HIGGS SEARCHES WITH THE ATLAS EXPERIMENT AT THE LHC

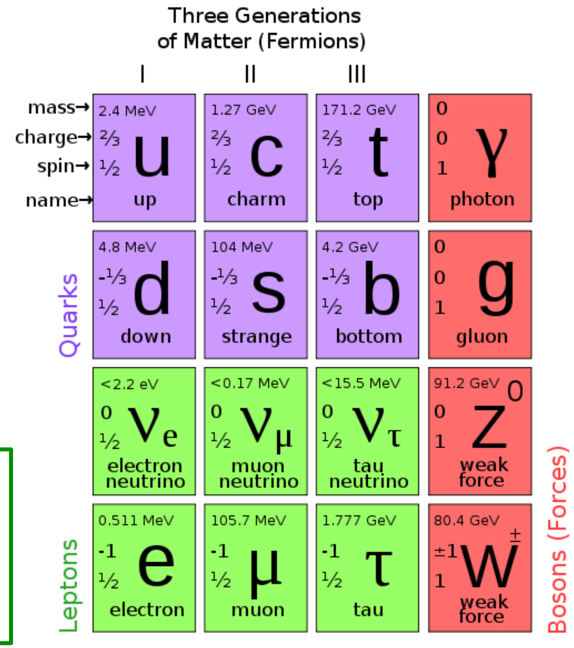
Marine Kuna
On behalf of The ATLAS Collaboration

Particle Physics and Cosmology 2012, Seoul

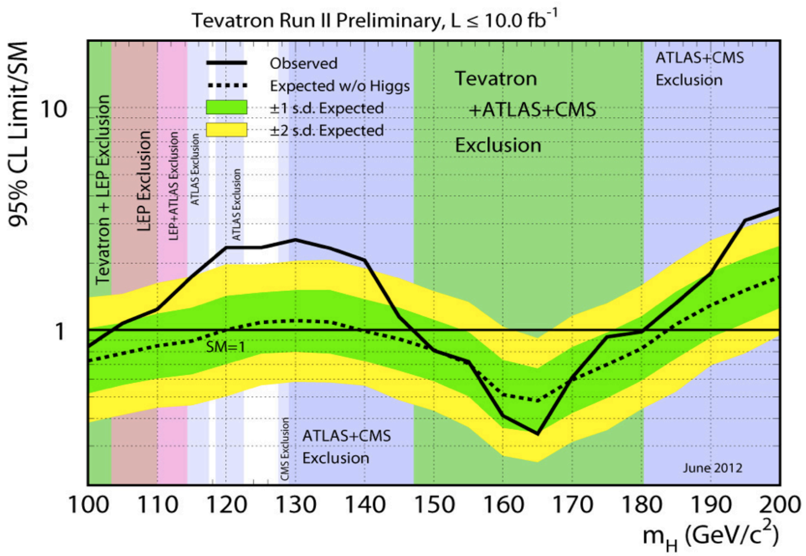
November 5, 2012

Motivations

- Standard Model of Particle Physics:
  - 6 quarks, 6 leptons, bosons: strong interaction (gluons) and electroweak (photon, Z°, W^+, W^-)
- Gauge bosons Z°, W^+, W^- have masses (resp. 91 and 80 GeV) → ElectroWeak Symmetry breaking:
  - Solution is introduction of a massive scalar particle (electric charge & spin = 0): the Higgs Boson



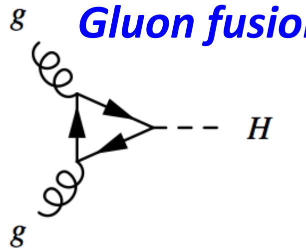
The Higgs boson is the only elementary particle from the Standard Model that had not been experimentally observed prior to this year.



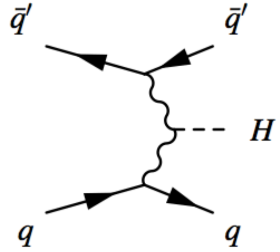
- Constraints on Higgs mass: previous collider experiments, electroweak precision measurements (indirect), theory
- Previous experimental results exclude: LEP (1989-2000) M_H < 114.4 GeV @ 95% CL and TeVatron between 147 and 180 GeV, and between 100 and 103 GeV

Higgs Search at the LHC

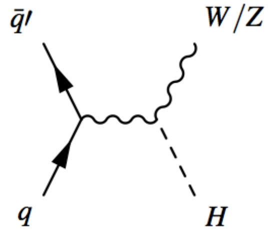
Gluon fusion

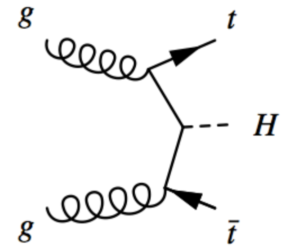


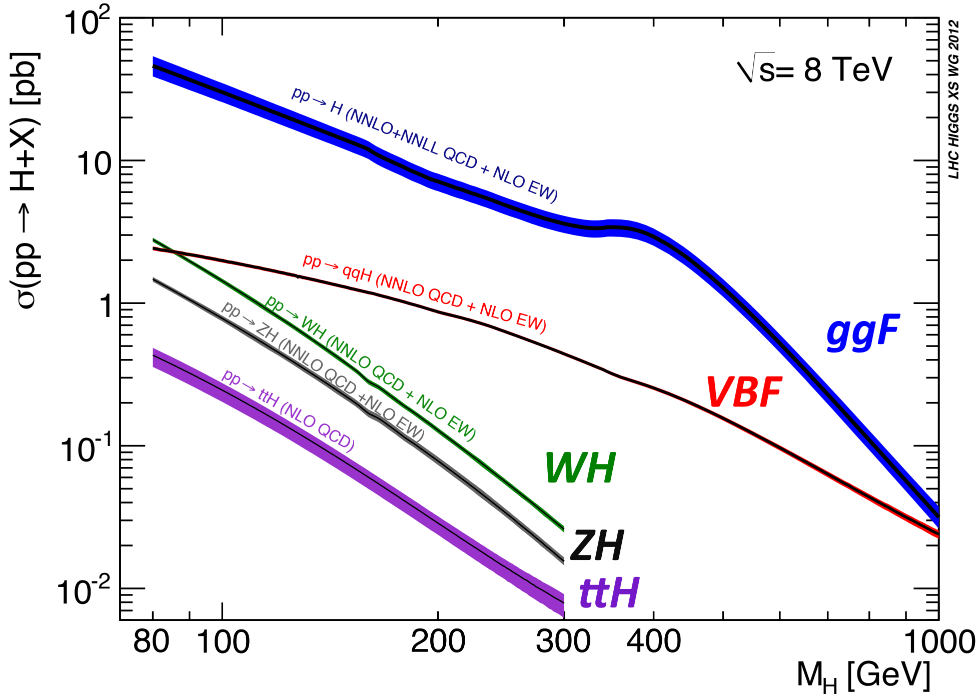
Vector Boson Fusion



***WH*, *ZH* and *ttH* associated production**

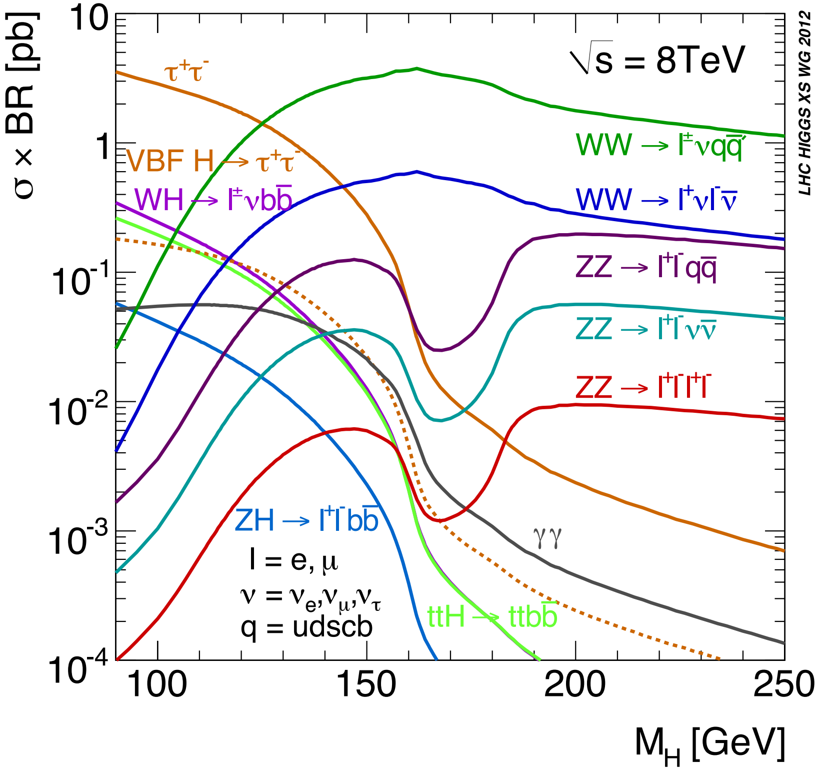




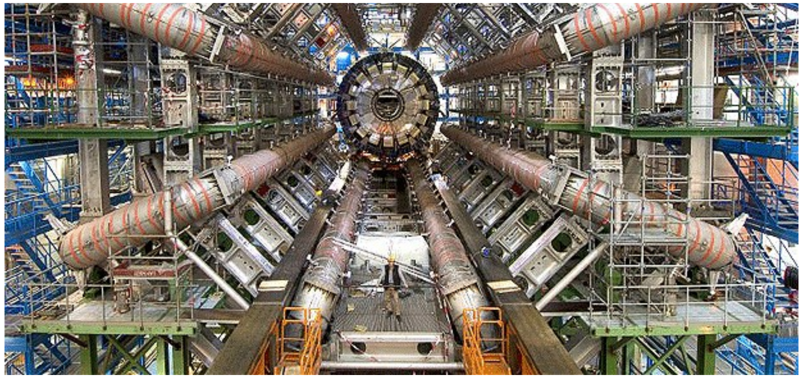


- → Gluon fusion: dominant production mode
- → Vector Boson Fusion: 2 energetic forward jets
- → Associated production: useful for trigger and bkg rejection for H→bb

Channels studied at the LHC



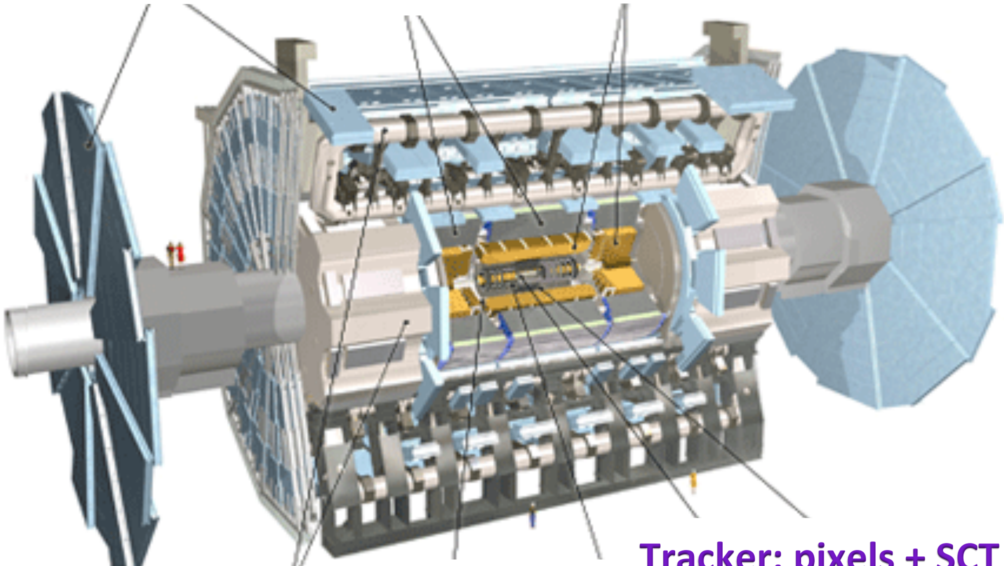
The ATLAS Experiment



Muon Spectrometer

Hadronic Calorimeter

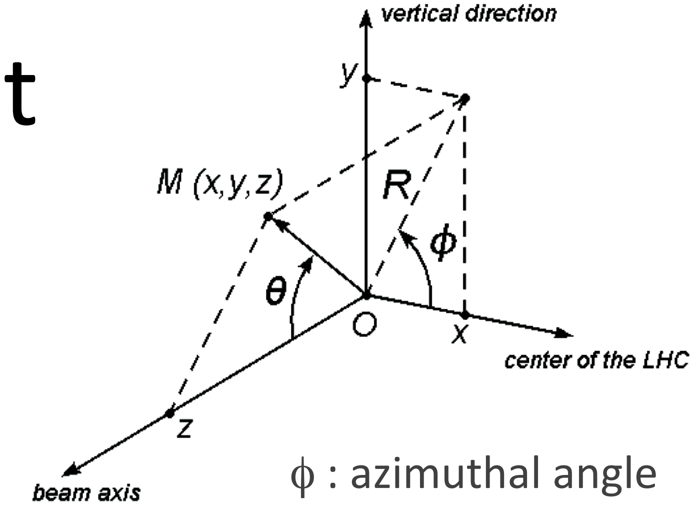
Electromagnetic Calorimeter



Toroidal Coils

Solenoidal Coil

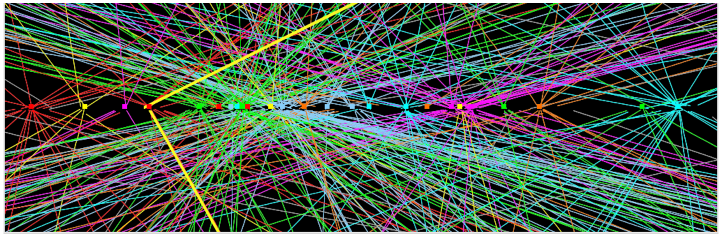
Tracker: pixels + SCT (precision)+ Transition Radiation Tracker



ϕ : azimuthal angle

$\eta = - \ln [\tan (\theta/2)]$

+ 3 Level Trigger System



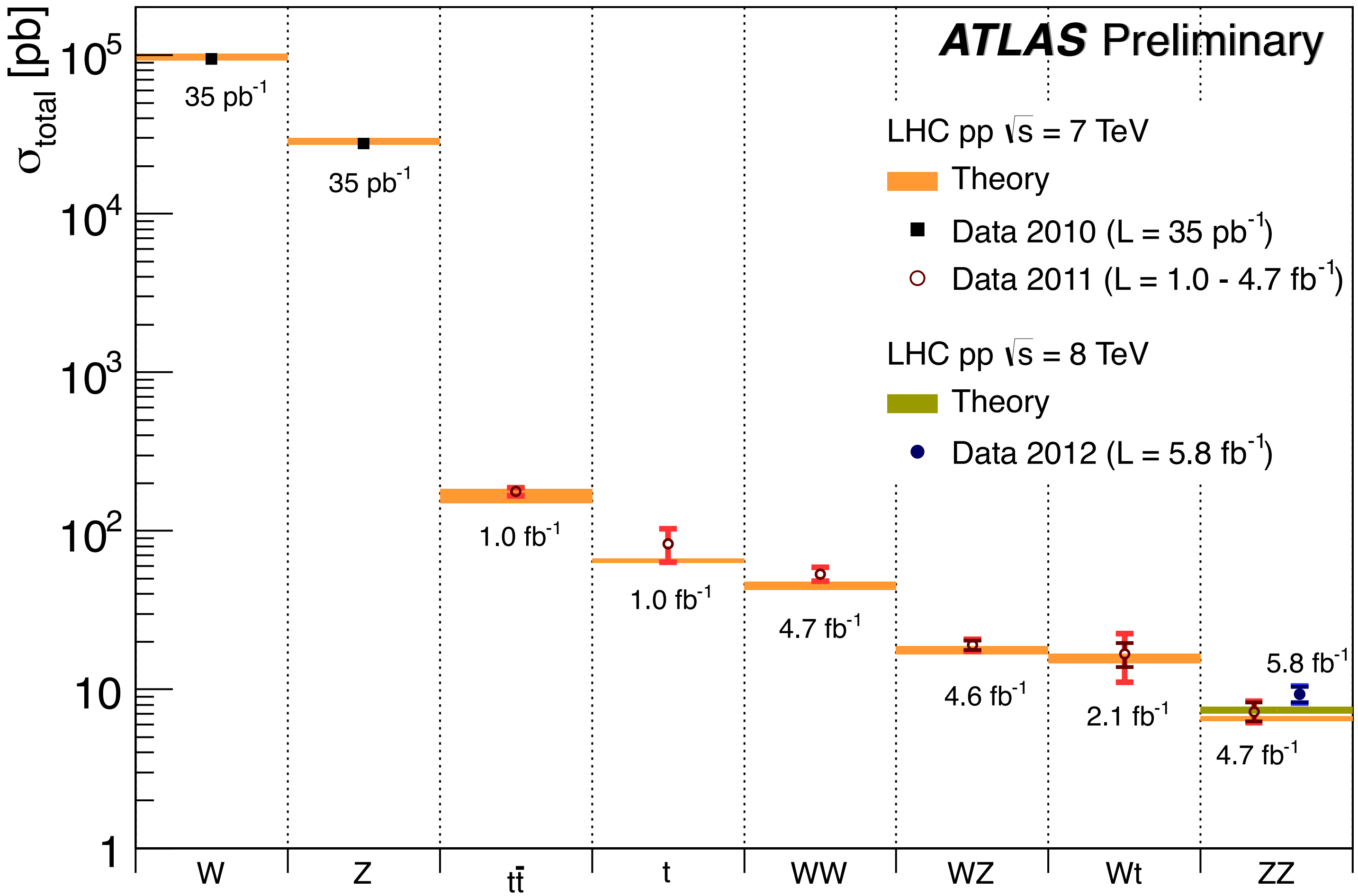
Z→μμ with 25 reconstructed interaction vertices

Instantaneous Luminosity up to $6.8 \times 10^{33} \text{cm}^{-2}\ \text{s}^{-1}$

Pile-up is a challenge: ~10 in 2011 and ~20 in 2012 average interactions per bunch crossing

Good Understanding of the SM

→ Important ground for Higgs searches: most of processes are backgrounds for Higgs



→ All the Standard Model processes are well measured and understood by ATLAS

Non Standard Model Higgs Searches

- In the Minimal Supersymmetric Standard Model (MSSM): 3 neutral Higgs: h, H and A

  + 2 charged Higgs: H^+ and H^-

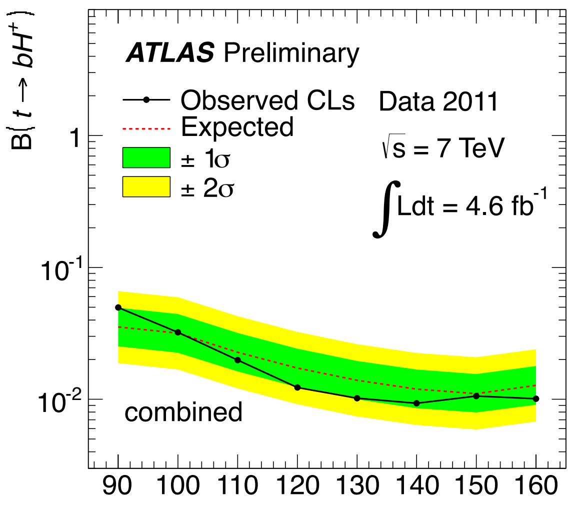
  - Results for Charged MSSM Higgs:

    → Combination for τ+ leptons and τ+ jets

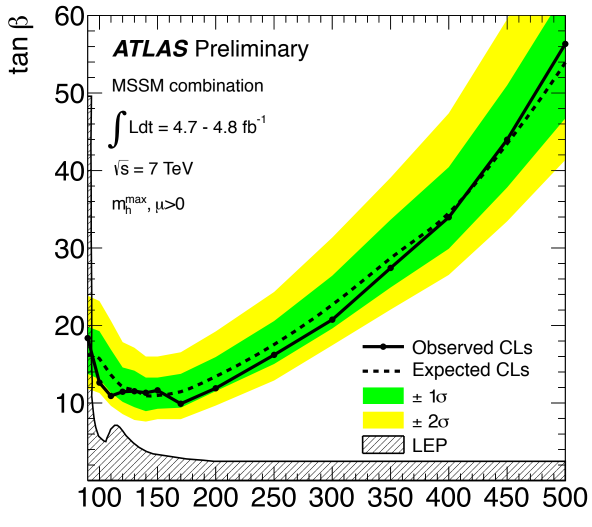
    → Upper limit on the top to bH+ branching ratio

  - Results for neutral MSSM Higgs:

    → Combination for μμ, τ(e) τ(μ), τ(lep)τ(had) and τ(had) τ(had) final states



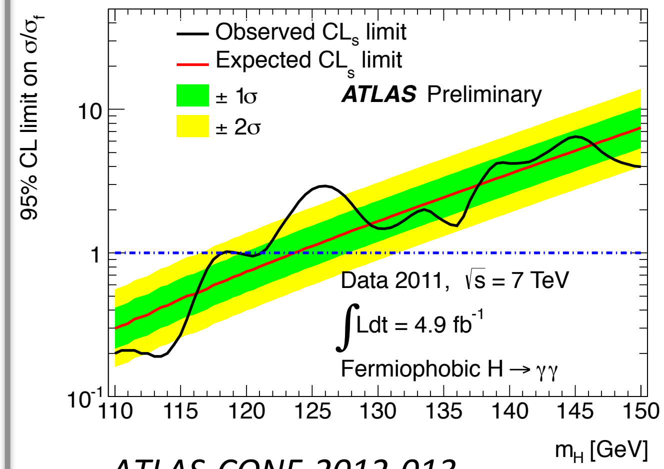
ATLAS-CONF-2012-011



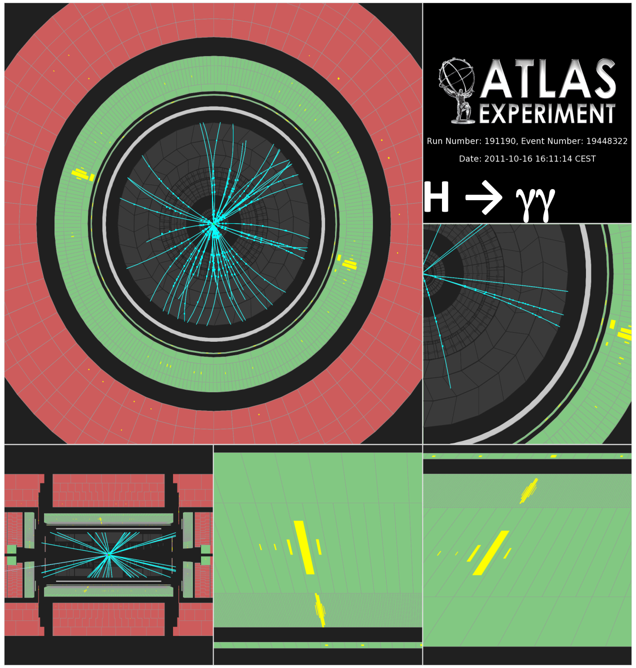
ATLAS-CONF-2012-094

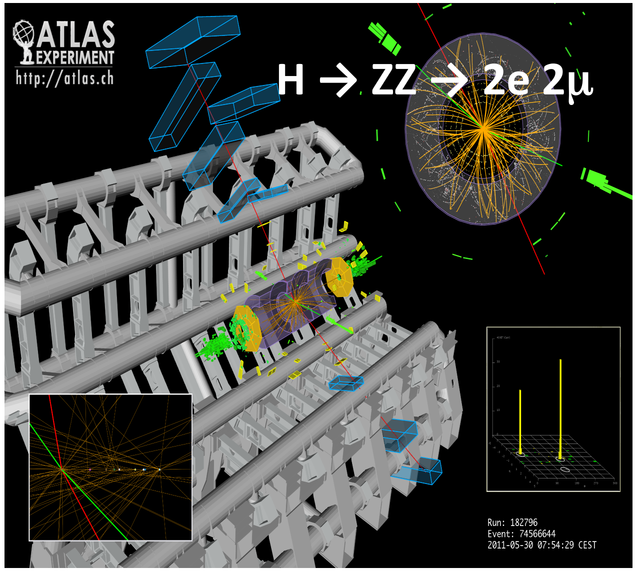
- The fermiophobic Higgs doesn't couple to fermions, so VBF and VH productions are the only ones not suppressed

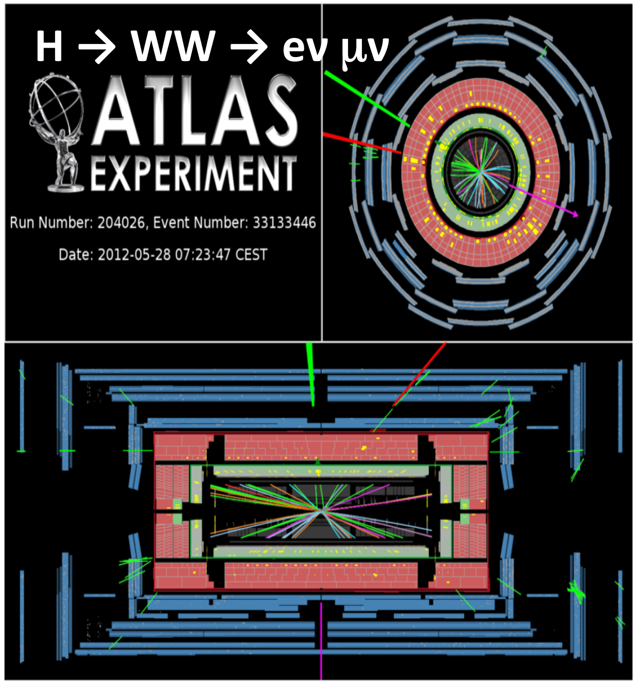
  - Exclusion: 110.0–118.0 GeV and 119.5 – 121.0 GeV at 95% confidence level



ATLAS-CONF-2012-013





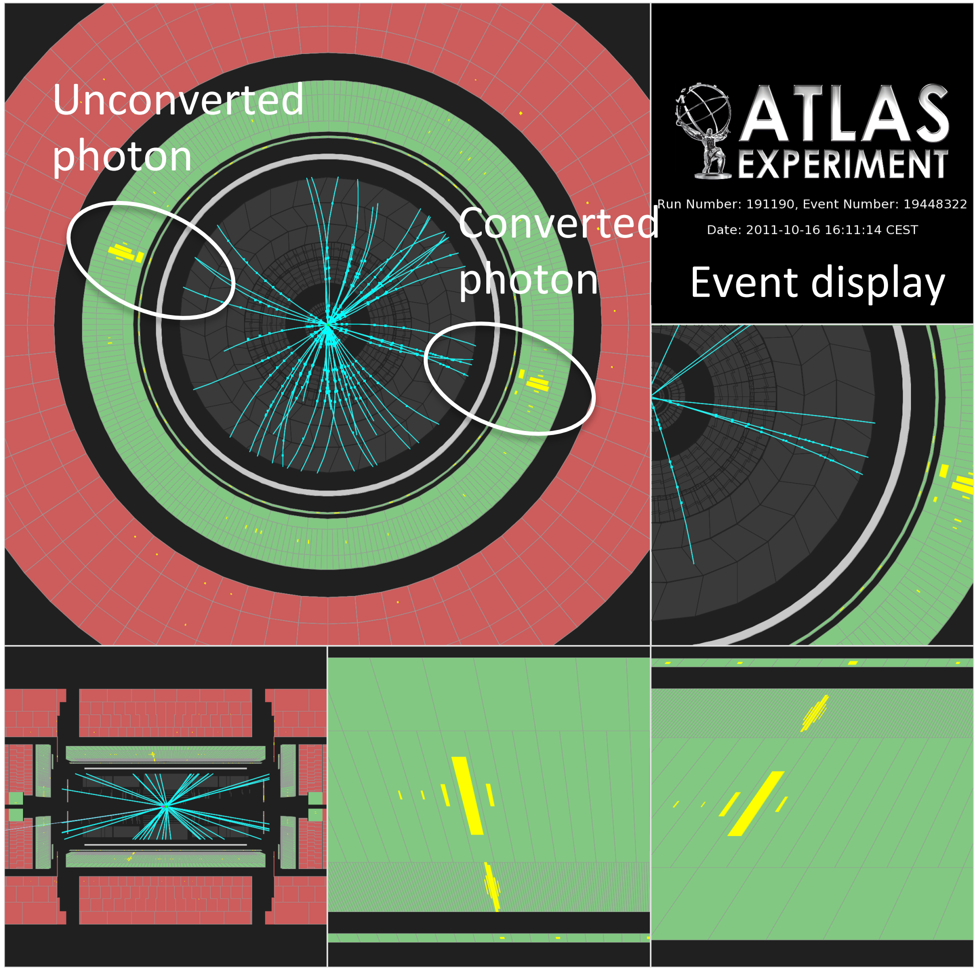


MOST SENSITIVE CHANNELS IN THE SEARCH OF SM HIGGS

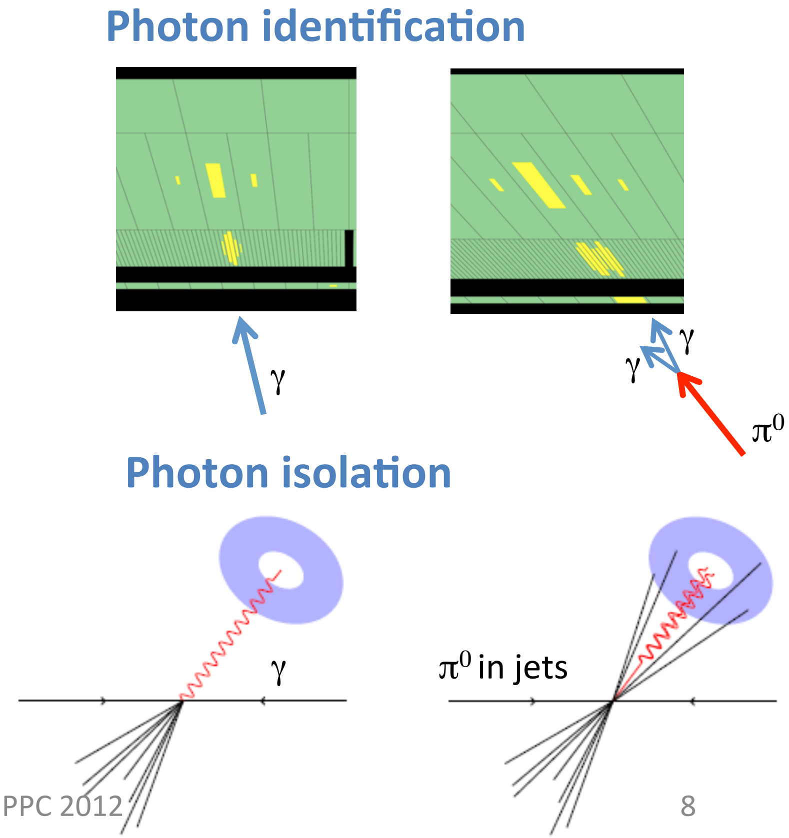
$H \rightarrow \gamma\gamma$

110-150 GeV

$\sigma \times BR \sim 50$ fb @ $m_H \sim 126$ GeV



- Small rate but good mass resolution
- QCD $\gamma\gamma$ (irreducible background)
- γj, jj where jets are mis-identified as a photon due to hard π^0 (reducible background):



Selection :

$P_T^{\gamma 1} > 40$ GeV, $P_T^{\gamma 2} > 25$ GeV

$|\eta_{1,2}| < 1.37$, $1.52 < |\eta_{1,2}| < 2.37$

H→γγ: signal resolution

- Discriminating variable for H→γγ analysis: the di-photon invariant mass. Look for a peak.

$$M_{\gamma\gamma} = 2 p_T^{\gamma_1} p_T^{\gamma_2} \left[\cosh(\eta_1 - \eta_2) - \cos(\varphi_1 - \varphi_2)\right]$$

Signal parameterisation as a Crystal Ball + Gaussian function

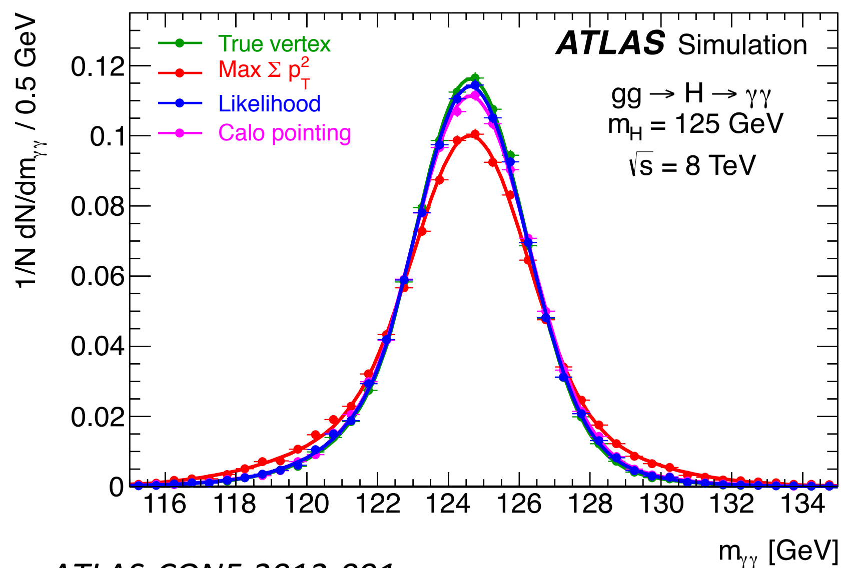
Photon energy scale extrapolated from electrons in Z→ee decays

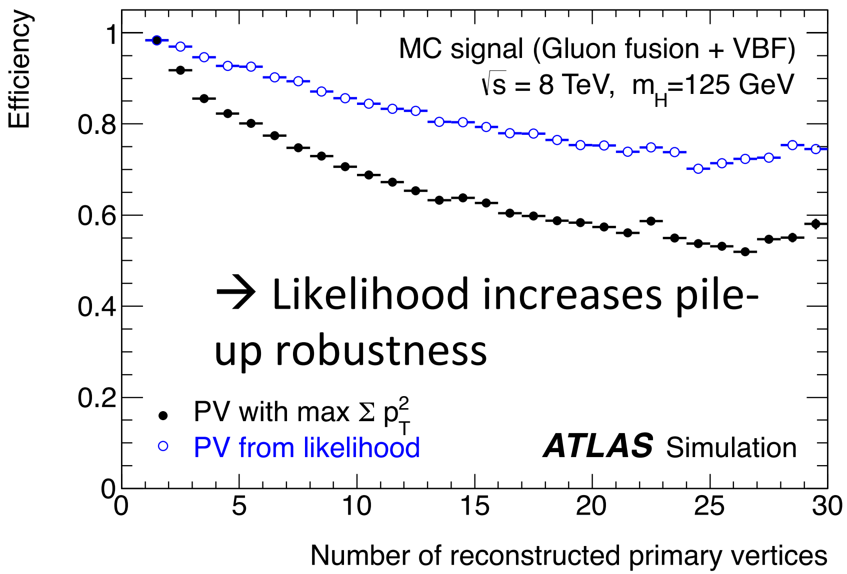
→ Small MC-based corrections for both converted and unconverted photons

Vertex selection

→ Calorimeter pointing (longitudinal segmentation)

→ Conversion vertex if available



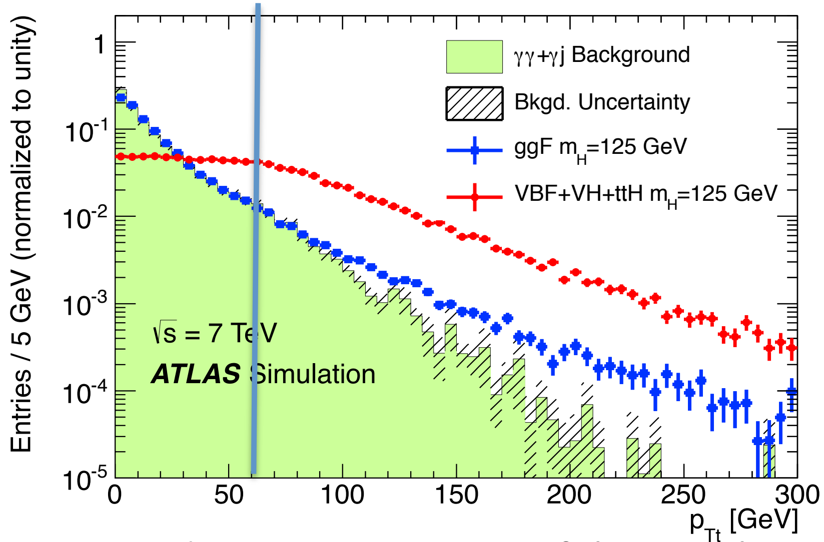


→ Likelihood increases pile-up robustness

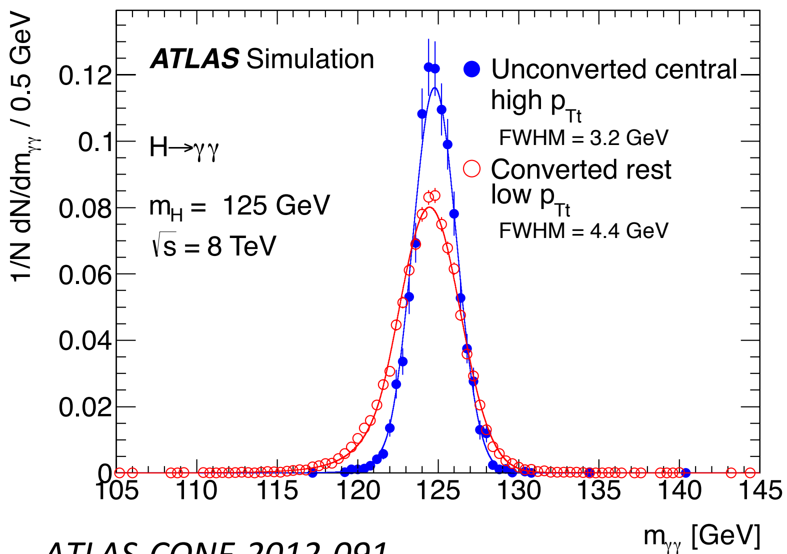
ATLAS-CONF-2012-091

$H \rightarrow \gamma\gamma$: Categorisation

- Motivation: optimising events categories by S/B with:
  - Both γ unconverted or at least one converted
  - Photons reconstructed in central, transition or other ("rest") regions in η (amount of upstream material affects energy resolution)
  - Di-photon transverse momentum with respect to thrust axis (p_{Tt}) > or < 60 GeV
  - + 1 category sensitive to VBF topology events (2 jets p_T> 30-25 GeV, $\Delta\eta$>2.8, m_{jj}>400 GeV, di-jet and di-photon systems back to back with $\Delta\phi$>2.6)



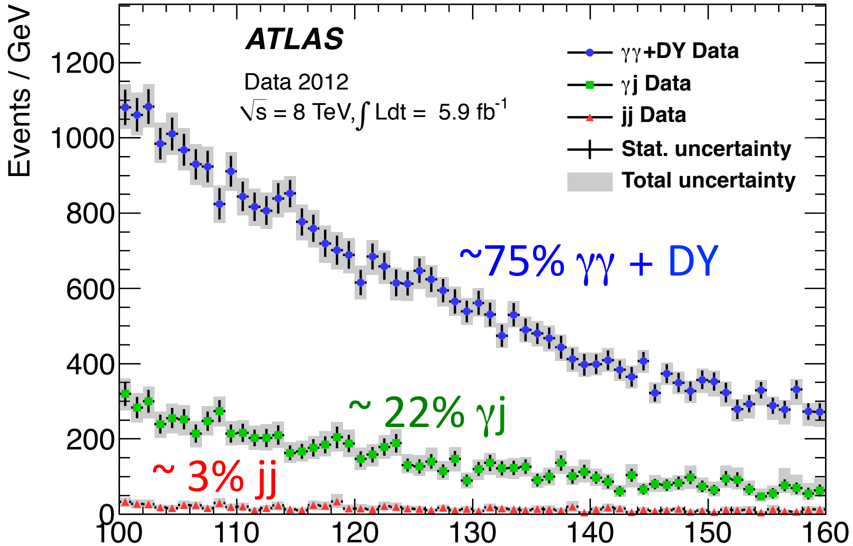
In a window containing 90% of the signal @ m_H = 126.5 GeV



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

ATLAS-CONF-2012-091

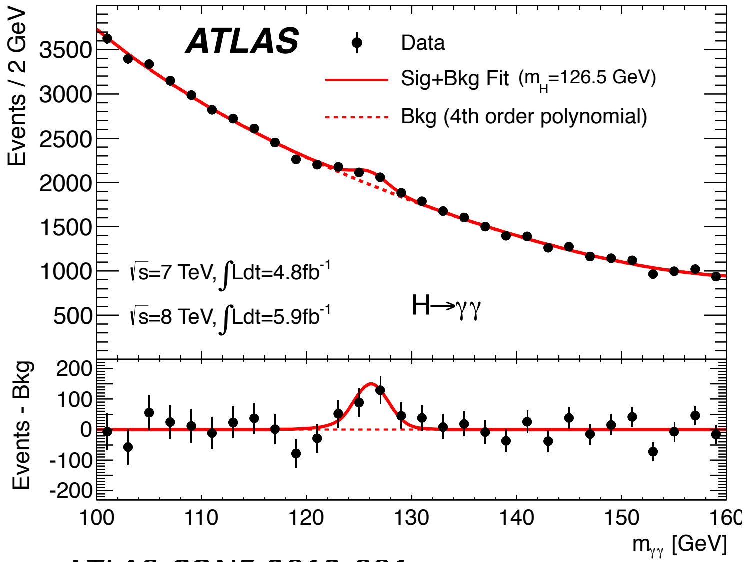
H→γγ: Background



Di-electron, Drell-Yan background < 1%

- Data-driven background estimation
- Background model choice:
  - Perform a S+B fit to bkg only high statistics MC → number of signal fitted is a bias
  - Among models with sufficiently low bias choose the one to optimise significance
  - Largest bias over 100-150 GeV taken as signal yield systematics

Category	Parametrization	Uncertainty [N_{evt}] $\sqrt{s}$ = 7 TeV	Uncertainty [N_{evt}] $\sqrt{s}$ = 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



ATLAS-CONF-2012-091

$H \rightarrow \gamma\gamma$: Systematic Uncertainties

- Profiled likelihood ratio with di-photon invariant mass is the discriminating variable:

$$f_{S+B}(m_{\gamma\gamma}) = n_S f_S(m_{\gamma\gamma}) + n_B f_B(m_{\gamma\gamma})$$

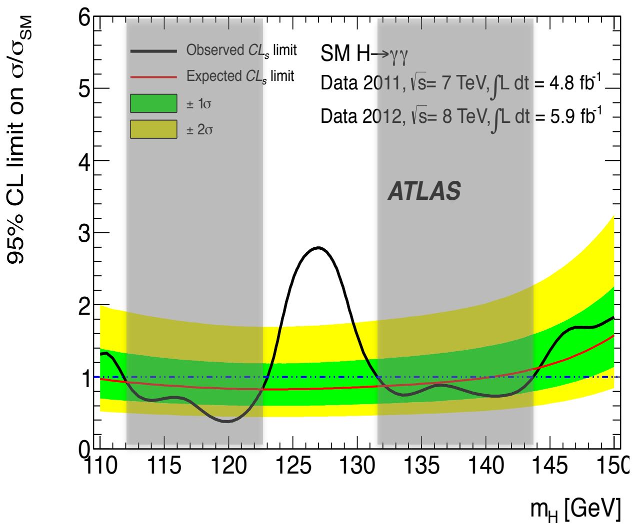
$$\lambda(\mu) = -2\ln \frac{L(\mu,\hat{\hat{\theta}})}{L(\hat{\mu},\hat{\theta})}$$

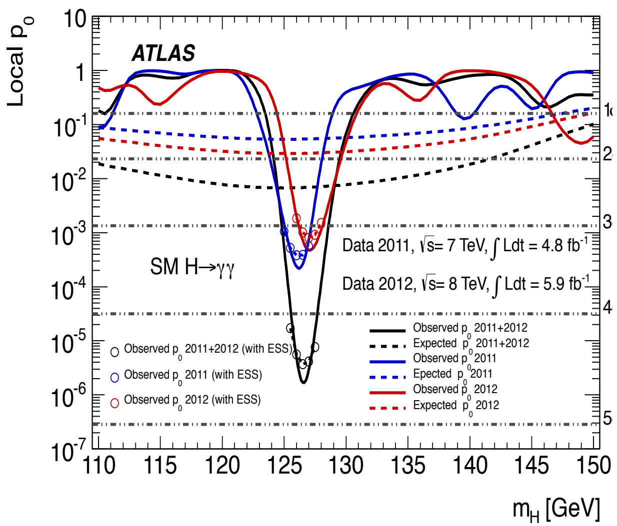
List of Dominant Systematics		Uncertainty
Signal Yield	Theory	~ 20%
	Photon Efficiency	~ 10%
	Background Model	~ 10%
Categories Migration	Higgs pT modelling	Up to ~ 10%
	Converted/Unconv γ	Up to ~ 6%
	Jet Energy Scale	Up to ~ 20% (2-jet cat)
	Underlying Event	Up to ~ 30% (2-jet cat)
$H \rightarrow \gamma\gamma$ mass resolution		~ 14%
Photon Energy Scale		~ 0.6%

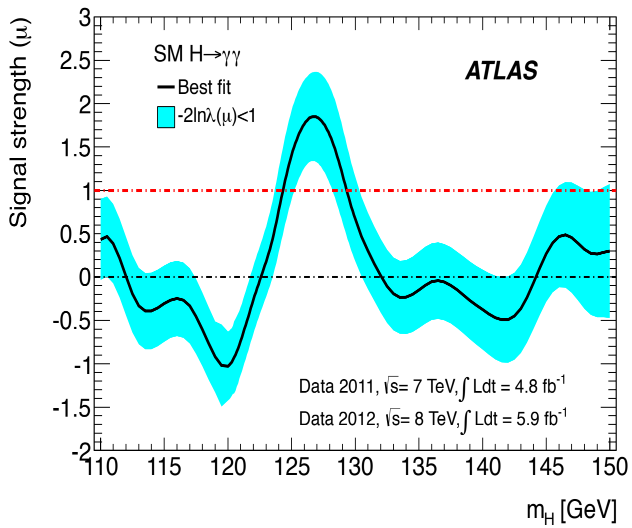
ATLAS-CONF-2012-091

H→γγ: Results

- Exclusion (signal strength in terms of SM cross section excluded at 95% CL):
  - Expected exclusion from 110-139.5 GeV
  - Observed exclusion from 112-122.5 GeV and 132-143 GeV
- p_0 (probability to be in agreement with background only hypothesis):
  - Most significant deviation from background hypothesis at m_H=126.5 GeV
  - Expected significance: 2.4 σ. Observed: local 4.7 σ (4.5 σ with ESS) global 3.6 σ
  - Similar size and compatible mass excesses for 2011 and 2012
- Fitted signal strength at 126.5 GeV: μ=1.9 ± 0.5

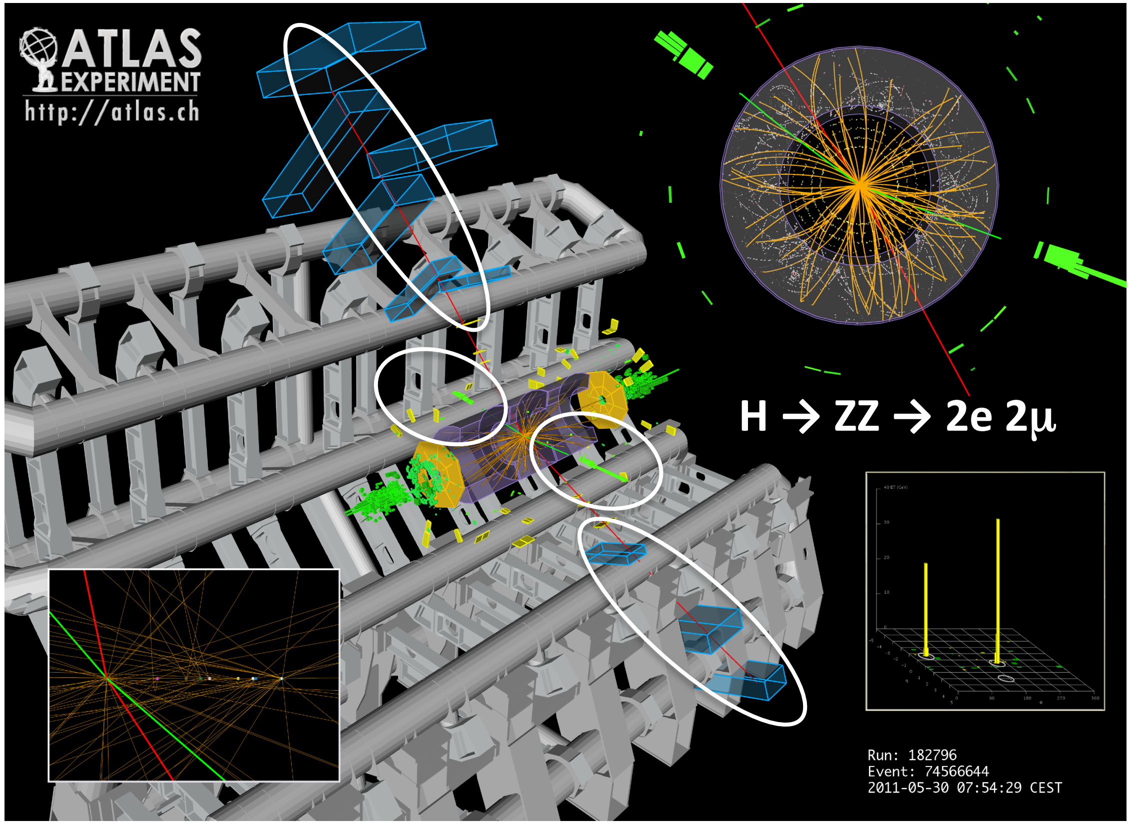






ATLAS-CONF-2012-091

H→ZZ(*)→4l (4e, 4μ, 2e2μ)



110- 600 GeV

σxBR ~ 2.5 fb @ m_H~126GeV

- Small rate, mass fully reconstructed so good resolution and very pure
- Largest background comes from continuum *ZZ*(∗) production (irreducible)
- For low-mass region $m_H < 2m_Z$: Zbb, Z+jets, ttbar with two fake leptons from b-jets or q-jets (reducible)

→ Suppressed with isolation and impact parameter cuts

Selection: 4 leptons: $pT_{1,2,3,4}$ > 20,15,10,7/6 (e/μ) GeV
50 < m_{12} < 106 GeV; m_{34} > 17.5-50 GeV (vs mH)
+ Isolation and impact parameter cuts on the four leptons

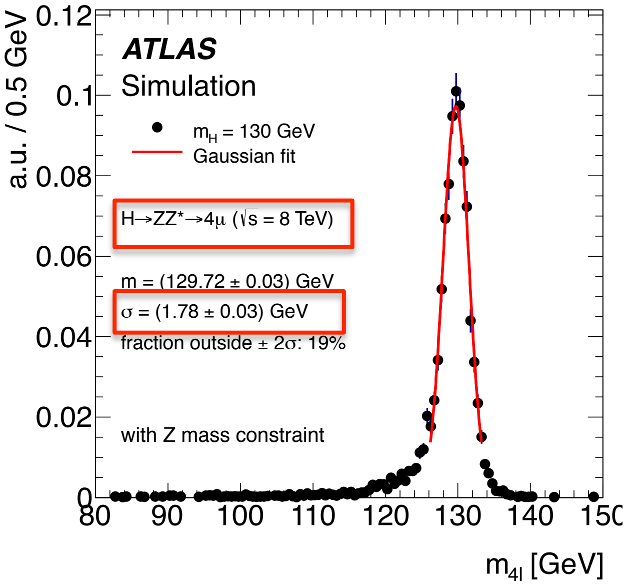
m_{12} = same flavour and opposite-sign lepton pair closest to the Z boson mass
m_{34} = remaining same flavour opposite sign lepton pair

H→ZZ: Signal Resolution

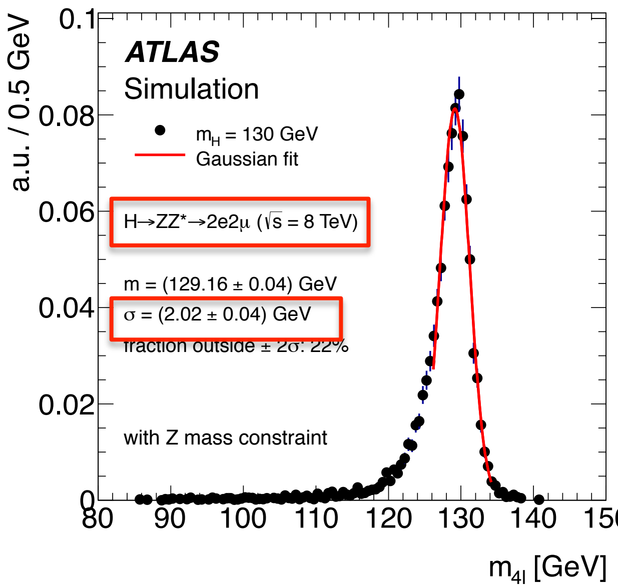
- The final discriminating variable for this search is the invariant mass of the 4 leptons (m_{4l}) and look for a peak.

→ The signal peak resolution is improved by constraining leading lepton pair to m_Z for m_{4l}<190 GeV, both pairs otherwise.

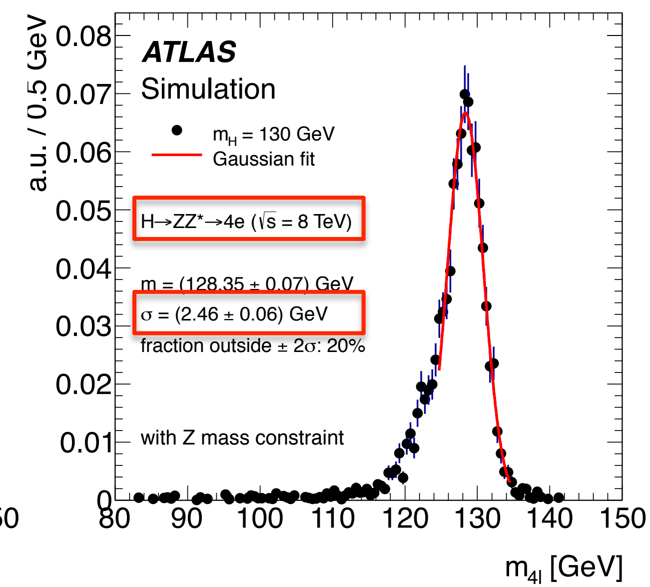
4μ
Before: σ = 2.13
After: σ = 1.78



2μ2e
Before: σ = 2.33
After: σ = 2.02



4e
Before: σ = 2.76
After: σ = 2.46

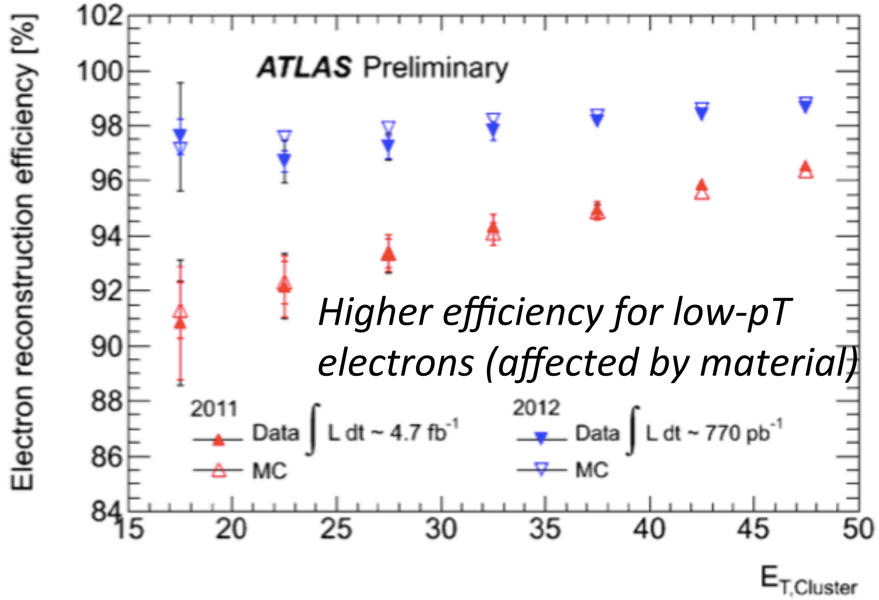


ATLAS-CONF-2012-092

H→ZZ: Analysis Optimisation

- Objective: increase the analysis acceptance to improve its significance
- Improved electron reconstruction and e-ID selection stable against pileup
- Allowing for bremsstrahlung in path reconstruction, electron tracks fitted
- Improvement of efficiency at low p_T

→ Total acceptance x efficiency for H→4e: ~23% (+60% gain)



Higher efficiency for low-pT electrons (affected by material)

Selection	Original	Optimised
Lepton p_T (e/μ)	20, 20, 7, 7	20, 15, 10, 7/6
m_{12} selection	$\|m_{12}-m_Z\|<15$	$50<m_{12}<106$
m_{34} selection	$m_{min}<m_{34}<115$	$m_{min}<m_{34}<115$

- Muons reconstructed down to pT = 6 GeV over $|\eta|<2.7$ (accept standalone $|\eta|>2.5$)

→ Total acceptance x efficiency for H→4μ: ~ 40% (+45% gain)

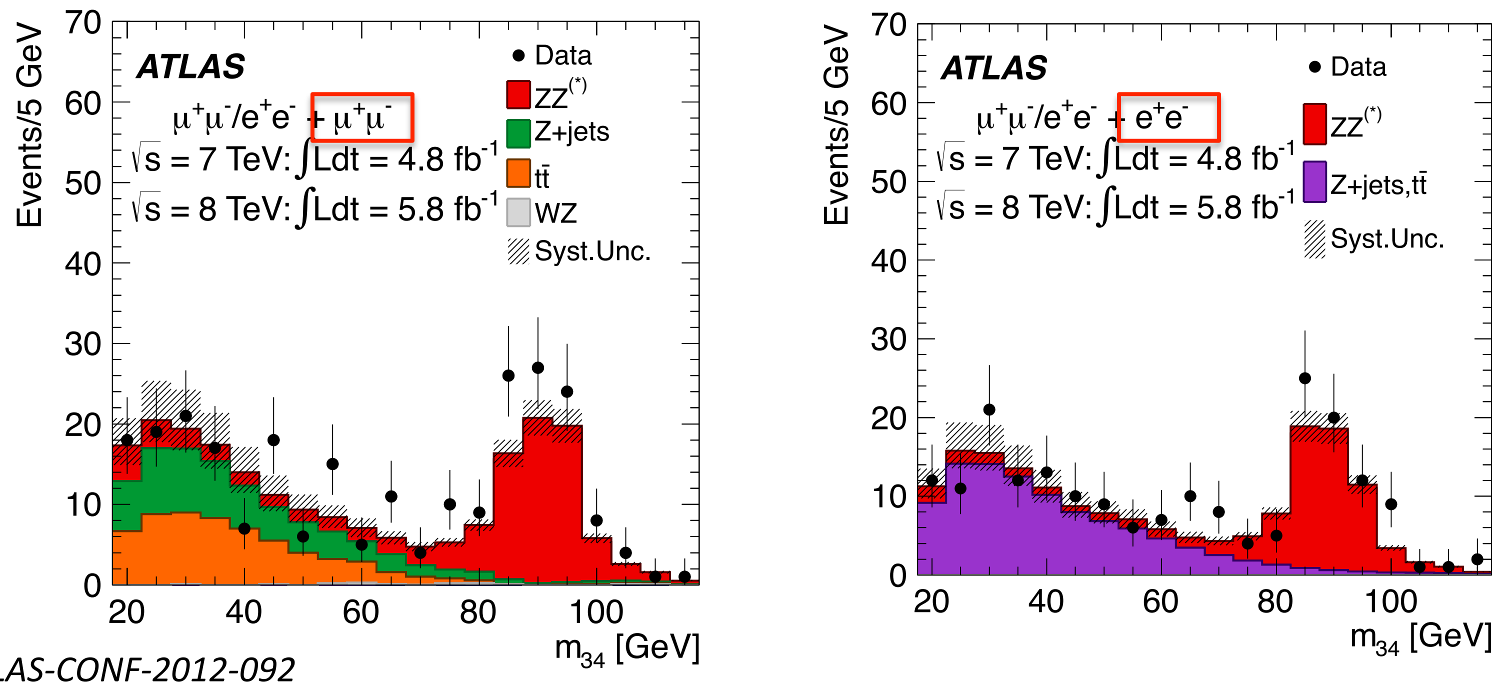
$m_{4\ell}$ [GeV]	≤120	130	150	160	165	180	≥190
m_{min} threshold [GeV]	17.5	22.5	30	30	35	40	50

ATLAS-CONF-2012-092

H→ZZ: Background (1)

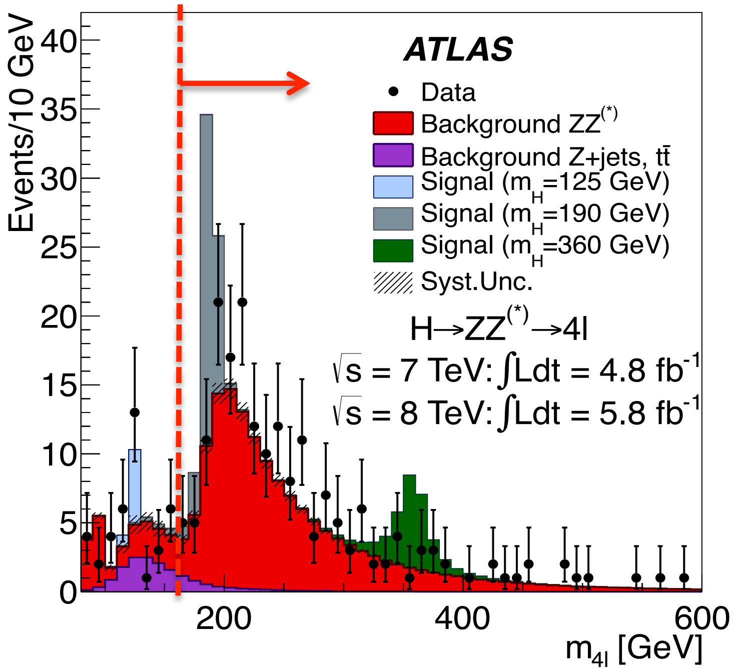
- Expected background yield and composition estimated:
  - For ZZ(∗) with MC simulation normalised to the ZZ(∗) theoretical cross section
  - With data-driven methods for the di-lepton + jets and $t\bar{t}$ processes.

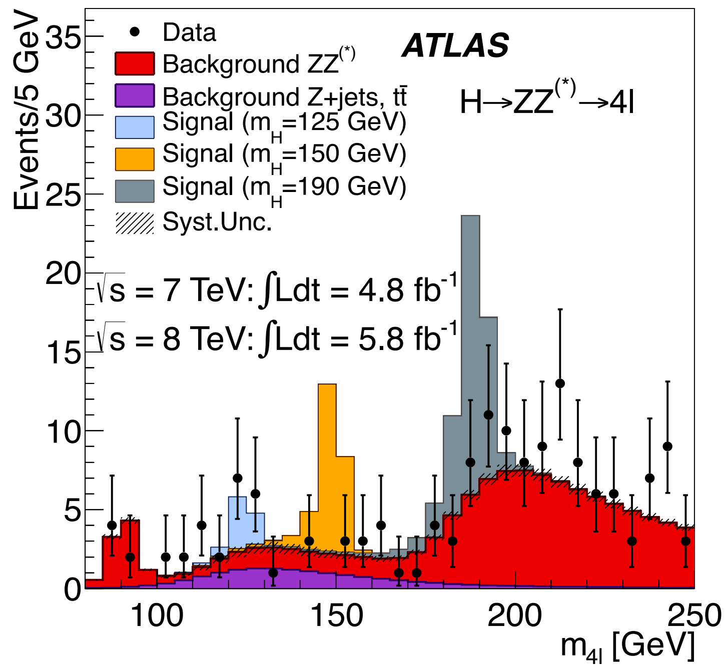
Cross-check background estimates by applying isolation to first lepton pair only
→ Agreement at high mass (ZZ(*)) and low mass (Zbb, Zqq, ttbar)



ATLAS-CONF-2012-092

H→ZZ: Background (2)





- 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 √s = 8 TeV

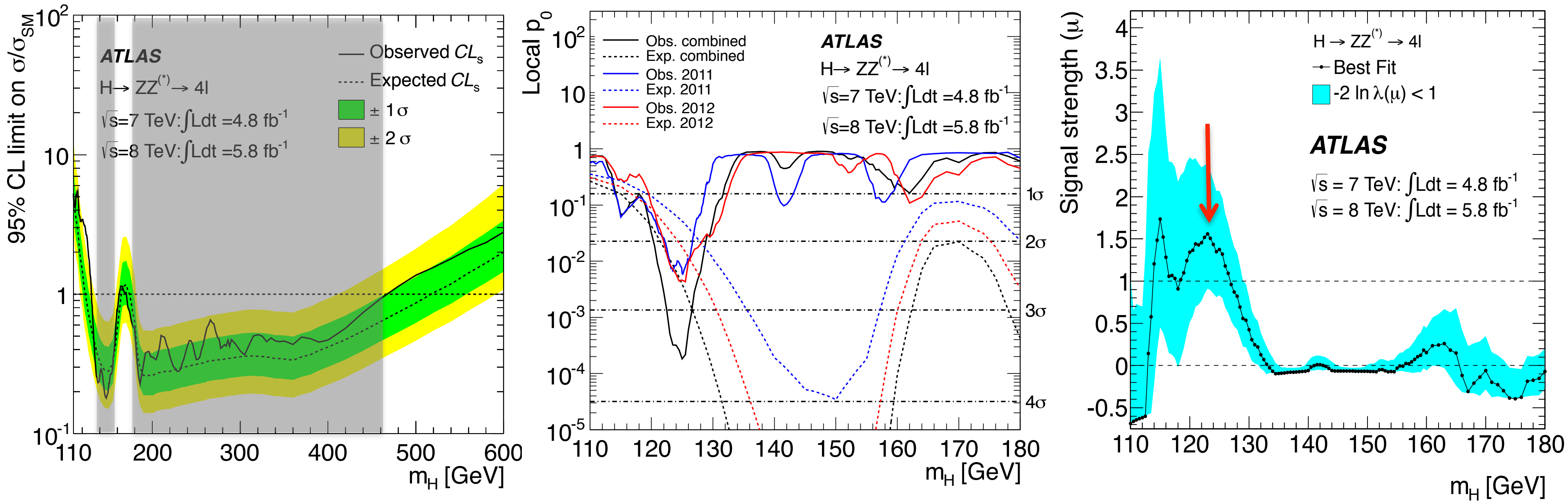
In the region m_H= 125 ± 5 GeV

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

ATLAS-CONF-2012-092

H→ZZ: Results

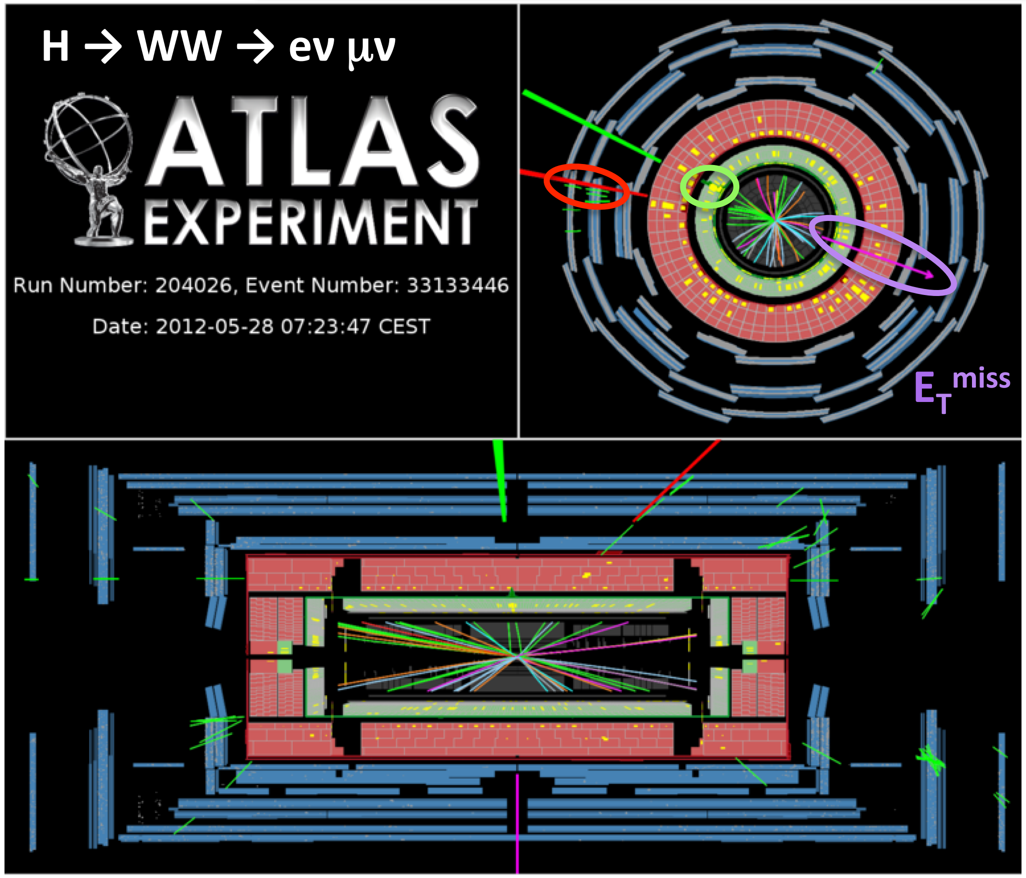
- The SM Higgs boson is excluded at 95% CL in the mass ranges 131– 162 GeV and 170–460 GeV
- An excess of events is observed around m_H = 125 GeV, whose local significance is 3.4σ, and globally 2.1σ with the Look Elsewhere Effect (LEE) over 110-600 GeV
- Both 2011 and 2012 data contribute to excess in same mass range
- Signal strength 125 GeV: μ=1.3 ± 0.6



ATLAS-CONF-2012-092

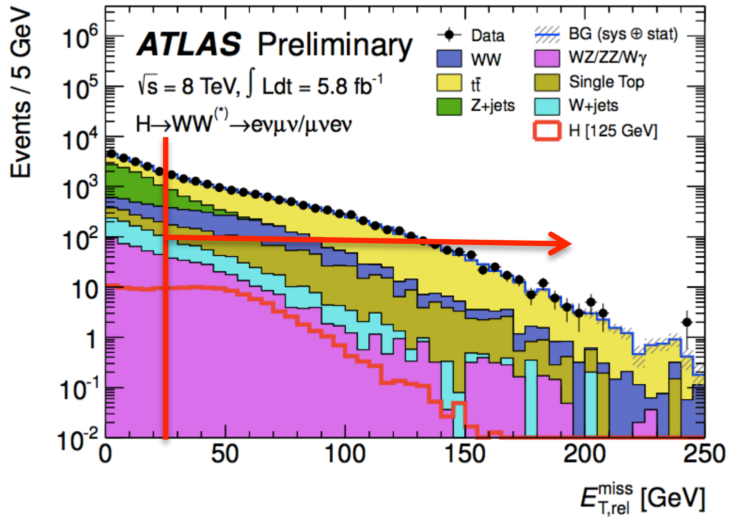
H→WW→eνμν, μνeν

110-200 GeV



σ x BR ~ 500 fb @ m_H~126GeV

- eμ final state provides the large majority of the sensitivity of the search → only this final state has been used in the 2012 analysis



Selection: exactly two oppositely charged leptons of different flavours, pT > 25, 15 GeV
fully identified electron, muons reconstructed in both Inner tracker and spectrometer
Isolated leptons, $E_{T,\,rel}^{miss}$ > 25 GeV, jets pT >25 GeV
Di-lepton angle and mass: $\Delta\varphi_{ll}$ < 1.8 & mll < 50 GeV (0/1 jet), < 80 GeV (2 jets)

$$E_{\rm T,rel}^{\rm miss} = E_{\rm T}^{\rm miss} \sin\Delta\phi_{\rm min}\ ,\ \Delta\phi_{\rm min} \equiv \min(\Delta\phi, \tfrac{\pi}{2})$$

$\Delta\phi$: angle between MET and nearest object

Drell-Yan and QCD multijet events are suppressed by requiring large E_T^{miss}

ATLAS-CONF-2012-098

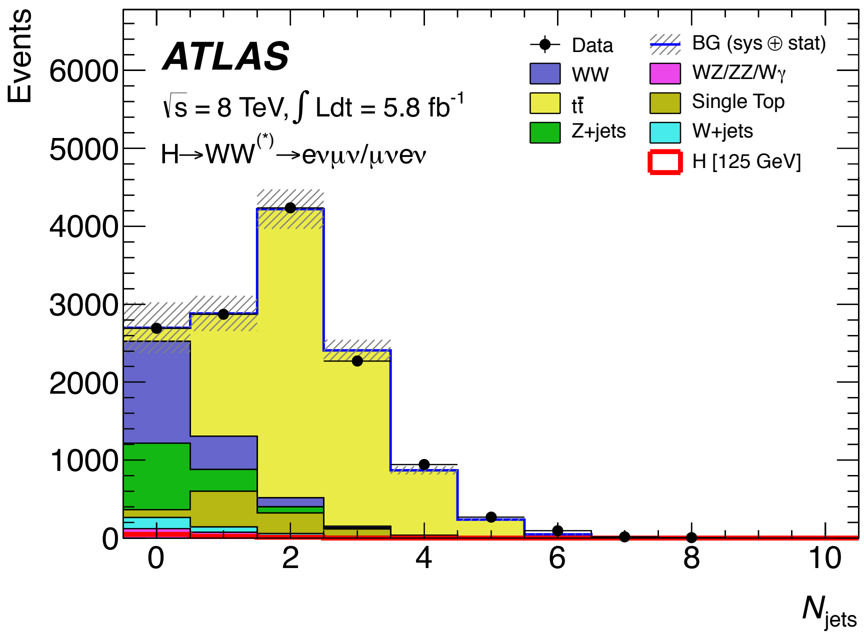
H→WW: Analysis

- Discriminating variable: reconstructed transverse mass

$$m_{\rm T} = \sqrt{(E_{\rm T}^{\ell\ell} + E_{\rm T}^{\rm miss})^2 - |\mathbf{p}_{\rm T}^{\ell\ell} + \mathbf{E}_{\rm T}^{\rm miss}|^2} \quad \text{where} \quad E_{\rm T}^{\ell\ell} = \sqrt{|\mathbf{p}_{\rm T}^{\ell\ell}|^2 + m_{\ell\ell}^2}$$

(ll stands for di-lepton)

- The background rate/composition & signal topology depend significantly on the jet multiplicity



ATLAS-CONF-2012-098

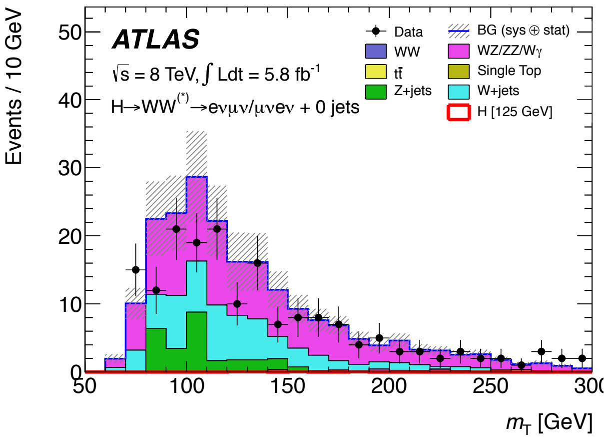
- Data subdivided into 3 jet bins. Their main backgrounds are:
  - ✓ H + 0-jet analysis: WW
  - ✓ H + 1-jet analysis: WW & top (ttbar & Wt single-top)
  - ✓ H + ≥2-jet analysis: top

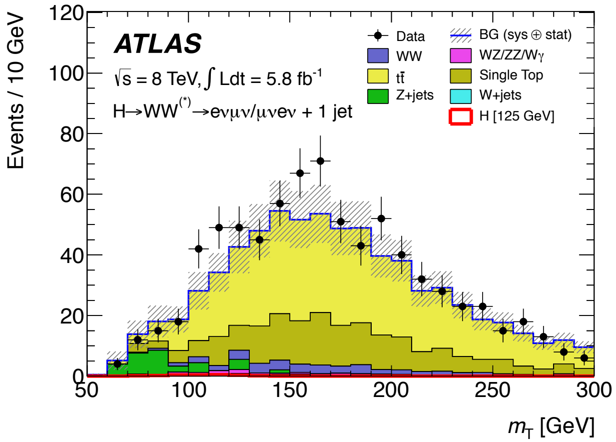
+ Subleading backgrounds: W+jets, W+γ, W+Z/γ*, Z/γ*

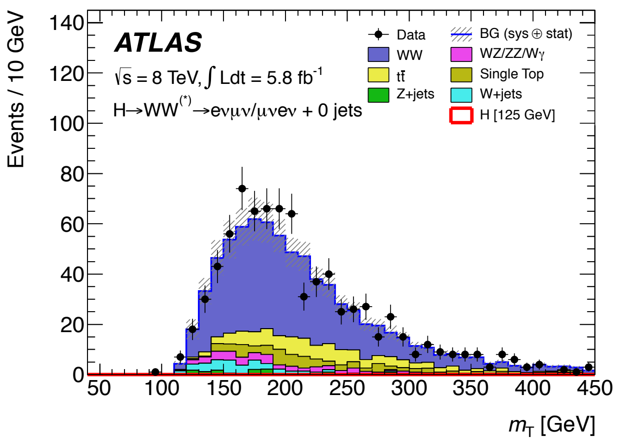
H→WW: Control Regions

- *WW* and top estimated using partially data-driven techniques, normalising the MC predictions to the data in control regions
- The *W*+jets background fully estimated from data for all jet multiplicities.
- Drell-Yan, diboson processes other than *WW*, and the *WW* background for the *H*+ 2-jet analysis estimated using simulation. VBF signal in the 2-jet bin is expected to be very low.

- W+jet control sample: one of the leptons fails tight ID/isolation criteria but pass relaxed ones ("anti-identified"), validated in the same-sign region where the OS requirement is inverted:
- Top control sample: Normalise 1-jet, 2-jet top background from b-tagged control region
- *WW* control sample (*H* + 0-jet and *H* + 1-jet) summed over lepton flavours, $\Delta\phi ll$ cut removed and $m ll$ relaxed < 80 GeV.



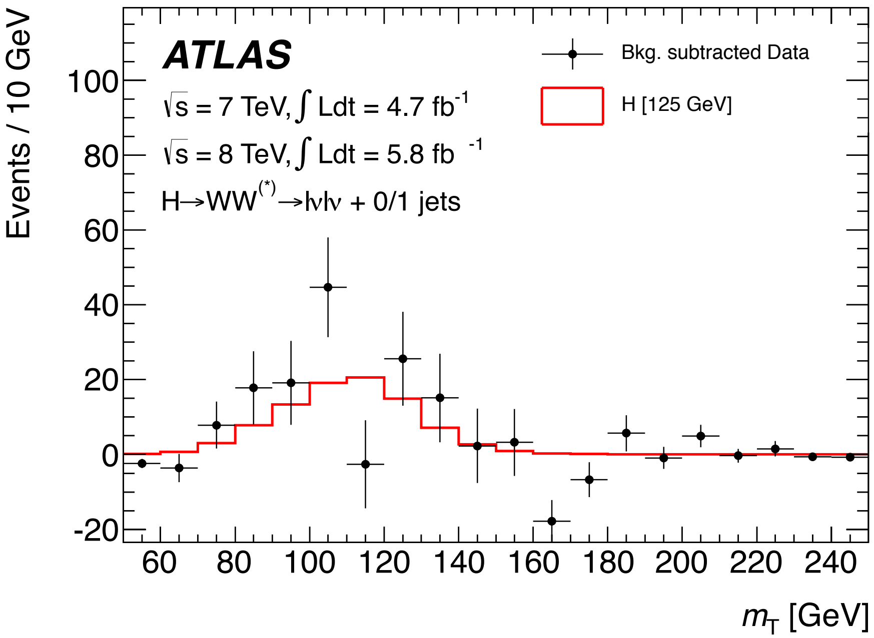




ATLAS-CONF-2012-098

H→WW: Yield

- Transverse mass distributions in data after all selection criteria have been applied, with the total estimated background subtracted



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

→ In the *H* + 2-jet channel only two events in the data pass all of the selection

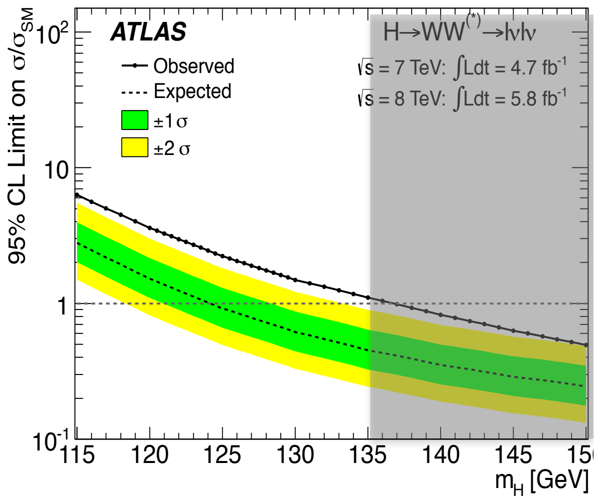
- The statistical analysis of the data employs a binned likelihood function L(μ, θ)

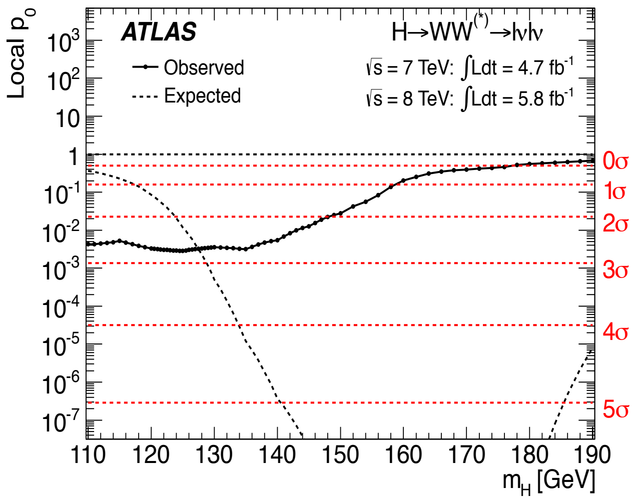
→ product of Poisson probability terms (low stat.) in each lepton flavour channel.

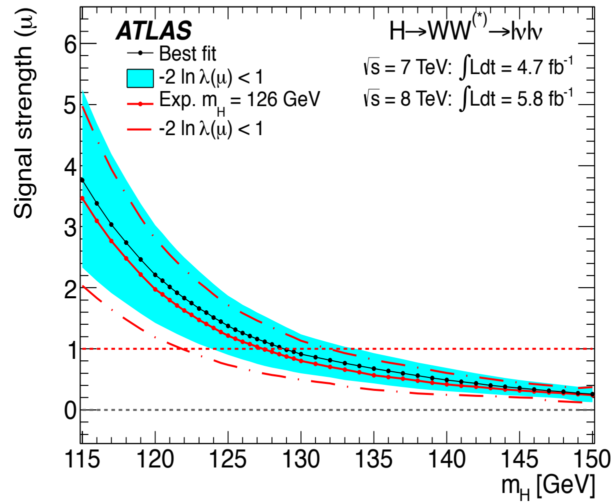
ATLAS-CONF-2012-098

H→WW: Results

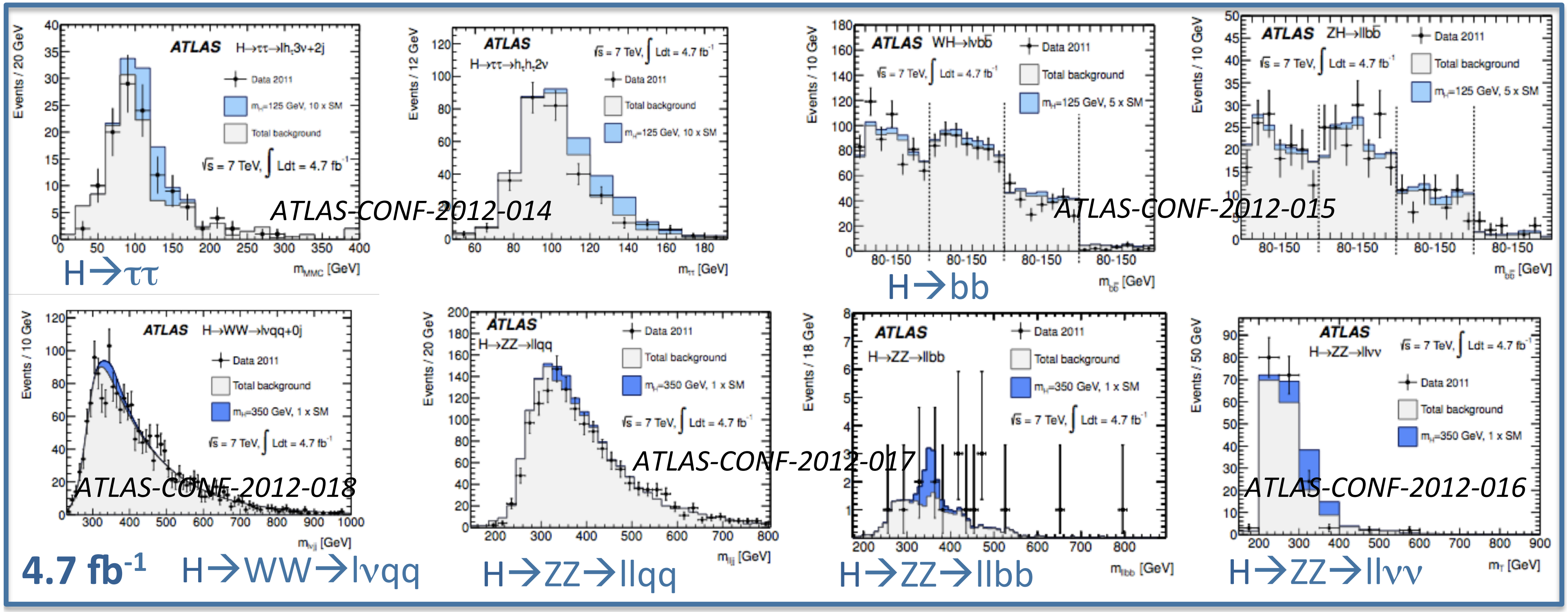
- The expected 95% *CLs* limit on σ/σ_{SM} excludes a SM Higgs boson with a mass down to 124 GeV. Observed: >137 GeV.
- For m_H=125 GeV, combination of $\sqrt{s}$ = 7 TeV and 8 TeV data, the observed excess in the *H*→ *WW*(∗)→ lνlν : 2.8 σ
- The fitted signal strength at *mH* = 126 GeV is μ = 1.3 ± 0.5



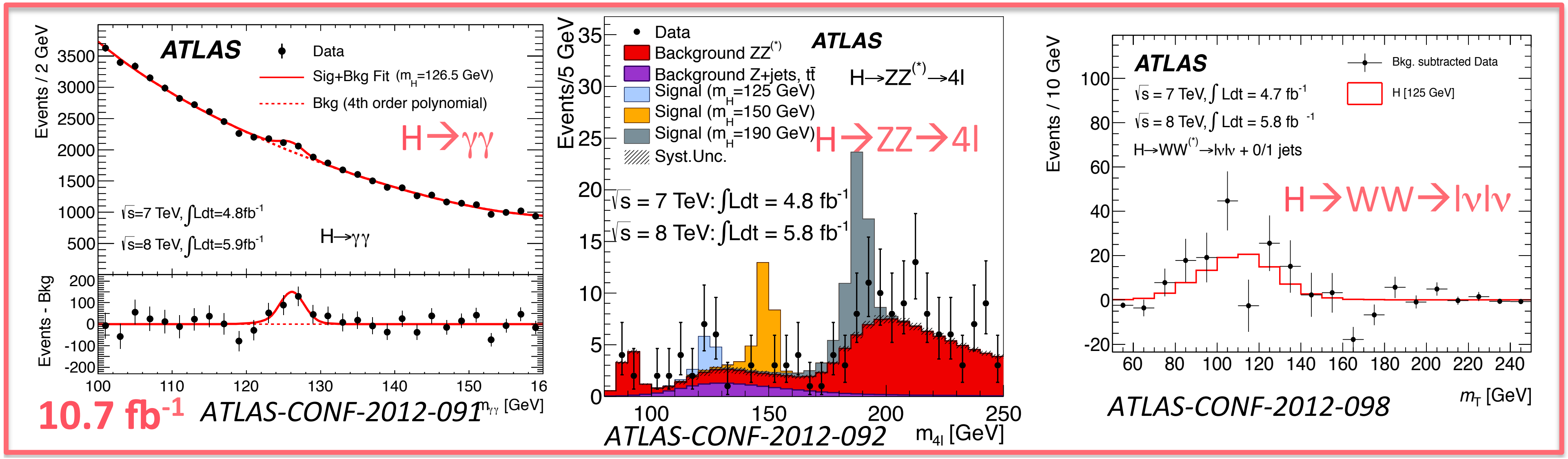




ATLAS-CONF-2012-098

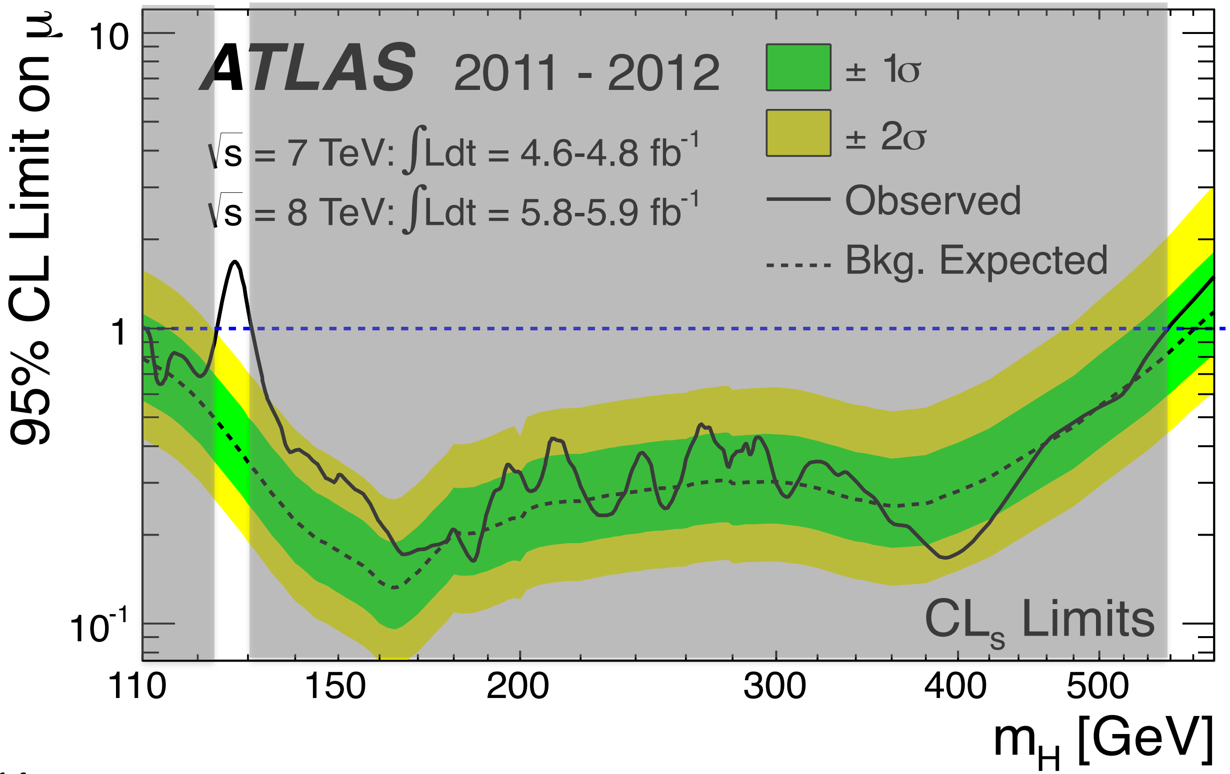


COMBINATION



Combined Results: Exclusion

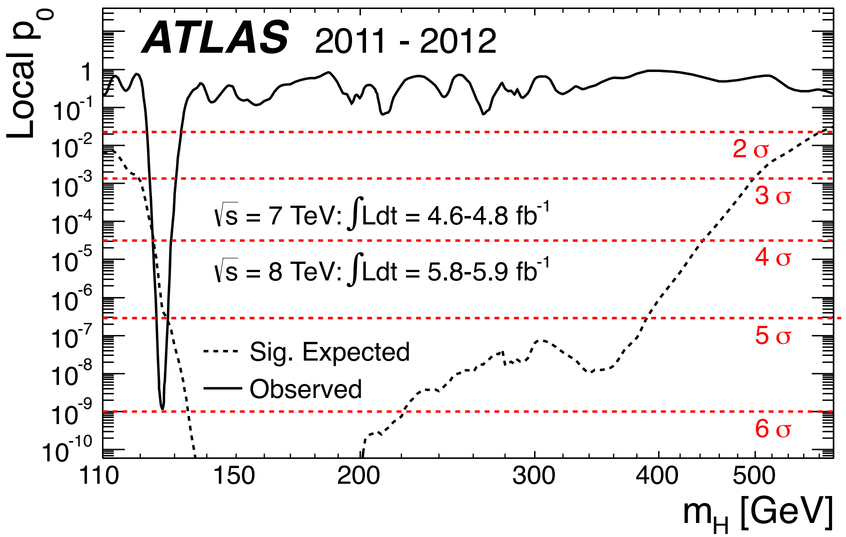
- Expected at 95% CL if no signal: 110-582 GeV
- Observed exclusion on the SM Higgs at 95% CL: 110-122.6 and 129.7-558 GeV
- Observed exclusion on the SM Higgs at 99% CL: 111.7-121.8 GeV and 130.7-523 GeV

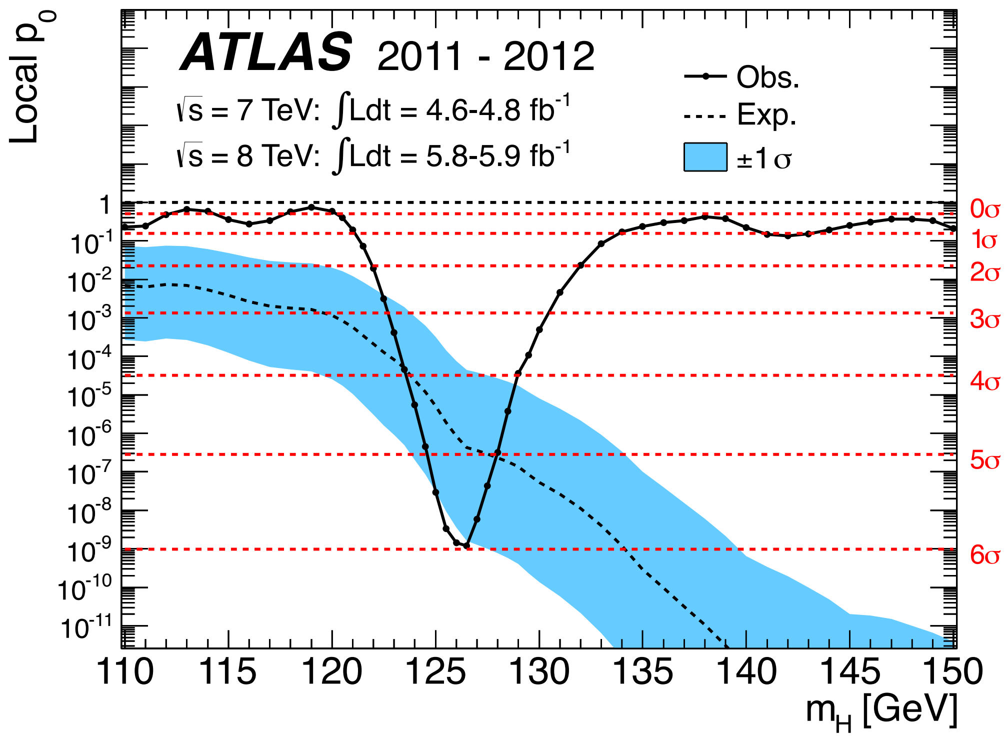


arXiv:1207.7214

Combined Results: Discovery

- Local significance of the excess: 5.9 σ at m_H = 126.5 GeV (4.8 expected)
- The global significance:
  - 5.1 σ in the range 110–160 GeV
  - 5.3 σ in the range 110–150GeV (mass range not excluded at the 99% CL by the LHC and the indirect constraints from the global fit to precision electroweak measurements)

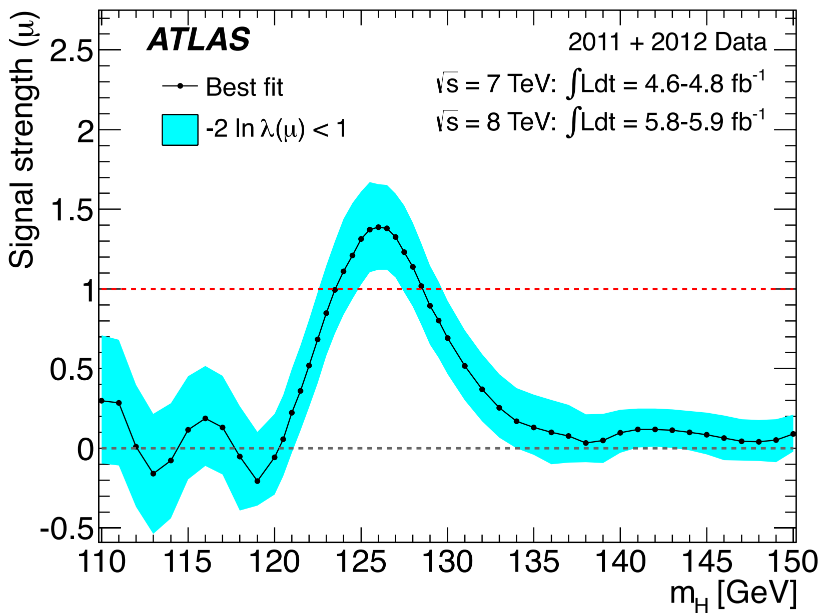


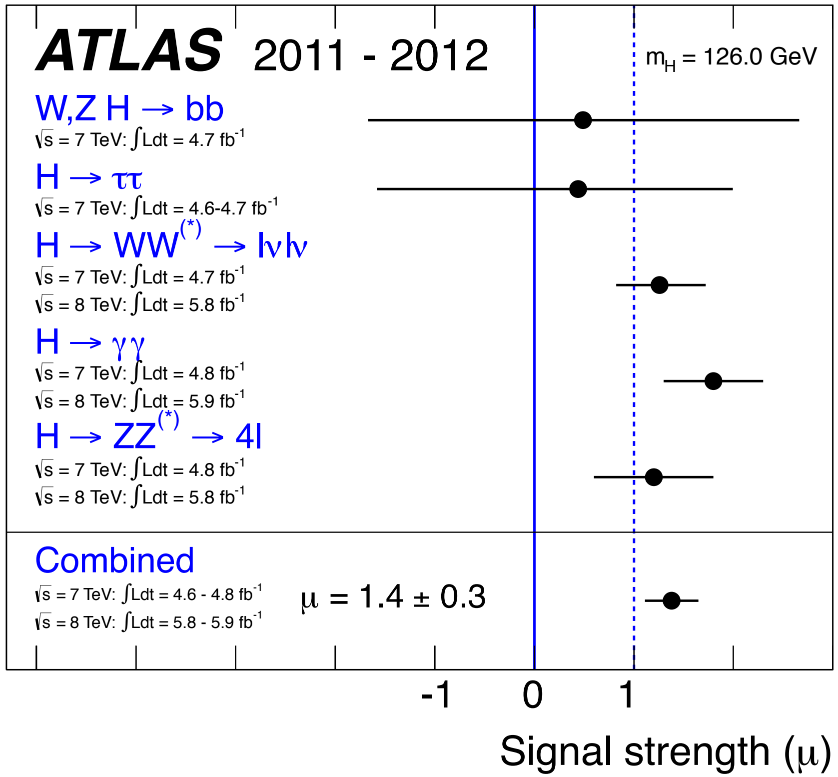


arXiv:1207.7214

Combined Results: Signal Strength

- Estimate for the mass of the observed particle is 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV
- Measurements of the signal strength parameter μ = 1.4 ± 0.3 for M_H = 126 GeV, which is consistent with the SM Higgs boson hypothesis μ = 1

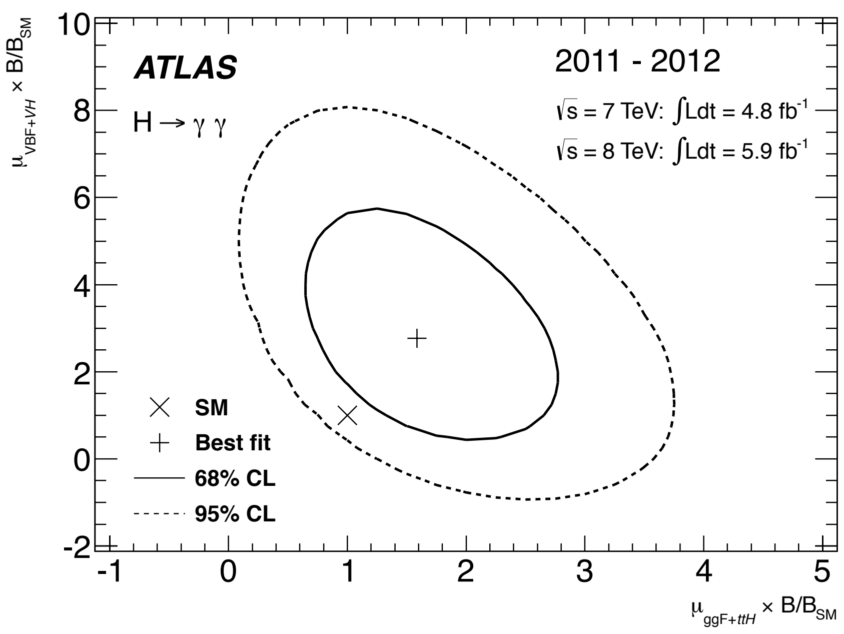


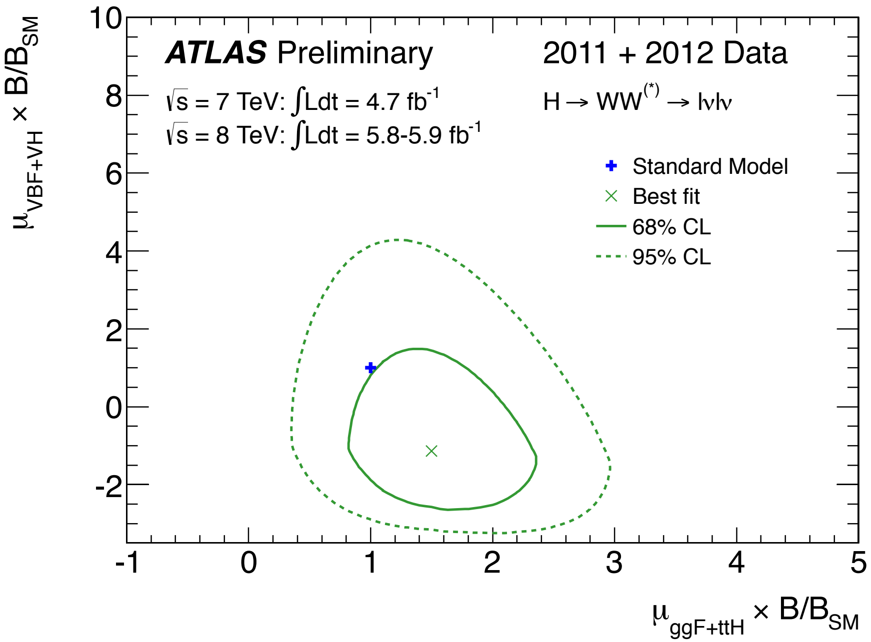


arXiv:1207.7214

Essential Property Measurements (1)

- The new observed boson is compatible with the Standard Model Higgs boson. Important checks in the future include:
  - Checking its spin. Presence of excess in the $H \rightarrow \gamma\gamma$ channel tells us spin is either 0 or 2 (spin 1 excluded by the Landau-Yang theorem)
  - Measure the couplings: check the μ_{ggF}, μ_{VBF}, μ_{VH}, μ_{ttH} are consistent with SM
  - First results with fits with 2 parameters: vector bosons μ_{VBF+VH} & fermions $\mu_{ggF+ttH}$





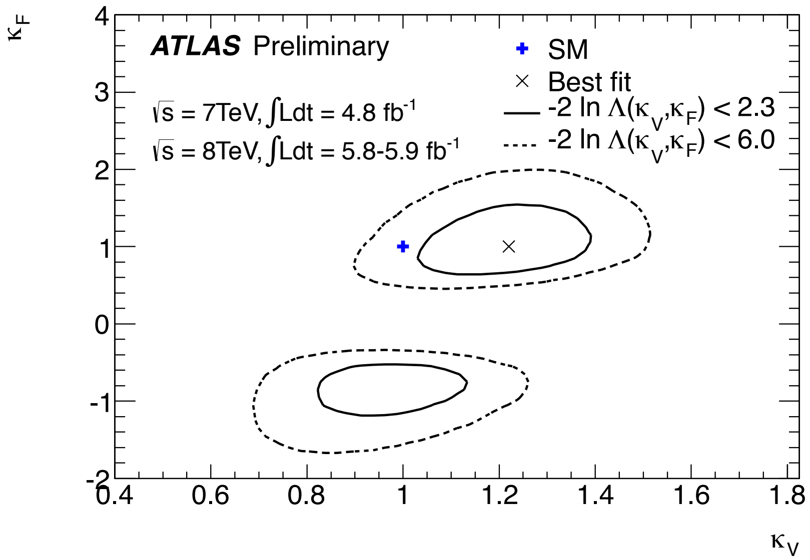
ATLAS-CONF-2012-127

Essential Property Measurements (2)

- For the moment compatible with SM, but more measurements will be pursued

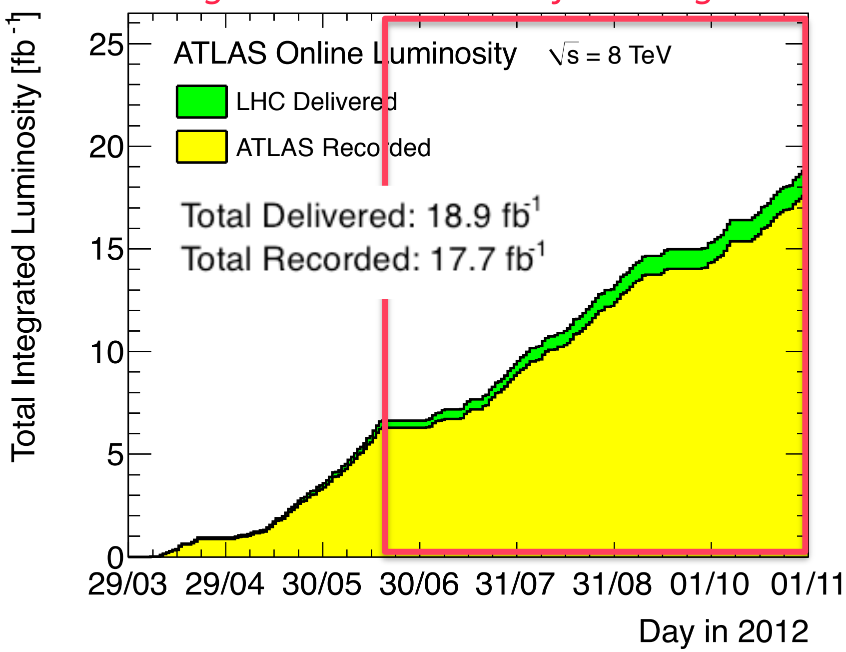
→ New particle in a mass range where it can be seen in many channels which is good for properties measurement

Correlation between coupling strength scale factors for fermions (κF) and vector bosons (κV)



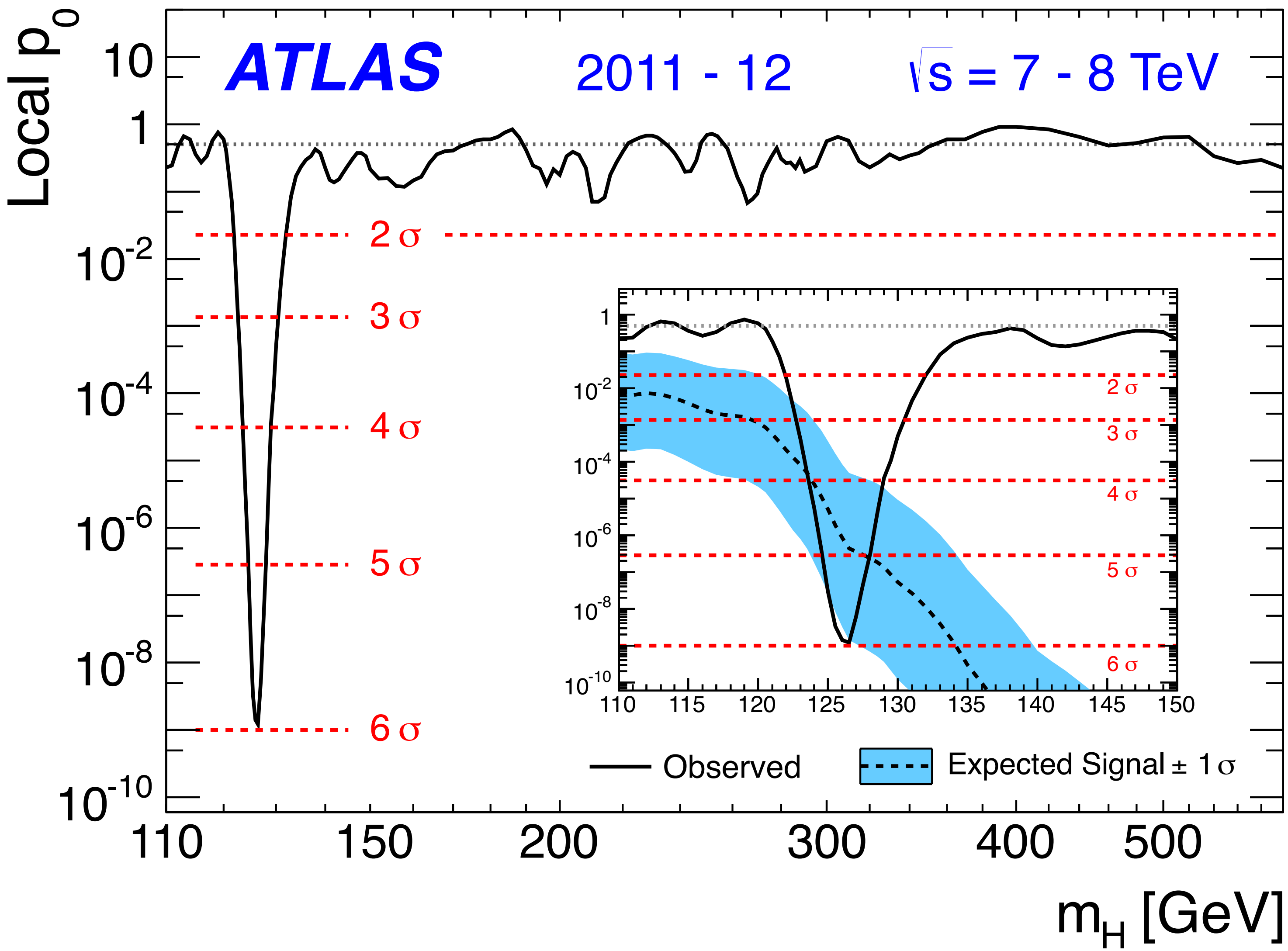
(Only the relative sign between κ_F and κ_V is physical)

Looking at additional data following in…



ATLAS-CONF-2012-127

This is an exciting time, and this is only the beginning !



BACKUP

Conclusions

- The search for a Standard Model Higgs boson with the ATLAS experiment with:
  - $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ\rightarrow 4l$, $H\rightarrow WW\rightarrow l\nu l\nu$ with up to 10.7 fb^{-1}
  - $H\rightarrow\tau\tau$, $H\rightarrow bb$, $H\rightarrow ZZ\rightarrow llqq$, $H\rightarrow ZZ\rightarrow ll\nu\nu$, $H\rightarrow WW\rightarrow l\nu qq$ with 4.7 fb^{-1}

- A boson with the SM cross section has been excluded
  - at 95% CL in the regions [110;122.6] and [129.7;558] GeV
  - at 99% CL in the regions [111.7;121.8] GeV and [130.7-523] GeV

- A neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV has been observed with a significance of 5.9 standard deviations (background fluctuation probability of 1.7×10^{-9}) This new particle is compatible with the production and decay of the Standard Model Higgs boson.

- After this observation we need to study the properties of this boson, in particular its
  - Spin
  - Couplings

Summary of Channels

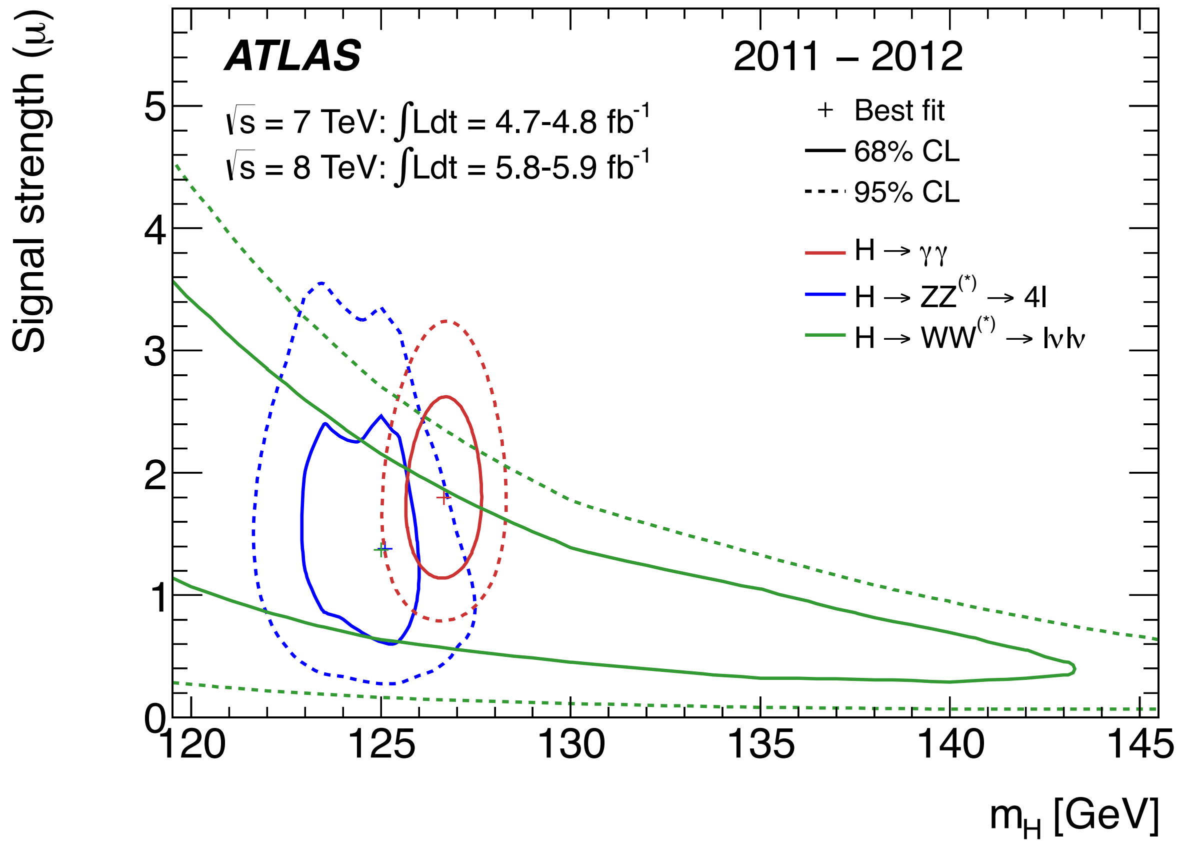
Higgs Boson Decay	Subsequent Decay	Sub-Channels	m_H Range [GeV]	$\int L\,dt$ [fb^{-1}]
2011 $\sqrt{s}$ =7 TeV				
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	110–600	4.8
	$\ell\ell\nu\bar{\nu}$	$\{ee, \mu\mu\} \otimes \{$low, high pile-up$\}$	200–280–600	4.7
	$\ell\ell q\bar{q}$	$\{b$-tagged, untagged$\}$	200–300–600	4.7
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet$\}$	110–150	4.8
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu/\mu e, \mu\mu\} \otimes \{$0-jet, 1-jet, 2-jet$\} \otimes \{$low, high pile-up$\}$	110–200–300–600	4.7
	$\ell\nu q q'$	$\{e, \mu\} \otimes \{$0-jet, 1-jet, 2-jet$\}$	300–600	4.7
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{$0-jet$\} \oplus \{\ell\ell\} \otimes \{$1-jet, 2-jet, $VH\}$	110–150	4.7
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{$0-jet$\} \otimes \{E_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} \geq 20$ GeV$\}$ $\oplus \{e, \mu\} \otimes \{$1-jet$\} \oplus \{\ell\} \otimes \{$2-jet$\}$	110–150	4.7
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{$1-jet$\}$	110–150	4.7
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\}$	110–130	4.6
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-200, \geq 200$ GeV$\}$	110–130	4.7
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-200, \geq 200$ GeV$\}$	110–130	4.7
2012 $\sqrt{s}$ =8 TeV				
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu\}$	110–600	5.8
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet$\}$	110–150	5.9
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes \{$0-jet, 1-jet, 2-jet$\}$	110–200	5.8

Summary of Excess and Exclusion

Search channel	Dataset	$m_{\max}$ [GeV]	Z_l [σ]	$E(Z_l)$ [σ]	$\hat{\mu}(m_H = 126\ \text{GeV})$	Expected exclusion [GeV]	Observed exclusion [GeV]
$H \to ZZ^{(*)} \to 4\ell$	7 TeV	125.0	2.5	1.6	1.4 ± 1.1		
	8 TeV	125.5	2.6	2.1	1.1 ± 0.8		
	7 & 8 TeV	125.0	3.6	2.7	1.2 ± 0.6	124–164, 176–500	131–162, 170–460
$H \to \gamma\gamma$	7 TeV	126.0	3.4	1.6	2.2 ± 0.7		
	8 TeV	127.0	3.2	1.9	1.5 ± 0.6		
	7 & 8 TeV	126.5	4.5	2.5	1.8 ± 0.5	110–140	112–123, 132–143
$H \to WW^{(*)} \to \ell\nu\ell\nu$	7 TeV	135.0	1.1	3.4	0.5 ± 0.6		
	8 TeV	120.0	3.3	1.0	1.9 ± 0.7		
	7 & 8 TeV	125.0	2.8	2.3	1.3 ± 0.5	124–233	137–261
Combined	7 TeV	126.5	3.6	3.2	1.2 ± 0.4		
	8 TeV	126.5	4.9	3.8	1.5 ± 0.4		
	7 & 8 TeV	126.5	6.0	4.9	1.4 ± 0.3	110–582 113–532 (*)	111–122, 131–559 113–114, 117–121, 132–527 (*)

Confidence Intervals from Channels

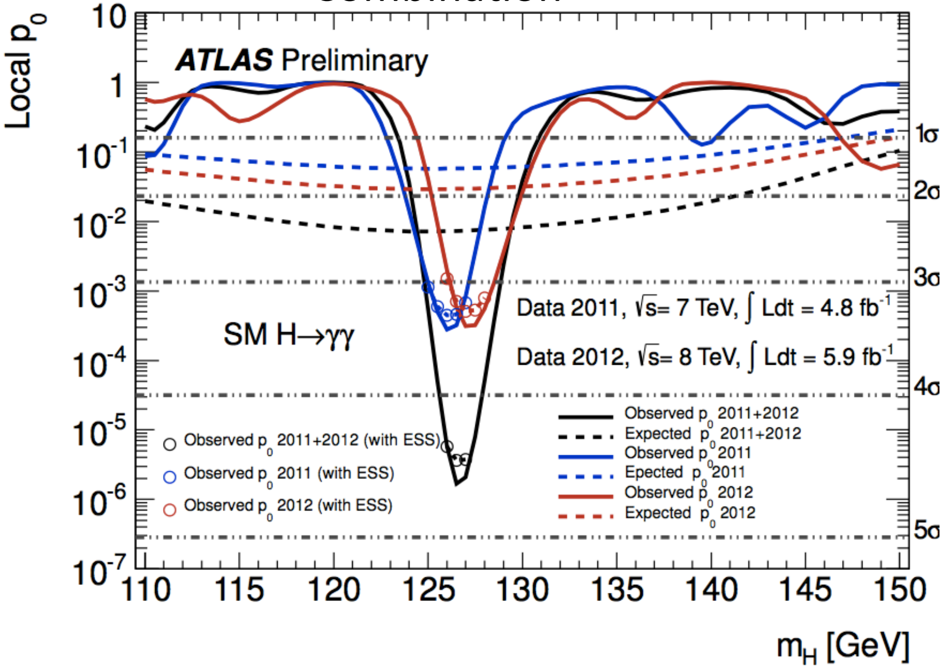
- Confidence intervals in the (mu, mH) plane for the H to ZZ(*) to 4l, H to gamma gamma, and H to WW(*) to l nu l nu channels, including all systematic uncertainties. The markers indicate the maximum likelihood estimates (muhat, mHhat) in the corresponding channels (the maximum likelihood estimates for H to ZZ(*) to 4l and H to WW(*) to l nu l nu coincide).



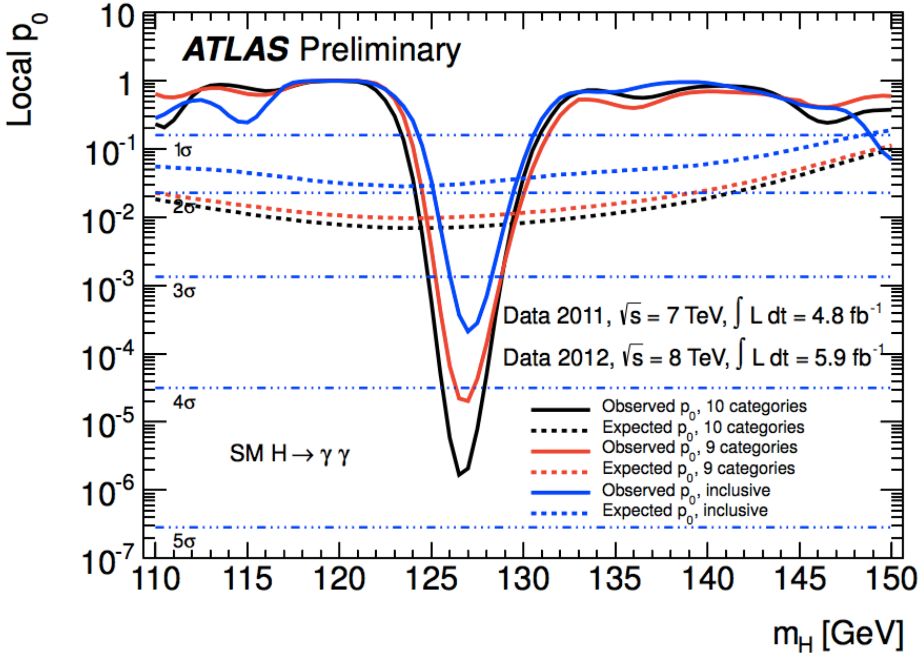
H→γγ

- Effect of categories

Combination



Effect of categories



H→γγ: Signal Strength per Category