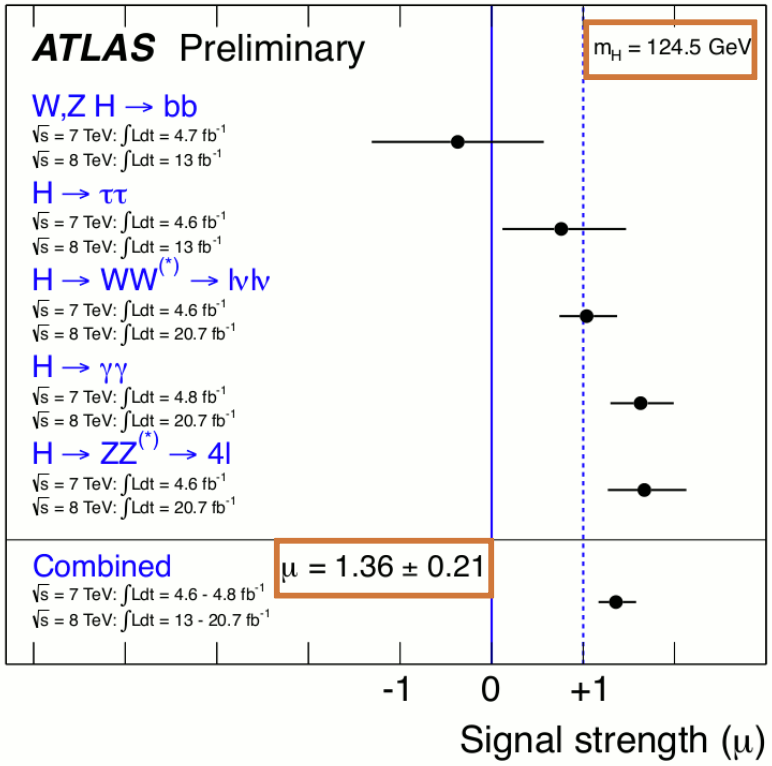

1.1 pb

0.1 pb




$$\Lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}}(\mu))}{L(\hat{\mu}, \hat{\theta})}$$

*nuisance parameters for the systematic uncertainties*


ATLAS Preliminary
$m_H$ = 124.5 GeV
W,Z H → bb
√s = 7 TeV: ∫Ldt = 4.7 fb⁻¹
√s = 8 TeV: ∫Ldt = 13 fb⁻¹
H → ττ
√s = 7 TeV: ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV: ∫Ldt = 13 fb⁻¹
H → WW(*) → lνlν
√s = 7 TeV: ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.7 fb⁻¹
H → γγ
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.7 fb⁻¹
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.7 fb⁻¹
Combined
μ = 1.36 ± 0.21
√s = 7 TeV: ∫Ldt = 4.6 - 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 13 - 20.7 fb⁻¹
-1
0
+1
Signal strength (μ)