Observation of Higgs Candidates around 114 GeV/c^2 at LEP's Highest Energies

Sau Lan Wu

University of Wisconsin - Madison

SLAC Departmental Colloquium
October 2, 2000
Palo Alto, California

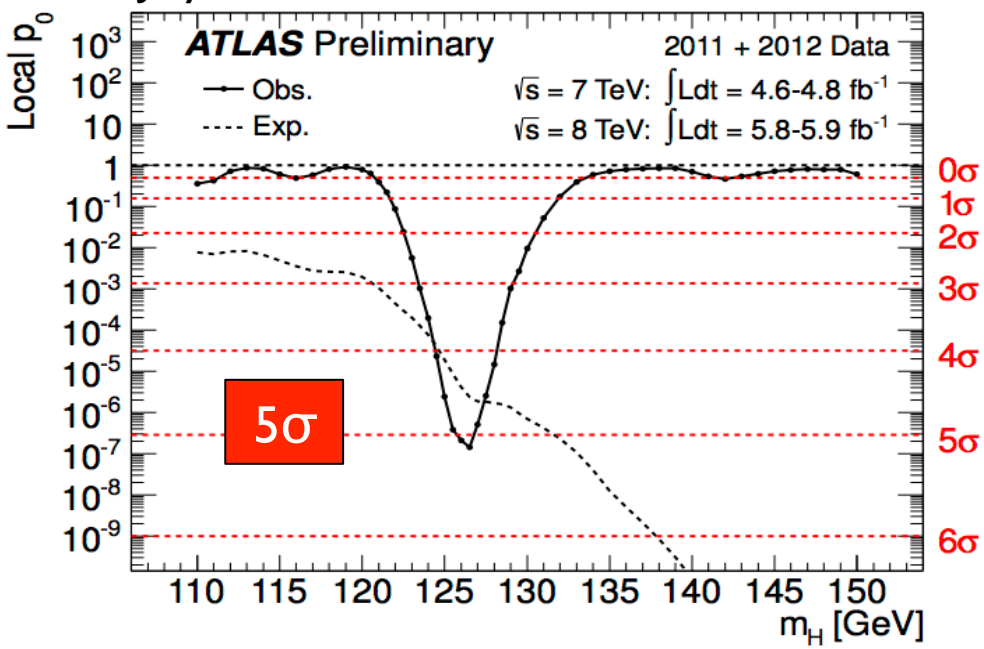
Oops!

- ***I am 12 years behind.***

- ***The Higgs has grown from 114 GeV to 126 GeV by gaining 1 GeV per year.***

Discovery of a narrow resonance around 126 GeV in the search for the Higgs Boson with ATLAS

July 4, 2012



Sau Lan Wu

University of Wisconsin-Madison

July 25, 2012

On behalf of ATLAS Collaboration

SLAC Summer Institute 2012

July 23-August 3, 2012

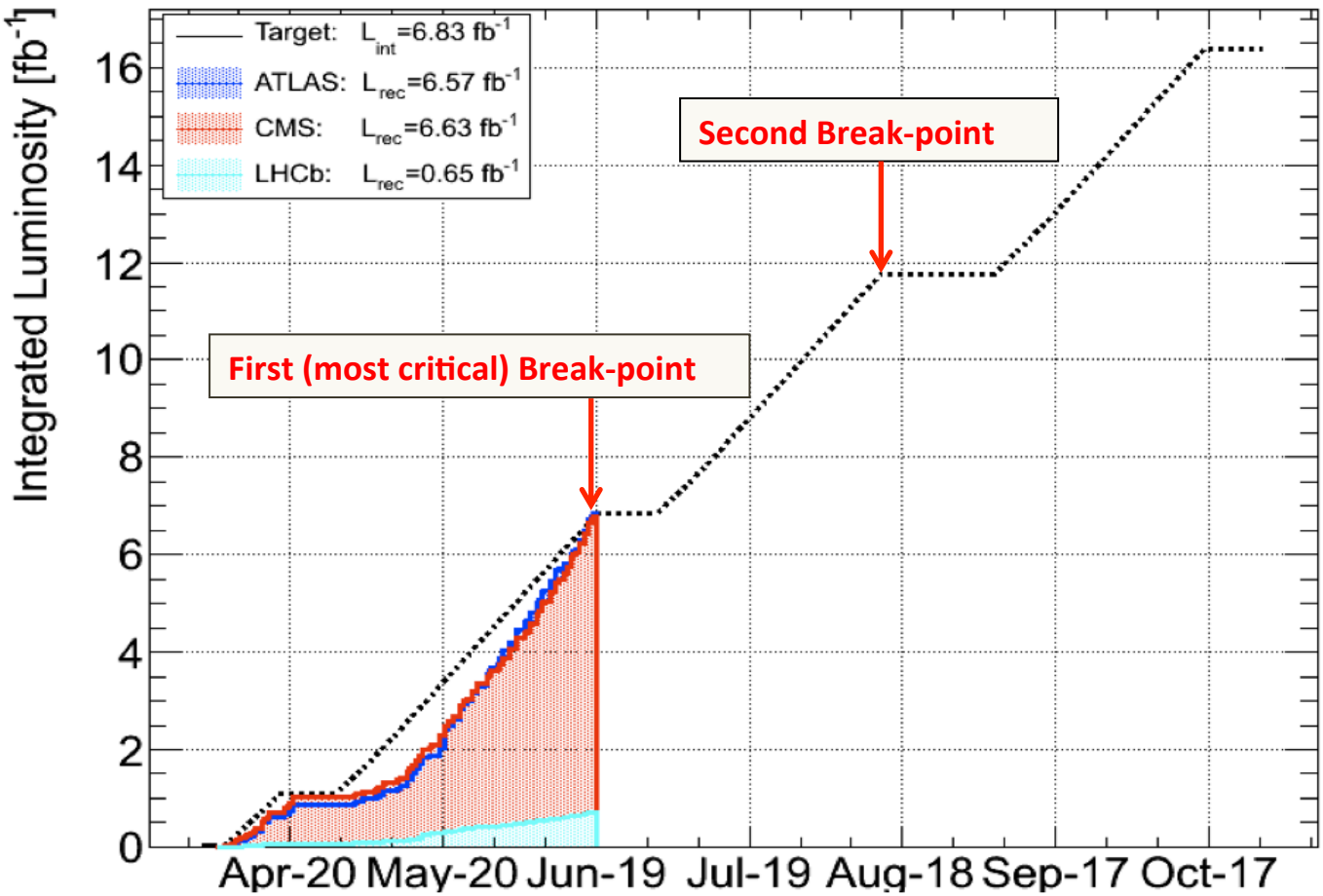
SLAC National Accelerator Laboratory

Menlo Park, California

Outline

- Introduction
- Status before July 4, 2012
- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^{(*)} \rightarrow 4$ leptons
- Higgs Combination (5σ!)
- Post July 4: $H \rightarrow WW^* \rightarrow e\mu\nu\nu$ *New*
- Conclusion and plan
- Excitement has just begun!

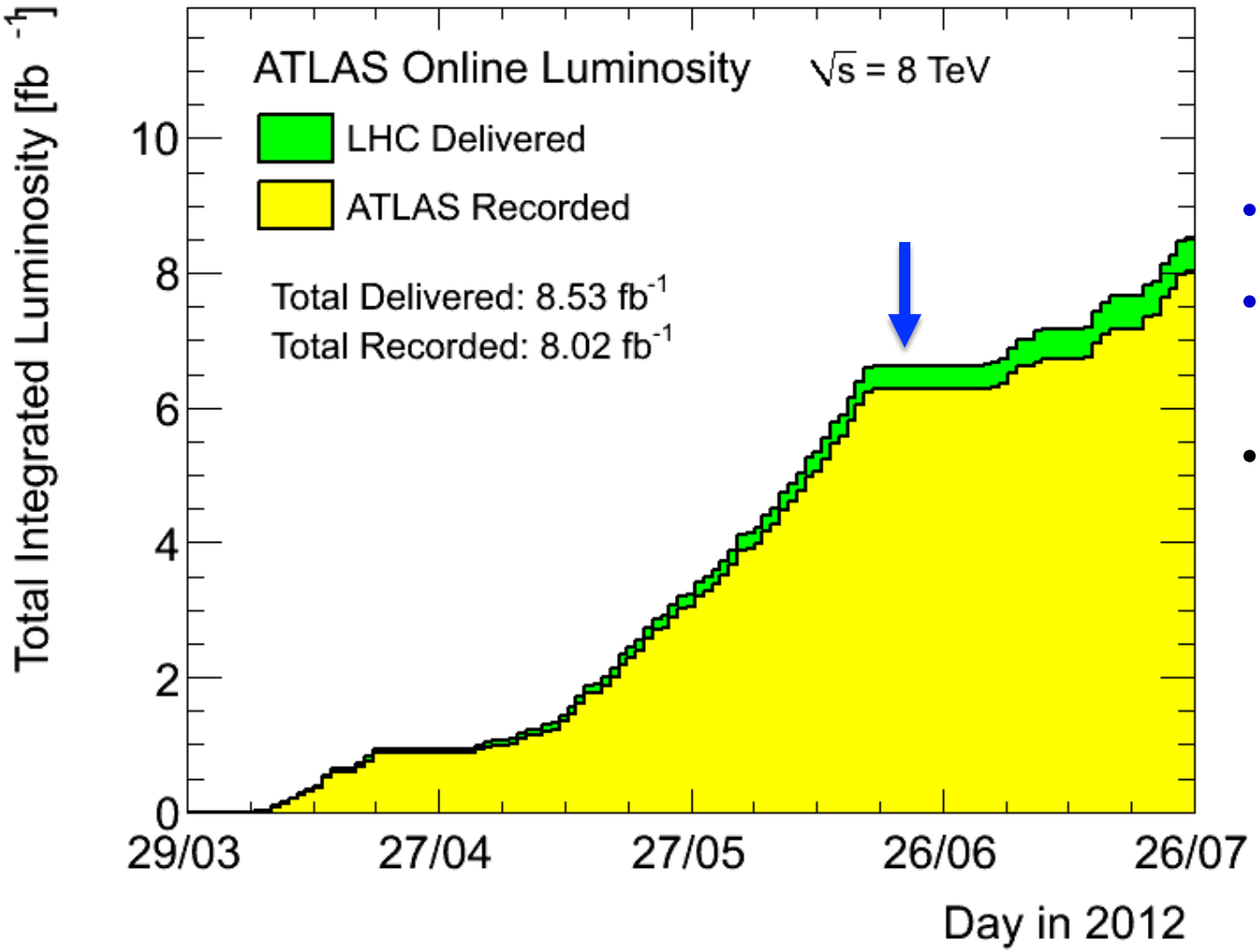
The center of mass energy of LHC was increased in 2012 from 7 to 8 TeV. The performance of this accelerator has been excellent.



Peak luminosity in 2012:
~ 6.8 x10^{33} cm^{-2} s^{-1}

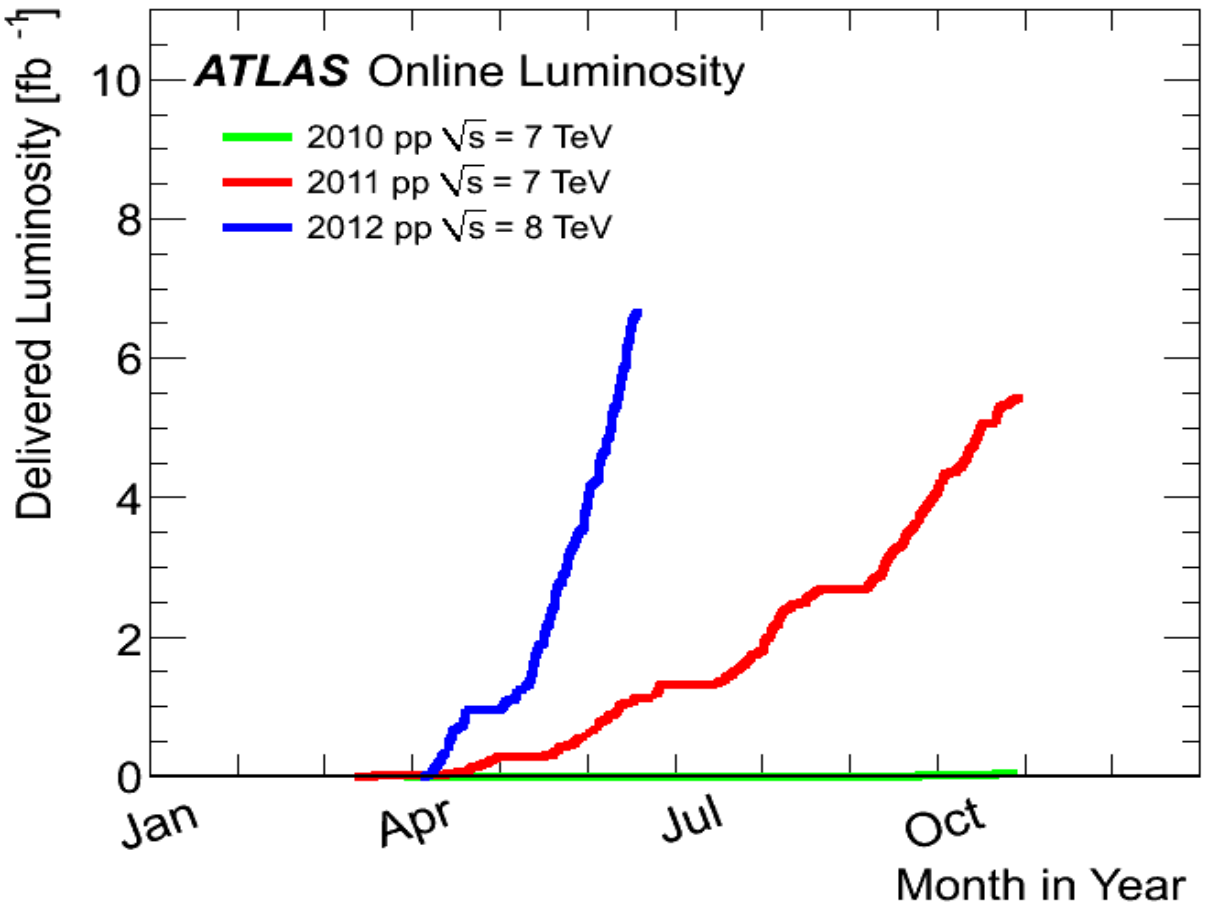
Design luminosity:
~ 10^{34} cm^{-2} s^{-1}
(14 TeV)

2012 ATLAS Data taking up to June 19, 2012 LHC Technical Stop



- ***6.63 fb^{-1} delivered***
- ***6.28 fb^{-1} recorded (efficiency 94.7%)***
- ***5.86 fb^{-1} after data quality requirements (available for physics analysis; efficiency 93.3%)***

Luminosity delivered to ATLAS



2010	*0.05 fb^{-1} (7 TeV)*
2011	*5.6 fb^{-1} (7 TeV)*
2012	*6.6 fb^{-1} (8 TeV)*

(Up to June 19, 2012)

- ***LHC plans to run p-p collisions until Dec. 17, 2012 before a two year shut down.***
- ***Expected in total ~25 fb^{-1} at 8 TeV in 2012***

Bunch spacing : 50 ns

ATLAS Higgs analysis strategy for July 4, 2012 (CERN Seminar)

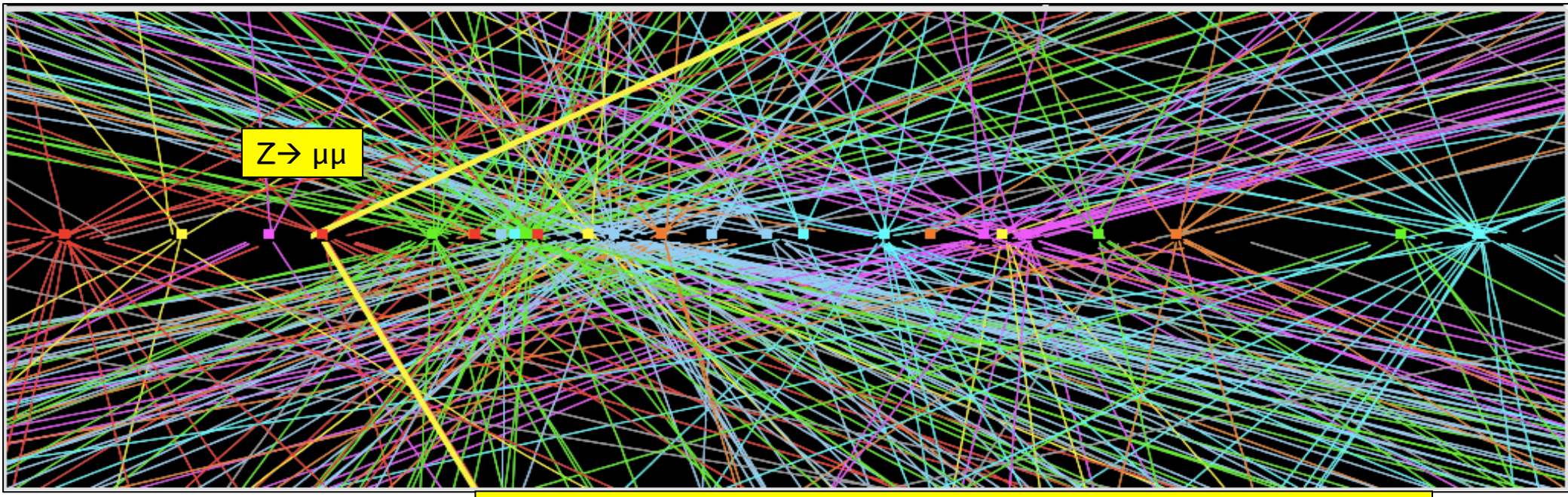
- **Concentrate on the two channels with the best mass resolution**
  - $H \to \gamma\gamma$, $H \to ZZ^{(*)} \to 4$ leptons

  with the full data set of 4.8 fb^{-1} at 7 TeV (2011), and 5.8 fb^{-1} at 8 TeV (2012).

- **Combined with published results of 2011 data for**
  - $H \to WW^{(*)}$ (Higgs combination update with 5.8 fb^{-1} of 2012 data soon to be official)
  - $H \to \tau\tau$ (update ~September 2012)
  - $H \to bb$ (update ~September 2012)

- **There will be a publication at the end of July 2012, at the same time as CMS and in the same journal.**

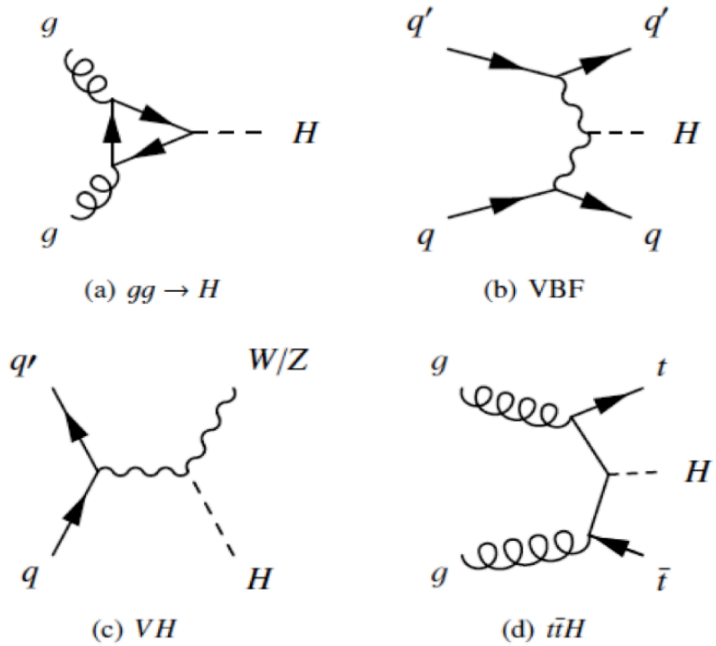
Pile-up

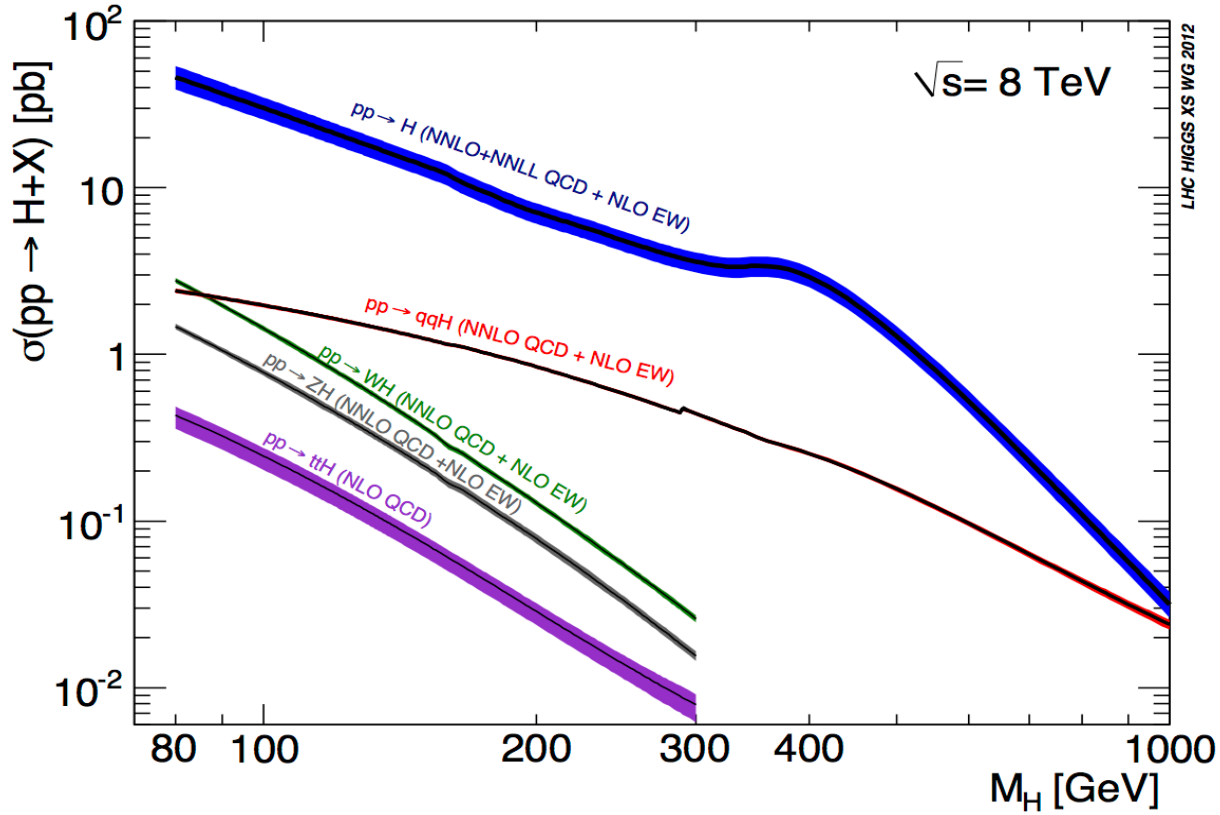


Z→ μμ event from 2012 data with 25 reconstructed vertices

- ***Pile-up robust algorithms developed (for both trigger and offline analyses)***
- ***Reconstruction and identification of physics objects (e, γ, μ, τ, jet, E_T^{miss}) optimized to be robust against pile-up.***

Standard Model Higgs production cross-section



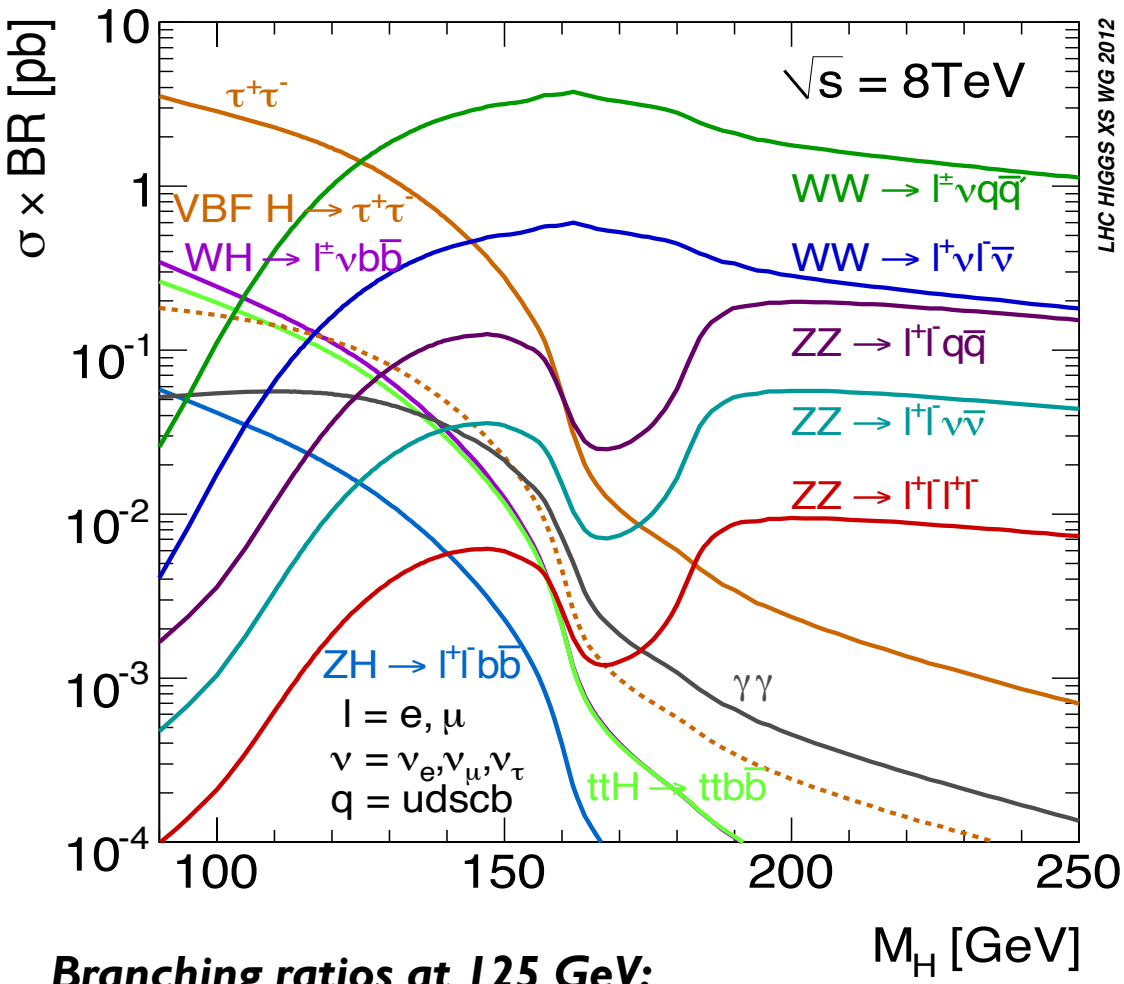


Cross sections increase from √s=7 to √s=8 TeV:

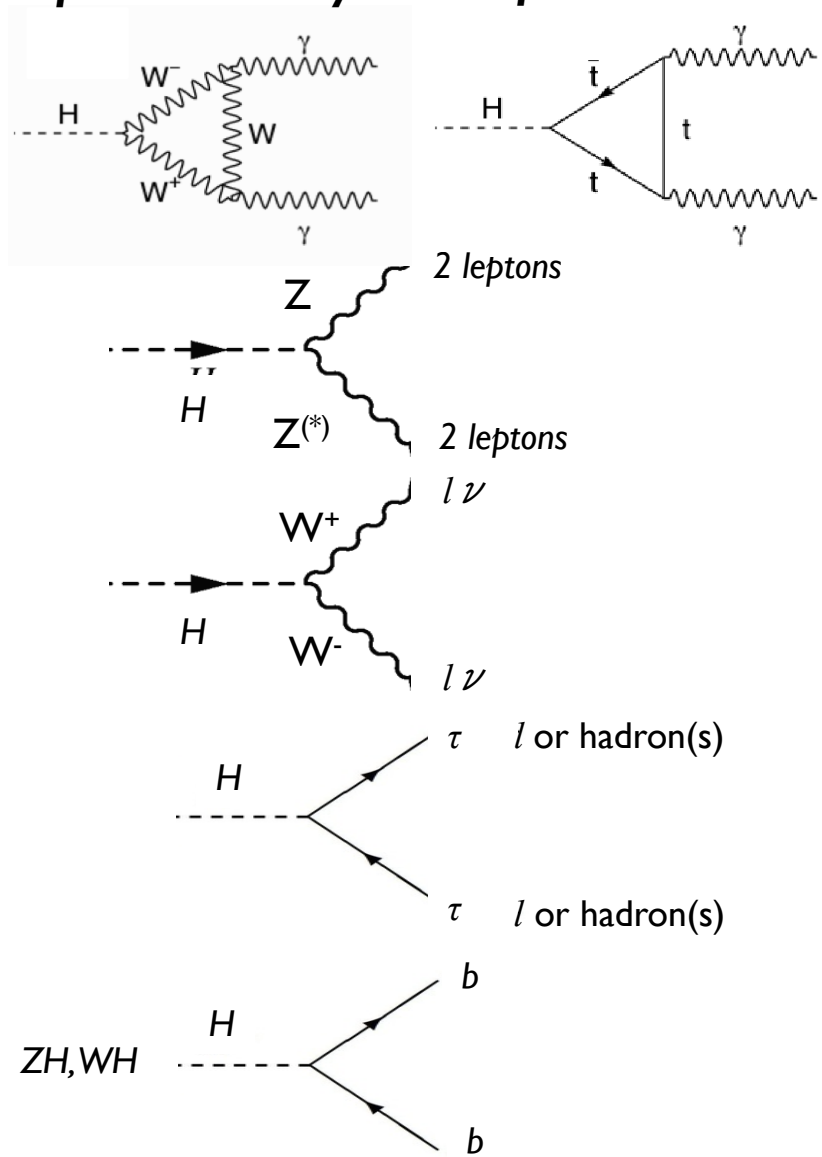
- ***Higgs (at m_H ~ 125 GeV) : 30%***
- ***Several irreducible backgrounds: 20-25% (γγ, di-bosons)***
- ***Reducible backgrounds : 30-40% (tt, Zbb)***

Overall effect on Higgs search sensitivity : 10 to 15%

Standard Model Higgs decay modes



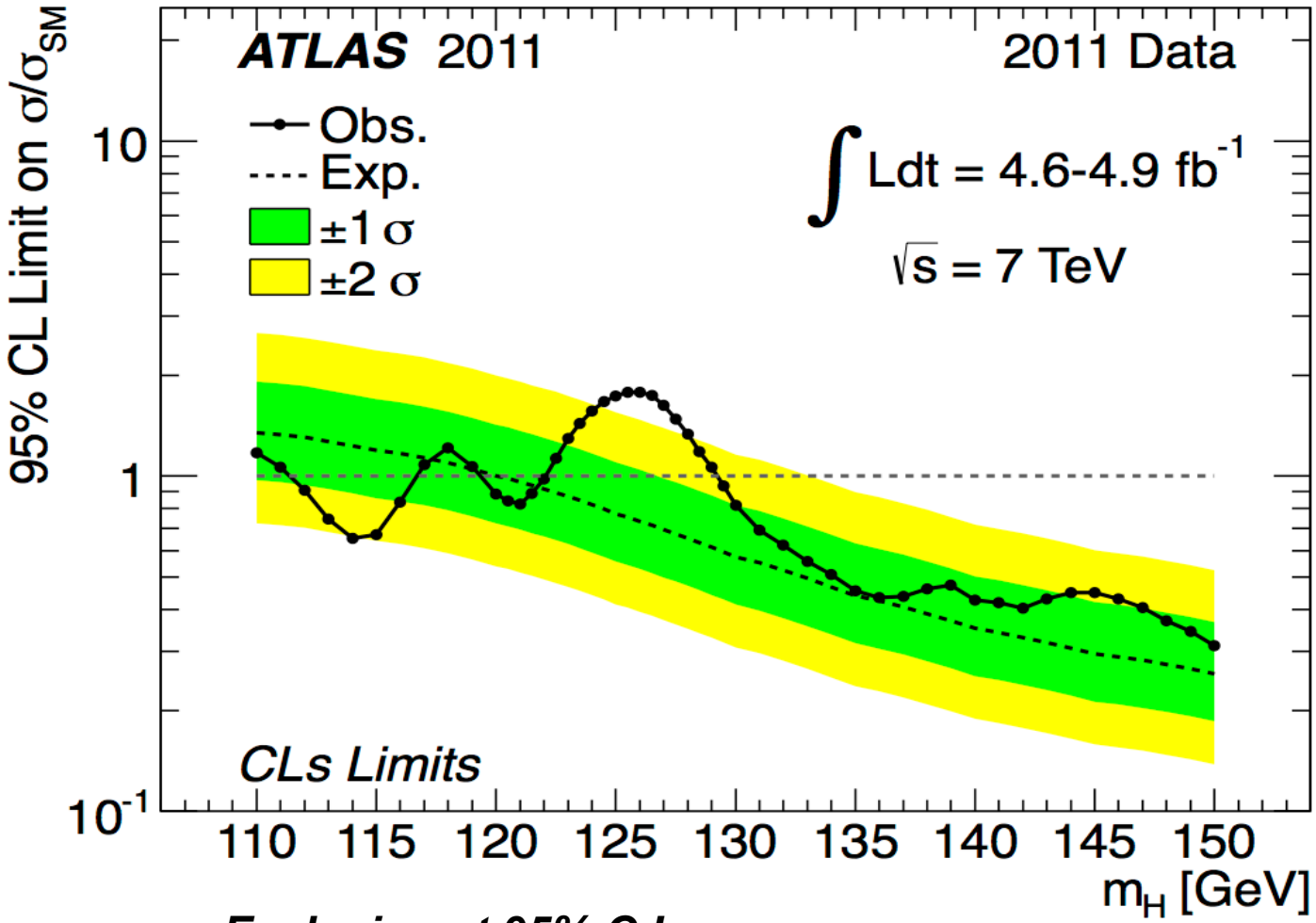
Important decay modes for 125 GeV



Branching ratios at 125 GeV:

bb:	**57.7%**	**ZZ:**	**2.6%**
WW:	**21.5%**	**γγ:**	**0.23%**
ττ:	**6.3%**		

Higgs Status before July 4th, 2012 (Submitted for publication)



Combination of 12 channels:

$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

$H \rightarrow ZZ^{(*)} \rightarrow llqq$

$H \rightarrow ZZ^{(*)} \rightarrow llvv$

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

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

$H \rightarrow \tau\tau$ *(3 final states)*

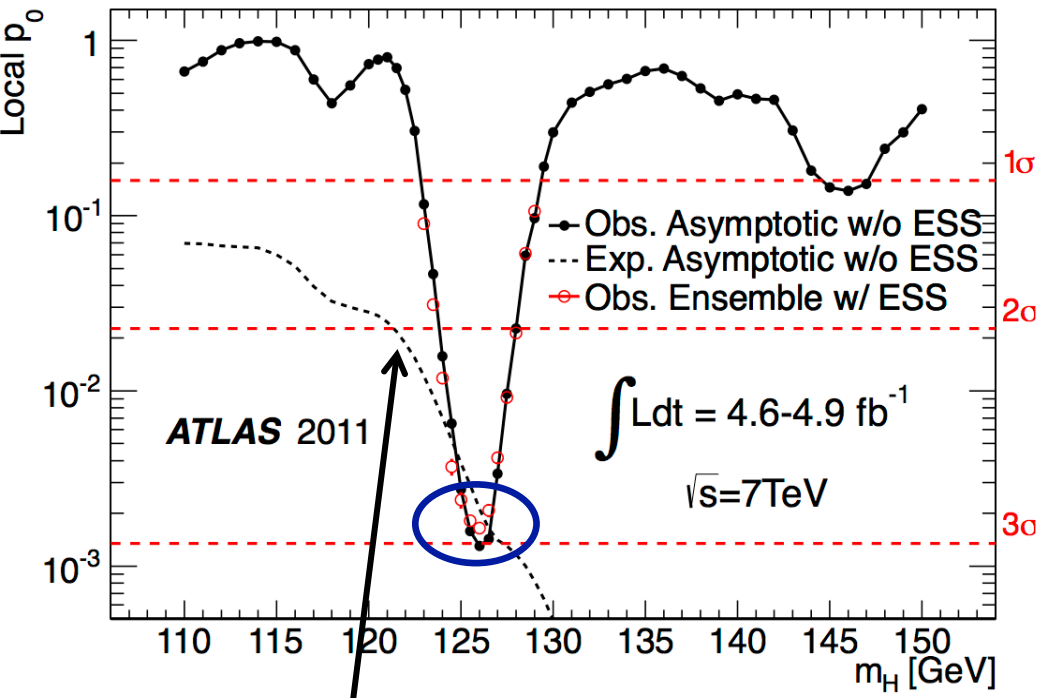
$W/ZH \rightarrow W/Z\ bb$ *(3 final states)*

Exclusion at 95% C.L. :

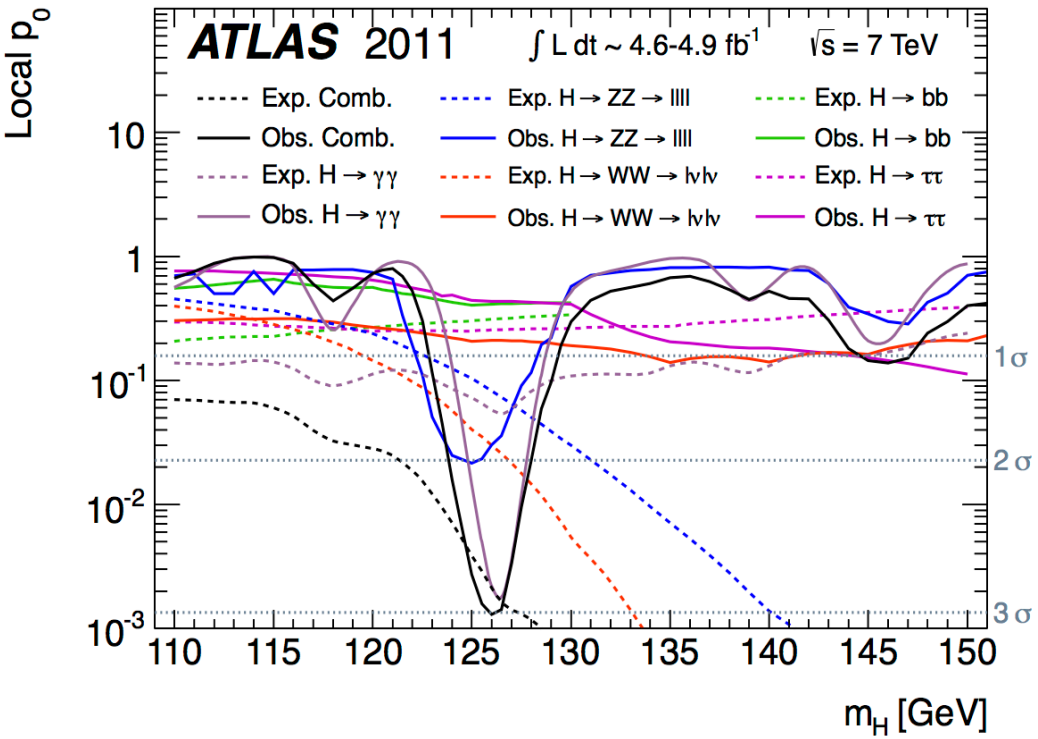
- ***Expected*** $120 < m_H < 560$ GeV
- ***Observed*** $111.4 < m_H < 122.1$ GeV (except 116.6-119.4)
  $129.2 < m_H < 541$ GeV

Higgs Status before July 4th, 2012 (Submitted for publication)

p_0 : probability that the background fluctuates to the observed data (or higher)



Expected from SM Higgs at given m_H

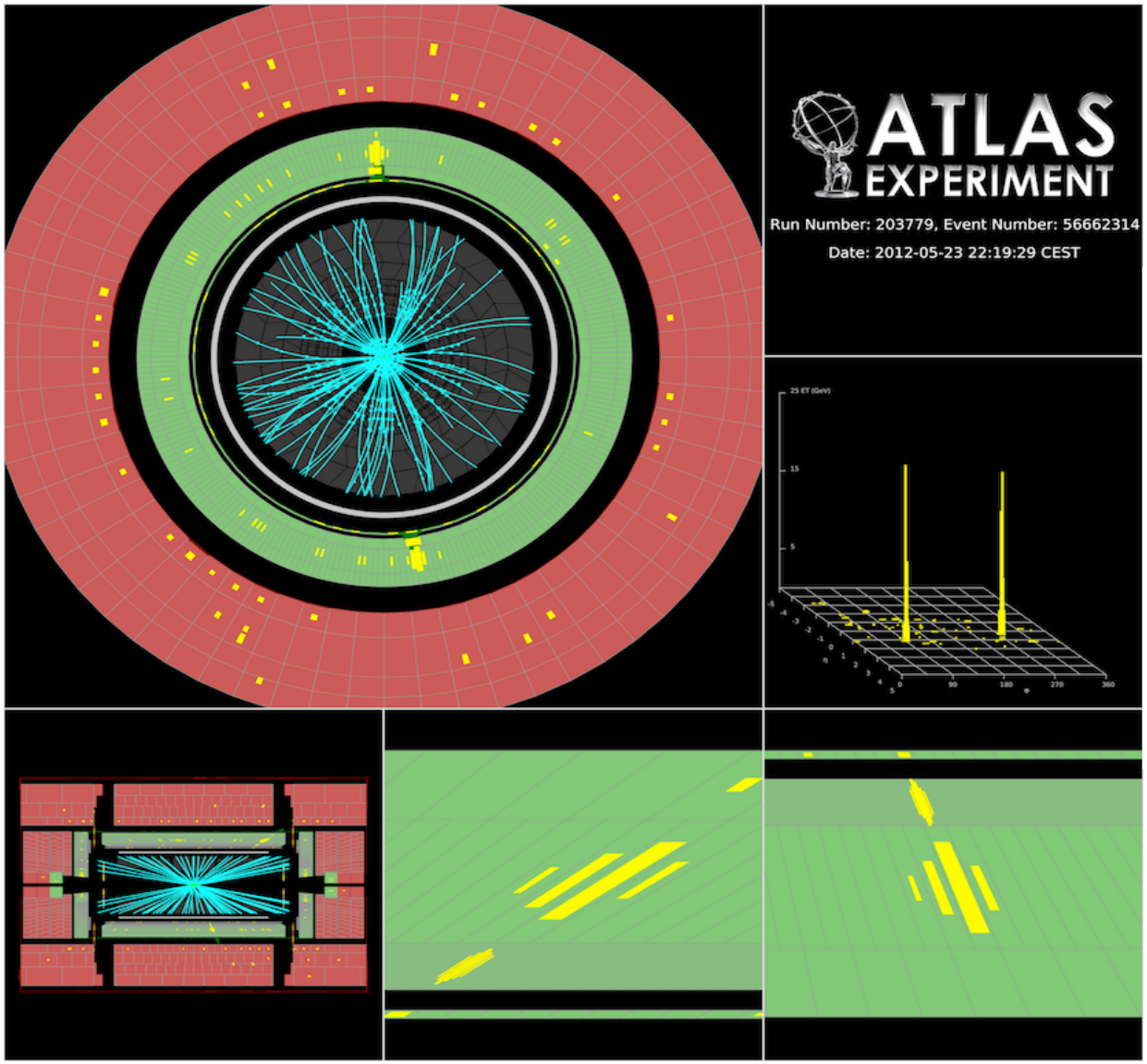


Max local significance	Observed	Expected
H→ γγ	2.8 σ	1.4 σ
H→ $ZZ^{(*)}$→4l	2.1 σ	1.4 σ
H→ $WW^{(*)}$→lνlν	0.8 σ	1.6 σ
Total	**2.9 σ**	**2.9 σ**

2.9σ excess observed for m_H ~126 GeV

Probability to occur anywhere over 110-600 (110-146 GeV): 15% (6%) ***(Look-Elsewhere Effect)***

$H \rightarrow \gamma\gamma$

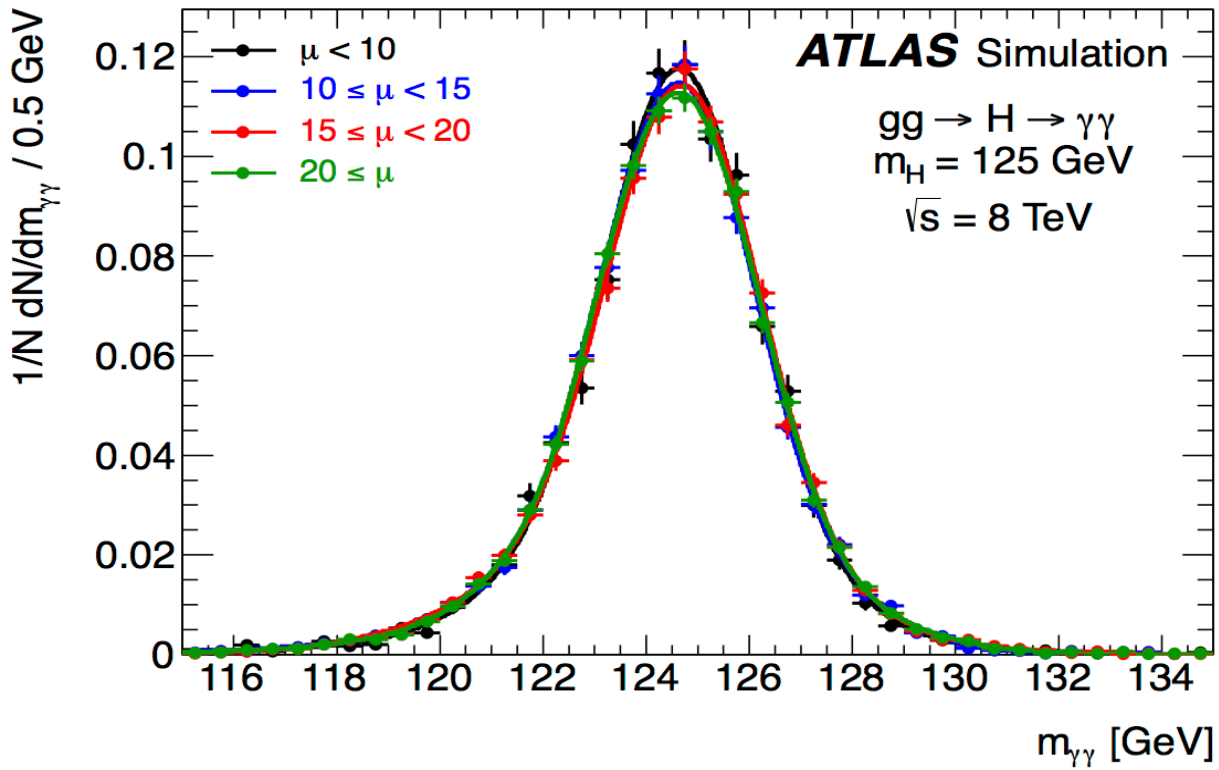


- $\sqrt{s} = 8$ TeV
- $E_{T1} = 62.2$ GeV
- $E_{T2} = 55.5$ GeV
- $E_1 = 66.9$ GeV
- $E_2 = 99.2$ GeV
- $M_{\gamma\gamma} = 126.9$ GeV

$H \rightarrow \gamma\gamma$ (2011+2012 data)

- **Look for narrow peak in $m_{\gamma\gamma}$ ($110 < m_{\gamma\gamma} < 150$ GeV)**

- $\sigma \times BR \sim 50$ fb @ $m_H \sim 126$ GeV
- Simple topology:
  2 high-p_T isolated photons
  $E_T(\gamma_1, \gamma_2) > 40, 30$ GeV
- Main background:
  - $\gamma\gamma$ continuum (irreducible)
  - γ-jet, jet-jet (reducible)
- Mass resolution of inclusive sample: σ=1.6 GeV

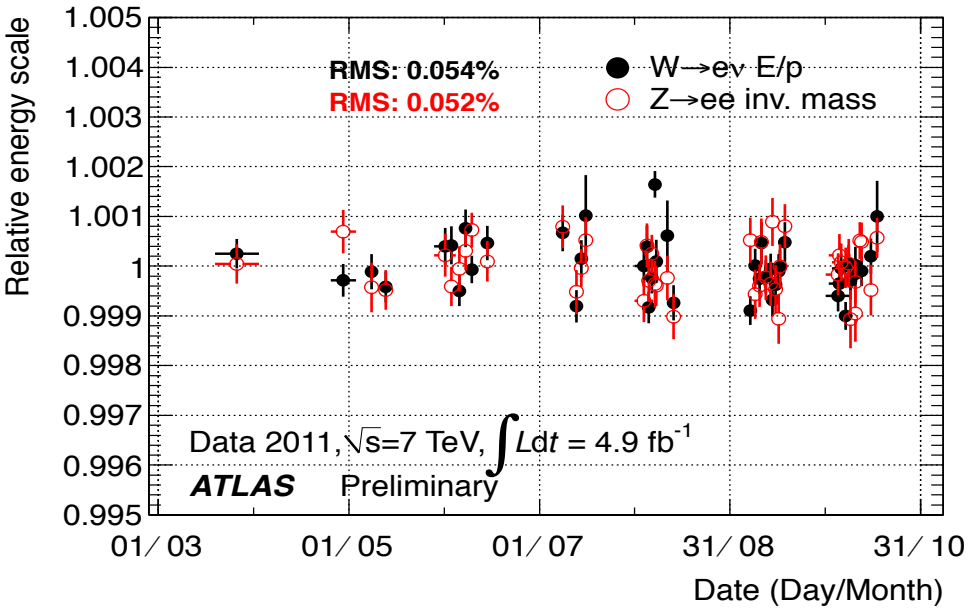


Mass resolution not affected by pile-up

$H \rightarrow \gamma\gamma$ Di-photon mass reconstruction

$$m^2_{\gamma\gamma} = 2\, E_1\, E_2\, (1-\cos\alpha)$$

Stability of EM calorimeter response vs time (and pile-up) during full 2011 run better than 0.1%

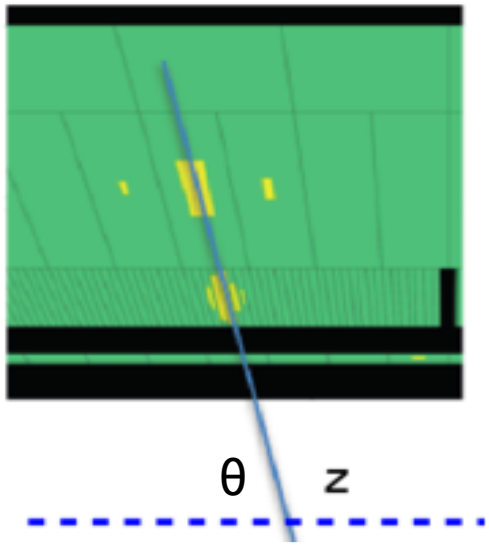


Calorimeter energy response calibration (from $Z \rightarrow ee$, $W \rightarrow e\nu$, $J/\Psi \rightarrow ee$):

- ***Energy scale at m_Z known to ~ 0.3%***
- ***Linearity better than 1%***
- ***Constant term of resolution: ~ 1% in barrel, 1.2-2.1% for end-cap***

$$m^2_{\gamma\gamma} = 2\, E_1\, E_2\, (1-\cos\alpha)$$

α=opening angle of the two photons



Measure γ direction with sampling calorimeter → get z of primary vertex

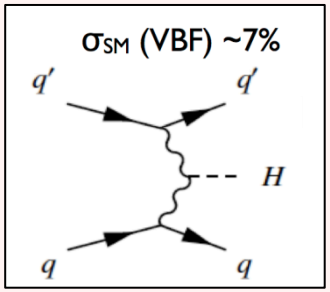
Calorimeter pointing reduces vertex uncertainty from beam-spot spread from ~ 5-6 cm to ~ 1.5 cm
Robust against pile-up
Angular contribution to mass resolution becomes negligible

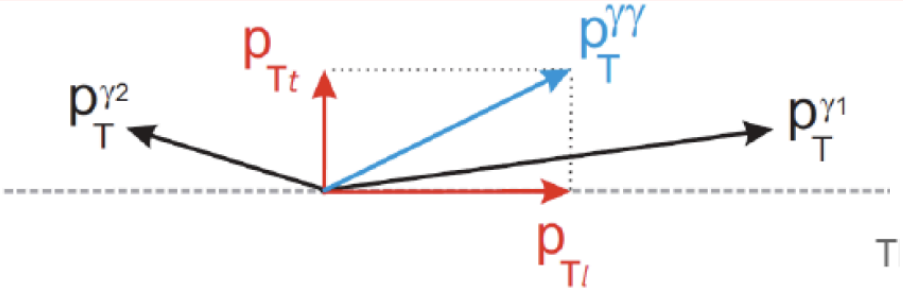
$H \rightarrow \gamma\gamma$ Analysis optimization

- Neural-net based photon ID for 2011 data
- Re-optimized cut-based photon ID for 2012, stable with high pileup
- New '2-jets' category for enhanced VBF sensitivity

Events divided in 10 categories based on:

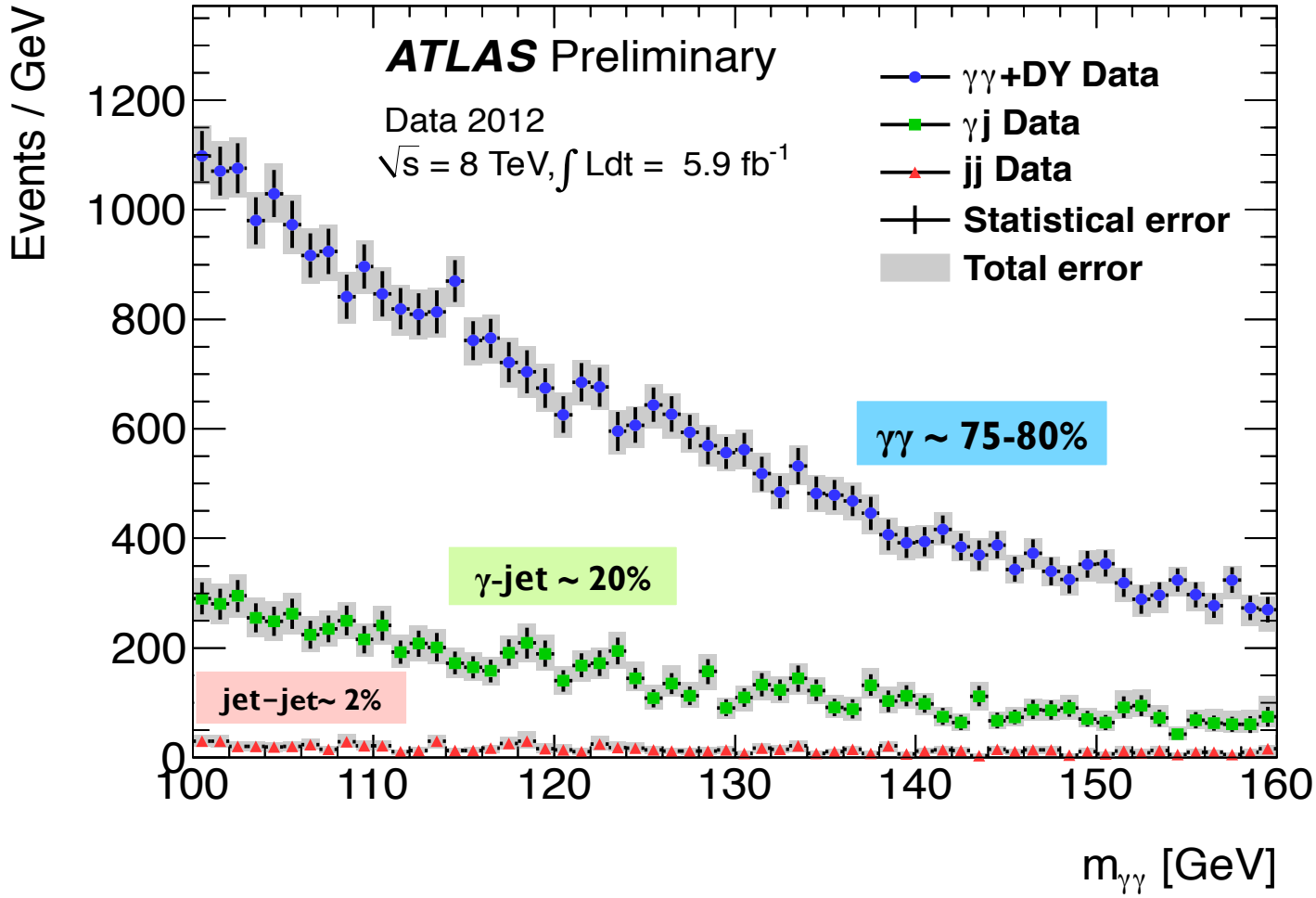
- γ rapidity,
- converted/unconverted γ;
- p_{Tt} ($p_T^{\gamma\gamma}$ perpendicular to $\gamma\gamma$ thrust axis);
- 2jets (VBF-like)





$H \rightarrow \gamma\gamma$ Background composition of $\gamma\gamma$ data sample

The $\gamma\gamma$, γ-jet and jet-jet contributions can be decomposed using control samples defined by photon identification and isolation.

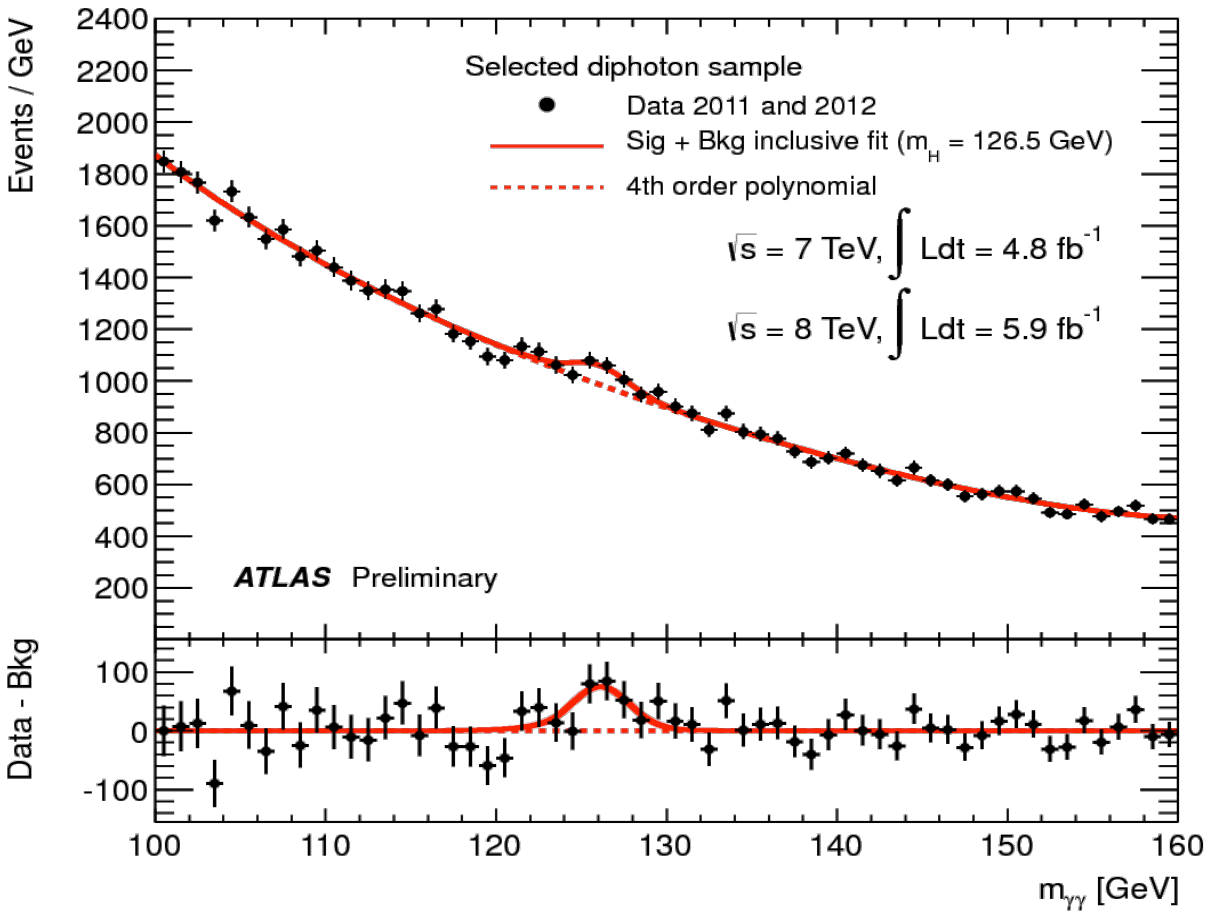


$H \rightarrow \gamma\gamma$ Background modeling

- ***Considerable effort has been made in background modeling, in order to avoid biases in the extraction of a potential Higgs signal.***
- ***Determine background model before looking at data.***
- ***The background modeling:***
  - ***Should be flexible enough to describe shape well in different categories.***
  - ***Different parameterizations for different categories.***
- ***Understand the background model uncertainty to the level as small as 20% of background statistical uncertainty or 10% of signal yield.***
- ***Various background models have been considered, for example:***
  - ***Single and double exponentials***
  - ***Exponential with modified turn-on***
  - ***Exponentials of 2nd or 3rd order polynomial***
  - ***Polynomials of various orders***

$H \rightarrow \gamma\gamma$ Invariant mass distributions

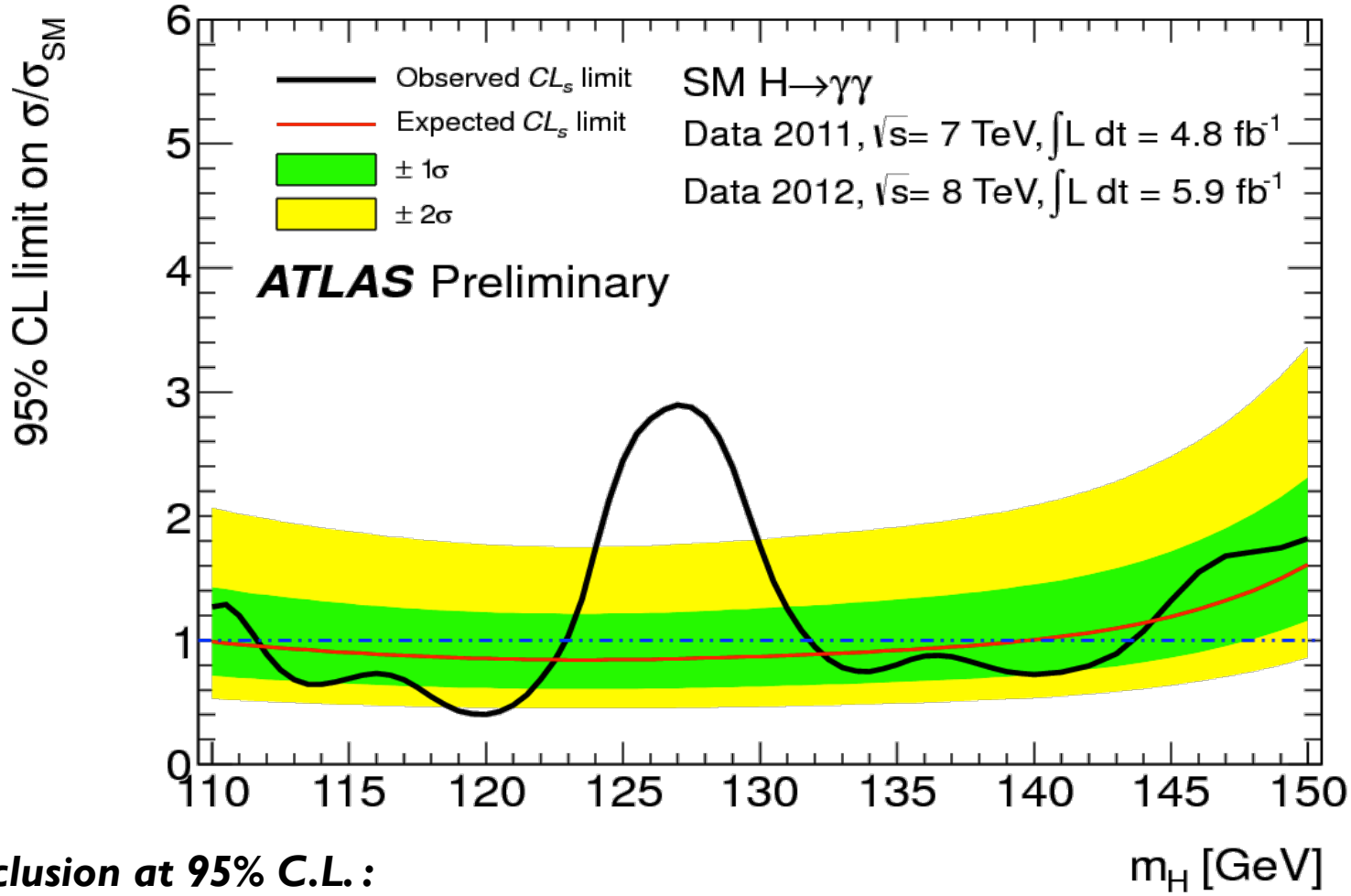
Unweighted invariant mass distribution of selected events combining 2012 (35271 events) and 2011(23788) data



- ***For m_H=125 GeV***
  - ***$\sigma \times BR$ = 40.3 fb at 7 TeV***
  - ***$\sigma \times BR$ = 51.3 fb at 8 TeV***
- ***Full results obtained by splitting this data into 10 categories and fitting mass distributions separately.***

Signal Yield	Observed	Expected
2011	146.9	79.4
2012	205.5	111.1

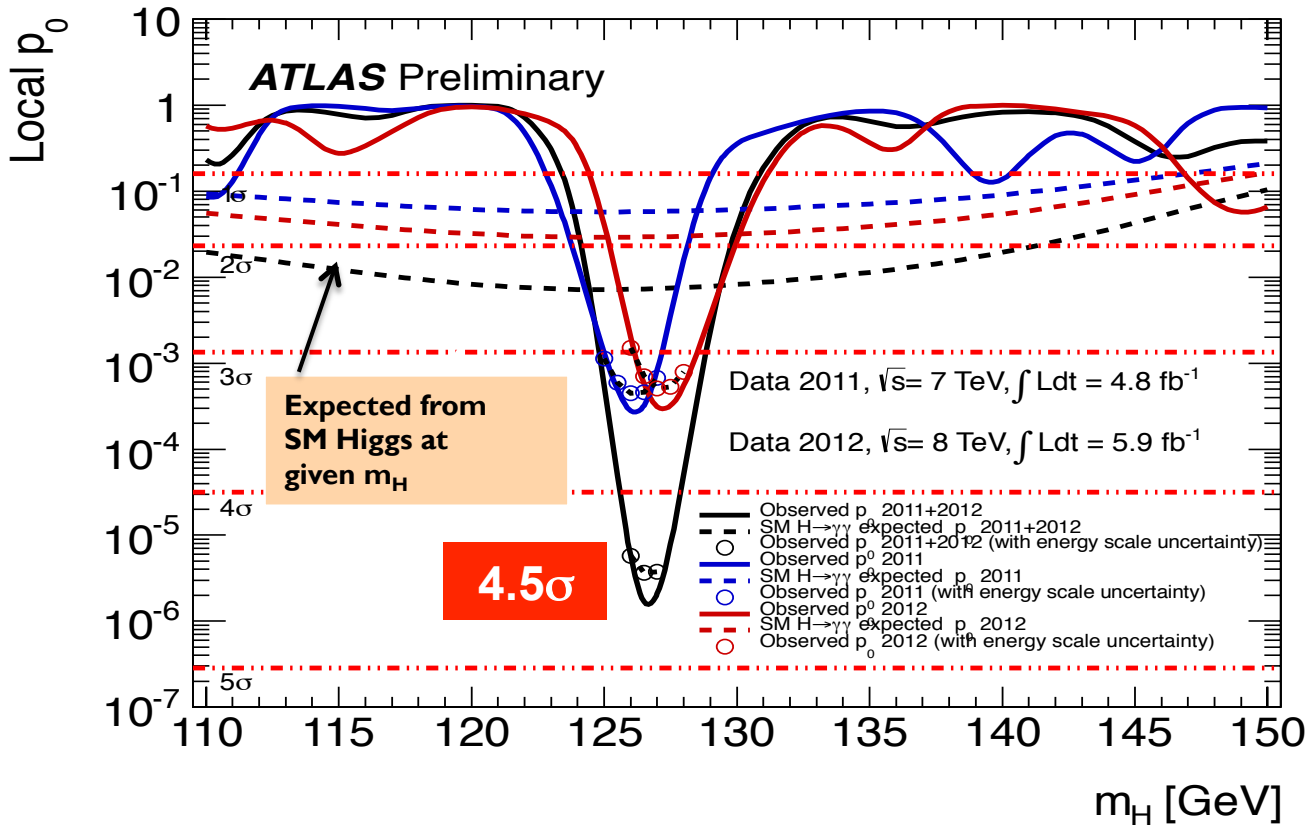
$H \rightarrow \gamma\gamma$ 10-category results



Exclusion at 95% C.L. :

- ***Expected*** $110 < m_H < 139.5$ GeV
- ***Observed*** $112 < m_H < 122.5$ GeV $132 < m_H < 143$ GeV

$H \rightarrow \gamma\gamma$ 10-category results



p_0: probability that the background fluctuates to the observed data (or higher)

Circles: effect of 0.6% uncertainty on photon energy scale: ~ 0.1 σ

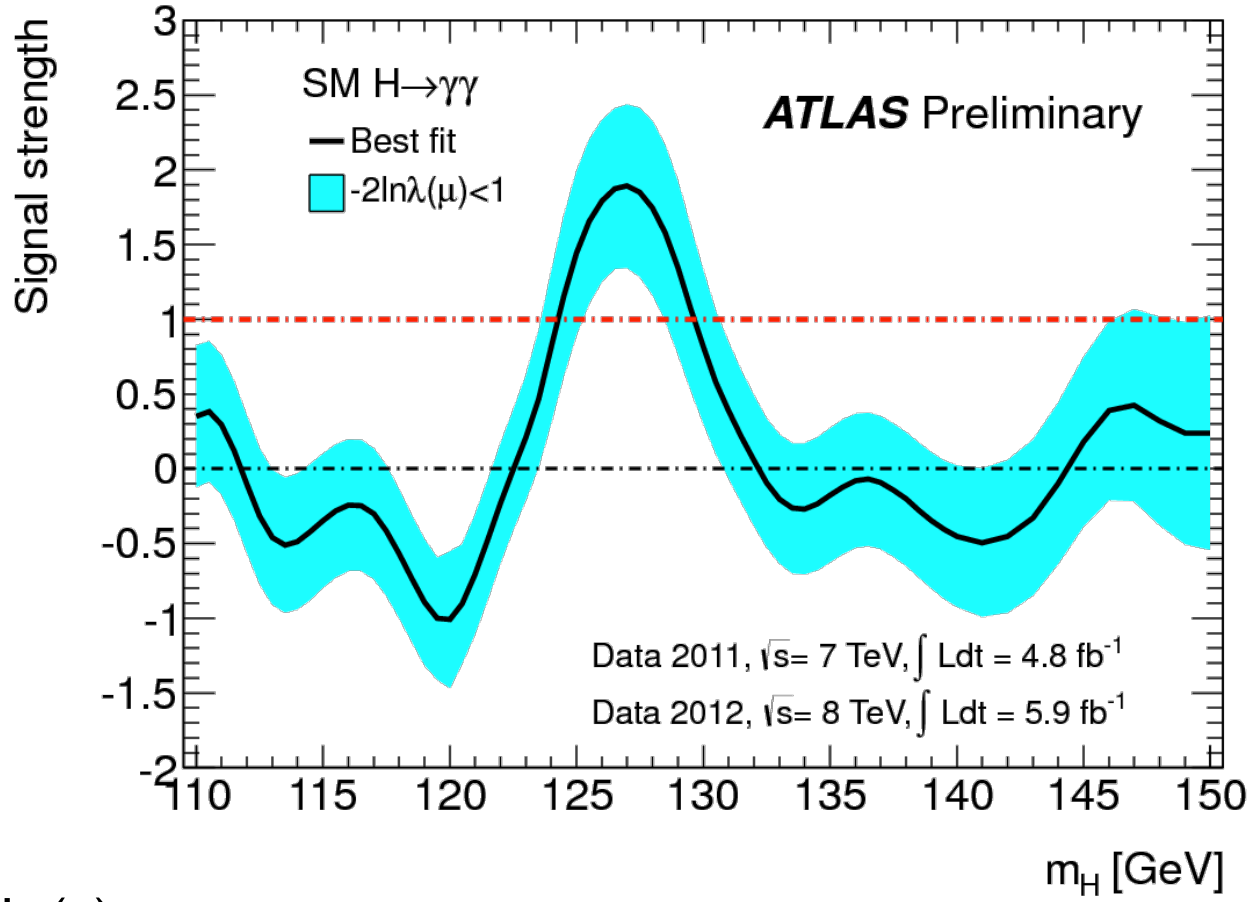
with energy scale systematics

Data sample	m_H at max deviation	local p-value	local significance	expected
2011	126 GeV	3×10^{-4}	3.3 σ	1.6 σ
2012	127 GeV	3×10^{-4}	3.3 σ	1.9 σ
2011+2012	126.5 GeV	2×10^{-6}	4.5 σ	2.4 σ

Global 2011+2012 (including LEE over 110-150 GeV range): 3.6 σ

$H \rightarrow \gamma\gamma$ Signal strength

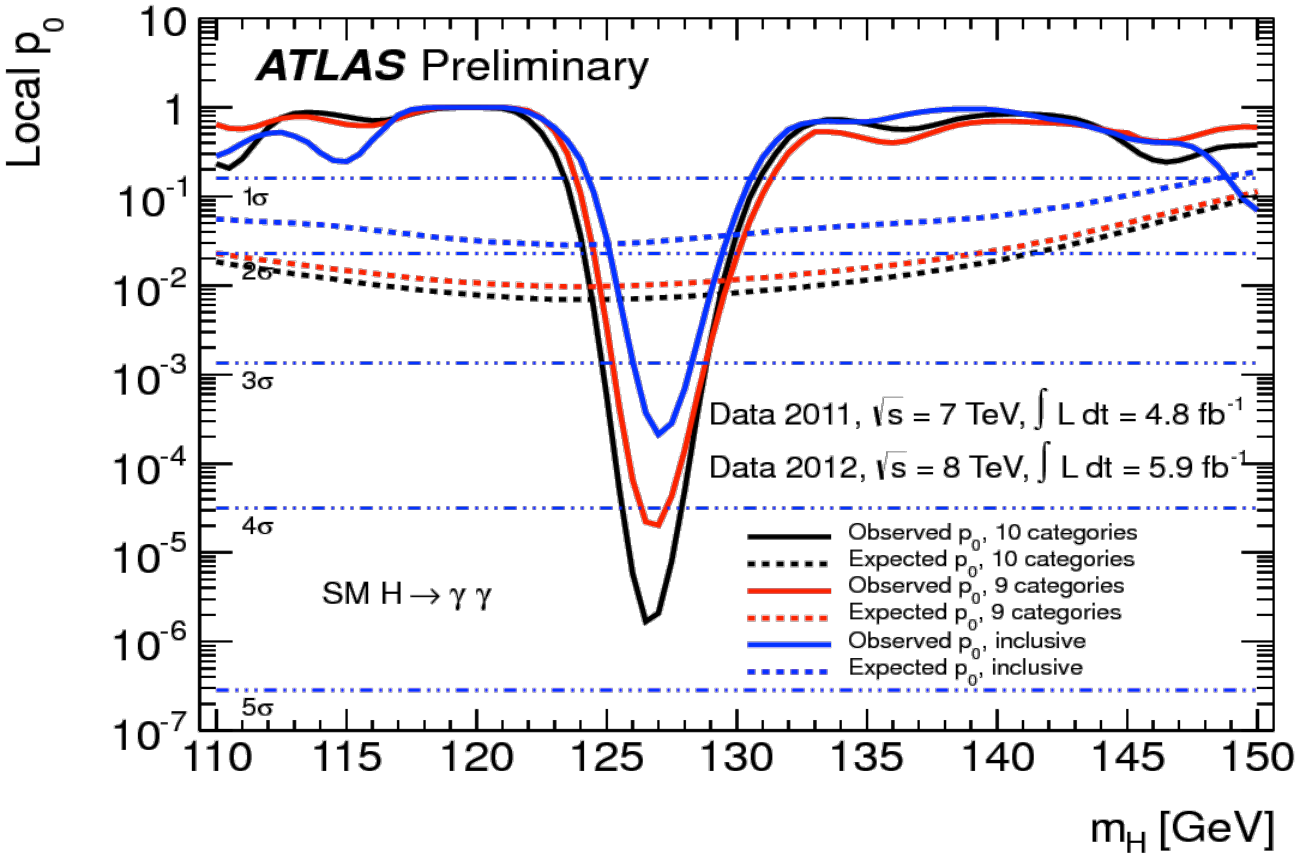
$$\mu = \frac{\sigma \cdot Br}{(\sigma \cdot Br)_{SM}}$$



- Signal strength (μ) =
  (signal rate from fit to data) / (expected SM signal rate at given m_H)
- ***Fitted signal strength μ=1.9±0.5 at m_H=126.5 GeV***
  (2011: μ = 2.0 ± 0.8, 2012: μ = 1.8 ± 0.7)

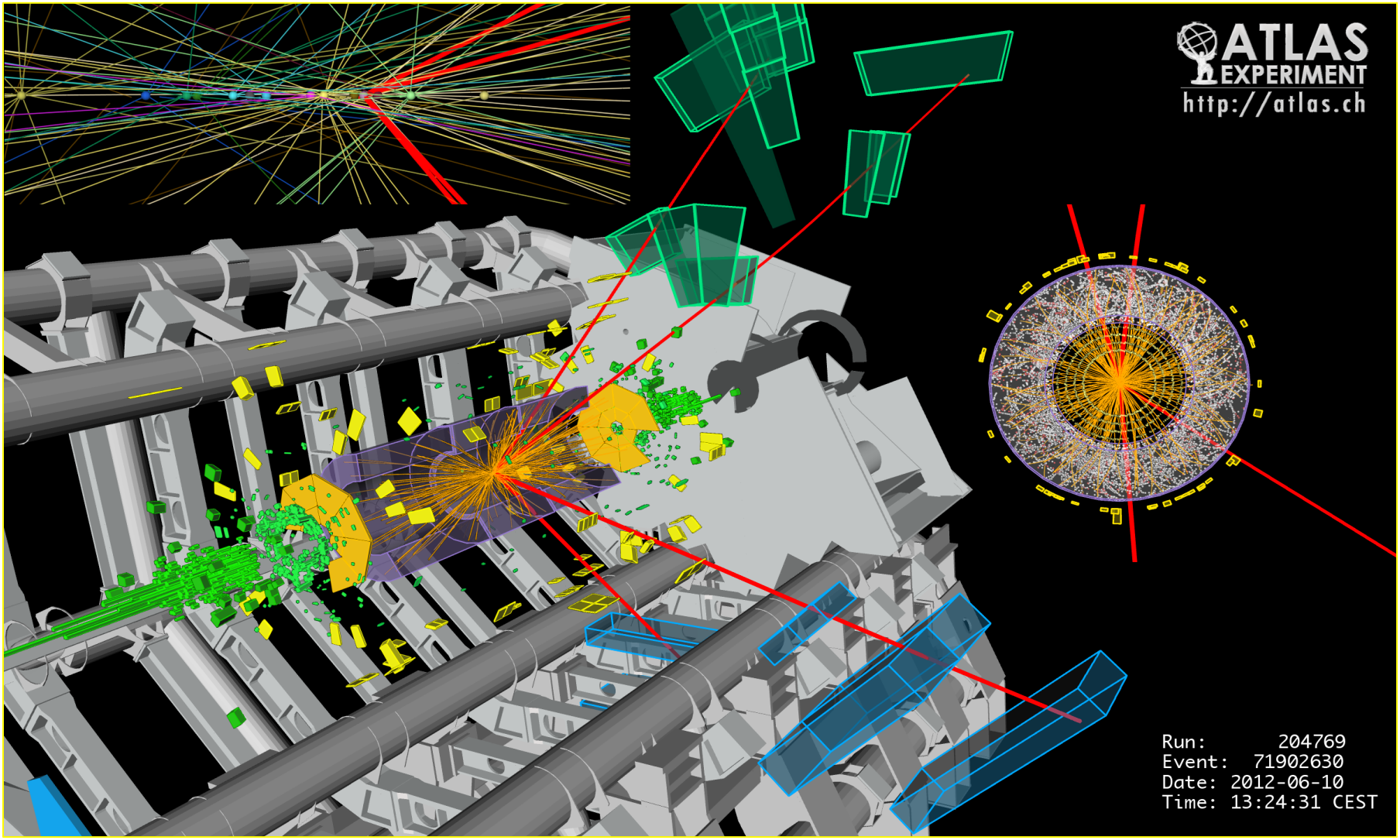
$H \rightarrow \gamma\gamma$ Effect of categories

- *Effect of simple fit to inclusive sample instead of 10 analysis categories*



Procedure	Local significance
inclusive sample	3.5 σ
9 categories	4.1 σ
10 categories	4.7 σ (4.5 σ with E.S.S)

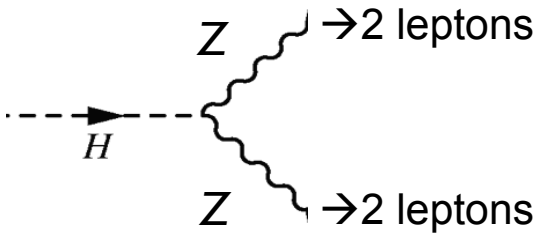
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ "Golden Channel"



4μ candidate with $m_{4\mu}$=125.1 GeV

p_T (muons)= 36.1, 47.5, 26.4, 71 .7 GeV m_{12}= 86.3 GeV, m_{34}= 31.6 GeV. 15 reconstructed vertices

$H \rightarrow ZZ^{(*)} \rightarrow 4l$



- **Signature: $H \rightarrow ZZ^{(*)} \rightarrow 4l$ (l = e, μ)**
- **The "golden channel":**
  - Small rates, but high S/B
  - Can be fully reconstructed; mass resolution ~2% at 130 GeV
- **Cross section times branching ratio (at m_H=125 GeV):**

  ~ 4 fb at $\sqrt{s}$=7 TeV

  ~ 5 fb at $\sqrt{s}$=8 TeV
- **Backgrounds:**
  - Irreducible: $pp \rightarrow ZZ^{(*)} \rightarrow 4l$
  - Reducible: Z+jets, Zbb, tt (sizeable at low Higgs masses)

    Suppress backgrounds with isolation and impact parameters cut on two softest leptons
- **Mass range under consideration: 110 GeV to 600 GeV**
- **Four final states: 4e, 4μ, 2e2μ, 2μ2e**

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ Event Selection

Updated analysis for 2011 and 2012 data

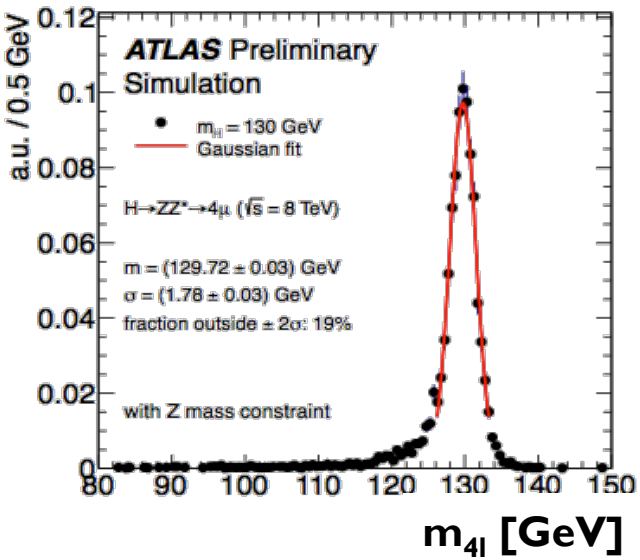
- *Improved expected sensitivity for low m_H*
- *Estimate backgrounds using data (sidebands, control regions)*
- *Development based only on 2011 data and 2012 control regions*

Selection

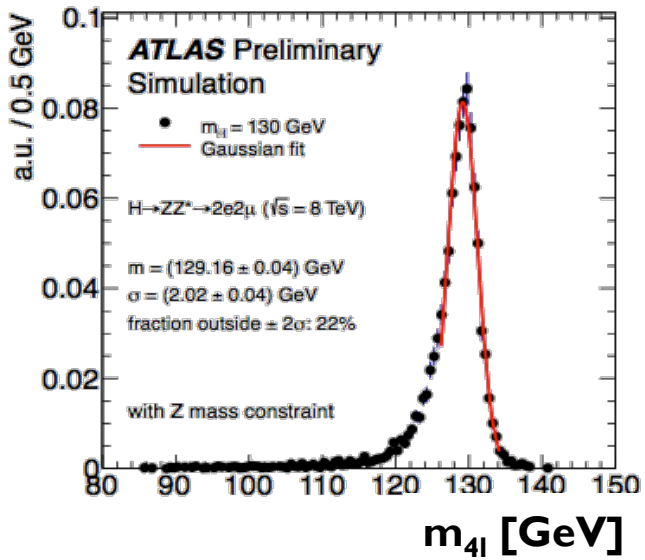
- *At least two pairs of opposite-charge, same-flavor leptons (e,μ)*
- *p_T thresholds: 20, 15, 10, 7 GeV (6 GeV for muons)*
- *$50 < m_{12} < 106$ GeV, m_{4l}-dependent cut on m_{34}, $m_{34} < 115$ GeV*
- *All same-flavor, opposite-sign pairs m_{ll}>5 GeV (J/ψ veto)*
- *$\Delta R(l,l') < 0.1$ (0.2) for all same (different)-flavor*
- *Tracking and calorimeter isolation*
- *Impact parameter significance*

- ***Mass resolution in simulated events at m_H=130 GeV***

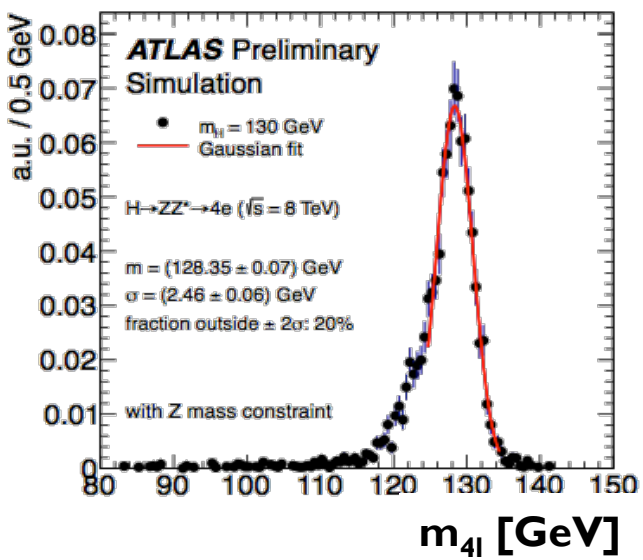
(with Z mass constraint for m_{12})



4μ: σ=1.8 GeV



2e2μ: σ=2.0 GeV



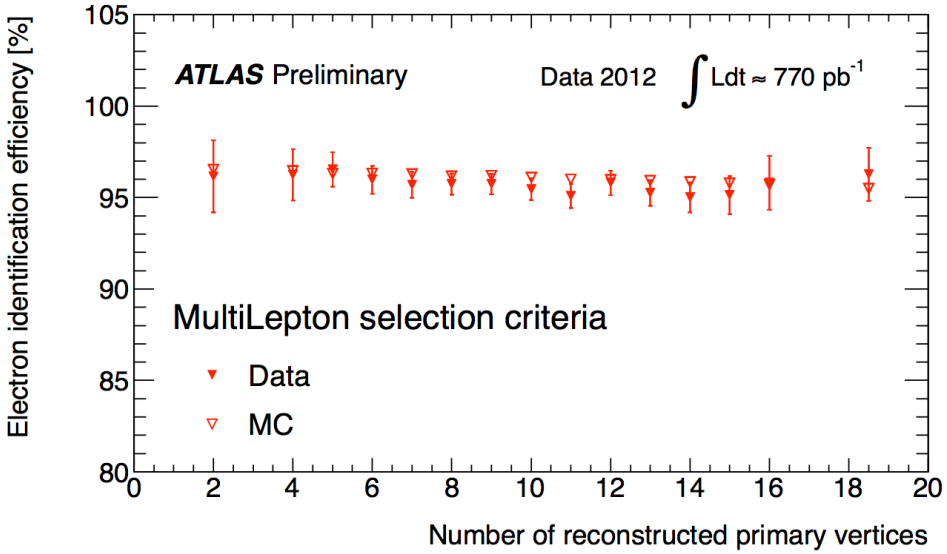
4e: σ=2.5 GeV

- ***Combined reconstruction / selection efficiency for m_H=130 GeV***
  - ***Significant gains from increased kinematic acceptance and e-ID***

Efficiency (%)	4μ	2e2μ	4e
2011 data (old)	27	18	14
2011 data	43	23	17
2012 data	41	27	23

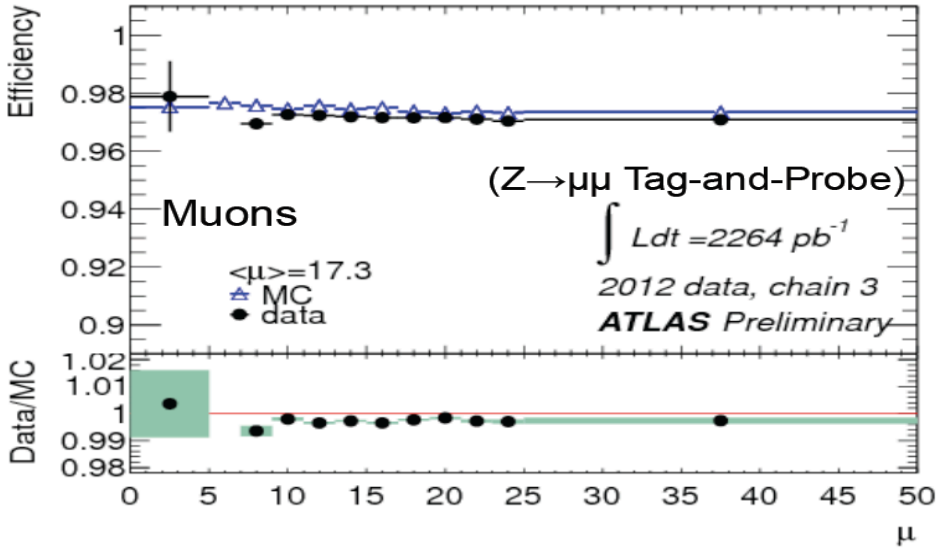
Electrons in 2012 data

- *Improved reconstruction*
  - *New pattern finding/track-fit*
- *Improved identification*
  - *Pile-up robust*
  - *Higher rejection and efficiency than in 2011*



Muons in 2102 data

- *Combine Inner Detector (ID) tracks with tracks in Muon Spectrometer (MS)*
- *Extended coverage:*
  - *ID-track + energy deposit in calorimeter (|η|<0.1, pT>15 GeV)*
  - *MS stand-alone (2.5<|η|<2.7)*



$H \rightarrow ZZ^{(*)} \rightarrow 4l$ Background estimation

Irreducible *($ZZ^{(*)}$): MC simulation normalized to theory cross section*

Reducible *(ll+jets and tt):*

- *Comparable to ZZ in the low mass region*
- *Estimated using data-driven methods*
- *Background composition depends on flavor of sub-leading lepton pair*
  → different approaches for ll+μμ and ll+ee:

  ll+μμ *(4μ, 2e2μ):*

  - *ttbar and Zbb from a fit to m_{12}*

  ll+ee *(2μ2e, 4e):*

  - ***Z+XX*** *control samples* ***X****: Electrons from heavy flavor,*
    Electrons from photon Conversions,
    jets misidentified as electrons ("Fakes")

- ***General strategy****: Loosen or revert selection, obtain composition, extrapolate to signal region*

- ***Two methods for each reducible background (nominal, cross-check)***

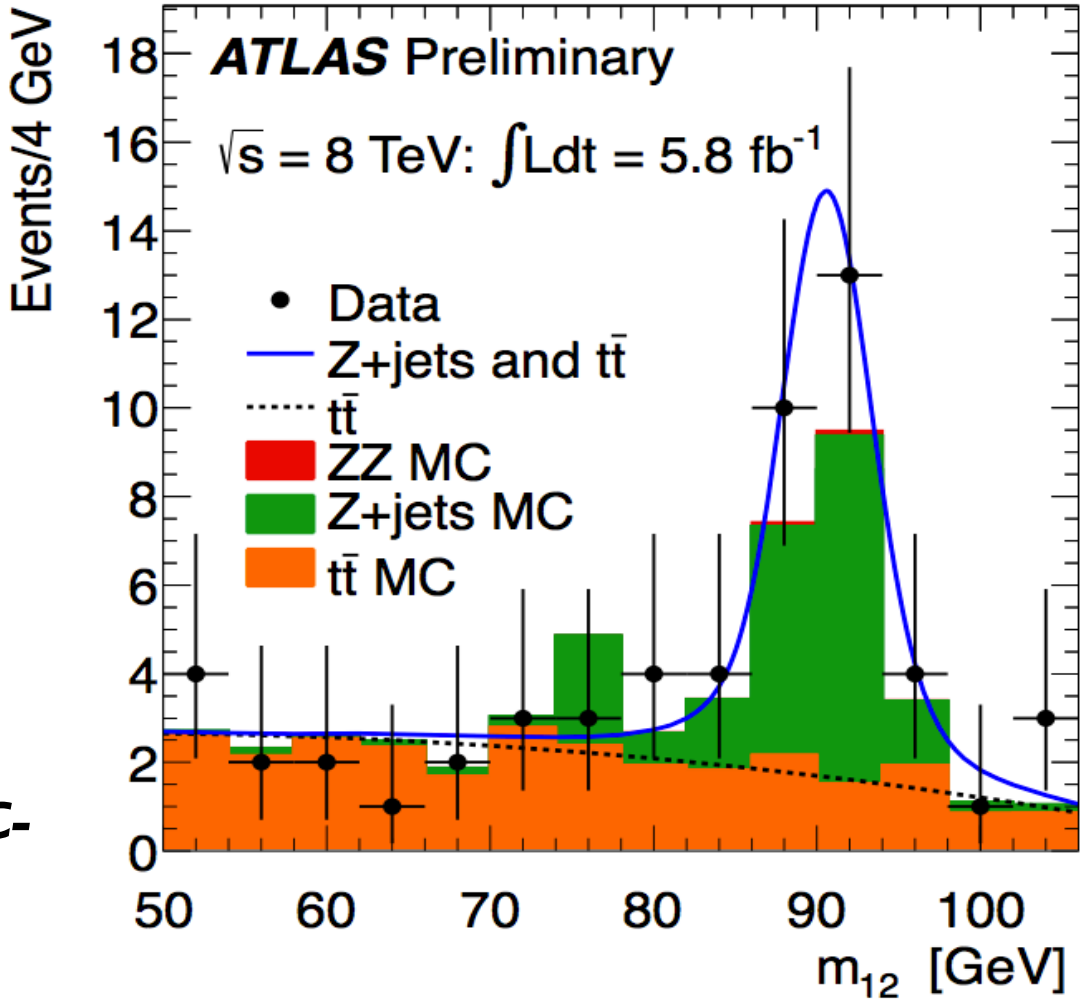
Background estimates : ll + μμ

Fit to m_{12}

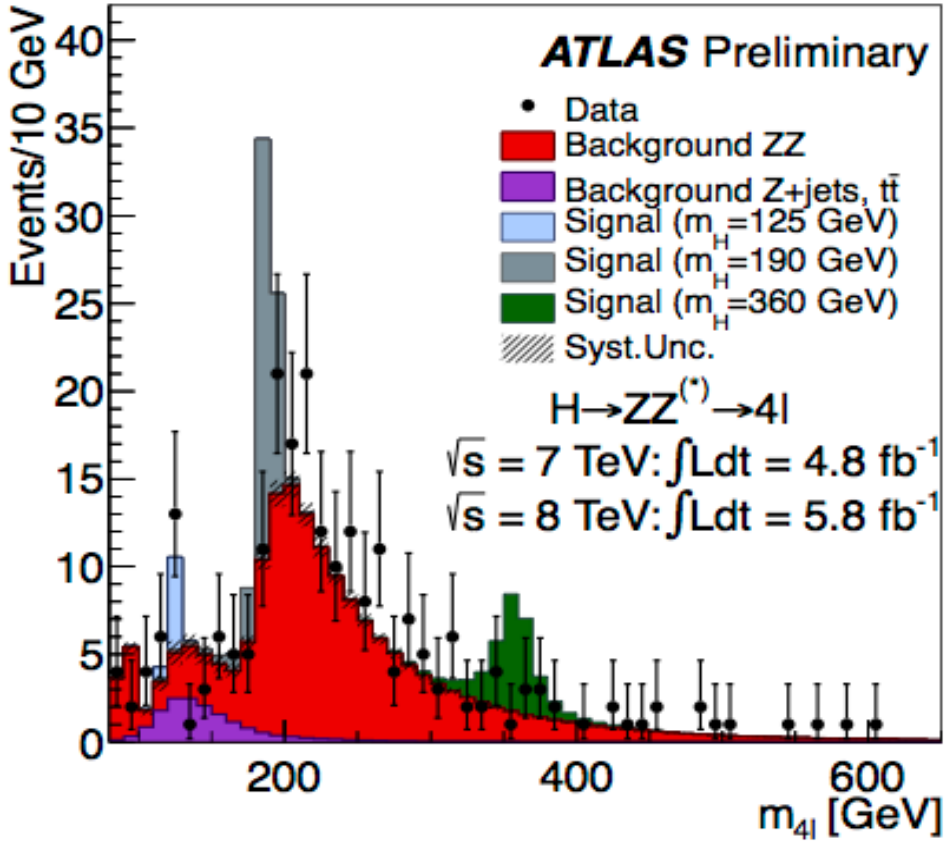
- **Loosened selection on sub-leading leptons (enhance tt, reduce ZZ):**
  - *No isolation cuts*
  - *At least one should fail the impact parameter cut*
- **tt and Z+jets estimated via a fit**

  Chebychev + BreitWigner⊗CrystalBall
- **Extrapolate to signal region via MC-based efficiency**

  (validated in Z+ μ control region)



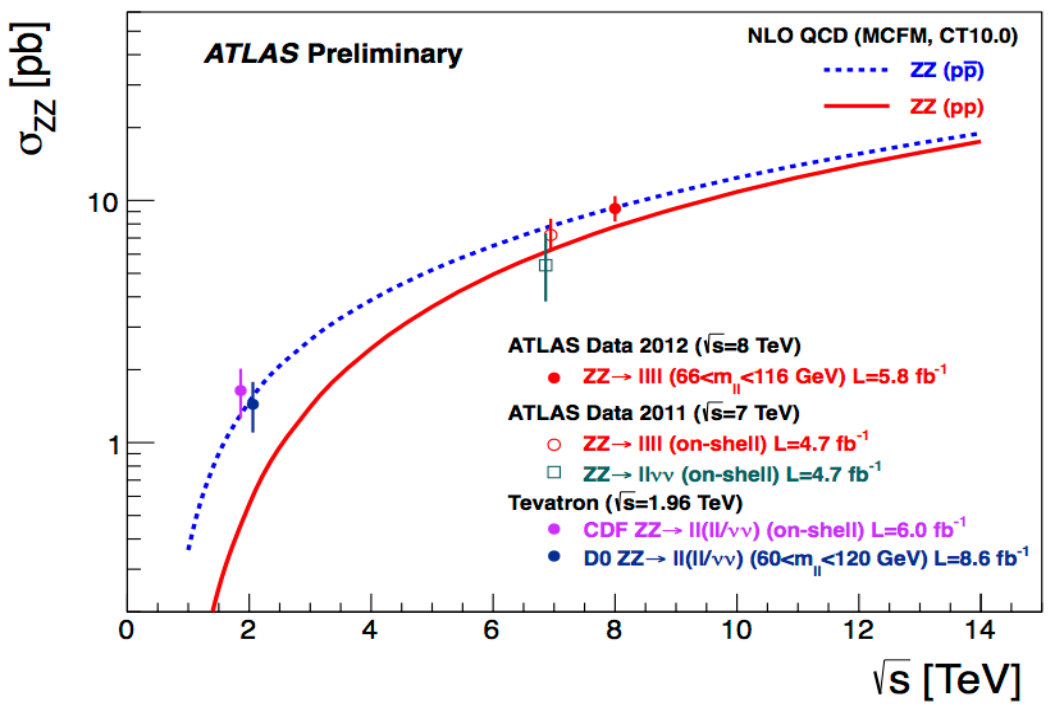
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ Mass spectrum after selection: 2011+2012 data



m_{4l} > 160 GeV (dominated by ZZ background):
147 ± 11 events expected
191 observed

~ 1.3 times more ZZ events in data than SM prediction → in agreement with measured ZZ cross-section in 4l final states at $\sqrt{s}$ = 8 TeV

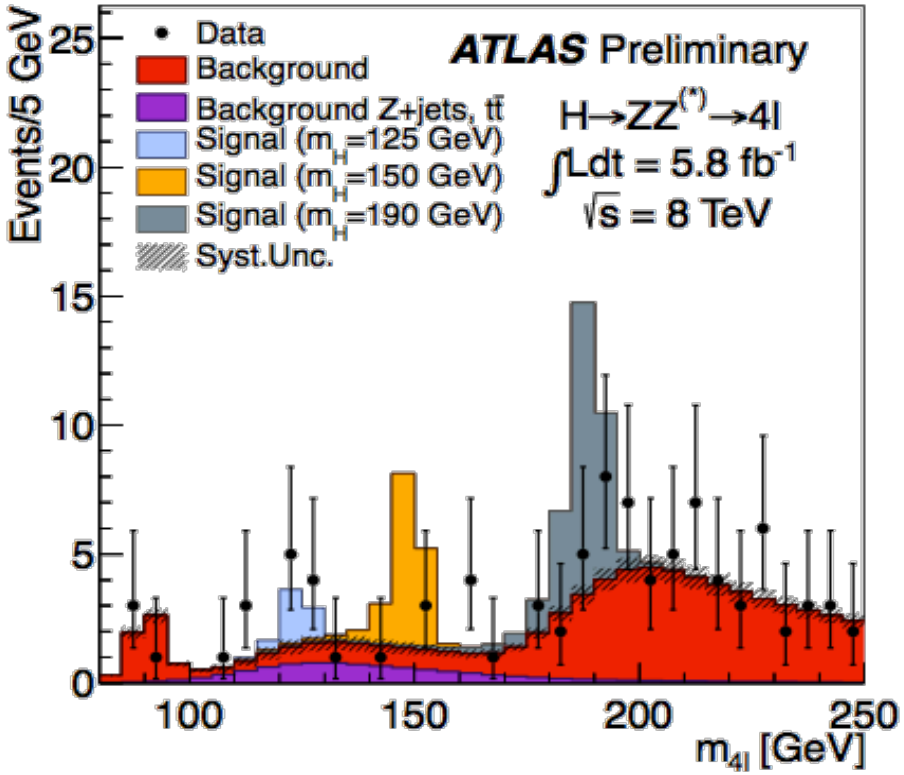
Measured σ (ZZ) = 9.3 ± 1.2 pb
SM (NLO) σ (ZZ) = 7.4 ± 0.4 pb

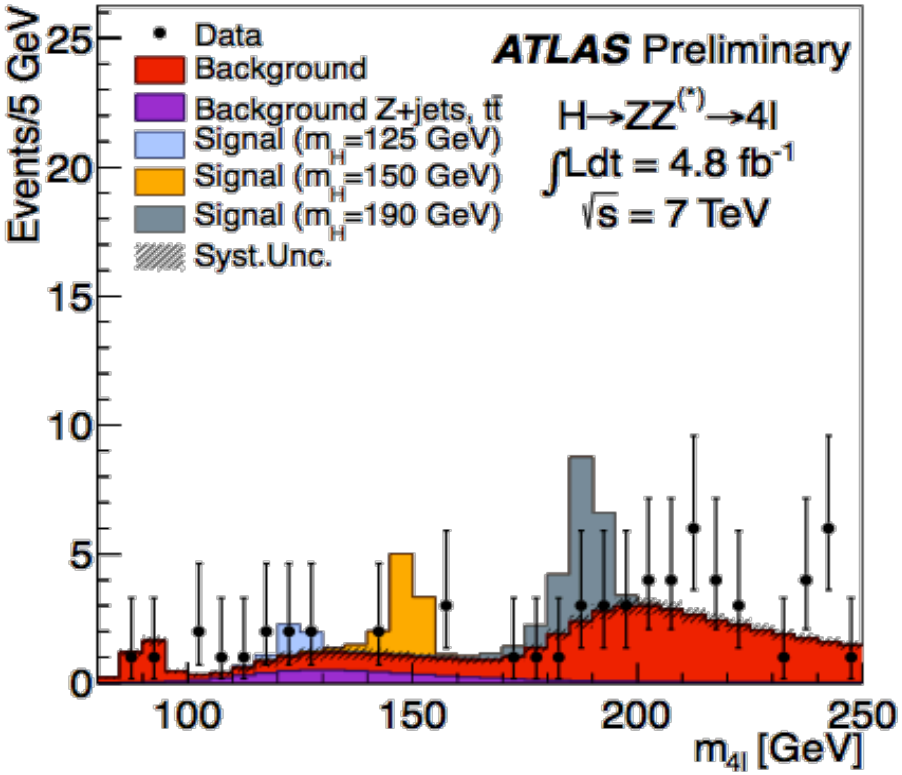


Discrepancy has negligible impact on the low-mass region < 160 GeV

(no change in results, if in the fit ZZ background is constrained within its uncertainty or left free)

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ Low mass candidates

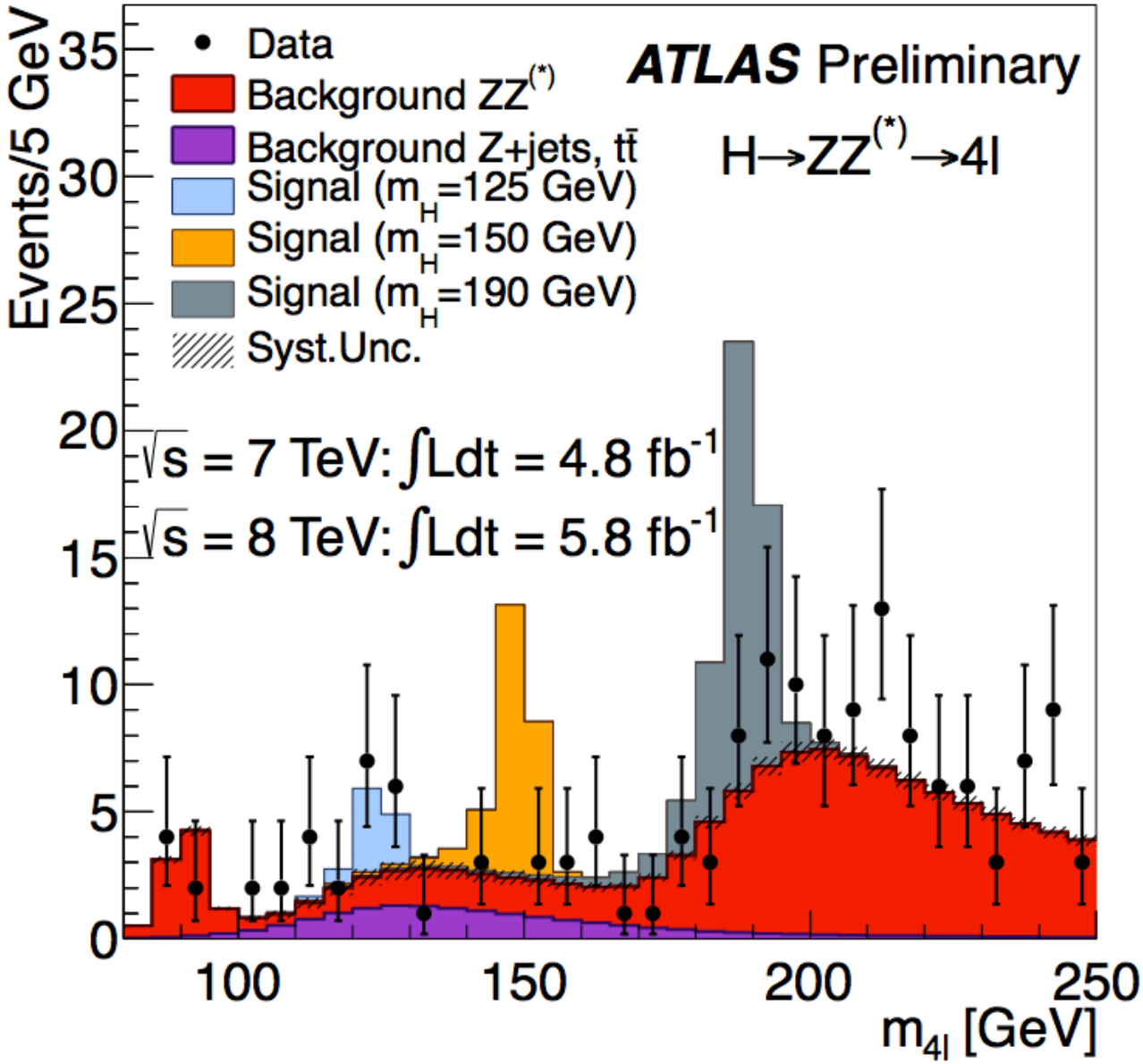




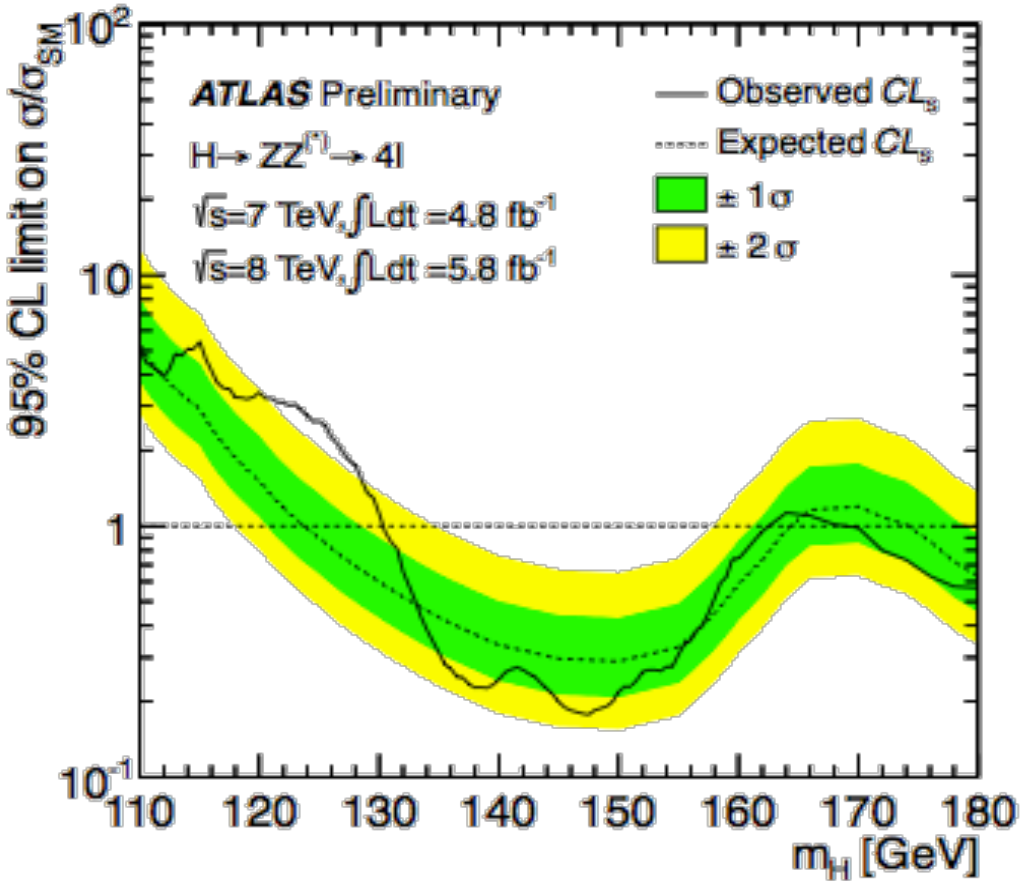
Event counts in $120<m_{4l}<130$ GeV

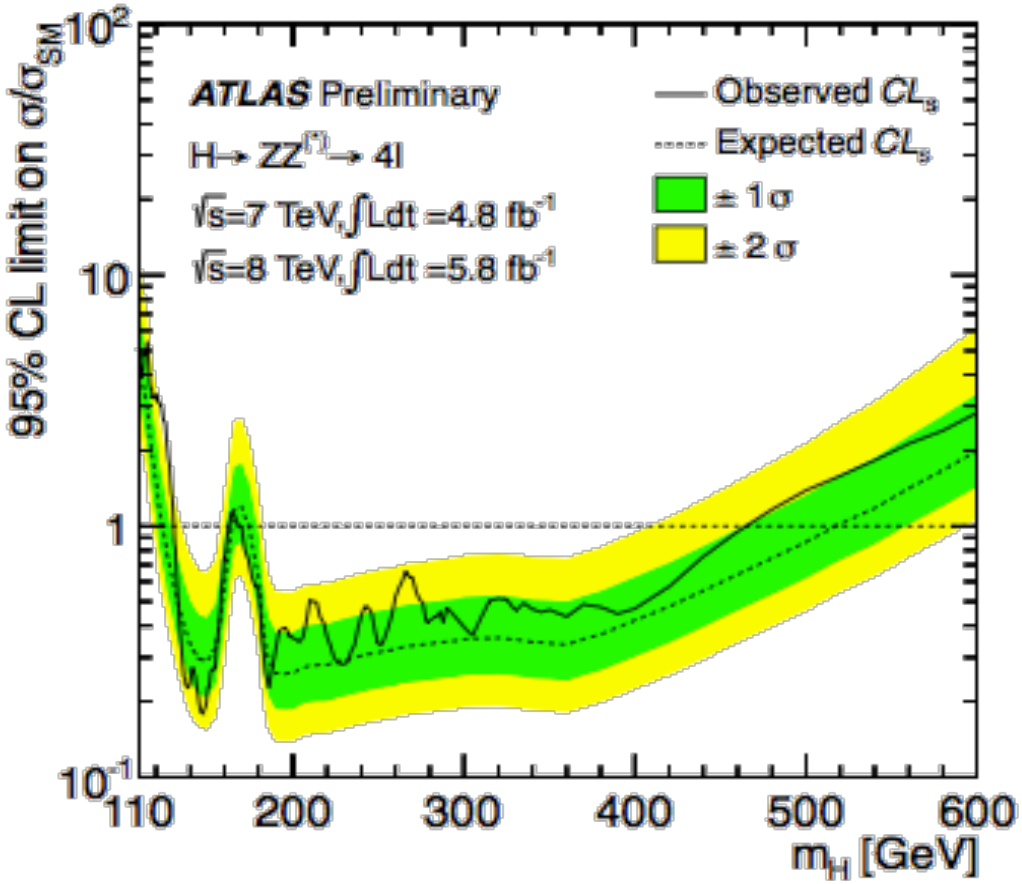
7+8 TeV	4μ	2e2μ + 2μ2e	4e	sum
Background	1.3 ± 0.1	2.2 ± 0.2	1.6 ± 0.2	5.1 ± 0.3
m_H=125 GeV	2.1 ± 0.3	2.3 ± 0.3	0.9 ± 0.1	5.3 ± 0.4
Data Observed	6	5	2	13
S/B	1.6	1.0	0.6	1.0

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ Low mass candidates



$H \rightarrow ZZ^{(*)} \rightarrow 4l$ Exclusions





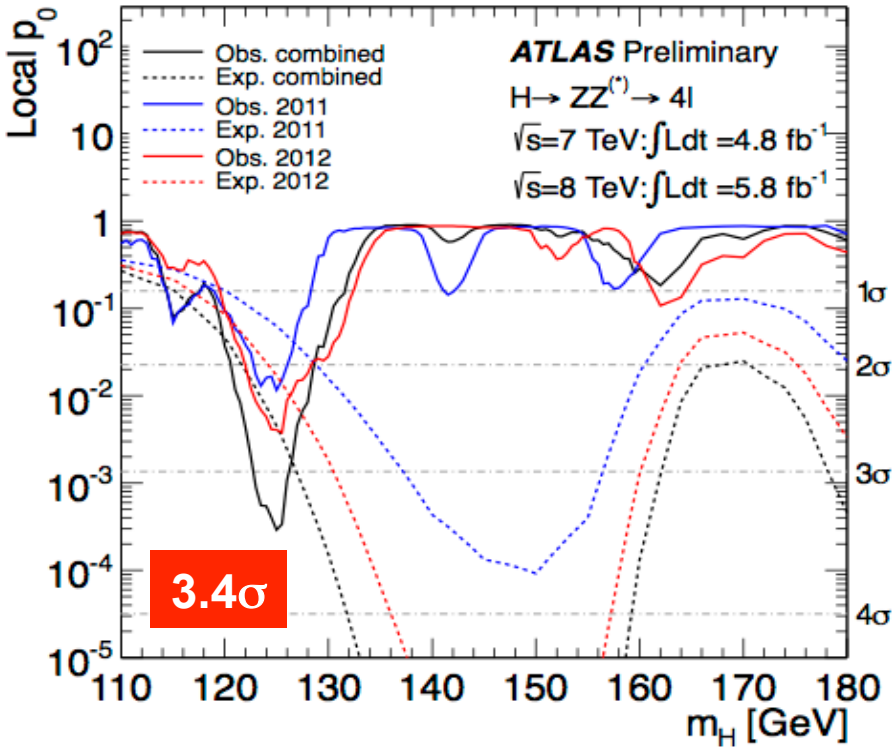
Exclusion at 95% C.L. :

- ***Expected*** $124 < m_H < 164$ GeV and $176 < m_H < 500$ GeV
- ***Observed*** $131 < m_H < 162$ GeV and $170 < m_H < 460$ GeV

For m_H ~120-130 GeV weaker limit than expected in background-only hypothesis

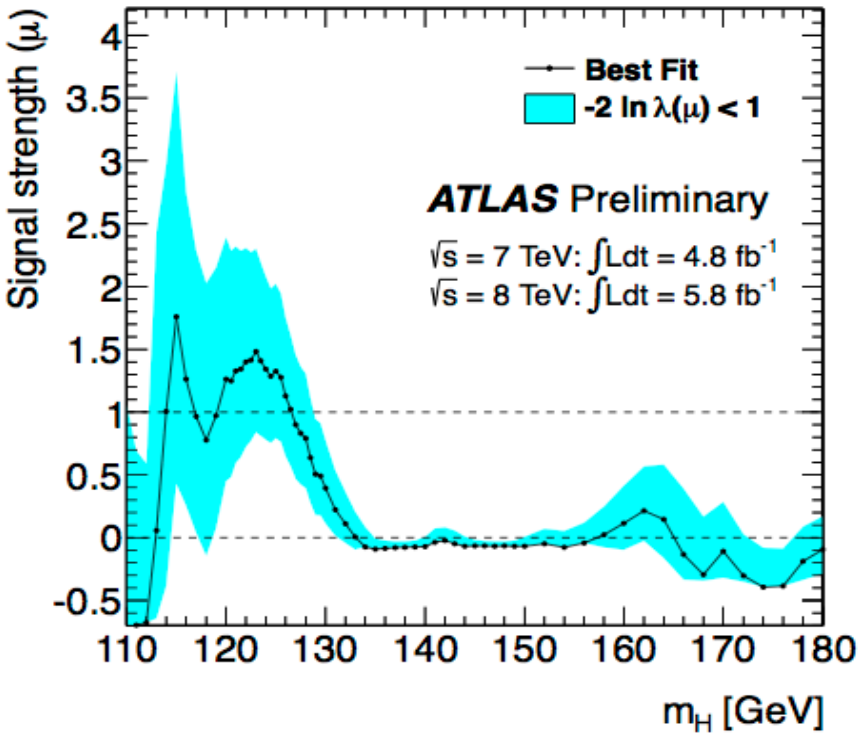
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ Significance

p_0: probability that the background fluctuates to the observed data (or higher)



Fitted signal strength

Best-fit value at 125 GeV: μ=1.3 ± 0.6



Data sample	m_H at max deviation	local p-value	local significance	expected
2011	125 GeV	1.1 %	2.3 σ	1.5 σ
2012	125.5 GeV	0.4 %	2.7 σ	2.1 σ
2011+2012	125 GeV	0.03 %	3.4 σ	2.6 σ

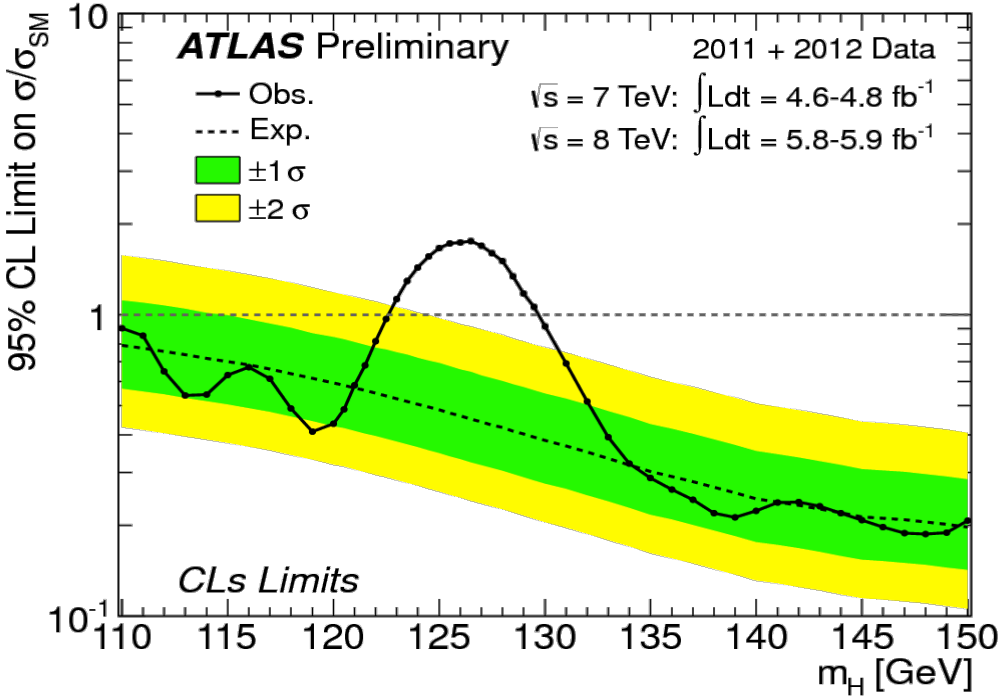
Global 2011+2012 (including LEE over full 110-141 GeV range): 2.5σ

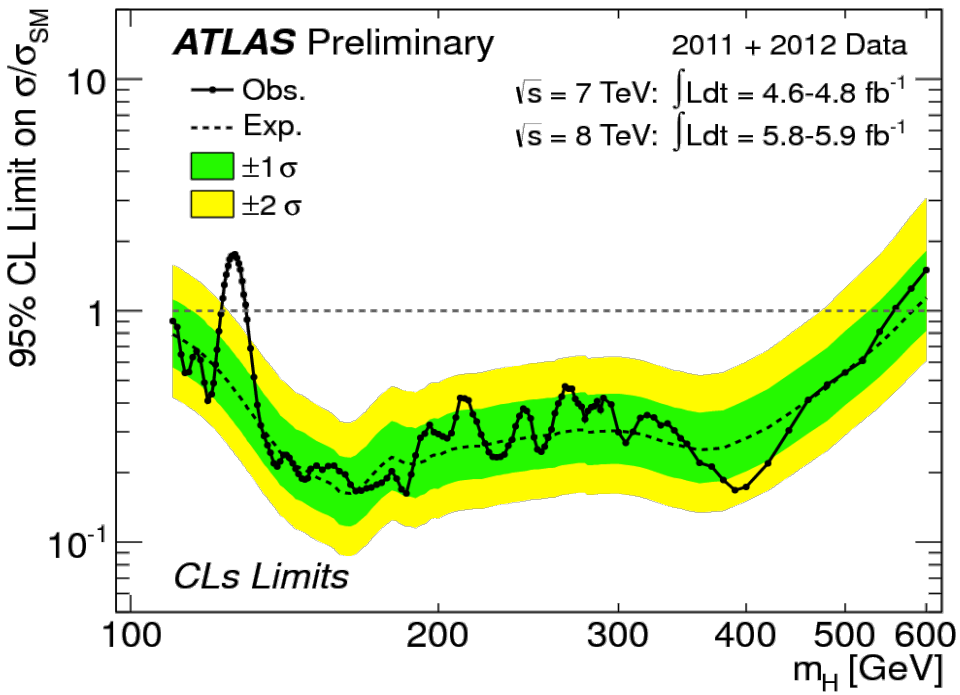
Higgs Combination Data Samples (July 4, 2012)

- **The following channels are used to calculate the Higgs combined significance (2011+2012)**
  - $H \rightarrow \gamma\gamma$ 7 TeV (4.8 fb^{-1}) + 8 TeV (5.9 fb^{-1})
  - $H \rightarrow ZZ^{(*)} \rightarrow 4$ leptons 7 TeV (4.8 fb^{-1}) + 8 TeV (5.8 fb^{-1})
  - $H \rightarrow WW$ 7 TeV (4.7 fb^{-1})
  - $H \rightarrow \tau\tau$ 7 TeV (4.7 fb^{-1})
  - $W,Z\ H \rightarrow bb$ 7 TeV (4.6-4.7 fb^{-1})

Higgs Combination Exclusion

Combining 2011+2012 γγ and 4-lepton analyses with other channels as before (2011)



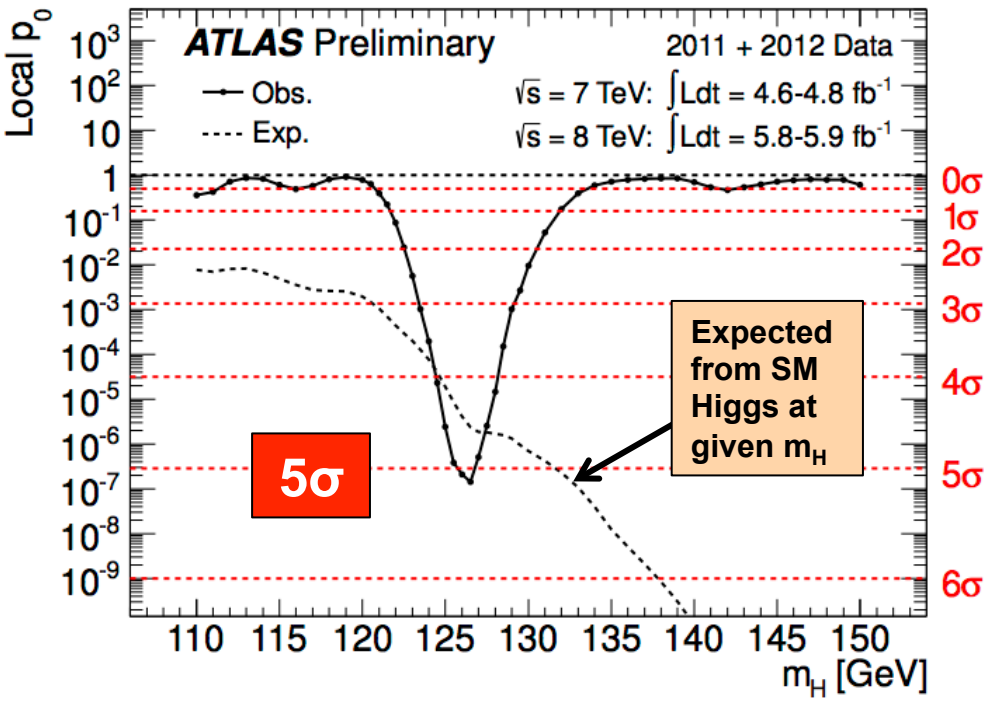


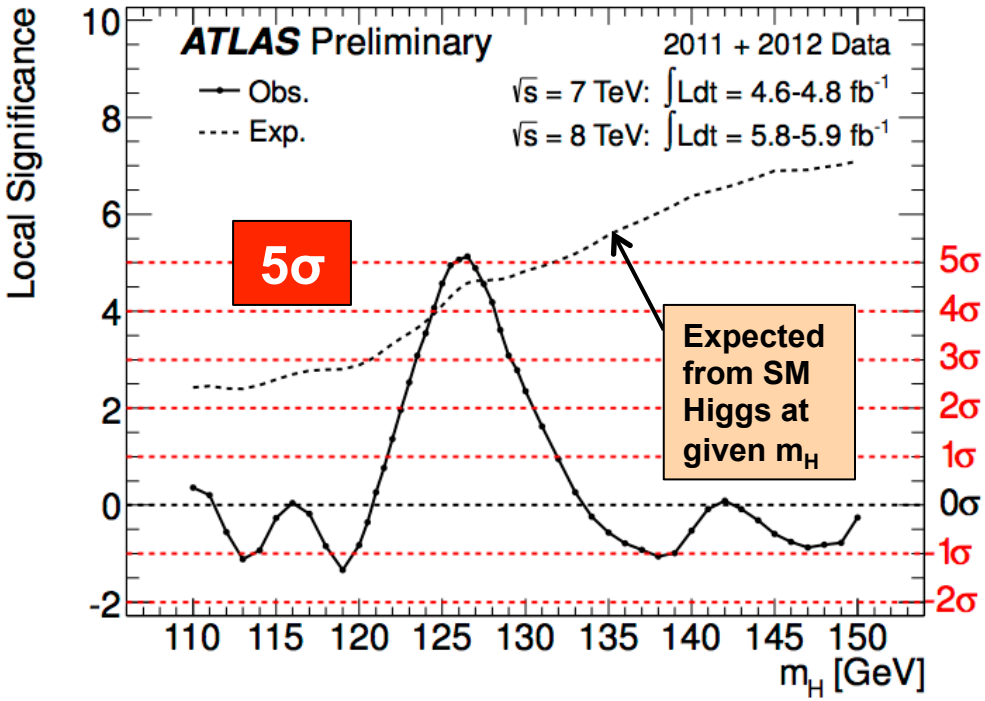
Exclusion at 95% C.L. :

- ***Expected*** $110 < m_H < 582$ ***GeV***
- ***Observed*** $110 < m_H < 122.6$ ***GeV,*** $129.7 < m_H < 558$ ***GeV***

Region around 126 GeV is not excluded

Higgs Combination The excess





Maximum excess observed at m_H = 126.5 GeV

Local significance *(including energy-scale systematics)*	***5.0 σ***
(p_0) *Probability that background fluctuates to the observed data (or higher)*	***3×10^{-7}***
Expected from SM Higgs m_H=126.5 GeV	***4.6 σ***

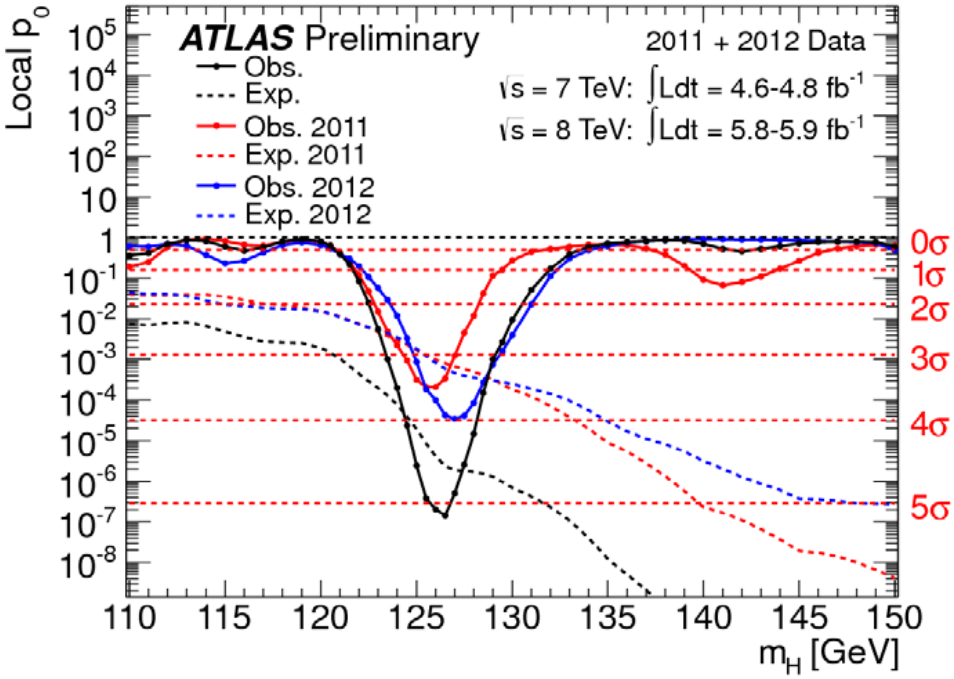
Global significance: 4.1-4.3 σ (for LEE over 110-600 or 110-150 GeV)

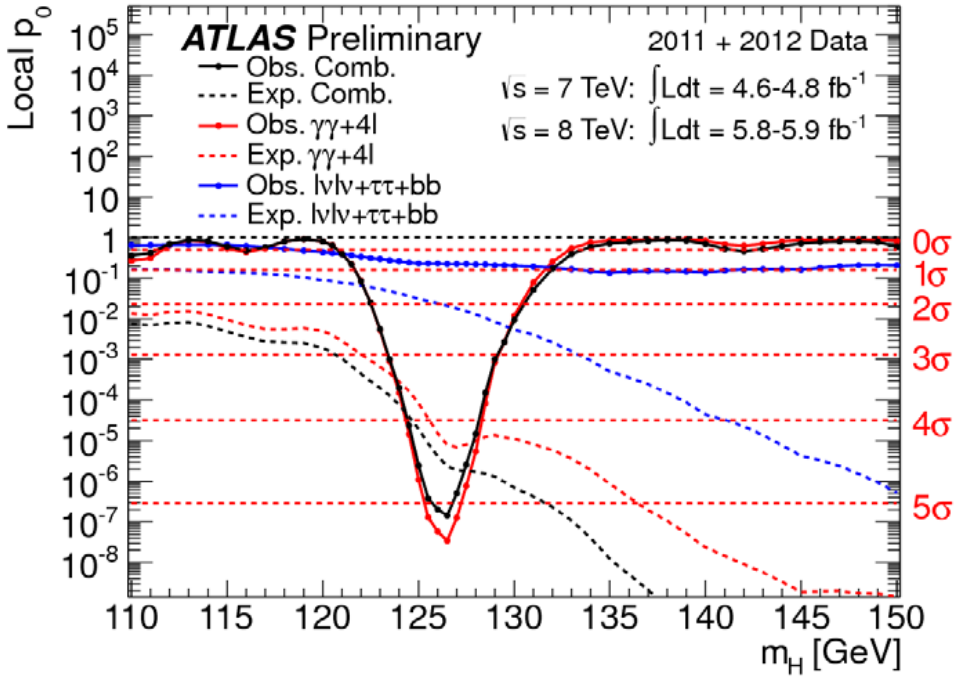
Higgs Combination

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.)

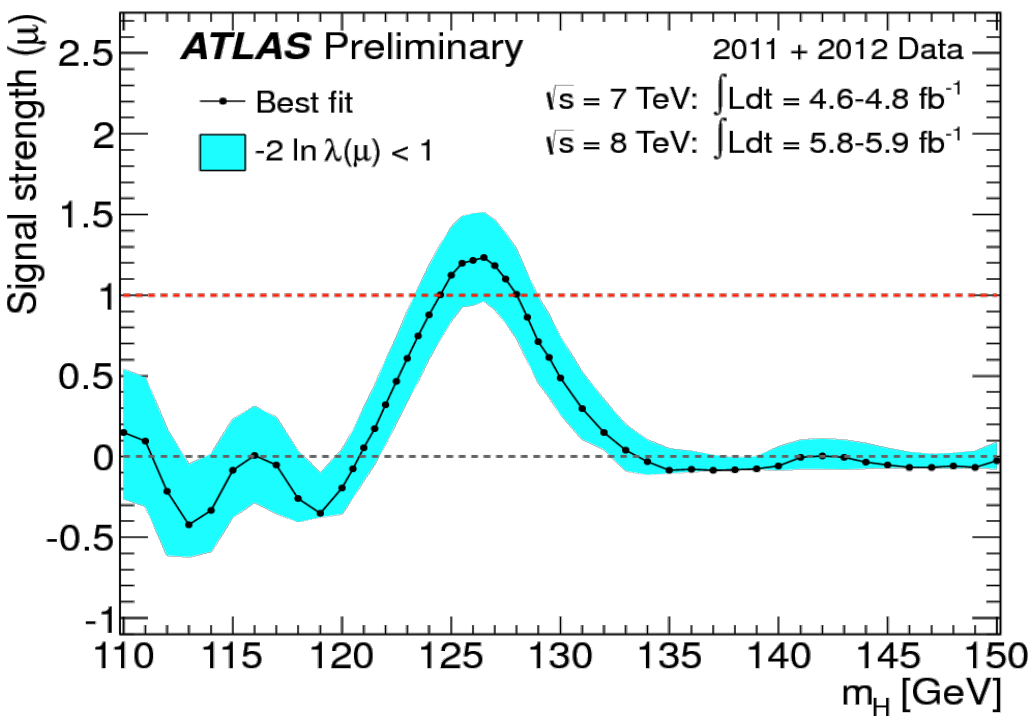


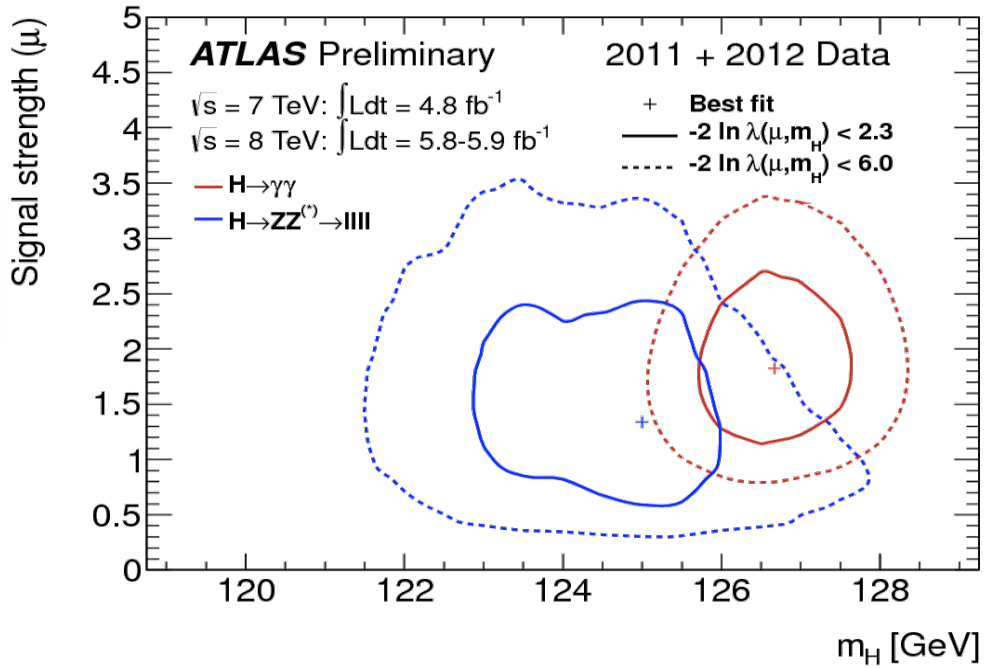


The excess for both years is dominated by H→γγ and H→ZZ→4 leptons

Higgs Combination Investigating the excess

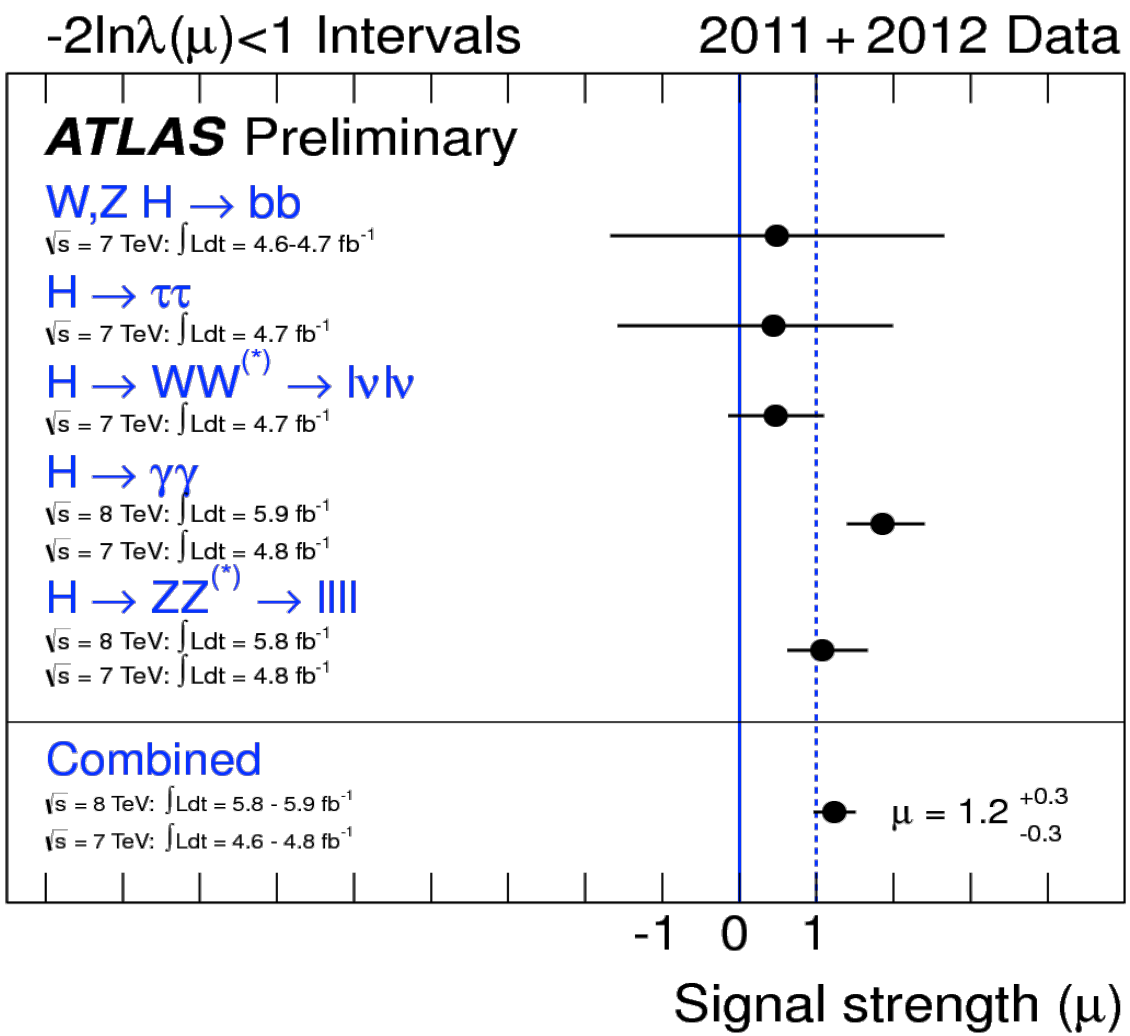
- ***Best fit signal strength (μ) vs m_H***
  - ***Scanning m_H to find best-fit value of μ at each m_H***
  - ***At 126.5 GeV, μ=1.2 ± 0.3***
    - ***Compatible with SM expectation (μ=1)***





- ***Let m_H and μ float, 2D contour plot around best fit values (~68% solid, 95% dashed)***
- ***Best fit masses for H→γγ and H→4-leptons are compatible.***

Higgs Combination
Contributions of the different channels at 126.5 GeV

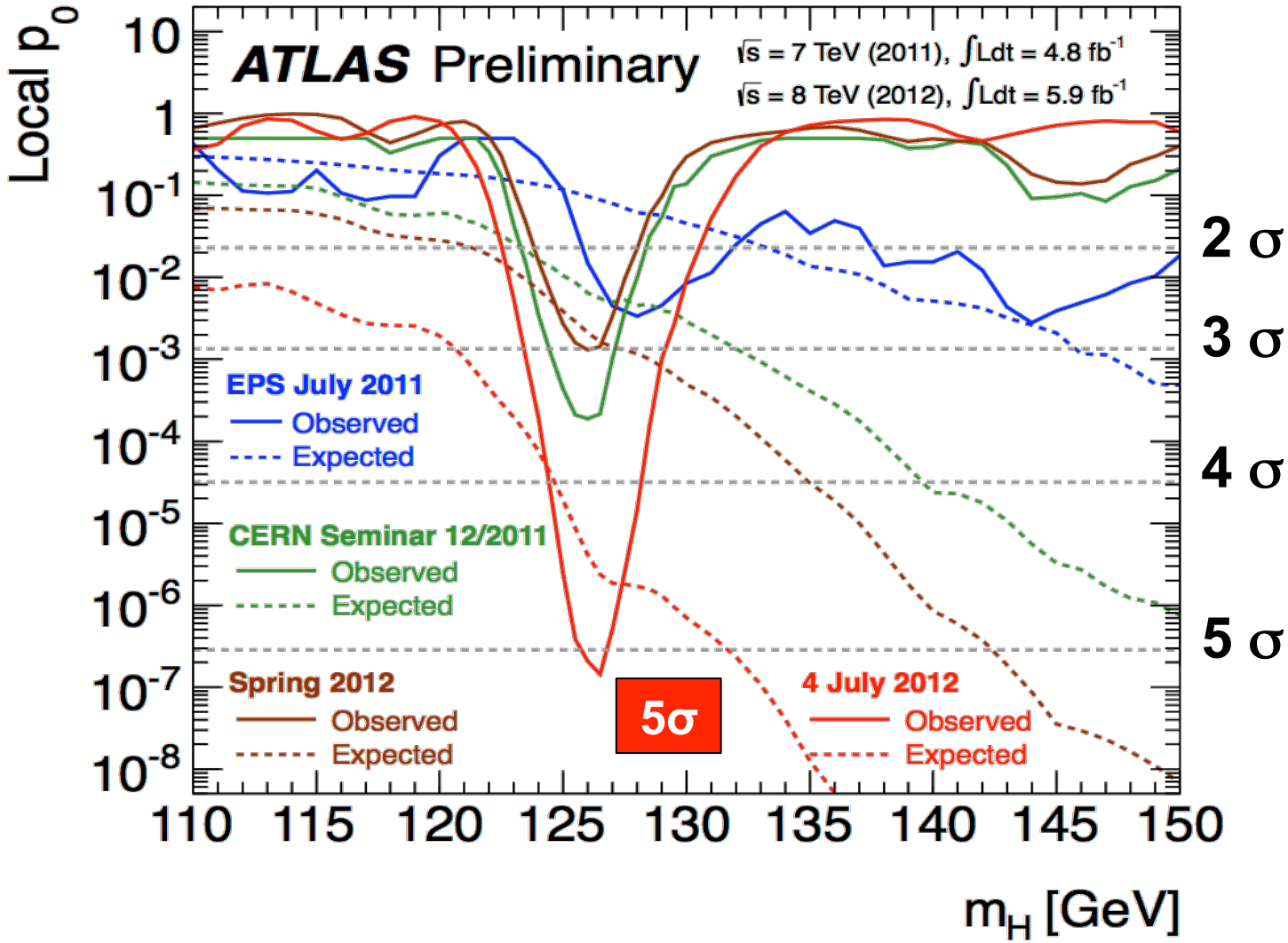


Combined signal strength:

μ=1.2 ± 0.3

Most important contributions from H→γγ, H→ZZ*→4l, H→WW*→lνlν

Higgs Combination
Development over time (history of p_0 values)



EPS July 2011

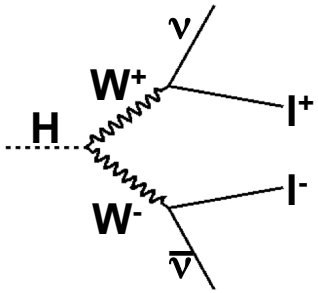
Council Dec 2011

Spring 2012

ICHEP 2012

(July 4, 2012)

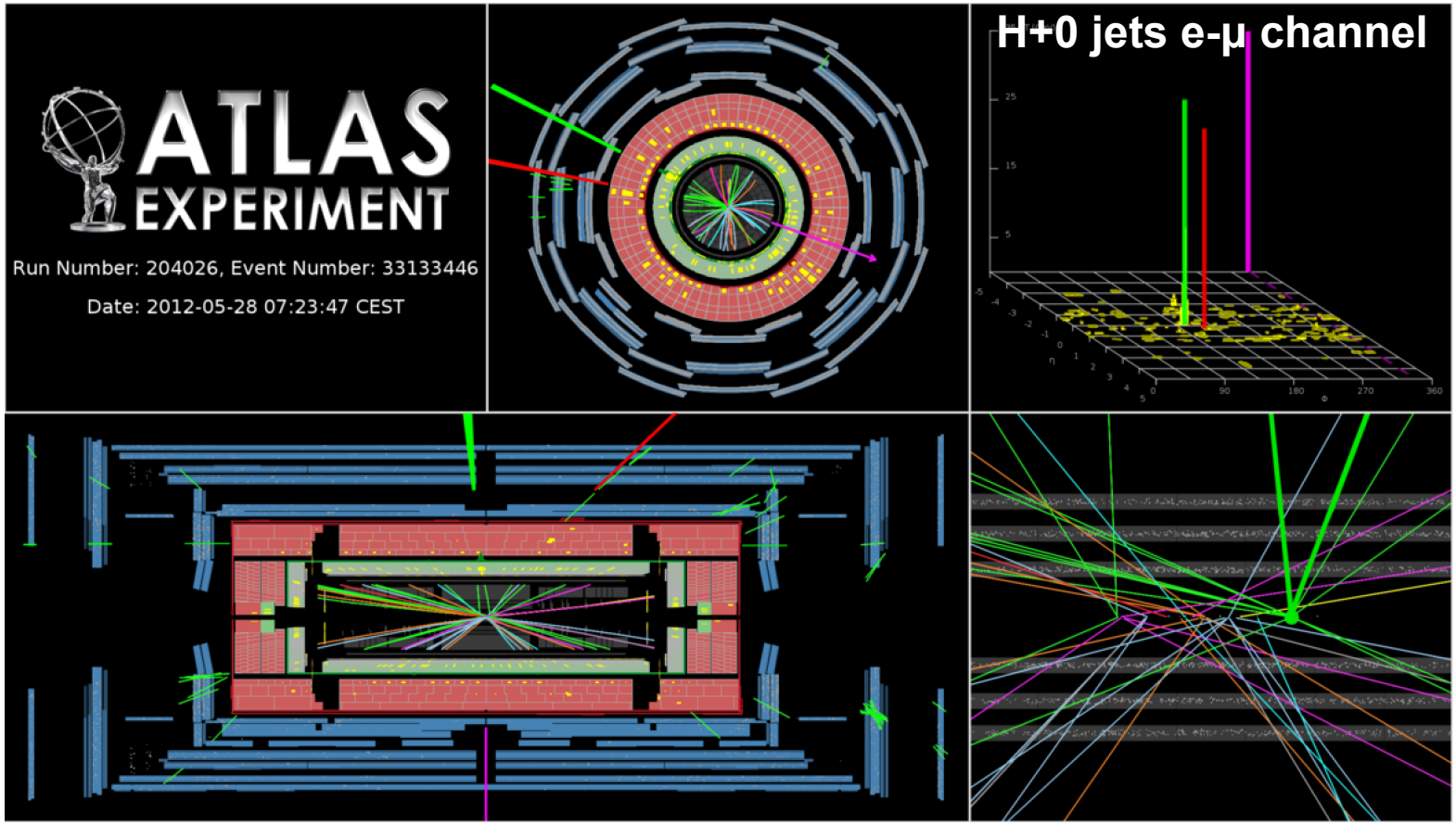
$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ *NEW* (Post July 4, 2012)



$\sigma(H \rightarrow WW^* \rightarrow \ell\nu\ell\nu) \approx$ 0.18 pb at 7 TeV ~ 900 in 5 fb-1

$\sigma(H \rightarrow WW^* \rightarrow \ell\nu\ell\nu) \approx$ 0.23 pb at 8 TeV ~ 1150 in 5 fb-1

(m_H=125 GeV)



p_T electron = 33 GeV

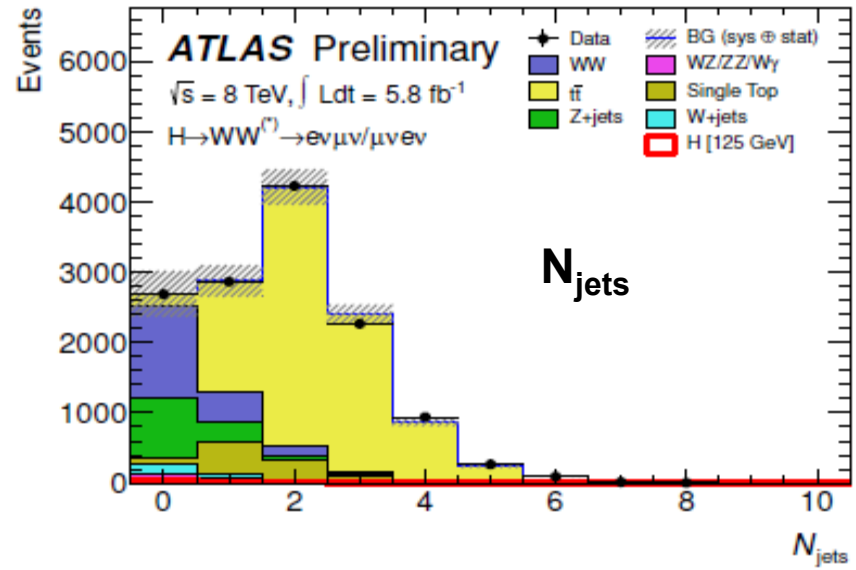
p_T muon = 29 GeV

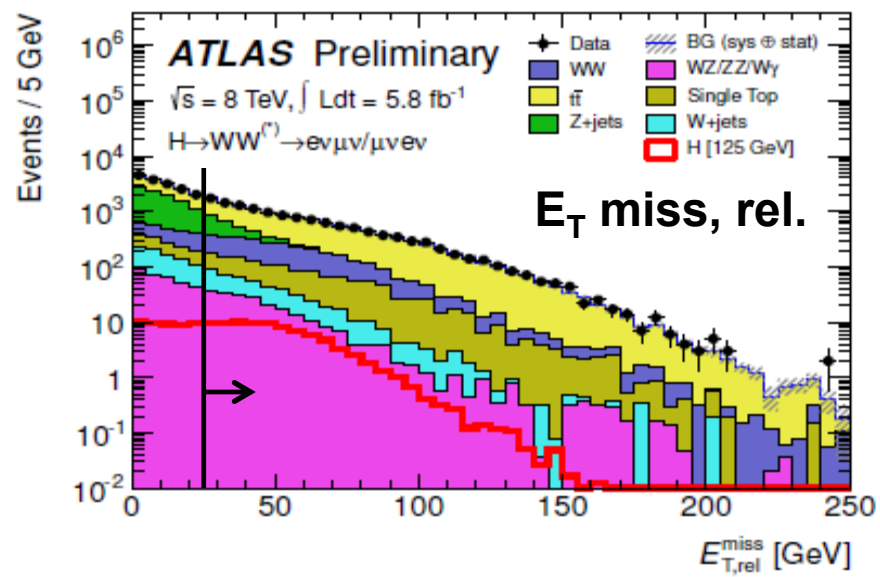
E_T miss, rel = 35 GeV

m_T = 94 GeV

$H \rightarrow WW^* \rightarrow e\mu\nu\nu$ Analysis strategy (Post July 4, 2012)

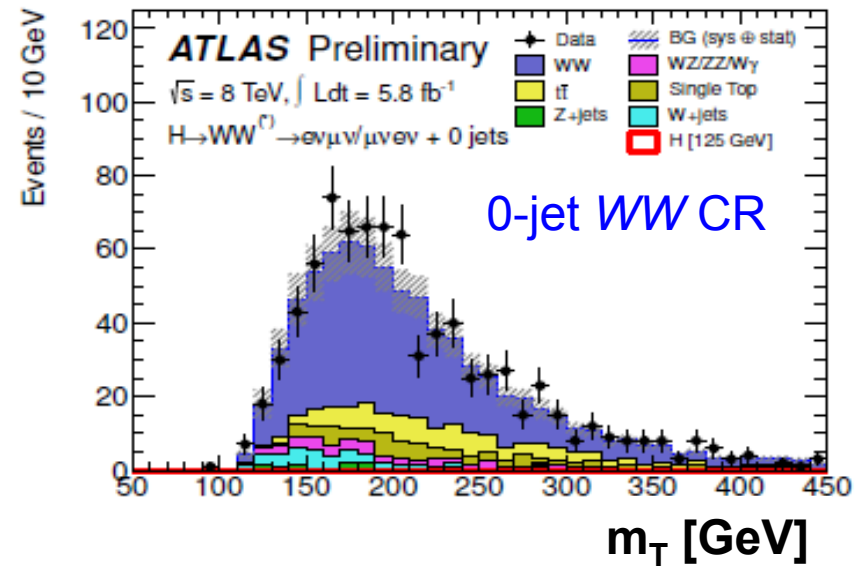
- ***Search in range $110 < m_H < 190$ GeV with 2012 data.***
- ***Analysis in 3 jet bins: 0-jet, 1-jet, at least 2 jets***
- ***Large pile-up in 2012 results in larger fake MET compared to 2011 data***
  - *Drell-Yan background much worse in ee, μμ final states*
- ***Only opposite-flavor final states used in 2012 analysis (μe, eμ)***
  - *eμ and μe channels separated based on which lepton has higher p_T*
  - *search sensitivity comes largely from opposite-flavor final states*
- ***Analysis blinded during development***

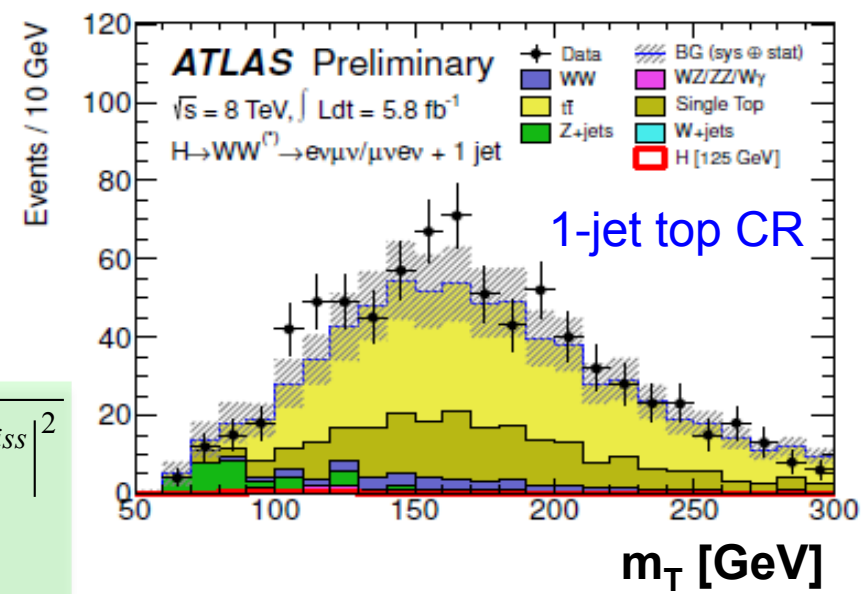




$H \rightarrow WW^* \rightarrow e\mu\nu\nu$ Backgrounds

- ***Major backgrounds determined and/or validated using data control regions (CRs)***
- ***W+jets:*** *fully data-driven; CR defined using loosely identified leptons*
- ***WW:*** *data CR defined using* $m_{\ell\ell} > 80$ *GeV, extrapolated to signal region using MC-derived scale factor*
- ***Top:*** *data CR defined by requiring b-tagged jet, extrapolated to signal region using MC-derived scale factor*
- ***Z+jets:*** *estimated from MC prediction*
- **Dibosons other than *WW*:** *estimated from MC prediction (validated using same-sign CR in data)*



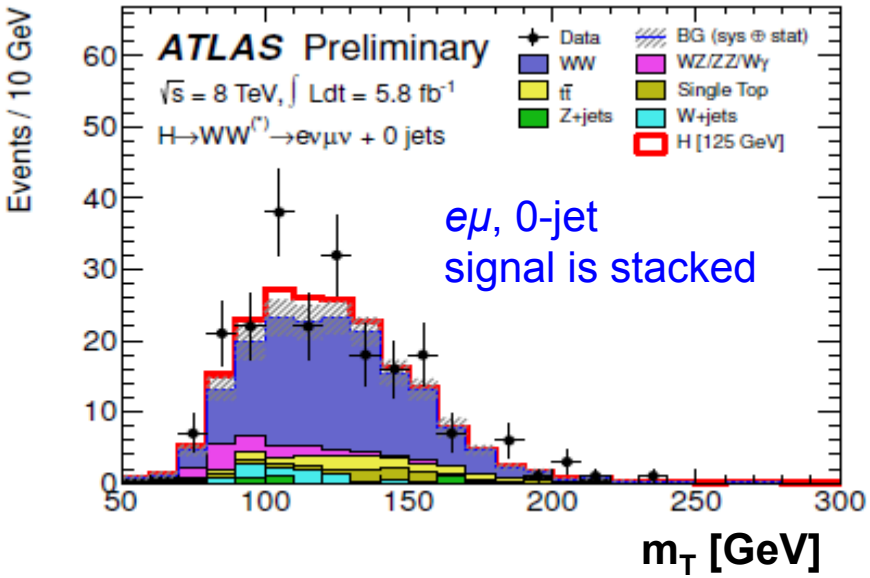


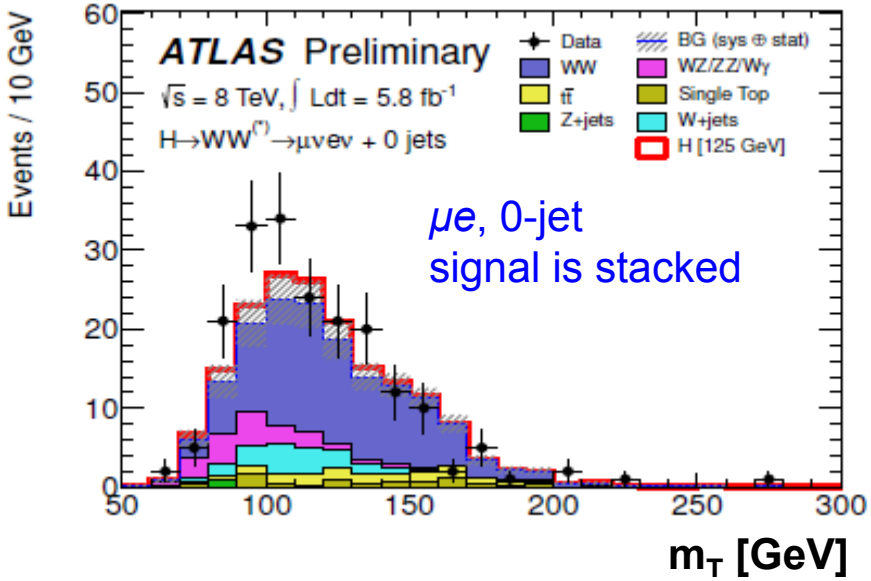
The transverse mass: $m_T = \sqrt{\left(E_T^{ll} + E_T^{miss}\right)^2 - \left|p_T^{ll} + E_T^{miss}\right|^2}$

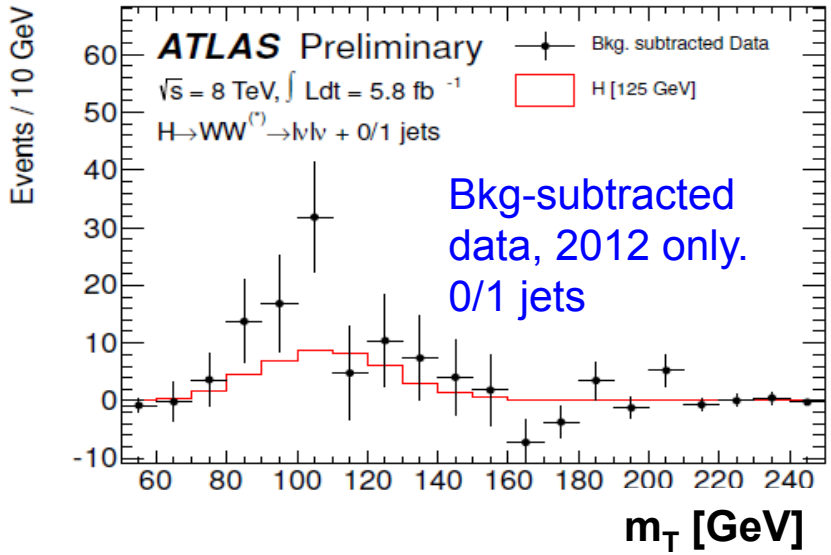
with $E_T^{ll} = \sqrt{\left|p_T^{ll}\right|^2 + m_{ll}^2}$

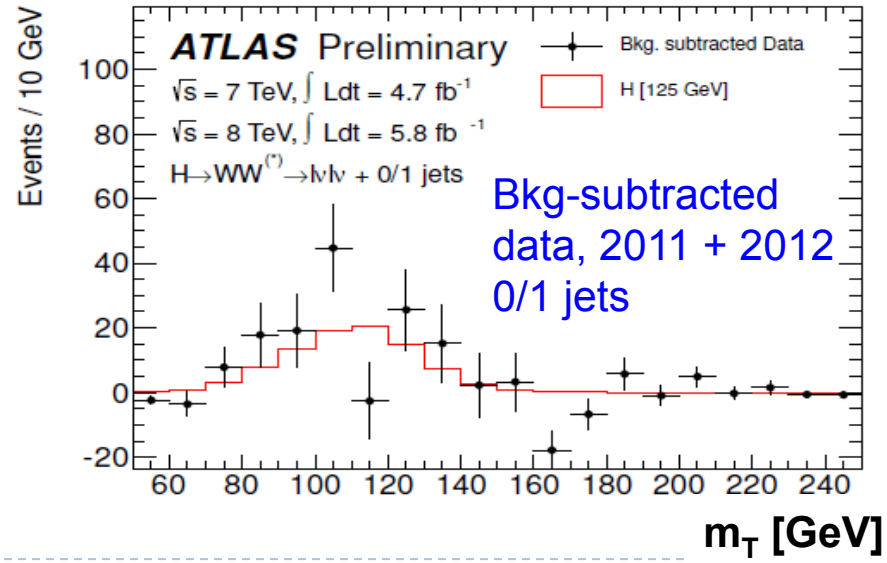
$H \rightarrow WW^* \rightarrow e\mu\nu\nu$ M_T distributions in signal region

- ***m_T shape is fitted to extract signal significance***

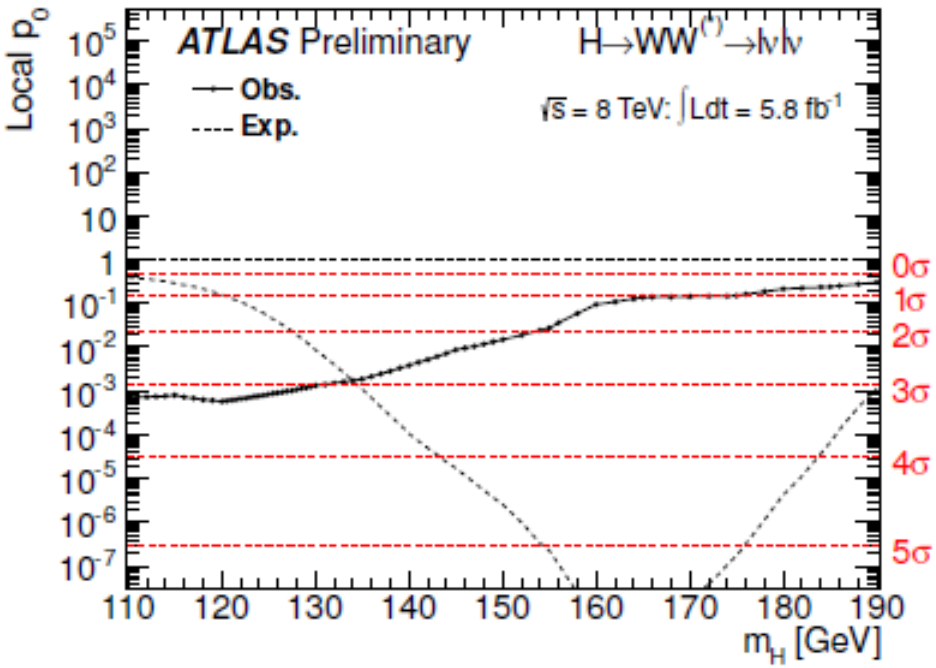


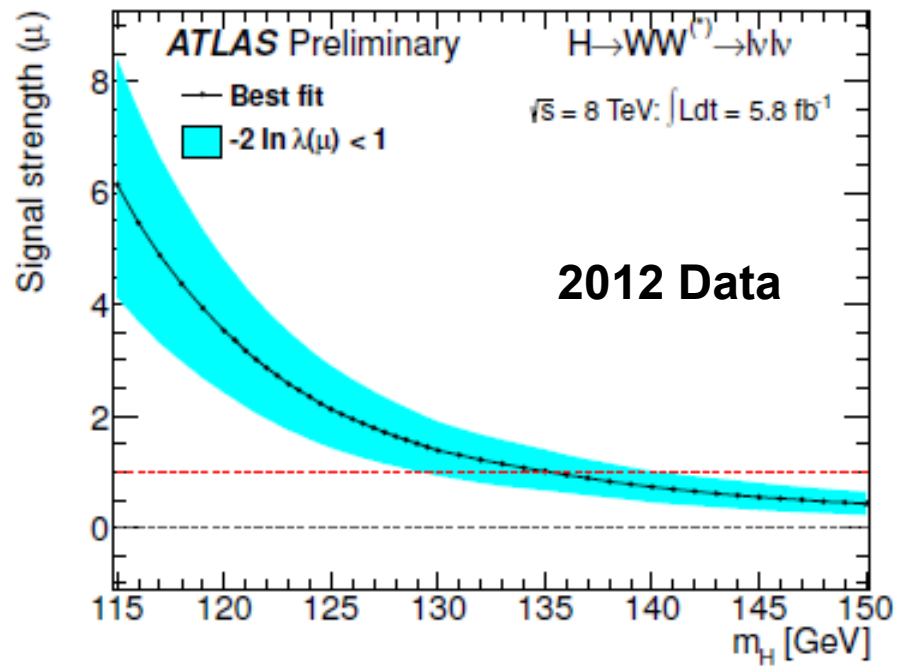






$H \rightarrow WW^* \rightarrow e\mu\nu\nu$ Results with 2012 data





m_H = 125 GeV

p_0	Observed significance	Expected significance
8×10^{-4}	3.1 σ	1.6 σ

At m_H = 125 GeV:

2011 signal strength (μ):

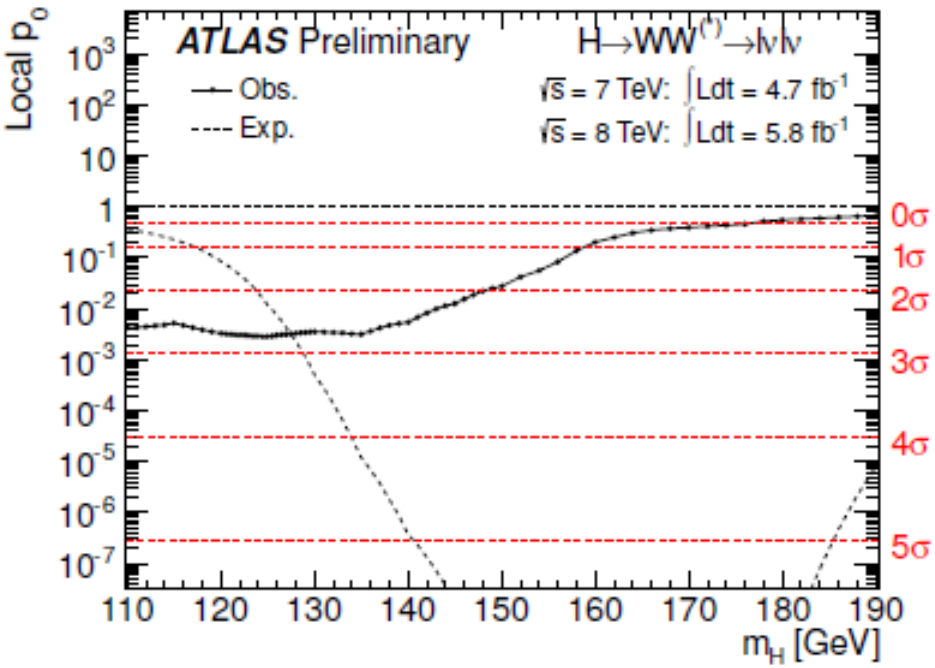
$$\mu = 0.5 \pm 0.7$$

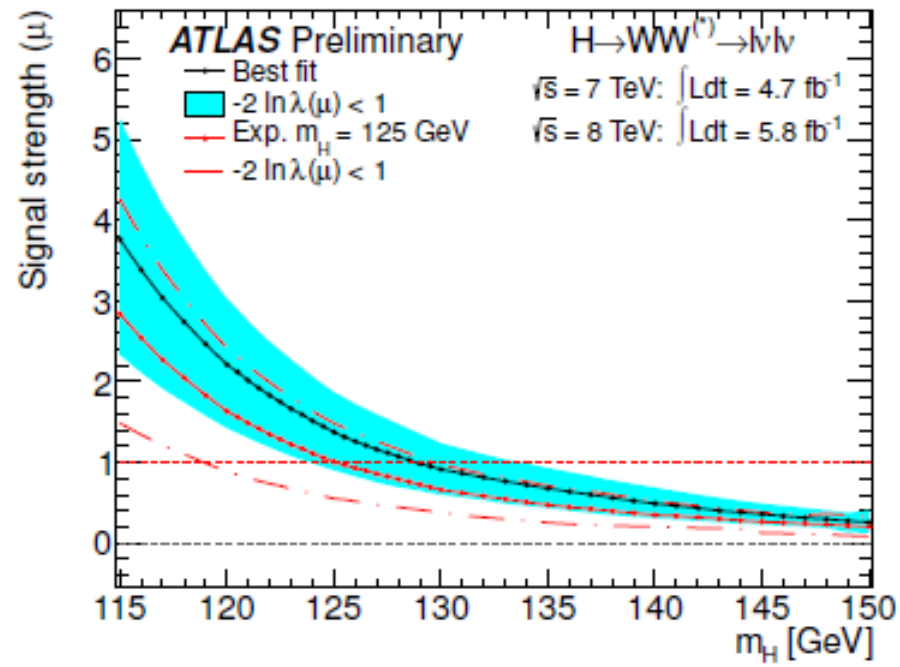
2012 signal strength (μ):

$$\mu = 2.1^{+0.8}_{-0.7}$$

2011, 2012 signal strengths compatible within 1.5 standard deviations

$H \rightarrow WW^* \rightarrow e\mu\nu\nu$ 2011 + 2012 data





m_H = 125 GeV

p_0	Observed significance	Expected significance
3×10^{-3}	**2.8 σ**	**2.3 σ**

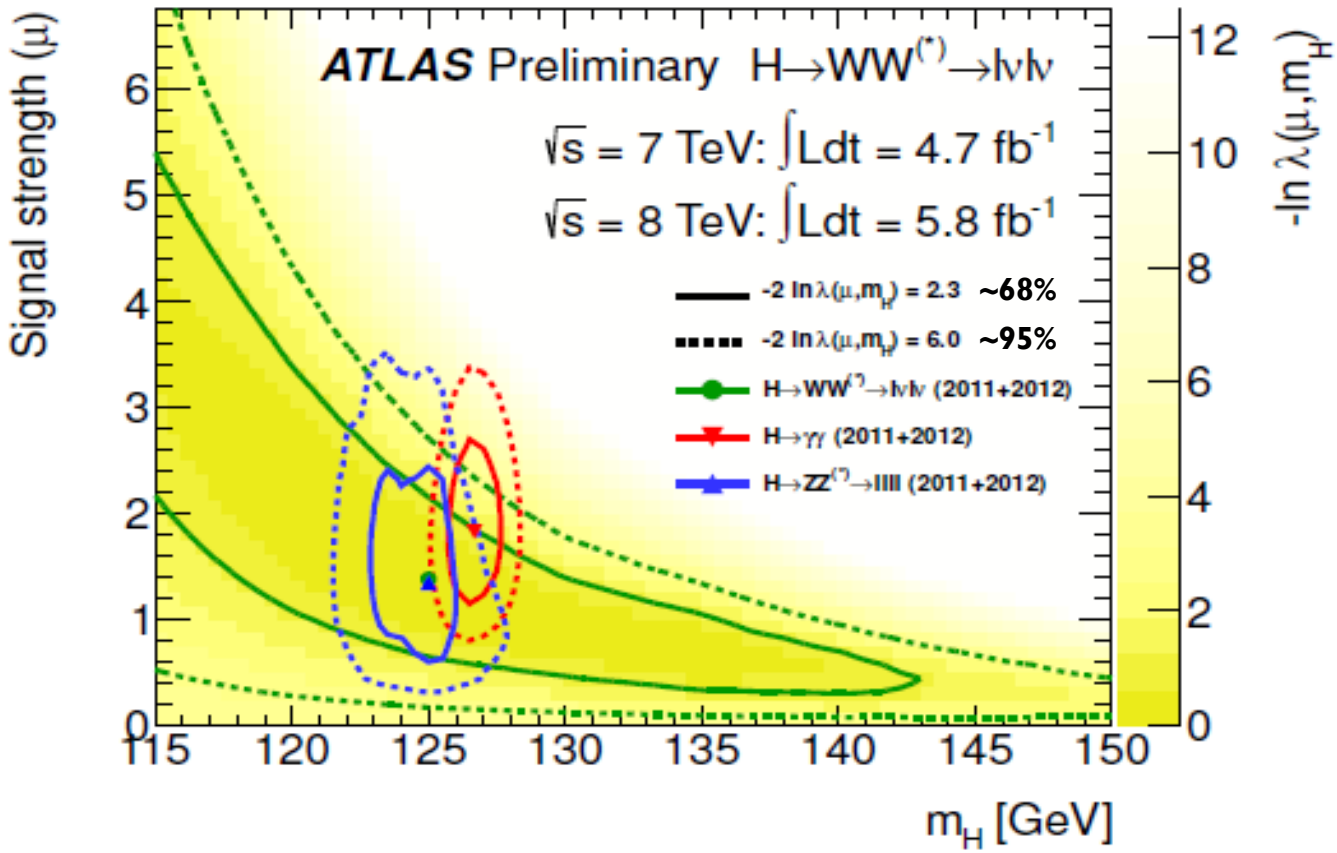
Signal strength (μ): $\mu = 1.4 \pm 0.5$

(At 126.5 GeV, $\mu = 1.2^{+0.5}_{-0.4}$ GeV)

Event yield in 2012

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

$H \rightarrow WW^* \rightarrow e\mu\nu\nu$ 2D likelihood contour



- *Likelihood ratio contours from scan of μ and m_H fits.*
- *Contours from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ overlay.*
- *In spite of poor mass resolution in $H \rightarrow WW$, good agreement among three analyses*

$H \rightarrow WW^* \rightarrow e\mu\nu\nu$ Preview

Adding 2012 WW data to ATLAS Higgs combination:

(Eilam Gross, presented in ICHEP by Biagio di Micco)

At m_H=126.5 GeV

- ***In case of no signal observed (μ=0) WW would bring the combined significance to 4.6 σ and the best fit to μ=0.99***
- ***In case of an observation at μ=1, the combined significance would go to 5.4 σ and μ=1.18***
- ***With an observation at μ=1.2 (at m_H=126.5 GeV), the significance will go to…***

Stay tuned for the July 31 publication!

Higgs Conclusions

- *"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, CERN Director General*

- *ATLAS searched for the SM Higgs in >10 fb^{-1} data*
- *Discovery of a new narrow resonance at 126.5 GeV* **5σ**
- *m_H region excluded at 95% C.L.: 110-557 GeV (except 122.7-129 GeV)*

	Observed significance	Expected significance	Signal strength (μ)
H→γγ	4.5 σ	2.4 σ	1.9 ± 0.5 at 126.5 GeV
H→4-leptons	3.4 σ	2.6 σ	1.3 ± 0.6 at 125 GeV
Combined with other channels	5.0 σ	4.6 σ	1.2 ± 0.3 at 126.5 GeV
Post July 4, 2012			
H→WW	2.8 σ	2.3 σ	1.4 ± 0.5 at 125 GeV
			(1.2 ± 0.4 at 126.5 GeV)

5.0σ: 1 in 3.5 million chances

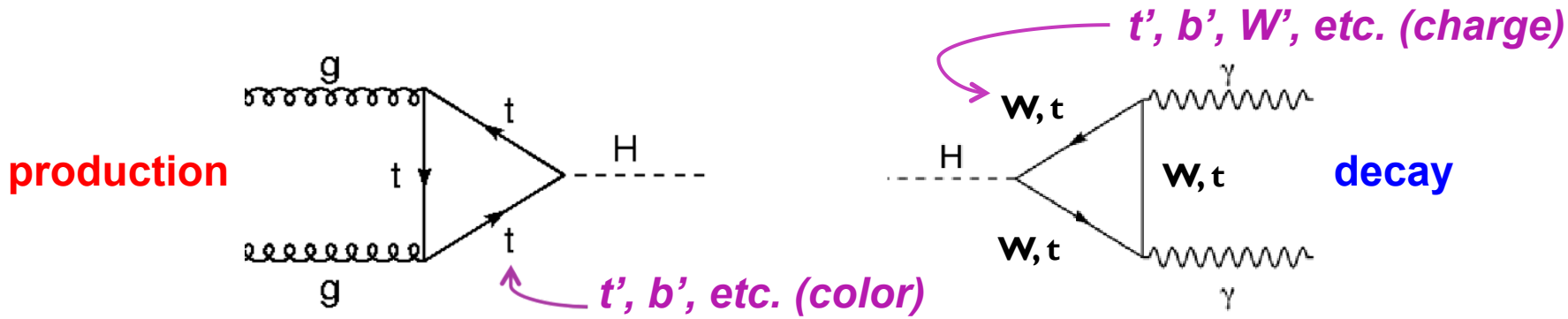
Higgs Plans

- ***ATLAS plans to submit a paper at the end of July, at the same time as CMS and to the same journal.***
- ***Plans for other channels:***
  - ***Include $H \rightarrow WW^{(*)} \rightarrow e\mu\nu\nu$ results in the July paper***
  - ***$H \rightarrow \tau\tau$, $W/ZH \rightarrow bb$: results with 2012 data in the Fall***
- ***Extension for data taking until December 17, 2012.***

  ~25 fb^{-1} expected at 8 TeV, to add to 5 fb^{-1} from 2011.
- ***Work in progress on properties of the new particle (spin, mass, couplings, cross-section) to test if they are consistent with the SM Higgs.***
- ***If confirmed, the LHC is the first accelerator to discover and study elementary particles of spin-0.***

Higgs Excitement has just begun

- ***The Higgs particle is the first known elementary spin-0 boson. There may well be others.***
- ***If the large signal strength (μ) for H→ γγ (1.9±0.5 for ATLAS, 1.6±0.4 for CMS) is sustained with higher statistics, then new physics will surface.***



- ***In the SM, the most important Higgs production process in pp interactions is gluon fusion through a top triangle.***
- ***If the SM is not the whole story, the situation becomes quite interesting: additional heavy particles could contribute to these triangles:***
  - ***New particles with color would contribute to the production triangle***
  - ***New particles with charge would contribute to the decay loop***
- ***The presence of such new particles may enhance Higgs production and its decay into two photons.***

Photos to celebrate…

On July 4, at the end of the CERN seminar I went to shake hands with Prof. Higgs. I told him "I have been looking for you for over 20 years". He replied "now, you have found me".

Photos to celebrate…

On July 4, 2012 the Higgs working group had a celebratory drink. Everyone is watching the corks of the champagne bottles flying up to the ceiling.

Photos to celebrate…

On July 4, 2012, Eilam Gross (ATLAS Higgs Convener) and Sau Lan

BACKUP

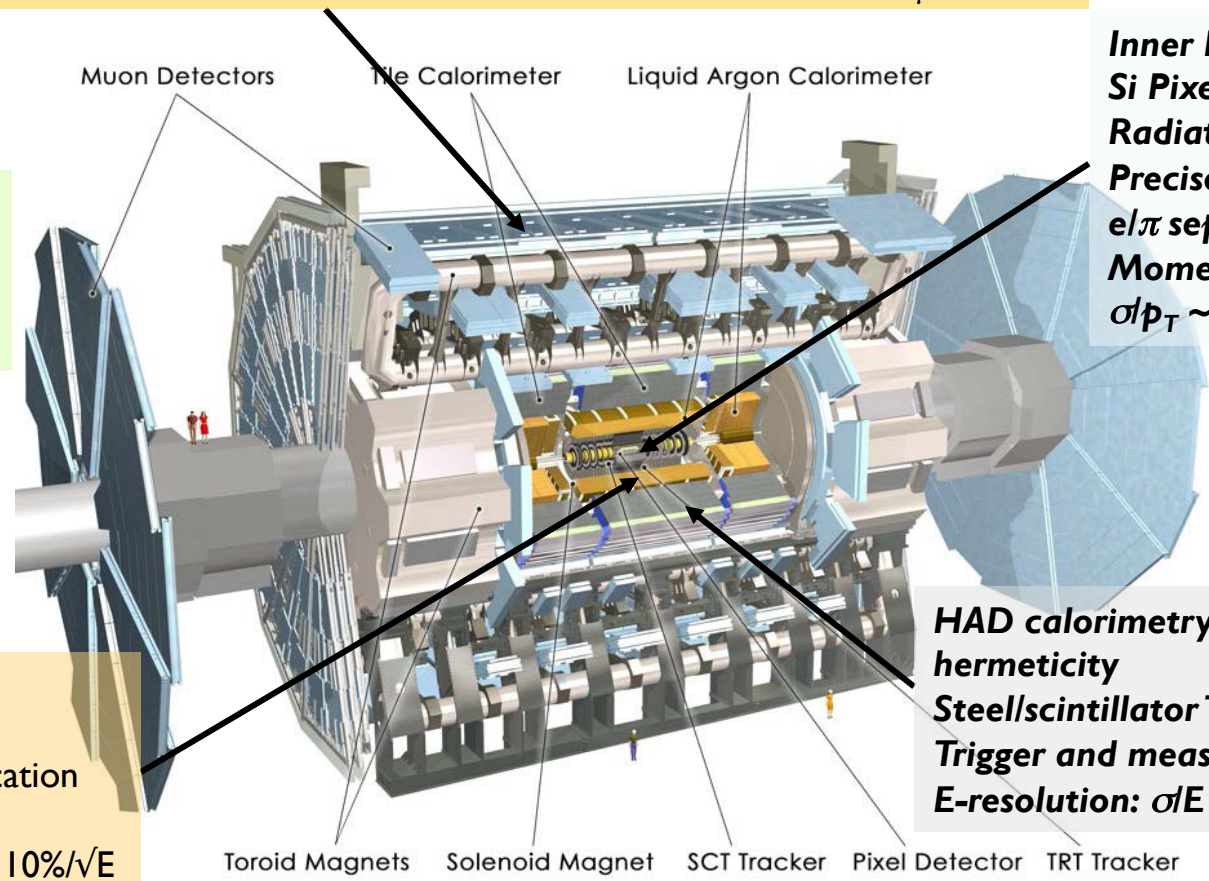
ATLAS

The ATLAS (A Toroidal LHC ApparatuS) Detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV

3-level trigger reducing the rate from 40 MHz to ~ 400 Hz

Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T\,(\mathrm{GeV}) \oplus 0.015$



EM calorimeter:
Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

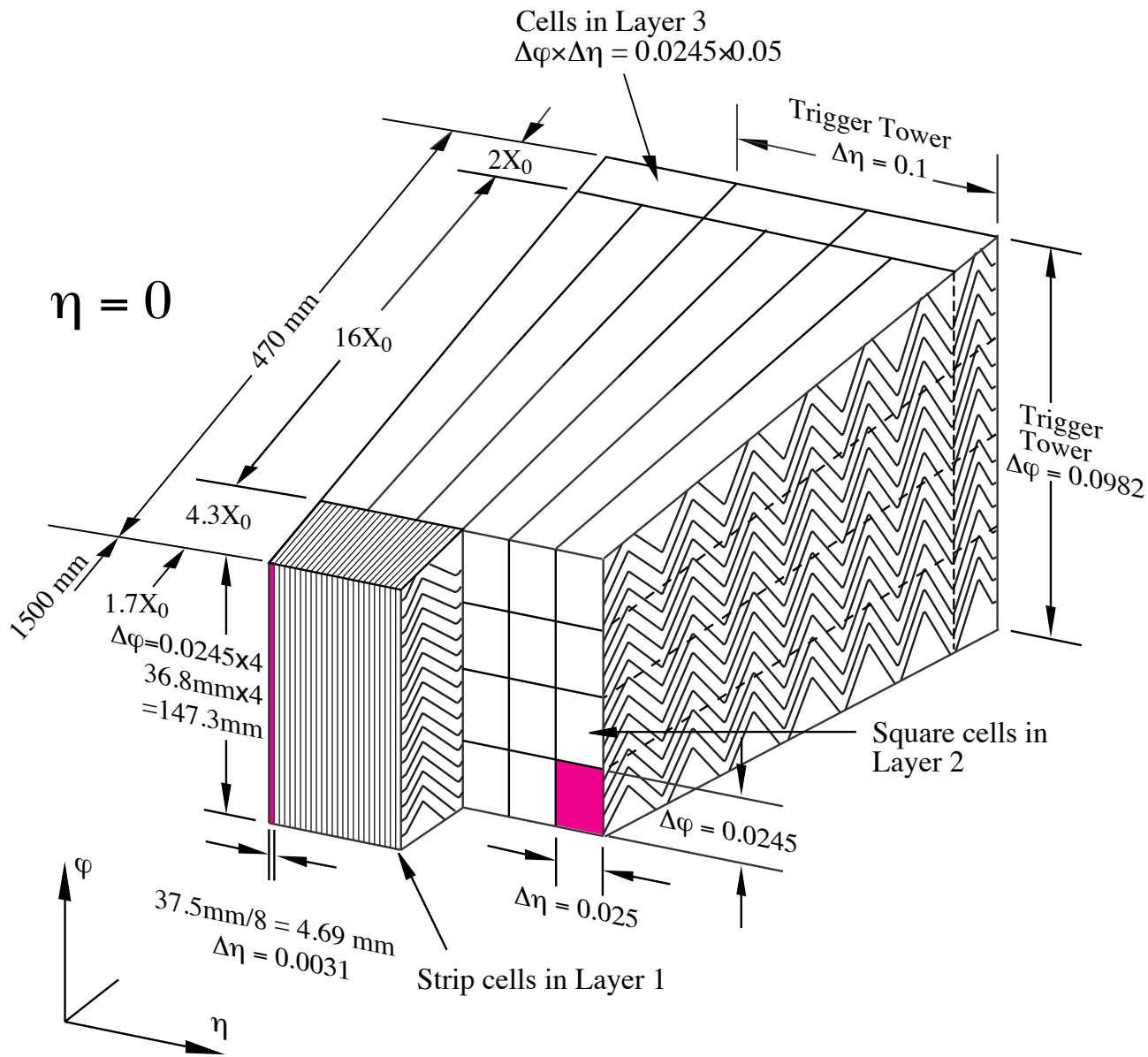
HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Steel/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

- ***Size: (length 45m, diameter 25m), 7000 tons***
- ***Fast response (~50ns) for analyzing up to 40 million collisions per second***
- ***10^8 electronic channels to reconstruct ~1000 particles / event with 10^{-5}m precision***

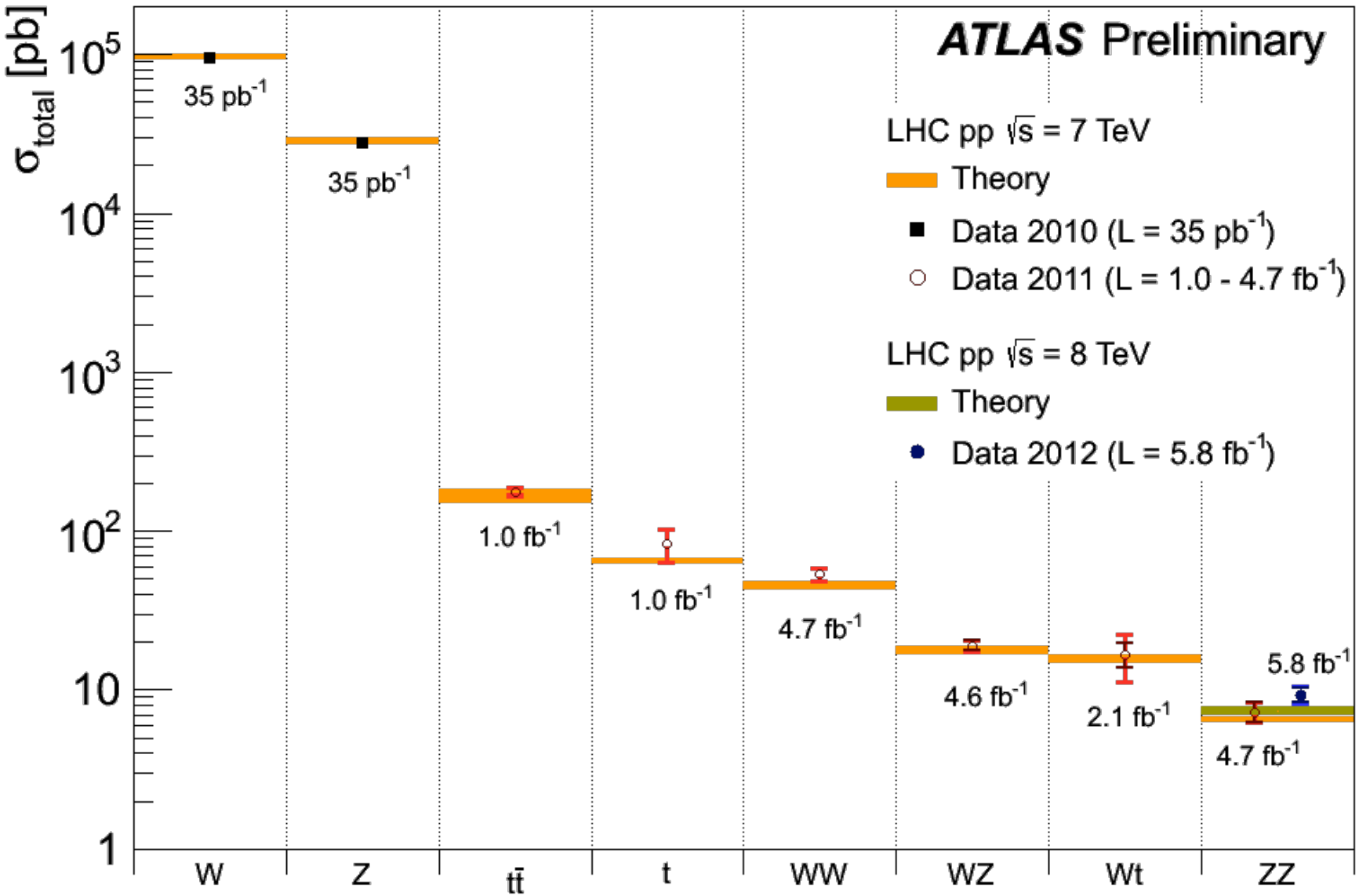
The ATLAS Collaboration

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

The ATLAS EM calorimeter

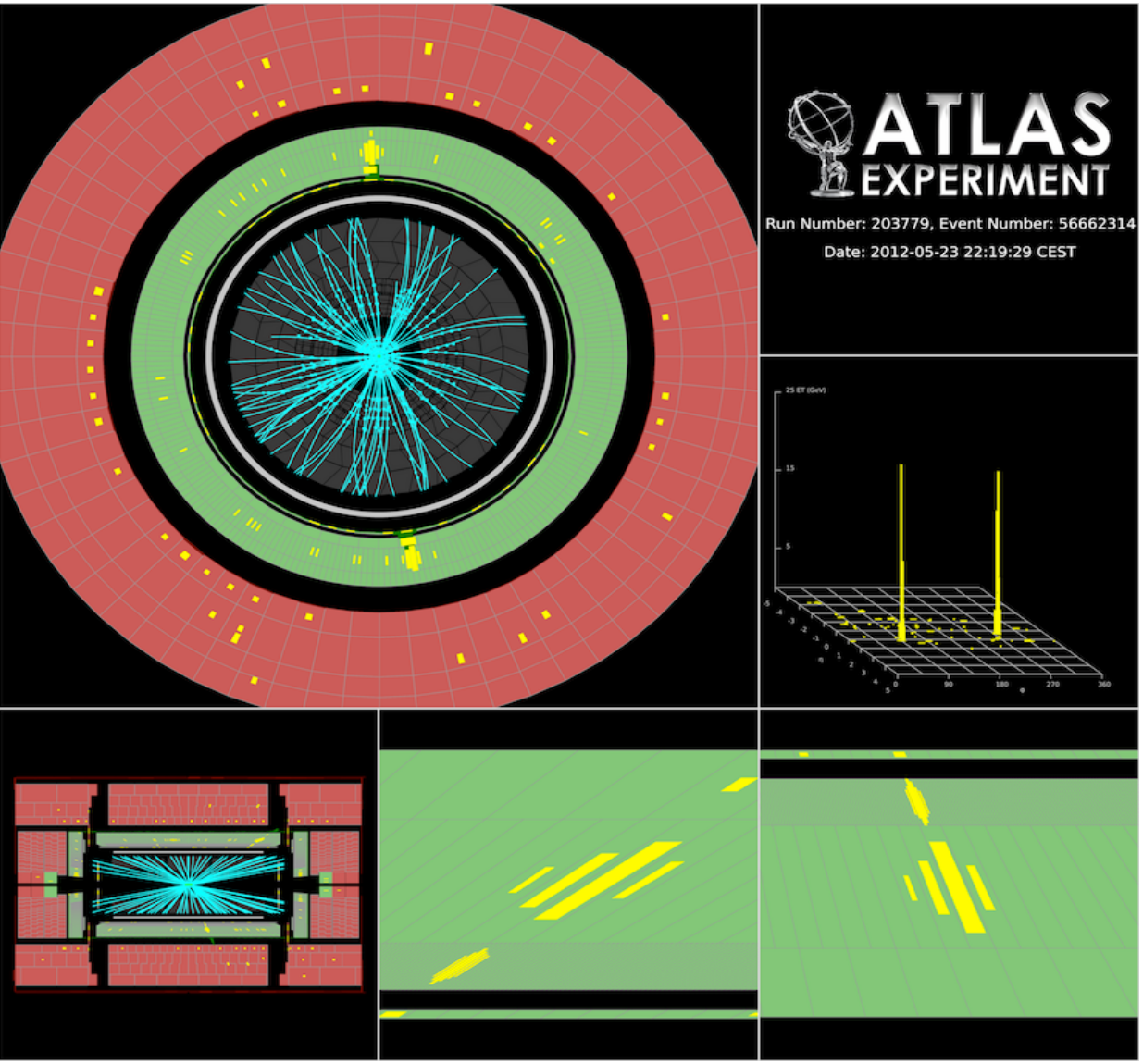


Most recent electroweak and top cross-section measurements

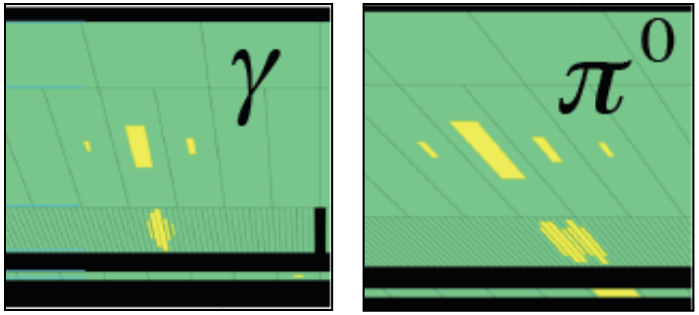


$H \rightarrow \gamma\gamma$

$H \rightarrow \gamma\gamma$ Separation of γ and π^0 in LAr calorimeter



- **Photon 'pointing' to locate primary vertex using finely segmented calorimeter layer.**



- **Composition of $\gamma\gamma$ sample:**
  - **75-80% QCD $\gamma\gamma$ production**
  - **20-25% γ-jet or jet-jet, jet mis-ID e.g. due to hard π^0**
- **Fraction of converted and unconverted γ vs pileup is stable (within 1%)**

$H \rightarrow \gamma\gamma$ Categories at 8 TeV

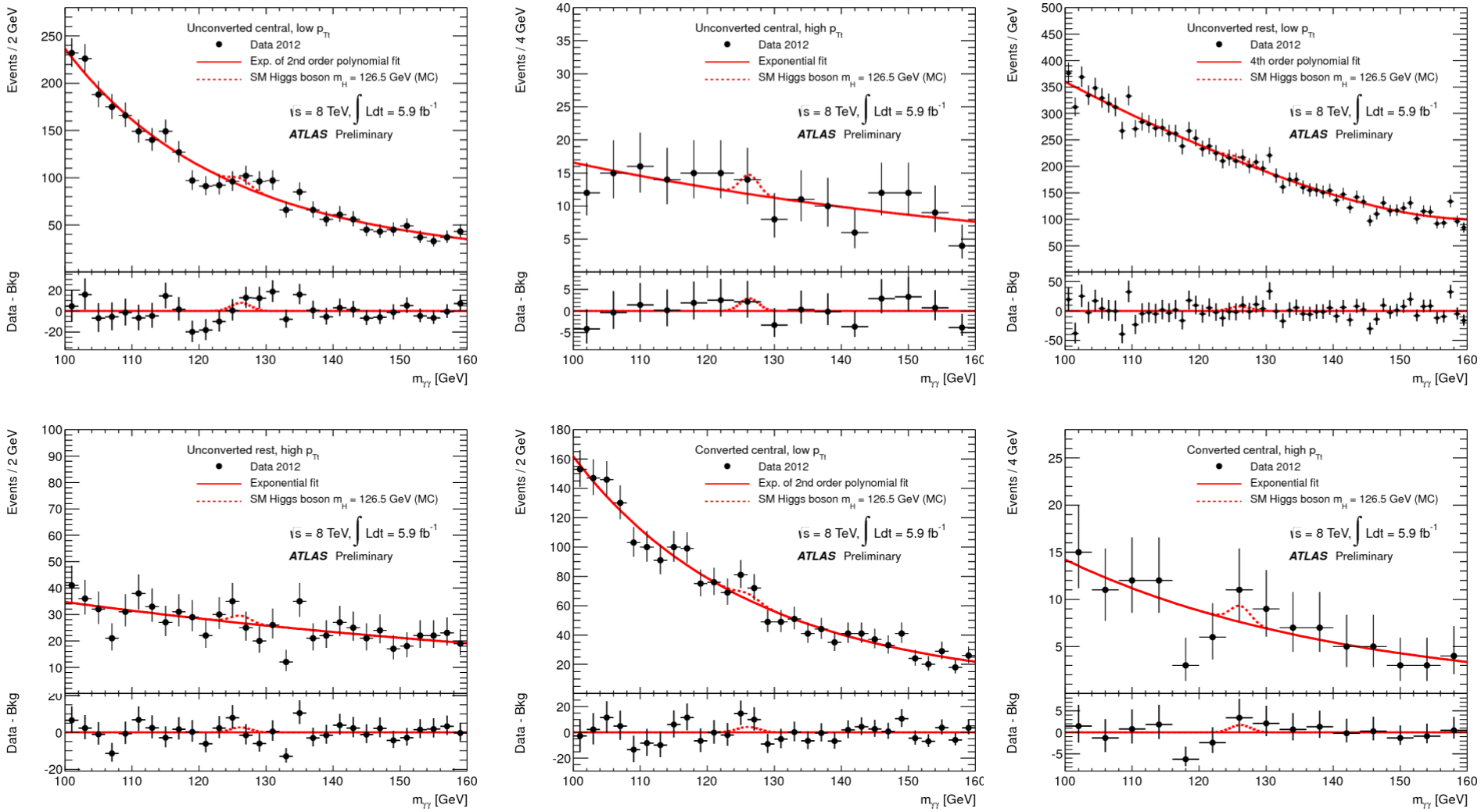
Strength of categorization: different resolution, different S/B (1%-20%)

Category	σ_{CB} [GeV]	FWHM [GeV]	Observed [N_{evt}]	S [N_{evt}]	B [N_{evt}]
Inclusive	1.63	3.87	3693	100.4	3635
Unconverted central, low p_{Tt}	1.45	3.42	235	13.0	215
Unconverted central, high p_{Tt}	1.37	3.23	15	2.3	14
Unconverted rest, low p_{Tt}	1.57	3.72	1131	28.3	1133
Unconverted rest, high p_{Tt}	1.51	3.55	75	4.8	68
Converted central, low p_{Tt}	1.67	3.94	208	8.2	193
Converted central, high p_{Tt}	1.50	3.54	13	1.5	10
Converted rest, low p_{Tt}	1.93	4.54	1350	24.6	1346
Converted rest, high p_{Tt}	1.68	3.96	69	4.1	72
Converted transition	2.65	6.24	880	11.7	845
2-jets	1.57	3.70	18	2.6	12

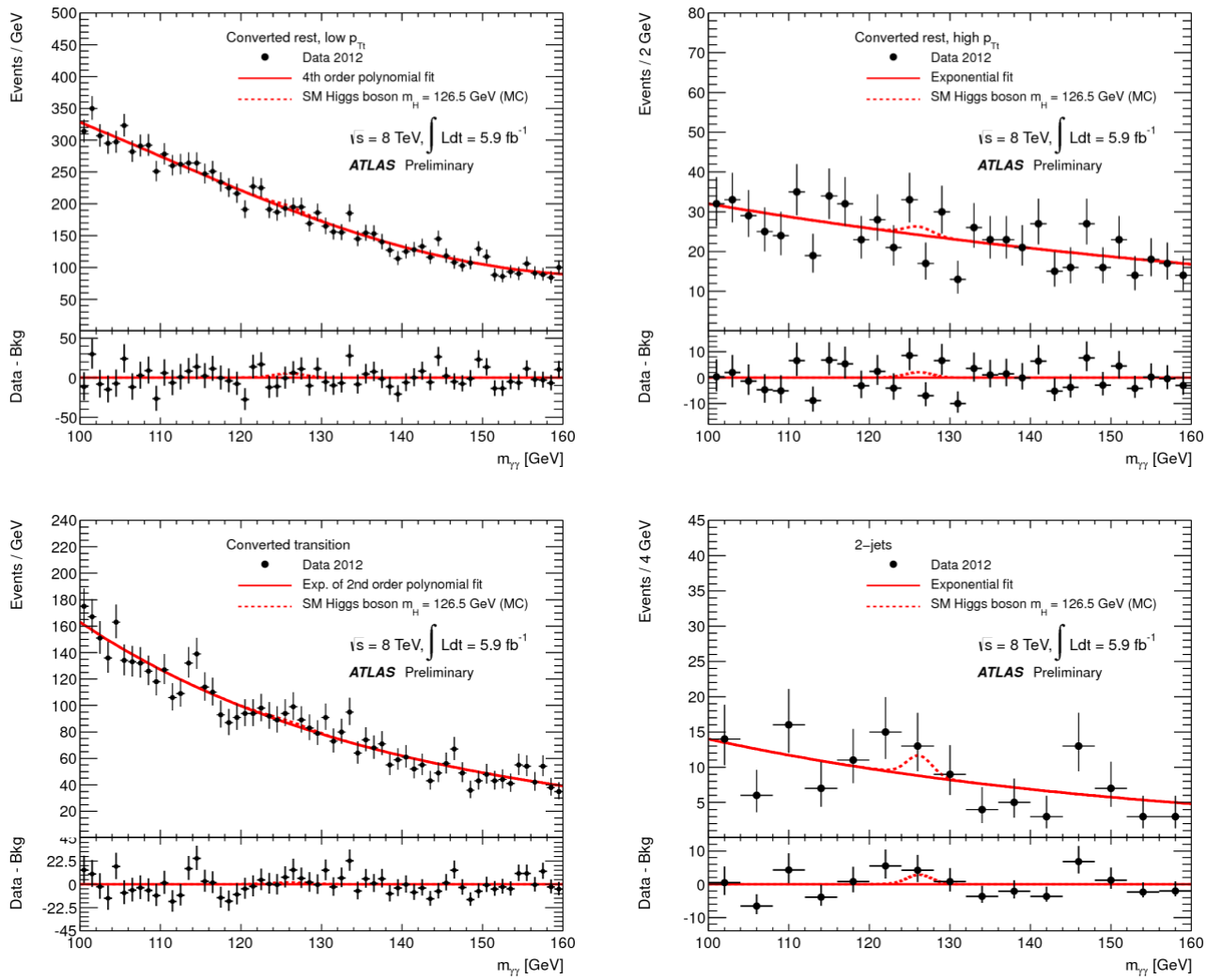
in a window that would contain 90% of signal events

"High"-statistics categories and 2-jets expected to dominate result

$H \rightarrow \gamma\gamma$ Invariant mass by category (8 TeV)



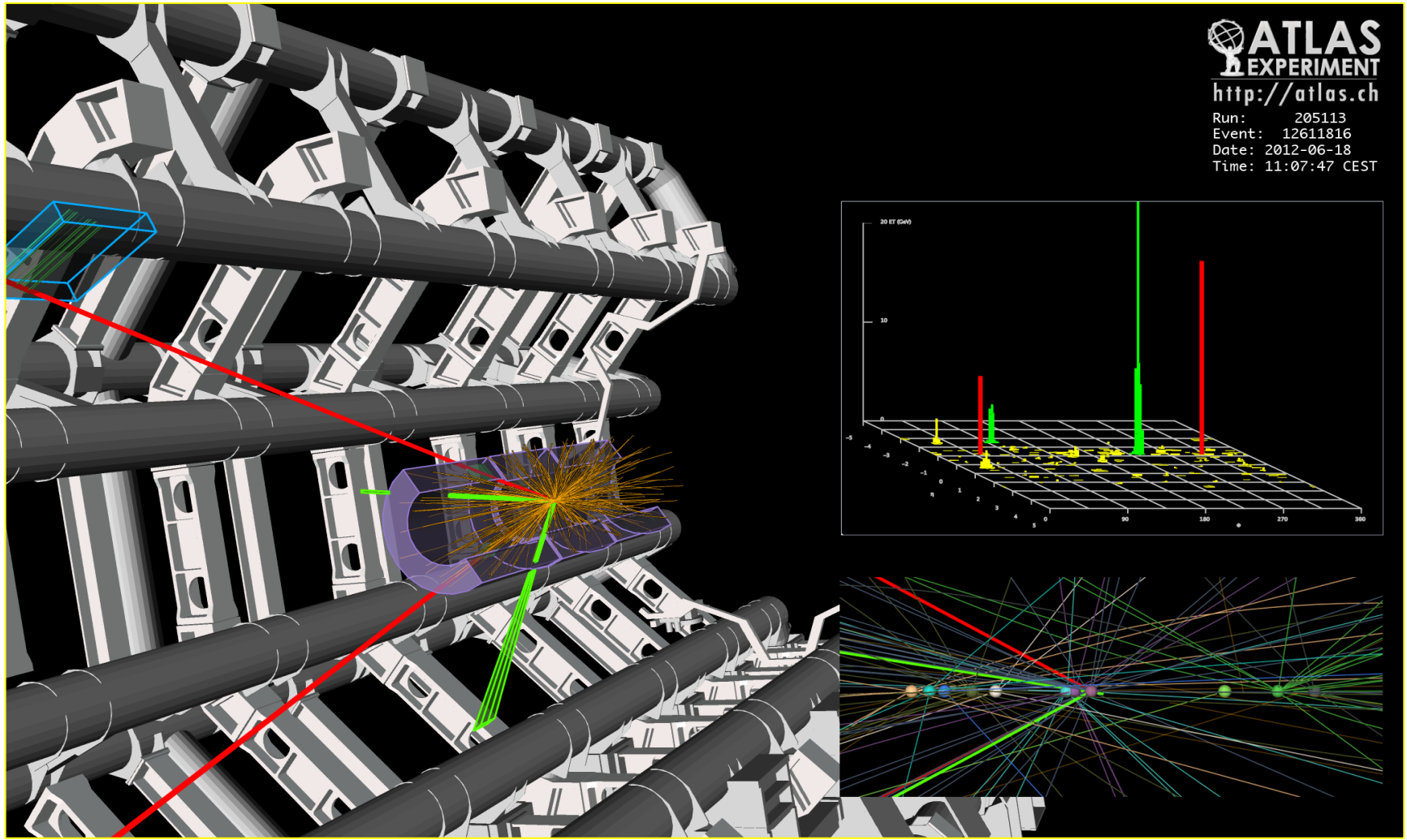
$H \rightarrow \gamma\gamma$ Invariant mass by category (8 TeV)



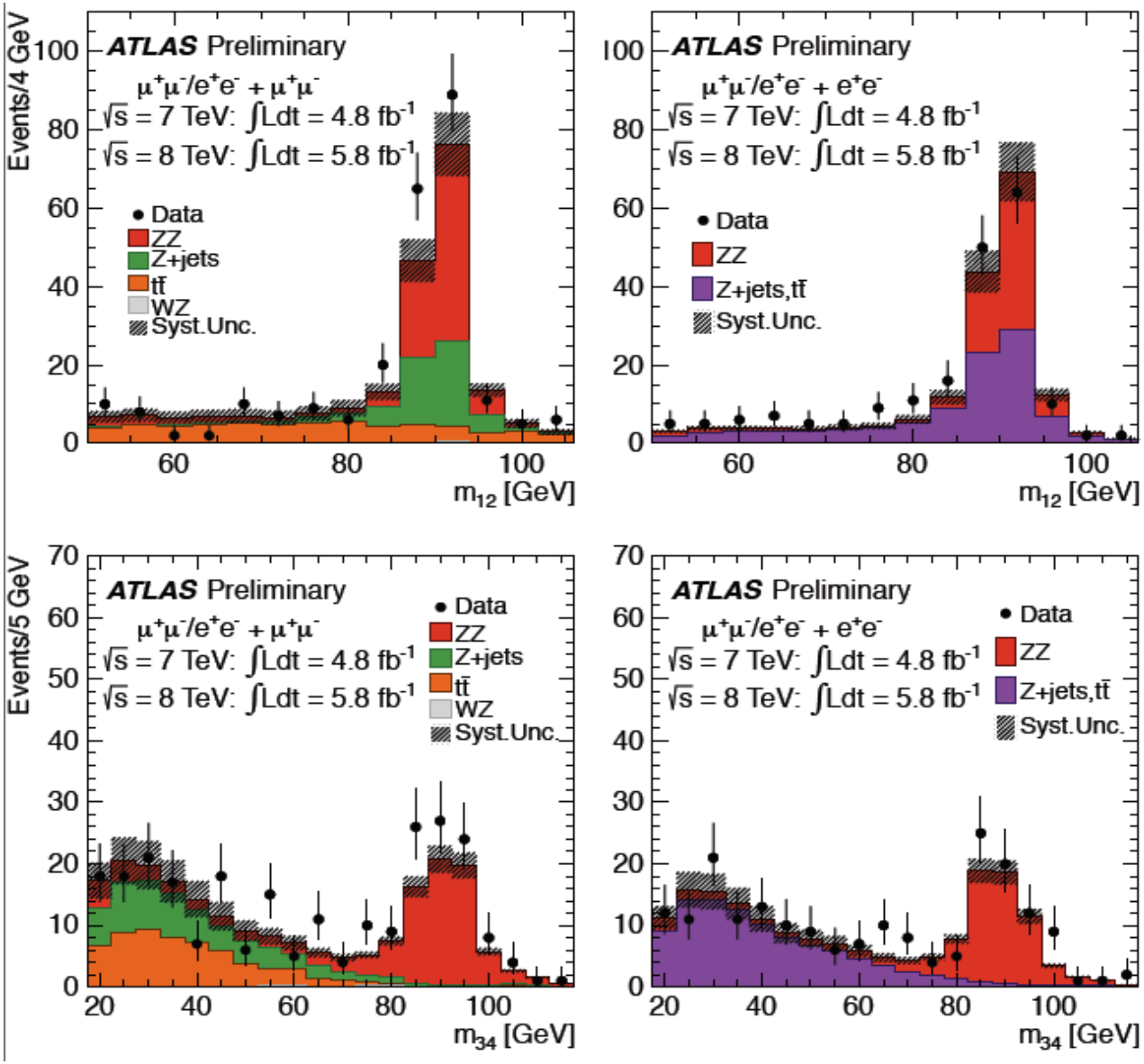
$H \rightarrow ZZ \rightarrow 4L$

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ 2e2μ candidate with $m_{2e2\mu}$ =123.9 GeV

p_T (e,e,μ,μ)= 18.7, 76, 19.6, 7.9 GeV, m (e^+e^-)= 87.9 GeV, m($\mu^+\mu^-$) =19.6 GeV
12 reconstructed vertices



$H \rightarrow ZZ^{(*)} \rightarrow 4l$ Background Estimates: Control Regions



Background-dominated Control Region

- **Remove isolation cut.**
- **Fail impact parameter cut.**
- **Normalize to data-driven estimates.**
- **Normalization/shape of reducible backgrounds well described.**

Summary of background estimations

8 TeV

Method	Estimated number of events
4μ	
m_{12} fit: Z + jets contribution	$0.51 \pm 0.13 \pm 0.16^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.044 \pm 0.015 \pm 0.015^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.058 \pm 0.015 \pm 0.019$
$2e2\mu$	
m_{12} fit: Z + jets contribution	$0.41 \pm 0.10 \pm 0.13^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.040 \pm 0.013 \pm 0.013^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{+} + \mu^{\pm}\mu^{+}$	$0.051 \pm 0.013 \pm 0.017$
$2\mu 2e$	
$\ell\ell + e^{\pm}e^{\mp}$	$4.9 \pm 0.8 \pm 0.7^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$4.1 \pm 0.6 \pm 0.8$
$3\ell + \ell$ (same-sign)	$3.5 \pm 0.5 \pm 0.5$
$4e$	
$\ell\ell + e^{\pm}e^{\mp}$	$3.9 \pm 0.7 \pm 0.8^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.1 \pm 0.5 \pm 0.6$
$3\ell + \ell$ (same-sign)	$3.0 \pm 0.4 \pm 0.4$

7 TeV

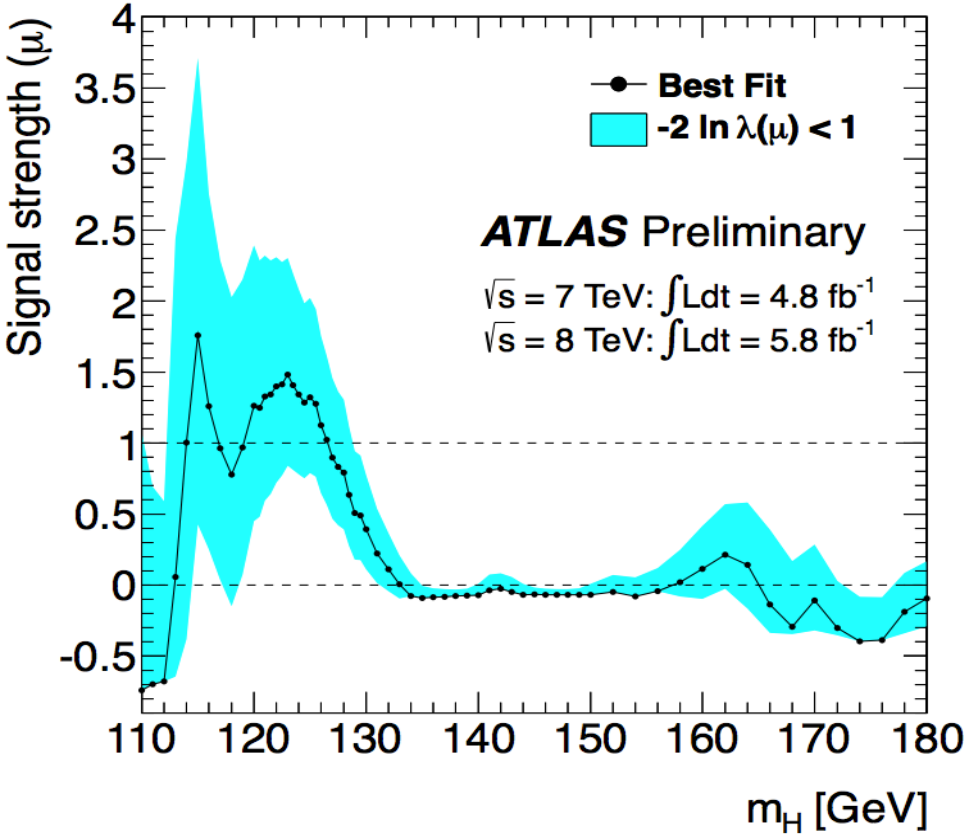
Method	Estimated number of events
4μ	
m_{12} fit: Z + jets contribution	$0.25 \pm 0.10 \pm 0.08^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.022 \pm 0.010 \pm 0.011^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.025 \pm 0.009 \pm 0.014$
$2e2\mu$	
m_{12} fit: Z + jets contribution	$0.20 \pm 0.08 \pm 0.06^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.020 \pm 0.009 \pm 0.011^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{+} + \mu^{\pm}\mu^{+}$	$0.024 \pm 0.009 \pm 0.014$
$2\mu 2e$	
$\ell\ell + e^{\pm}e^{\mp}$	$2.6 \pm 0.4 \pm 0.4^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.7 \pm 0.9 \pm 0.6$
$3\ell + \ell$ (same-sign)	$2.0 \pm 0.5 \pm 0.3$
$4e$	
$\ell\ell + e^{\pm}e^{\mp}$	$3.1 \pm 0.6 \pm 0.5^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.2 \pm 0.6 \pm 0.5$
$3\ell + \ell$ (same-sign)	$2.2 \pm 0.5 \pm 0.3$

More than one method per channel, compatible results

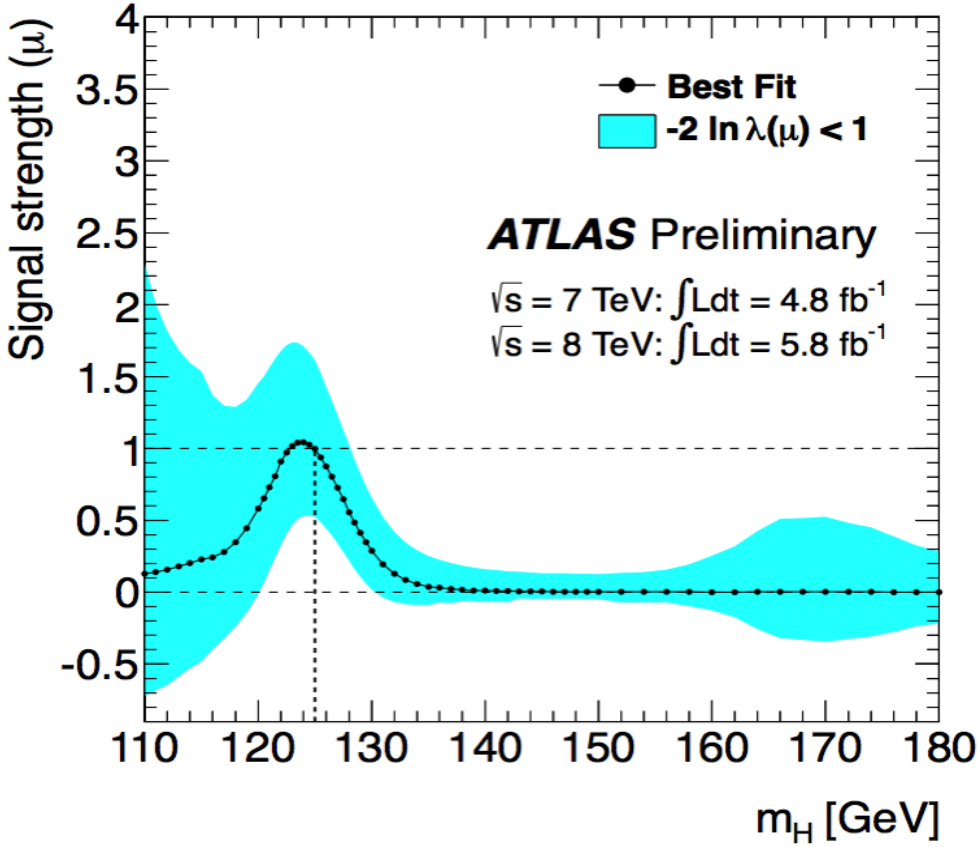
Uncertainties 20%-70% depending on background and data sample

Signal Strength

DATA



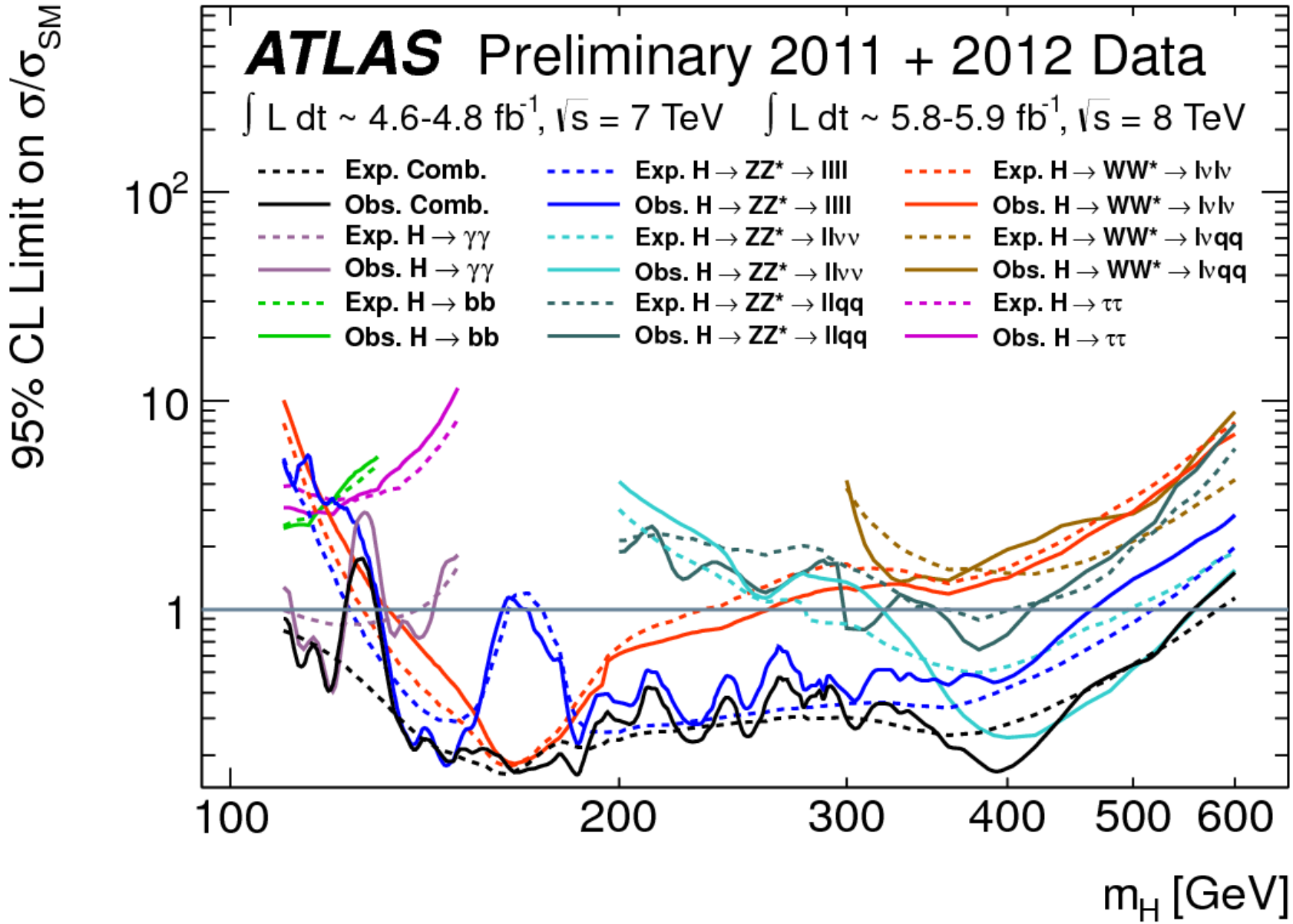
Signal injection at m_H=125 GeV



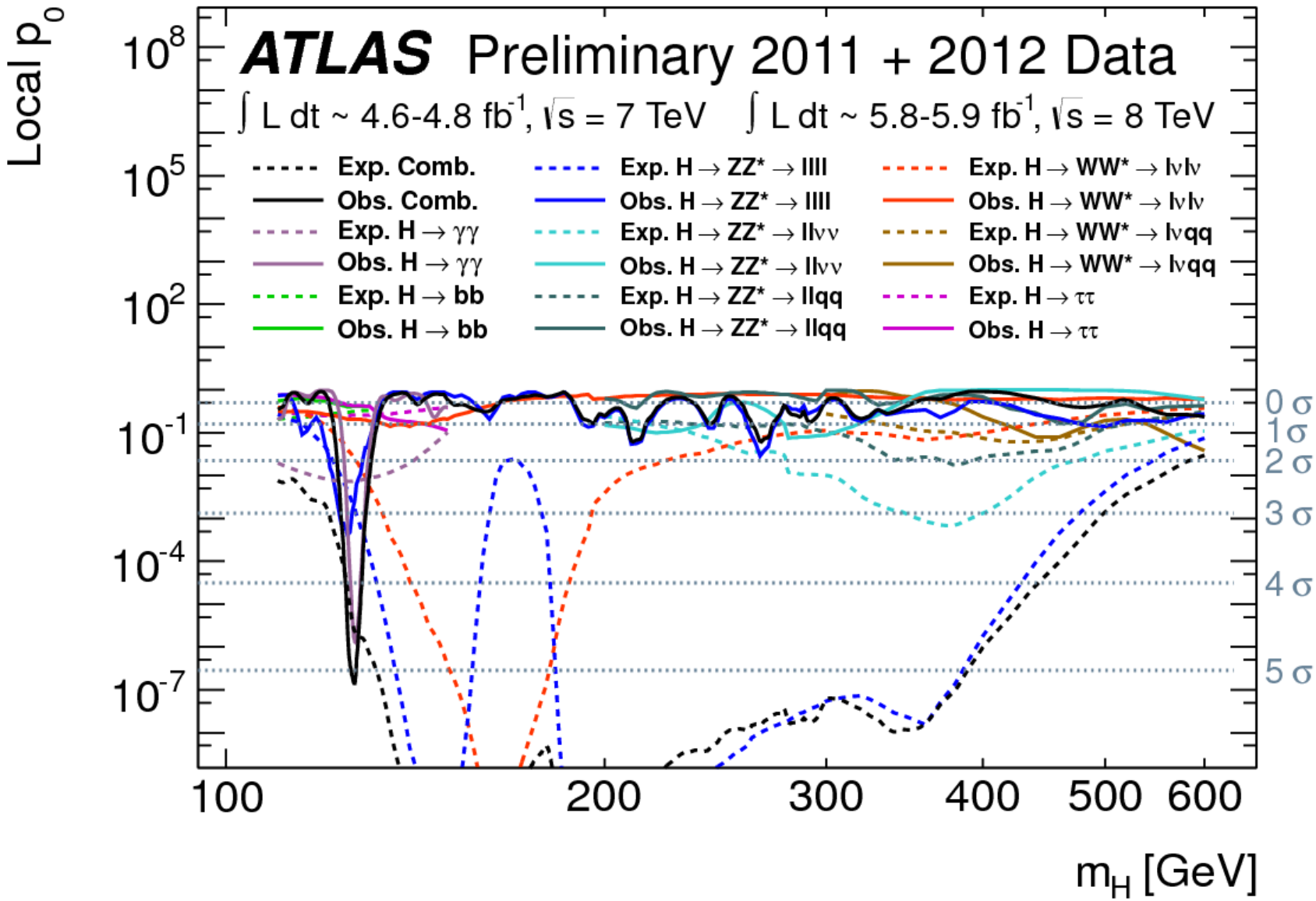
- *μ = (best fit signal rate at m_H)/(expected SM rate at m_H)*
- *Best fit value at m_H=125 GeV (lowest p_0): 1.3 ± 0.6*

Higgs Combination

Higgs Combination



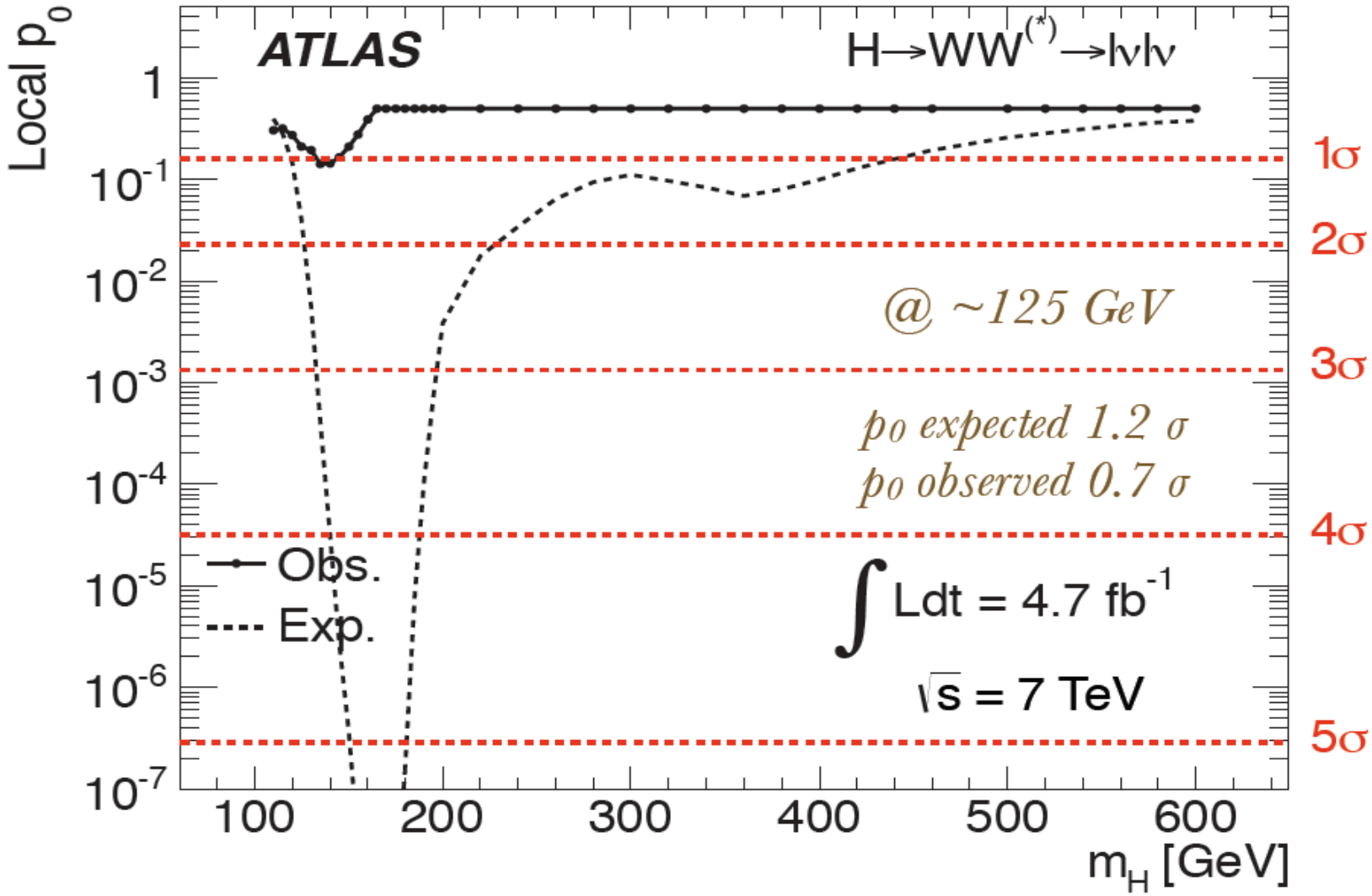
Higgs Combination



$H \rightarrow WW \rightarrow l\nu l\nu$ (7 TeV)

H→WW (7 TeV)

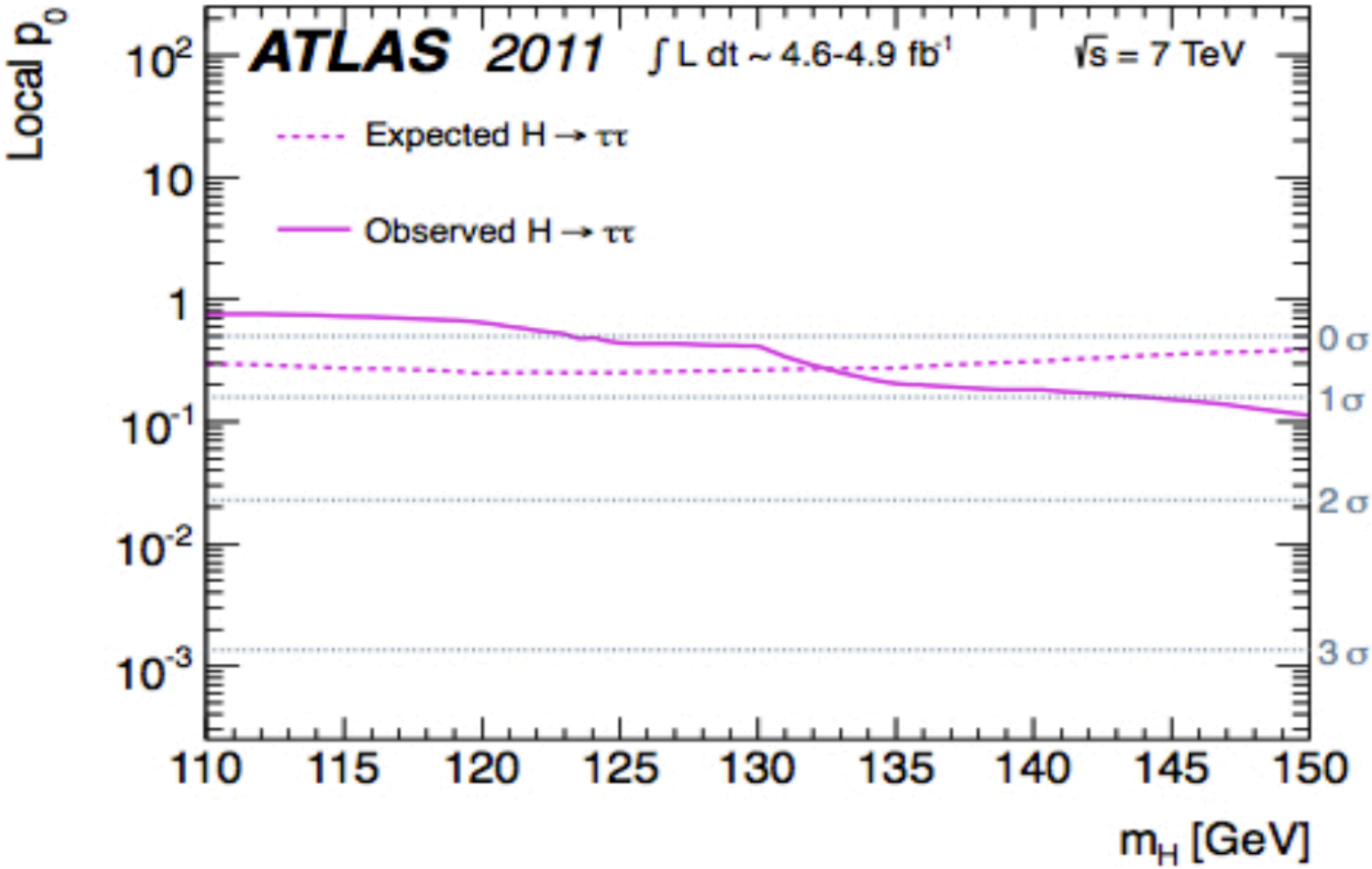
At 125 GeV, observed (expected) significance = 0.7 (1.2) σ



$H \rightarrow \tau\tau$ (7TeV)

$H \to \tau\tau$ (7 TeV: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$)

At 125 GeV, observed(expected) significace = 0.2 (0.7) σ



Conclusions