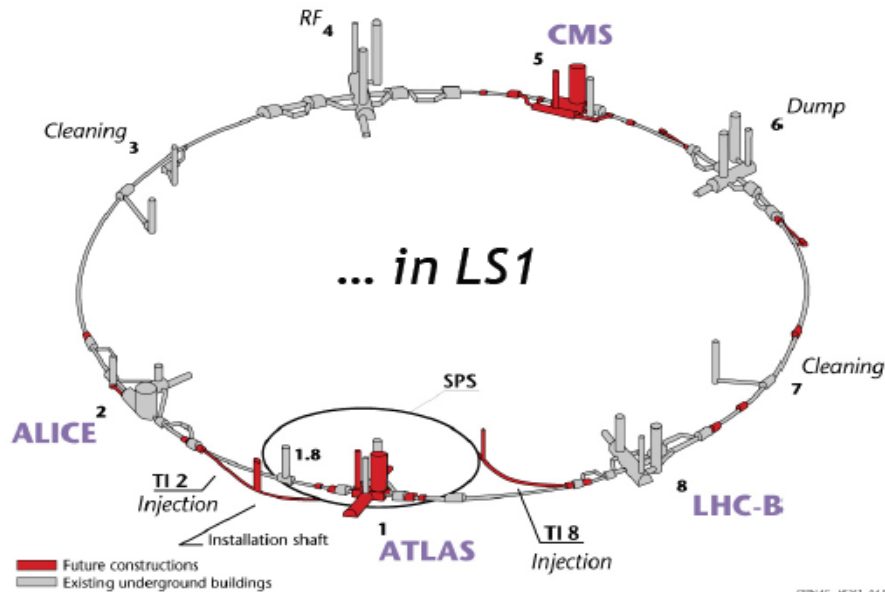


Wstęp do fizyki cząstek elementarnych: część eksperymentalna

Odkrycie cząstki Higgsa
Masa, spin, sprzężenia

Three years of LHC operations

Energy frontier



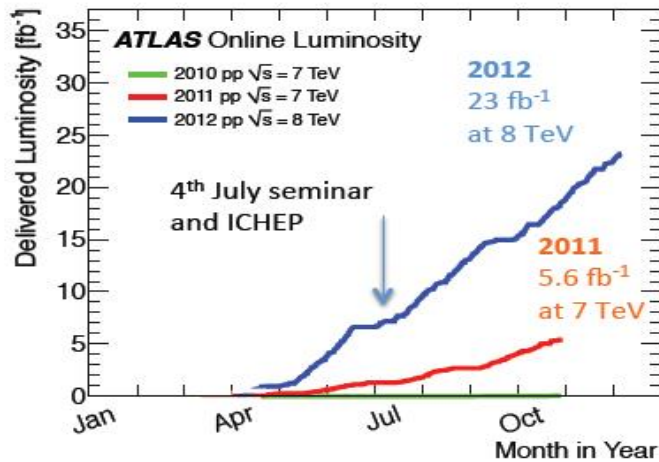
The LHC

- 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)

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

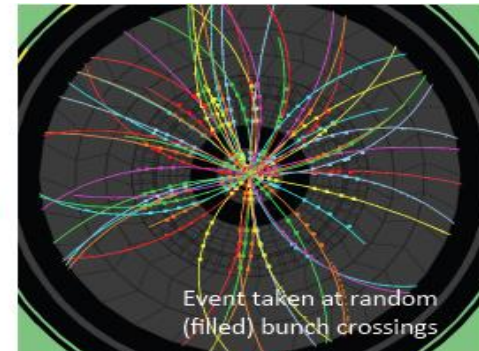
Parameter	2010	2011	2012	Nominal
C.O.M Energy	7 TeV	7 TeV	8 TeV	14 TeV
Bunch spacing / k	150 ns / 368	50 ns / 1380	50 ns / 1380	25 ns / 2808
ϵ (mm rad)	2.4-4	1.9-2.3	2.5	3.75
β^* (m)	3.5	1.5-1	0.6	0.55
L (cm ⁻² s ⁻¹)	2x10 ³²	3.3x10 ³³	~7x10 ³³	10 ³⁴

The first LHC run



2010
O(2) Pile-up events

150 ns inter-bunch spacing

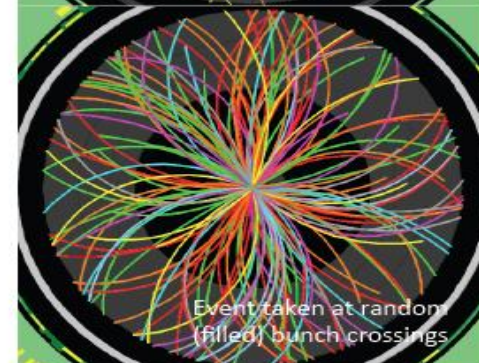


2010
0.05 fb^{-1}
at 7 TeV

2011

O(10) Pile-up events

50 ns inter-bunch spacing

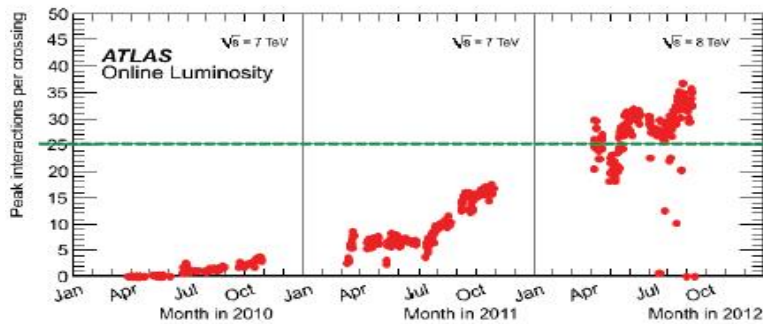


Design value
(expected to be reached at $L=10^{34}$!)

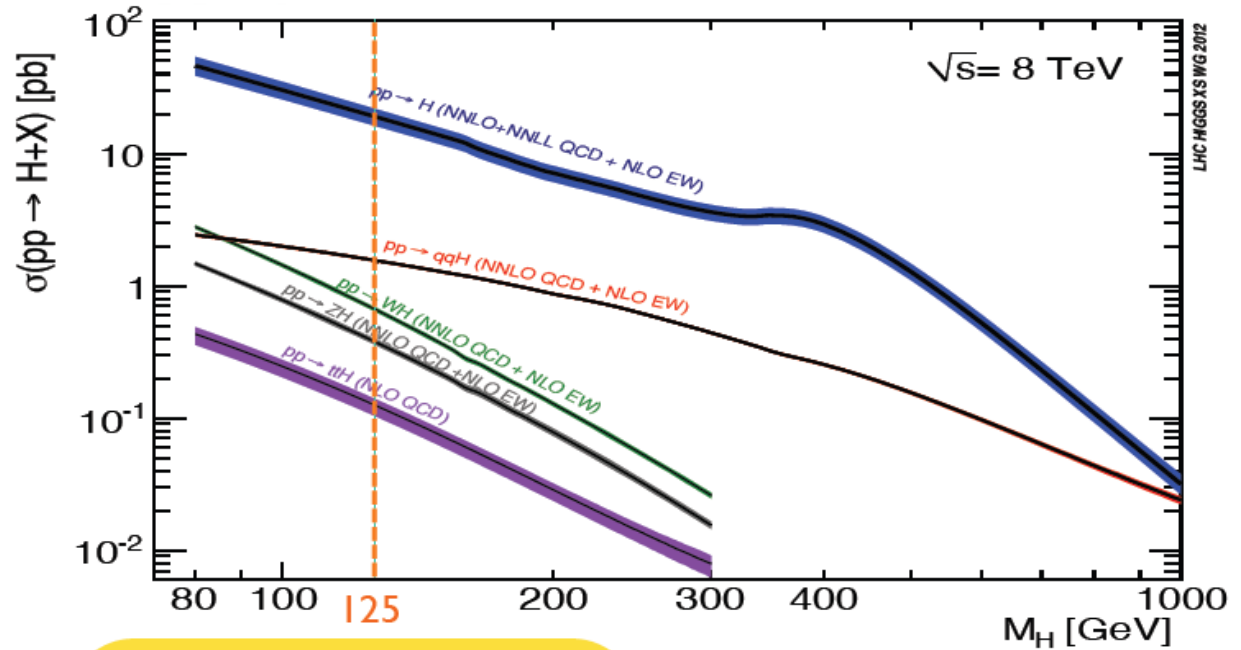
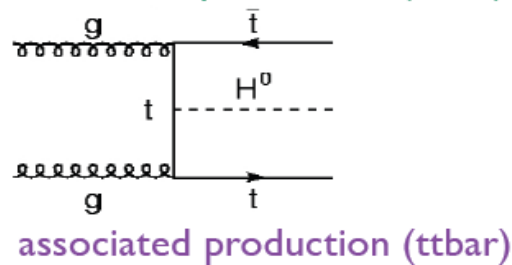
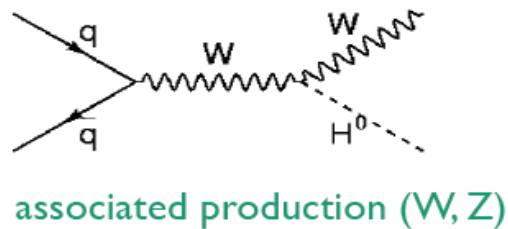
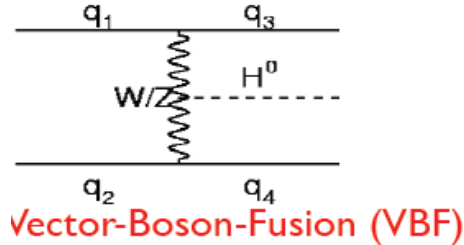
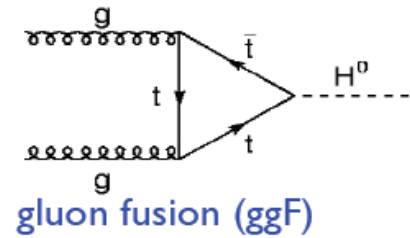
2012

O(20) Pile-up events

50 ns inter-bunch spacing

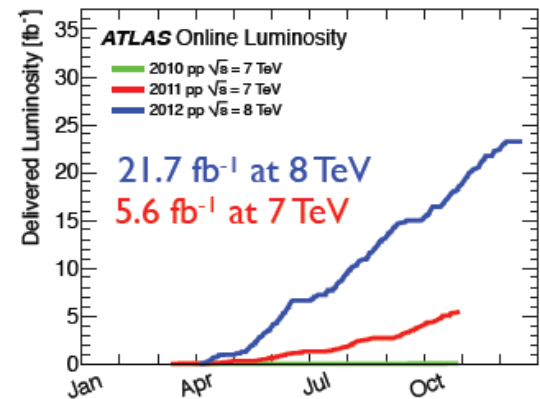


SM Higgs production at the LHC

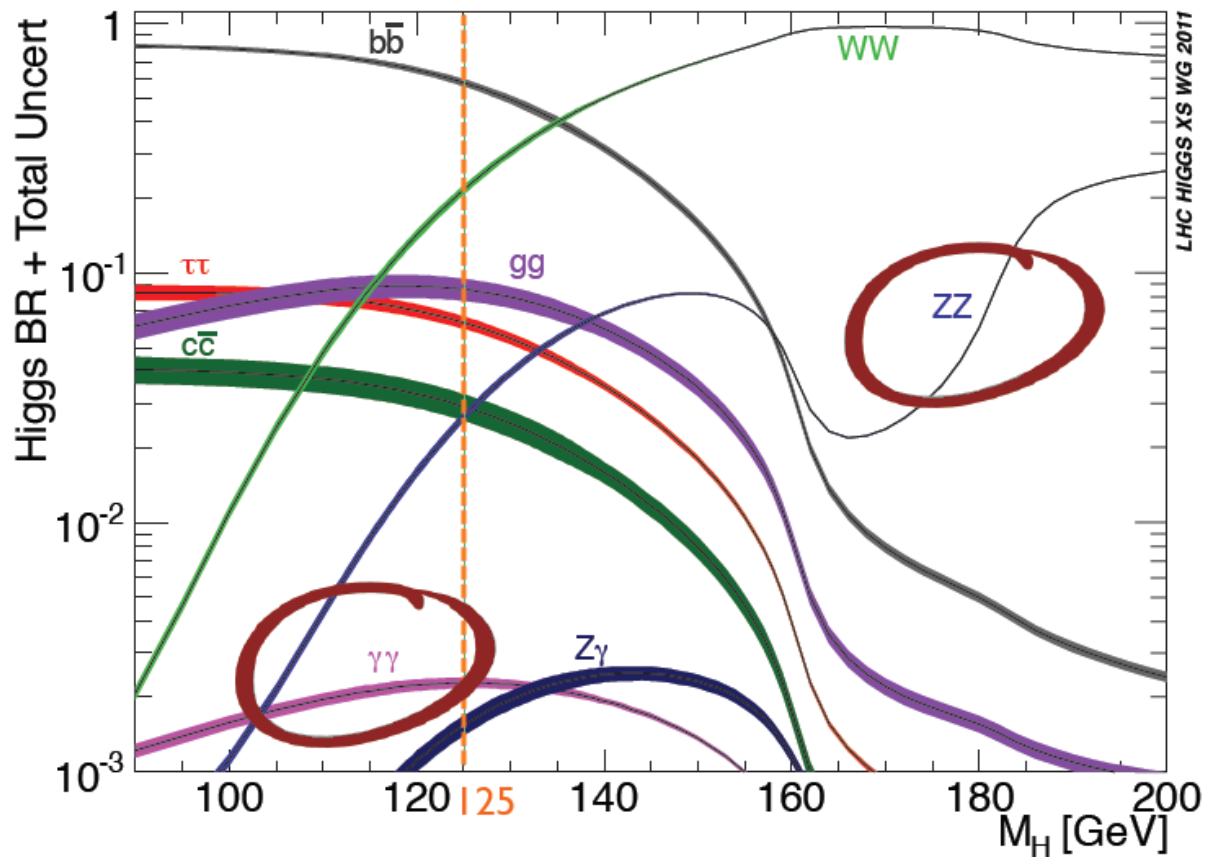


$$\sigma(125 \text{ GeV}) = 22.3 \text{ pb}$$

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



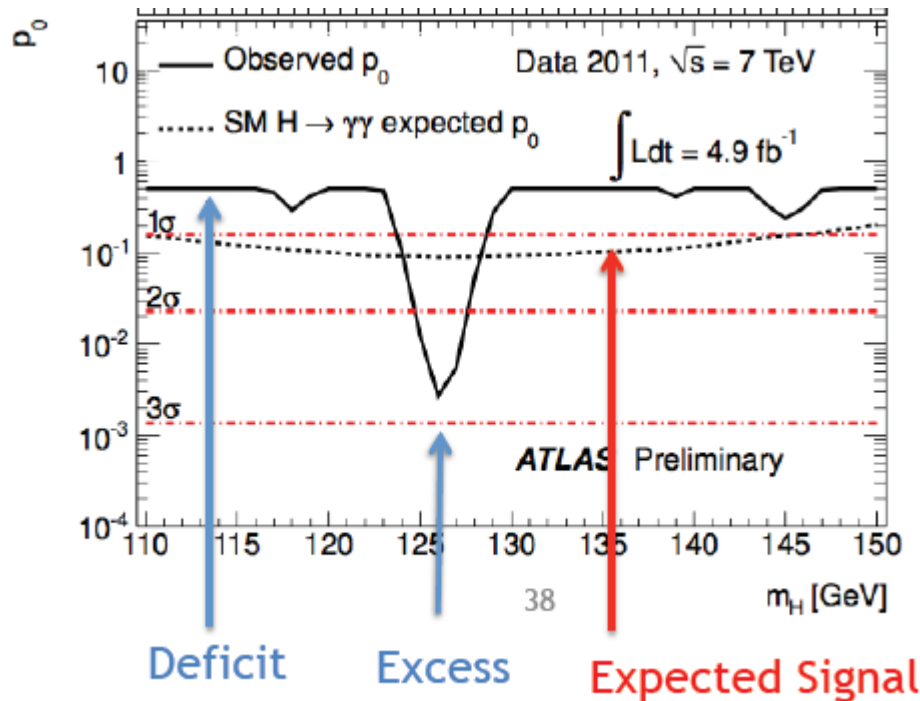
SM Higgs decays



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

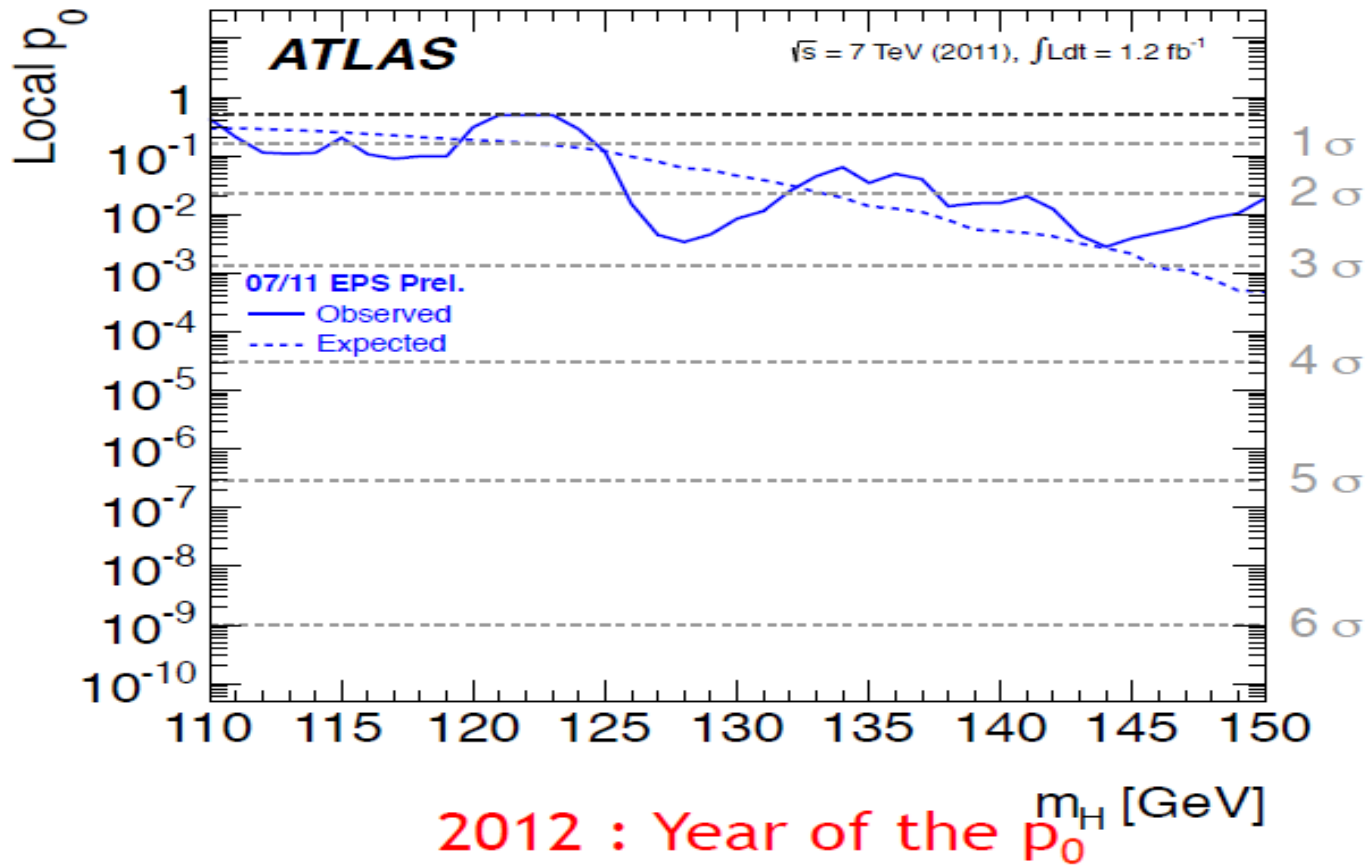
Local p_0

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.



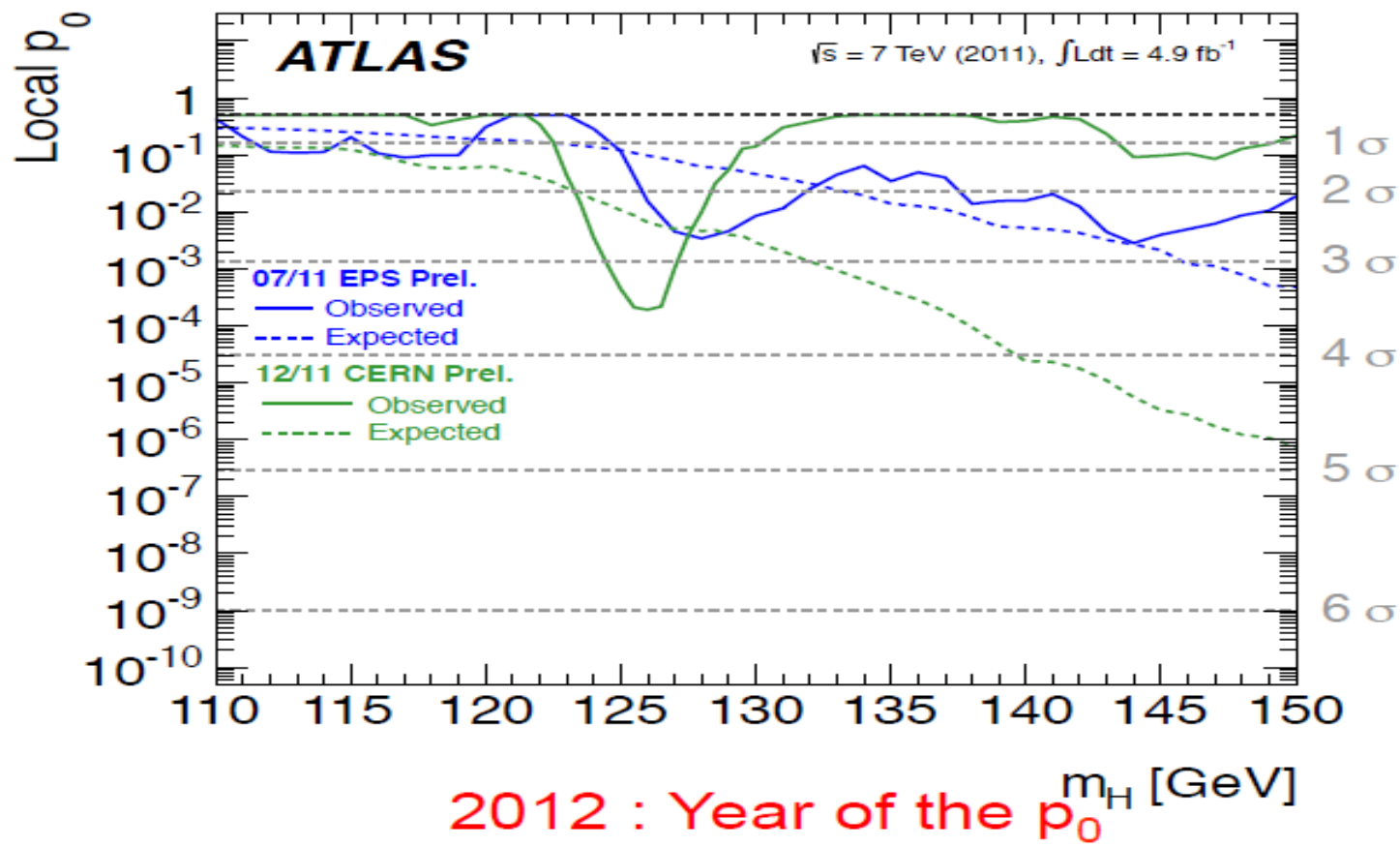
Since conference EPS 2011

Birth of a particle (different prospective)



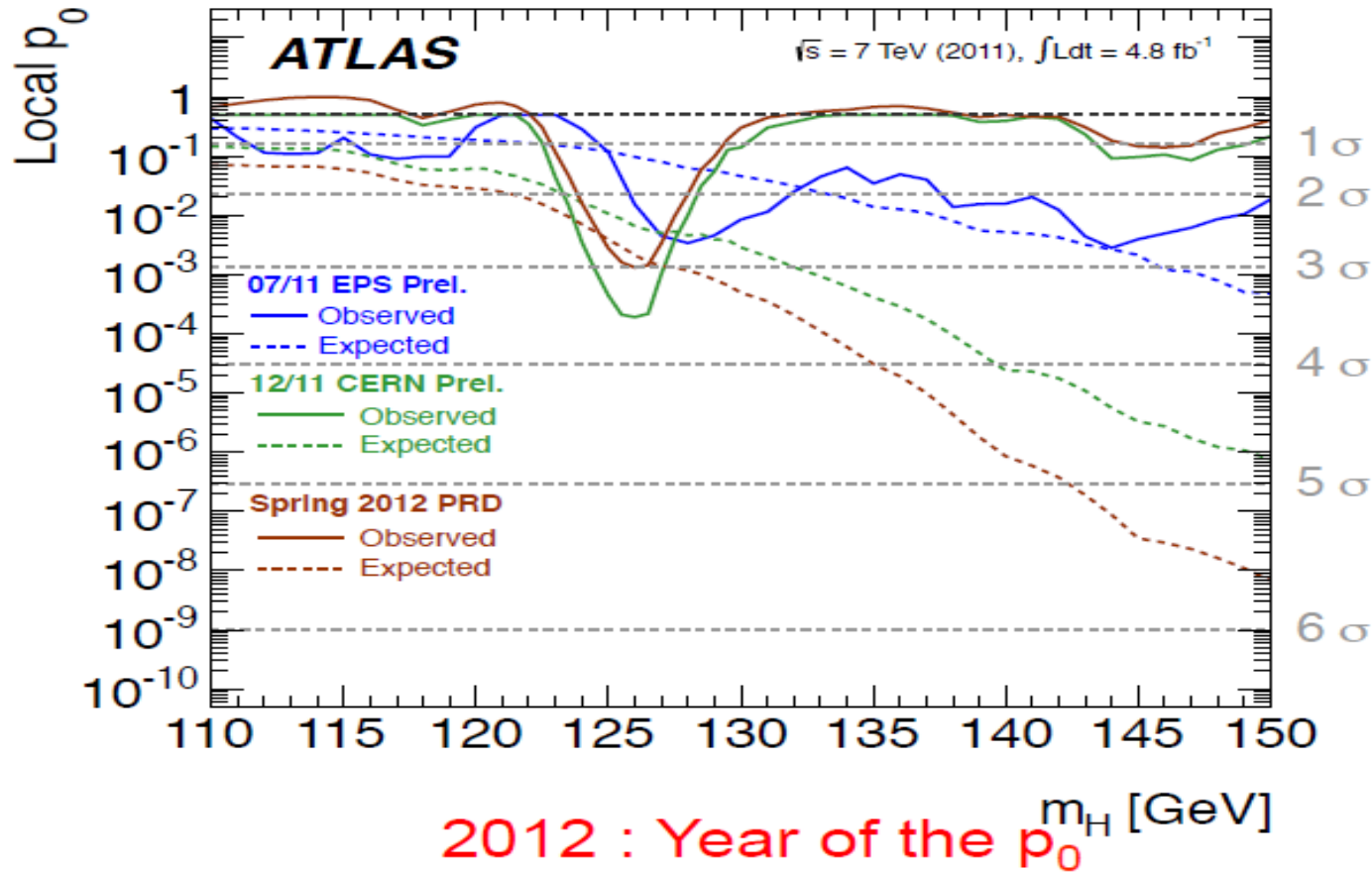
Since conference EPS 2011

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



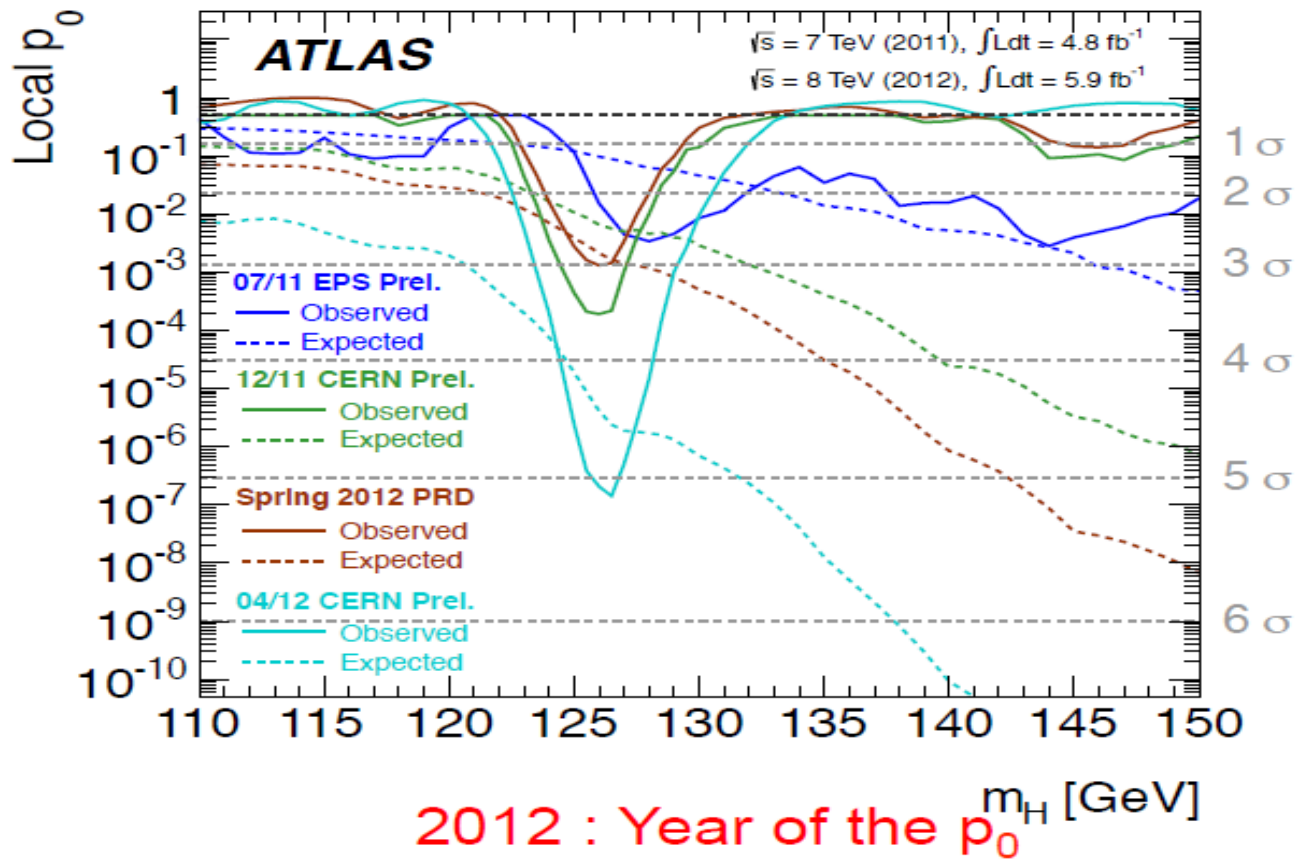
Since conference EPS 2011

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



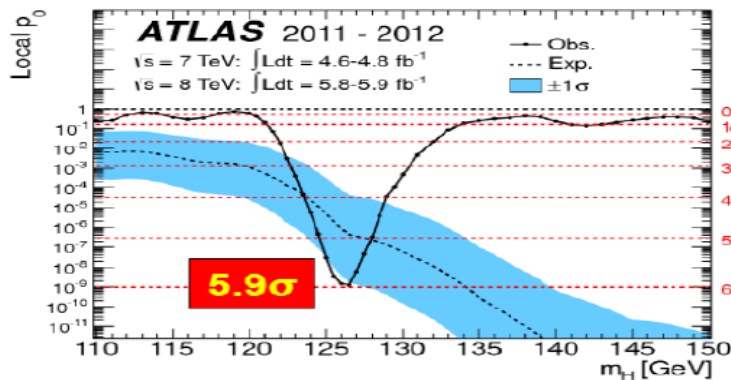
Since conference EPS 2011

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



Higgs-like particle

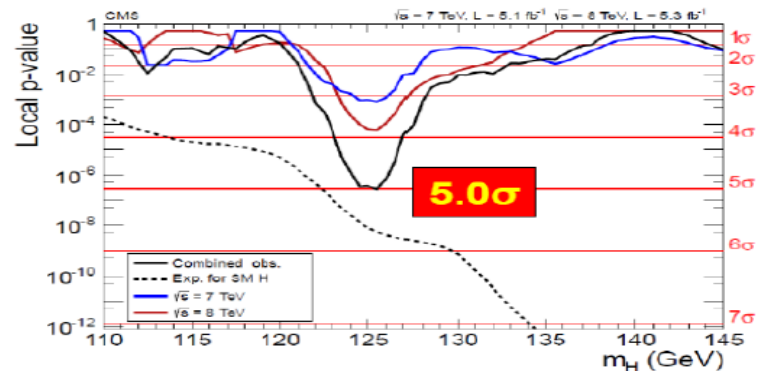
- We are living in a privileged moment in the history of High Energy Physics: **first fundamental scalar**
- The discovery came at half of the design energy, much more severe pile-up and one-third of integrated luminosity than was originally judged as necessary.



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

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

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



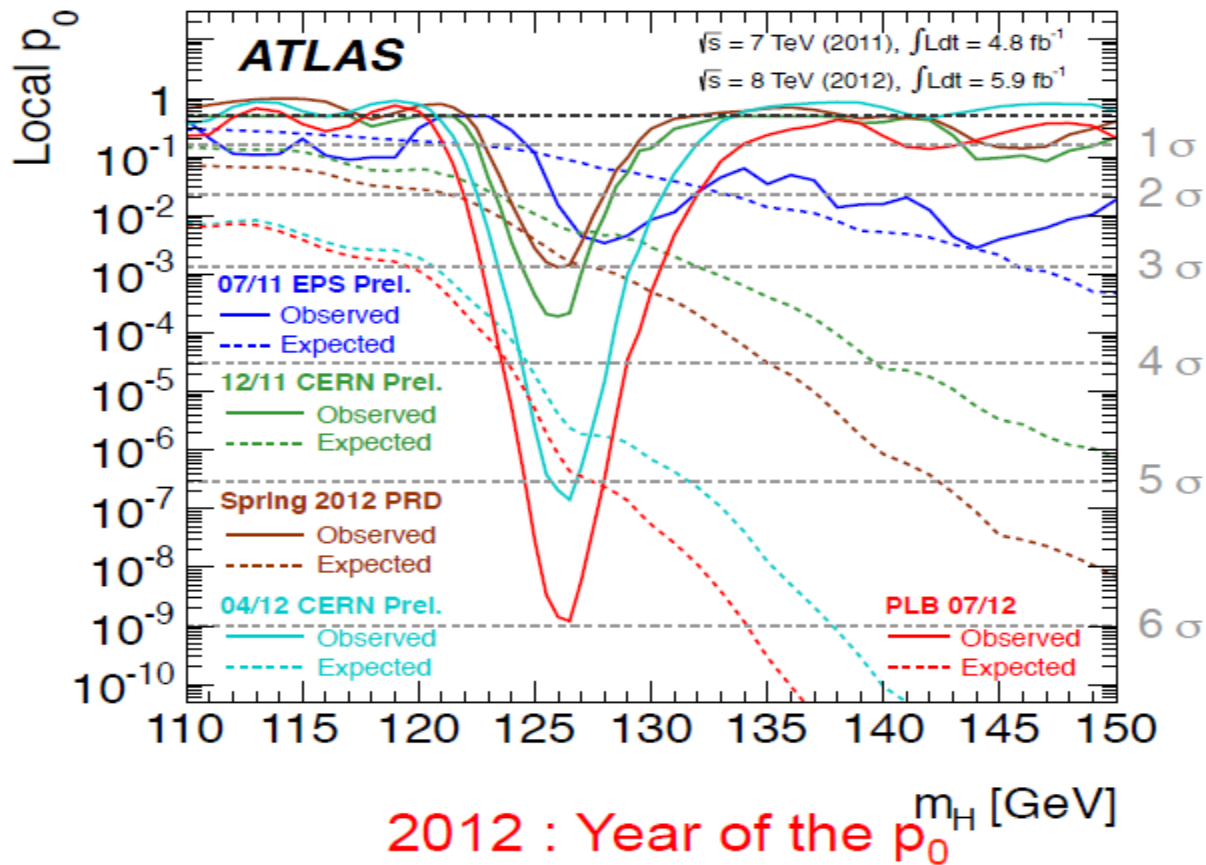
CMS [PLB 716 \(2012\) 30-61](#), Sept 17 (2012)

Largest local excess:
5.0σ at $m_H = 125.5$ GeV

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

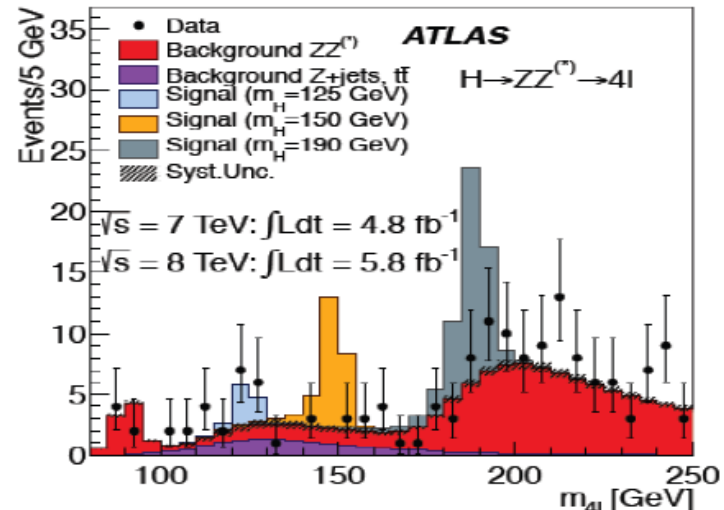
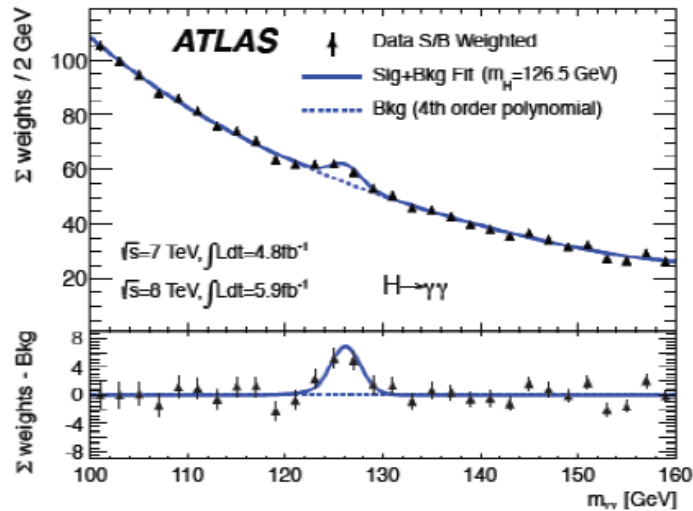
Since conference EPS 2011

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

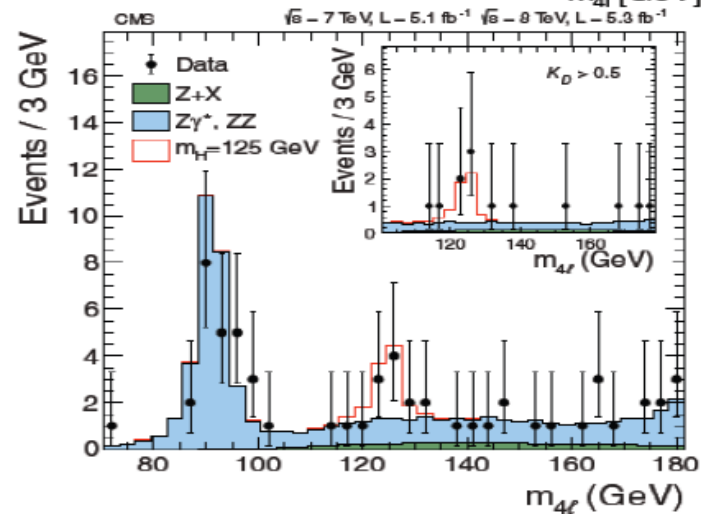
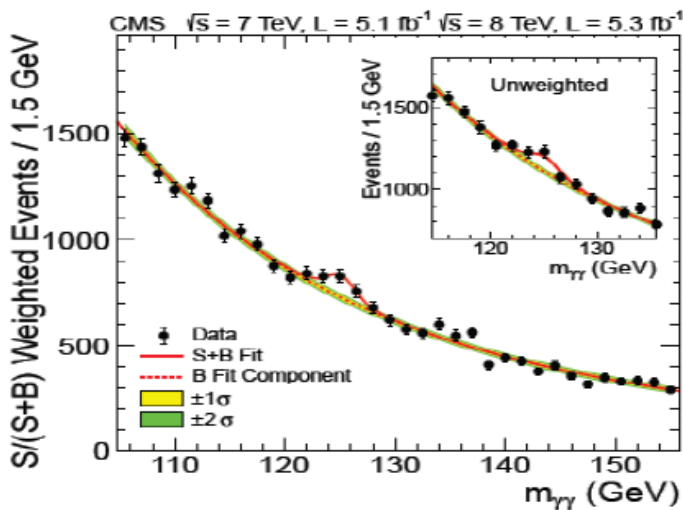


Higgs-like particle

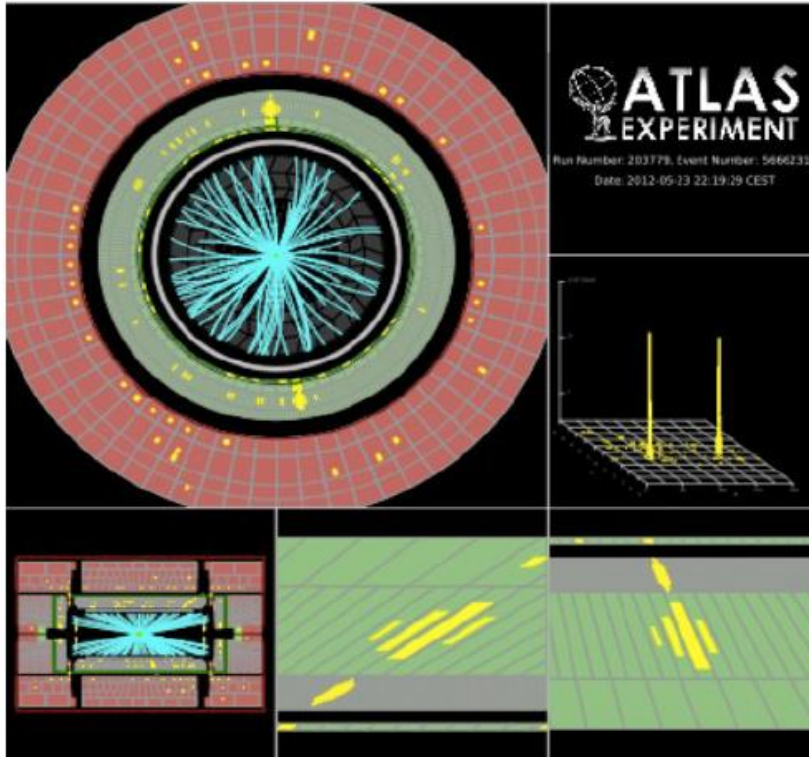
Phys.Lett. B716 (2012) 1-29



Phys.Lett. B716 (2012) 30-61



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



Simple event signature

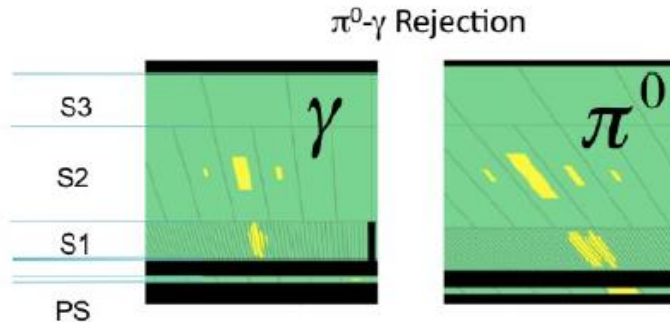
- ❑ Two high p_T photons
 $p_{T_1} > 40$ GeV and $p_{T_2} > 30$ GeV
- ❑ High trigger efficiency
~99%
- ❑ High event selection efficiency despite high jet-jet & γ -jet production
~40%
- ❑ High signal over background
~3-10 % (depending on sub-category)

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



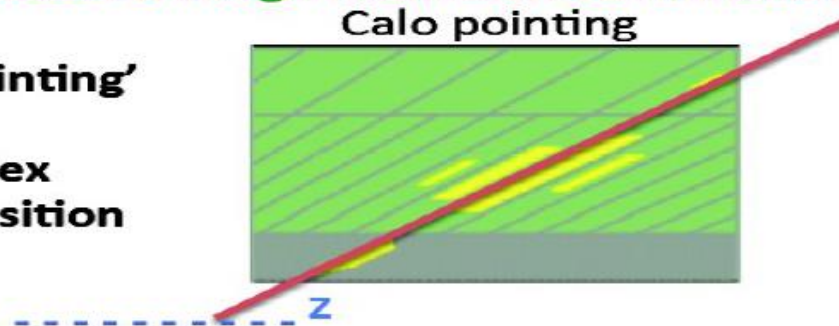
- Photons shower shape distributions in LAr sampling layers - different for signal and background (π^0)

Vertex Reconstruction

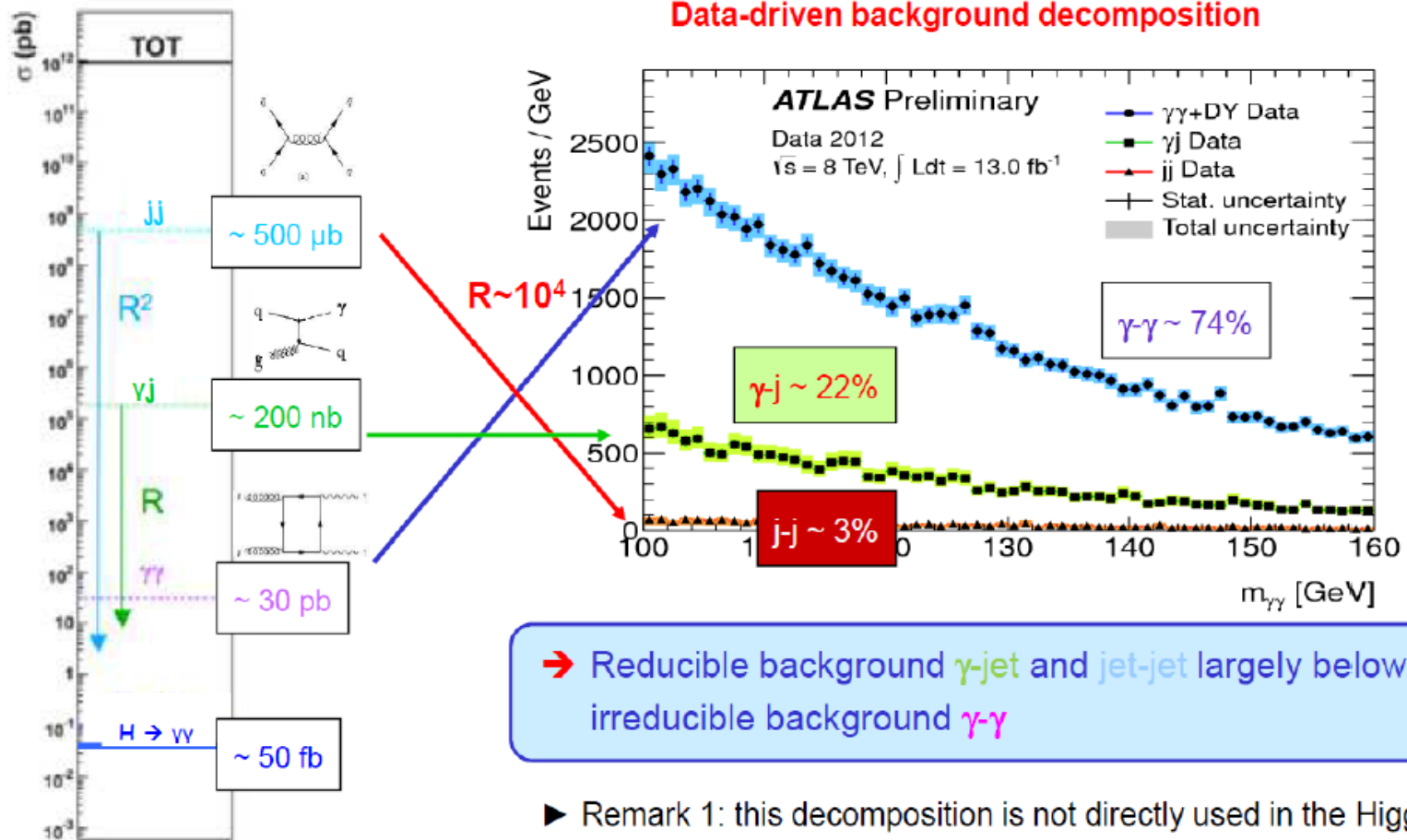
$$m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos \alpha)$$

- Vertex reconstructed through likelihood combination

- Calorimeter 'pointing'
- Σ tracks pT^2
- Conversion vertex
- Mean vertex position



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



➔ Reducible background γ -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

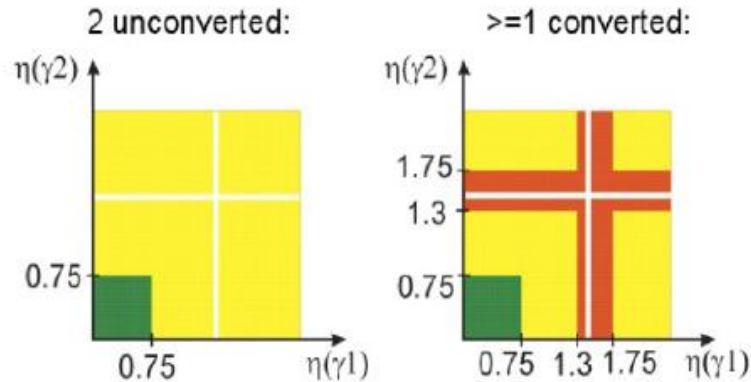
Event categories based on eta, p_{Tt} , and conversion

Both unconverted:

- Central
- Rest

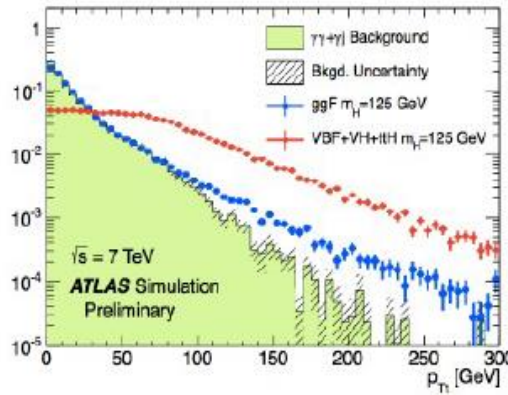
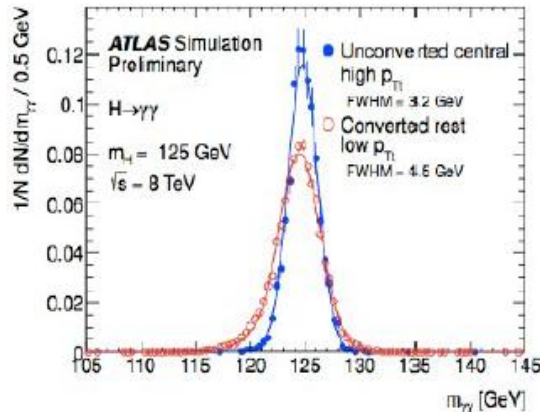
At least one converted:

- Central
- Transition
- Rest

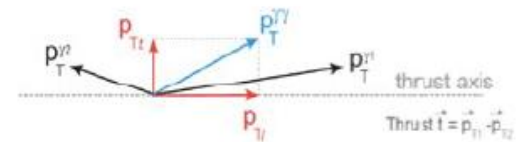


Resolution:

- Good
- Medium
- Poor



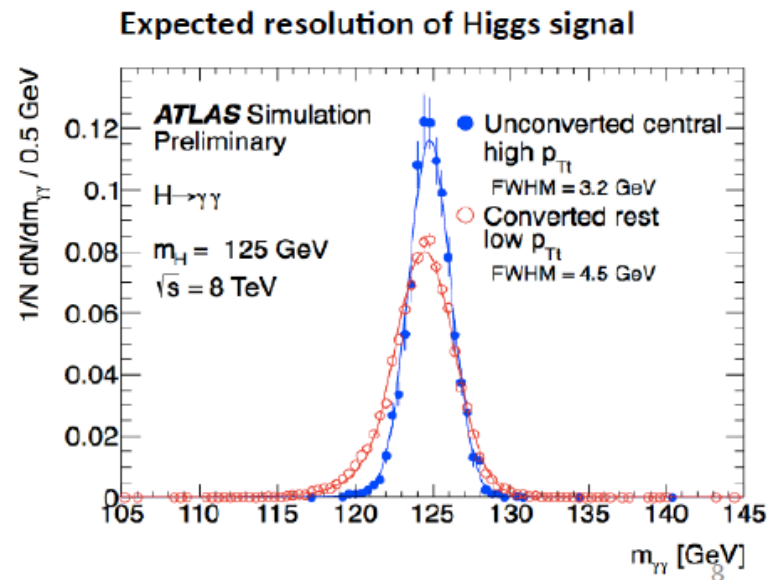
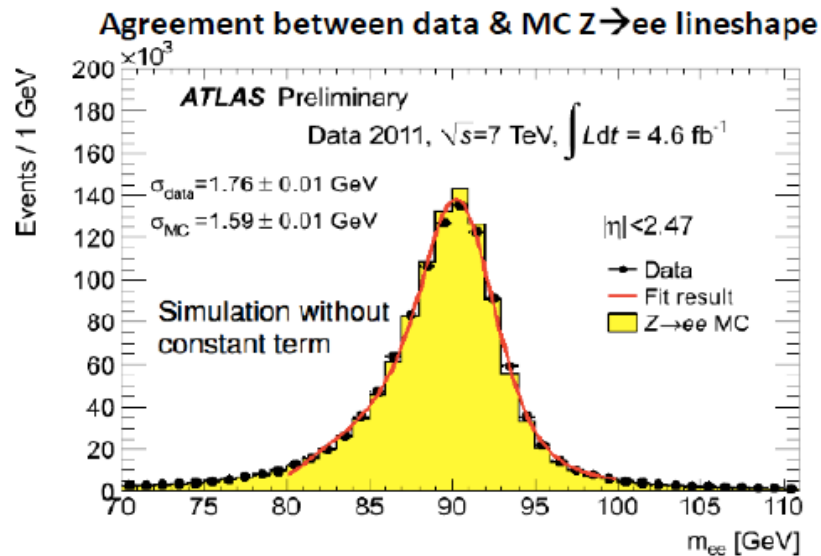
Central and Rest divided into $p_{Tt} < 60$ GeV and $p_{Tt} > 60$ GeV



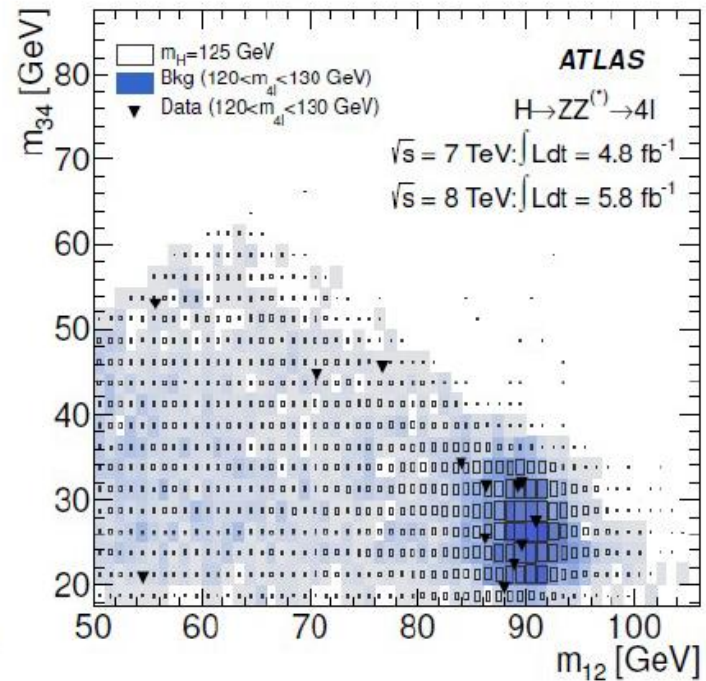
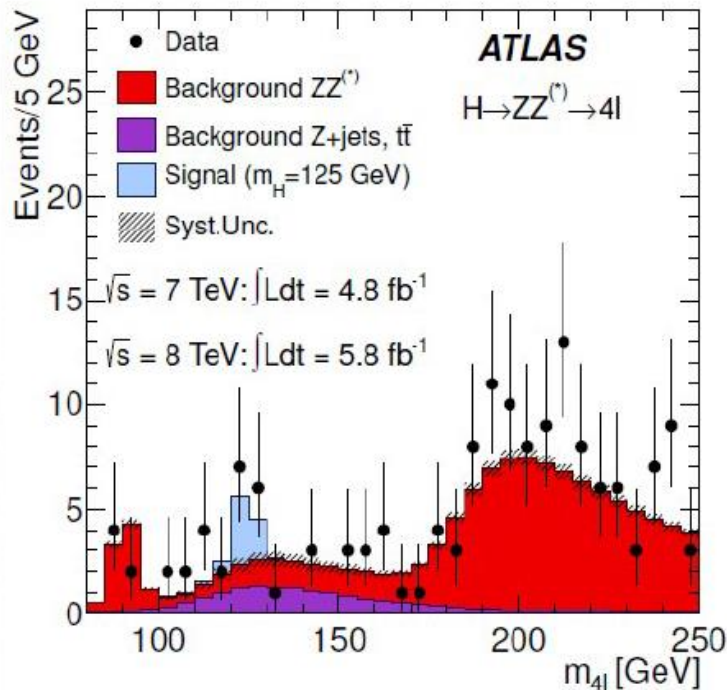
Energy calibration and resolution

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

- 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



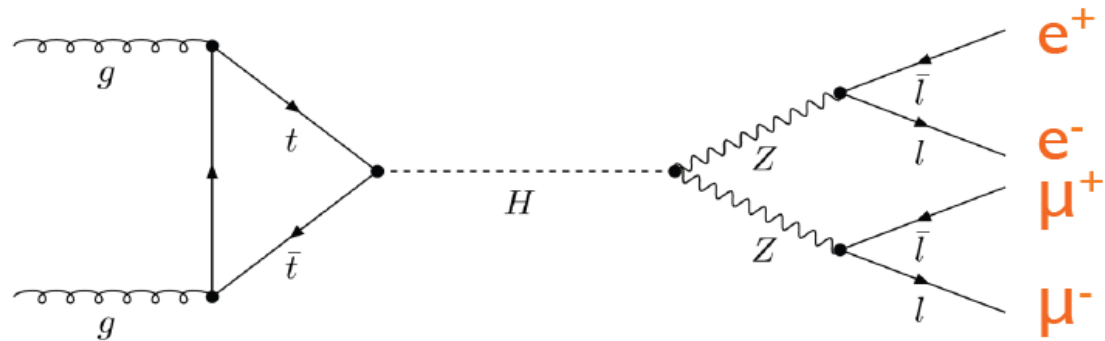
The golden channel $Z \rightarrow ll$



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

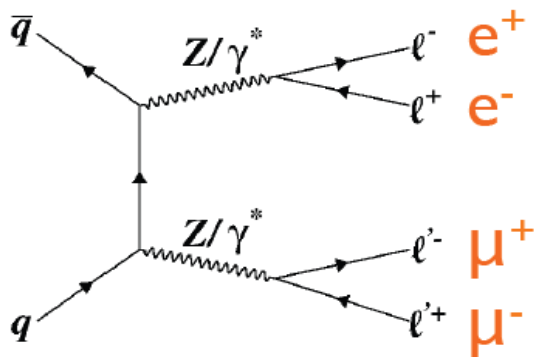
	Signal	$ZZ^{(*)}$	$Z + \text{jets}, t\bar{t}$	Observed
4μ	2.09 ± 0.30	1.12 ± 0.05	0.13 ± 0.04	6
$2e2\mu/2\mu2e$	2.29 ± 0.33	0.80 ± 0.05	1.27 ± 0.19	5
$4e$	0.90 ± 0.14	0.44 ± 0.04	1.09 ± 0.20	2

Signal and background



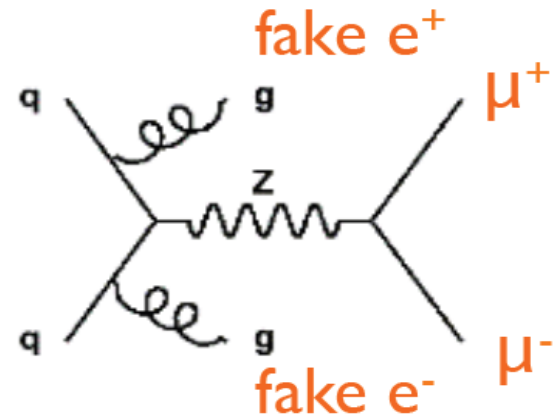
Irreducible background

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



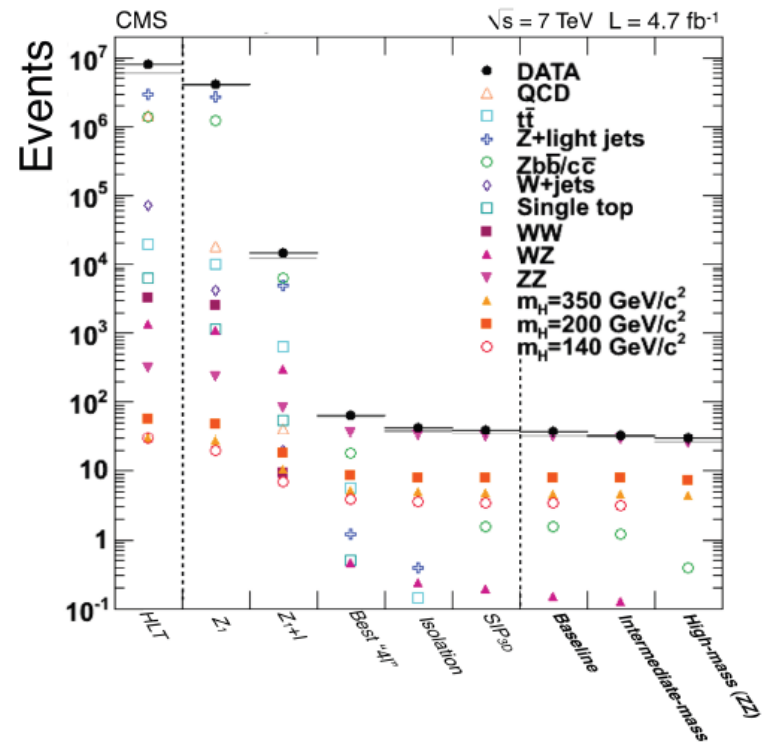
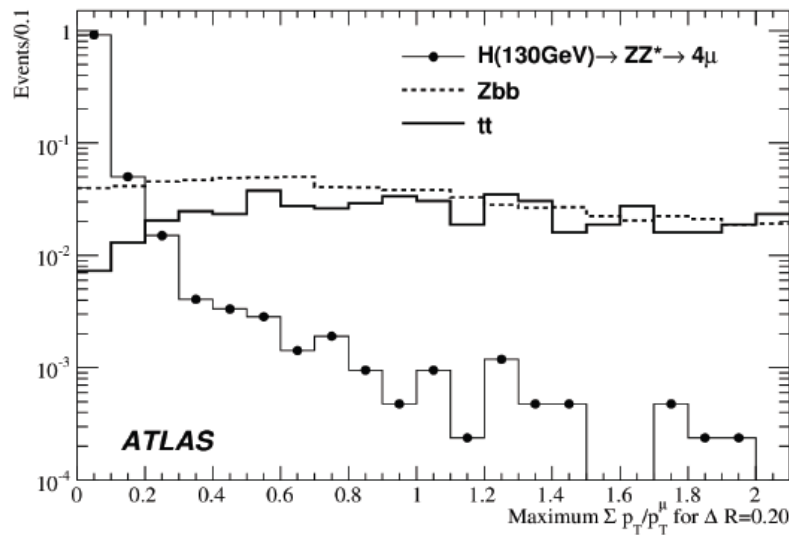
Reducible background

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

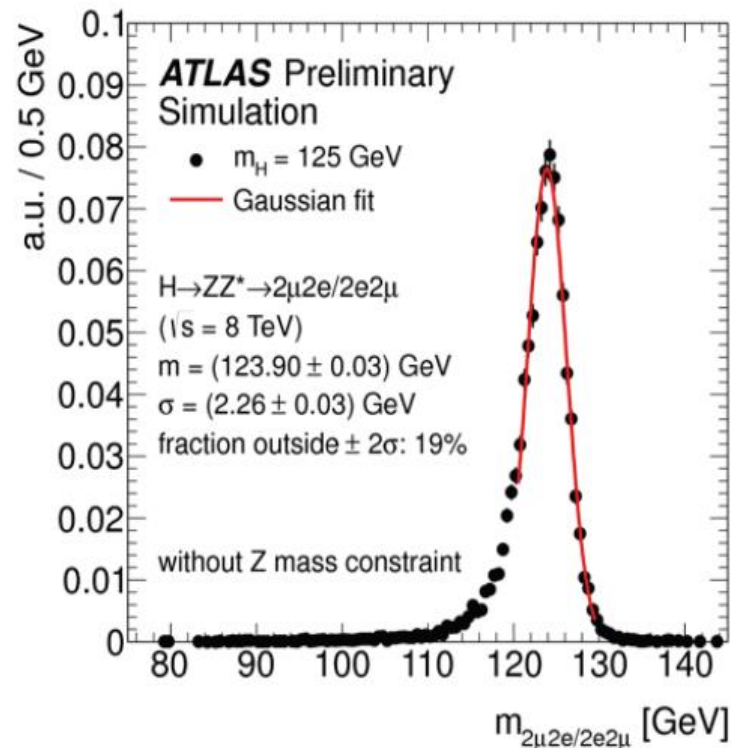


Reconstruct properties of initial particles

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

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

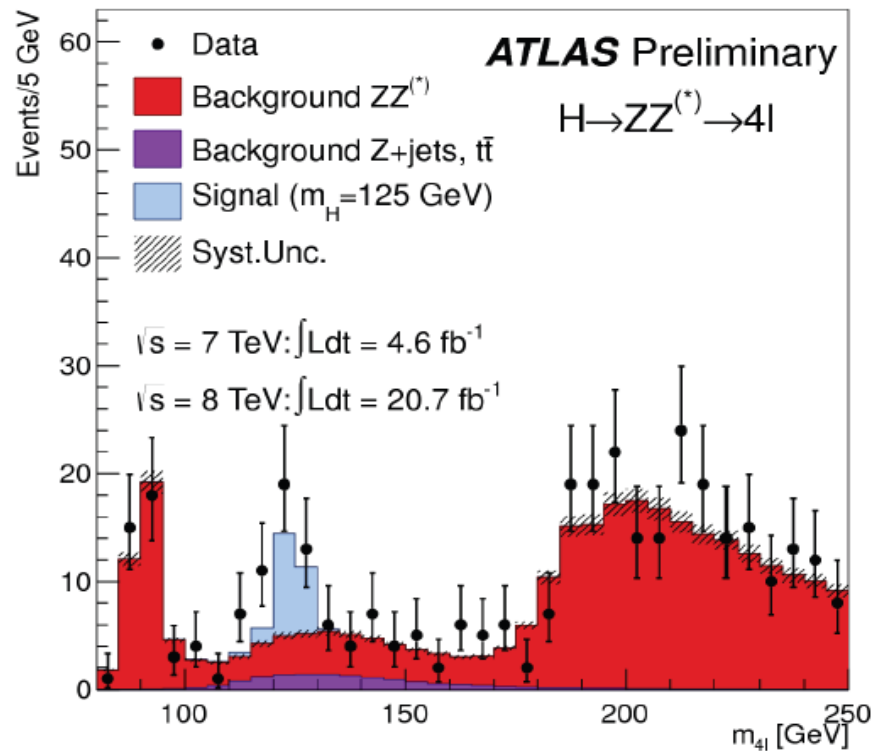
- Reconstruct invariant mass from the 4 particles
$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



Signal and background

Background gets estimated...

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



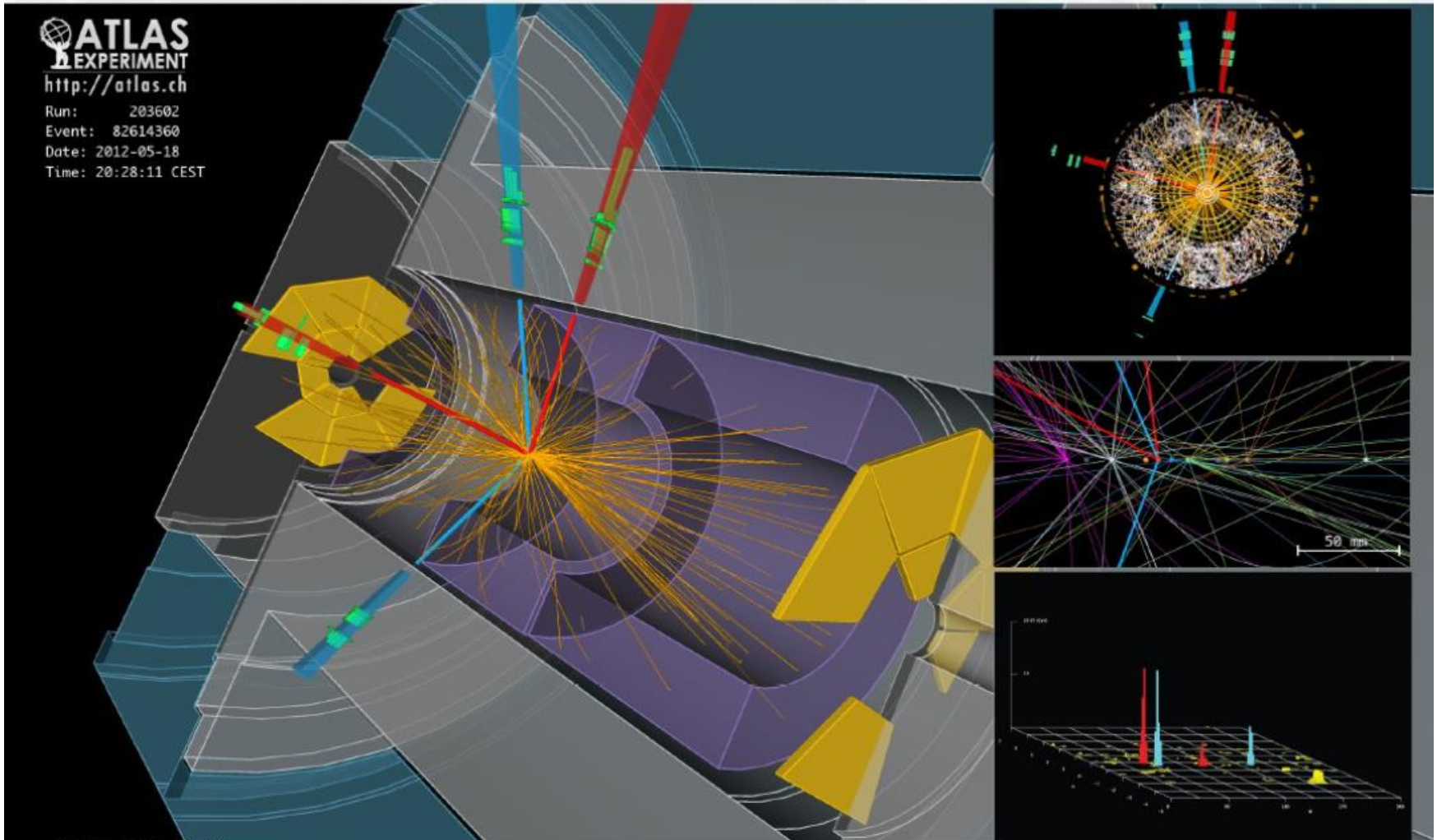
4e candidate. $m_{4\ell} = 124.6$ GeV, $m_{12} = 70.6$ GeV, $m_{34} = 44.7$ GeV.

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, $\eta = -0.12$, $\phi = 1.45$

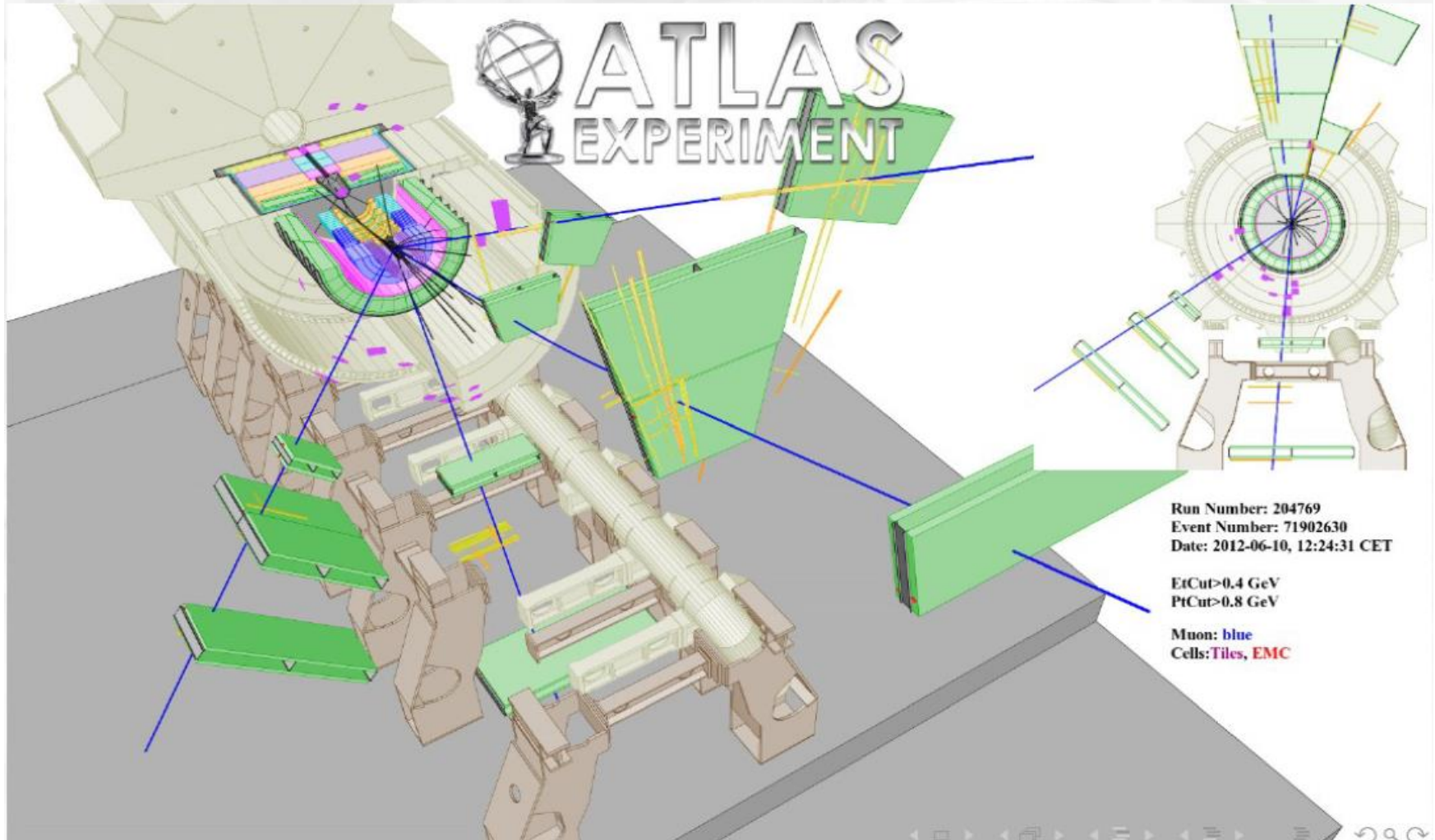
e_4 : $P_T = 17.8$ GeV, $\eta = -0.51$, $\phi = 2.84$



4μ 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, $\eta = 0.69$, $\phi = -1.65$

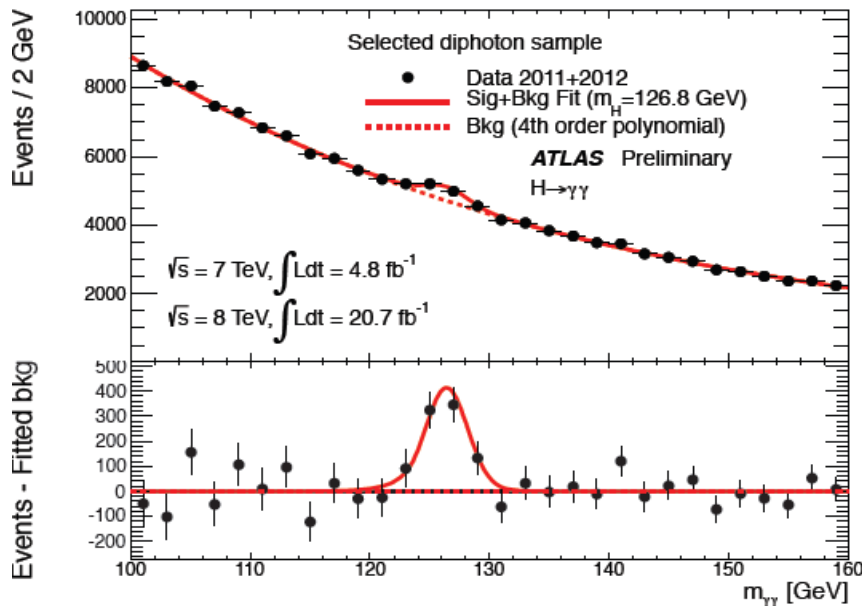
$\mu_3: P_T = 26.4$ GeV, $\eta = 0.47$, $\phi = -2.51$ $\mu_4: P_T = 71.7$ GeV, $\eta = 1.85$, $\phi = 1.65$



Higgs like signal with 7 TeV and 8 TeV data

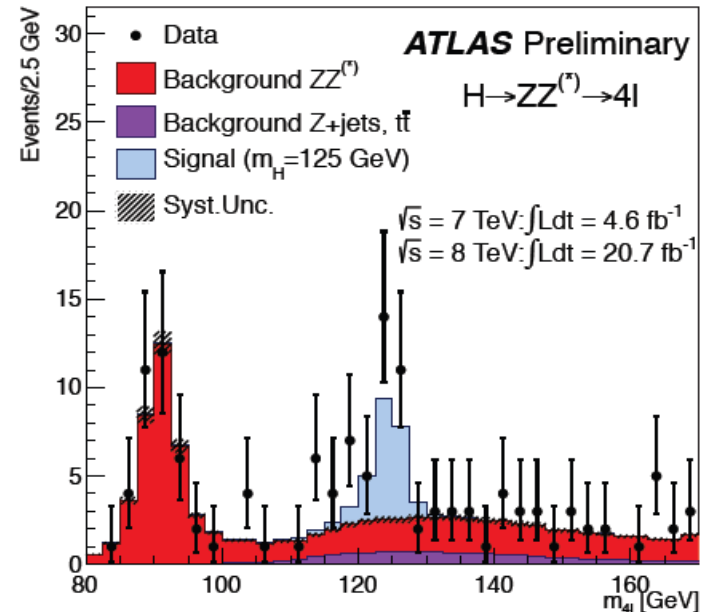
2013

$H \rightarrow \gamma\gamma$



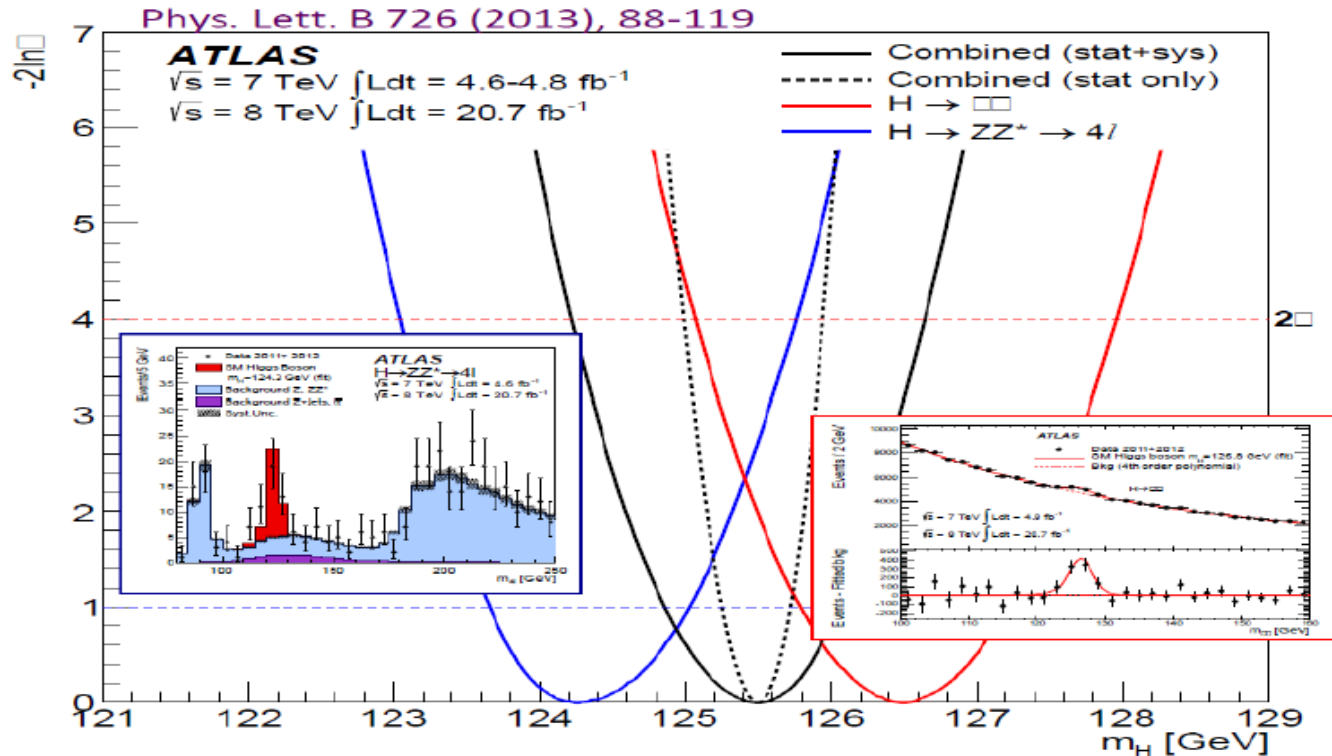
- Signal significance = 7.4σ
- $m_H = 126.8 \pm 0.2$ (stat) ± 0.7 (syst) GeV
- $\mu = 1.65 \pm 0.34$ (deviation w.r.t. SM at 2.3σ)

$H \rightarrow 4l$



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

Mass measurement



$$4\ell: M_H = 124.3 \pm 0.6_{\text{stat}} \pm 0.4_{\text{sys}} \text{ GeV}$$

$$\gamma\gamma: M_H = 126.8 \pm 0.2_{\text{stat}} \pm 0.7_{\text{sys}} \text{ GeV}$$

$$\text{Combined: } M_H = 125.5 \pm 0.2_{\text{stat}} \pm 0.6_{\text{sys}} \text{ GeV}$$

And since then (2013)

Panorama of ATLAS Higgs (125) Analyses

channel	ggF	VBF	VH	ttH	Yield	S/B (%)	Res. (GeV/c ²)
$\gamma\gamma$	✓	✓	✓	✓	~ 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

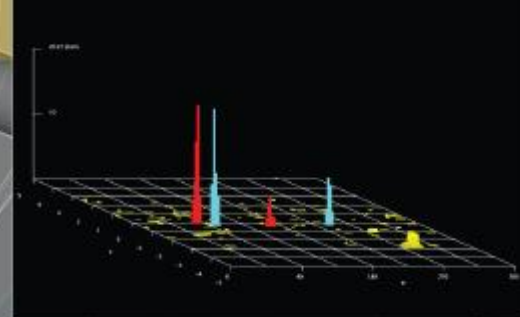
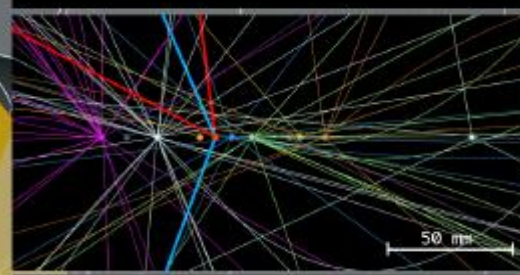
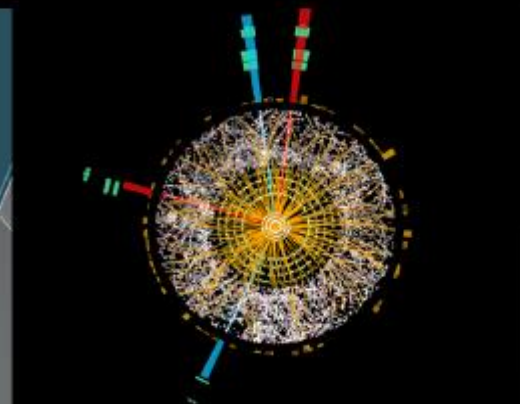
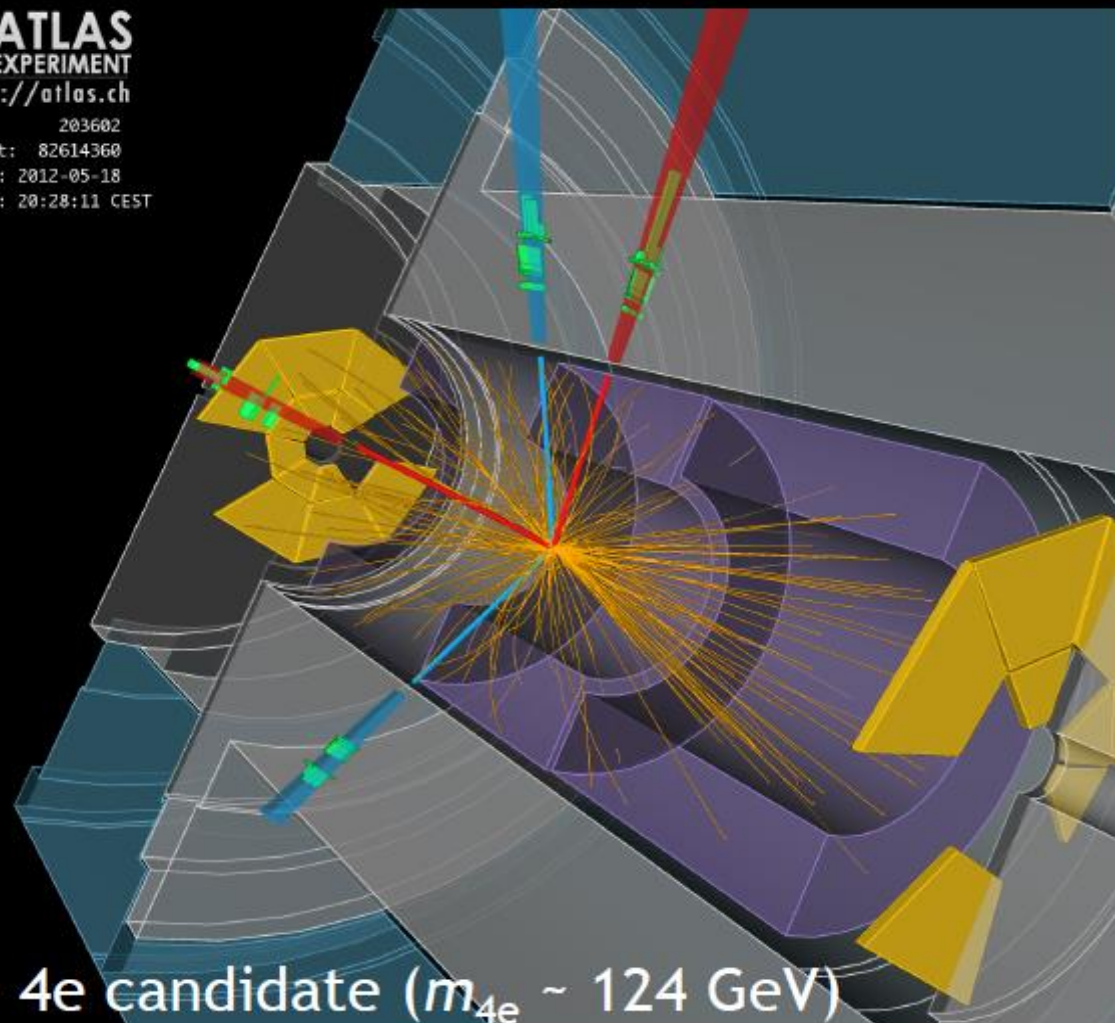


Run Number: 204769, Event Number: 24947130

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 :

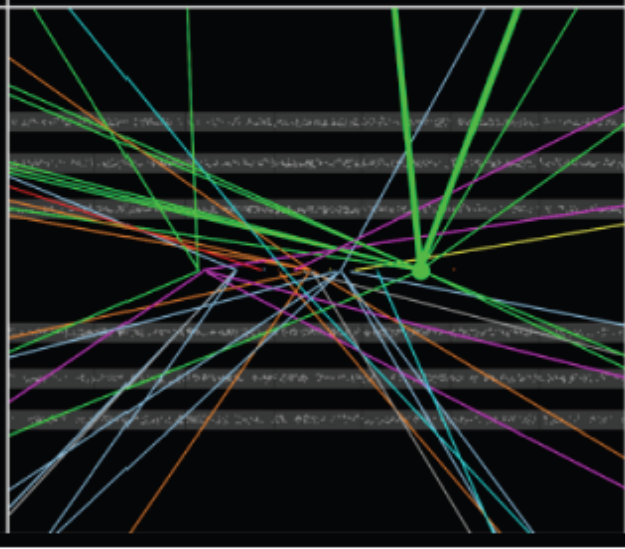
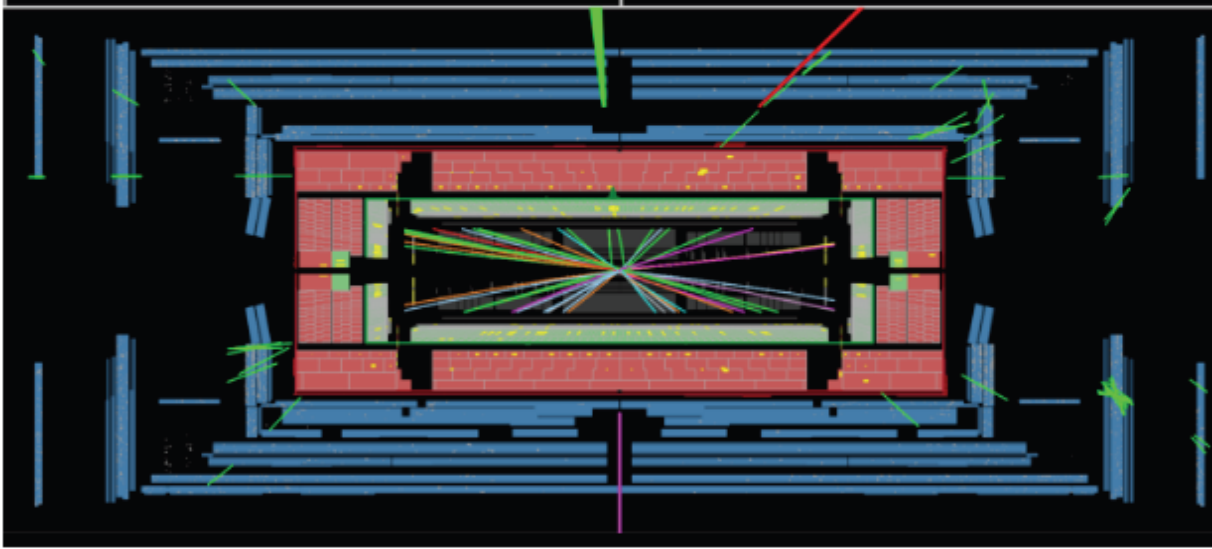
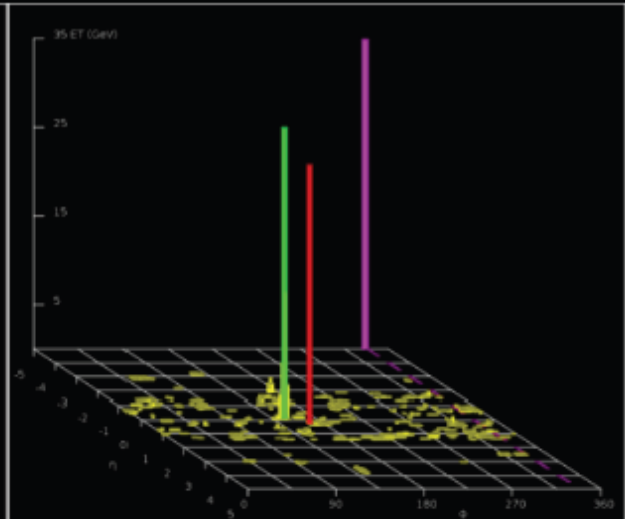
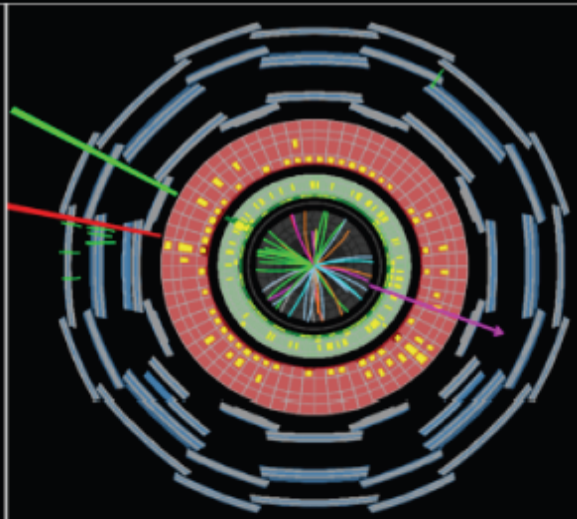
Signal	Signal Purity s/b	Main backgrounds	Production	7 & 8 TeV $\int L dt$
~ 16	~ 1.5	ZZ, Z+jets, top	ggH, VBF & VH	4.9 & 20.7 fb ⁻¹

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

$$ll + 2\nu$$

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 ⁻¹

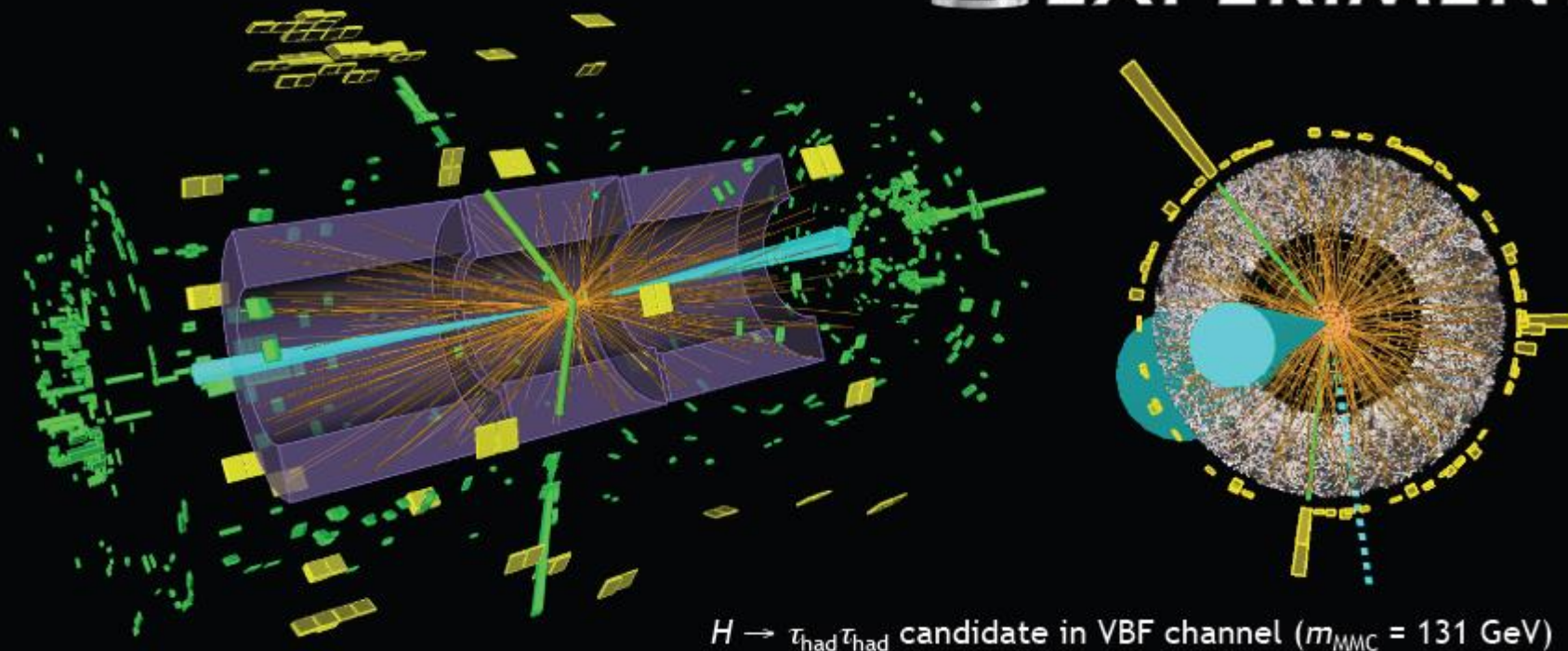
$H \rightarrow \tau\tau$

Reoptimised 7+8 TeV analysis

ATLAS-CONF-2012-160



ATLAS
EXPERIMENT

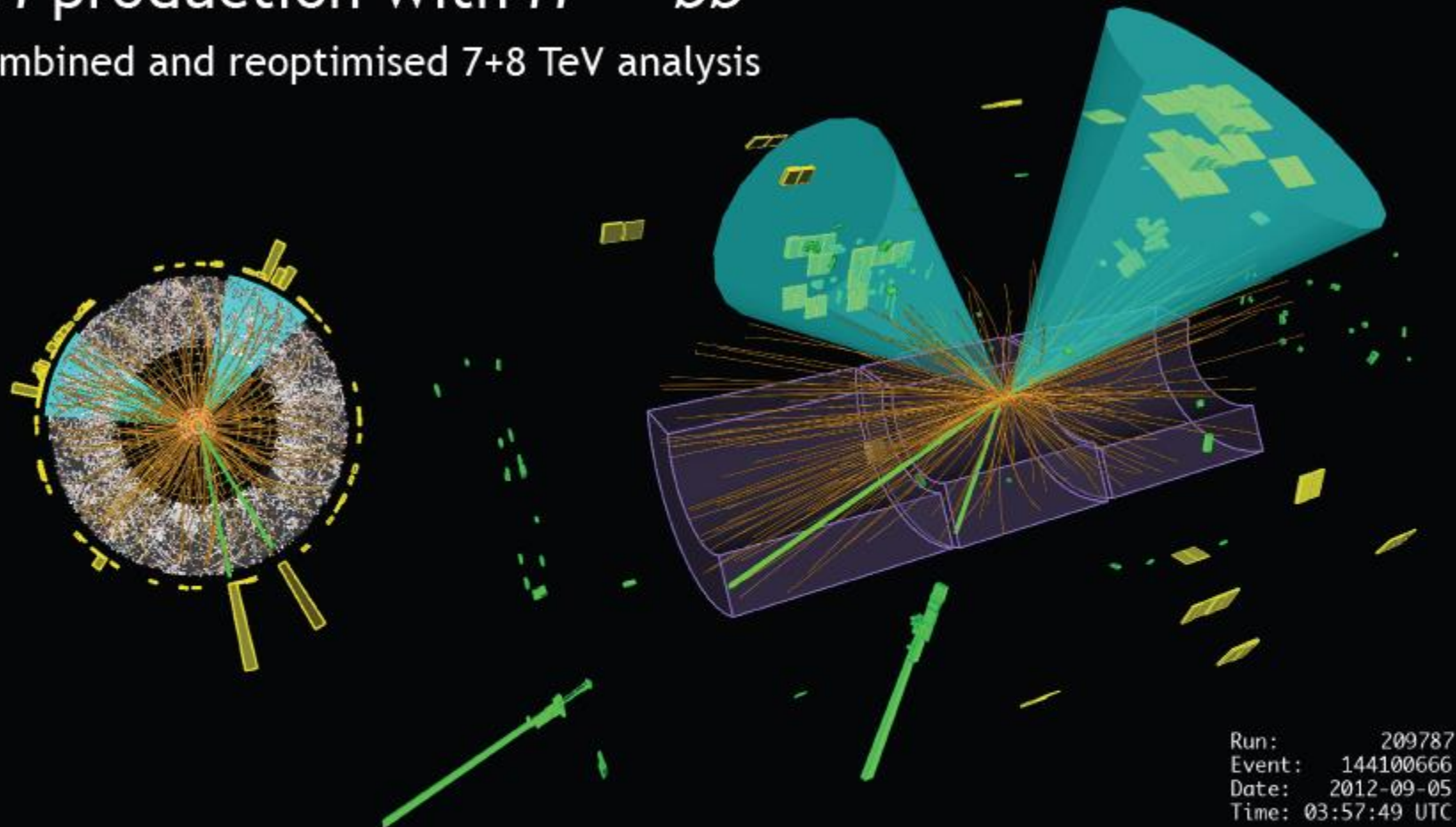


$\tau\tau$ channel basic facts sheet :

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 ⁻¹

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 ⁻¹

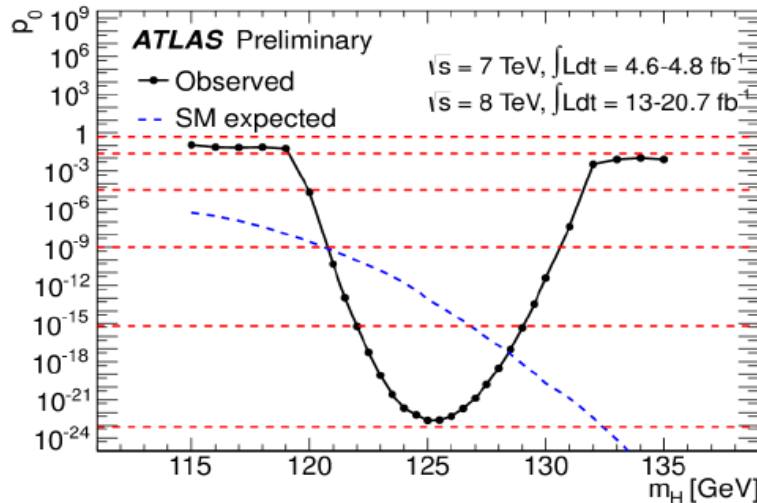
How significant is the signal for the new particle?

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 ± 0.37 (stat) ± 0.18 (syst) GeV [ATLAS]
 125.03 ± 0.26 (stat) ± 0.14 (syst) GeV [CMS]

Signal strength

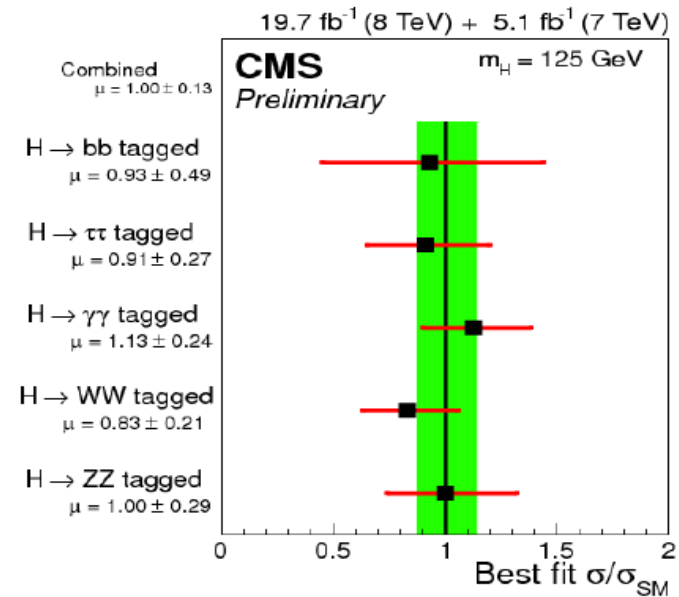
$\mu = 0$ background only hypothesis
 $\mu = 1$ SM Higgs hypothesis



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 ~ 125.6 GeV

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

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

CMS: $m_H = 125.7 \pm 0.3$ (stat) ± 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 $T_3 = 0$

NODE=S055CNT

H^0 (Higgs Boson)

NODE=S055210

NODE=S055210

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.

H^0 MASS

UNDE (GeV)

125.0 ± 0.4 OUR AVERAGE

125.0 ± 0.4 ± 0.4

126.0 ± 0.4 ± 0.4

••• We do not use the following data for averages, fits, limits, etc. •••

126.2 ± 0.0 ± 0.2

125.3 ± 0.4 ± 0.5

DOCUMENT ID TECN COMMENT

¹ CHATRCHYAN13J CMS pp, 7 and 8 TeV

² AAD 12N ATLAS pp, 7 and 8 TeV

³ CHATRCHYAN13J CMS pp, 7 and 8 TeV

⁴ CHATRCHYAN12N CMS pp, 7 and 8 TeV

¹ Combined value from ZZ and $\gamma\gamma$ final states.

² 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 3.9σ is observed at $m_{H^0} = 126\text{ GeV}$. See also AAD 12DA.

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

⁴ 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 5.0σ is observed at about $m_{H^0} = 125\text{ GeV}$. See also CHATRCHYAN 12DY.

NODE=S055HBM
NODE=S055HBM

OCCUR=2

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 : γ

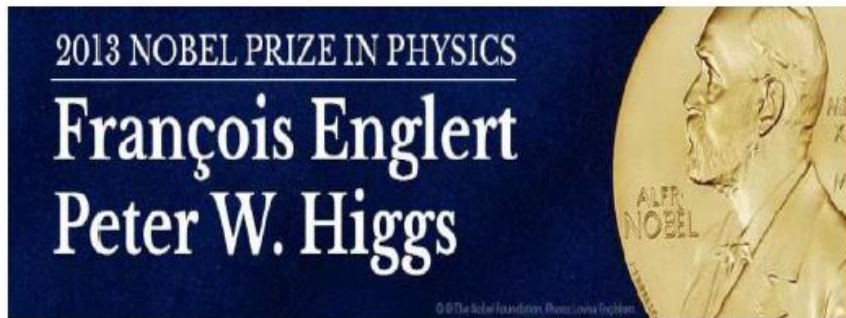
weak : W^+ , W^- , Z

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 →		u up	c charm	t top	γ 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	
		d down	s strange	b bottom	g 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	
		ν_e neutrino électronique	ν_μ neutrino muonique	ν_τ neutrino tauique	Z^0 boson Z^0	
		0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV	interaction faible
		-1	-1	-1	± 1	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		e électron	μ muon	τ tau	W^\pm boson W	
					~ 126 GeV	interaction faible
					0	
					0	
					H 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 październik 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

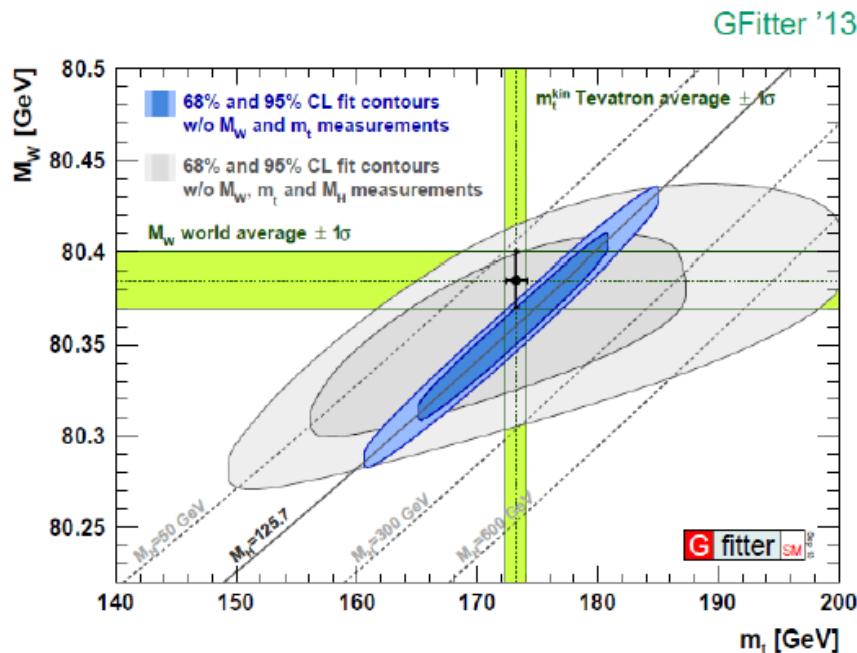
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

1 strona

Standard Model after Higgs discovery

- Good agreement between measured mass and indirect prediction
- Very good agreement over large number of observables



Direct measurements:

$$M_W = 80385 \pm 15 \text{ MeV}$$

$$m_t = 173.24 \pm 0.95 \text{ GeV}$$

Indirect prediction:

$$M_W = 80358 \pm 7 \text{ MeV}$$

$$m_t = 177.0 \pm 2.1 \text{ GeV}$$

More precise estimate of m_W than the direct measurement!

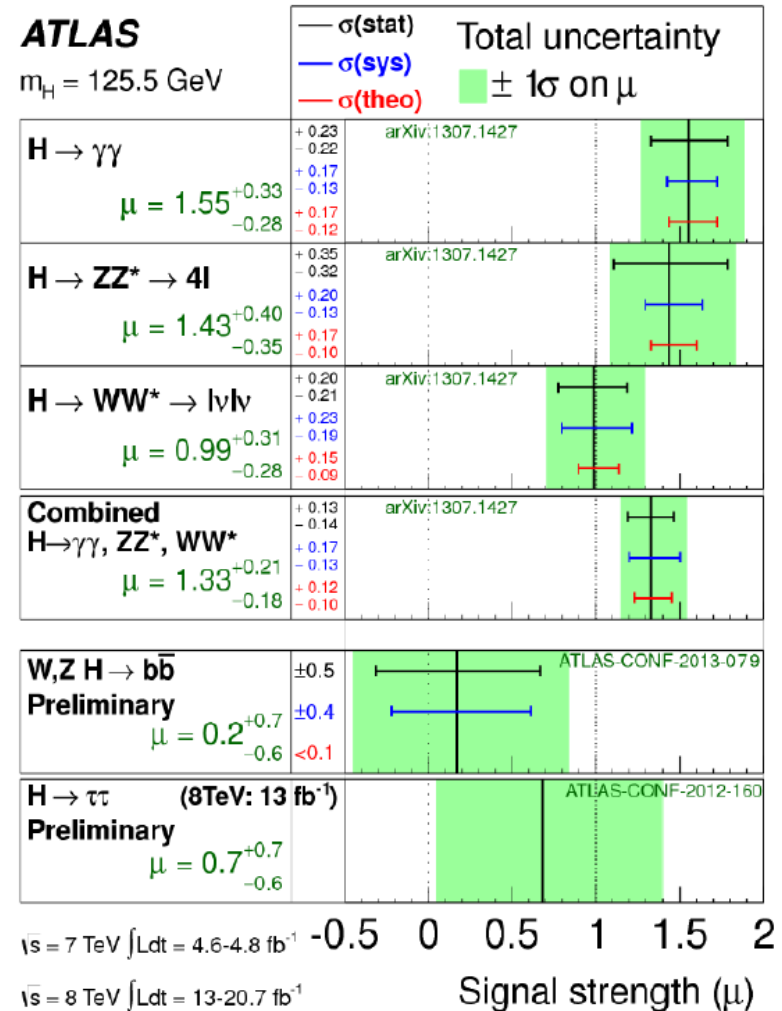
Higgs boson signal strength

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

Individual channels are consistent

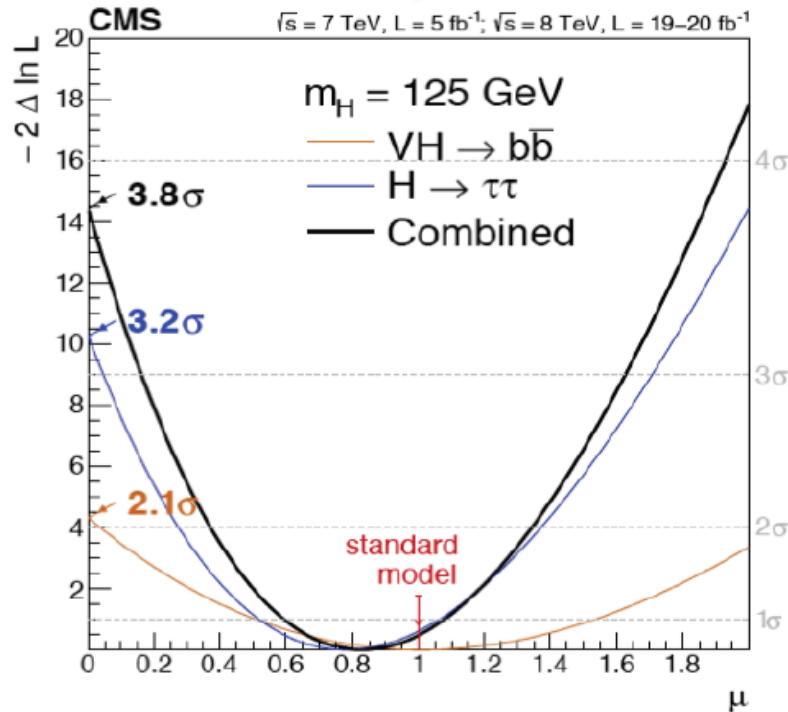
SM describes the rates well, so far

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



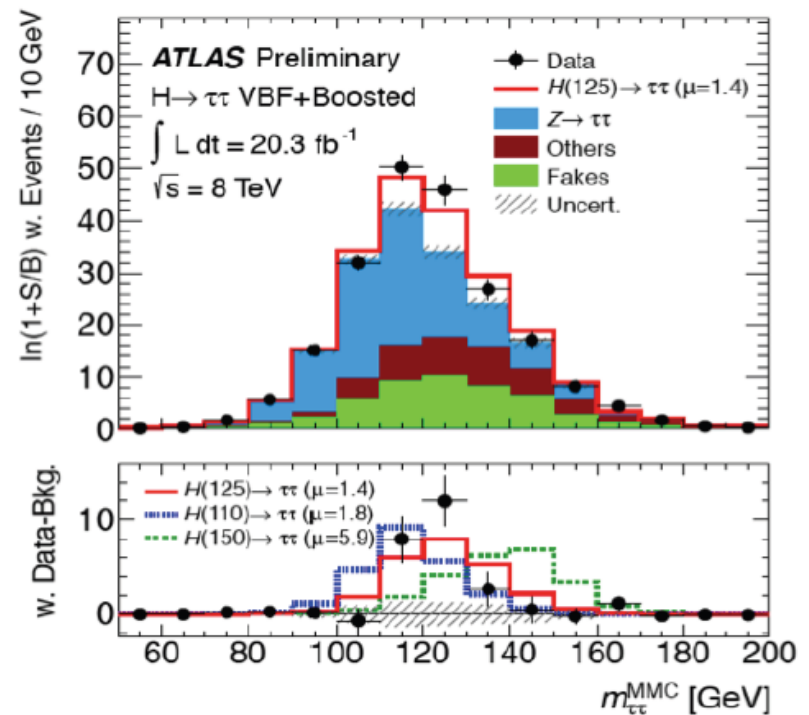
Higgs decays to fermions (2014)

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



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

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

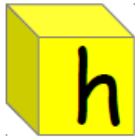


Significance	Exp	Obs
ATLAS ($\tau\tau$)	3.2 σ	4.1 σ

Tevatron: exp (2.1 σ), obs (3.0 σ)

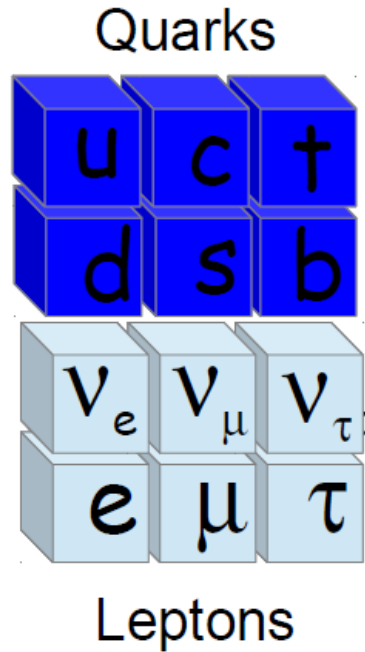
What spin do particles have?

boson



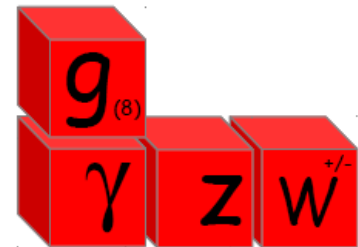
Spin 0

fermions



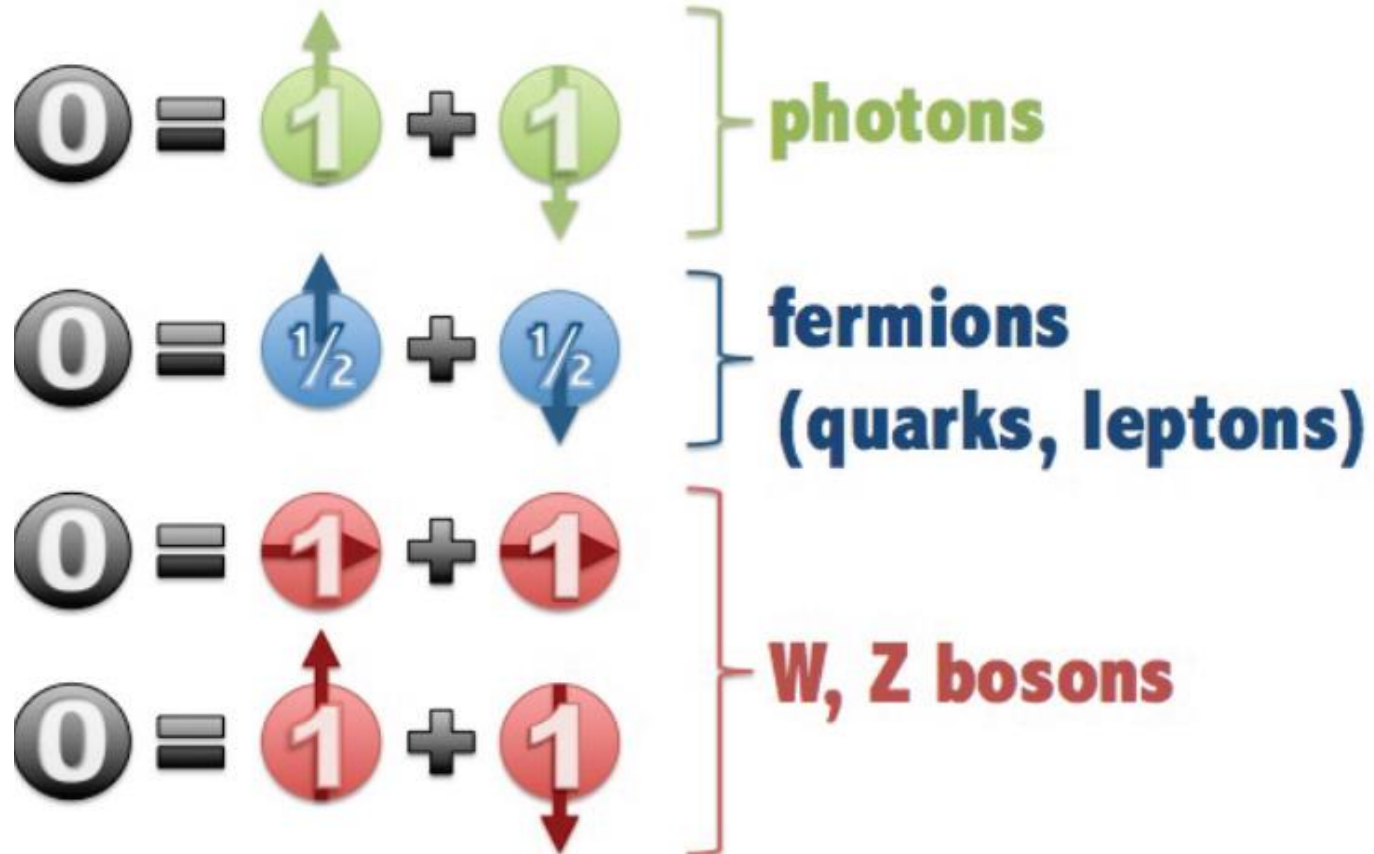
Spin 1/2

bosons

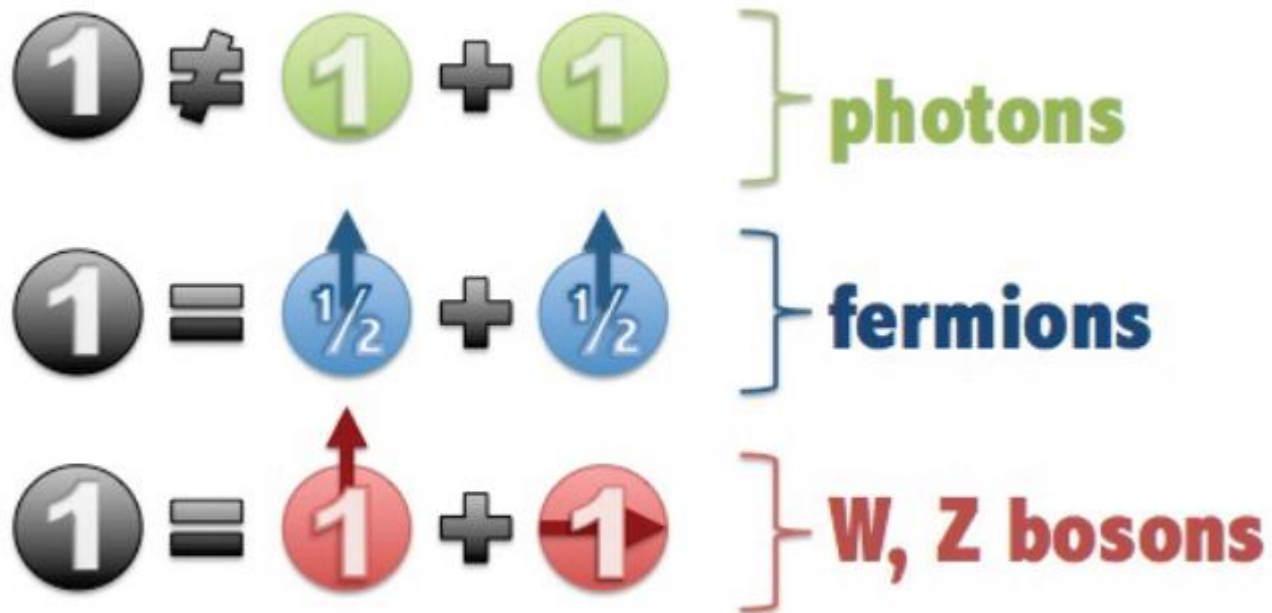


Spin 1

What can a spin 0 particle decay to?



What can a spin 1 particle decay to?



What can a spin 2 particle decay to?

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







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

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

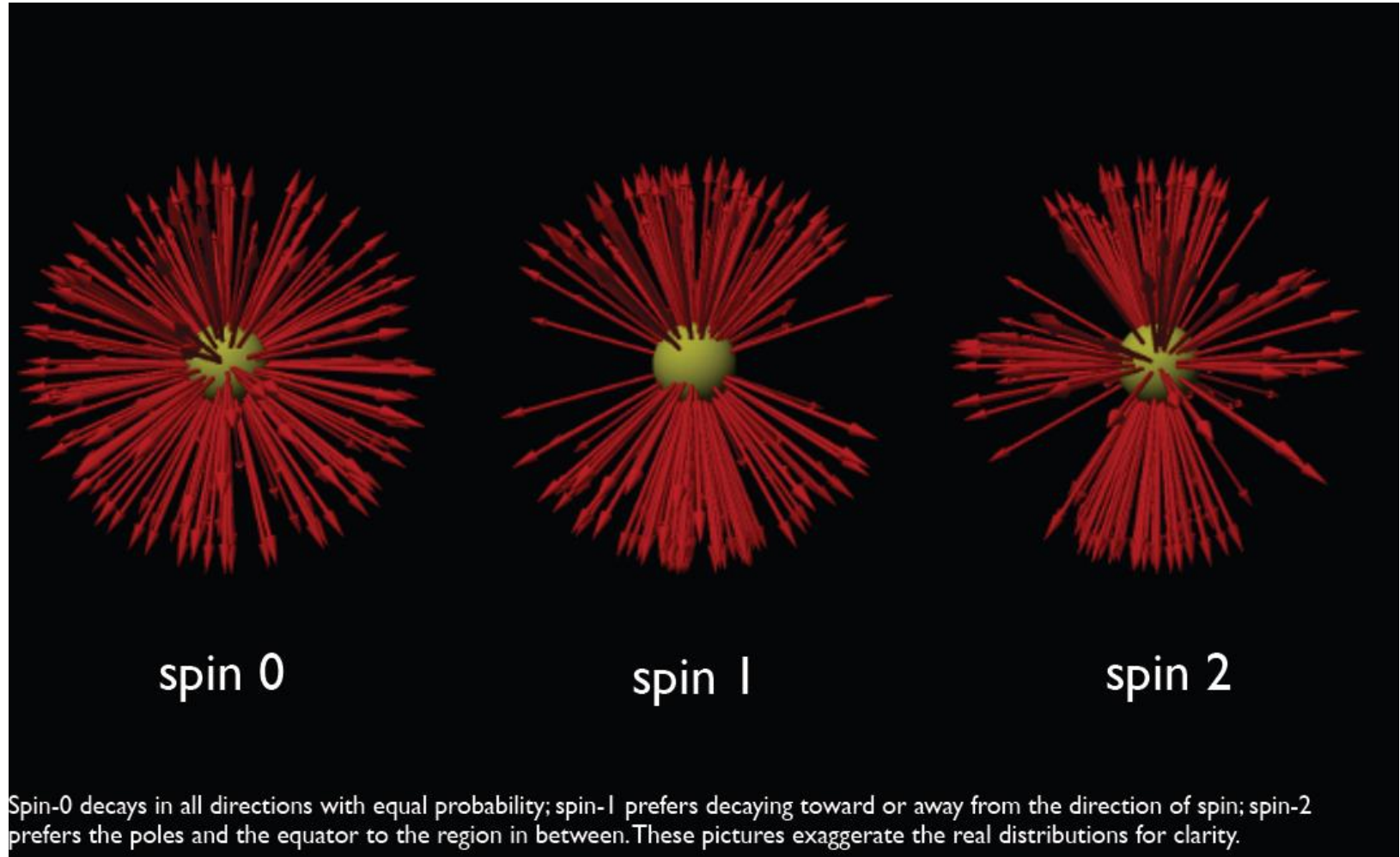
$$\textcircled{2} = \textcircled{\frac{1}{2}}^{\uparrow} + \textcircled{\frac{1}{2}}^{\uparrow} + \textcircled{1}^{\uparrow} \quad \left. \vphantom{\textcircled{2}} \right\} \text{b quarks+gluon}$$

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

So what spin has Higgs-like particle?

Spin of particle	$\gamma\gamma$	ZZ^*
Spin 0		
Spin 1		
Spin 2		

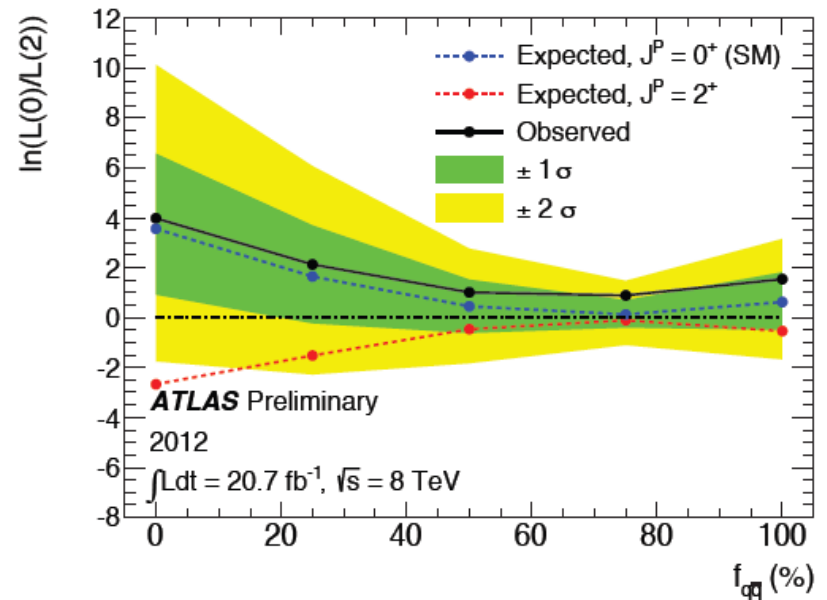
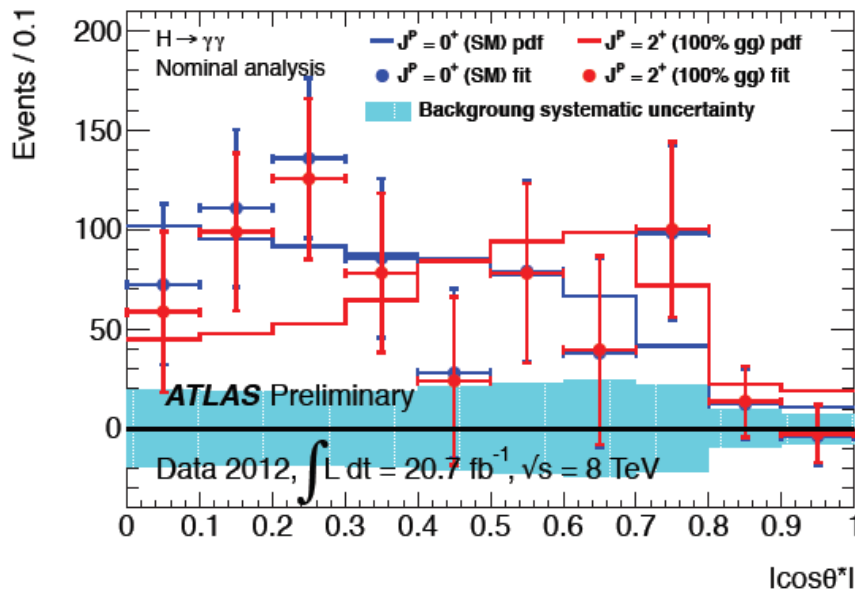
How we can recognize spin?



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

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

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



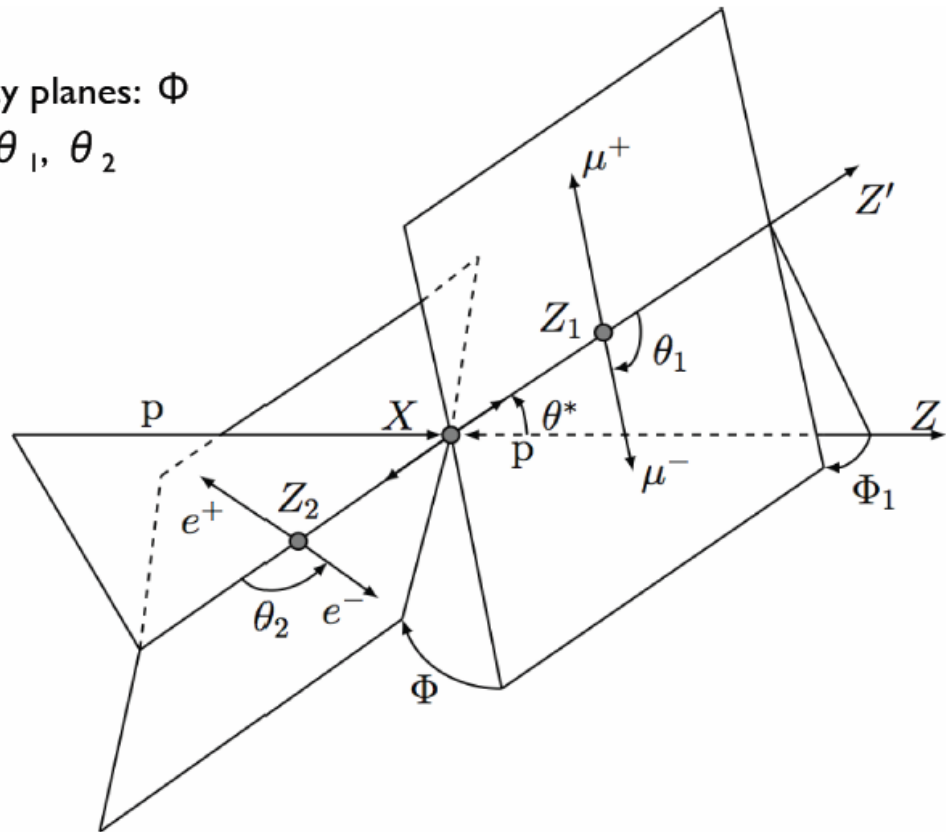
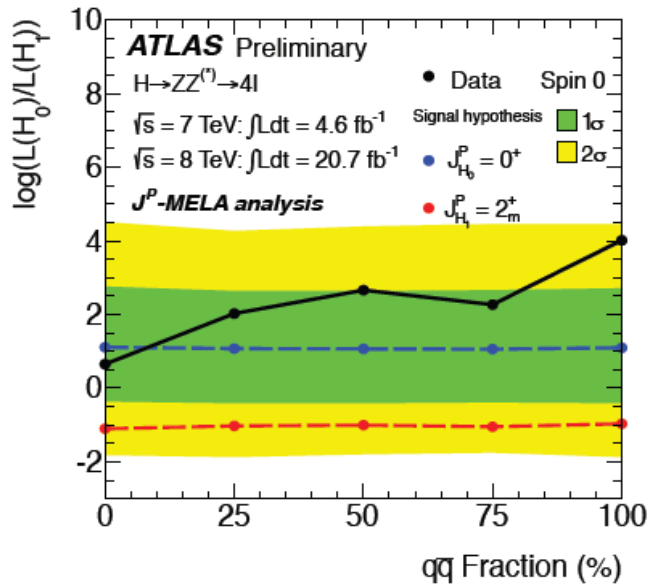
- If spin-2 resonance is produced 100% by gluon fusion, observed **rejection p-values** are:
 - ✓ spin-0 \rightarrow **58.8%** (1.2% expected) \rightarrow good agreement with spin-0 hypothesis
 - ✓ spin-2 \rightarrow **0.3%** (0.5% expected) \rightarrow **spin-2 excluded at 99.3% CL**

Spin study with $H \rightarrow 4l$

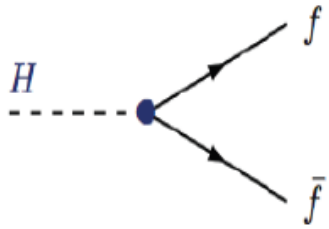
- Sensitive variables

- ✓ Intermediate boson masses: m_{Z_1}, m_{Z_2}
- ✓ Z_1 production angle: θ^*
- ✓ Z_1 decay plane angle: Φ_1
- ✓ Angle between the Z_1 and Z_2 decay planes: Φ
- ✓ Decay angles of negative leptons: θ_1, θ_2

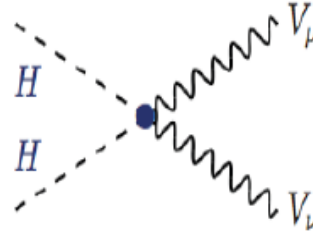
- Expected separation $> 2.5 \sigma$, except for $2+m$ ($\sim 1.5 \sigma$)
 - ✓ New boson compatible with SM $0+$ Higgs hypothesis when compared pair-wise with $0-, 1-, 1+, 2+m$



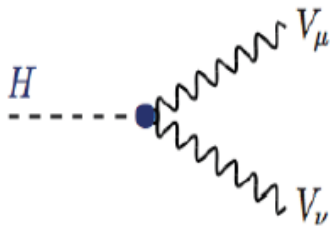
Higgs boson couplings



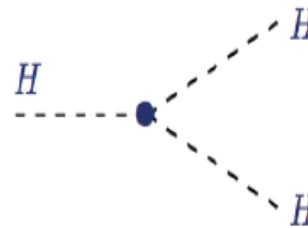
$$g_{Hff} = m_f/v$$



$$g_{HHVV} = 2M_V^2/v^2$$

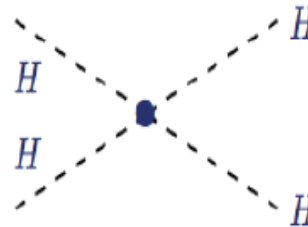


$$g_{HVV} = 2M_V^2/v$$



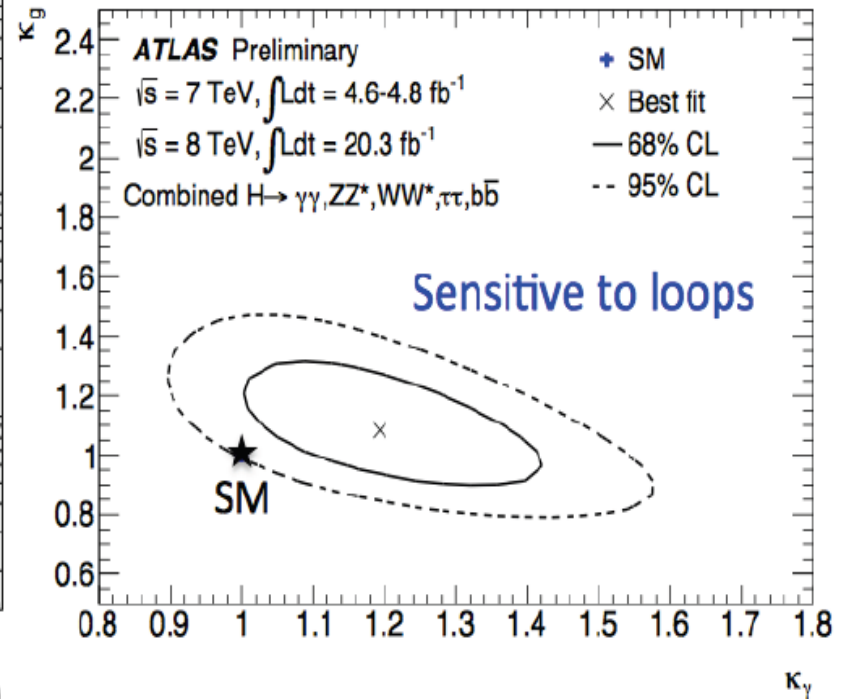
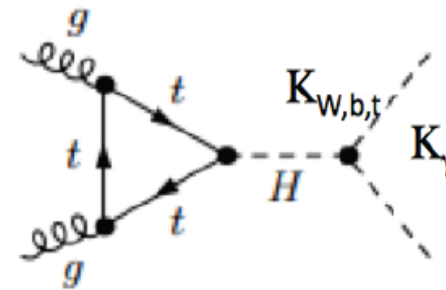
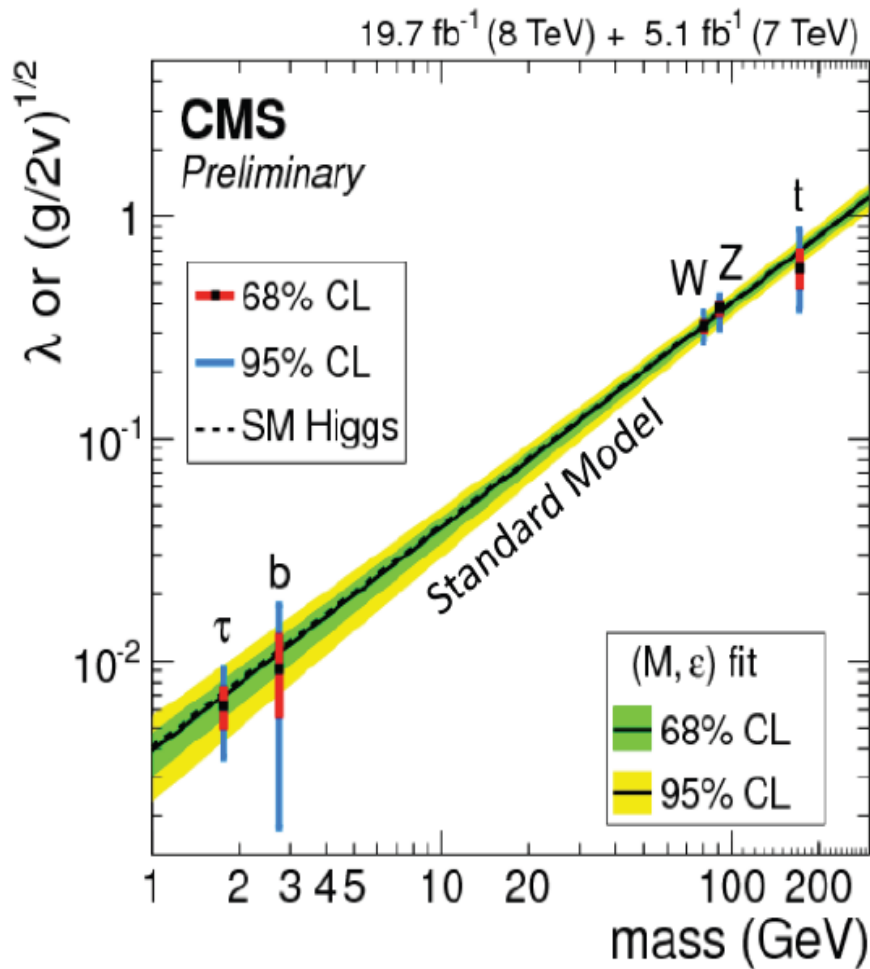
$$g_{HHH} = 3M_H^2/v$$

For the time being only
test the bosonic and
fermionic sector



$$g_{HHHH} = 3M_H^2/v^2$$

Higgs boson couplings

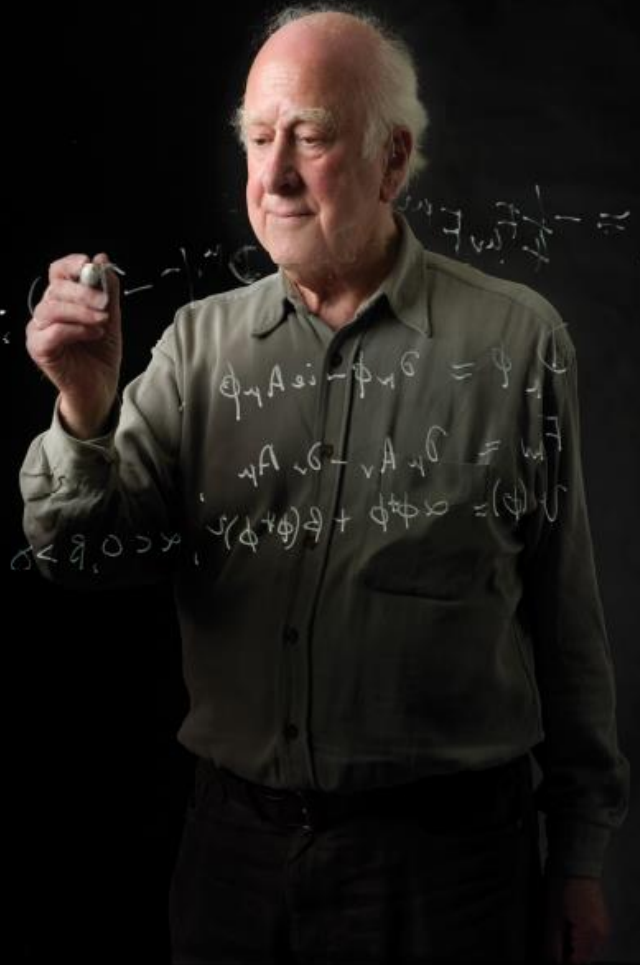


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i\bar{\psi} \not{D} \psi + \text{h.c.}$$

$$+ \bar{\psi}_i \gamma_{ij} \psi_j \phi + \text{h.c.}$$

$$+ |D_\mu \phi|^2 - V(\phi)$$



Higgs boson couplings

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

- Signals originate from single resonance with mass ~ 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” κ_i : cross-section or partial width scale with κ_i^2

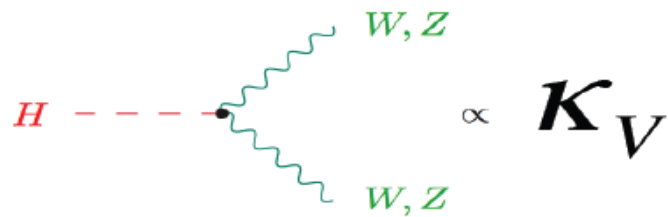
$$\begin{aligned} \mathcal{L} = & \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\ & + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi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

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

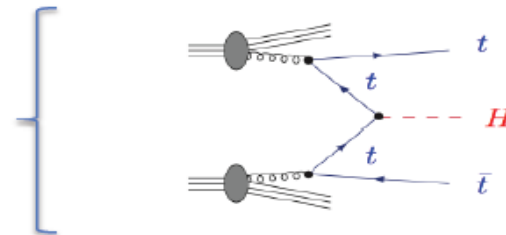
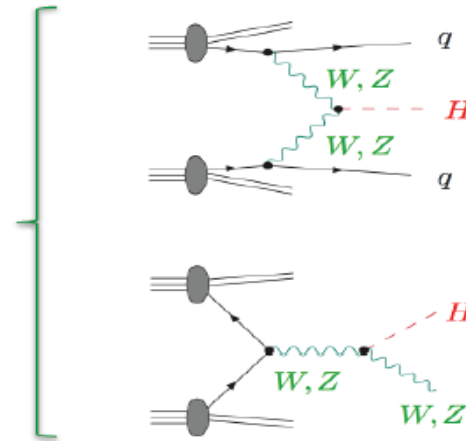
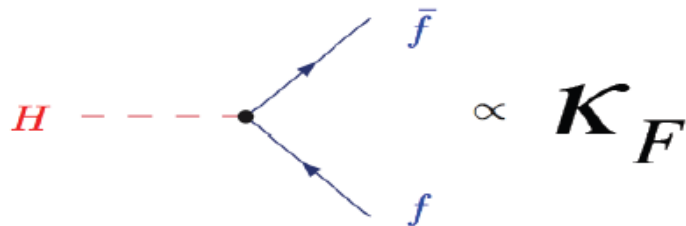
$$k_i^2 = \frac{\Gamma_i}{\Gamma_I^{SM}} \quad k_H^2 = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$$

Cpuplings scale factors

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

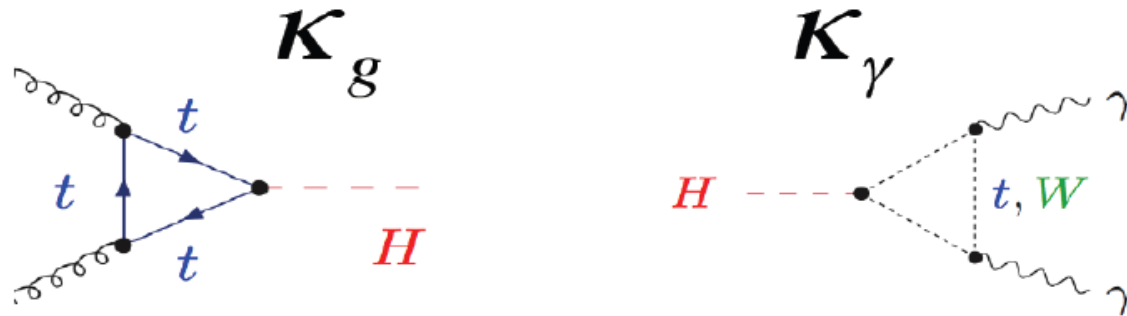


Affecting decay and production modes



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)

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

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

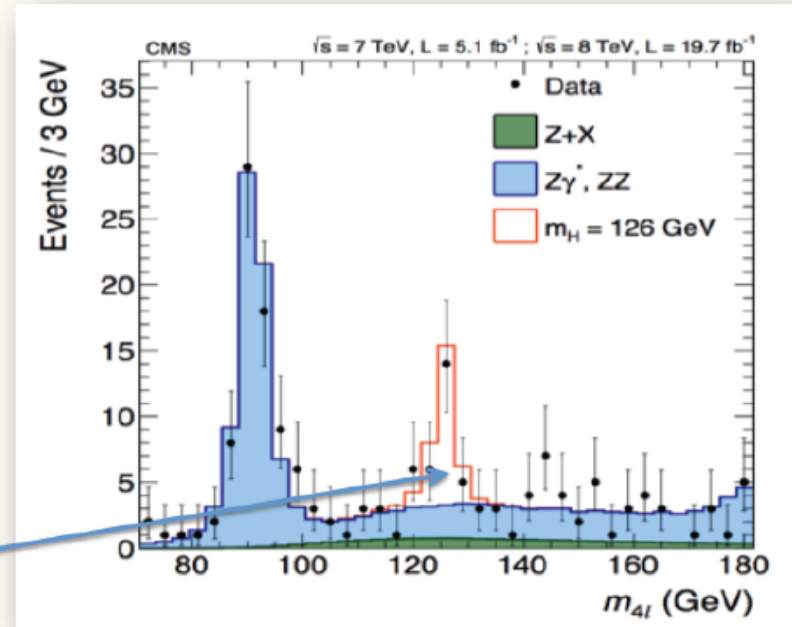
What do we measure?

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 σ (4.4 exp) ATLAS

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

6.8 σ (6.7 exp) CMS

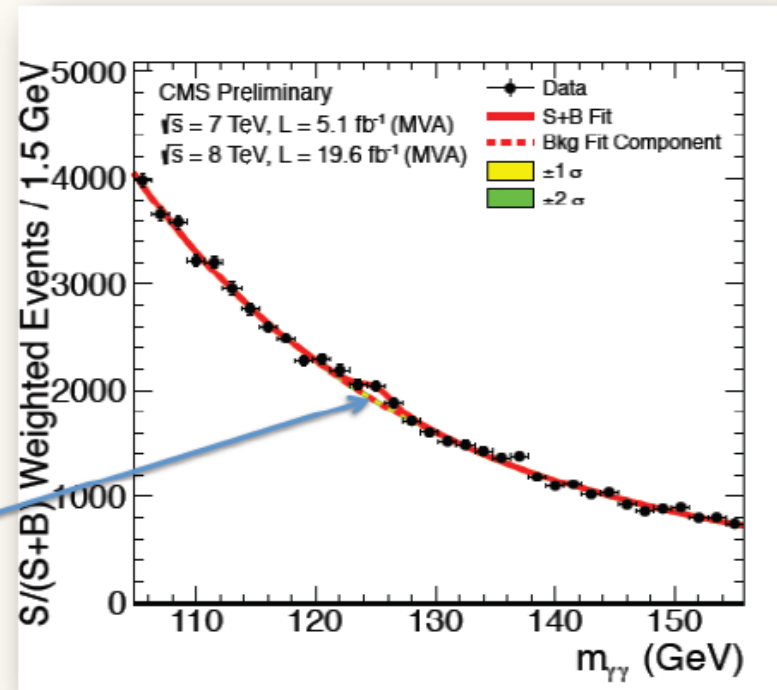
What do we measure?

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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

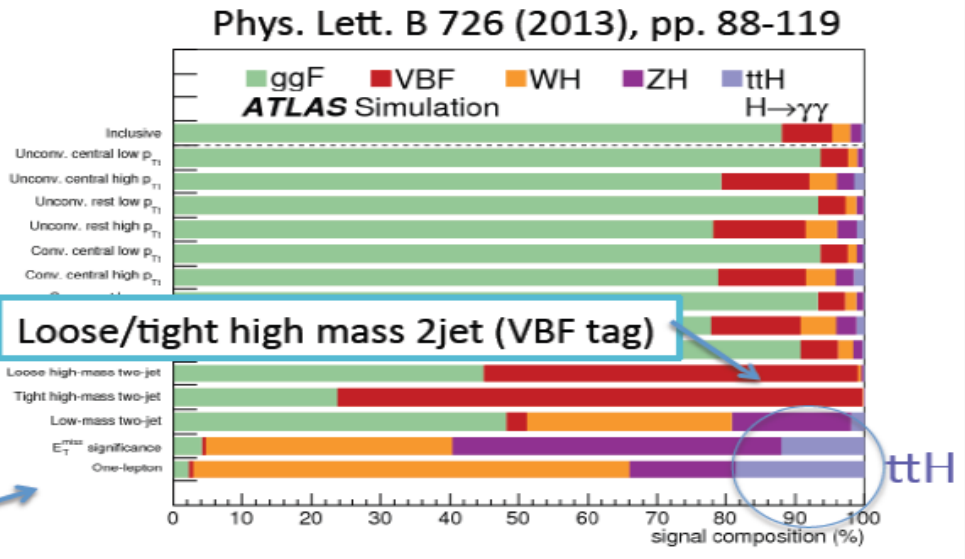


$$n_s^i = \mu^i \times \sum_p (\sigma^p \times Br^i)_{SM} \times A_p^i \times \epsilon_p^i \times Lumi$$

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

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 σ (4.3 σ)

6.6 σ (4.4 σ)

3.8 σ (3.8 σ)

4.1 σ (3.2 σ)

0.36 σ (1.64 σ)

Obs. (Exp.)

3.2 σ (4.2 σ)

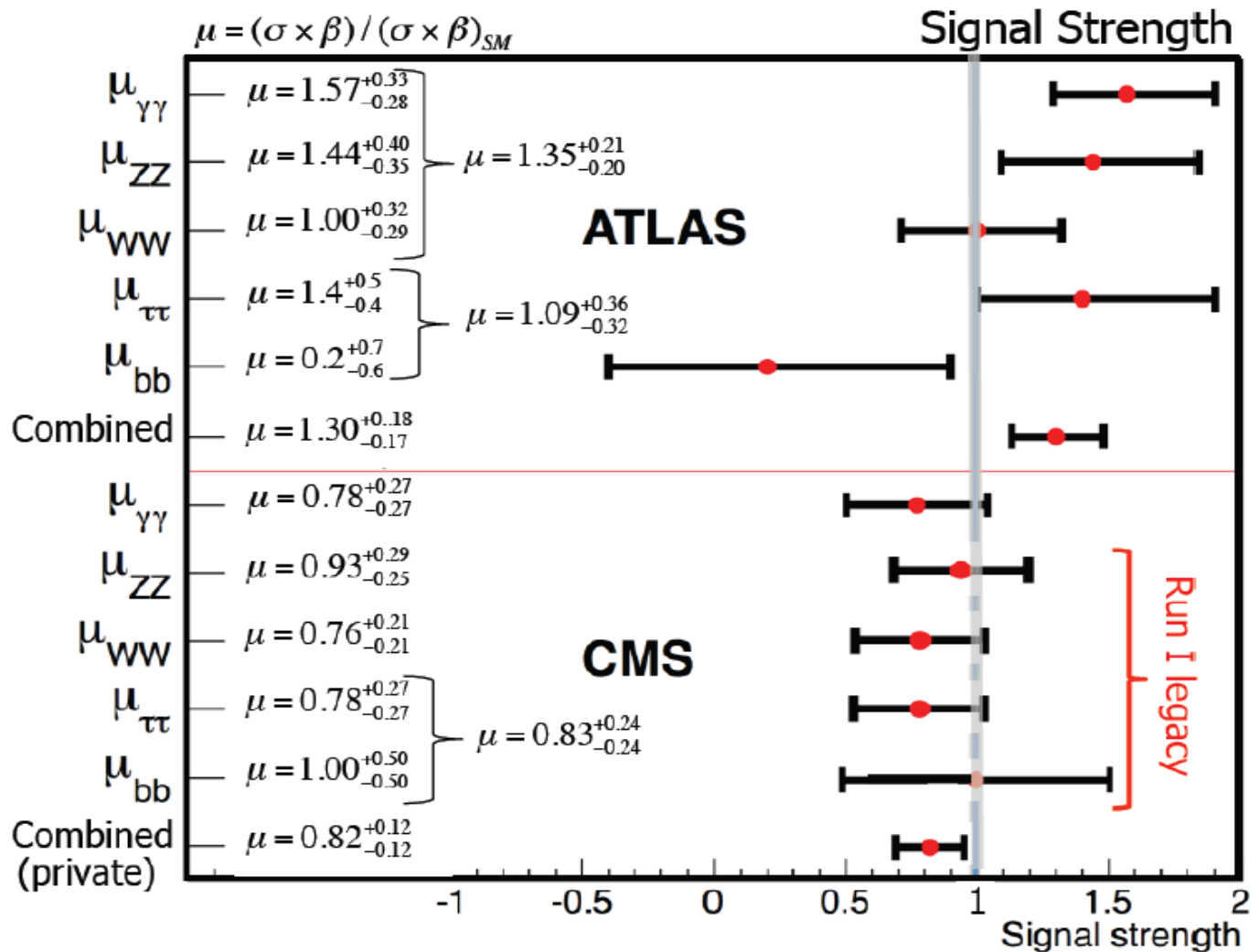
6.8 σ (6.7 σ)

4.3 σ (5.8 σ)

3.3 σ (3.7 σ)

2.1 σ (2.1 σ)

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

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

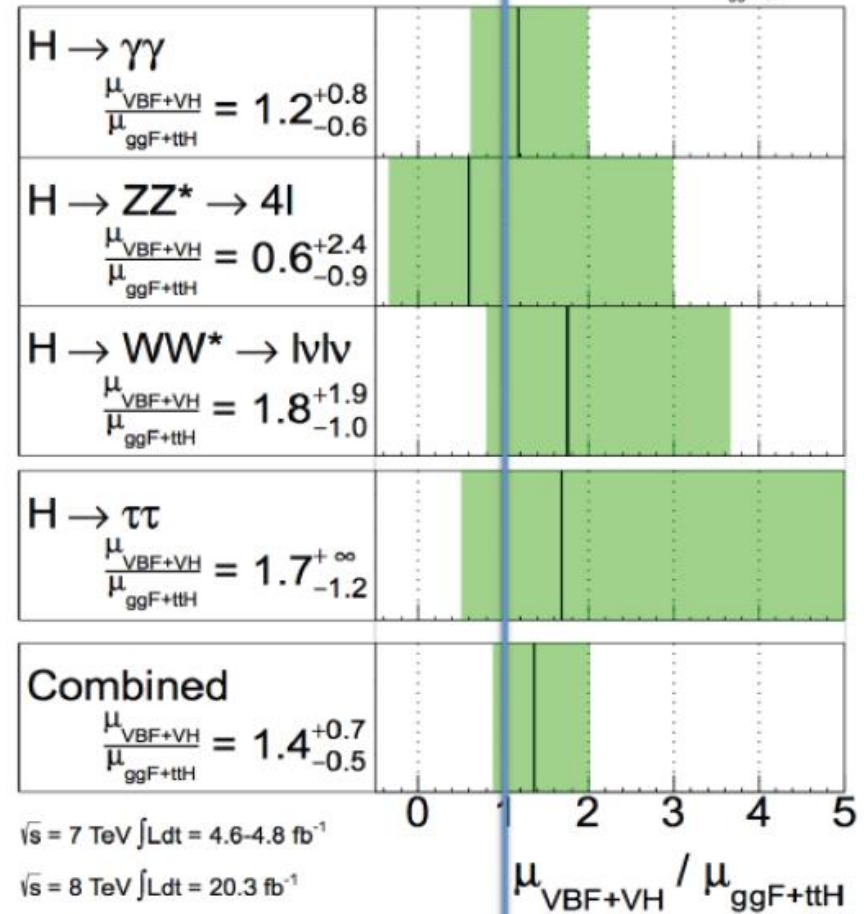
This ratio is INDEPENDENT of the decay channel so we can combine

ATLAS Preliminary

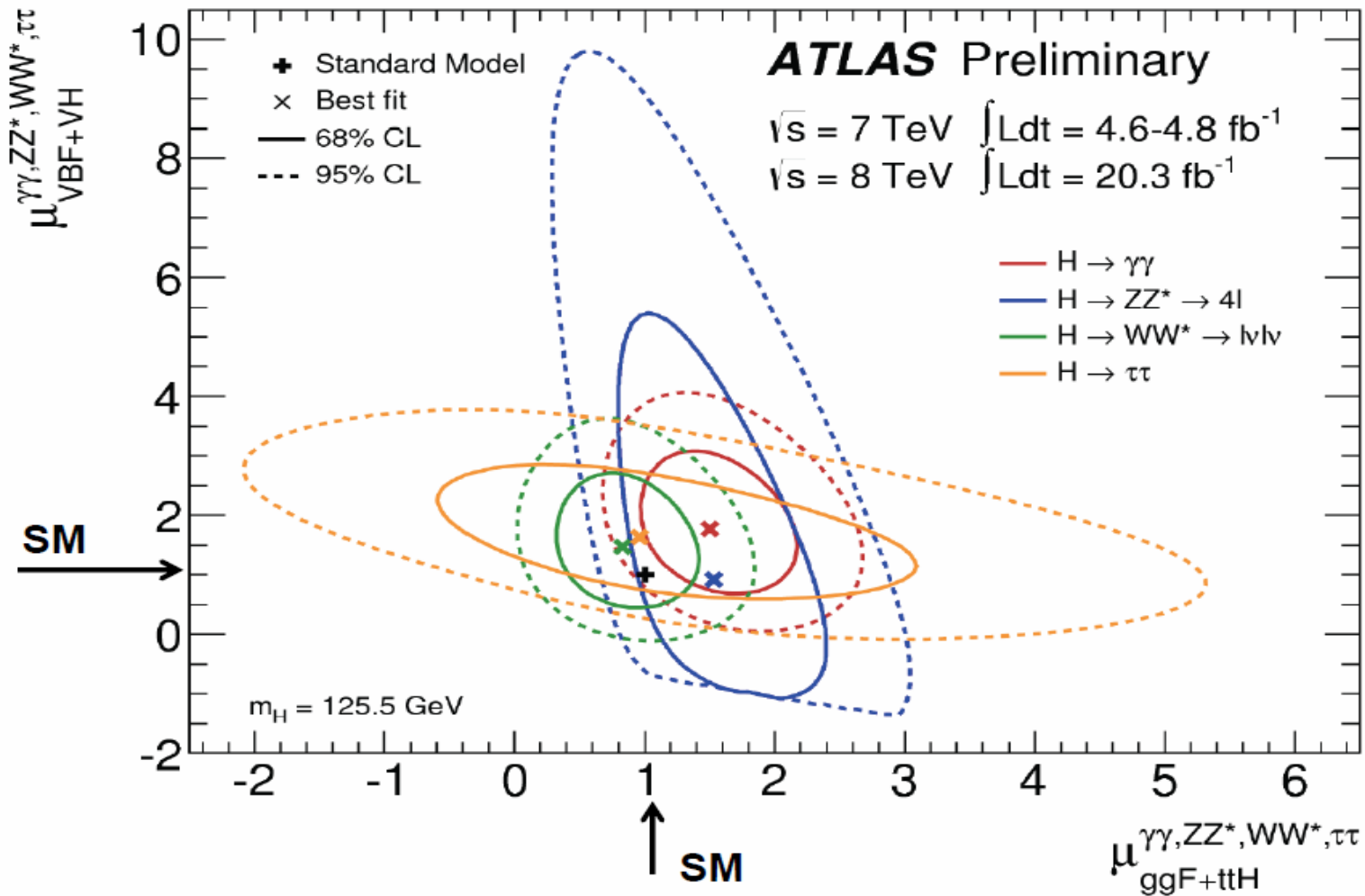
$m_H = 125.5 \text{ GeV}$

Total uncertainty

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



Probe the production mode



Overall comparison of all couplings results

