

# Standard Model Higgs results at the LHC

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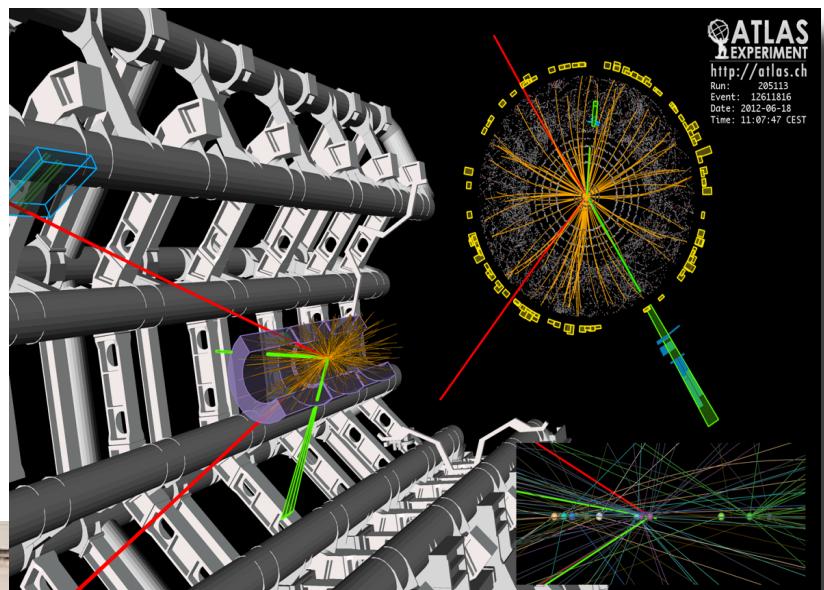
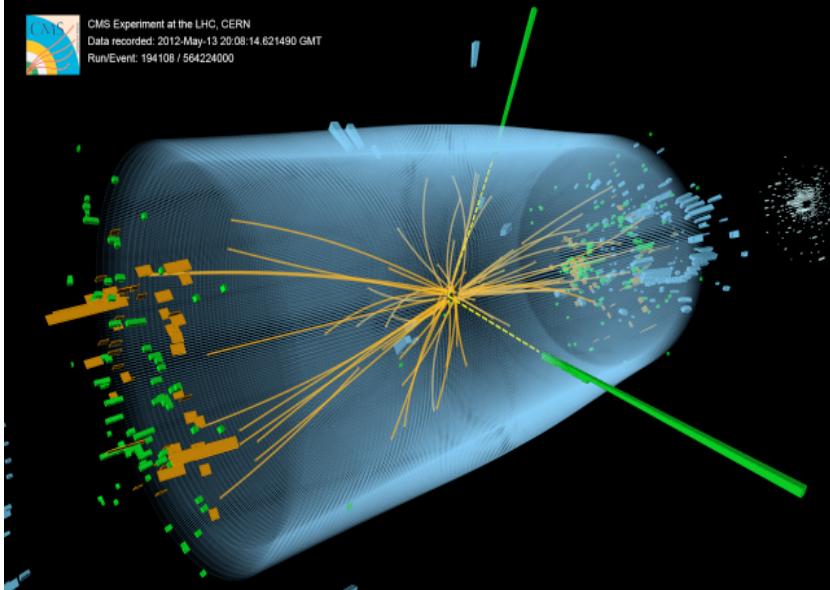
University of Florida

on behalf of **ATLAS and CMS Collaborations**

**Joint TeVPA/IDM Astroparticle Physics Conference  
Amsterdam, June 26, 2014**

July 4, 2012. A new boson discovery announced.

Is it the Higgs particle as predicted in the Standard Model?



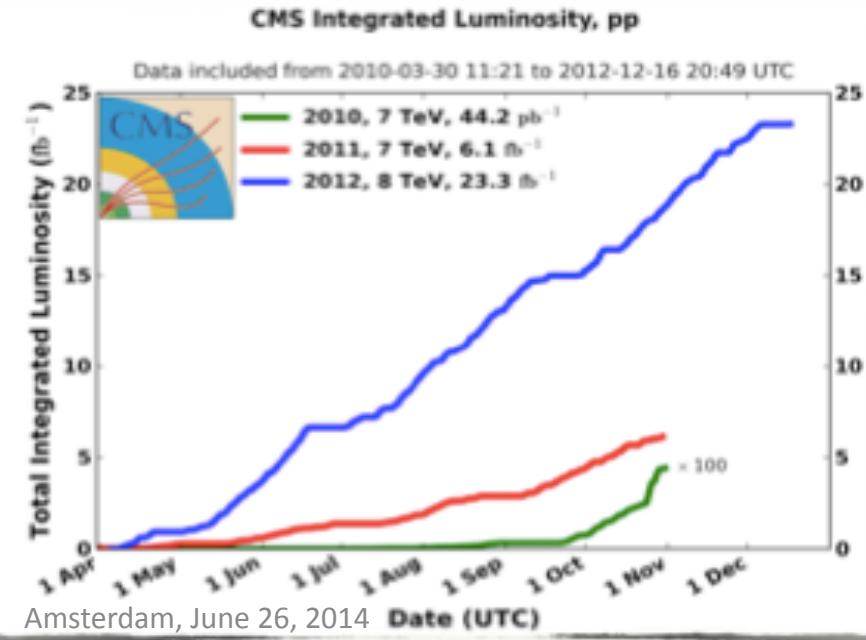
# LHC performance in 2010-2012



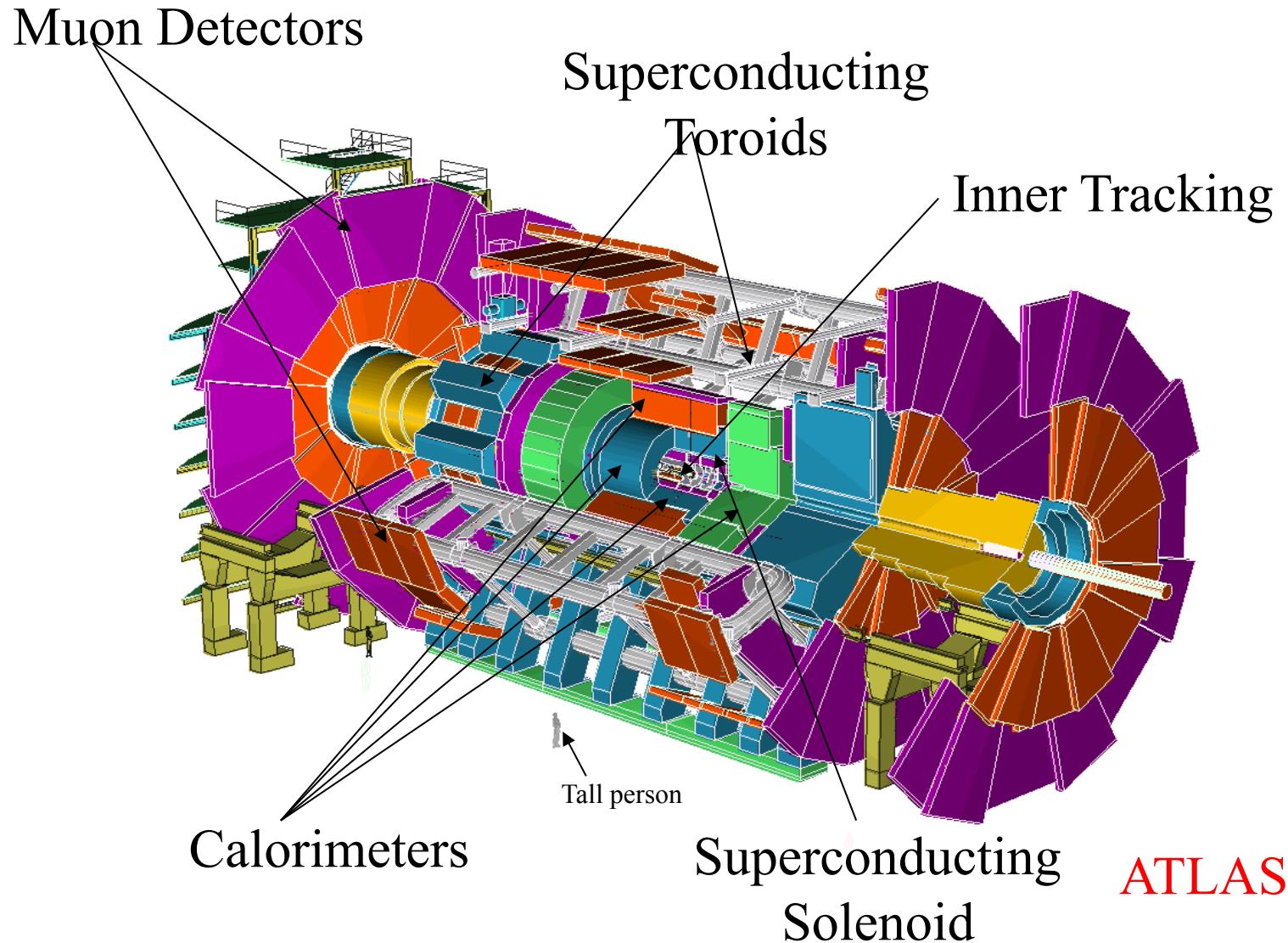
pp collisions in CMS

2011:  $\sim 6 \text{ fb}^{-1}$  @ 7 TeV

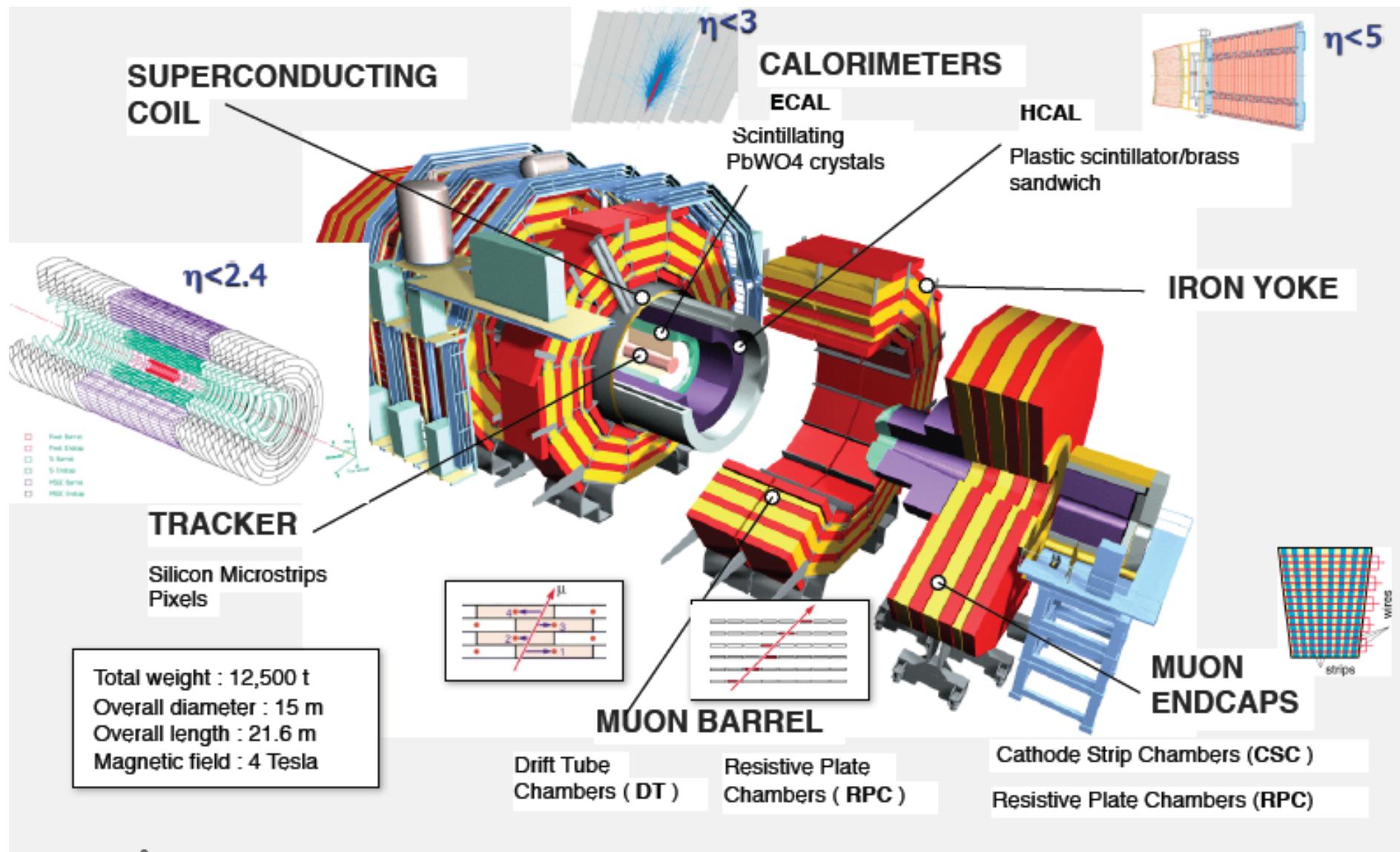
2012:  $\sim 23 \text{ fb}^{-1}$  @ 8 TeV



# ATLAS: A Toroidal LHC ApparatuS

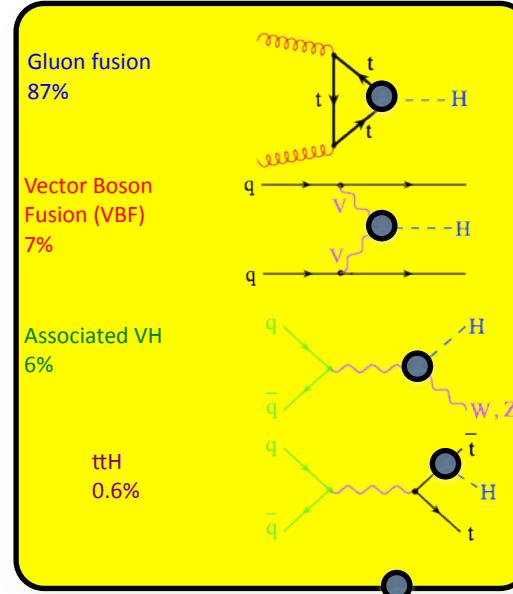
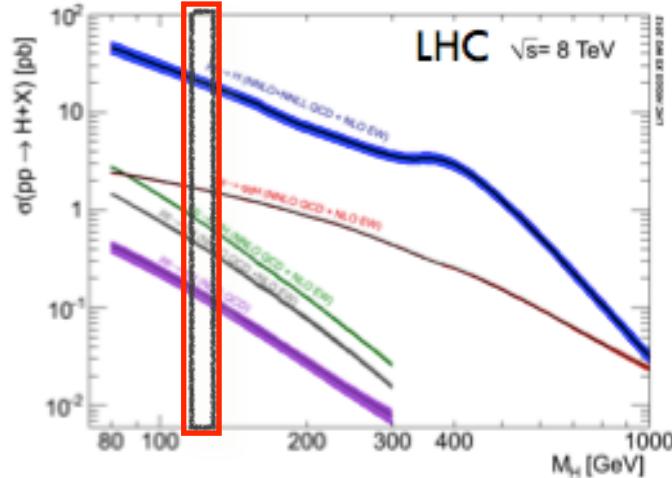


# CMS: The Compact Muon Solenoid

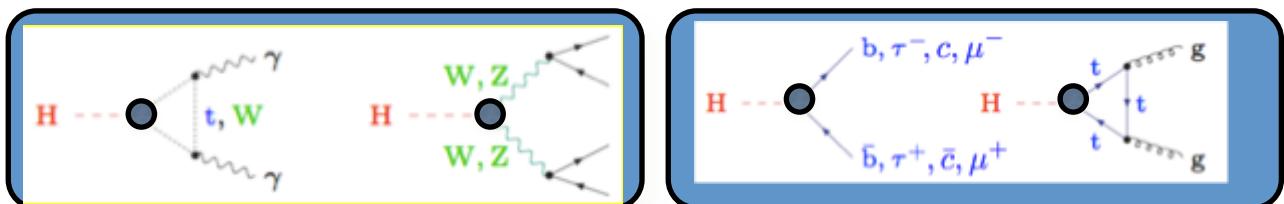
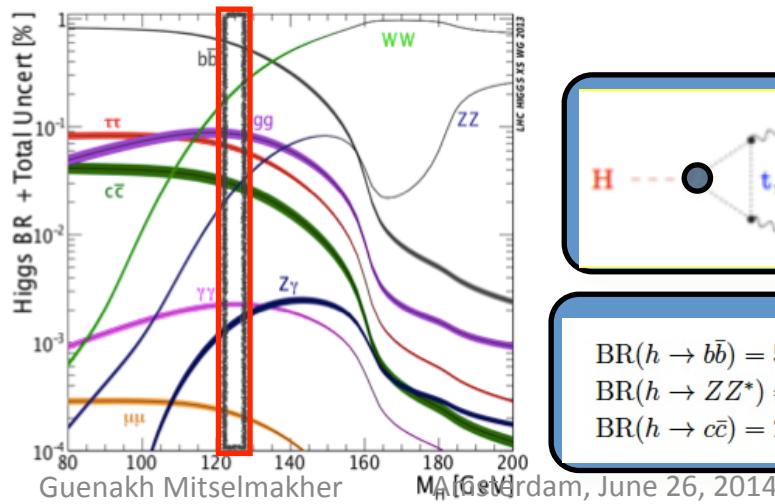


# Predicted Higgs production and decay

## Production



## Decays



$BR(h \rightarrow b\bar{b}) = 58\%$ ,	$BR(h \rightarrow WW^*) = 21.6\%$ ,	$BR(h \rightarrow \tau^+\tau^-) = 6.4\%$ ,
$BR(h \rightarrow ZZ^*) = 2.7\%$ ,	$BR(h \rightarrow gg) = 8.5\%$ ,	$BR(h \rightarrow \gamma\gamma) = 0.22\%$ ,
$BR(h \rightarrow c\bar{c}) = 2.7\%$		

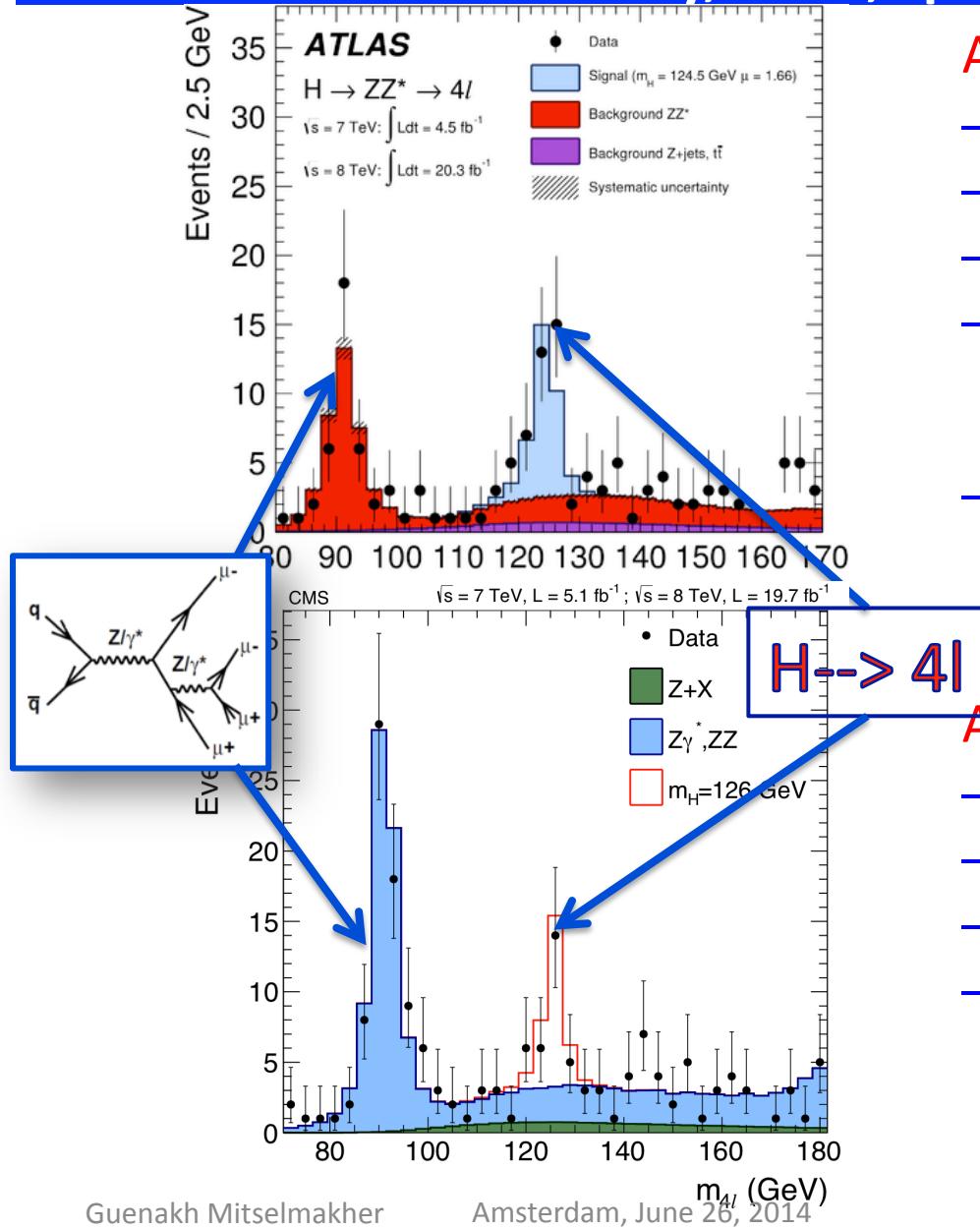
At Higgs mass ~125 GeV we have access to several decay modes, which allows for detailed studies of couplings  
We are lucky!

# Higgs particles produced in ATLAS + CMS (estimate)

- Number of SM Higgs particles produced in ATLAS and CMS in 2011-2012 = 1,100,000  
(total Cross Section 22 pb)  $\times$  (25 fb-1)  $\times$  (2experiments)
- Contribution of different production mechanisms (wrt the total Cross Section)
  - ggF = 87%
  - VBF = 7%
  - VH = 5%
  - ttH = 0.6%
- Decay modes ( $l = e$  or  $\mu$ )
  - BR(bb) = 57%
  - BR(tautau) = 6%
  - BR(WW- $\rightarrow$ 2l2v) = 22%  $\times$  (0.22) $^2$  = 1.1%
  - BR(gamgam) = 0.23%
  - BR(ZZ- $\rightarrow$ 4l) = 2.8%  $\times$  (0.06) $^2$  = 0.013%
  - BR(mumu) = 0.022%
- Discussion in this talk is limited to the better measured 5 decay modes:  
ZZ, gamgam, WW, tautau, bb

# $H \rightarrow ZZ \rightarrow 4l$

used for: discovery, mass, spin/parity, coupling to bosons



## Analysis strategy:

- Four leptons (muons or electrons)
- four-lepton mass** is the key observable
- split events into 4e, 4μ, 2e2μ channels
- Exploit differences in differential distributions for separation from bkgd, and for spin-parity measurements
- Backgrounds:
  - ZZ (dominant): from Monte Carlo (MC)
  - reducible (with non-isolated or “fake” leptons): from control region

## Analysis features:

- high S/B-ratio (~2:1)
- but very small event yield
- excellent mass resolution = 1-2%
- $Z \rightarrow 4l$  decay peak conveniently nearby, natural validation of the discovered peak

# $H \rightarrow ZZ \rightarrow 4l$

Separation from background:

- ATLAS (not updated):  $6.6\sigma$  observed (4.4. expected)
- CMS:  $6.8\sigma$  observed (6.7 expected)

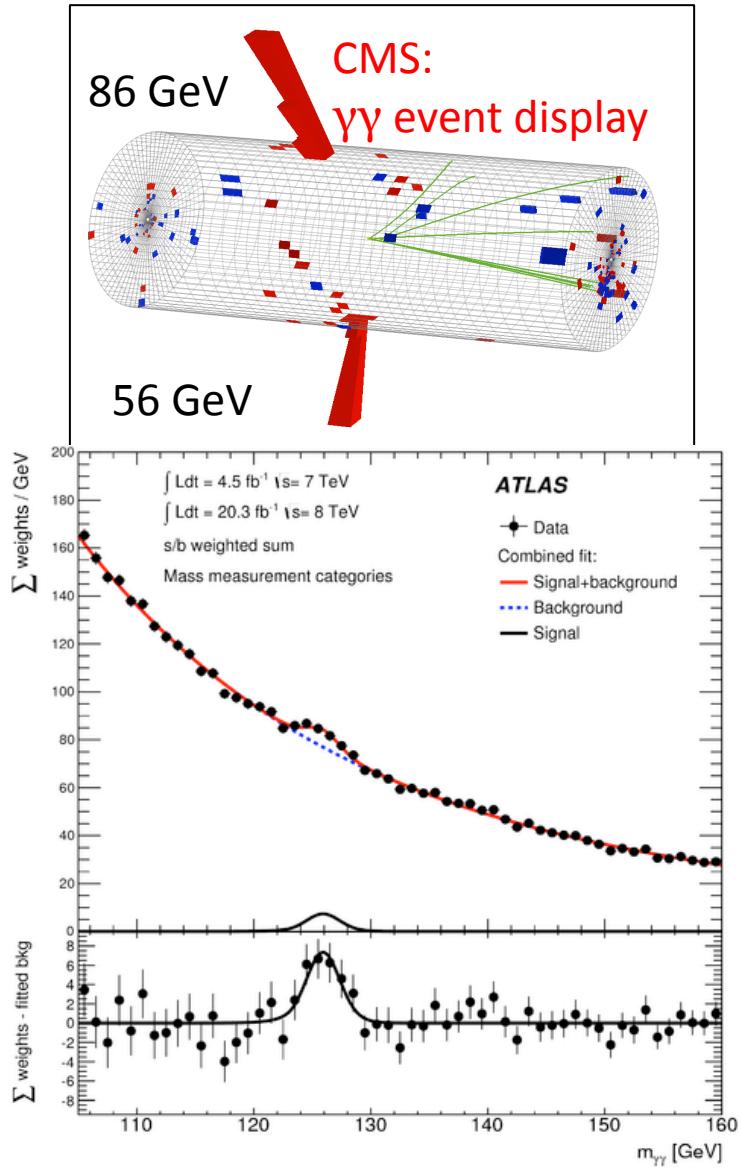
Signal strength/SM prediction:

- ATLAS:  $\mu = 1.66+0.45-0.38$  (June 2014 )
- CMS:  $\mu = 0.93+0.29-0.25$

(ATLAS mu value is taken from the mass measurements, and the final mu values will be available soon in combination couplings analysis)

# H $\rightarrow$ $\gamma\gamma$

used for: discovery, mass, couplings



## Analysis strategy:

- Two high momentum photons selected
- Narrow state predicted on non-resonant background, using excellent 2-photon mass resolution: 1-2%
- Large “irreducible” background from two photons
- Smaller reducible “fake” photon background

## Analysis features:

- High event yield ( $\sim 400$  events)
- Poor S/B ratio  $\sim 1:20$
- Background can be measured in sidebands

# $H \rightarrow \gamma\gamma$

Separation from background:

- ATLAS :  $7.4\sigma$  observed (4.3 expected)
- CMS:  $3.2\sigma$  observed (4.2 expected)

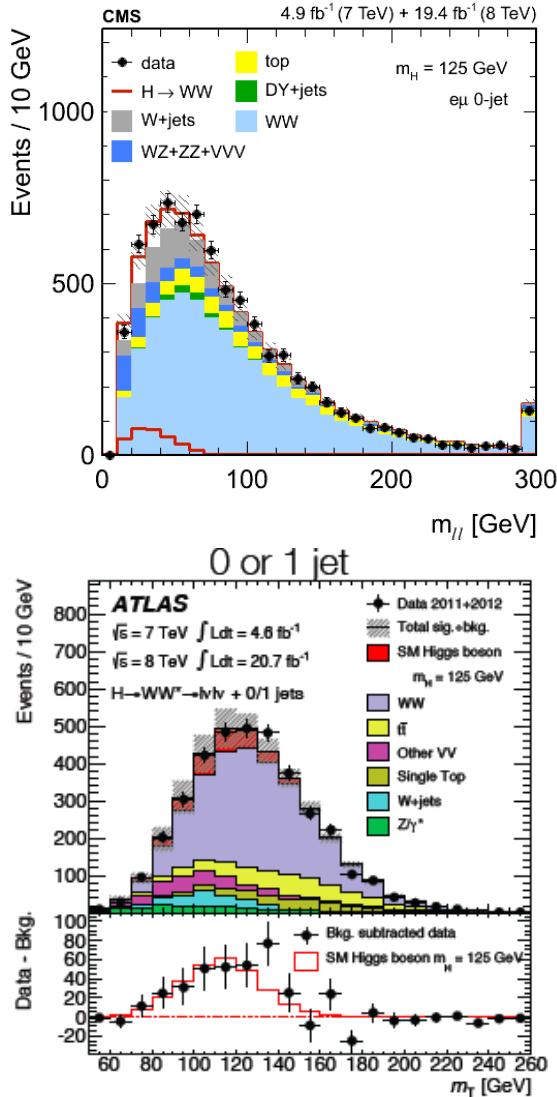
Signal strength/SM prediction:

- ATLAS:  $\mu = 1.29 \pm 0.30$  (June 2014)
- CMS:  $\mu = 0.78+0.28-0.26$

(ATLAS mu value is taken from the mass measurements, and the final mu values will be available soon in combination couplings analysis)

# $H \rightarrow WW \rightarrow l\bar{l}l\bar{l}$

## used for: coupling to bosons, spin-parity



### Analysis strategy:

- two prompt high- $p_T$  leptons
- Large MET
- Large SM backgrounds mostly measured in control regions
  - WW, tt, W+jets, DY+jets, Wy: from control regions
  - ZW, ZZ: from MC (very small contribution)

### Analysis features:

- S/B-ratio 1/10
- fair signal event yield ( $\sim 300$  events)
- poor mass resolution  $\approx 20\%$

# $H \rightarrow WW$

Separation from background:

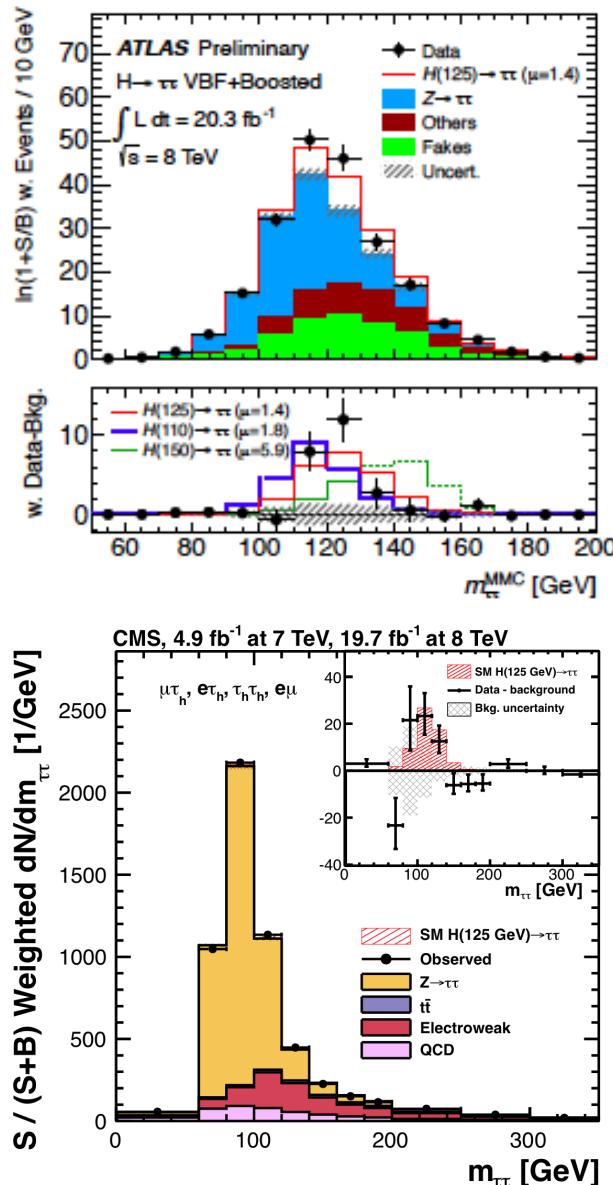
- ATLAS :  $3.8\sigma$  observed (3.7 expected)
- CMS:  $4.3\sigma$  observed (5.8 expected)

Signal strength/SM prediction:

- ATLAS:  $\mu = 1.01 \pm 0.31$
- CMS:  $\mu = 0.72+0.20-0.18$

# H $\rightarrow$ $\tau\tau$

## used for: coupling to fermions (3<sup>rd</sup> generation)



### Analysis strategy

- $\tau\tau$  – candidates in CMS:  $e\tau_h, \mu\tau_h, e\mu, \mu\mu, ee, \tau_h\tau_h,$
- further split into more categories
- ATLAS 3-channels (lep-lep),(lep-had),(had-had), further split into more categories
- $\tau\tau$  - mass (including MET): the key distribution
- Use of MVA for optimization

### Analyses features:

- low S/B-ratio  $\sim 1/50$  (in CMS)
- Higgs is on falling slope of Z-decays, natural calibration
- poor mass resolution ( $\approx 15\%$ )

# $H \rightarrow \tau\tau$

Separation from background:

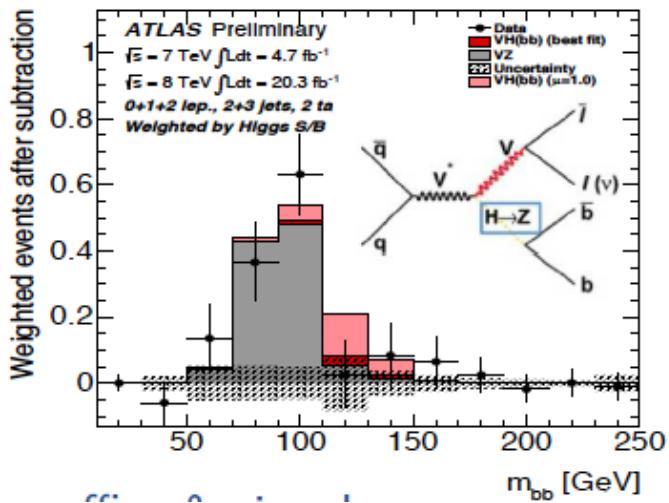
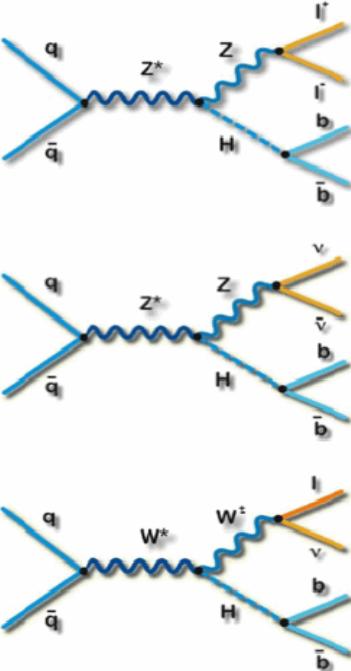
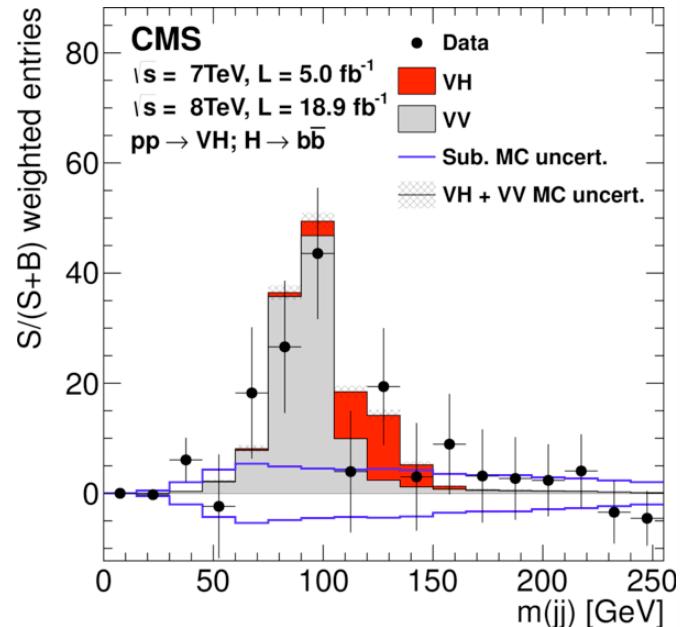
- ATLAS :  $4.1\sigma$  observed ( $3.2$  expected)
- CMS:  $3.4\sigma$  observed ( $3.6$  expected)

Signal strength/SM prediction:

- ATLAS:  $\mu = 1.4 + 0.5 - 0.4$
- CMS:  $\mu = 0.78 \pm 0.27$

# $H \rightarrow bb$

used for: coupling to fermions (3<sup>rd</sup> generation)



## Analysis strategy:

- VH Higgs (using V-tag)
- Trigger on leptons and MET
- Higgs on a shoulder of  $Z \rightarrow$  calibrations
- B-jets identified (displaced tracks)
- Go to high Pt where Higgs is enhanced
- Backgrounds mostly from control regions

## Analysis features:

- By far the largest number of Higgs decays
- But lots of QCD background
- Some bb-mass resolution (~10% CMS)
- S/B  $\sim 1/20$  in the end (CMS)

# $H \rightarrow bb$

Separation from background (significance):

- ATLAS : no significant signal over background
- CMS:  $2.1\sigma$  observed ( $2.1$  expected)

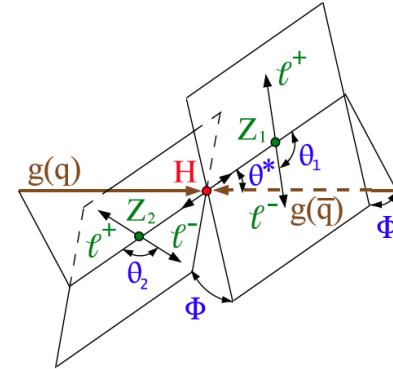
Signal strength/SM prediction:

- ATLAS:  $\mu = 0.2 \pm 0.7$
- CMS:  $\mu = 1.0 \pm 0.5$

# New particle Spin-parity tests

## $H \rightarrow ZZ \rightarrow 4l$

- 4l system is fully reconstructed
- use leptons momenta to construct discriminants



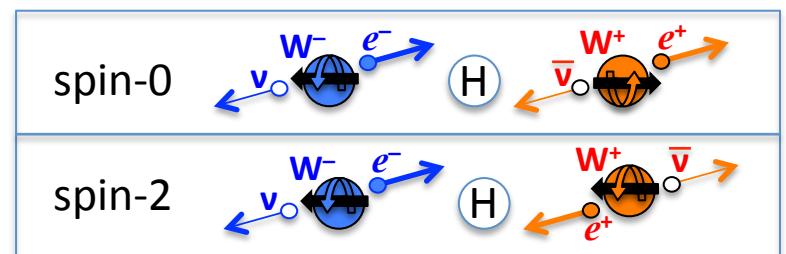
CMS:  
ME-based discriminant

$$D = \frac{|ME(event|J')|^2}{|ME(event|H)|^2}$$

ATLAS: MVA-based discriminant

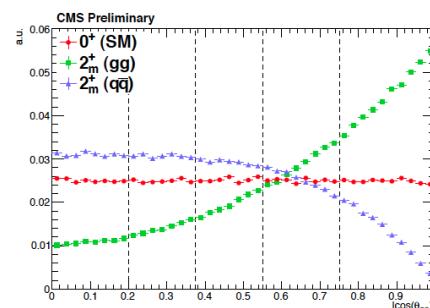
## $H \rightarrow WW \rightarrow ll\bar{l}\bar{l}$

- dilepton angle is sensitive to spin of the original H-boson



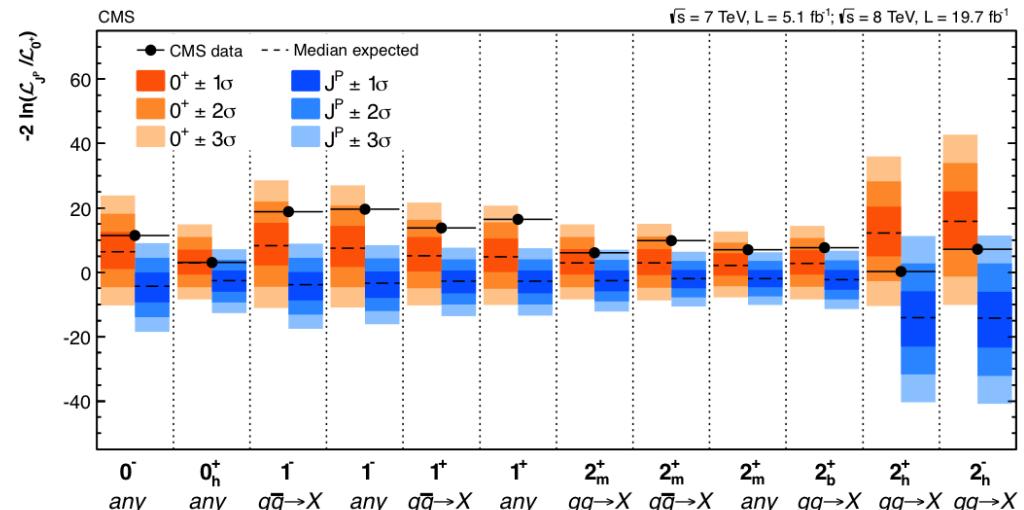
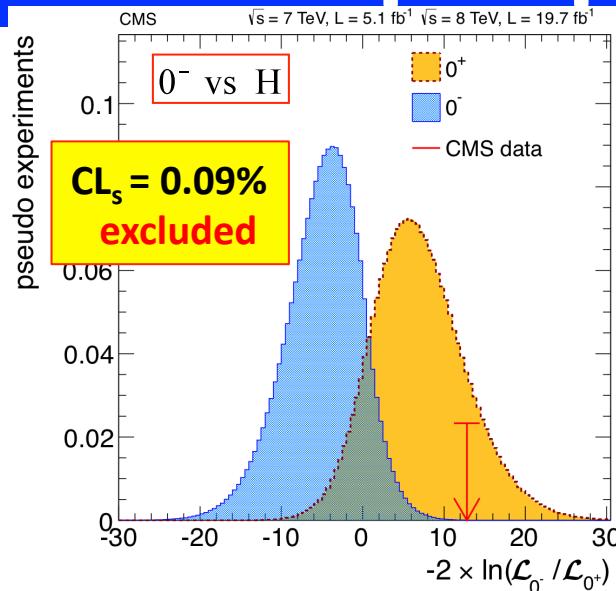
## $H \rightarrow \gamma\gamma$

- $J=1$  forbidden (Landau-Yang theorem)
- $\cos\theta^*$  is the only variable sensitive to  $J^P$  information at leading order



- Left plot before acceptance and reconstruction.
- after acceptance x reconst., discrim. power lessens
- poor S:B makes the measurement very difficult

# Spin-parity results (CMS)



	$0^-$	$0_h^+$	$q\bar{q} \rightarrow 1^-$	$q\bar{q} \rightarrow 1^+$	$gg \rightarrow 2_m^+$	$q\bar{q} \rightarrow 2_m^+$	$gg \rightarrow 2_b^+$	$gg \rightarrow 2_h^+$	$gg \rightarrow 2_h^-$
ZZ	0.09%	7.1%	0.001%	0.03%	1.9%	0.03%	0.9%	3.1%	1.7%
WW	35%				16%	0.2%			
$\gamma\gamma$			forbidden		poor sensitivity				

## Summary:

- **$0^-, 1^\pm, \text{five } J=2 \text{ models excluded at 95\% CL or higher}$**
- $0_h^+$  – on a borderline of being excluded (CMS)
- Most of the alternative models in CMS and ATLAS are the same, results are similar (see next slide)

# Spin-parity results (ATLAS)

- Use MVA-based discriminants, find sensitive observables
- Test several alternative spin-parity hypotheses  $J^P$  ( $0^-, 1^+, 1^-, 2^+$ ) compared to SM hypothesis:  $0^+$
- Production modes
  - spin-2 : test production mechanism via combination of ggF & qbar annihilation
  - spin-1 : signal produced via qbar annihilation (ggF forbidden)
  - spin-0 : ggF (qbar annihilation negligible)

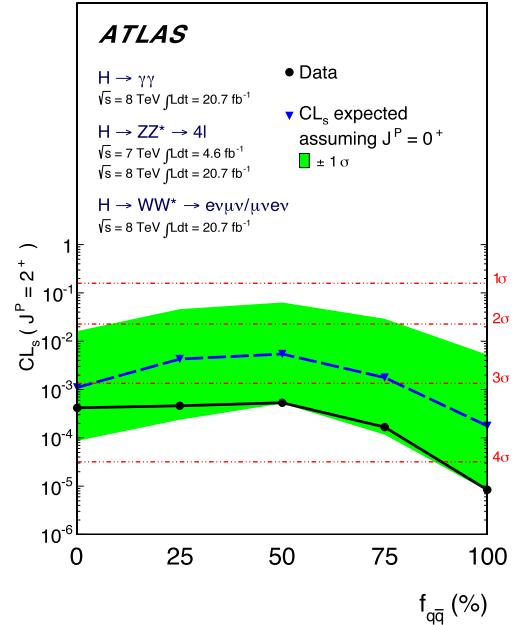
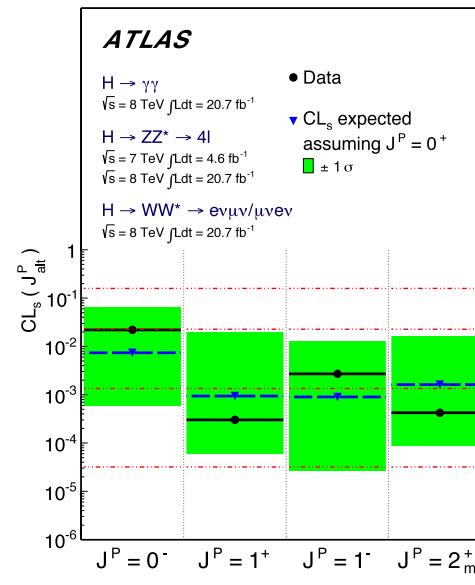
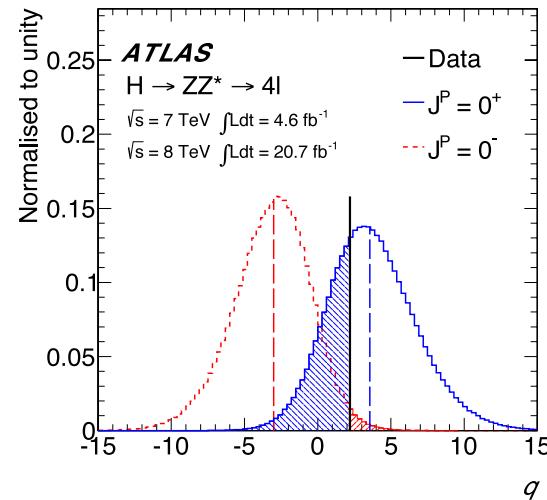
$0^+$  vs  $0^-$  (only ZZ): 97.8% CL

$0^+$  vs  $1^+$  (ZZ +WW): 99.97% CL

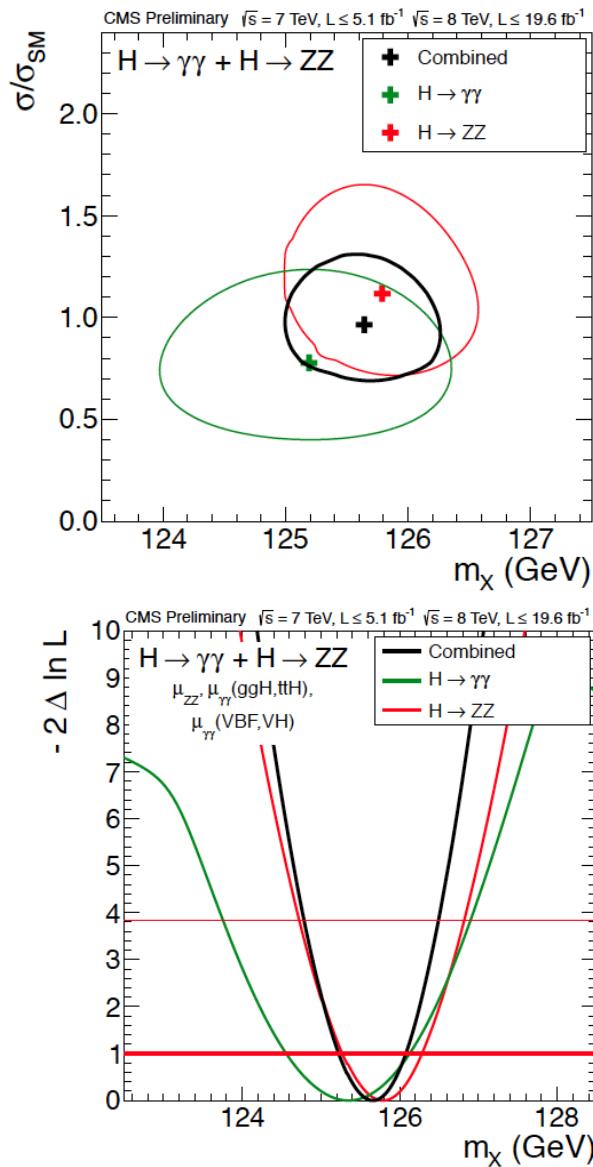
$0^+$  vs  $1^-$  (ZZ+WW): 99.7% CL

$0^+$  vs  $2^+$  ( $\gamma\gamma$  +ZZ+WW)>99.9% CL

All tested alternative spin hypotheses excluded at  $> 97.8\%$  CL



# CMS: Combined ZZ + $\gamma\gamma$ mass measurement



- A narrow resonance is seen with high significance in the two good mass resolution channels

**ZZ(4l): March 2013**  $m_X = 125.8 \pm 0.5 \text{ (stat)} \pm 0.2 \text{ (syst)} \text{ GeV}$

**FINAL ZZ**  $m_X = 125.6 \pm 0.4 \text{ (stat)} \pm 0.2 \text{ (syst)} \text{ GeV}$

main sources of systematic uncertainties:

- electron energy scale: 0.3%
- muon energy scale: 0.1%

**$\gamma\gamma$ :** March 2013  $m_X = 125.4 \pm 0.5 \text{ (stat)} \pm 0.6 \text{ (syst)} \text{ GeV}$

**FINAL  $\gamma\gamma$ :** awaiting...

main sources of systematic uncertainties:

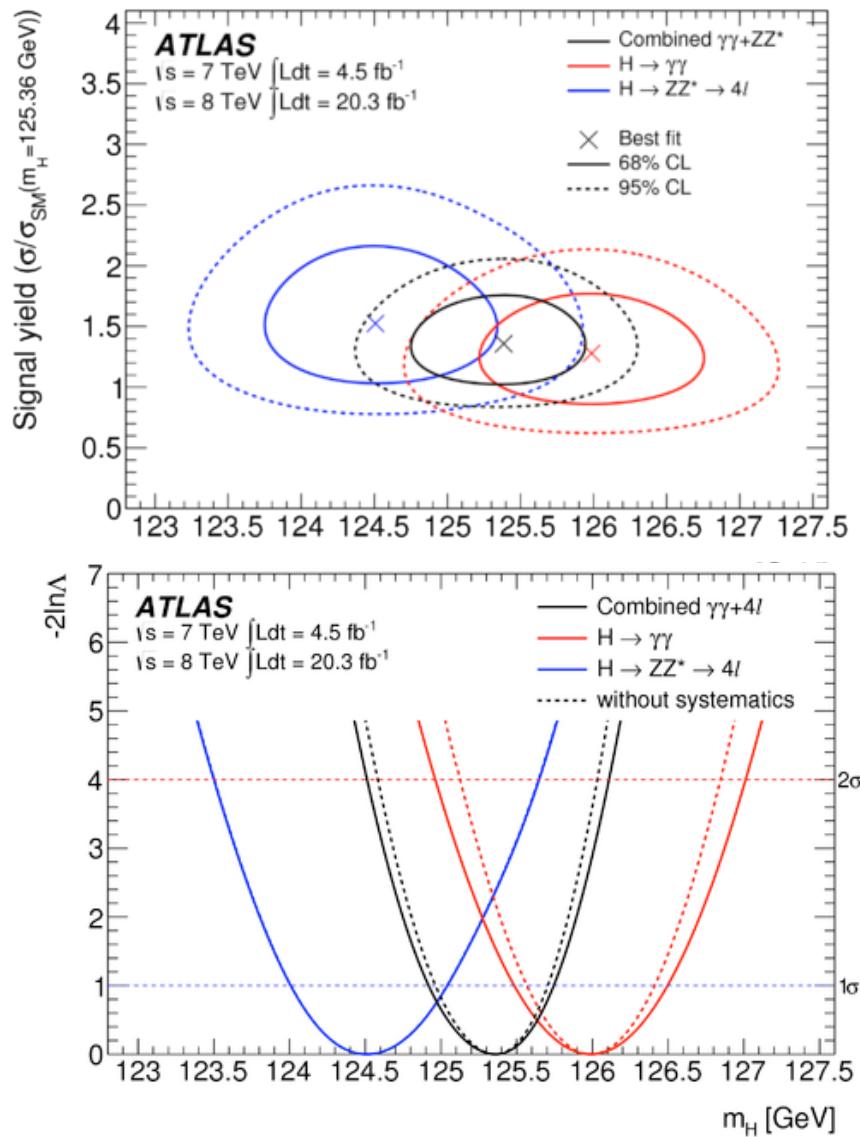
- electron-photon extrapolation
- $E_T$  scale extrapolation from  $m_Z/2$  to  $m_H/2$

- Results are consistent with one particle X  
→ proceed with a combined mass measurement  
→ do not assume that ZZ and  $\gamma\gamma$  event rates are tied by SM

**CMS March 2013 combination (not updated):**

$$m_X = 125.7 \pm 0.3 \text{ (stat)} \pm 0.3 \text{ (syst)} \text{ GeV}$$

# ATLAS: Combined ZZ + $\gamma\gamma$ mass measurement



A recent update on the Higgs mass measurement by ATLAS (June 2014)

A significant improvement in systematical errors, due to detailed work on calibrations and resolution model

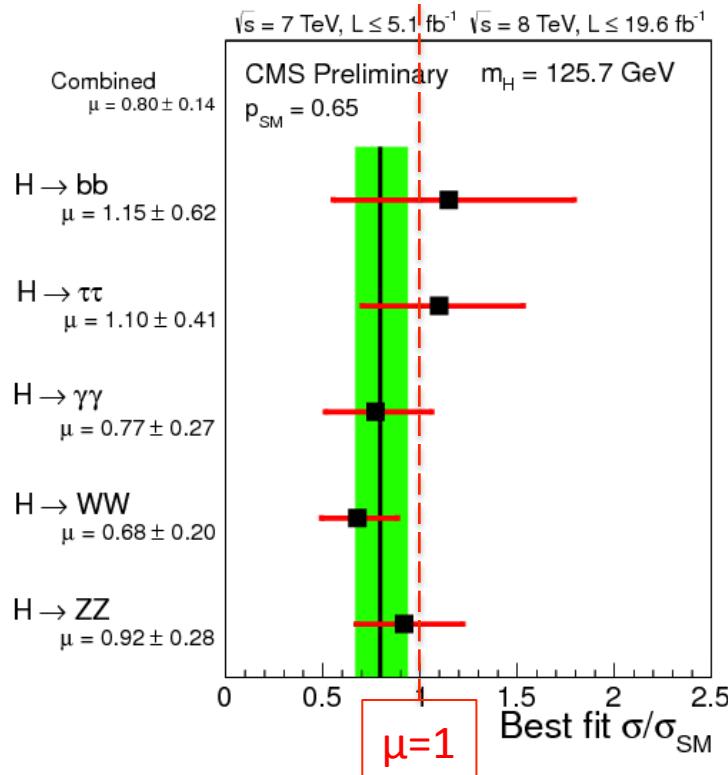
The difference in mass between the two channels, ZZ and  $\gamma\gamma$ , is measured to be  $\Delta m_H = 1.47 \pm 0.67 \text{ (stat)} \pm 0.28 \text{ (sys)} \text{ GeV}$ , (2.0 $\sigma$  compatibility, compared to 2.5 $\sigma$  in previous Higgs mass analysis by ATLAS)

Channel	Mass measurement [GeV]
$H \rightarrow \gamma\gamma$	$125.98 \pm 0.42 \text{ (stat)} \pm 0.28 \text{ (syst)} = 125.98 \pm 0.50$
$H \rightarrow ZZ^* \rightarrow 4l$	$124.51 \pm 0.52 \text{ (stat)} \pm 0.06 \text{ (syst)} = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst)} = 125.36 \pm 0.41$

CMS and ATLAS combined mass measurements are compatible

# CMS and ATLAS: Consistency of event yields in 5 main Higgs decay channels with Standard Model

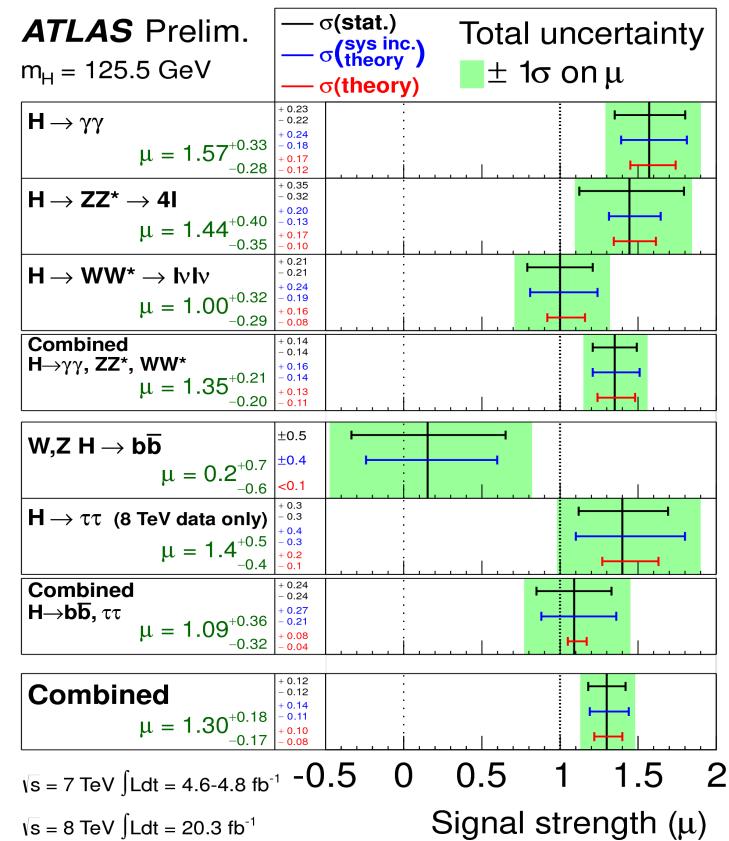
CMS, Spring 2013



Higgs signal strength in CMS

$$\mu = 0.80 \pm 0.14 \quad (\text{not updated})$$

ATLAS, Spring 2014



Higgs signal strength in ATLAS

$$\mu = 1.30 \pm 0.12 \text{ (stat)}^{+0.14}_{-0.11} \text{ (sys)} \quad (\text{not updated})$$

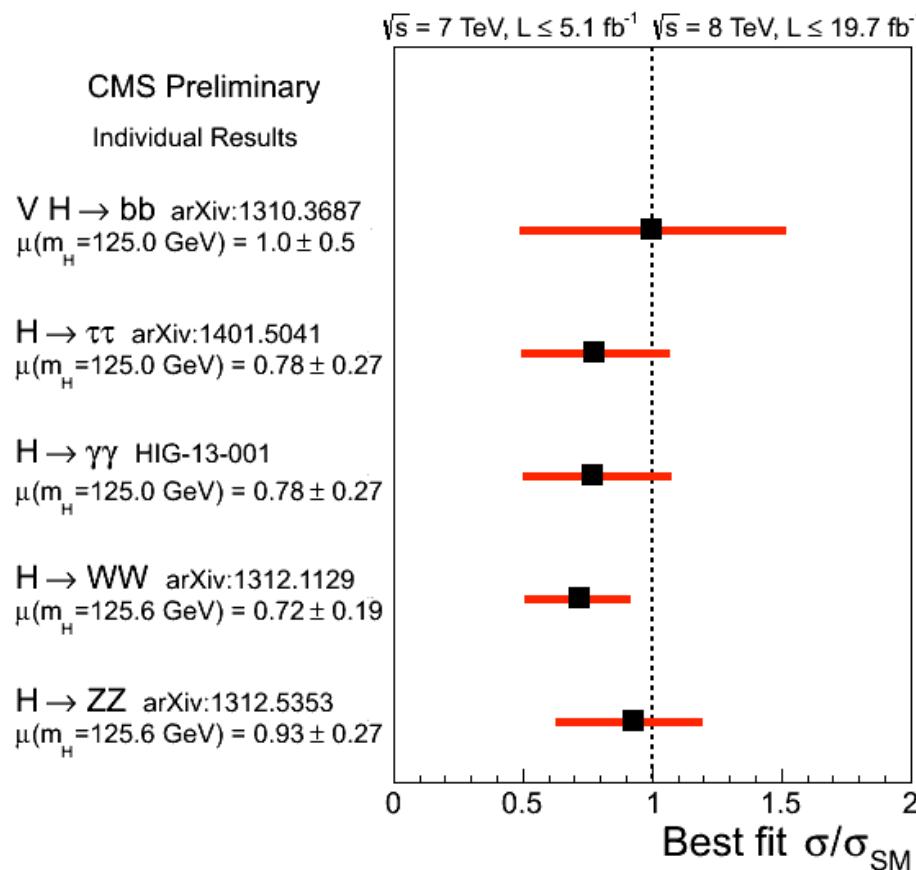
# Summary

- The H125 GeV is by now measured (at different level of precision) in several decay channels: ZZ, WW,  $\gamma\gamma$ ,  $\tau\tau$ , bb
- Is H125 boson the SM Higgs particle?
  - event yields in all the individual channels are consistent with the SM Higgs boson
  - couplings agree with the SM Higgs with the current statistical accuracy (20-50%)
  - $J^{CP} = 0^-$ ,  $1^\pm$ , and a number of  $J=2$  states are excluded at >95% CL or higher
- It certainly looks like the SM Higgs, no deviations observed yet



- Still plenty of room for deviations from SM Higgs (within errors) exist. We are at the beginning of the program of precision measurements of the H125 GeV particle with a hope to find BSM physics via deviations from the SM predictions. Higgs boson is very unusual, and studying it may be a good way to look for BSM.

# Backup



- Resent CMS plot with updated yields in individual Higgs decay channels, except  $H \rightarrow \gamma\gamma$ , which is still preliminary (update imminent), and without updated overall fit of the Higgs signal strength (compare to the complete older plot from Spring 2013, on slide 22)