Search for the Standard Model Higgs Boson with the ATLAS detector

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Outline

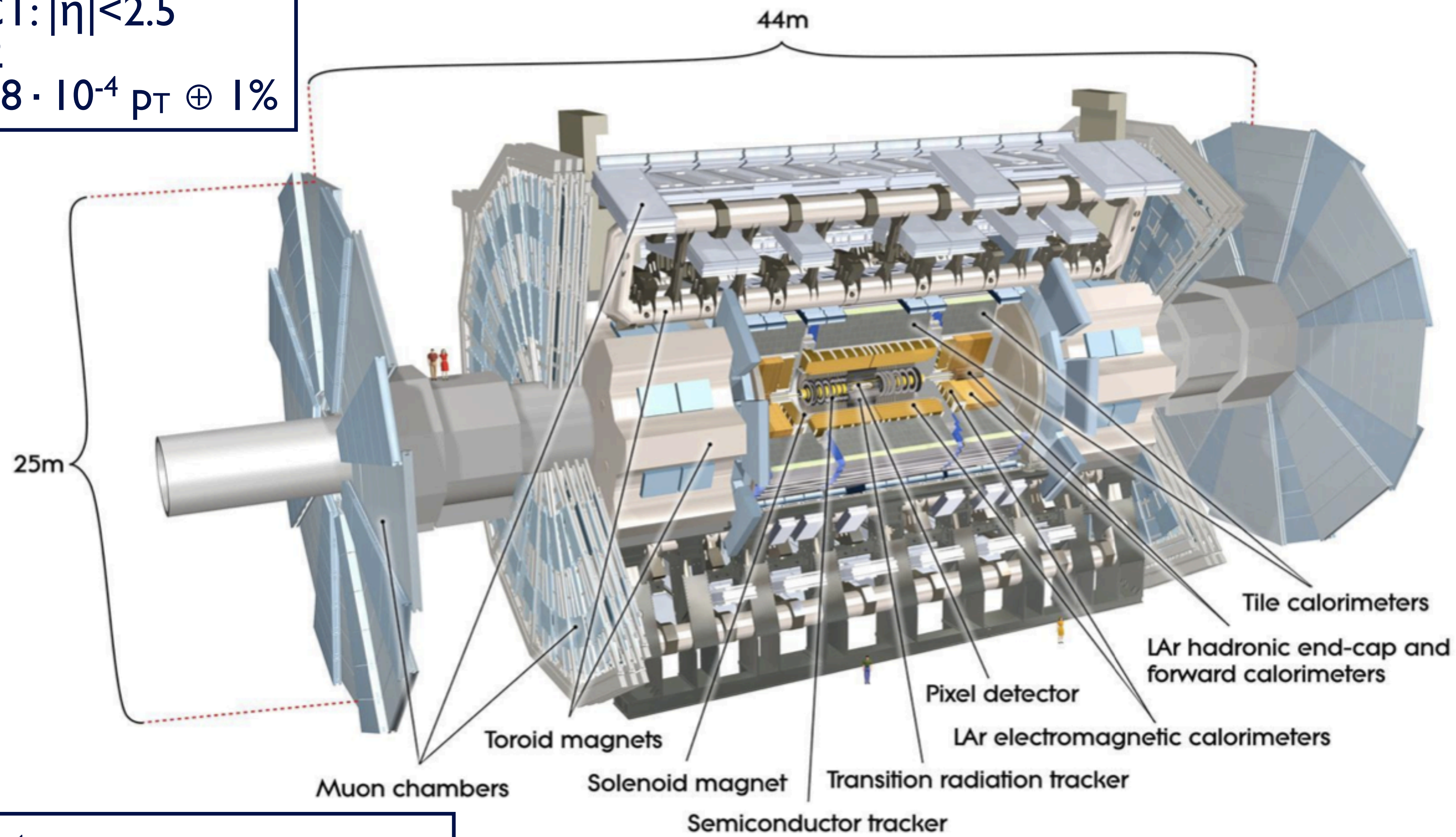
- The ATLAS experiment and the 2011 data taking
- SM Higgs production and decay modes
- Search for the SM Higgs Boson
- Combination of all channels
- Conclusions

IFAE 2012 - Ferrara - 11-13 April 2012

The ATLAS detector

Trigger:
3 levels, rate reduction 40MHz ⇒ <500Hz

Inner detector:
Pixel + SCT: $|\eta|<2.5$
TRT: $|\eta|<2$
$\sigma_{p_T}/p_T \approx 3,8 \cdot 10^{-4}\, p_T \oplus 1\%$

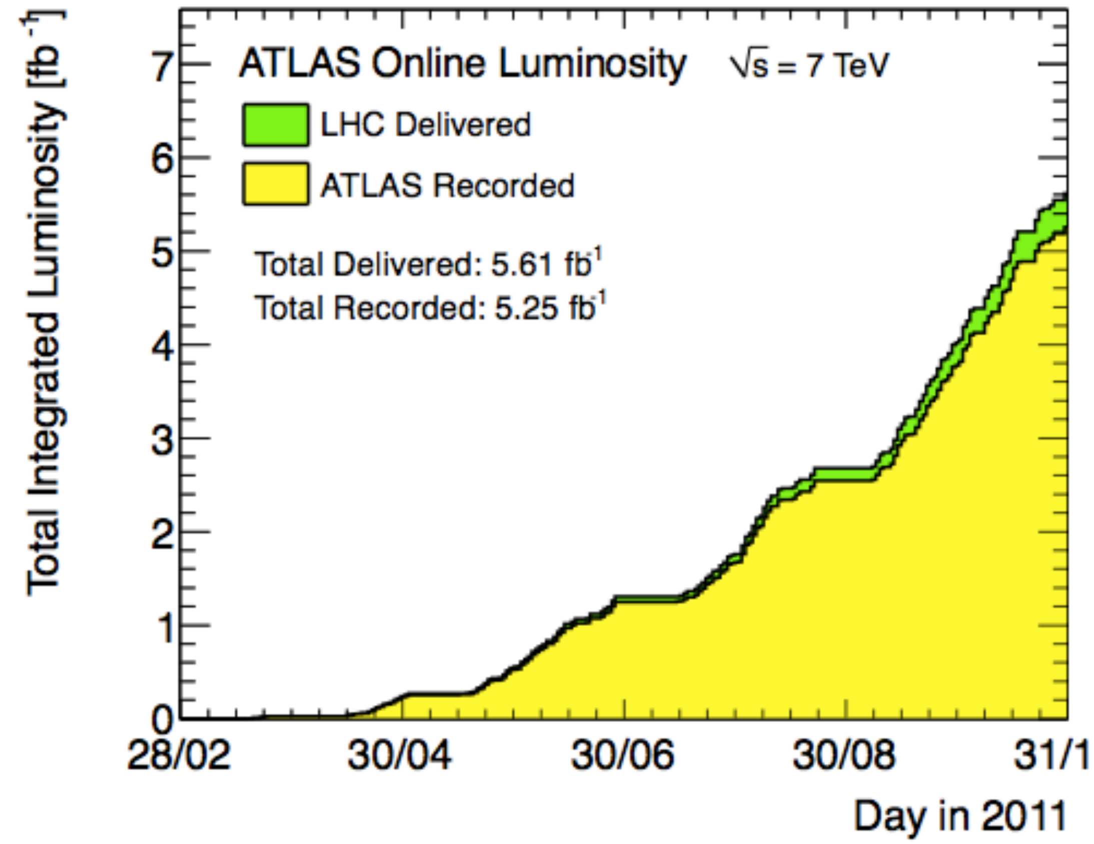


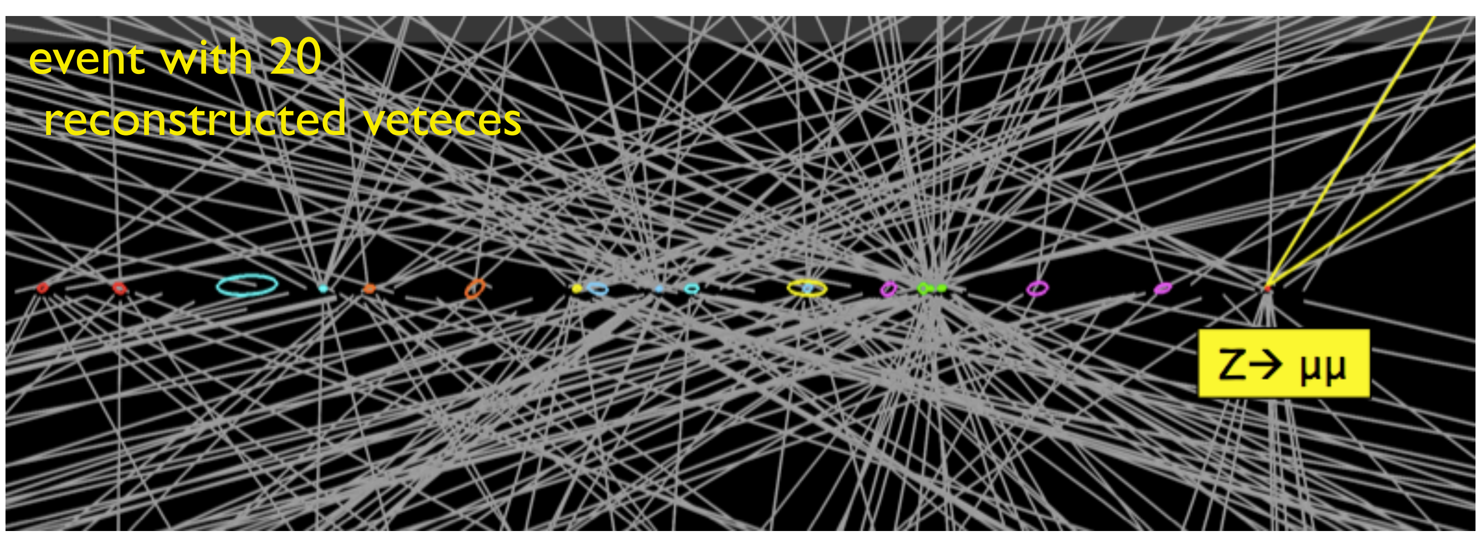
Calorimetry:
LAr + Tile: $|\eta|<3.2$
FCAL: $|\eta|<4.9$
EM: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$
Hadronic: $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$

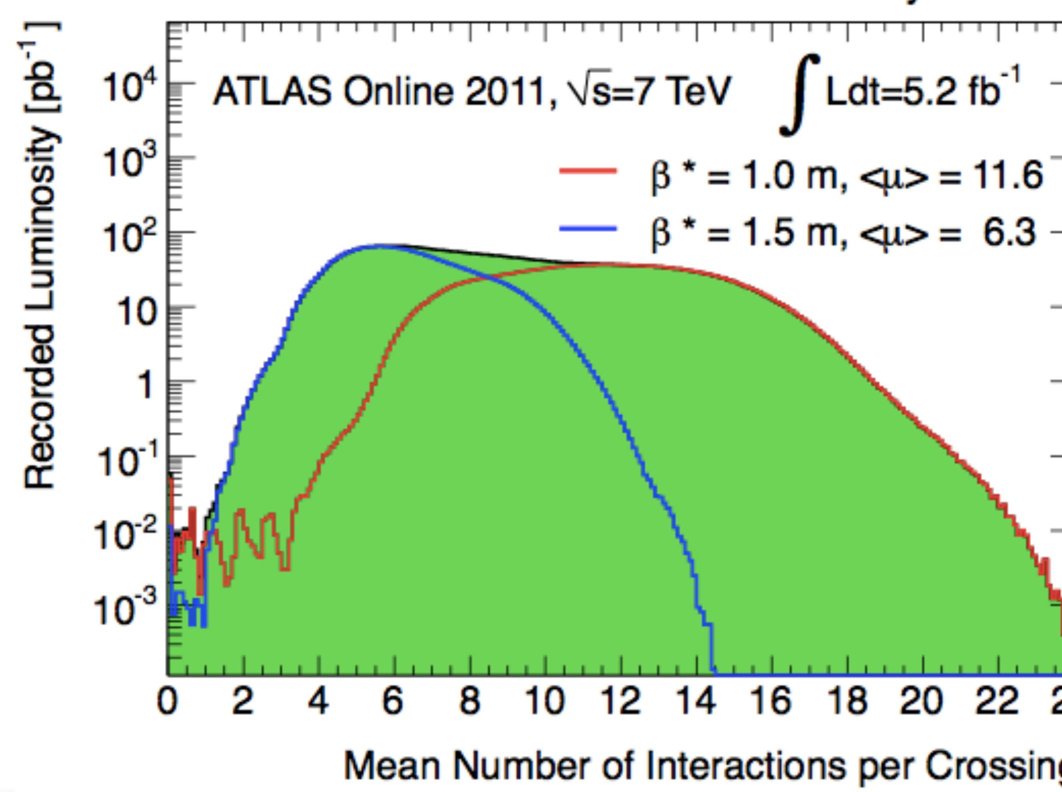
Muons:
RPC + TGC (trigger): $|\eta|<2.4$
MDT + CSC: $|\eta|<2.7$
momentum resolution <10% up to 1 TeV

Atlas data taking in 2011

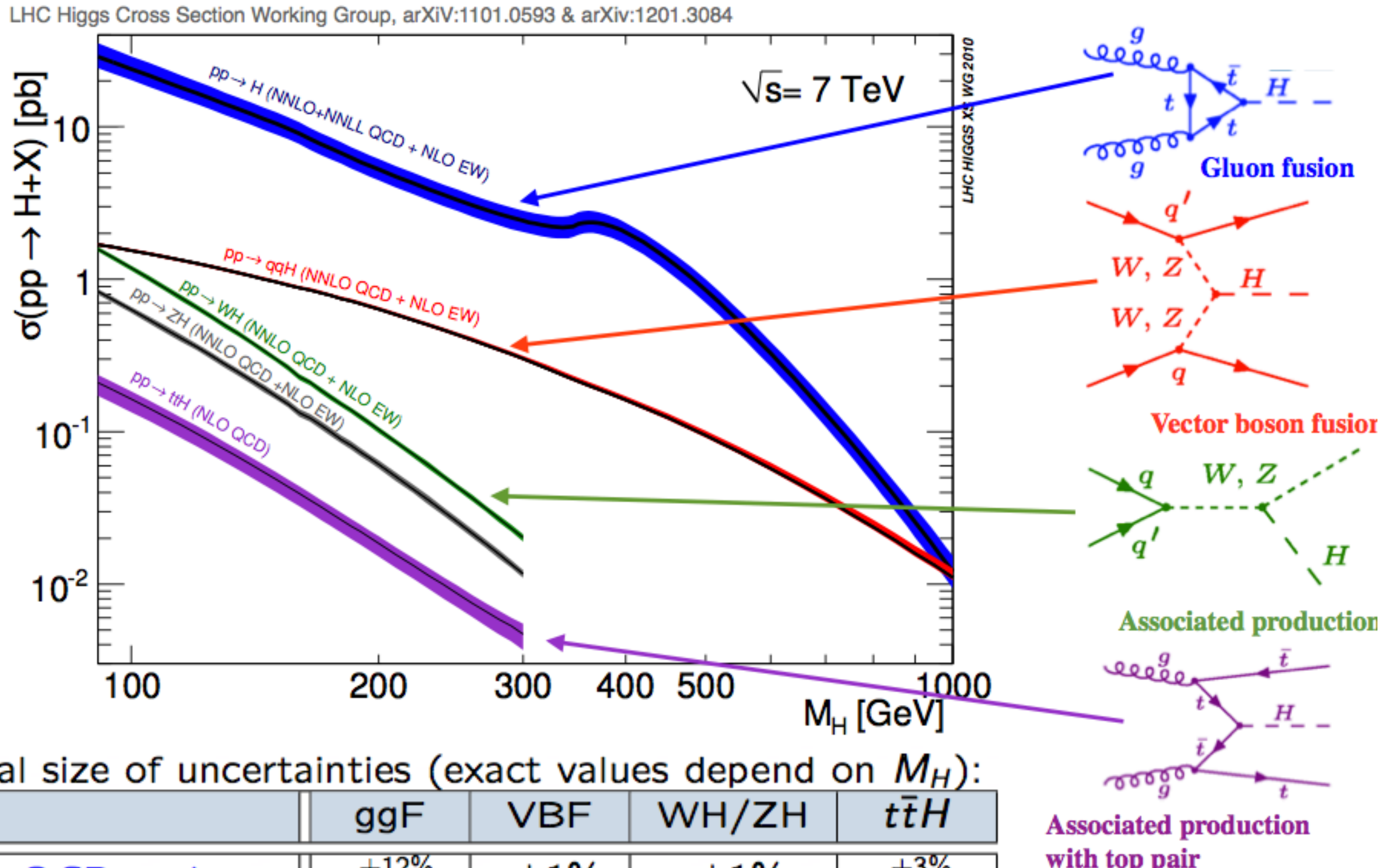
- Excellent LHC performance
  - integrated luminosity: 5.6 fb^{-1}
  - peak luminosity: 3.6 10^{33} $cm^{-2}s^{-1}$
    $\Rightarrow$ high pile-up
- Excellent ATLAS performance
  - high data taking efficiency (>93%)







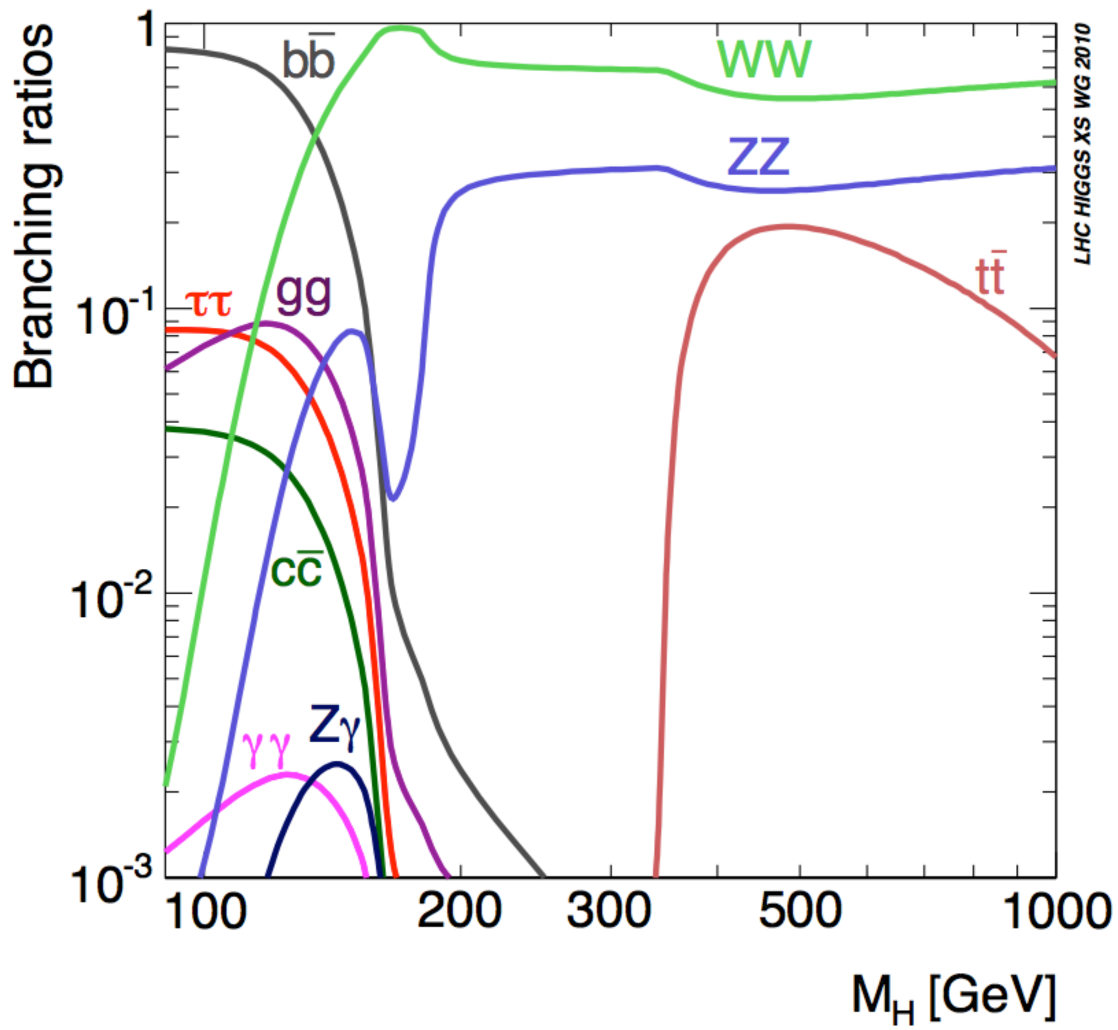
Higgs production at the LHC

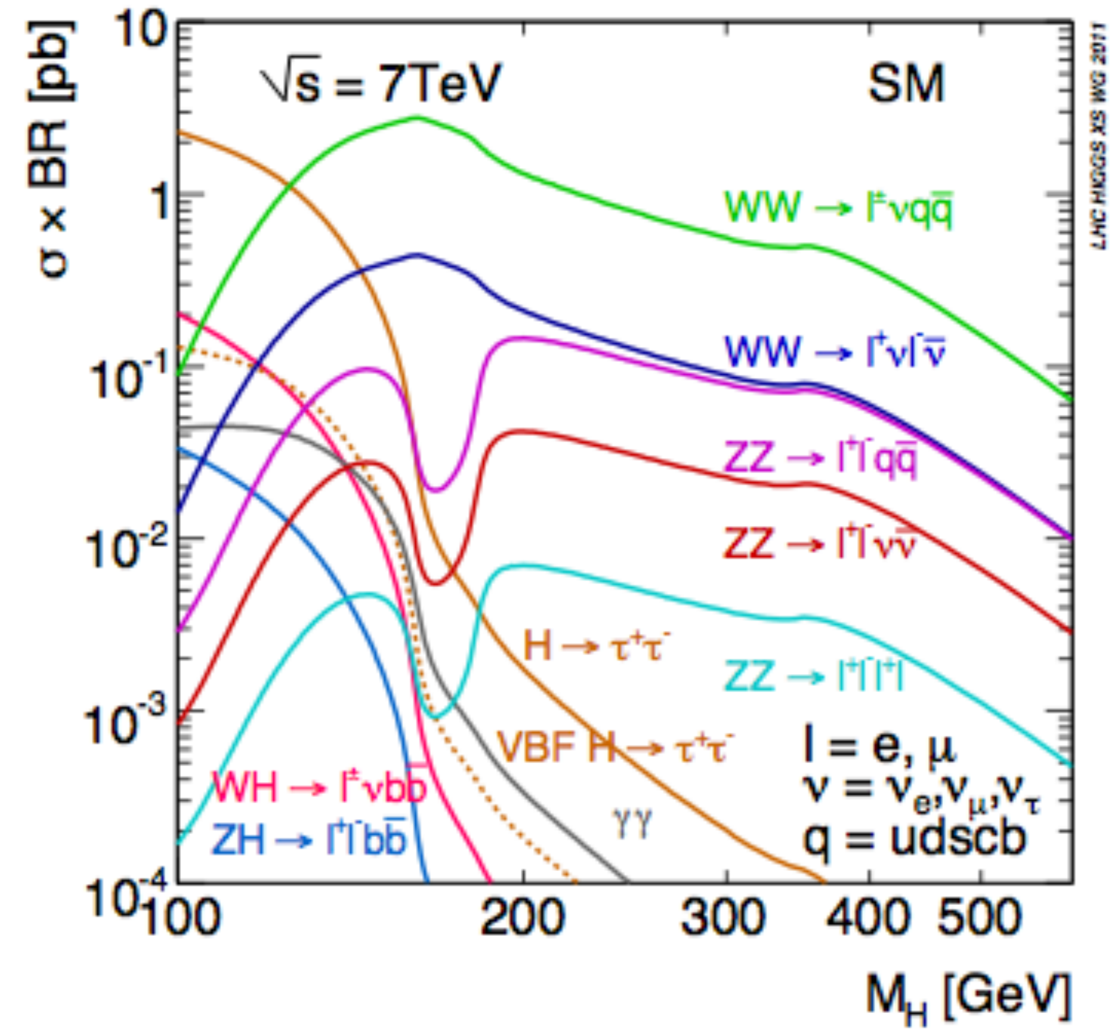


Typical size of uncertainties (exact values depend on M_H):

	ggF	VBF	WH/ZH	$t\bar{t}H$
QCD scale:	$^{+12\%}_{-8\%}$	$\pm1\%$	$\pm1\%$	$^{+3\%}_{-9\%}$
PDF + α_s:	$\pm8\%$	$\pm4\%$	$\pm4\%$	$\pm8\%$

Higgs boson decays





- $M_H < 135$ GeV
  - $H \to \tau\tau$, $H \to bb$ dominate, $H \to WW^{(*)}$, $H \to ZZ^{(*)}$ and $H \to \gamma\gamma$ (small branching ratio but clean signature) are the most sensitive
- $M_H > 135$ GeV
  - $H \to WW$ and $H \to ZZ$ dominates ($H \to ZZ \to ll\nu\nu$ most sensitive)

Higgs boson search strategies

Summary of ATLAS search analyses:

- cut based strategies
- background estimates relies on data-driven techniques using control regions

Channel	m_H range (GeV)	Background	$\mathscr{L}$(fb^{-1})	s/b	Sensitivity (σ_{SM})	Reference*)
Low-m_H - good mass resolution						
$H\rightarrow\gamma\gamma$	110-150	$\gamma\gamma$, γj, jj	4.9	0.02	1.6-2.6	arXiv:1202.1414
$H\rightarrow ZZ^{(*)}\rightarrow 4\ell$	110-600	$ZZ^{(*)}$, Z+jets, tt	4.8	1.5	0.6-9	arXiv:1202.1415
Low-m_H - limited mass resolution						
$H\rightarrow WW(*)\rightarrow\ell\nu\ell\nu$	110-600	WW	4.7	0.3	0.2-8	CONF-2012-012
$H\rightarrow\tau\tau$	100-150	$Z\rightarrow\tau\tau$, tt	4.7	0.02	3-12	CONF-2012-014
VH, $H\rightarrow bb$	110-130	W/Z+jets, tt	4.7	5 10^{-3}	2.5-5	CONF-2012-015
High-m_H						
$H\rightarrow ZZ\rightarrow\ell\ell\nu\nu$	200-600	diboson, tt, Z+jet	4.7	0.3	0.5-2.5	CONF-2012-016
$H\rightarrow ZZ\rightarrow\ell\ell jj$	200-600	Z+jets, tt, diboson	4.7	0.5	0.9-9	CONF-2012-017
$H\rightarrow WW\rightarrow\ell\nu jj$	300-600	W+jets, tt, multi-jets	4.7	10^{-3}	1.8-5	CONF-2012-018

(Mainly focusing on the low-m_H region)

*) CONF-2012-XXX= ATLAS-CONF-2012-XXX

Higgs searches in the high mass region

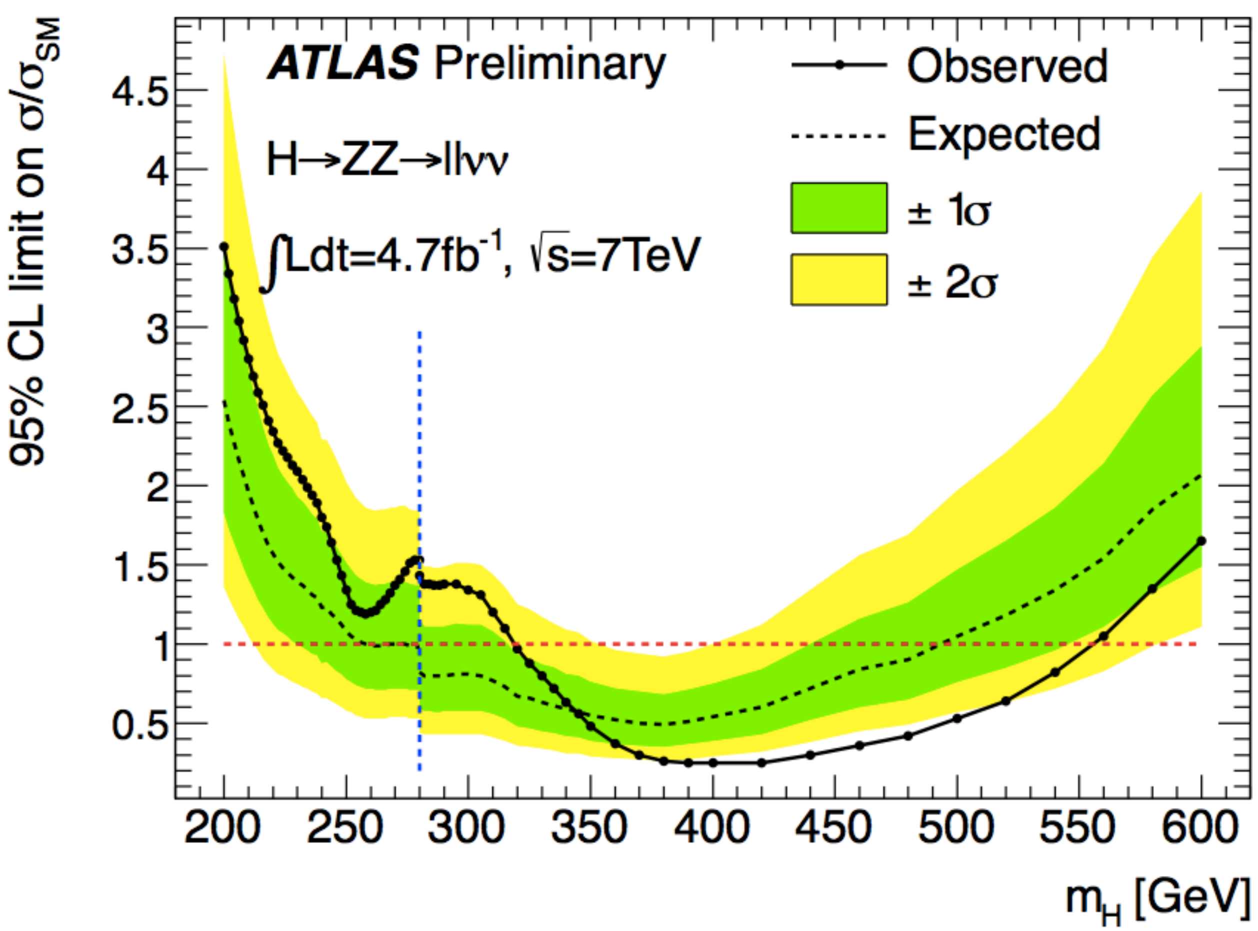
The three channels sensitive to a high m_H are: $H\to ZZ\to ll\nu\nu$, $H\to ZZ\to lljj$, $H\to WW\to l\nu jj$

($WW\to l\nu jj$ in M. Biglietti's talk)

$H\to ZZ\to ll\nu\nu$:

most sensitive channel at high m_H

Limit extraction based on m_T



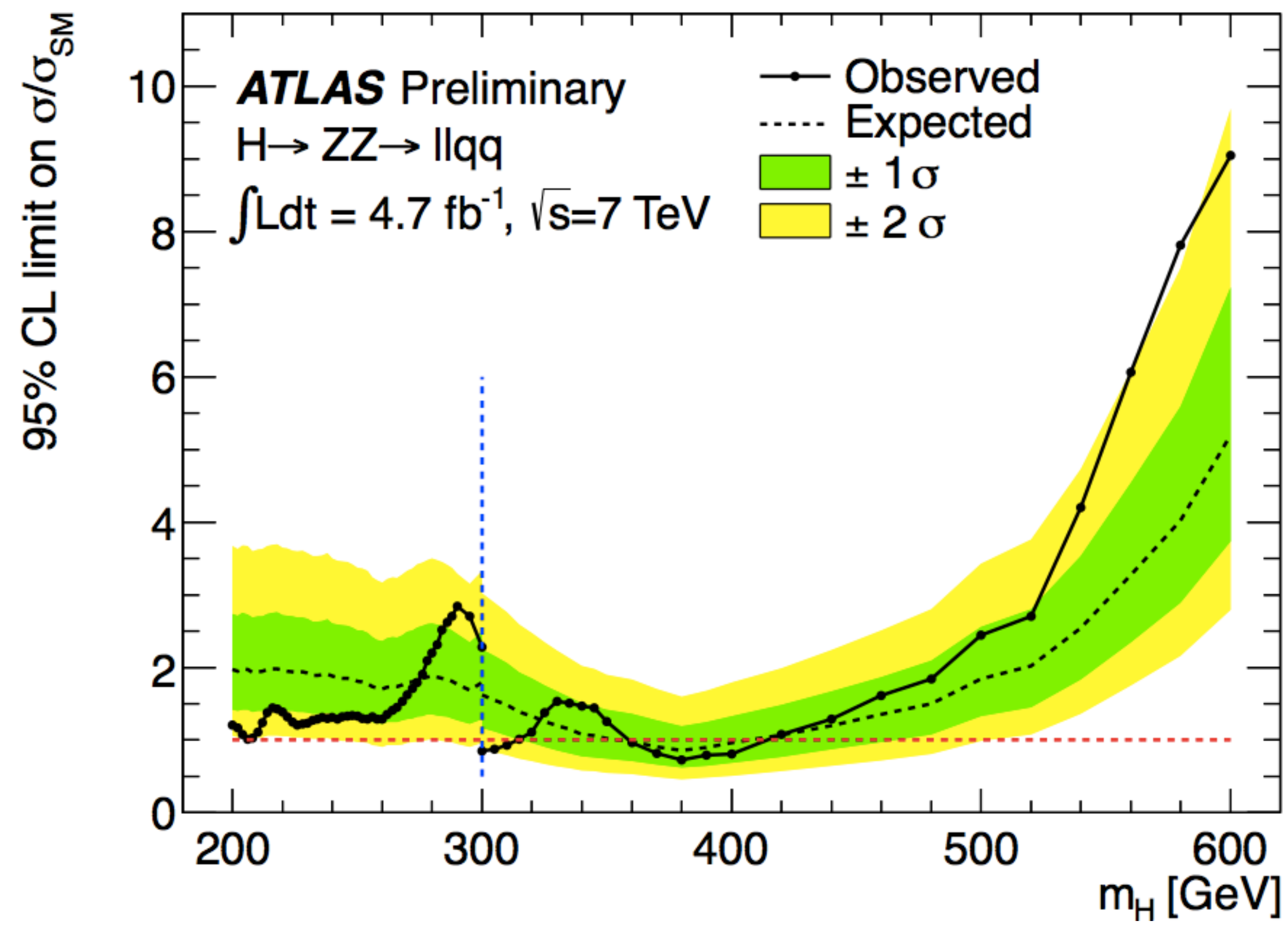
Exclusion Limit:

260-460 GeV (Expected)

320-560 GeV(Observed)

$H\to ZZ\to lljj$:

Limit extraction based on m_{lljj}



Exclusion Limit:

360-400 GeV (Expected)

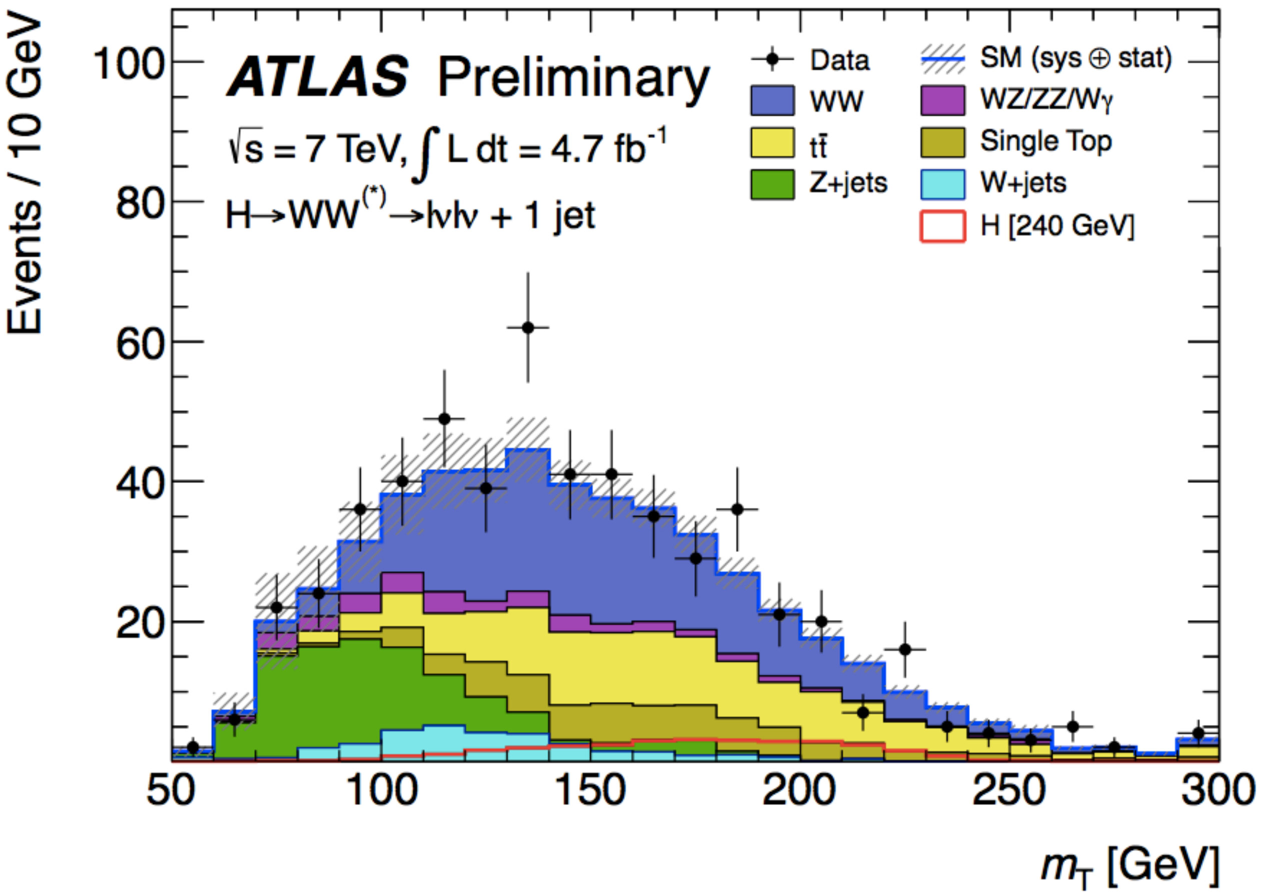
300-310; 360-400 GeV (Observed)

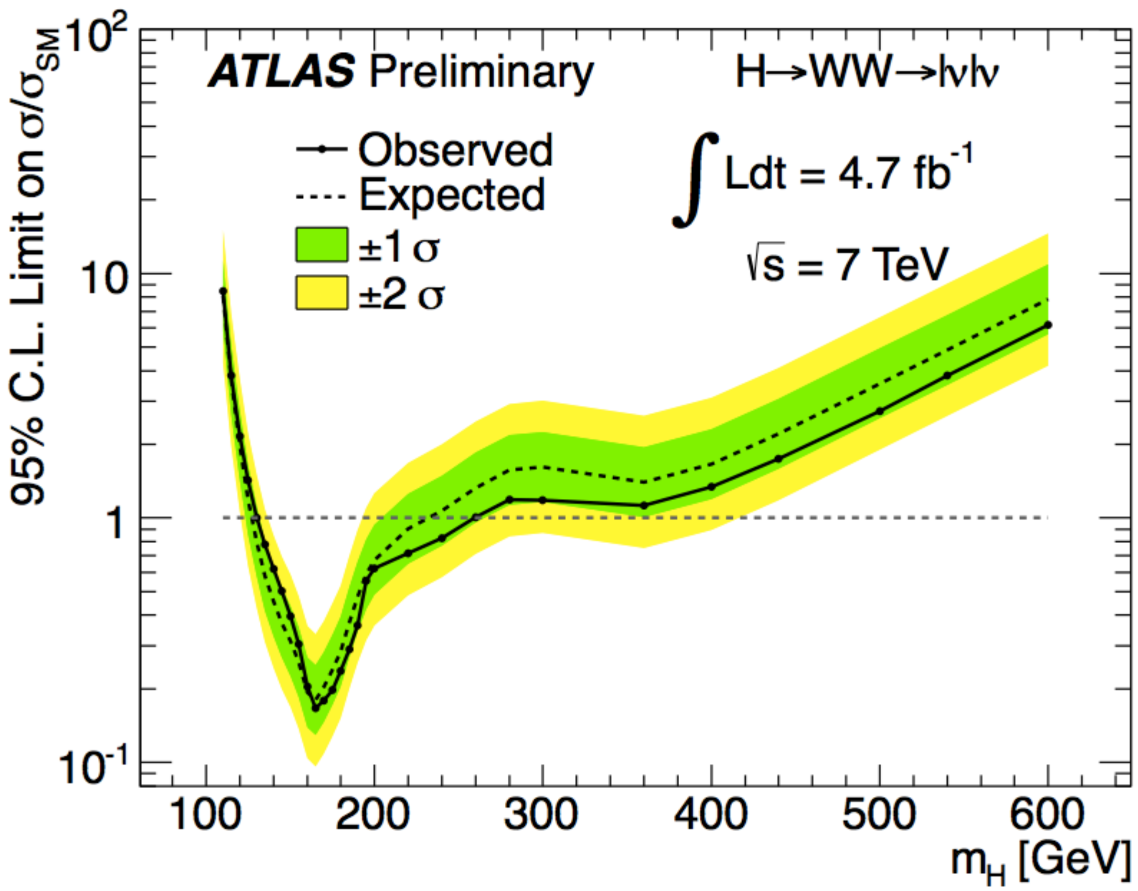
$H \Rightarrow WW^{(*)} \Rightarrow l\nu l\nu$

(more in M. Biglietti's talk)

Most sensitive channel $125<m_H<180$ GeV

- Selection criteria (function of n-jet)
  - 2lep. p_T>25(15)GeV, E_T^{miss}>45GeV, m_{ll}<50(80)GeV, $\Delta\Phi_{ll}$<1.8, p_T^{ll}>45(30)GeV, $\mathbf{p}_T^{tot}$<30GeV, b-tag veto
- Background
  - *WW* ➠ $\Delta\Phi_{ll}$ sidebands
  - top ➠ no tagging requirement
  - *Z/W*+jet ➠ control sample
    Z peak / reverted lepton ID





m_H=125 GeV	0-jet ee	0-jet $\mu\mu$	0-jet $e\mu$
Total bkg.	58±5	114±10	257±13
Signal	3.8±0.1	9.0±0.1	25±0.2
Observed	52	138	237

m_H=125 GeV	1-jet ee	1-jet $\mu\mu$	1-jet $e\mu$
Total bkg.	21±3	37±5	76±6
Signal	1.1±0.1	2.3±0.1	6.0±0.1
Observed	19	36	90

(Statistical uncertainties only.)

Exclusion Limit:

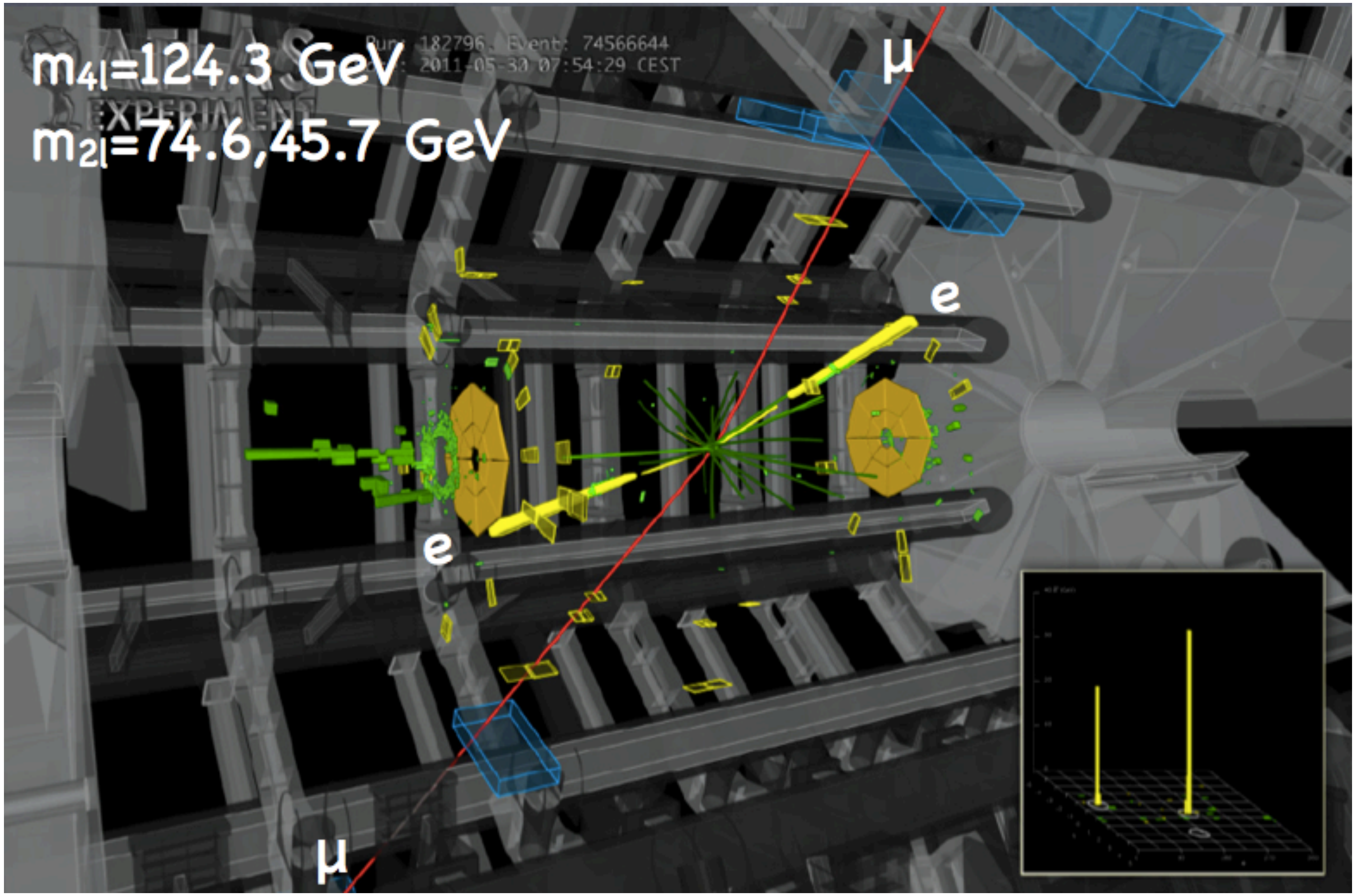
127-234 GeV (Expected)

130-260 GeV(Observed)

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

The golden channel

- High mass resolution
  - 1.5-2% @ 130 GeV
  - natural width dominates above 350 GeV
- High lepton performances
  - high lepton efficiency down to p_T of 7 GeV
  - independent of pile-up
  - 0.2-2% uncertainty on signal yield
  - 0.6% uncertainty on m_{4e} scale
  - lepton performance well modeled by sim.



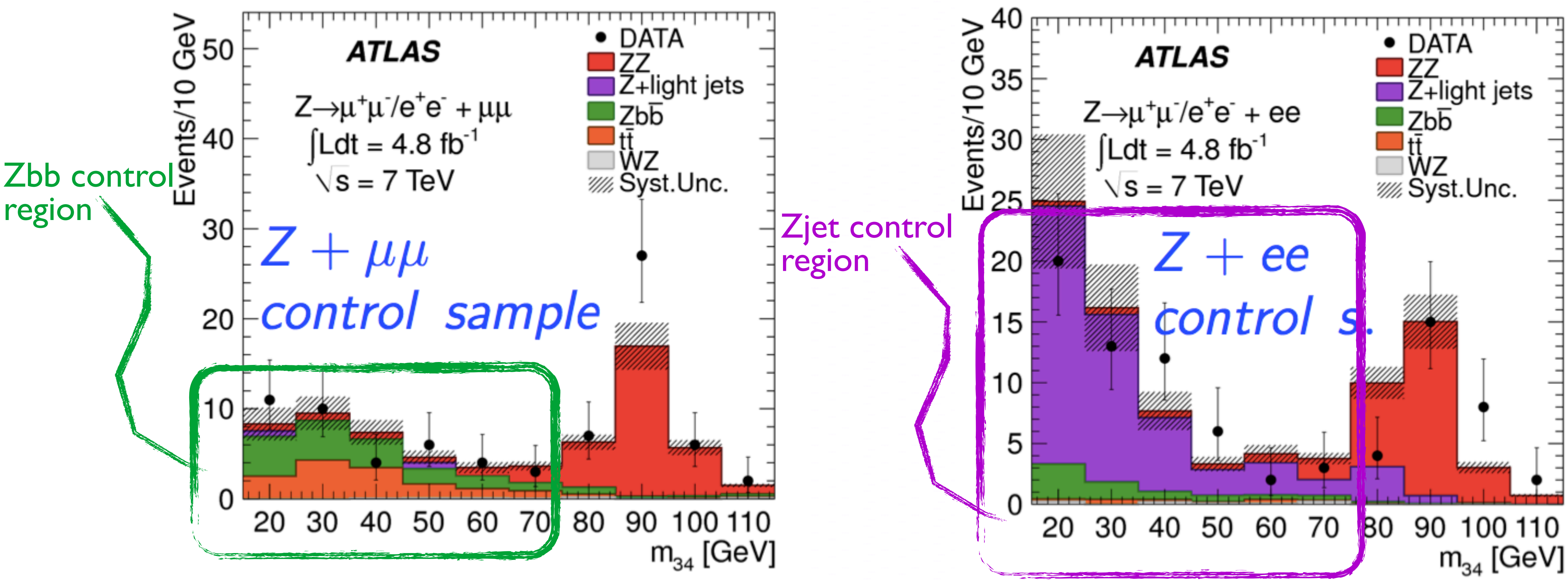
$H \Rightarrow ZZ^{(*)} \Rightarrow 4l$

Selection

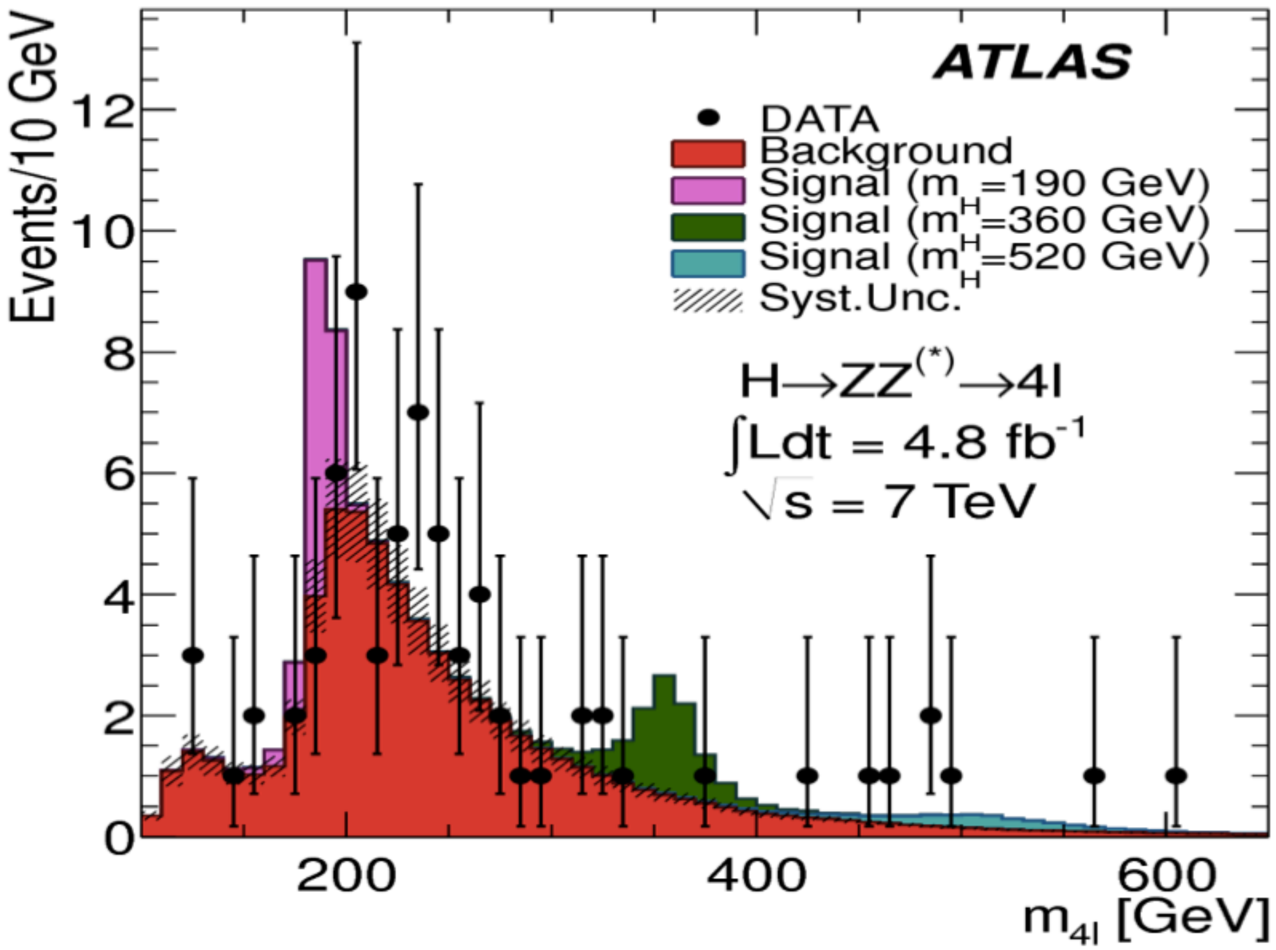
- 4leptons, $p_T^{1,2(3,4)}$>20(7) GeV; $|\eta_e|$<2.47 and $|\eta_\mu|$<2.7; track and calorimeter isolation
- m_{12}< $m_Z \pm$ 15 GeV m_{34} > 15-60 GeV (depending m_H)
- selection efficiency at m_H=130 (360) GeV: 27(60)% 4μ; 18(52)% 2μ2e; 14(45)% 4e

Background

- $ZZ^{(*)}$ ➠ simulation (QCD: 5%; PDF+α_s: 4-8%, 10% on gg→ZZ)
- Z+jets ➠ control region without charge, isolation, and impact parameter criteria on the second lepton pair (40-45% uncertainty)
- top ➠ $e^{\pm}\mu^{\mp}$ pair consistent with m_Z, and 2 additional same-flavor leptons

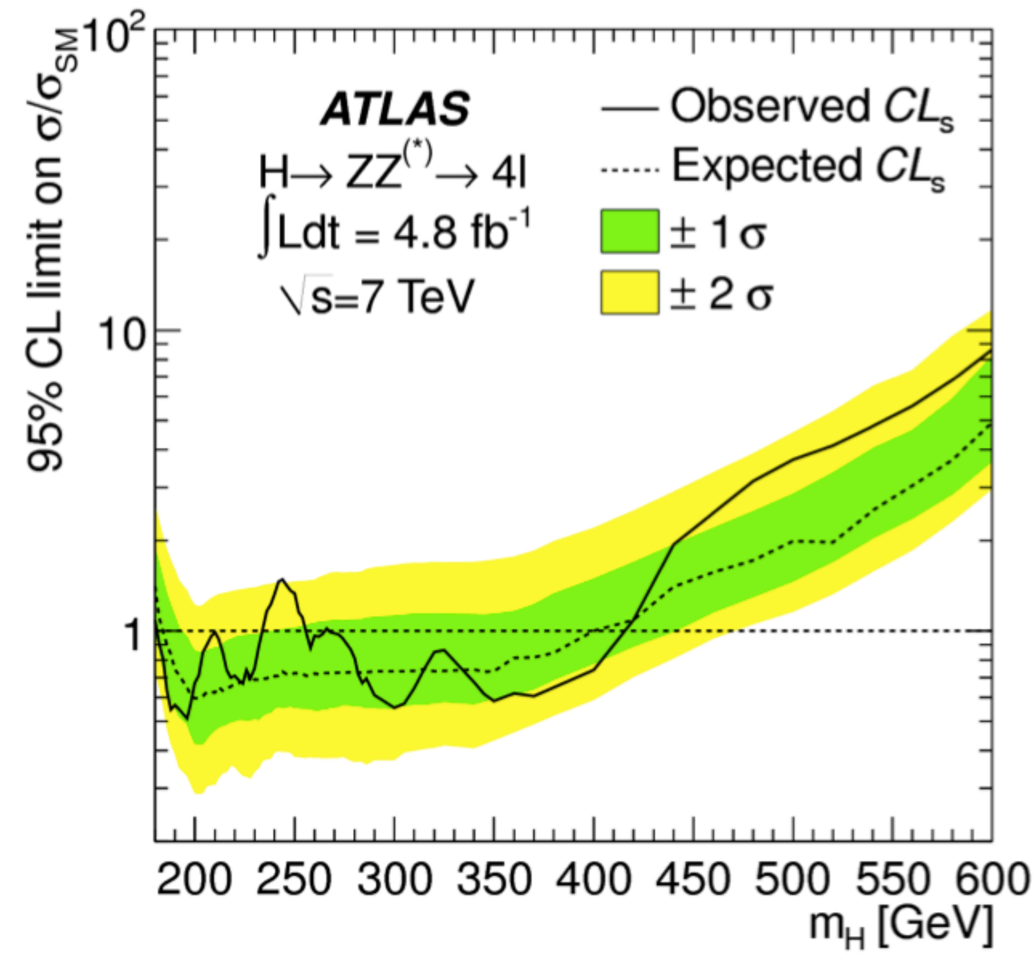


$H \Rightarrow ZZ^{(*)} \Rightarrow 4l$: results



number of events in the full mass range			
	4μ	2e2μ	4e
Expected	18.6±2.8	29.7±4.5	13.4±2.0
Observed	24	30	17

Local significance of excess			
	125 GeV	244 GeV	500 GeV
Expected	1.3σ	3.0σ	1.5σ
Observed	2.1σ	2.2σ	2.1σ



Expected exclusion limit:
137-157, 184-400 GeV

Observed exclusion limit:
134-156, 182-233, 256-265, 268-415 GeV

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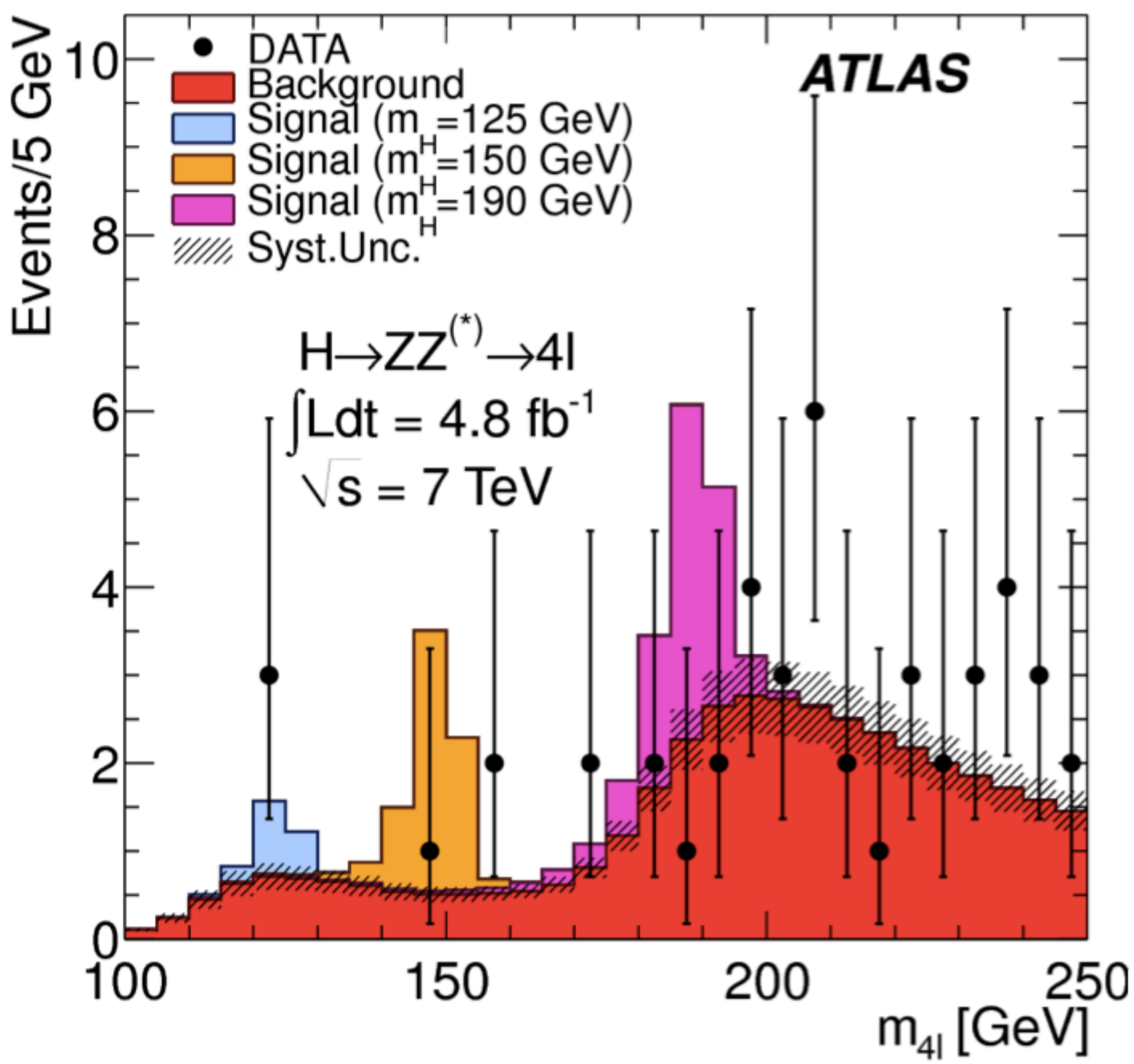

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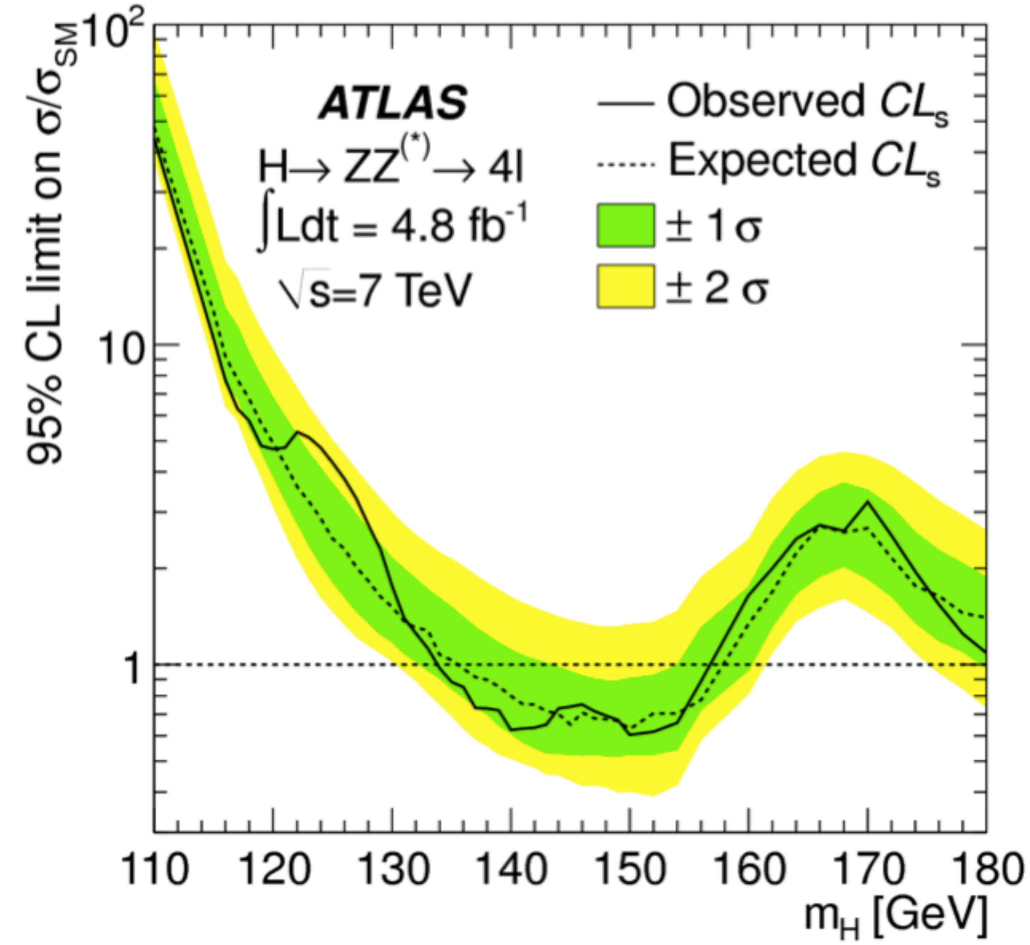
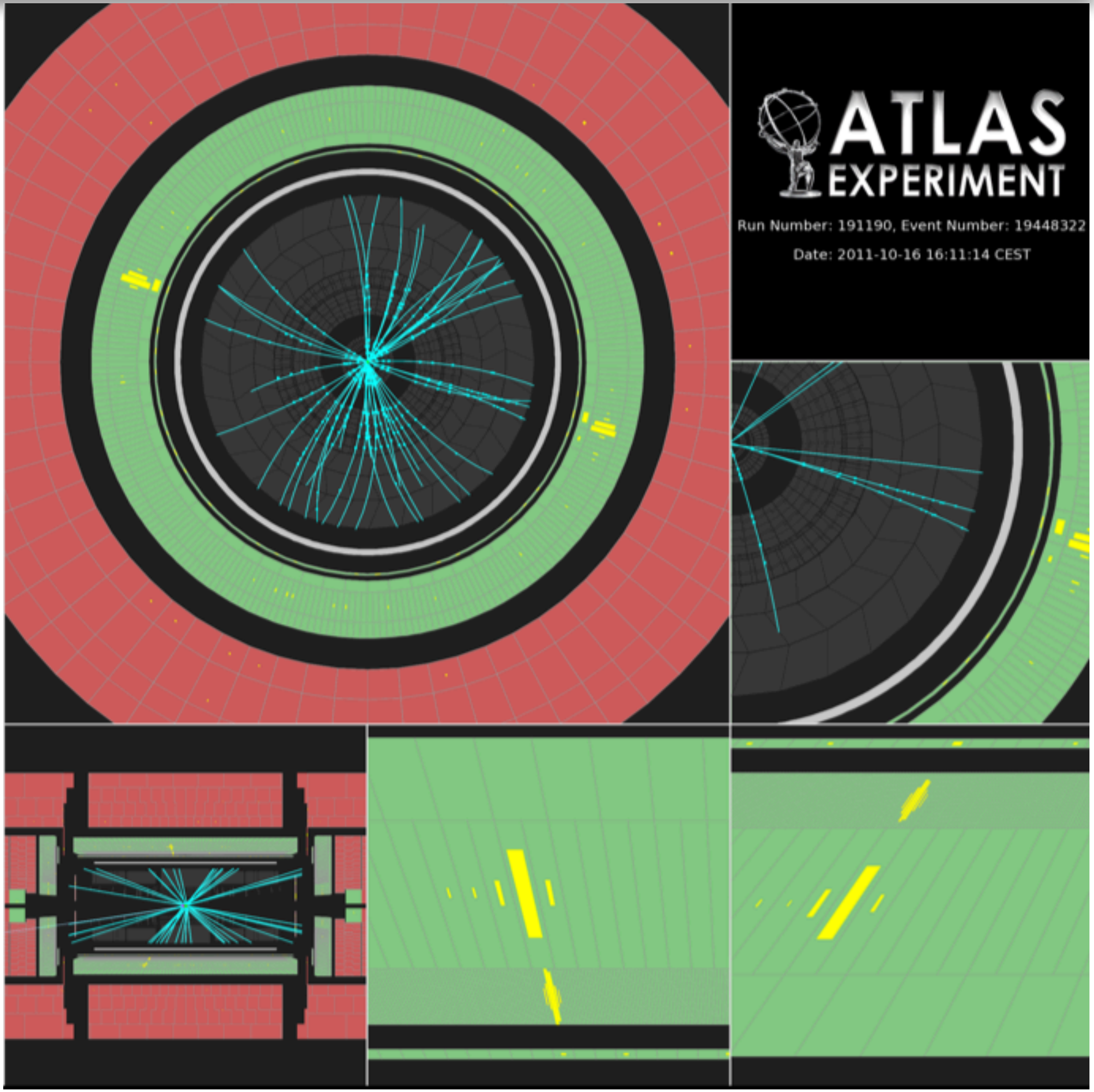


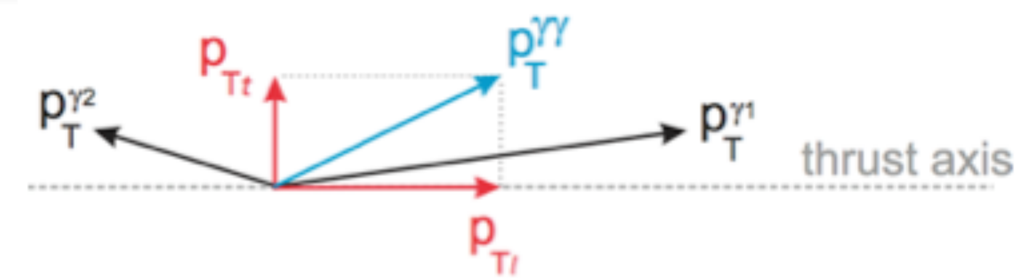
$H \Rightarrow \gamma\gamma$

- 2 photons
  - $ET(\gamma_1) > 40$ GeV
  - $ET(\gamma_2) > 25$ GeV
- Powerful γ-jet separation
  - η-strips (4mm) $\Rightarrow \gamma$ vs $\pi^0 \rightarrow \gamma\gamma$
- High mass resolution:
  - excellent energy resolution
  - long. segmentation ⇒
    - γγ angular separation
    - z-vertex determination

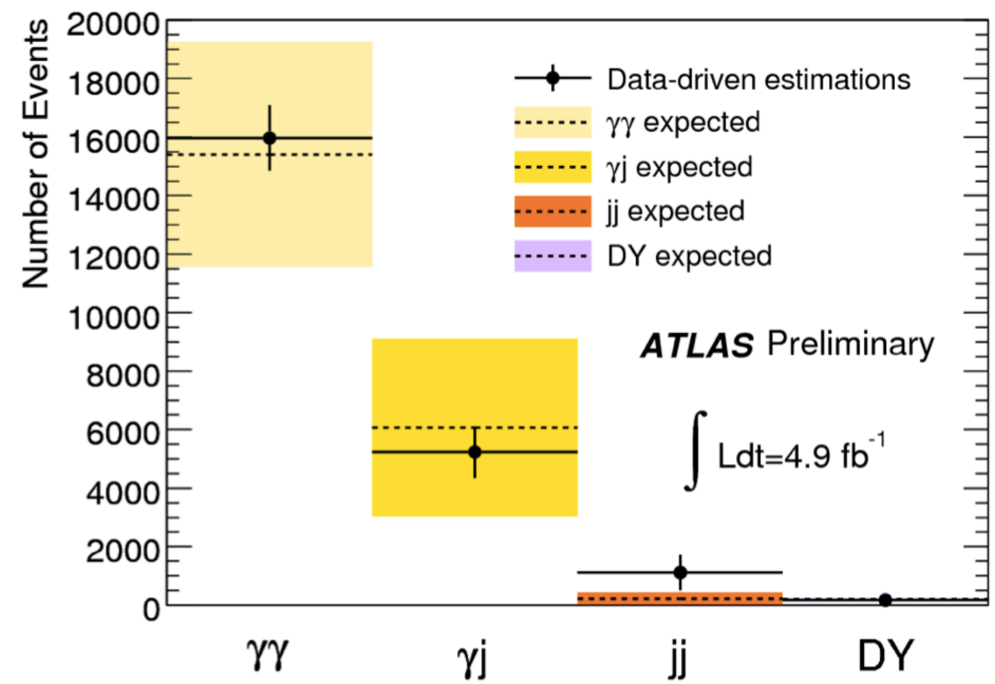


$H \Rightarrow \gamma\gamma$

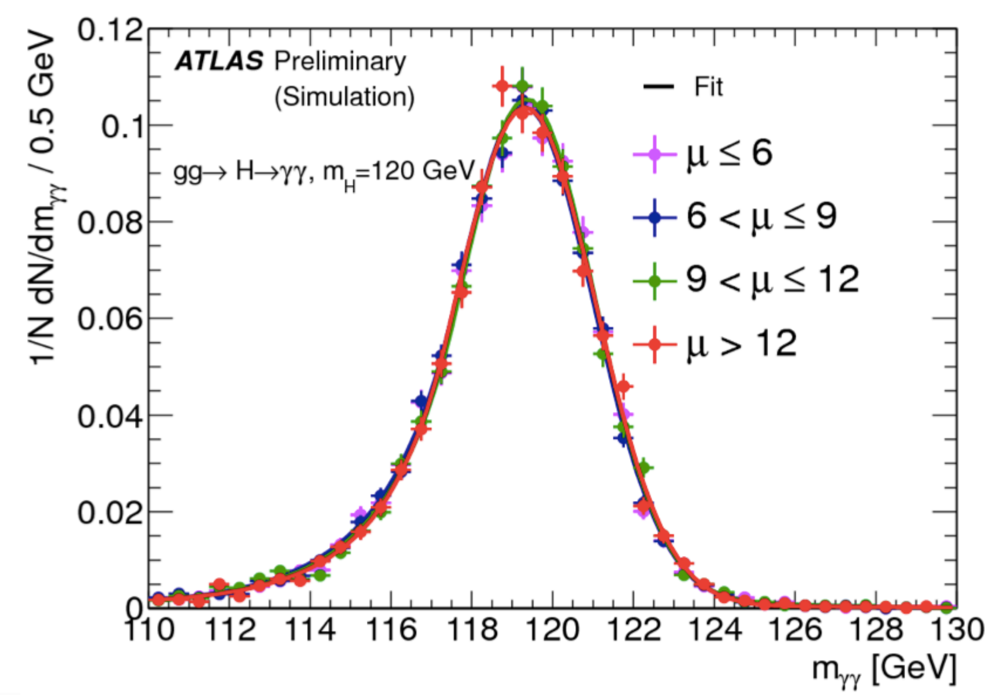
9 categories: $\eta_\gamma \otimes$ conversion status $\otimes$ $p_{T\text{-thrust}}^{\gamma\gamma}$



- Background composition tested on data
  - inverted photon isolation and ID criteria
  - fraction of true $\gamma\gamma$ = (71±5)%
- Background normalization from fit to $m_{\gamma\gamma}$ spectrum
  - simultaneous fit to the 9 categories
  - Exponential function (free slope and norm.)

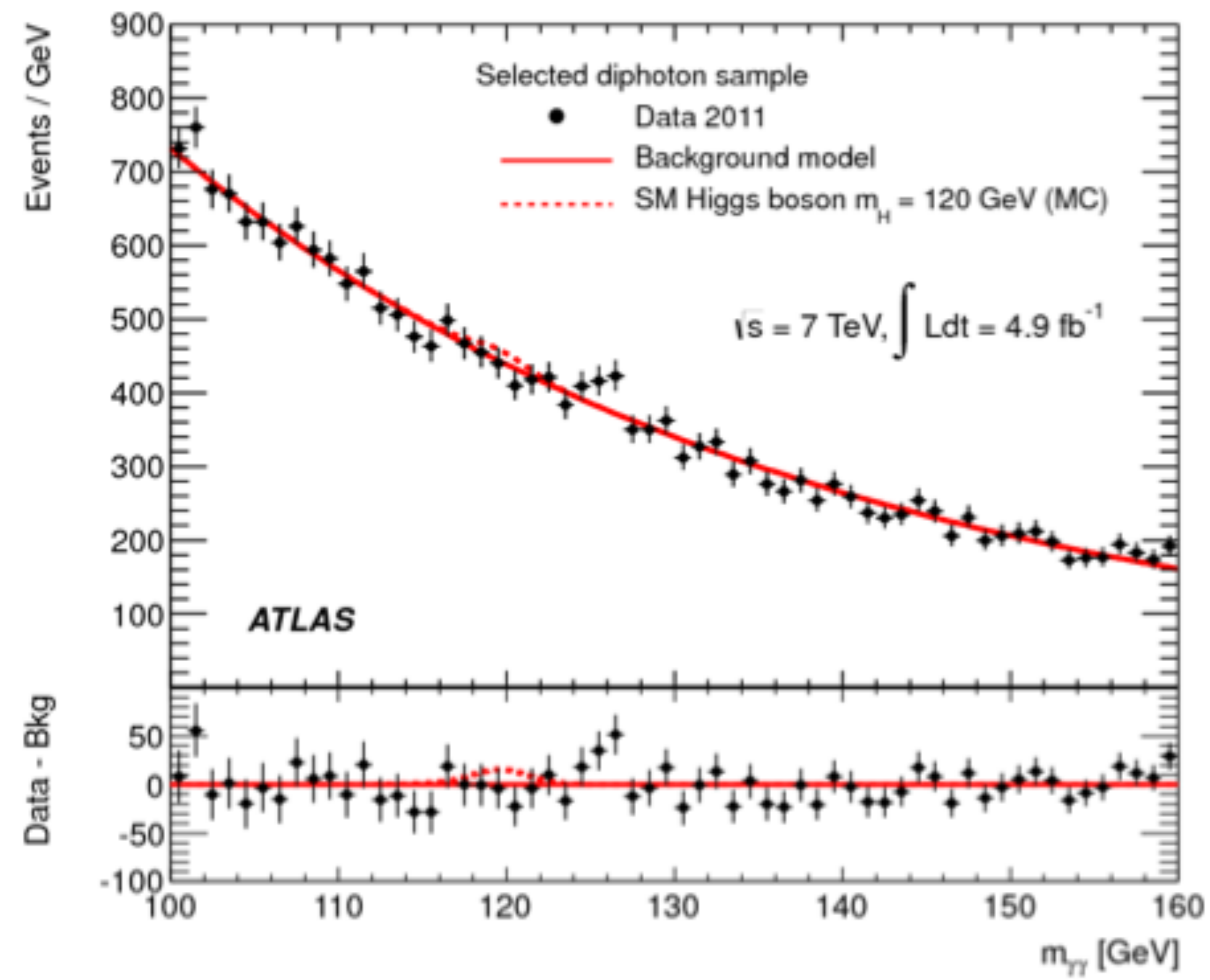


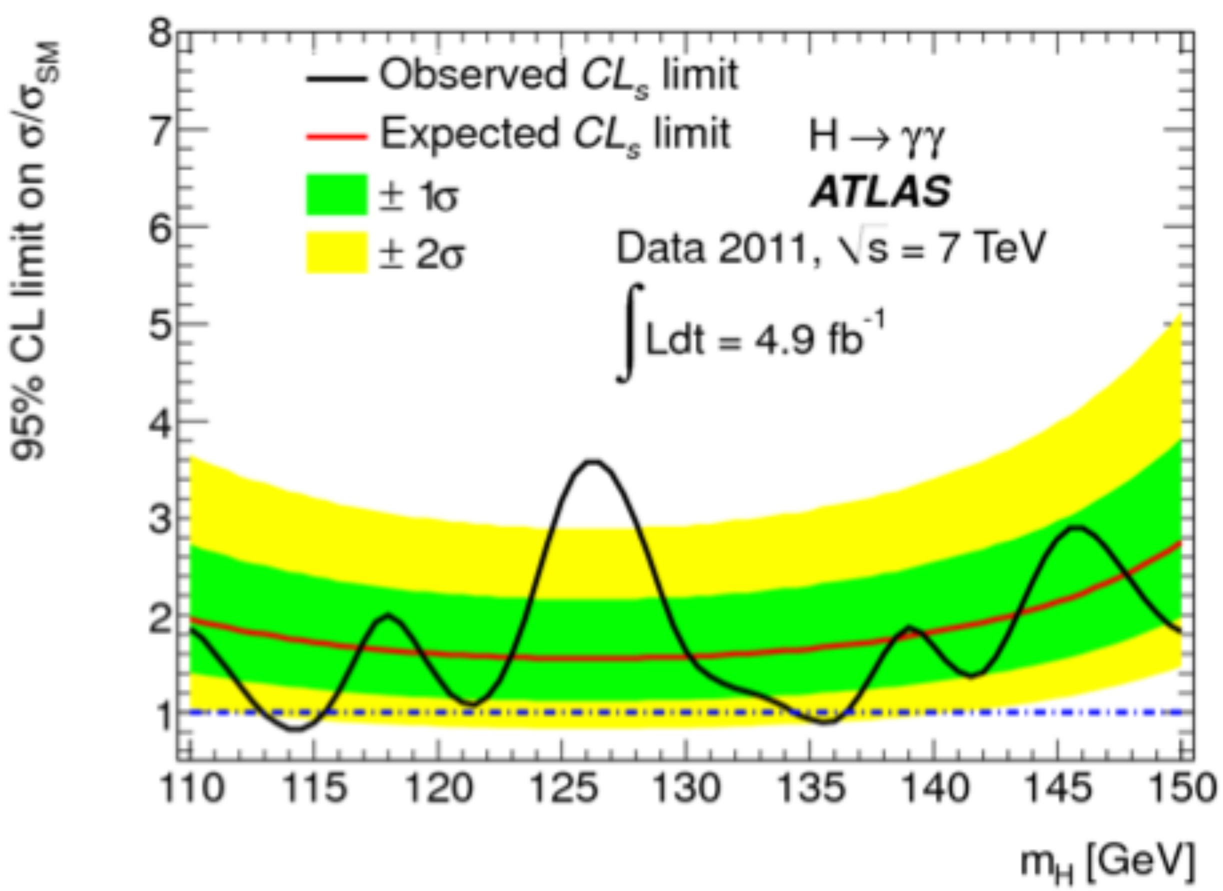
- signal $m_{\gamma\gamma}$ mass modeling
  - sum of crystal ball (core)
  - Gaussian function (tails)
  - $\sigma_{CB}(m_H=120\ \text{GeV}) = 1.4\text{-}2.3\ \text{GeV}$ (category dep.)
  - FWHM (m_H=120 GeV) = 3.3-5.9GeV (category dep.)
  - mass scale uncertainty: 0.7 GeV (m_H=120 GeV)



$H \Rightarrow \gamma\gamma$: results

- s/b ≈ 2% @ m_H=125GeV
  - $H \to \gamma\gamma$ yield ≈ 70 events
  - ≈3000 observed events
- Main systematics uncertainties:
  - Expected signal yield: ≈20%
  - $H \to \gamma\gamma$ mass resolution: ≈14%
  - $H \to \gamma\gamma$ p_T modeling: ≈8%
  - background modeling: 0.1-7.9 events





Observed exclusion limit:
113-115, 134.5-136 GeV

Unable to exclude the Higgs over the full range due to an excess of events observed at 126 GeV

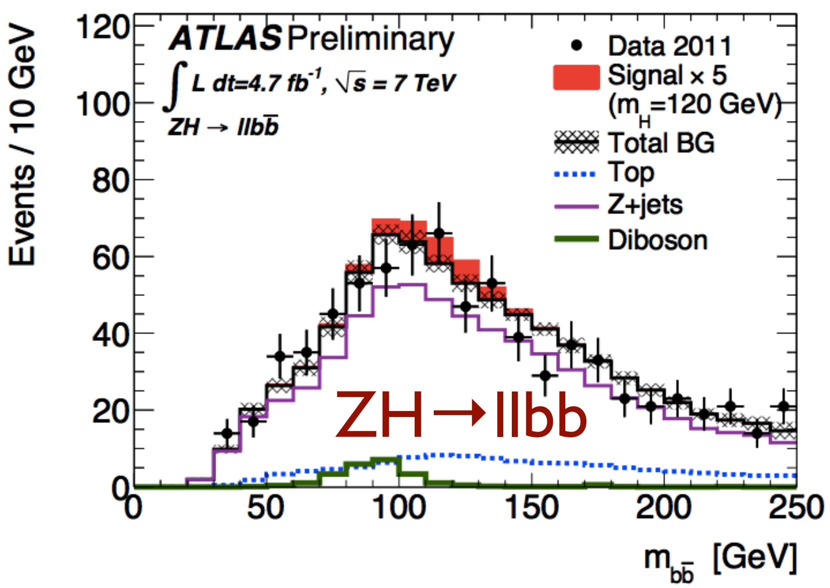
- local significance: 2.8σ (expected ~1.3σ)
- global 110<m_H<150GeV: 1.5σ

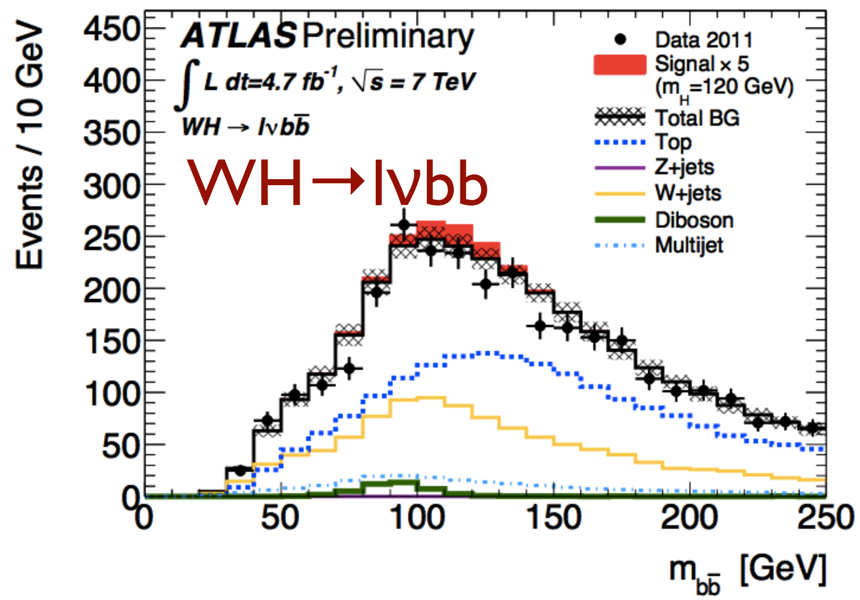
W/ZH⇒(ll,lν,νν)bb

11 categories: (ll,lν) ⊗ 4 p_T^V-bin ⊕ νν ⊗ 3 E_T^{miss}-bin

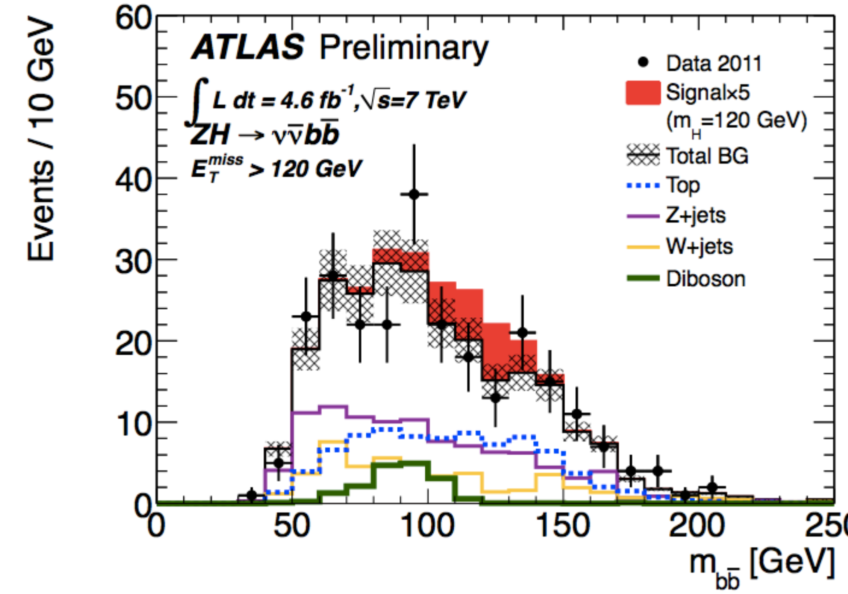
High p_T^V better s/b ratio

Limit extraction based on invariant mass m_{bb} shape ($m_{l\nu} = m_W$)

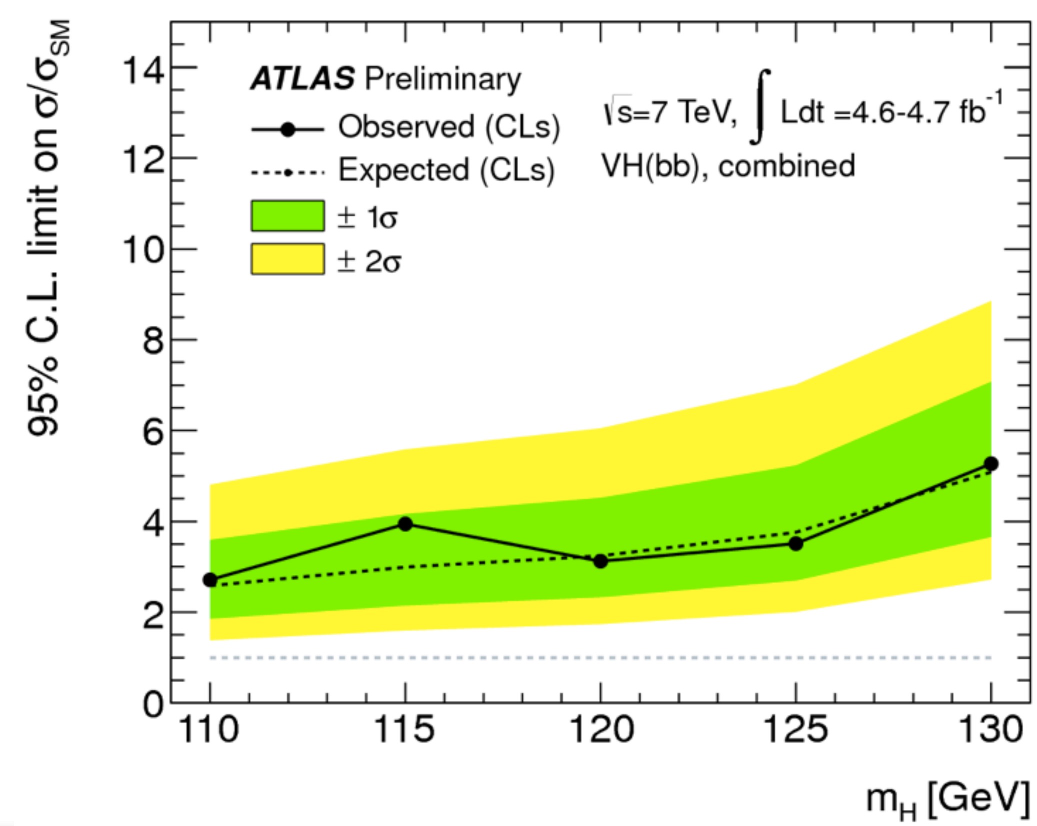




ZH→ννbb



- **Selection Criteria**
  - 2(1)lep., E_T^{miss}, m_{ll} (m_T), $\Delta\Phi_{ll}$, at least(exactly) 2 jets; exactly 2 b-tags
- **Background**
  - top ➟ shape: sim.; norm.: fit m_{bb}>150 GeV
  - W/Z+jet ➟ shape: sim.; norm.: fit m_{bb}<85 GeV
  - multijet ➟ reversed lepton ID; $\Delta\Phi(\boldsymbol{E}_T^{miss},\boldsymbol{p}_T^{miss})$

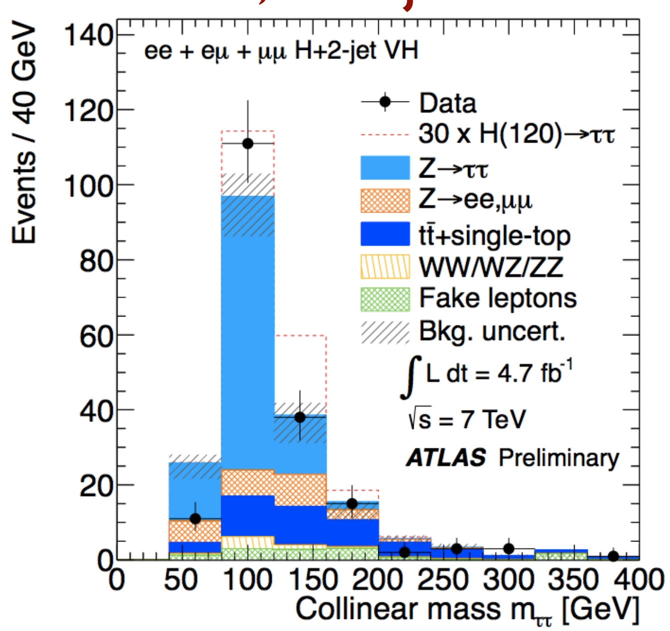


$H \Rightarrow \tau\tau \Rightarrow (ll4\nu,\ l\tau_{had}3\nu, 2\tau_{had}2\nu)$

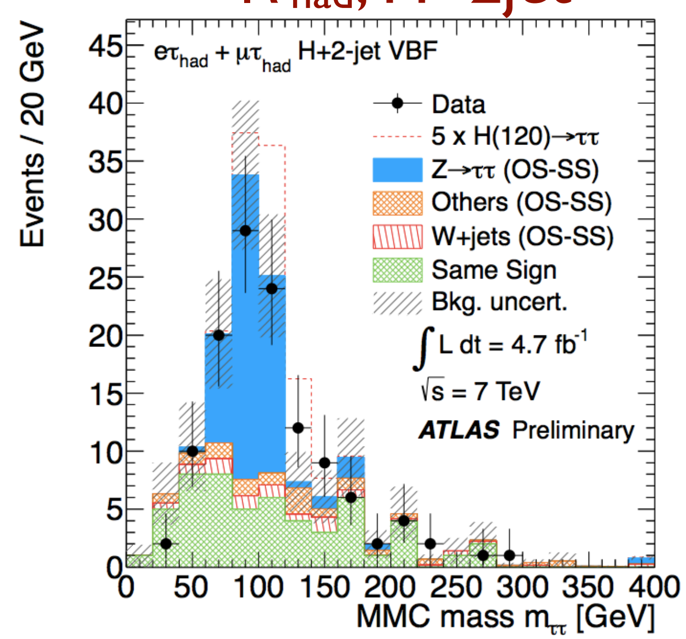
12 categories: decay channel ($ll4\nu$, $l\tau_{had}3\nu$, $2\tau_{had}2\nu$) and jet mult. (0-, 1-, 2-jet VH, 2-jet VBF)

Limit extraction based on invariant mass $m_{\tau\tau}$ shape *(thanks to the collinearity of the τ decay products)*

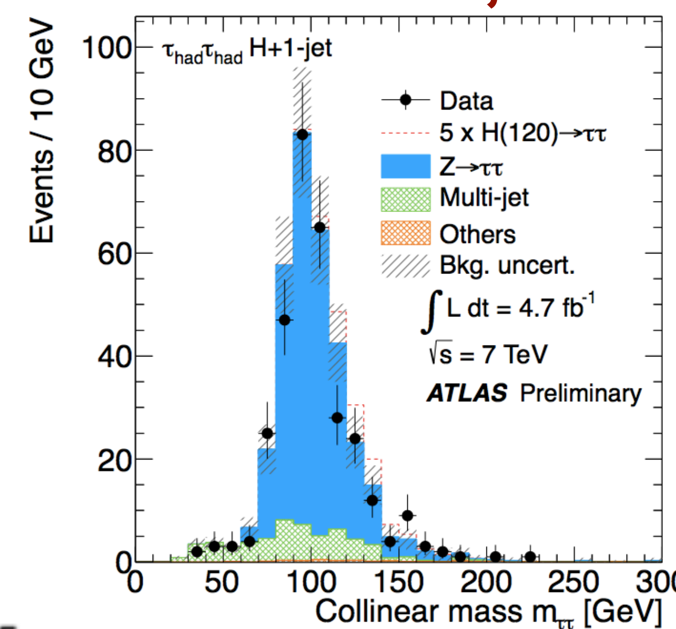
$ll4\nu$; H+2jet

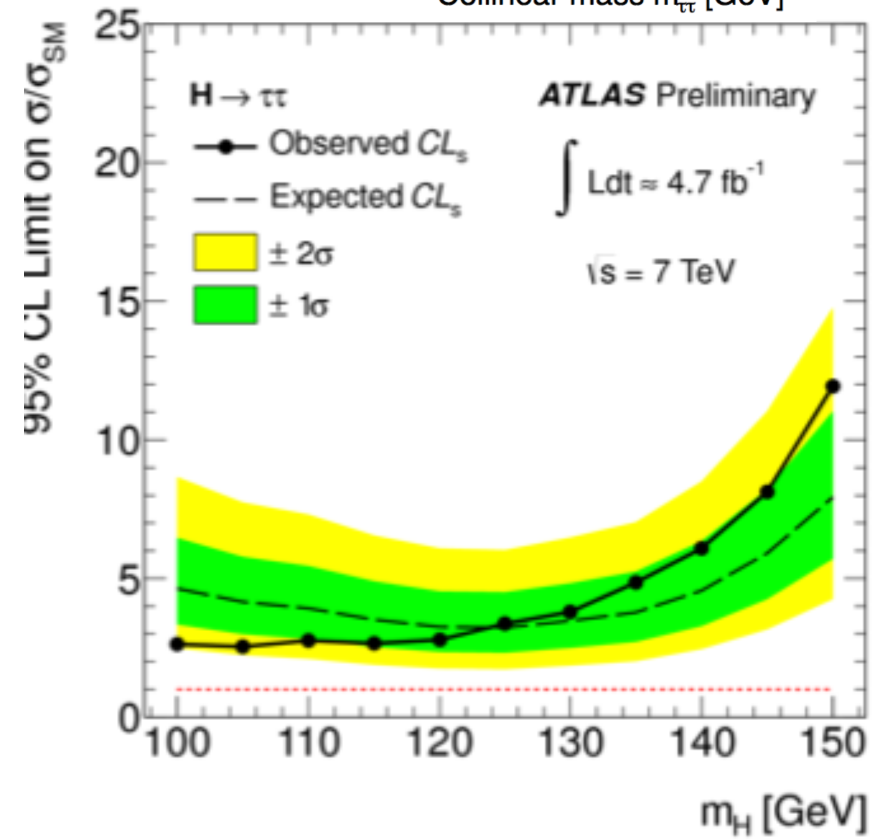


$l\tau_{had}$; H+2jet



$2\tau_{had}$: H+1jet



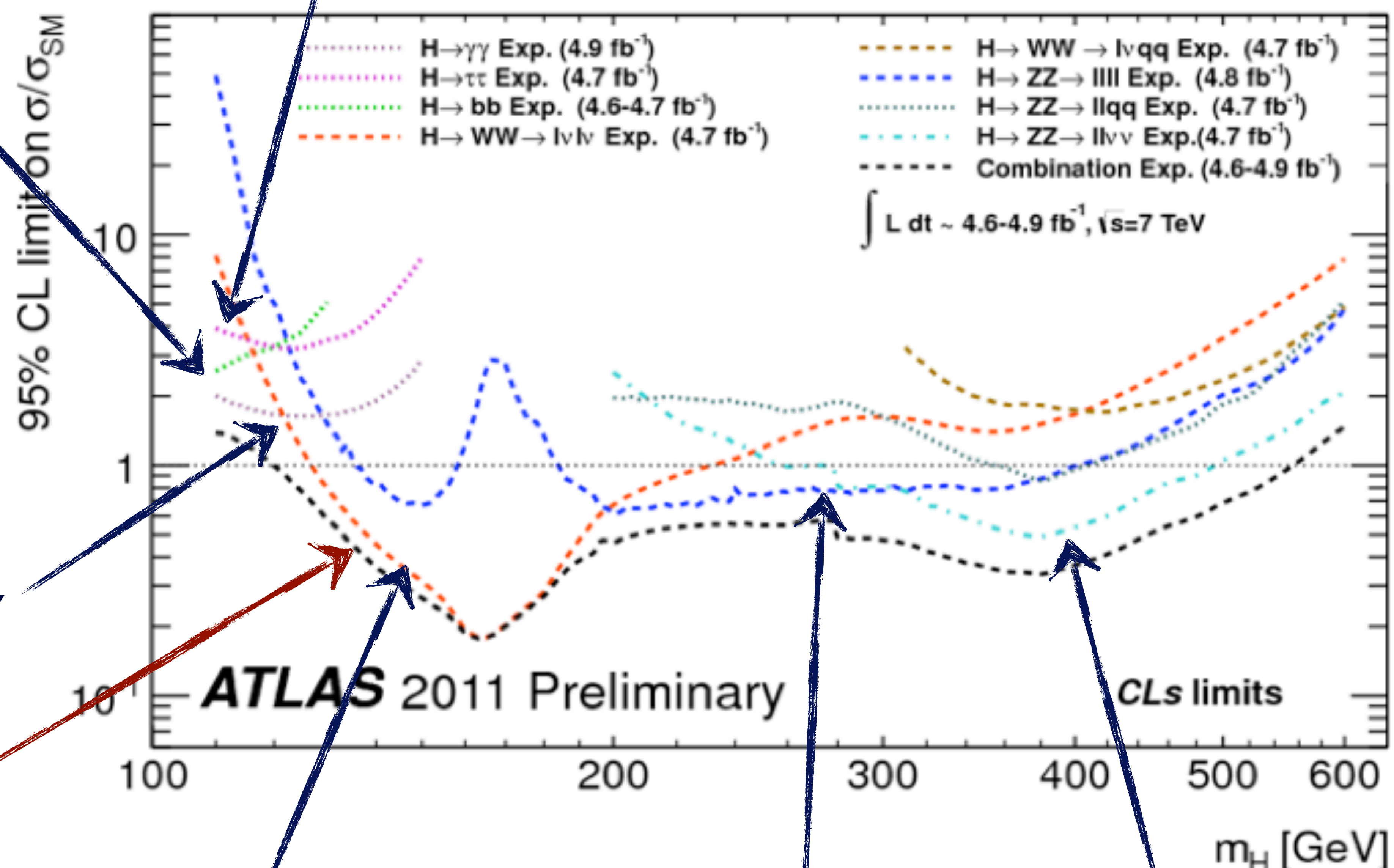


- Selection criteria
  - 2,1,0lep.+0,1,2τ_{had}, E_T^{miss}, m_{ll} (m_T), $\Delta\Phi_{ll}$, jet mult. 0,1,2
- Background
  - $Z \to \tau\tau$ ➠ norm from theory; shape from $Z \to \mu\mu$
  - fake leptons and τ-jets:
    - $ll4\nu$: reversed lepton isolation
    - $l\tau_{had}3\nu$: same-sign charge
    - $l\tau_{had}\tau_{had}2\nu$: track multiplicity

Combination

W/ZH⇒(ll,lν,νν)bb

H⇒ττ



H⇒γγ

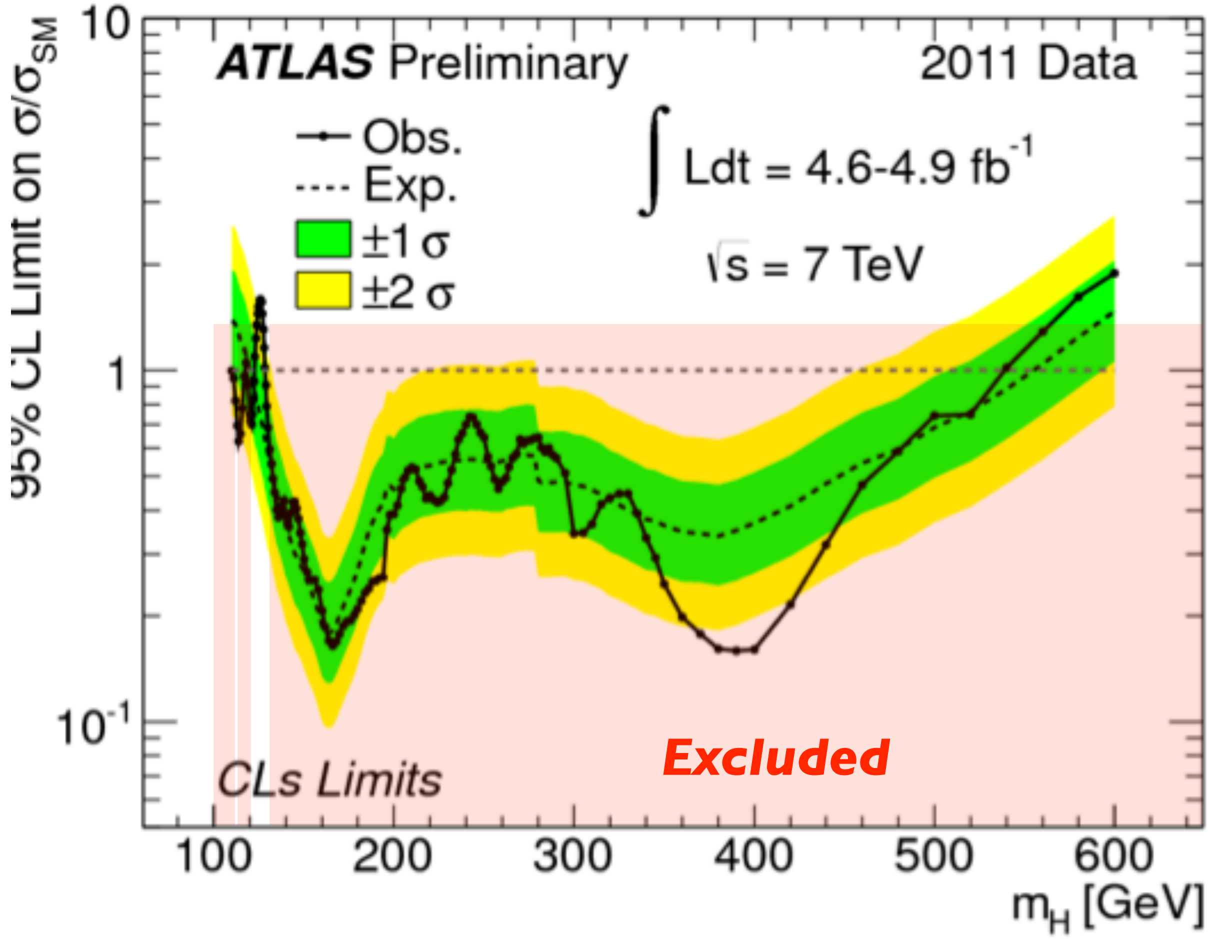
Combined

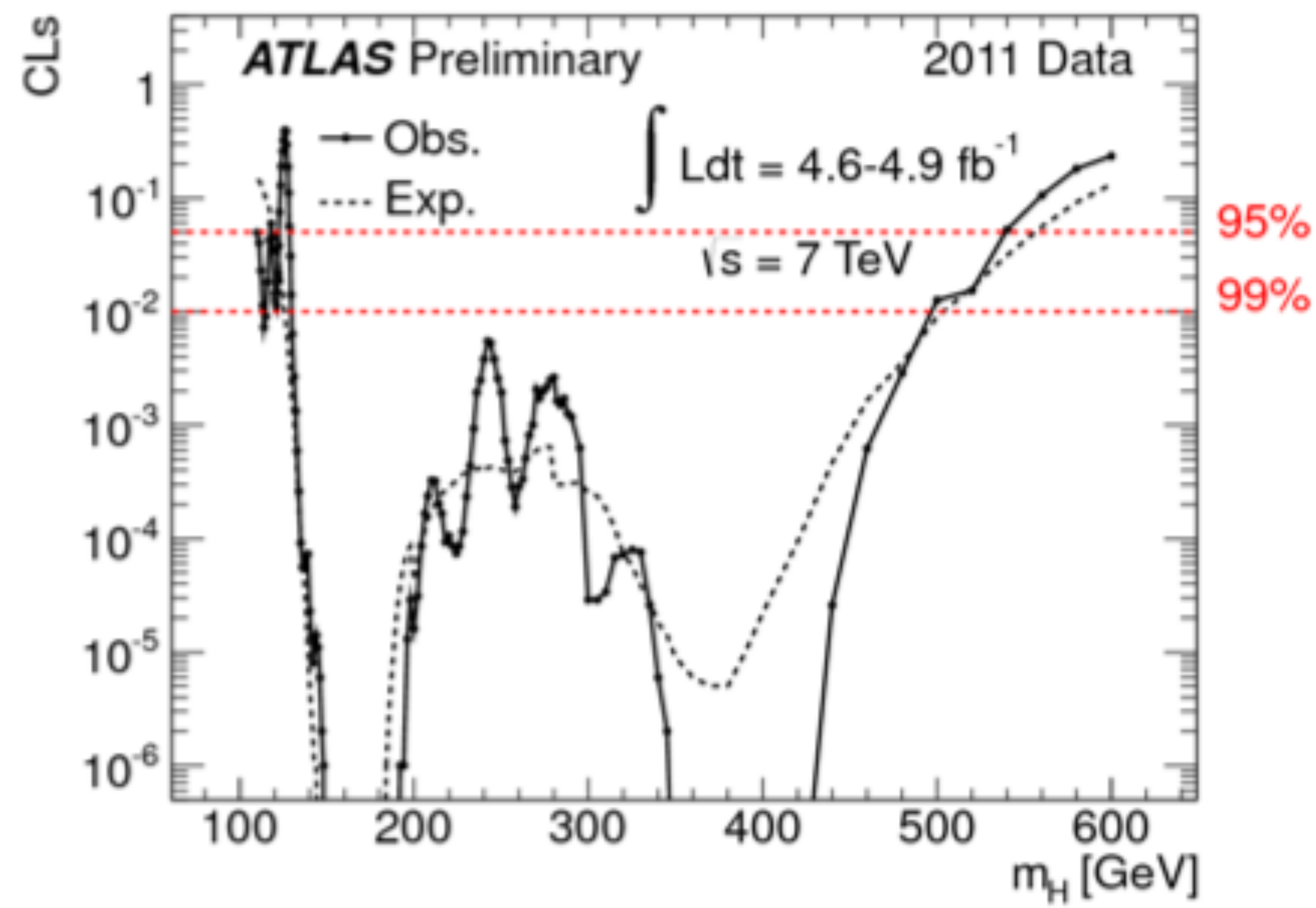
H⇒WW (*)⇒lνlν

H⇒ZZ(*)⇒llll

H→ZZ→llνν

Combined exclusion limit

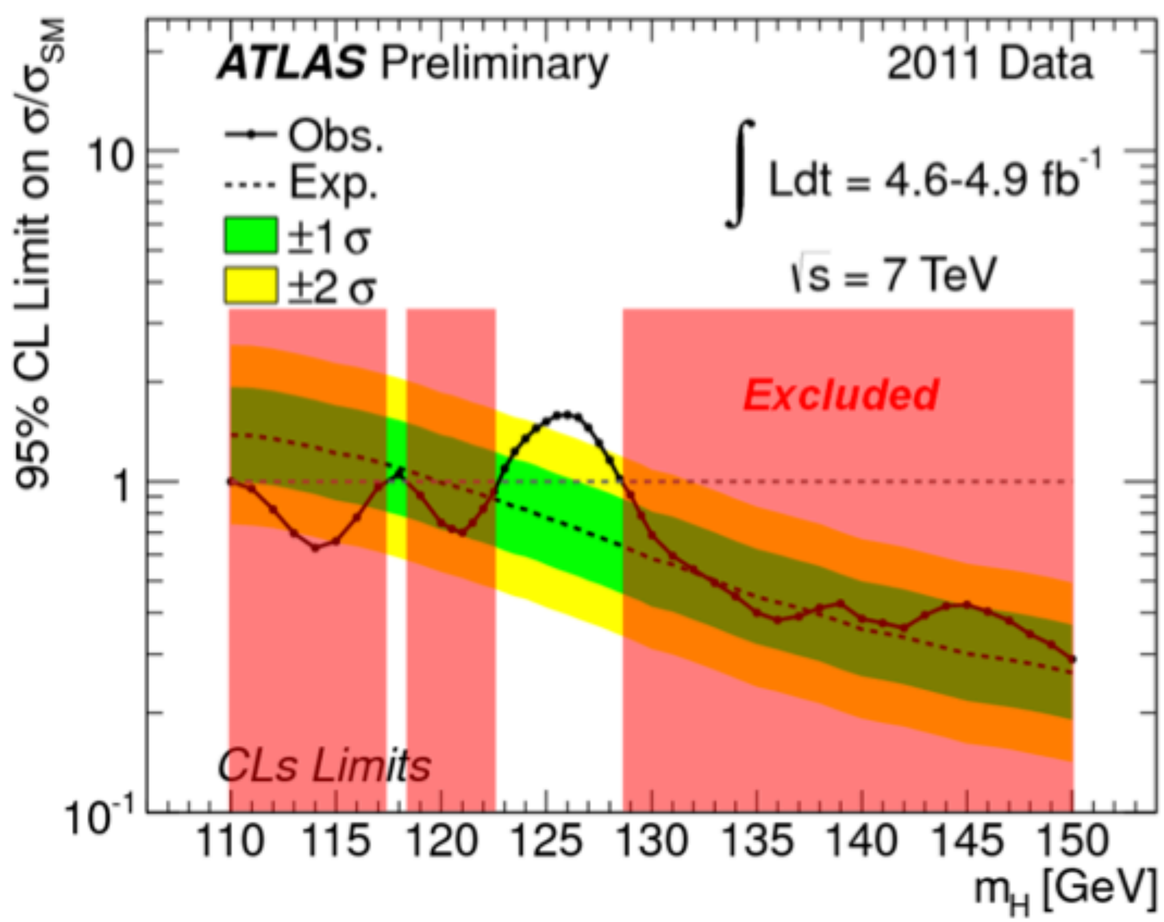


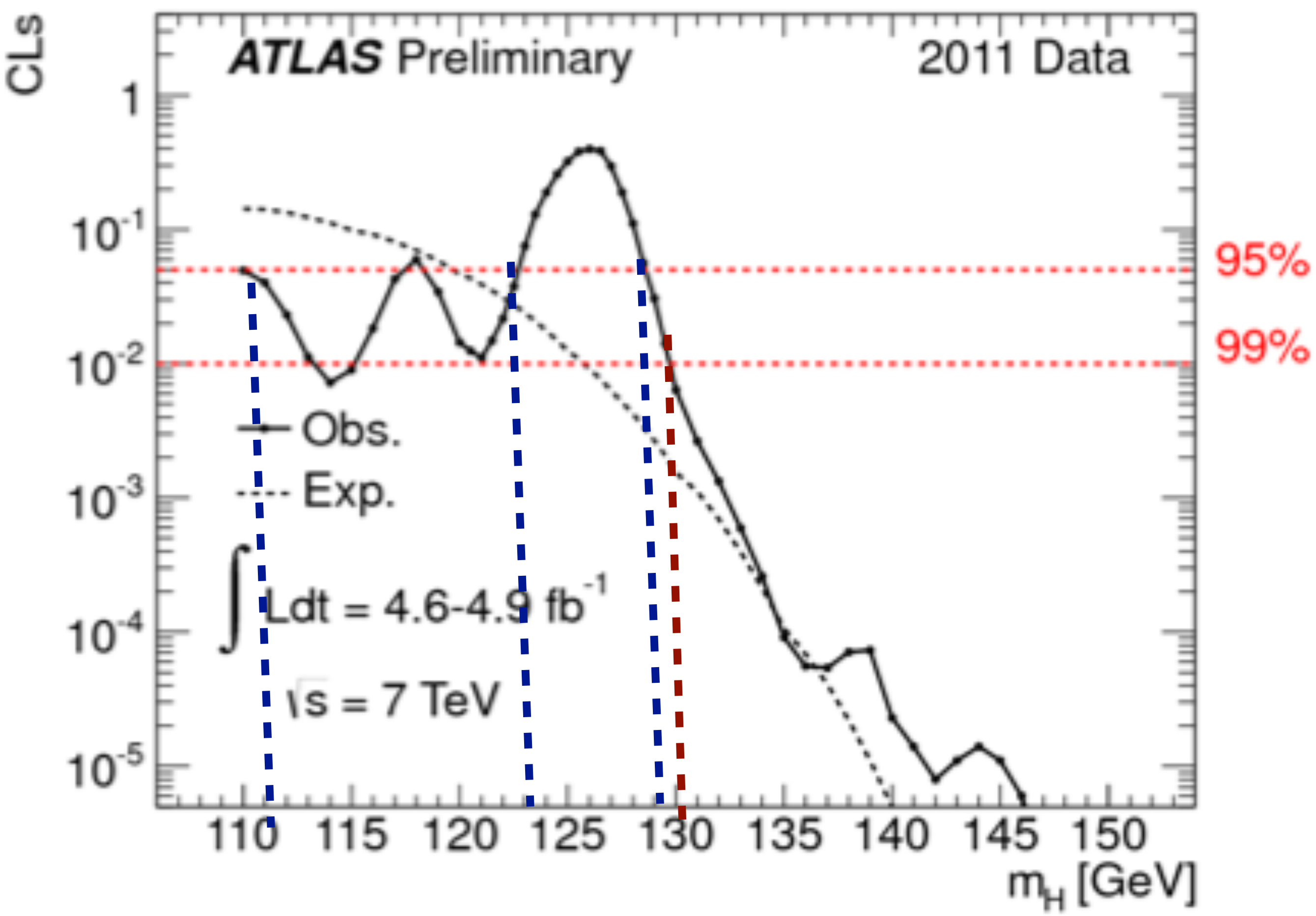


Expected exclusion limit at 95% CL:	$120 < m_H < 555$ GeV
Observed exclusion limit at 95% CL:	$110 < m_H < 117.5$ GeV
	$118.5 < m_H < 122.5$ GeV
	$129 < m_H < 539$ GeV
Observed exclusion limit at 99% CL:	$130 < m_H < 486$ GeV

Combined exclusion limit: low m_H region

Zoom in the low mass region





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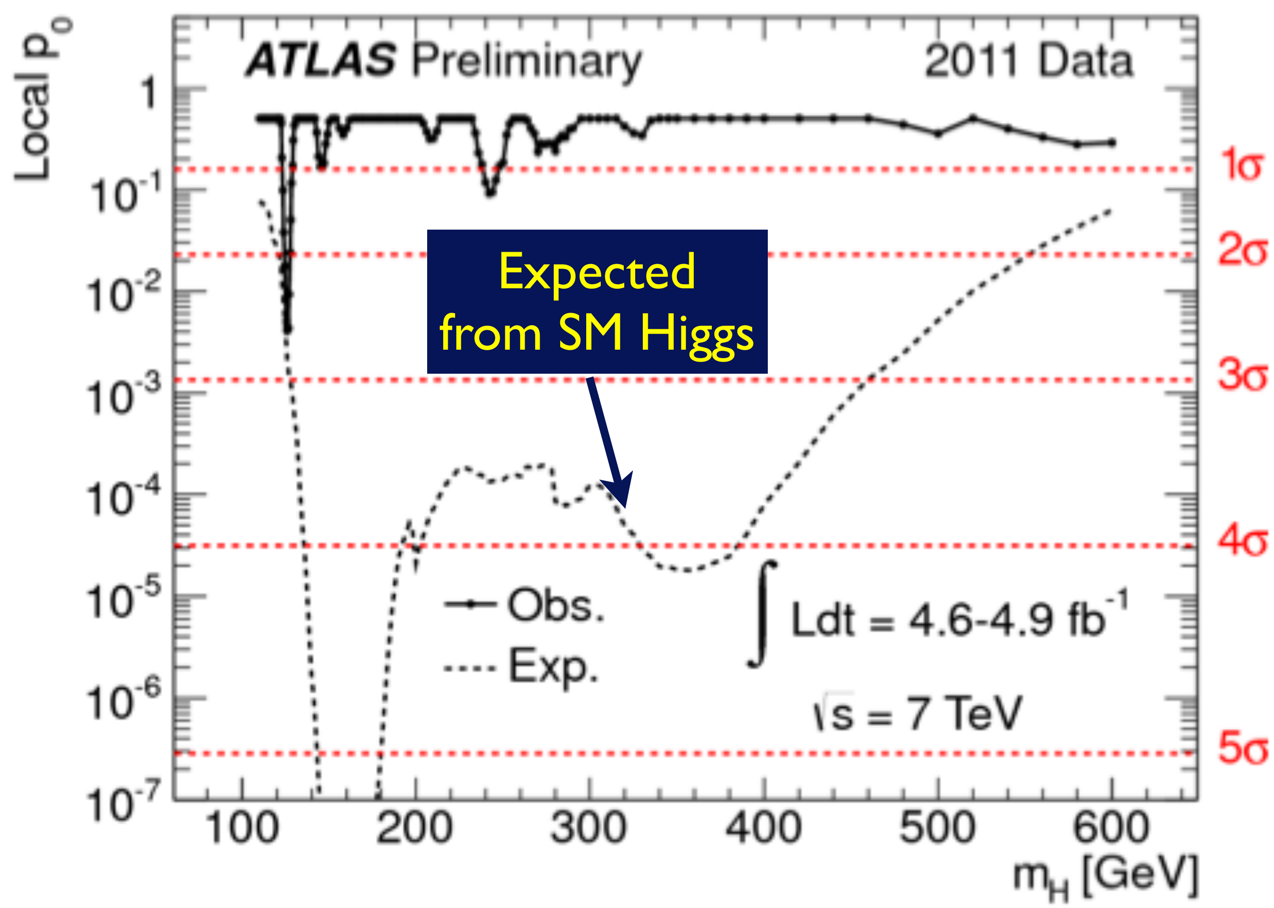
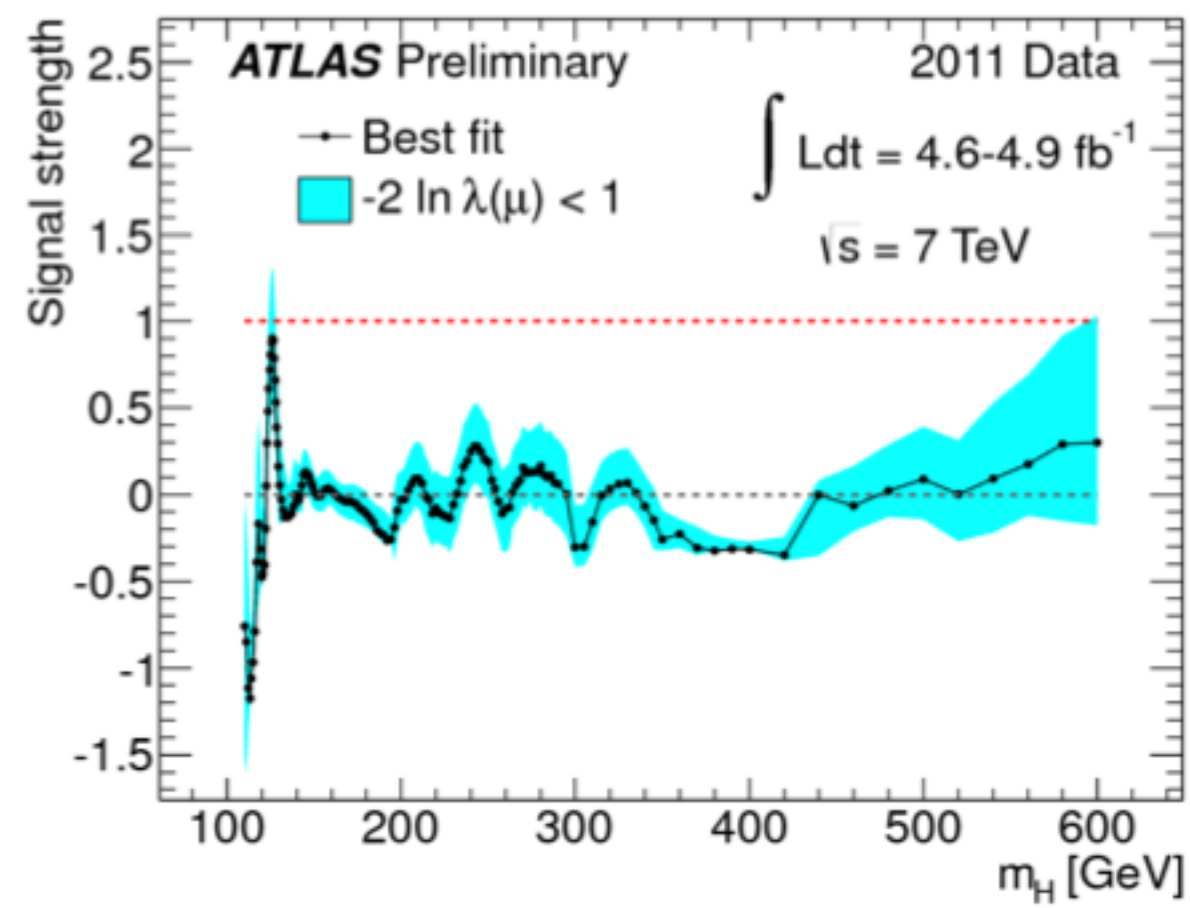
Combined p-value

Under the background-only hypothesis probability to observe such or a higher fluctuation than the observed one



Best fit signal strength $\mu=\sigma/\sigma_{SM}$



Combined p-value: low m_H region

Zoom in the low mass region

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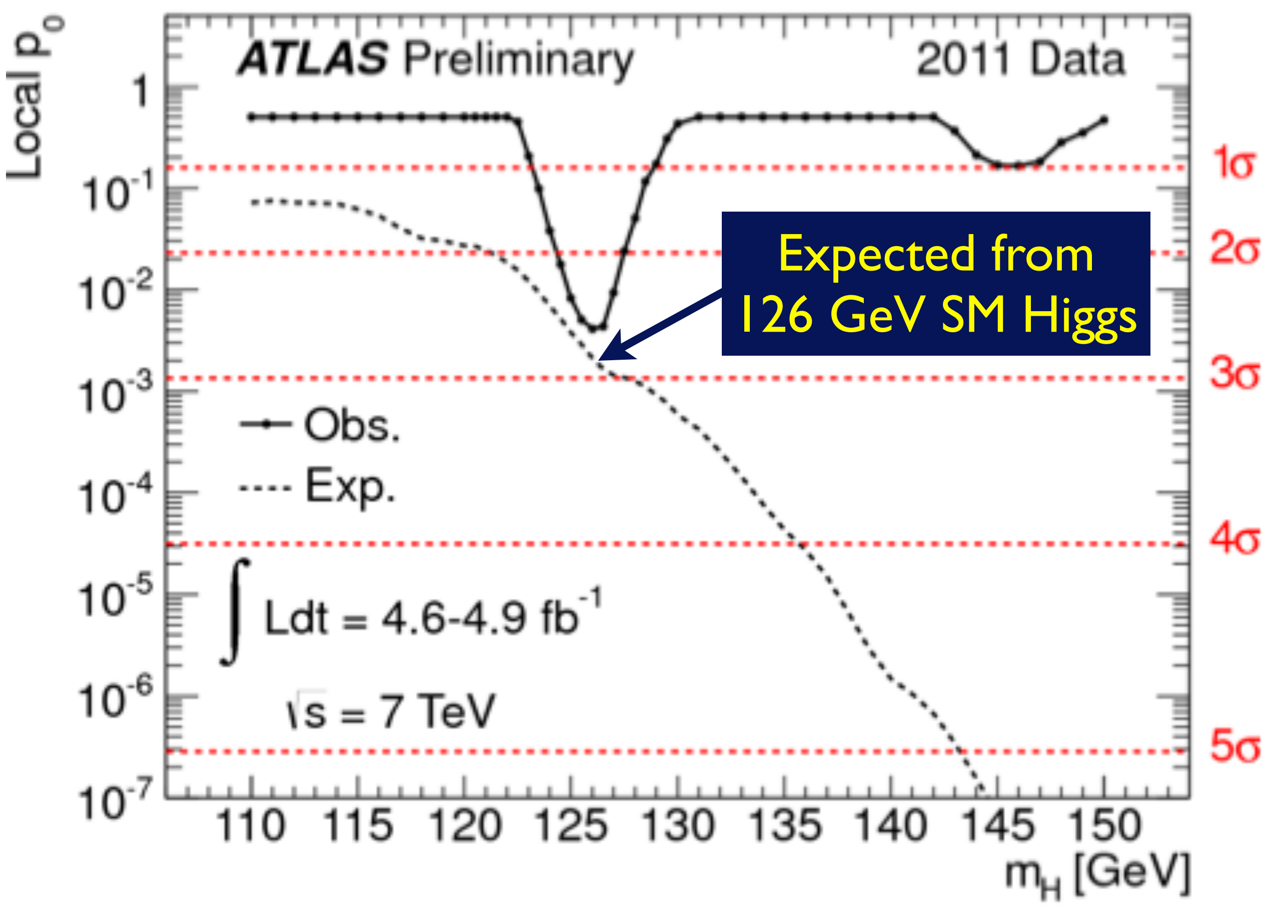

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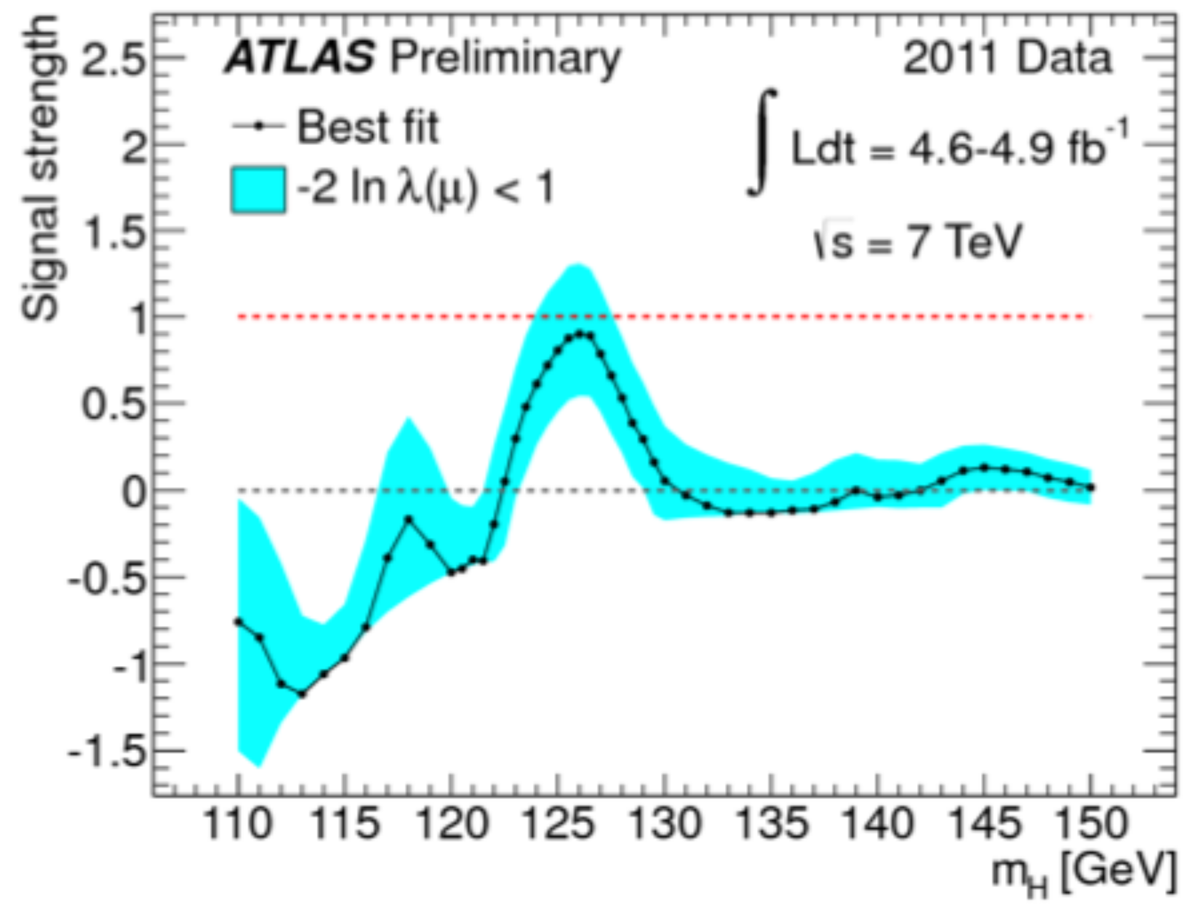
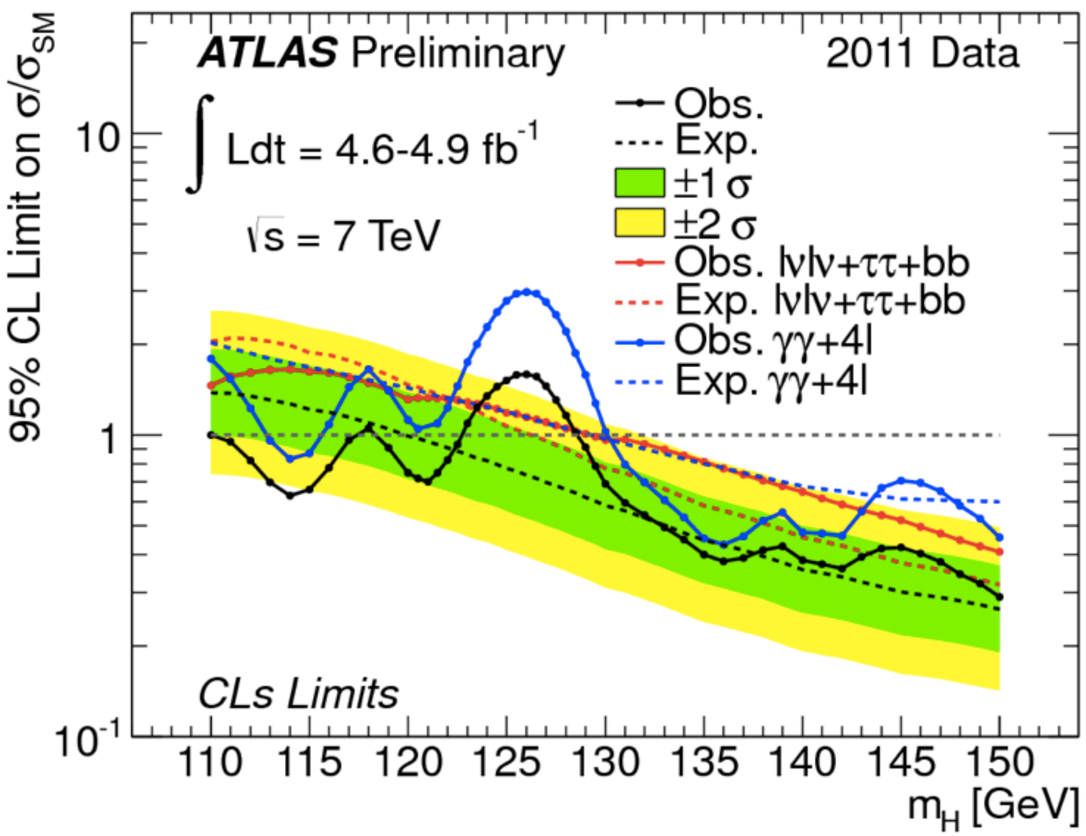


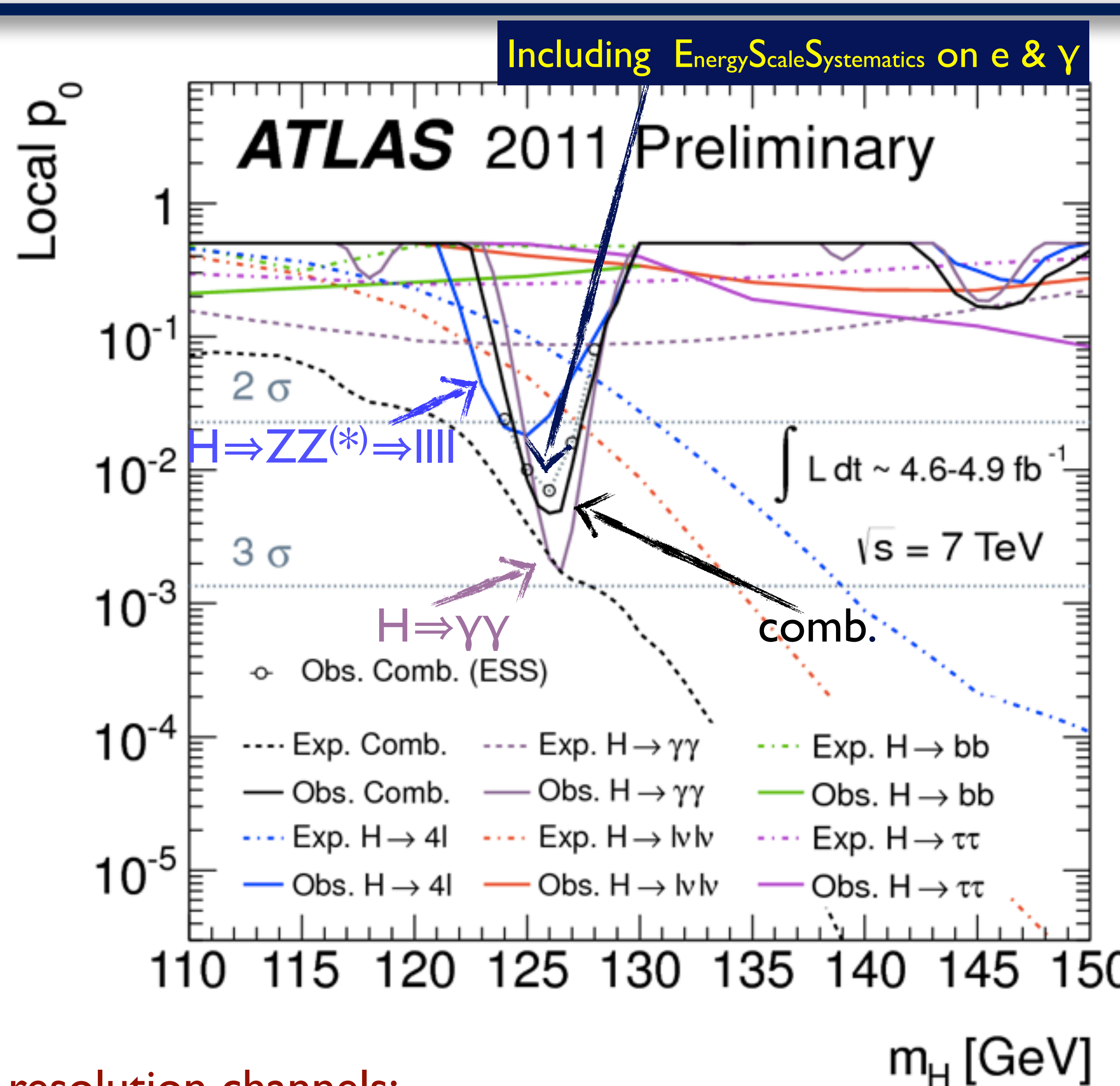
Observed local significance for m_H = 126 GeV is 2.5σ (expected 2.8σ)

Best-fit signal strength at m_H = 126 GeV is $\mu = 0.9^{+04}_{-0.3}$

Global probability to observe such a fluctuation over 110-600 GeV (110-146 GeV not excluded at 99% CL by LHC) is 30% (10%)

Anatomy of the observed excess

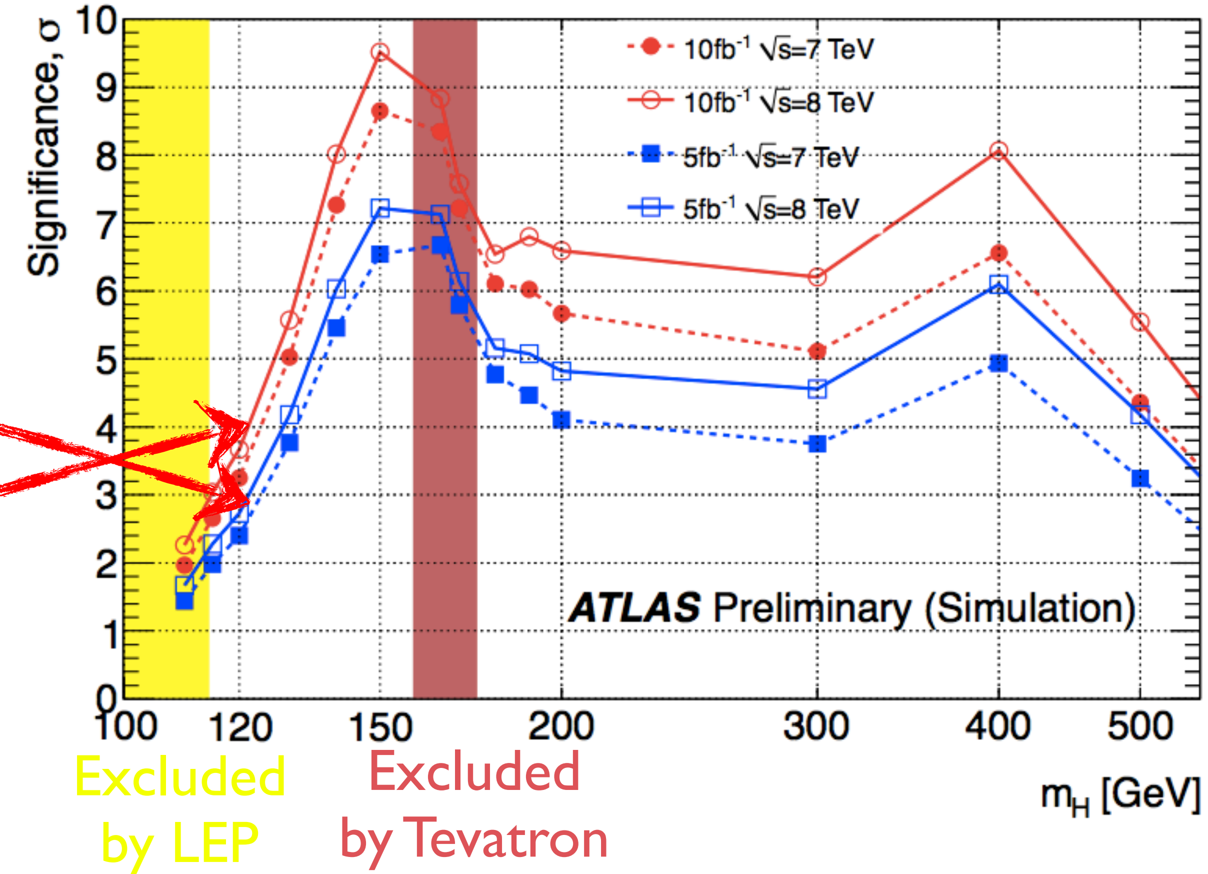


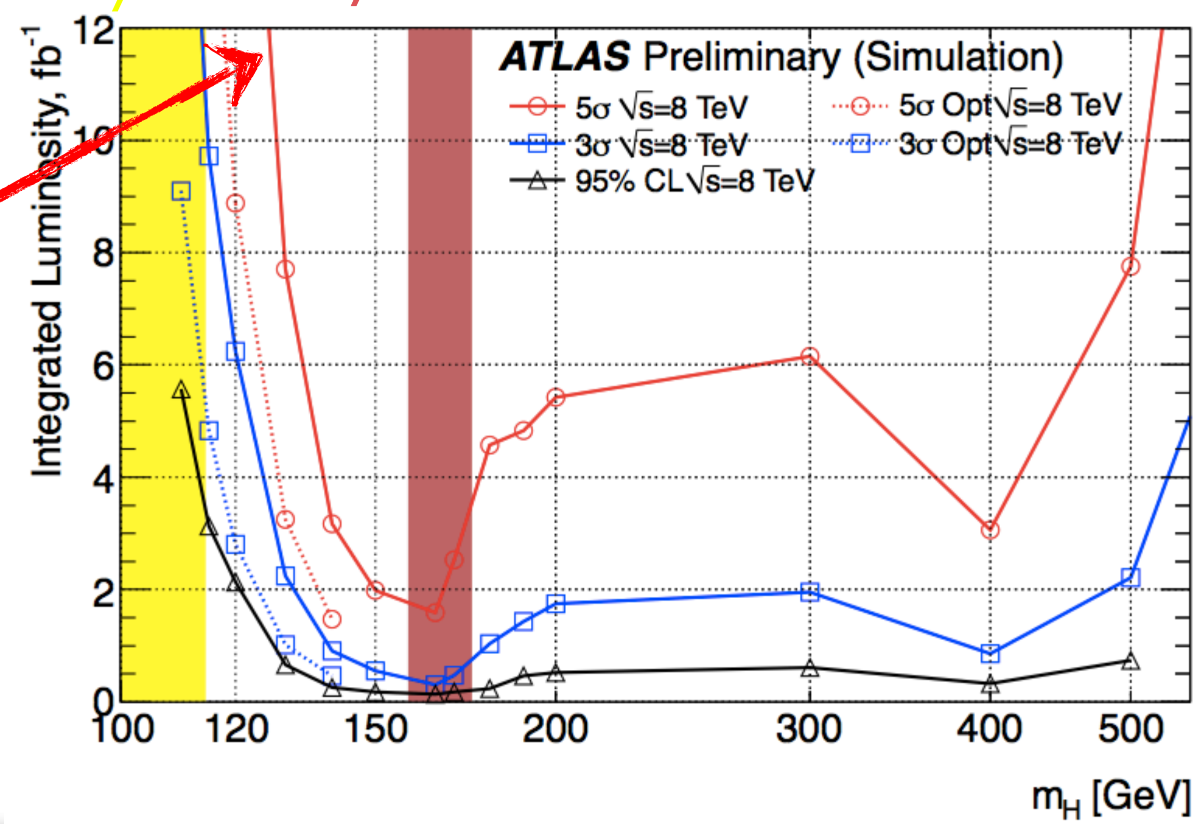


- An excess is observed in the two high resolution channels:
  - $H \to \gamma\gamma$ (2.8[1.4]σ)and $H \to ZZ^{(*)} \to 4l$(2.1[1.4]σ) combined ⇒ 3.4σ local significance
- No such an excess in $H \to WW^{(*)} \to l\nu l\nu$ (0.2σ[1.6σ]), $H \to \tau\tau$, $H \to bb$
  - All channels combined: observed 2.5[expected 2.9]σ local significance

2012 perspectives

- ATLAS expected sensitivity with 5 fb^{-1} @ 7 TeV is 3σ
- 2 times ATLAS (ATLAS+CMS with 5 fb^{-1} @ 7 TeV) is 4σ
- Gain in sensitivity from 7→8 TeV is 10% in significance (equivalent to 20% in luminosity)
- Need about 12 fb^{-1} @ 8 TeV for a 5σ discovery per experiment (after analysis optimization)





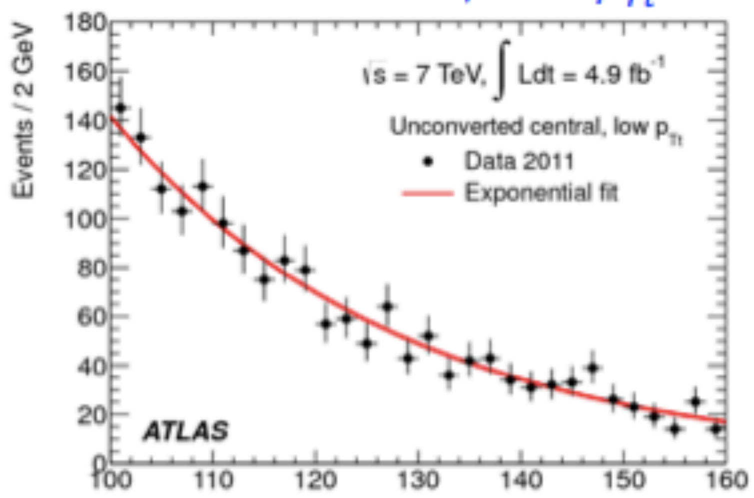
Conclusions

- ATLAS has performed great in 2011
- thanks to the excellent performance of LHC, ATLAS has collected $5.3fb^{-1}$ of data
- ATLAS has confined the possible presence of a SM Higgs boson to small regions: $117.5<m_H<118.5$ GeV or $122.5<m_H<129$ GeV at 95% CL
- An excess is seen around 126 GeV with a (local) significance of 2.5σ, however both signal and background only hypothesis are still alive
- More data are needed for a conclusive statement

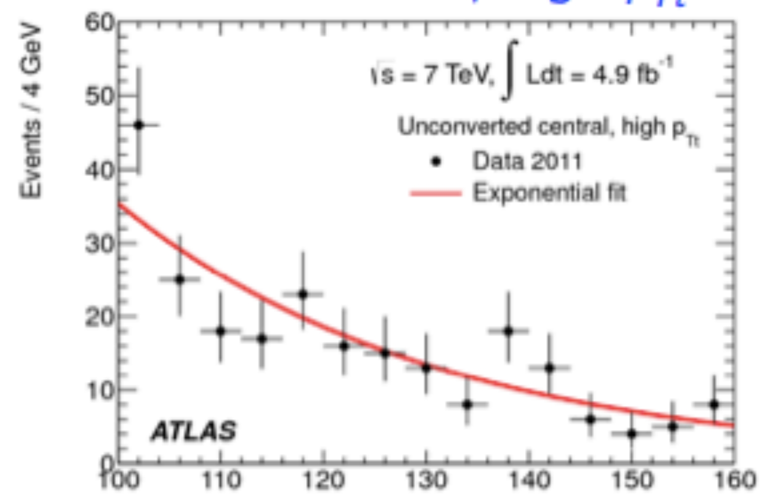
Additional material

$H \Rightarrow \gamma\gamma$: $m_{\gamma\gamma}$ in the 9 categories

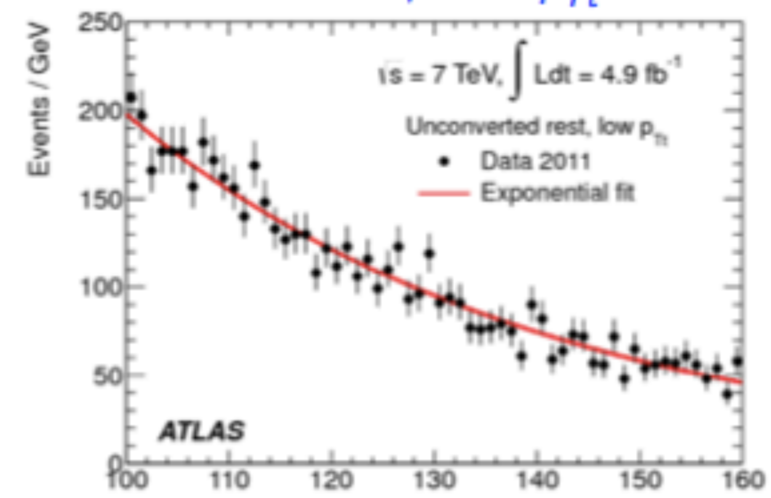
unconverted central, low p_{Tt}



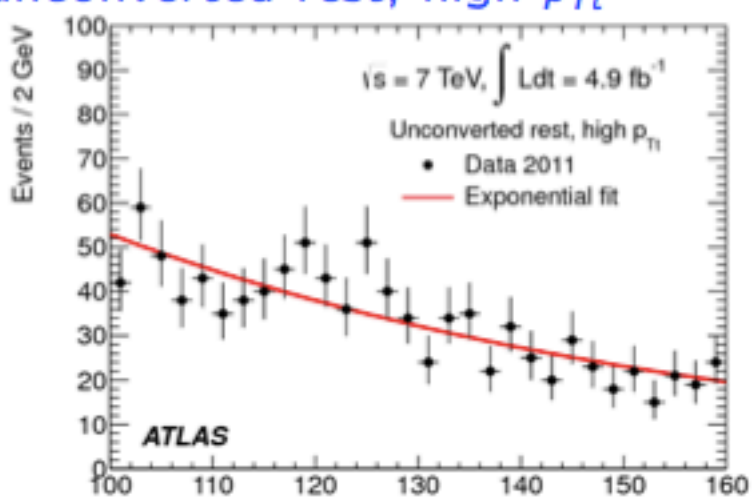
unconverted central, high p_{Tt}



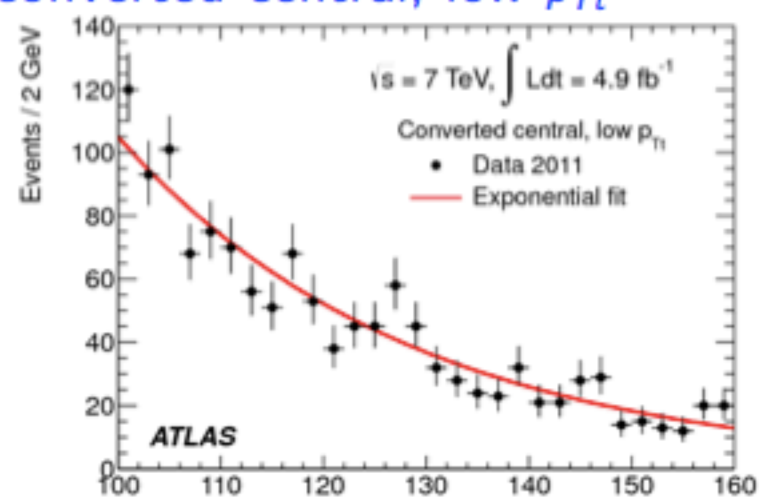
unconverted rest, low p_{Tt}



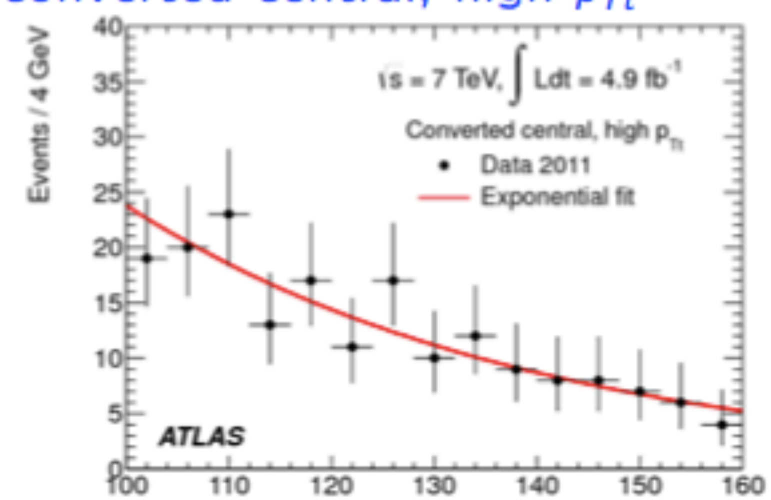
unconverted rest, high p_{Tt}



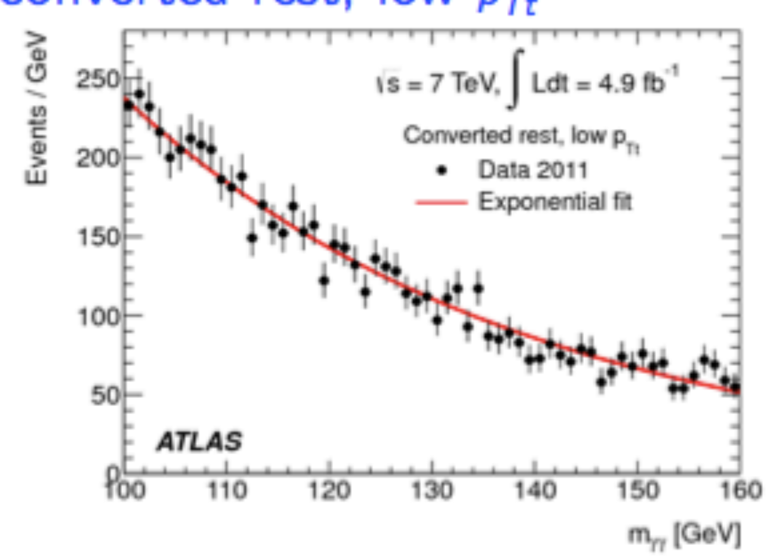
converted central, low p_{Tt}



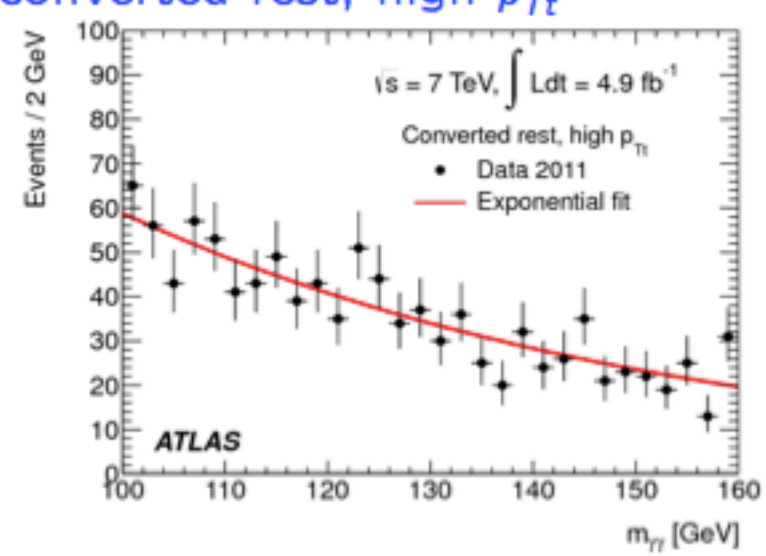
converted central, high p_{Tt}



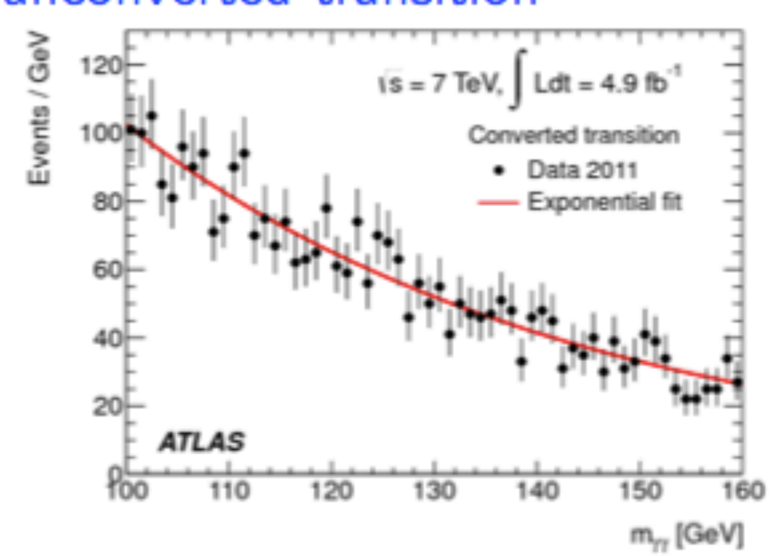
converted rest, low p_{Tt}



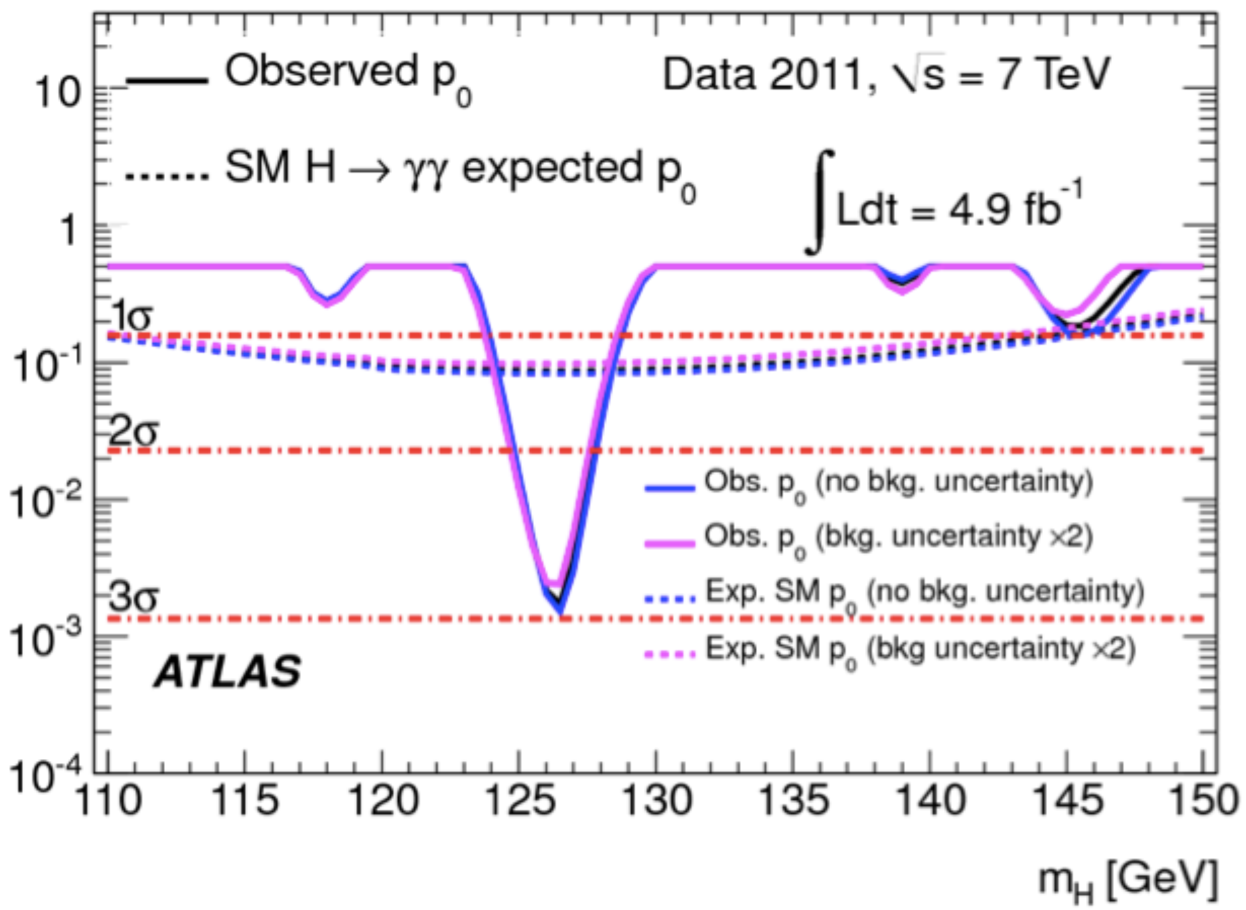
converted rest, high p_{Tt}

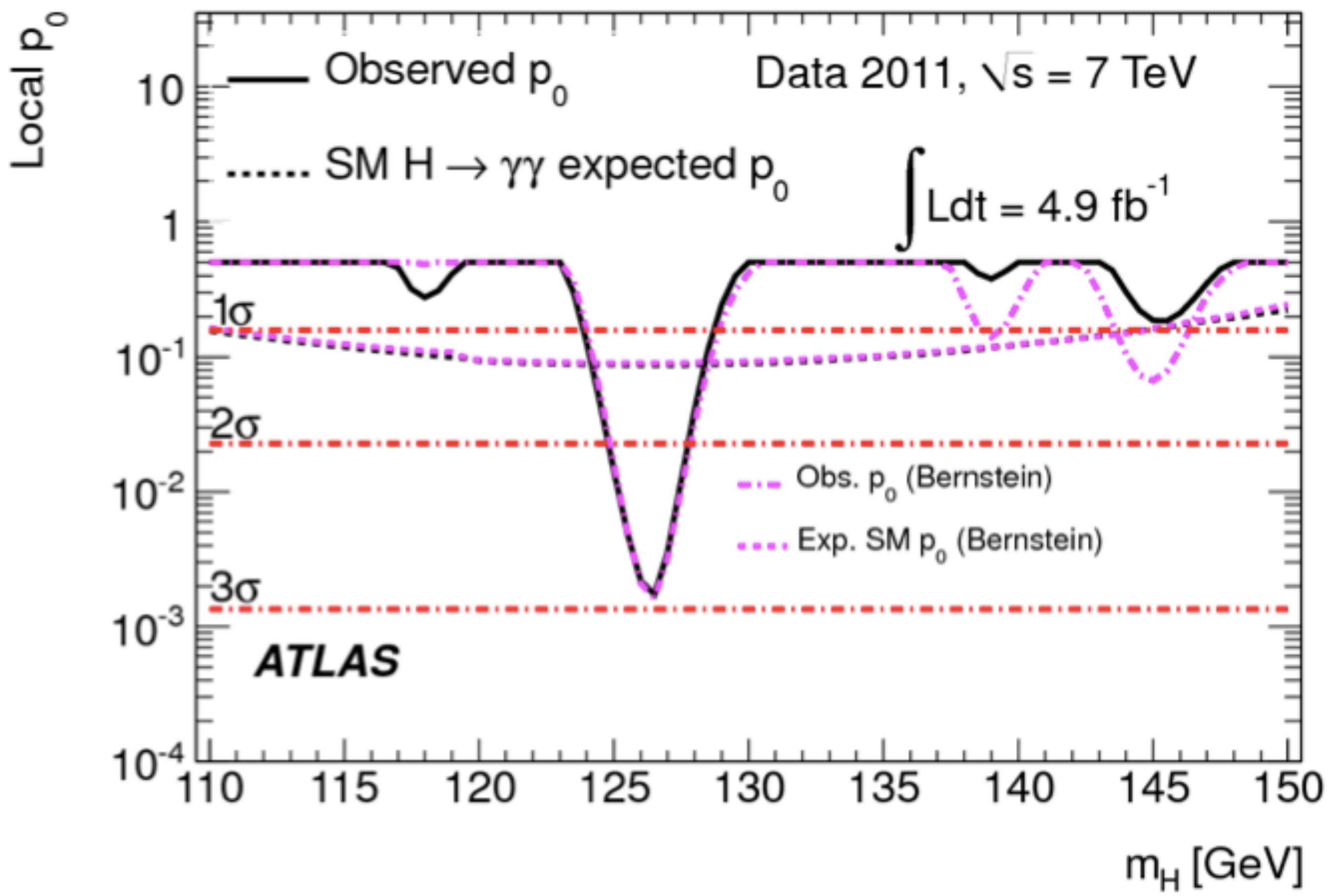


unconverted transition

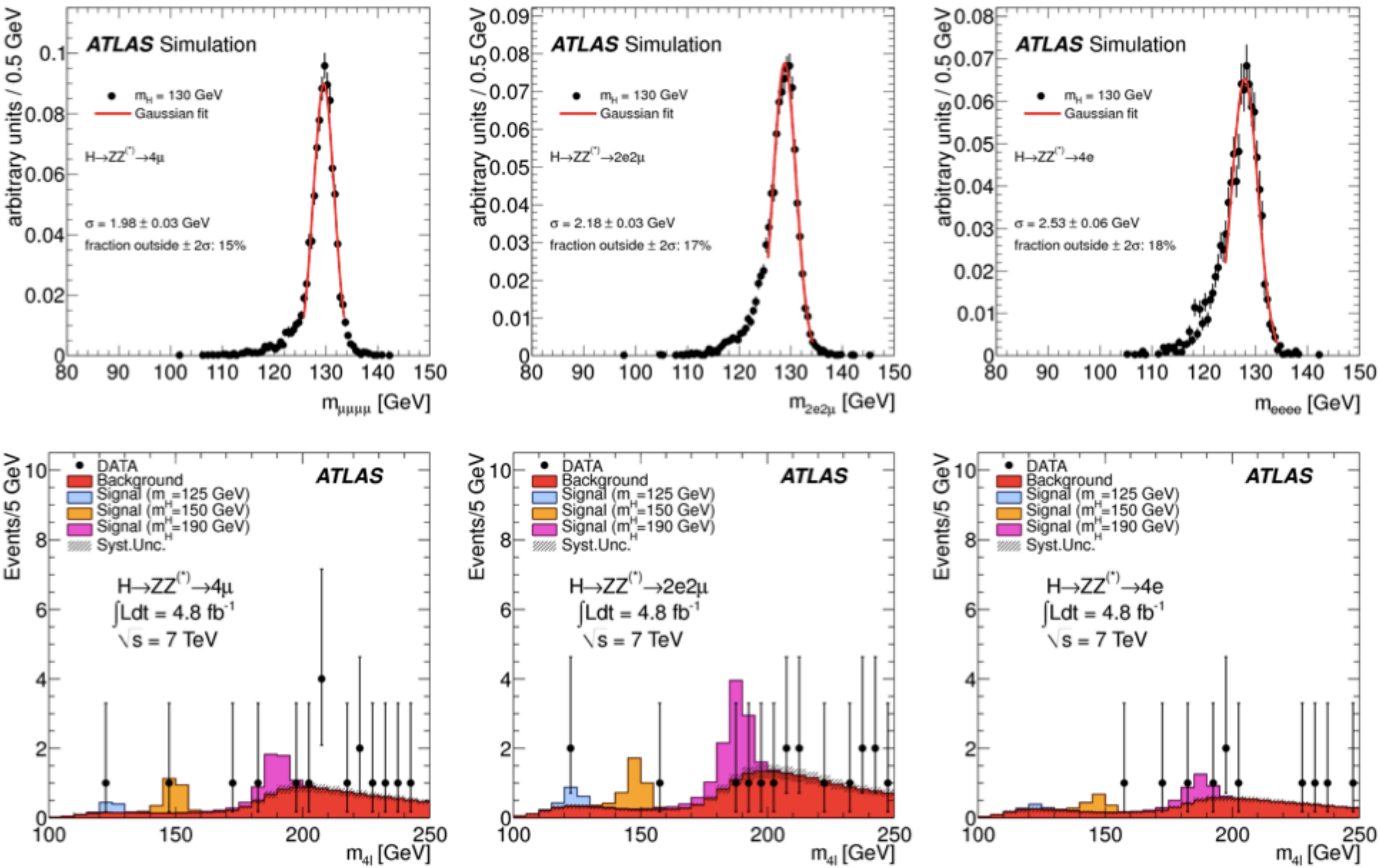


$H \Rightarrow \gamma\gamma$: background modeling

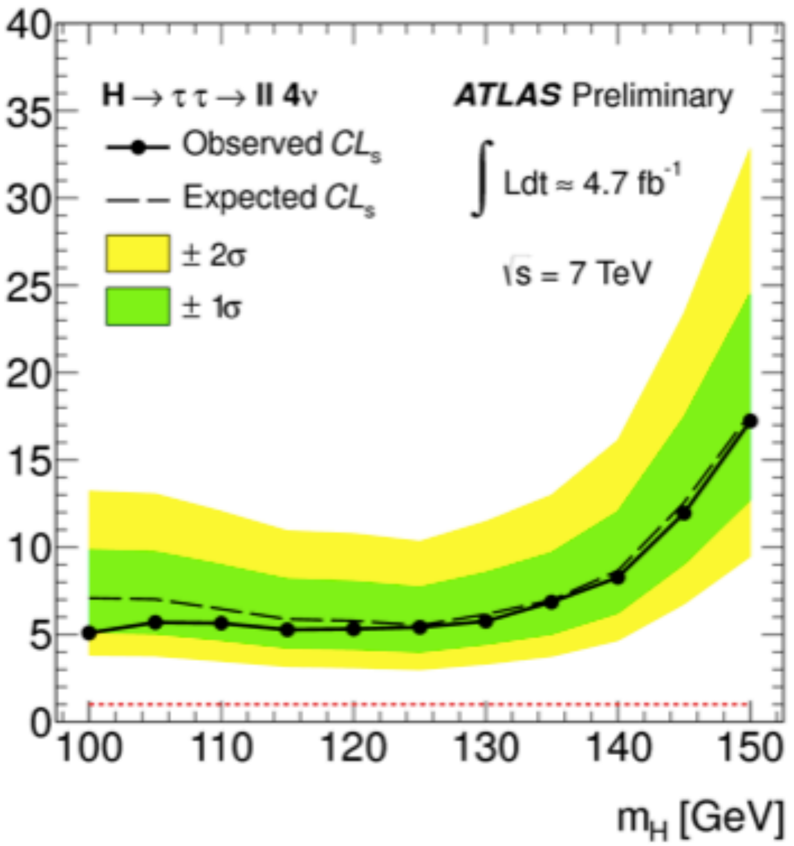


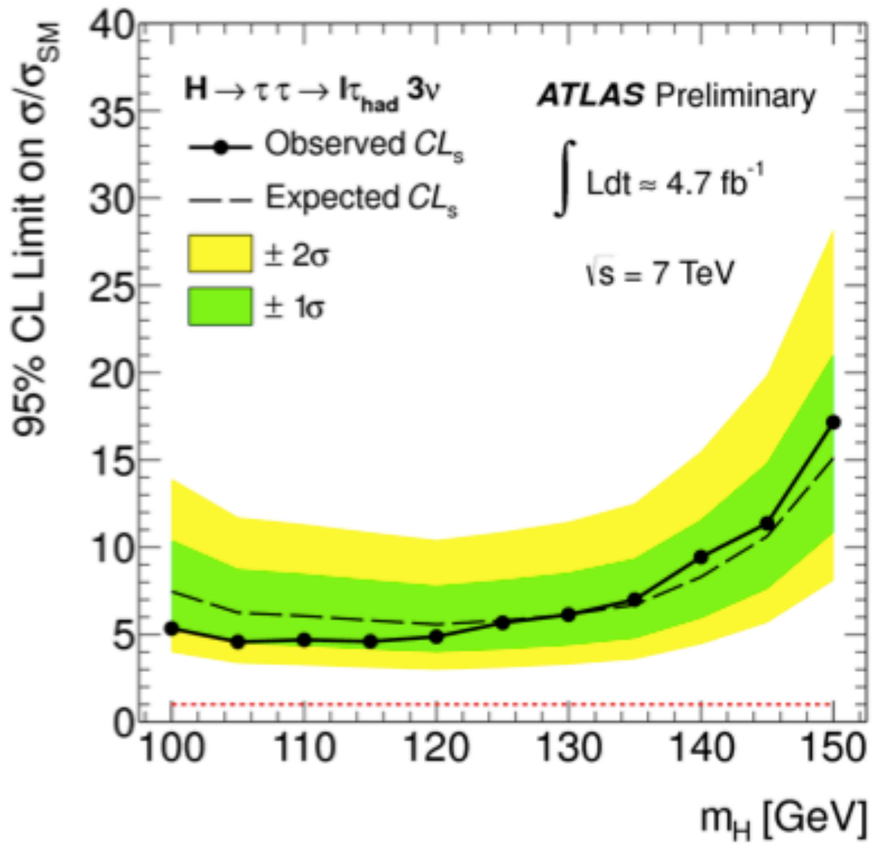


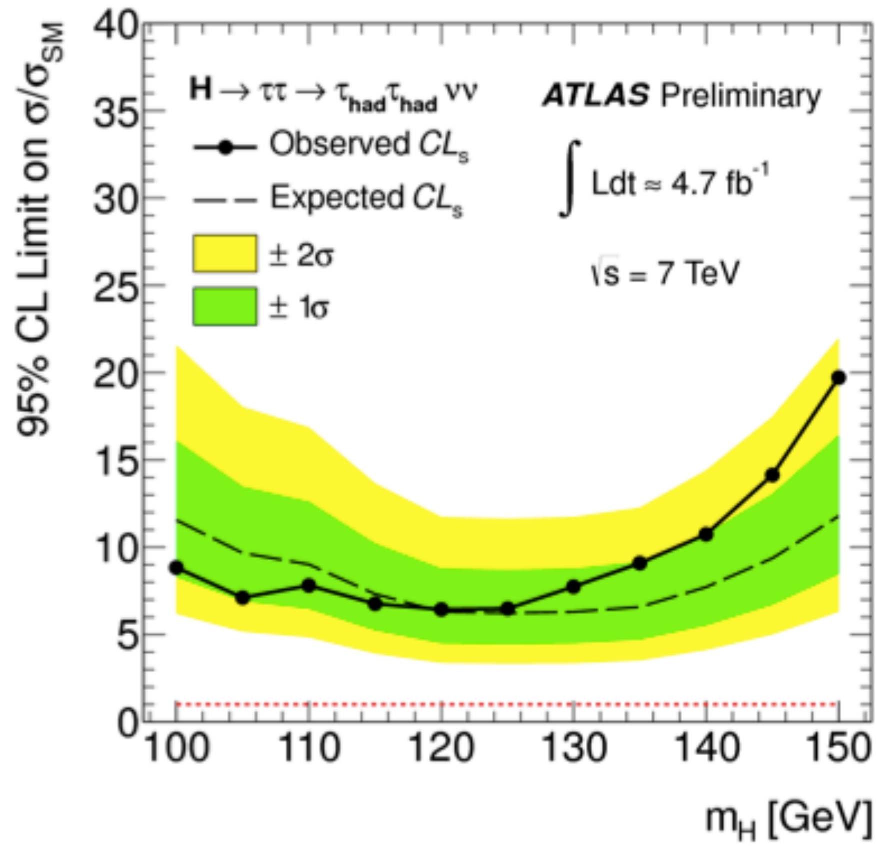
H⇒ZZ(*)⇒4l: mass distributions



$H \Rightarrow \tau\tau$



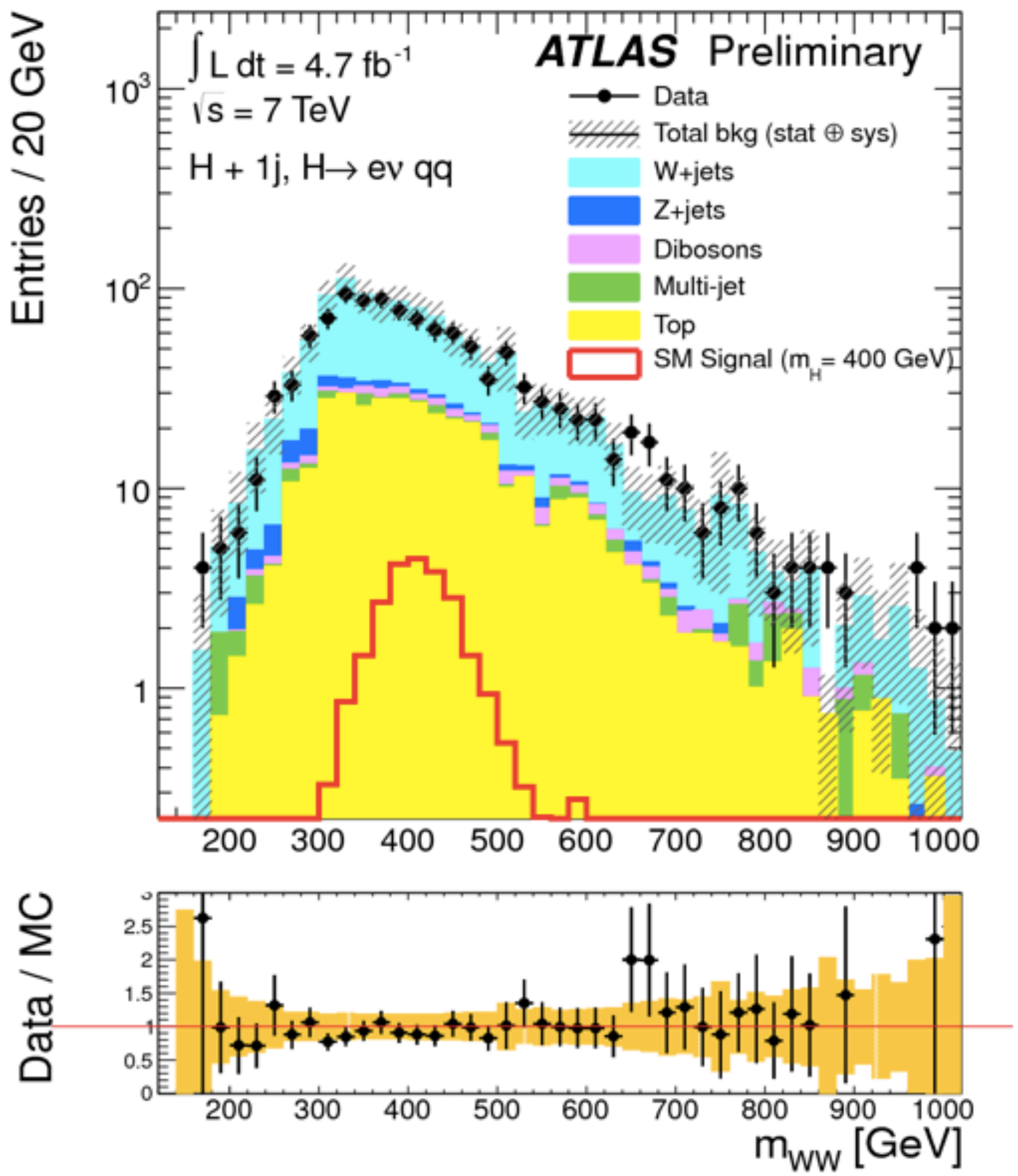




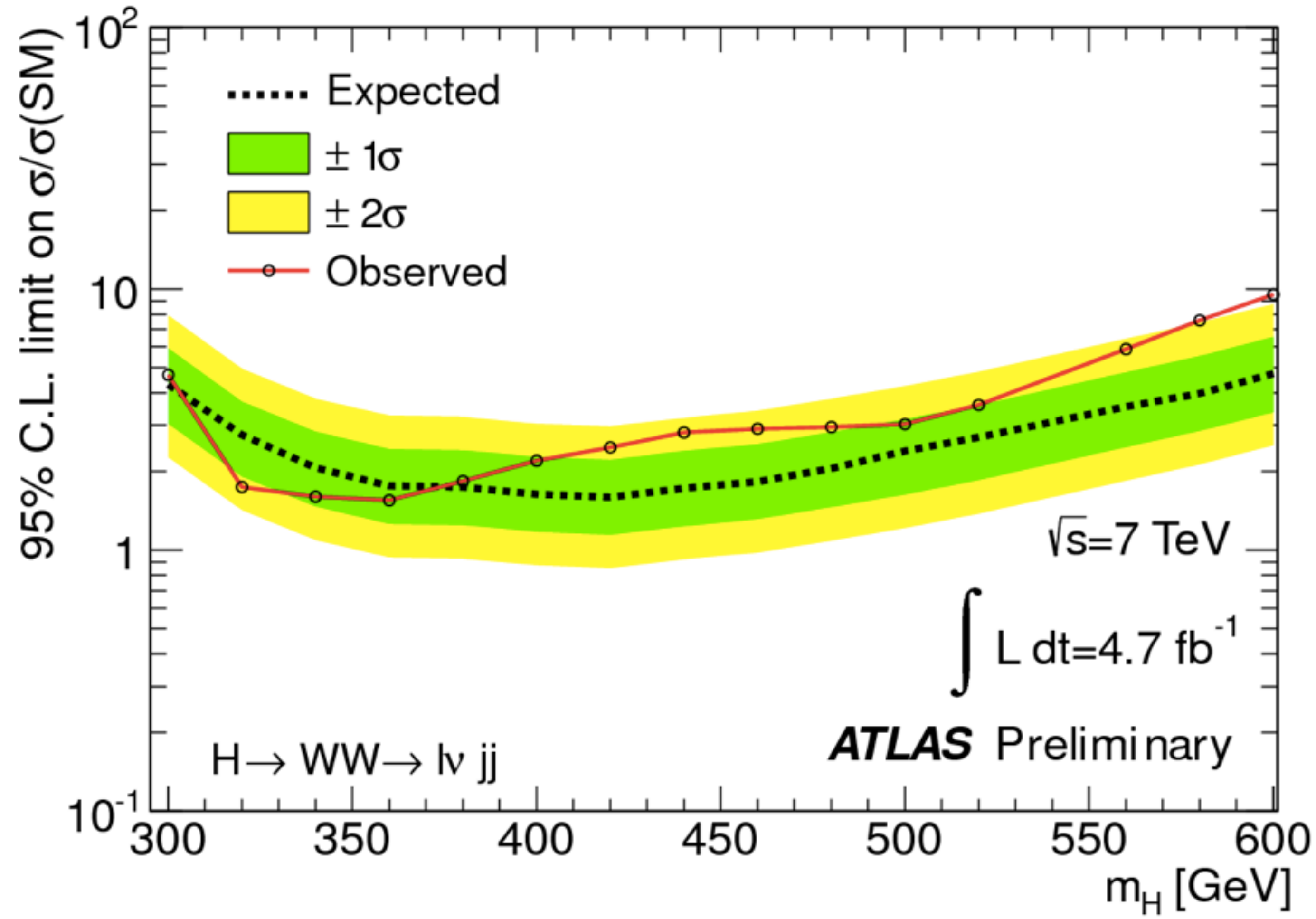
H⇒WW⇒lνjj

6 categories (e, μ)⊗(0-,1-, 2-jet VBF)

Limit extraction based on invariant mass $m_{l\nu jj}$ shape ($m_{l\nu} = m_W$)



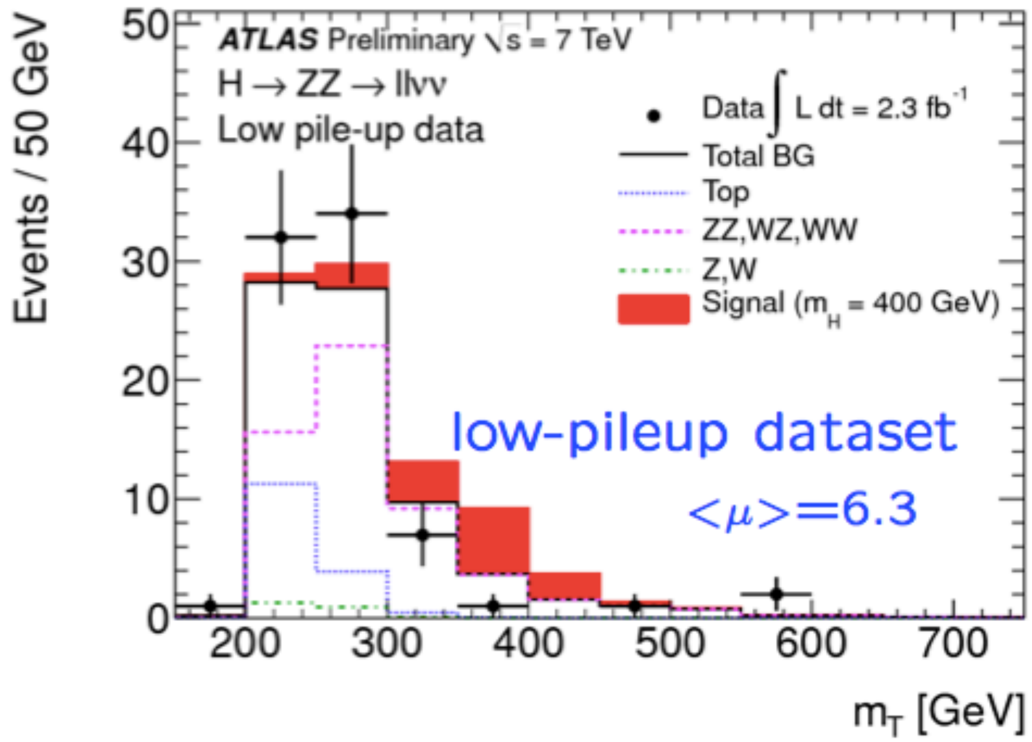
- Background modeled from fit to lνjj mass spectrum
- Main systematics
  - jet energy scale and resolution (10-20%)
  - pileup (10-15%)

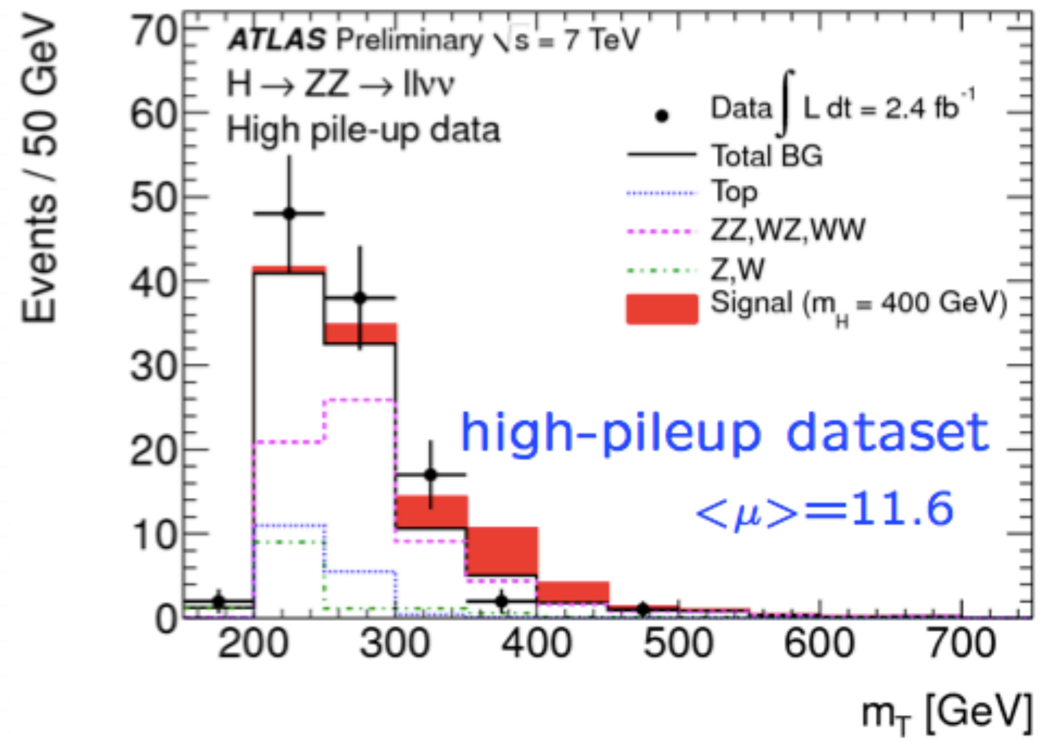


H⇒ZZ⇒llνν

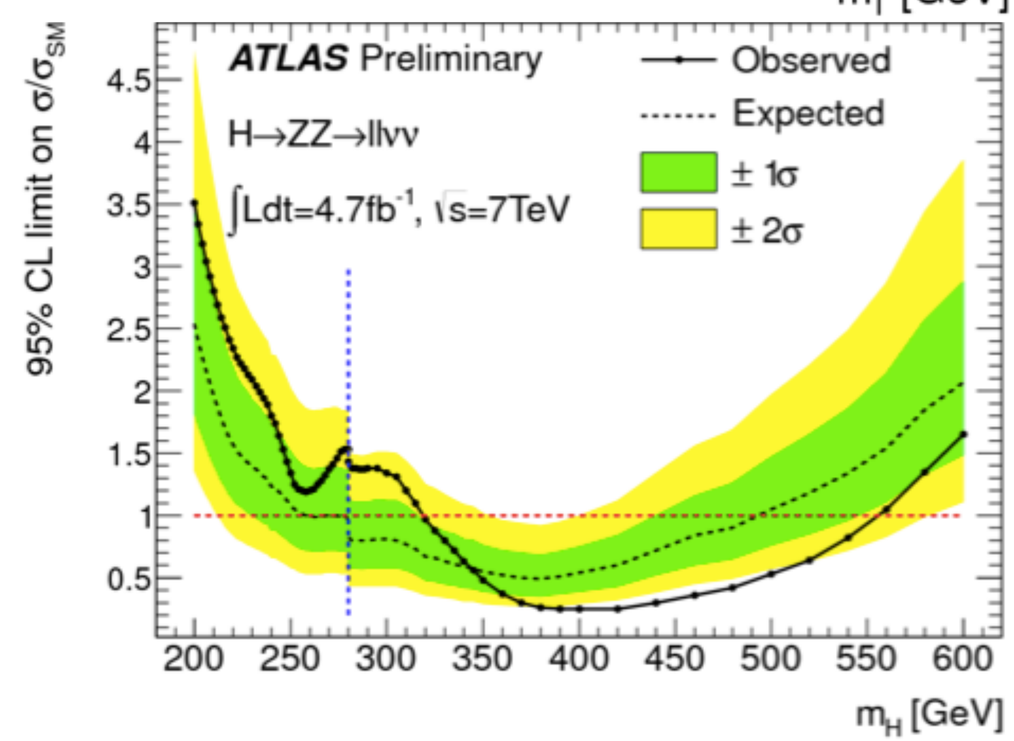
Most sensitive channel in high Higgs mass range, 4 categories (ee, μμ)⊗(low, high-pileup)

Limit extraction based on transverse mass m_T shape ⇒ dependent on pile-up due to E_T^{Miss}





- Different selection for M_H<280 GeV &M_H>280 GeV
  - cuts on: E_T^{miss}, m_{ll}, $\Delta\Phi_{ll}$ and $\Delta\Phi(\mathbf{p}_T^{miss},\mathbf{p}_T^{ll})$ (boost), $\Delta\Phi(\mathbf{p}_T^{miss},\mathbf{p}_T^{jet})$ background rejection
- Background
  - ZZ ➠ simulation (11% norm. uncertainty)
  - WZ ➠ 3-lepton events
  - top ➠ eμ events & m_{ll} sidebands
  - W/Z+jet ➠ ee, eμ same-sign & low $\Delta\Phi(\mathbf{p}_T^{miss},\mathbf{p}_T^{jet})$

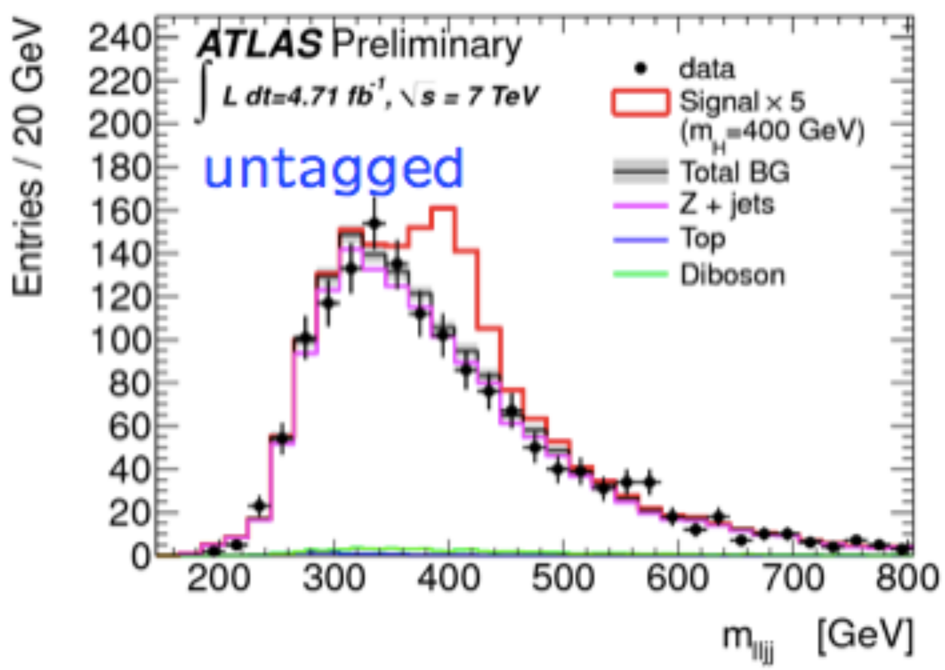


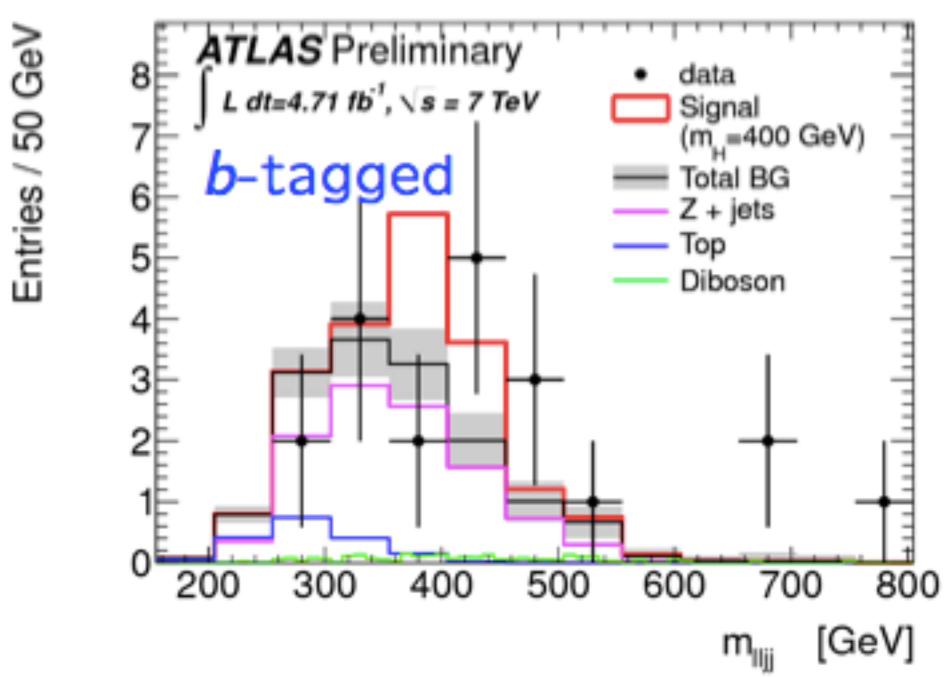
Exclusion Limit: 260-460 GeV (Expected)
320-560 GeV(Observed)

H⇒ZZ⇒lljj

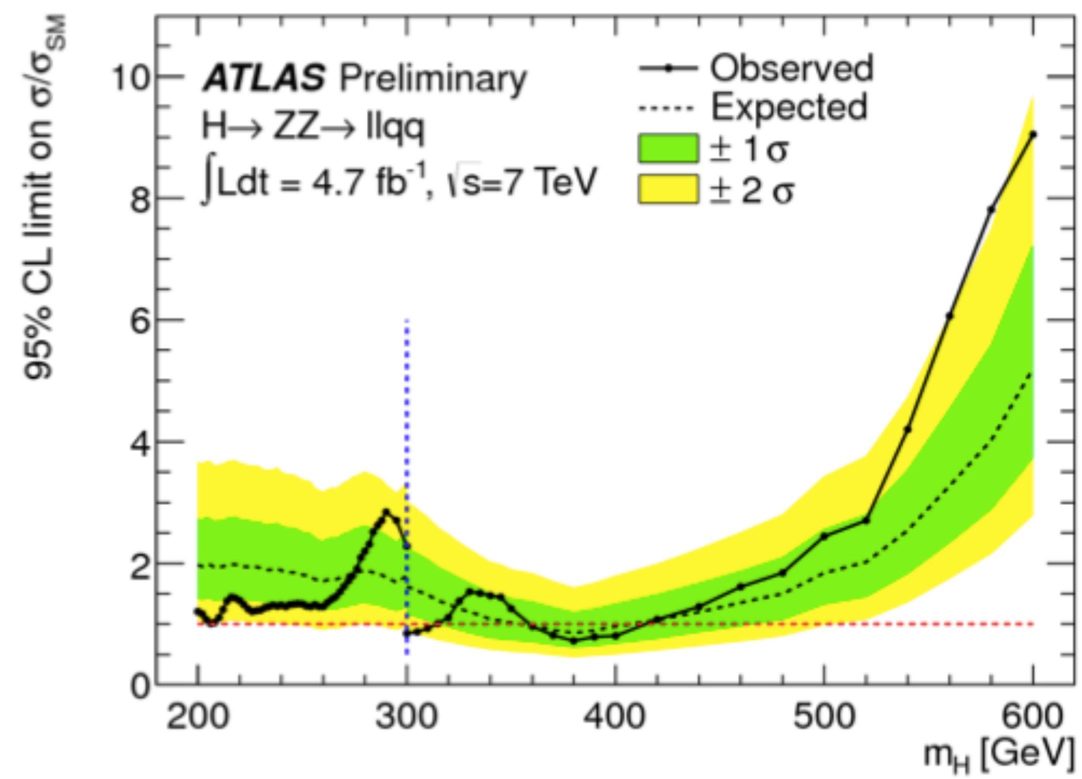
2 categories (>2 b-tag, 2 b-tag)

Limit extraction based on transverse mass m_{lljj}



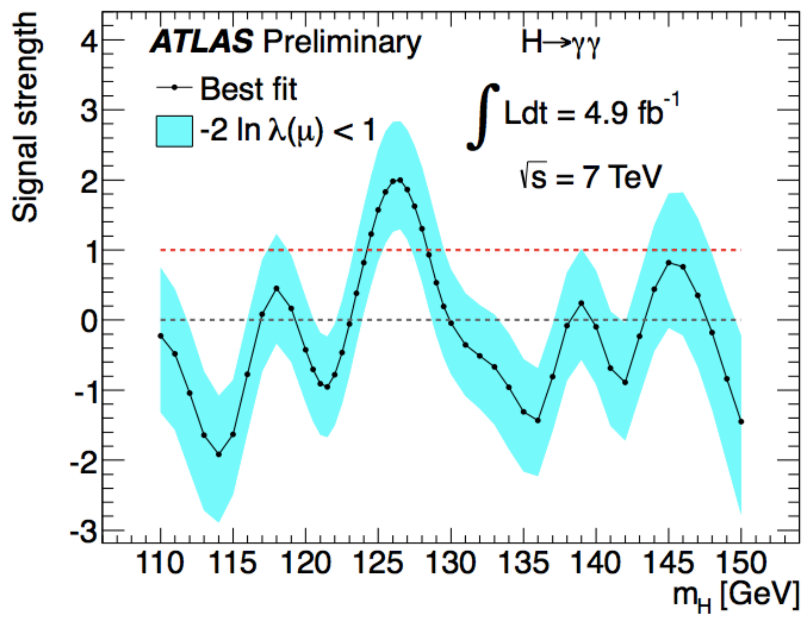


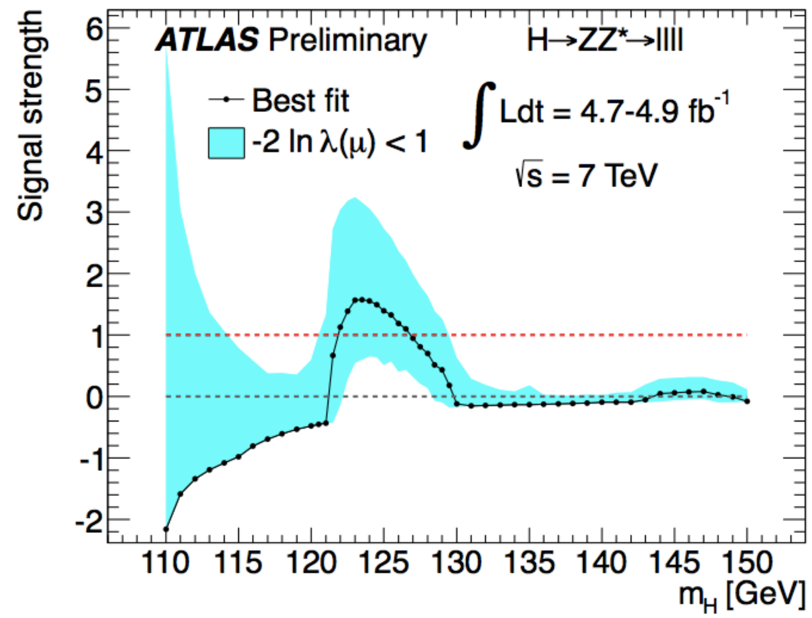
- Different selection for M_H<300 GeV & M_H>300 GeV
  - cuts on: E_T^{miss}, m_{ll}, m_{jj}, ΔR_{jj} and $\Delta\Phi_{ll}$, $\Delta\Phi_{jj}<\pi/2$ (boost),
- Background
  - Z+jet ➠ mll sidebands
  - diboson ➠ simulation (11% norm. uncertainty)
  - top ➠ m_{ll} sidebands
  - multi-jet ➠ revert lepton ID (50% uncertainty)

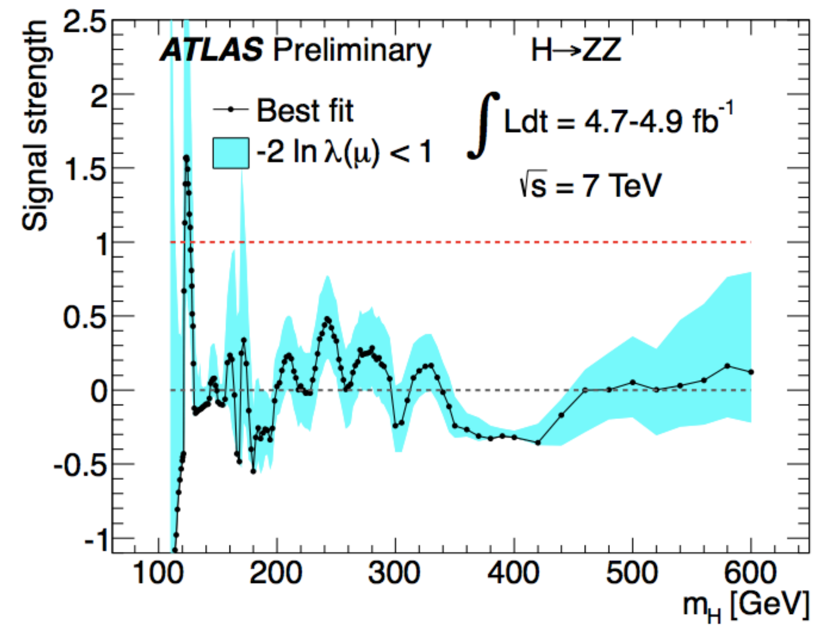


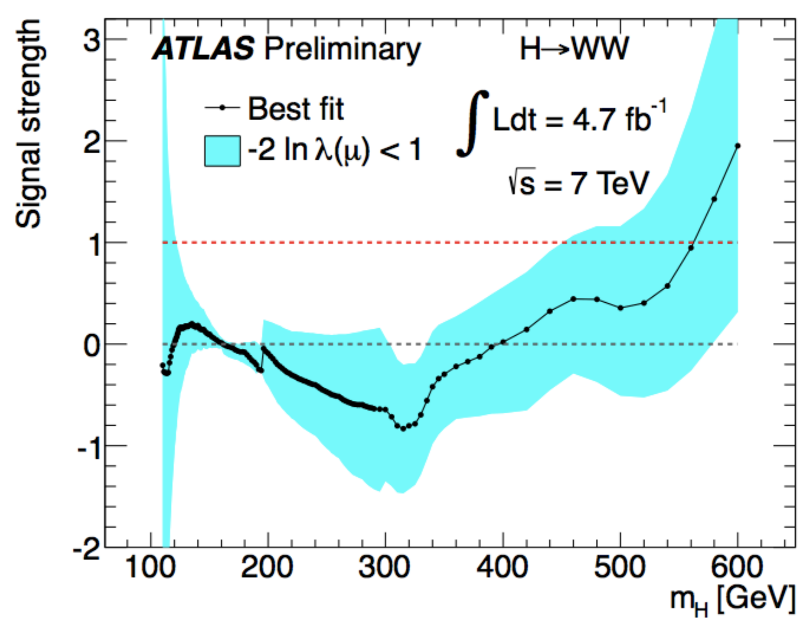
Exclusion: 360-400 GeV (Expected)
300-310; 360-400 GeV (Observed)

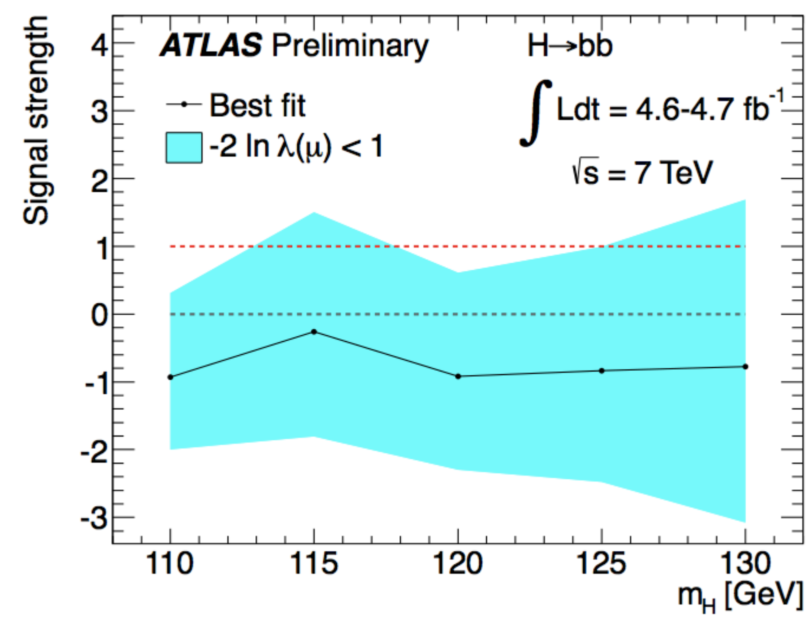
Signal strength in individual channels

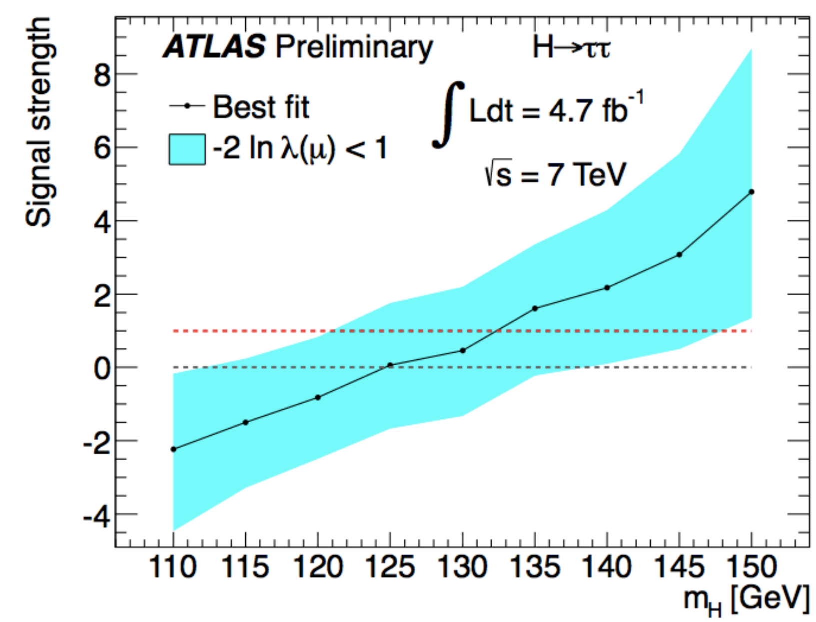












Detector related systematic uncertainties

Physics object	Source	Uncertainty on signal yield	Most affected channels
	luminosity	3.9%	
Photon	efficiency	11%	$\gamma\gamma$
Electron	efficiency	<3%	4ℓ
	energy scale	<1%	
	energy resolution	<0.5%	
Muon	efficiency	<1%	4ℓ
	momentum resolution	<1%	
Jet	energy scale	up to 12%	$\tau\tau$, $b\bar{b}$, $\ell\ell jj$, $\ell\nu jj$
	resolution	up to 20%	$\ell\nu jj$
b-tagging	efficiency	up to 15%	$b\bar{b}$
τ-jet	efficiency	up to 8%	$\tau\tau$