Observation of a Narrow Resonance at ATLAS

Introduction

H→γγ

H→ZZ*→4l

H→WW*→eμνν new

Combination

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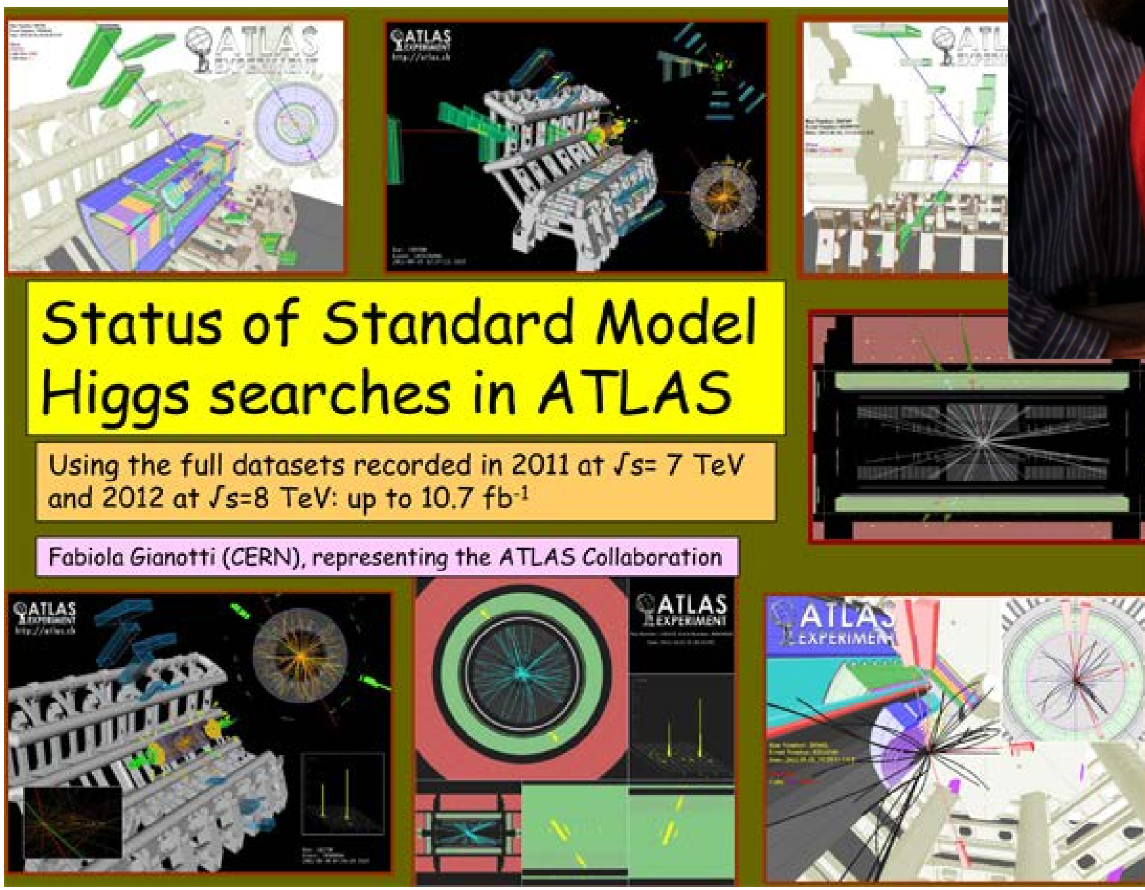
On behalf of the ATLAS collaboration

SLAC Seminar, July 20, 2012

CERN Higgs Search Update

July 4, 2012:
Planned as an update…
going out with a bang!



"We have now found the missing cornerstone of particle physics. We have a discovery. We have observed a new particle that is consistent with a Higgs boson."

- Rolf Heuer

Standard Model

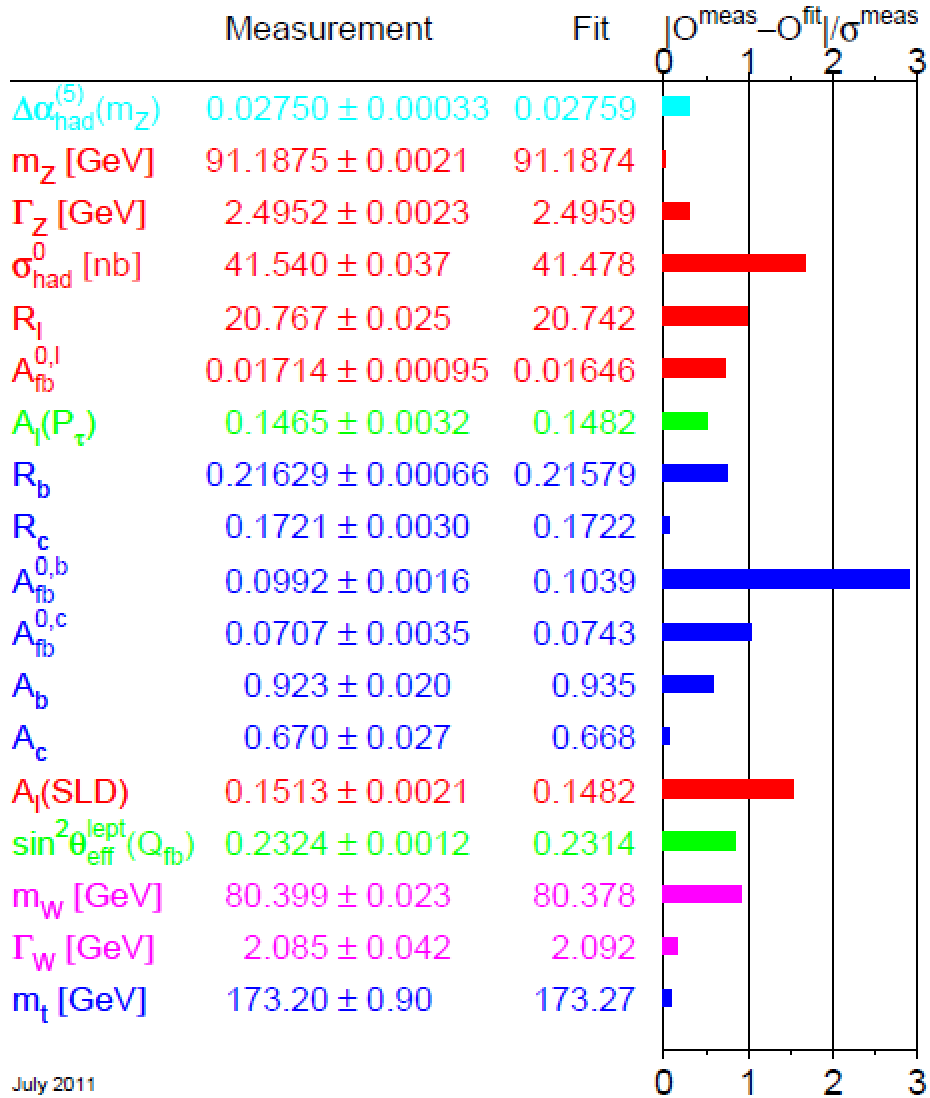
Standard model does not answer all the questions, but it does describe existing data remarkable well

Nevertheless, there are a few known anomalies

- **ttbar F-B charge asymmetry**
- **$\mu^\pm\mu^\pm$ charge asymmetry**
- **…**

The EW symmetry breaking mechanism in the SM is not confirmed

$\Rightarrow$ Hunting for Higgs boson

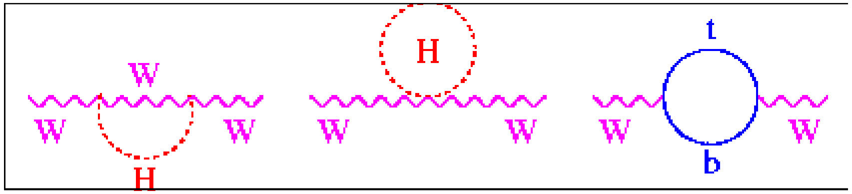


Higgs Boson Mass Constraint

Direct searches at LEP:

$$m_H > 114.4 \text{ GeV @ 95\% CL}$$

Precision electroweak data are sensitive to Higgs mass

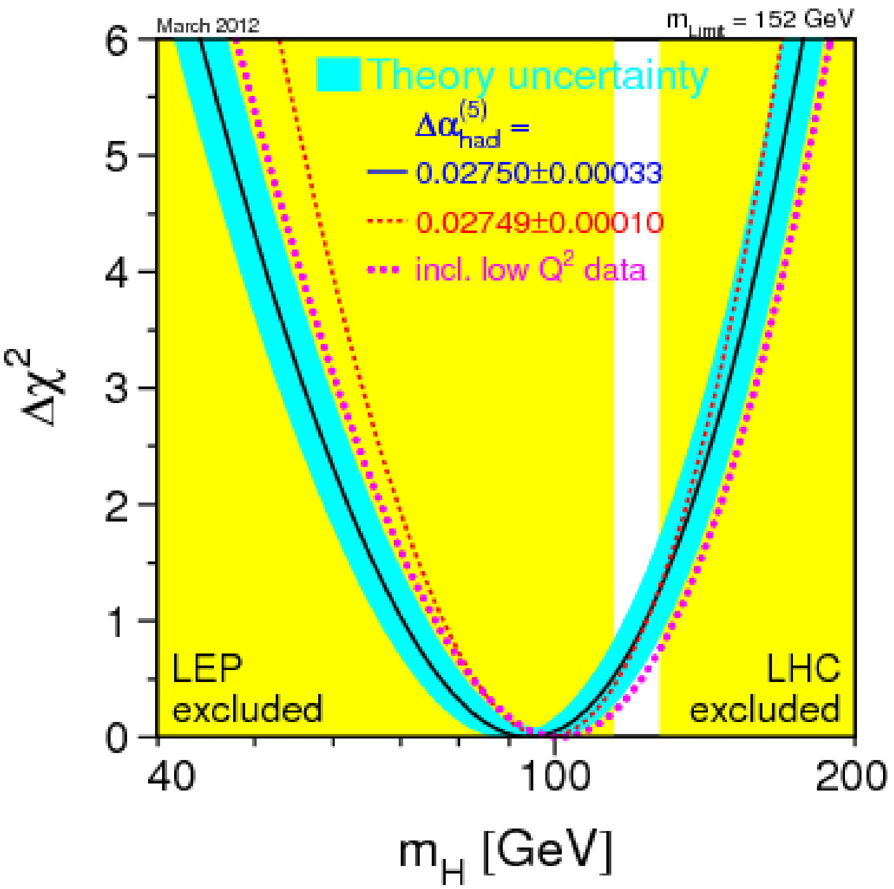


Preferred value from global fit:

$$m_H = 94^{+29}_{-24} \text{ GeV}$$

and 95% CL upper bound

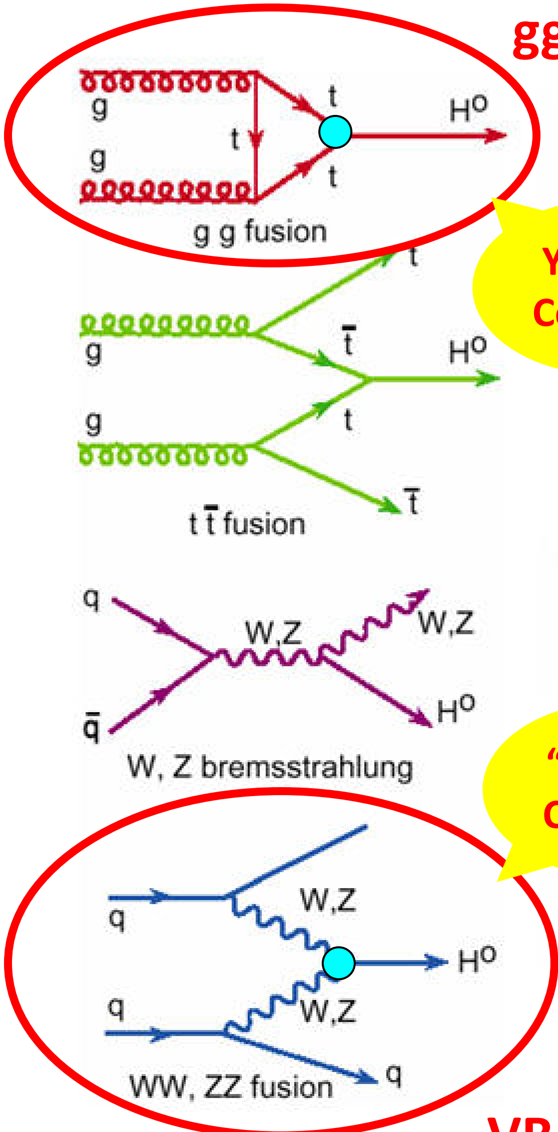
$$m_H < 152 \text{ GeV}$$



Existing data suggests a low mass standard model Higgs boson and direct experimental searches exclude all except the a narrow mass window of 114.4-127 GeV !

Higgs Boson Production

ggF

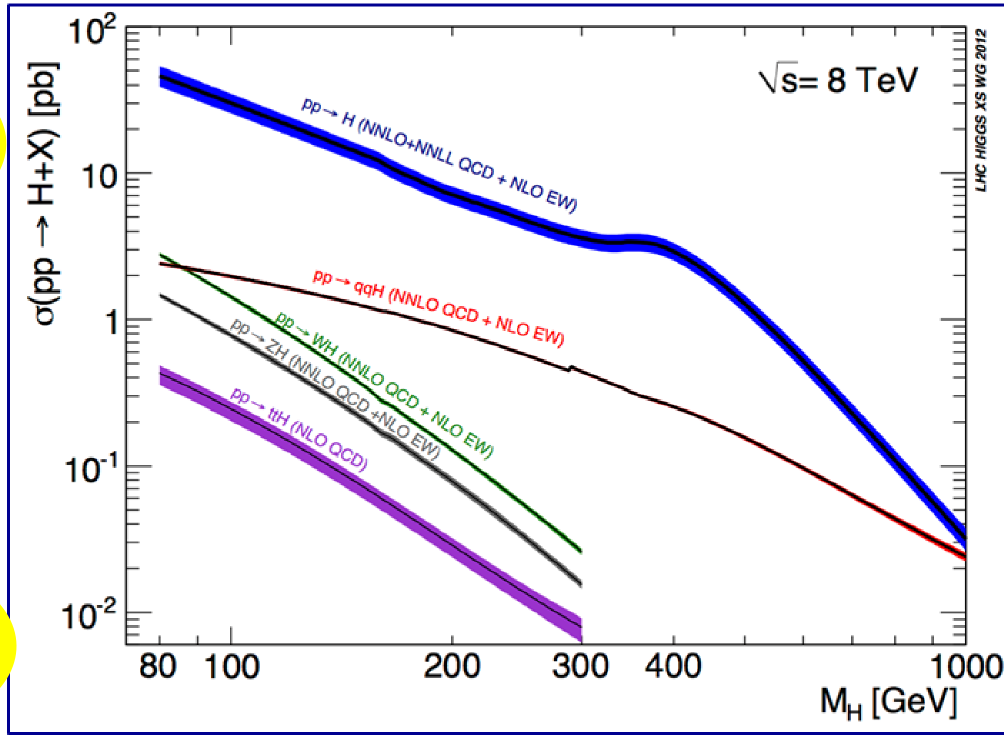


Yukawa Coupling

"Gauge" Coupling

VBF

gluon-gluon fusion gg→H and vector-boson fusion qq→qqH diagrams dominate



@125 GeV: $\sigma_{ggH} = 19.5$ pb, $\sigma_{VBF} = 1.6$ pb,

$\sigma_{WH} = 0.70$ pb, $\sigma_{ZH} = 0.39$ pb, $\sigma_{ttH} = 0.13$ pb

⇒ ~230k events in 2011 and 2012 samples !

Higgs Boson Decay

To all particles kinematically allowed, but two dominant modes:

$$- H \to b\bar{b} \quad \text{for } m_H < 135 \text{ GeV;}$$
$$- H \to WW \ \text{ for } m_H > 135 \text{ GeV}$$

Neither is ideal for the search and the study of properties

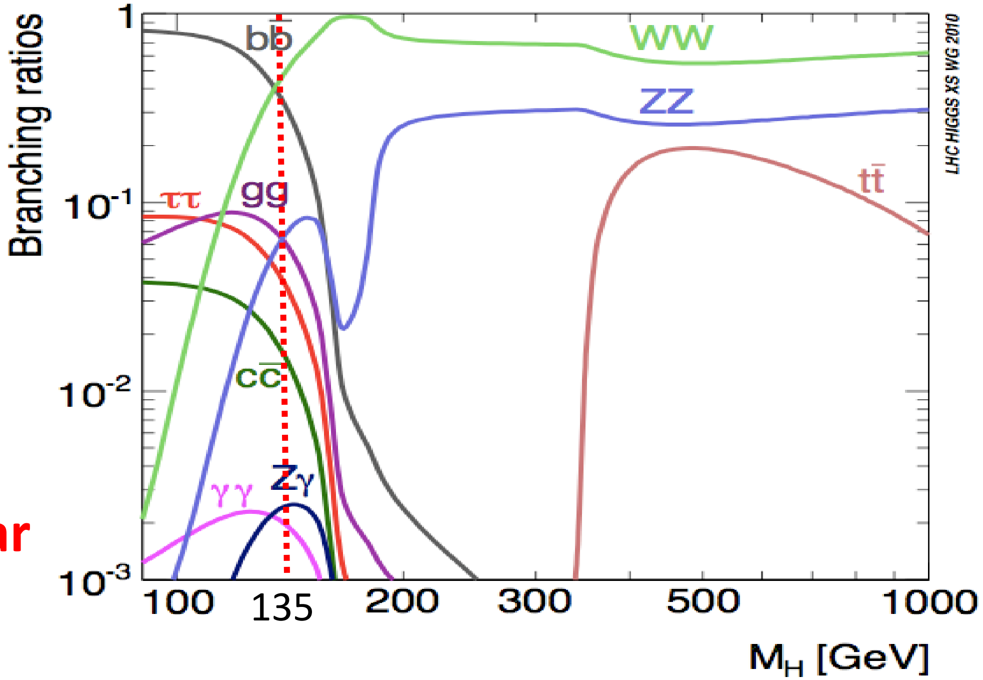
- $b\bar{b}$ by itself suffers from huge QCD backgrounds
- WW: easy identification in dilepton mode, complex backgrounds and no full reconstruction

Branching ratios at 125 GeV

$b\bar{b}$: 57.7%
WW: 21.5%
ττ: 6.3%
ZZ: 2.6%
γγ: 0.23%

Difficulty level (least to most):

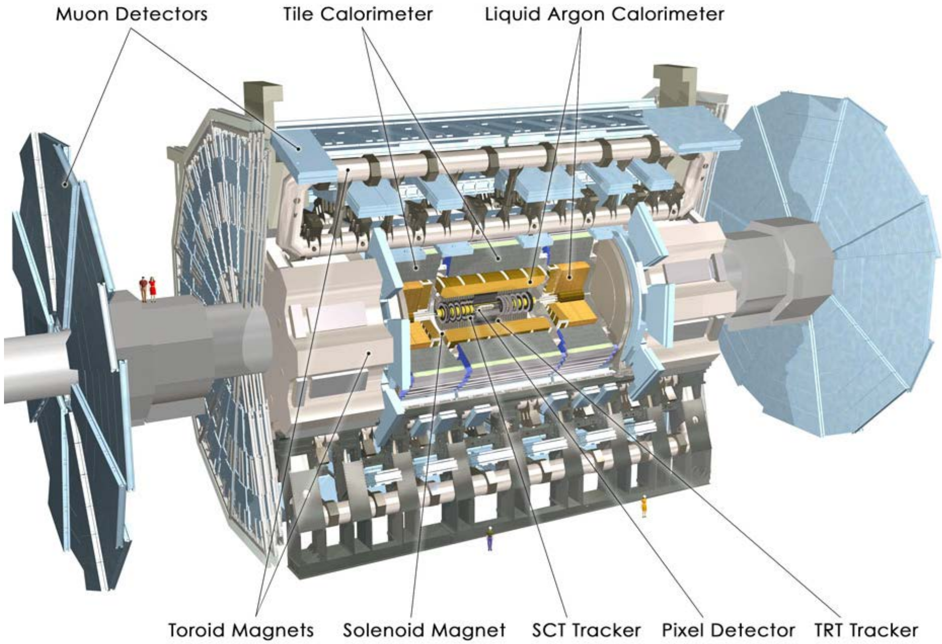
γγ, ZZ*→4l, WW*→lνlν ⇒ This seminar
bb and ττ



ATLAS Collaboration

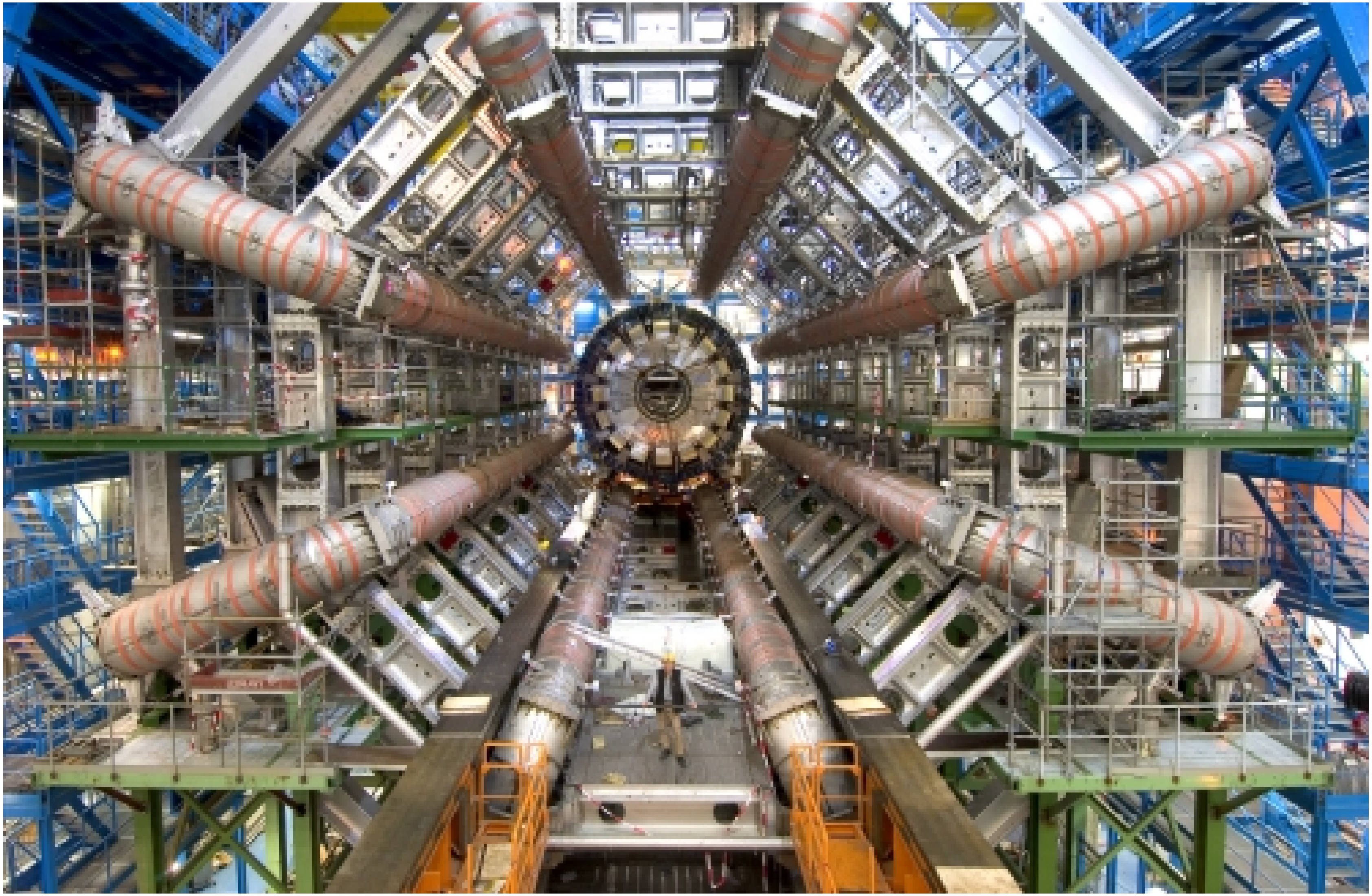
- **Detector: A Toroidal LHC ApparatuS**
  - **7000 tons, 25m high, 46m long and 100 million electronic channels**

- **Collaboration:**
  - **~3000 collaborators;**
  - **~1000 students;**
  - **178 institutions;**
  - **38 countries**

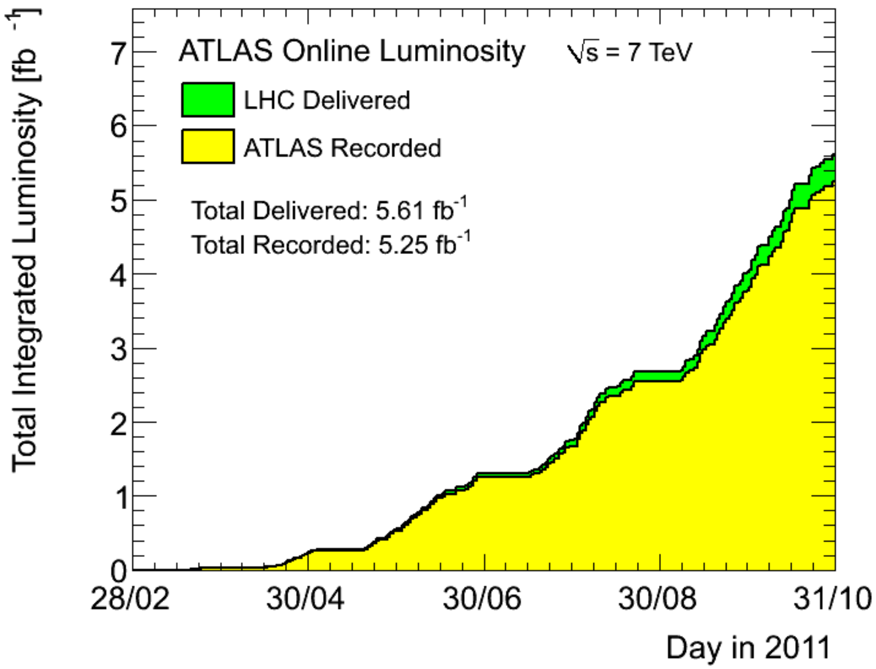


20+ years of worldwide collaborative effort

ATLAS Detector



Data Samples



2011 data taking at 7 TeV

5.3 fb^{-1} recorded

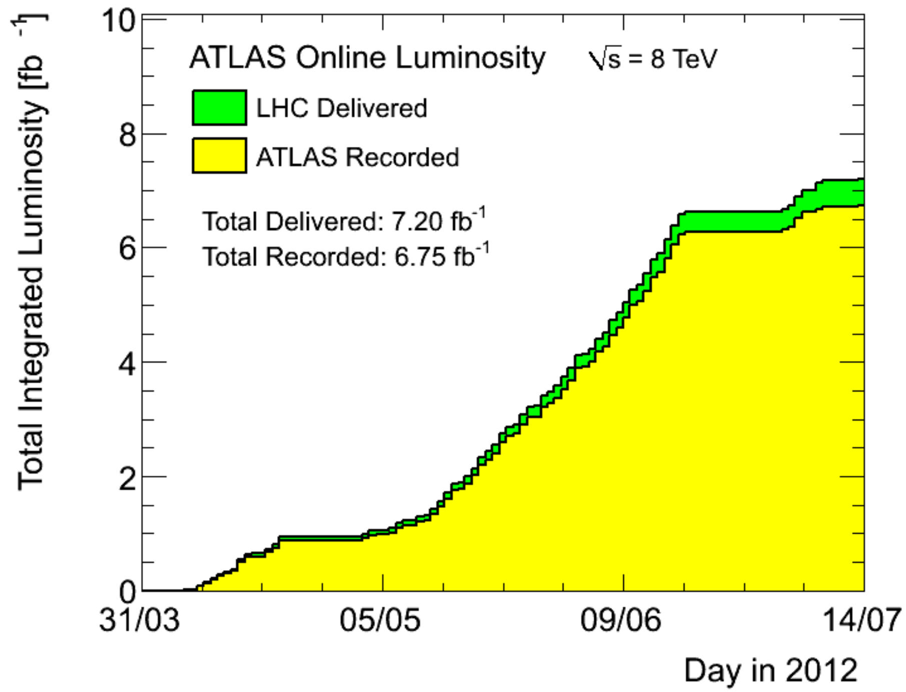
~4.8 fb^{-1} for analysis

2012 data taking at 8 TeV

"ICHEP" dataset

6.3 fb^{-1} recorded till 22/6

~5.8 fb^{-1} for analysis

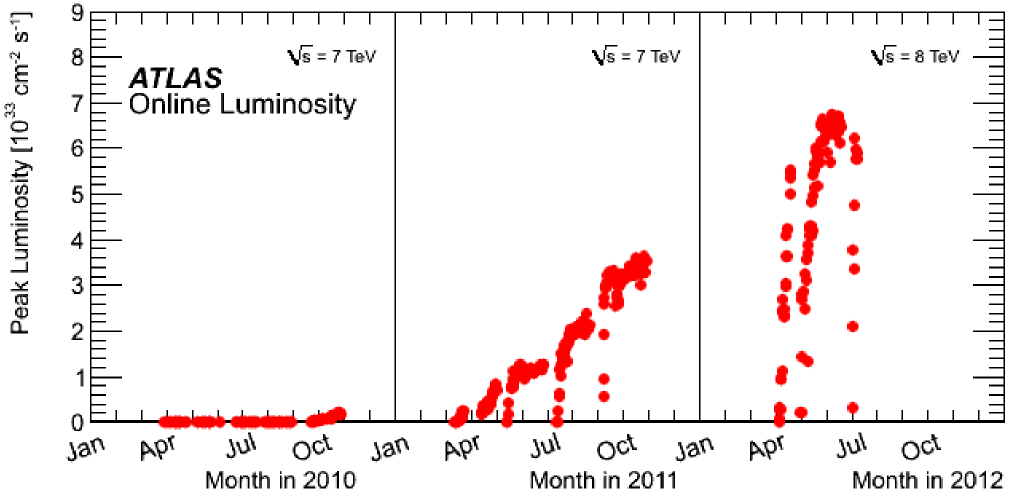


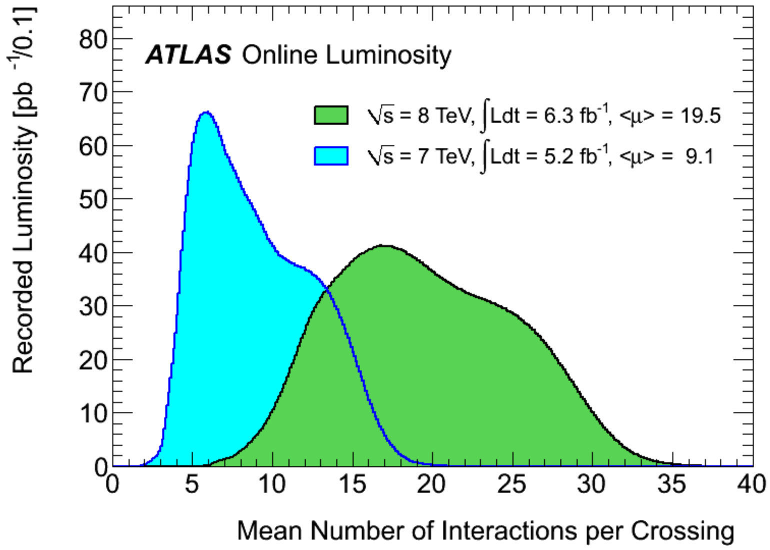
Data-taking efficiency: ~94%

Good data fraction: ~93%

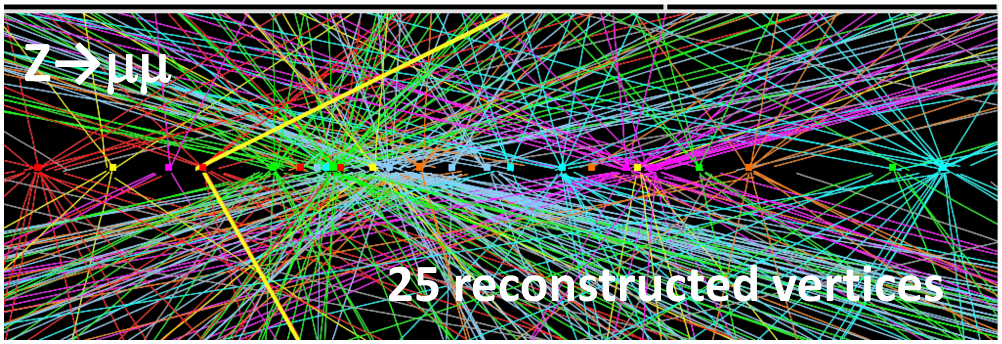
Challenge of High Luminosity

Peak luminosity





Multiple interactions !



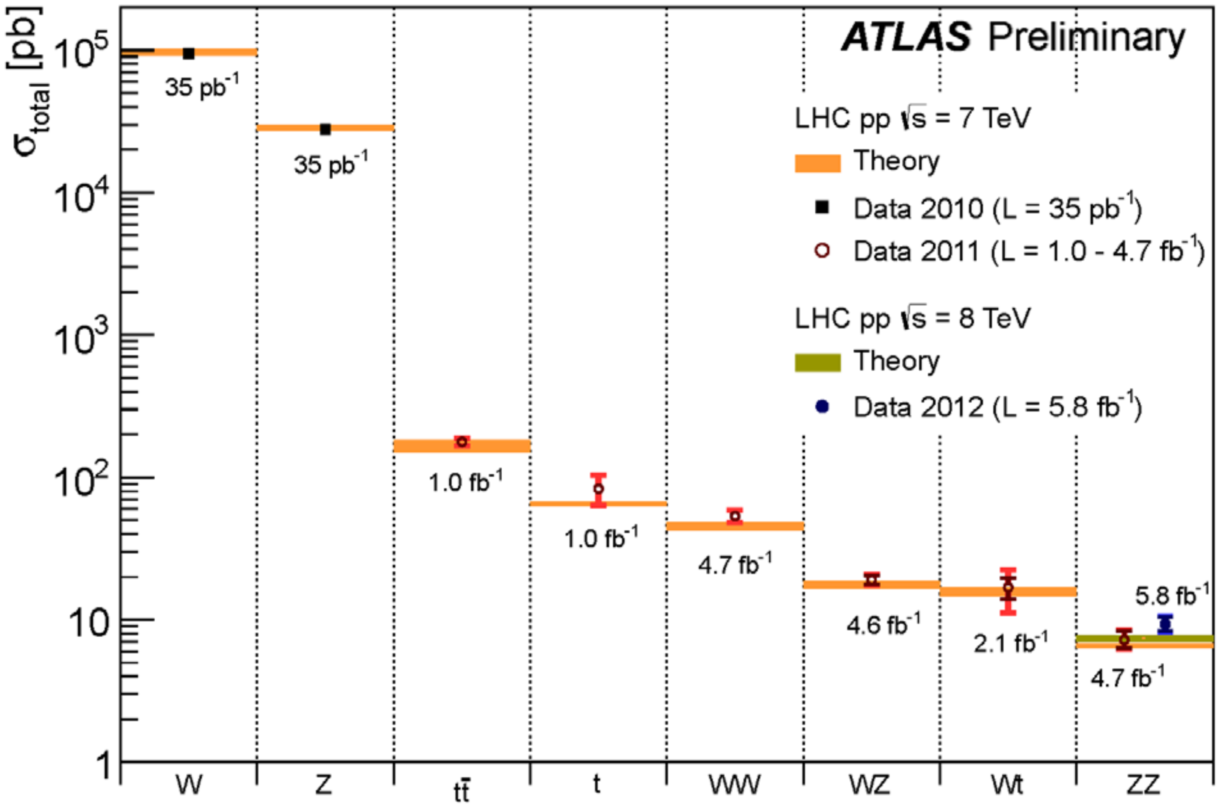
Challenging pileup issues:

- Lepton reconstruction and isolation
- Primary vertex identification
- Jet energy and multiplicity
- ETmiss resolution

In particular, understanding ETmiss takes time…

Cross Section Measurements

Higgs searches are built upon the successes of numerous studies/measurements of Standard Model physics



These measurements validate detector/physics simulation, object reconstructions, event selections and in general analysis techniques

Search Overview

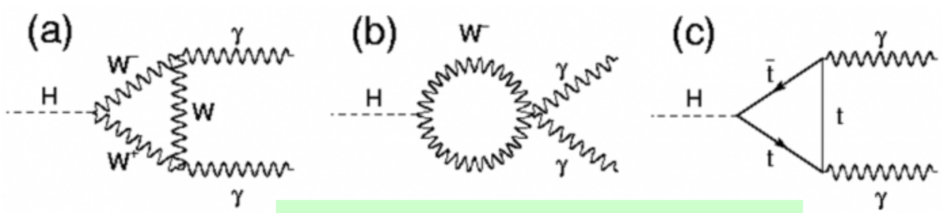
High resolution channels: clean signature, full reconstruction, good mass resolution. ***updated with 2012 data for the July 4th seminar.***

Channel	Mass range (GeV)	Key detector requirements	Main backgrounds
$H \rightarrow \gamma\gamma$	110-150	photon	$\gamma\gamma$, γj, jj
$H \rightarrow ZZ \rightarrow 4l$	110-600	lepton	ZZ, Z+jets, top
$H \rightarrow bb$ (WH/ZH)	110-130	jets, b-tagging	W/Z+jets, top
$H \rightarrow \tau\tau$ (ll, $l\tau_h$, $\tau_h\tau_h$)	100-150	lepton, jets, ETmiss	Z+jets, jets
$H \rightarrow WW \rightarrow l\nu l\nu$	110-600	lepton, jets, ETmiss, b-veto	WW, W/Z+jets, top, Wγ
$H \rightarrow WW \rightarrow l\nu qq$	300-600	lepton, jets, ETmiss, b-veto	W+jets, jets
$H \rightarrow ZZ \rightarrow ll\nu\nu$	200-600	lepton, ETmiss	Z+jets, ZZ, top
$H \rightarrow ZZ \rightarrow llqq$	200-600	lepton, jets, ETmiss, b-veto	Z+jets, ZZ, top

Low resolution channels: poor mass resolution, strong dependence on jet and ETmiss performance, ***only WW*→lvlv updated with 2012 data.***

H → γγ

- **Very simple signature, but small rate Br(H→γγ) ~ 2×10^{-3};**
- **Important decay mode for the low mass region (100-140 GeV)**

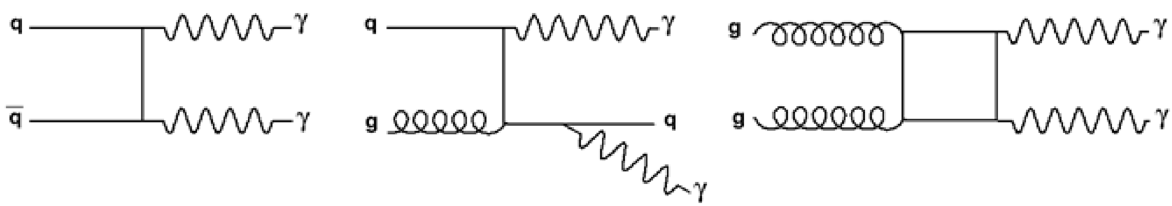


$$\sigma_H \times Br\left(H \to \gamma\gamma\right) \sim 50 \text{ fb}$$
$$@ \; m_H = 125 \text{ GeV}$$

Decay through loops !

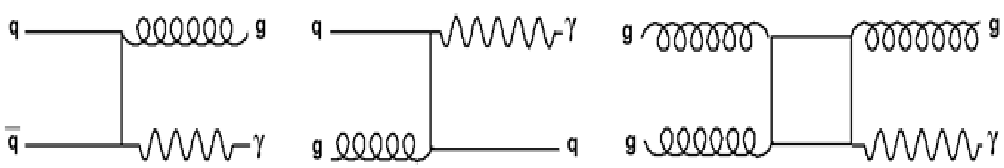
~500 events in 2011+2012 sample!

- **Irreducible background from γγ production**



$$\sigma\left(\gamma\gamma\right) \sim 40 \text{ pb}$$

- **Reducible background from γj and jj productions**



$$\sigma\left(\gamma j\right) \sim 3\times10^5 \text{ pb}$$
$$\sigma\left(jj\right) \sim 6\times10^8 \text{ pb}$$

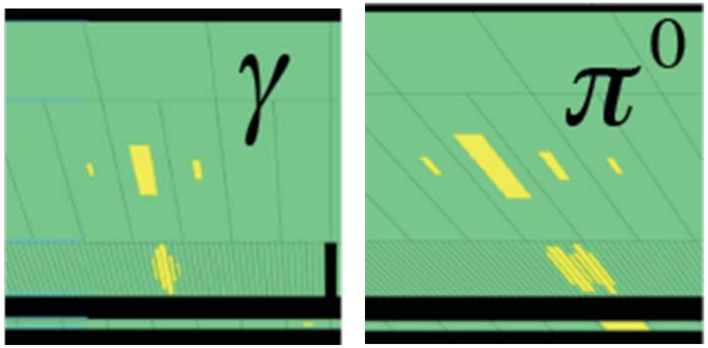
Theoretical uncertainty $\Delta\sigma/\sigma \sim 30\%$, not reliable !

$H \rightarrow \gamma\gamma$

Photon identification

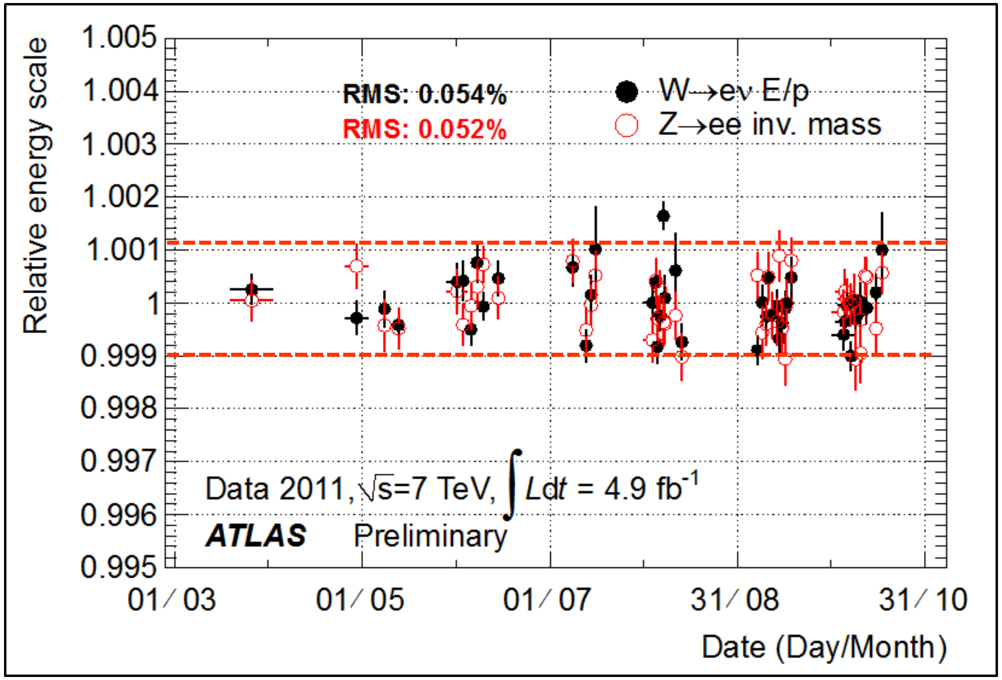
- Longitudinal and lateral shower profiles;
- No track or tracks consistent with photon conversions (~40% γ converts!);
- Main background: π^0 from jets;
- Neural network ID used for 2011, Cut-based ID for 2012

⇒ 85+% efficiency



Energy calibration

- Calibrating from Z, $J/\psi \rightarrow ee$ and $W \rightarrow e\nu$ events;
- Extrapolating to photon using MC;
- Energy scale at M_Z known to ~0.3%;
- Linearity better than 1%;
- Stable within 0.1% in 2011



$H \rightarrow \gamma\gamma$

Two isolated high pT photons with E_T > 40, 30 GeV and |η|<2.37

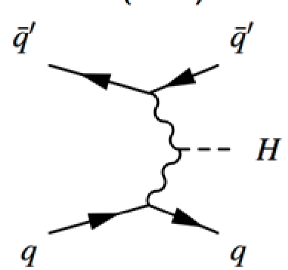
(exclude 1.37<|η|<1.52)

- efficiency ~40%
- S/B ratio ~ 3%

New since 2011:

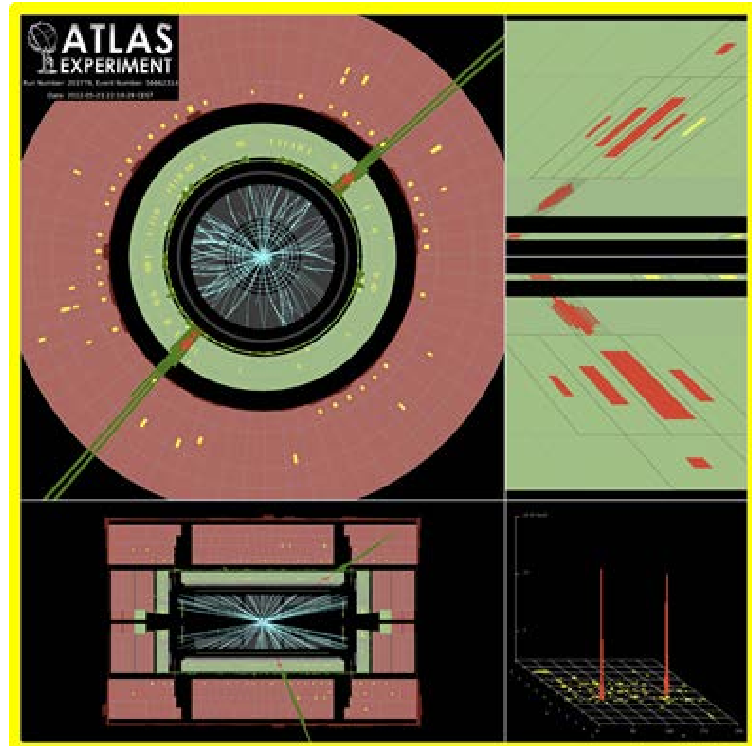
- 2-jet selection ⇒ VBF process
- S/B ~ 20%

σ_{SM} (VBF) ~7%



2 jets with
p_T > 25-30 GeV
$|\eta|$<4.5
$|\Delta\eta|_{jj}$ > 2.8
M_{jj} > 400 GeV
$|\Delta\varphi|$ ($\gamma\gamma$-jj) > 2.6

Expected gain in sensitivity: 3%



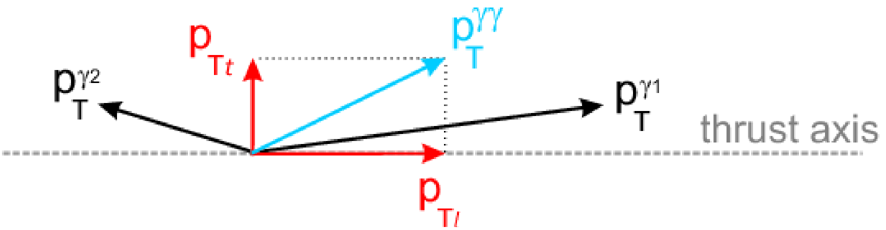
Keys to the search

- $\gamma\gamma$ mass resolution;
- Background suppression and modeling

H → γγ

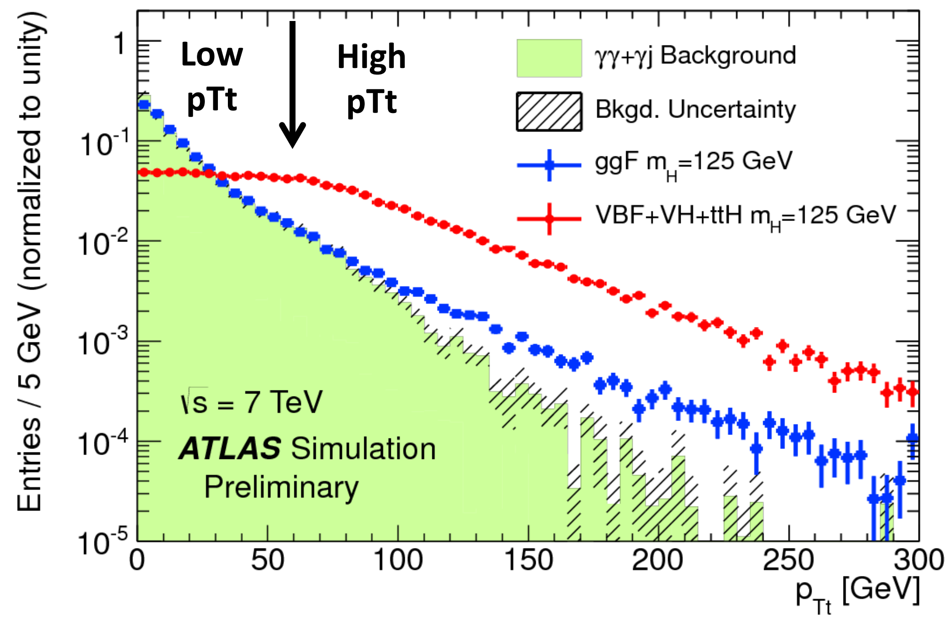
Taking advantage of different mass resolutions and signal-background ratios, data sample is split into 10 categories

- Converted photons vs unconverted photons;
- Detector regions: central, transition and forward
- Low and high pTt



S/B ~ 1-20%

Category
Unconverted central, low p_{Tt}
Unconverted central, high p_{Tt}
Unconverted rest, low p_{Tt}
Unconverted rest, high p_{Tt}
Converted central, low p_{Tt}
Converted central, high p_{Tt}
Converted rest, low p_{Tt}
Converted rest, high p_{Tt}
Converted transition
2-jets



⇒ **improve sensitivity by ~20%**

H → γγ

Full reconstruction of the Higgs decay final state, very little else to distinguish signal from backgrounds other than mass:

$$m^2 = 2E_{\gamma_1}E_{\gamma_2}\left(1-\cos\Delta\phi_{\gamma\gamma}\right)$$

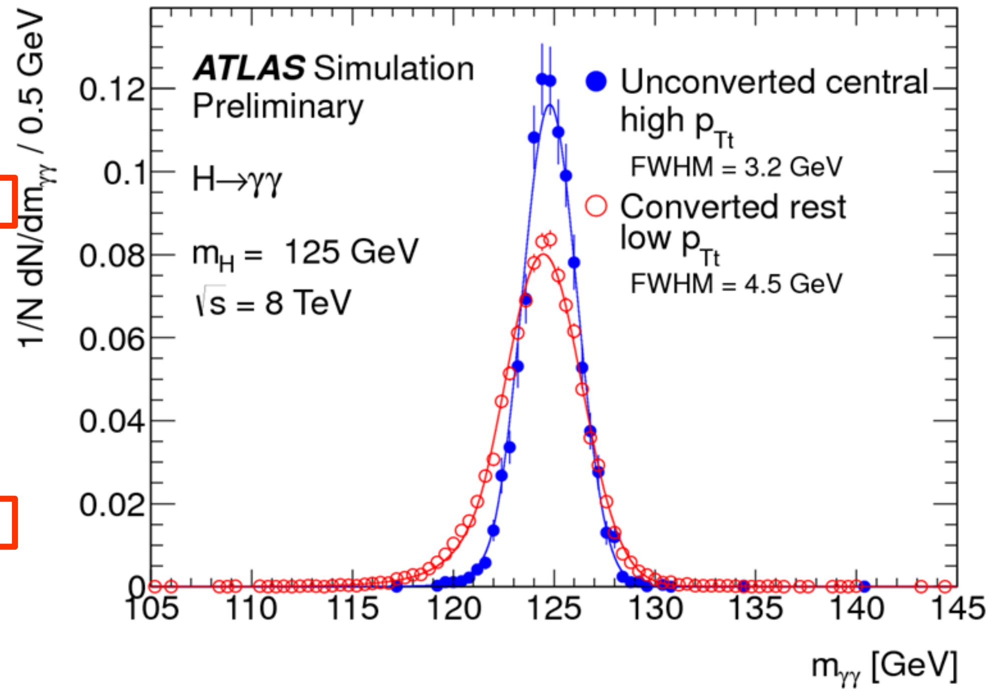
Mass resolution is the key, dominated by the energy resolution.

Category	σ_{CB} [GeV]	FWHM [GeV]
Inclusive	1.63	3.87
Unconverted central, low p_{Tt}	1.45	3.42
Unconverted central, high p_{Tt} (Best)	1.37	3.23
Unconverted rest, low p_{Tt}	1.57	3.72
Unconverted rest, high p_{Tt}	1.51	3.55
Converted central, low p_{Tt}	1.67	3.94
Converted central, high p_{Tt}	1.50	3.54
Converted rest, low p_{Tt}	1.93	4.54
Converted rest, high p_{Tt}	1.68	3.96
Converted transition (Worst)	2.65	6.24
2-jets	1.57	3.70

Best

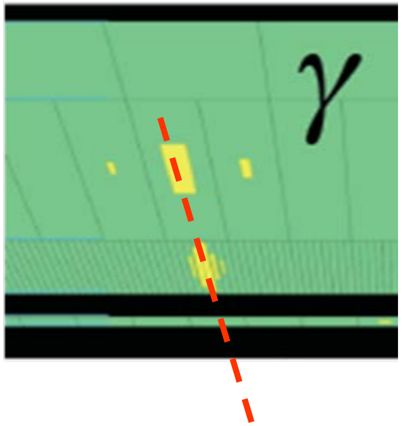
Worst

(mH=125 GeV)



H → γγ

LHC beam size δz~5-6 cm, vertex reconstruction through



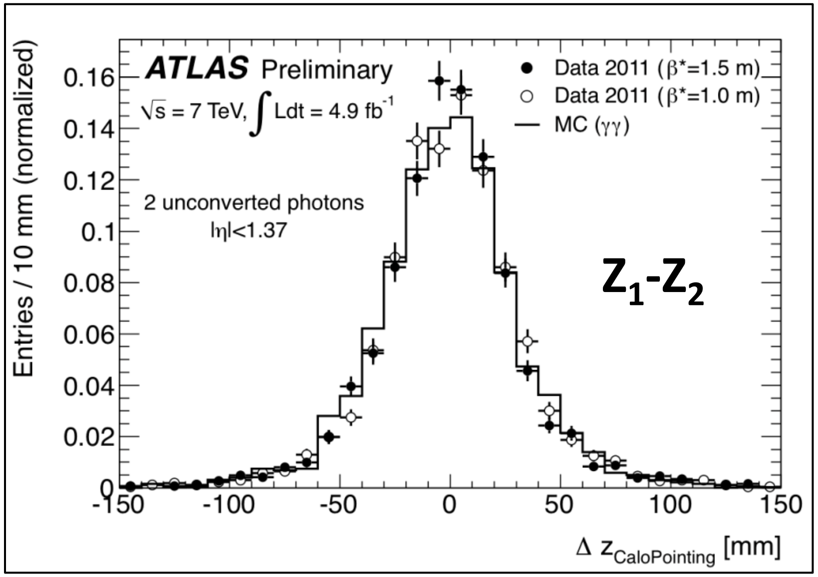
Unconverted photon:

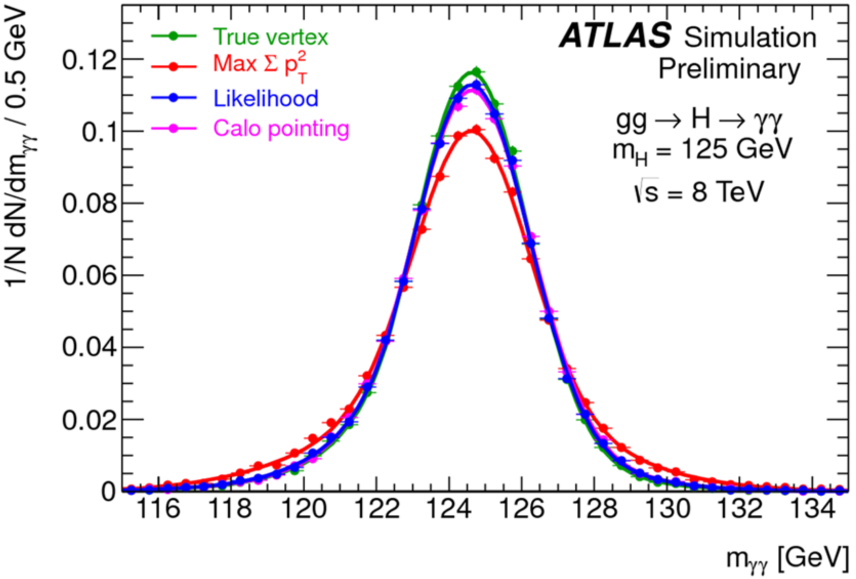
- **Calorimeter pointing of longitudinal samplings**
- **Resolution: δz~1.5 cm**

Converted photon:

- **calorimeter pointing and conversion vertex extrapolation**

Calorimeter pointing alone sufficient for a good di-photon mass resolution

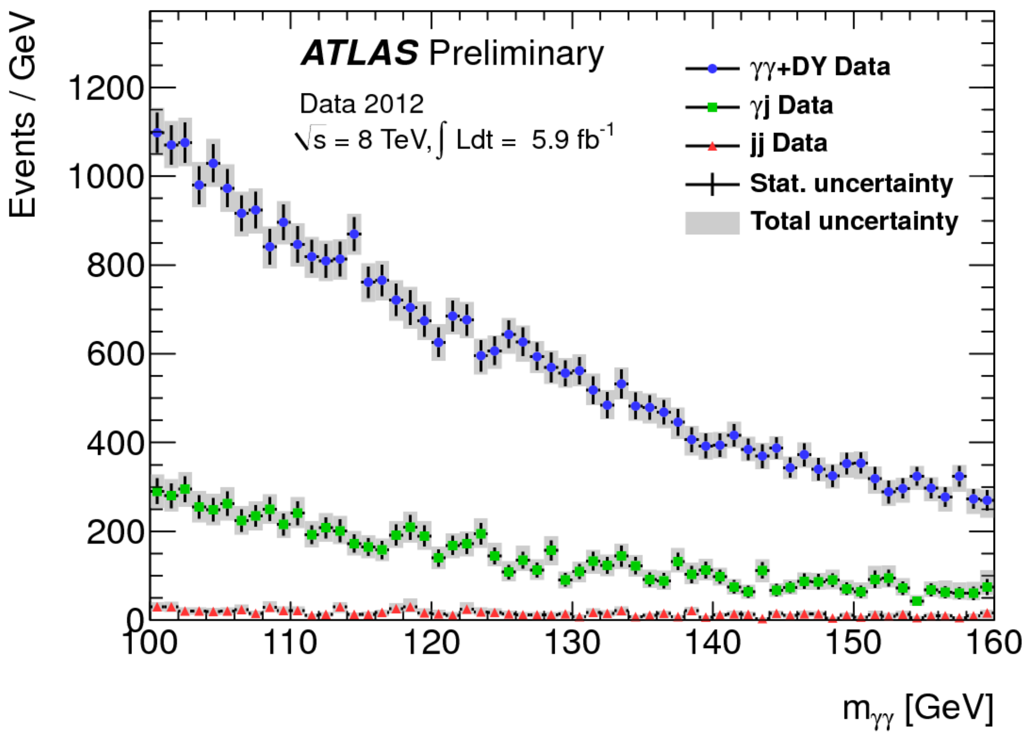




H → γγ

The γγ, γj and jj contributions can be decomposed through the analysis of photon identification and isolation.

- Determine the shape of these variables for real and fake photons from control samples and MC simulation;
- Fit the observed distribution to the sum of three components



2012 breakdowns

γγ: 75%
γj: 22%
jj: 3%

Background models:

γγ: RESBOS, DIPHOX, SHERPA
γj: SHERPA
jj: PYTHIA6

H → γγ

Signal: Crystal-Ball function (core) + Gaussian (outlier)

Backgrounds: exponentials, polynomials, ...

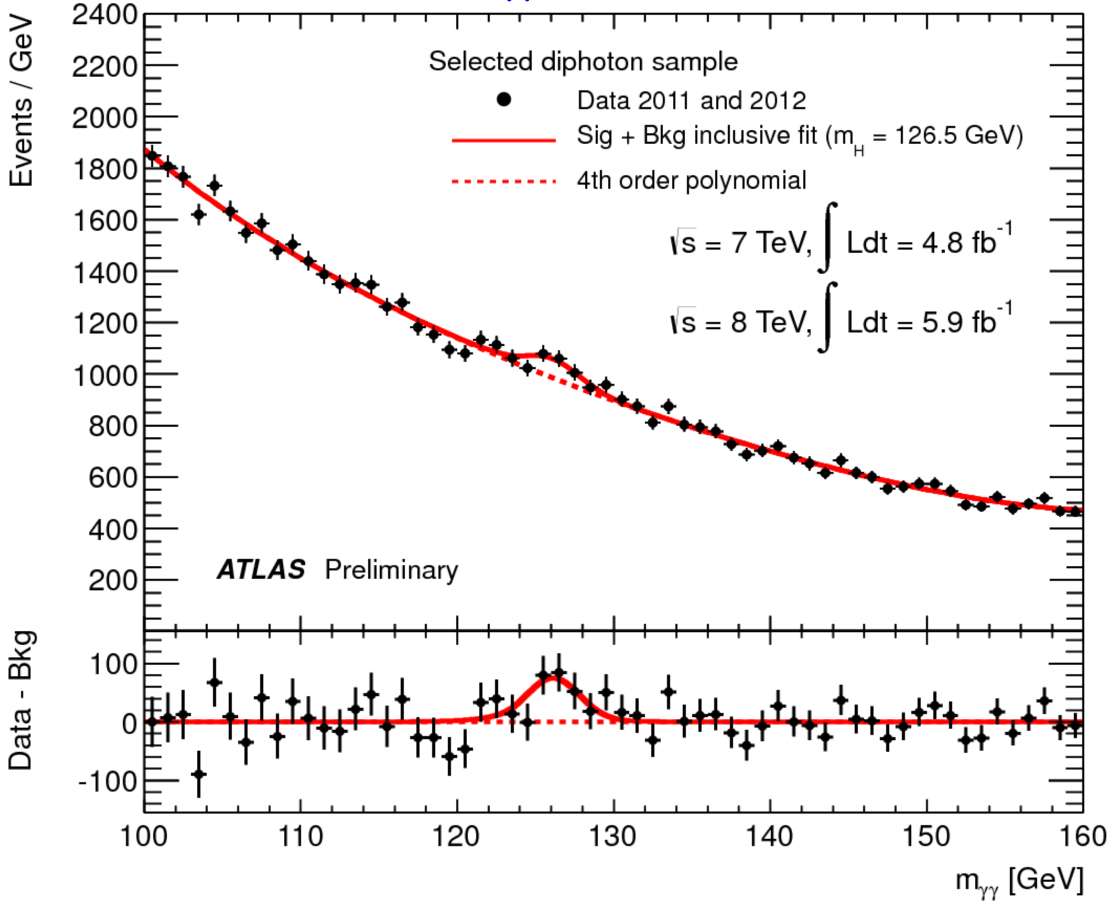
- **Category-dependent, choose the ones with best sensitivities and assign systematics based on spurious signals from MC studies**
- **Low statistics categories: Exponential**
- **High statistics categories: Exponential of 2^{nd} order polynomials**

Category	Parametrization	Uncertainty [N_{evt}]	
		$\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV
Inclusive	4th order pol.	7.3	10.6
Unconverted central, low p_{Tt}	Exp. of 2nd order pol.	2.1	3.0
Unconverted central, high p_{Tt}	Exponential	0.2	0.3
Unconverted rest, low p_{Tt}	4th order pol.	2.2	3.3
Unconverted rest, high p_{Tt}	Exponential	0.5	0.8
Converted central, low p_{Tt}	Exp. of 2nd order pol.	1.6	2.3
Converted central, high p_{Tt}	Exponential	0.3	0.4
Converted rest, low p_{Tt}	4th order pol.	4.6	6.8
Converted rest, high p_{Tt}	Exponential	0.5	0.7
Converted transition	Exp. of 2nd order pol.	3.2	4.6
2-jets	Exponential	0.4	0.6

10-20% uncertainties on signal yields from background modeling

H → γγ

Inclusive $m_{\gamma\gamma}$ Distribution

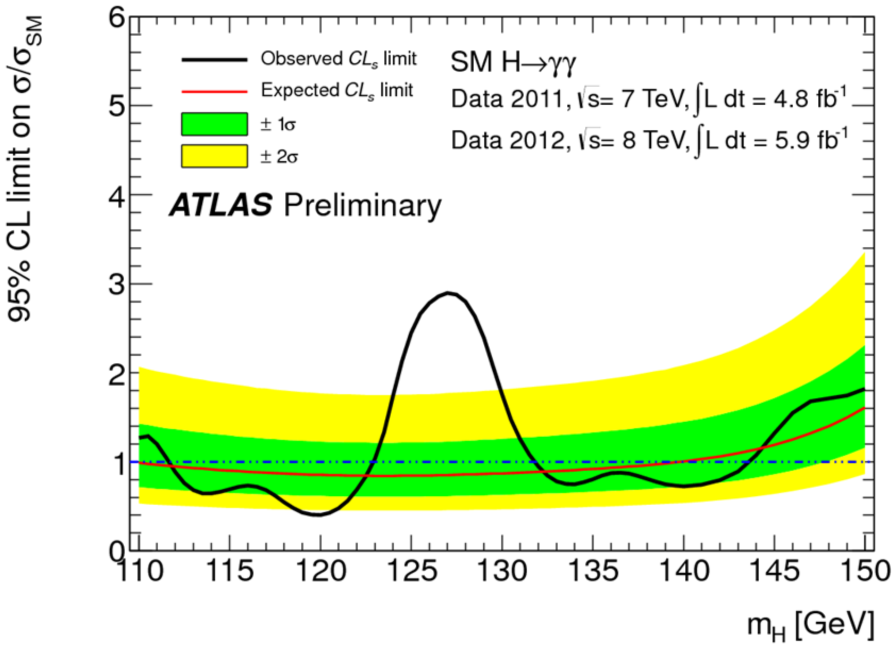


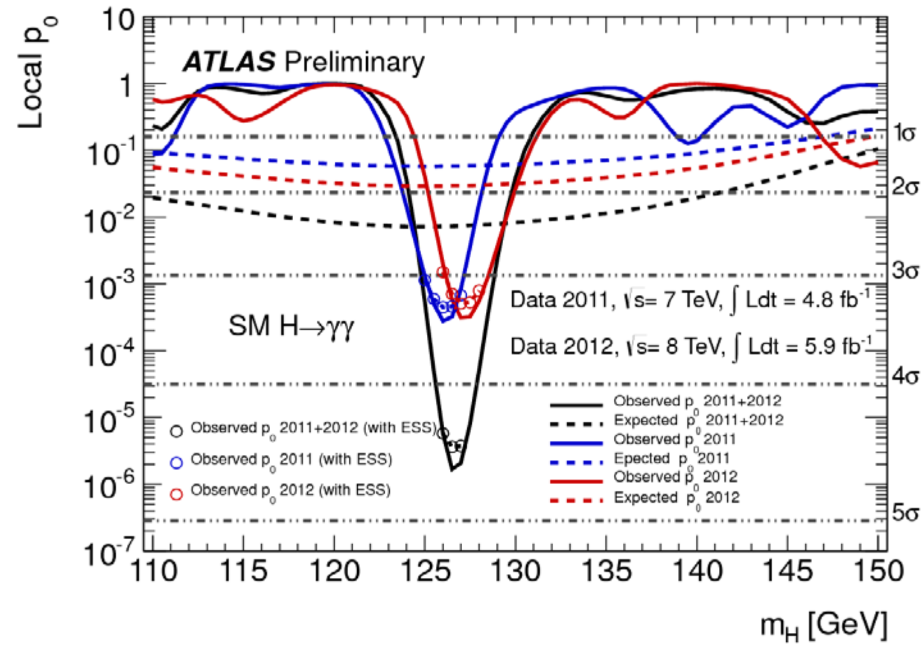
A total 59059 events selected, expect ~170 signal events at 126 GeV with a S/B ~ 3%

(The background is parameterized using 4th order Bernstein polynomial)

H → γγ

Exclusions: 112-122.5 GeV, 132-143 GeV (observed); 110-139.5 GeV (expected)





A minimum p_0 at 126.5 GeV

$$p_0 = 2\times 10^{-6} \quad \Rightarrow \quad 4.5\sigma$$

(Expected: 2.4σ from a SM Higgs boson)

(Global observed significance: 3.6σ over 110-150 GeV)

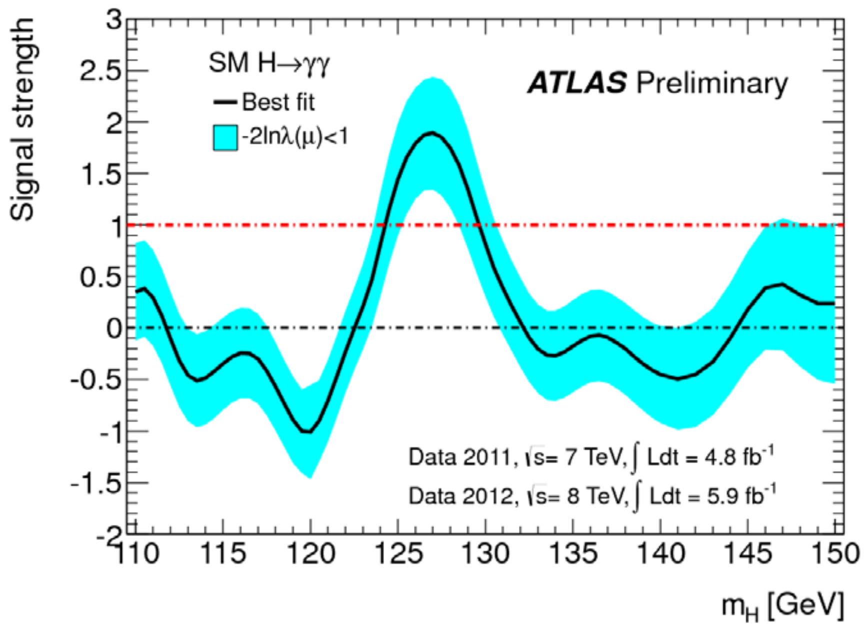
$H \to \gamma\gamma$

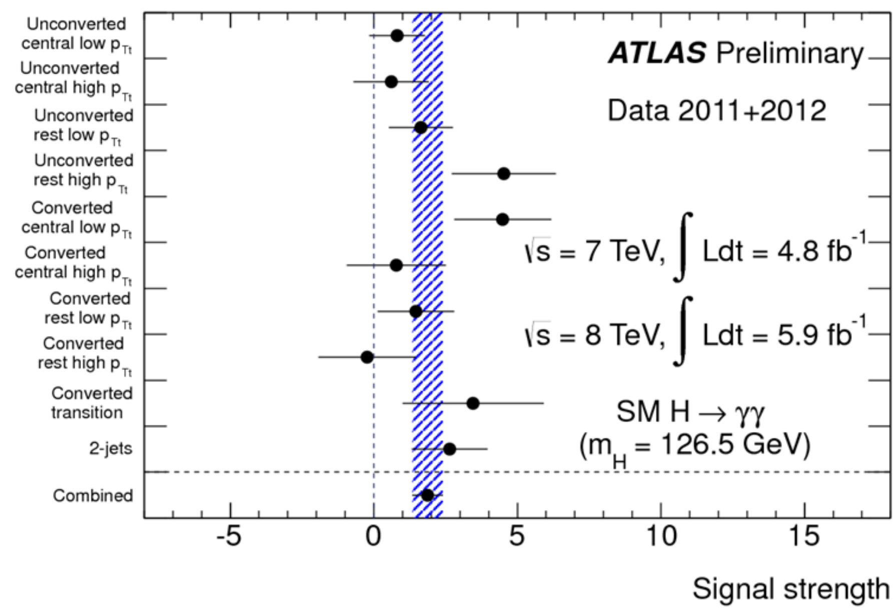
Consistent excesses are observed in both 2011 and 2012 data

Samples	Mass (GeV)	p-value	Obs. Sig.	Exp. Sig.
2011	126	3×10^{-4}	3.5σ	1.6σ
2012	127	3×10^{-4}	3.4σ	1.9σ
Combined	126.5	2×10^{-6}	4.5σ	2.4σ

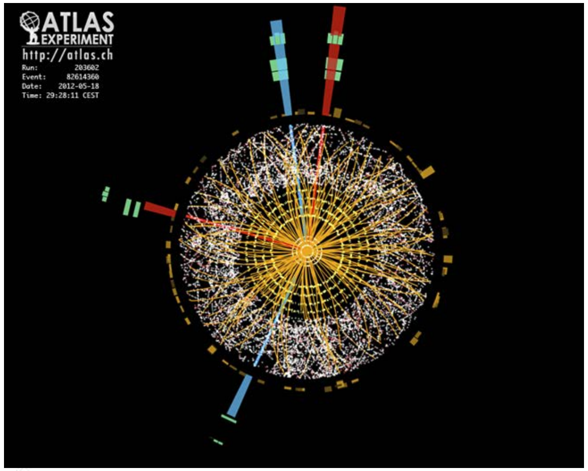
The measured signal strength, the excess relative to the SM expectation, at 126.5 GeV:

$$\mu = \frac{\sigma \cdot Br}{(\sigma \cdot Br)_{SM}} = 1.9 \pm 0.5$$





H→ZZ*→4l



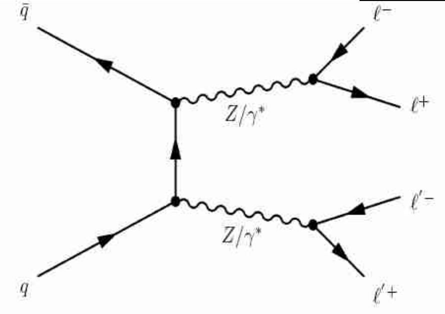
The gold-plated channel over a wide range of potential Higgs mass.

Clean signature:

- 4 isolated leptons, full reconstruction;
- Mass peak over backgrounds, good mass resolution.

Small backgrounds:

Irreducible SM ZZ* production and reducible Z+jets, top, …



$\ell = e, \mu$

But even smaller signal rate:

@125 GeV

$$\mathrm{BR}\left(ZZ \to 4\ell\right) = 0.45\%,\ \mathrm{BR}\left(H \to ZZ^*\right) = 2.6\%$$
$$\Rightarrow\ \sigma_H \times \mathrm{BR}\left(H \to ZZ \to 4\ell\right) = 2.6\ \mathrm{fb}$$

⇒ ~25 events in 2011+2012 samples

Selection efficiency to the 4th power of lepton efficiency:

$0.7^4 \sim 0.25$, $0.8^4 \sim 0.41$ ⇒ critical to improve lepton selection!

H→ZZ*→4l

Two same-flavor and opposite-sign isolated lepton pairs:

$$4 \text{ leptons with } p_T > 20,\ 15,\ 10,\ 7(6 \text{ for } \mu) \text{ GeV;}$$

$$50 < m_{12} < 106 \text{ GeV and } m_{\min}(m_{4\ell}) < m_{34} < 115 \text{ GeV}$$

$$m_{\min}(m_{4\ell}) = 17.5 - 50 \text{ GeV}$$

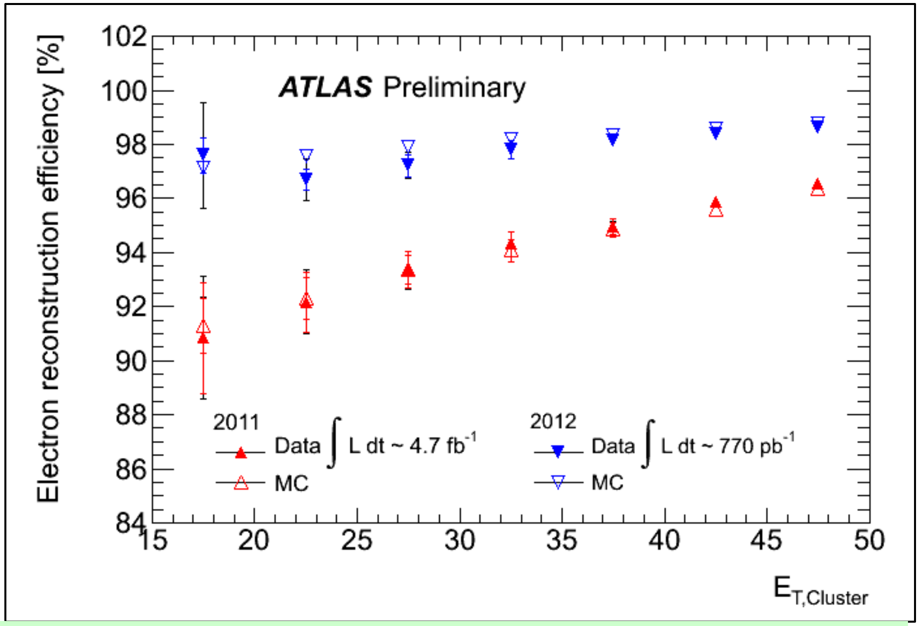
$$m_{\ell\ell} > 5 \text{ GeV for same-flavor and opposite-charge pair}$$

(Leading lepton pair: the pair with its closest to Mz)

Analysis improvements since 2011 publication

- **Relax m_{12} requirement ;**
- **Increased electron efficiency at low pT through the recovery of hard Bremsstrahlung radiation**

⇒ 20-30% gain in sensitivity for a low mass Higgs boson.

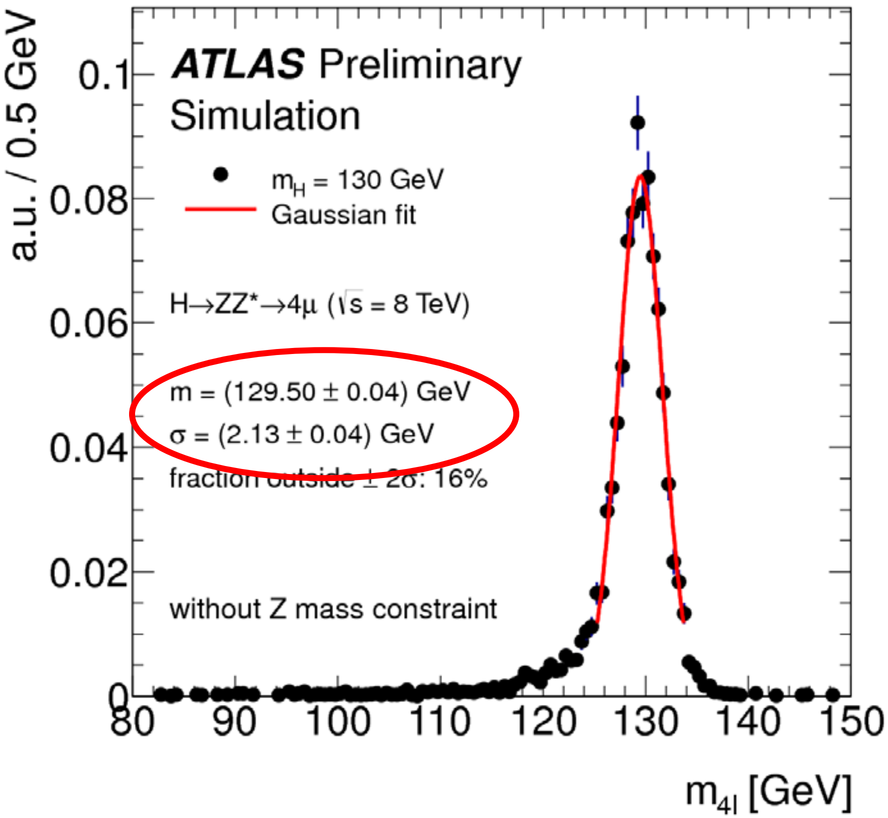


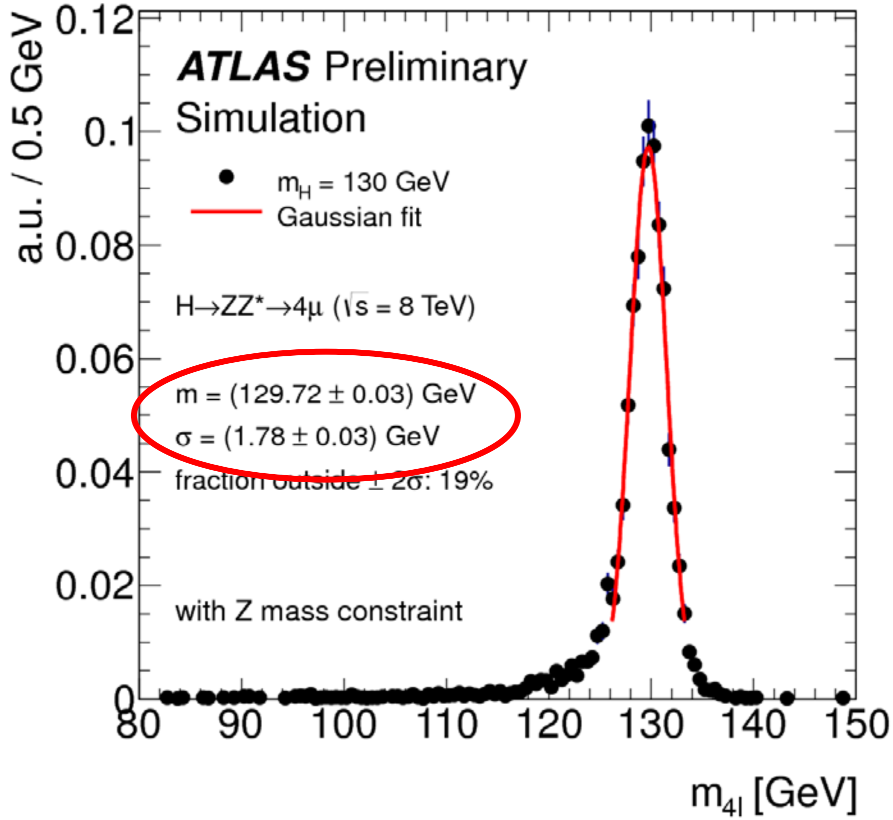
Selection efficiency (m_H=130 GeV): 41% (4μ), 27% (2e/2μ), 23% (4e)

H→ZZ*→4l

Improving resolution by applying a Z-mass constraint for the leading dilepton pair:

4μ: 2.13 → 1.78 GeV, 2e/2μ: 2.33 → 2.02 GeV, 4e: 2.76 → 2.46 GeV
10-20% improvement





H→ZZ*→4l

SM ZZ* background:

irreducible and estimated through MC simulation

Z+jets and top backgrounds:

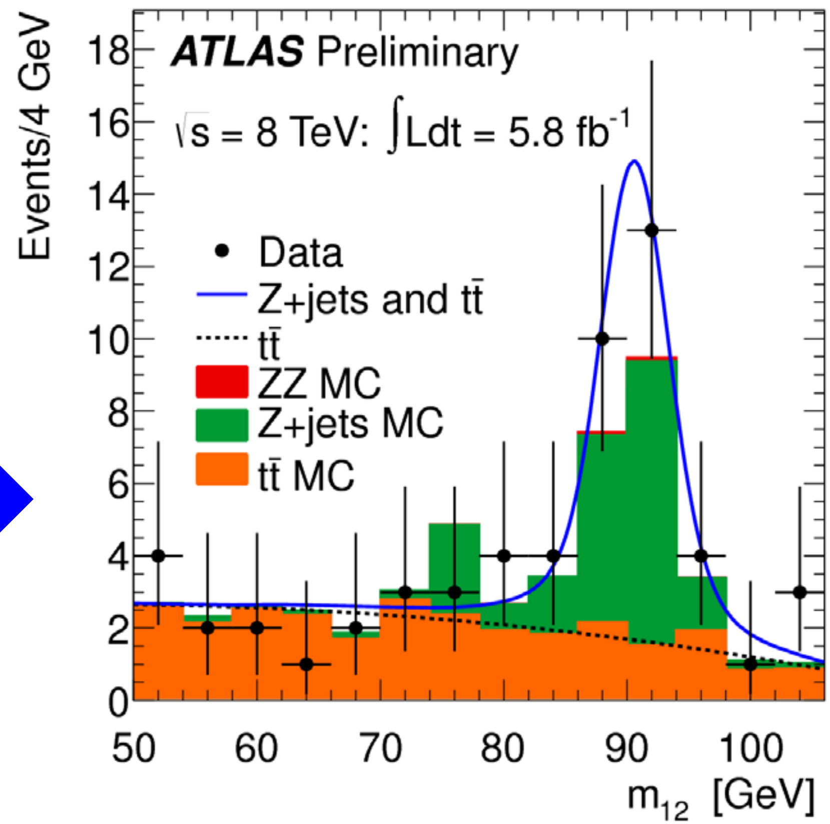
reducible and estimated from data

Control sample for $\ell\ell + \mu\mu$

For sub-leading dimuon pair:

- Remove isolation requirement
- At least one μ failing IP cut

The m_{12} distribution clearly shows a Z peak (Z+jets) over a continuum (top)



- Fit the m_{12} distributions to Z+jets and top components;
- Extrapolate to the signal region

Both background shape and extrapolation from MC

H→ZZ*→4l

	4μ		$2e2\mu/2\mu2e$		$4e$	
	Low mass	High mass	Low mass	High mass	Low mass	High mass
			$\sqrt{s} = 8$ TeV			
Int. Luminosity	5.8 fb^{-1}		5.8 fb^{-1}		5.9 fb^{-1}	
$ZZ^{(*)}$	6.3±0.3	27.5±1.9	3.7±0.2	41.7±3.0	2.9±0.3	17.7±1.4
Z + jets, and $t\bar{t}$	0.4±0.2	0.15±0.07	3.9±0.9	1.4±0.3	2.9±0.8	1.0±0.3
Total Background	6.7±0.3	27.6±1.9	7.6±1.0	43.1±3.0	5.7±0.8	18.8±1.4
Data	4	34	11	61	7	25
$m_H = 125$ GeV	1.4±0.2		1.7±0.2		0.8±0.1	
$m_H = 150$ GeV	4.5±0.6		5.9±0.8		2.7±0.4	
$m_H = 190$ GeV	8.2±1.0		12.5±1.7		5.3±0.8	
$m_H = 400$ GeV	3.9±0.5		6.6±0.9		2.9±0.4	
			$\sqrt{s} = 7$ TeV			
Int. Luminosity	4.8 fb^{-1}		4.8 fb^{-1}		4.9 fb^{-1}	
$ZZ^{(*)}$	4.9±0.2	18.1±1.3	3.1±0.2	27.3±2.0	1.6±0.2	10.2±0.8
Z + jets, and $t\bar{t}$	0.2±0.1	0.07±0.03	2.1±0.5	0.7±0.2	2.3±0.6	0.8±0.2
Total Background	5.1±0.2	18.2±1.3	5.1±0.5	28.0±2.0	3.9±0.6	11.0±0.8
Data	8	25	5	28	4	18
$m_H = 125$ GeV	1.0±0.1		1.0±0.1		0.37±0.05	
$m_H = 150$ GeV	3.0±0.4		3.4±0.5		1.4±0.2	
$m_H = 190$ GeV	5.1±0.6		7.4±1.0		2.8±0.4	
$m_H = 400$ GeV	2.3±0.3		3.8±0.5		1.6±0.2	

S~3.9 events

S~2.4 events

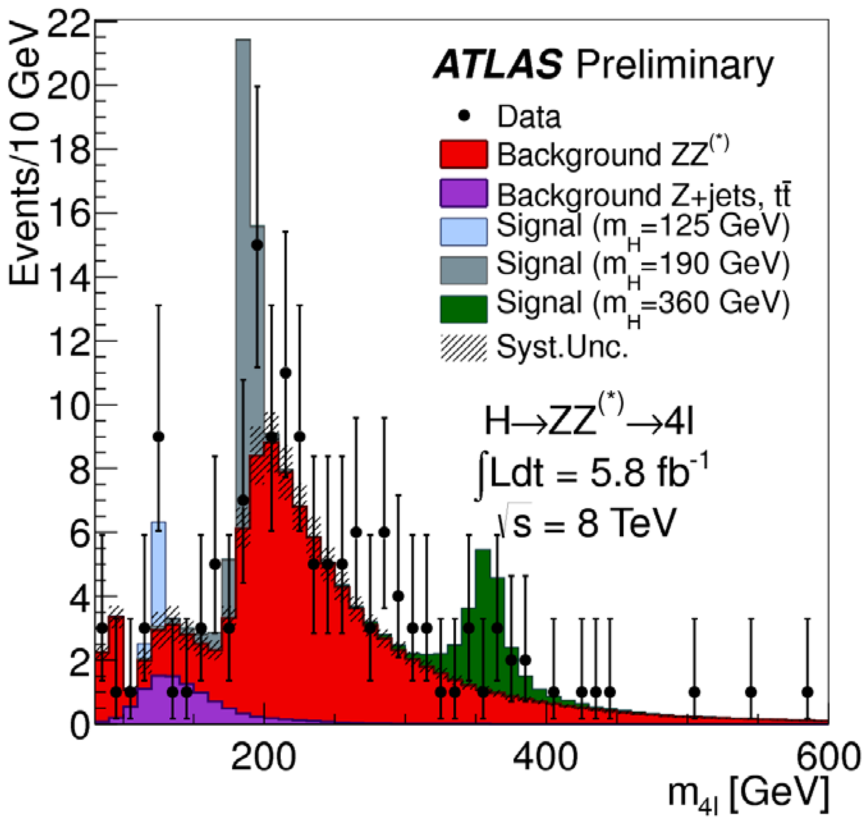
Low mass: m_{4l}<160 GeV, high mass: m_{4l}>160 GeV

H→ZZ*→4l

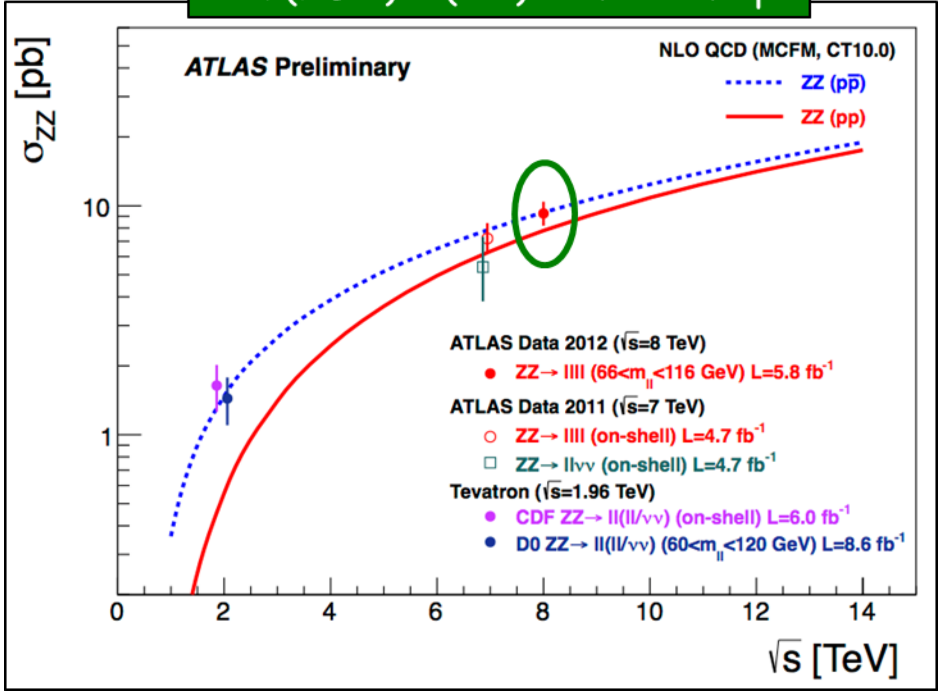
See significantly more events than expected:

- 2011: 88 observed with 71±5 expected
- 2012: 142 observed with 109±7 expected

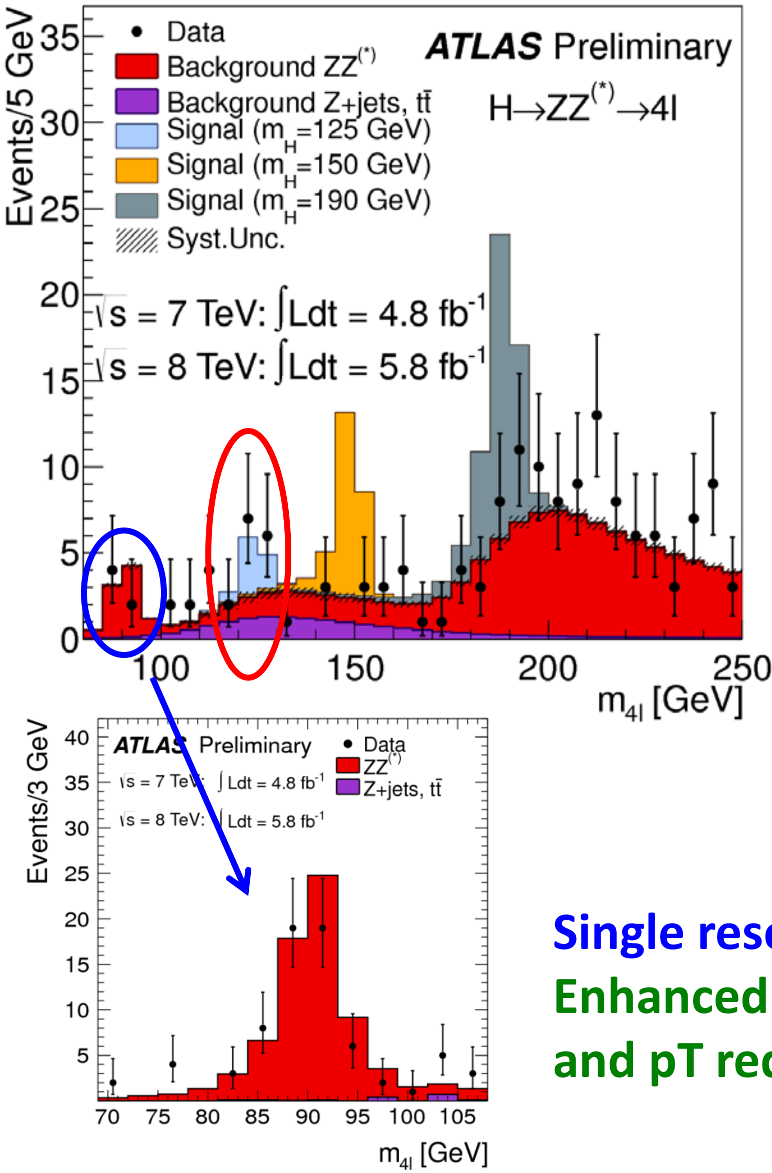
The excess is mostly for m_{4l}>160 GeV ⇒ significantly higher measured ZZ cross section



Measured σ (ZZ) = 9.3 ± 1.2 pb
SM (NLO) σ (ZZ) = 7.4± 0.4 pb



H→ZZ*→4l



A small cluster of events populates around 125 GeV

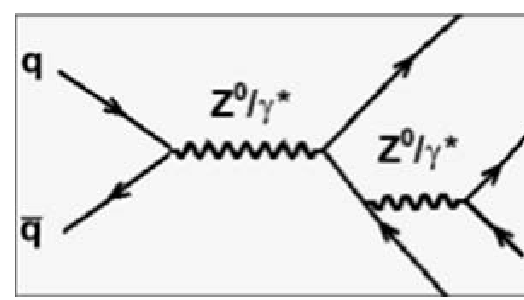
In the region 125 ± 5 GeV

Dataset	2011	2012	2011+2012
Expected B only	2±0.3	3±0.4	5.1±0.8
Expected S m_H=125 GeV	2±0.3	3±0.5	5.3±0.8
Observed in the data	4	9	13

2011+ 2012	4μ	2e2μ	4e
Data	6	5	2
Expected S/B	1.6	1	0.5
Reducible/total background	5%	45%	55%

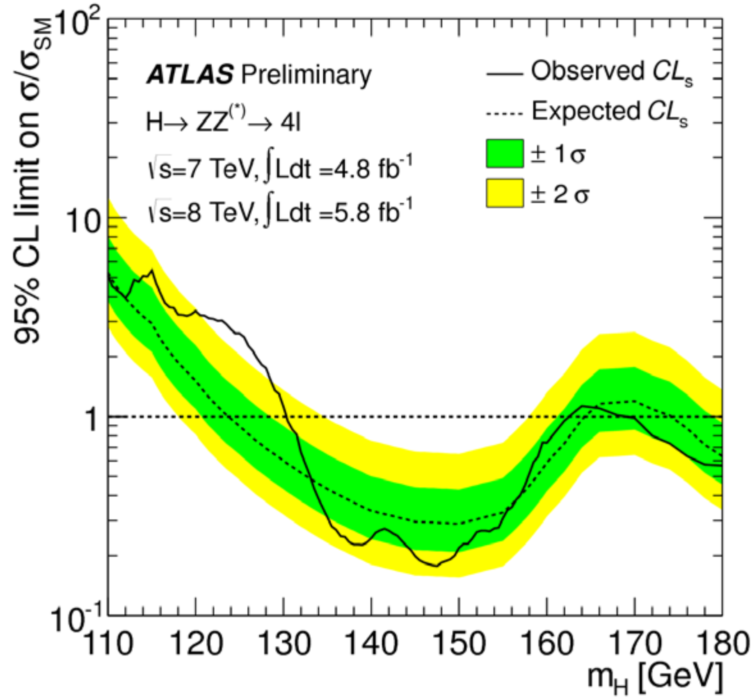
Single resonant contributions

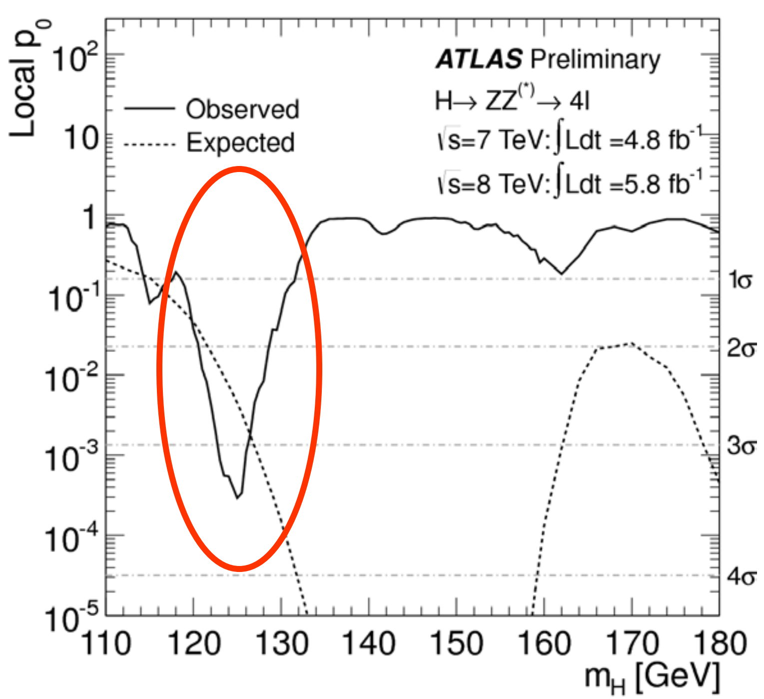
Enhanced by relaxing mass and pT requirements



H→ZZ*→4l

Exclusion: 131-162 GeV and 170-460 GeV (observed)
124-164 GeV and 176-500 GeV (expected)





A minimum p_0 at 125 GeV

$$p_0 = 3\times10^{-4} \quad \Rightarrow \quad 3.4\sigma$$

(Expected: 2.6σ from a SM Higgs boson)

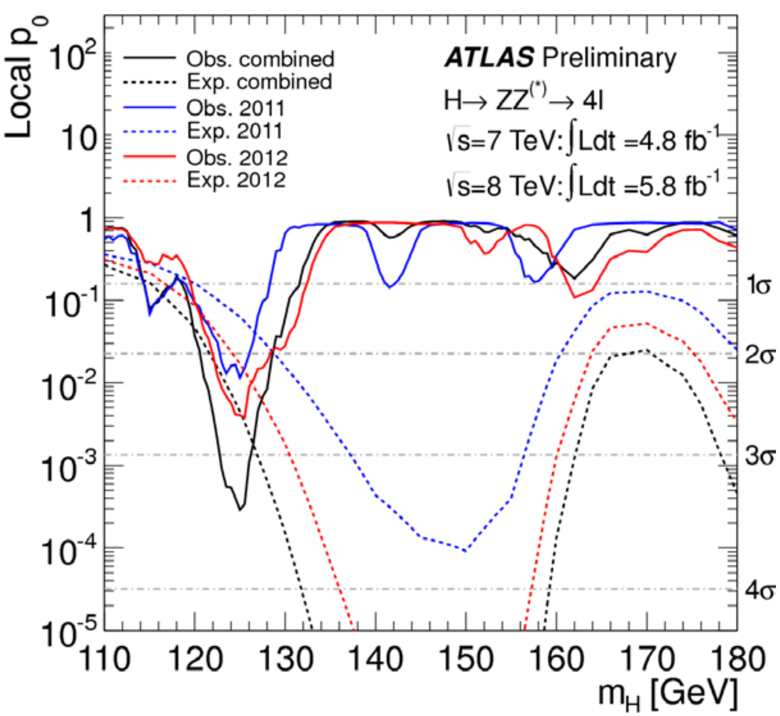
(Global significance: 2.5σ over 110-141 GeV)

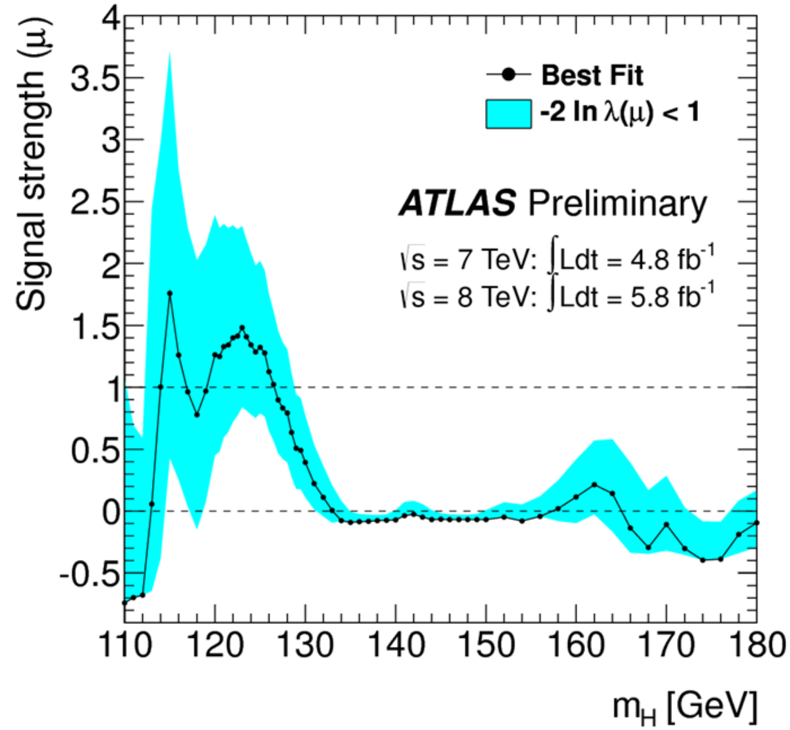
H→ZZ*→4l

Excess is seen in both 2011 and 2012 at about the same mass.

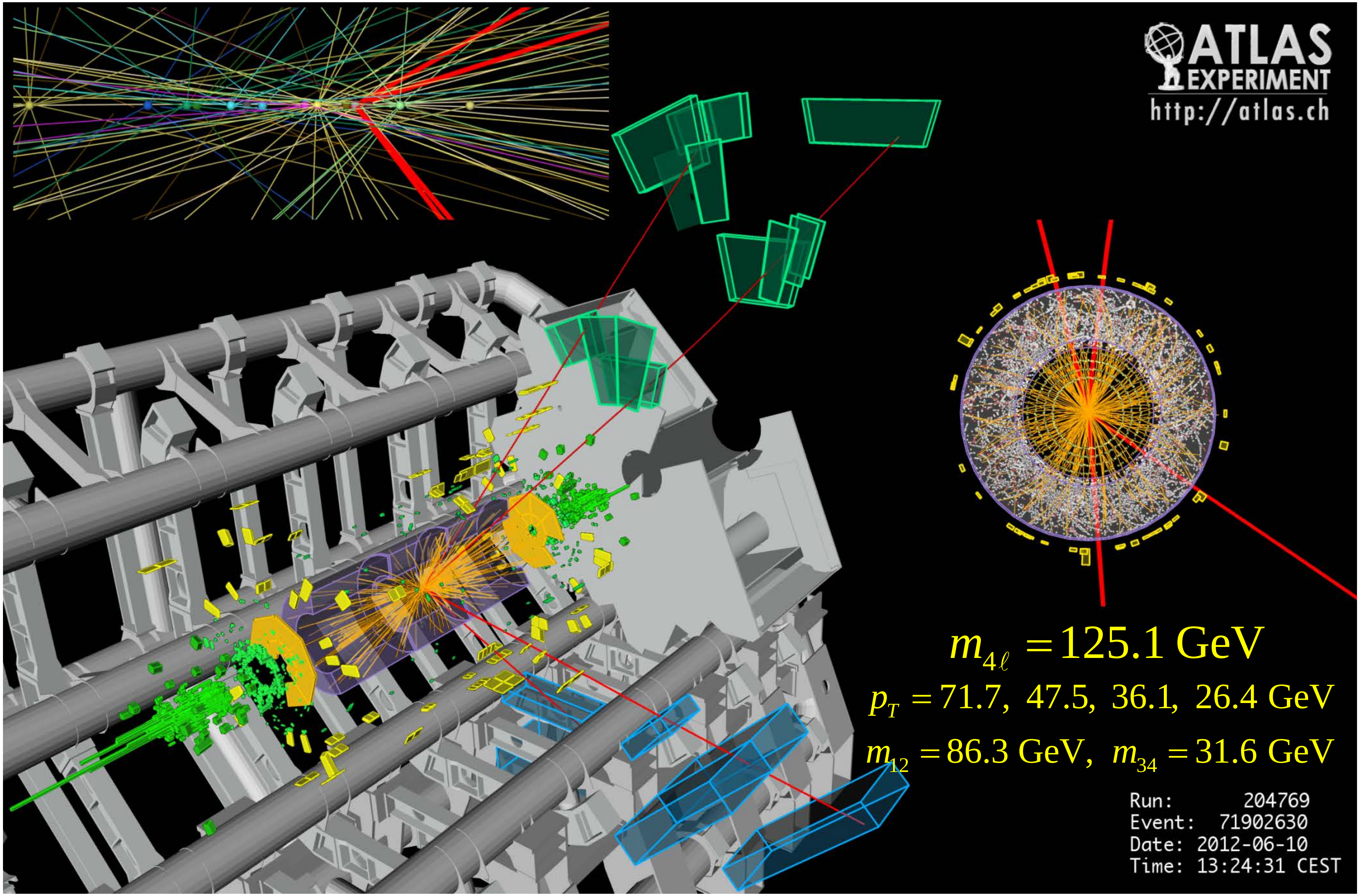
Samples	Mass (GeV)	p-value	Obs. Sig.	Exp. Sig.
2011	125	1.10%	2.3σ	1.5σ
2012	125.5	0.40%	2.7σ	2.1σ
Combined	125	0.03%	3.4σ	2.6σ

Signal strength at the lowest p_0 (125 GeV): μ=1.3 ± 0.6

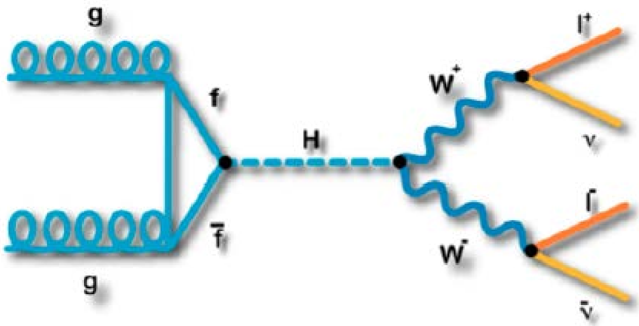




H→ZZ*→4l

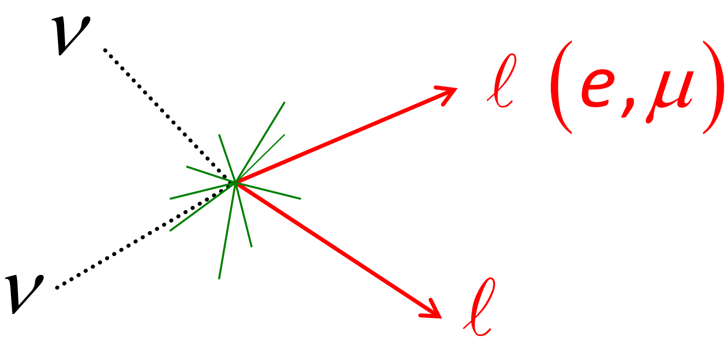

ATLAS EXPERIMENT
http://atlas.ch
$m_{4\ell} = 125.1$ GeV
$p_T = 71.7,\ 47.5,\ 36.1,\ 26.4$ GeV
$m_{12} = 86.3$ GeV, $m_{34} = 31.6$ GeV
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

H→WW*→lνlν



$$\sigma(H \to WW^* \to \ell\nu\ell\nu) \approx 220 \text{ fb}$$
(8 TeV, m_H=125 GeV)

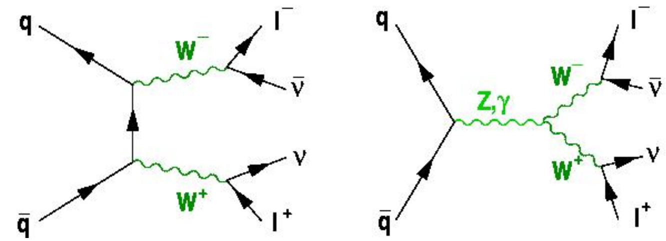
⇒ ~2300 events in 2011+2012 samples



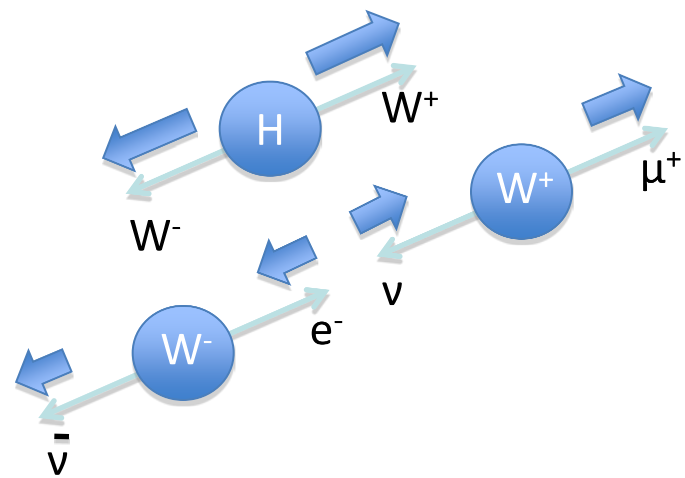
Main background:

WW, $t\bar{t}$, W/Z+jets, WZ/ZZ/Wγ,...

The SM WW is said to be "irreducible"



However, WW from the scalar Higgs is expected to have different kinematics



The spin correlation leads to a smaller average opening angle between the two leptons

H→WW*→eμνν

Due to large pileups in 2012, *only eμ final state has been analyzed*

$$\text{6 categories: } (e\mu, \mu e) \otimes (\text{0-jet, 1-jet, 2-jet})$$

(Separate final states with leading electron or leading muon)

Preselection:

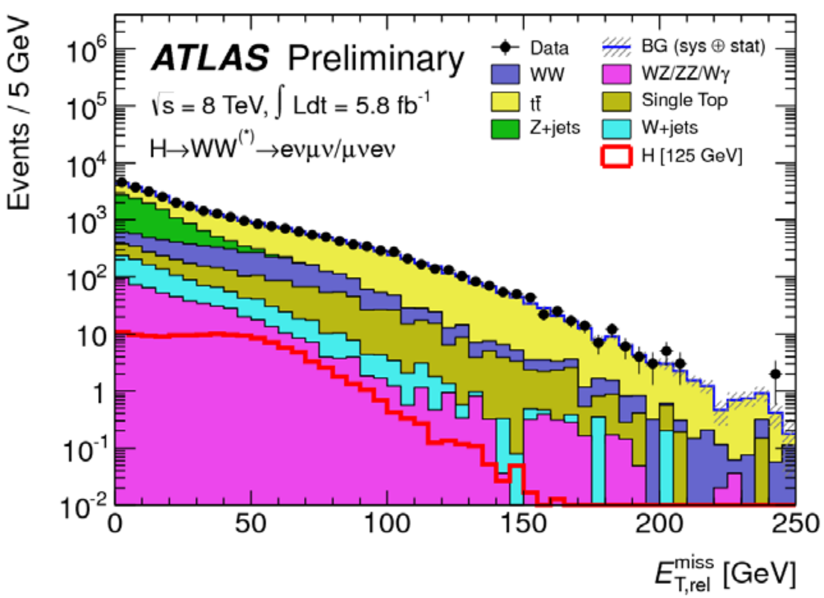
$$E_{T,\text{Rel}}^{\text{miss}} = \begin{cases} E_T^{\text{miss}} & \Delta\phi \geq \pi/2 \\ E_T^{\text{miss}} \sin\Delta\phi & \Delta\phi < \pi/2 \end{cases}$$

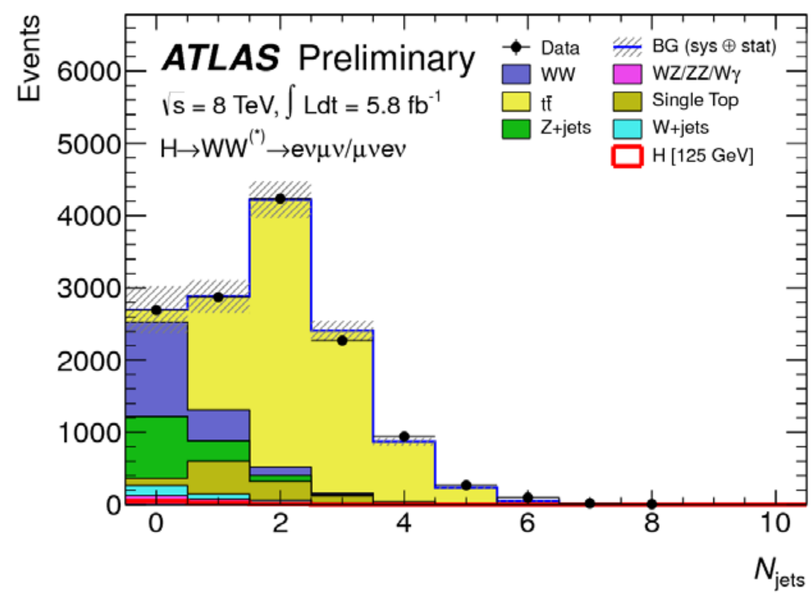
$$\Delta\phi = \min\left\{\Delta\phi\left(\vec{E}_T^{\text{miss}}, \ell/\text{jets}\right)\right\}$$

– $p_T^{\ell_1,\ell_2} > 25{,}15$ GeV with $|\eta| < 2.5$;

– $E_{T,\text{Rel}}^{\text{miss}} > 25$ GeV;

– Jets: $p_T > 25$ GeV and $|\eta| < 2.5$ otherwise $p_T > 30$ GeV





H→WW*→eμνν

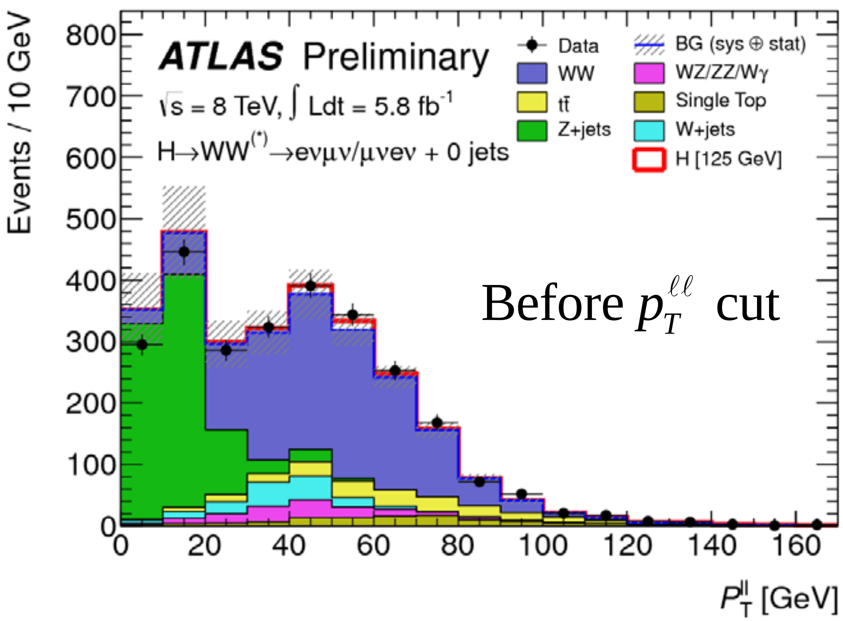
Significant background remains after pre-selection, apply topological selections for further background reduction:

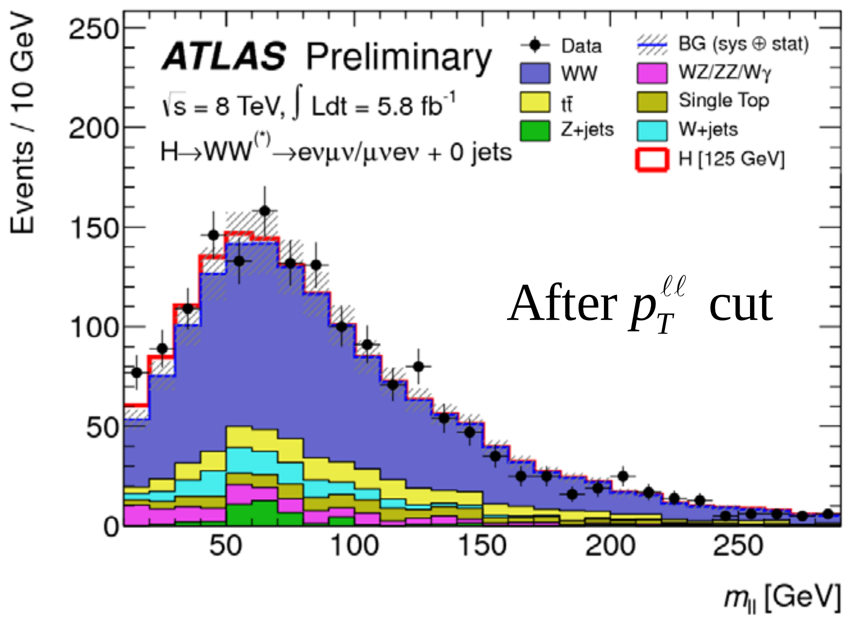
<u>0-jet selections</u>

$$- p_T^{\ell\ell} > 30 \text{ GeV};$$
$$- m_{\ell\ell} < 50 \text{ GeV};$$
$$- \Delta\phi_{\ell\ell} < 1.8$$

⇒ **Focus on low mass region. No change in the selections from 2011.**

Similar for 1-jet analysis, with additional b-jet veto





H→WW*→eμνν

Non-WW dibosons (WZ/ZZ/Wγ) and Z/DY:

Diboson: real leptons, real ETmiss; Z/DY: real lepton, fake or real ETmiss

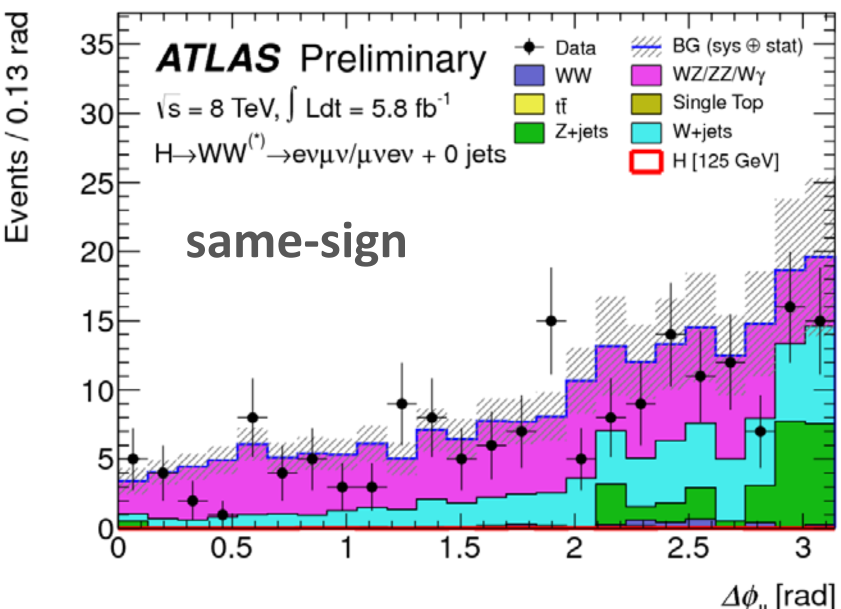
Both normalization and m_T shape from MC

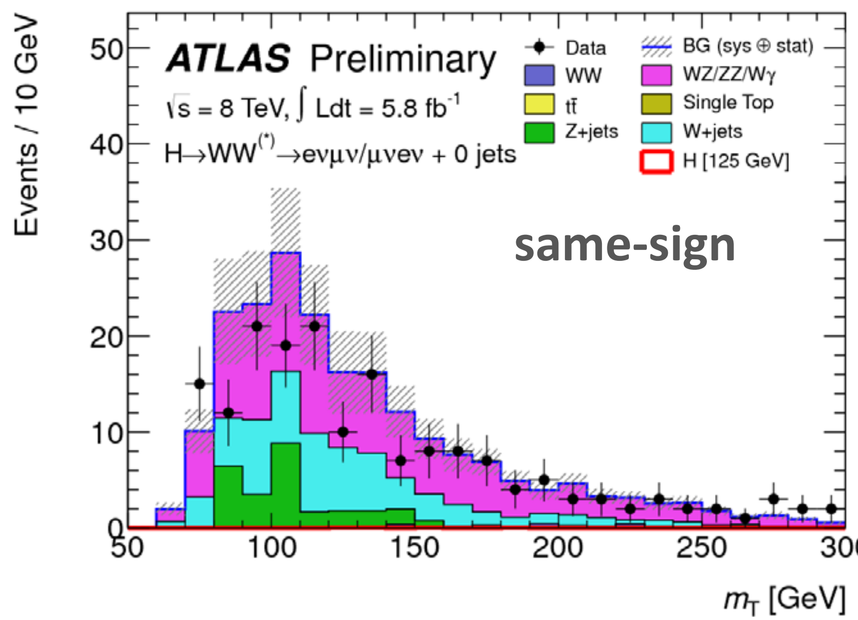
$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left(\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right)^2}$$

W+jets

Fake leptons, real ETmiss: both normalization and m_T shape from data

Non-WW dibosons and W+jets processes contribute to both same- and opposite-sign dilepton events ⇒ validation with same-sign events





H→WW*→eμνν

Top and WW backgrounds: real leptons and real ETmiss

Normalization from data and m_T shape from MC

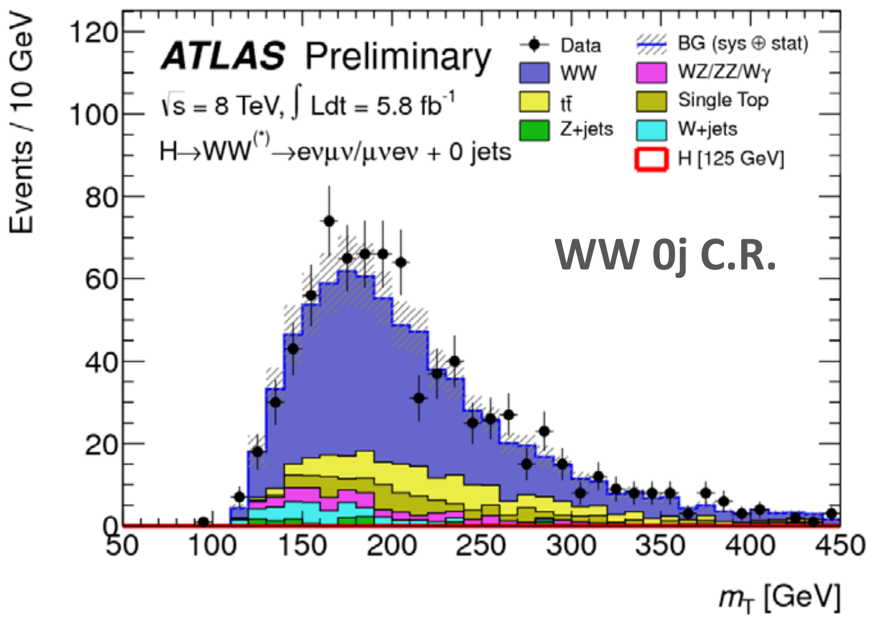
Estimating WW and top background from data:

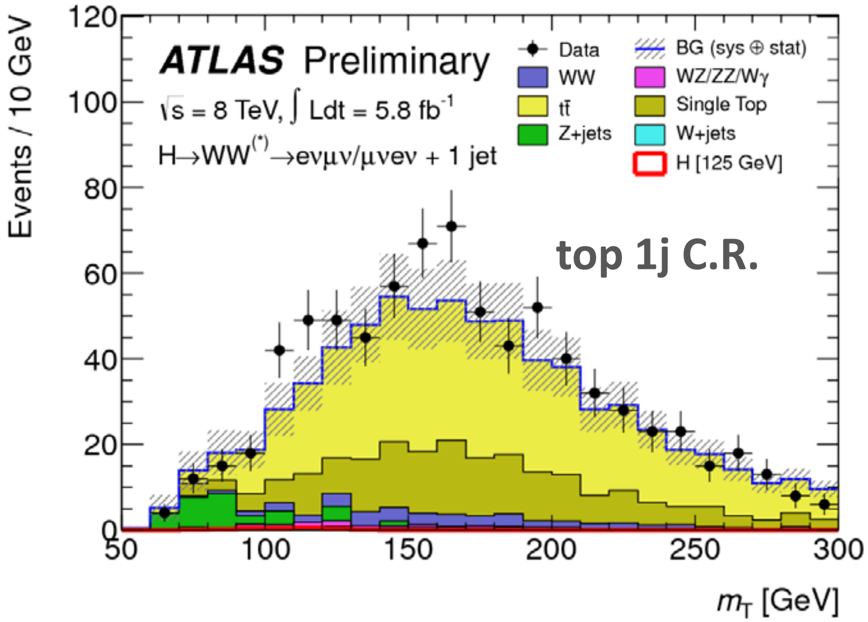
$$N^{est.}_{S.R.} = \left(\frac{N_{S.R.}}{N_{C.R.}}\right)_{MC} \times N^{Data}_{C.R.} = \alpha_{MC} \times N^{Data}_{C.R.}$$

scaling using data control regions (C.R.):

$WW:\ m_{\ell\ell} > 80$ GeV and no topological selection;

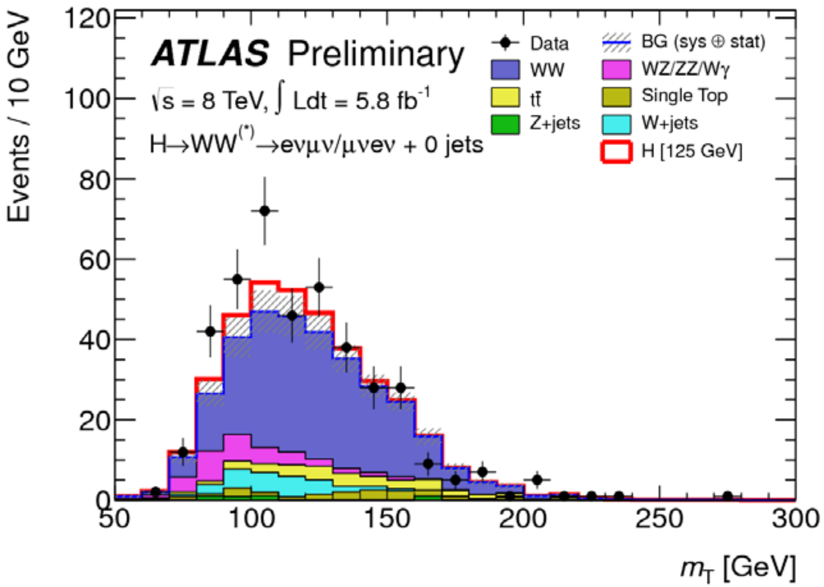
$Top:$ reverse b-jet veto (1j, 2j)

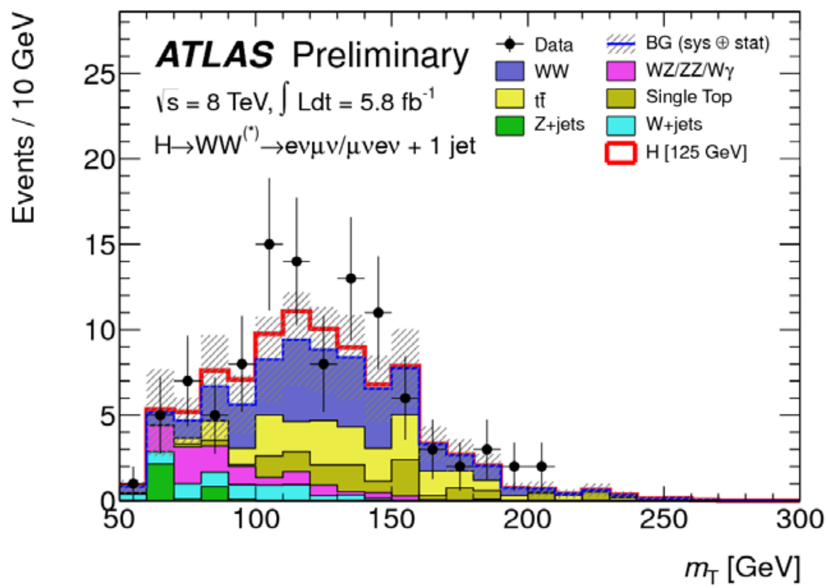




H→WW*→eμνν

The transverse mass as the final discriminant $m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left(\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right)^2}$





125 GeV: $0.75 m_H < m_T < m_H$ (illustration only)

	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W +$ jets	Total Bkg.	Obs.
$H+$ 0-jet	20 ± 4	101 ± 13	12 ± 3	8 ± 2	3.4 ± 1.5	1.9 ± 1.3	15 ± 7	142 ± 16	185
$H+$ 1-jet	5 ± 2	12 ± 5	1.9 ± 1.1	6 ± 2	3.7 ± 1.6	0.1 ± 0.1	2 ± 1	26 ± 6	38
$H+$ 2-jet	0.34 ± 0.07	0.10 ± 0.14	0.10 ± 0.10	0.15 ± 0.10	-	-	-	0.35 ± 0.18	0

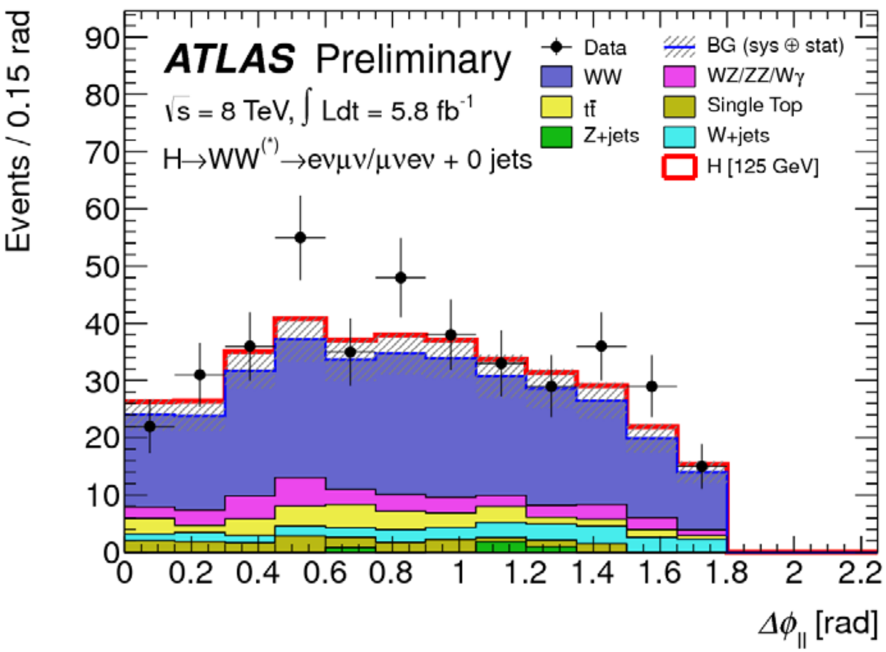
Significant excess over estimated background in both 0j and 1j channels !

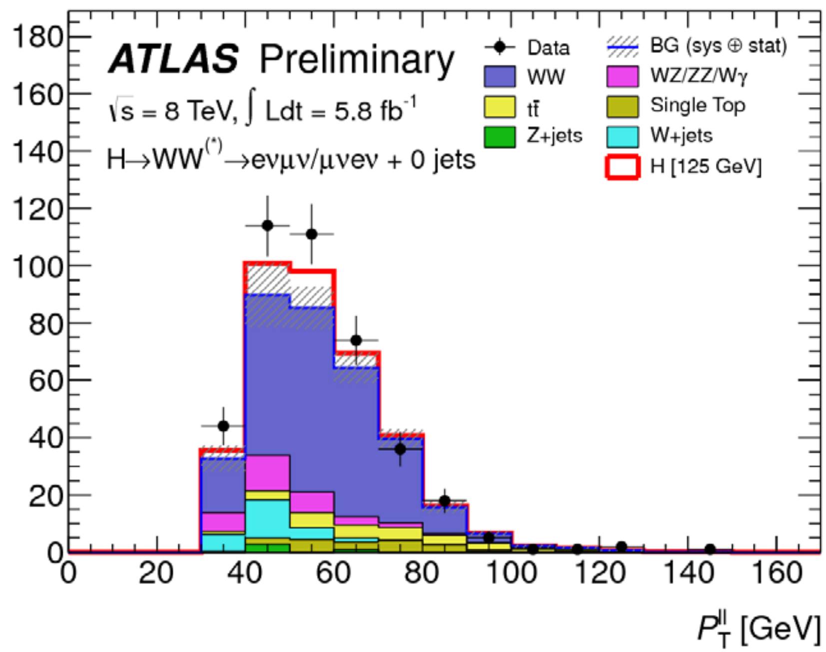
H→WW*→eμνν

After $\Delta\phi < 1.8$ cut

Signal region yield for $e\mu$ and μe channels separately				
	0-jet $e\mu$	0-jet μe	1-jet $e\mu$	1-jet μe
Total bkg.	177 ± 4	162 ± 4	43 ± 2	40 ± 3
Signal	18.7 ± 0.3	14.9 ± 0.2	4.3 ± 0.1	4.2 ± 0.1
Observed	213	194	54	52

All four categories show excess





No strange feature about the excess …

H→WW*→eμνν

Fit the observed m_T distributions to improve sensitivity:

5 bins for 0-jet, 3 bins for 1-jet and 1 bin for 2-jet

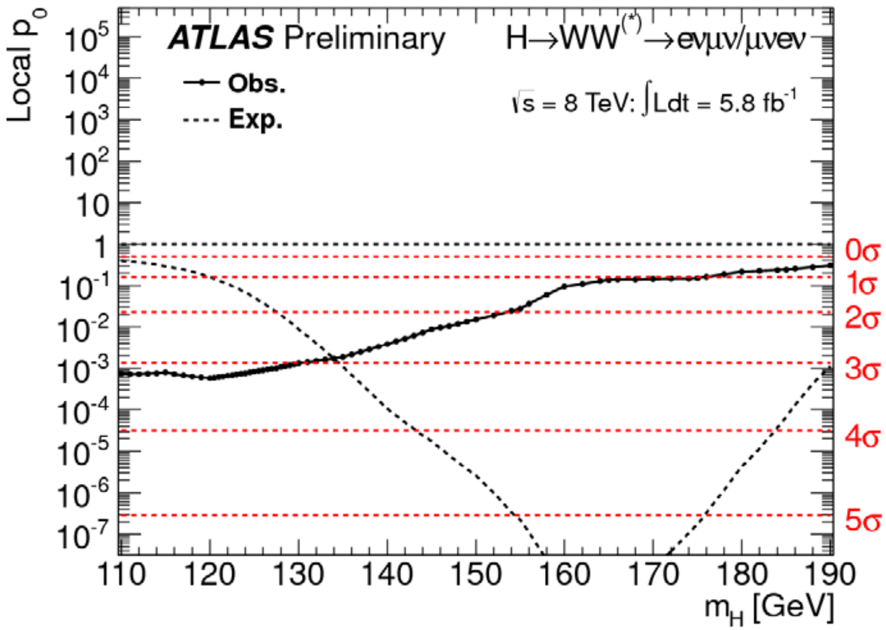
Broad excess due to the limited mass resolution

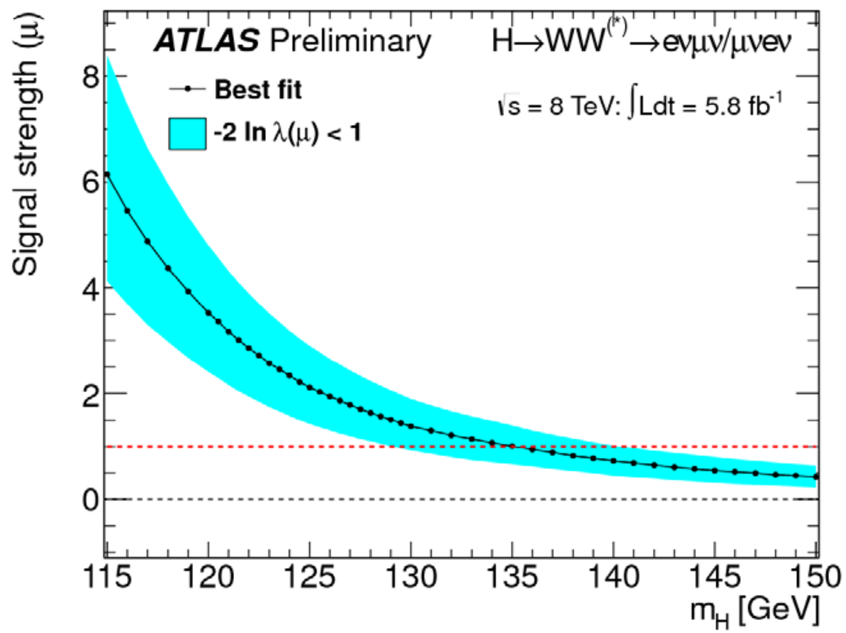
$$@120\ \text{GeV}: p_0 = 6\times10^{-4} \Rightarrow 3.2\sigma$$
$$@125\ \text{GeV}: p_0 = 8\times10^{-4} \Rightarrow 3.1\sigma$$

(cut-and-count: 3.0s at 125 GeV)

Signal strength

$$\mu = 2.1^{+0.8}_{-0.7}\ @\ 125\ \text{GeV}$$





H→WW*→eμνν

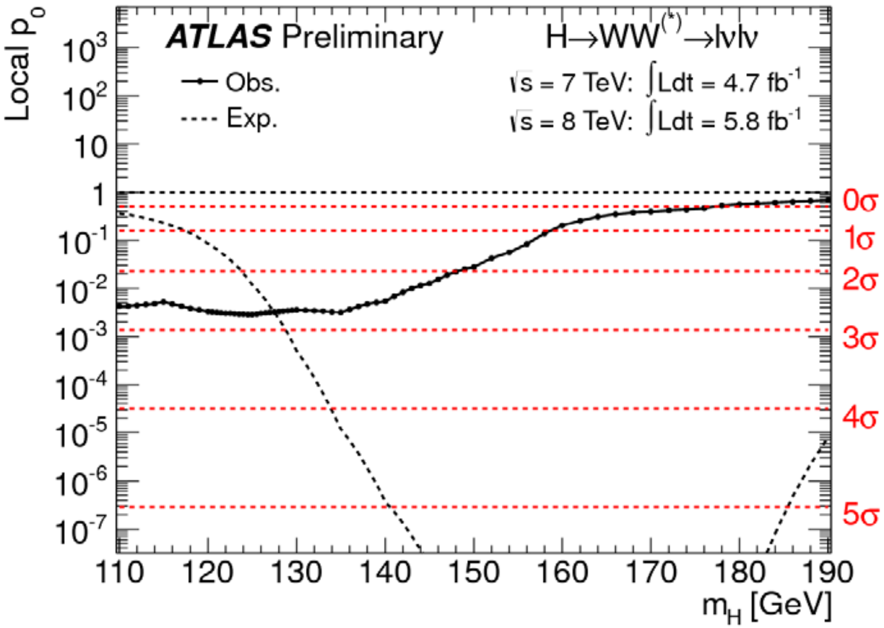
Combining with the published 2011 results (http://arxiv.org/abs/1206.0756)

A minimum p_0 value at 125 GeV

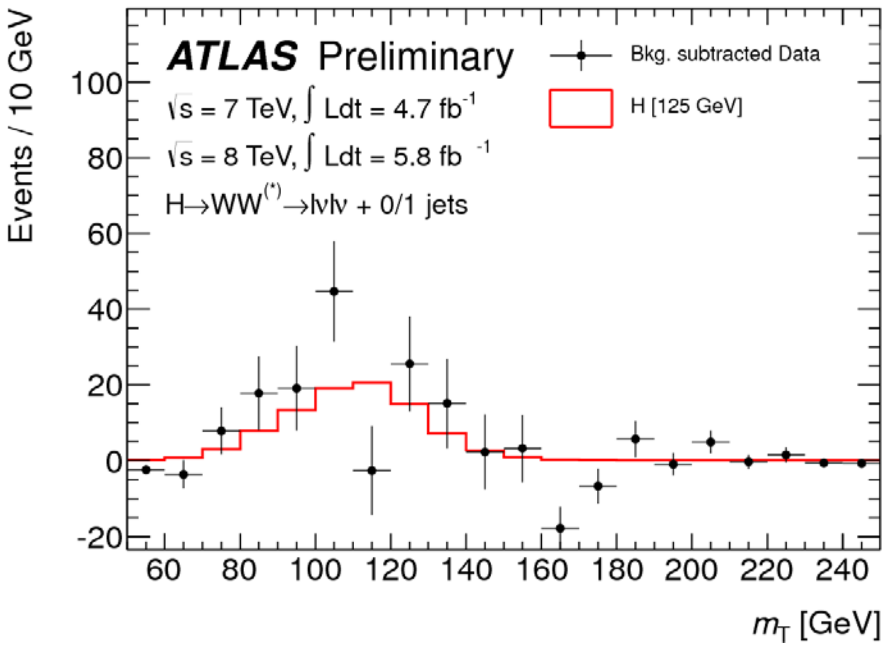
$$p_0 = 3\times10^{-3} \quad \Rightarrow \quad 2.8\sigma$$

$$\left(\text{Expected: } p_0 = 0.01 \text{ and } 2.3\sigma\right)$$

Combined p-value



Data-background



H→WW*→eμνν

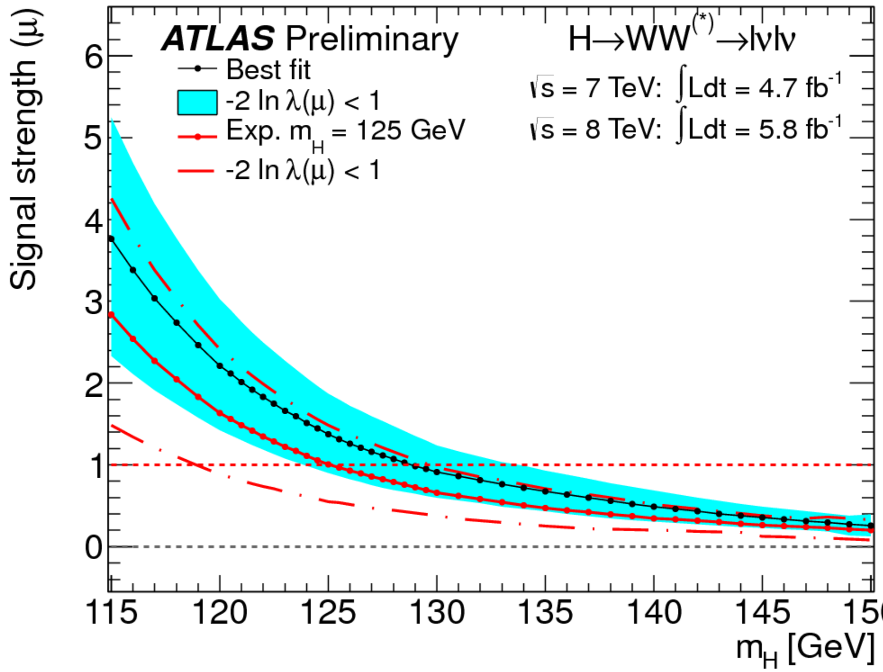
With a combined signal strength consistent with the SM expectation

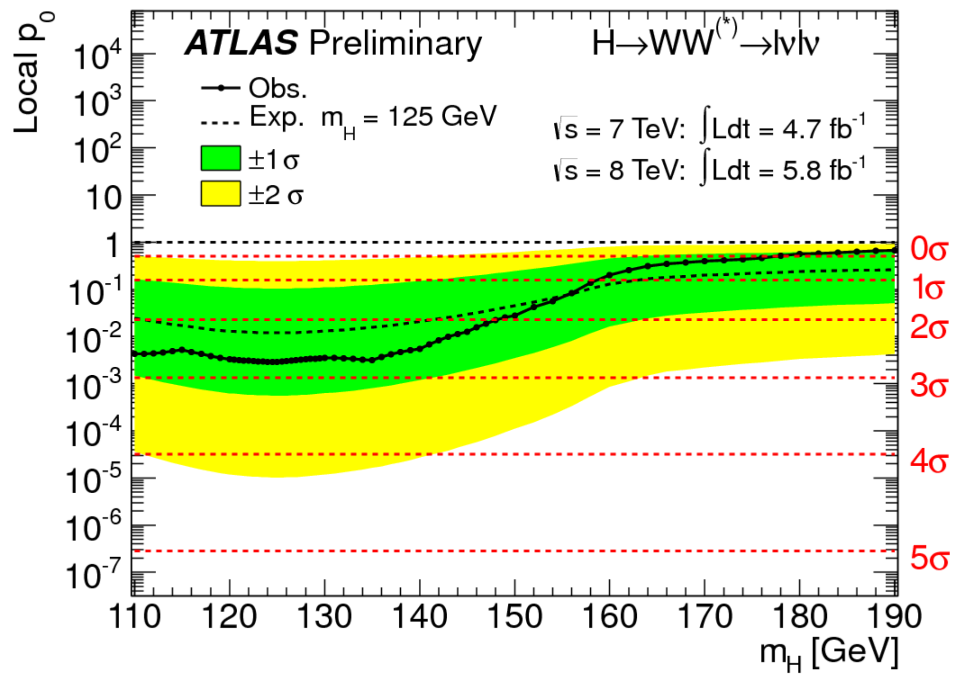
$$\mu = \frac{\sigma \cdot Br}{(\sigma \cdot Br)_{SM}} = 1.4 \pm 0.5$$

2011: $\mu = 0.5 \pm 0.7$
2012: $\mu = 2.1^{+0.8}_{-0.7}$
Compatible within 1.5σ

Confirmed through signal injection:

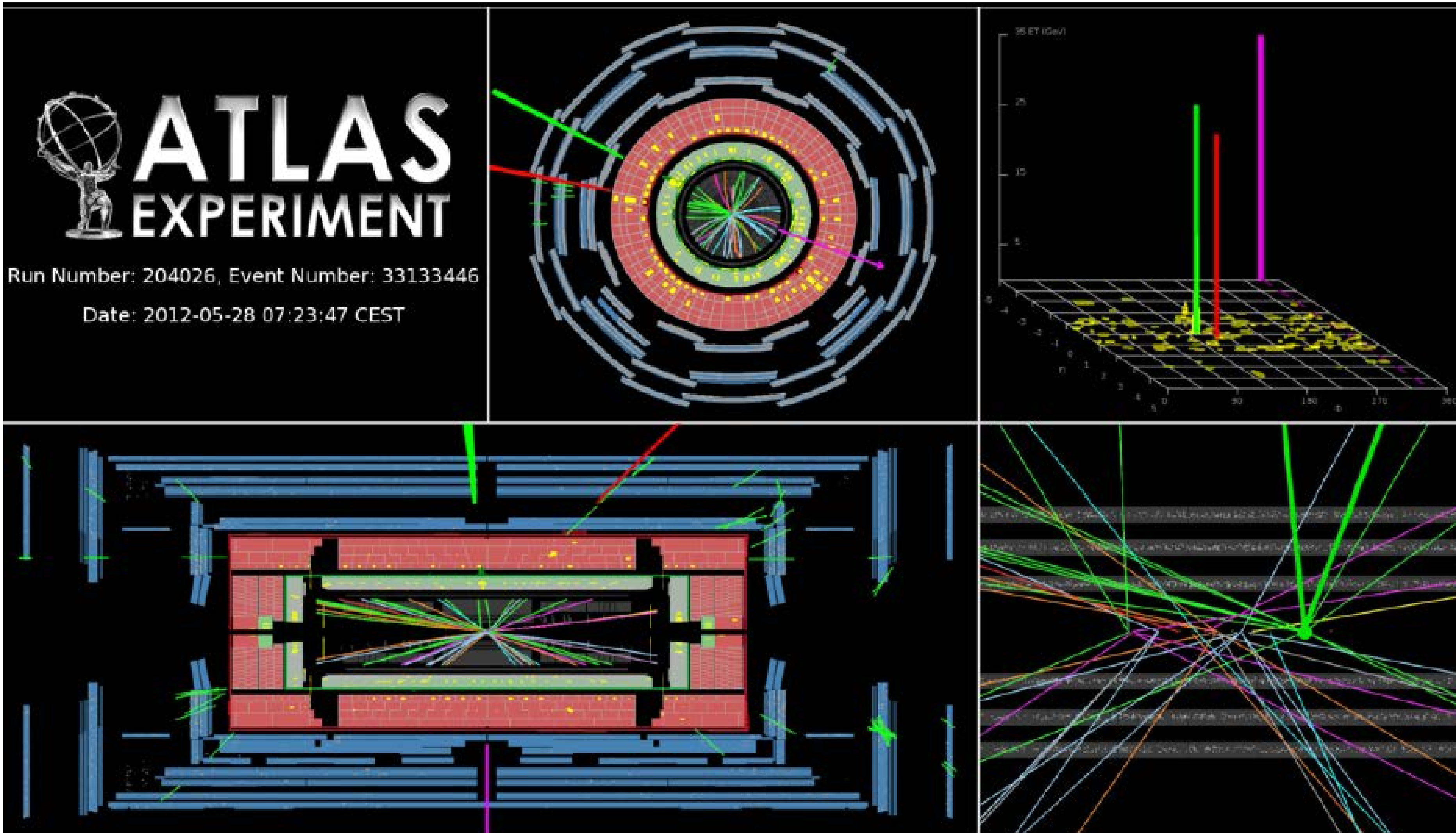
The observation is within one-sigma band of the expected signal





$H \to WW^* \to e\mu\nu\nu$

$$m_T\left(e\mu E_T^{miss}\right) = 94\ \text{GeV}$$

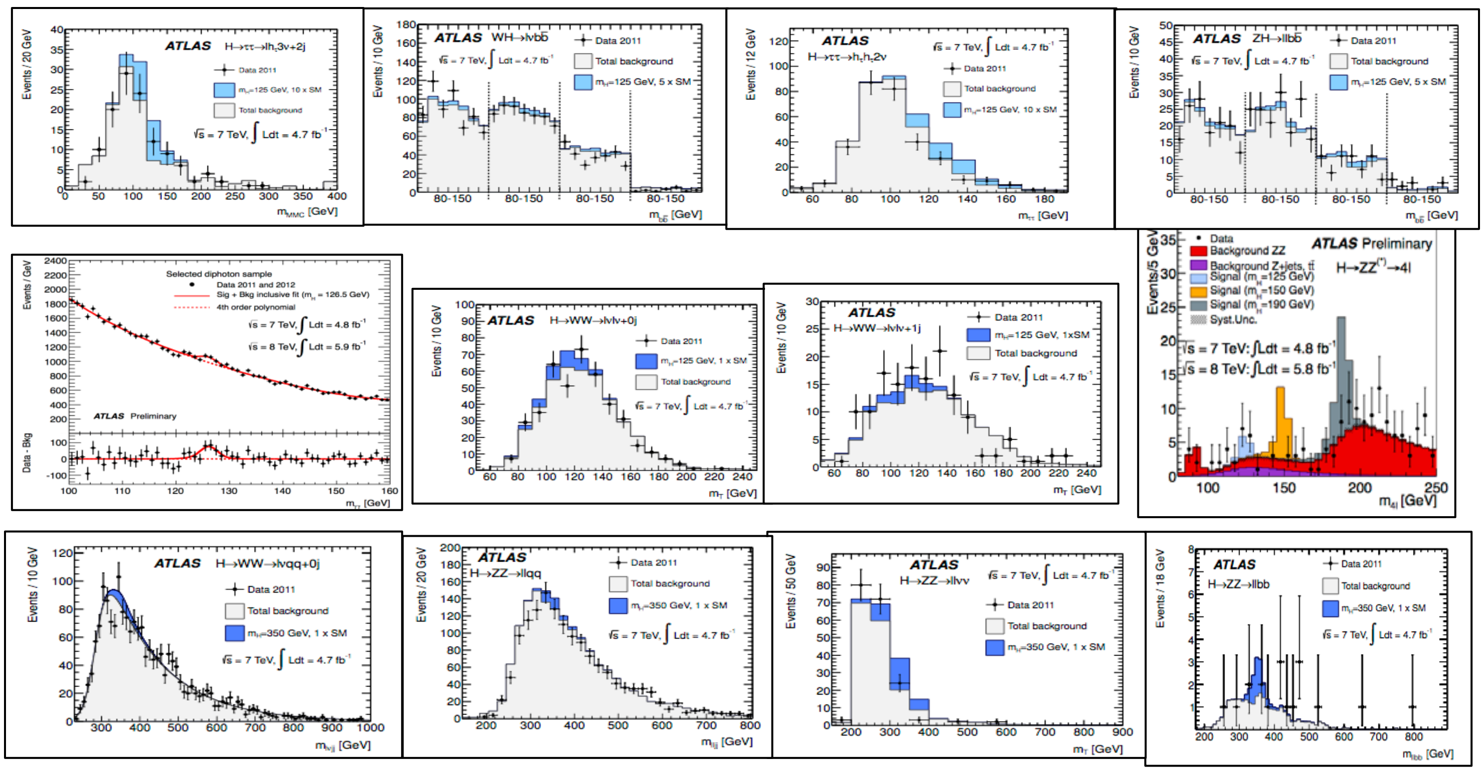


Combination

Combination inputs

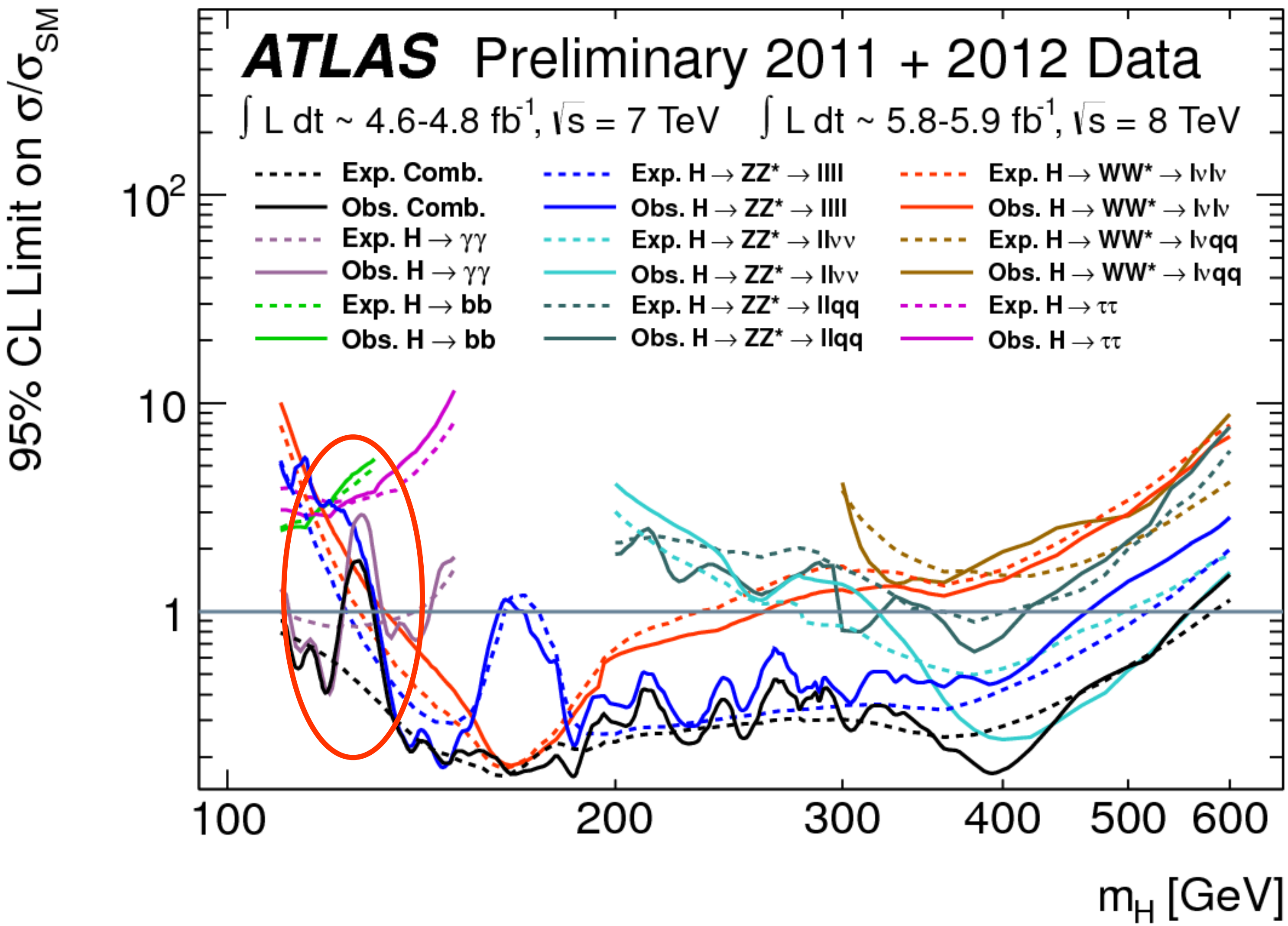
- 2011 + 2012 H→γγ
- 2011 + 2012 H→ZZ*→4l
- 2011 results for the rest
  (2012 results not yet available)

- 2011 H→WW*→lνlν
  2012 results approved this week,
  approval of its combination in process



Combination

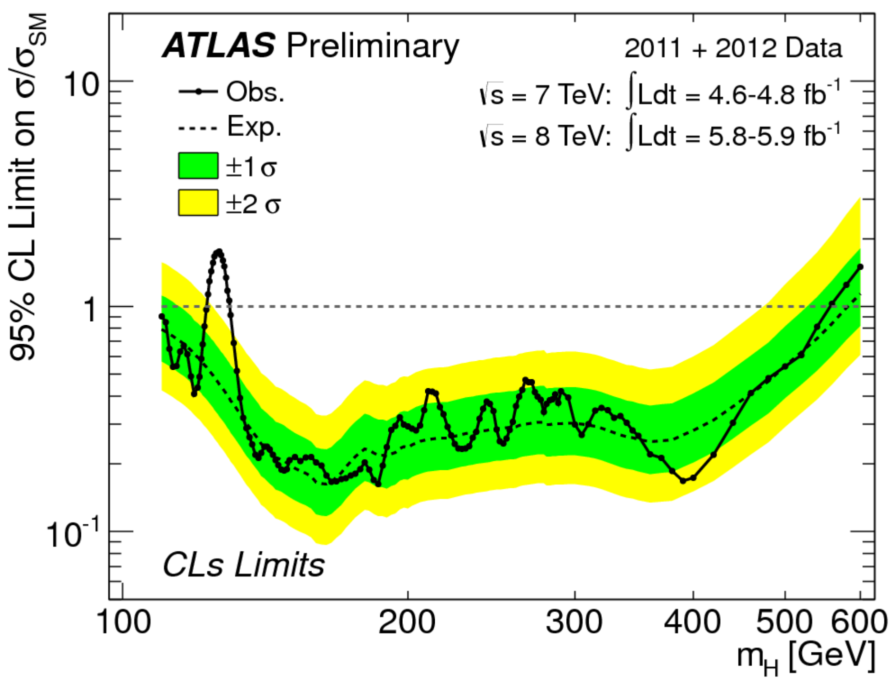
Individual Channel Limits

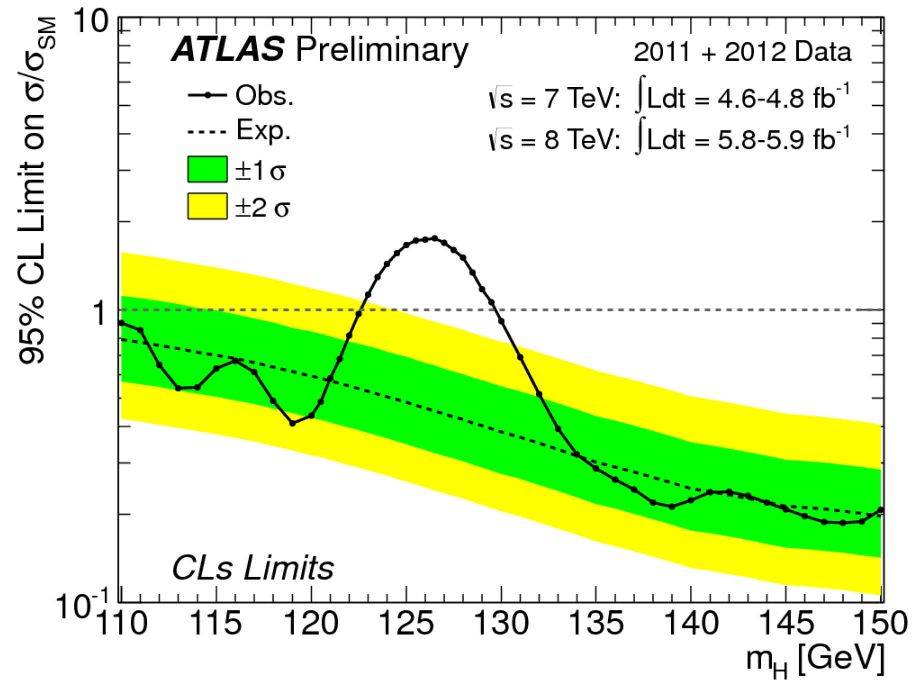


Combination

Combined Limits

Expected exclusion at 95% CL : 110-582 GeV
Observed exclusion: 110-122.6 GeV and 129.7-558 GeV

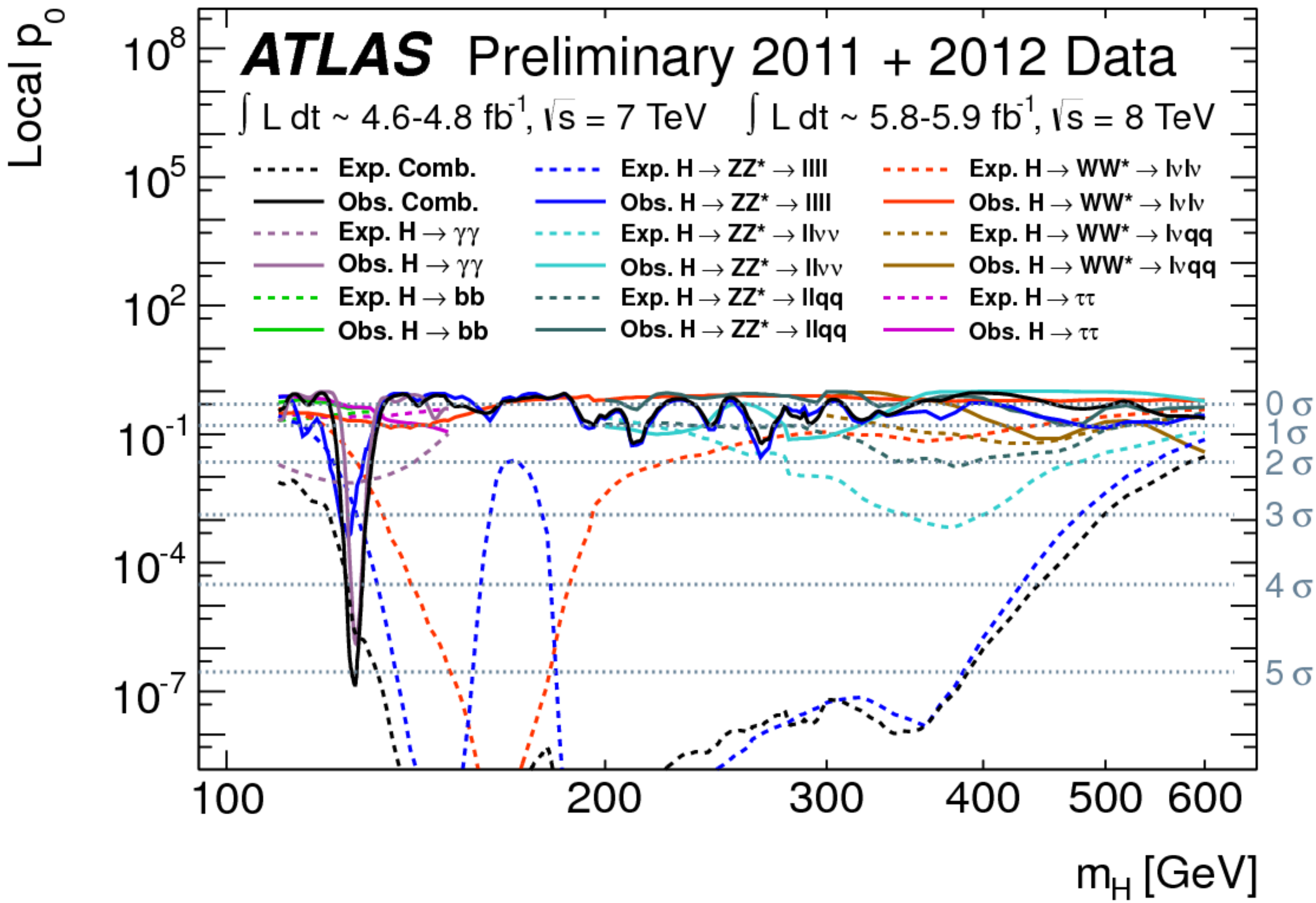




A SM Higgs boson is excluded:
110-122.6 GeV and 129.7-558 GeV @ 95% CL
111.7-121.8 GeV and 130.7-523 GeV @ 99% CL

Combination

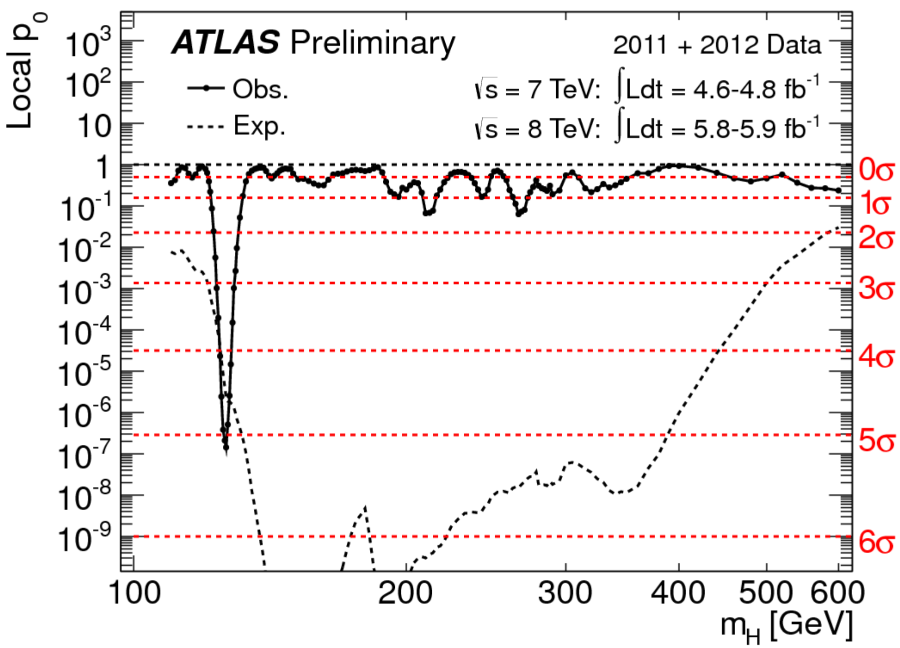
Individual Channel p-Values

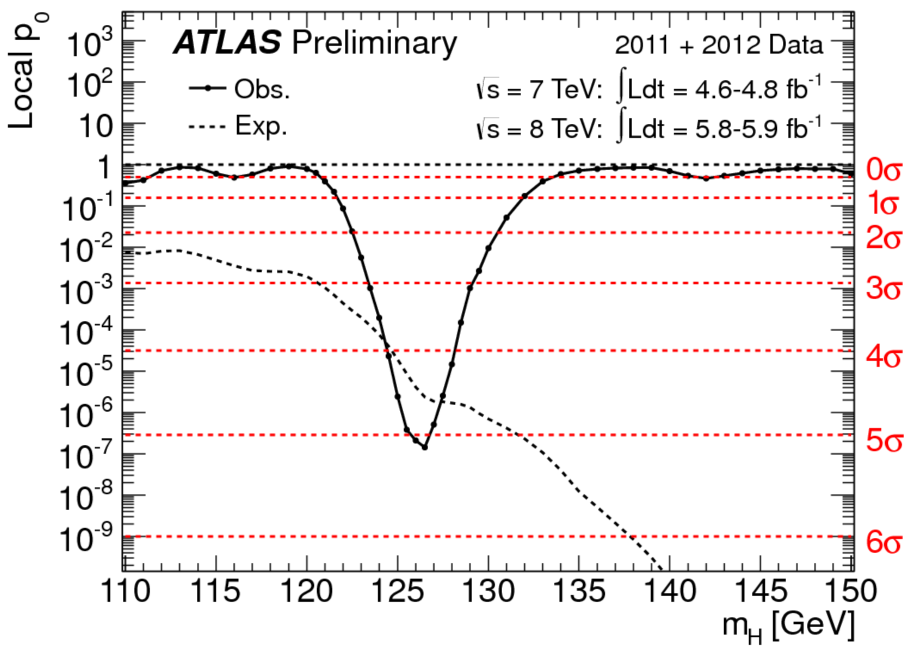


Combination

Combined p-Values

The combined results are consistent with background-only hypothesis over the entire search range except the mass region around 125 GeV



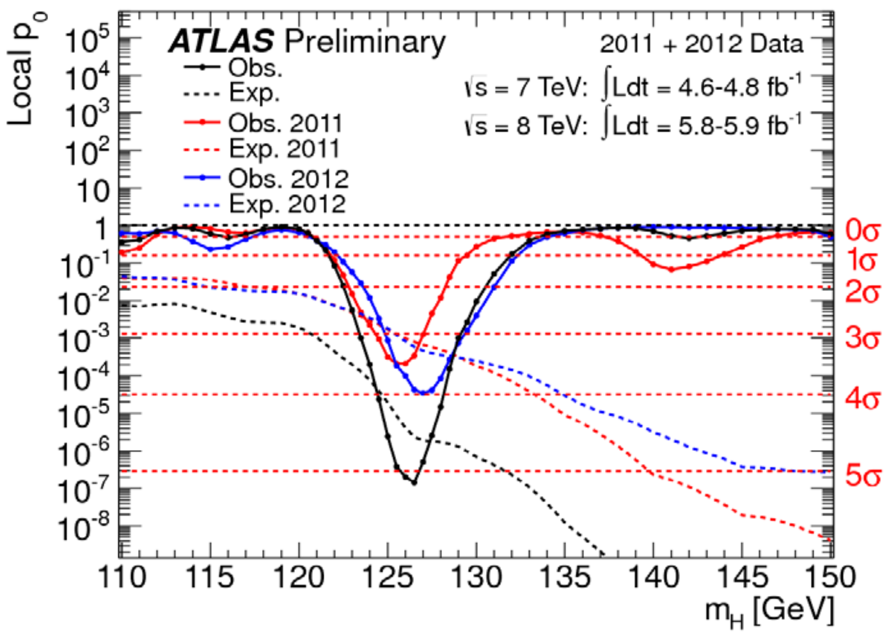


The significance of the excess at ~126 GeV is 5.1σ

(including energy scale systematics in γγ reduces it to 5.0σ)

Combination

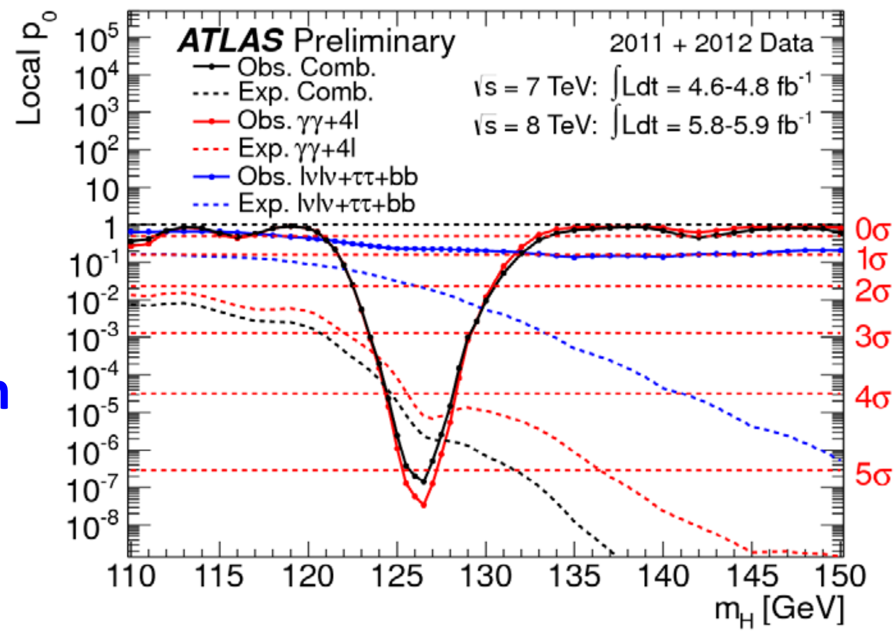
Excess breakdowns



The excess is seen in both 2011 and 2012 data:

2011: 3.5σ (obs.) and 3.1σ (exp.)

2012: 4.0σ (obs.) and 3.3σ (exp.)



But is dominated by high-resolution channels: γγ and 4l.

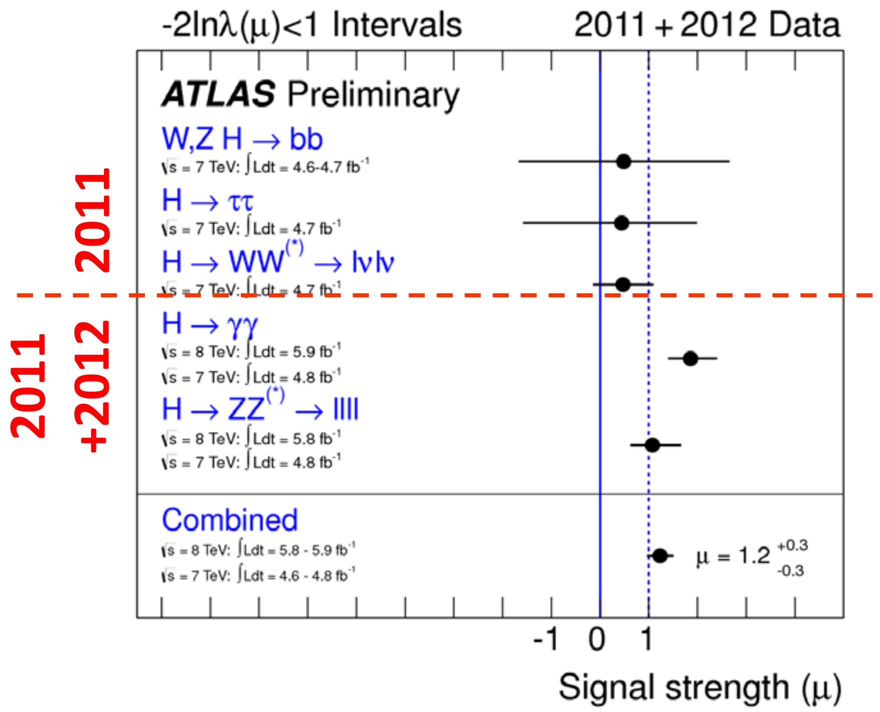
(2012 H→WW*→eμνν not included)

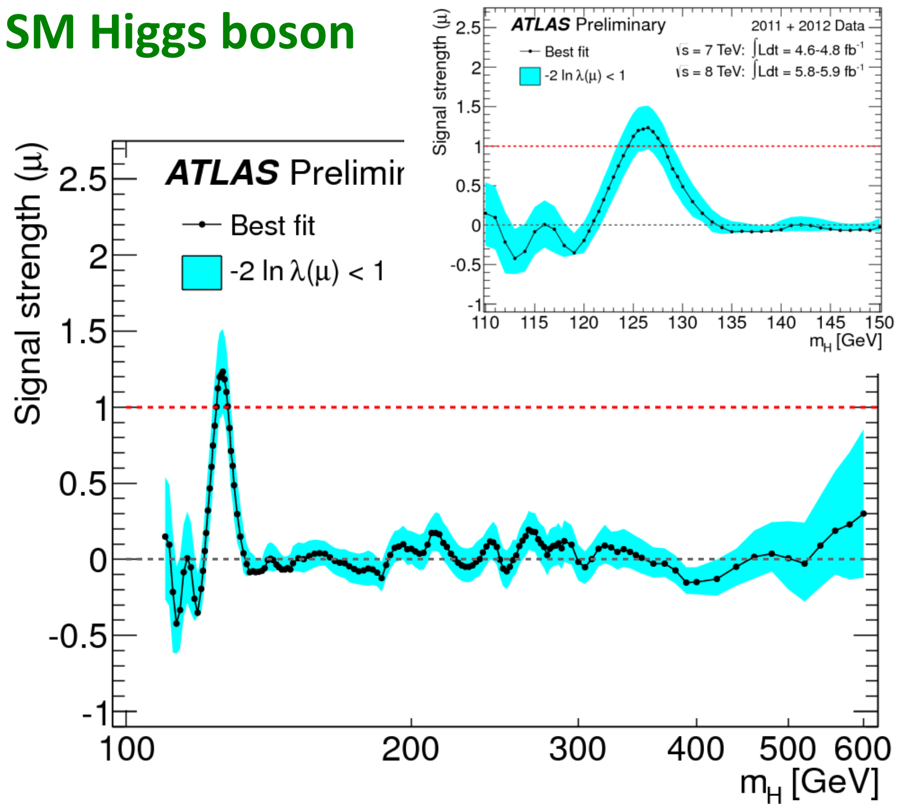
Combination

Signal strength: rate relative to the SM expectation

The value at the lowest p_0
μ=1.2±0.3

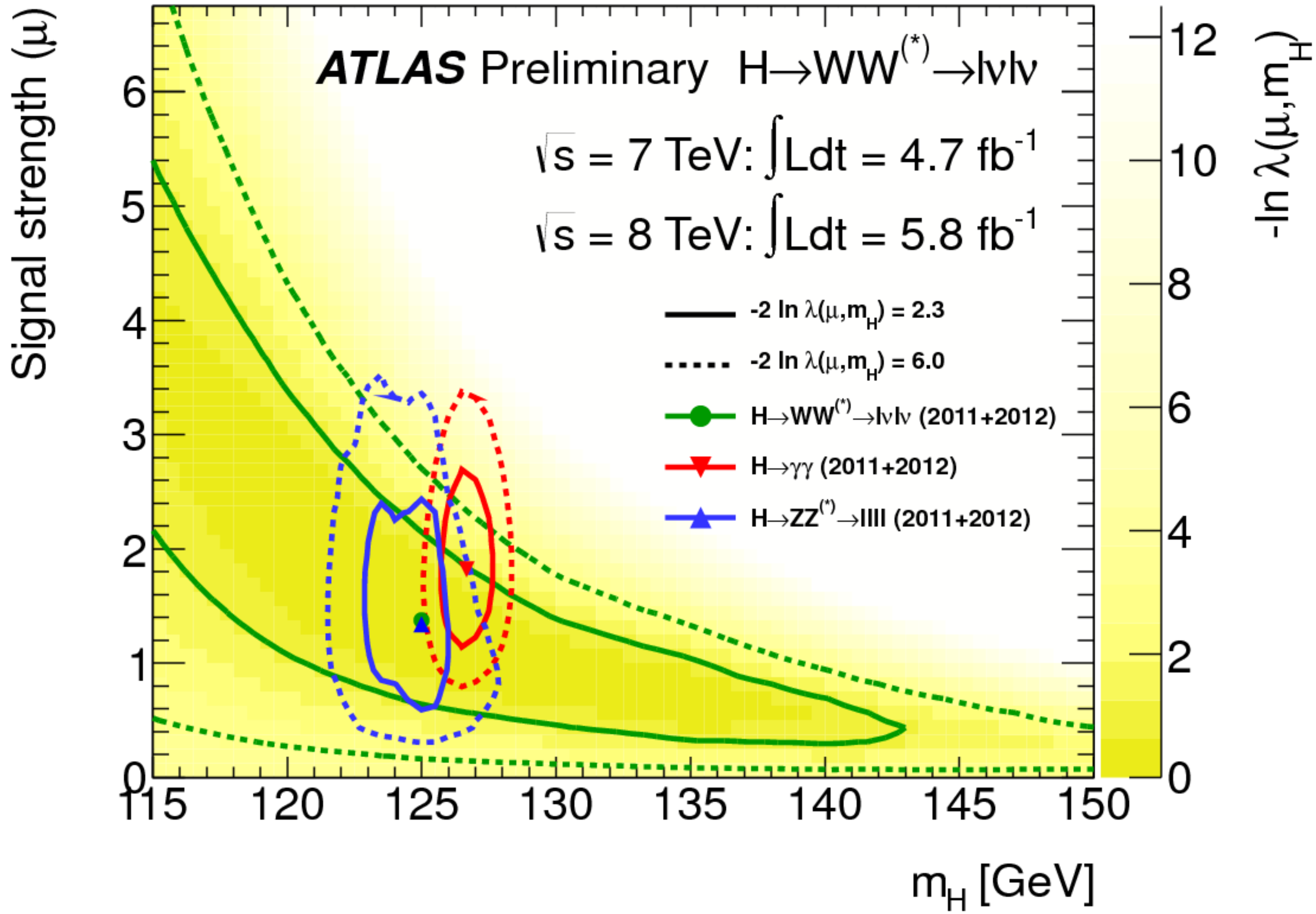
Consistent with the expectation of a SM Higgs boson





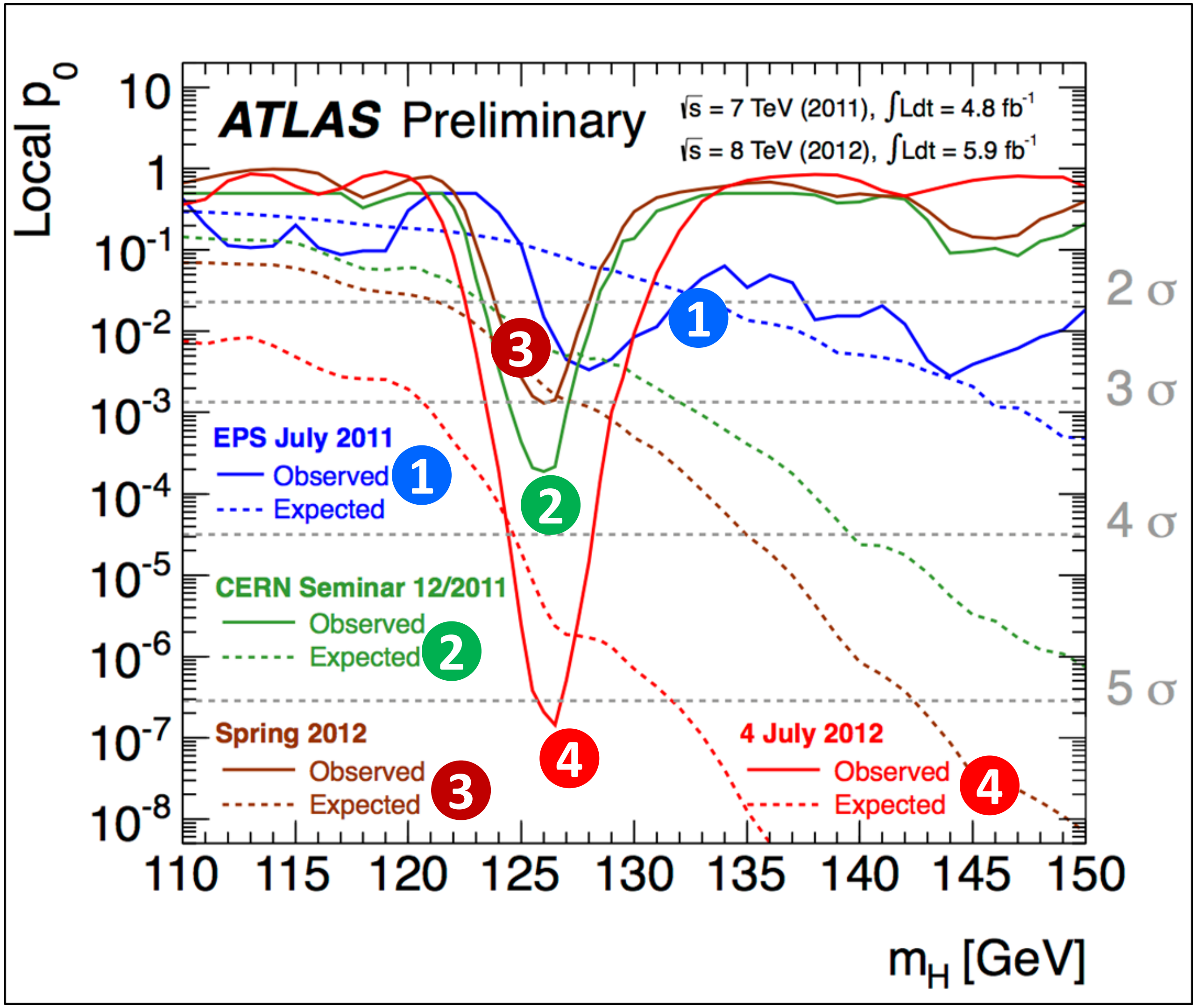
Combination

Consistency among individual channels



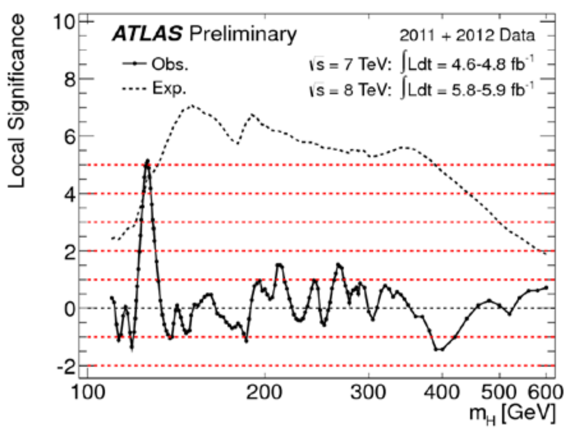
Combination

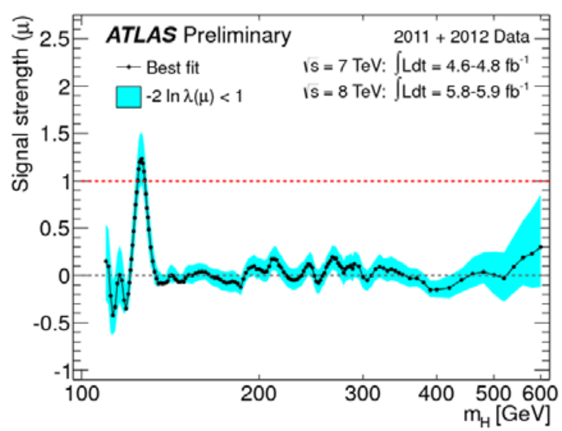
Time evolution

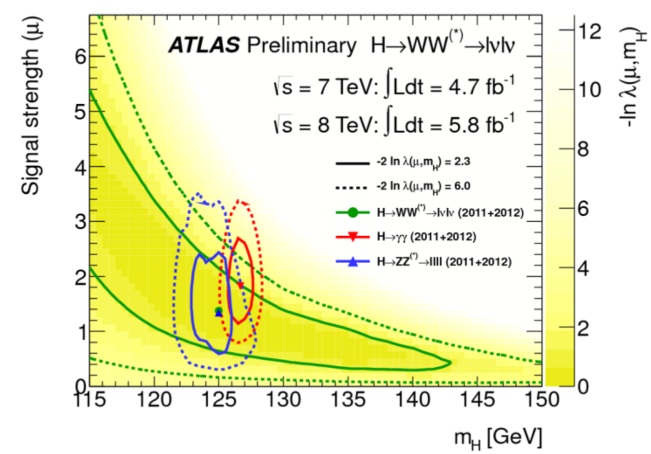


Summary

We have observed a narrow resonance at ~126 GeV, consistent with the Standard Model Higgs boson !







July 31: publication with H→γγ, H→ZZ*→4l, H→WW*→lvlv
Fall: results of H→bb and H→ττ

References

Observation of an excess of events in the search for the Standard Model Higgs boson in the gamma-gamma channel with the ATLAS detector
https://cdsweb.cern.ch/record/1460410/files/ATLAS-CONF-2012-091.pdf

Observation of an excess of events in the search for the Standard Model Higgs boson in the H→ZZ*→4l channel with the ATLAS detector
https://cdsweb.cern.ch/record/1460411/files/ATLAS-CONF-2012-092.pdf

Observation of an Excess of Events in the Search for the Standard Model Higgs boson with the ATLAS detector at the LHC
http://cdsweb.cern.ch/record/1460439/files/ATLAS-CONF-2012-093.pdf

Observation of an Excess of Events in the Search for the Standard Model Higgs Boson in the $H \to WW^{(*)} \to \ell\nu\ell\nu$ Channel with the ATLAS Detector
https://cdsweb.cern.ch/record/1462530/files/ATLAS-CONF-2012-098.pdf

Higgs Boson Width

Strong mass dependence

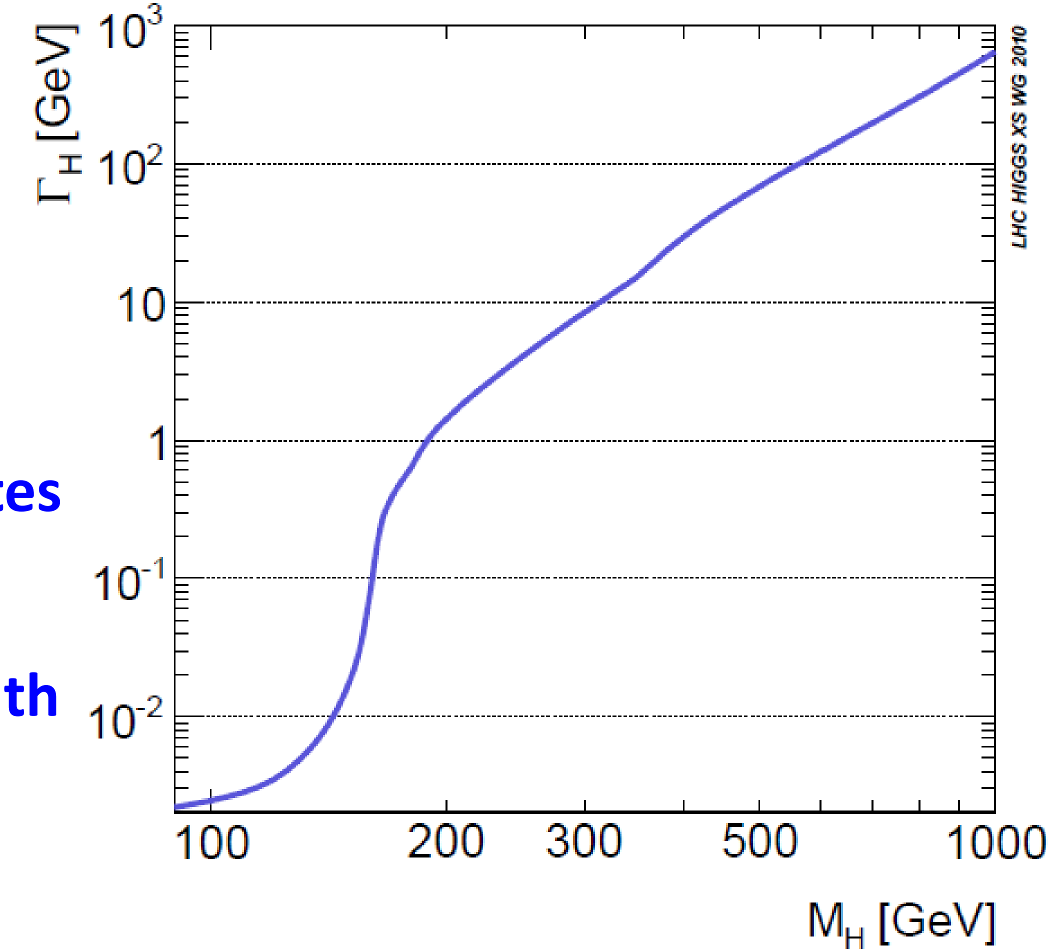
$$\Gamma_H = 3.5 \text{ MeV @ } 120 \text{ GeV}, \\ 1.43 \text{ GeV @ } 200 \text{ GeV}, \\ 8.43 \text{ GeV @ } 300 \text{ GeV}, \\ 68.0 \text{ GeV @ } 500 \text{ GeV}$$

At low mass (<300 GeV), detector resolution dominates mass resolution.

At higher mass, intrinsic width becomes dominant.

$$\Gamma_H \approx \frac{3G_F M_H^3}{16\pi\sqrt{2}}$$

$$\approx 500 \text{ GeV} \cdot \left(\frac{M_H}{1 \text{ TeV}}\right)^3$$



Statistical Methods

Construct likelihood from Poisson probabilities :

$$L\left(\text{data} \mid \mu,\theta\right)=\text{Poisson}\left(\text{data} \mid \mu\cdot s\left(\theta\right)+b\left(\theta\right)\right)\times p\left(\tilde{\theta}\mid\theta\right)$$

μ: signal strength; θ: 'nuisance' parameters (efficiencies...)

Compare data with background-only and signal+background models using test statistics

$$q_{\mu}=-2\ln\frac{L\left(\text{data} \mid \mu,\hat{\theta}_{\mu}\right)}{L\left(\text{data} \mid \hat{\mu},\hat{\theta}\right)}$$

Calculate the ratio of these two p-values

$$CL_{s}\left(\mu\right)=\frac{CL_{s+b}}{CL_{b}}=\frac{P\left(q_{\mu}>q_{\mu}^{obs} \mid s+b\right)}{P\left(q_{\mu}>q_{\mu}^{obs} \mid b\right)}$$

The signal model is excluded at 95% CL if

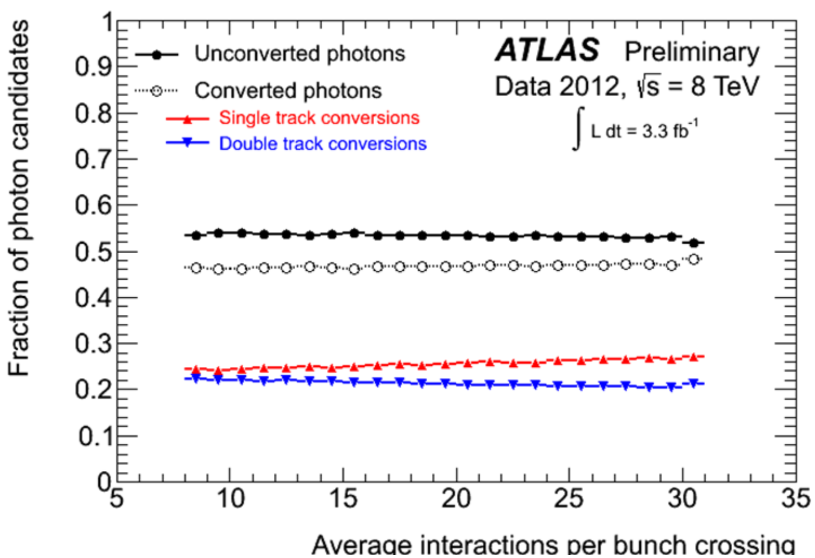
$$CL_{s}\left(\mu=1\right)<5\%$$

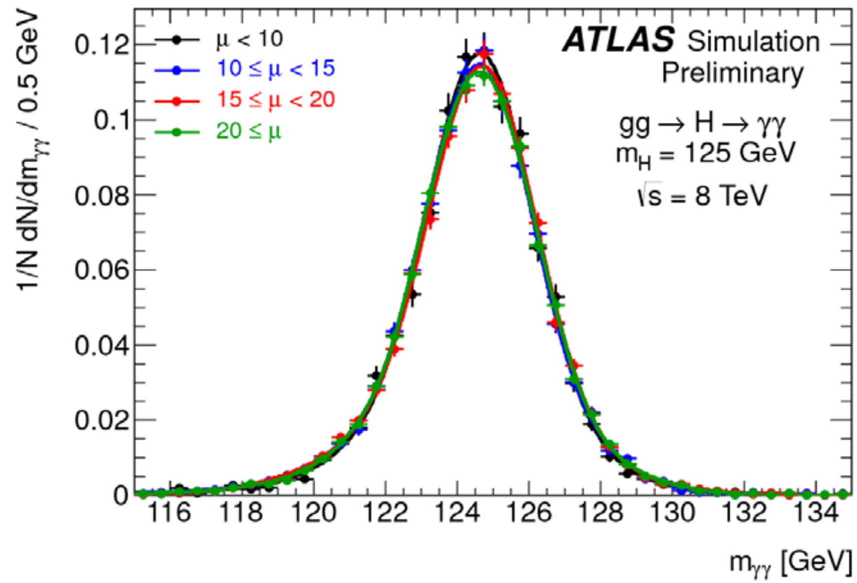
For significance calculation, the background only p-value is computed from test statistics q_0:

$$p_{0}=P\left(q_{0}>q_{0}^{obs} \mid b\right)\quad\Rightarrow\quad Z=\Phi^{-1}\left(1-p_{0}\right)$$

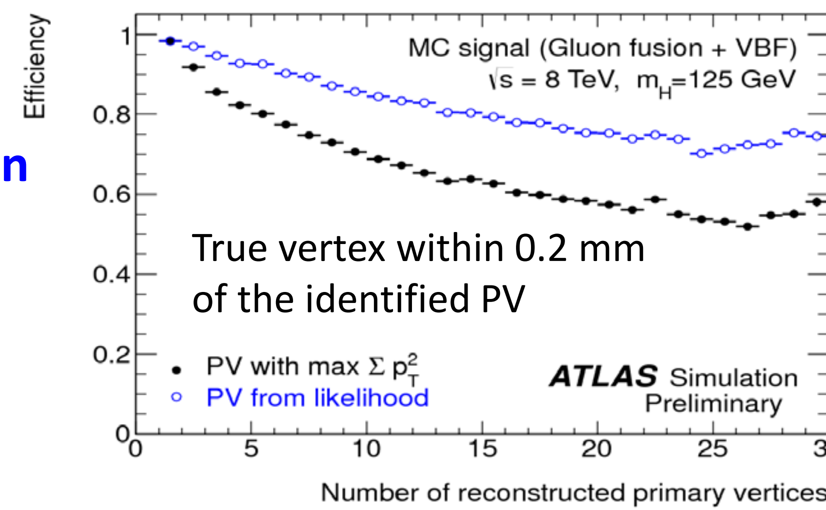
H → γγ

Photon reconstruction and γγ mass resolution are stable against pileup





Degrading primary vertex identification no effect on most of the categories, only needed for jet association of the 2jet analysis.



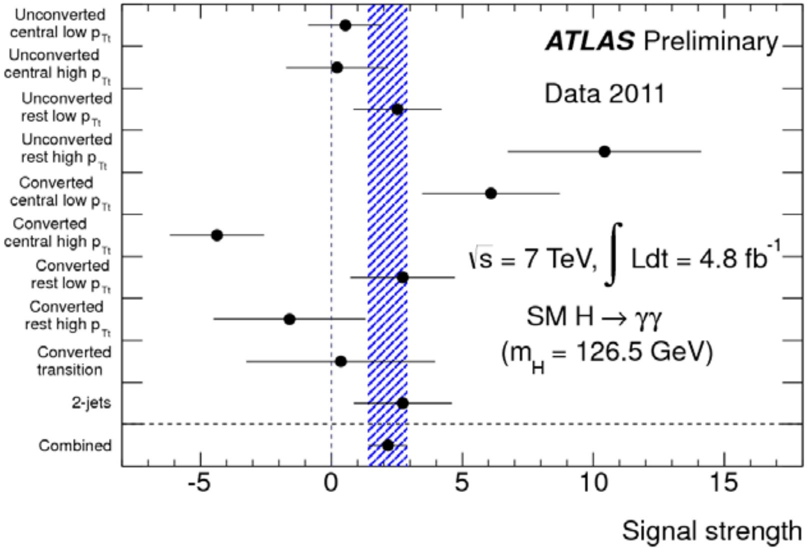
H → γγ

Numbers of expected signal and background events in a mass window around 126.5 GeV that contains 90% expected signal

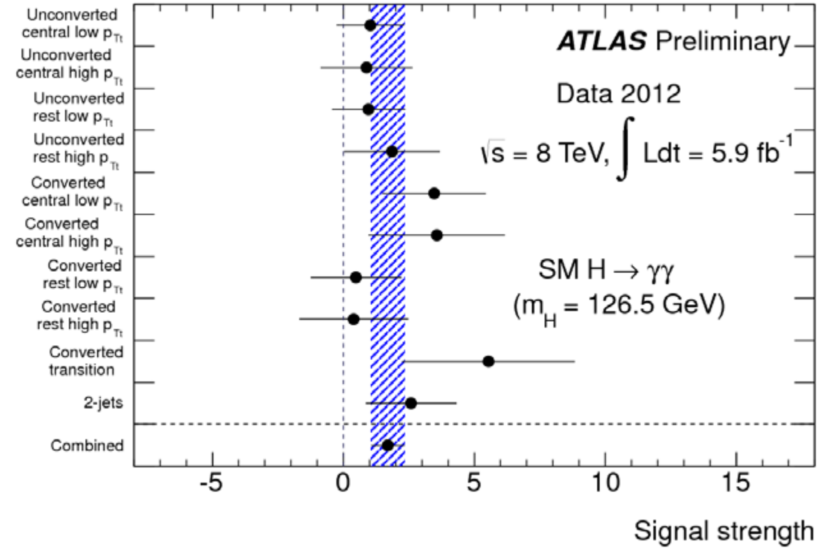
2012 analysis

	Category	σ_{CB} [GeV]	Observed [N_{evt}]	S [N_{evt}]	B [N_{evt}]	
	Inclusive	1.63	3693	100.4	3635	
	Unconverted central, low p_{Tt}	1.45	235	13.0	215	
16%	Unconverted central, high p_{Tt}	1.37	15	2.3	14	⇐ 2nd best S/B
	Unconverted rest, low p_{Tt}	1.57	1131	28.3	1133	
	Unconverted rest, high p_{Tt}	1.51	75	4.8	68	
	Converted central, low p_{Tt}	1.67	208	8.2	193	
15%	Converted central, high p_{Tt}	1.50	13	1.5	10	⇐ 3rd best S/B
	Converted rest, low p_{Tt}	1.93	1350	24.6	1346	
	Converted rest, high p_{Tt}	1.68	69	4.1	72	
	Converted transition	2.65	880	11.7	845	
22%	2-jets	1.57	18	2.6	12	⇐ Best S/B

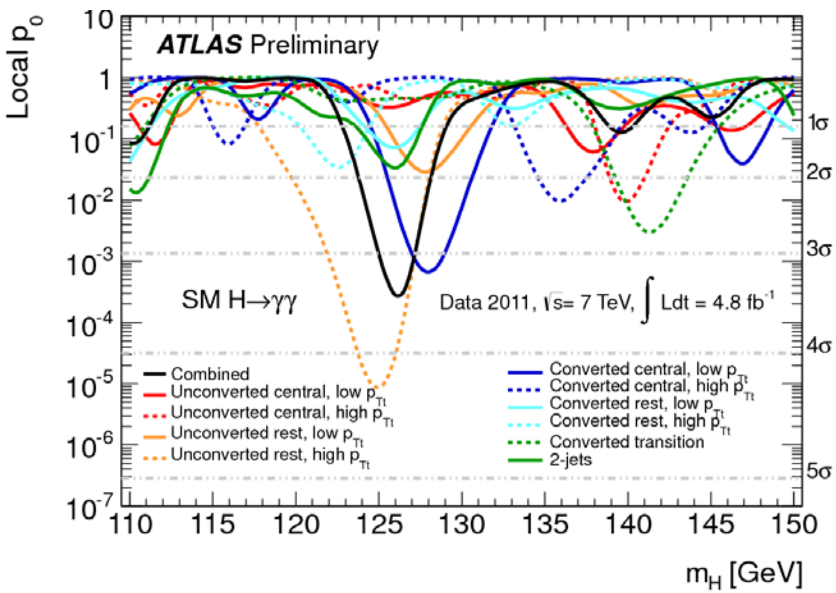
H → γγ



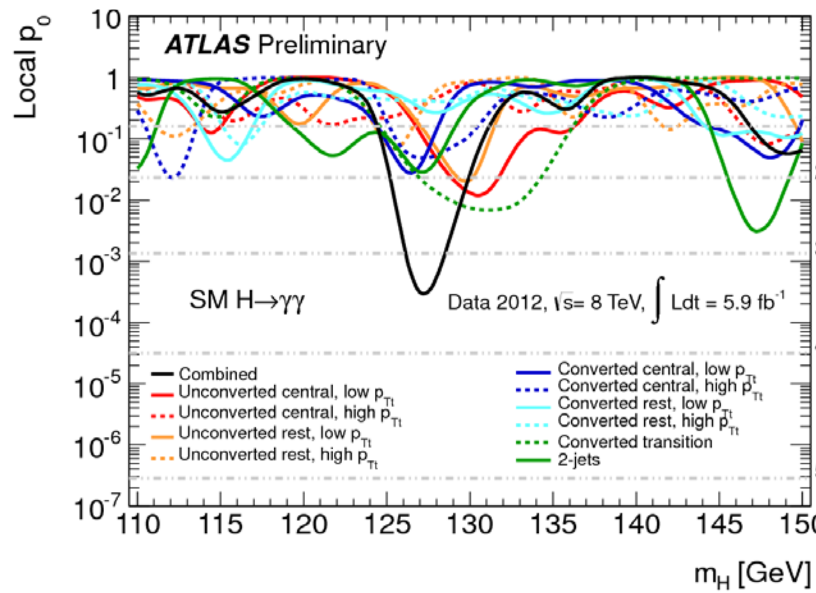
ATLAS Preliminary
Data 2011
$\sqrt{s}$ = 7 TeV, $\int$ Ldt = 4.8 fb^{-1}
SM H → γγ
(m_H = 126.5 GeV)
Unconverted central low p_{Tt}
Unconverted central high p_{Tt}
Unconverted rest low p_{Tt}
Unconverted rest high p_{Tt}
Converted central low p_{Tt}
Converted central high p_{Tt}
Converted rest low p_{Tt}
Converted rest high p_{Tt}
Converted transition
2-jets
Combined
-5
0
5
10
15
Signal strength



ATLAS Preliminary
Data 2012
$\sqrt{s}$ = 8 TeV, $\int$ Ldt = 5.9 fb^{-1}
SM H → γγ
(m_H = 126.5 GeV)
Unconverted central low p_{Tt}
Unconverted central high p_{Tt}
Unconverted rest low p_{Tt}
Unconverted rest high p_{Tt}
Converted central low p_{Tt}
Converted central high p_{Tt}
Converted rest low p_{Tt}
Converted rest high p_{Tt}
Converted transition
2-jets
Combined
-5
0
5
10
15
Signal strength



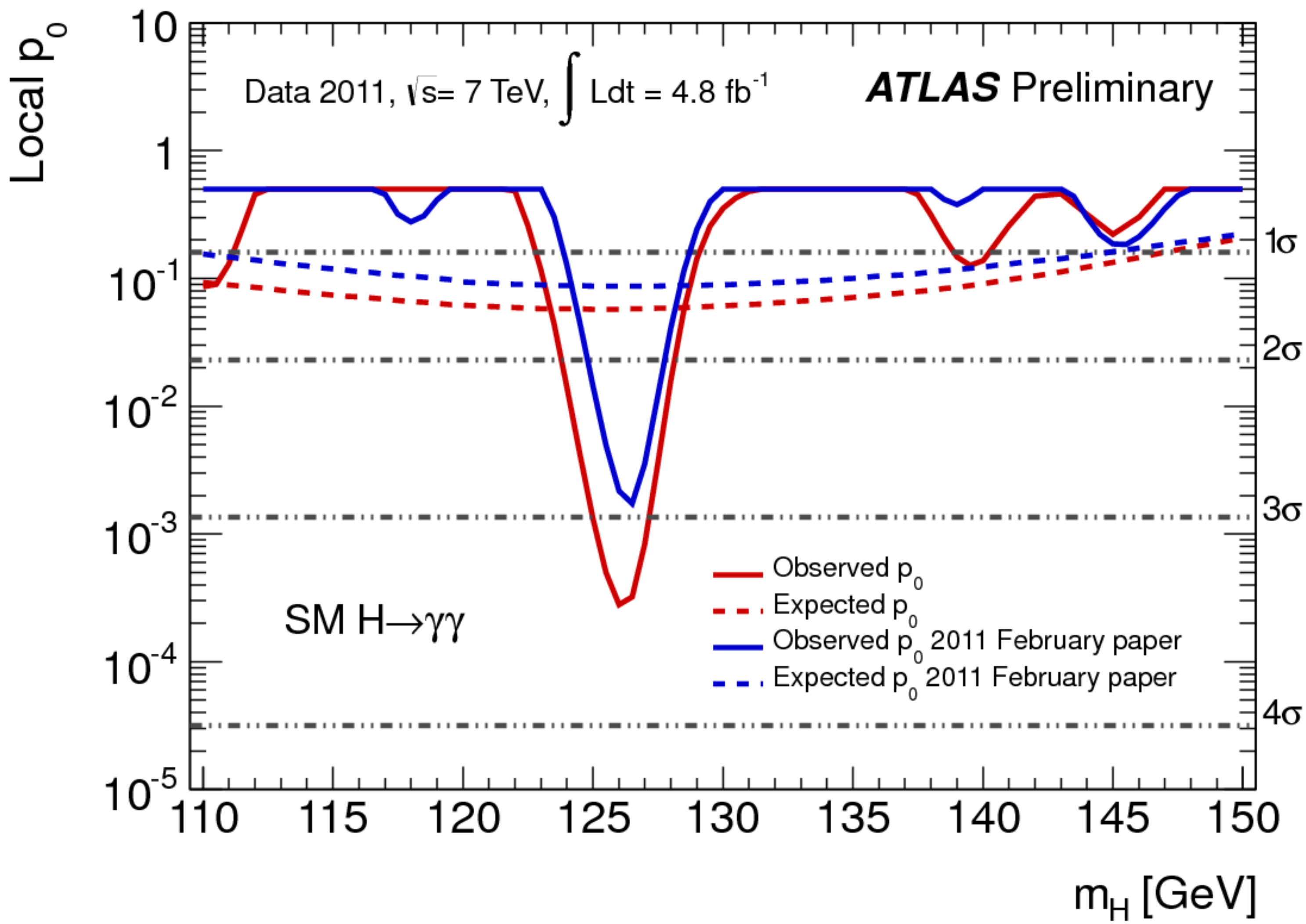
ATLAS Preliminary
Local p_0
SM H→γγ
Data 2011, $\sqrt{s}$= 7 TeV, $\int$ Ldt = 4.8 fb^{-1}
1σ
2σ
3σ
4σ
5σ
Combined
Unconverted central, low p_{Tt}
Unconverted central, high p_{Tt}
Unconverted rest, low p_{Tt}
Unconverted rest, high p_{Tt}
Converted central, low p_{Tt}
Converted central, high p_{Tt}
Converted rest, low p_{Tt}
Converted rest, high p_{Tt}
Converted transition
2-jets
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
110
115
120
125
130
135
140
145
150
m_H [GeV]



ATLAS Preliminary
Local p_0
SM H→γγ
Data 2012, $\sqrt{s}$= 8 TeV, $\int$ Ldt = 5.9 fb^{-1}
1σ
2σ
3σ
4σ
5σ
Combined
Unconverted central, low p_{Tt}
Unconverted central, high p_{Tt}
Unconverted rest, low p_{Tt}
Unconverted rest, high p_{Tt}
Converted central, low p_{Tt}
Converted central, high p_{Tt}
Converted rest, low p_{Tt}
Converted rest, high p_{Tt}
Converted transition
2-jets
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
110
115
120
125
130
135
140
145
150
m_H [GeV]

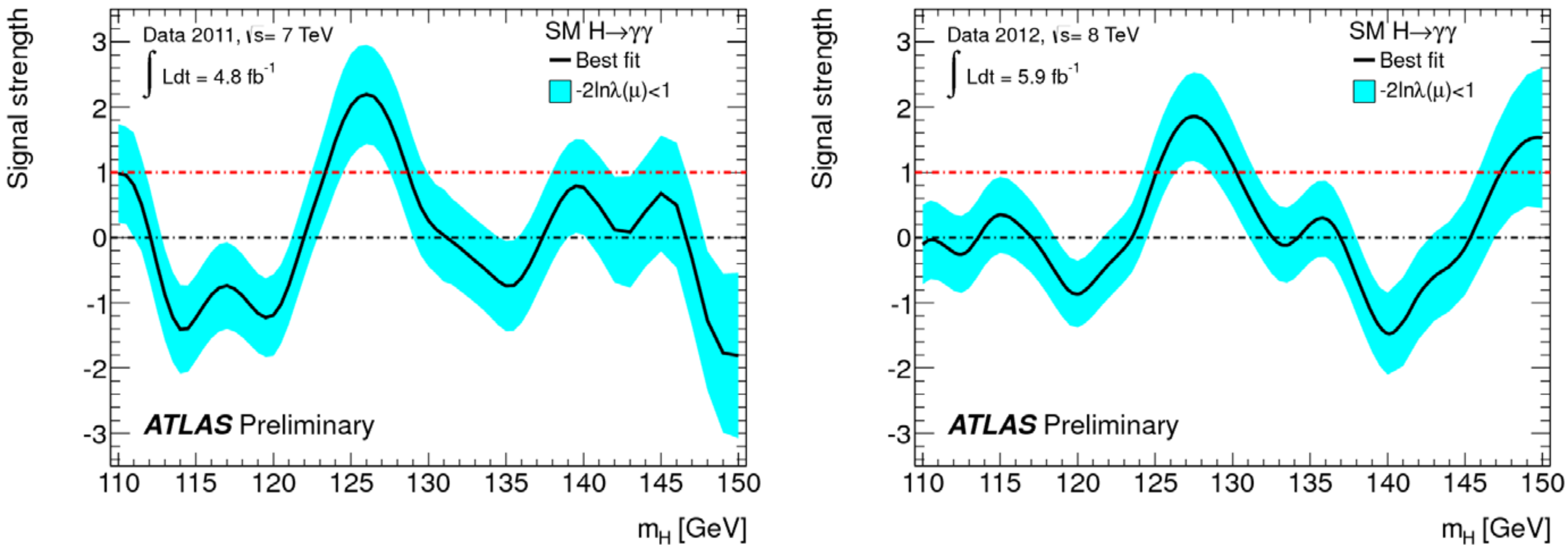
$H \rightarrow \gamma\gamma$

Reanalysis of 2011 data



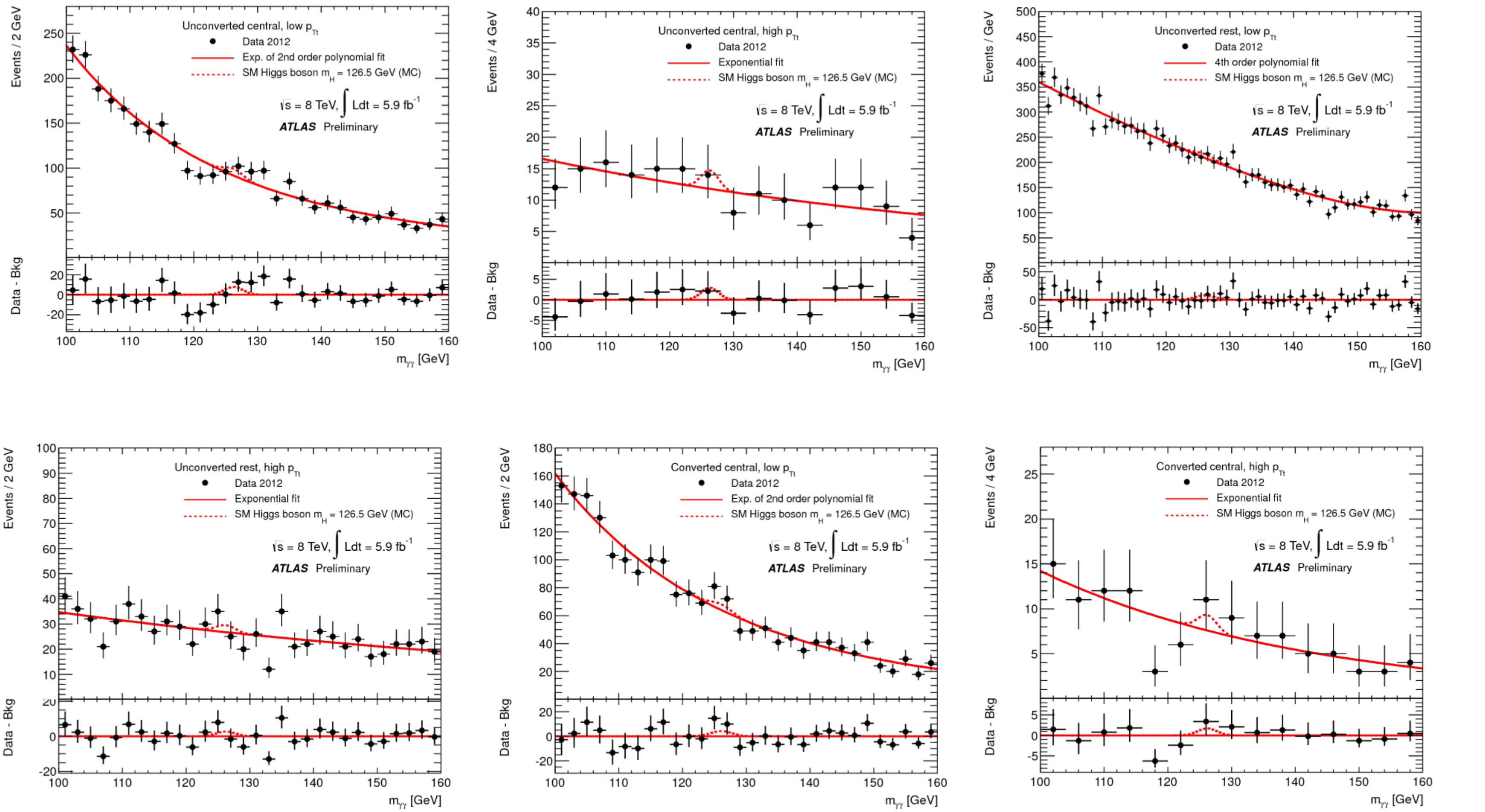
$H \rightarrow \gamma\gamma$

Samples	Mass (GeV)	p-value	Observed sig.	Expected sig.
2011	126	3×10^{-4}	3.5σ	1.6σ
2012	127	3×10^{-4}	3.4σ	1.9σ
Combined	126.5	2×10^{-6}	4.5σ	2.4σ



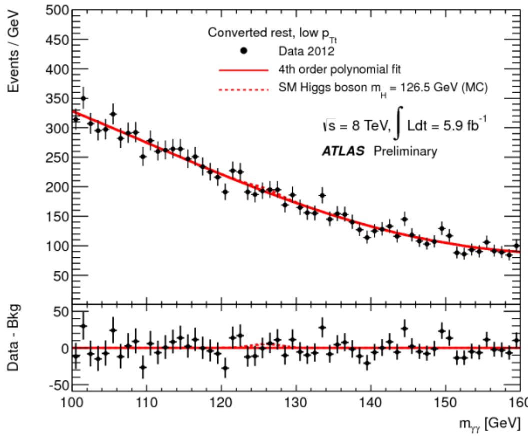
H → γγ

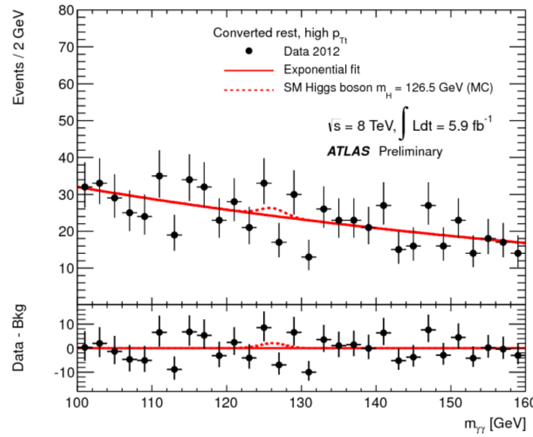
2012 individual categories

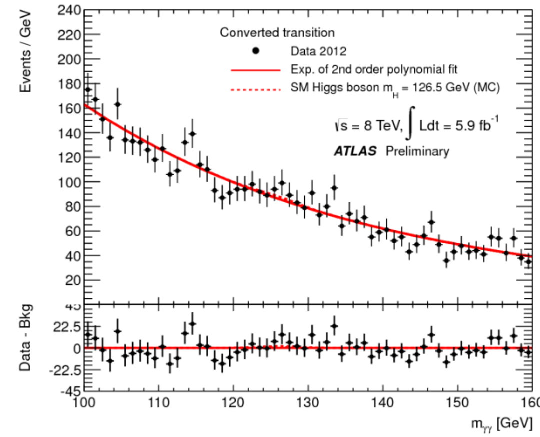


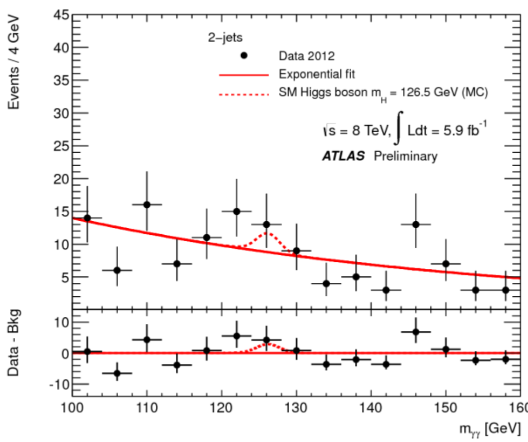
H → γγ

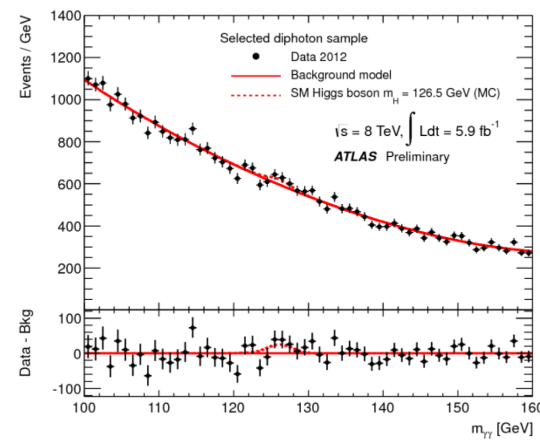
2012 individual categories







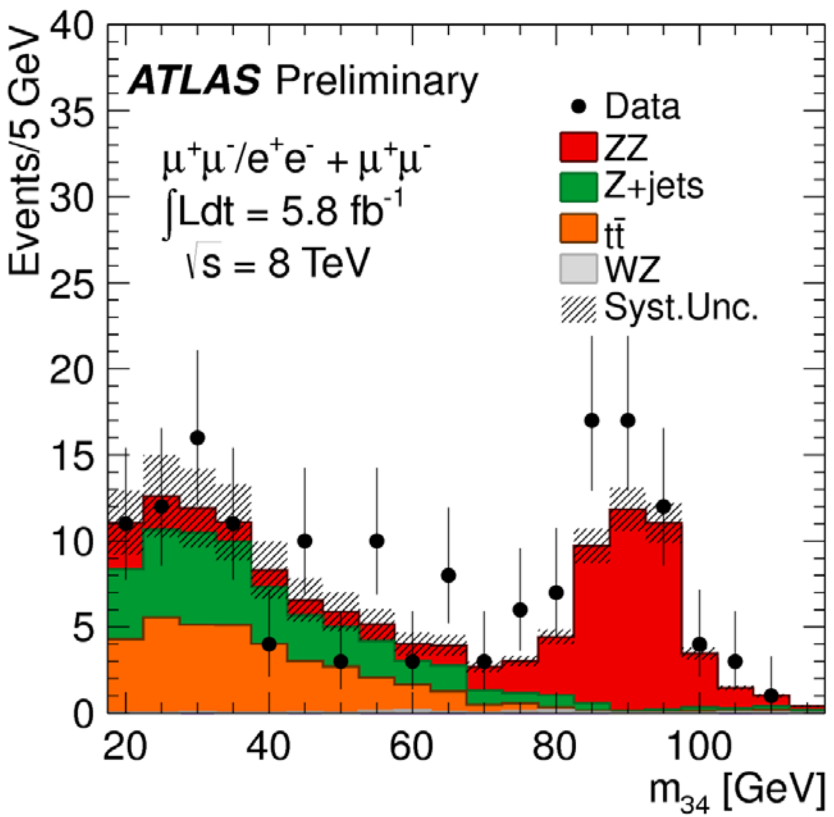


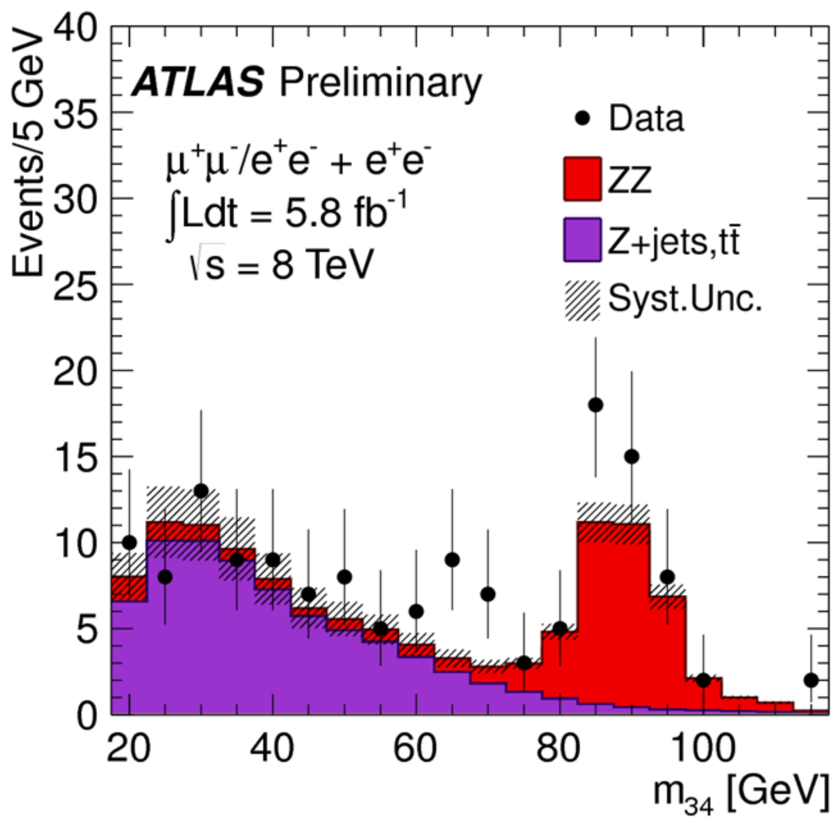


H→ZZ*→4l

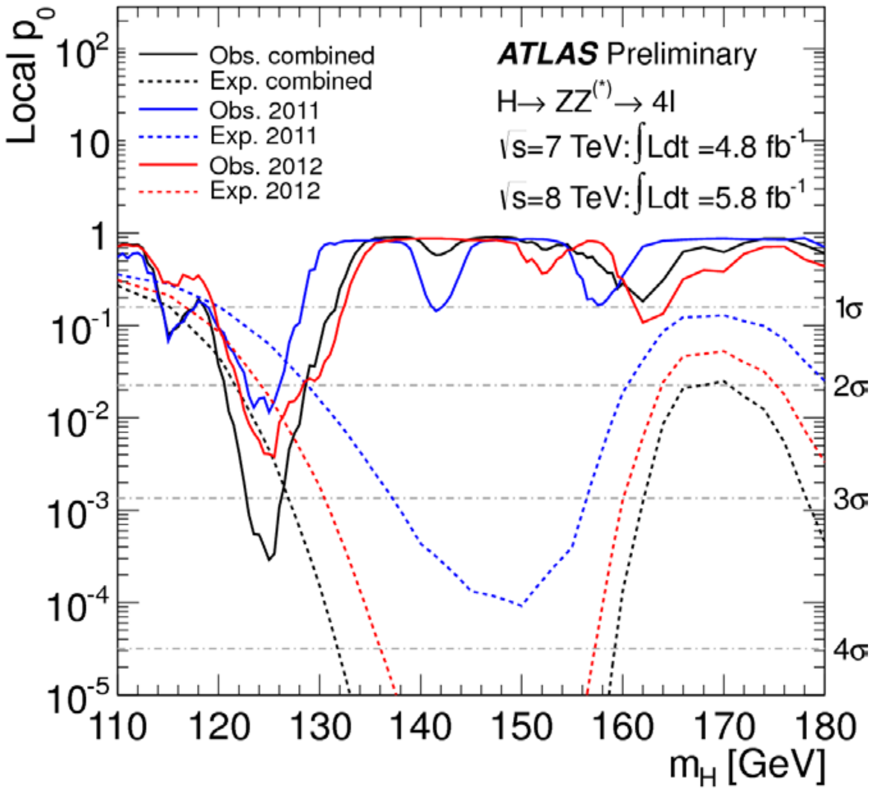
Same requirements as the nominal selection except no isolation requirement on the subleading lepton pair

- ⇒ **Let in a lot more Z+jets and top backgrounds;**
- ⇒ **Data overshoot the expectation in ZZ dominated phase space**



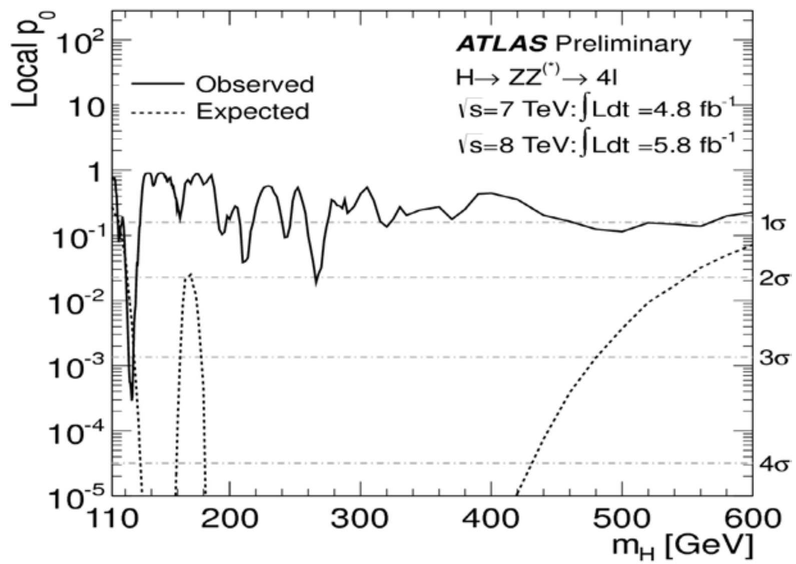


H→ZZ*→4l



Excess is seen in both 2011 and 2012 at about the same mass.

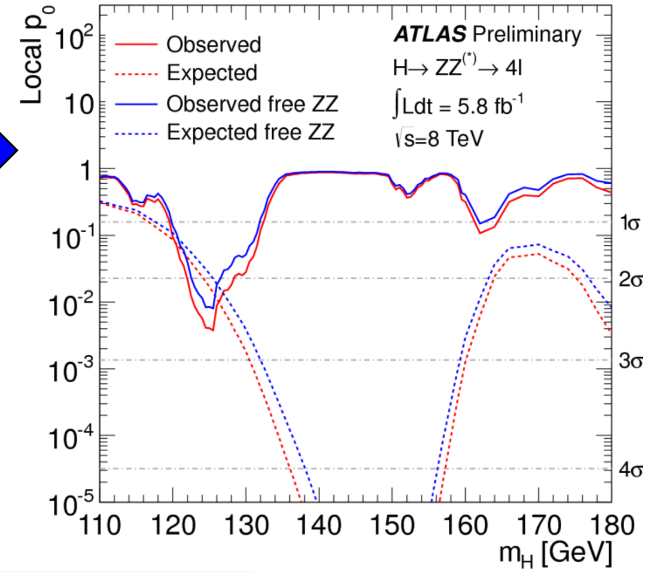
It is the most significant excess over the entire search range.



Samples	Mass (GeV)	p-value	Observed sig.	Expected sig.
2011	125	1.10%	2.3σ	1.5σ
2012	125.5	0.40%	2.7σ	2.1σ
Combined	125	0.03%	3.4σ	2.6σ

H→ZZ*→4l

Floating ZZ normalization reduces the significance slightly



4μ contributes the most to the excess