Higgs Mass and Couplings in ATLAS and CMS

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Standard Model @ LHC
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Combination:

Introduction

ATLAS:

- **Update** of the channels **H→γγ, H→ZZ** and **H→WW** with **~21fb-1** in 2012 (+2011)
- H→bb and H→tt with ~13fb-1 in 2012 (+2011)

→ **~10σ**

Channel - *ATLAS* -	$\int Ldt$ 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	7.4σ (4.1σ)	1.6 ± 0.3	126.8 ± 0.2 (stat) ± 0.7 (syst)
$H \to ZZ \to 4l$	4.6 + 20.7	ggH, VBF, VH	6.6σ (3.7σ)	1.5 ± 0.4	$124.3\ ^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst)
$H \to WW \to lvlv$	4.6 + 20.7	ggH, VBF	3.8σ (3.7σ)	1.0 ± 0.3	-
$H \to \tau\tau$	4.6 + 13	ggH, VBF, VH	-	0.8 ± 0.7	-
$VH \to Vbb$	4.6 + 13	VH	-	-0.4 ± 1.0	-

CMS:

- **H→γγ uses ~5fb-1** in 2012 (+2011)
- All other channels use **~12fb-1** in 2012 (+2011)

→ **~7σ**

Channel - *CMS* -	$\int Ldt$ in fb^{-1} (2011 +2012)	Tagged categories	Observed (expected) significance	Signal Strength	Mass (GeV)
$H \to \gamma\gamma$	5.1 + 5.3	ggH, VBF	4.0σ (2.8σ)	1.6 ± 0.4	125.2 ± 0.5 (stat) ± 0.6 (syst)
$H \to ZZ$	5.0 + 12.2	ggH	4.4σ (5.0σ)	0.8 ± 0.3	126.2 ±0.6 (stat) ±0.2 (syst)
$H \to WW$	5.0 + 5.1-12.1	ggH, VBF, VH	3.0σ (4.3σ)	0.7 ± 0.2	-
$H \to \tau\tau$	5.0 + 0-12.1	ggH, VBF, VH	1.8σ (2.1σ)	0.9 ± 0.5	-
$VH \to Vbb$	5.0 + 0-12.1	VH, ttH	1.8σ (2.2σ)	1.1 ± 0.6	-

Introduction

not yet used for the combination

- CMS recently updated the individual channels:
  - H→ZZ (see talk by T.Cheng)
  - H→γγ (see talk by S. de Cecco)
  - H→WW (see talk by R. Polifka)
  - H→ττ (see talk by J.F Benitez)

Channel - ***CMS*** -	$\int Ldt$ in fb^{-1} (2011 +2012)	Observed (expected) significance	Signal Strength	Mass (GeV)
$H \to \gamma\gamma$ (MVA)	5.1 + 19.6	3.2σ (4.2σ)	0.78 ± 0.3	125.4 ± 0.5 (stat) ± 0.6 (syst)
$H \to ZZ \to 4l$	5.0 + 19.6	6.7σ (7.2σ)	0.9 ± 0.3	125.8 ±0.5 (stat) ±0.2 (syst)
$H \to WW \to lvlv$	4.9 + 19.5	4.0σ (5.1σ)	0.8 ± 0.2	-
$H \to \tau\tau$	4.9 + 19.4	2.85σ (2.55σ)	1.1 ± 0.4	$120\ ^{+9}_{-7}$ (stat+syst)

Combined Mass Measurement

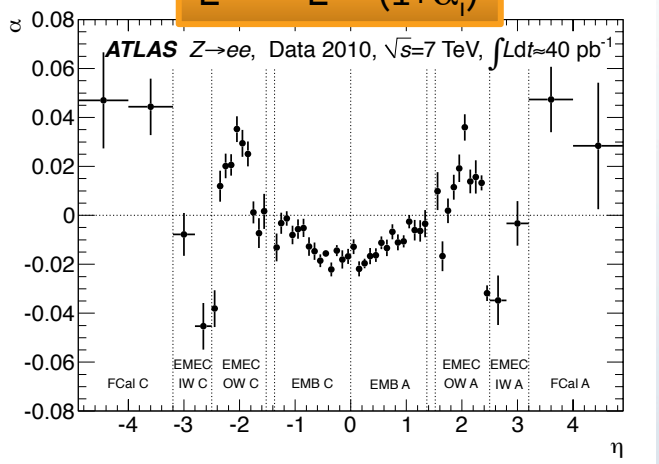
The uncertainty on energy scale

Main uncertainty on the mass measurement

Muons: very low uncertainty on their energy scale (derived from J/ψ→μμ , Υ→μμ and Z→μμ)

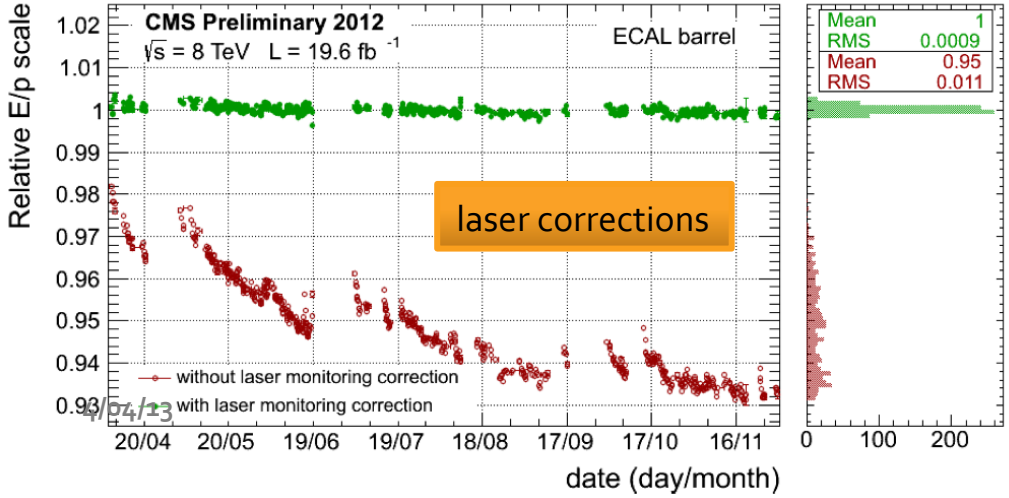
Electrons and photons: sizeable uncertainty on their energy scale (derived from J/ψ→ee, Z→ee , W→eν + validation with Zγ events)

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



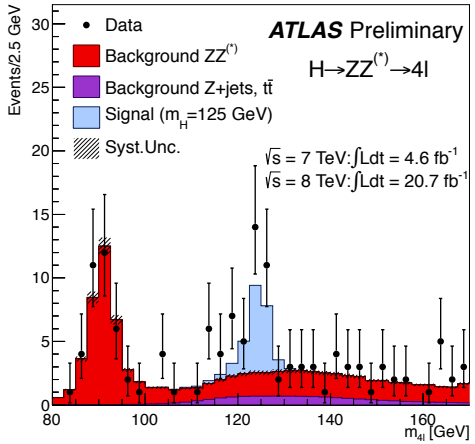
ATLAS

	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%



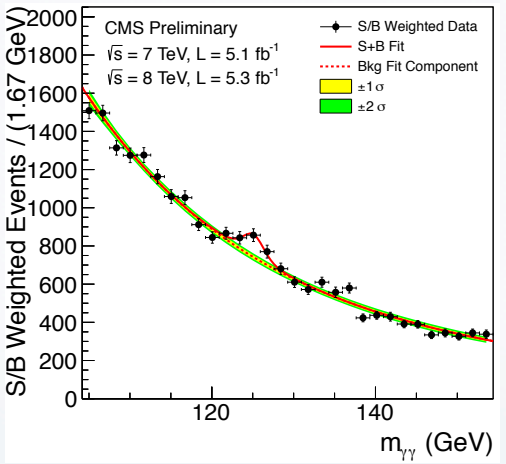
CMS

Channel	Global energy scale systematic from Z
$H \to \gamma\gamma$	±0.5%
$H \to 4e$	±0.2%
$H \to 2e2\mu$	±0.2%
$H \to 4\mu$	±0.1%



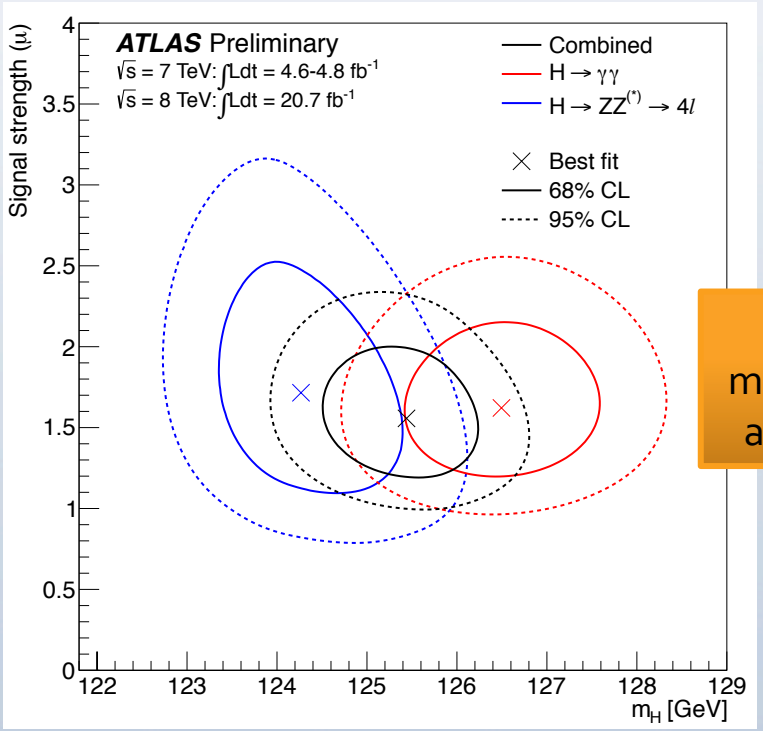
Mass

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

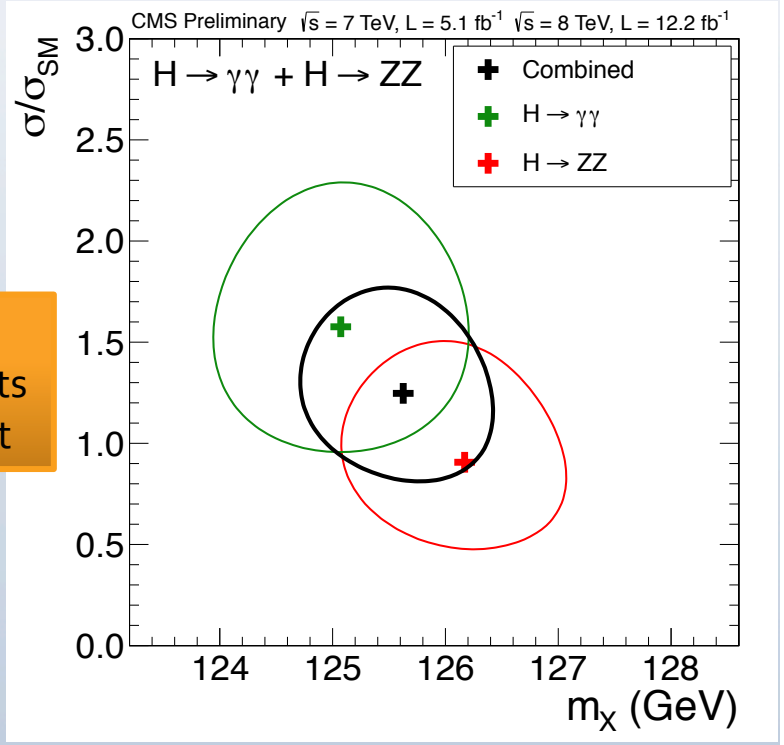


$$m_H = 125.5 \pm 0.2\,(stat)\,^{+0.5}_{-0.6}\,(syst)\,GeV$$

$$m_H = 125.8 \pm 0.4\,(stat)\,\pm 0.4\,(syst)\,GeV$$



ATLAS and CMS mass measurements are very consistent



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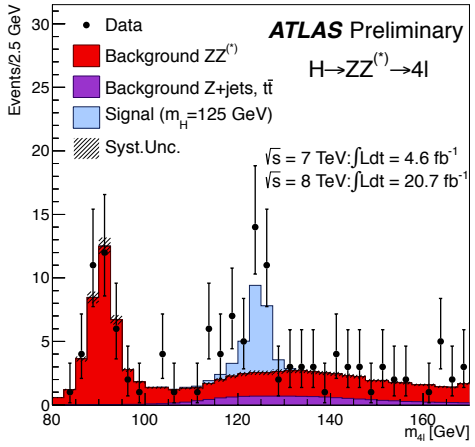

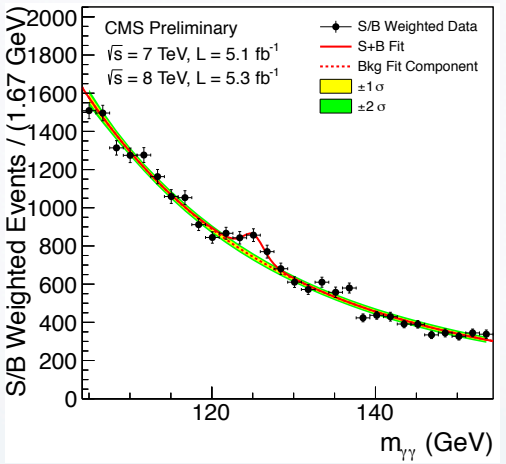

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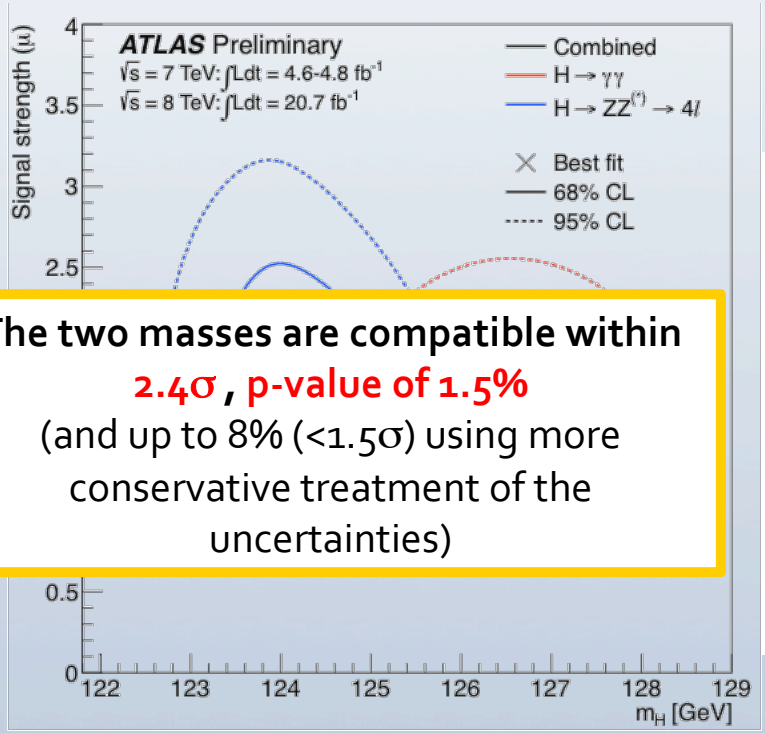
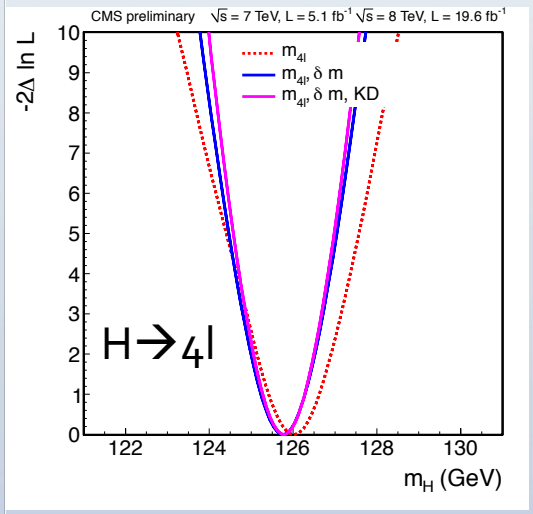
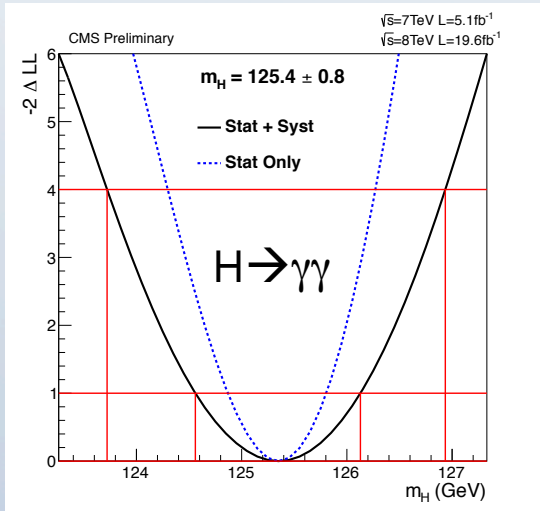


The two masses are compatible within
2.4σ , p-value of 1.5%
(and up to 8% (<1.5σ) using more conservative treatment of the uncertainties)

Individuals fits with updated analyses





$$m_H = 125.4 \pm 0.8\,GeV$$

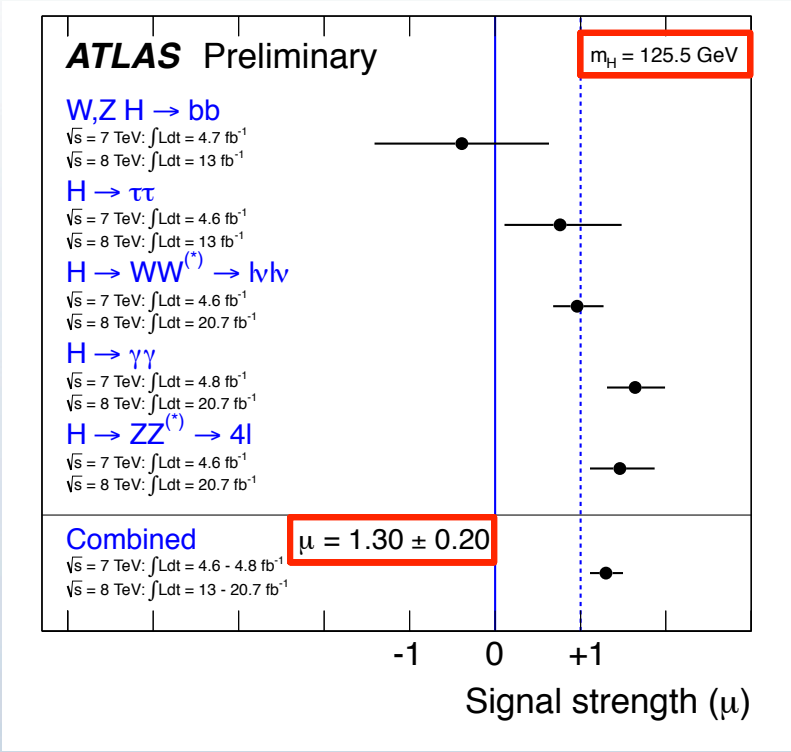
$$m_H = 125.8 \pm 0.5\,GeV$$

Signal strengths

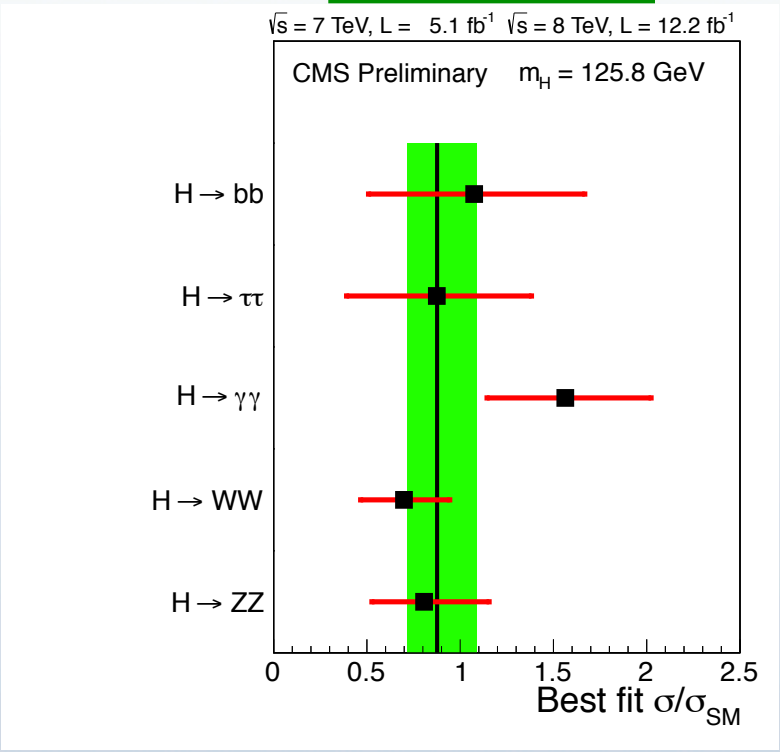
Signal Strength

- Measure the number of signal in each channel $n_{signal} \propto \mu \cdot \sigma_{SM} \cdot B_{SM}$
- Combined value (at 125.5 GeV for ATLAS, 125.8 GeV for CMS)

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



$\hat{\mu} = 0.88 \pm 0.21$



- Both experiment have a good compatibility with the SM assumption (with a probability of 0.009 for ATLAS, 0.65 for CMS)
- Almost independent of the mass on which it is evaluated
  (ATLAS: changing the mass hypothesis from 124.5 to 126.5 changes μ by ~4%)

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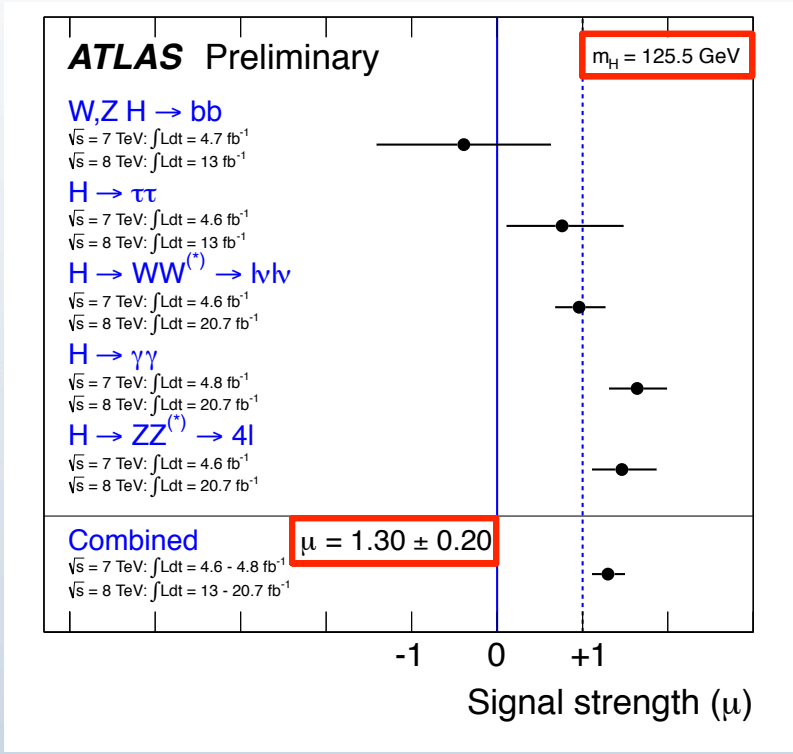
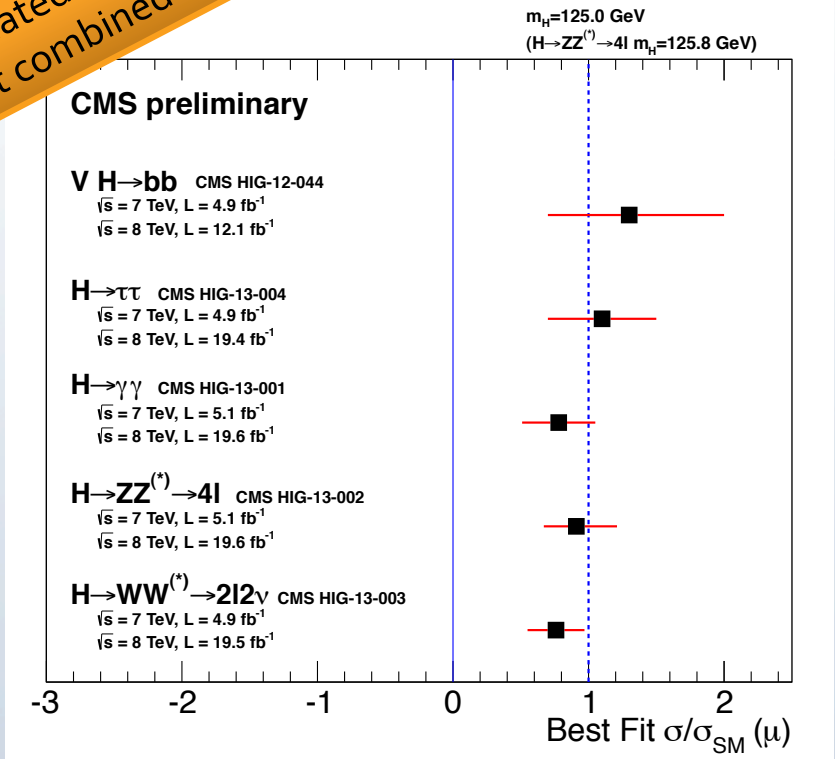


With updated channels
Not combined



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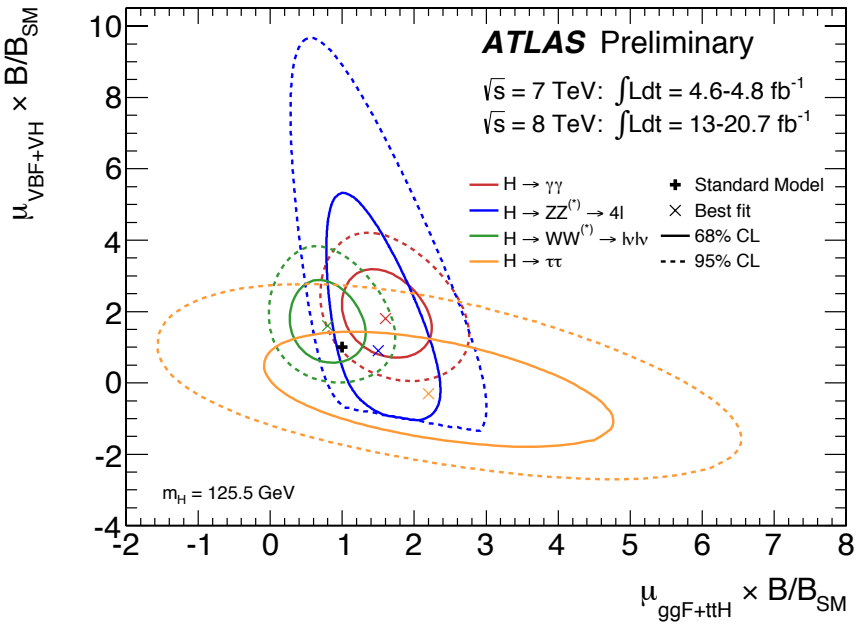
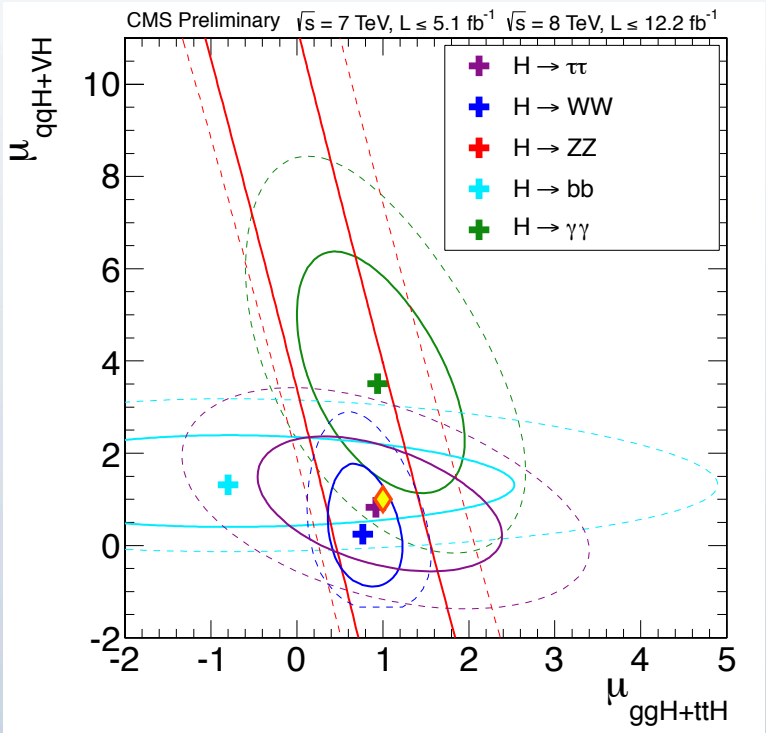
Production modes: fermion vs boson mediated

- Test two kind of production: $n_{signal} \propto \mu_i \cdot \sigma_{SM} \cdot \mu_f \cdot B_{SM}$

→ fermion mediated (ggH and ttH processes) : $\mu_{ggH+ttH}$ *(too low cross section for ttH alone)*

→ boson mediated (VBF and VH processes) : μ_{VBF}, μ_{VH}, μ_{VBF+VH}



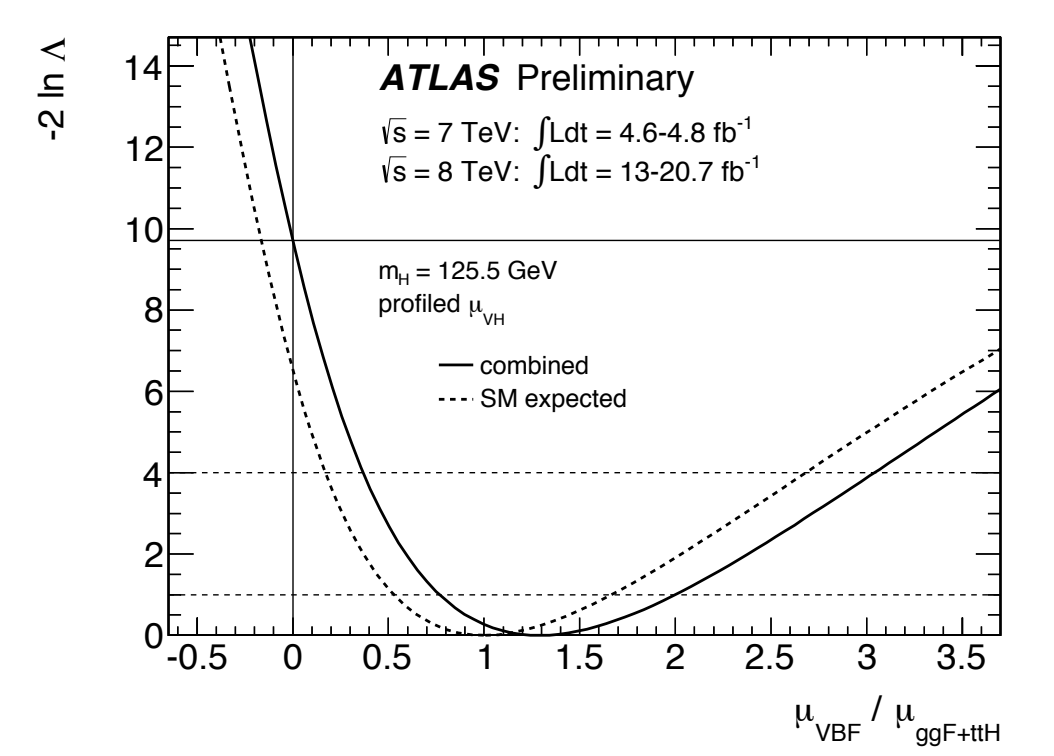


→Compatible with SM expectation of unity.

Production modes: fermion vs boson mediated

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

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



→ATLAS: 3.1σ evidence for non-zero VBF production

Probing the couplings

- Fermion vs gauge vectors couplings
- Custodial symmetry
- Beyond standard model contributions
- Asymmetries in couplings to fermions

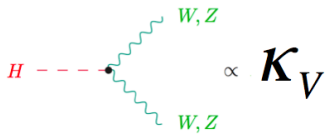
ATLAS and CMS General Framework for couplings, assume:

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

Couplings: Fermion vs gauge vector

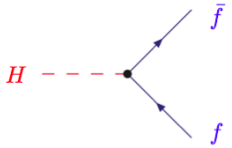
(does the new state couple to vectors and fermions ?)

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



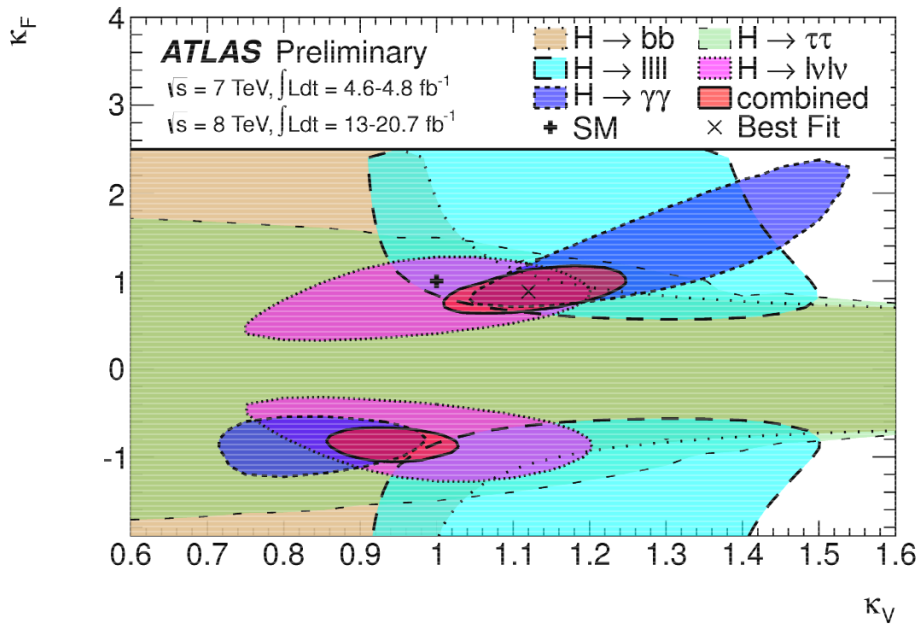
$\propto \kappa_V$

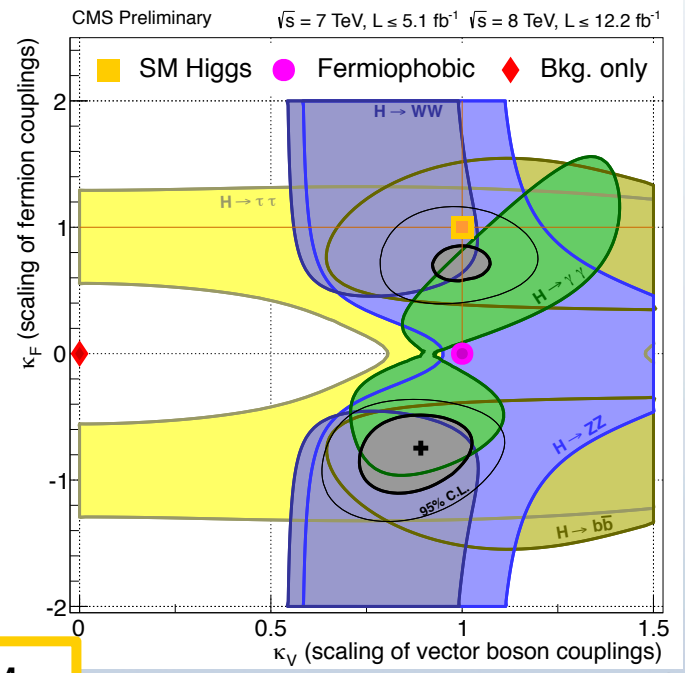
$$\kappa_i^2 \sim \frac{\Gamma_i}{\Gamma_{i(SM)}}$$



$\propto \kappa_F$

Assume:
- single common scaling factor κ_f for fermions couplings
- single common scaling factor κ_V for bosons couplings
- only SM particles contribute to the H→γγ and gg→H vertex loops.
- no contribution of BSM particles to total width

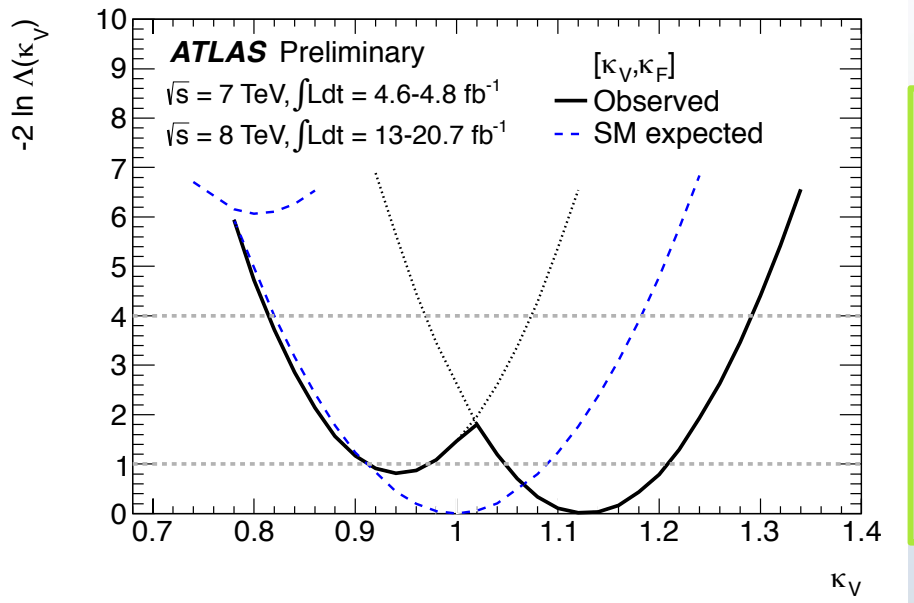




- 2D best fit point compatible with SM
- **κ_f = 0 excluded at >3σ in this model**

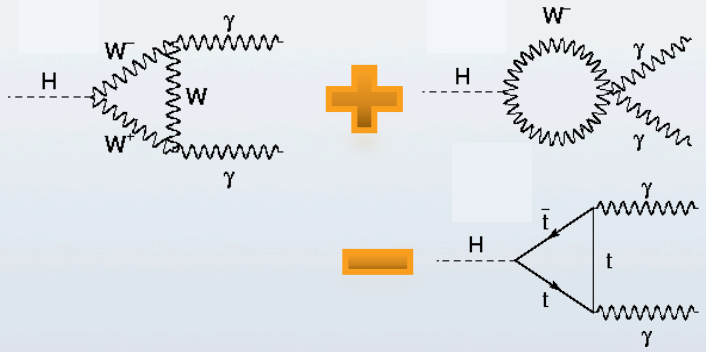
Couplings: Fermion vs gauge vector

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



➡ **H->γγ is the only channel sensitive to to the relative sign of κ_V and κ_f**

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



only relative sign between κ_V and κ_F is physical
→ assume κ_V>0

➢ Already 2σ sensitivity to sign non degeneracy.

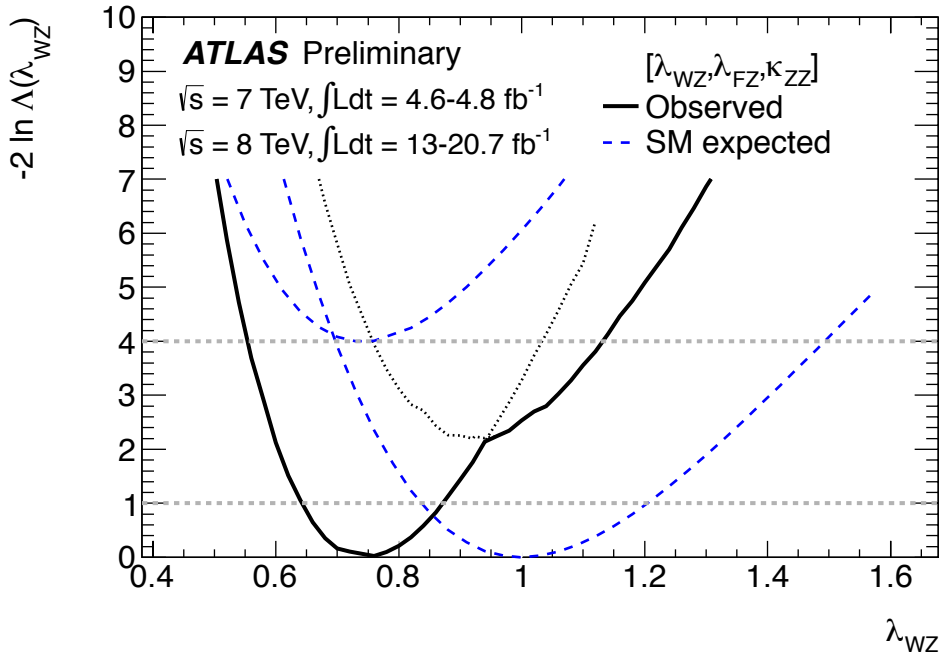
Couplings: probing custodial symmetry

- 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.
- Use the $\lambda_{WZ} = \kappa_W/\kappa_Z$ scale factor,

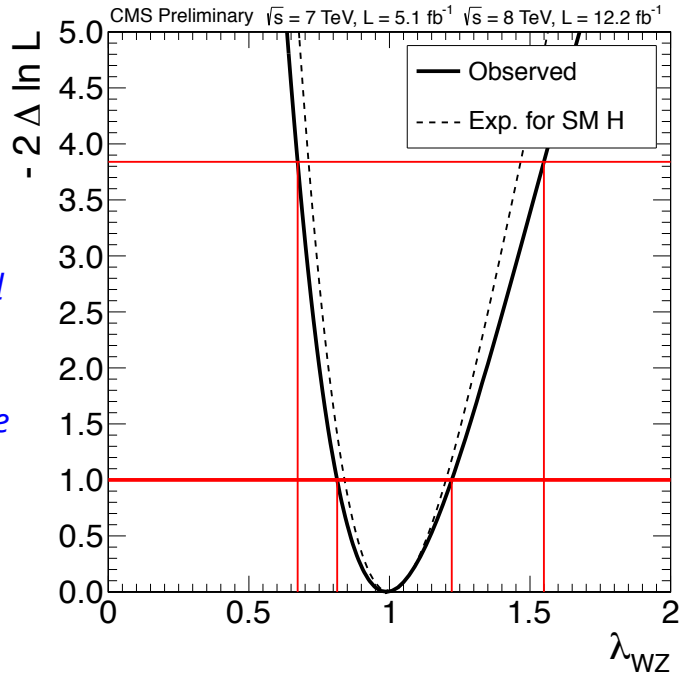
Assume:
- single common scaling factor κ_f for fermions couplings
- no assumption on the total width

ATLAS: $\lambda_{WZ} \in$ **[0.55,1.13]** 95% CL
CMS: $\lambda_{WZ} \in$ **[0.67,1.55]** 95% CL
→ Both compatible with SM hypothesis within 95% interval.

other parameters are profiled

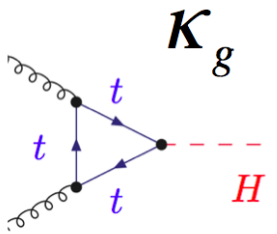


λ_{WZ} is scanned whereas the other parameters are profiled

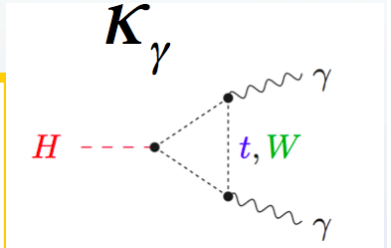


Couplings: Beyond Standard Model contributions

- Allow for extra contribution from new particles in the loops: H→γγ and gg→H loops
- Two effective scale factors introduced κ_g **and** κ_γ

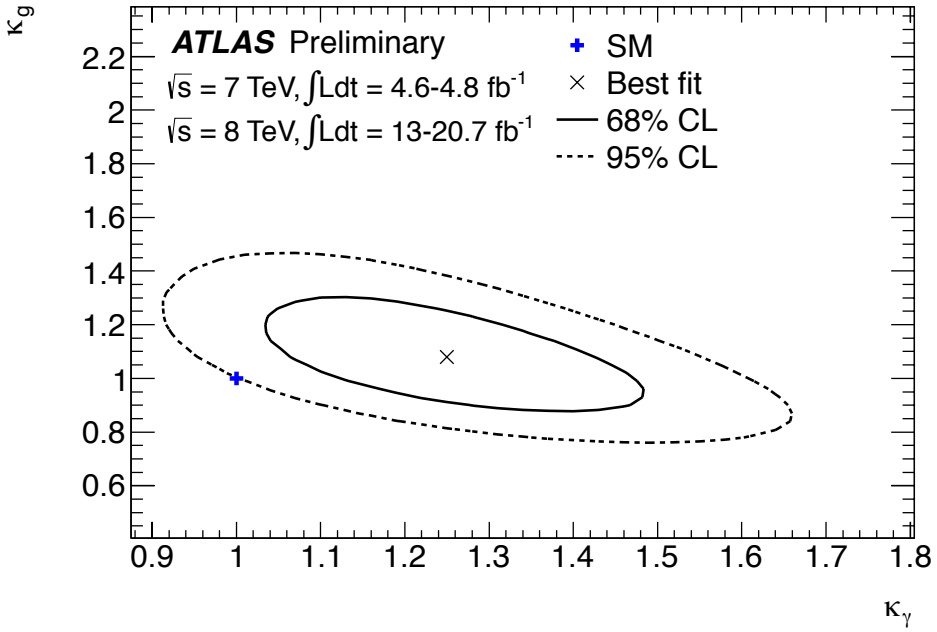


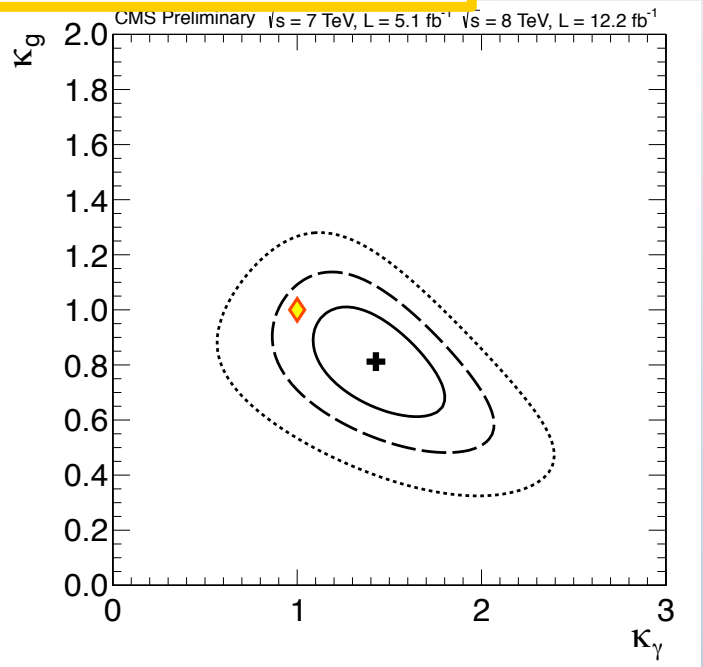
Assume:
- ➢no sizeable contribution of BSM particles to total width
- ➢all scaling factors for couplings but κ_γ and κ_g = 1 (SM)



ATLAS: $\kappa_\gamma \in$ **[0.98,1.57]** ; $\kappa_g \in$ **[0.82,1.39]** at 95% CL
CMS: $\kappa_\gamma \in$ **[0.98,1.92]** ; $\kappa_g \in$ **[0.55,1.07]** at 95% CL

→ Both compatible SM hypothesis within 95% interval.





Couplings: Beyond Standard Model contributions

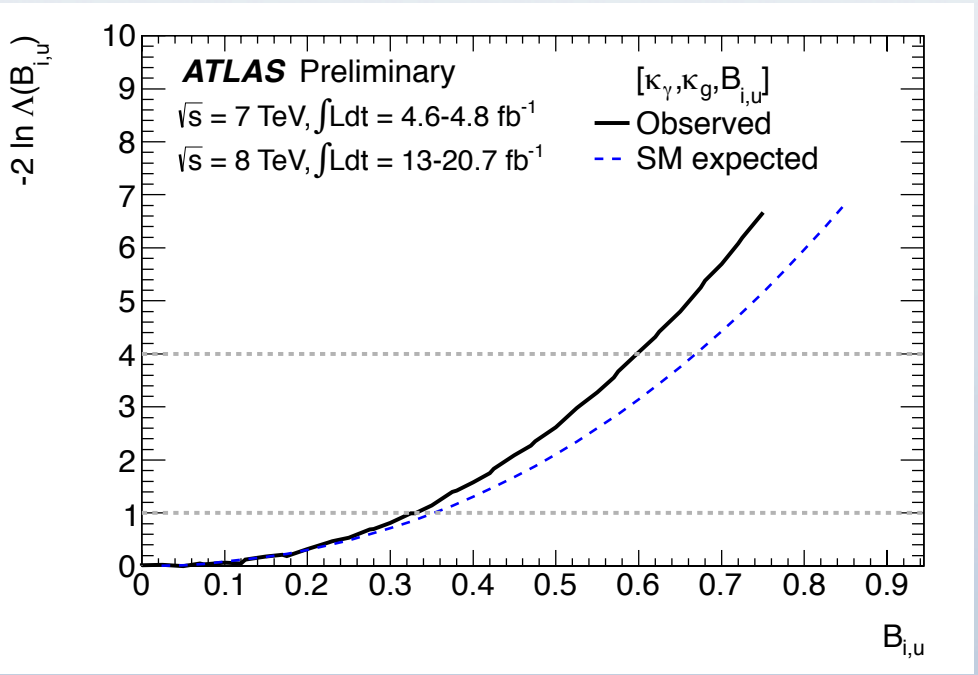
- The non-SM particles may contribute through invisible (i) or undetectable (u) final states

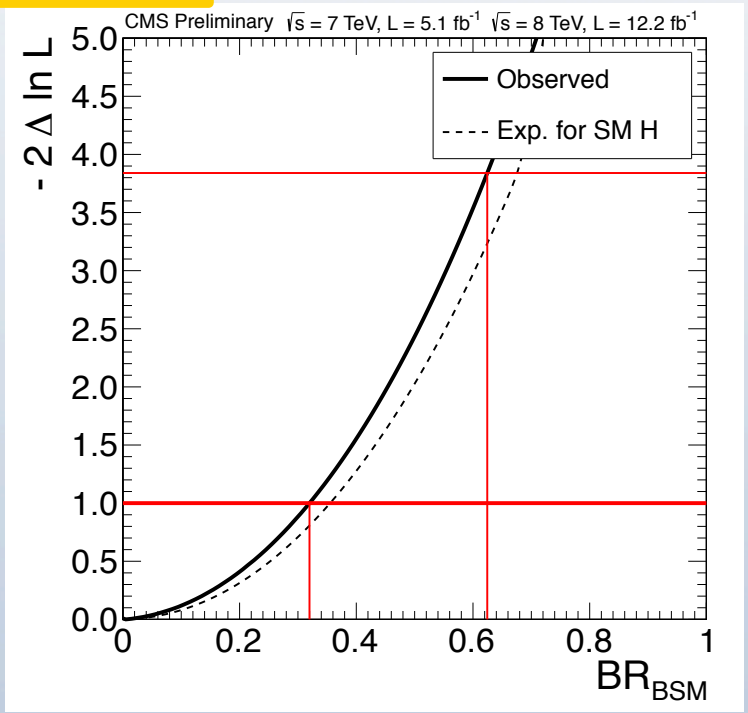
  → add a third free parameter: $BR_{i,u}$ (BR_{BSM})

ATLAS: $\mathbf{BR_{i,u}}$ **<0.60** at 95% CL
CMS: $\mathbf{BR_{BSM}}$ **<0.62** at 95% CL

→Both compatible SM hypothesis within 95% interval.

other parameters are profiled





Asymmetries in couplings to fermions

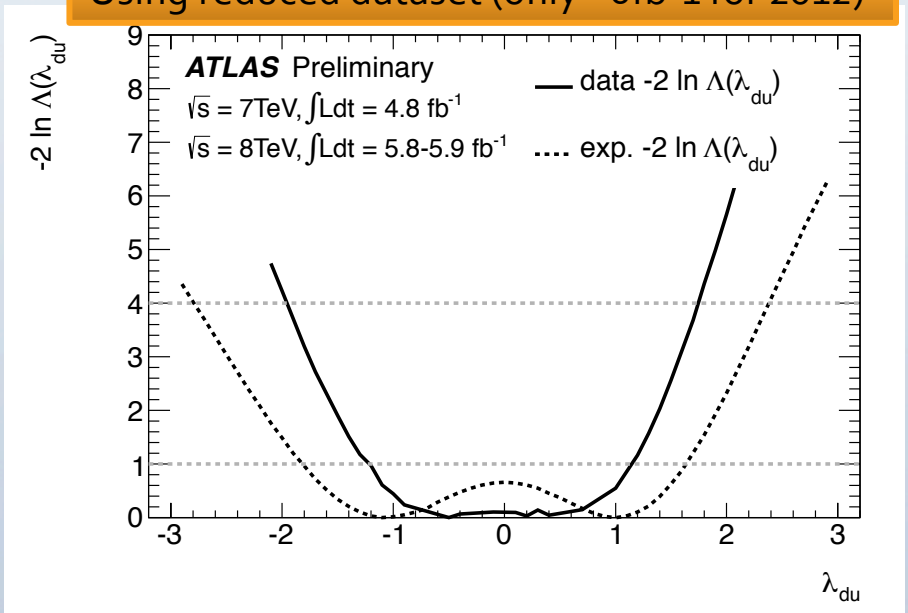
- In BSM models, couplings of neutral Higgs to fermions can be modified
- ATLAS and CMS performed a test of
  - up vs down type fermions couplings ($\lambda_{du} = \kappa_d/\kappa_u$)
  - quarks vs leptons couplings ($\lambda_{lq} = \kappa_l/\kappa_q$)

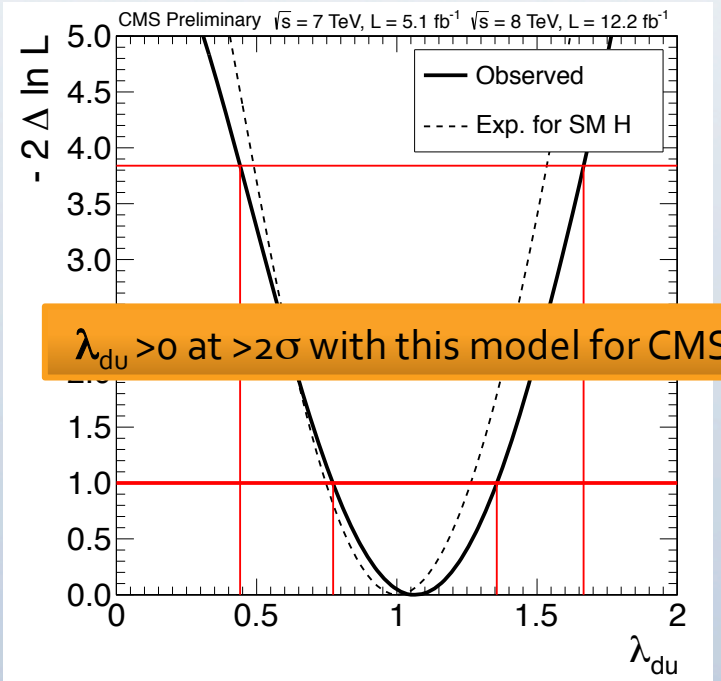
Assume:
➢ no sizeable contribution of BSM particles to total width
➢ λ_{du}, λ_{lq} positive **for CMS**

CMS: $\lambda_{du} \in$ **[0.45,1.66]** at 95% CL
$\lambda_{lq} \in$ [0.00,2.11] at 95% CL
→ Both compatible SM hypothesis within 95% interval.

other parameters are profiled

Using reduced dataset (only ~6fb-1 for 2012)





λ_{du} >0 at >2σ with this model for CMS

Asymmetries in couplings to fermions

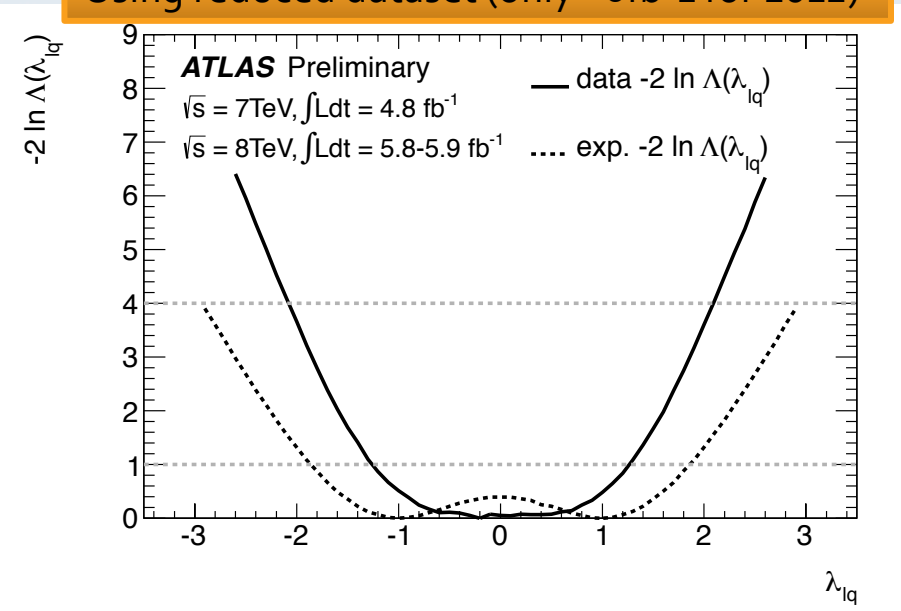
- In BSM models, couplings of neutral Higgs to fermions can be modified
- ATLAS and CMS performed a test of
  - up vs down type fermions couplings ($\lambda_{du} = \kappa_d/\kappa_u$)
  - quarks vs leptons couplings ($\lambda_{lq} = \kappa_l/\kappa_q$)

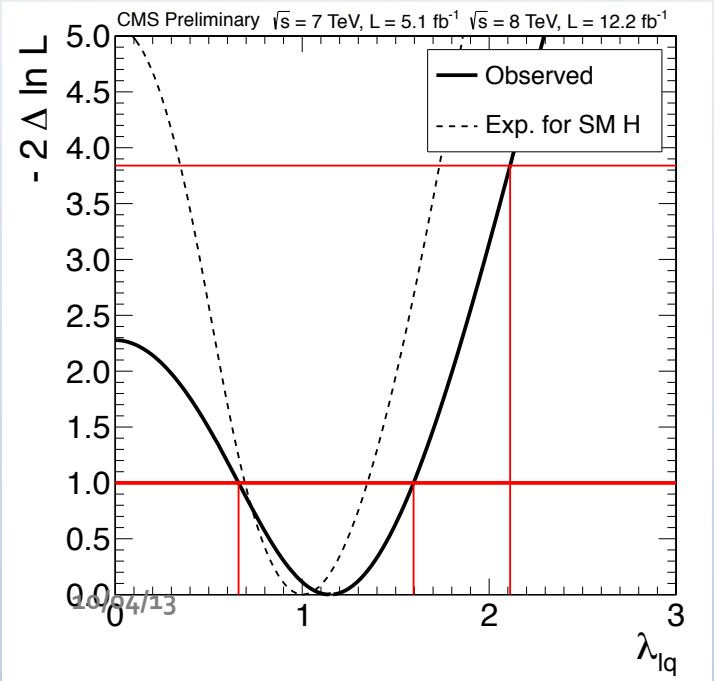
Assume:
➢ no sizeable contribution of BSM particles to total width
➢ λ_{du}, λ_{lq} positive **for CMS**

CMS: $\lambda_{du} \in [0.45, 1.66]$ at 95% CL
$\lambda_{lq} \in$ **[0.00,2.11]** at 95% CL
→ Both compatible SM hypothesis within 95% interval.

other parameters are profiled

Using reduced dataset (only ~6fb-1 for 2012)

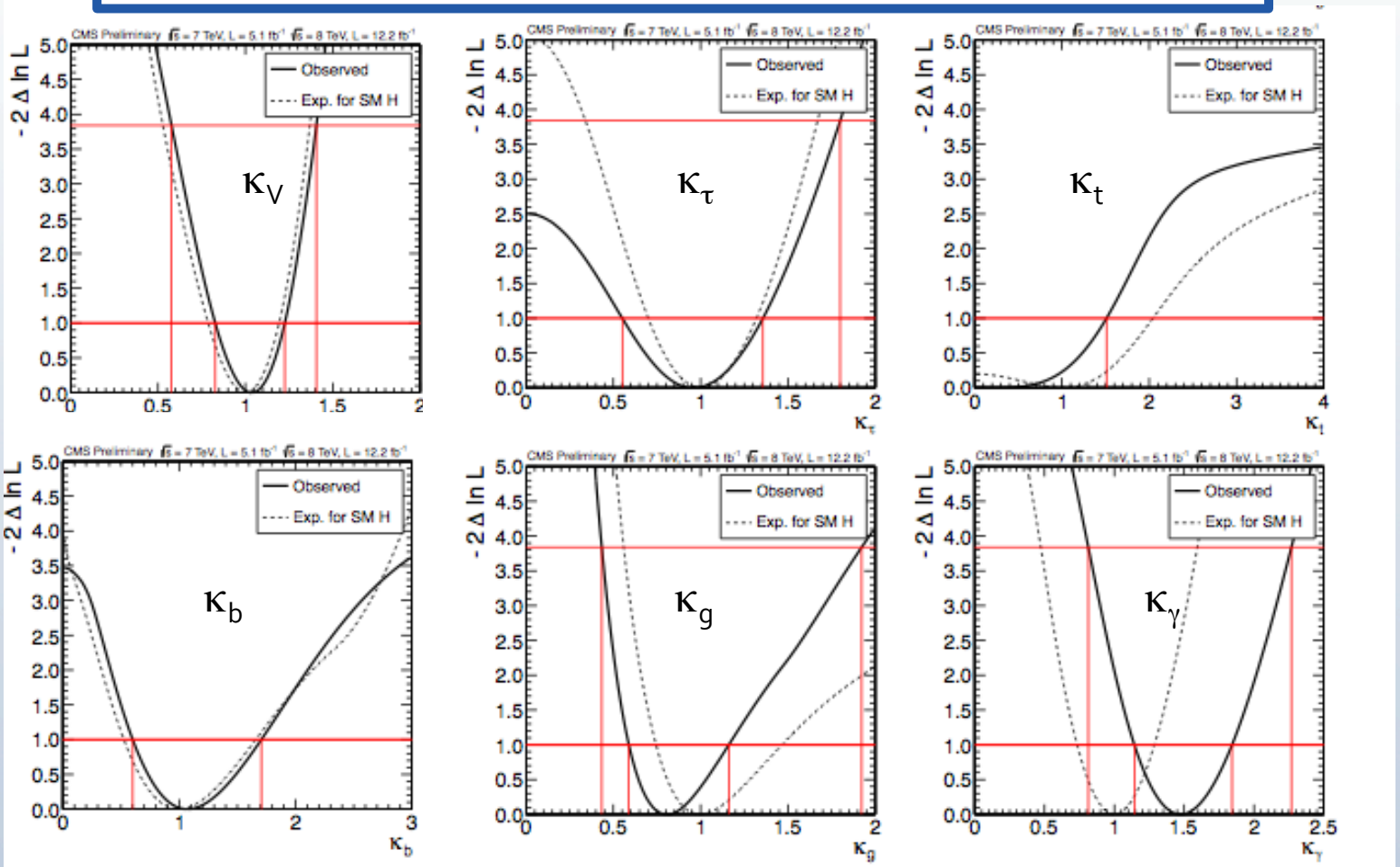




Assessing individual couplings (CMS)

- Model with 6 independent parameters
- Fit each of these parameters while profiling the others
- Goodness of fit between fitted parameters and SM prediction:

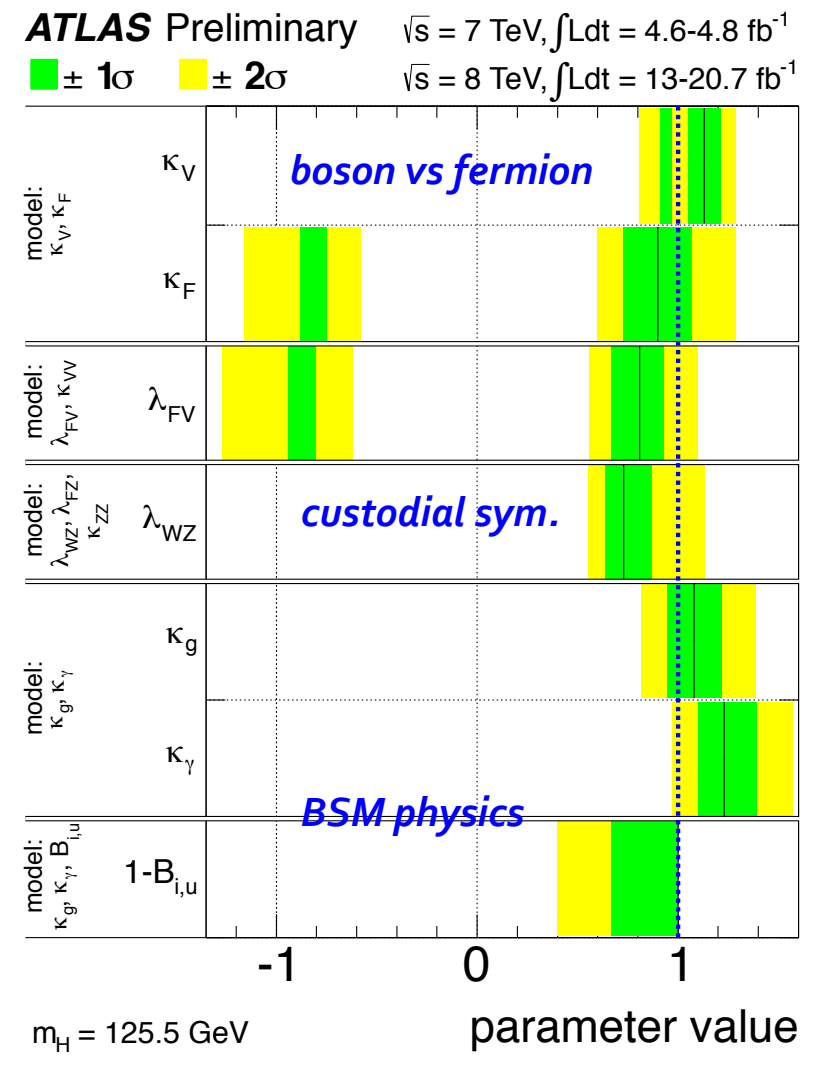
χ^2/ndf=4.7/5 ; p-value=0.58

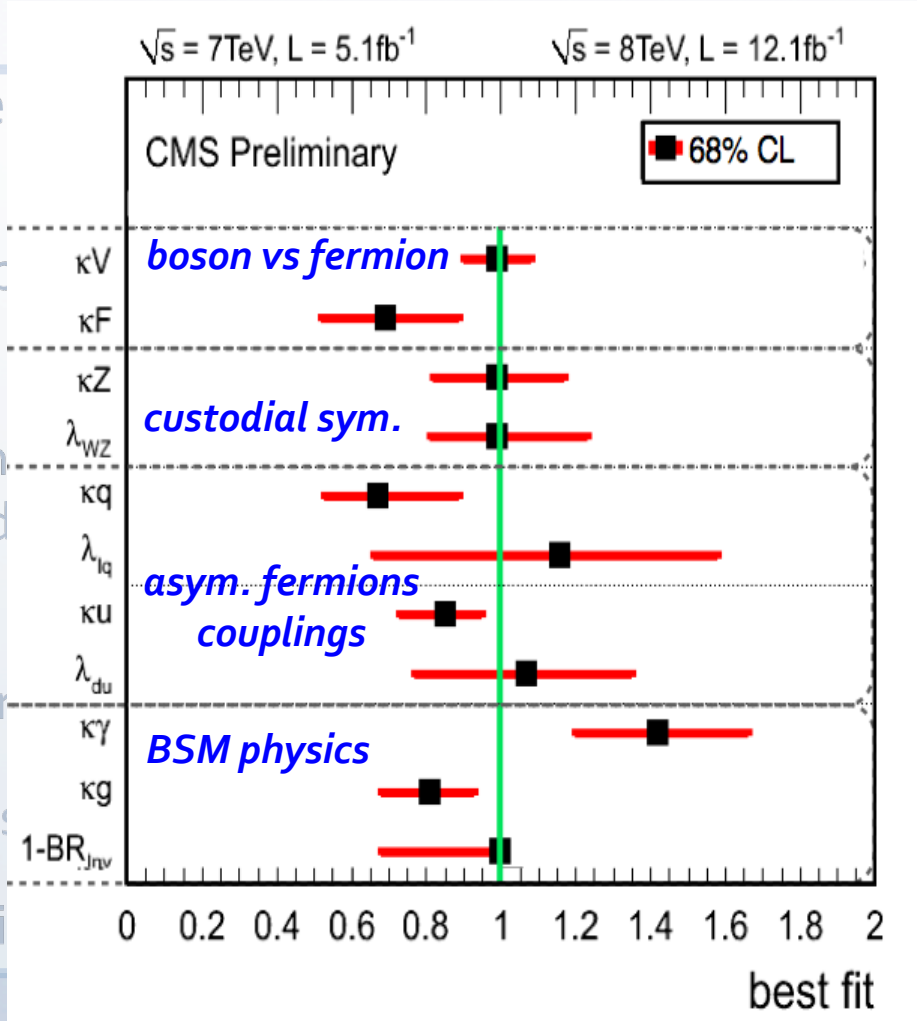


Conclusions

- ATLAS and CMS see both a new state with a compatible mass
- Both experiment are compatible with the SM predictions at better than 95%
  - strength parameter
  - evidence of VBF production mode in ATLAS
  - strong indication of direct (indirect) fermion couplings in CMS (ATLAS)
  - custodial symmetry
  - symmetrical couplings to quarks an leptons and to up/down type fermions (CMS)
  - no sign of new physics in loops or decays
- Would be interesting to combine the two experiments !

Conclusions





Back-up slides

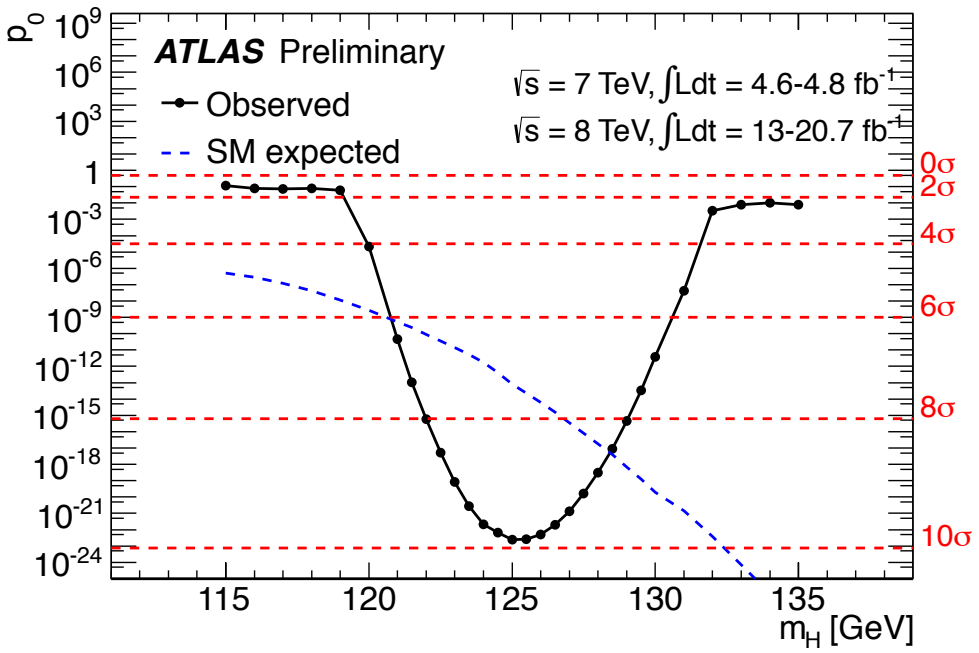
References

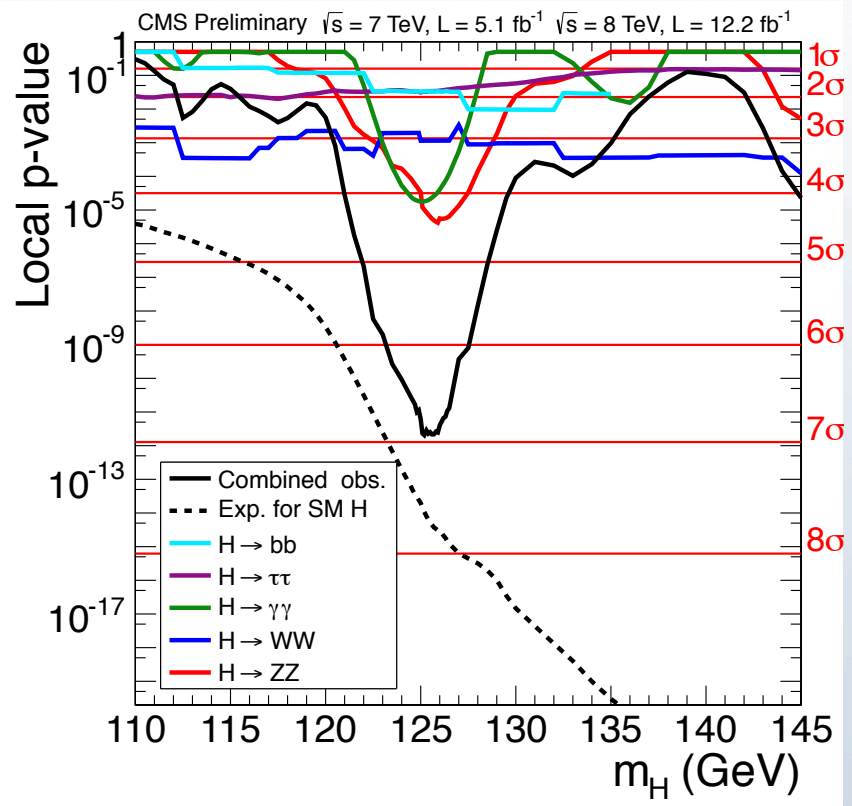
- LHC Higgs XS WG
  http://arxiv.org/abs/1209.0040

- ATLAS:
  WW channel: ATLAS-CONF-2013-030,
  γγ channel: ATLAS-CONF-2013-012,
  ZZ channel: ATLAS-CONF-2013-013,
  bb channel: ATLAS-CONF-2012-161,
  ττ channel: ATLAS-CONF-2012-160,
  Combination couplings: ATLAS-CONF-2013-034,
  Combination mass: ATLAS-CONF-2013-014
  Invisible decays:: ATLAS-CONF-2013-011

- CMS
  WW channel: CMS-PAS-HIG-12-003 , CMS-PAS-HIG-12-046 (lνjj), CMS-PAS-HIG-11-024, CMS-PAS-HIG-12-042 (fully leptonic), CMS-PAS-HIG-12-003 (3l), CMS-PAS-HIG-13-003
  γγ channel: CMS-PAS-HIG-12-015, CMS-PAS-HIG-13-001
  ZZ channel: CMS-PAS-HIG-12-041 , CMS-PAS-HIG-13-002
  bb channel: CMS-PAS-HIG-12-044, CMS-PAS-HIG-12-025
  ττ channel: : CMS-PAS-HIG-12-043, CMS-PAS-HIG-12-051 , CMS-PAS-HIG-13-004
  Combination : CMS-PAS-HIG-12-045 ,

Combined po


ATLAS Preliminary
√s = 7 TeV, ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV, ∫Ldt = 13-20.7 fb-1
Observed
SM expected
p0
mH [GeV]
0σ
2σ
4σ
6σ
8σ
10σ

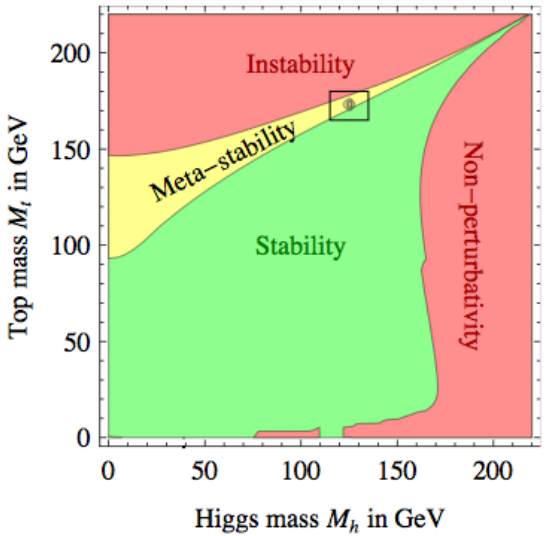

CMS Preliminary √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 12.2 fb-1
Local p-value
Combined obs.
Exp. for SM H
H → bb
H → ττ
H → γγ
H → WW
H → ZZ
mH (GeV)
1σ
2σ
3σ
4σ
5σ
6σ
7σ
8σ

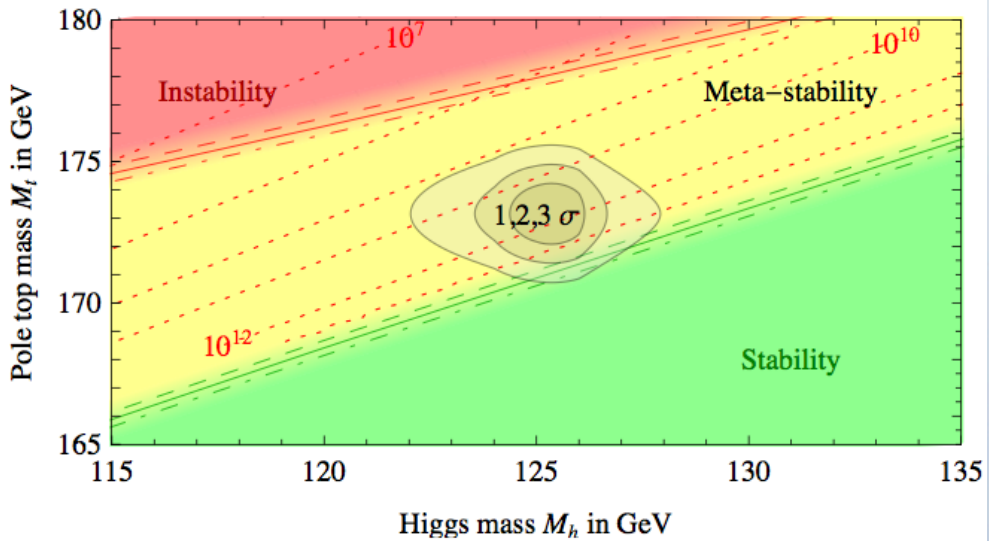
Interest of the mass measurement

- 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



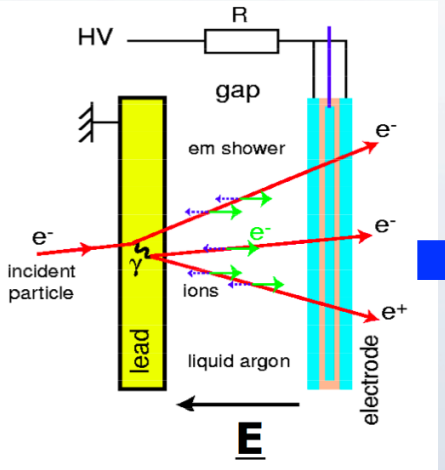


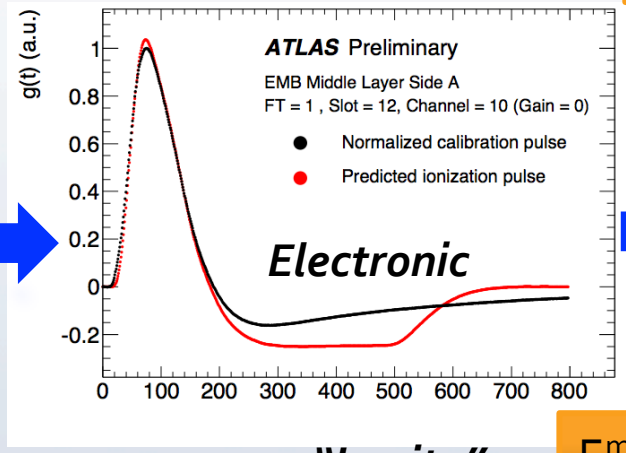
The uncertainty on energy scale (ATLAS)

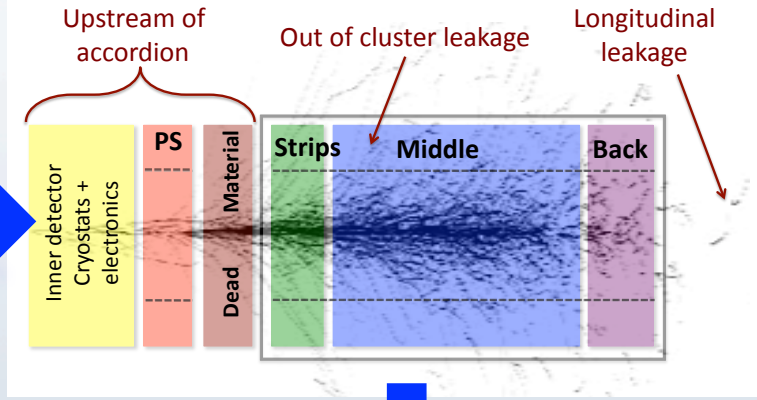
- Main uncertainty on the mass measurement
- Energy of electrons and photons are collected in the electromagnetic calorimeter
- From the electronic signal to the final energy, there are 3 main step of calibration:

Simulation

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

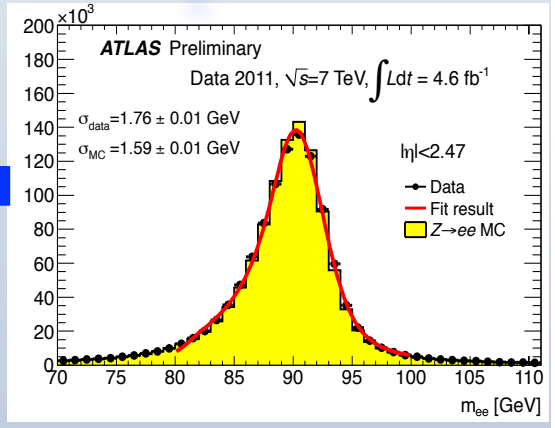


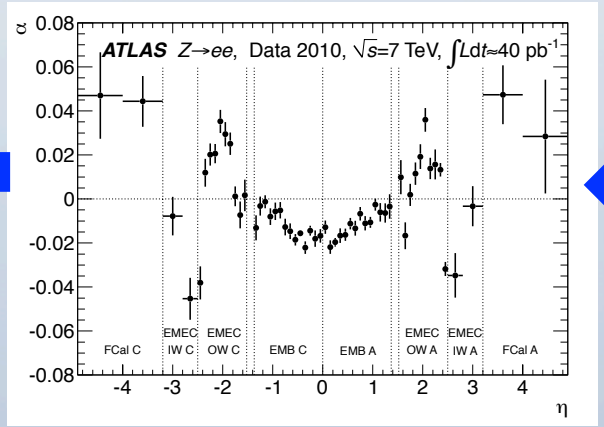




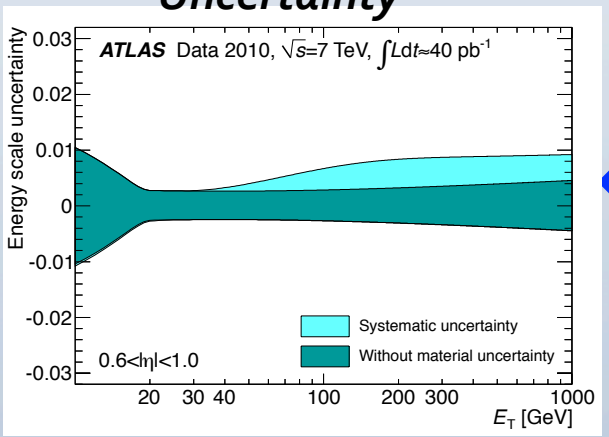
"In-situ"

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

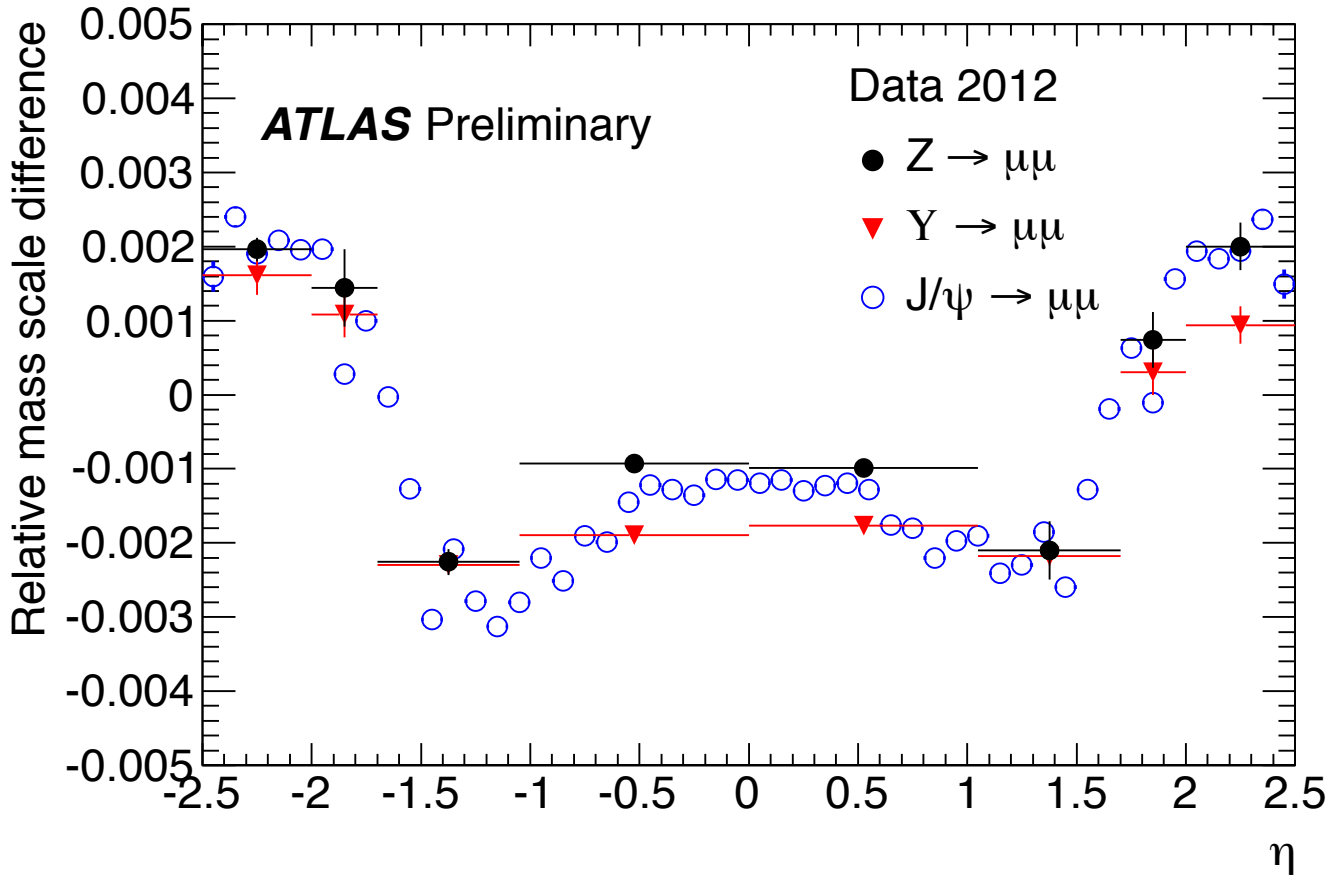




Uncertainty



Muon momentum scale (ATLAS)



$H \rightarrow \gamma\gamma$ 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

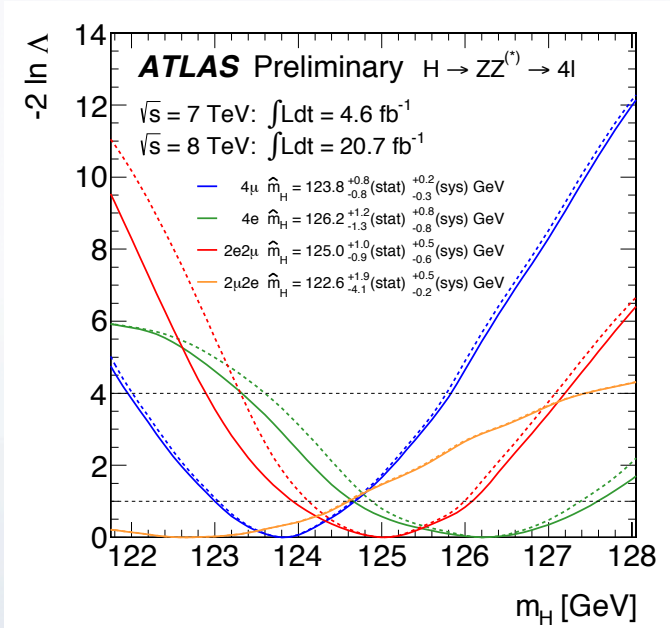
•Further investigation and extensive checks have not lead to additional substantial sources of systematic uncertainty :

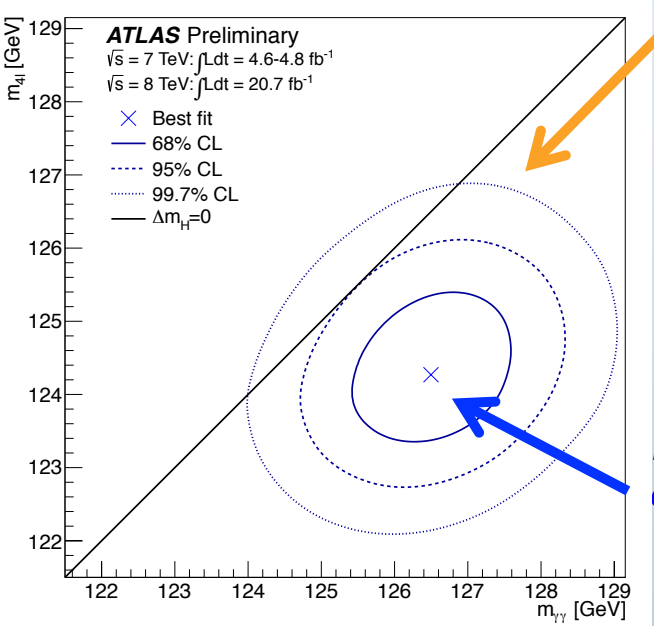
- Measurement with MS and ID alone
- Local detector biases checked event by event
- Local resolution effects checked using event- by-event error;
- kinematic distributions in agreement with expectation
- FSR simulation
- Different mass reconstruction using Z-mass constraint (+400 MeV shift)

Mass Difference

- In ATLAS, sizeable difference between the mass measured in the γγ and ZZ channels
- Quantify the consistency between the two masses in γγ and ZZ channels
- With the updated analysis, the mass difference is

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





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

Gives a compatibility of **1.5% (2.4σ)** and up to 8% using more conservative treatment of the uncertainties.

~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

• 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

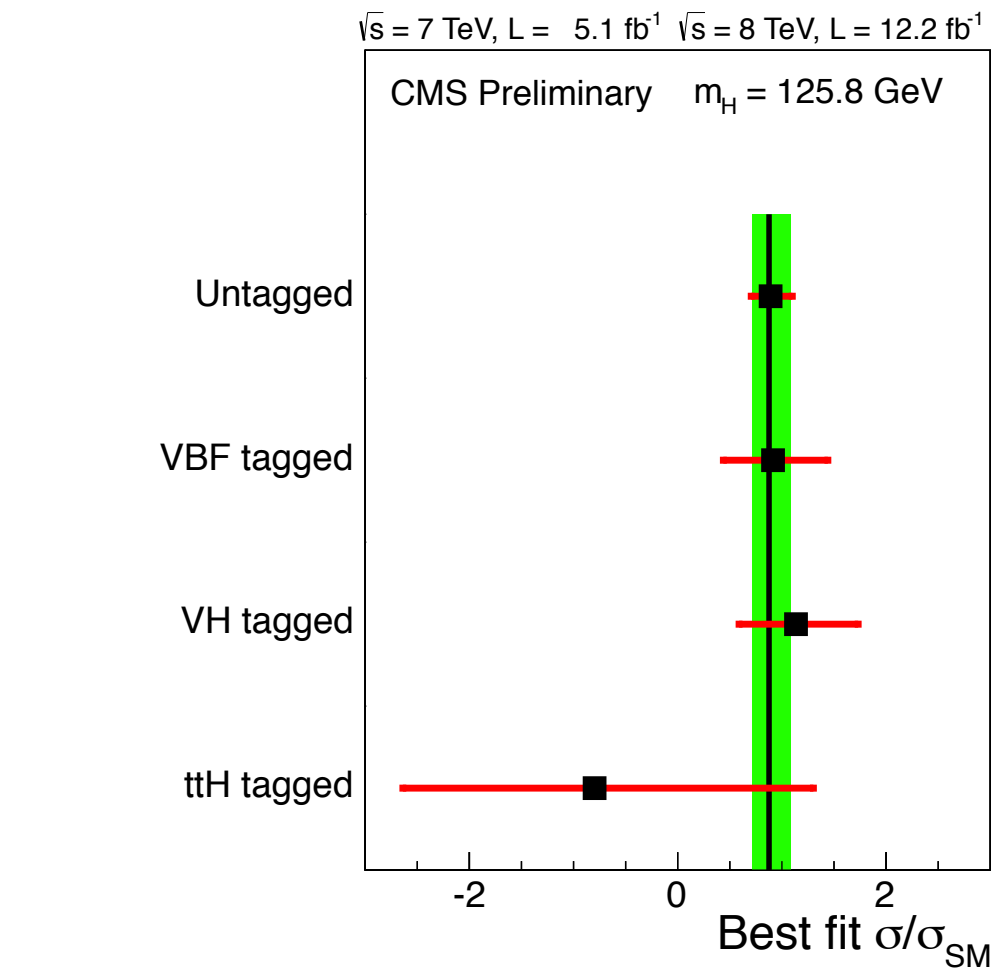
$$\mu_i = \sigma_i / \sigma_{i,\text{SM}}$$

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

$$\mu = \mu_i . \mu_f$$

global signal strength

Production modes: fermion vs boson mediated (CMS)



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

$$\kappa_i^2 \sim \frac{\Gamma_i}{\Gamma_{i(SM)}} \qquad \kappa_H^2 \sim \frac{\Gamma_{tot}}{\Gamma_{tot(SM)}}$$

production *decay*

$$\Rightarrow \quad n_{signal} \sim \frac{\kappa_{XX}^2 \cdot \kappa_{YY}^2}{\kappa_H^2}$$

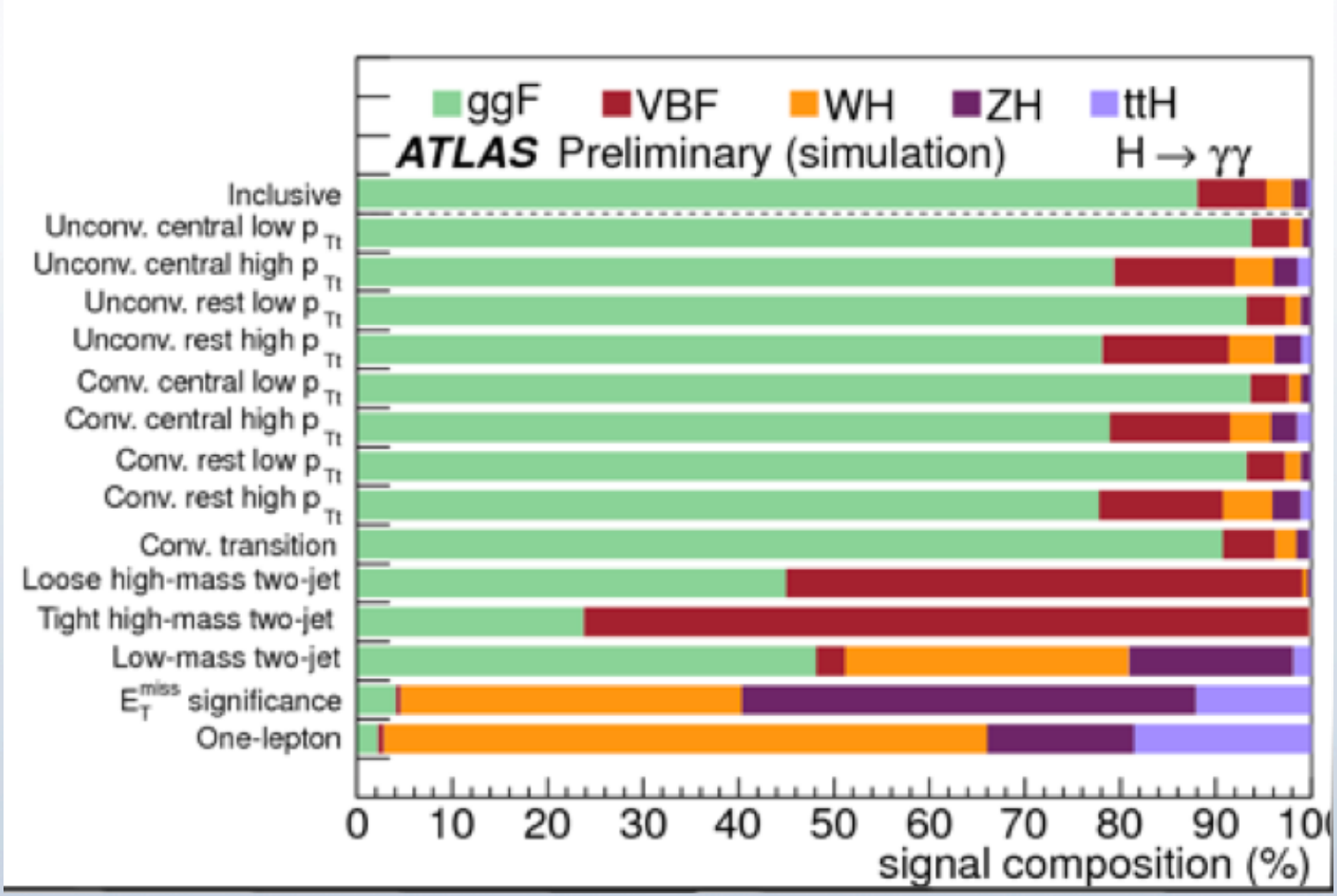
- The relevant parameters for the current searches are:

κ_f, κ_V, κ_W, κ_Z, κ_g, κ_γ, Γ_{BSM}, κ_d, κ_u, κ_l, κ_q

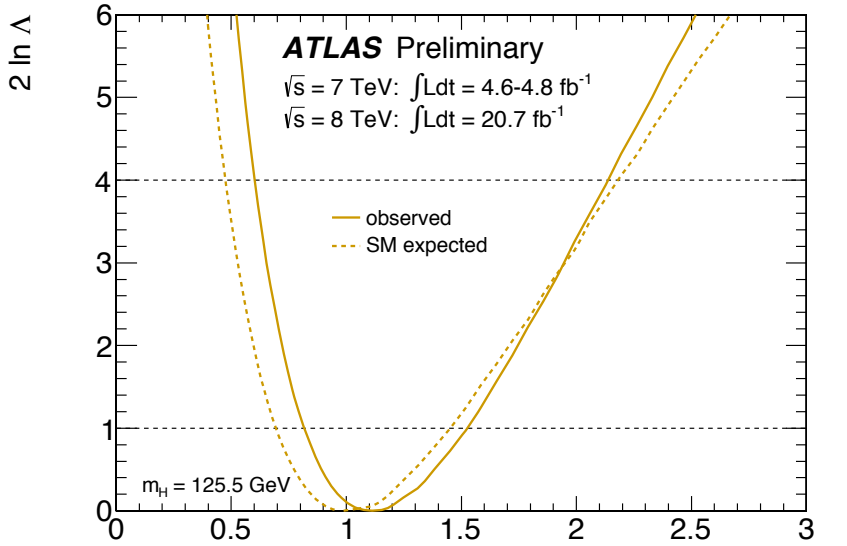
ATLAS and CMS General Framework for couplings, assume:

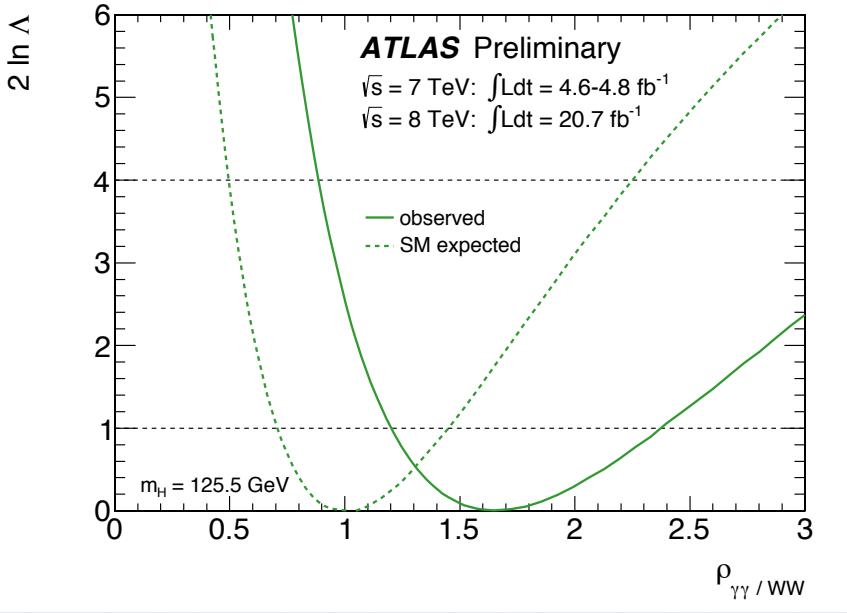
- single narrow resonance
- Zero-width approximation
- tensors structure of the couplings same as in the SM

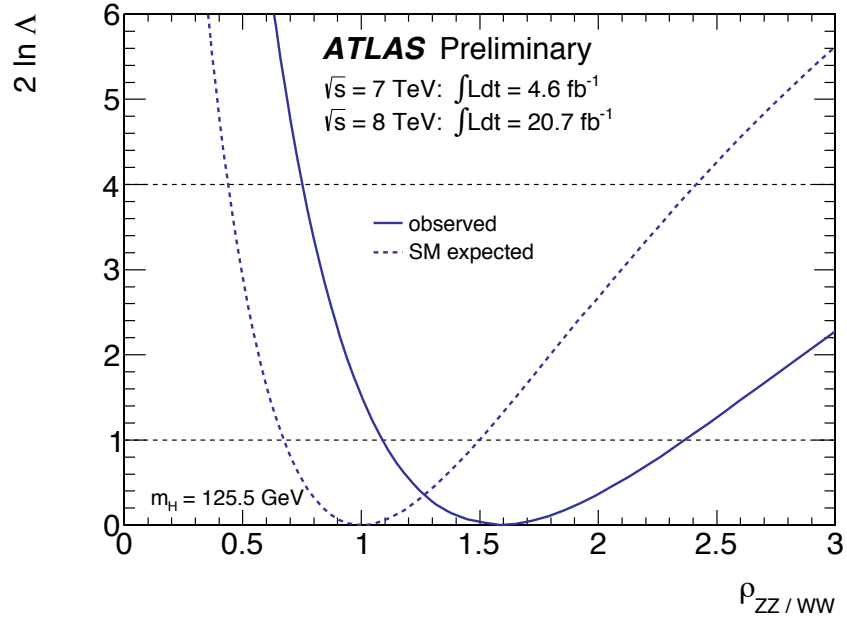
Signal composition (H→γγ)



Testing the Branching ratio

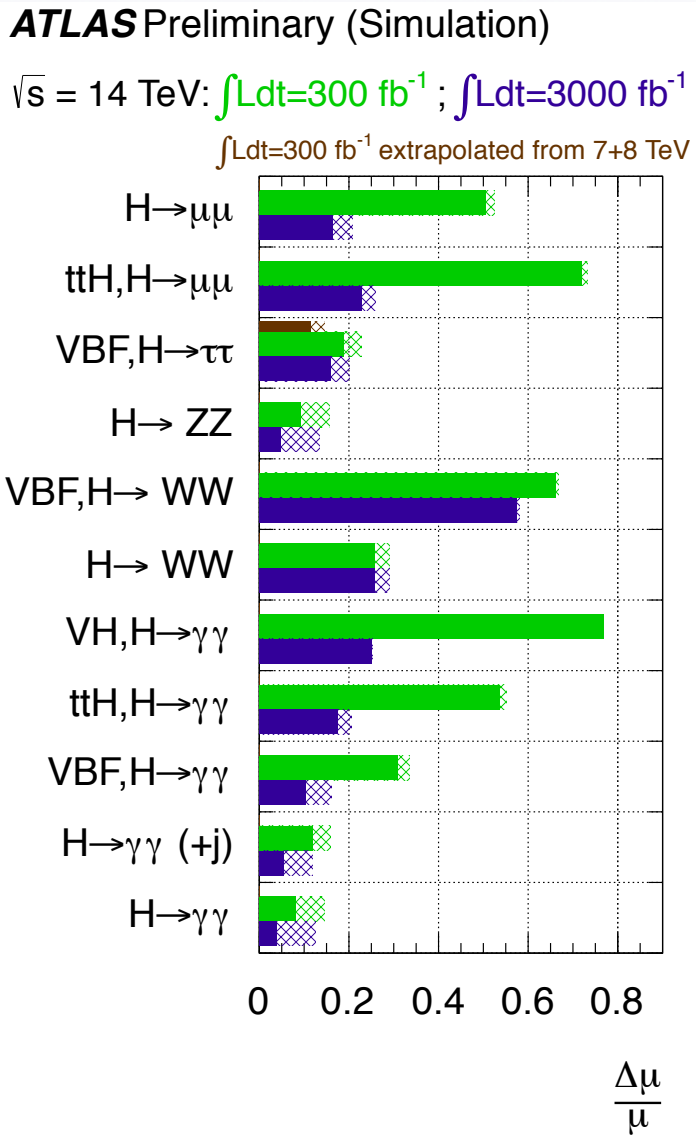


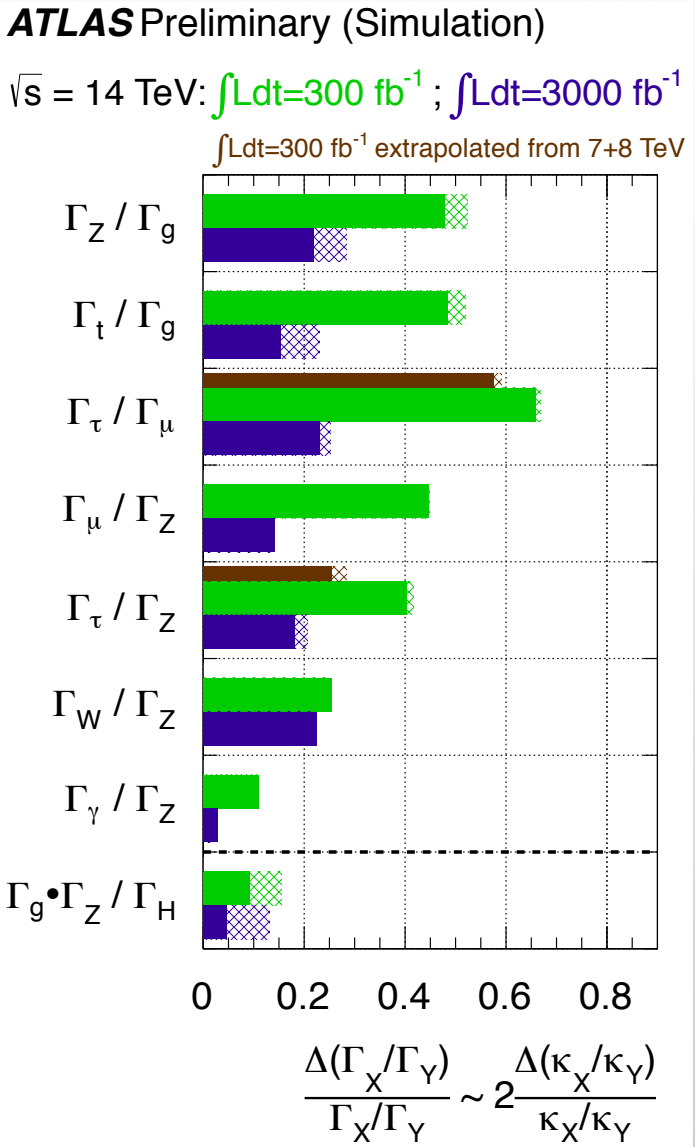




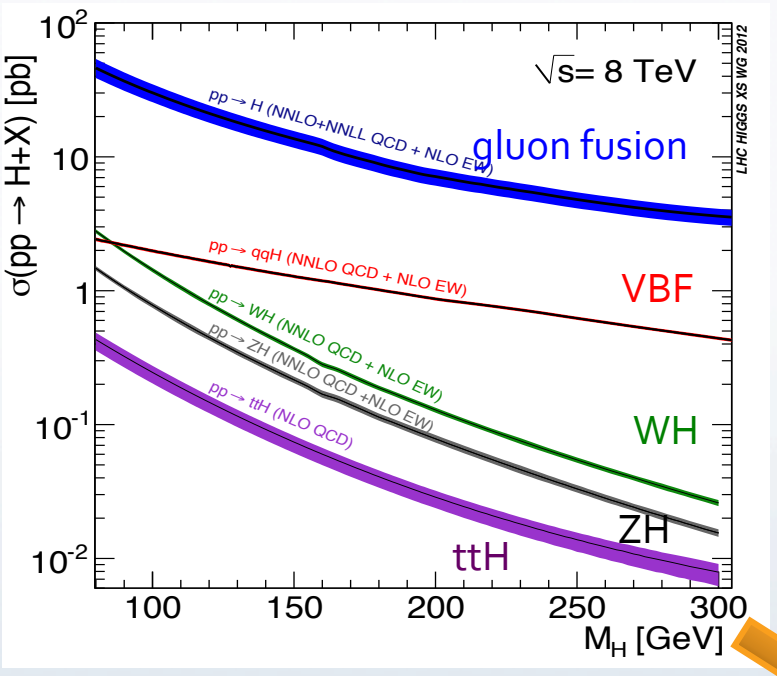
$$\rho_{XX/YY} = \frac{BR(H \to XX)}{BR(H \to YY)} \times \frac{BR_{SM}(H \to XX)}{BR_{SM}(H \to YY)}$$

Prospects...



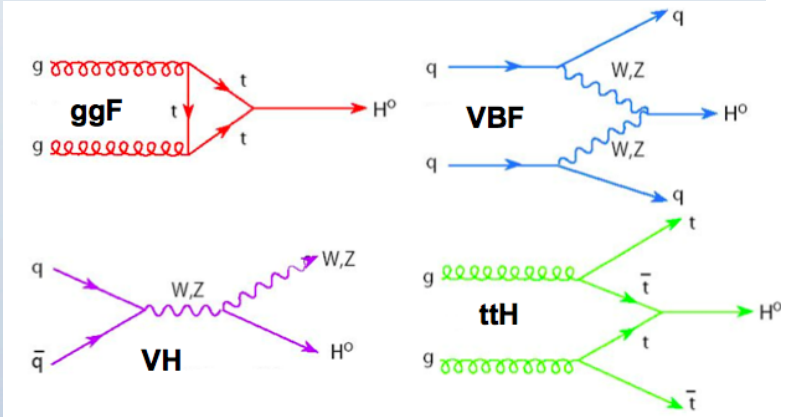


Dashed areas include current theory uncertainties from QCD scale and PDF variations for luminosities of 300 fb-1 and 3000 fb-1



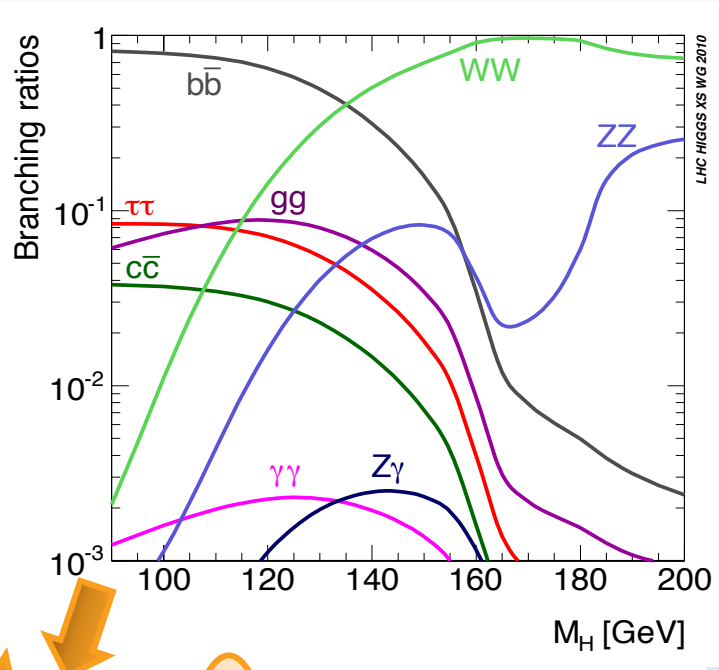
19.5 pb

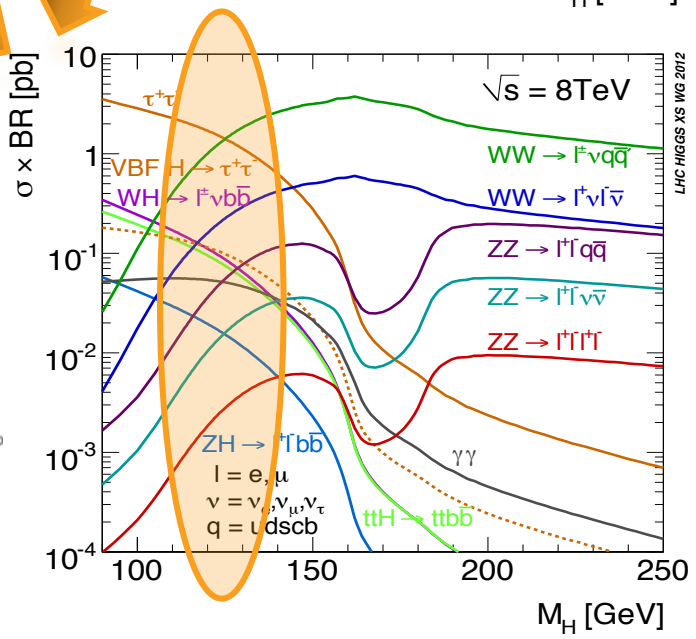
1.6 pb



1.1 pb

0.1 pb





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

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

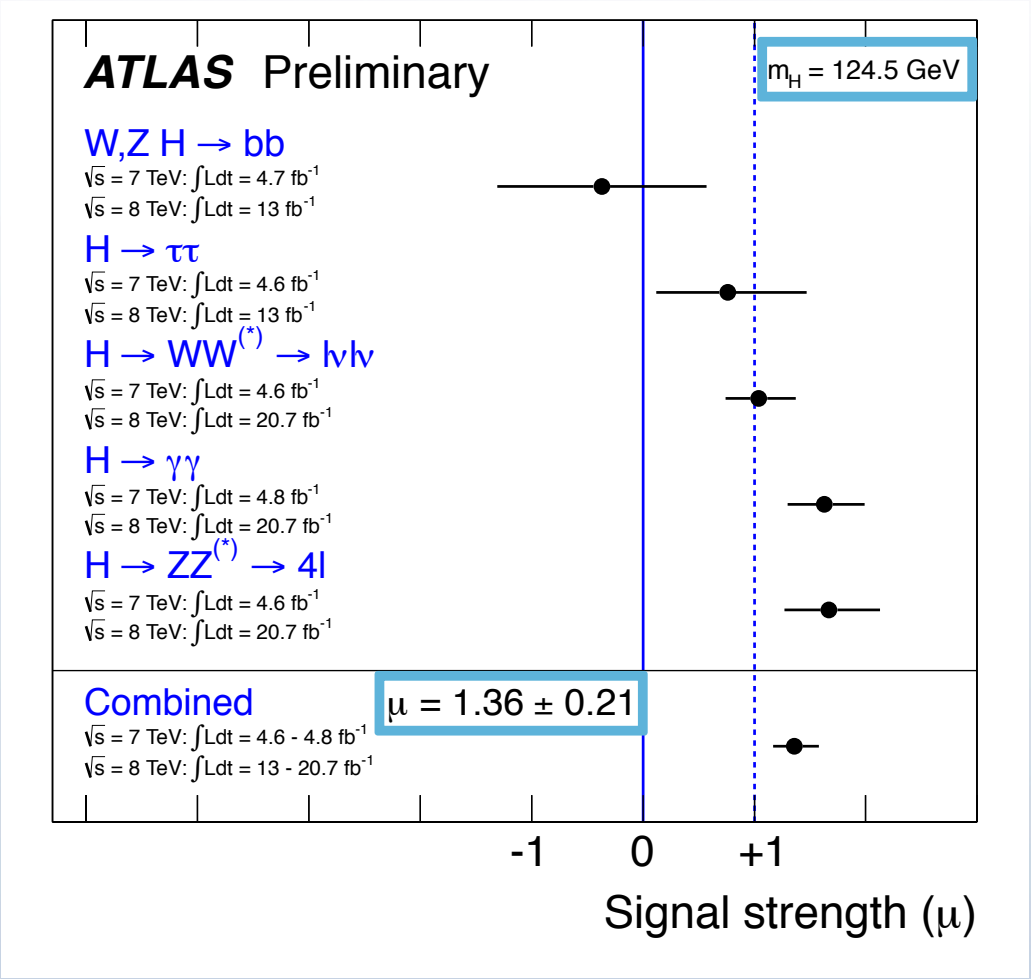
$$\mu = \mu_i . \mu_f$$

global signal strength

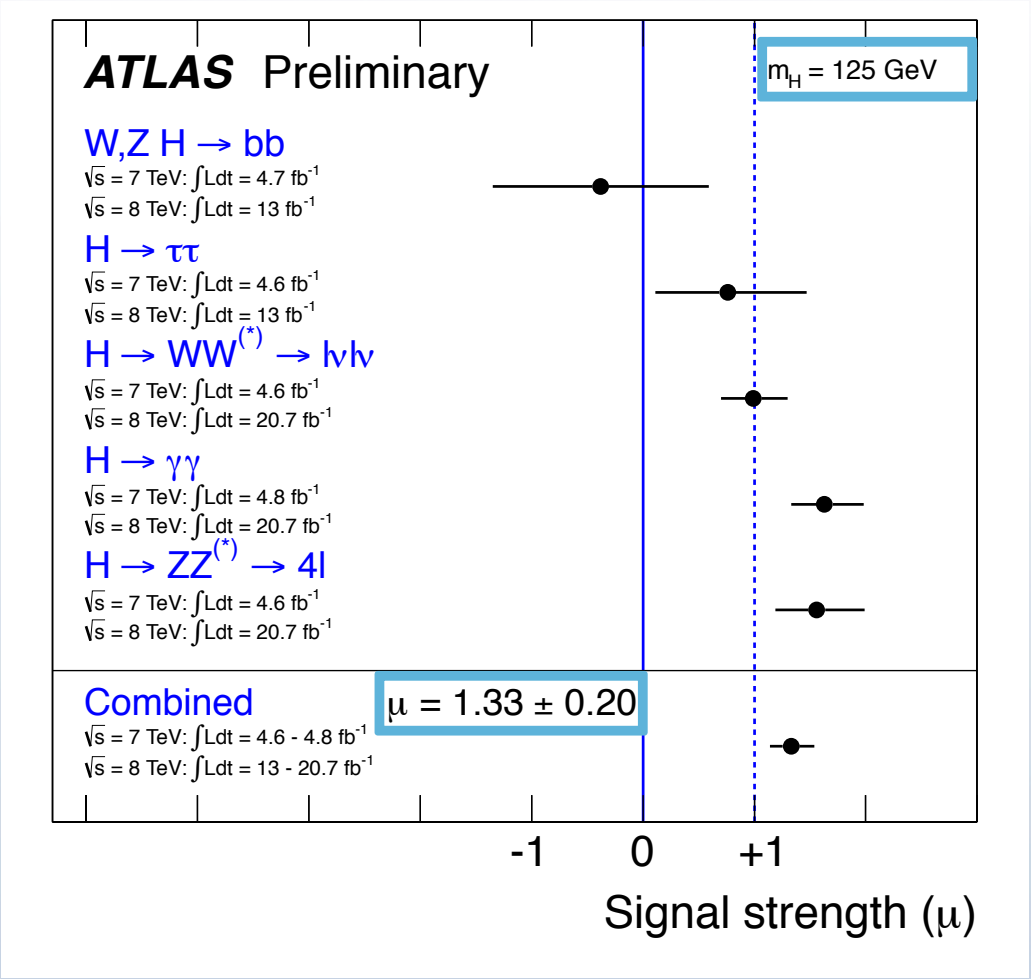
$$\Lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}}(\mu))}{L(\hat{\mu}, \hat{\theta})}$$

nuisance parameters for the systematic uncertainties

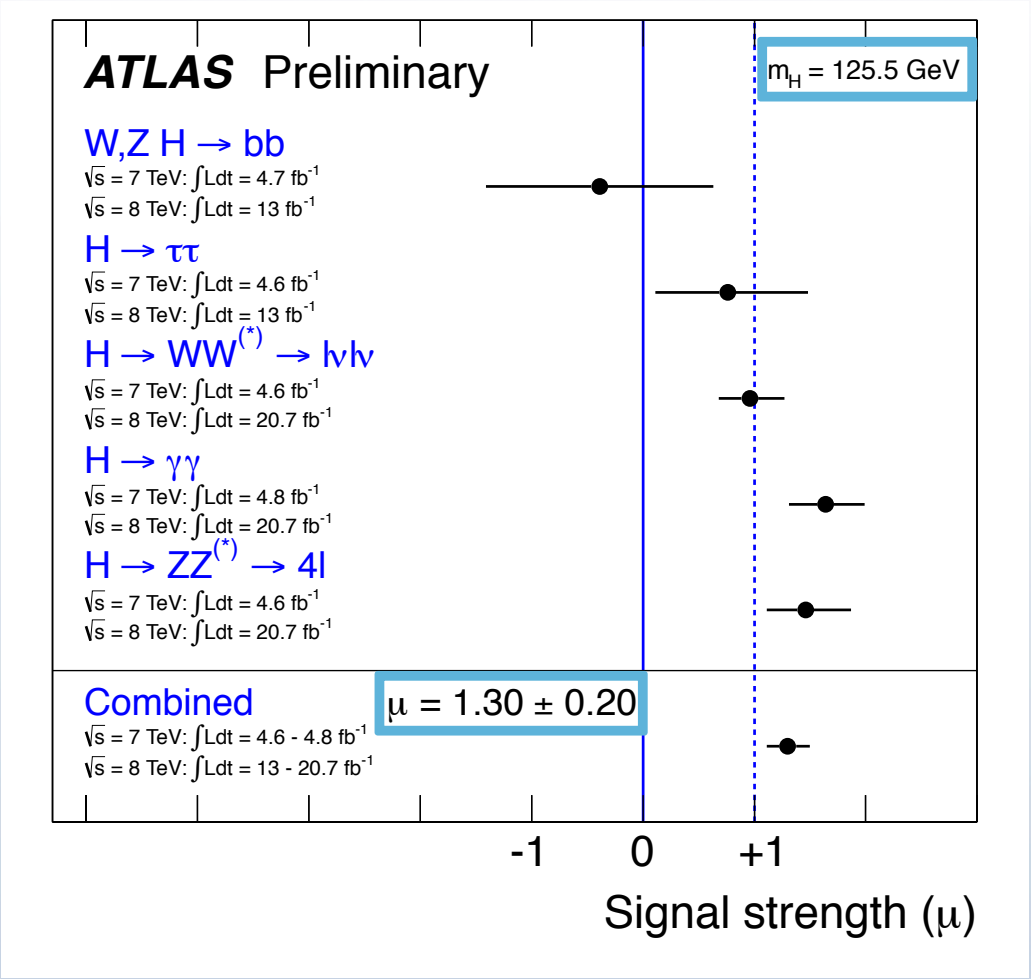
Strength parameter



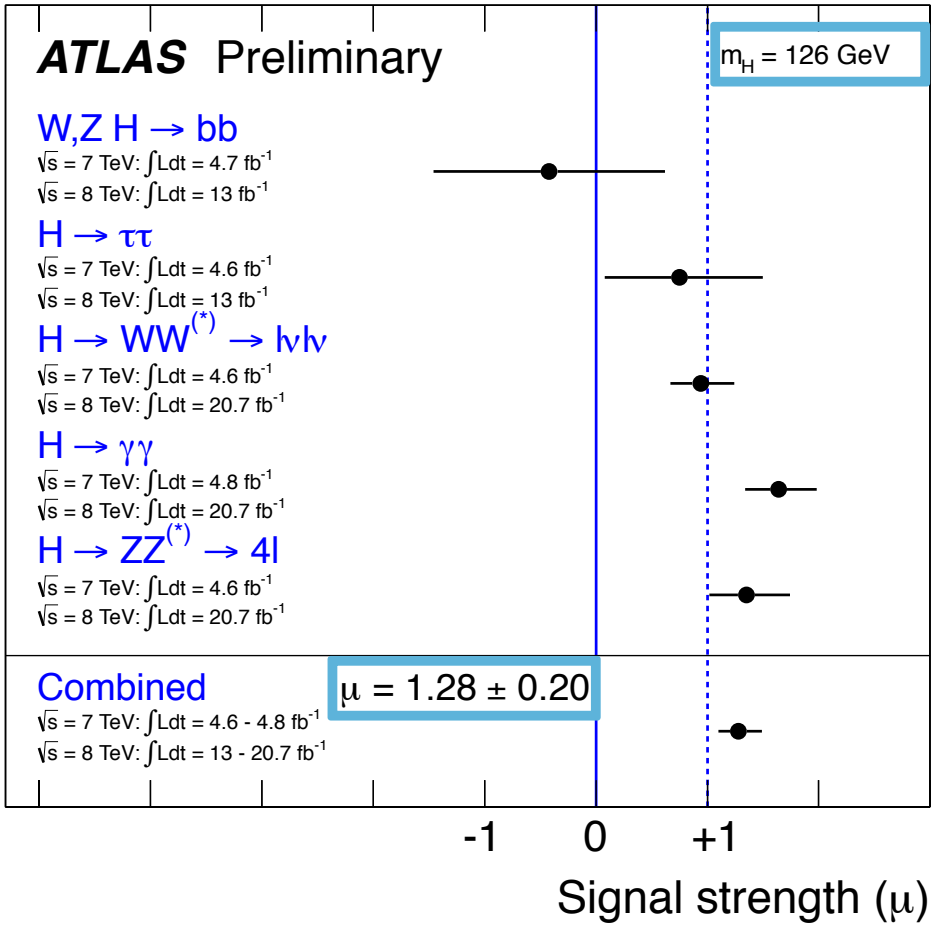
Strength parameter



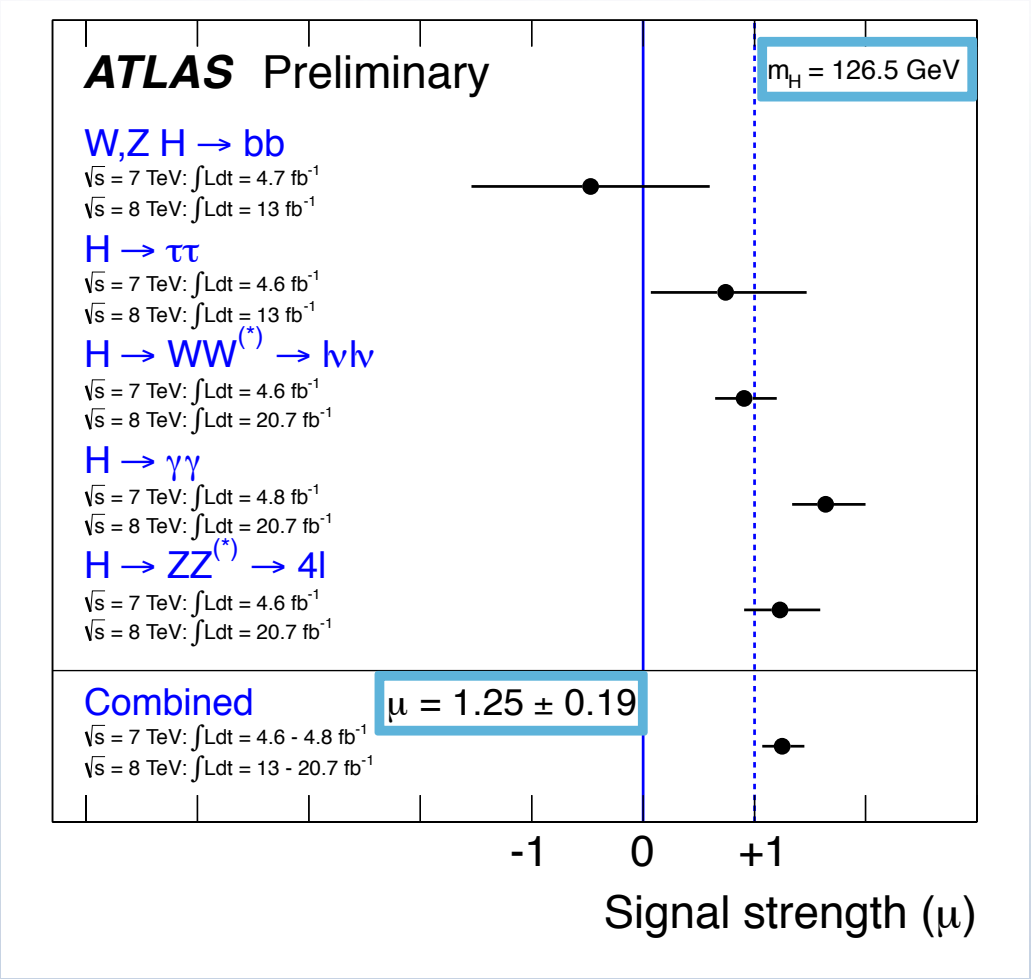
Strength parameter



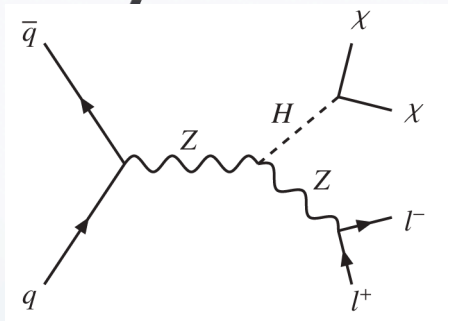
Strength parameter



Strength parameter

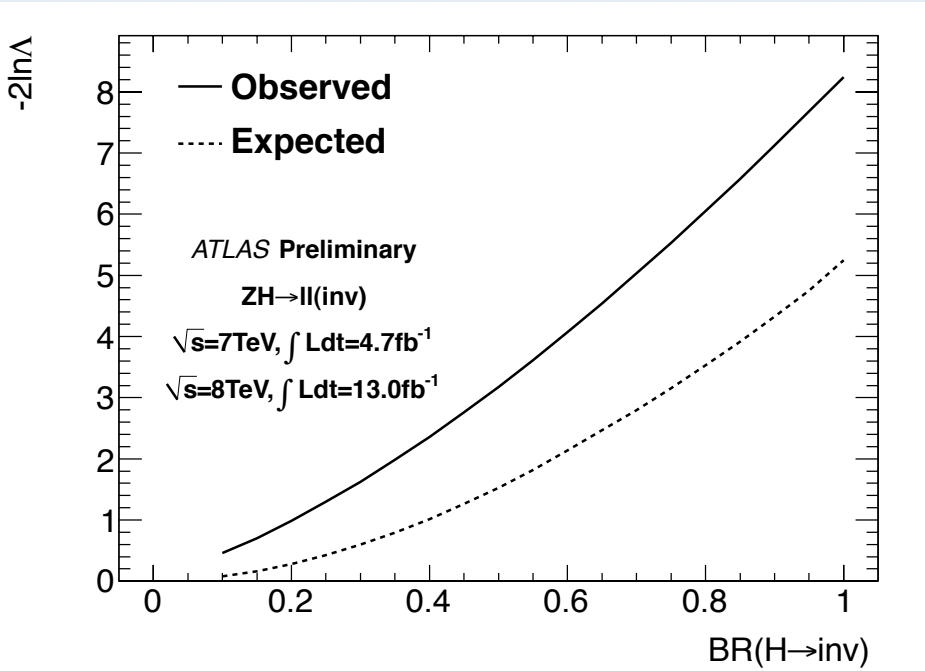


Direct search for invisible Higgs decays

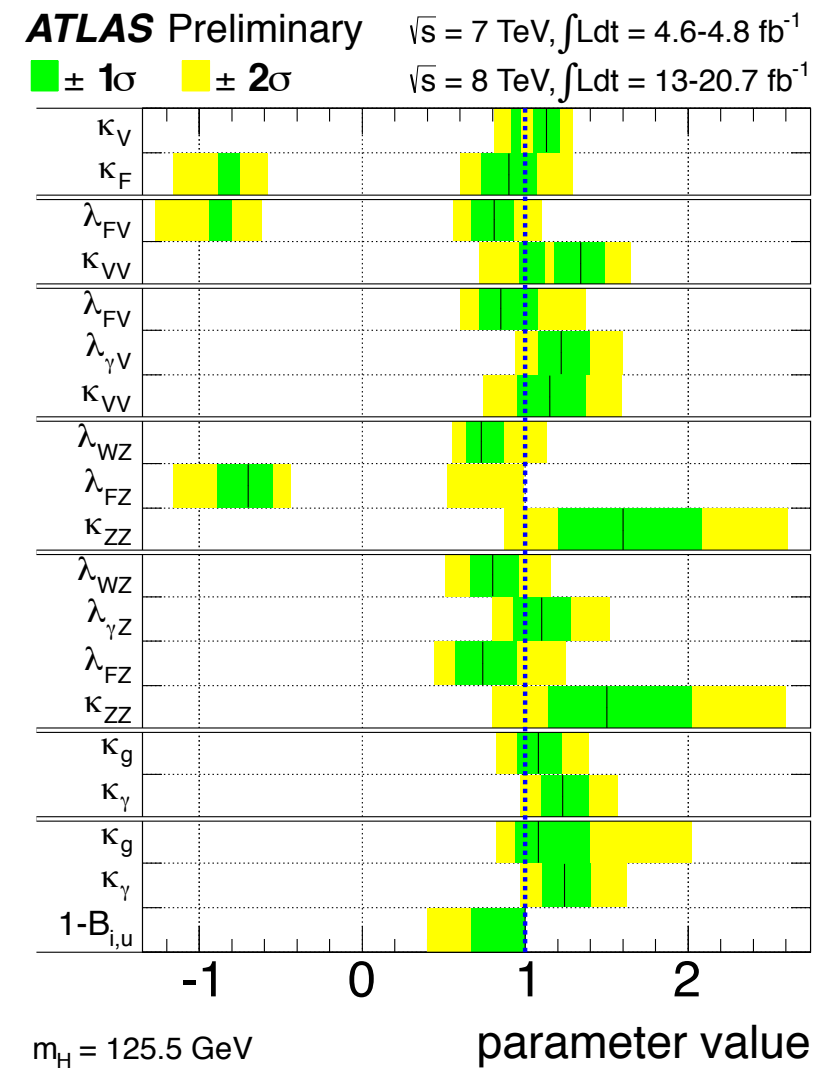


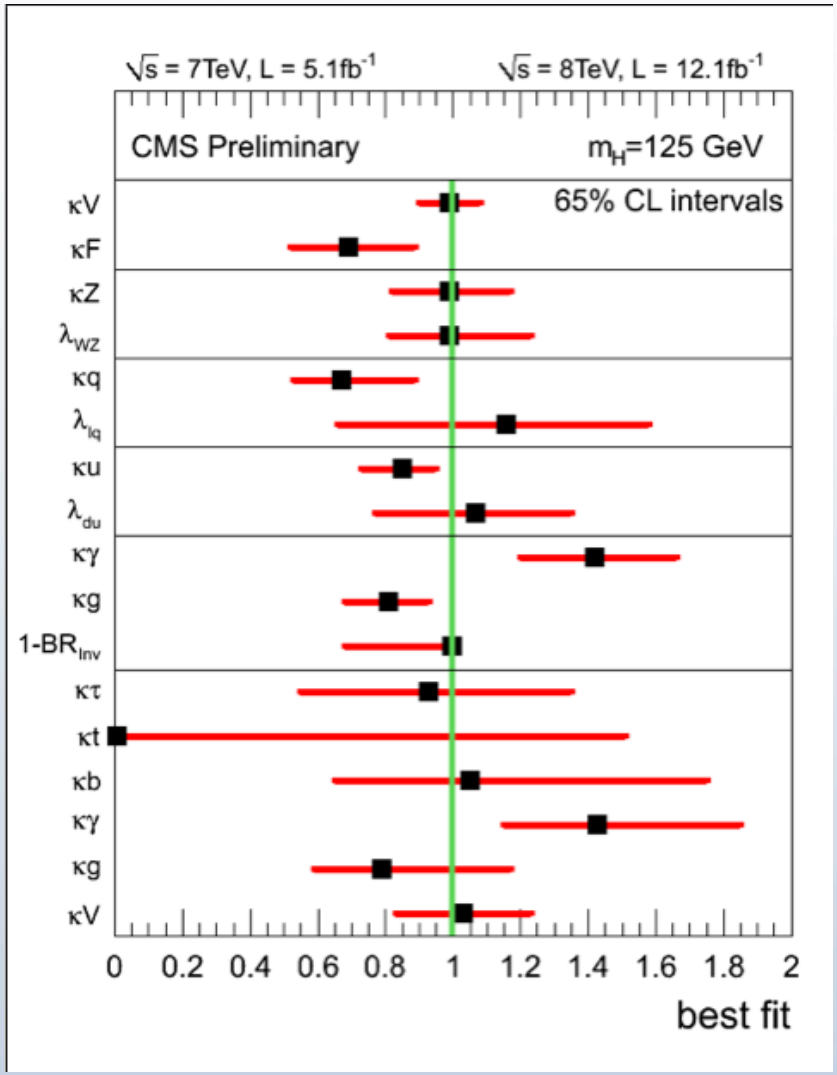
- ATLAS analysis: searches for an excess of events over the SM contribution in the dilepton + large missing transverse energy final states
- Use 4.7fb-1 (2011)+ 13fb-1(2012)
- VH production mode

→Invisible branching fraction greater than 65% is excluded with a 95% confidence level



Summary


ATLAS Preliminary
√s = 7 TeV, ∫Ldt = 4.6-4.8 fb-1
± 1σ ± 2σ
√s = 8 TeV, ∫Ldt = 13-20.7 fb-1
κV
κF
λFV
κVV
λFV
λγV
κVV
λWZ
λFZ
κZZ
λWZ
λγZ
λFZ
κZZ
κg
κγ
κg
κγ
1-Bi,u
-1
0
1
2
mH = 125.5 GeV
parameter value


√s = 7TeV, L = 5.1fb-1
√s = 8TeV, L = 12.1fb-1
CMS Preliminary
mH=125 GeV
65% CL intervals
κV
κF
κZ
λWZ
κq
λlq
κu
λdu
κγ
κg
1-BRInv
κτ
κt
κb
κγ
κg
κV
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
best fit