Recent Higgs Search Results at the LHC

LCWS12, Higgs-EWSB Session

Oct. 23, 2012

Jae Yu

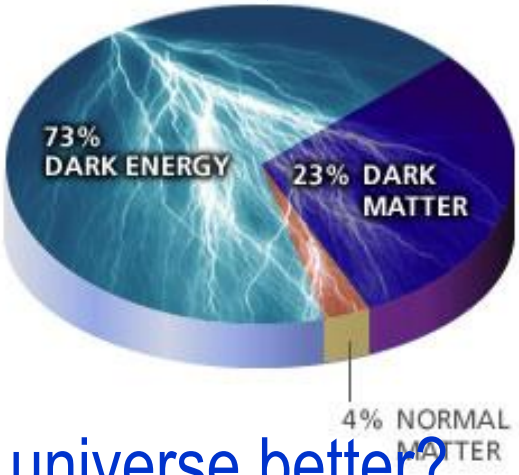
University of Texas at Arlington

Outline

- Introduction
- The apparatus
- Standard Model Higgs searches, the latest results
- Going Beyond

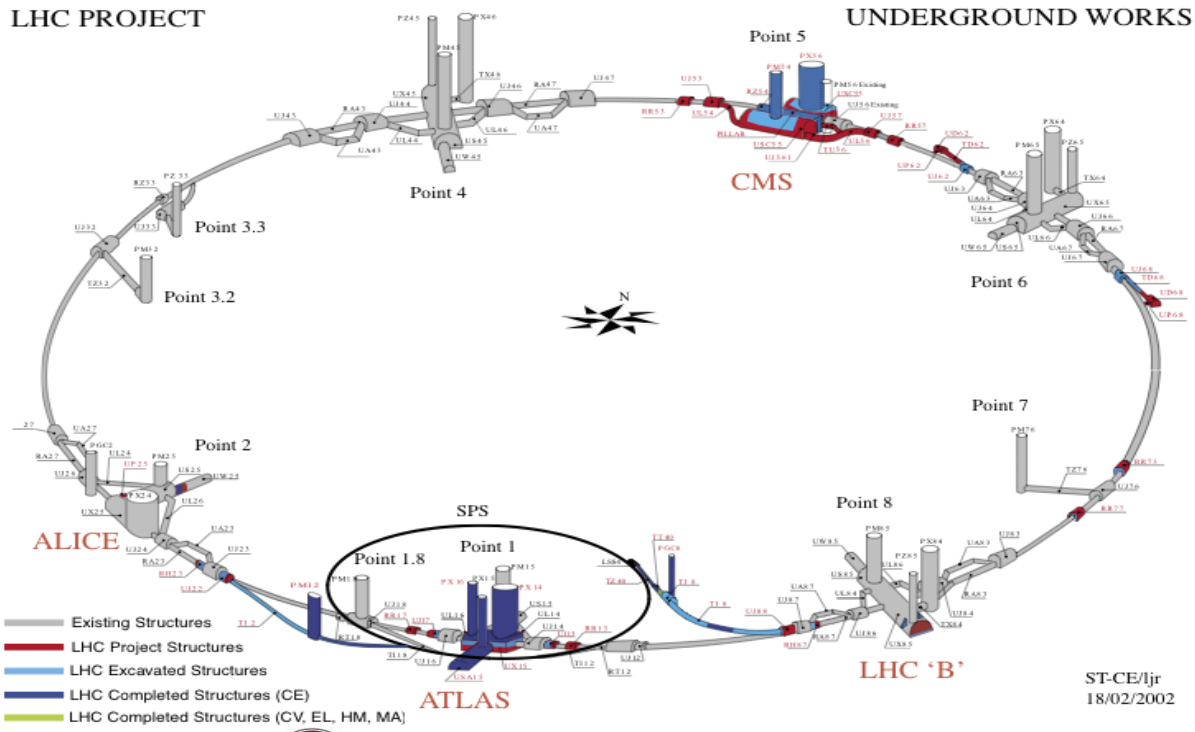
Introduction

- Why is the mass range so large ($0.1m_p$ – $175\ m_p$)?
- How do matters acquire mass?
  - Higgs mechanism, did we find the Higgs?
- Why is the matter in the universe made only of particles?
- Neutrinos have mass!! What are the mixing parameters, CP violations and mass ordering?
- Why are there only three apparent forces?
- Is the picture we present the real thing?
  - What makes up the 96% of the universe?
  - How about extra-dimensions?
- Are there any other theories that describe the universe better?
  - Does the super-symmetry exist?
- Where is new physics?

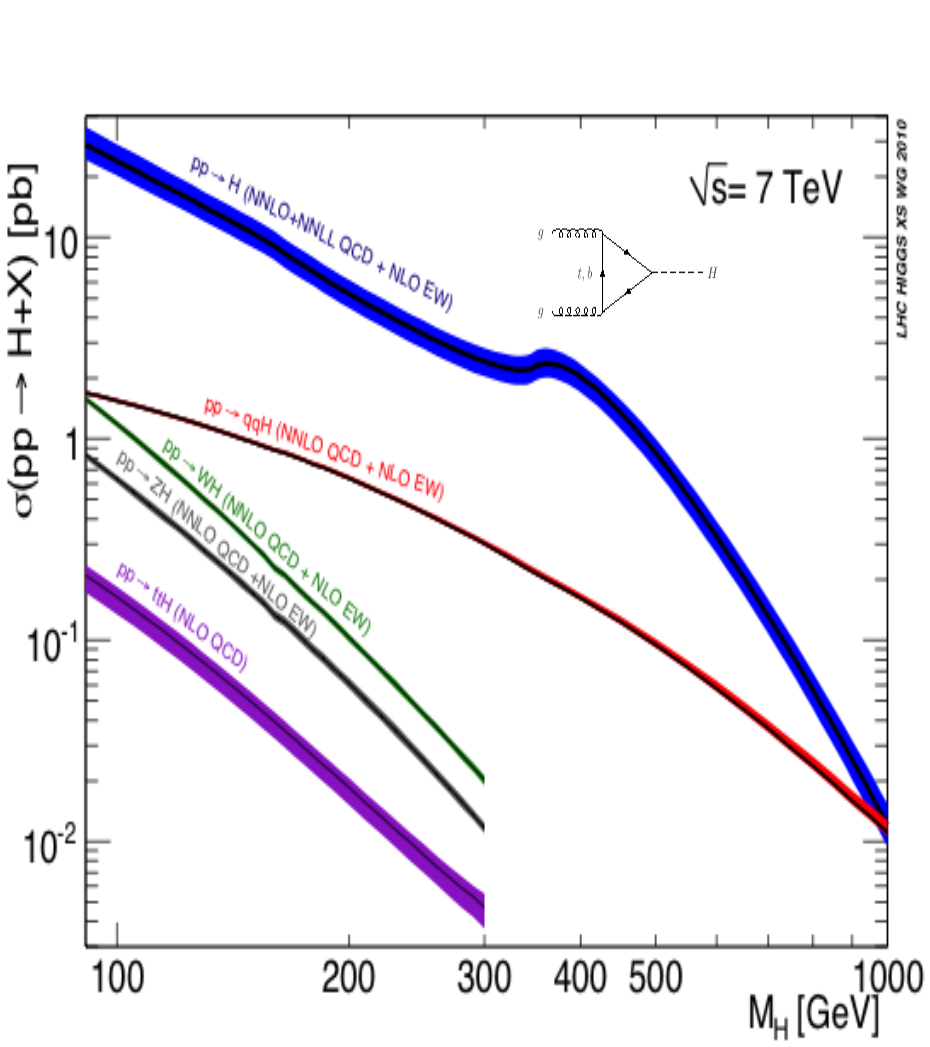


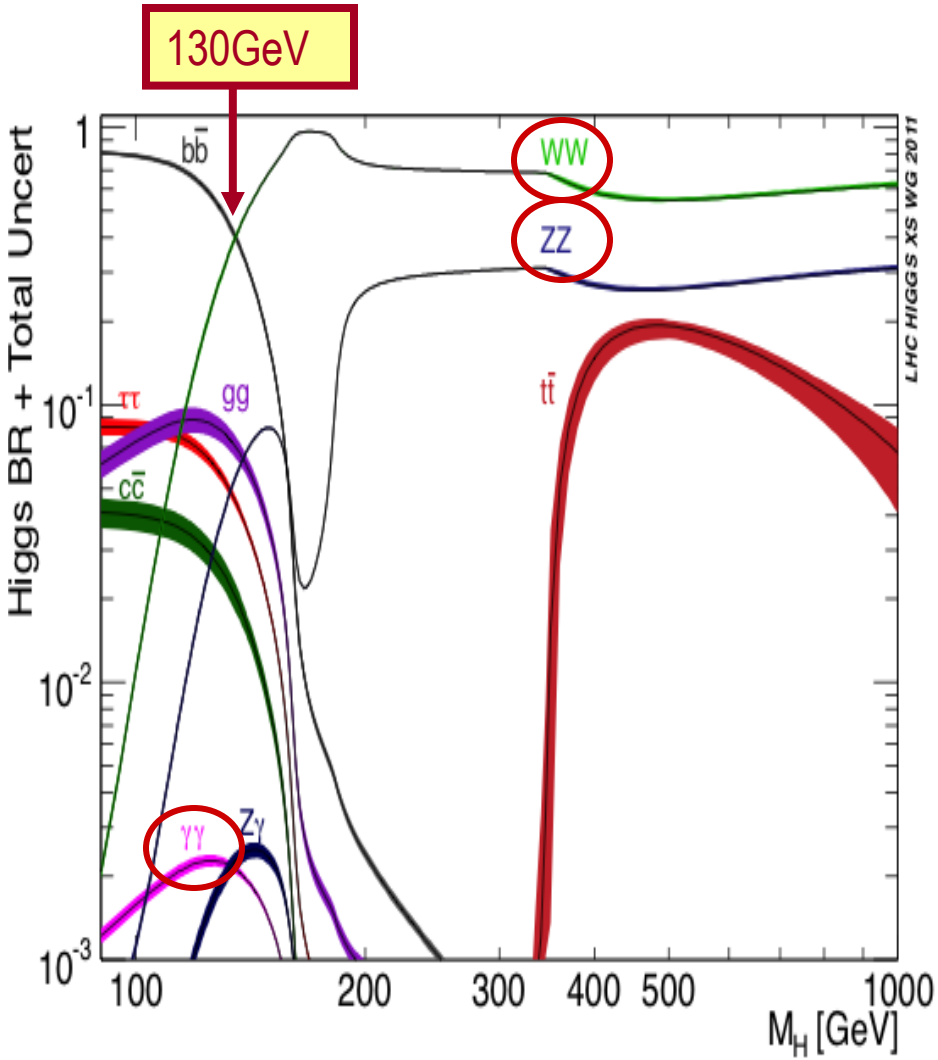
The LHC at CERN

- World's Highest Energy p-p collider
  - 27km circumference, 100m underground
  - Design E_{cm}=14 TeV (=44x10^{-7}J/p) & L~10^{34}cm^{-2}s^{-1}
- Delivered 7TeV collision data at 5.6 fb^{-1}
- **First 8TeV collisions in 2012 on April 5, 2012 ➔ Accumulated 17fb^{-1} thus far (~1fb^{-1}/wk)**
  - **About 7 more weeks of data taking left before switching to HI in 2013(7fb^{-1})**



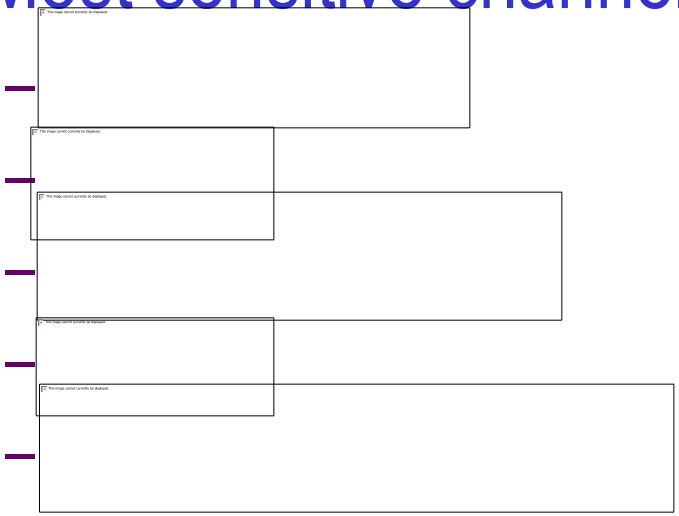
Higgs Production X-sec and BR





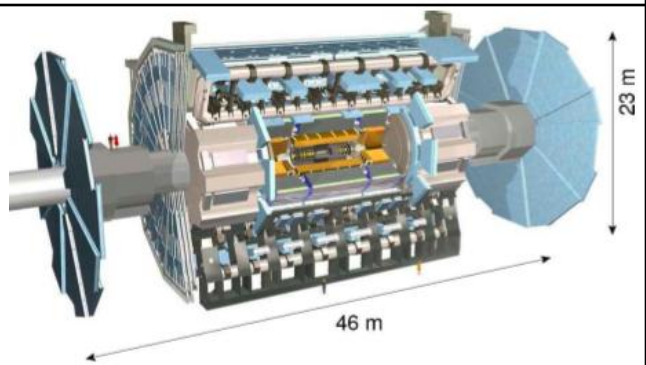
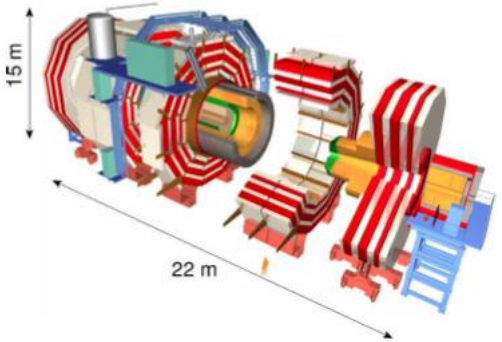
Higgs Search Strategies Thus Far

- Use $gg \to H$ production (highest production mode)
- Most sensitive channels in $120<M_H<130$GeV are

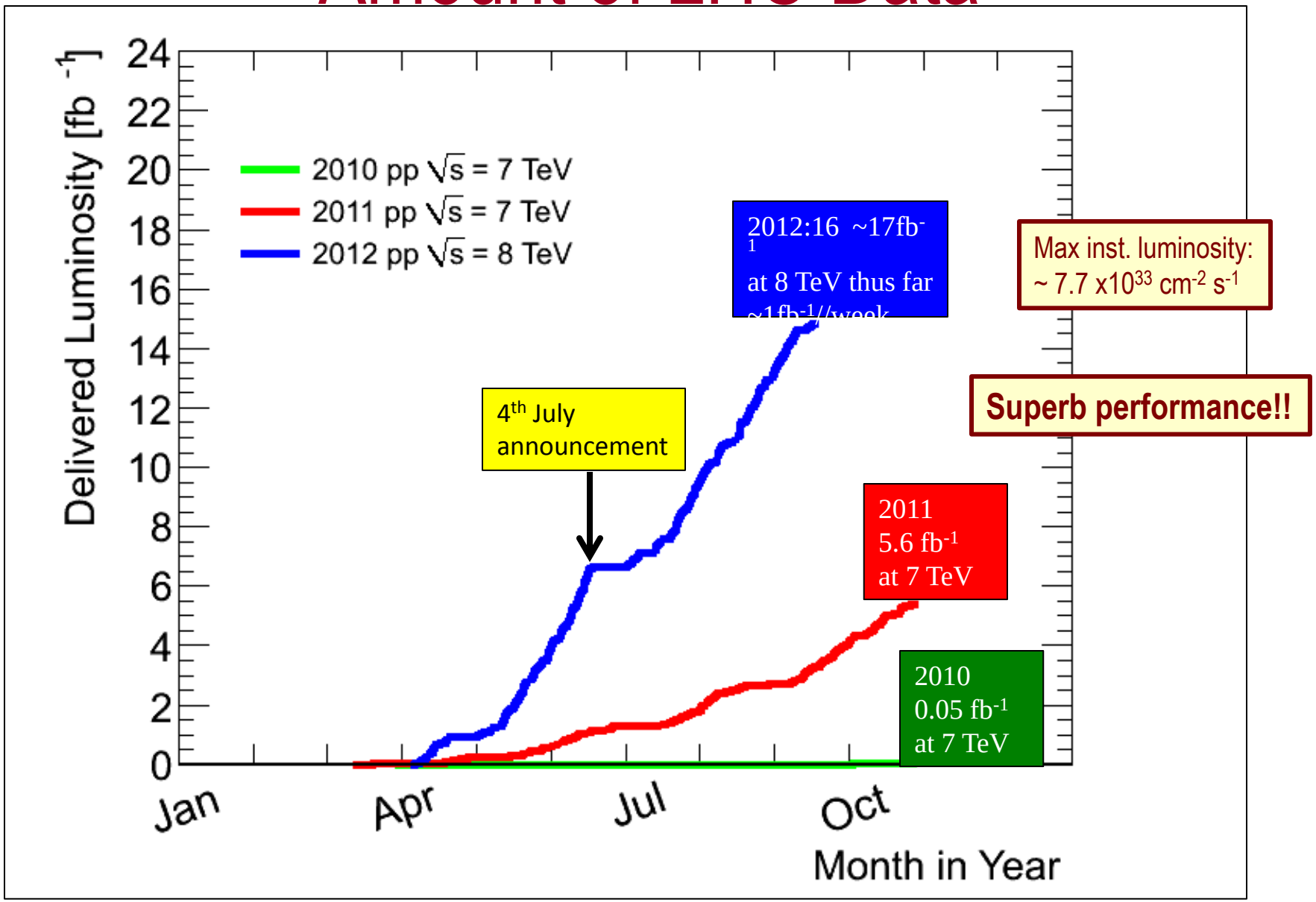


- Look for high p_T isolated photons, electrons and muons and their specific geometric signatures – such as $\otimes$)
- Look for missing E_T signatures

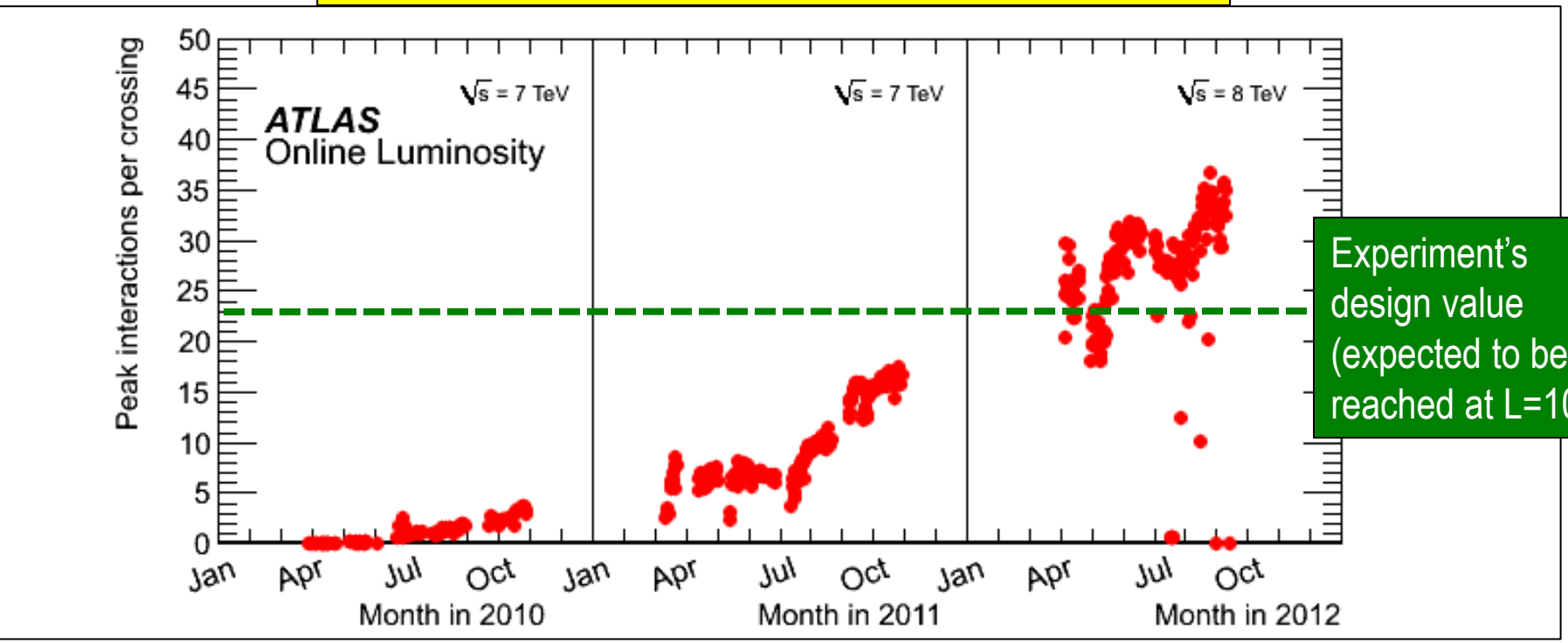
The ATLAS and CMS Detectors

Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-LAr Sampling w/ fine longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\%$ (at 50 GeV) $\sim 11\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

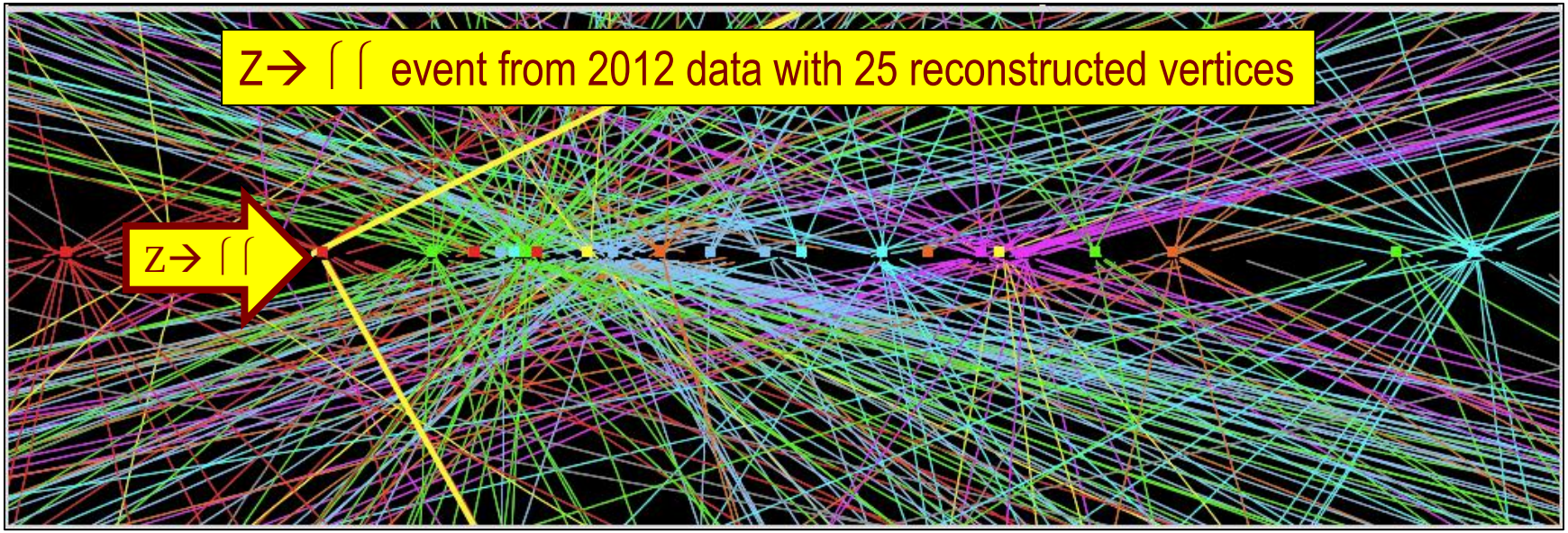
Amount of LHC Data



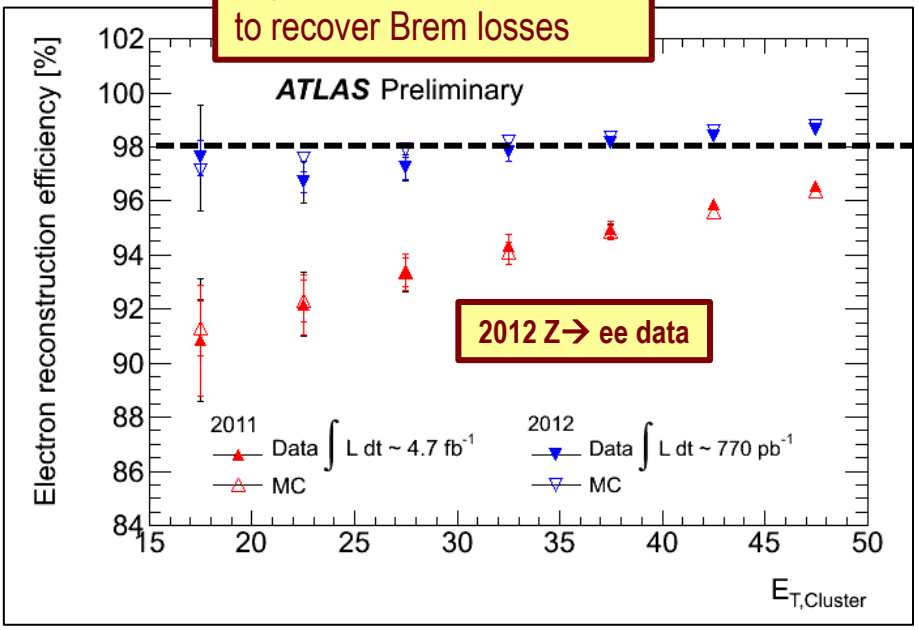
The BIG challenge in 2012: PILE-UP



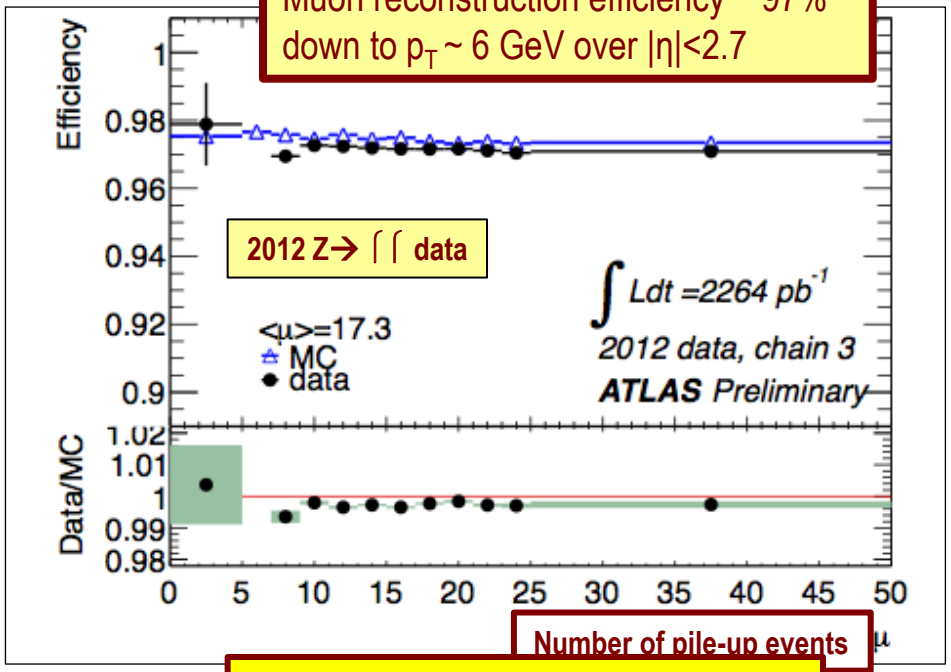
Experiment's design value (expected to be reached at $L=10^{34}$!)



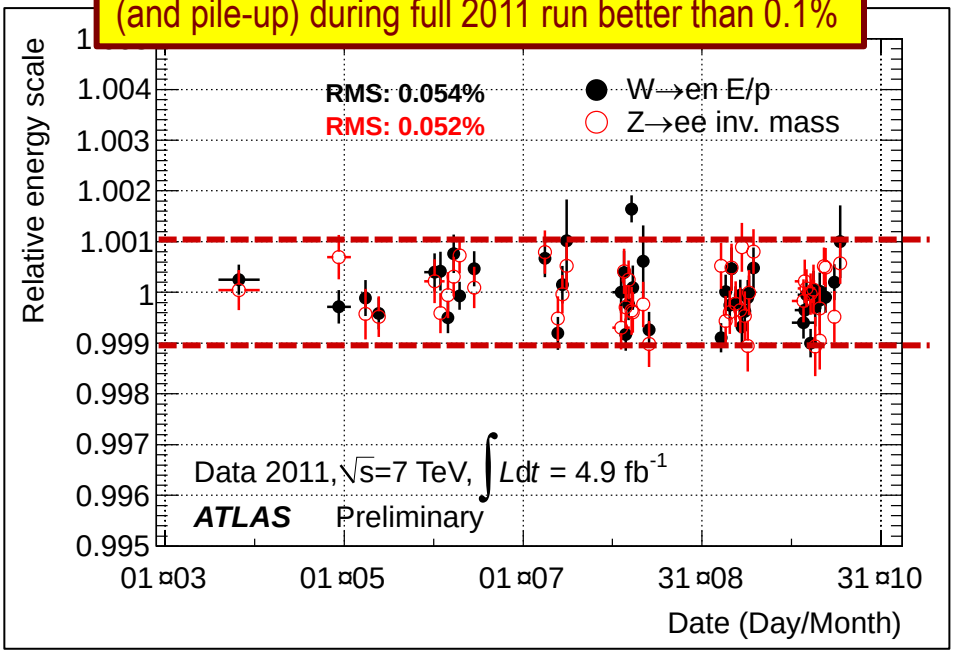
Improved e± reconstruction to recover Brem losses



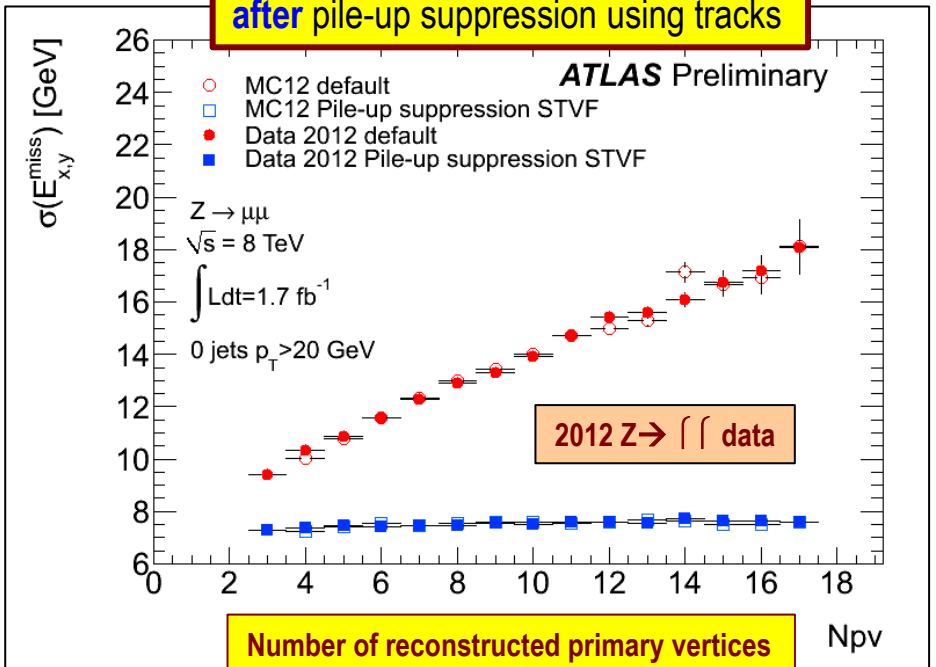
Muon reconstruction efficiency ~ 97% down to p_T ~ 6 GeV over |η|<2.7



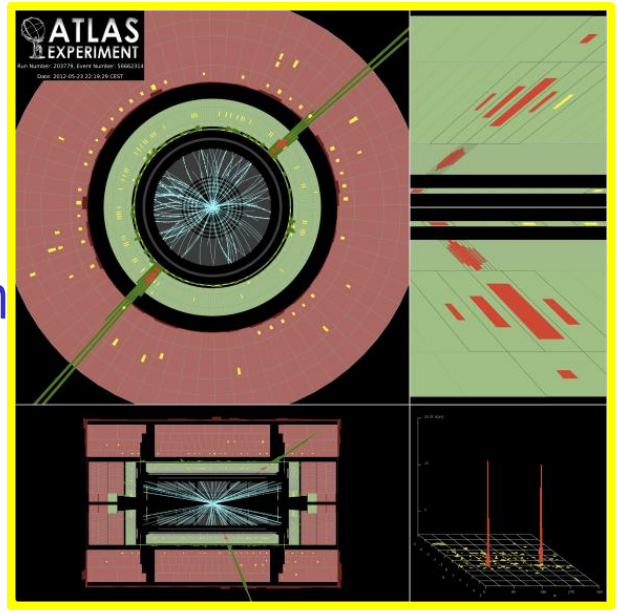
Stability of EM calorimeter response vs time (and pile-up) during full 2011 run better than 0.1%



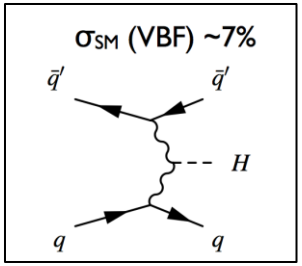
E_T^{miss} resolution vs pile-up **before** and **after** pile-up suppression using tracks



H→©©Channel

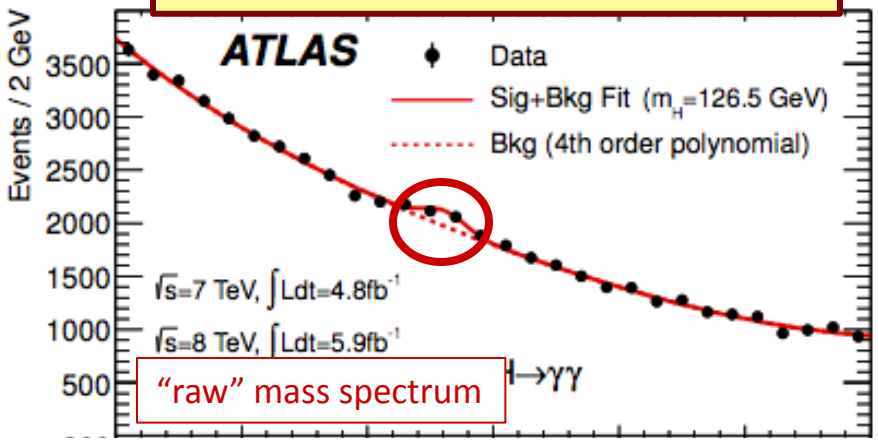


- Sensitive to 110<M_H<150GeV
- Low BR and low x-sec but main bck ©©continuum
  - (∫xBR~50fb @ M_H=126GeV) ➔ high sensitivity
- Requires excellent photon ID and □^{0} bck rejection
- Simple topology: 2 high PT isolated photons
  - Require ET(©$_1$,©$_2$)>40,30 GeV
- To increase sensitivity, candidates are split into several categories depending on photons' rapidity, conversions, angle between p_T and thrust axis, presence of two forward jets (for VBF), etc

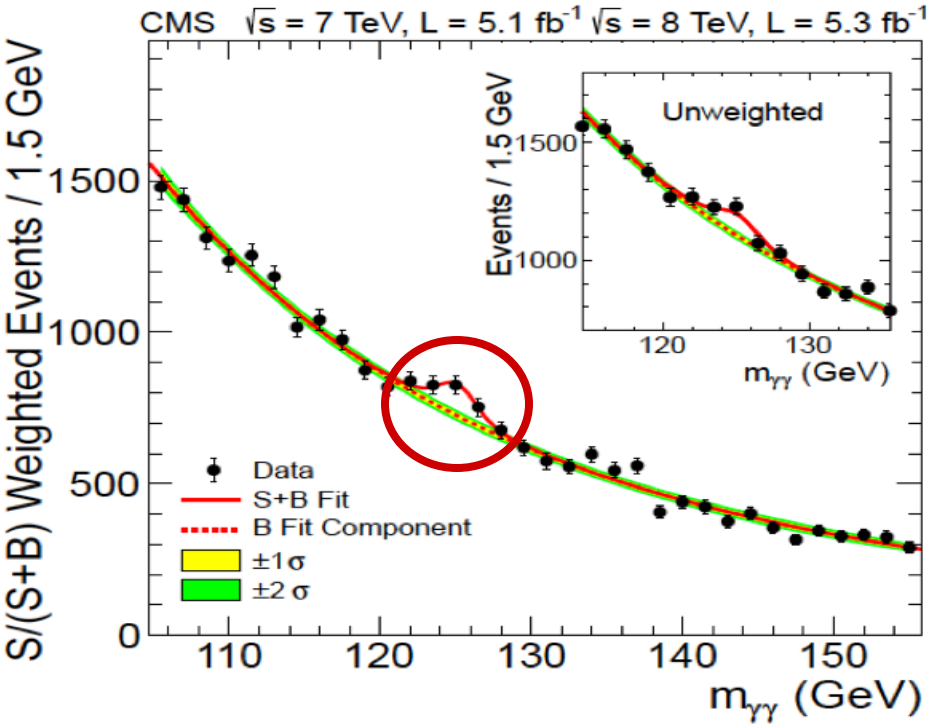


- With a total of 10.7fb^{-1}, expected ~170 signal evt., ~6340 bck ➔ S/B~3% (ATLAS)

After all selections: 59059 events

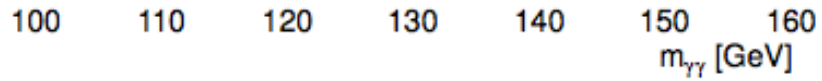


"raw" mass spectrum

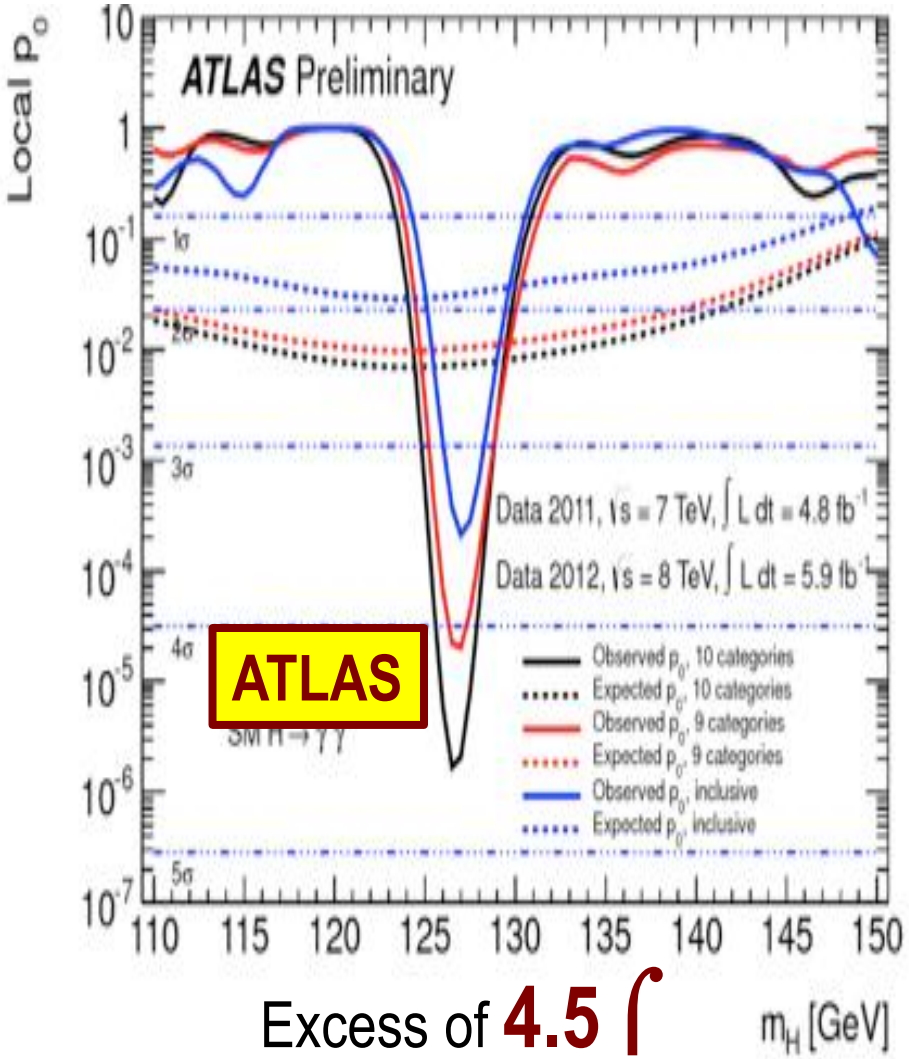


Data sample	m_H of max significance	local significance **obs.** (exp. SM H)
2011	126 GeV	**3.4 σ** (1.6)
2012	127 GeV	**3.2 σ** (1.9)
2011+2012	126.5 GeV	**4.5 σ**(2.5) ATLAS
2011+2012	125.5GeV	**4.1 σ**(2.8) CMS

peak above a large smooth background, relies upon excellent mass resolution

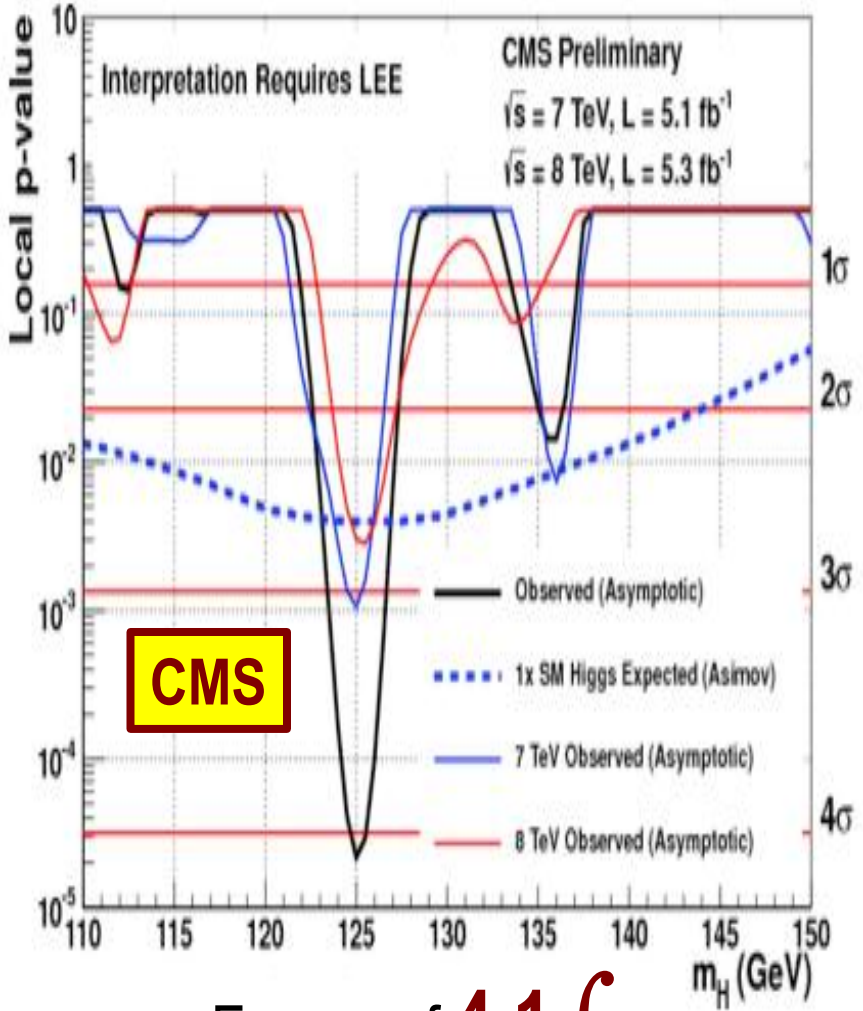


H→ℂℂ Significance



ATLAS

Excess of **4.5** ∫



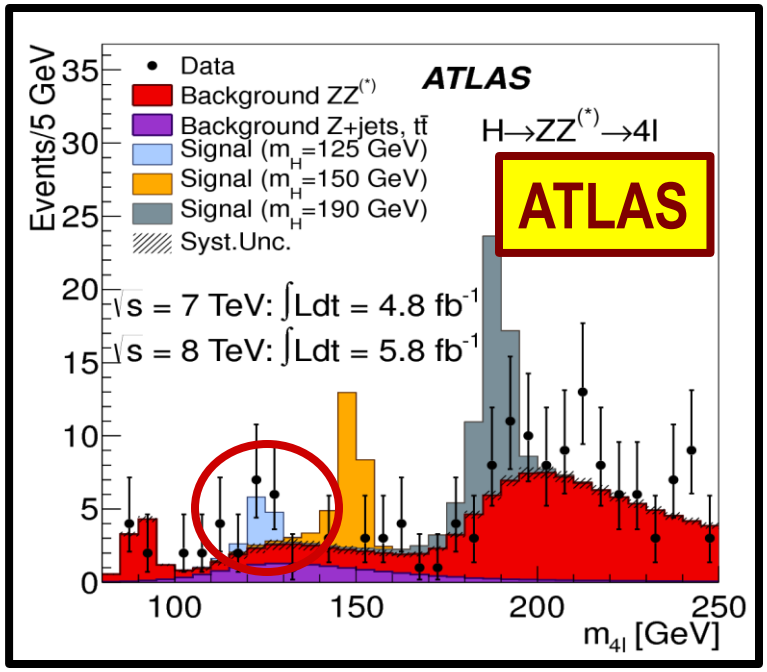
CMS

Excess of **4.1** ∫

H→ZZ→4l Channel

- Sensitive to $110<M_H<600$GeV
- Very low BR and low x-sec at low mass but pure
  - ($\int$xBR~2.5fb @ M_H=126GeV) ➔ S/B~1
  - Full mass reconstruction possible
- Require leptons: $p_T^{1,2,3,4}$ > 20,15,10,7-6 (e-$\int$) GeV; 50 < m_{12} < 106 GeV; m_{34} > 17.5-50 GeV (depending on m_H)
- Requires
  - Excellent electron and muon ID
  - High acceptance and good energy/momentum resolution
- Primary irreducible background ZZ*
  - Good control of this background crucial ➔ MC alone insufficient due to uncertainties from heavy quark effect, etc ➔ Requires MC validation with data
- With a total of 10.7fb^{-1}, expected ~5.3 signal evt., 4.9 bck ➔ S/B~1 (ATLAS)

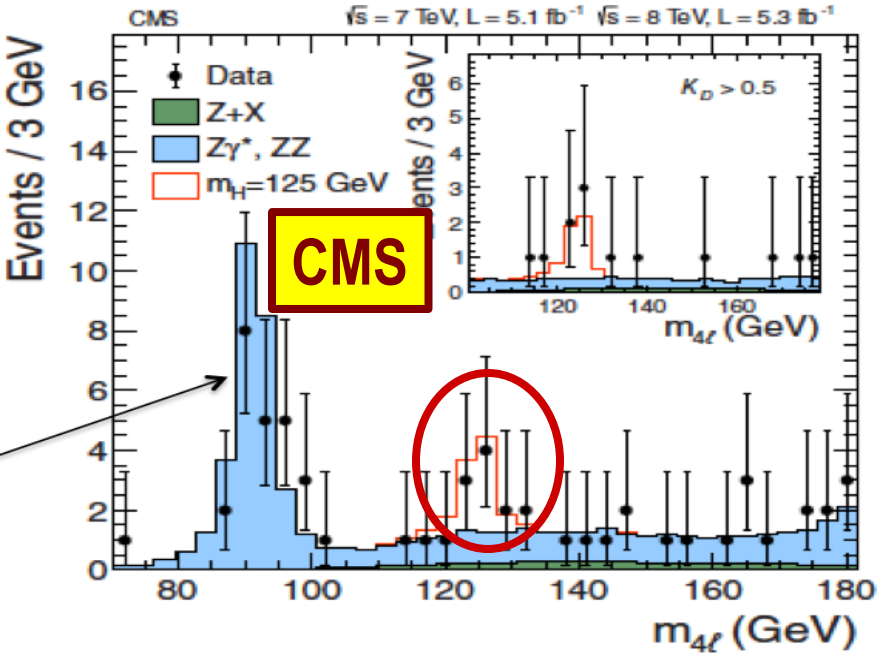
Reconstructed m_{4l} after all cuts



In the region 125 ± 5 GeV

Observed	13 events
Expected from background only	4.9 ± 1
Expected from Higgs signal	5.3 ± .8

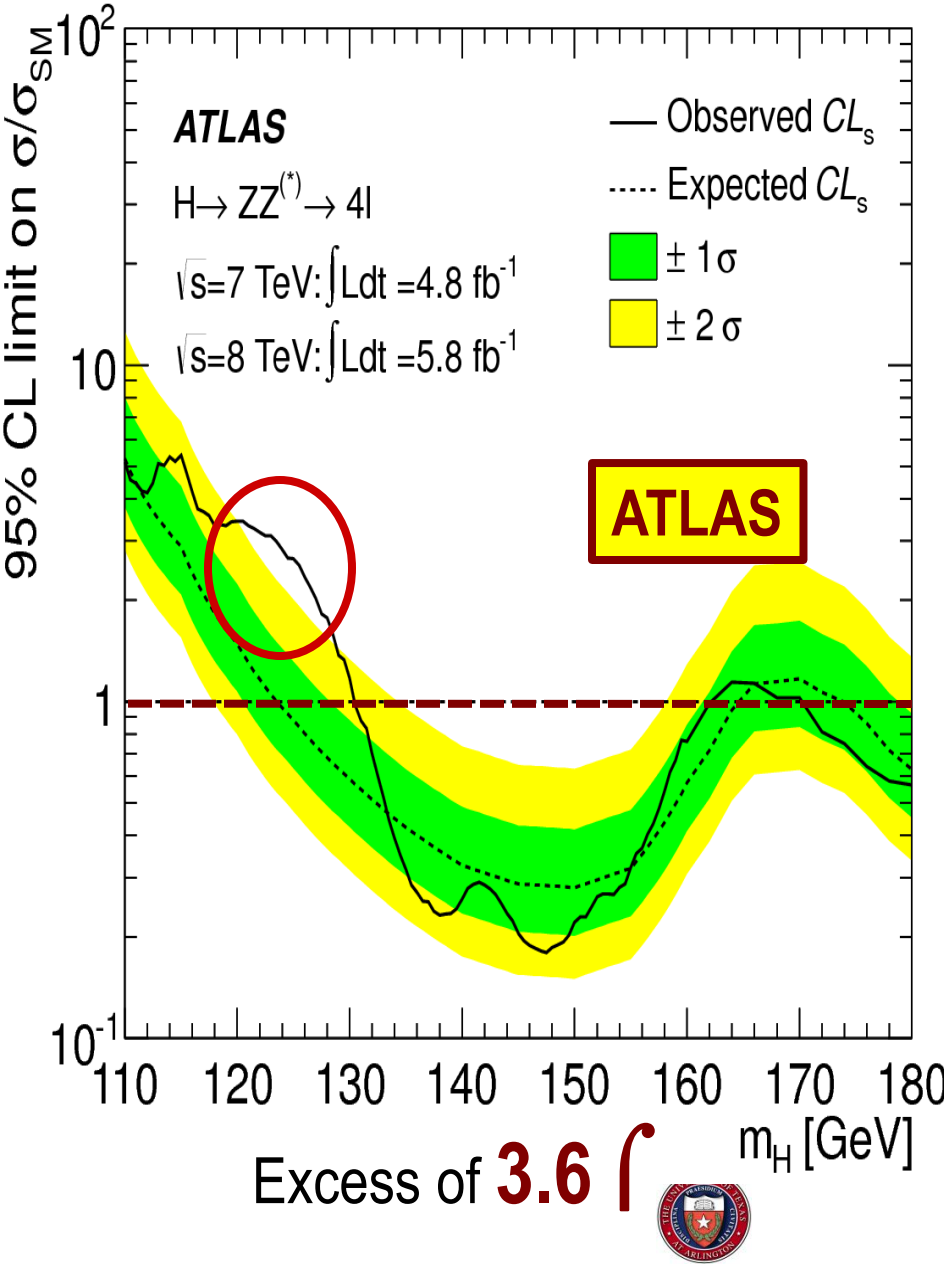
	4μ	2e2μ	4e
Data	6	5	2
Expected S/B	1.6	1.1	0.6
Reducible/total B	10%	60%	70%

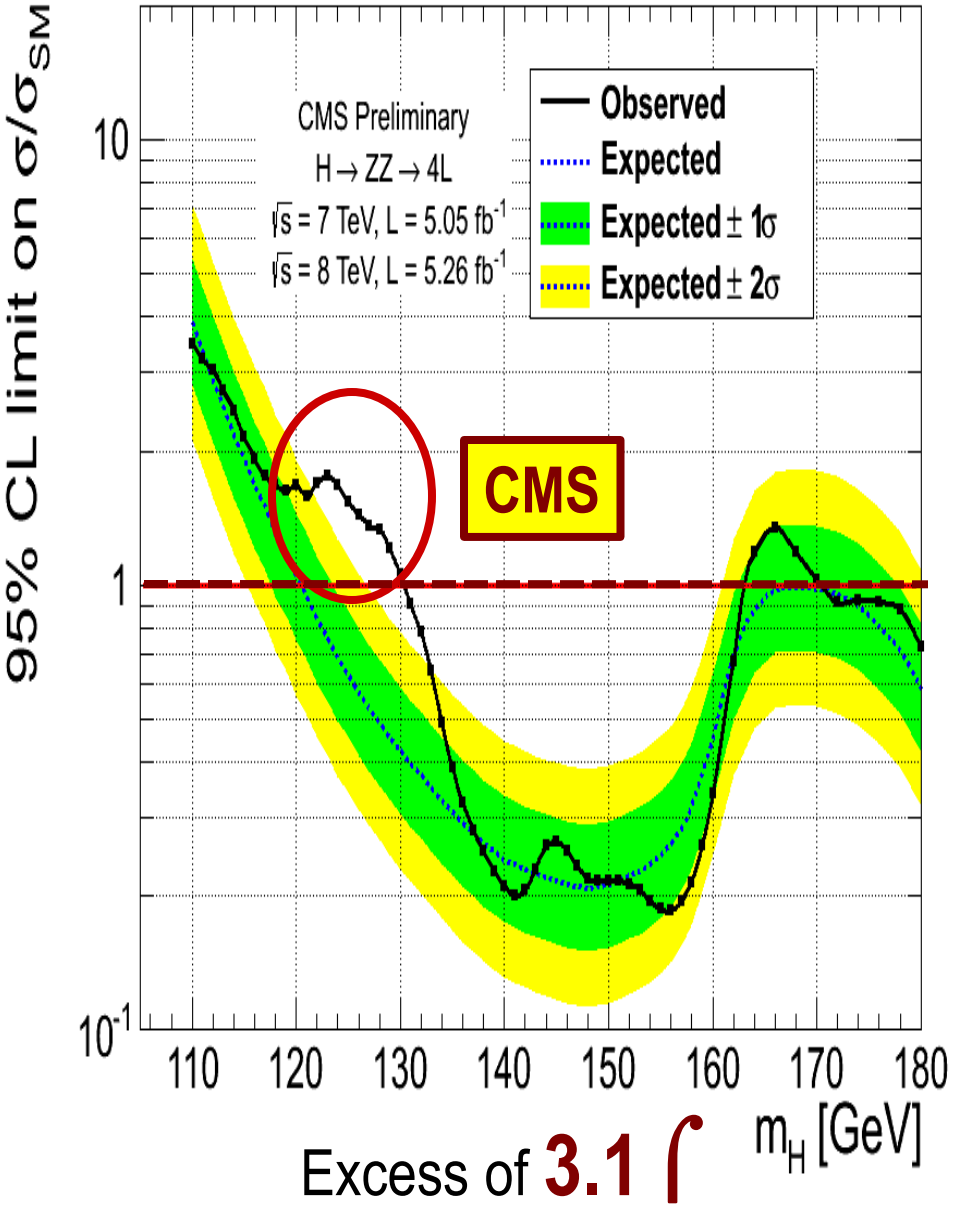


Data sample	m_H of max significance	local significance obs. (exp. SM H)
2011	125 GeV	2.5 σ (1.6)
2012	125.5 GeV	2.6 σ (2.1)
2011+2012	125 GeV	3.6 σ (2.7) ATLAS
2011+2012	125.6GeV	3.1 σ CMS

small peak on a small background, relies upon high efficiency

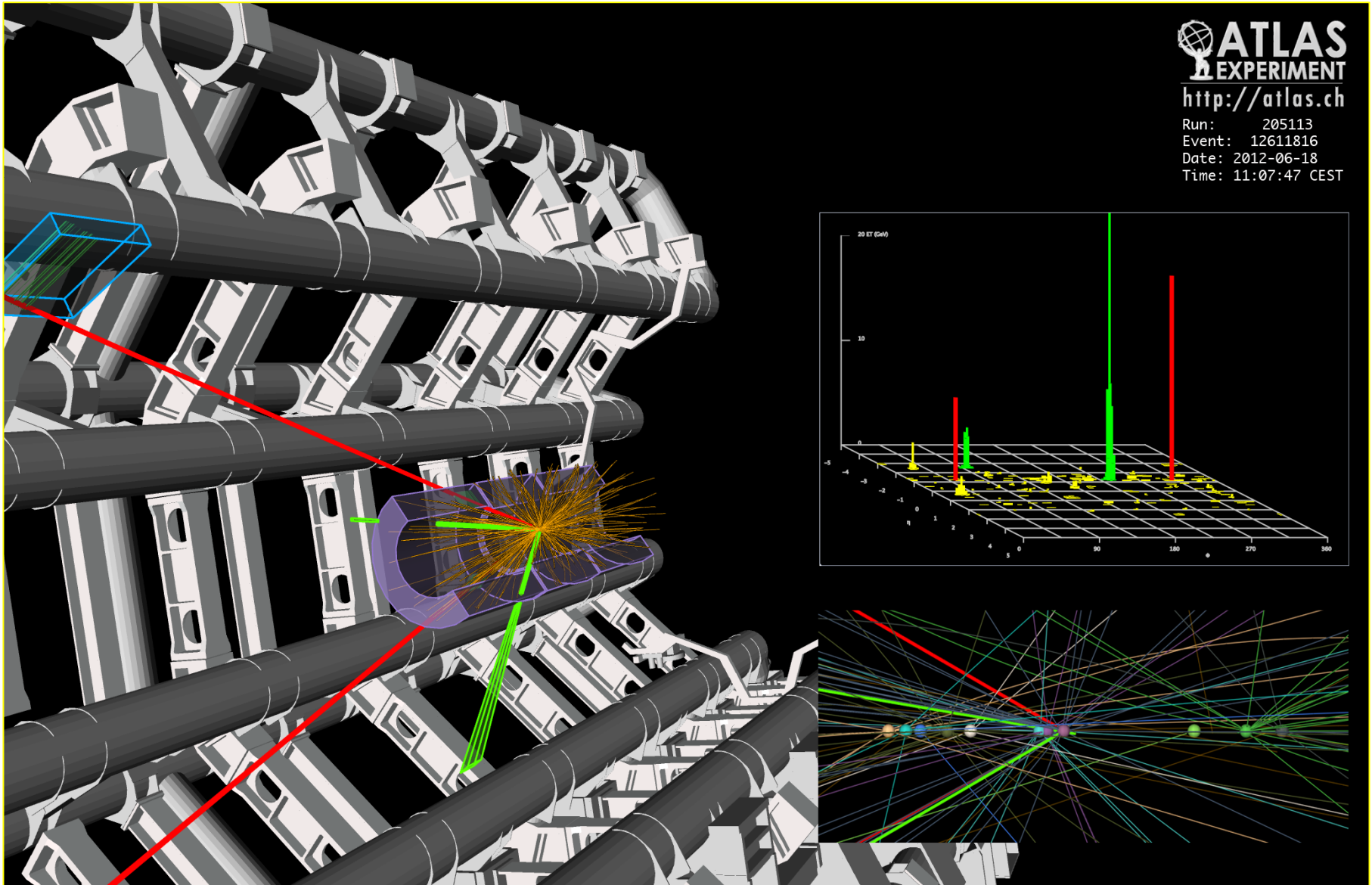
H→ZZ→4l Limits





2e2⌈ candidate event w/ M2e2⌈ =123.9GeV

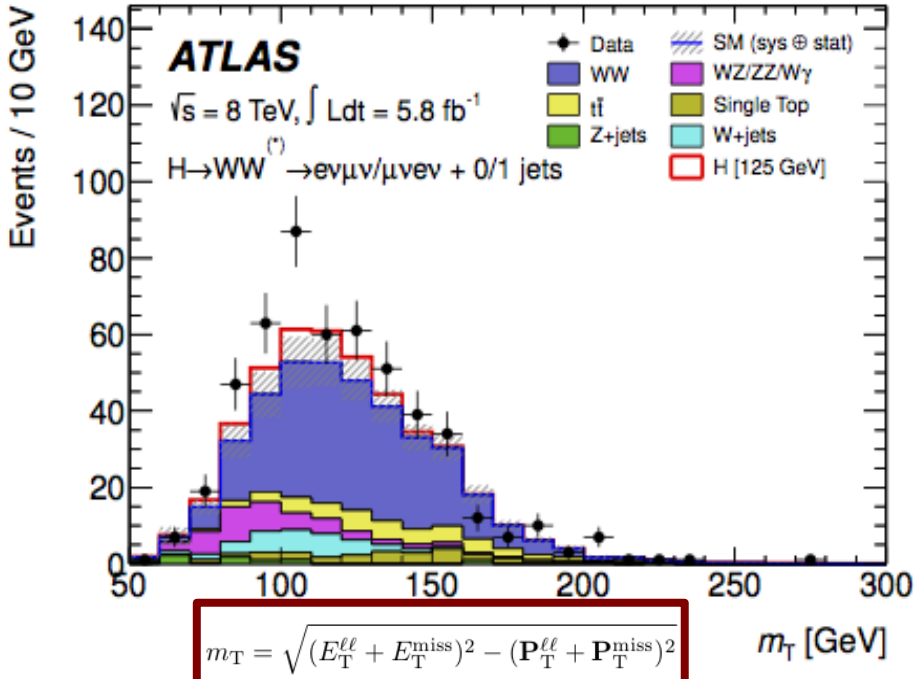
p_T (e,e,μ,μ)= 18.7, 76, 19.6, 7.9 GeV, m (e^+e^-)= 87.9 GeV, m($\mu^+\mu^-$) =19.6 GeV
12 reconstructed vertices



H→WW*→2l2ν (eeνν, μμνν, eμνν)Channel

- Sensitive to 110<M_H<600GeV
- Large cross section: BR and low x-sec at low mass but pure
  - (∫xBR~200fb @ M_H=125GeV)
  - Thanks to 2n, mass resolution is unideal and peak cannot be clearly recoed.
- Require two isolated opposite leptons: $p_T^{1,2}$> 25,15 GeV; large MET, M_{ll}≠M_Z, ⊗)
- Requires
  - Excellent electron and muon ID
  - Good understanding of MET
- Primary irreducible background from WW*, top, W/Z+jets
  - Good control of this background crucial ➔ MC alone insufficient due to uncertainties from heavy quark effect, etc ➔ Use signal free control region
- With a total of 10.7fb^{-1}, expected ~25 signal evt., 168 bck ➔ S/B~15% (ATLAS)

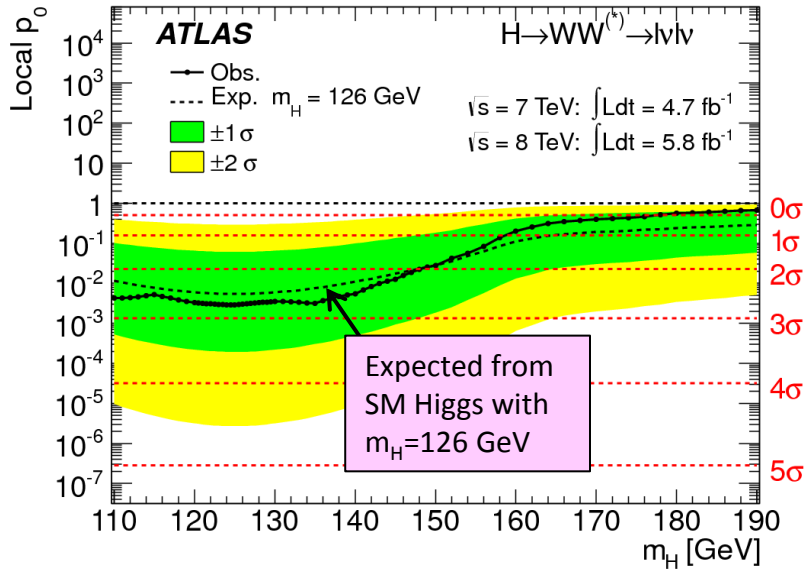
$m^{T}_{2l2\nu}$ after all cuts



Observed:	223 events
expected from **background** only	168 ± 20
expected from **Higgs** m_H=126 GeV	25 ± 5

Data sample	m_H of max significance	local significance **obs.** (exp. SM H)
2011	135 GeV	**1.1 σ** (3.4)
2012	120 GeV	**3.3 σ** (1.0)
2011+2012	125 GeV	**2.8 σ** (2.3)

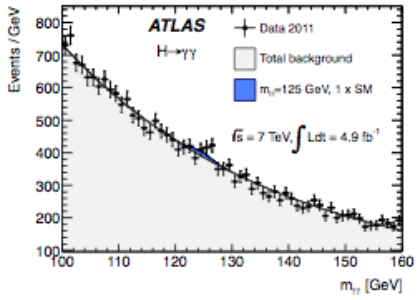
Broad excess, extending over > 50 GeV in mass, due to poor mass resolution

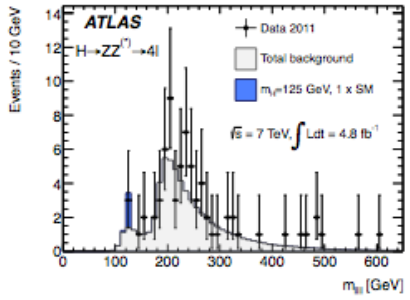


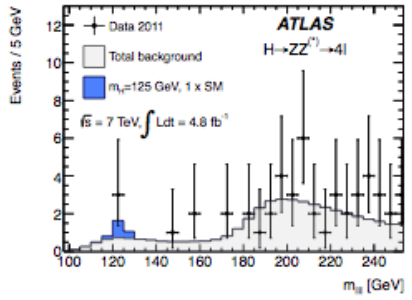
The Search Channels Involved (ATLAS)

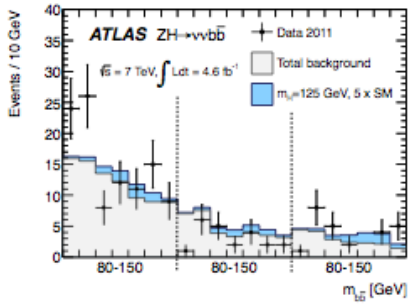
Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	4.8	[3]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet}\}$	4.8	[4]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu/\mu e, \mu\mu\} \otimes \{\text{0-jet, 1-jet, 2-jet}\} \otimes \{\text{low, high pile-up}\}$	4.7	[5]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{\text{0-jet}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jet, } VH\}$	4.7	[6]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e,\mu\} \otimes \{\text{0-jet}\} \otimes \{E_{\mathrm{T}}^{\mathrm{miss}} < 20\ \mathrm{GeV}, E_{\mathrm{T}}^{\mathrm{miss}} \geq 20\ \mathrm{GeV}\}$ $\oplus \{e,\mu\} \otimes \{\text{1-jet}\} \oplus \{\ell\} \otimes \{\text{2-jet}\}$	4.7	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{\text{1-jet}\}$	4.7	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200\ \mathrm{GeV}\}$	4.6	[7]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{<50, 50-100, 100-200, \geq 200\ \mathrm{GeV}\}$	4.7	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{<50, 50-100, 100-200, \geq 200\ \mathrm{GeV}\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	5.8	[3]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet}\}$	5.9	[4]
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes \{\text{0-jet, 1-jet, 2-jet}\}$	5.8	[8]

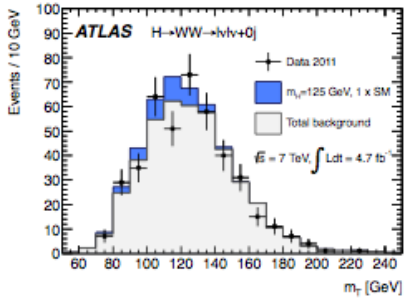
70 different channels altogether…

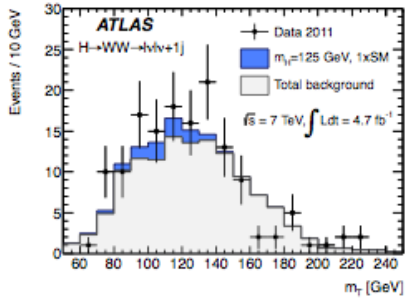

ATLAS
H→γγ
Data 2011
Total background
m_H=125 GeV, 1 x SM
√s = 7 TeV, ∫ Ldt = 4.9 fb⁻¹
Events / GeV
m_γγ [GeV]

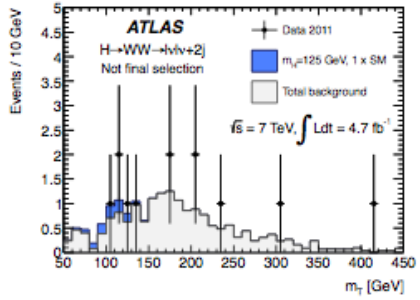

ATLAS
H→ZZ^(*)→4l
Data 2011
Total background
m_H=125 GeV, 1 x SM
√s = 7 TeV, ∫ Ldt = 4.8 fb⁻¹
Events / 10 GeV
m_4l [GeV]

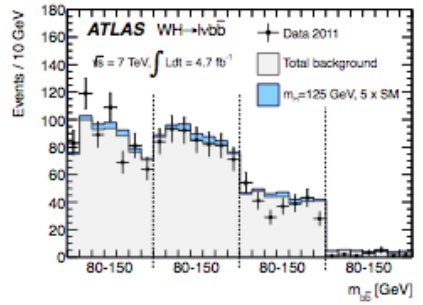

ATLAS
H→ZZ^(*)→4l
Data 2011
Total background
m_H=125 GeV, 1 x SM
√s = 7 TeV, ∫ Ldt = 4.8 fb⁻¹
Events / 5 GeV
m_4l [GeV]

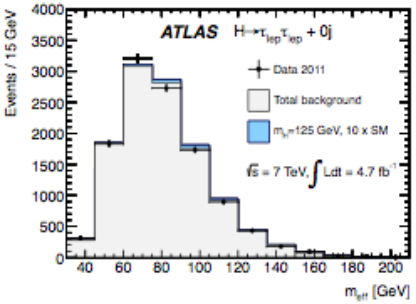

ATLAS
ZH→νν̄bb̄
Data 2011
Total background
m_H=125 GeV, 5 x SM
√s = 7 TeV, ∫ Ldt = 4.6 fb⁻¹
Events / 10 GeV
80-150
m_bb̄ [GeV]

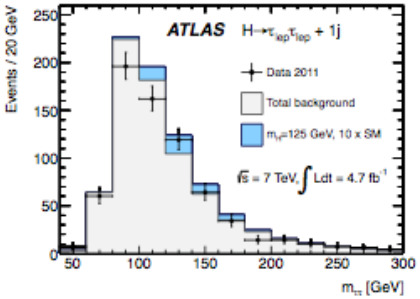

ATLAS
H→WW→lνlν+0j
Data 2011
m_H=125 GeV, 1 x SM
Total background
√s = 7 TeV, ∫ Ldt = 4.7 fb⁻¹
Events / 10 GeV
m_T [GeV]

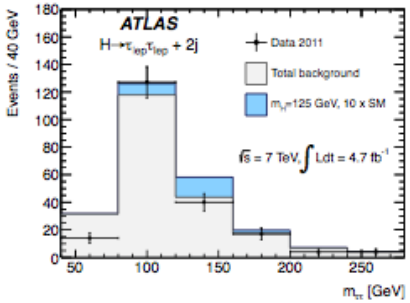

ATLAS
H→WW→lνlν+1j
Data 2011
m_H=125 GeV, 1xSM
Total background
√s = 7 TeV, ∫ Ldt = 4.7 fb⁻¹
Events / 10 GeV
m_T [GeV]

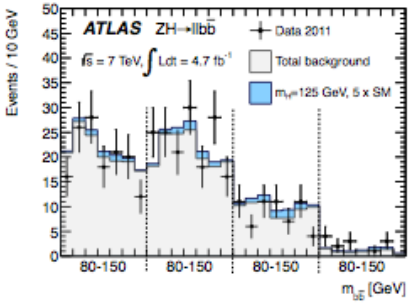

ATLAS
H→WW→lνlν+2j
Not final selection
Data 2011
m_H=125 GeV, 1 x SM
Total background
√s = 7 TeV, ∫ Ldt = 4.7 fb⁻¹
Events / 10 GeV
m_T [GeV]

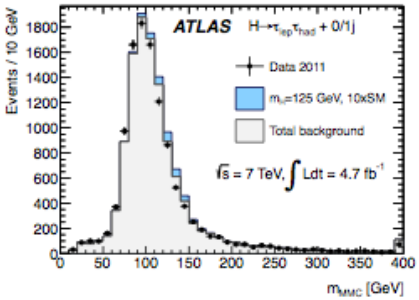

ATLAS
WH→lνbb̄
Data 2011
Total background
m_H=125 GeV, 5 x SM
√s = 7 TeV, ∫ Ldt = 4.7 fb⁻¹
Events / 10 GeV
80-150
m_bb̄ [GeV]

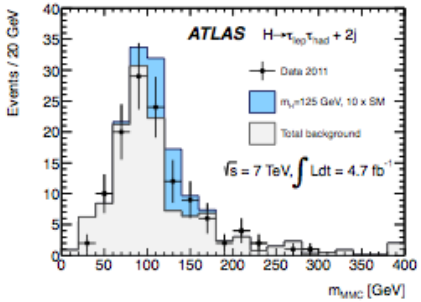

ATLAS
H→τ_lep τ_lep + 0j
Data 2011
Total background
m_H=125 GeV, 10 x SM
√s = 7 TeV, ∫ Ldt = 4.7 fb⁻¹
Events / 15 GeV
m_ττ [GeV]

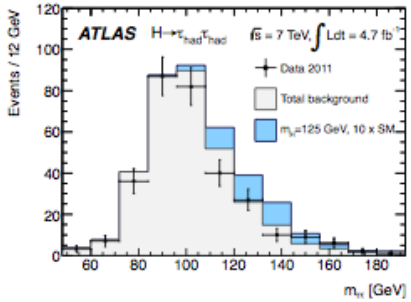

ATLAS
H→τ_lep τ_lep + 1j
Data 2011
Total background
m_H=125 GeV, 10 x SM
√s = 7 TeV, ∫ Ldt = 4.7 fb⁻¹
Events / 20 GeV
m_ττ [GeV]


ATLAS
H→τ_lep τ_lep + 2j
Data 2011
Total background
m_H=125 GeV, 10 x SM
√s = 7 TeV, ∫ Ldt = 4.7 fb⁻¹
Events / 40 GeV
m_ττ [GeV]

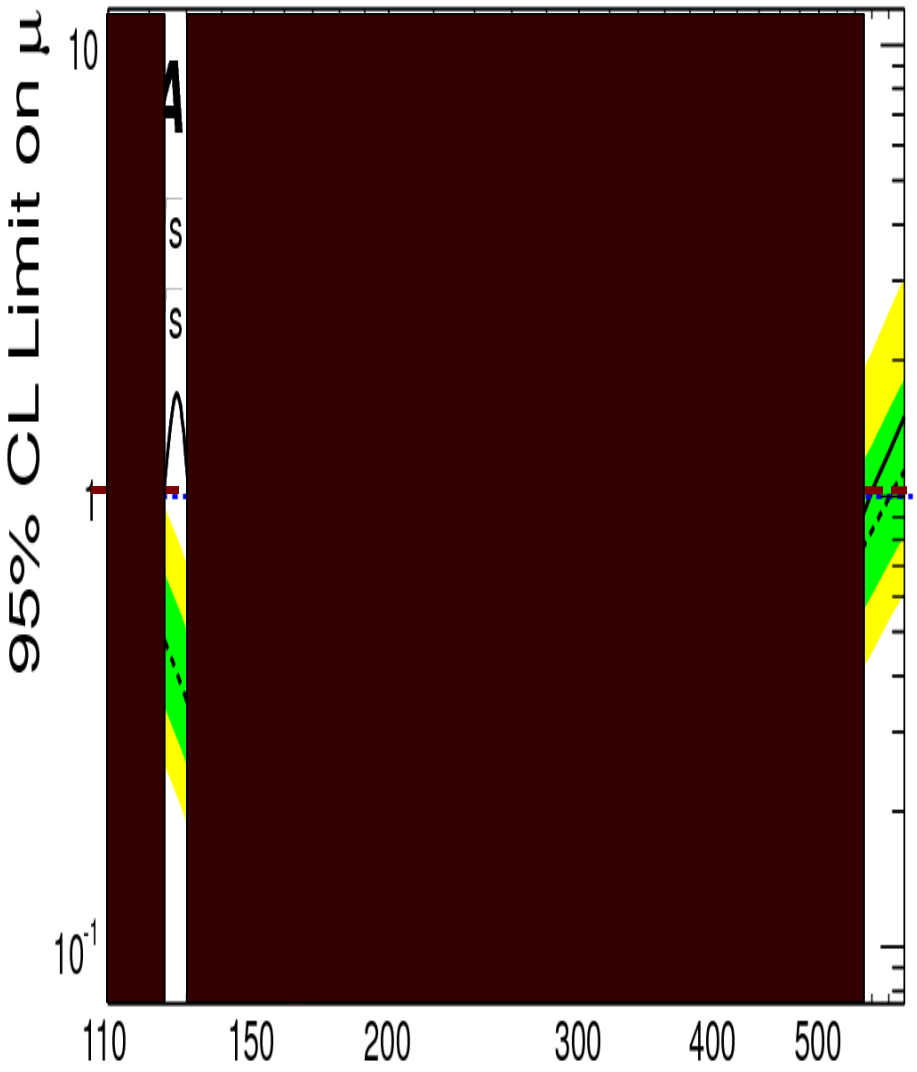

ATLAS
ZH→llbb̄
Data 2011
Total background
m_H=125 GeV, 5 x SM
√s = 7 TeV, ∫ Ldt = 4.7 fb⁻¹
Events / 10 GeV
80-150
m_bb̄ [GeV]


ATLAS
H→τ_lep τ_had + 0/1j
Data 2011
m_H=125 GeV, 10xSM
Total background
√s = 7 TeV, ∫ Ldt = 4.7 fb⁻¹
Events / 10 GeV
m_MMC [GeV]

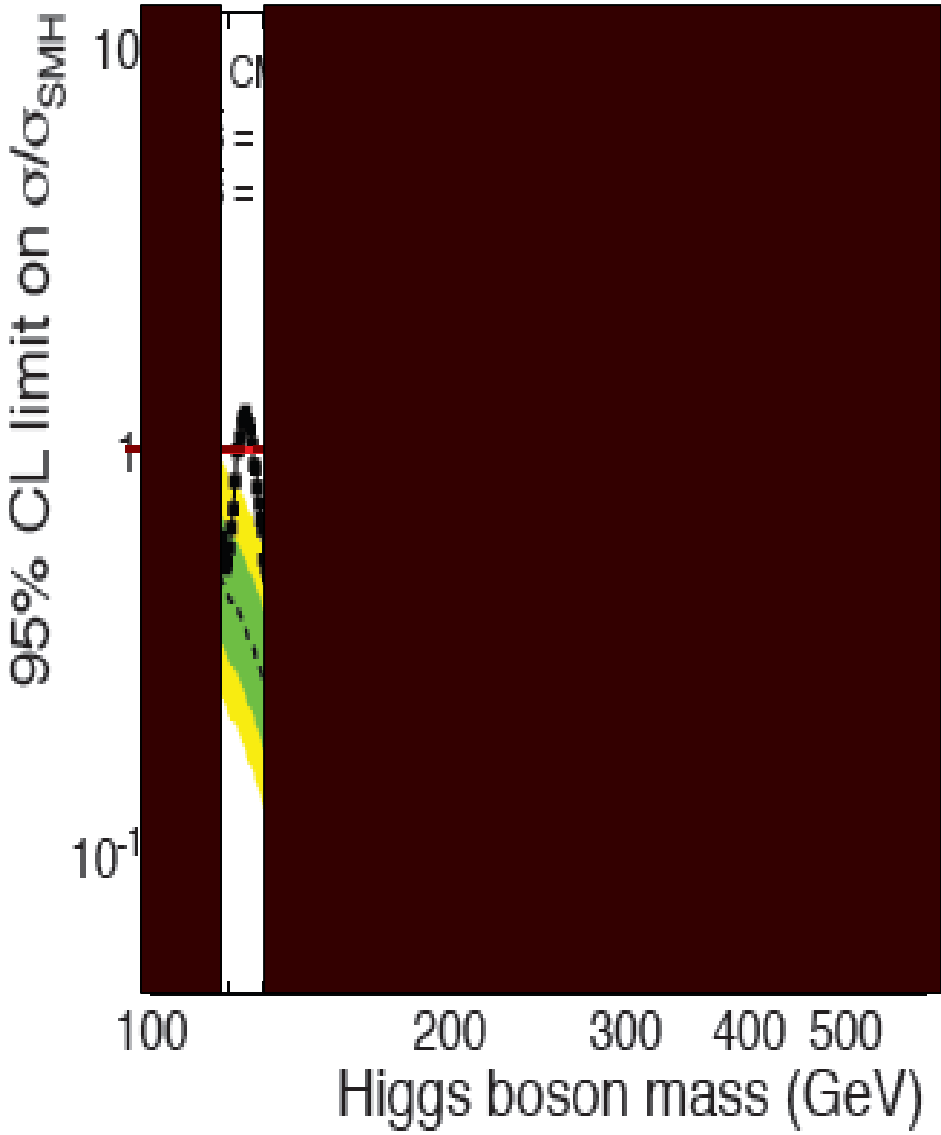

ATLAS
H→τ_lep τ_had + 2j
Data 2011
m_H=125 GeV, 10 x SM
Total background
√s = 7 TeV, ∫ Ldt = 4.7 fb⁻¹
Events / 20 GeV
m_MMC [GeV]


ATLAS
H→τ_had τ_had
√s = 7 TeV, ∫ Ldt = 4.7 fb⁻¹
Data 2011
Total background
m_H=125 GeV, 10 x SM
Events / 12 GeV
m_τ [GeV]

All Channel Combined Exclusion

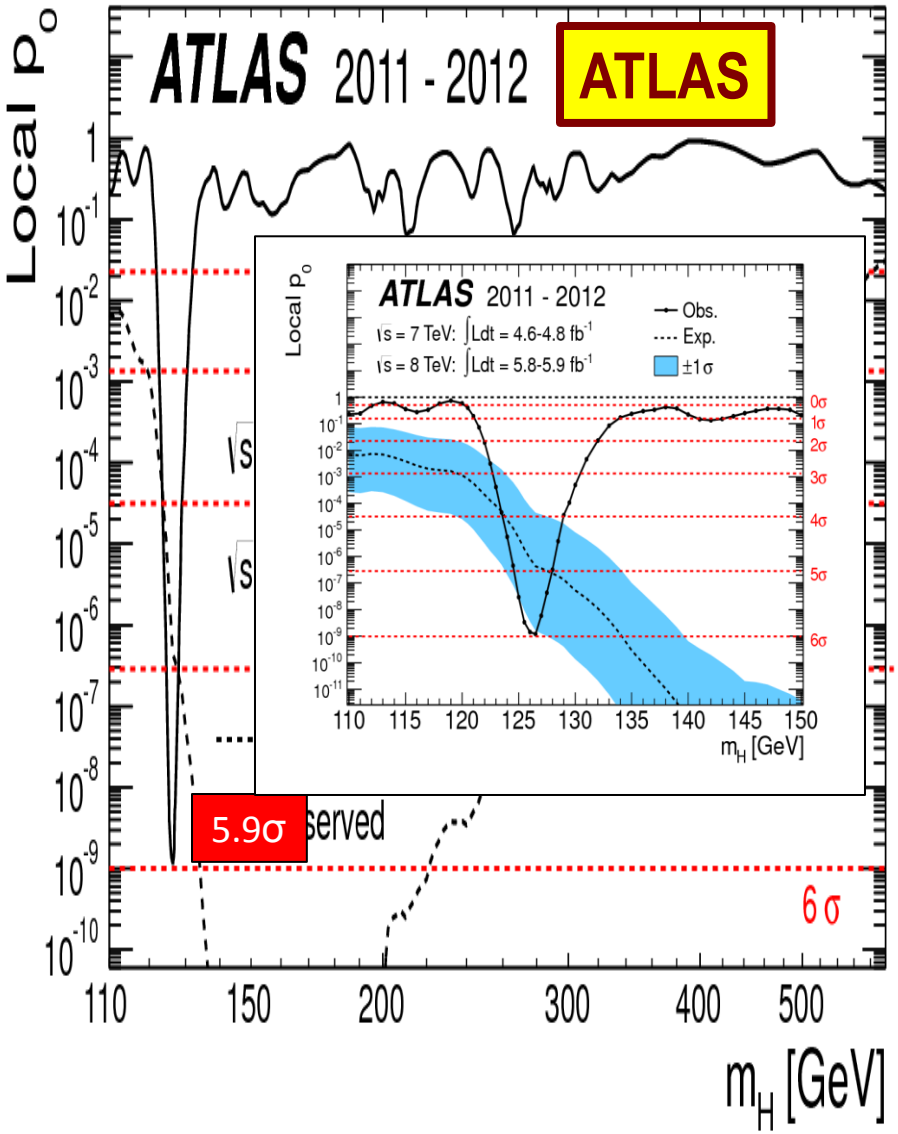


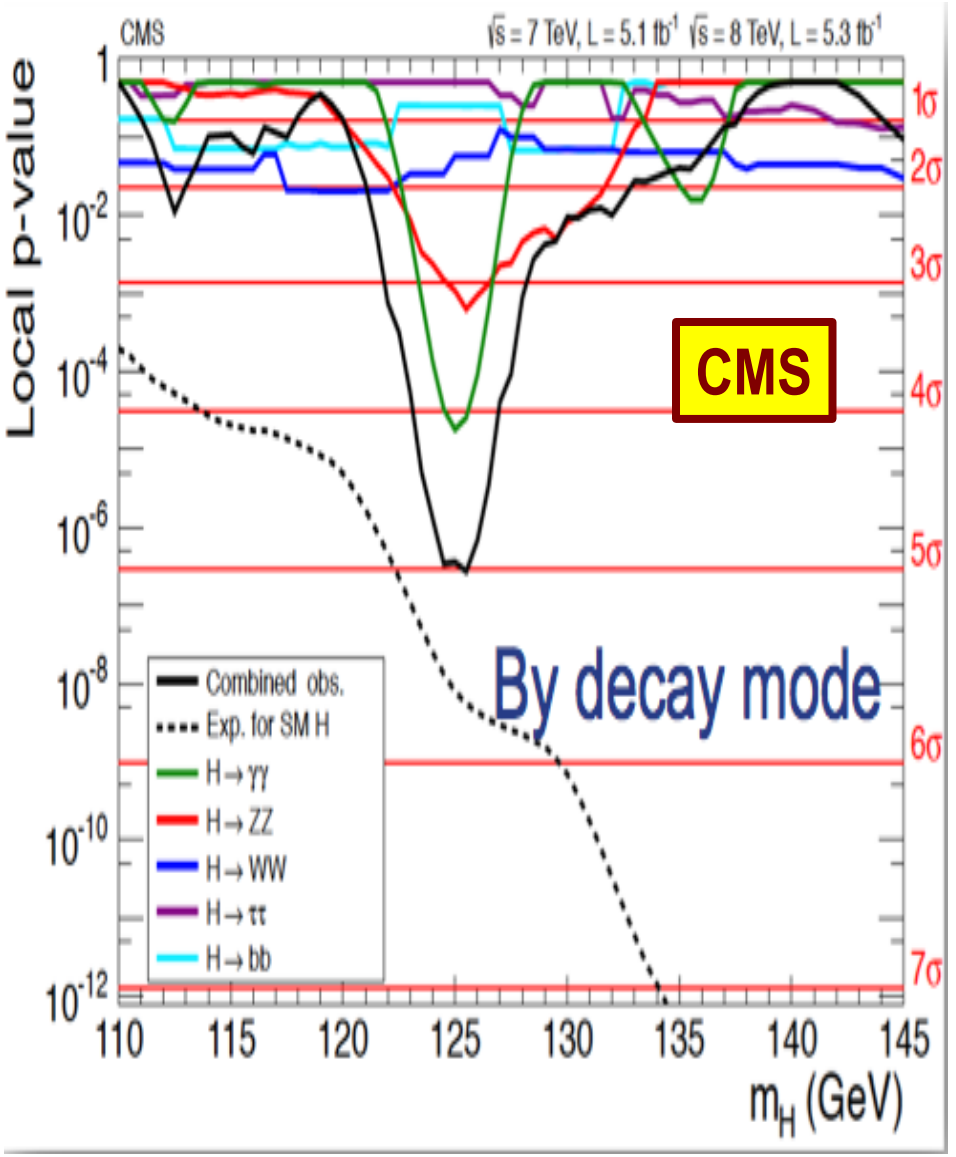
Excluded at 95% CL:
112-122, 131-559 GeV



Only little sliver in 122 – 135 GeV and high mass left

All Channel Combined Significance





Search Channel Significance

CMS

Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.6	3.1
$\tau\tau$ + bb	2.4	0.4
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0

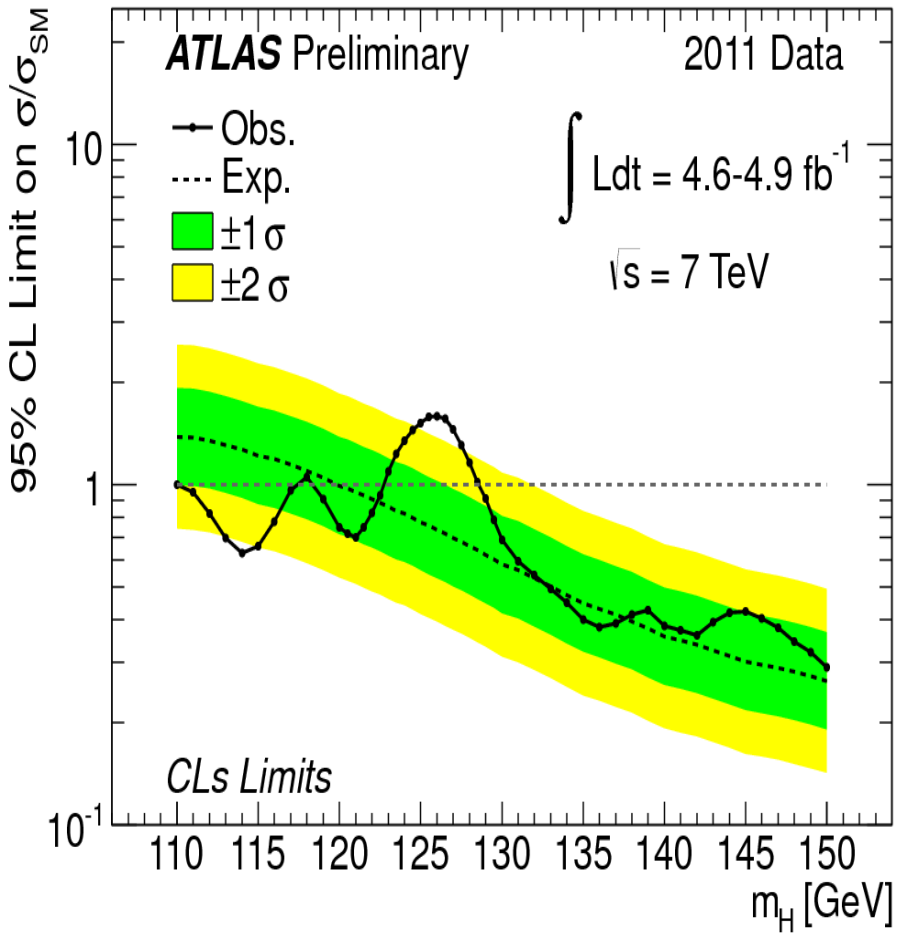
5.0 ∫ observed
5.8 ∫ Expected

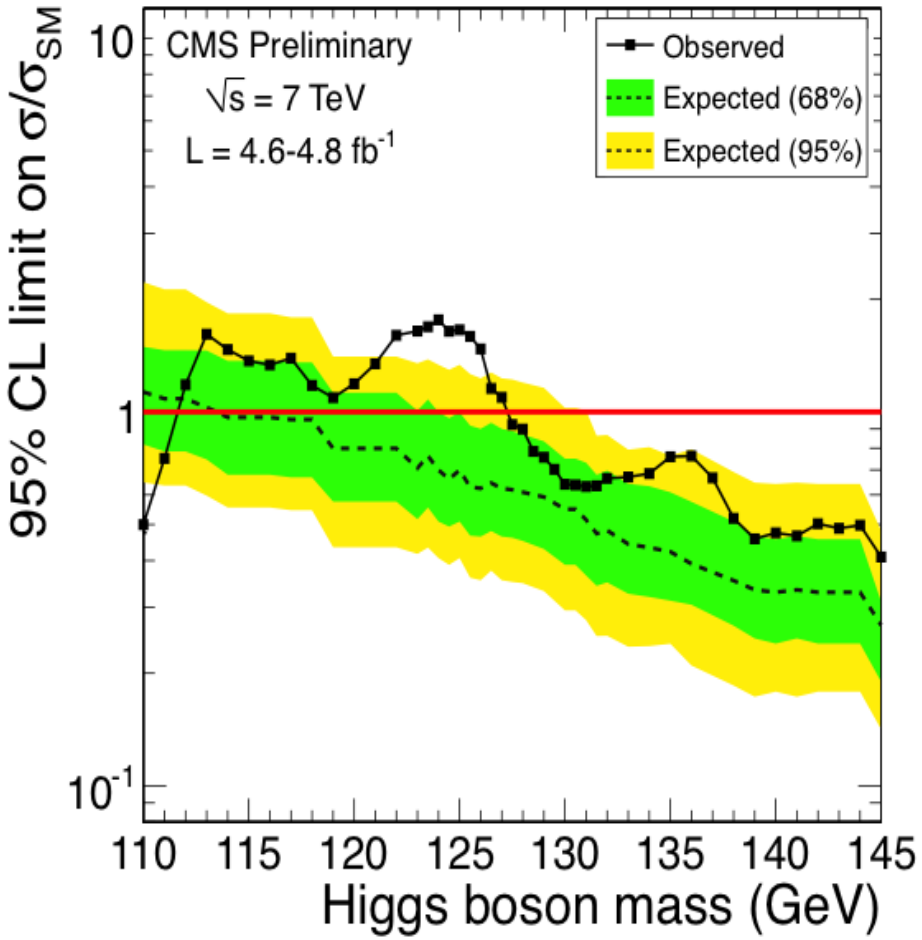
ATLAS

Channel	m_H of max significance	local significance **obs.** (exp. SM H)
H → ©©	126.5 GeV	**4.5 σ** (2.5)
H →ZZ→ 4l	125 GeV	**3.6 σ** (2.7)
H → lvlv	125 GeV	**2.8 σ** (2.3)
Combined	126.5 GeV	**5.9 σ** (4.9)

5.9 ∫ observed
4.8 ∫ Expected

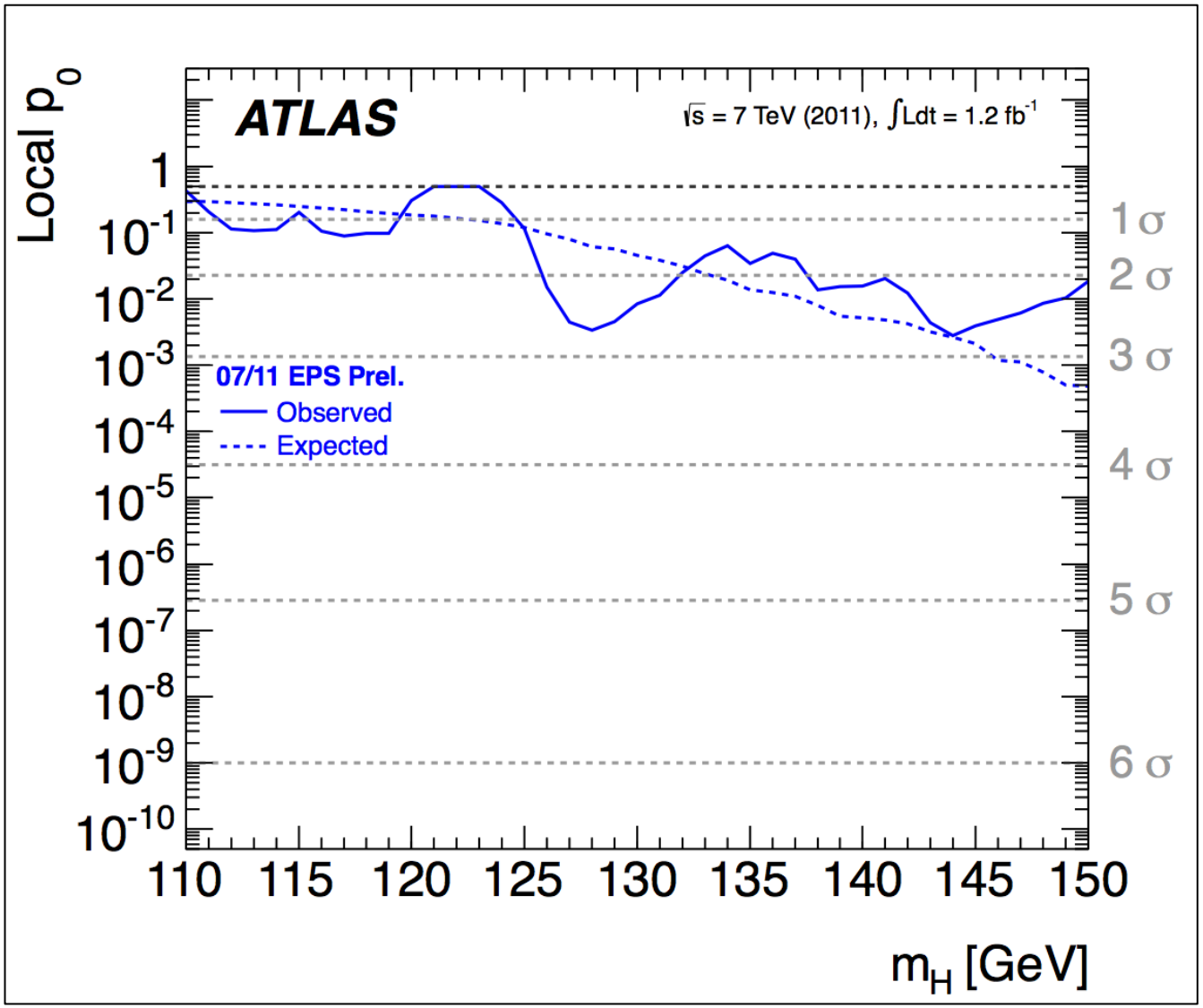
ATLAS and CMS Combined Higgs – end of 2011



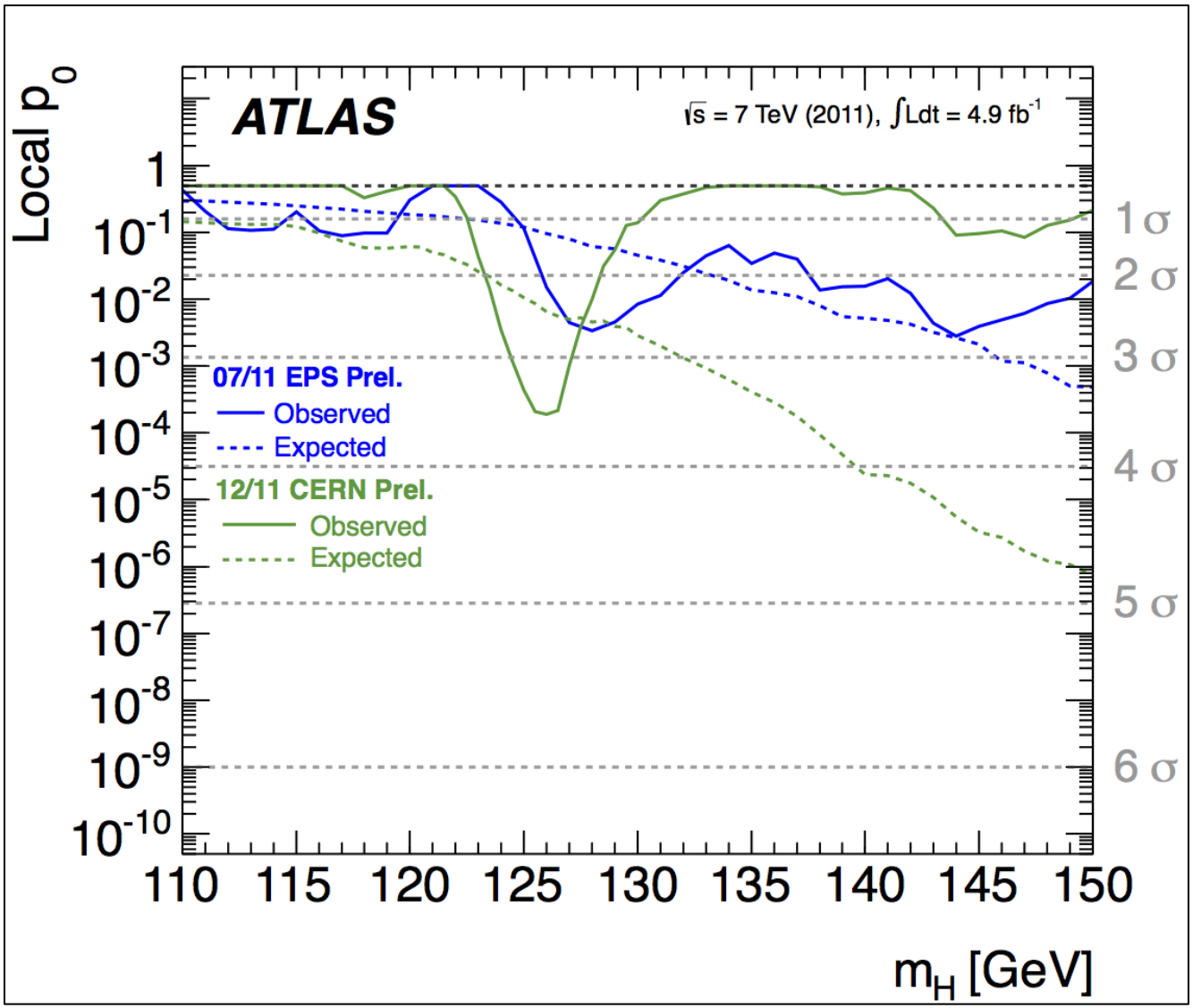


Standard Model Higgs excluded in $110.0 < M_H < 117.5$ GeV, $118.5 < M_H < 122.5$ GeV, and $129 < M_H < 539$ GeV & $127.5 < M_H < 543$GeV

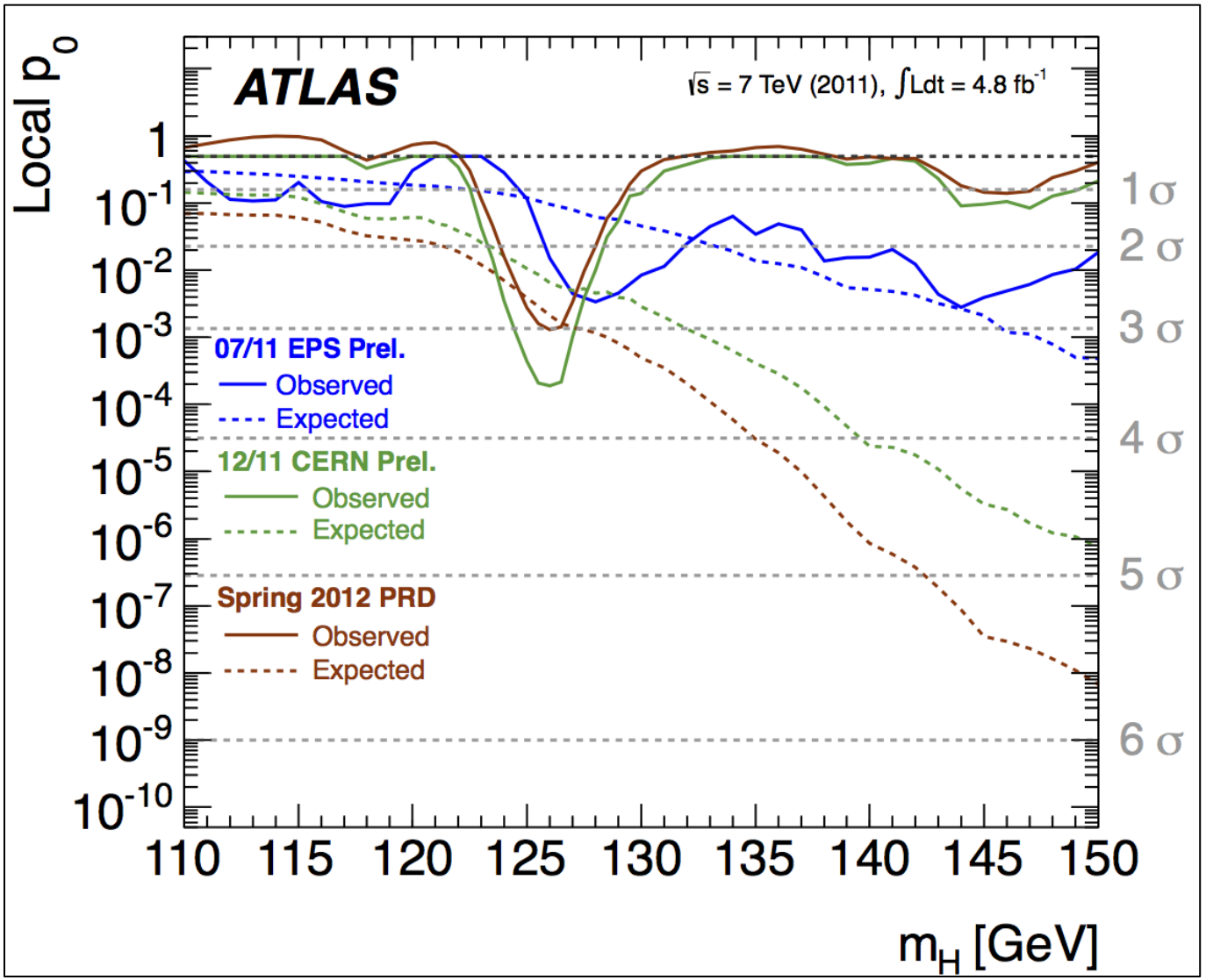
Evolution of the excess with time



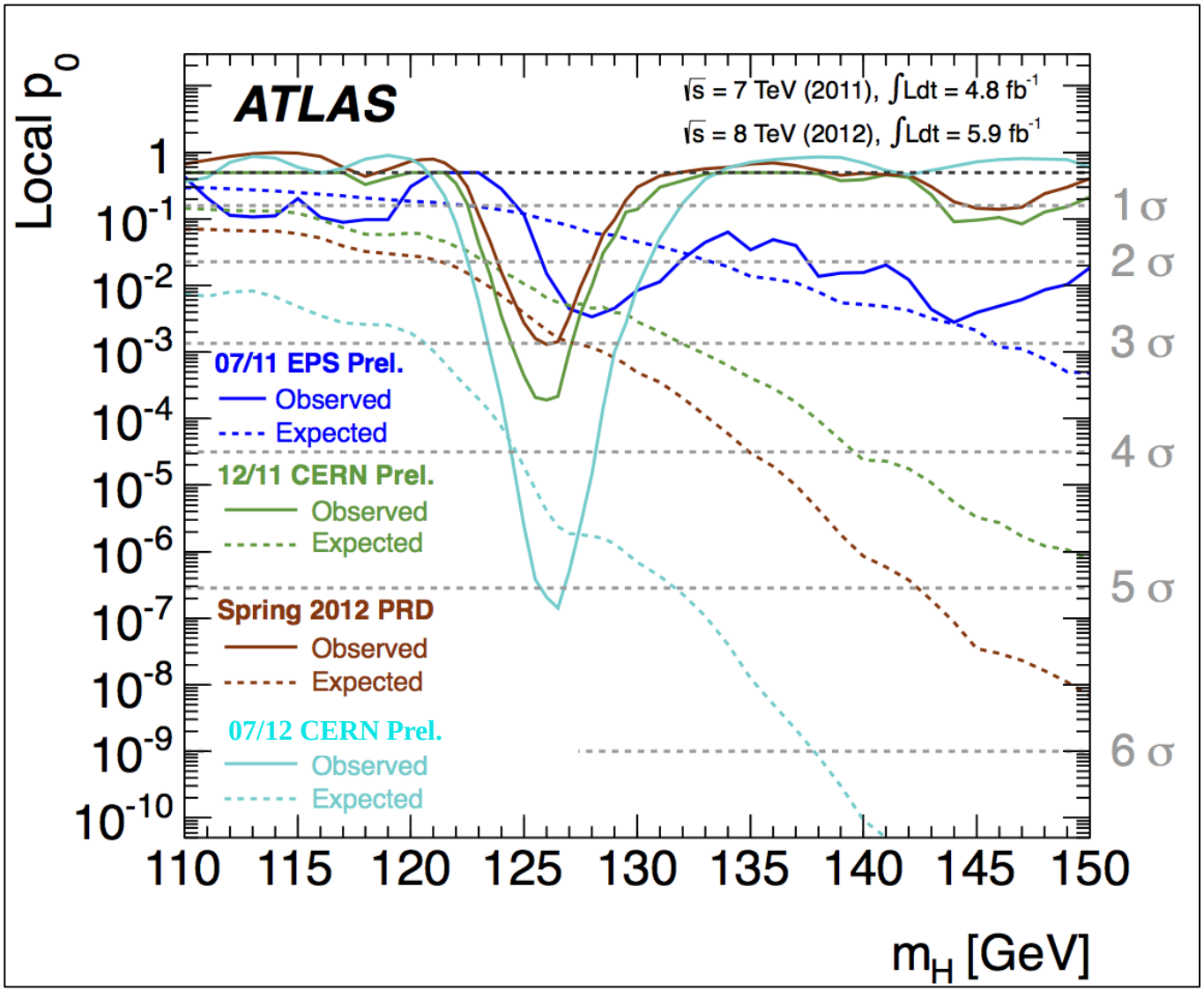
Evolution of the excess with time



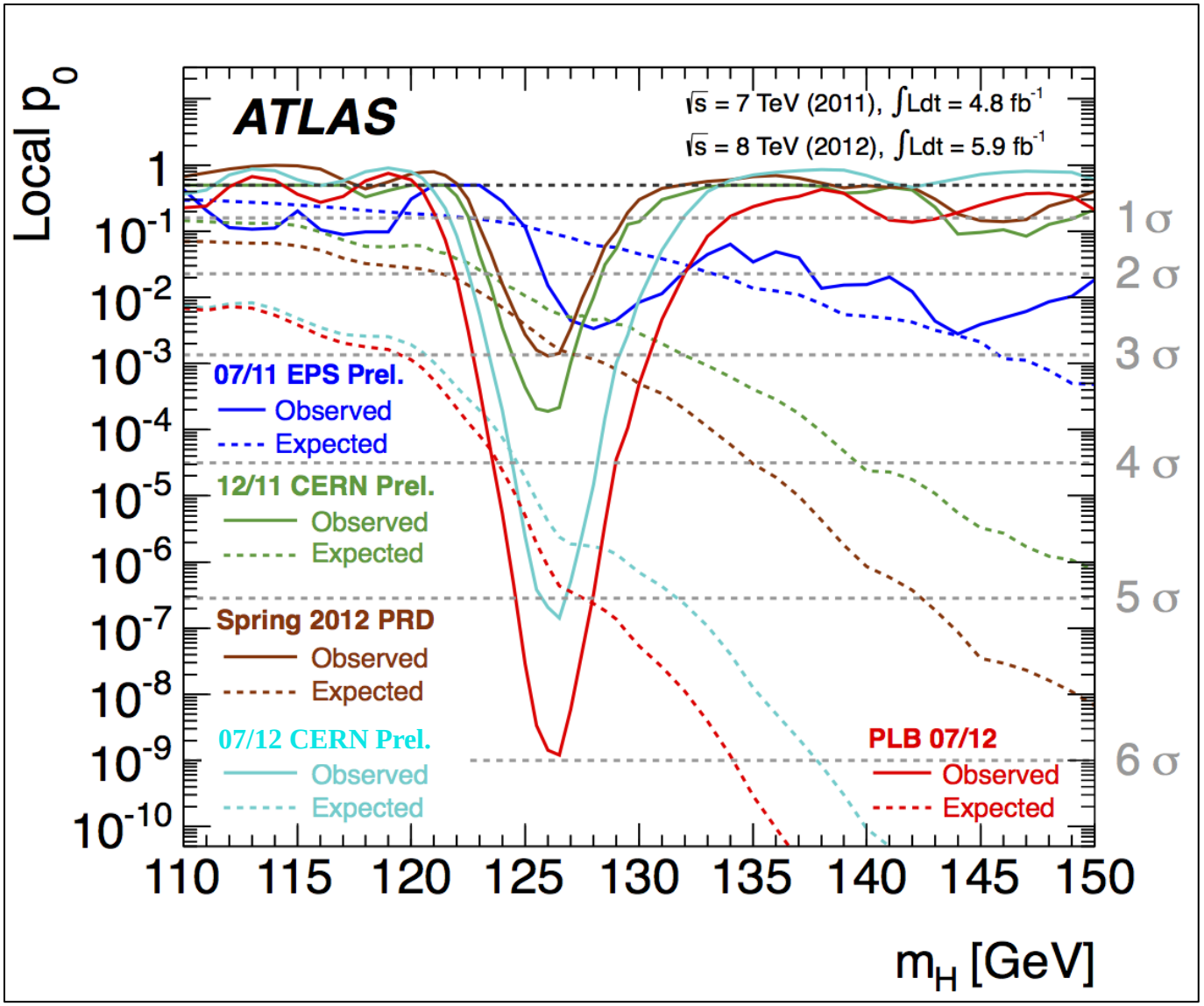
Evolution of the excess with time



Evolution of the excess with time



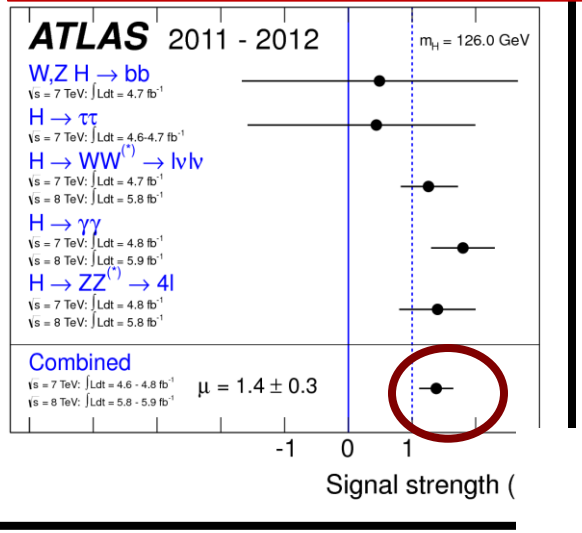
Evolution of the excess with time



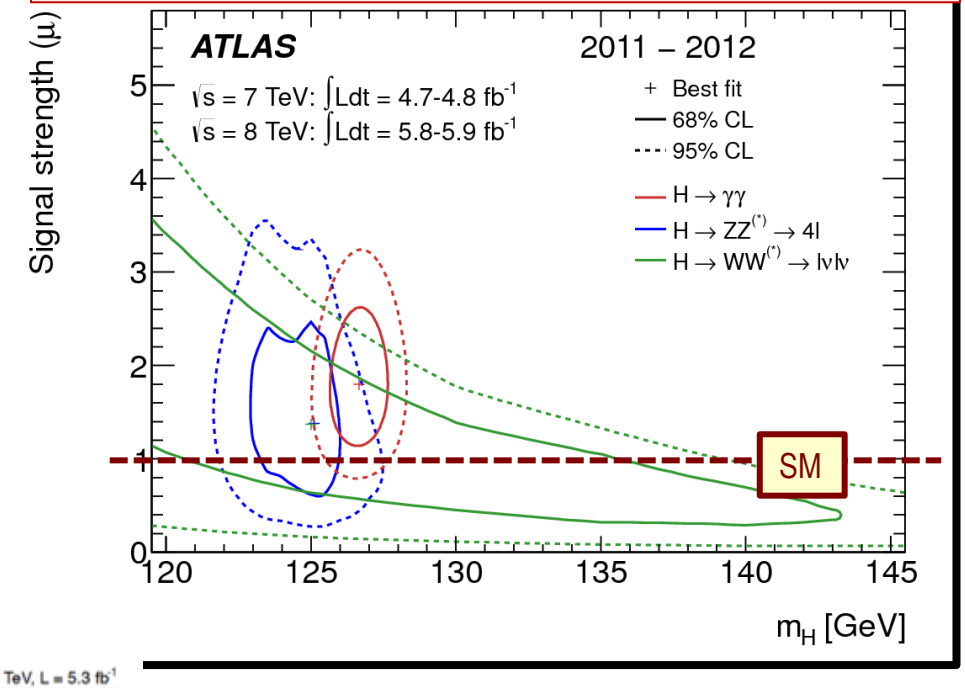
Characterizing the new particle: **mass** and **signal strength**

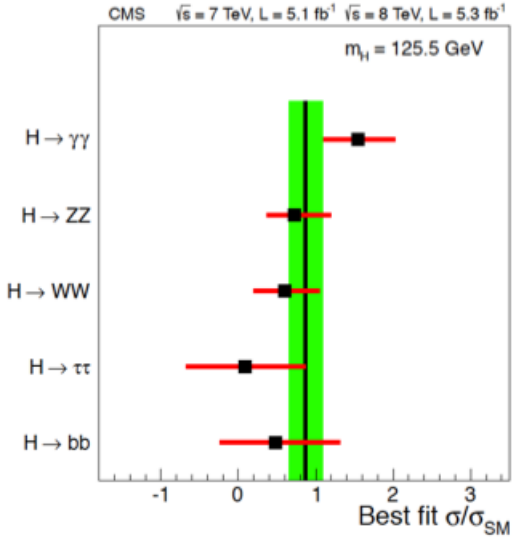
Estimated mass (ATLAS):
m_H = 126 ± 0.4 (stat) ± 0.4 (syst) GeV

Γ = signal strength normalized to the SM Higgs expectation at m_H = 126 GeV



2-dim likelihood fit to signal mass and strength





Best-fit value:

$\Gamma = \Gamma_M / \Gamma_{SM}$ = **1.4 ± 0.3 @126 GeV (ATLAS)/ 0.87 ± 0.23@125.5GeV (CMS)**

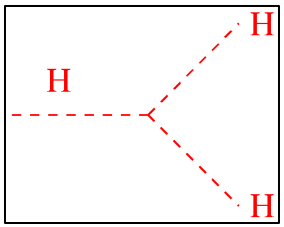
→ good agreement with the expectation for a SM Higgs within the present statistical uncertainty

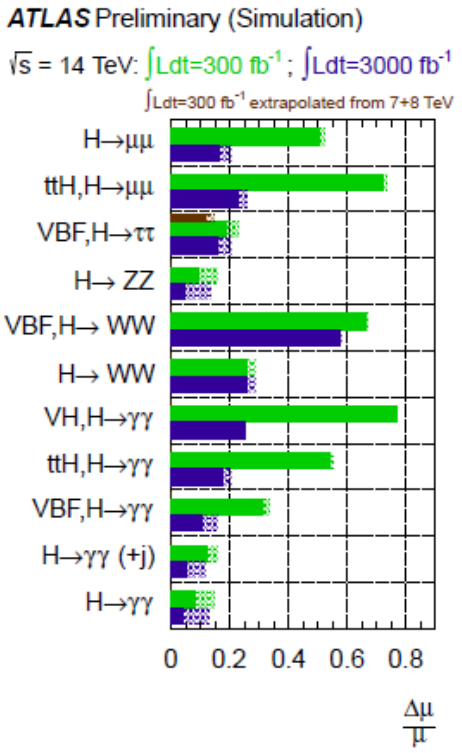
Long Term LHC Plans

- 2012 run will end with ~25fb^{-1}
  - Combined with 2011 run (5.6fb^{-1}), a total of 30fb^{-1}
- 2013 – 2014: shutdown (LS1) to go to design energy (13 – 14TeV) at high inst. Luminosity
- 2015 – 2017: $\sqrt{s}$=13 – 14TeV, L~10^{34}, ~100fb^{-1}
- 2018: Shut-down (LS2)
- 2019 – 2021: $\sqrt{s}$~=13 – 14TeV, L~2x10^{34}, ~300fb^{-1}
- 2022 – 2023: Shut-down (LS3)
- 2023 – 2030(?): $\sqrt{s}$=13 – 14TeV, L~5x10^{34} (HL-LHC), ~3000fb^{-1}

Higgs' Future @ the LHC

- Increase statistics
  - Essential to make observations of Higgs in the remaining decay modes
  - Measure precisely the properties of this new particle
    - Couplings 20 – 30% with 300fb^{-1} & 5 – 25% with 3ab^{-1} (see Dirk's talk for details)
    - Spin/CP can be determined > 5 ∫ with 300fb^{-1}
    - 3 ∫ Self-coupling observation with 3ab^{-1}
    - Compatibility to SM Higgs





- With anticipated ~30fb^{-1} data end of 2012
  - 4 – 5 ∫ each from H→©©, H→ZZ→4l and H→WW→ĸ ĸ per experiment
  - ~3 ∫ for H→ | | and WH/ZH→W/Z+bb
  - Separation of 0+/2+ and 0+/0- at 4 ∫ with ATLAS and CMS combinations

Conclusions

- The LHC opened up a whole new kinematic regime
  - The LHC performed extremely well in 2011 and 2012!
    - In 2011, 1fb^{-1} expected but obtained 5.5fb^{-1}
    - Accumulated 17.6fb-1 thus far, and still have 7 weeks to go – additional ~7fb^{-1} expected!
- Searches conducted with 4.8fb^{-1} at 7TeV and 5.8fb^{-1} at 8TeV of data
- Observed a neutral boson couple to vector bosons and whose measured mass is

  - At 5.9 $\int$/5.0 $\int$ significance, corresponds to 1.7x10^{-9} bck fluctuation probability!
  - Compatible with production and decay of SM Higgs boson
- Excluded M_H=112 – 122 and 131 – 559GeV (ATLAS) @95% CL
- Higgs searches in VBF picking up steam with two forward jet tags
- Property measurements – such as BR and couplings – in progress, amid high statistical uncertainties
- LHC shuts down end of Feb. 2013 for about 18 months to go to full design energy and luminosity ➔ A new kinematic regime will be accessible