

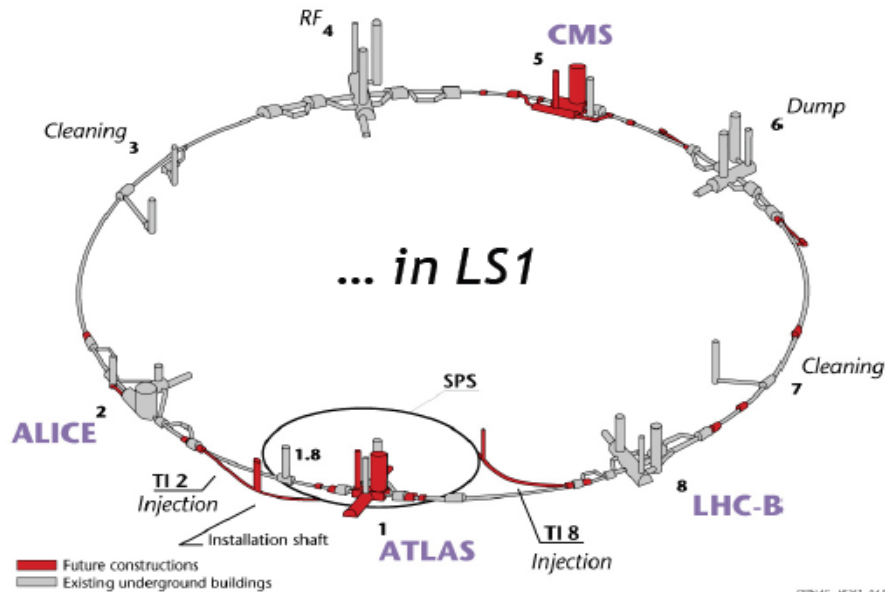
# Introduction to particle physics: experimental part

**Discovery of the Higgs boson**

**Measurements: mass, spin, couplings**

# Three years of LHC operations

## Energy frontier



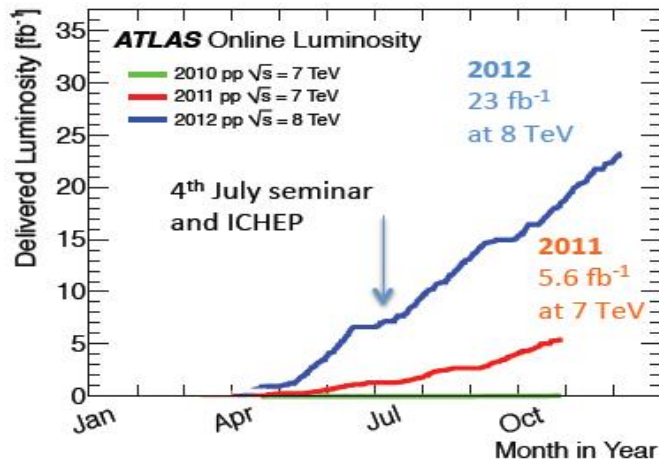
### The LHC

- Circumference 27 km
- Up to 175 m underground
- Total number of magnets 9 553
- Number of dipoles 1 232
- Operation temperature 1.9 K (Superfluid He)

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

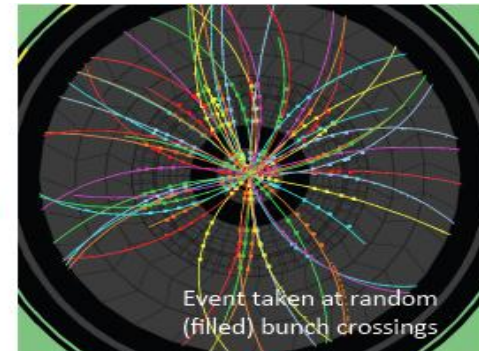
Parameter	2010	2011	2012	Nominal
C.O.M Energy	7 TeV	7 TeV	8 TeV	14 TeV
Bunch spacing / k	150 ns / 368	50 ns / 1380	50 ns / 1380	25 ns / 2808
$\epsilon$ (mm rad)	2.4-4	1.9-2.3	2.5	3.75
$\beta^*$ (m)	3.5	1.5-1	0.6	0.55
L (cm <sup>-2</sup> s <sup>-1</sup> )	2x10 <sup>32</sup>	3.3x10 <sup>33</sup>	~7x10 <sup>33</sup>	10 <sup>34</sup>

# The first LHC run



**2010**  
O(2) Pile-up events

150 ns inter-bunch spacing



**2010**  
0.05  $\text{fb}^{-1}$   
at 7 TeV

**2011**

O(10) Pile-up events

50 ns inter-bunch spacing

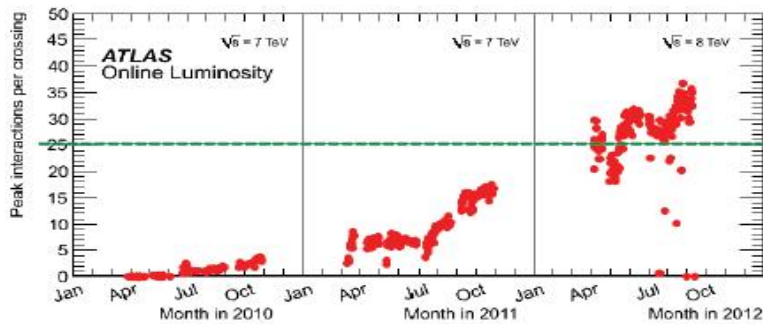


Design value  
(expected to be  
reached at  $L=10^{34}$  !)

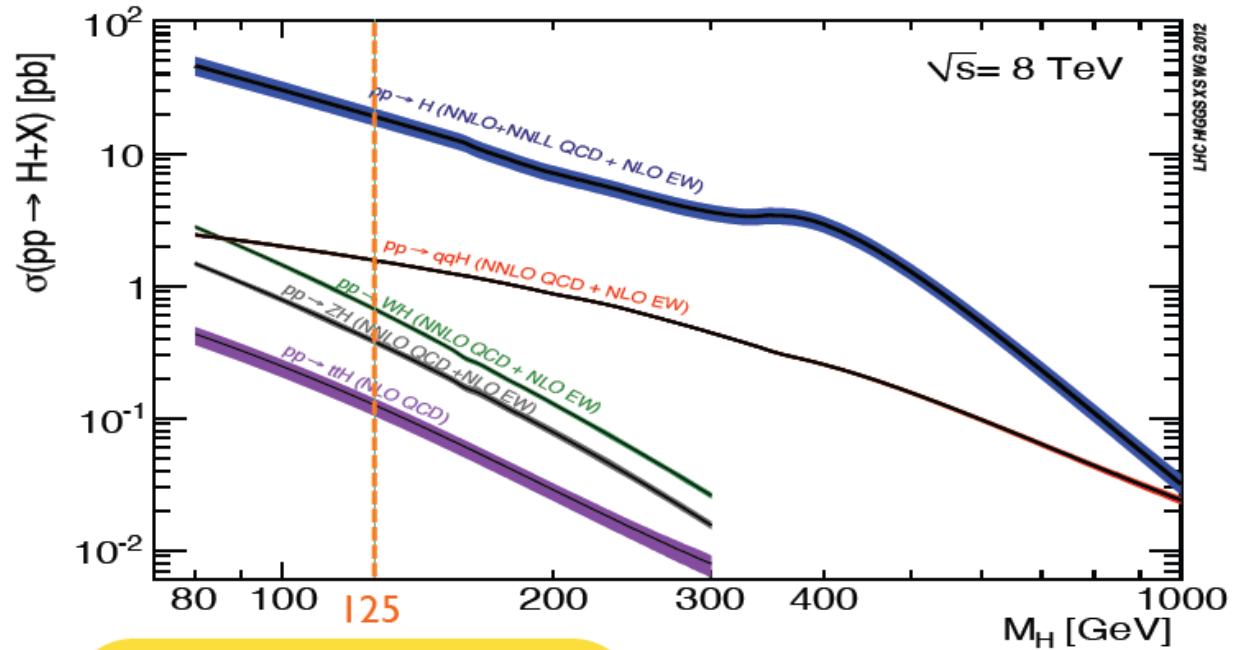
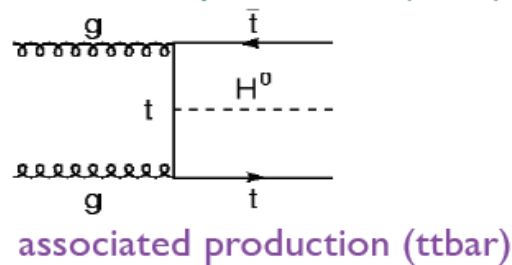
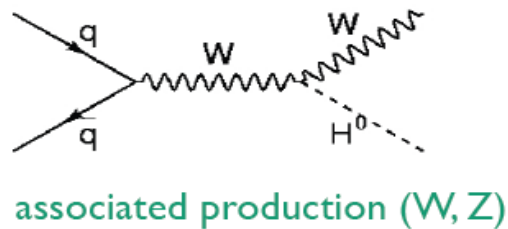
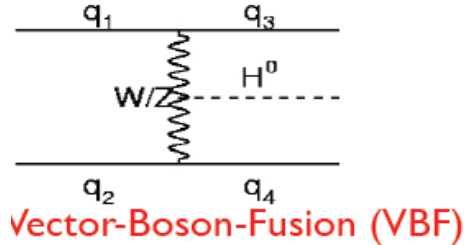
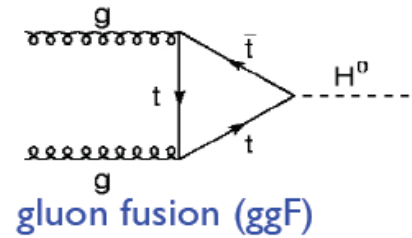
**2012**

O(20) Pile-up events

50 ns inter-bunch spacing

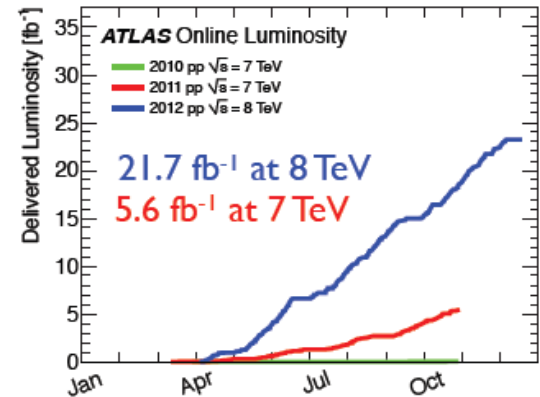


# SM Higgs production at the LHC

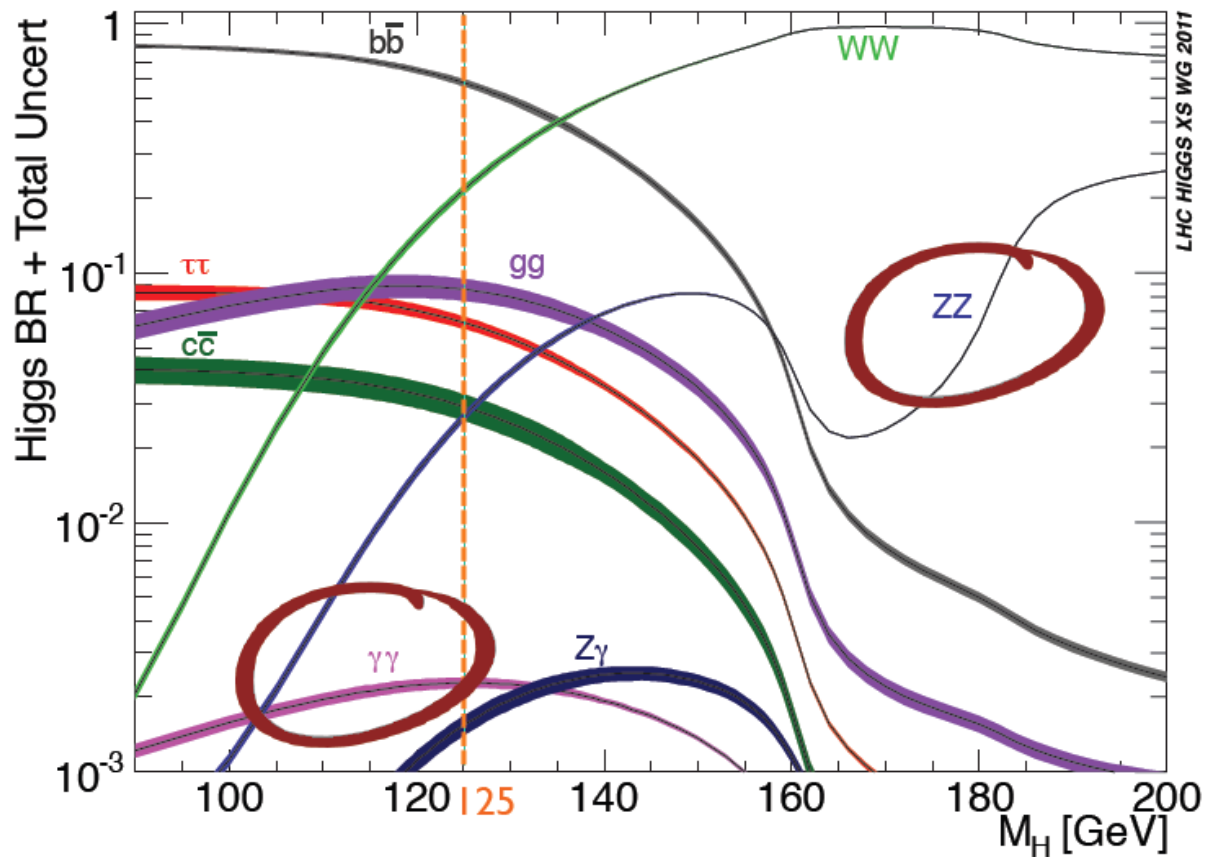


$$\sigma(125 \text{ GeV}) = 22.3 \text{ pb}$$

2 Higgs bosons @  
 $m_H$  125 GeV produced  
 at LHC in 2012 every  
 $10^{10}$  pp collisions



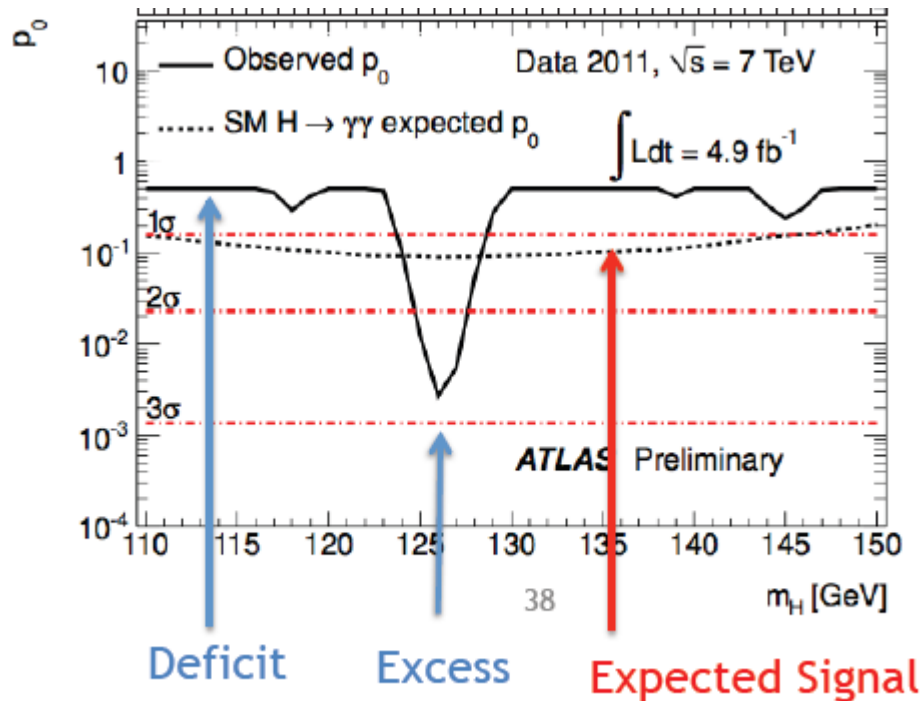
# SM Higgs decays



- 1 Higgs every 10 s
- 1  $H \rightarrow \gamma\gamma$  every 1.5 h
- 1  $H \rightarrow ZZ \rightarrow 4\ell$  ( $\ell = e$  or  $\mu$ ) every 2 days

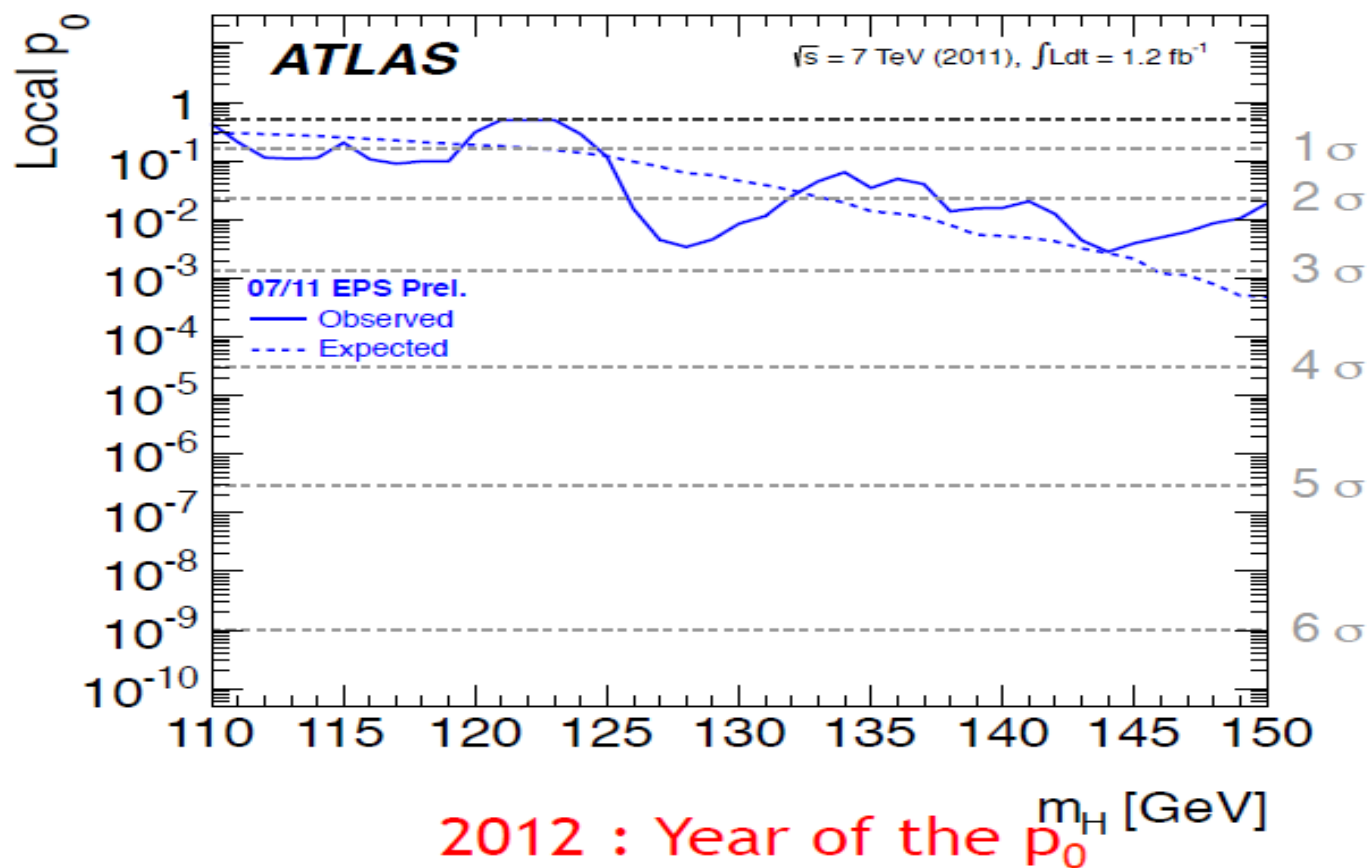
# Local $p_0$

Probability that the background can produce a fluctuation greater than or equal to the excess observed in data. Equivalent in terms of number of standard deviations is called local significance.



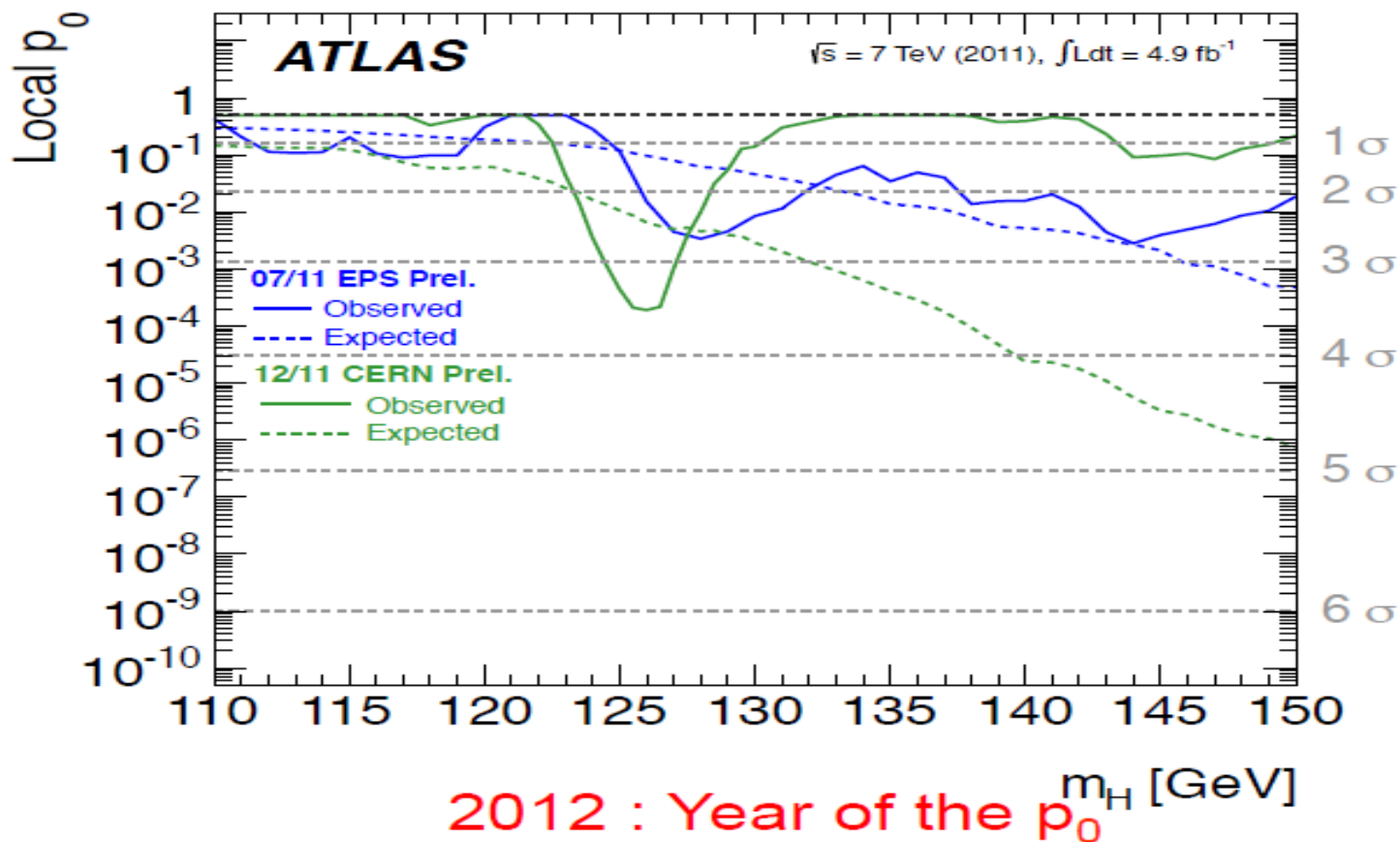
# Since conference EPS 2011

Birth of a particle (different prospective)



# Since conference EPS 2011

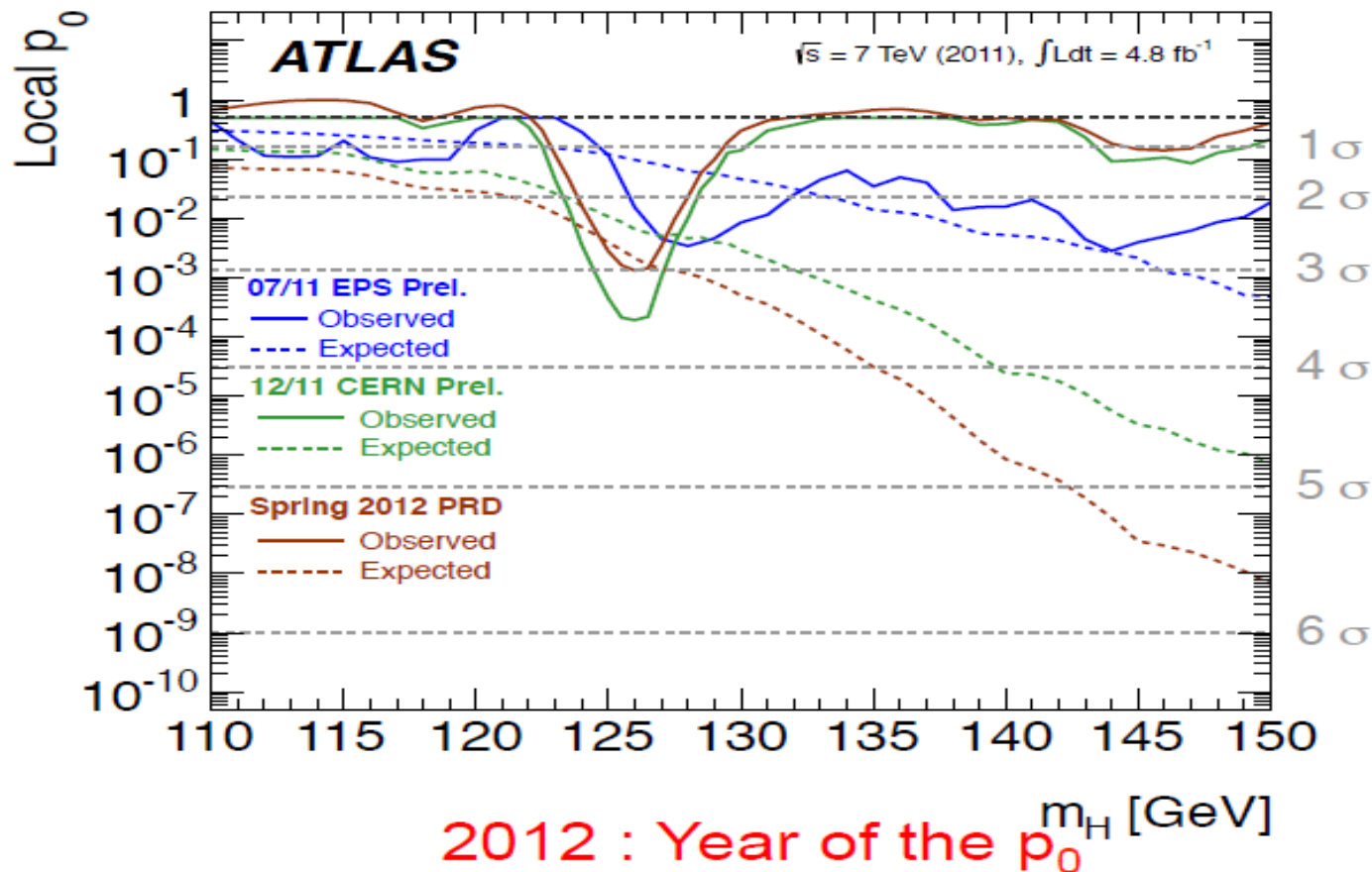
Birth of a particle (different prospective)  
CERN Council (December 2011)





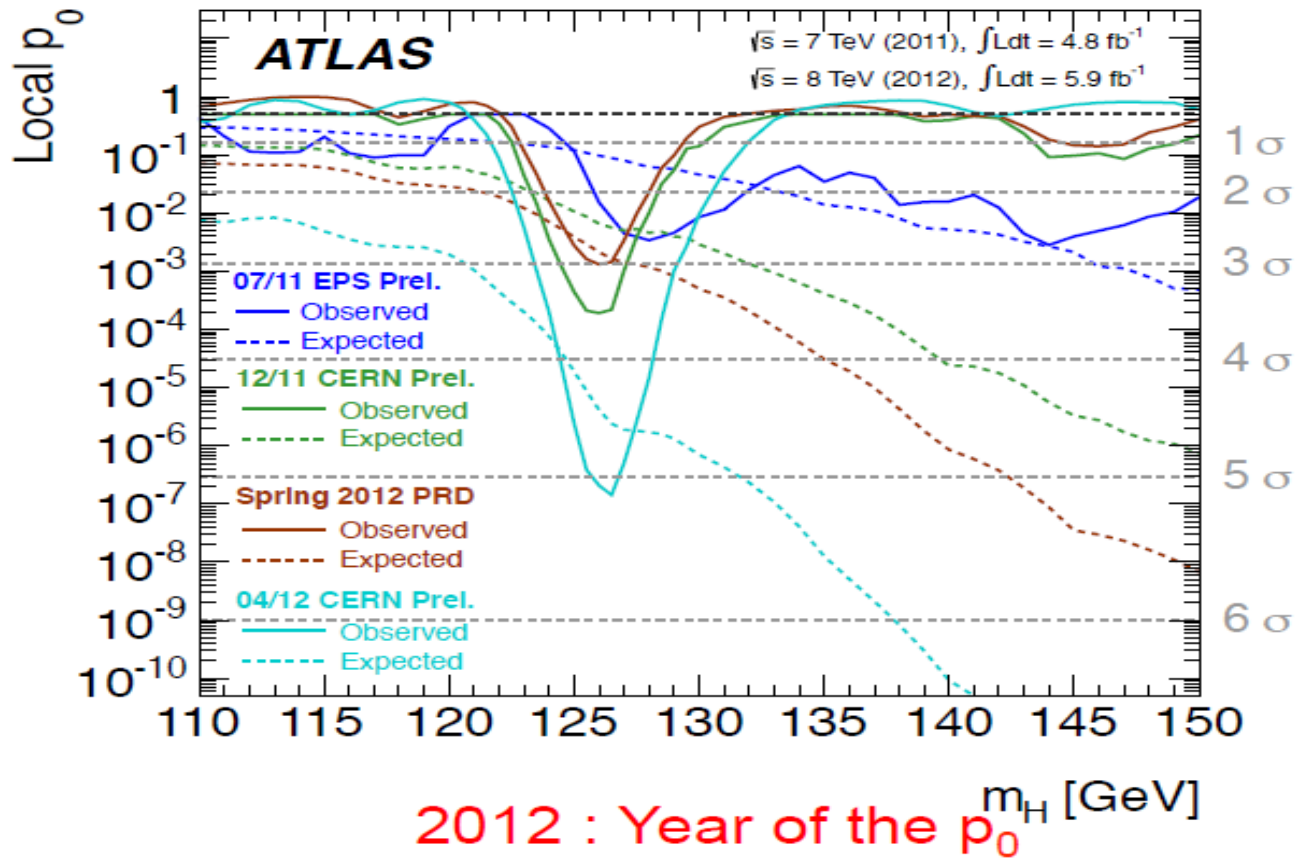
# Since conference EPS 2011

Birth of a particle (different prospective)  
Moriond (March 2012)



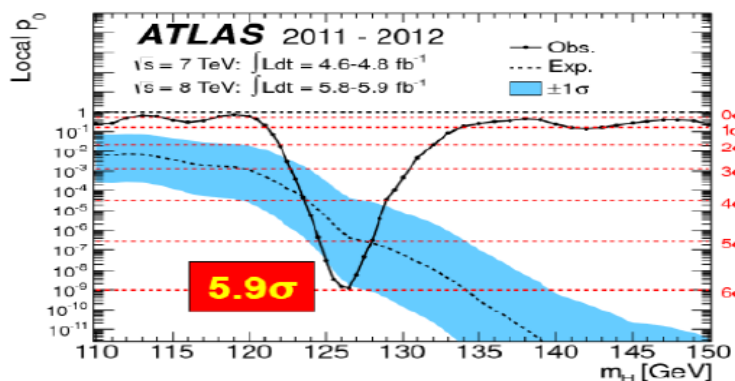
# Since conference EPS 2011

## Birth of a particle (different prospective) ICHEP (July 2012)



# Higgs-like particle

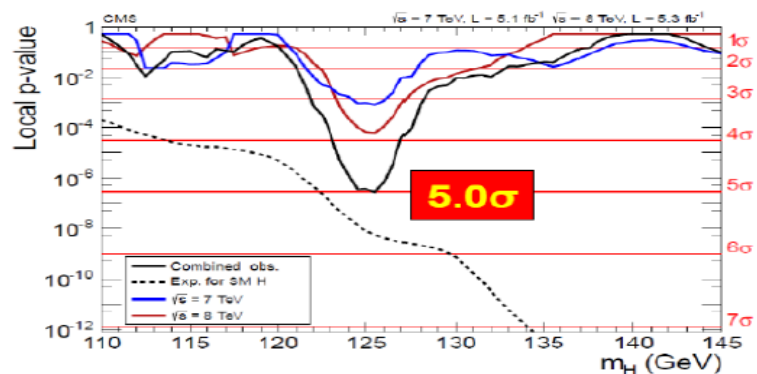
- We are living in a privileged moment in the history of High Energy Physics: **first fundamental scalar**
- The discovery came at half of the design energy, much more severe pile-up and one-third of integrated luminosity than was originally judged as necessary.



**ATLAS** [PLB 716 \(2012\) 1-29](#), Sept 17 (2012)

**Largest local excess:**  
**5.9σ at  $m_H = 126.5$  GeV**

$H \rightarrow \gamma\gamma, bb, \tau\tau, WW(l\nu l\nu, l\nu q\bar{q}), ZZ(4l, ll\nu\nu, llq\bar{q})$



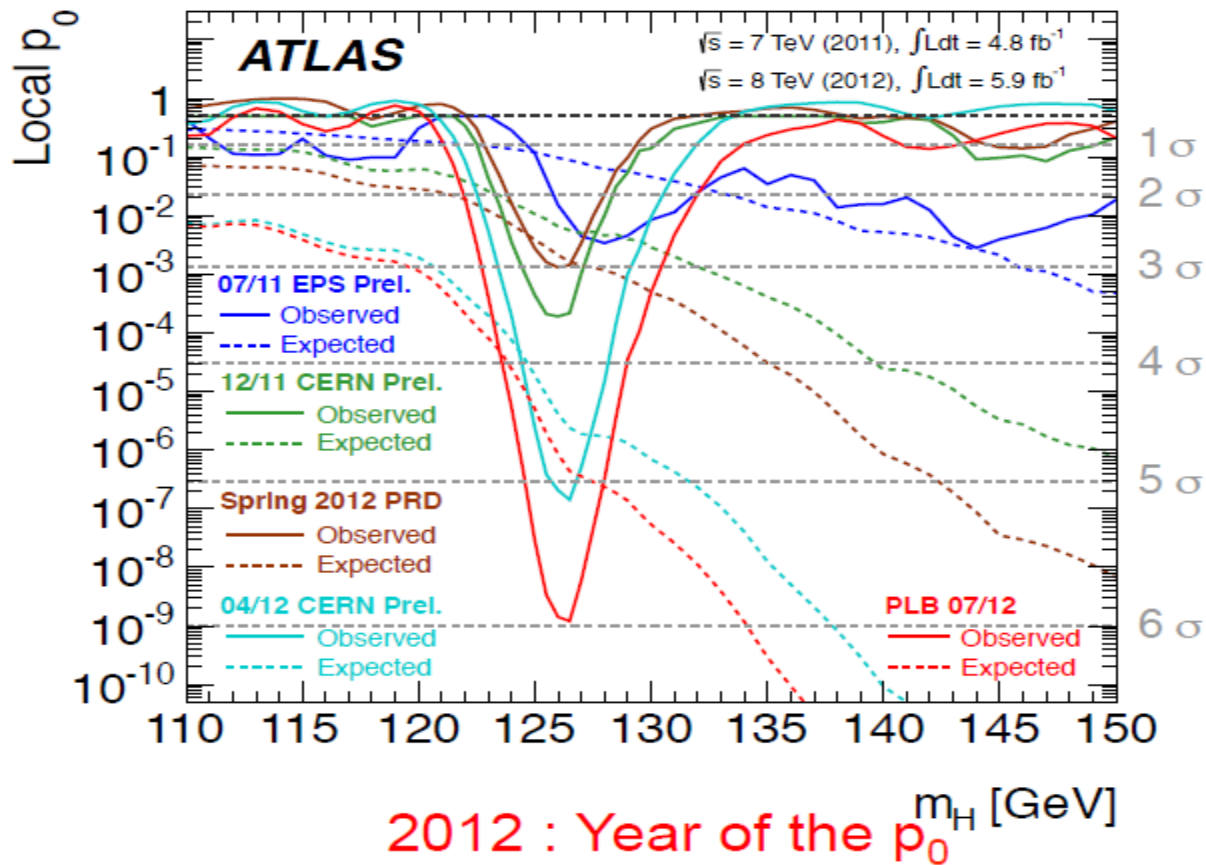
**CMS** [PLB 716 \(2012\) 30-61](#), Sept 17 (2012)

**Largest local excess:**  
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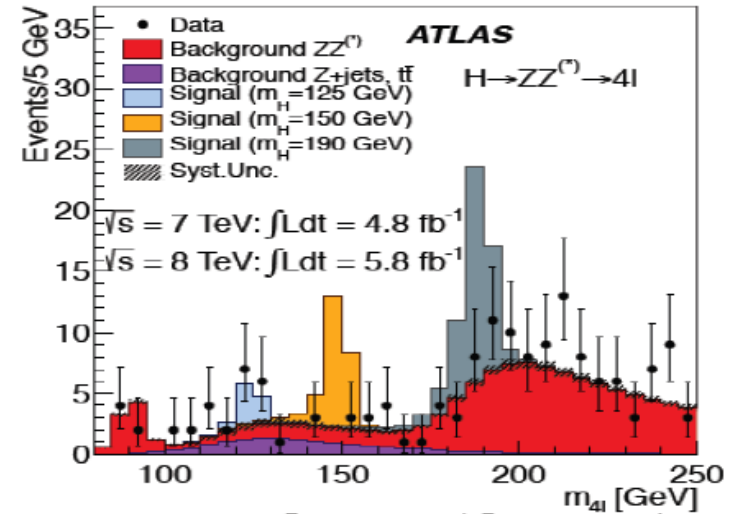
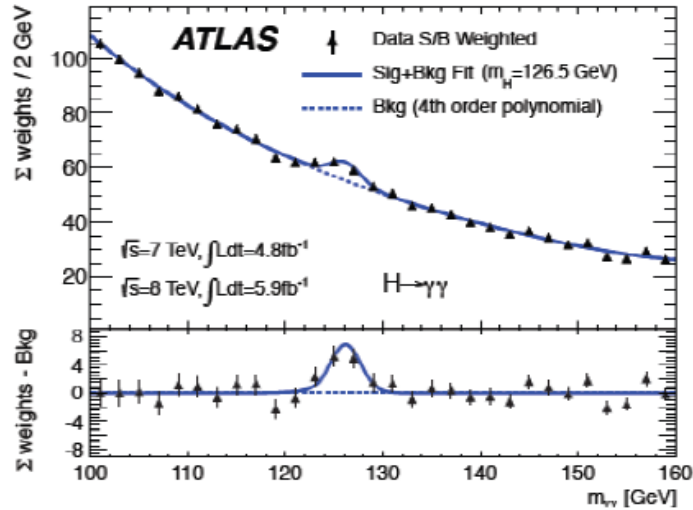
# Since conference EPS 2011

## Birth of a particle (different prospective) PLB (August 2012)

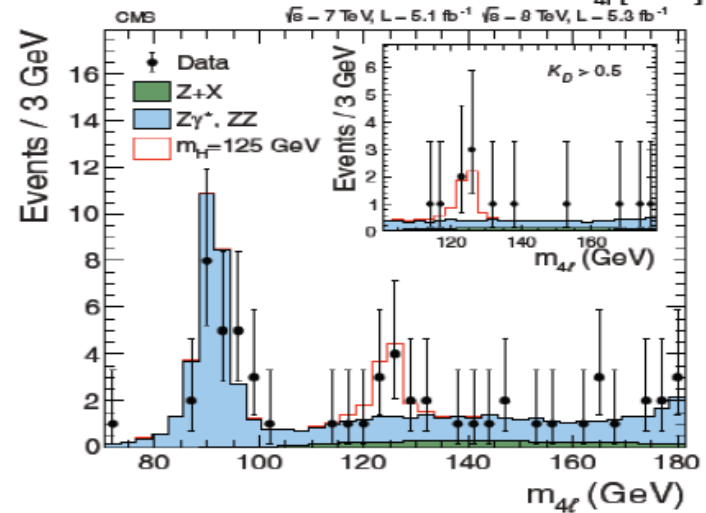
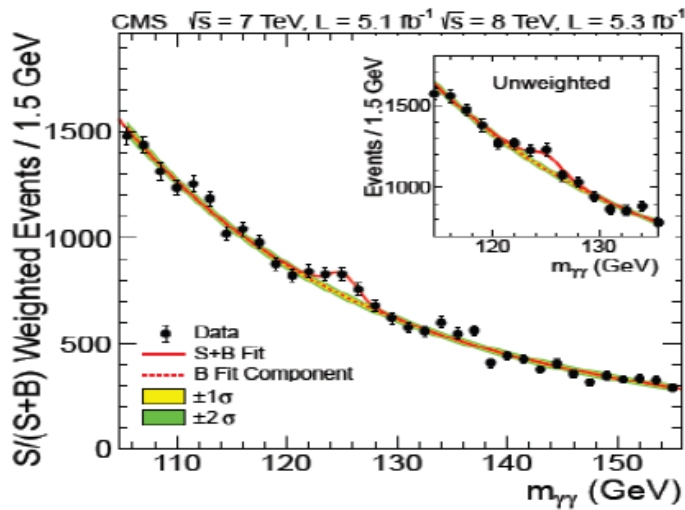


# Higgs-like particle

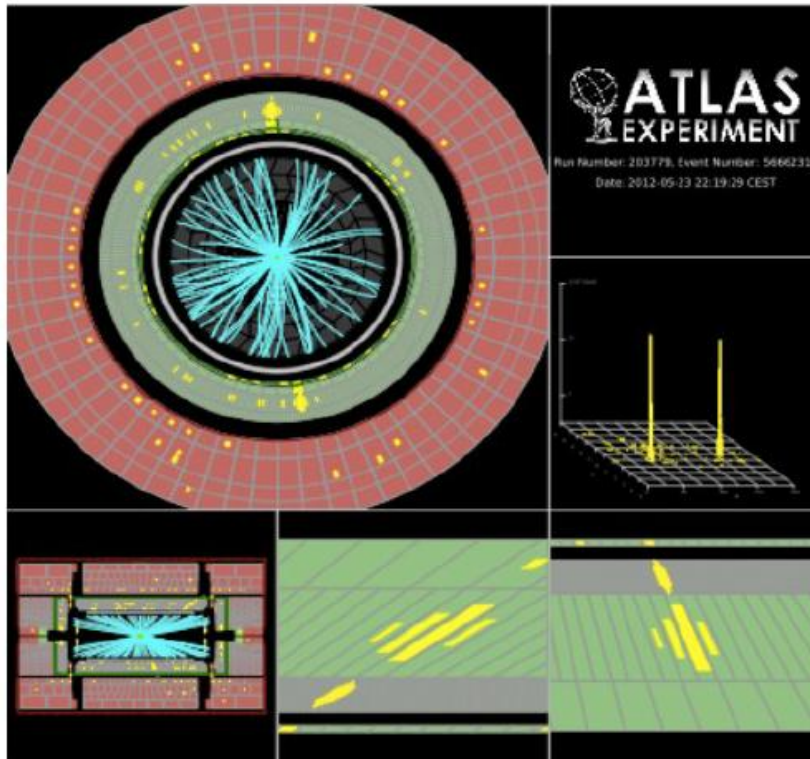
Phys.Lett. B716 (2012) 1-29



Phys.Lett. B716 (2012) 30-61



# H- $\rightarrow\gamma\gamma$ : events signature



## Simple event signature

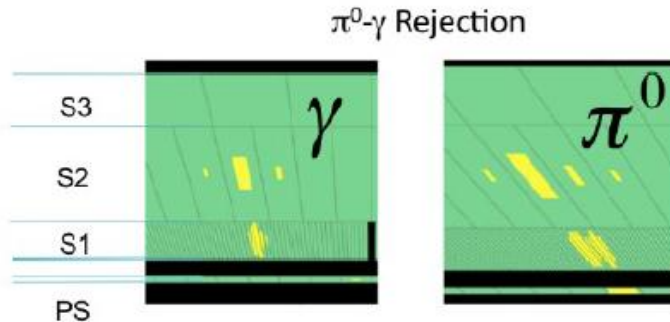
- ❑ Two high  $p_T$  photons  
 $p_{T_1} > 40$  GeV and  $p_{T_2} > 30$  GeV
- ❑ High trigger efficiency  
~99%
- ❑ High event selection efficiency despite high jet-jet &  $\gamma$ -jet production  
~40%
- ❑ High signal over background  
~3-10 % (depending on sub-category)

Invariant mass reconstruction  $m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos \alpha)$

- ❑ Good energy calibration
- ❑ Robust primary vertex reconstruction
- ➔ Excellent invariant mass resolution ~1.6 GeV with 90% of events within  $\pm 2\sigma$

# Shower shapes and vertex reconstr.

## Photon ID 2 – Photon shower shapes and background rejection



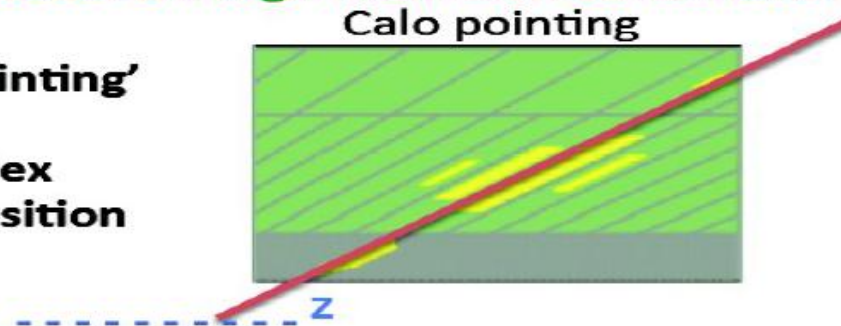
- Photons shower shape distributions in LAr sampling layers - different for signal and background ( $\pi^0$ )

## Vertex Reconstruction

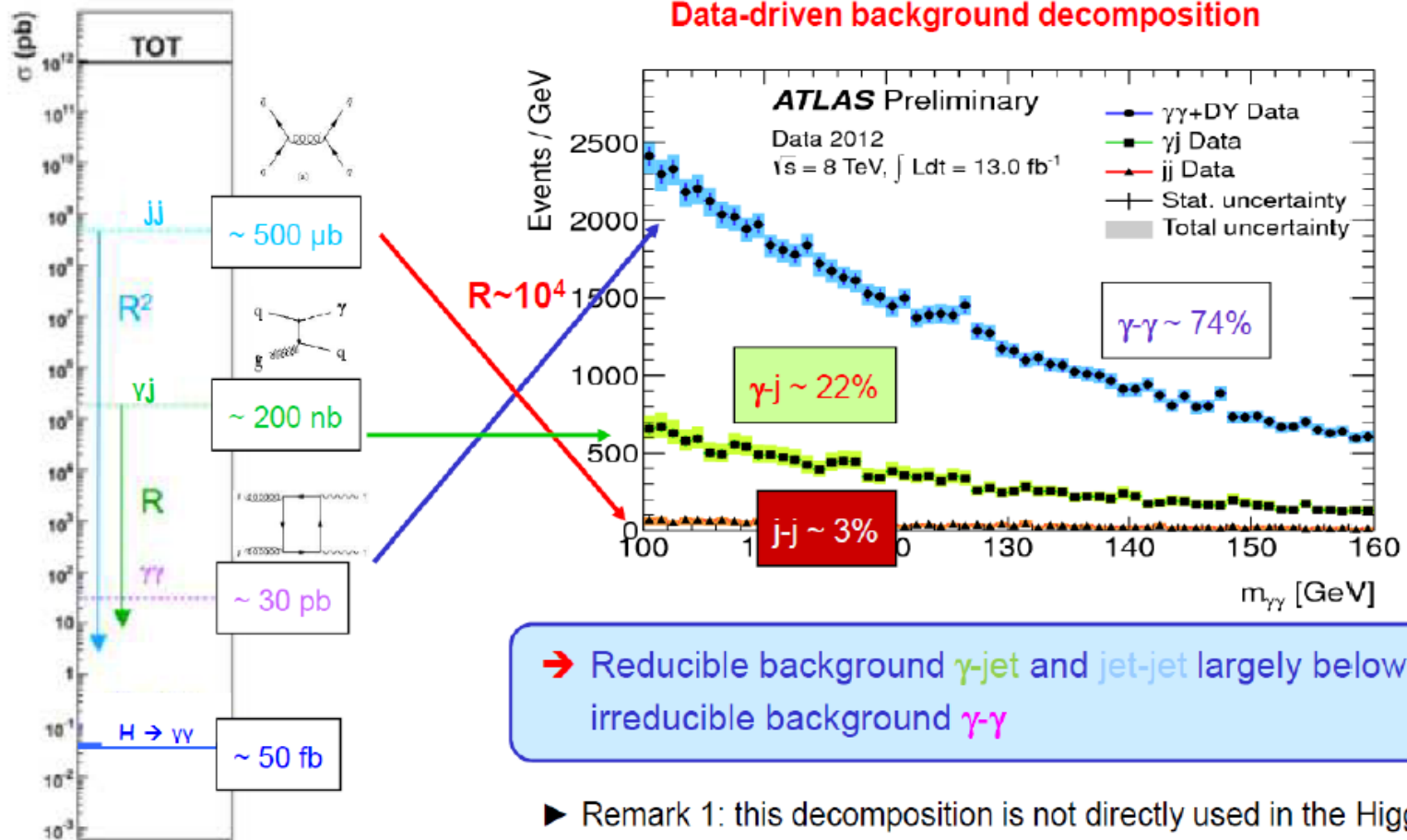
$$m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos \alpha)$$

□ Vertex reconstructed through likelihood combination

- Calorimeter 'pointing'
- $\Sigma$  tracks  $pT^2$
- Conversion vertex
- Mean vertex position



# H- $\rightarrow\gamma\gamma$ : background rejection



➔ Reducible background  $\gamma$ -jet and jet-jet largely below irreducible background  $\gamma\gamma$

- ▶ Remark 1: this decomposition is not directly used in the Higgs search: the background is extrapolated from data sidebands
- ▶ Remark 2: Drell-Yan  $\sim$ negligible for  $m_{\gamma\gamma} > 100 \text{ GeV}$  ( $\sim 1\%$ )



# Event categorisation

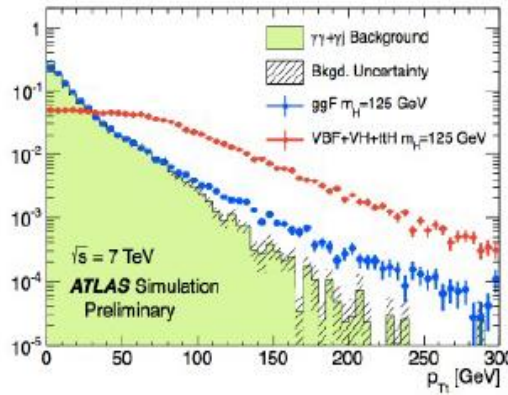
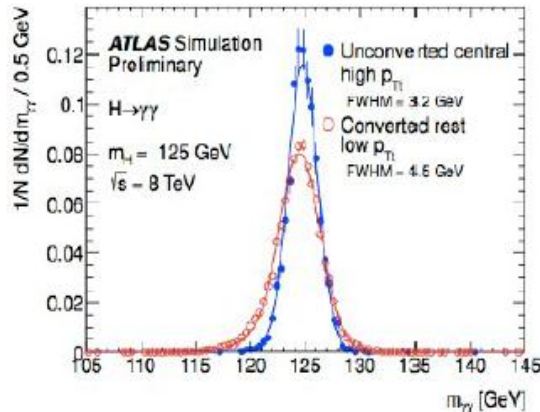
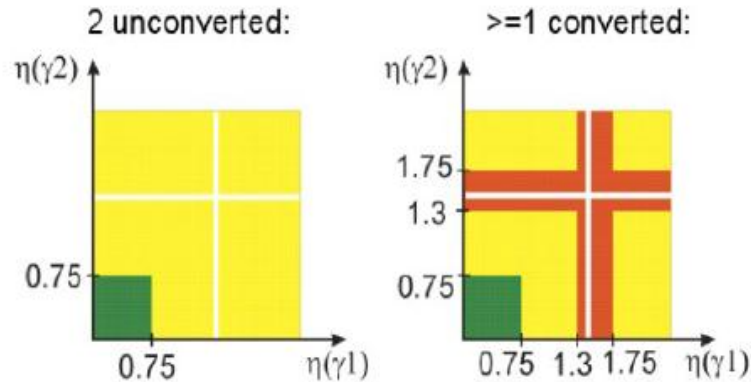
Event categories based on eta,  $p_{Tt}$ , and conversion

Both unconverted:

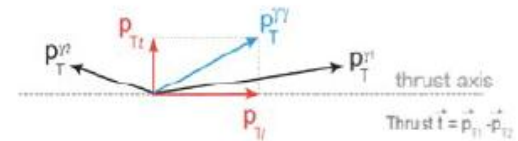
- Central
- Rest

At least one converted:

- Central
- Transition
- Rest



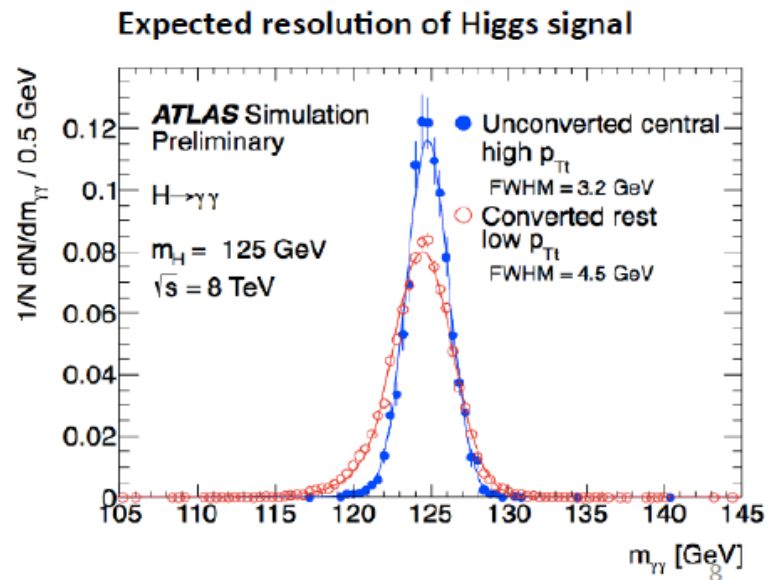
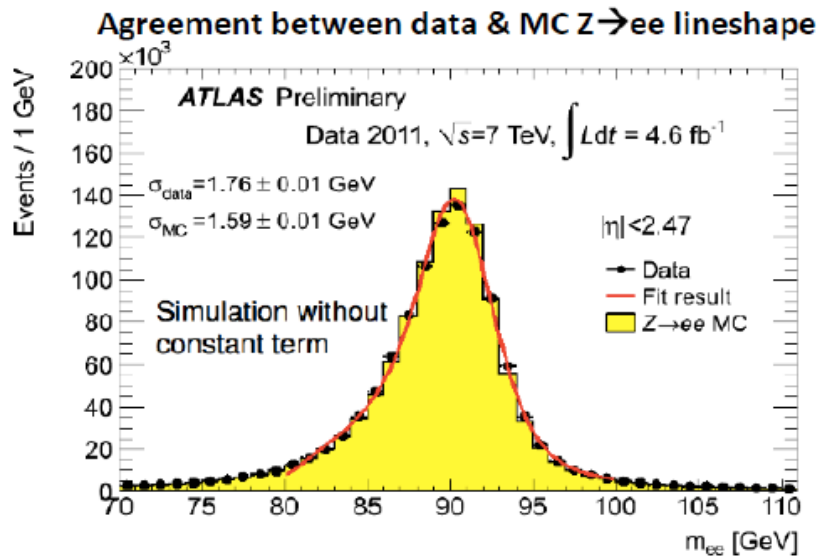
Central and Rest divided into  $p_{Tt} < 60 \text{ GeV}$  and  $p_{Tt} > 60 \text{ GeV}$



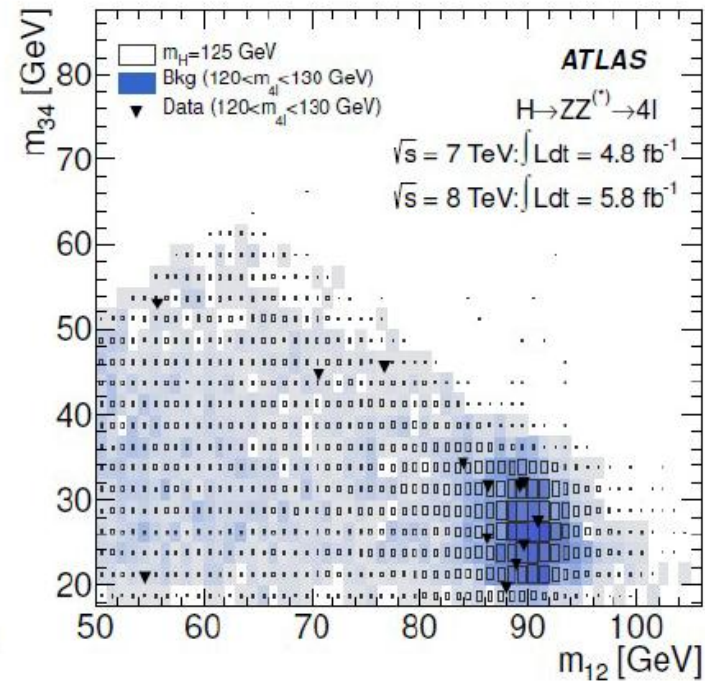
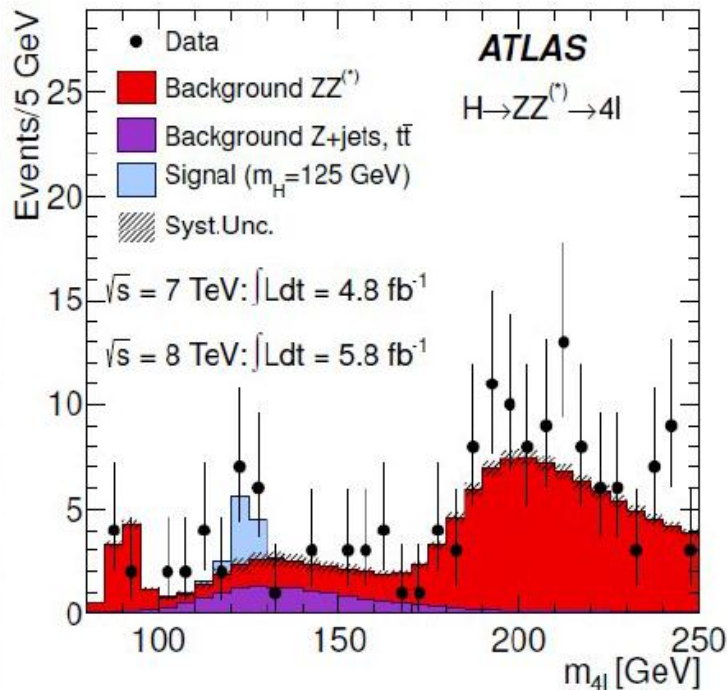
# Energy calibration and resolution

$$m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos \alpha)$$

- MC based calibration improved with energy scale and resolution corrections based on in-situ analysis of  $Z \rightarrow ee$ ,  $W \rightarrow ev$  and  $J/\psi \rightarrow ee$
- Energy scale at  $m_Z$  known to 0.3%, uniformity (constant term) 1% in barrel, 1.2 – 2.1% in endcap



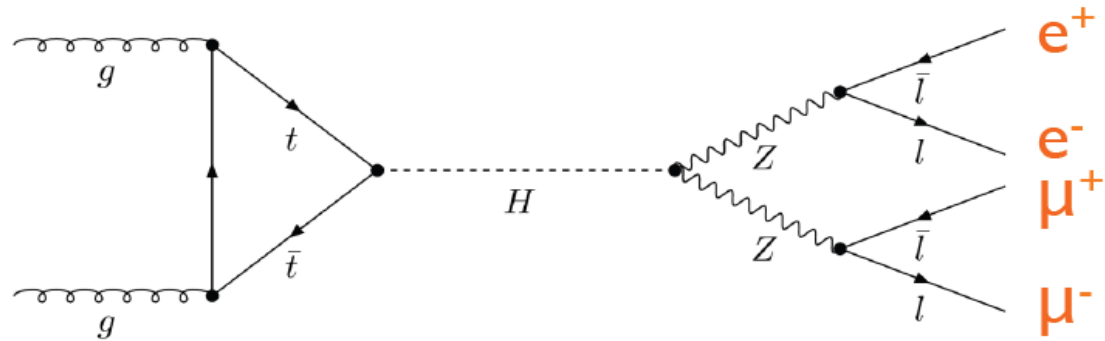
# The golden channel $Z \rightarrow ll$



In a  $m_{4l}$  window  
 around 120-130 GeV:

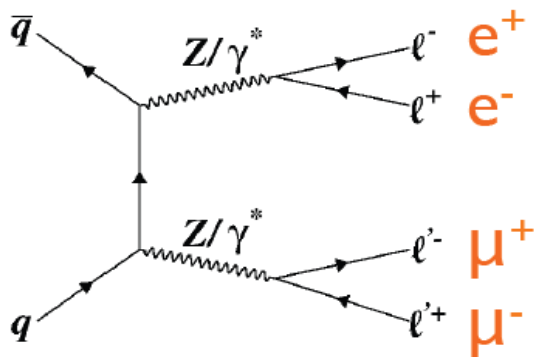
	Signal	$ZZ^{(*)}$	$Z + \text{jets}, t\bar{t}$	Observed
$4\mu$	$2.09 \pm 0.30$	$1.12 \pm 0.05$	$0.13 \pm 0.04$	6
$2e2\mu/2\mu2e$	$2.29 \pm 0.33$	$0.80 \pm 0.05$	$1.27 \pm 0.19$	5
$4e$	$0.90 \pm 0.14$	$0.44 \pm 0.04$	$1.09 \pm 0.20$	2

# Signal and background



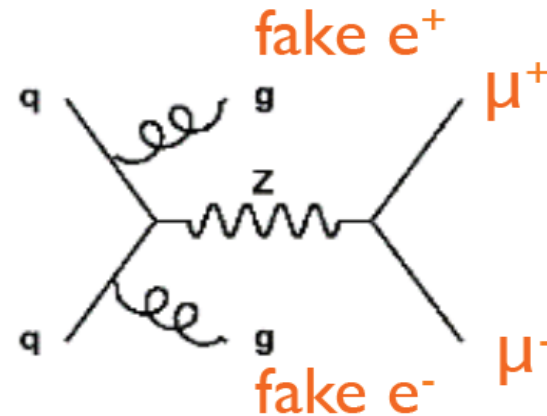
## Irreducible background

The final state is exactly the same, but it does not come from the particle you are looking for



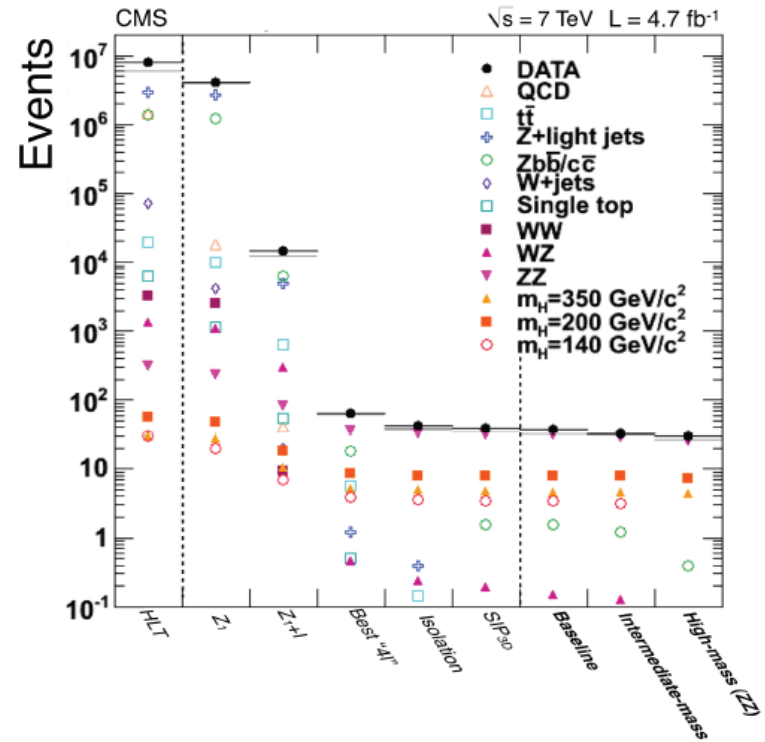
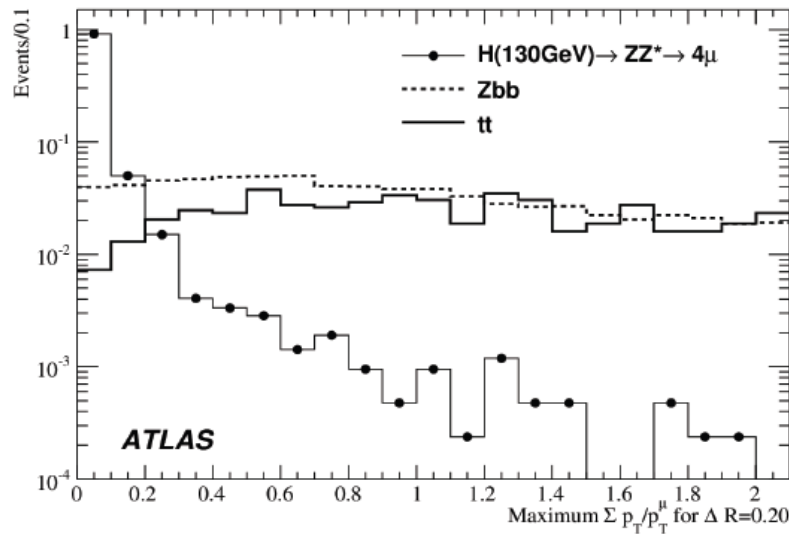
## Reducible background

The final state looks like the same, but some of the particles fake what you are looking for



# Selection

- Cut on particle properties to reduce reducible background
  - ✓ Shower shapes, track properties, ...
- Cut on event properties to distinguish signal from background
  - ✓ Particle kinematics, decay kinematics event shape, ...
- Try to keep signal while reducing background!
  - ✓ Increase S/B



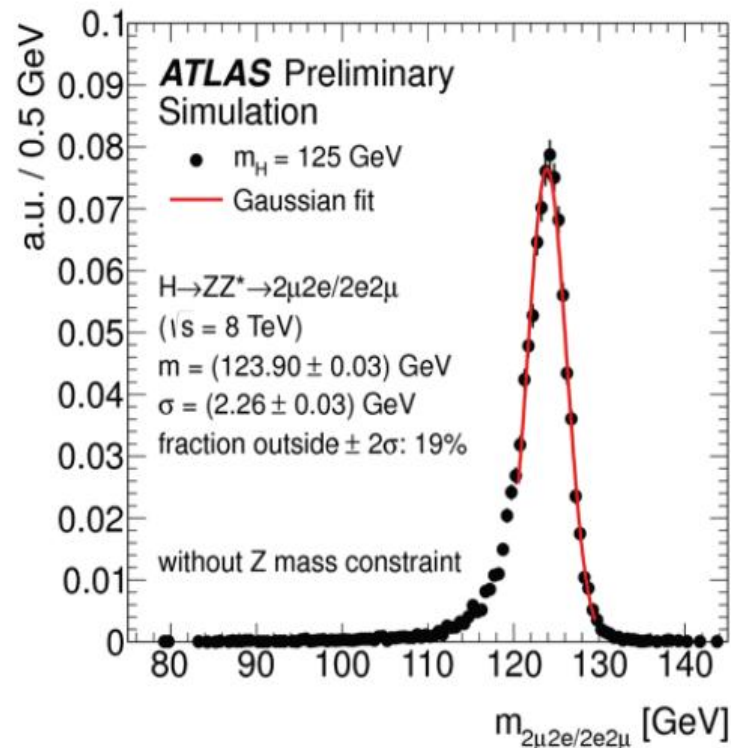
# Reconstruct properties of initial particles

- We have 4 particles...
  - ✓ ... with their energy (calorimeters), charge and momentum (tracker)

- Use pairs of opposite sign  $e^+e^-$  and  $\mu^+\mu^-$

- Reconstruct invariant mass from the 4 particles

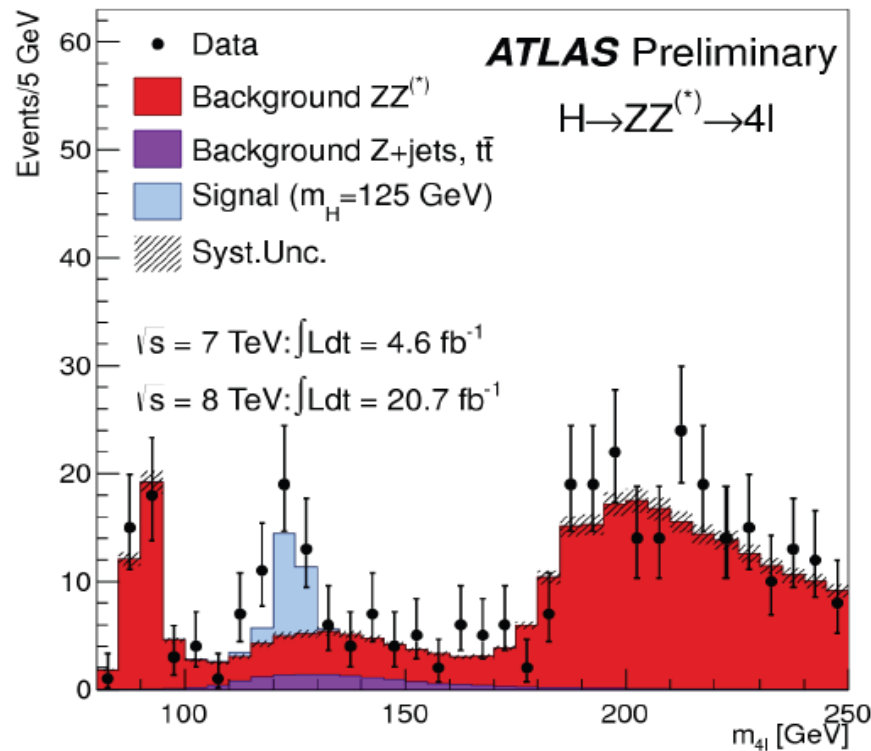
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



# Signal and background

Background gets estimated...

- ✓ ... from simulation (normalized to data)
- ✓ ... directly from data (“control regions”, enriched in background events)



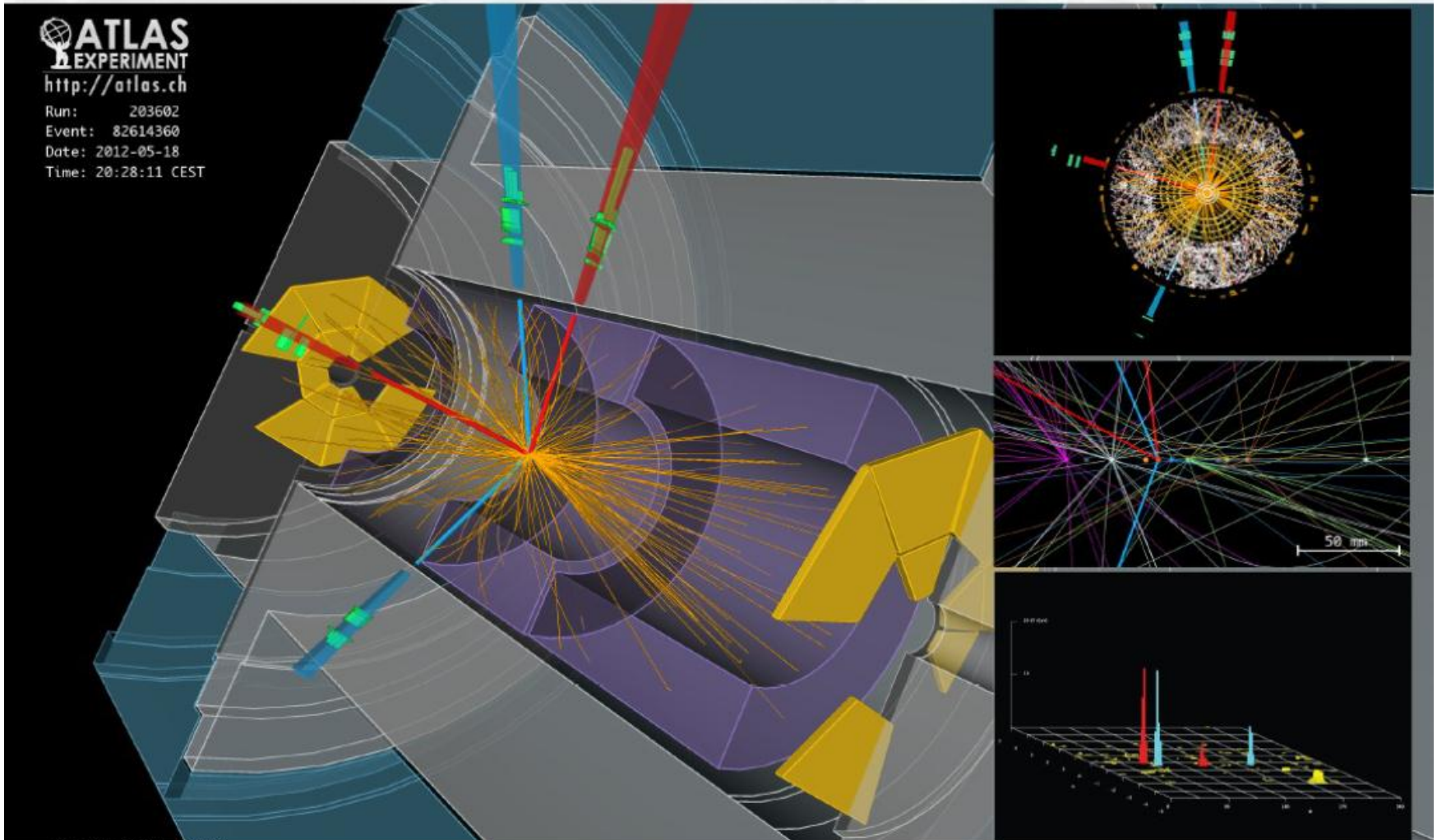
4e candidate.  $m_{4\ell} = 124.6$  GeV,  $m_{12} = 70.6$  GeV,  $m_{34} = 44.7$  GeV.

$e_1$ :  $P_T = 24.9$  GeV,  $\eta = -0.33$ ,  $\phi = 1.98$

$e_2$ :  $P_T = 53.9$  GeV,  $\eta = -0.40$ ,  $\phi = 1.69$

$e_3$ :  $P_T = 61.9$  GeV,  $\eta = -0.12$ ,  $\phi = 1.45$

$e_4$ :  $P_T = 17.8$  GeV,  $\eta = -0.51$ ,  $\phi = 2.84$

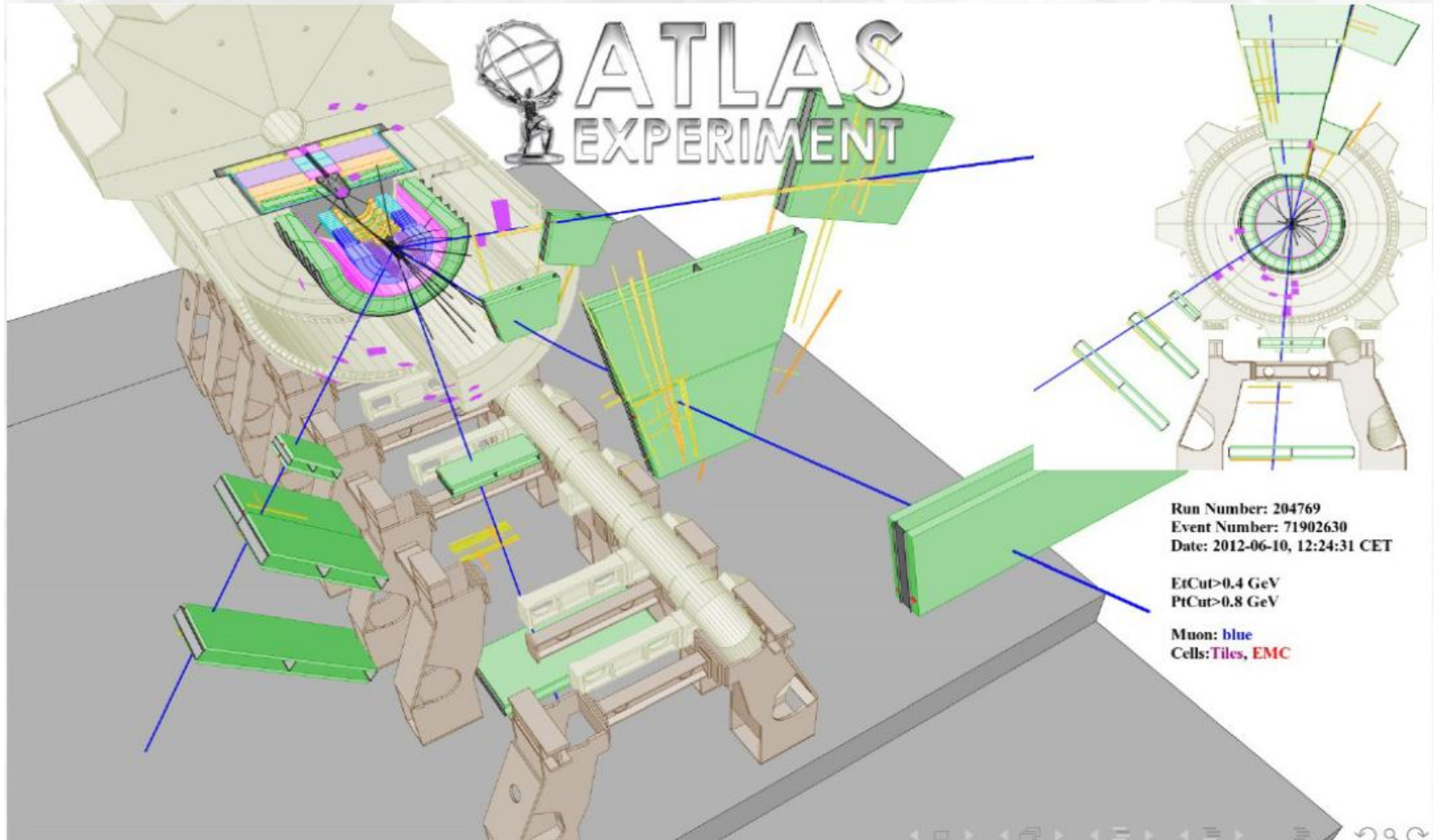




$4\mu$  candidate.  $m_{4\ell} = 125.1$  GeV,  $m_{12} = 86.3$  GeV,  $m_{34} = 31.6$  GeV.

$\mu_1: P_T = 36.1$  GeV,  $\eta = 1.29$ ,  $\phi = 1.33$        $\mu_2: P_T = 47.5$  GeV,  $\eta = 0.69$ ,  $\phi = -1.65$

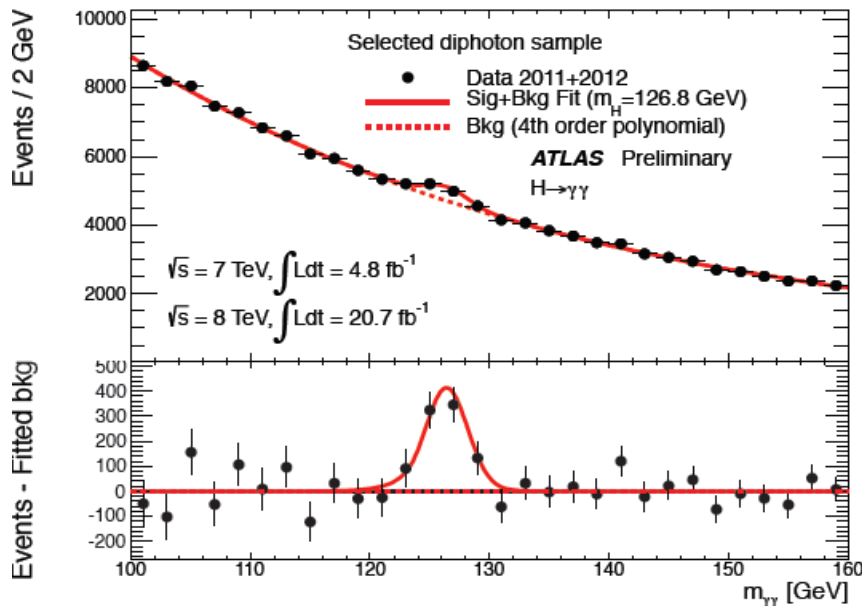
$\mu_3: P_T = 26.4$  GeV,  $\eta = 0.47$ ,  $\phi = -2.51$        $\mu_4: P_T = 71.7$  GeV,  $\eta = 1.85$ ,  $\phi = 1.65$



# Higgs like signal with 7 TeV and 8 TeV data

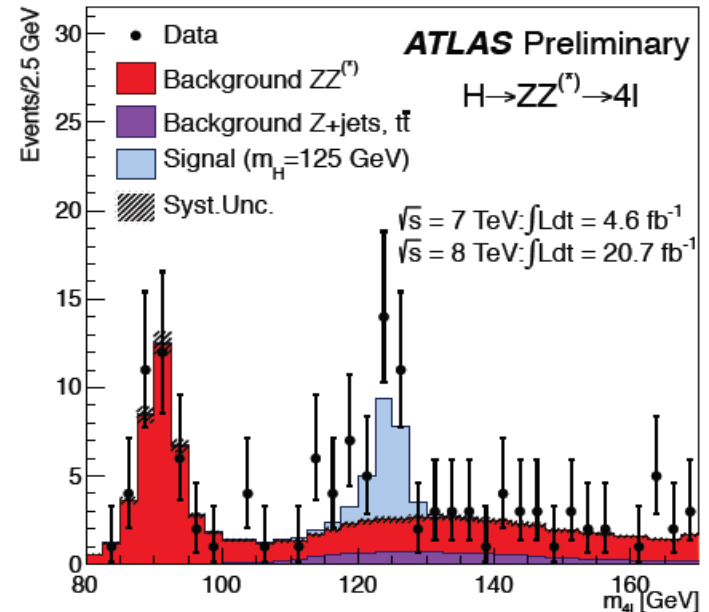
2013

$H \rightarrow \gamma\gamma$



- Signal significance =  $7.4 \sigma$
- $m_H = 126.8 \pm 0.2$  (stat)  $\pm 0.7$  (syst) GeV
- $\mu = 1.65 \pm 0.34$  (deviation w.r.t. SM at  $2.3\sigma$ )

$H \rightarrow 4l$



- Signal significance =  $6.6 \sigma$
- $m_H = 124.3^{+0.6}_{-0.5}$  (stat)  $^{+0.6}_{-0.3}$  (syst) GeV
- $\mu = 1.7 \pm 0.34$

# And since then .... (2013)

## Panorama of ATLAS Higgs (125) Analyses

channel	ggF	VBF	VH	ttH	Yield	S/B (%)	Res. (GeV/c <sup>2</sup> )
$\gamma\gamma$	✓	✓	✓	✓	~ 450	1 - 20%	~ 1.6
$ZZ \rightarrow 4l$	✓				~ 16	1	~ 2.2
$WW \rightarrow l\nu l\nu$	✓	✓	✓		~ 250	10%	Poor
$\tau\tau$	✓	✓	✓		~ 330	0.3 – 30%	~ 20
VH(bb)			✓		~ 50	1 - 10%	~ 15
ttH(bb)				✓	~20	Up to ~5%	Poor (combinatorial)
$\mu\mu$	Inclusive				~ 40	~ 0.2 %	~ 2.5
Invisible	(✓)		✓		~ 30	~ 0.2	Poor
$Z\gamma$	Inclusive				~ 15	~ 0.5%	~ 1.8

# $H \rightarrow \gamma\gamma$ Update

Since “Discovery Paper” PLB 716  
ATLAS-CONF-2013-012

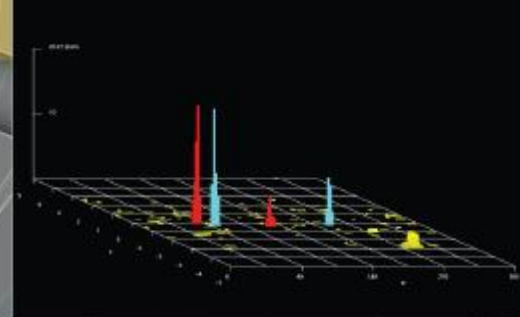
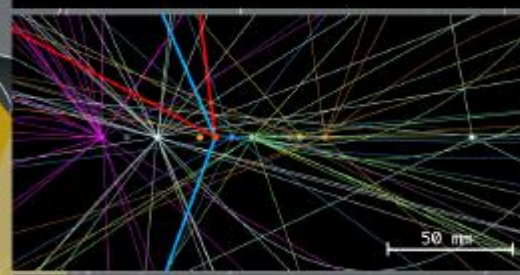
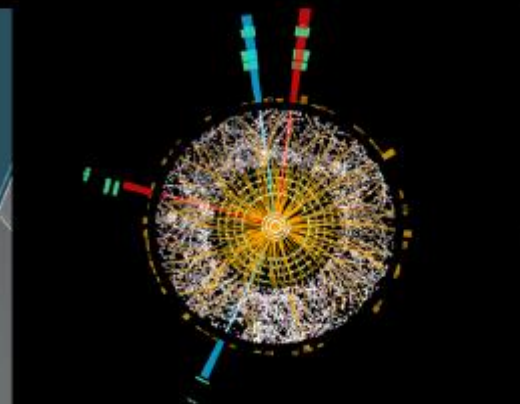
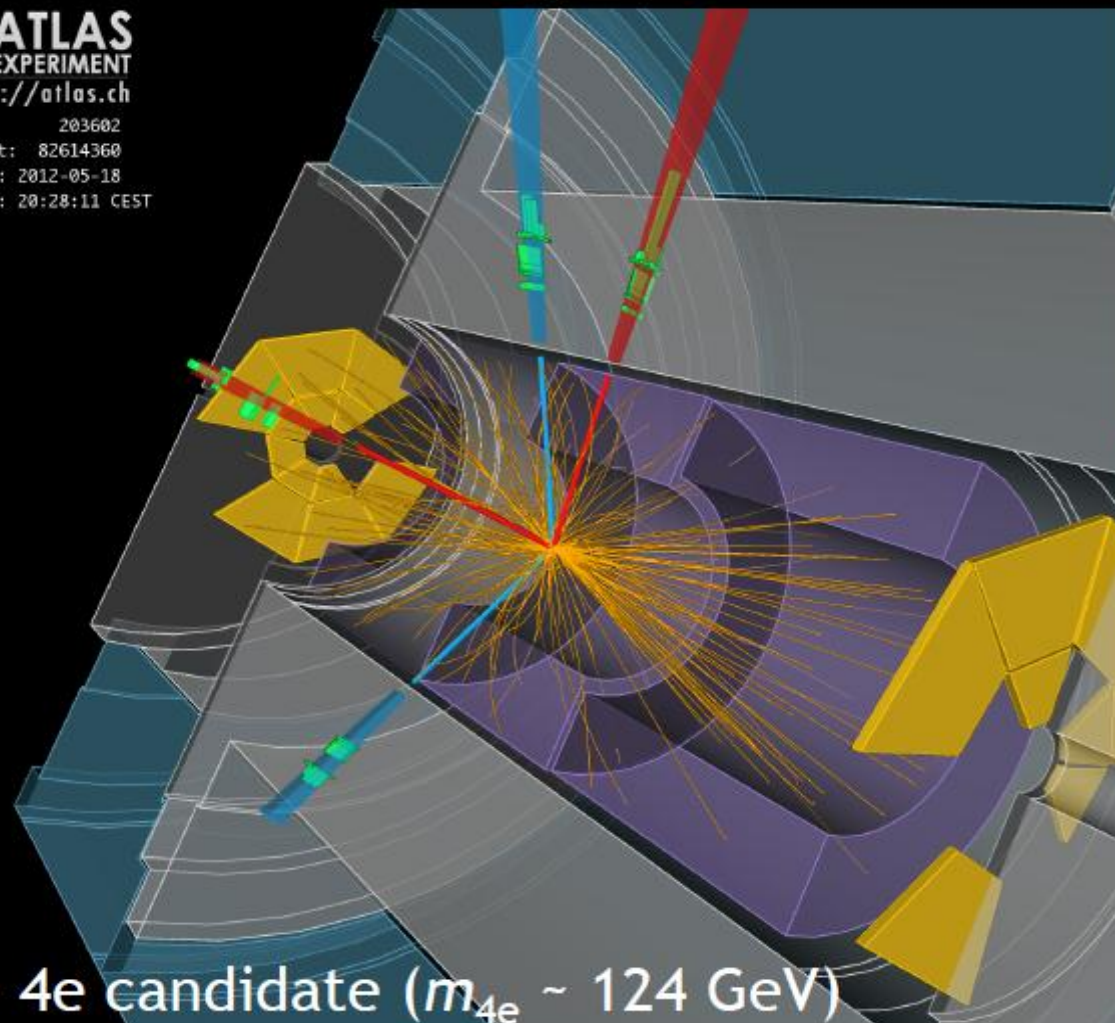


Run Number: 204769, Event Number: 24947130

Date: 2012-06-10 08:17:12 UTC

## $\gamma\gamma$ channel basic facts sheet :

Signal ( $SM_{126 \text{ GeV}}$ )	Signal purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L dt$
~450	2% - 60%	$\gamma\gamma, \gamma j$ and $jj$	Hgg, VBF, VH	4.9 & 20.7 $fb^{-1}$



$H \rightarrow 4e$  candidate ( $m_{4e} \sim 124$  GeV)

4l channel basic facts sheet :

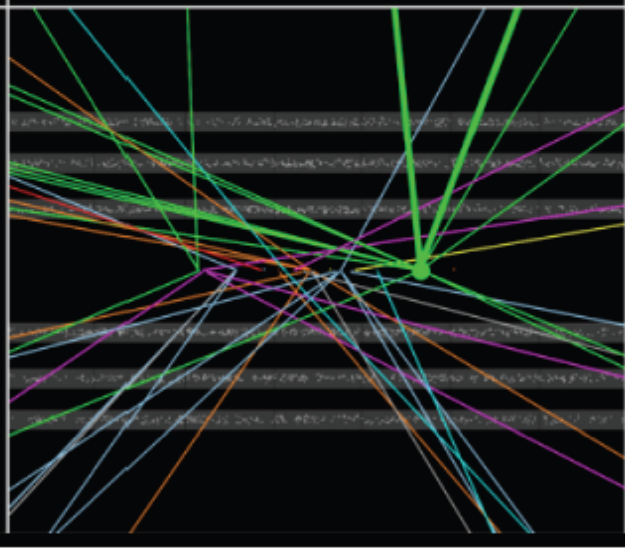
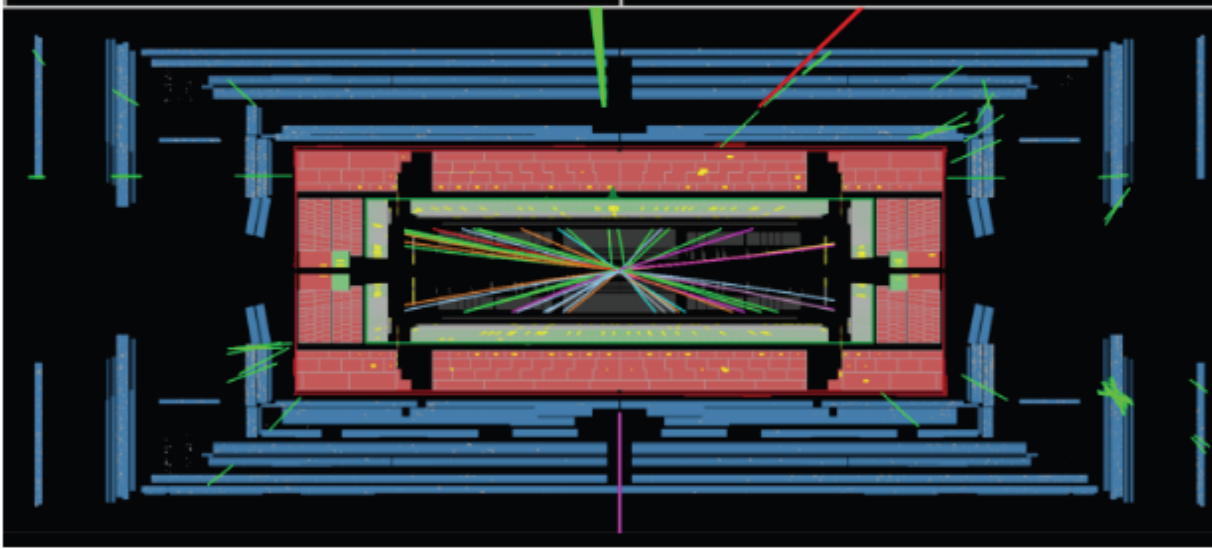
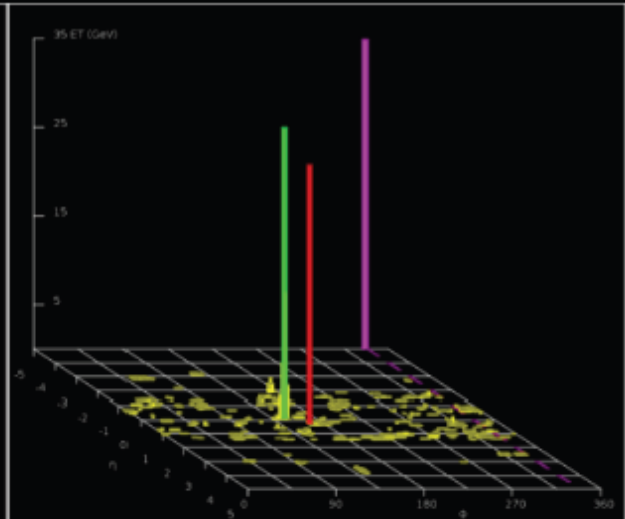
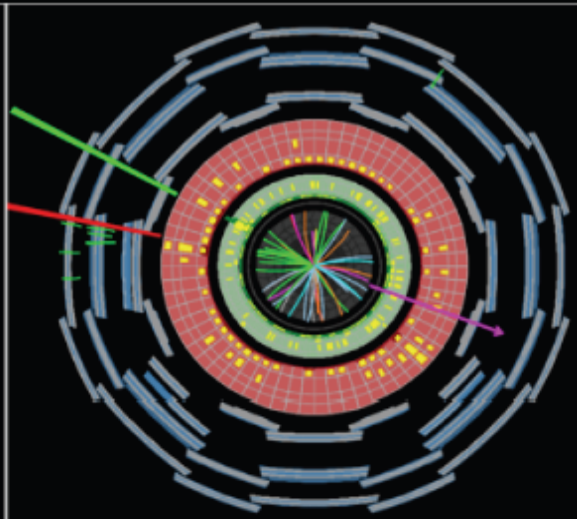
Signal	Signal Purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L dt$
$\sim 16$	$\sim 1.5$	ZZ, Z+jets, top	ggH, VBF & VH	4.9 & 20.7 fb <sup>-1</sup>

$$H \rightarrow WW^{(*)}$$

$$ll + 2\nu$$

0,1, 2 jet Channel

ATLAS-CONF-2013-030



WW channel basic facts sheet :

Signal	Sig. Purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L dt$
~250	~5%-40%	WW, W+jets, top, etc...	ggH & VBF	25fb <sup>-1</sup>

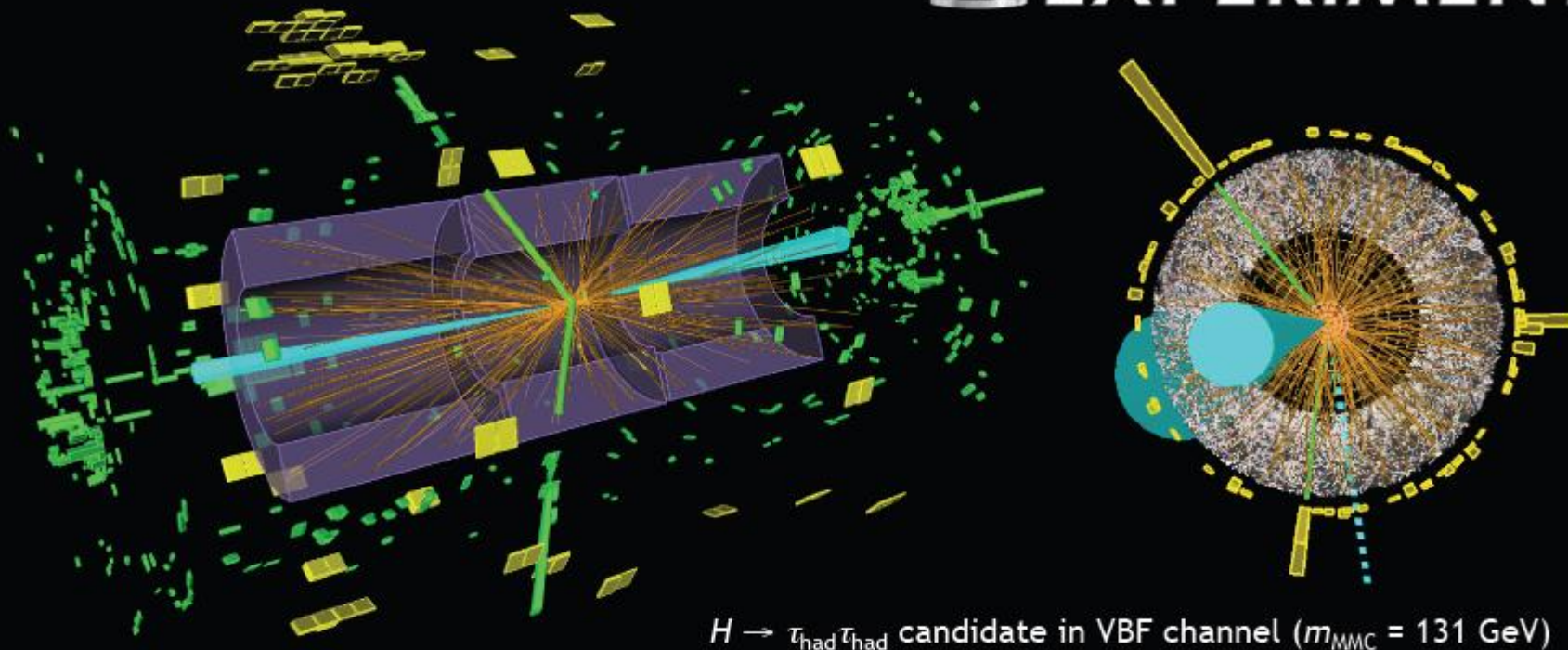
$H \rightarrow \tau\tau$

Reoptimised 7+8 TeV analysis

ATLAS-CONF-2012-160



ATLAS  
EXPERIMENT

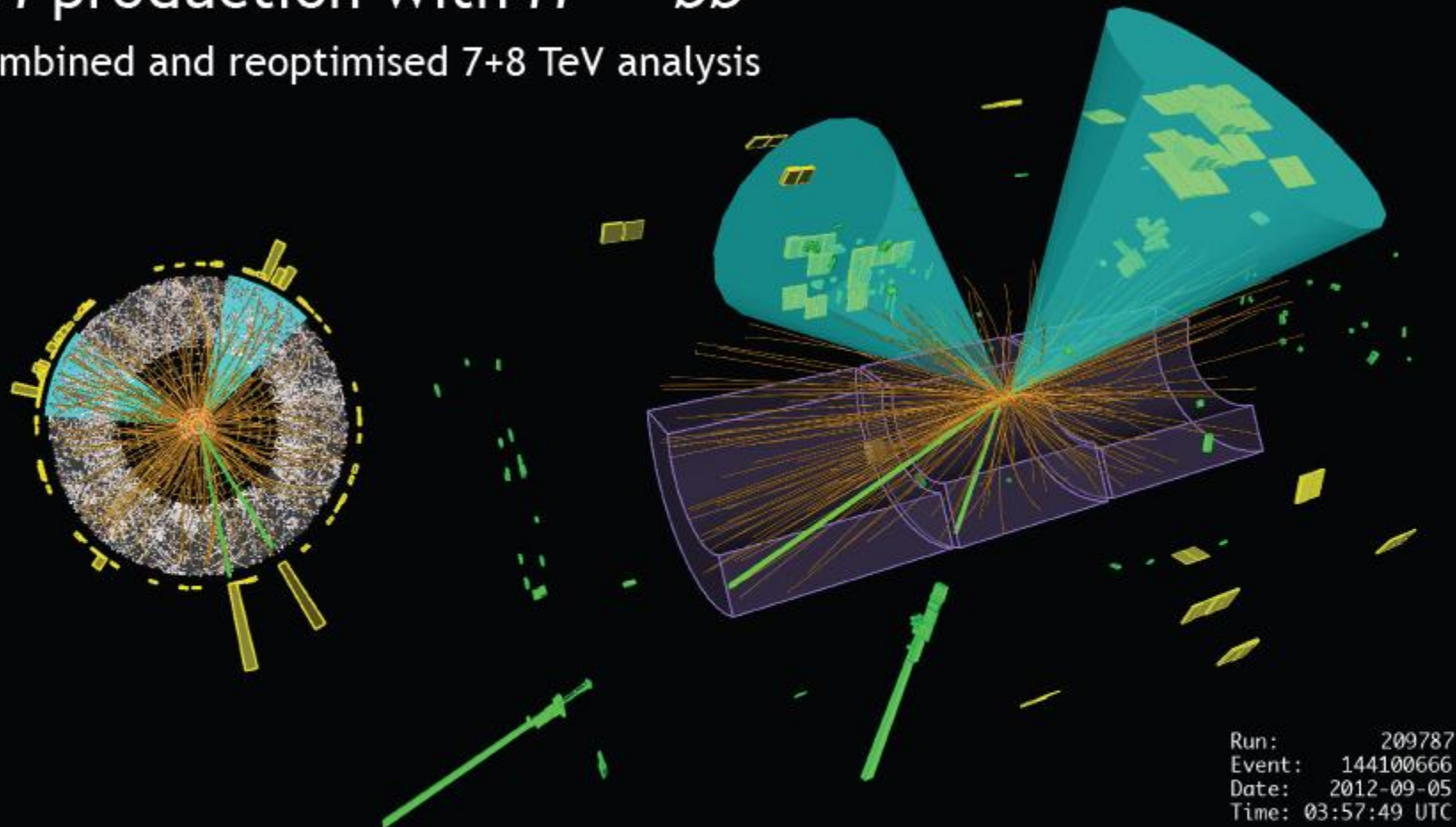


$\tau\tau$  channel basic facts sheet :

Signal (SM)	Signal purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L dt$
~330	0.3% - 30%	ZZ, Z+jets, top	VBF, Hgg, VH	4.9 & 13 fb <sup>-1</sup>

# VH production with $H \rightarrow bb$

Combined and reoptimised 7+8 TeV analysis



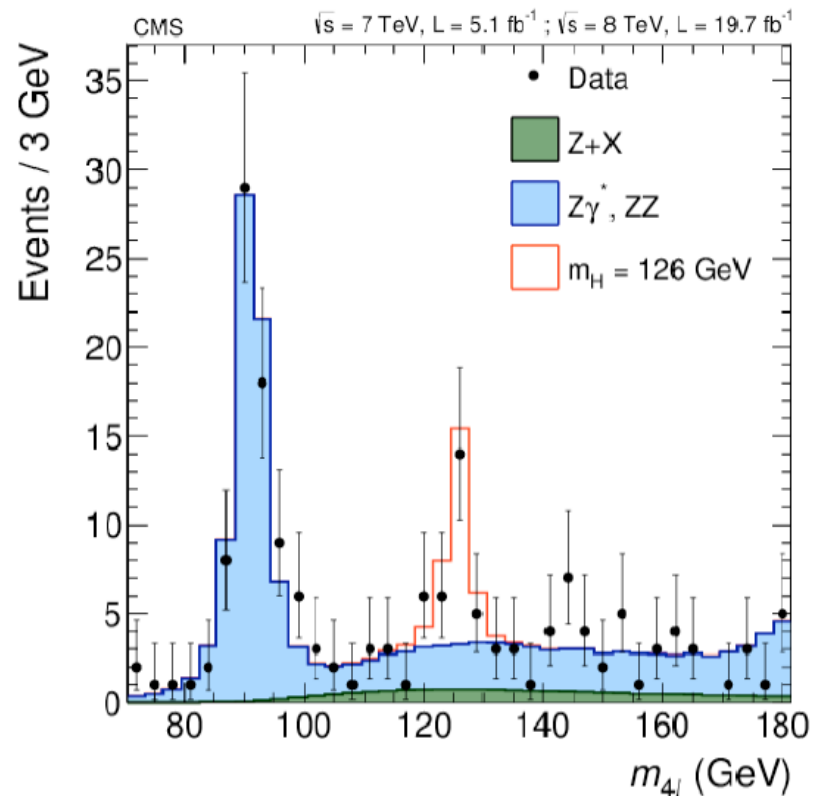
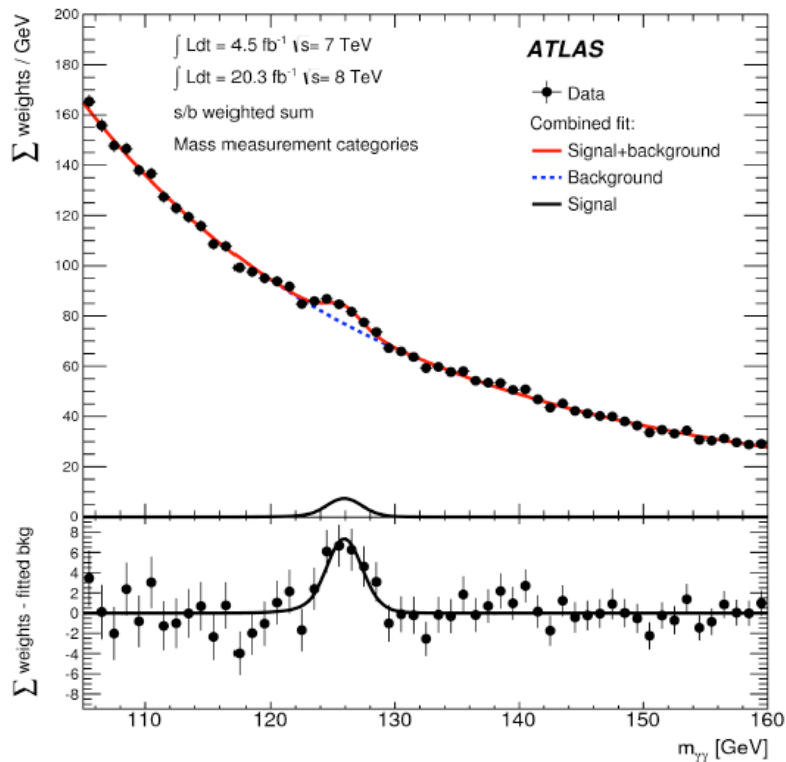
## VH(bb) channel basic facts sheet :

Signal (SM)	Signal purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L dt$
~50	~1% - 10%	Wbb,Zbb, top, etc...	VH	4.9 & 13 fb <sup>-1</sup>



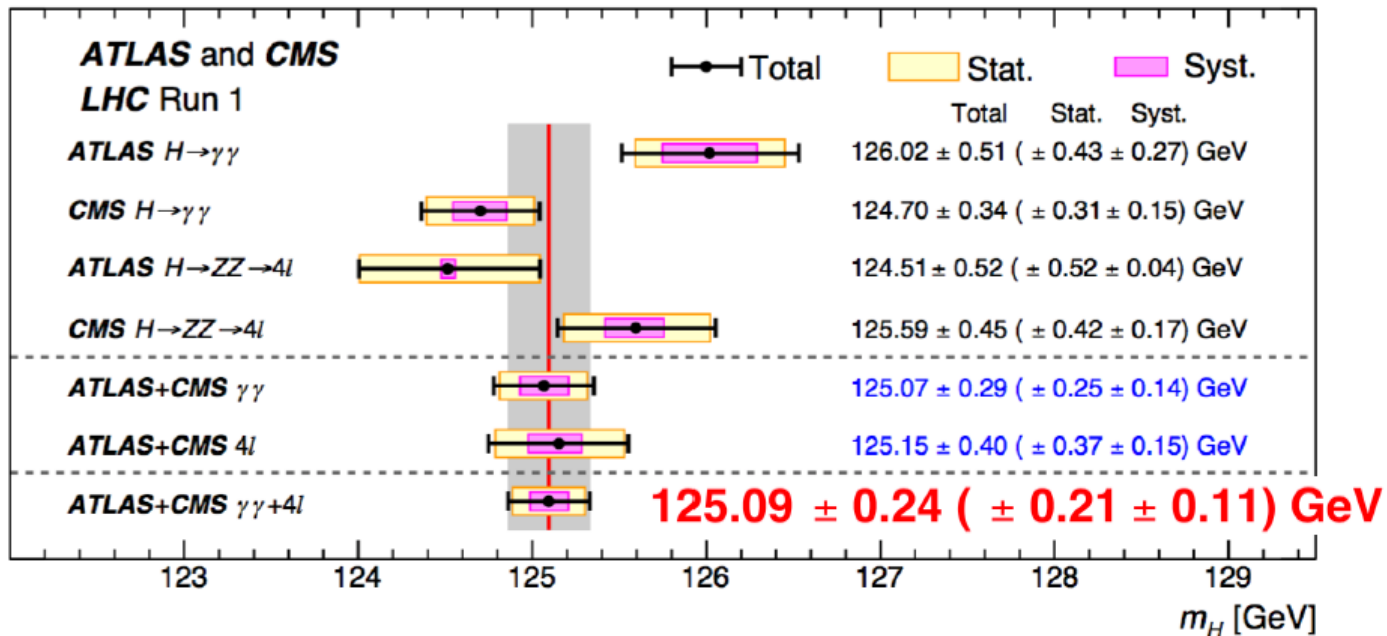
# Mass measurement

- ATLAS+CMS combination on mass measurement with high-resolution channels:  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ \rightarrow 4l$



# Mass measurement

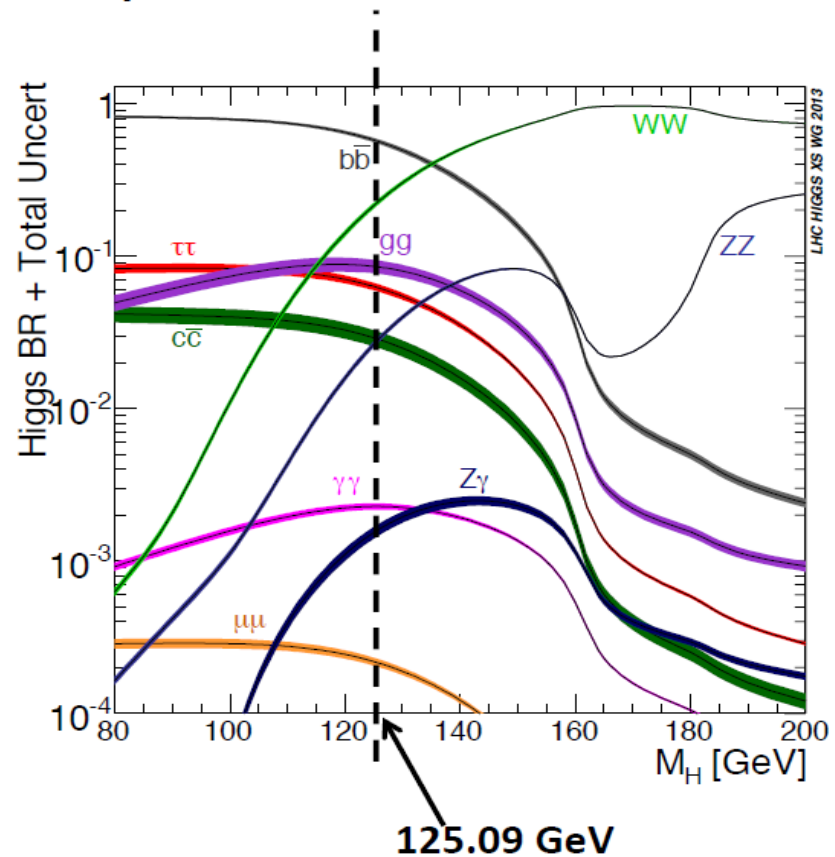
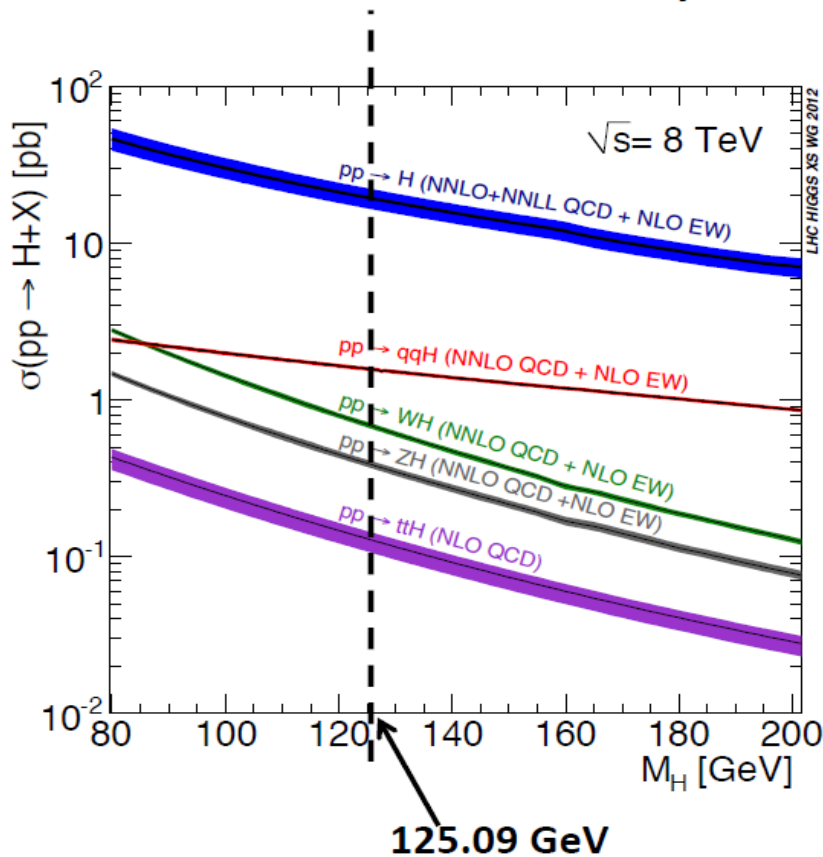
ATLAS+CMS combination on mass measurement with high-resolution channels:  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ \rightarrow 4l$



- Mass of Higgs boson measured with <0.2% precision
- Statistical uncertainty still dominates
- Dominant systematics: energy/momentum scale for  $\gamma, e, \mu$

# With the mass measured

- SM predictions for production mode cross sections and decay BR fully determined



# How significant is the signal for the new particle?

**Parameters scale cross sections and BRs relative to SM**

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \quad \mu^f = \frac{\text{BR}^f}{\text{BR}_{\text{SM}}^f}$$

**Scaling of generic  $i \rightarrow \text{H} \rightarrow f$  process**

$$\mu_i^f \equiv \frac{\sigma_i \cdot \text{BR}^f}{(\sigma_i \cdot \text{BR}^f)_{\text{SM}}} = \mu_i \times \mu^f$$

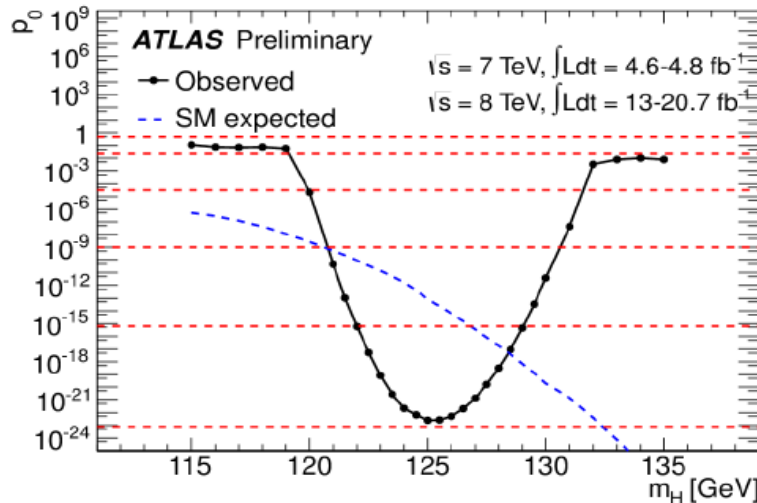
# How significant is the signal for the new particle?

Observed data compared to the probability that the background fluctuates to fake the observed excess of events, and what is expected from a SM Higgs

Mass =  $125.36 \pm 0.37$  (stat)  $\pm 0.18$  (syst) GeV [ATLAS]  
 $125.03 \pm 0.26$  (stat)  $\pm 0.14$  (syst) GeV [CMS]

Signal strength

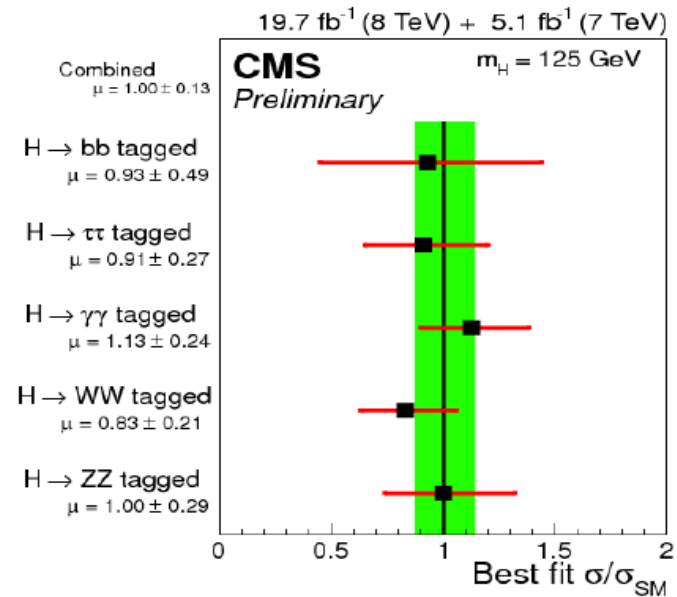
$\mu = 0$  background only hypothesis  
 $\mu = 1$  SM Higgs hypothesis



ATLAS-CONF-2013-034, 2014-009

CMS-PAS-HIG-14-009

Phys. Rev. D 90 (2014) 052004



$\mu = 1.30 \pm 0.18$  [ATLAS]

$\mu = 1.00 \pm 0.13$  [CMS]

112

# Which Higgs boson we have discovered?

Higgs boson was discovered in  $ZZ^*$ ,  $\gamma\gamma$  and  $WW^*$  decays

- Higgs boson mass is  $\sim 125.6$  GeV

Measured in  $H \rightarrow ZZ^* \rightarrow 4l$  and  $H \rightarrow \gamma\gamma$

ATLAS:  $m_H = 125.5 \pm 0.2$  (stat)  $\pm 0.6$  (syst) GeV

CMS:  $m_H = 125.7 \pm 0.3$  (stat)  $\pm 0.3$  (syst) GeV

- ATLAS and CMS data strongly favour  $J^P = 0^+$  SM quantum numbers; alternative models excluded at 95% CL.
- Signal strength  $\mu = \sigma/\sigma_{SM}$  consistent with 1

## Summer 2013:

All measured properties are compatible with SM hypothesis.

# Entrance of the Higgs into PDG

2013

## Higgs Bosons — $H^0$ and $H^\pm$

A REVIEW GOES HERE – Check our WWW List of Reviews

NODE=S055  
NODE=S055

### CONTENTS:

NODE=S055CNT  
NODE=S055CNT

#### $H^0$ (Higgs Boson)

- $H^0$  Mass
- $H^0$  Spin
- $H^0$  Decay Width
- $H^0$  Decay Modes
- $H^0$  Signal Strengths in Different Channels
  - Combined Final States
  - $W^+W^-$  Final State
  - $ZZ^*$  Final State
  - $\gamma\gamma$  Final State
  - $b\bar{b}$  Final State
  - $\tau^+\tau^-$  Final State
- Standard Model  $H^0$  (Higgs Boson) Mass Limits
  - $H^0$  Direct Search Limits
  - $H^0$  Indirect Mass Limits from Electroweak Analysis
- Searches for Other Higgs Bosons
  - Mass Limits for Neutral Higgs Bosons in Supersymmetric Models
    - $H^0$  (Higgs Boson) Mass Limits in Supersymmetric Models
    - $A^0$  (Pseudoscalar Higgs Boson) Mass Limits in Supersymmetric Models
  - $H^0$  (Higgs Boson) Mass Limits in Extended Higgs Models
    - Limits in General two-Higgs-doublet Models
    - Limits for  $H^0$  with Vanishing Yukawa Couplings
    - Limits for  $H^0$  Decaying to Invisible Final States
    - Limits for Light  $A^0$
    - Other Limits
  - $H^\pm$  (Charged Higgs) Mass Limits
  - Mass Limits for  $H^{\pm\pm}$  (doubly-charged Higgs boson)
    - Limits for  $H^{\pm\pm}$  with  $T_3 = \pm 1$
    - Limits for  $H^{\pm\pm}$  with  $T_3 = 0$

#### $H^0$ (Higgs Boson)

NODE=S055CNT

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

NODE=S055210

NODE=S055210

#### $H^0$ MASS

VALUE (GeV)

#### 125.0 ± 0.4 OUR AVERAGE

	DOCUMENT ID	TECN	COMMENT
125.0 ± 0.4 ± 0.4	<sup>1</sup> CHATRCHYAN13J	CMS	$pp$ , 7 and 8 TeV
126.0 ± 0.4 ± 0.4	<sup>2</sup> AAD	12N ATLAS	$pp$ , 7 and 8 TeV
••• We do not use the following data for averages, fits, limits, etc. •••			
126.2 ± 0.0 ± 0.2	<sup>3</sup> CHATRCHYAN13J	CMS	$pp$ , 7 and 8 TeV
125.3 ± 0.4 ± 0.5	<sup>4</sup> CHATRCHYAN12N	CMS	$pp$ , 7 and 8 TeV

NODE=S055HBM  
NODE=S055HBM

OCCUR=2

<sup>1</sup> Combined value from  $ZZ$  and  $\gamma\gamma$  final states.

<sup>2</sup> AAD 12N obtain results based on  $4.6\text{--}4.8\text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{CM}} = 7\text{ TeV}$  and  $5.9\text{--}5.9\text{ fb}^{-1}$  at  $E_{\text{CM}} = 8\text{ TeV}$ . An excess of events over background with a local significance of  $3.9\sigma$  is observed at  $m_{H^0} = 126\text{ GeV}$ . See also AAD 120A.

<sup>3</sup> Result based on  $ZZ \rightarrow 4\ell$  final states in  $5.1\text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{CM}} = 7\text{ TeV}$  and  $12.2\text{ fb}^{-1}$  at  $E_{\text{CM}} = 8\text{ TeV}$ .

<sup>4</sup> CHATRCHYAN 12N obtain results based on  $4.9\text{--}5.1\text{ fb}^{-1}$  of  $pp$  collisions at  $E_{\text{CM}} = 7\text{ TeV}$  and  $5.1\text{--}5.1\text{ fb}^{-1}$  at  $E_{\text{CM}} = 8\text{ TeV}$ . An excess of events over background with a local significance of  $5.0\sigma$  is observed at about  $m_{H^0} = 125\text{ GeV}$ . See also CHATRCHYAN 120Y.

NODE=S055HBM;LINKAGE=CA  
NODE=S055HBM;LINKAGE=AA

NODE=S055HBM;LINKAGE=CT

NODE=S055HBM;LINKAGE=CH

Inaugural entrance of the Higgs boson in the PDG particle listing !

# $H^0$

# Standard Model particles

Model interaction  
between fermions  
**quarks**  
**leptons**

Through **boson**  
exchange

EM :  $\gamma$

weak :  $W^+$ ,  $W^-$ ,  $Z$

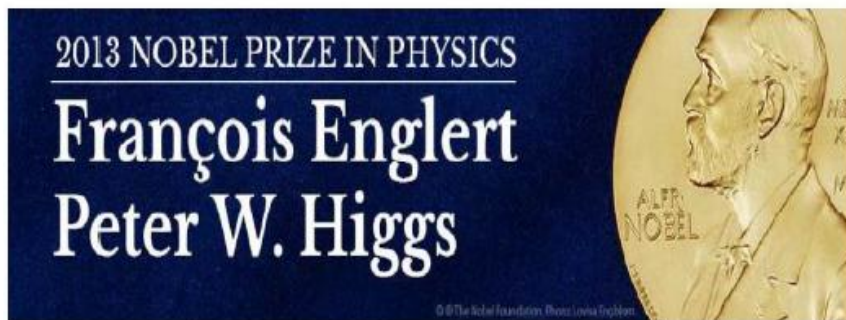
strong : gluons

Higgs boson

		fermions (3 générations de la matière)			bosons (forces)	
		I	II	III		
masse →		2.4 MeV	1.27 GeV	171.2 GeV	0	électromagnétisme
charge →		$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	
spin →		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
nom →		<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b><math>\gamma</math></b> photon	
	Quarks	4.8 MeV	104 MeV	4.2 GeV	0	interaction forte
		$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon	
	Leptons	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV	interaction faible
		0	0	0	0	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		<b><math>\nu_e</math></b> neutrino électronique	<b><math>\nu_\mu</math></b> neutrino muonique	<b><math>\nu_\tau</math></b> neutrino tauique	<b><math>Z^0</math></b> boson $Z^0$	
		0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV	interaction faible
		-1	-1	-1	$\pm 1$	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		<b>e</b> électron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b><math>W^\pm</math></b> boson W	
					$\sim 126$ GeV	interaction faible
					0	
					0	<b>H</b> Higgs



**W dniu 4 lipca 2012, eksperymenty ATLAS i CMS na akceleratorze LHC w laboratorium CERN ogłosiły odkrycie nowej cząstki zgodnej z przewidywaniami tzw. mechanizmu Higgsa.**



8 października 2013

Królewska Szwedzka Akademia Nauk przyznaje Nagrodę Nobla w dziedzinie fizyki

***„ za sformułowanie mechanizmu który wyjaśnia źródło masy cząstek elementarnych i który został potwierdzony poprzez odkrycie przewidywanej przez ten mechanizm cząstki elementarnej (eksperymenty ATLAS i CMS na LHC) ”.***

VOLUME 13

PHYSICAL REVIEW LETTERS

1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS\*

F. Englert and R. Brout

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

(Received 26 June 1964)

2 strony

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

1 strona

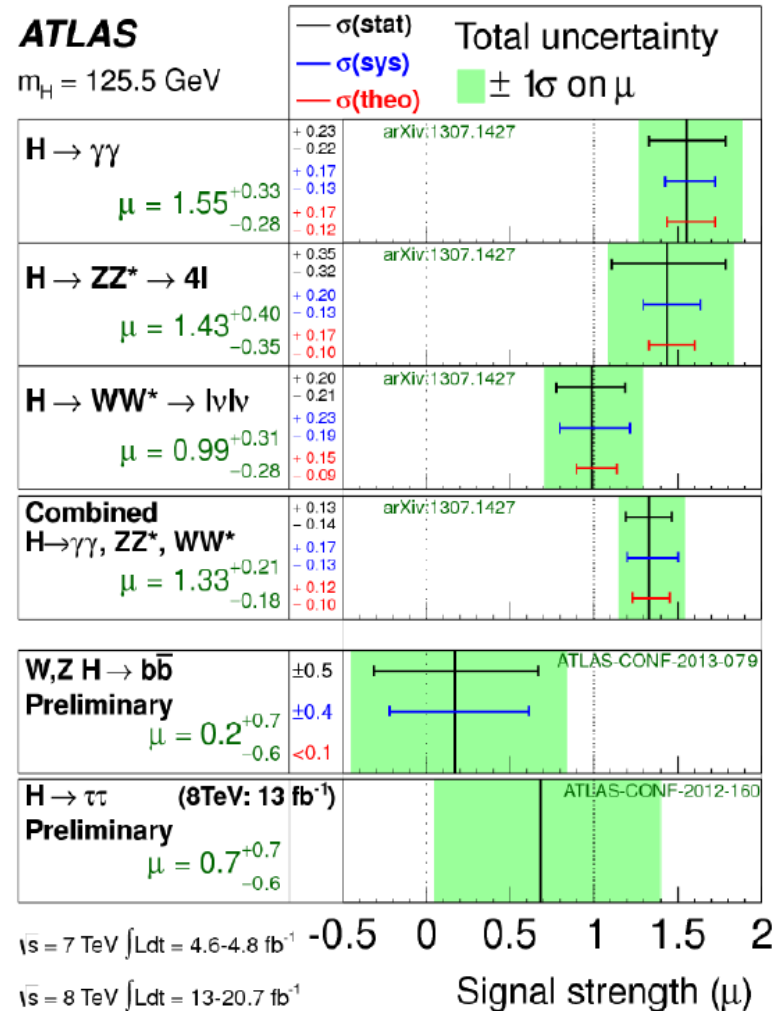
# Higgs boson signal strength

$$\mu = \sigma / \sigma_{SM}$$

Individual channels are consistent

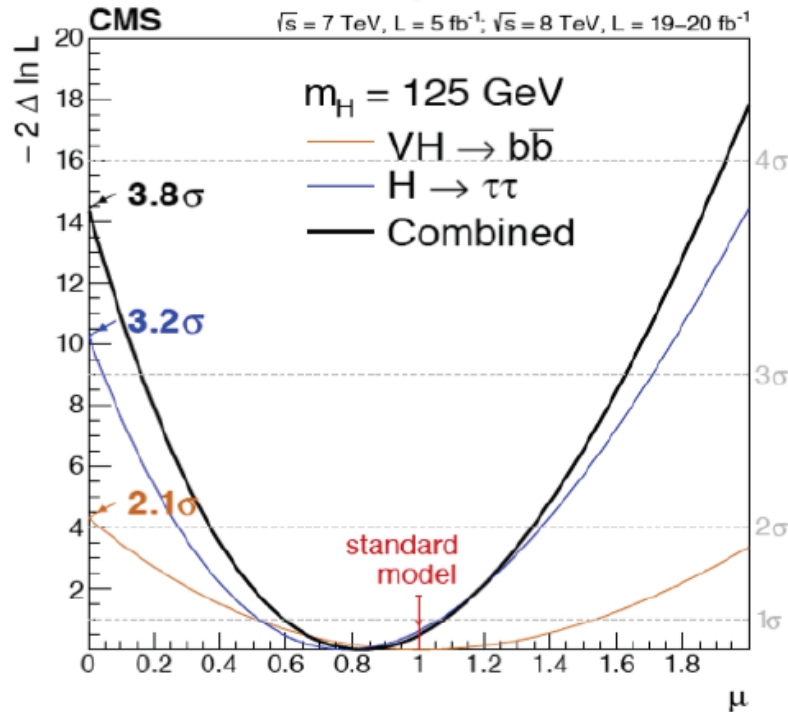
SM describes the rates well, so far

More detailed studies have been done of coupling constraints which can be derived, including on new processes in the loops



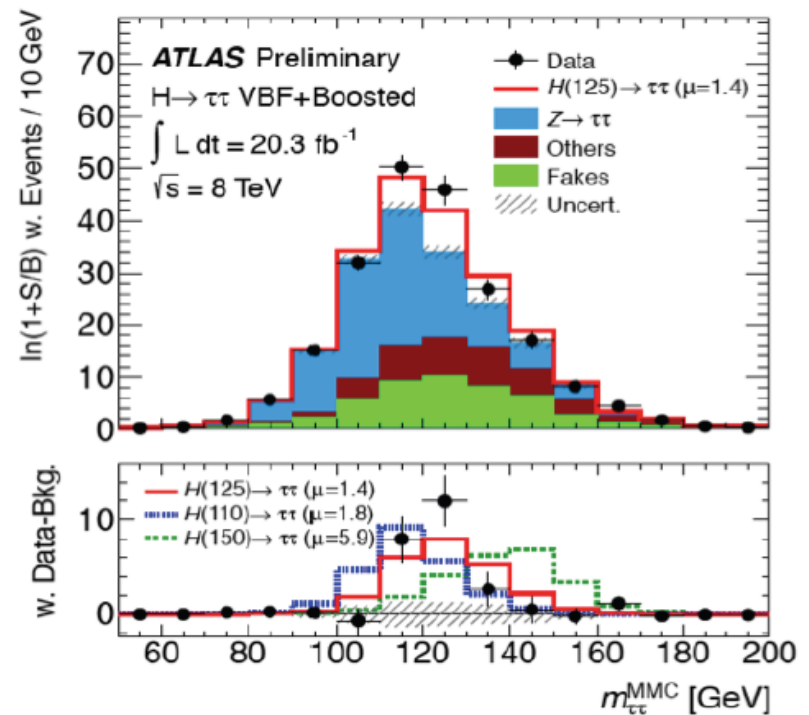
# Higgs decays to fermions (2014)

CMS:  $H \rightarrow \tau\tau, bb$  Channels



Significance	Exp	Obs
CMS ( $\tau\tau$ )	3.4 $\sigma$	3.2 $\sigma$
CMS (bb)	2.1 $\sigma$	2.1 $\sigma$

ATLAS:  $H \rightarrow \tau\tau$  Channel



Significance	Exp	Obs
ATLAS ( $\tau\tau$ )	3.2 $\sigma$	4.1 $\sigma$

Tevatron: exp (2.1 $\sigma$ ), obs (3.0 $\sigma$ )

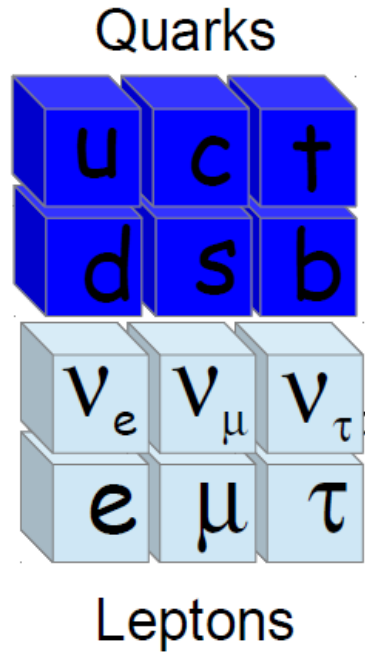
# What spin do particles have?

boson



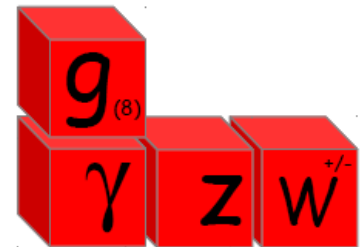
Spin 0

fermions



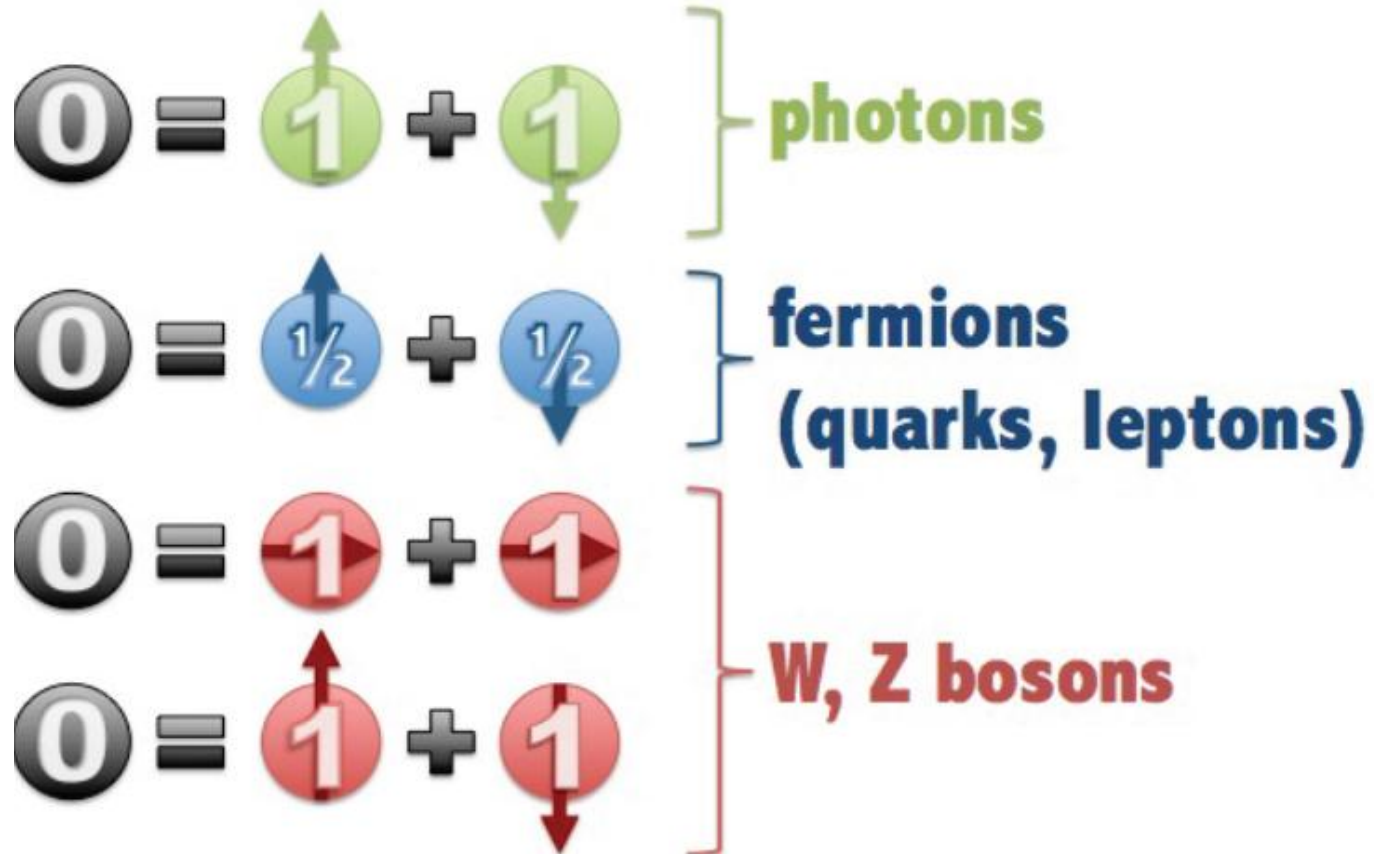
Spin 1/2

bosons

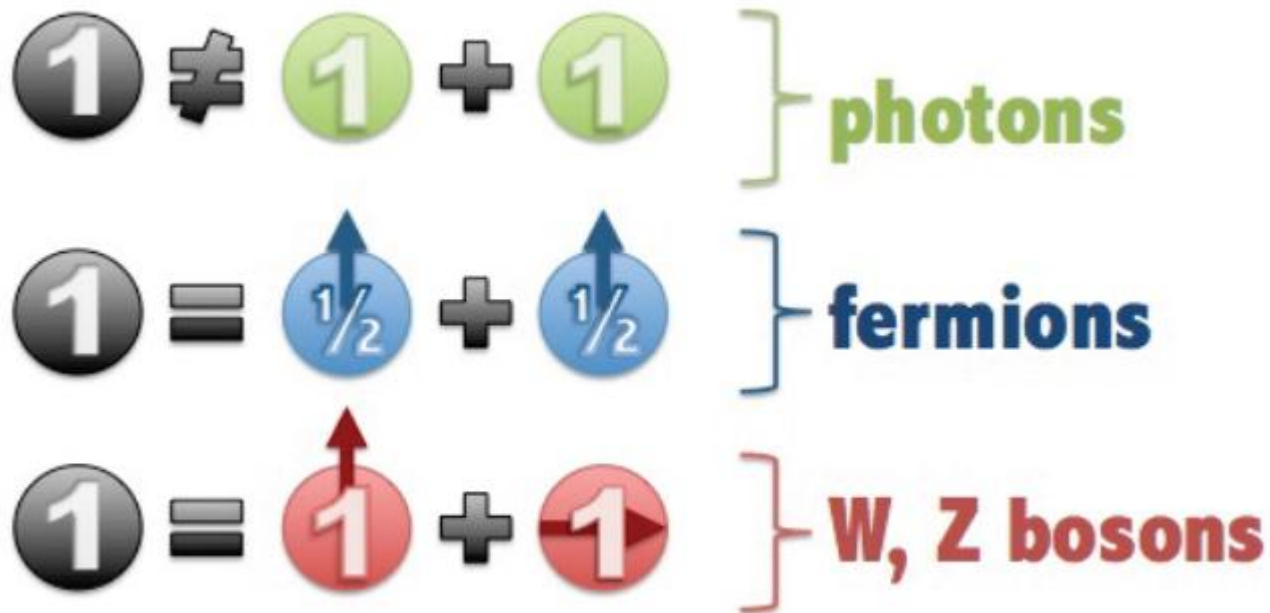


Spin 1

# What can a spin 0 particle decay to?



# What can a spin 1 particle decay to?



# What can a spin 2 particle decay to?

$$\textcircled{2} = \textcircled{1}^{\uparrow} + \textcircled{1}^{\uparrow} \quad \left. \vphantom{\textcircled{2}} \right\} \text{photons}$$







$$\textcircled{2} \neq \textcircled{\frac{1}{2}} + \textcircled{\frac{1}{2}} \quad \left. \vphantom{\textcircled{2}} \right\} \text{fermions}$$

$$\textcircled{2} = \textcircled{1}^{\uparrow} + \textcircled{1}^{\uparrow} \quad \left. \vphantom{\textcircled{2}} \right\} \text{W, Z bosons}$$

$$\textcircled{2} = \textcircled{\frac{1}{2}}^{\uparrow} + \textcircled{\frac{1}{2}}^{\uparrow} + \textcircled{1}^{\uparrow} \quad \left. \vphantom{\textcircled{2}} \right\} \text{b quarks+gluon}$$

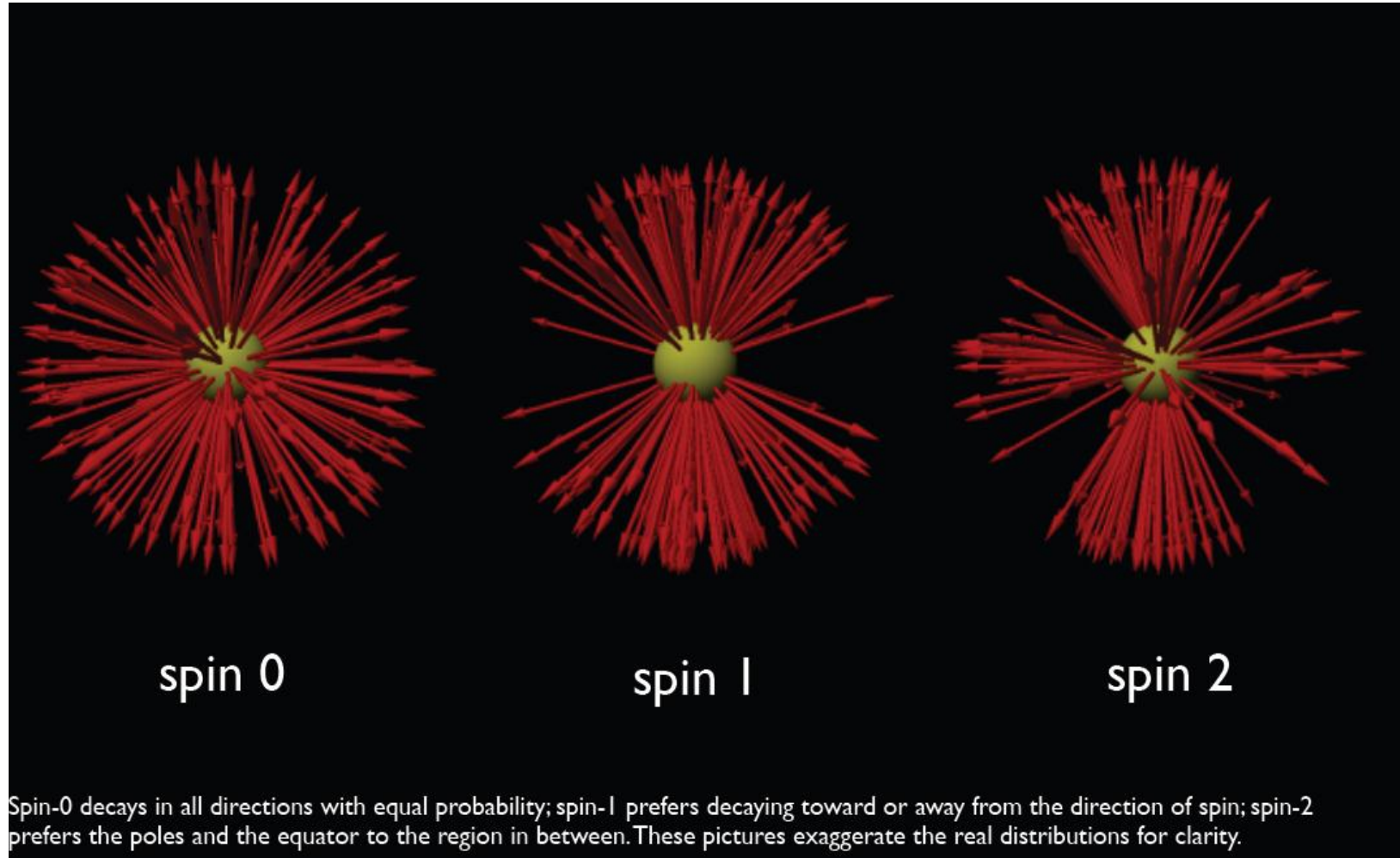
$$\textcircled{2} \neq \textcircled{\frac{1}{2}} + \textcircled{\frac{1}{2}} \quad \left. \vphantom{\textcircled{2}} \right\} \tau \text{ leptons}$$

# So what spin has Higgs-like particle?

<b>Spin of particle</b>	<b><math>\gamma\gamma</math></b>	<b><math>ZZ^*</math></b>
<b>Spin 0</b>		
<b>Spin 1</b>		
<b>Spin 2</b>		



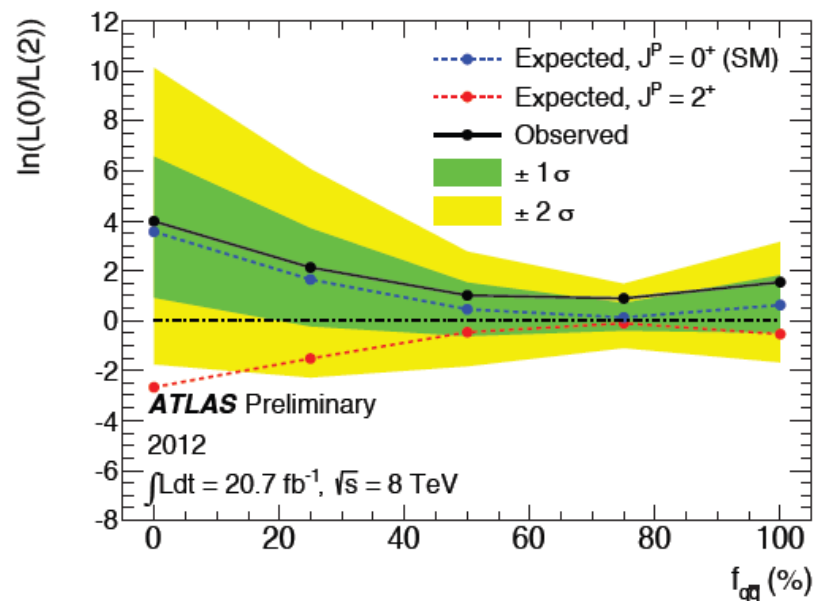
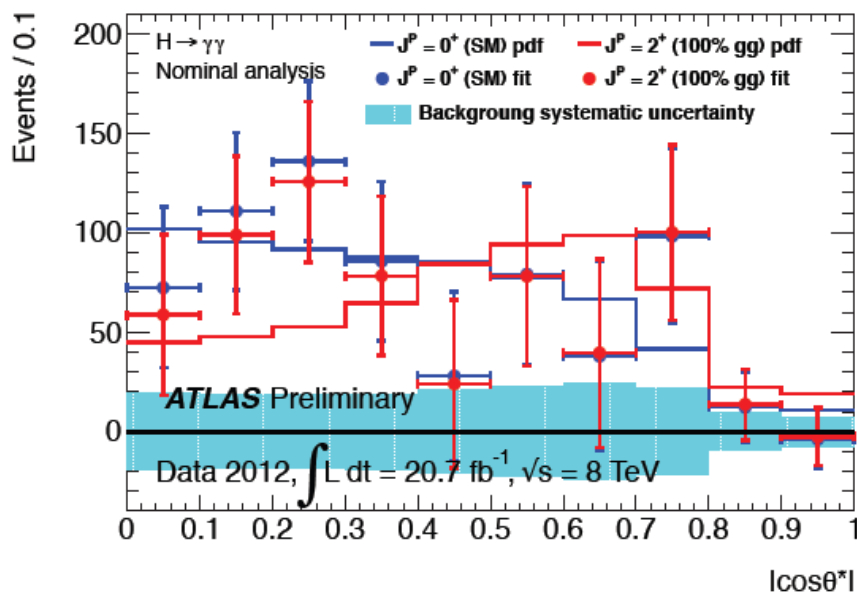
# How we can recognize spin?



# Spin study with $H \rightarrow \gamma\gamma$

$\gamma\gamma$  polar angle  $\theta^*$   
with respect to Z-axis  
in Colin-Sopper frame

$$\cos \theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + (p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \cdot \frac{2p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$



- If spin-2 resonance is produced 100% by gluon fusion, observed *rejection p-values* are:
  - ✓ spin-0  $\rightarrow$  58.8% (1.2% expected)  $\rightarrow$  good agreement with spin-0 hypothesis
  - ✓ spin-2  $\rightarrow$  0.3% (0.5% expected)  $\rightarrow$  spin-2 excluded at 99.3% CL

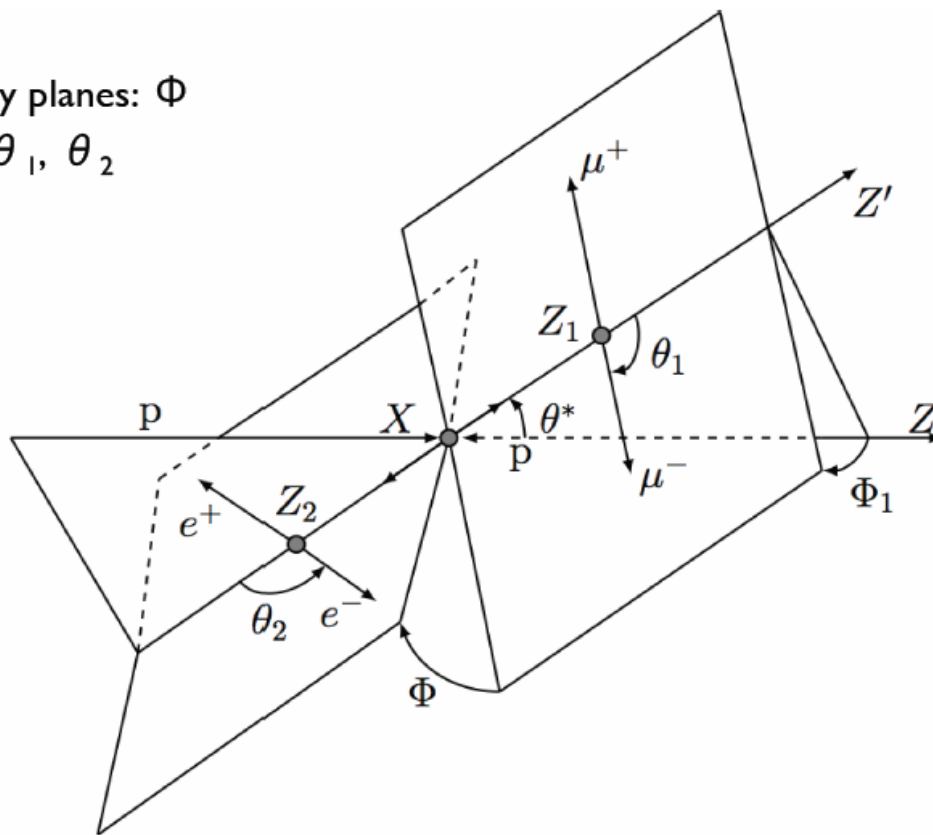
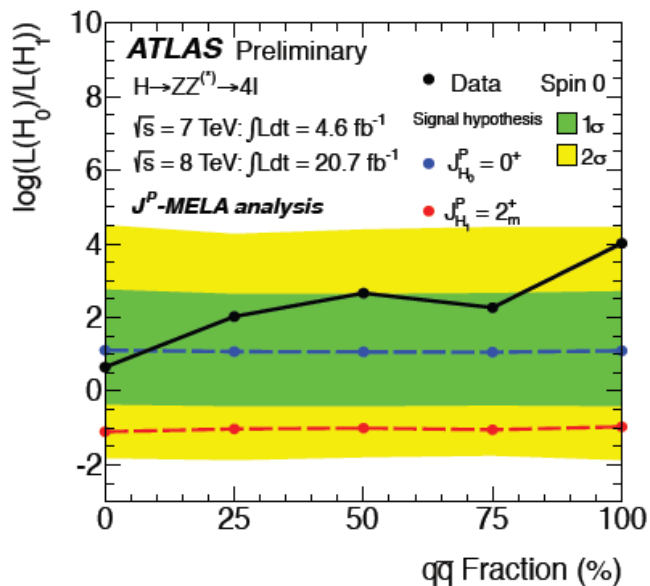
# Spin study with $H \rightarrow 4l$

- Sensitive variables

- ✓ Intermediate boson masses:  $m_{Z_1}, m_{Z_2}$
- ✓  $Z_1$  production angle:  $\theta^*$
- ✓  $Z_1$  decay plane angle:  $\Phi_1$
- ✓ Angle between the  $Z_1$  and  $Z_2$  decay planes:  $\Phi$
- ✓ Decay angles of negative leptons:  $\theta_1, \theta_2$

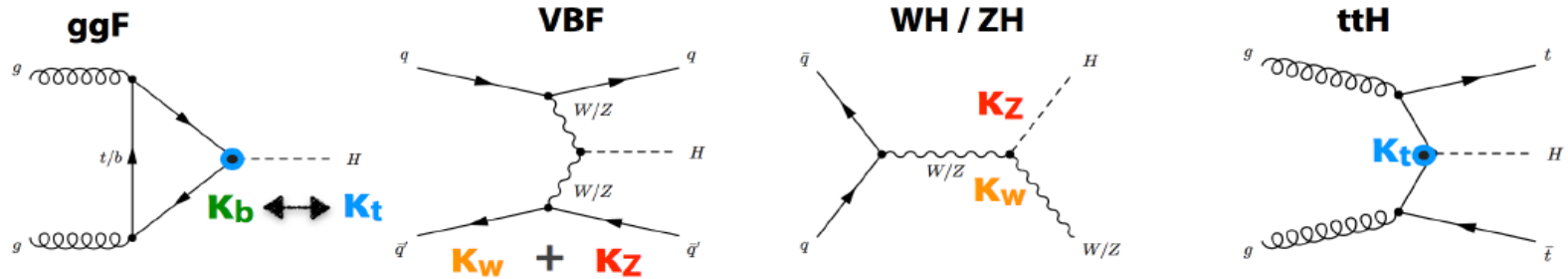
- Expected separation  $> 2.5 \sigma$ , except for  $2+m$  ( $\sim 1.5 \sigma$ )

- ✓ New boson compatible with SM  $0+$  Higgs hypothesis when compared pair-wise with  $0-, 1-, 1+, 2+m$

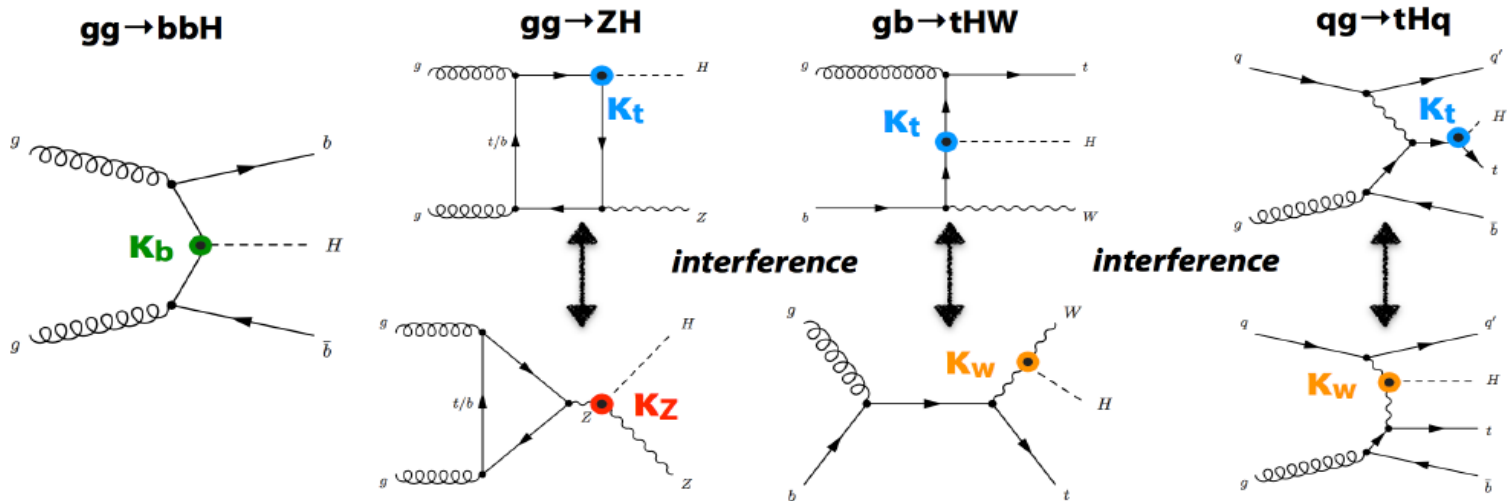


# Higgs boson couplings

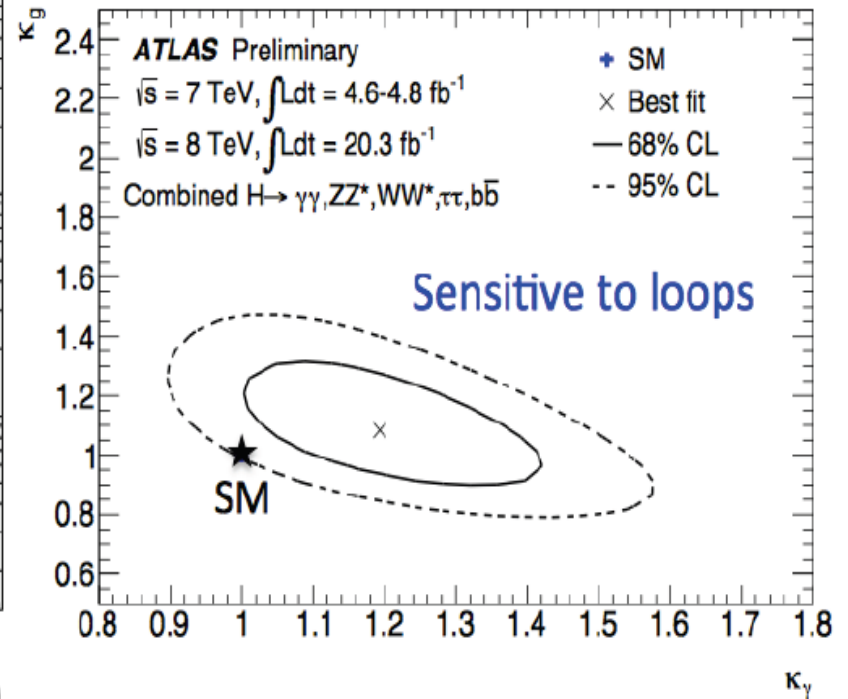
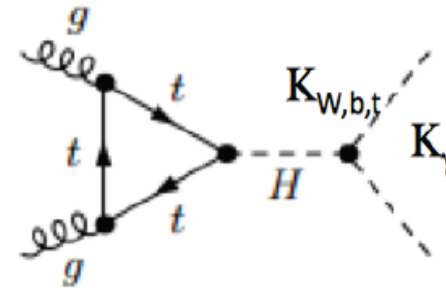
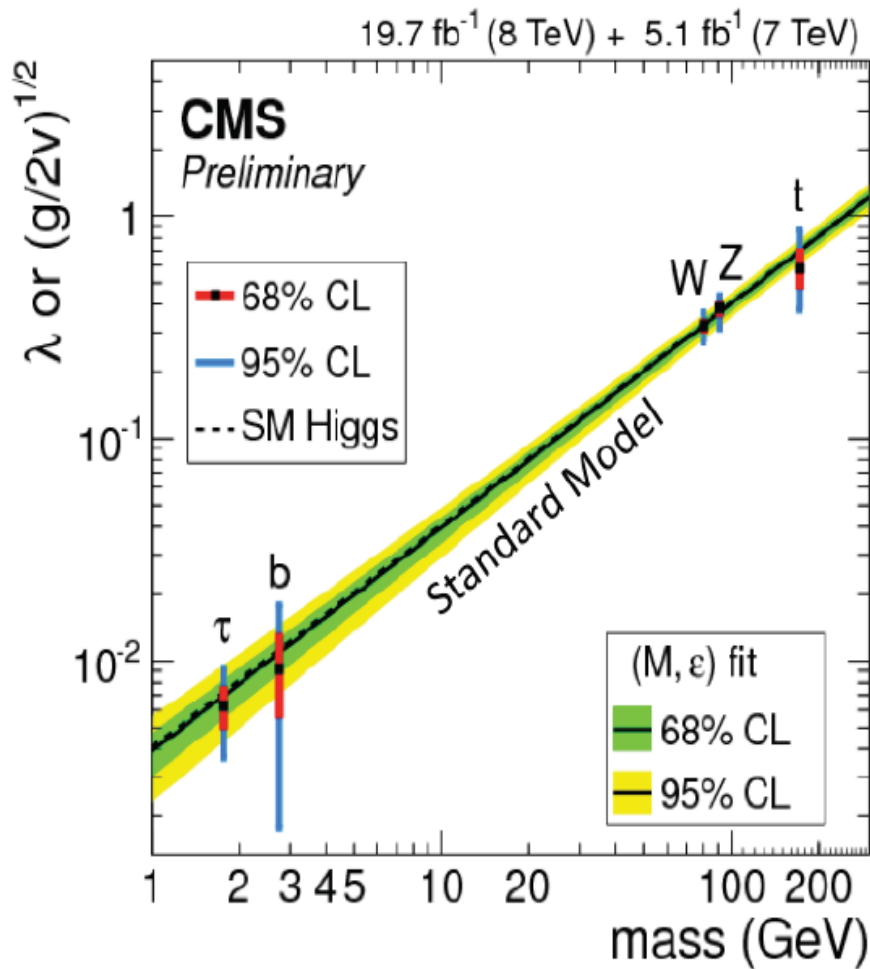
- Usual suspects:



- Rare (less dominant) processes:



# Higgs boson couplings



# The global signal strength

- Assuming SM ratios of production cross-sections and decay rates

$$\mu = 1.09^{+0.11}_{-0.10}$$

*Most precise result at the expense of the largest assumptions*

$$= 1.09^{+0.07}_{-0.07} \text{ (stat)} \quad ^{+0.04}_{-0.04} \text{ (expt)} \quad ^{+0.03}_{-0.03} \text{ (thbgd)} \quad ^{+0.07}_{-0.06} \text{ (thsig)}$$

*Stat and Th.Sig of comparable size  
(Th.Sig dominated by ggF cross-section uncertainty)*

# **Additional material**

# Higgs boson couplings

- **Simplified framework** (LO –like):

- Signals originate from single resonance with mass  $\sim 125$  GeV
- The width of the assumed Higgs boson is neglected, i.e. zero-width approximation is used

$$(\sigma \cdot \text{BR}) (ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$$

- **Only modifications of coupling strengths are considered**, the tensor structure is assumed as in the SM i.e. assume that it is „Higgs-like” resonance.
- **Couplings represent pseudo-observables**, i.e. are not measured directly, certain „unfolding” procedure required to extract information



# Measuring Higgs boson couplings

Rather than discussing couplings, introduce concept of „scale factors”  $\kappa_i$ : cross-section or partial width scale with  $\kappa_i^2$

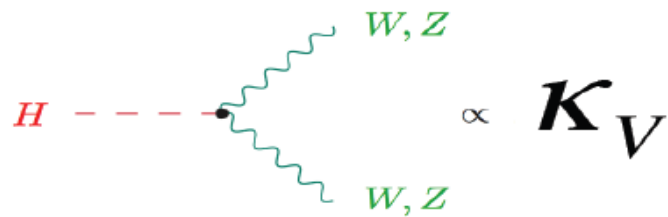
$$\begin{aligned} \mathcal{L} = & \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\ & + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\ & + \kappa_{VV} \frac{\alpha}{2\pi v} (\cos^2 \theta_W Z_{\mu\nu} Z^{\mu\nu} + 2W_{\mu\nu}^+ W^{-\mu\nu}) H \\ & - \left( \kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H. \end{aligned}$$

Define the normalized coupling constants (w.r.t. the SM couplings)

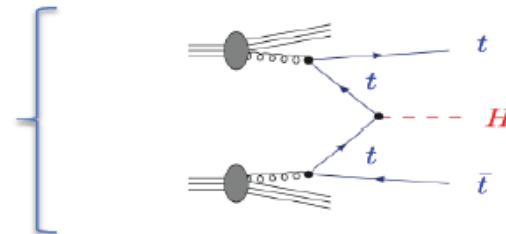
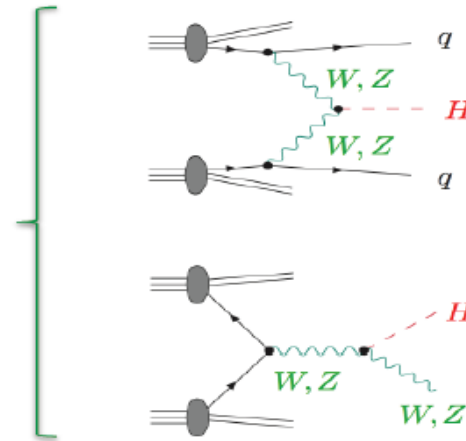
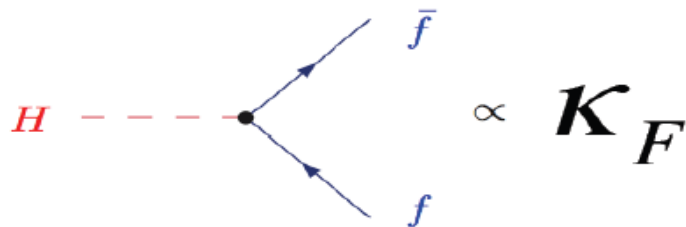
$$k_i^2 = \frac{\Gamma_i}{\Gamma_I^{SM}} \quad k_H^2 = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$$

# Cpuplings scale factors

## (I) Tree Level Couplings scale factors **w.r.t. SM**

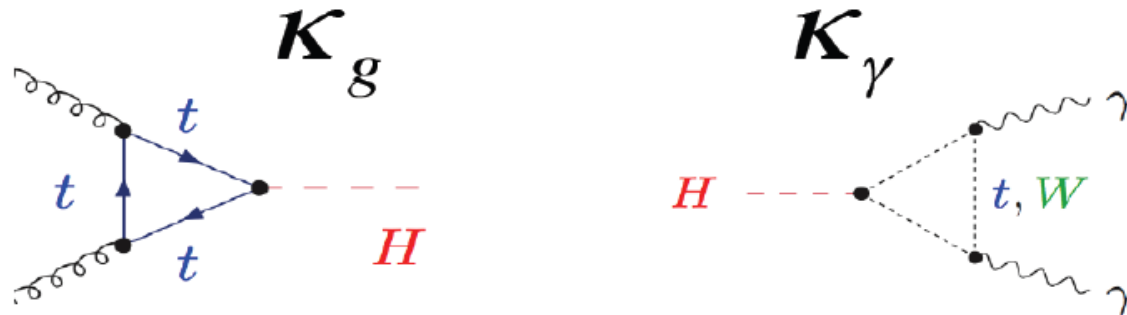


Affecting decay and production modes



# Couplings scale factors

(II) Scale factors of loop induced couplings w.r.t. SM



- Loop expression ambiguity :

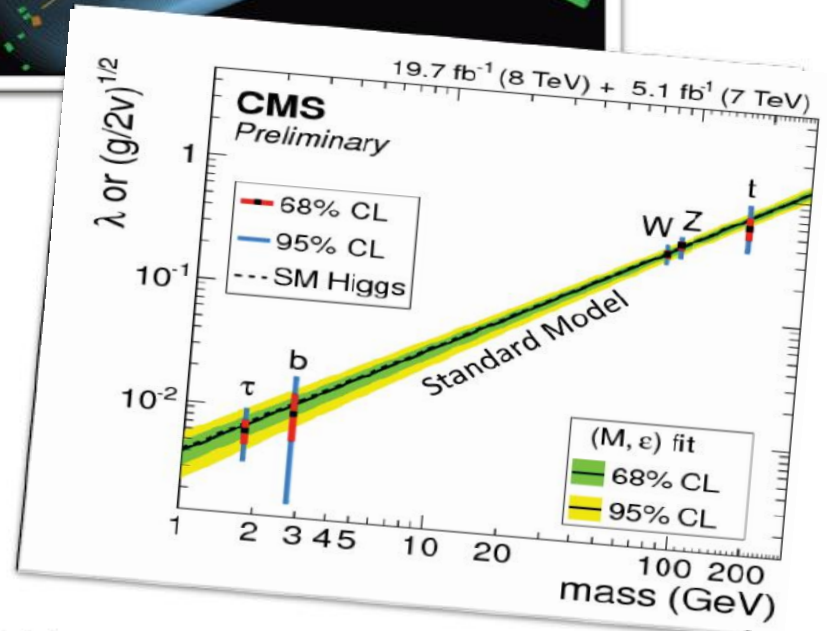
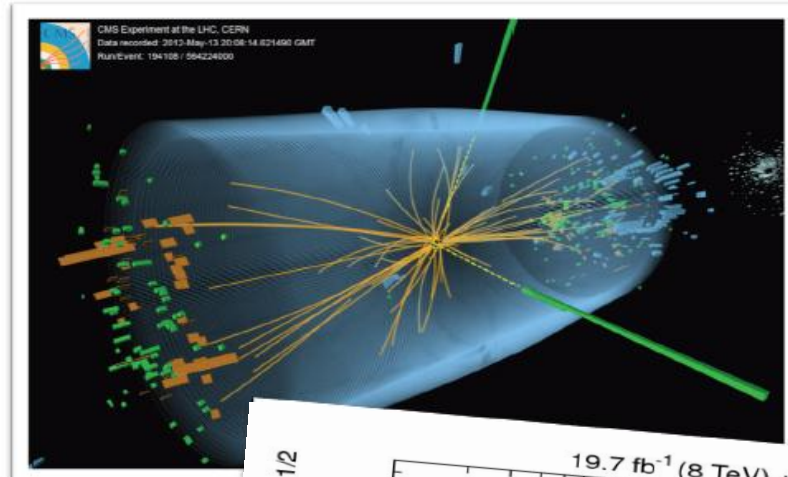
- Can be expressed in terms of  $k_F$  and  $k_V$  (Assuming the SM field content)
- Or treated effectively (Allowing for possible additional particles)

$$\kappa_g^2(\kappa_b, \kappa_t, m_H) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt}(m_H) + \kappa_b^2 \cdot \sigma_{ggH}^{bb}(m_H) + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}(m_H)}{\sigma_{ggH}^{tt}(m_H) + \sigma_{ggH}^{bb}(m_H) + \sigma_{ggH}^{tb}(m_H)}$$

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}(m_H)}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}(m_H)}$$

# Experiment = probing theories with data

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^\nu \partial_\nu g_\mu^\mu - g_s f^{abc} \partial_\mu g_\nu^a g_\nu^b g_\mu^c - \frac{1}{2} g_s^2 f^{abc} f^{ade} g_\mu^a g_\nu^b g_\mu^c g_\nu^d g_\mu^e + \\
 & \frac{1}{2} 19 g_1^2 (\bar{q}^i \gamma^\mu q_j^i) g_\mu^0 + G^a \partial^\mu G^a + g_s f^{abc} \partial_\mu G^a G^b G_\mu^c - \partial_\mu W_\nu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2} M_Z^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\nu A_\mu - \frac{1}{2} \partial_\mu H \partial_\nu H - \\
 & \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\nu \phi^\alpha \partial_\nu \phi^\alpha - \frac{1}{2} M \phi^\alpha \phi^\alpha - \beta_h \frac{[2M]^2}{2} + \\
 & \frac{2M}{\Lambda} H + \frac{1}{\Lambda} (H^2 + \phi^\alpha \phi^\alpha + 2\phi^+ \phi^-) + \frac{2M^4}{\Lambda^2} \alpha_h - ig_{c_w} [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+) + Z_\mu^0 (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\mu W_\mu^+) - ig_{s_w} [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^- W_\mu^+) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\mu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) - \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\nu^+ W_\mu^- + \\
 & \frac{1}{2} g^2 W_\mu^- W_\nu^+ W_\nu^- W_\mu^+ + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^-) + g^2 s_w^2 (W_\mu^+ W_\nu^-) + \\
 & g^2 s_w^2 (A_\mu W_\nu^+ A_\nu W_\mu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^- W_\mu^+) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^2 + H\phi^\alpha \phi^\alpha + 2(H\phi^+ \phi^-)^2] - \\
 & \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^\alpha)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
 & g M W_\mu^+ W_\nu^- H - \frac{1}{2} g \frac{M}{c_w} Z_\mu^0 Z_\nu^0 H - \frac{1}{2} ig [W_\mu^+ (\partial_\nu \phi^\alpha \phi^\alpha - \phi^- \partial_\nu \phi^0) - \\
 & W_\nu^- (\phi^0 \partial_\nu \phi^+ - \phi^+ \partial_\nu \phi^0)] + \frac{1}{2} ig [W_\mu^+ (H \partial_\nu \phi^- - \phi^- \partial_\nu H) - W_\nu^- (H \partial_\nu \phi^+ - \\
 & \phi^+ \partial_\nu H)] + \frac{1}{2} g \frac{1}{c_w} (Z_\mu^0 (H \partial_\nu \phi^- - \phi^- \partial_\nu H) - ig_{c_w}^2 M Z_\mu^0 (W_\mu^+ \phi^- - W_\nu^- \phi^+) + \\
 & ig_{s_w} M A_\mu (W_\mu^+ \phi^- - W_\nu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\nu \phi^- - \phi^- \partial_\nu \phi^+) - \\
 & ig_{s_w} A_\mu (\phi^+ \partial_\nu \phi^- - \phi^- \partial_\nu \phi^+) - \frac{1}{2} g^2 W_\mu^+ W_\nu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4} g^2 \frac{1}{c_w} Z_\mu^0 Z_\nu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{2c_w}{c_w} Z_\mu^0 \phi^\alpha (W_\mu^+ \phi^- + \\
 & W_\nu^- \phi^+) - \frac{1}{2} ig^2 \frac{2c_w}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\nu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^\alpha (W_\mu^+ \phi^- + \\
 & W_\nu^- \phi^+) + \frac{1}{2} ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\nu^- \phi^+) - g^2 \frac{2c_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- - e^2 (\gamma \partial + m_\tau^2) e^\lambda - \rho^2 \gamma \partial \nu^\lambda - u_3^2 (\gamma \partial + m_\tau^2) u_3^\lambda + \\
 & d_3^2 (\gamma \partial + m_\tau^2) d_3^\lambda + ig_{s_w} A_\mu [-(e^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (u_3^\lambda \gamma^\mu u_3^\lambda) - \frac{1}{3} (d_3^\lambda \gamma^\mu d_3^\lambda)] + \\
 & \frac{19}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (u_3^\lambda \gamma^\mu (\frac{2}{3} s_w^2 - \\
 & 1 - \gamma^5) u_3^\lambda) + (d_3^\lambda \gamma^\mu (1 - \frac{2}{3} s_w^2 - \gamma^5) d_3^\lambda)] + \frac{19}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + \\
 & (d_3^\lambda \gamma^\mu (1 + \gamma^5) C_{3\lambda} d_3^\lambda)] + \frac{19}{2\sqrt{2}} W_\mu^- [(e^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (d_3^\lambda \gamma^\mu d_3^\lambda) - \\
 & \gamma^5 u_3^\lambda] + \frac{19}{2\sqrt{2}} \frac{M}{\Lambda} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (e^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{19}{2} \frac{M^2}{\Lambda} [H (e^\lambda e^\lambda) + i\phi^0 (e^\lambda \gamma^5 e^\lambda)] + \frac{19}{2\sqrt{2}} \frac{M^2}{\Lambda} \phi^+ [-m_\tau^2 (u_3^\lambda C_{3\lambda} (1 - \gamma^5) d_3^\lambda) + \\
 & m_\tau^2 (d_3^\lambda C_{3\lambda}^* (1 + \gamma^5) u_3^\lambda)] - m_\tau^2 (d_3^\lambda C_{3\lambda}^* (1 - \gamma^5) u_3^\lambda) - \frac{19}{2} \frac{M^2}{\Lambda} H (d_3^\lambda d_3^\lambda) + \frac{19}{2} \frac{M^2}{\Lambda} \phi^0 (\bar{u}_3^\lambda \gamma^5 u_3^\lambda) - \\
 & \frac{19}{2} \frac{M^2}{\Lambda} \phi^0 (\bar{d}_3^\lambda \gamma^5 d_3^\lambda) + \bar{X}^+ (\partial^\mu - M^2) X^+ + \bar{X}^- (\partial^\mu - M^2) X^- + \bar{X}^0 (\partial^\mu - \\
 & \frac{M^2}{\Lambda} \phi^0 \partial^\mu + \bar{Y} \partial^\mu Y + ig_{c_w} W_\mu^+ (\partial_\nu \bar{X}^0 X^- - \partial_\nu \bar{X}^+ X^0) + ig_{s_w} W_\mu^+ (\partial_\nu \bar{X}^+ X^- - \\
 & \partial_\nu \bar{X}^+ Y) + ig_{c_w} W_\mu^- (\partial_\nu \bar{X}^- X^0 - \partial_\nu \bar{X}^- X^+) + ig_{s_w} W_\mu^- (\partial_\nu \bar{X}^- Y - \\
 & \partial_\nu \bar{X}^- X^+) + ig_{c_w} Z_\mu^0 (\partial_\nu \bar{X}^+ X^- + \partial_\nu \bar{X}^- X^+) + ig_{s_w} A_\mu (\partial_\nu \bar{X}^+ X^- + \\
 & \partial_\nu \bar{X}^- X^+) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{\Lambda} \bar{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^- - \bar{X}^0 X^+ \phi^+] + \\
 & ig M s_w [\bar{X}^0 X^- \phi^- - \bar{X}^0 X^+ \phi^+] + \frac{1}{2} ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$



- Delamater

(experimental) LHC physics

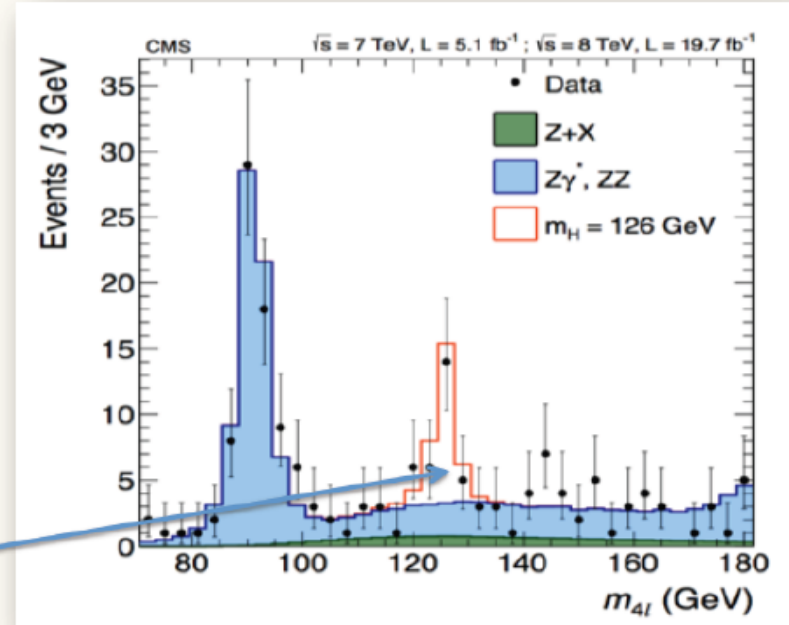
# What do we measure?

We measure event yields

We want to derive couplings and signal strengths

The first thing we want to measure is the the "signal strength" per channel

The analysis is using discriminators (usually reconstructed mass related) to increase S/B



$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \epsilon_p^i \times Lumi$$

$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$

$$\mu^{ZZ}(@125.5 \text{ GeV}) = 1.44^{+0.40}_{-0.35}$$

6.6 $\sigma$  (4.4 exp) ATLAS

$$\mu^{ZZ}(@125.6 \text{ GeV}) = 0.93^{+0.26+0.13}_{-0.23-0.09}$$

6.8 $\sigma$  (6.7 exp) CMS

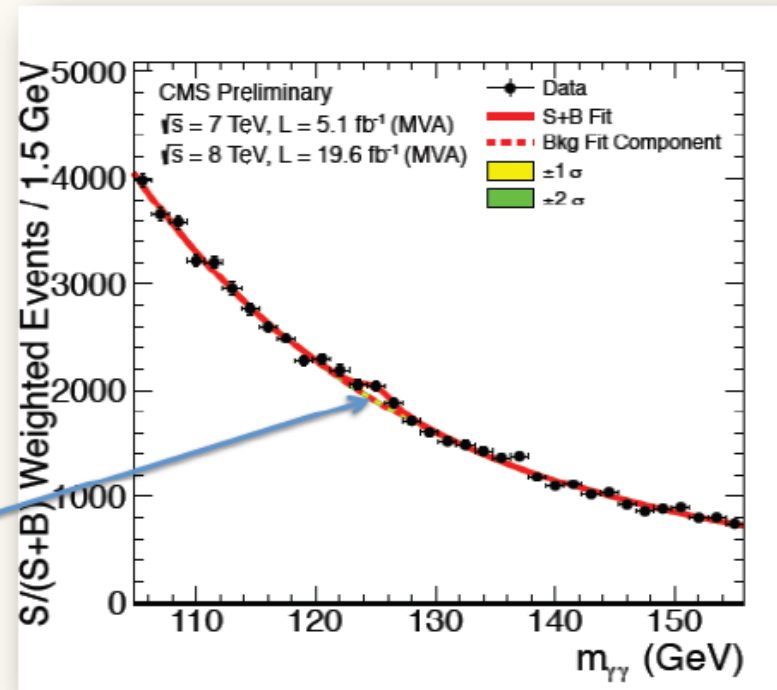
# What do we measure?

We measure event yields

We want to derive couplings and signal strengths

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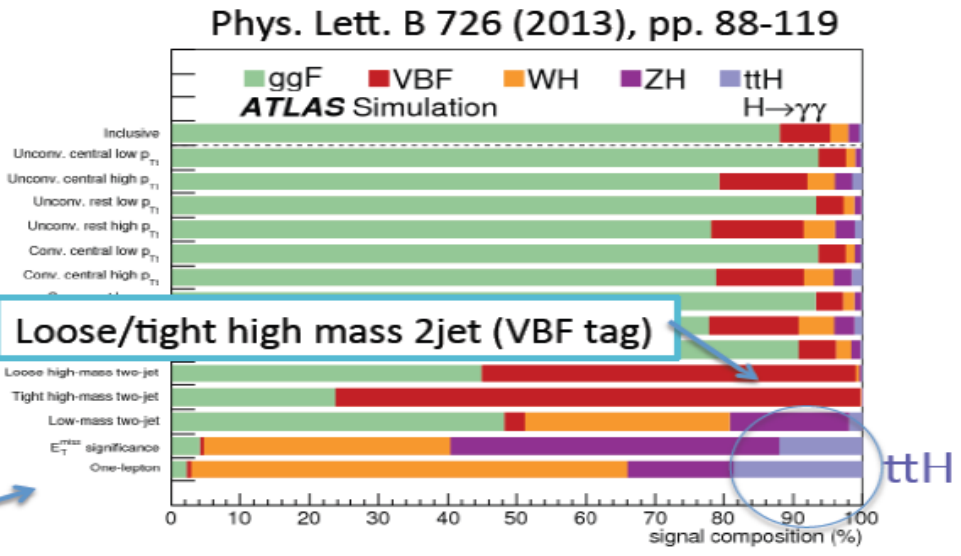


$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \epsilon_p^i \times Lumi$$

$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$

# What do we measure?

We increase sensitivity by classifying the events via categories and measure the signal strength per category and then combining them taking all the systematic and statistical errors uncertainties into account



The categories are also sensitive to different production modes, allowing the measurement of the couplings

$$n_s^{c,i} = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \epsilon_p^{c,i} \times Lumi$$

$p \in (ggF, VBF, VH, ttH)$      $i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$

$$\mu^{\gamma\gamma}(@125.5 \text{ GeV}) = 1.57^{+0.33}_{-0.28} \quad 7.4\sigma \text{ (4.3 exp) ATLAS}$$

$$\mu^{\gamma\gamma}(@125.7 \text{ GeV}) = 0.77^{+0.29}_{-0.26} \quad 3.2\sigma \text{ (3.9 exp) CMS}$$

# Higgs boson decay channels

## Significance

7.4 $\sigma$  (4.3 $\sigma$ )

6.6 $\sigma$  (4.4 $\sigma$ )

3.8 $\sigma$  (3.8 $\sigma$ )

4.1 $\sigma$  (3.2 $\sigma$ )

0.36 $\sigma$  (1.64 $\sigma$ )

Obs. (Exp.)

3.2 $\sigma$  (4.2 $\sigma$ )

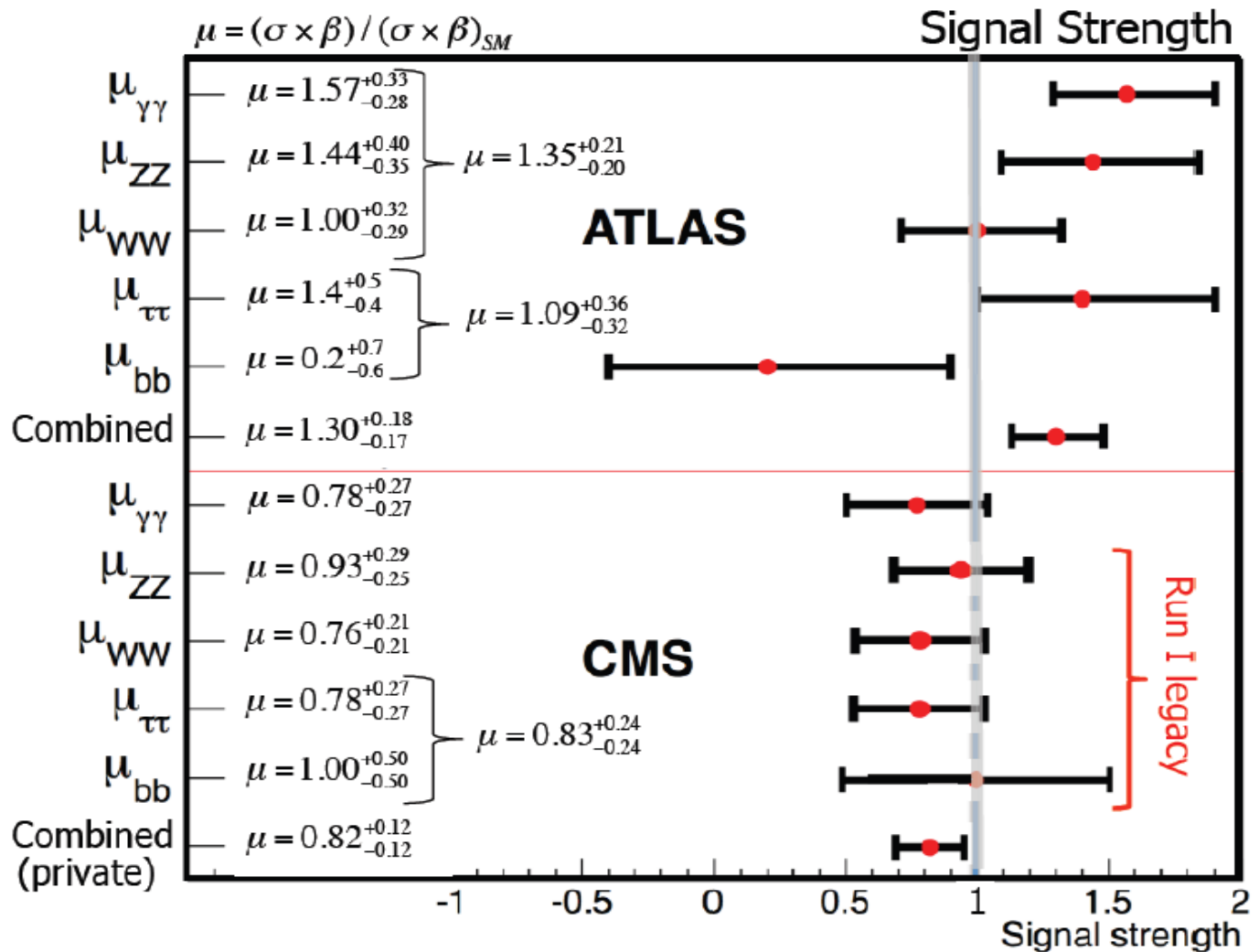
6.8 $\sigma$  (6.7 $\sigma$ )

4.3 $\sigma$  (5.8 $\sigma$ )

3.3 $\sigma$  (3.7 $\sigma$ )

2.1 $\sigma$  (2.1 $\sigma$ )

Obs. (Exp.)





# Probe the production mode

We fitted

$$\mu_{VBF+VH}^i \equiv \left[ \mu_{VBF+VH} \times \mu_{BR}^i \right]$$

$$\mu_{ggF+ttH}^i \equiv \left[ \mu_{ggF+ttH} \times \mu_{BR}^i \right]$$

Taking one decay mode at a time we can go one step further and fit the ratio per channel

$$\frac{\mu_{VBF+VH}^i}{\mu_{ggF+ttH}^i} = \frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$$

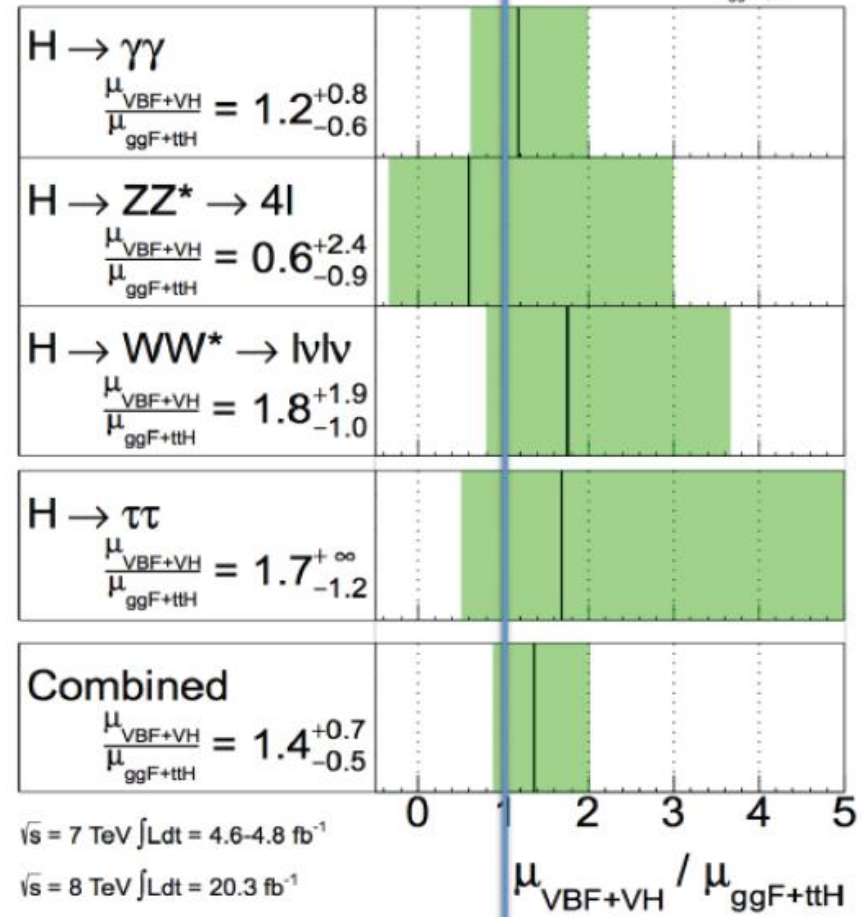
**This ratio is INDEPENDENT of the decay channel so we can combine**

**ATLAS Preliminary**

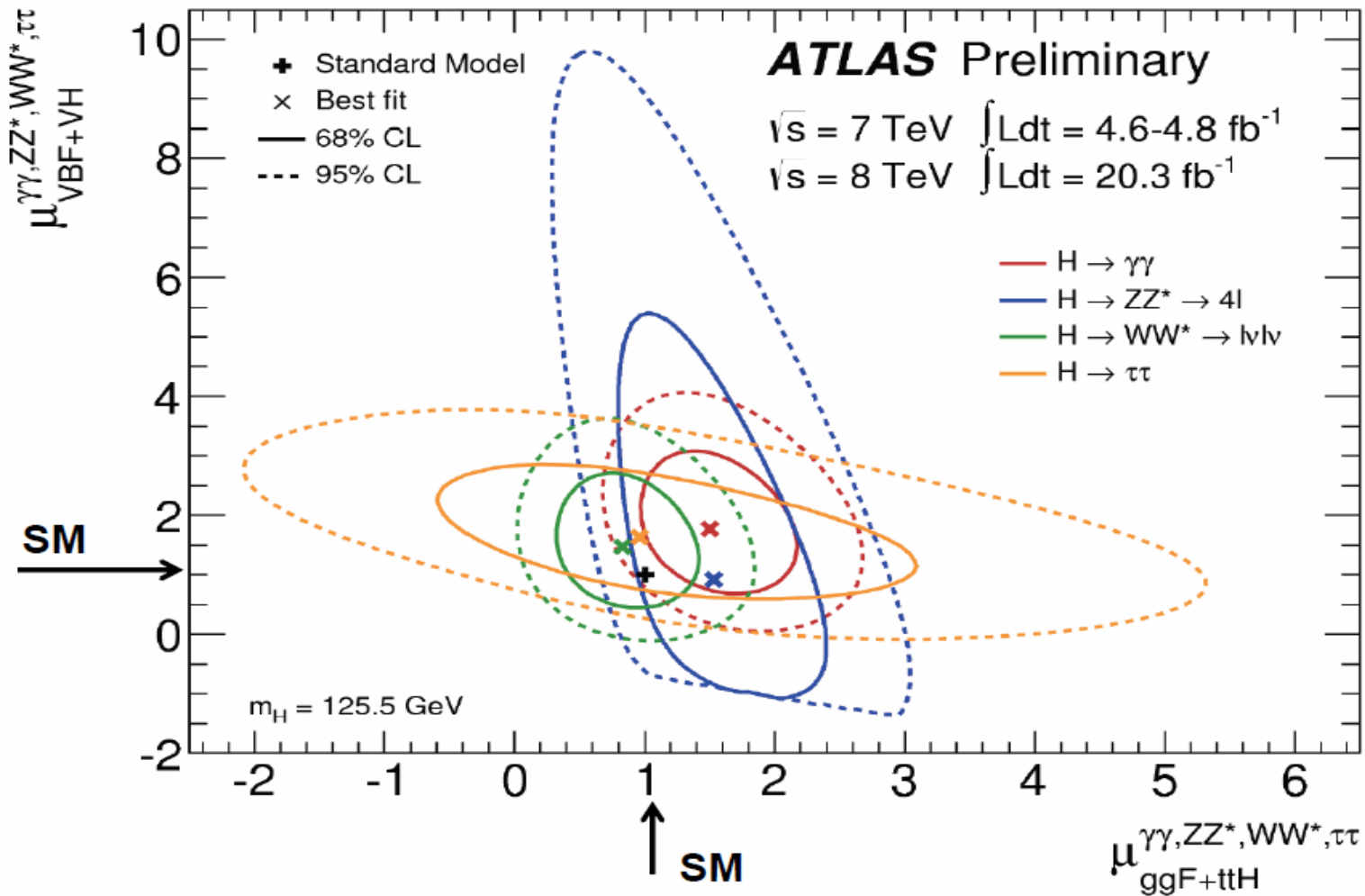
$m_H = 125.5 \text{ GeV}$

Total uncertainty

■  $\pm 1\sigma$  on  $\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$



# Probe the production mode



# Combination of two experiments

(ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002)

By fitted production mode arXiv:1507.04548 [hep-ex]

