Standard Model Higgs boson at ATLAS

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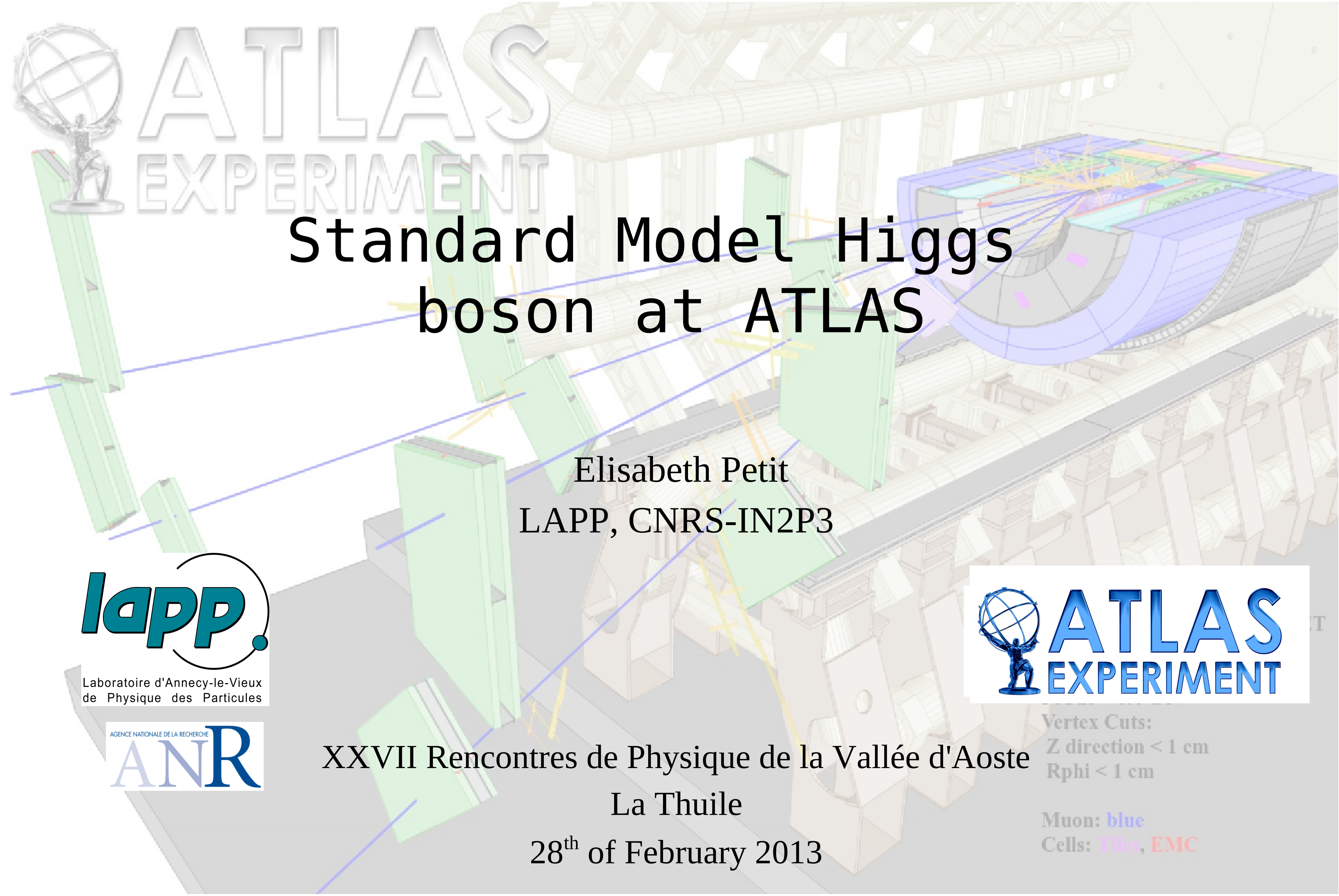


Introduction

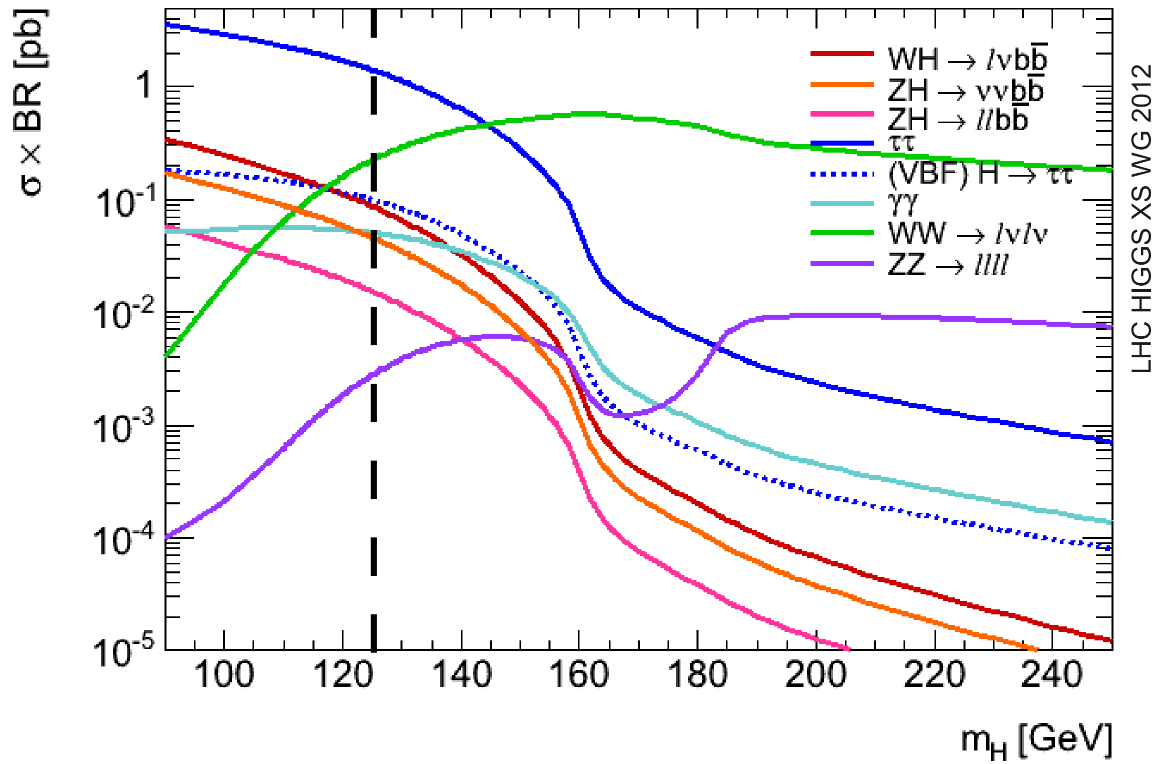
- July 2012: discovery of new boson compatible with Higgs boson

- Not seen for each individual channel yet

- Property measurements
  - mass
  - spin
  - couplings

- Here: 2011 data (5 fb^{-1}) + 2012 data (13 fb^{-1})
  - 65% of 2012 data

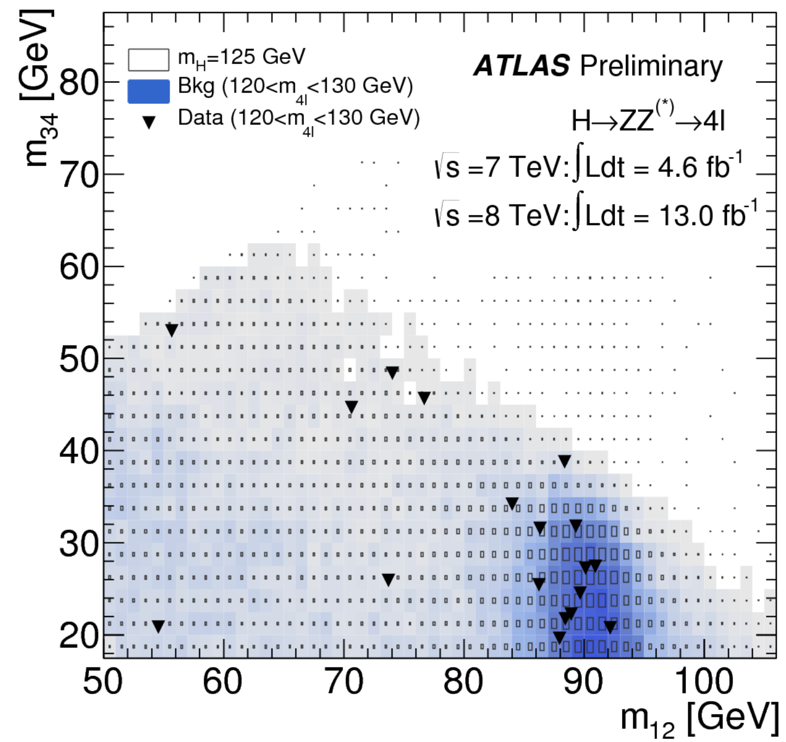
Channels studied



	expected reco Nsignal	S/B	main backgrounds
ZZ→4l	~10	100%	ZZ, Z+jets, top
γγ	~300	1-20%	γγ, γj, jj
WW→lνlν	~60	10%	WW, W+jets, top, ...
ττ	~150	0.3-30%	Z, Z+jets, top
VH→bb̄	~70	0.3-2%	Wbb, Zbb, top

H→ZZ* (1)

- Two same flavour, opposite sign lepton pairs
  - well identified and isolated
  - p_T^l > 20-15-10-7/6 GeV
- $50 < m_{12} < 106$ GeV
- $17.5 < m_{34} < 115$ GeV for $m_{4l} < 145$ GeV



m_H = 125 GeV		4μ	2e2μ/2μ2e	4e
7 TeV	$\varepsilon_{selection}$	39%	21%	15%
8 TeV	$\varepsilon_{selection}$	37%	23%	20%

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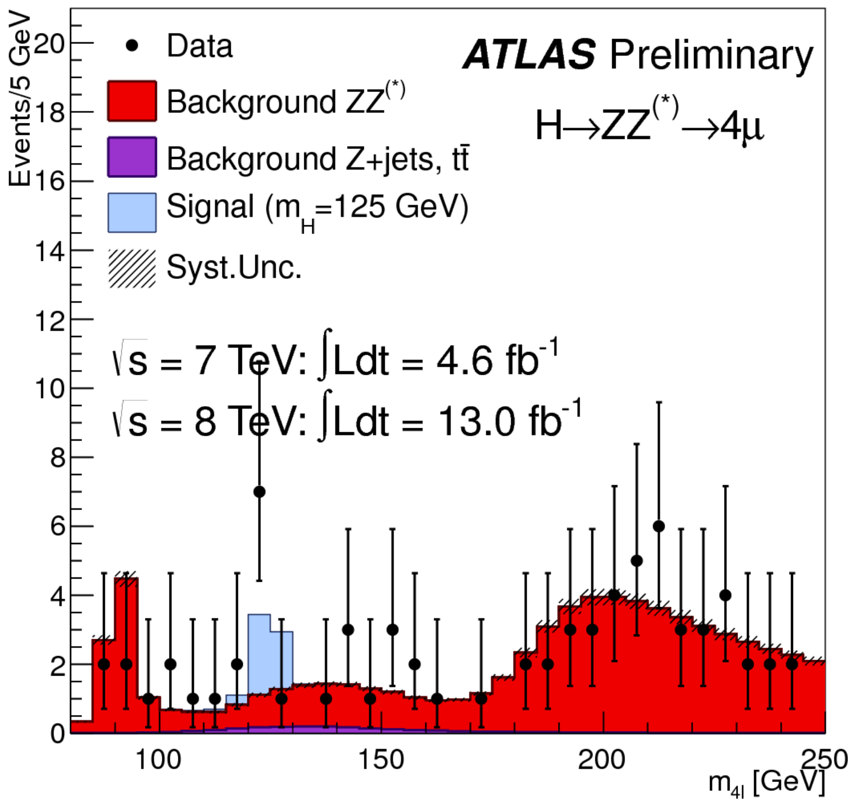
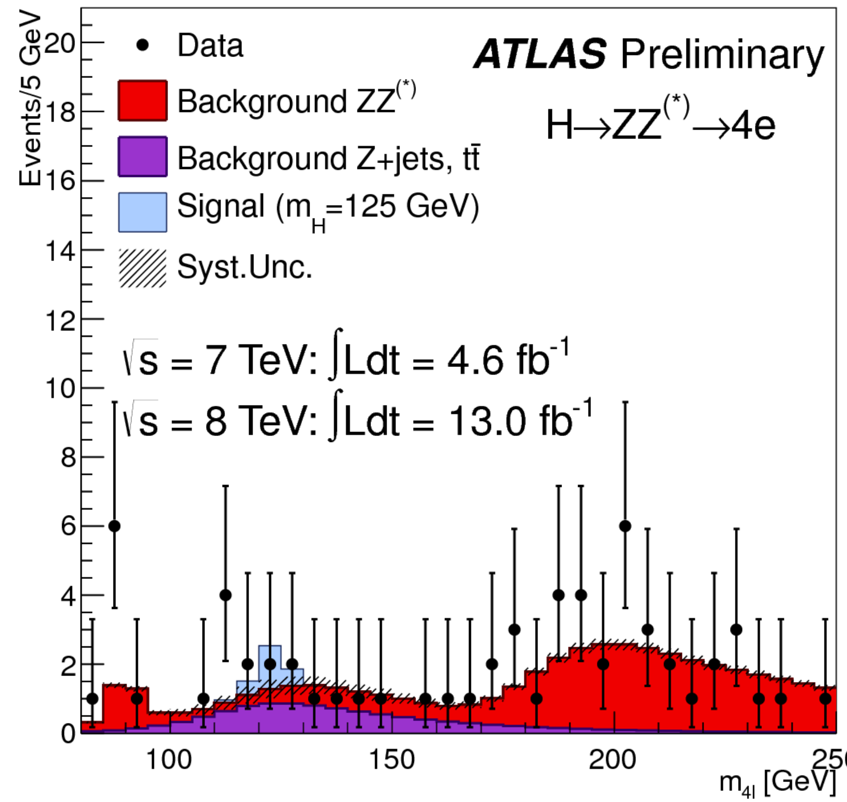
H→ZZ* (2)



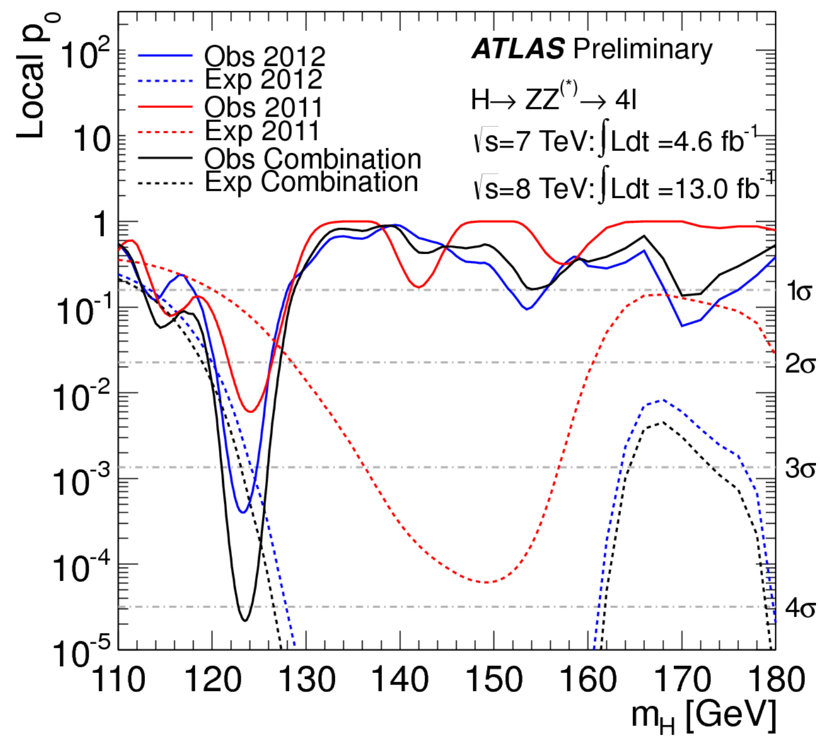


- In 120-130 GeV window (7+8 TeV):

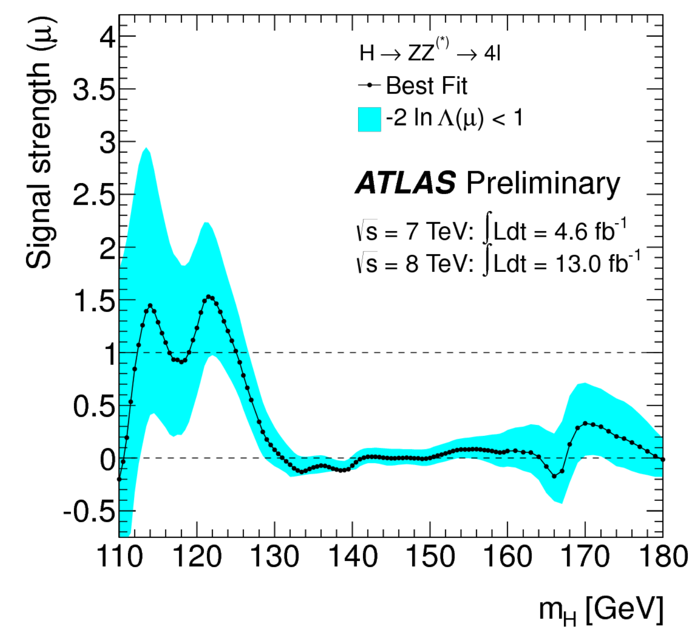
	4μ	2e2μ	2μ2e	4e	total
signal	4.0	2.4	1.7	1.8	9.9
ZZ	2.03	1.02	0.70	0.94	4.7
Z, Zbb̄, tt̄	0.36	0.30	1.21	1.72	3.6
observed	8	4	2	4	18

H→ZZ* (3)

- Excess:
  - expected: 3.1σ
  - observed: 4.1σ



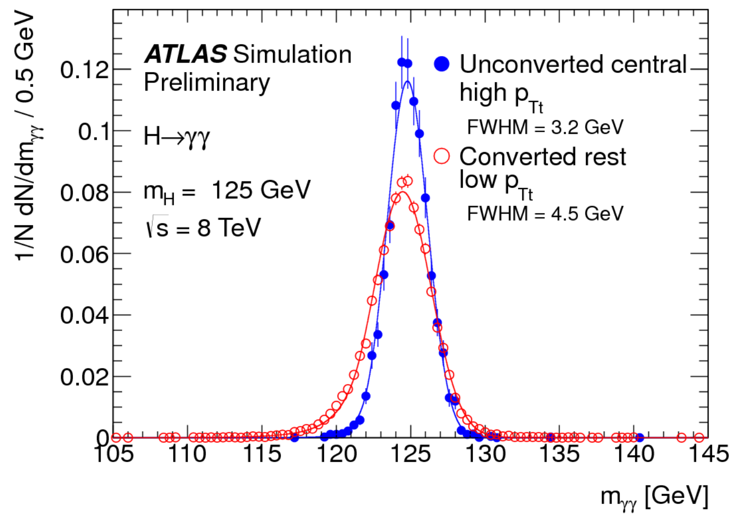
- Best fit for mass:
  123.5 ± 0.9 (stat) ± 0.3 (syst) GeV
- Signal strength at 123.5 GeV: $\boxed{\mu = 1.30^{+0.5}_{-0.4}}$

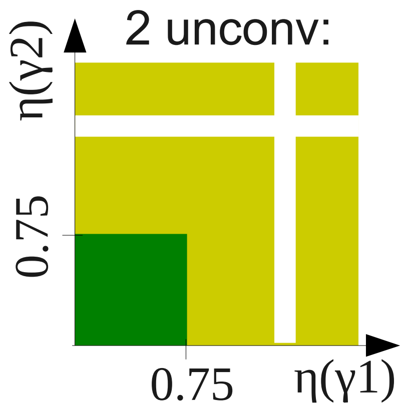


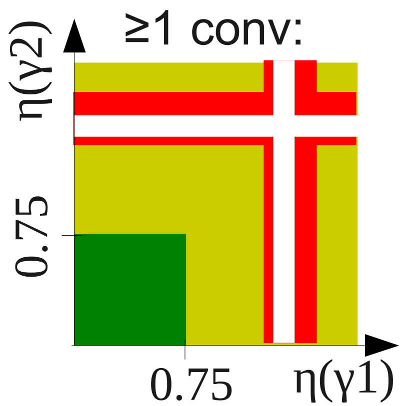
$$\mu = \frac{N^{observed}}{N^{SM}}$$

H→γγ (1)

- Two well identified and isolated photons
  - $E_T^{\gamma 1} > 40$ GeV, $E_T^{\gamma 2} > 30$ GeV
  - γγ purity: 75%
- Events divided in 12 exclusive categories
  - with ≠ resolution: 1.4 → 2.5 GeV
  - with ≠ S/B: 0.014 → 0.204
  - with ≠ production modes fractions
    - 9 ggF enriched
    - 1 VBF enriched
    - 2 VH enriched







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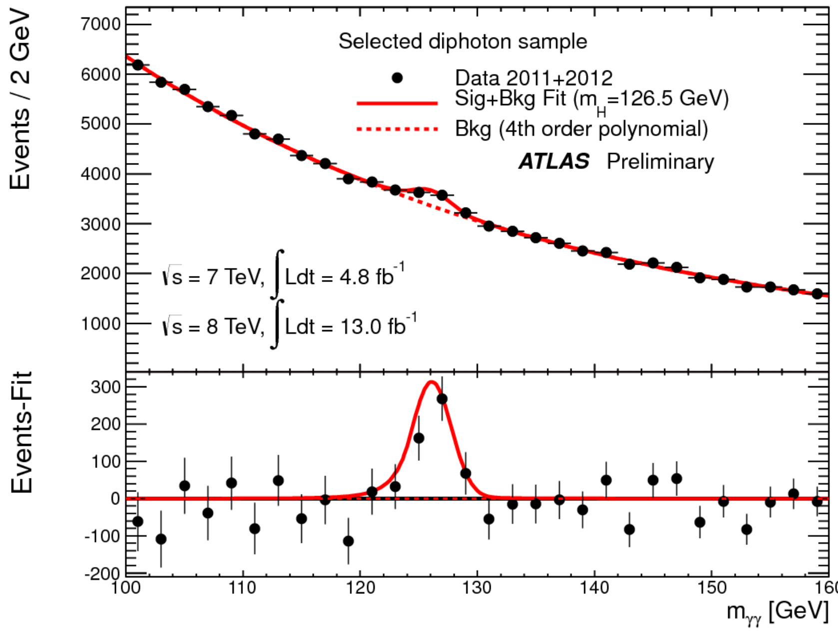
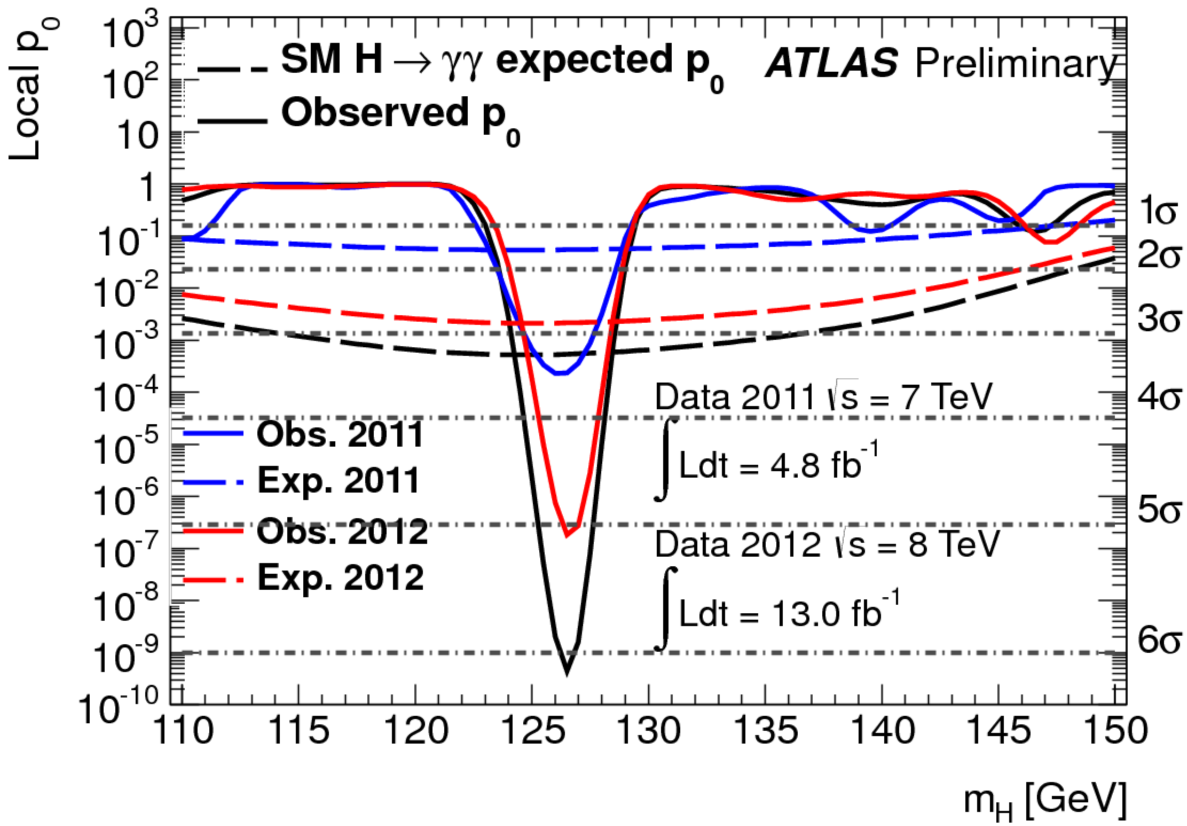
H→γγ (2)

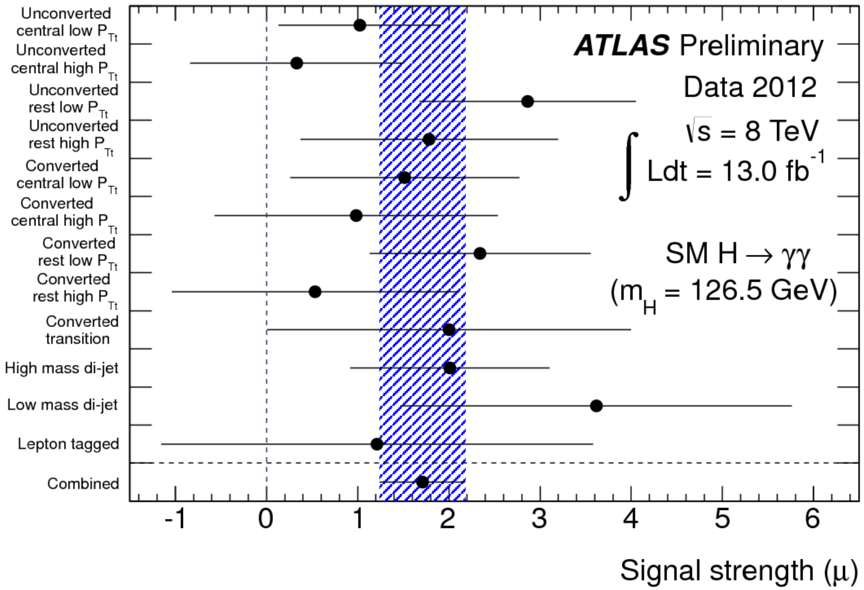
- Observation confirmed for γγ channel alone!
  - observed: 6.1σ at 126.5 GeV
  - expected: 3.3σ

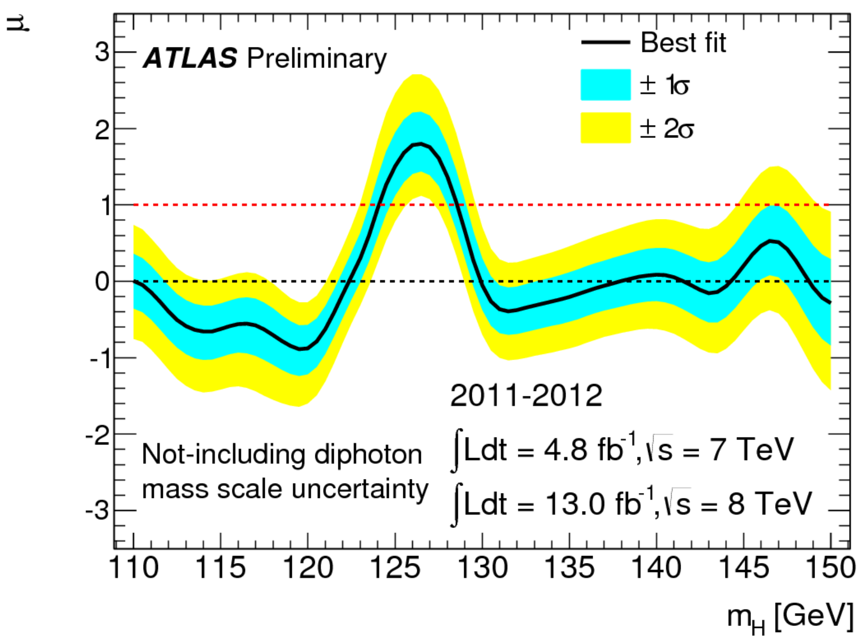




H→γγ (3)

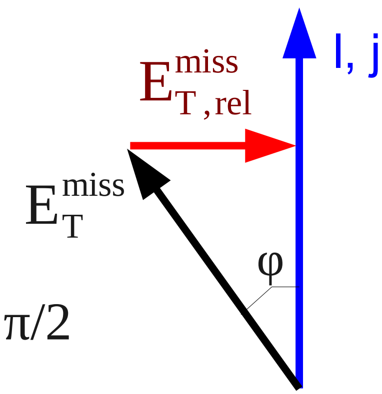
- Best fit for mass:
  - 126.6 ± 0.3 (stat) ± 0.7 (syst) GeV
- Best fit signal strength at 126 .6 GeV
  - $\boxed{\mu = 1.80 \pm 0.30\,(\mathrm{stat})^{+0.21}_{-0.15}\,(\mathrm{syst})^{+0.20}_{-0.14}\,(\mathrm{theory})}$
  - 2.4 σ from SM hypothesis

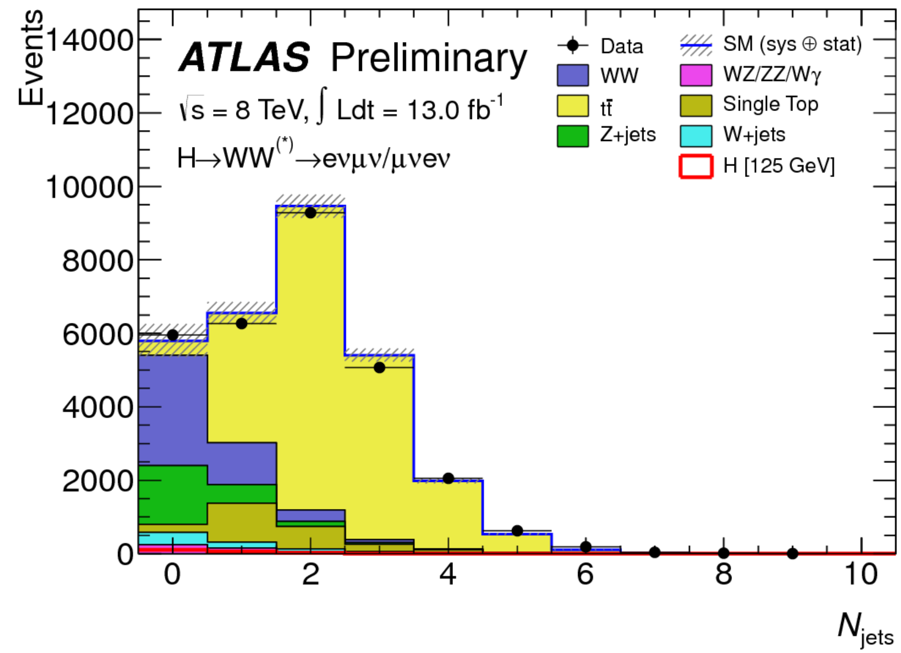




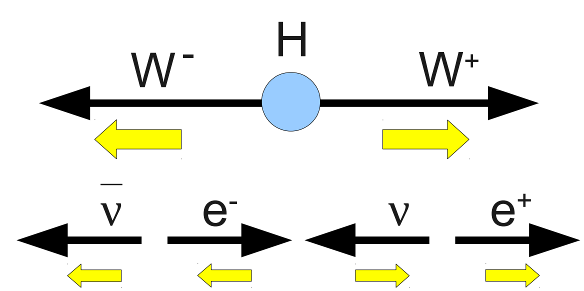
H→WW* (1)

- H → WW* → eνμν only
- isolated leptons with p_T > 25/15 GeV
- $E_T^{miss}{}_{rel}$ > 25 GeV
  - E_T^{miss} if $\Delta\varphi > \pi/2$
  - $E_T^{miss}.\sin(\Delta\varphi)$ if $\Delta\varphi < \pi/2$





- Spin correlations
  - m_{ll} < 50 GeV and $\Delta\varphi_{ll}$ < 1.8



- Divide events in H+0 jet and H+1 jet

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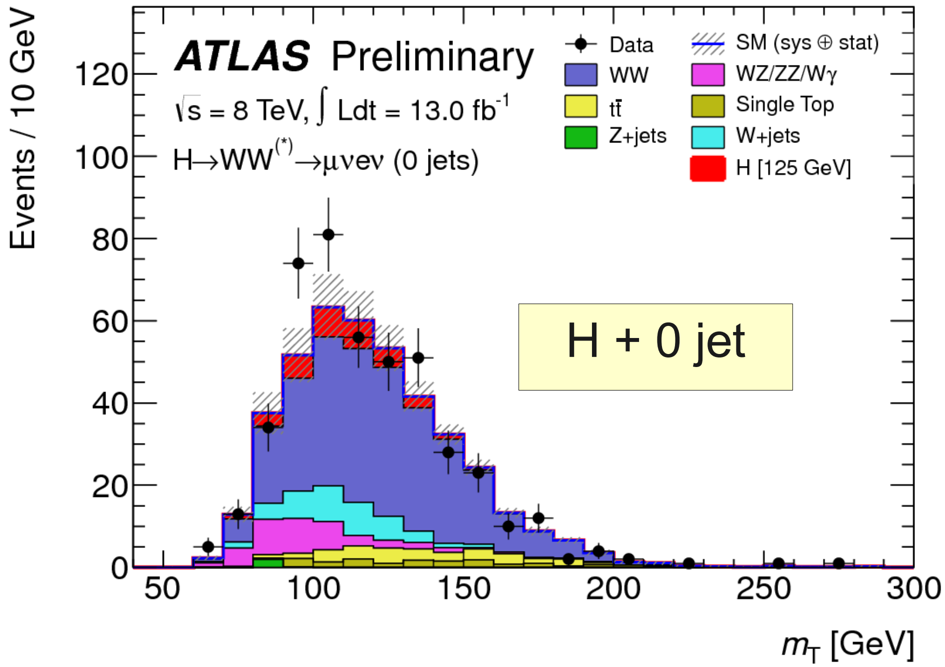
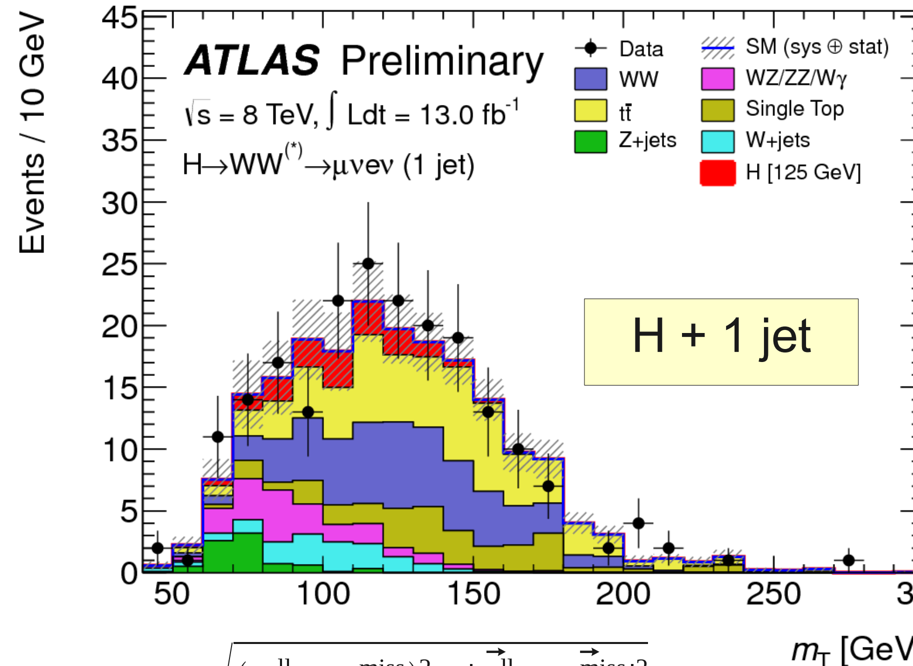
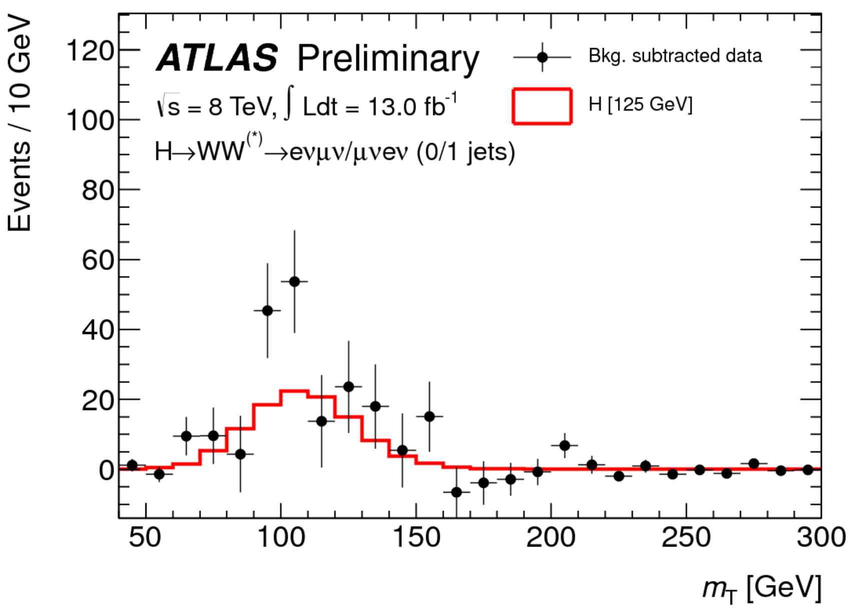
H→WW* (2)





$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - |\vec{p}_T^{\,ll} + \vec{E}_T^{miss}|^2}$$

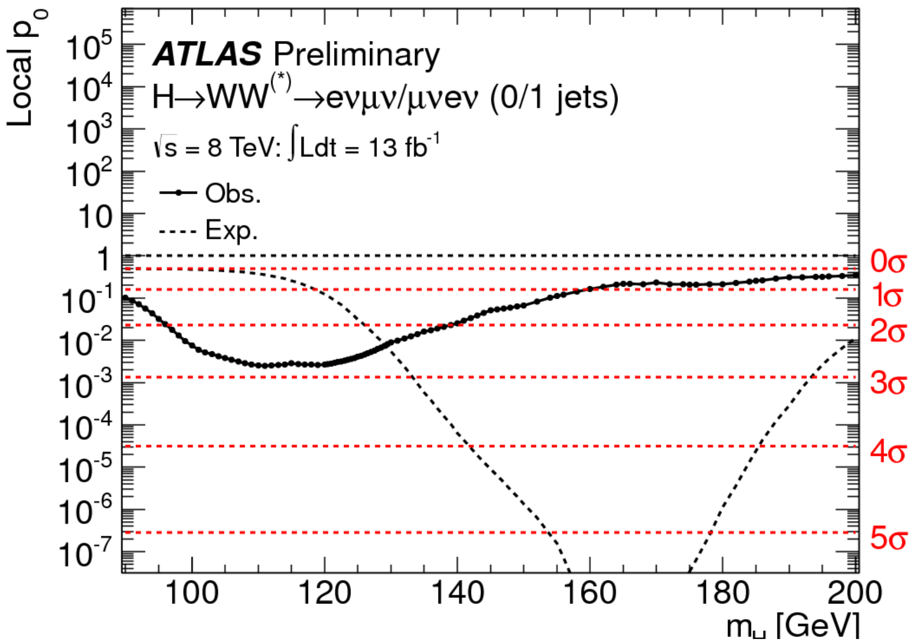
$$E_T^{ll} = \sqrt{|\vec{p}_T^{\,ll}|^2 + m_{ll}^2}$$

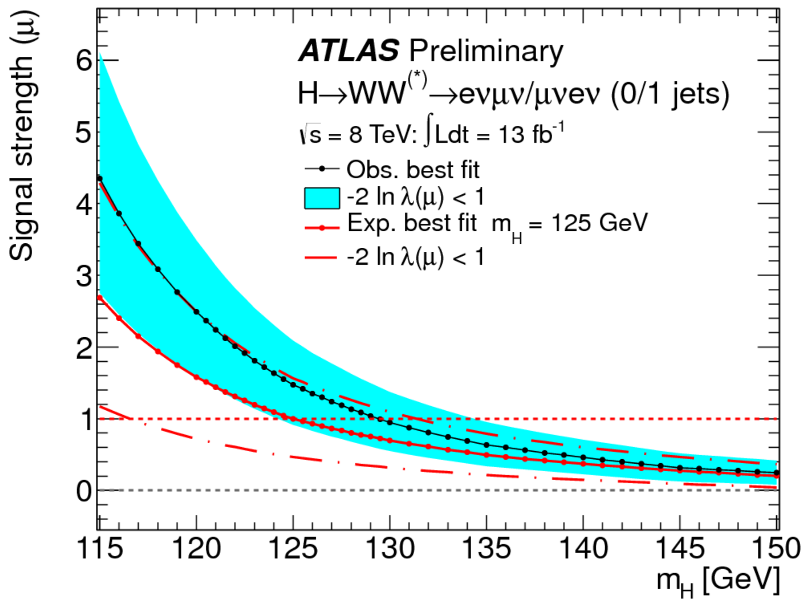


	H + 0 jet	H + 1jet
signal	45	18
background	334	114
observed	423	141

H→WW* (3)

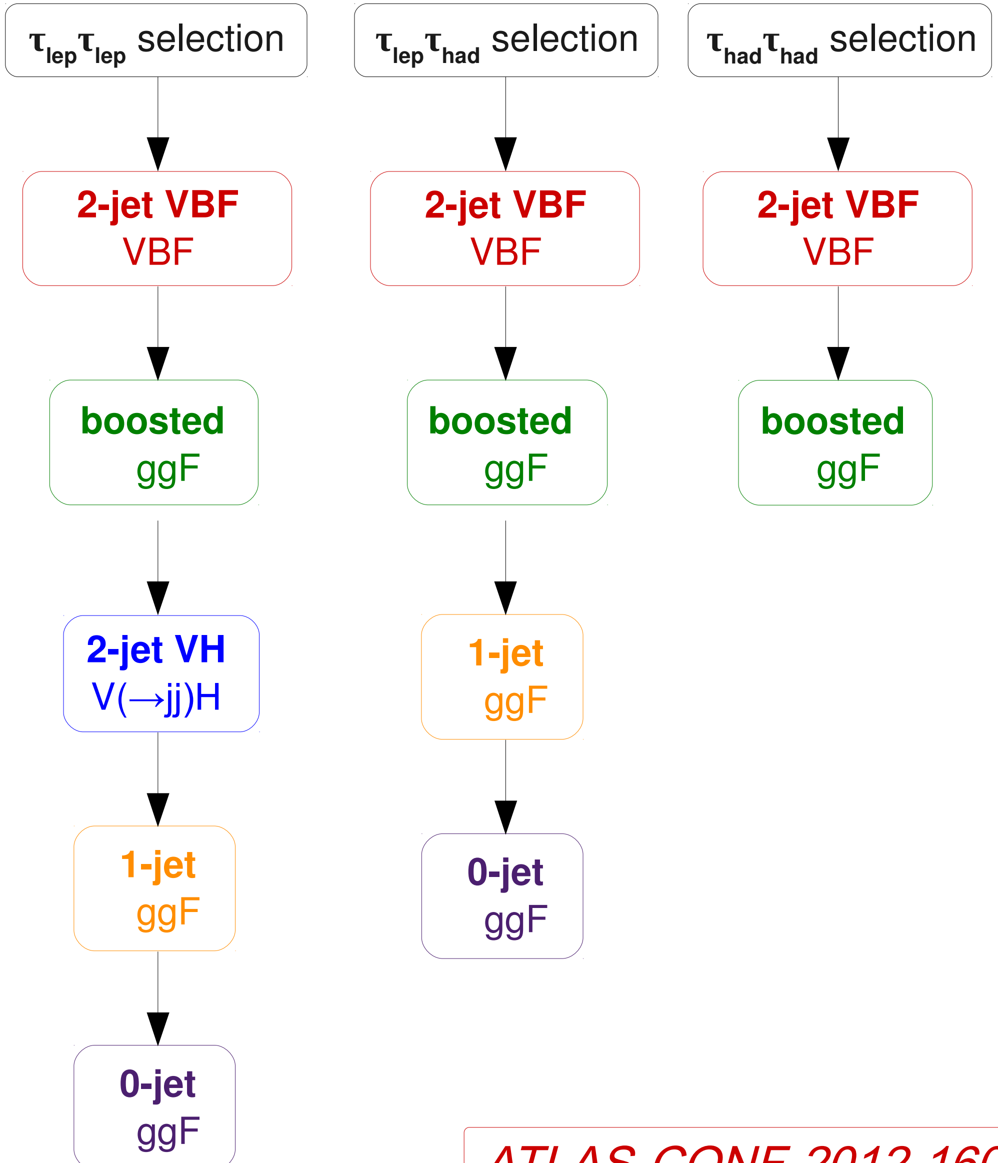
- Excess of events for m_H < 150 GeV
- For m_H = 125 GeV
  - observed: 2.6σ
  - expected: 1.9σ
- Signal strength at 125 GeV:
  - $\boxed{\mu = 1.5 \pm 0.6}$





$H \to \tau\tau$ (1)

- Quite large σxBR,
  - but large bkg from $Z \to \tau\tau$
- Separate $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
- VBF category
  - 2 forward jets
- Boosted category
  - $m_{\tau\tau}$ better resolution



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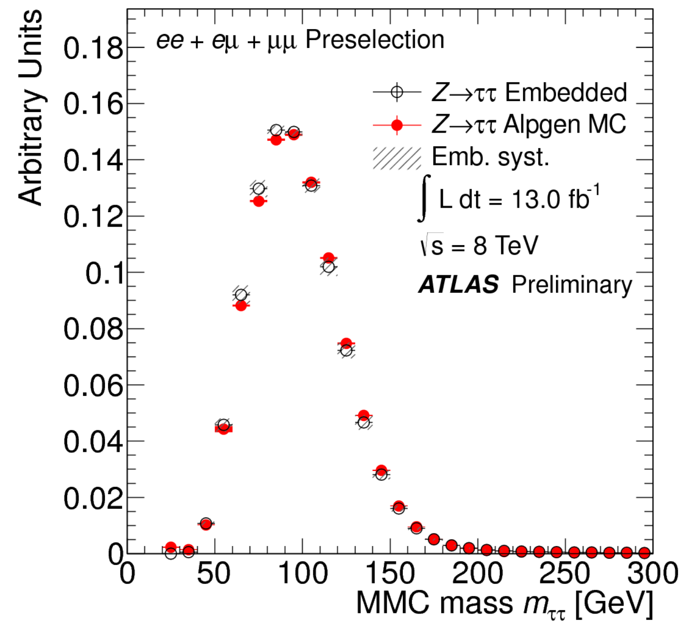
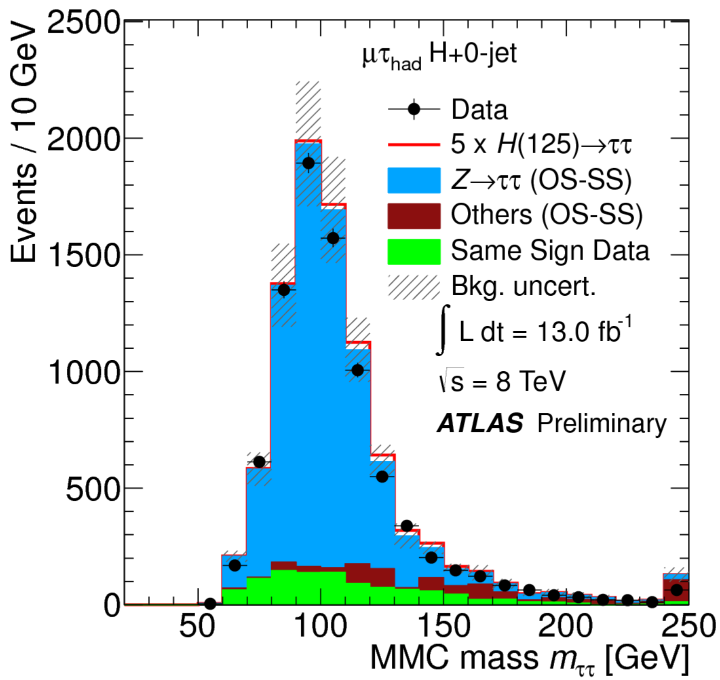
H→ττ (2)

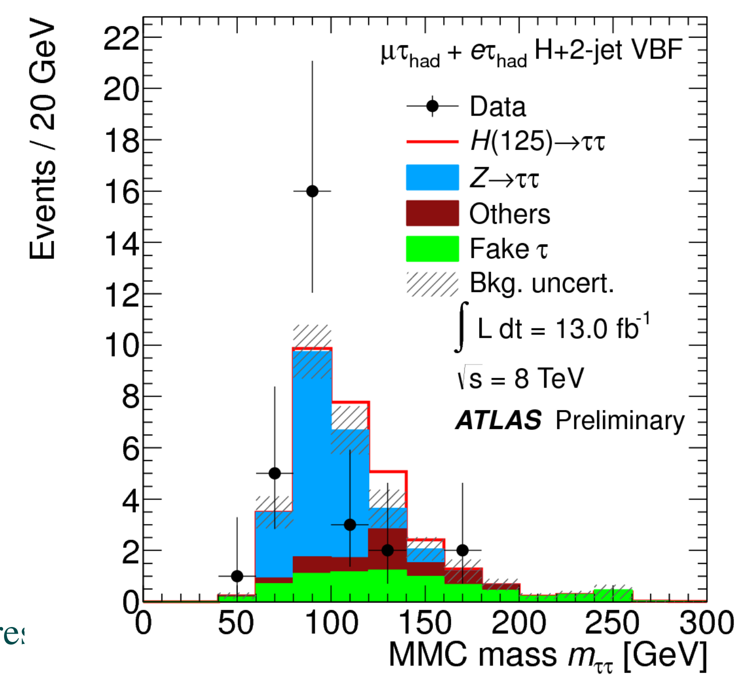
- Main background: Z → ττ, "embedded"
  - data Z → μμ
  - μ replaced by simulated τ



- Lowest and highest S/B:

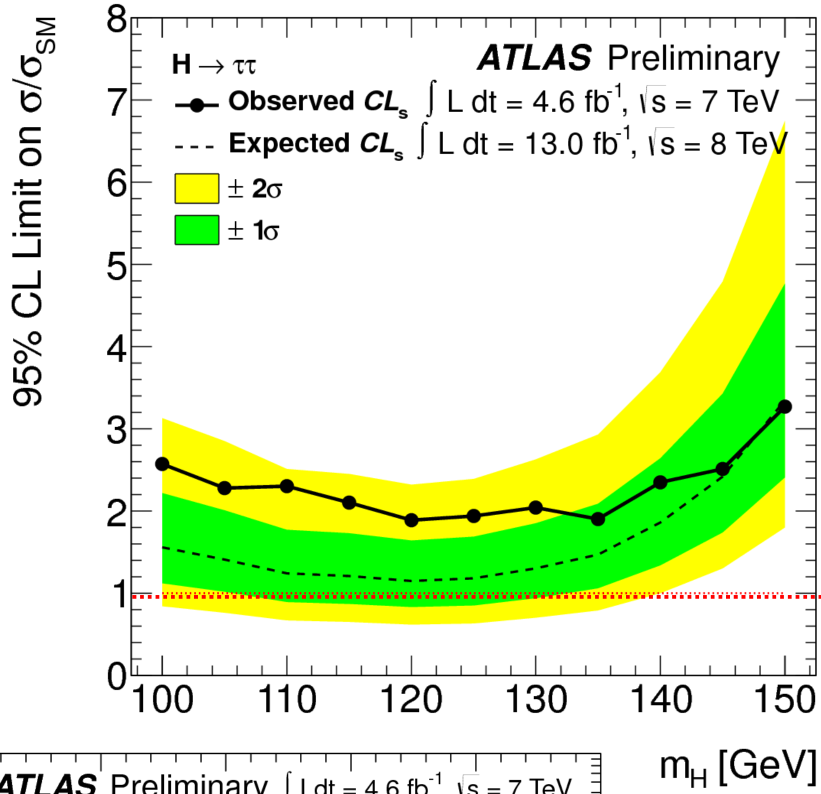
τlepτhad	H + 0 jet	VBF
signal	76.3	4.04
background	18100	38.5
observed	17334	39

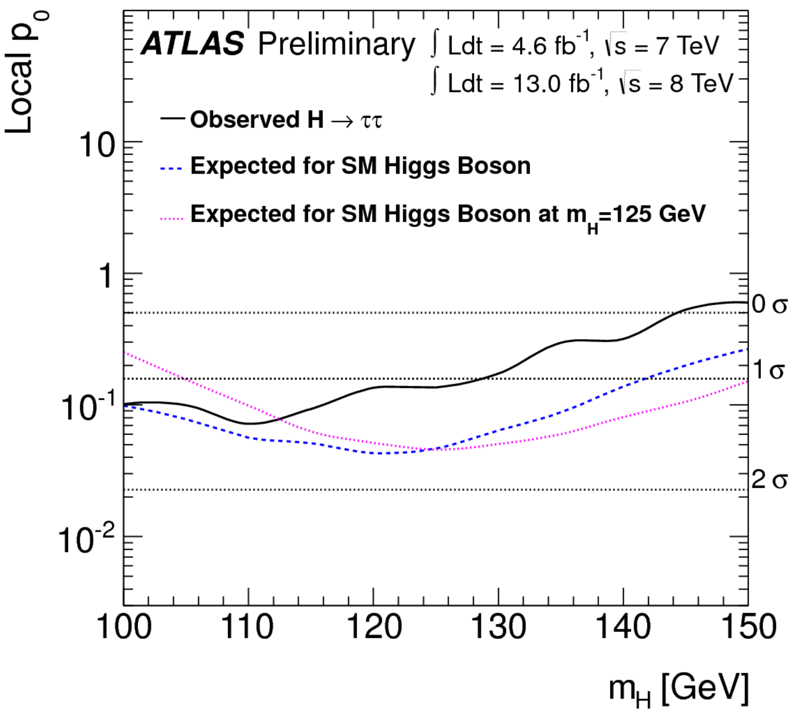




H→ττ (3)

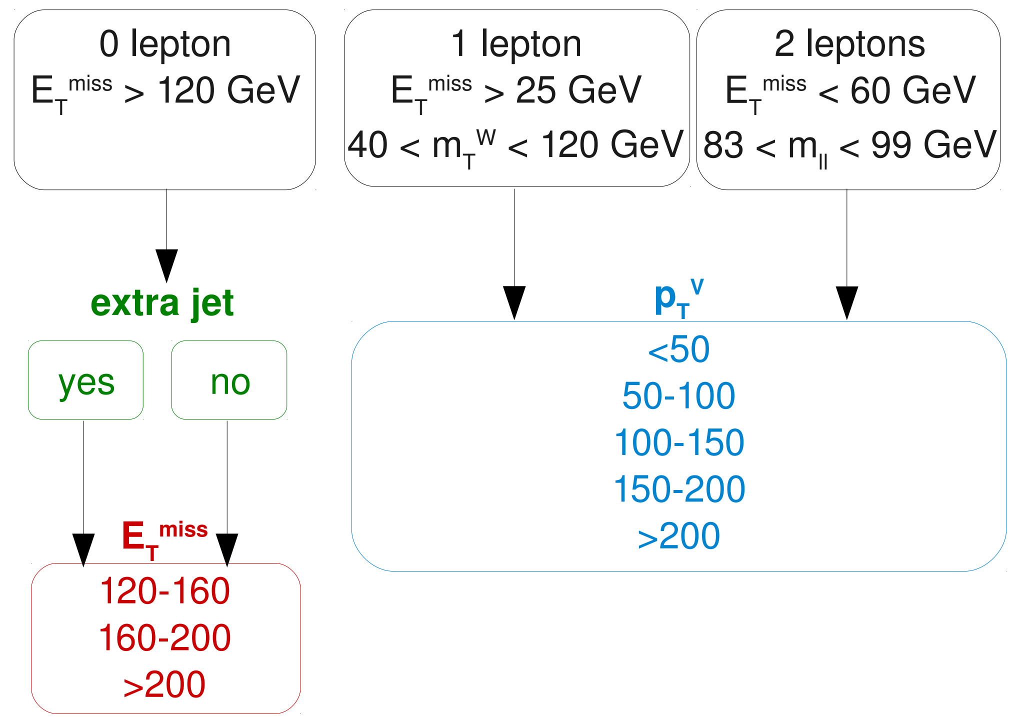
- 95% CL exclusion at m_H = 125 GeV:
  - observed: 1.9*SM
  - expected: 1.2*SM
- p_0 at m_H = 125 GeV:
  - observed: 1.1σ
  - expected: 1.7σ
- Signal strength at m_H = 125 GeV:
  - $\boxed{\mu = 0.7 \pm 0.7}$





$H \to b\bar{b}$ (1)

- $BR(H \to b\bar{b}) = 57.7\%$ at $m_H = 125$ GeV
  - but only WH, ZH
- 2 b-jets
  - 70% eff
  - $p_T > 45/20$ GeV
- $Z(\to \nu\nu)H$, $W(\to l\nu)H$, $Z(\to ll)H$
- 16 categories



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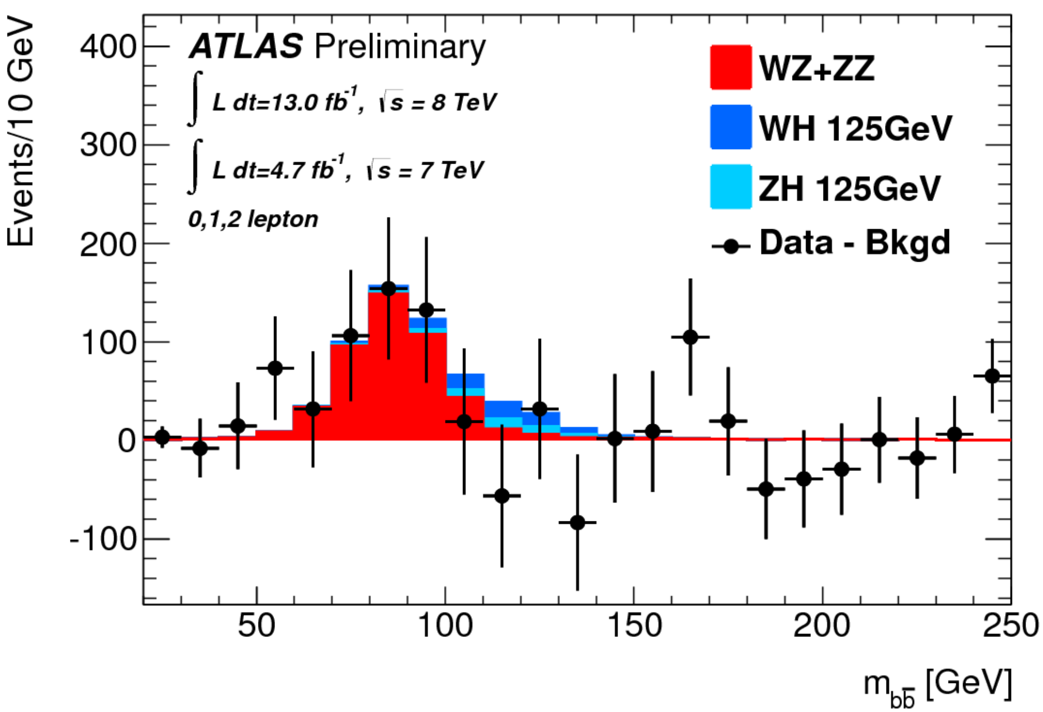
$H\to b\bar{b}$ (2)

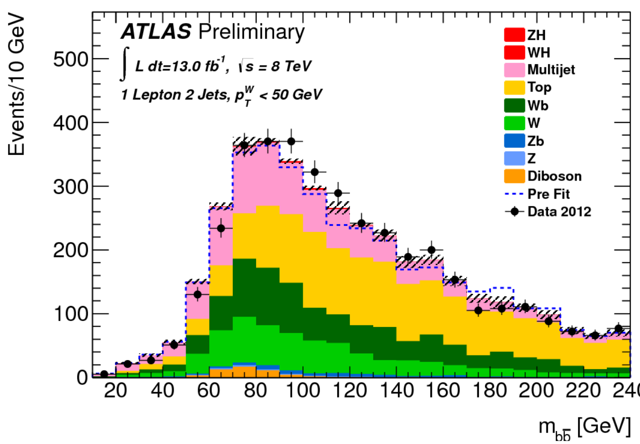
- Main backgrounds
  - $t\bar{t}$
  - W+jets, Z+jets

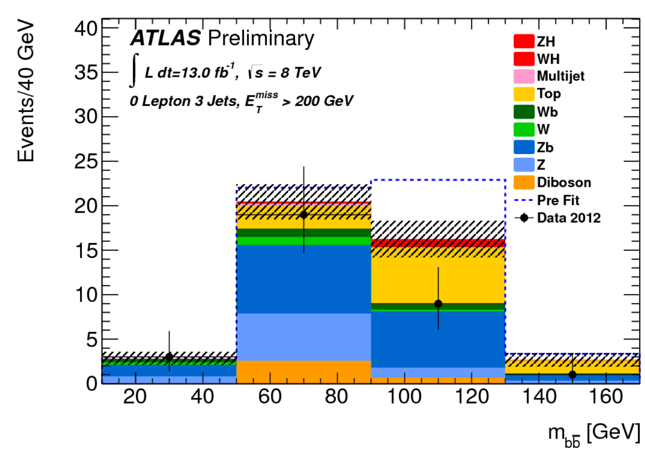
- Lowest and highest S/B:

	1 lepton p_T^W<50 GeV	0 lepton, 3 jets E_T^{miss} > 200 GeV
signal	10.9	1.3
background	3810	42
observed	3821	32

- All but di-boson bkg substraction:



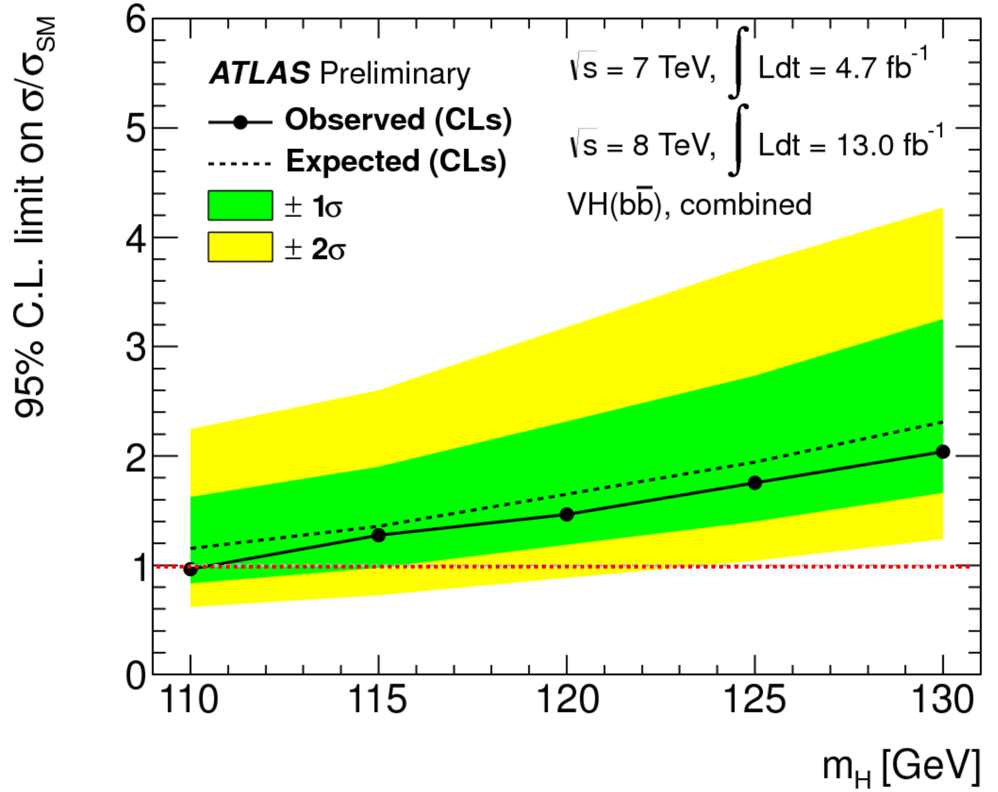


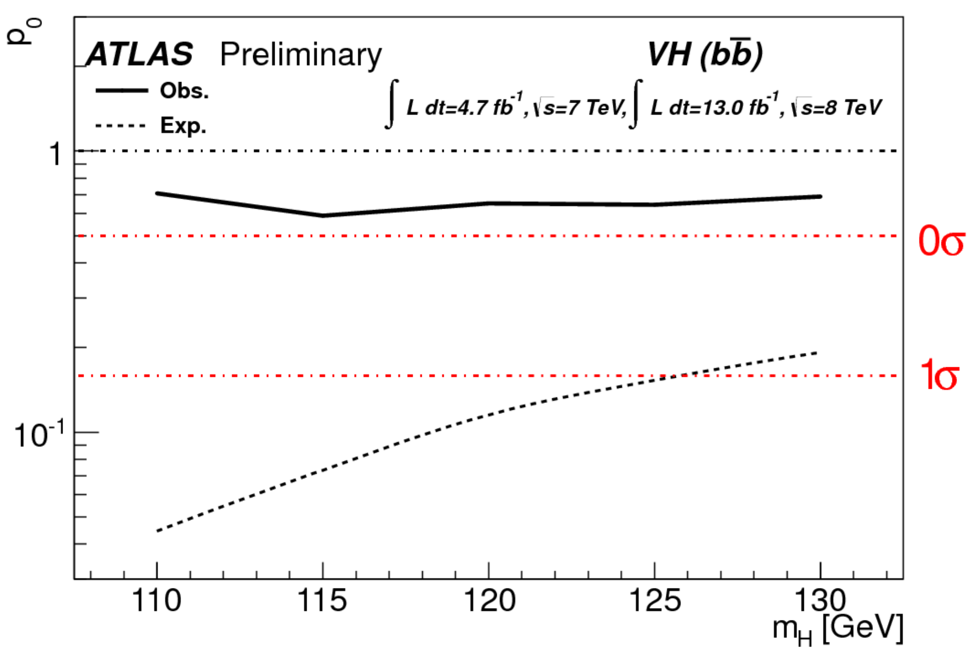


H→b$\bar{b}$ (3)

- 95% CL exclusion at m_H = 125 GeV:
  - observed: 1.8*SM
  - expected: 1.9*SM

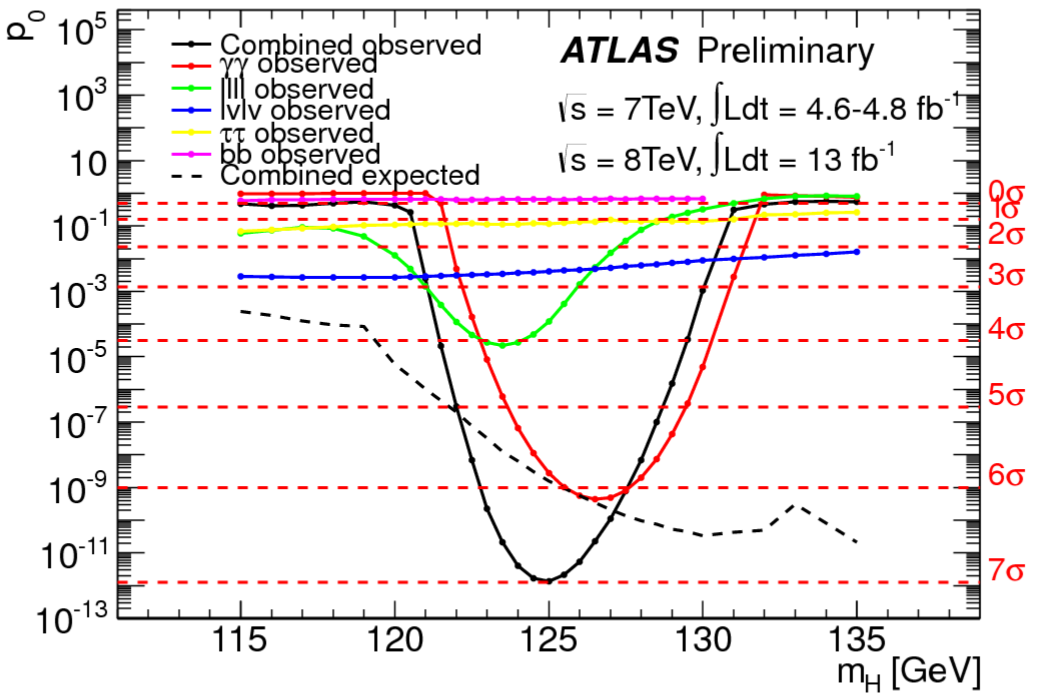
- Signal strength at m_H = 125 GeV:
  - μ = -0.4 ± 0.7 (stat) ± 0.8 (syst)



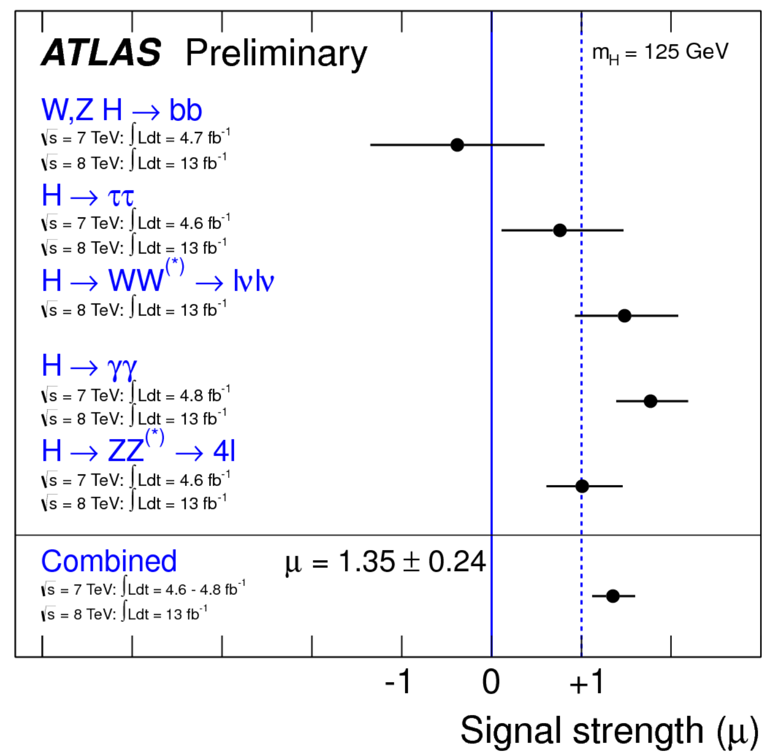


Combination: excess

- Largest local p_0: 7.0σ
  - expected: 5.9 σ



- Signal strength at m_H = 125 GeV
  - $\boxed{\mu = 1.35 \pm 0.19\ (\text{stat}) \pm 0.15\ (\text{syst})}$

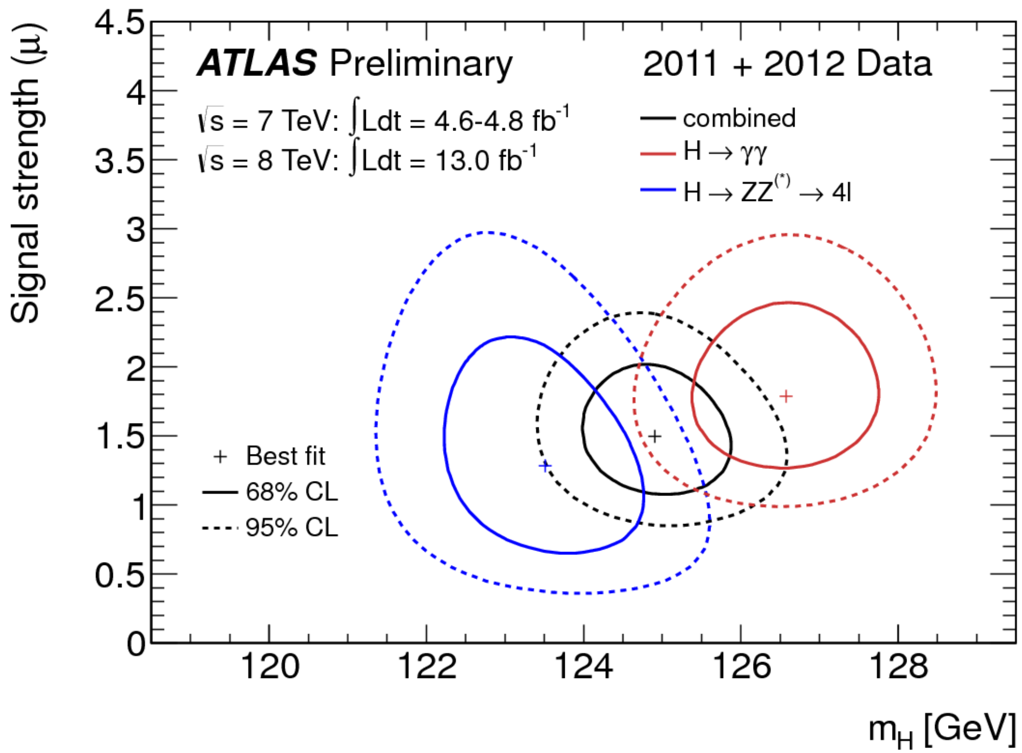


Combination: mass

- Mass from individual channels:
  - $H \rightarrow ZZ^*$: 123.5 ± 0.8 (stat) ± 0.3 (syst) GeV
  - $H \rightarrow \gamma\gamma$: 126.6 ± 0.3 (stat) ± 0.7 (syst) GeV

- Difference between both:
  $3.0 \pm 0.8(\text{stat})^{+0.7}_{-0.6}(\text{syst})\,\text{GeV}$
  - 2.3 to 2.7 standard deviation

- Combined mass:
  125.2 ± 0.3 (stat) ± 0.6 (syst) GeV



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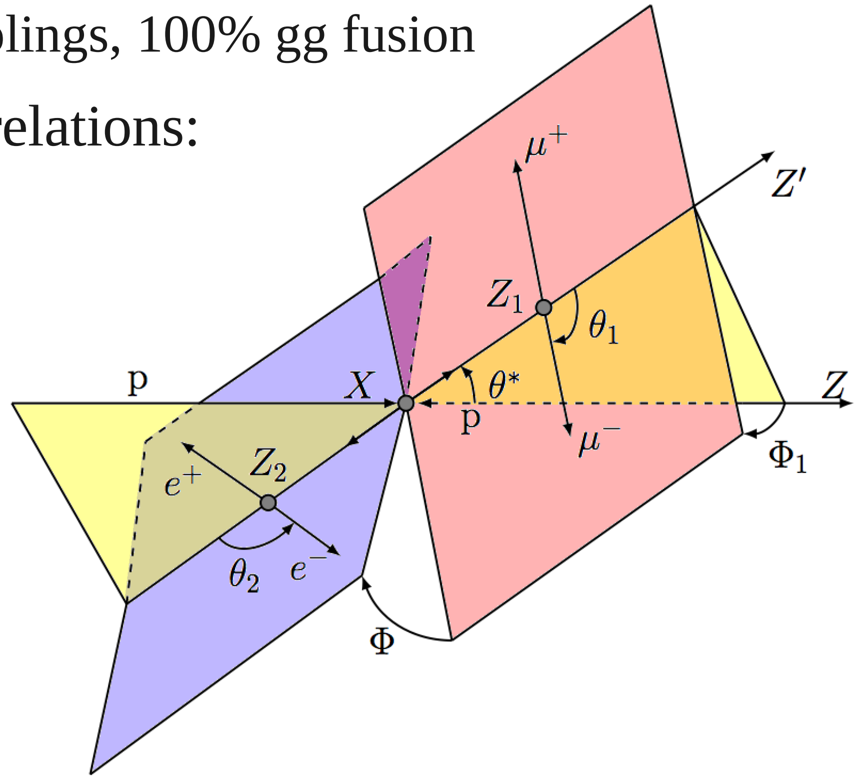
Spin: introduction

- Possible spin value/channel:

	spin 0	spin 1	spin 2
H→VV	✔	✔	✔
γγ	✔	✘	✔
H→f$\bar{f}$	✔	✔	✘

- For the moment, 0^+ (SM Higgs), 0^-, 2^+ (graviton-like), 2^- (pseudo-tensor)
  - 2^+: minimal couplings, 100% gg fusion
- Use of angular correlations:



Spin with H→γγ (1)

- Compare 0^+ and 2^+
- Use of cosθ*
  - flat for SM Higgs
- Events in 123.8-128.6 GeV
  - 199 expected signal

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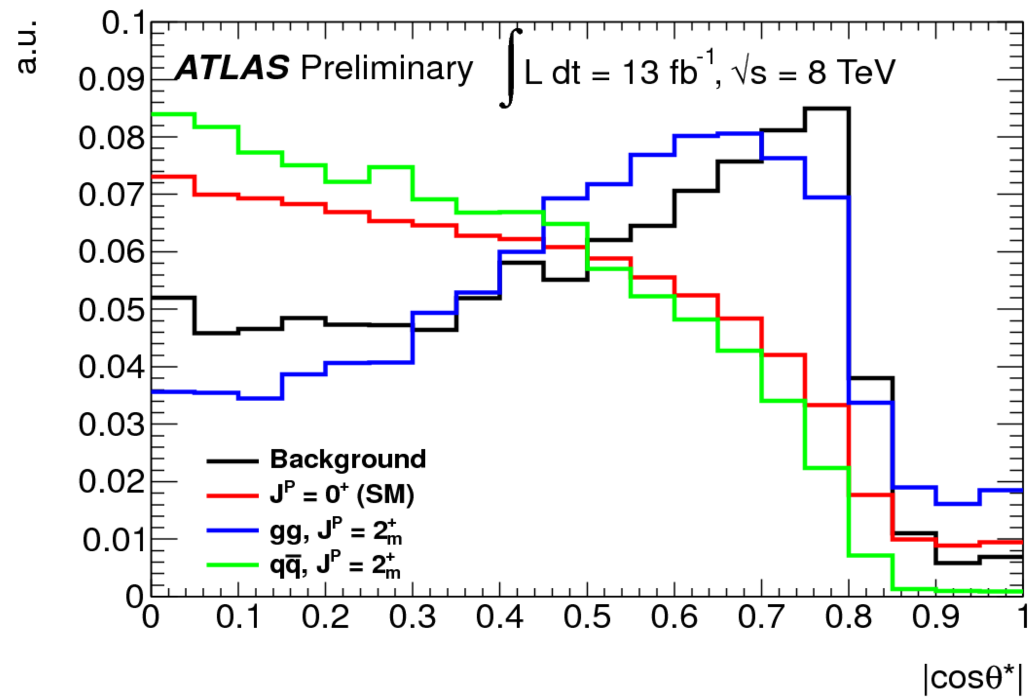
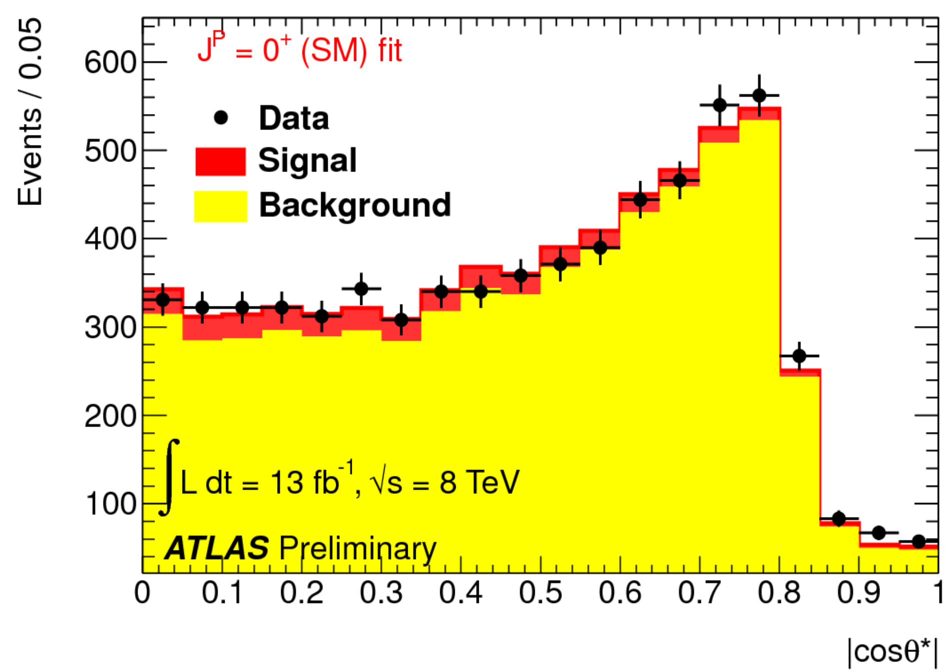
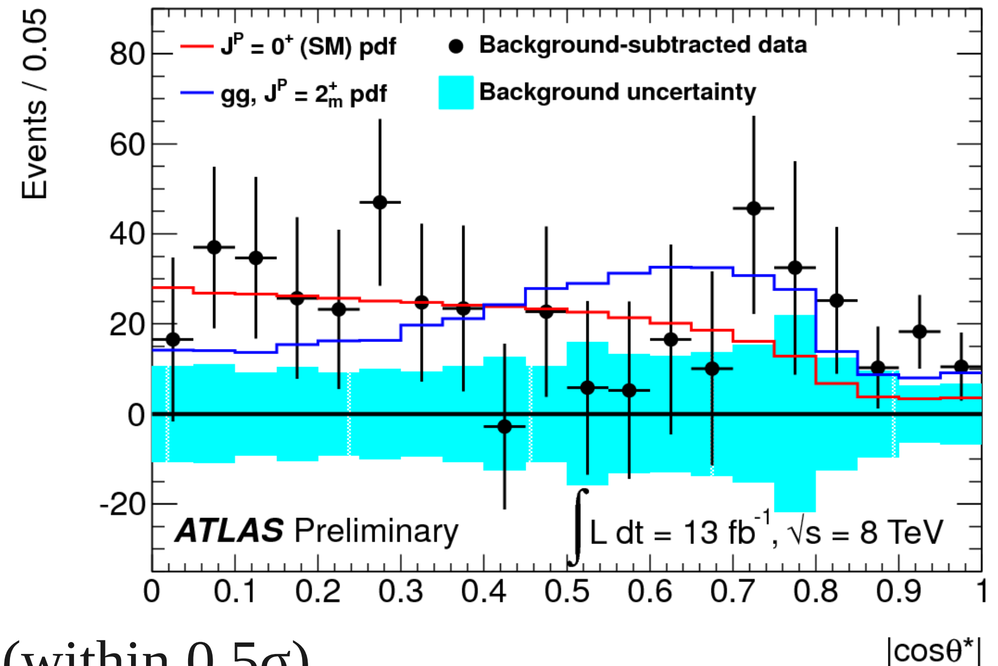


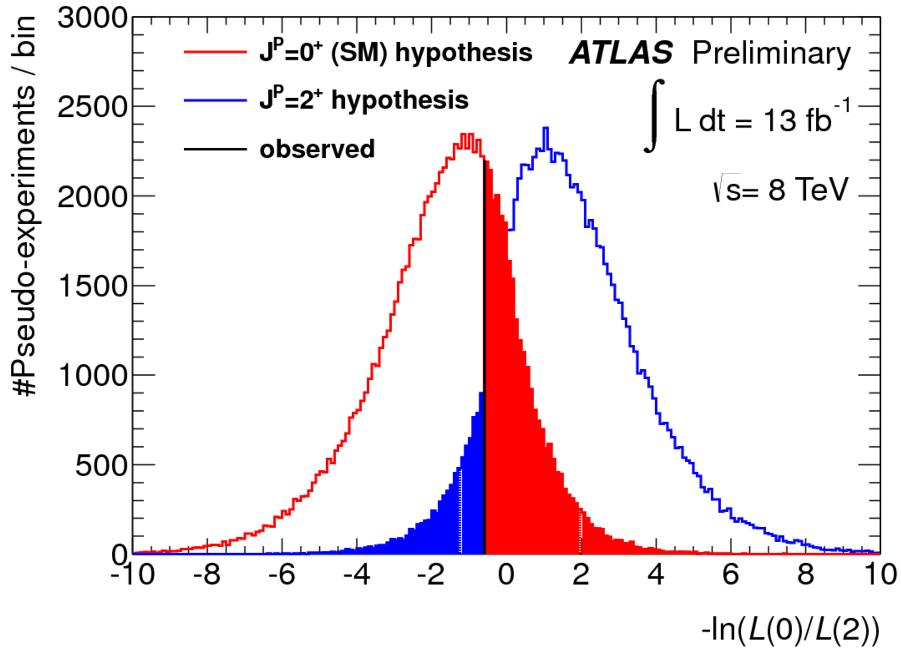


Spin with H→γγ (2)

- Bkg substracted:

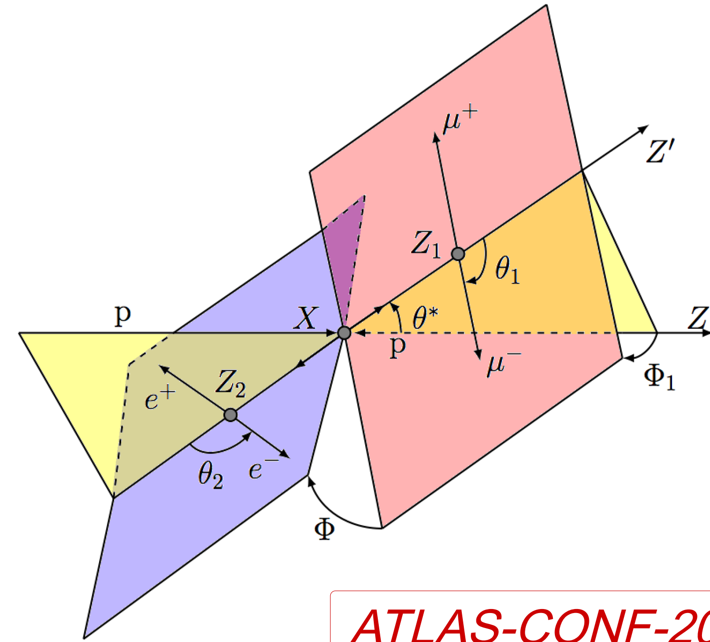


- Exclusion spin 2^+ (gg) hypothesis
  - expected: at 97% CL
  - observed: at 91% CL
- Observation compatible with spin 0 (within 0.5σ)



Spin with H→ZZ* (1)

- Compare 0^+, 0^-, 2^+ , 2^-
- Events in 115-130 GeV
- Use of 5 angles + m_{12}, m_{34}
  - in BDT
  - in Matrix element (MELA) distribution



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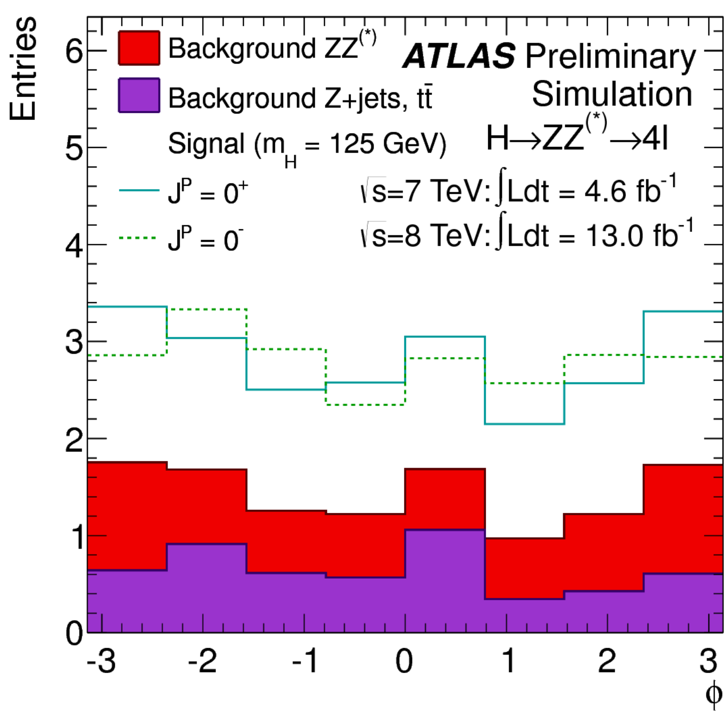
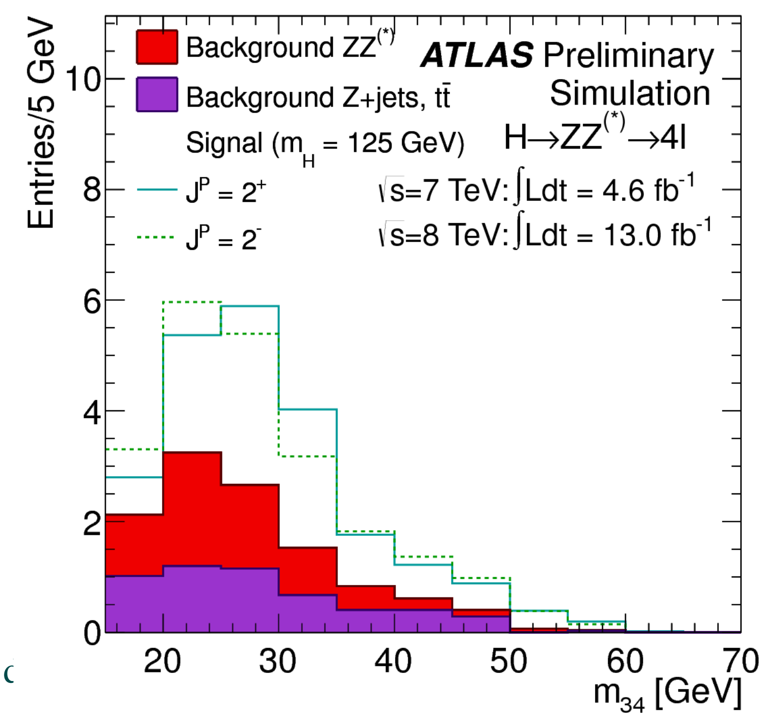
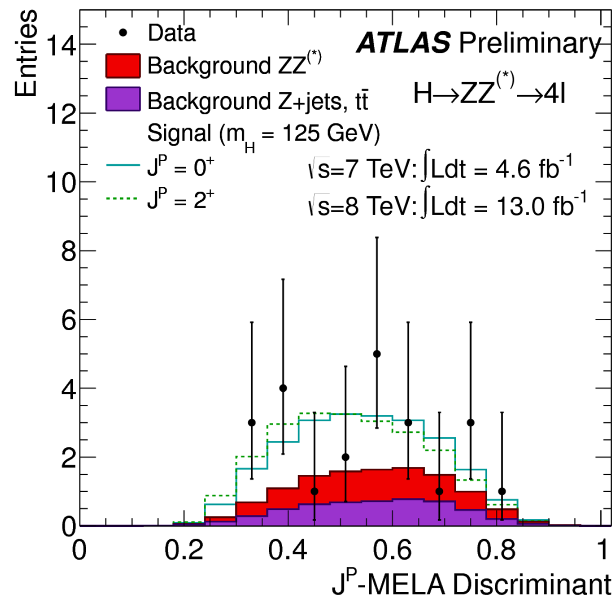
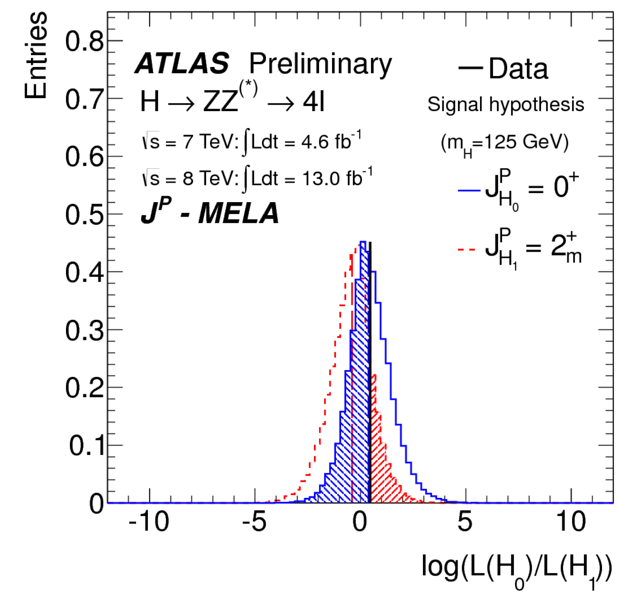




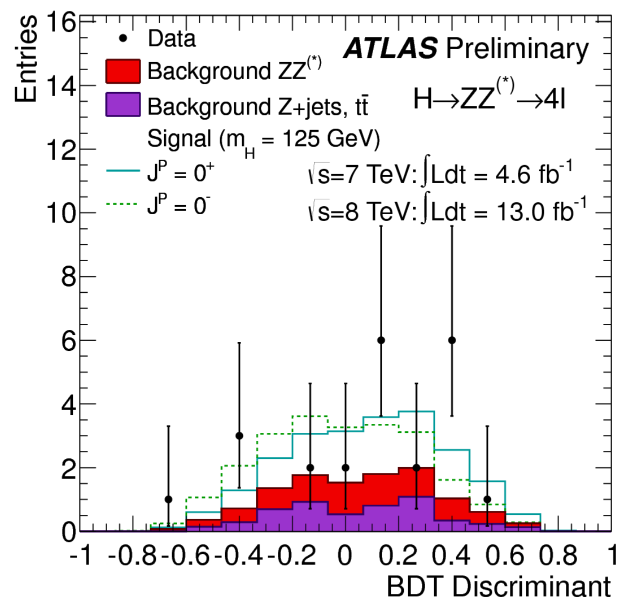
Spin with H→ZZ* (2)

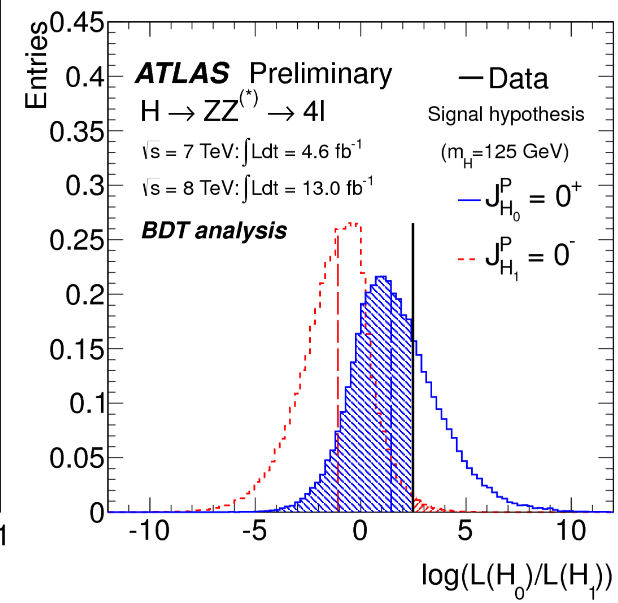
- Exclusion spin 2^+ hypothesis
  - expected: at 80% CL
  - observed: at 85% CL
  - compatible with spin 0 (within 0.18σ)





- Exclusion spin 0^- hypothesis
  - expected: at 96% CL
  - observed: at 99% CL
  - compatible with spin 0 (within 0.5σ)





Conclusions

- Most recent ATLAS results on search/study of Higgs-like boson with 13 fb^{-1}
- Observation in $H \rightarrow \gamma\gamma$ channel (6.1σ)
- Sensitivity close to 1 for fermion decays ($\tau\tau$, $b\bar{b}$)
- Mass of particle:
  125.2 ± 0.3 (stat) ± 0.6 (syst) GeV
- Signal strength:

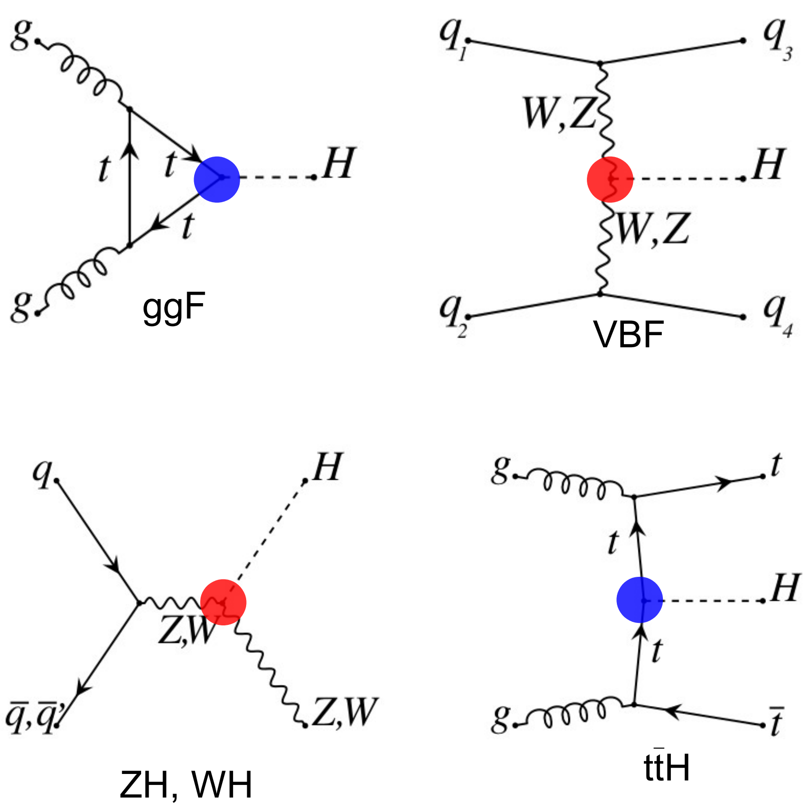
  $\mu = 1.35 \pm 0.19$ (stat) ± 0.15 (syst)
- Spin 2 and 0^- disfavored by data
- More soon with whole LHC Run-1 dataset (5+21 fb^{-1})

- Higgs-like boson couplings: see talk by Marco Rescigno tomorrow morning
  - also $H \rightarrow \gamma\gamma/ZZ$ in ATLAS by Maud Schwoerer and Antonio Salvucci in Young Scientists Forum

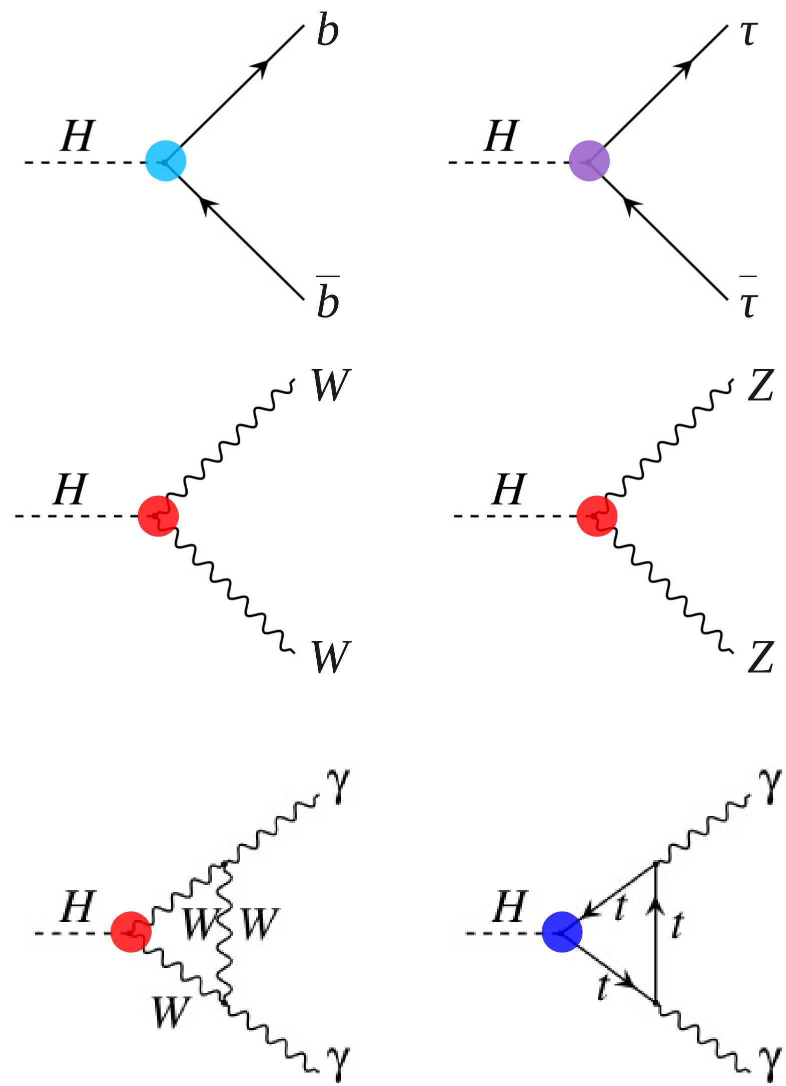
Back-up slides

Higgs boson production and decays modes

- Production modes:

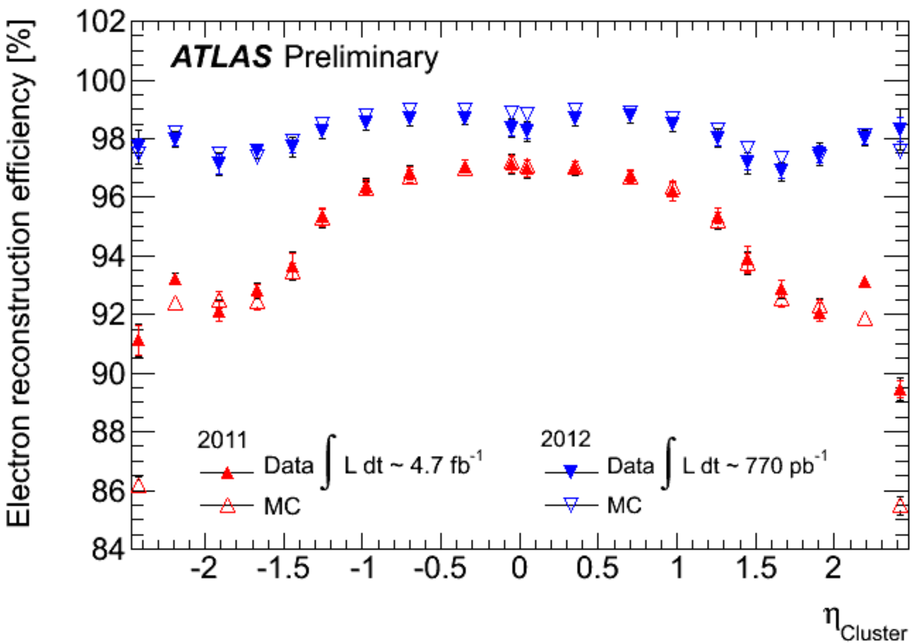


- Decay modes:

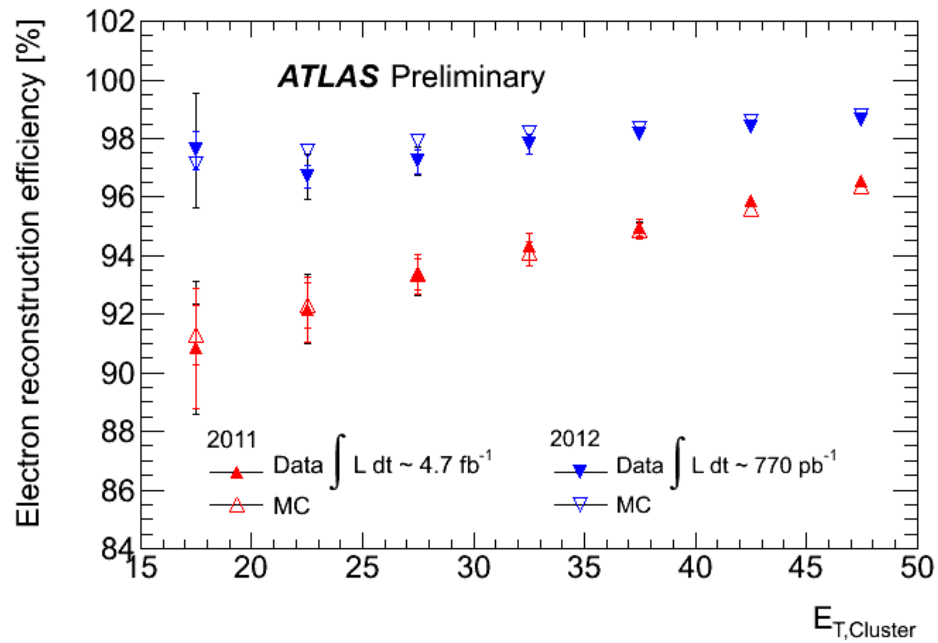


: fermions (t, b, τ)
: vector bosons

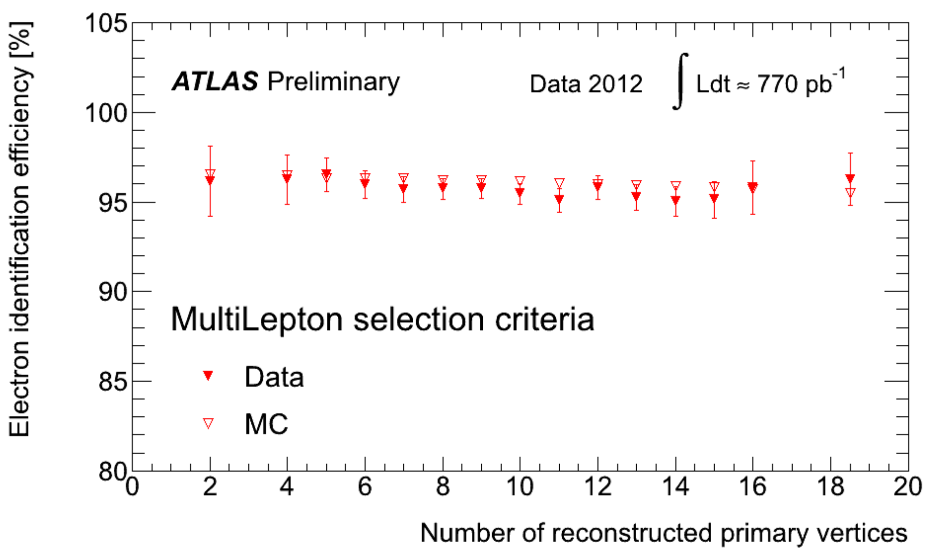
Electrons



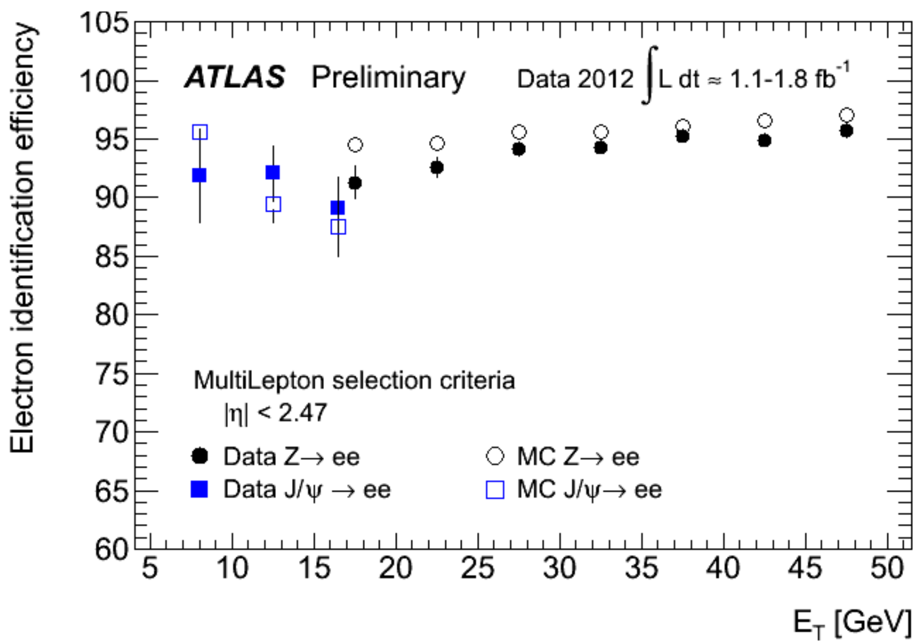
ATLAS Preliminary
Electron reconstruction efficiency [%]
2011 Data ∫L dt ~ 4.7 fb⁻¹
MC
2012 Data ∫L dt ~ 770 pb⁻¹
MC
η_Cluster



ATLAS Preliminary
Electron reconstruction efficiency [%]
2011 Data ∫L dt ~ 4.7 fb⁻¹
MC
2012 Data ∫L dt ~ 770 pb⁻¹
MC
E_T,Cluster

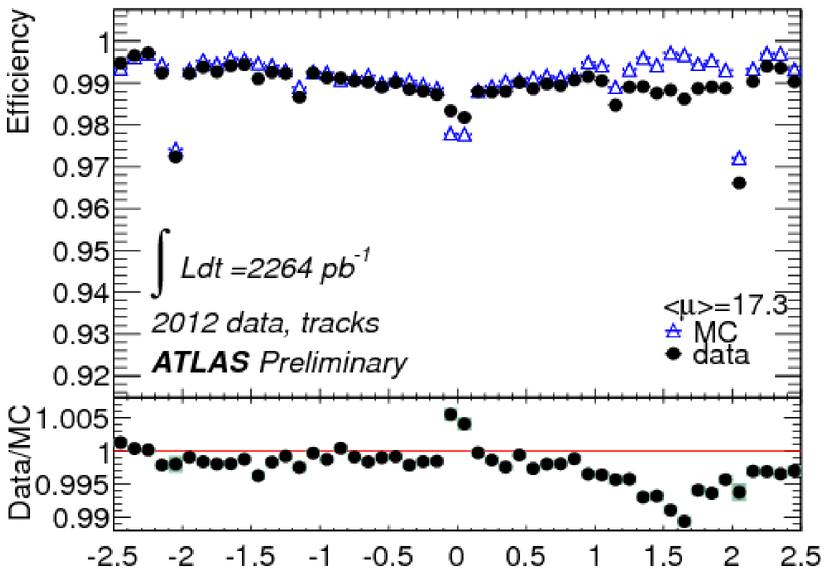


ATLAS Preliminary
Data 2012 ∫Ldt ≈ 770 pb⁻¹
Electron identification efficiency [%]
MultiLepton selection criteria
Data
MC
Number of reconstructed primary vertices

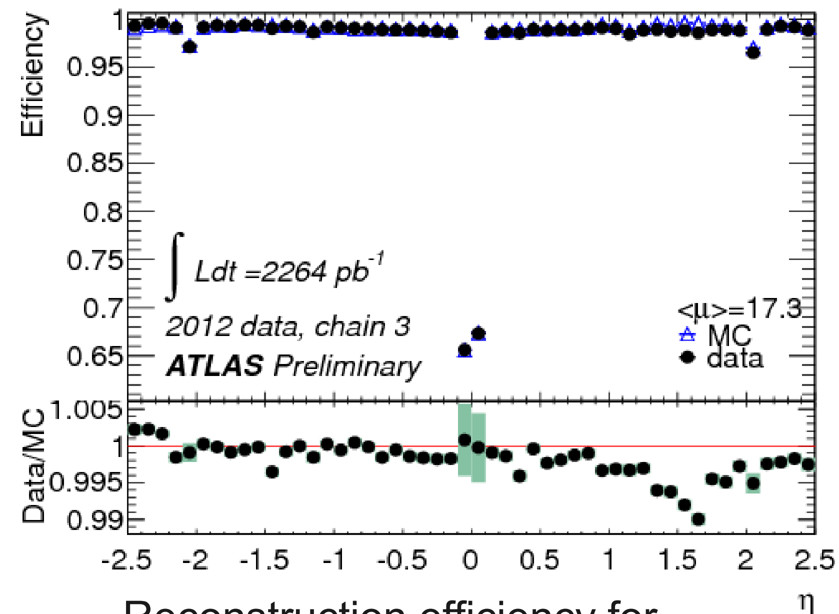


ATLAS Preliminary
Data 2012 ∫L dt ≈ 1.1-1.8 fb⁻¹
Electron identification efficiency
MultiLepton selection criteria
|η| < 2.47
Data Z→ ee
MC Z→ ee
Data J/ψ → ee
MC J/ψ→ ee
E_T [GeV]

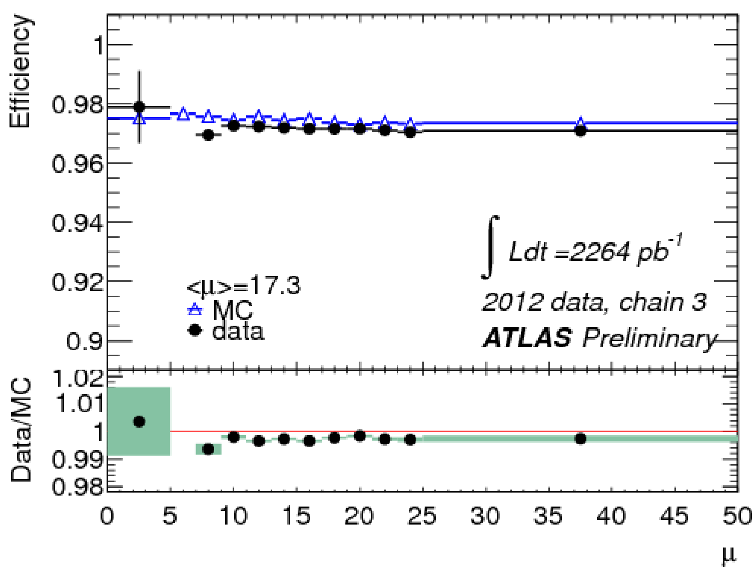
Muons



Inner detector reconstruction efficiency



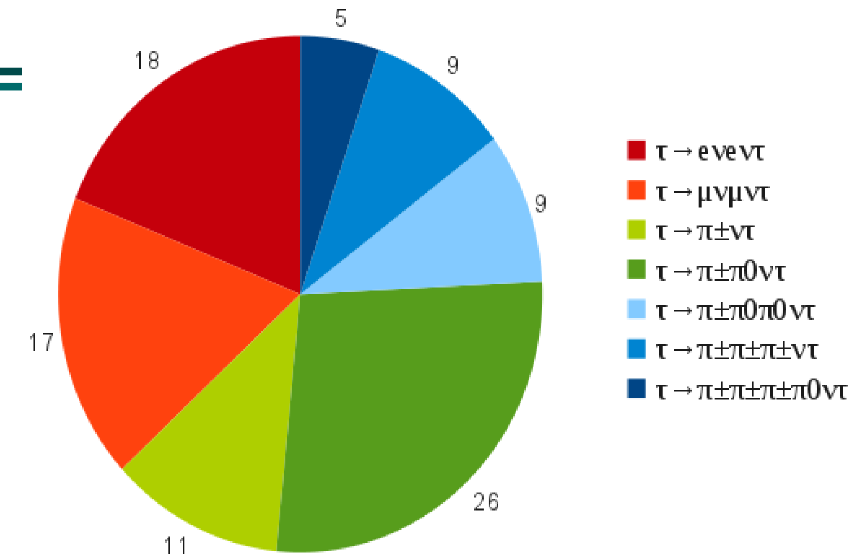
Reconstruction efficiency for
combined+segment tagged muons



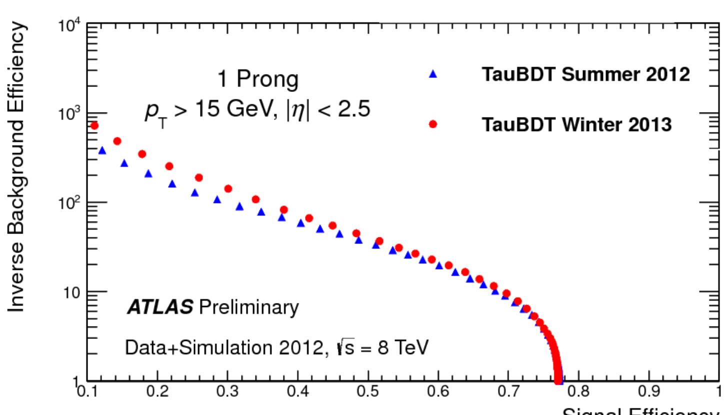
Reconstruction efficiency for
combined+segment tagged muons

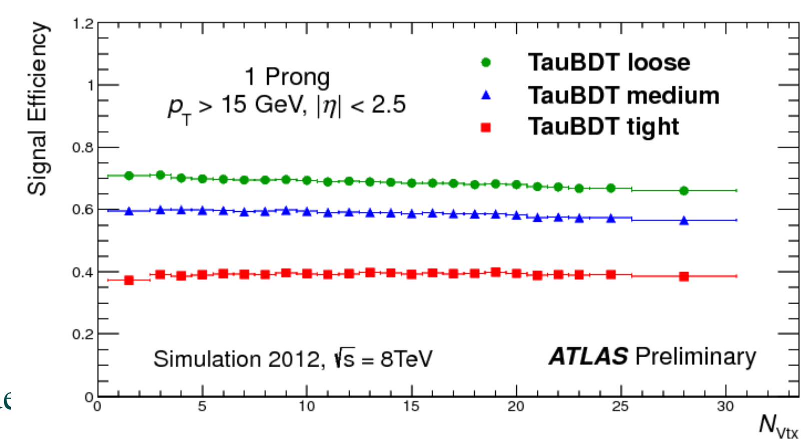
Taus

- Hadronic tau reco
  - narrow isolated jet
  - jet of cone $\Delta R<0.4$, $p_T>10$ GeV and $|\eta|<2.5$
  - energy: calo topoclusters in $\Delta R<0.2$
  - isolation: cone $0.2<\Delta R<0.4$



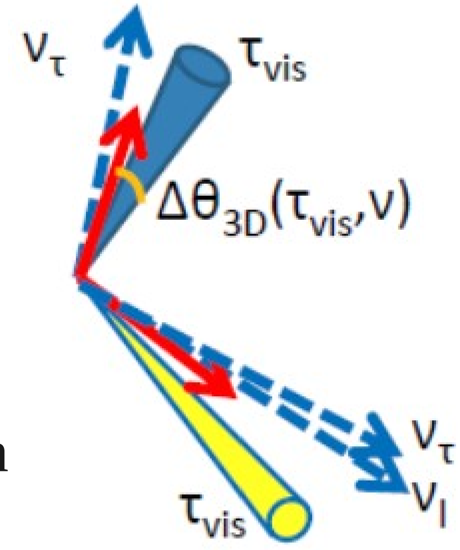
- Identification: τ_{had} jets from QCD jets and electrons
  - discriminating variables: isolation, energy profiles, fractions of EM & Had, energy, angular distances
  - MVA discriminator
  - 1 prompt and 3 prompt separated

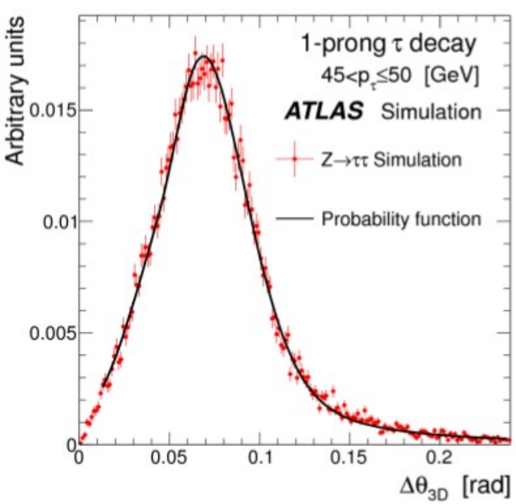




Di-taus mass reconstruction

- Missing mass calculator (MMC)
  - 2 to 4 neutrinos ⇒ missing info to solve system
- Solve equations for each point of grid[$\Delta\varphi(\tau_1,\nu_i)$, $\Delta\varphi(\tau_2,\nu_i)$]
- Weight solutions based on kinematic properties of tau lepton
  - $\Delta\theta 3D(\tau_{vis},\nu)$ template from simulation as PDF
  - Likelihood



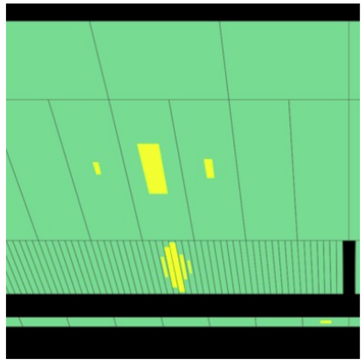


b-tagging

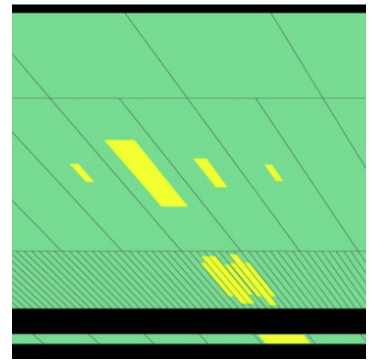
- Impact parameters (IP) of tracks in jet
  - IP3D: track weights based on longitudinal and transverse IP significance
- Displaced secondary vertex
  - SV1: inclusive displaced vertex
  - JetFitter: mutiple vertices along implied b-hadron line of flight
- NN algorithms:
  - JetFitterCombNN: IP3D+JetFitter
  - MV1: IP3D+JetFitterCombNN+SV1

Photon reconstruction

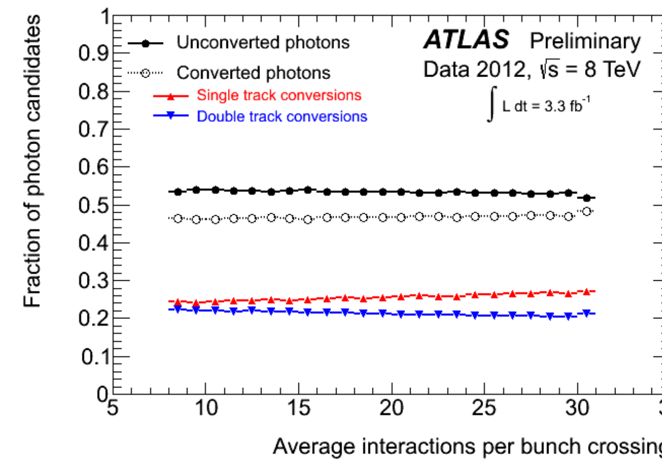
- Identification based on shower shapes in calorimeter:



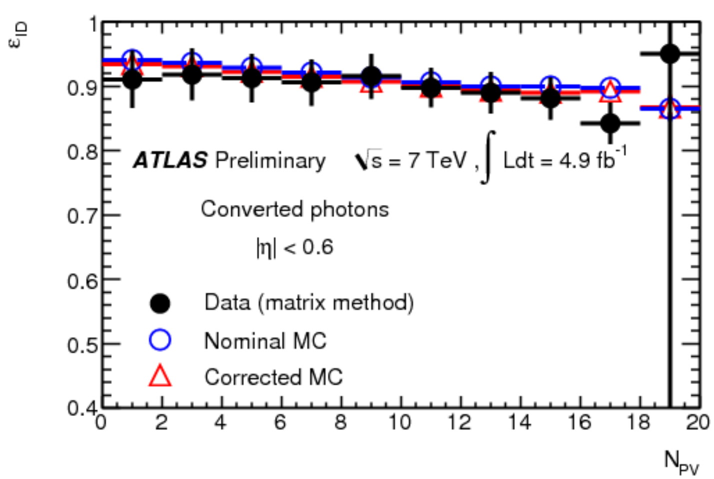
photon

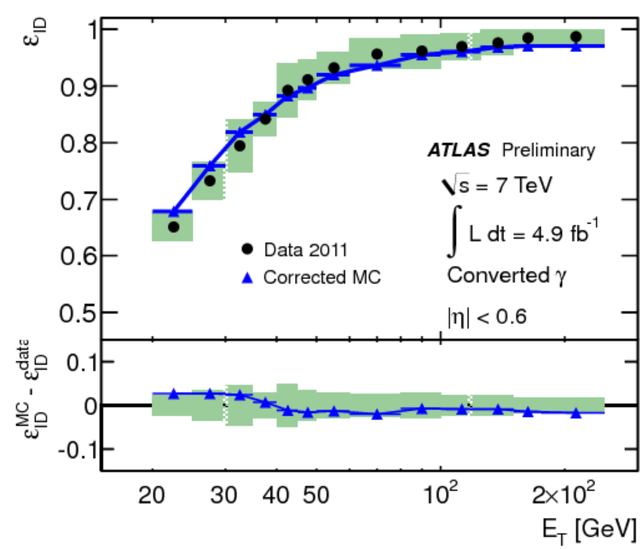


π^0



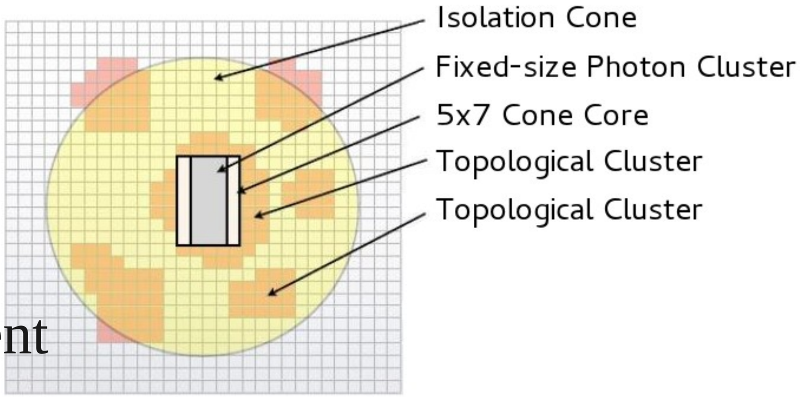
- Data driven efficiency estimate
  - robust against pile-up

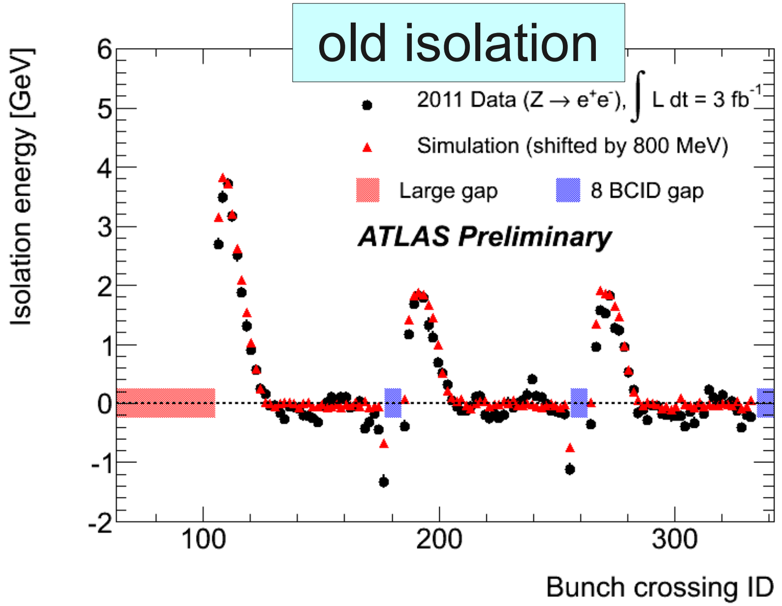


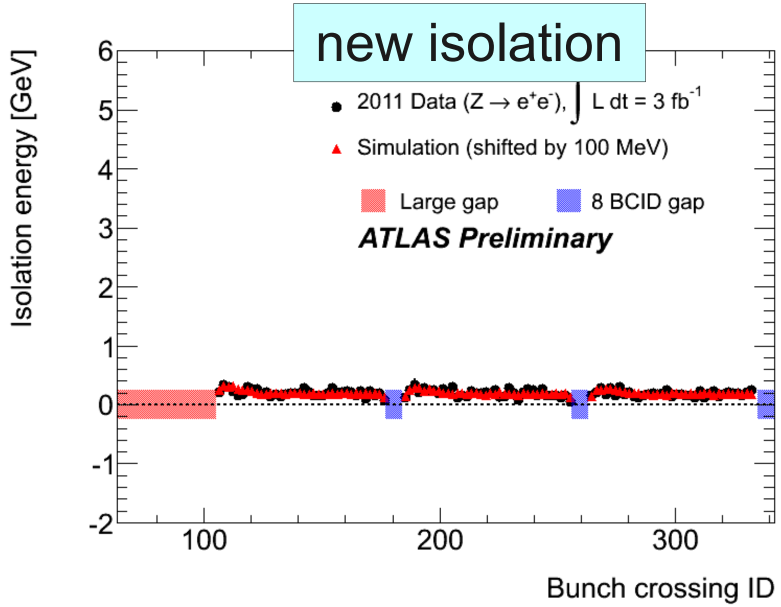


Photon isolation

- Computed from positive-energy topological clusters in calorimeter with $\Delta R < 0.4$
- Corrected for pileup and underlying event by subtracting ambient energy density event-by-event







- Good stability with position of colliding bunches in train → robust with pileup
- Uncertainty on signal yied: 0.4-0.5%

$H \rightarrow ZZ^*$: Selection cuts (1)

Electron

- Trigger:
  - single (24 GeV threshold)
  - di-electron (12 GeV threshold)
  - 100% efficiency
- Reconstruction
  - bremsstralhung recovery
  - identification on shower-shapes
- $p_T > 20/15/10/7$ GeV
- impact parameter
  - along beam axis: 10 mm from PV
- $\Sigma E_T^{\Delta R=0.2}/E_T < 0.2$
- $d_0/\sigma_{d0} < 6.5$

Muon

Trigger:
- single (24 GeV threshold)
- di-muon (13 GeV or 18/8 GeV threshold)
- >97% efficiency

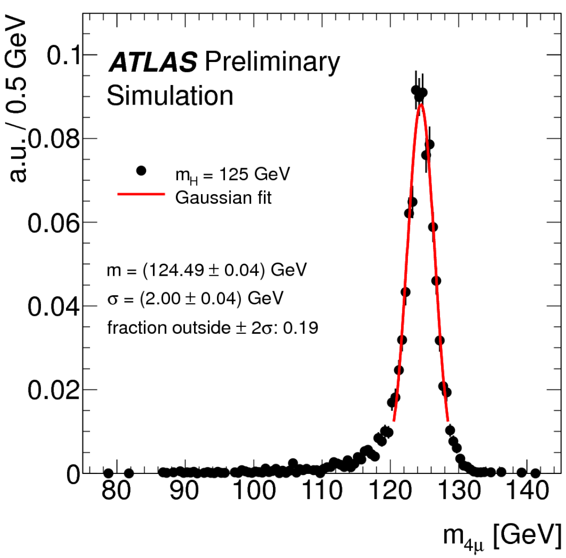
- Reconstruction
  - ID+MS
- $p_T > 20/15/10/6$ GeV
- impact parameter
  - along beam axis: 10 mm from PV
  - along bending plane: 1 mm
- $\Sigma E_T^{\Delta R=0.2}/p_T < 0.3$ (0.15 if no ID track)
- $d_0/\sigma_{d0} < 3.5$

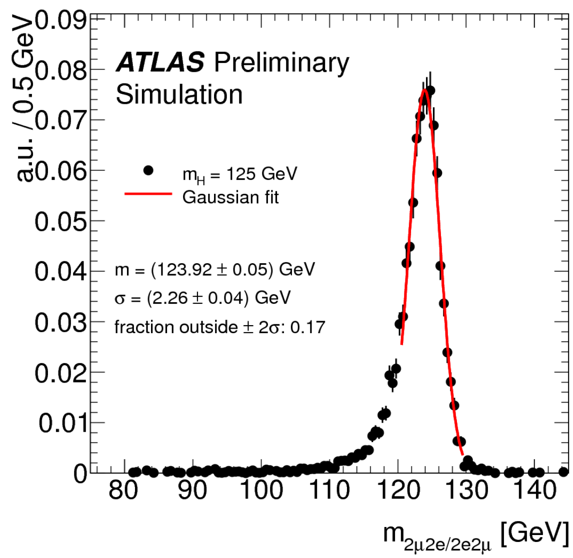
H→ZZ*: Selection cuts (2)

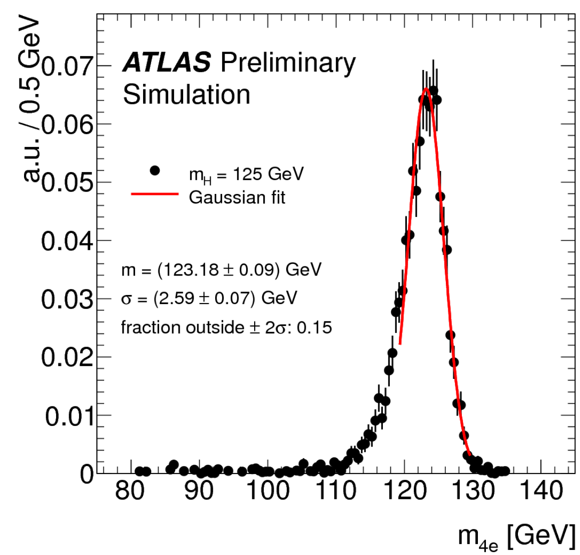
- $\Delta R(e;\mu) > 0.2$, $\Delta R(e;e) > 0.1$, $\Delta R(\mu;\mu) > 0.1$
- $50 < m_{12} < 106$ GeV
  - closest to Z mass
- $m_{min} < m_{34} < 115$ GeV

$m_{4\ell}$ (GeV)	≤ 140	160	165	180	≥ 190
m_{min} (GeV)	17.5	30	35	40	50

- All possible same-flavour opposite-cahrge di-lepton have $m_{\ell\ell} > 5$ GeV

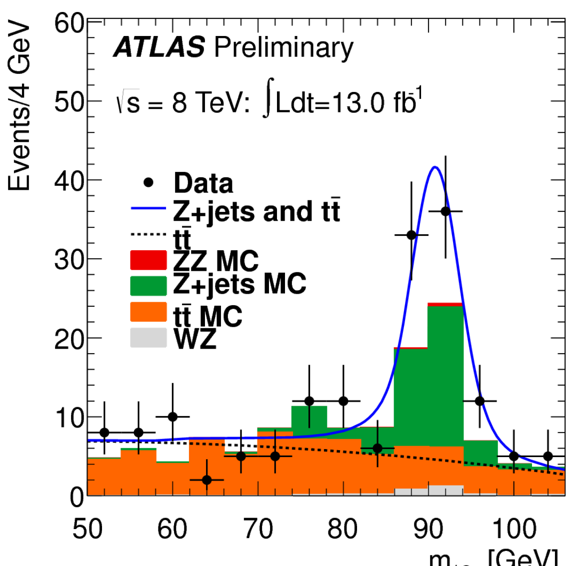


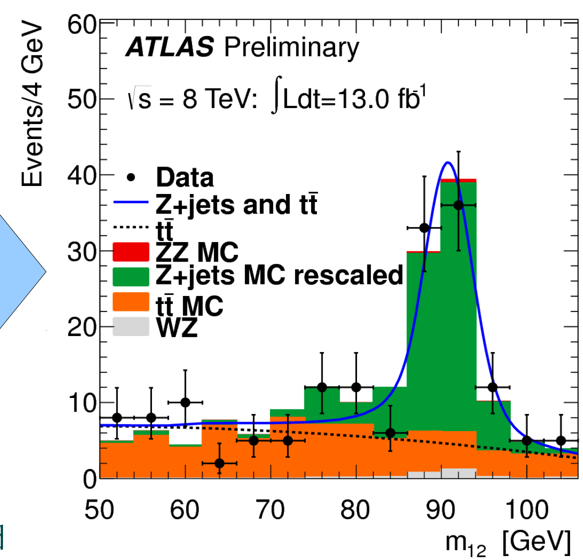




H→ZZ*: Background estimation (1)

- Flavor subleading pair: ℓℓ+μμ
- Main reducible backgrounds: $t\bar{t}$ and Z+jets ($Zb\bar{b}$ + π/K in-flight decays)
  - ~20% of total bkg
- Control region: no isolation cut on sub-leading pair + fail d_0/σ_{d0} cut (remove ZZ) ⇒ $b\bar{b}$ contribution enhanced:
- tt and Z+jets estimated simultaneously through fit to m_{12}
- Extrapolation to signal region through MC transfer factor (with bb MC)
- Checks of background with other control regions (e.g. fail track isolation, eμ+μμ SS pair, ...): compatible results



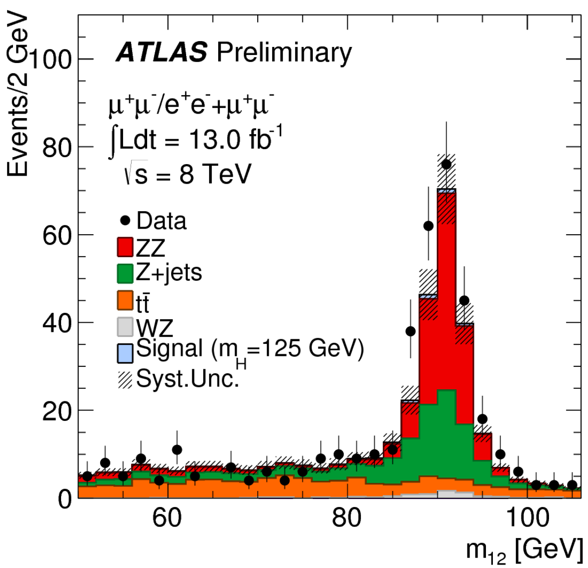


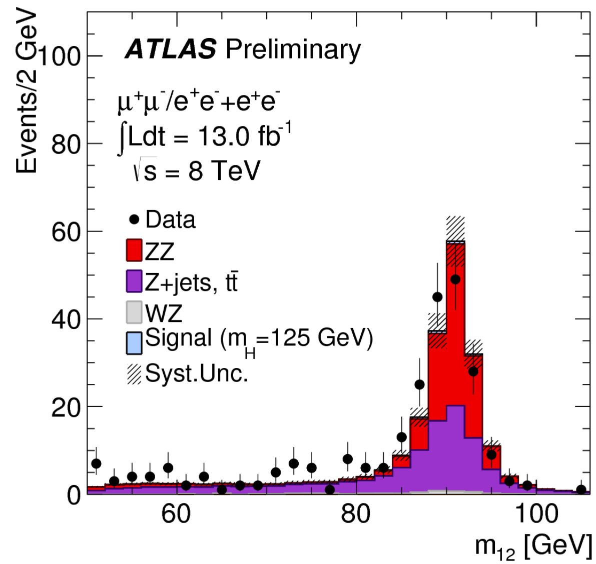
H→ZZ*: Background estimation (2)

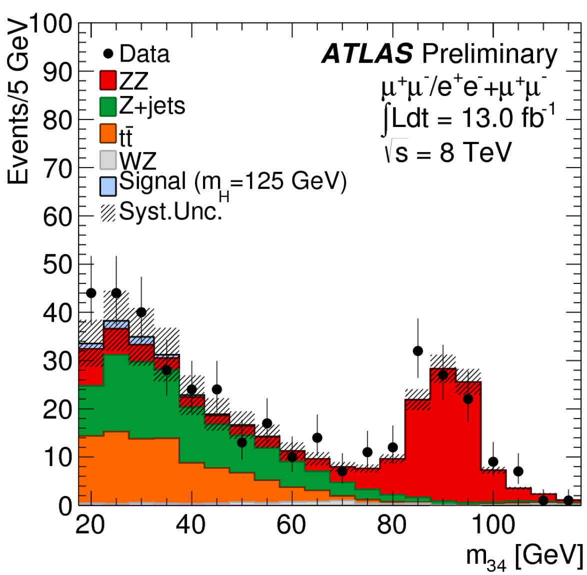
- Flavor subleading pair: ℓℓ+ee
- Main reducible backgrounds: $t\bar{t}$ and Z+jets (heavy flavour decays, jets faking electrons, photon conversion)
  - ~20% of total bkg
- Relax identification criteria
- Separate electron-like and fake-like with shower shapes
- Extrapolate with efficiencies from MC
- Cross check: eg same-sign sub-leading di-electrons

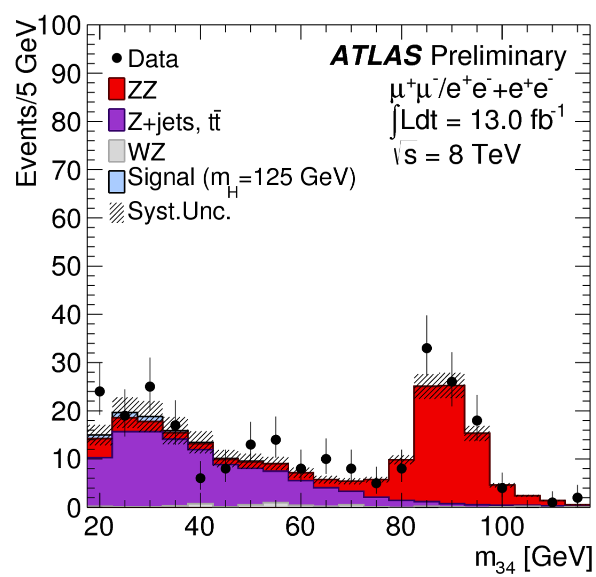
H→ZZ*: Background estimation (3)

- Control region: isolation and impact parameter on the first lepton pair only









H→ZZ*: Background estimation (4)

- Summary:

Method	Estimated number of events
4μ	
m_{12} fit: $Z+$jets contribution	$0.27{\pm}0.10{\pm}0.08^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.02{\pm}0.01{\pm}0.01^{\dagger}$
Sub-leading same sign full analysis	0
$2e2\mu$	
m_{12} fit: $Z+$jets contribution	$0.21{\pm}0.08{\pm}0.06^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.02{\pm}0.01{\pm}0.01^{\dagger}$
Sub-leading same sign full analysis	0
$2\mu 2e$	
$\ell\ell + e^{\pm}e^{\mp}$	$2.6{\pm}\,0.4\,{\pm}0.4^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.7{\pm}\,0.9\,{\pm}0.6$
$3\ell + \ell$ (same-sign)	$2.0{\pm}\,0.5\,{\pm}0.3$
Sub-leading same sign full analysis	0
$4e$	
$\ell\ell + e^{\pm}e^{\mp}$	$3.1{\pm}\,0.6\,{\pm}0.5^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.2{\pm}\,0.6\,{\pm}0.5$
$3\ell + \ell$ (same-sign)	$2.2{\pm}\,0.5\,{\pm}0.3$
Sub-leading same sign full analysis	2

7 TeV

Method	Estimate
4μ	
m_{12} fit: $Z+$jets contribution	$1.8 \pm 0.4 \pm 0.4^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.07 \pm 0.02 \pm 0.02^{\dagger}$
Sub-leading same sign full analysis	0
$2e2\mu$	
m_{12} fit: $Z+$jets contribution	$1.5 \pm 0.3 \pm 0.3^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.08 \pm 0.02 \pm 0.03^{\dagger}$
Sub-leading same sign full analysis	0
$2\mu 2e$	
$\ell\ell + e^{\pm}e^{\mp}$	$4.7 \pm 0.7 \pm 0.7^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.5 \pm 0.7 \pm 0.7$
$3\ell + \ell$ (same-sign)	$4.9 \pm 0.3 \pm 0.5$
Sub-leading same sign full analysis	2
$4e$	
$\ell\ell + e^{\pm}e^{\mp}$	$7.2 \pm 0.9 \pm 0.7^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$4.3 \pm 0.8 \pm 0.6$
$3\ell + \ell$ (same-sign)	$4.5 \pm 0.4 \pm 0.6$
Sub-leading same sign full analysis	6

8 TeV

H→ZZ*: Final selection (1)

100 < m4l < 160 GeV

m4l > 160 GeV

	4μ		$2\mu 2e/2e2\mu$		$4e$	
	Low mass	High mass	Low mass	High mass	Low mass	High mass
$\sqrt{s} = 8$ TeV Integrated Luminosity 13.0 fb^{-1}						
$ZZ^{(*)}$	8.7 ± 0.4	60.3 ± 4.4	7.2 ± 0.4	91.8 ± 7.0	4.4 ± 0.4	38.9 ± 3.1
Z, $Zb\bar{b}$, and $t\bar{t}$	1.4 ± 0.4	0.4 ± 0.1	4.6 ± 1.0	1.4 ± 0.3	5.2 ± 0.8	1.56 ± 0.2
Total Background	10.1 ± 0.6	60.7 ± 4.4	11.8 ± 1.2	93.2 ± 7.0	9.6 ± 0.9	40.5 ± 3.1
Data	16	56	14	115	13	45
$m_H = 123$ GeV	2.7 ± 0.4		3.0 ± 0.4		1.5 ± 0.2	
$m_H = 125$ GeV	3.5 ± 0.4		3.9 ± 0.5		1.9 ± 0.3	
$m_H = 127$ GeV	4.3 ± 0.5		5.0 ± 0.7		2.3 ± 0.3	
$m_H = 400$ GeV	8.6 ± 1.1		14.8 ± 2.0		6.4 ± 1.0	
$m_H = 600$ GeV	1.7 ± 0.2		3.1 ± 0.4		1.4 ± 0.2	
$\sqrt{s} = 7$ TeV Integrated Luminosity 4.6 fb^{-1}						
$ZZ^{(*)}$	2.5 ± 0.1	17.8 ± 1.3	1.8 ± 0.1	26.8 ± 2.0	0.9 ± 0.1	9.8 ± 0.8
Z, $Zb\bar{b}$, and $t\bar{t}$	0.2 ± 0.1	0.06 ± 0.03	2.1 ± 0.5	0.6 ± 0.2	2.3 ± 0.6	0.7 ± 0.2
Total Background	2.7 ± 0.2	17.8 ± 1.3	3.9 ± 0.5	27.4 ± 2.0	3.2 ± 0.6	10.5 ± 0.8
Data	8	25	3	23	3	18
$m_H = 125$ GeV	1.00 ± 0.13		0.98 ± 0.13		0.38 ± 0.05	
$m_H = 400$ GeV	2.18 ± 0.29		3.65 ± 0.51		1.51 ± 0.23	
$m_H = 600$ GeV	0.41 ± 0.05		0.71 ± 0.10		0.32 ± 0.05	

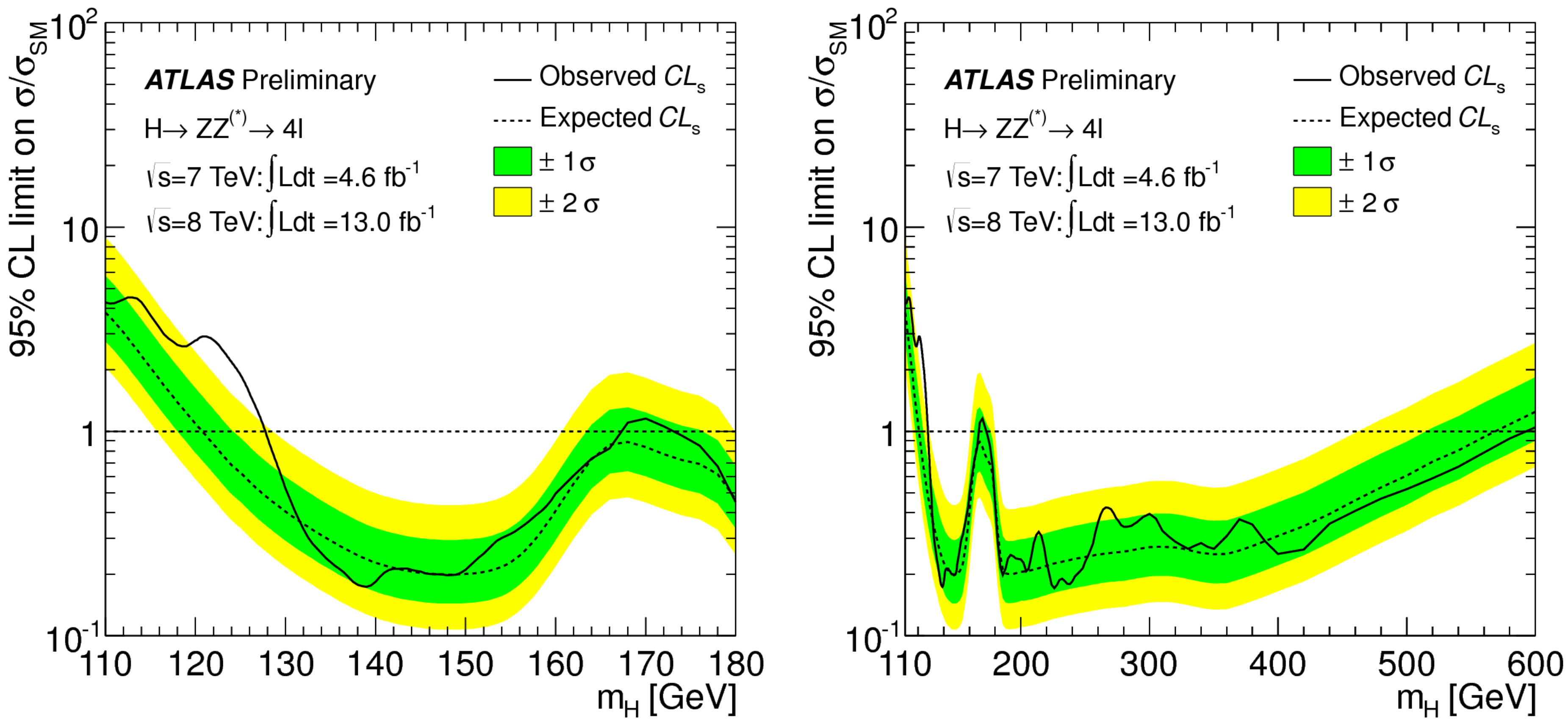
H→ZZ*: Final selection (2)

- In 120- 130 GeV window:

	Signal (m_H=125 GeV)	$ZZ^{(*)}$	$Z+\text{jets}, t\bar{t}$	Observed
		$\sqrt{s}=8$ TeV		
4μ	3.1 ± 0.4	1.55 ± 0.07	0.31 ± 0.09	6
$2\mu 2e$	1.4 ± 0.2	0.56 ± 0.04	0.78 ± 0.16	1
$2e2\mu$	1.9 ± 0.3	0.80 ± 0.04	0.26 ± 0.07	3
$4e$	1.5 ± 0.2	0.77 ± 0.08	1.20 ± 0.19	4
total	7.9 ± 1.1	3.7 ± 0.2	2.6 ± 0.3	14
		$\sqrt{s}=7$ TeV		
4μ	0.88 ± 0.11	0.48 ± 0.02	0.05 ± 0.02	2
$2\mu 2e$	0.32 ± 0.05	0.14 ± 0.01	0.43 ± 0.09	1
$2e2\mu$	0.48 ± 0.06	0.22 ± 0.01	0.04 ± 0.02	1
$4e$	0.28 ± 0.04	0.17 ± 0.02	0.52 ± 0.13	0
total	2.0 ± 0.3	1.0 ± 0.1	1.0 ± 0.2	4
		$\sqrt{s}=8$ TeV and $\sqrt{s}=7$ TeV		
4μ	4.0 ± 0.5	2.03 ± 0.09	0.36 ± 0.09	8
$2\mu 2e$	1.7 ± 0.2	0.70 ± 0.05	1.21 ± 0.18	2
$2e2\mu$	2.4 ± 0.3	1.02 ± 0.05	0.30 ± 0.07	4
$4e$	1.8 ± 0.3	0.94 ± 0.09	1.72 ± 0.23	4
total	9.9 ± 1.3	4.7 ± 0.3	3.6 ± 0.3	18

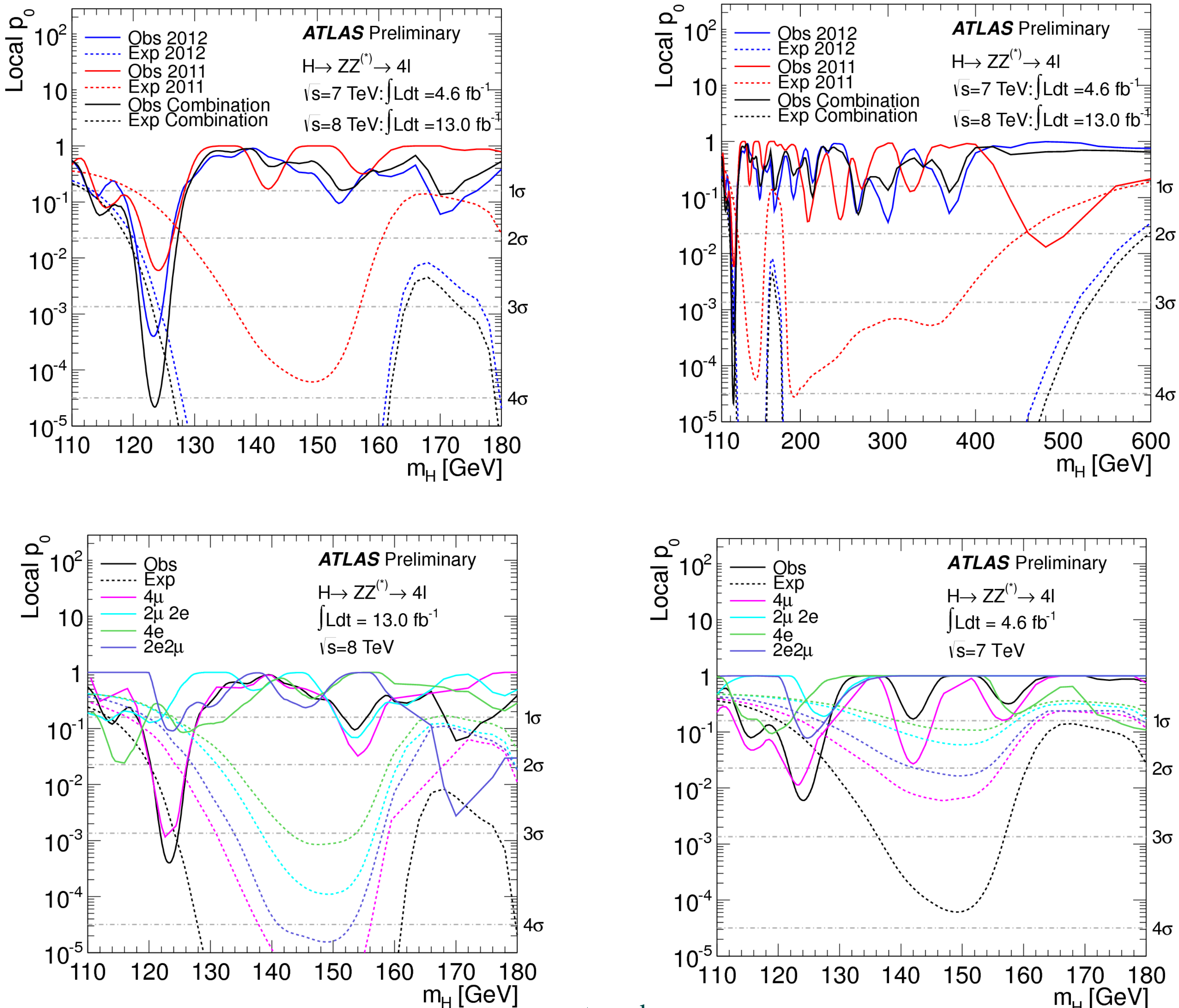
H→ZZ*: Exclusion

- S



H→ZZ*: p0

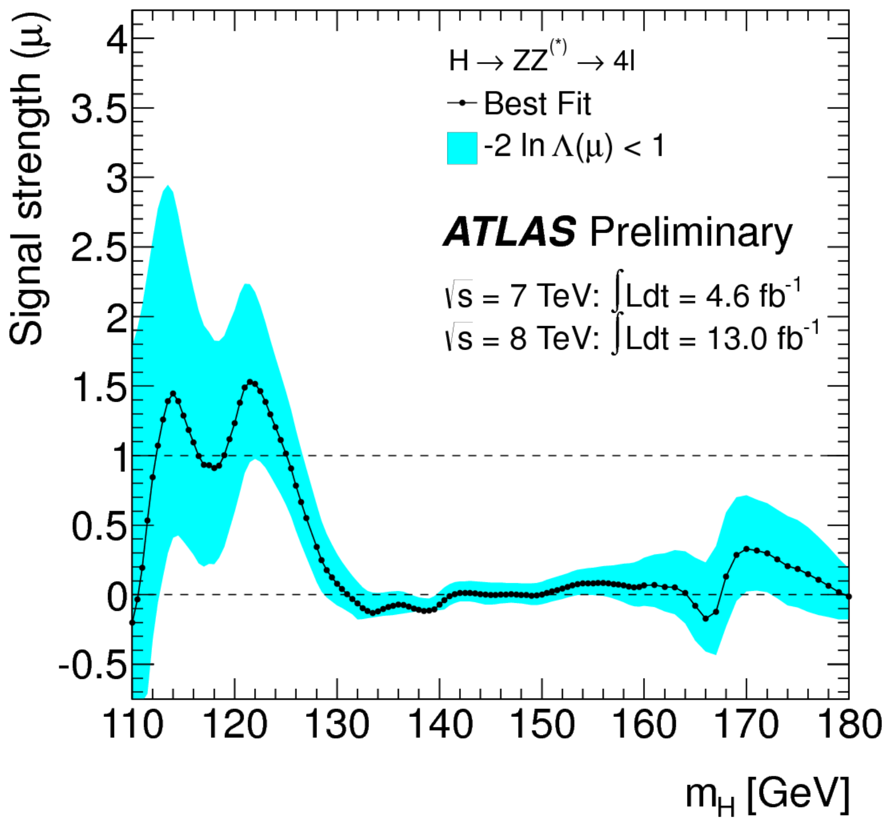
- S

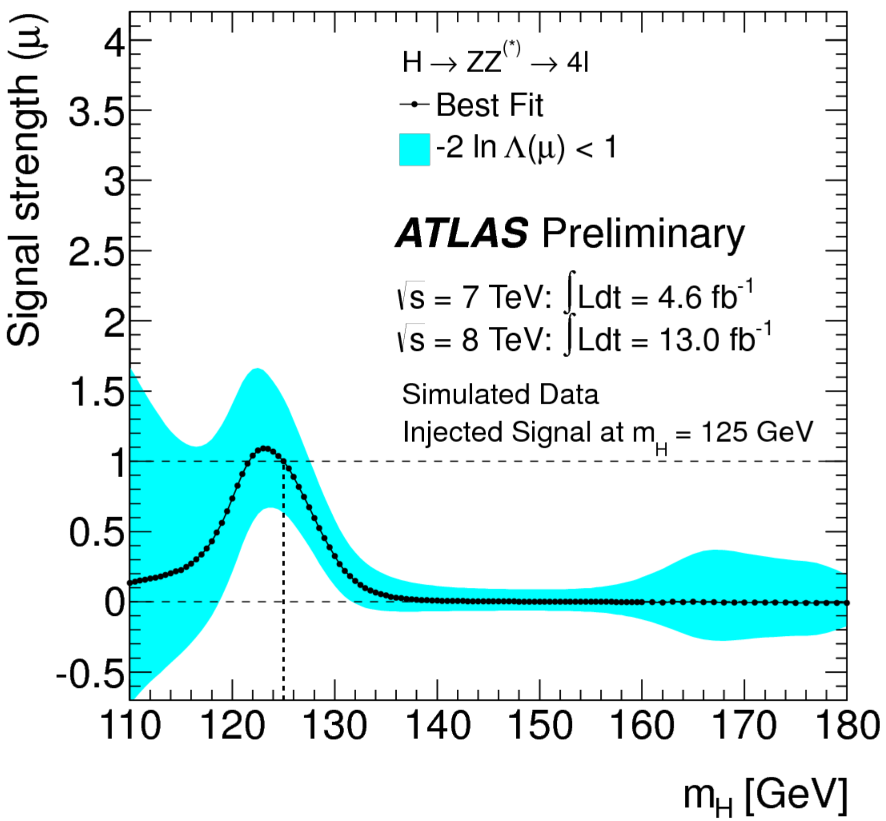


Local p_0
Obs 2012
Exp 2012
Obs 2011
Exp 2011
Obs Combination
Exp Combination
ATLAS Preliminary
H→ ZZ(*)→ 4l
√s=7 TeV: ∫Ldt =4.6 fb-1
√s=8 TeV: ∫Ldt =13.0 fb-1
1σ
2σ
3σ
4σ
m_H [GeV]
Obs
Exp
4μ
2μ 2e
4e
2e2μ
∫Ldt = 13.0 fb-1
√s=8 TeV
∫Ldt = 4.6 fb-1
√s=7 TeV

H→ZZ*: signal strength

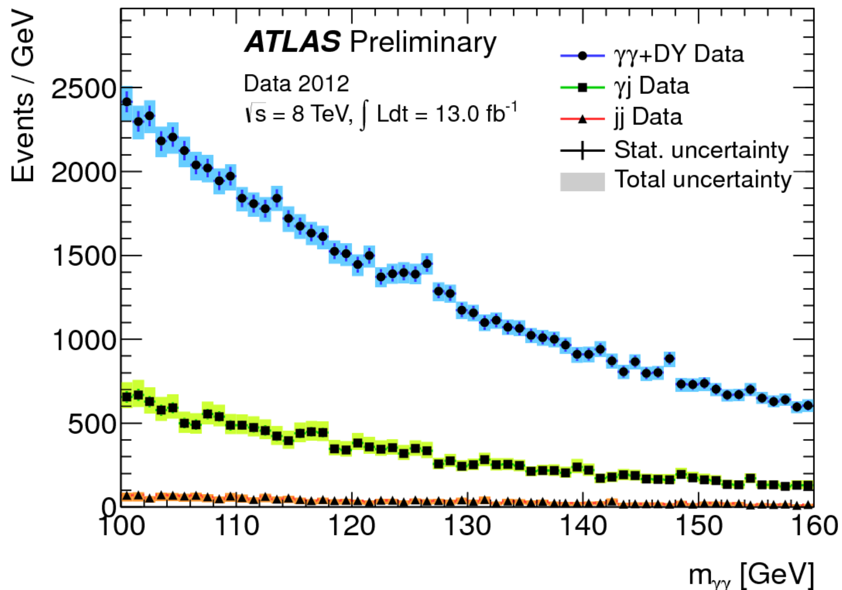
- $\mu = 1.3^{+0.5}_{-0.4}$ at 123.5 GeV (best fit mass)
- $\mu = 0.8^{+0.4}_{-0.3}$ at 126 GeV



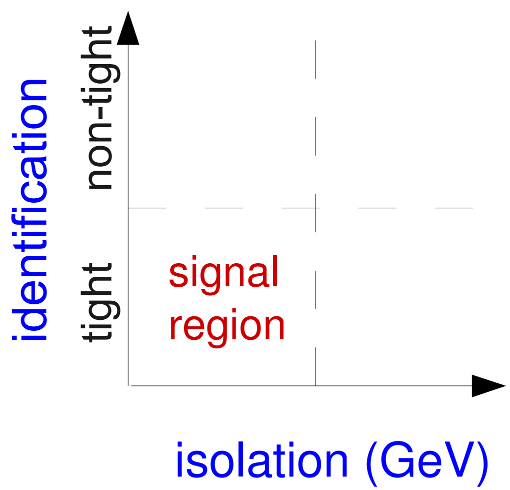


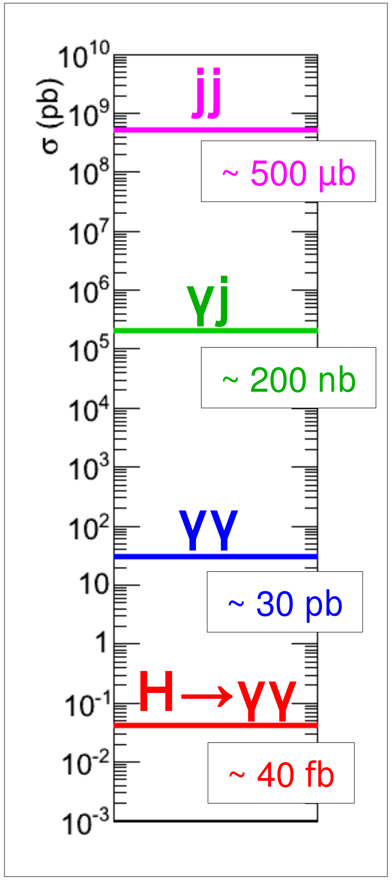
H→γγ: Background composition

- Di-photon purity: data-driven estimate



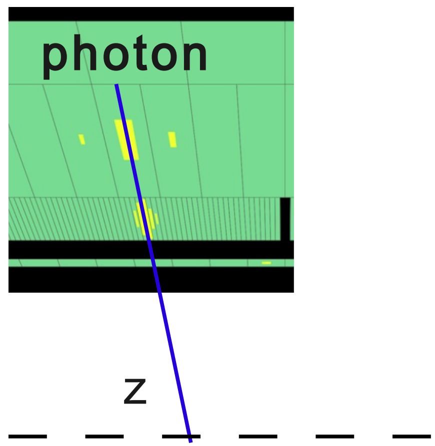
- 2x2D side-band method

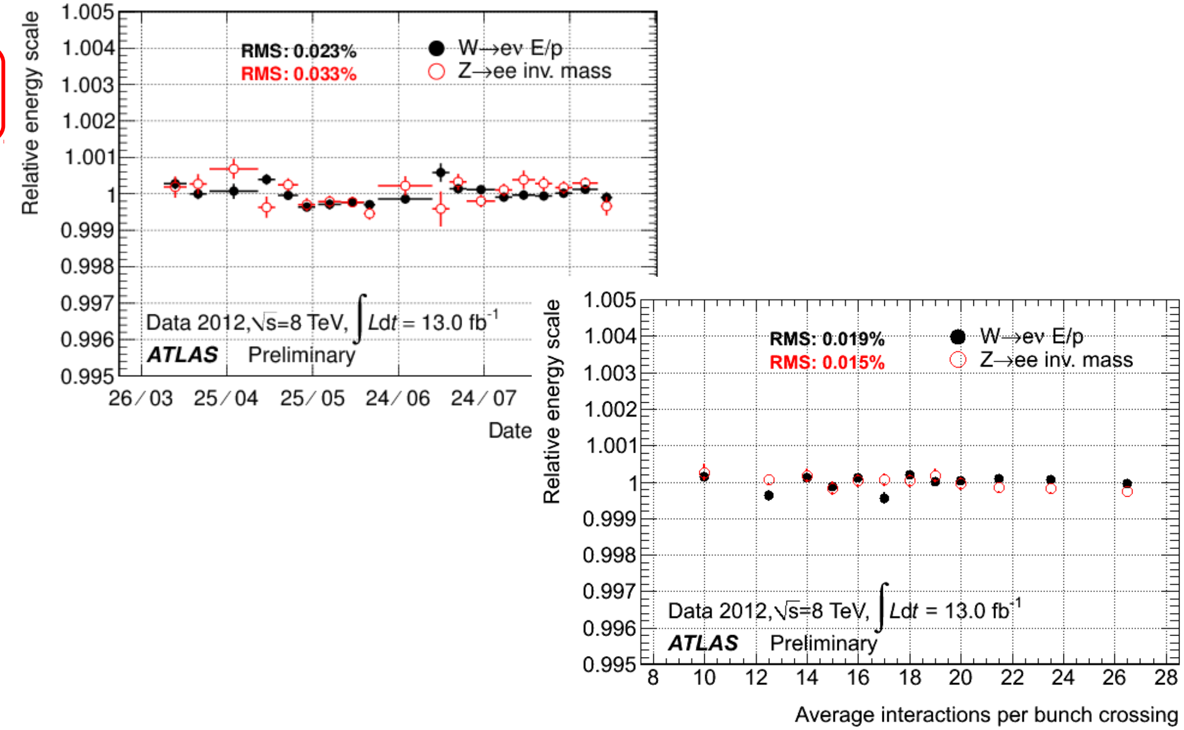


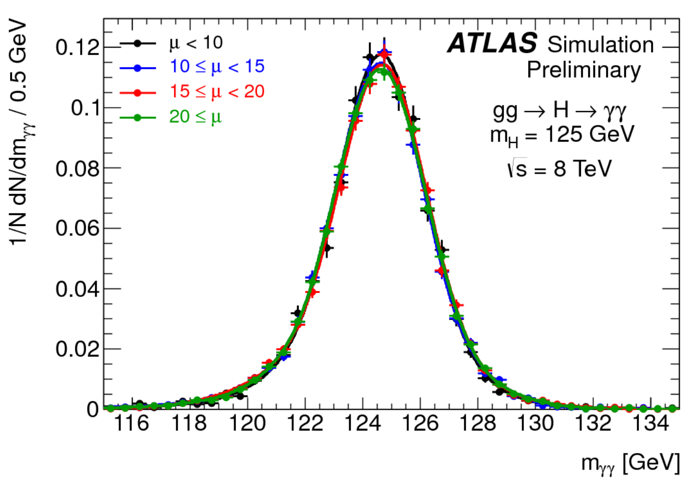


H→γγ: Mass resolution

- $m_{\gamma\gamma}^2 = 2\,E_1\,E_2\,(1-\cos\Delta\varphi(\gamma_1;\gamma_2))$
- Di-photon primary vertex: Calo-pointing







$\sqrt{s}$	8 TeV					
Category	$\sigma_{CB}(GeV)$	FWHM (GeV)	Observed	N_S	N_B	N_S/N_B
Unconv. central, low p_{Tt}	1.47	3.45	569	29	538	0.053
Unconv. central, high p_{Tt}	1.37	3.22	25	4.2	25	0.168
Unconv. rest, low p_{Tt}	1.59	3.75	2773	61	2610	0.023
Unconv. rest, high p_{Tt}	1.52	3.59	148	8.7	138	0.063
Conv. central, low p_{Tt}	1.64	3.86	446	18	417	0.044
Conv. central, high p_{Tt}	1.49	3.51	18	2.8	17	0.163
Conv. rest, low p_{Tt}	1.83	4.32	2898	54	2763	0.019
Conv. rest, high p_{Tt}	1.7	4.00	144	7.4	138	0.053
Conv. transition	2.35	5.57	1872	25	1825	0.014
High Mass two-jet	1.55	3.65	47	6.8	33	0.204
Low Mass two-jet	1.46	3.45	62	4.2	45	0.093
One-lepton	1.63	3.85	18	1.7	16	0.108
Inclusive	1.64	3.87	8802	223	8284	0.027

H→γγ: Categorisation

di-photon selection

↓

1 lepton
W(→ℓν)H, Z(→ℓℓ)H

↓

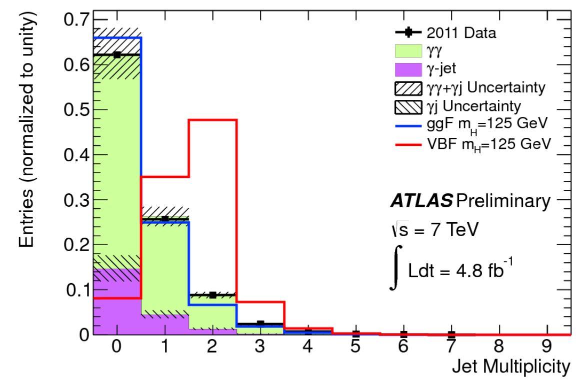
low-mass 2-jets
V(→jj)H

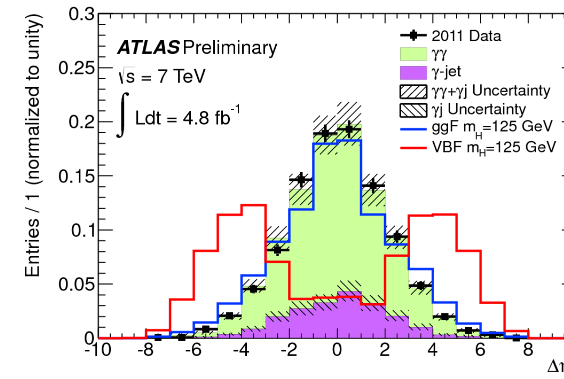
↓

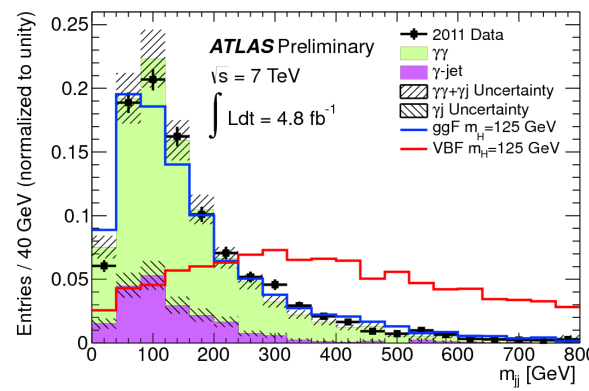
high-mass 2-jets
VBF

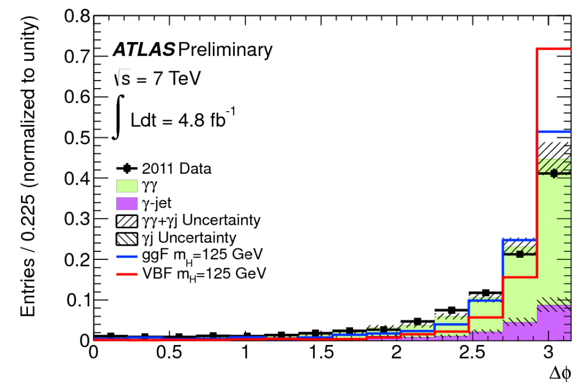
↓

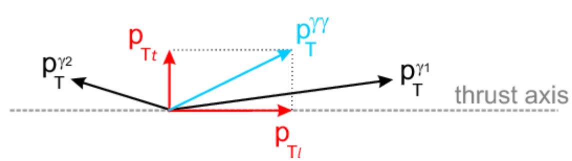
9 p_{Tt} - η - conversion categories
ggF



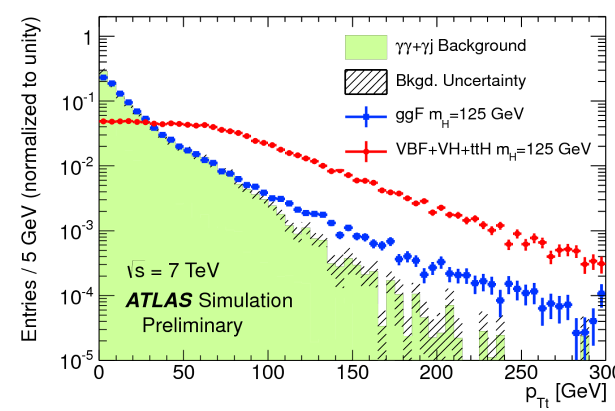








$$\hat{t} = \frac{\vec{p}_T^{\,\gamma 1} - \vec{p}_T^{\,\gamma 2}}{\|\vec{p}_T^{\,\gamma 1} - \vec{p}_T^{\,\gamma 2}\|}$$



H→γγ: Systematic uncertainties

- yield
- resolution
- migration between categories

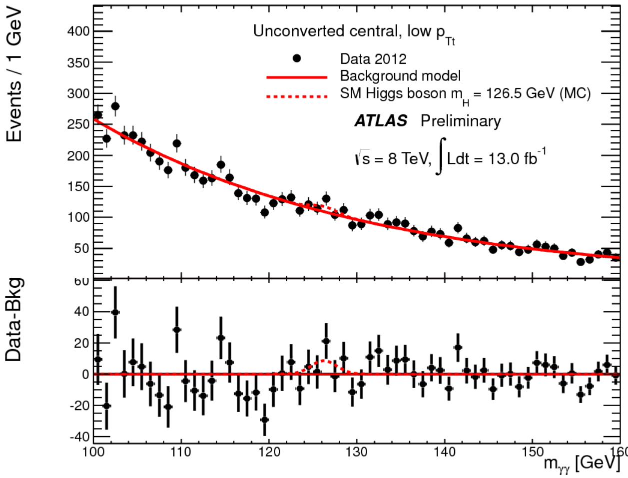
Table 5: Summary of systematic uncertainties impact on the signal yield for the analysis of the 8 data

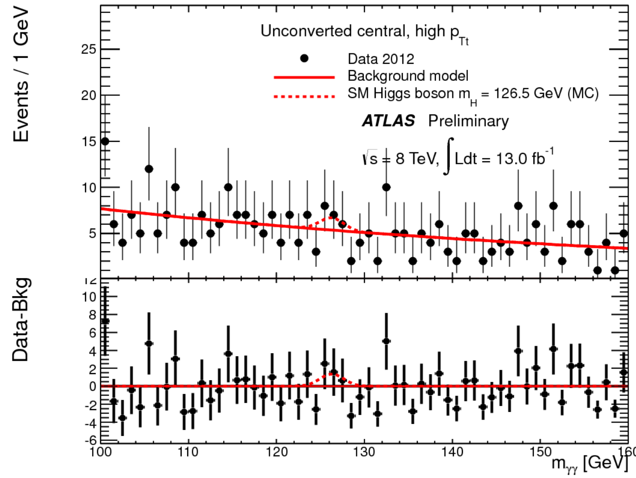
Systematic uncertainties	Value(%)			Constraint
Luminosity	±3.6			
Trigger	±0.5			
Photon ID	±5.3			Log-normal
Isolation	±1.0			
Photon Energy Scale	±0.4			
Branching ratio	±5.9% – ±2.1% (m_H = 110 - 150 GeV)			Asymmetric Log-normal
Scale	ggH: $^{+7.2}_{-7.8}$ ZH: $^{+1.6}_{-1.5}$	VBF: $^{+0.2}_{-0.2}$ ttH: $^{+3.8}_{-9.3}$	WH: $^{+0.2}_{-0.6}$	Asymmetric Log-normal
Pdf+α_s	ggH: $^{+7.5}_{-6.9}$ WH: ±3.5	VBF: $^{+2.6}_{-2.7}$ ZH: ±3.6	ttH: ±7.8	Asymmetric Log-normal
Theory cross section on ggF	High Mass two-jet: 25		Low Mass two-jet: 30	Log-normal

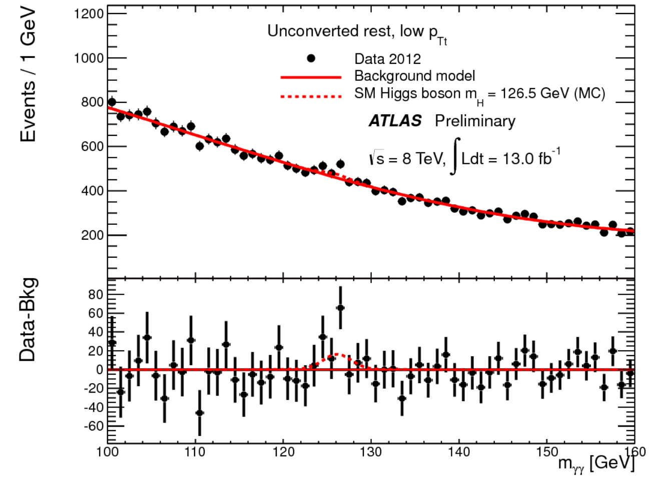
- Resolution:
  - calorimeter energy resolution: 12%.
  - extrapolation of electron calibration to photons (material): 6%
  - pile-up: 1.5%

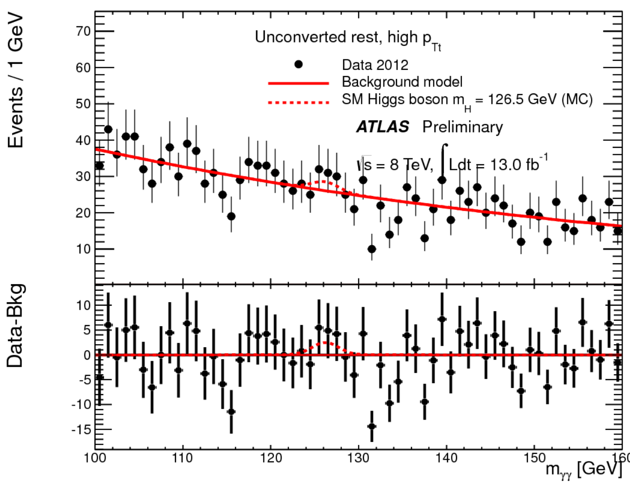
Systematic uncertainties	Value(%)		
Underlying Event	High Mass two-jet category		
	ggH: ±30	VBF: ±6	VH, ttH: ±30
	Low Mass two-jet category		
	ggH: ±7	VBF: ±11	VH, ttH: ±7
Jet Energy Scale	Low p_{Tt}		
resp. Base	ggH: −0.1	VBF: −1.6	Others: −0.2
Flavour (q/g)	−0.1	−1.4	−0.1
Forward	−0.1	−1.6	−0.1
	High p_{Tt}		
	ggH: −0.6	VBF: −2.7	Others: −0.4
	−0.7	−2.5	−0.5
	−0.5	−2.7	−0.2
	High Mass two-jet		
	ggH: +9.2	VBF: +4.5	Others: +13.5
	+9.7	+4.1	+7.0
	+10.7	+4.8	+18.2
	Low Mass two-jet		
	ggH: +2.4	VBF: +4.1	Others: +0.8
	+2.4	+4.1	+0.7
	+0.6	+1.7	+0.04
	one-lepton		
	ggH: +0.0	VBF: +0.0	Others: −0.03
	+0.0	+0.0	−0.03
	+0.0	+0.0	+0.0
Higgs p_T	Low p_{Tt}: +1.3	High p_{Tt}: −10.0	High Mass two-jet: −8.7
	Low Mass two-jet category: −11.00		
	one-lepton category: −0.45		
Material Mismodeling	Unconv: −4.0	Conv: +3.5	
JVF	High Mass two-jet: 18		Low Mass two-jet: 12
e reco	one-lepton category: 2		
e Escale and resolution	one-lepton category: < 1		
μ reco, ID resolution	one-lepton category: < 1		
μ spectrometer resolution	one-lepton category: 2		

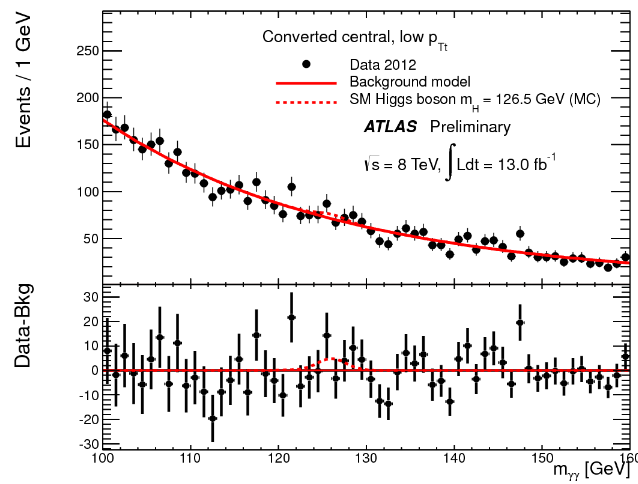
H→γγ: mγγ distributions (1)

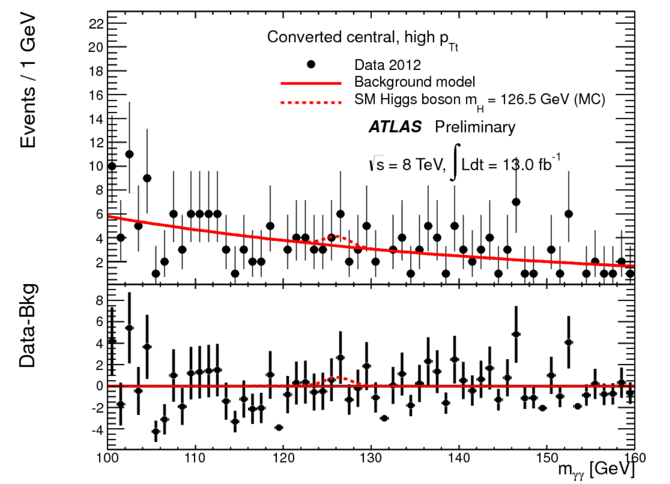




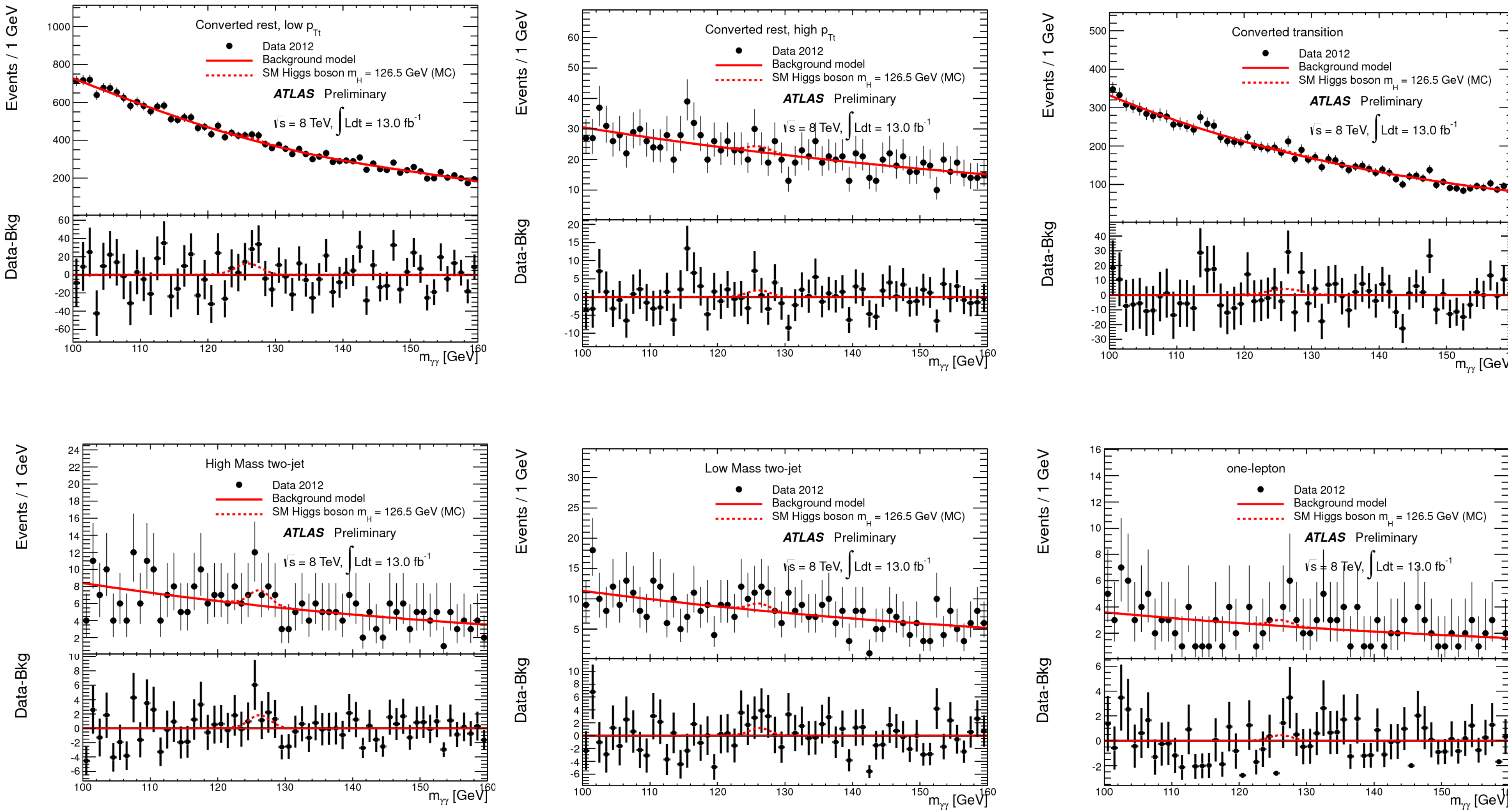






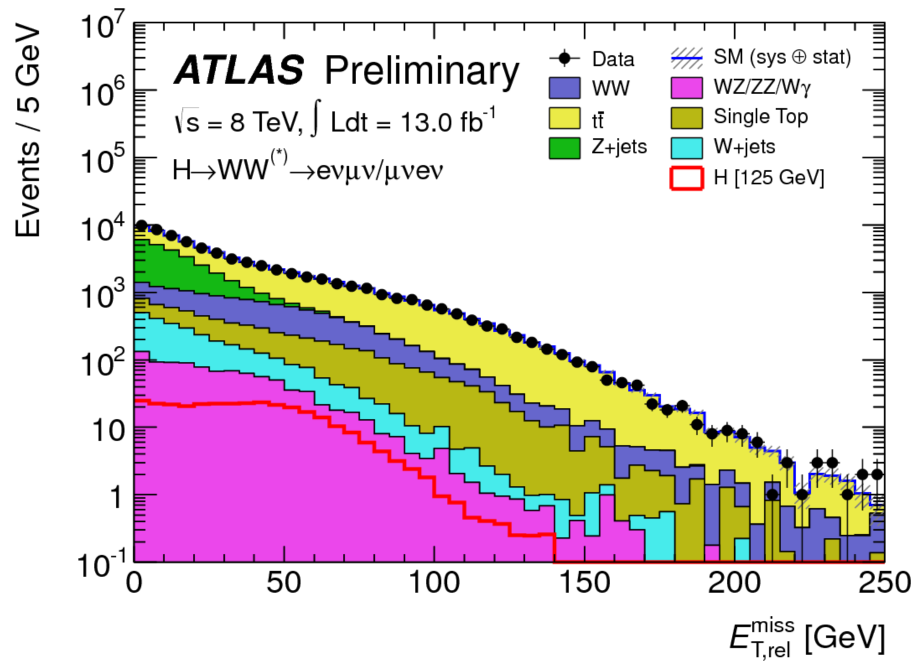


H→γγ: mγγ distributions (2)



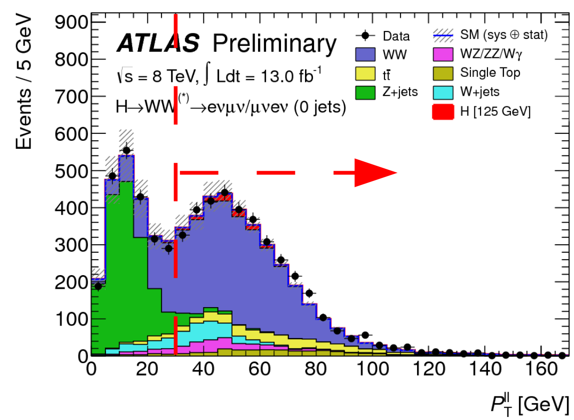
H→WW: Selection cuts (1)

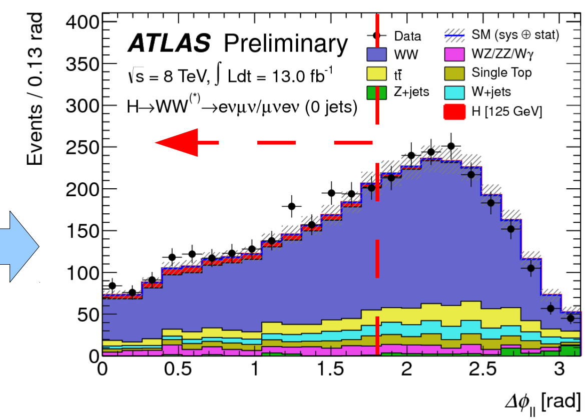
- Reconstruction/identification
  - electron: tight cuts (shower-shapes)
  - muon: ID + muon spectrometer
- p_T > 25/15 GeV
- 10 < $m_{\ell\ell}$ < 50 GeV
- isolation: $\Sigma p_T^{\Delta R=0.2\text{-}0.3}/p_T$ < 0.12-0.2
- $E_T^{miss,rel}$ > 25 GeV
- impact parameter
- $\Delta\varphi_{\ell\ell}$ < 1.8

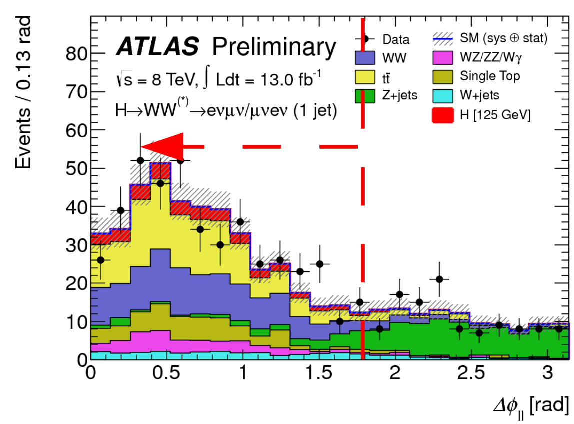


H→WW: Selection cuts (2)

- Jets:
  - anti-kT, $\Delta R = 0.4$
  - $p_T > 25$ GeV for $|\eta| < 2.5$, $p_T > 30$ GeV for $2.5\ |\eta| < 4.5$
- b-tagging:
  - neural network combining track impact parameter and secondary vertex information
  - 85% efficiency
- H + 0 jet
  - $p_T^{\ell\ell} > 30$ GeV
  - $\Delta\varphi(\ell\ell, E_T^{miss}) > \pi/2$
- H + 1 jet
  - jet in not b-tagged
  - rejet $|m_{\tau\tau} - m_Z| < 25$ GeV

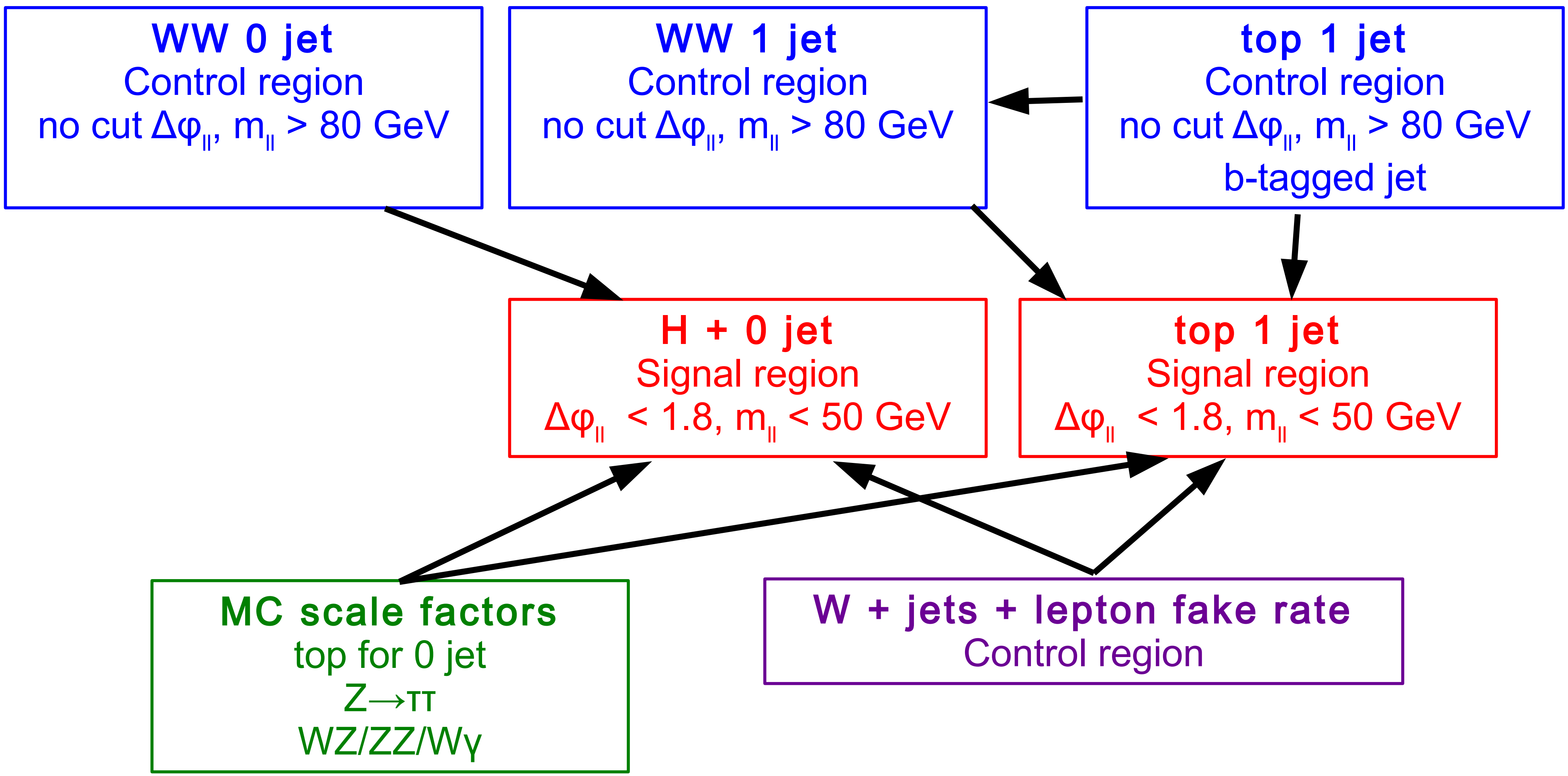






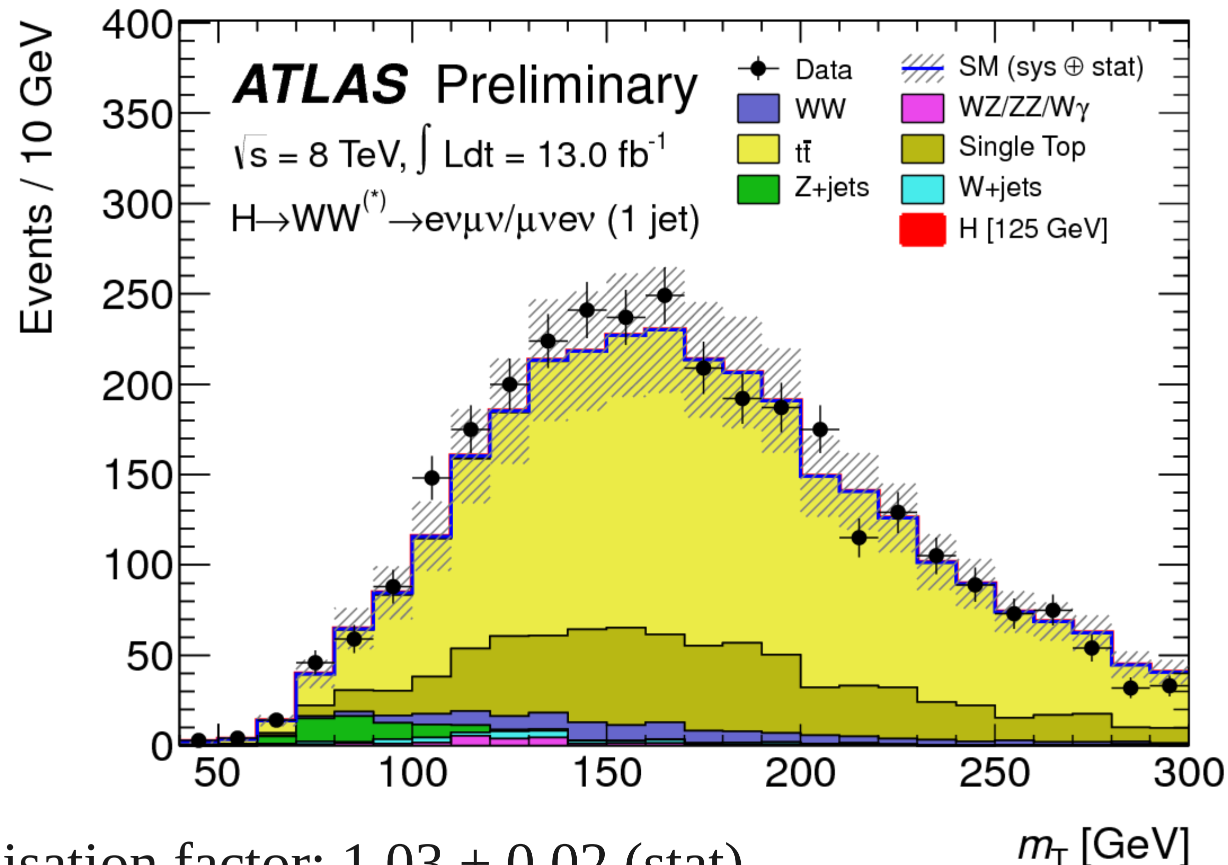
H→WW: Background estimation (1)

- General strategy:



H→WW: Background estimation (2)

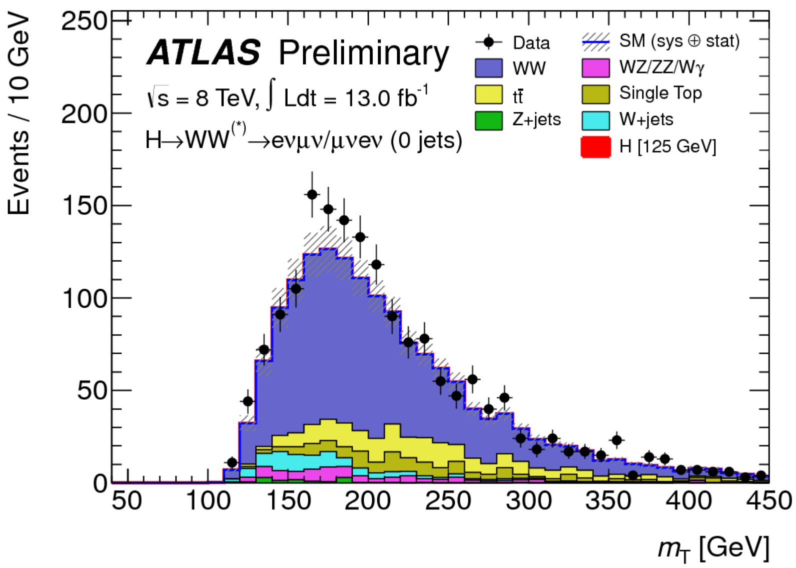
- Top quark control region
  - b-tagged jet
  - remove cuts on $\Delta\varphi_{ll}$ and m_{ll}

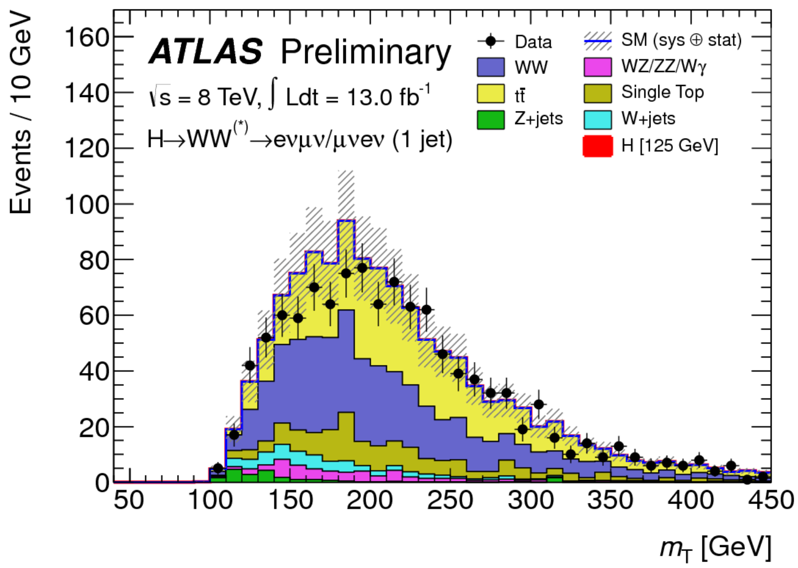


- Normalisation factor: 1.03 ± 0.02 (stat)
- Total uncertainty: 37%

H→WW: Background estimation (3)

- WW control region
  - remove cut on $\Delta\varphi_{ll}$
  - $m_{ll} > 80$ GeV





- Disagreement: jet multiplicity + showering algorithm
- H + 0 jet
  - normalisation factor: 1.13 ± 0.04 (stat)
  - total uncertainty: 13%
- H + 1 jet
  - normalisation factor: 0.84 ± 0.08 (stat)
  - total uncertainty: 54%

H→WW: Background estimation (4)

- W+jets control region
  - anti-identification/isolation on one of leptons
  - extrapolated to signal region: fake-rates
- WZ, ZZ, Wγ from MC
- $Z \rightarrow \tau\tau$
  - $\Delta\varphi_{ll} > 2.8$, $m_{ll} < 80$ GeV
  - difference between data and MC
  - normalisation factors: 0.87± 0.03 (0 jet), 0.85± 0.03 (1 jet)
  - uncertainties: 100 % (0 jet), 42% (1 jet)

H→WW: Background estimation (5)

- Summary:

Cutflow evolution in the different signal regions

$H+$ 0-jet	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W+$ jets	Total Bkg.	Obs.
Jet veto	110 ± 1	3004 ± 12	242 ± 8	387 ± 8	215 ± 8	1575 ± 20	340 ± 5	5762 ± 28	5960
$\Delta\phi_{\ell\ell,E_T^{miss}} > \pi/2$	108 ± 1	2941 ± 12	232 ± 8	361 ± 8	206 ± 8	1201 ± 21	305 ± 5	5246 ± 28	5230
$p_{T,\ell\ell} > 30$ GeV	99 ± 1	2442 ± 11	188 ± 7	330 ± 7	193 ± 8	57 ± 8	222 ± 3	3433 ± 19	3630
$m_{\ell\ell} < 50$ GeV	78.6 ± 0.8	579 ± 5	69 ± 4	55 ± 3	34 ± 3	11 ± 4	65 ± 2	814 ± 9	947
$\Delta\phi_{\ell\ell} < 1.8$	75.6 ± 0.8	555 ± 5	68 ± 4	54 ± 3	34 ± 3	8 ± 4	56 ± 2	774 ± 9	917
$H+$ 1-jet	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W+$ jets	Total Bkg.	Obs.
One jet	59.5 ± 0.8	850 ± 5	158 ± 7	3451 ± 24	1037 ± 17	505 ± 9	155 ± 5	6155 ± 33	6264
b-jet veto	50.4 ± 0.7	728 ± 5	128 ± 5	862 ± 13	283 ± 10	429 ± 8	126 ± 4	2555 ± 20	2655
$Z \to \tau\tau$ veto	50.1 ± 0.7	708 ± 5	122 ± 5	823 ± 12	268 ± 9	368 ± 8	122 ± 4	2411 ± 19	2511
$m_{\ell\ell} < 50$ GeV	37.7 ± 0.6	130 ± 2	39 ± 2	142 ± 5	55 ± 4	99 ± 3	30 ± 2	495 ± 8	548
$\Delta\phi_{\ell\ell} < 1.8$	34.9 ± 0.6	118 ± 2	35 ± 2	134 ± 5	52 ± 4	22 ± 2	24 ± 1	386 ± 8	433

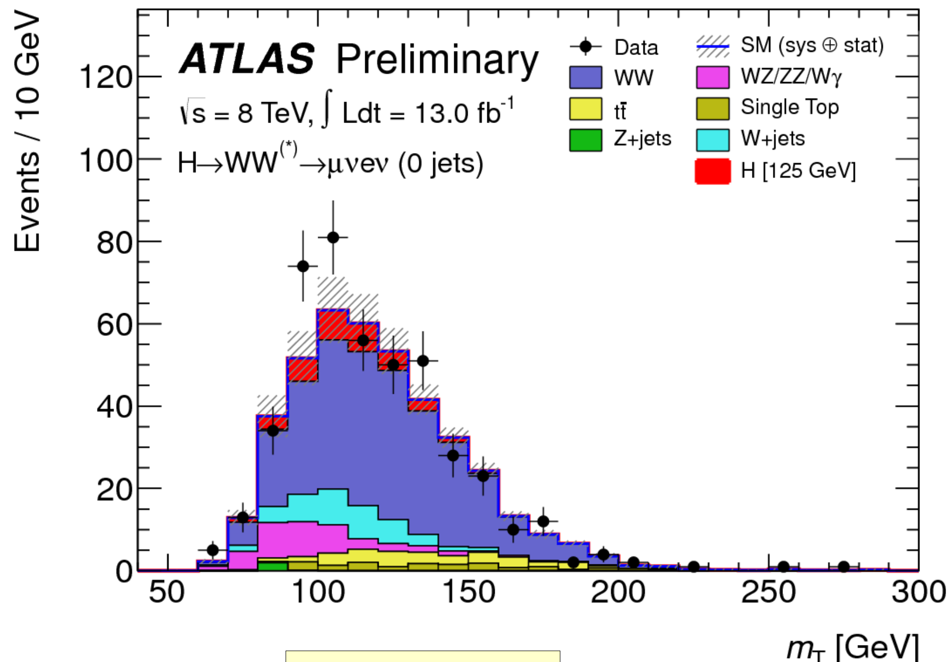
- For $0.75\ m_H < m_T < m_H$ ($m_H = 125$ GeV):

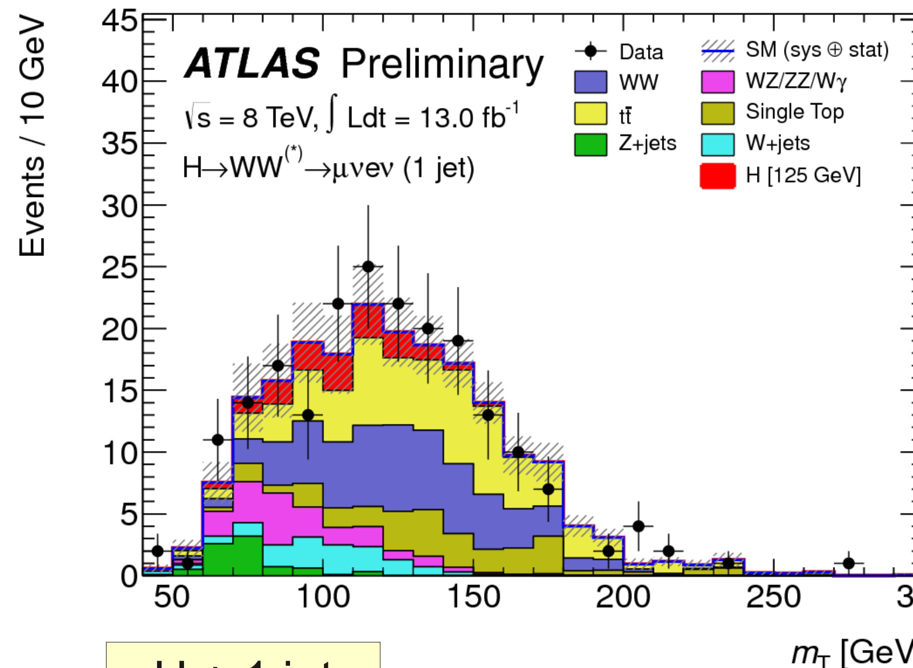
	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W+$ jets	Total Bkg.	Obs.
$H+$ 0-jet	45 ± 9	242 ± 32	26 ± 4	16 ± 2	11 ± 2	4 ± 3	34 ± 17	334 ± 28	423
$H+$ 1-jet	18 ± 6	40 ± 22	10 ± 2	37 ± 13	13 ± 7	2 ± 1	11 ± 6	114 ± 18	141

H→WW: Background estimation (6)

- After all cuts:

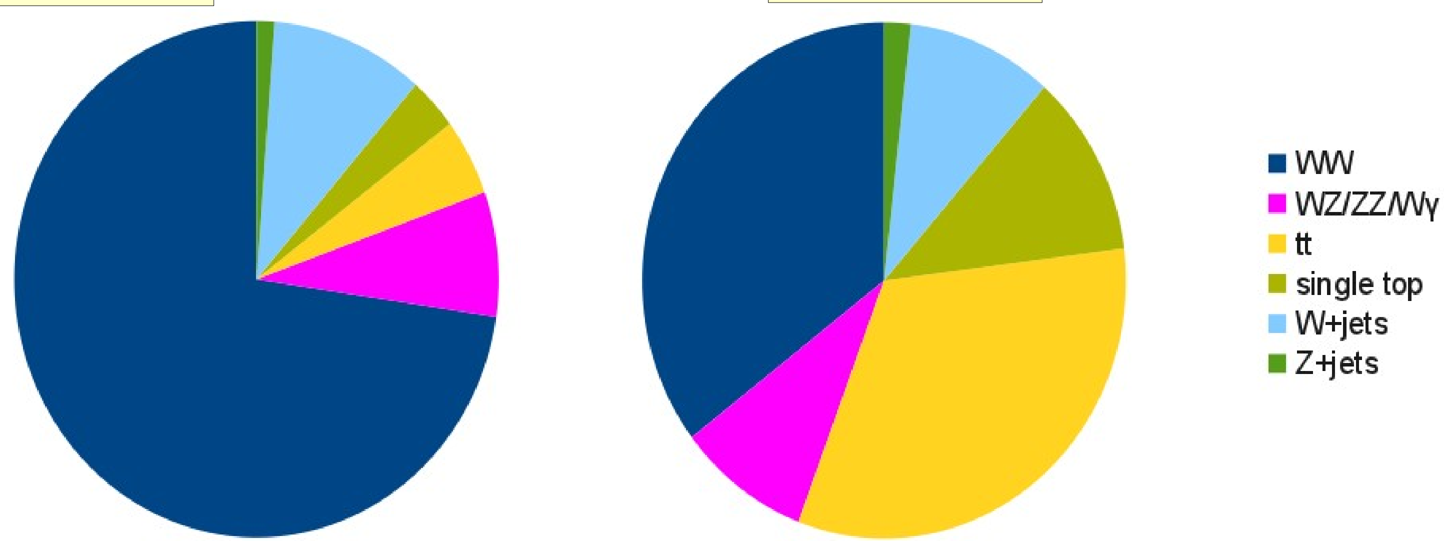
$$m_T = \sqrt{(E_T^{ll}+E_T^{miss})^2 - |\vec{p}_T^{\,ll}+\vec{E}_T^{miss}|^2}$$





H + 0 jet

H + 1 jet



H→WW: Systematic uncertainties

- On signal and bkg events:

Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	13	-
1-jet incl. ggF signal ren./fact. scale	10	-
PDF model (signal only)	8	-
QCD scale (acceptance)	4	-
Jet energy scale and resolution	4	2
W+jets fake factor	-	5
WW theoretical model	-	5
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal ren./fact. scale	26	-
2-jet incl. ggF signal ren./fact. scale	15	-
Parton shower/ U.E. model (signal only)	10	-
b-tagging efficiency	-	11
PDF model (signal only)	7	-
QCD scale (acceptance)	4	2
Jet energy scale and resolution	1	3
W+jets fake factor	-	5
WW theoretical model	-	3

- On signal strength:

Source	Upward uncertainty (%)	Downward uncertainty (%)
Statistical uncertainty	+23	-22
Signal yield ($\sigma \cdot \mathcal{B}$)	+14	-9
Signal acceptance	+9	-6
WW normalisation, theory	+20	-20
Other backgrounds, theory	+9	-9
W+jets fake rate	+11	-12
Experimental + bkg subtraction	+14	-11
MC statistics	+8	-8
Total uncertainty	+41	-38

H→ττ: trigger

- Example of 8 TeV data:

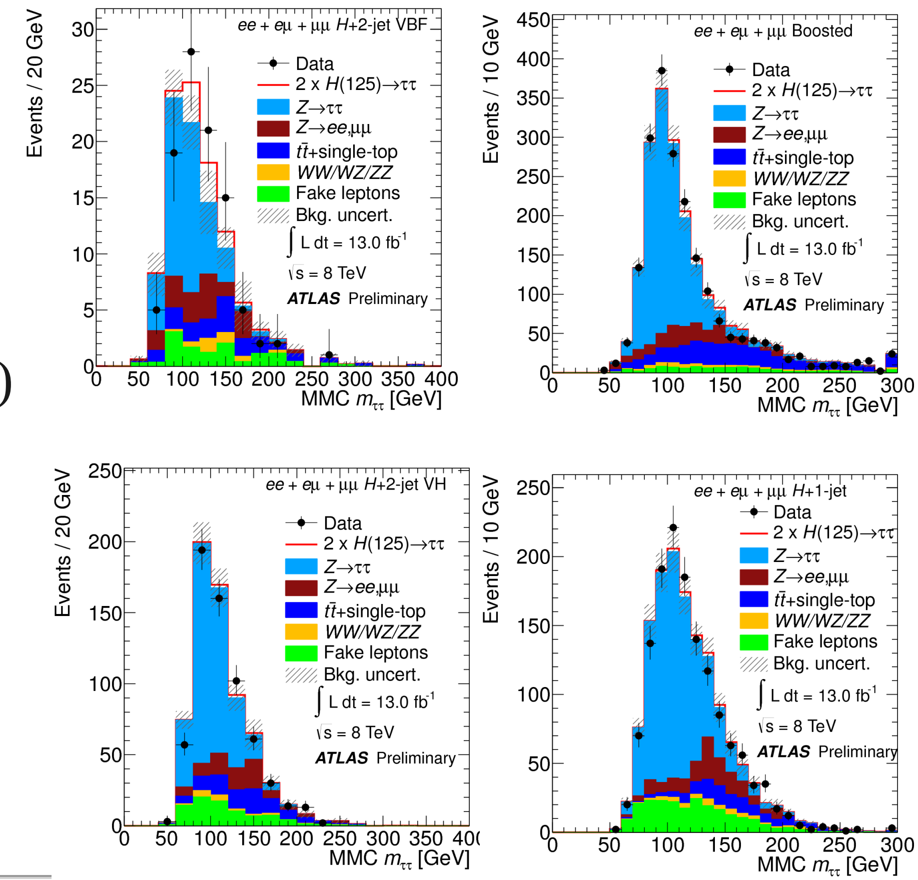
Channel	Trigger	Trigger p_T Threshold (GeV)	Offline p_T Threshold (GeV)
$H \to \tau_{lep}\tau_{lep}$	single electron	${p_T}^e > 24$	${p_T}^e > 25$ ${p_T}^\mu > 10$
	di-electron	${p_T}^{e1} > 12$ ${p_T}^{e2} > 12$	${p_T}^{e1} > 15$ ${p_T}^{e2} > 15$
	di-muon	${p_T}^{\mu 1} > 18$ ${p_T}^{\mu 2} > 8$	${p_T}^{\mu 1} > 20$ ${p_T}^{\mu 2} > 10$
	$e - \mu$ combined	${p_T}^e > 12$ ${p_T}^\mu > 8$	${p_T}^e > 15$ ${p_T}^\mu > 10$
$H \to \tau_{lep}\tau_{had}$	single electron	${p_T}^e > 24$ –	${p_T}^e > 26$ ${p_T}^{\tau_{\text{had-vis}}} > 20$
	single muon	${p_T}^\mu > 24$ –	${p_T}^\mu > 26$ ${p_T}^{\tau_{\text{had-vis}}} > 20$
	combined $e + \tau_{\text{had-vis}}$	${p_T}^e > 18$ ${p_T}^{\tau_{\text{had-vis}}} > 20$	$20 < {p_T}^e < 26$ ${p_T}^{\tau_{\text{had-vis}}} > 25$
	combined $\mu + \tau_{\text{had-vis}}$	${p_T}^\mu > 15$ ${p_T}^{\tau_{\text{had-vis}}} > 20$	$17 < {p_T}^\mu < 26$ ${p_T}^{\tau_{\text{had-vis}}} > 25$
$H \to \tau_{had}\tau_{had}$	combined two τ_{had}	${p_T}^{\tau_{\text{had-vis}}} > 29$ ${p_T}^{\tau_{\text{had-vis}}} > 20$	${p_T}^{\tau_{\text{had-vis}}} > 40$ ${p_T}^{\tau_{\text{had-vis}}} > 25$

$H \rightarrow \tau_{lep}\tau_{lep}$: selection

2-jet VBF	Boosted	2-jet VH	1-jet
Pre-selection: exactly two leptons with opposite charges			
30 GeV $< m_{\ell\ell} <$ 75 GeV (30 GeV $< m_{\ell\ell} <$ 100 GeV) for same-flavor (different-flavor) leptons, and $p_{T,\ell 1} + p_{T,\ell 2} >$ 35 GeV			
At least one jet with $p_T >$ 40 GeV ($\lvert JVF_{\mathrm{jet}}\rvert >$ 0.5 if $\lvert\eta_{\mathrm{jet}}\rvert <$ 2.4)			
$E_{\mathrm{T}}^{\mathrm{miss}} >$ 40 GeV ($E_{\mathrm{T}}^{\mathrm{miss}} >$ 20 GeV) for same-flavor (different-flavor) leptons			
$H_{\mathrm{T}}^{\mathrm{miss}} >$ 40 GeV for same-flavor leptons			
$0.1 < x_{1,2} < 1$			
$0.5 < \Delta\phi_{\ell\ell} < 2.5$			
$p_{T,j2} >$ 25 GeV (JVF)	excluding 2-jet VBF	$p_{T,j2} >$ 25 GeV (JVF)	excluding 2-jet VBF, Boosted and 2-jet VH
$\Delta\eta_{jj} > 3.0$	$p_{T,\tau\tau} >$ 100 GeV	excluding Boosted	$m_{\tau\tau j} >$ 225 GeV
$m_{jj} >$ 400 GeV	b-tagged jet veto	$\Delta\eta_{jj} < 2.0$	b-tagged jet veto
b-tagged jet veto	–	30 GeV $< m_{jj} <$ 160 GeV	–
Lepton centrality and CJV		b-tagged jet veto	
0-jet (7 TeV only)			
Pre-selection: exactly two leptons with opposite charges			
Different-flavor leptons with 30 GeV $< m_{\ell\ell} <$ 100 GeV and $p_{T,\ell 1} + p_{T,\ell 2} >$ 35 GeV			
$\Delta\phi_{\ell\ell} > 2.5$			
b-tagged jet veto			

H→$\tau_{lep}\tau_{lep}$: background estimation

- $Z\to\tau\tau$: embedding procedure
- top: from MC
  - scale factors from control region (b-tagged)
- $Z\to ee,\ \mu\mu$: from MC
  - scale factors from control region (low E_T^{miss})
- fake leptons: data
  - control region with reversed isolation
- Diboson: MC
  - checked from control region (3 leptons)
- Summary for 8 TeV:



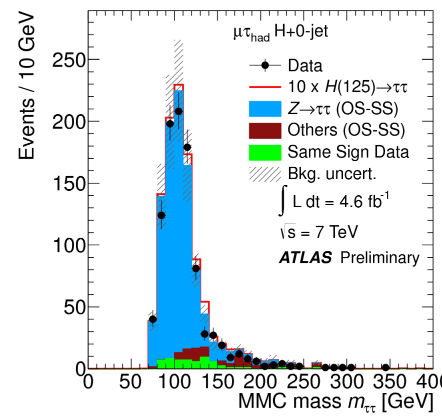
	ee + μμ + eμ			
	VBF category	Boosted category	VH category	1-jet category
$gg\to H$ (125 GeV)	$1.3\pm0.2\pm0.4$	$12.4\pm0.6\pm2.9$	$2.5\pm0.3\pm0.6$	$7.0\pm0.5\pm1.6$
VBF H (125 GeV)	$3.63\pm0.10\pm0.02$	$3.36\pm0.09\pm0.30$	$0.21\pm0.03\pm0.02$	$1.82\pm0.07\pm0.18$
VH (125 GeV)	$0.01\pm0.01\pm0.01$	$2.20\pm0.05\pm0.22$	$0.64\pm0.03\pm0.09$	$0.44\pm0.02\pm0.05$
$Z/\gamma^*\to\tau\tau$ embedded	$47\pm2\pm1$	$(1.24\pm0.01\pm0.08)\times10^3$	$393\pm7\pm26$	$(0.86\pm0.01\pm0.06)\times10^3$
$Z/\gamma^*\to\ell\ell$	$14\pm3\pm2$	$(0.21\pm0.02\pm0.04)\times10^3$	$(0.08\pm0.01\pm0.02)\times10^3$	$(0.16\pm0.01\pm0.03)\times10^3$
Top	$15\pm2\pm3$	$(0.39\pm0.01\pm0.07)\times10^3$	$87\pm4\pm23$	$117\pm5\pm18$
Diboson	$3.6\pm0.8\pm0.6$	$55\pm3\pm10$	$15\pm1\pm4$	$40\pm3\pm7$
Backgrounds with fake leptons	$12\pm2\pm3$	$102\pm7\pm23$	$86\pm4\pm16$	$230\pm8\pm52$
Total background	$91\pm5\pm5$	$(2.01\pm0.03\pm0.12)\times10^3$	$(0.66\pm0.02\pm0.05)\times10^3$	$(1.40\pm0.02\pm0.08)\times10^3$
Observed data	98	2014	636	1405

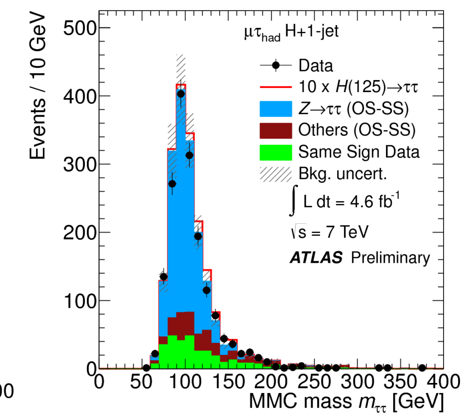
$H \rightarrow \tau_{lep} \tau_{had}$: selection

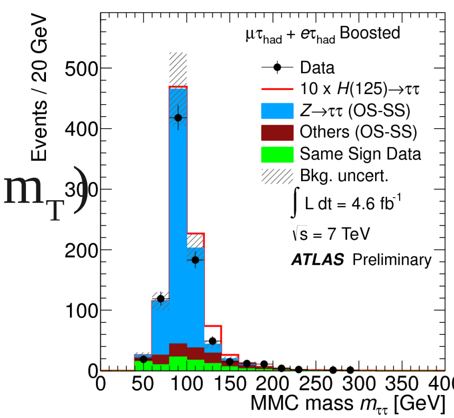
7 TeV		8 TeV	
VBF Category	Boosted Category	VBF Category	Boosted Category
▹ $p_T^{\tau_{\text{had-vis}}}$ >30 GeV	–	▹ $p_T^{\tau_{\text{had-vis}}}$ >30 GeV	▹ $p_T^{\tau_{\text{had-vis}}}$ >30 GeV
▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV
▹ ≥ 2 jets	▹ $p_T^H > 100$ GeV	▹ ≥ 2 jets	▹ $p_T^H > 100$ GeV
▹ $p_T^{j1}, p_T^{j2} > 40$ GeV	▹ $0 < x_1 < 1$	▹ $p_T^{j1} > 40$, p_T^{j2} >30 GeV	▹ $0 < x_1 < 1$
▹ $\Delta\eta_{jj} > 3.0$	▹ $0.2 < x_2 < 1.2$	▹ $\Delta\eta_{jj} > 3.0$	▹ $0.2 < x_2 < 1.2$
▹ $m_{jj} > 500$ GeV	▹ Fails VBF	▹ $m_{jj} > 500$ GeV	▹ Fails VBF
▹ centrality req.	–	▹ centrality req.	–
▹ $\eta_{j1} \times \eta_{j2} < 0$	–	▹ $\eta_{j1} \times \eta_{j2} < 0$	–
▹ $p_T^{\text{Total}} < 40$ GeV	–	▹ $p_T^{\text{Total}} < 30$ GeV	–
–	–	▹ p_T^{ℓ} >26 GeV	–
• m_T <50 GeV	• m_T <50 GeV	• m_T <50 GeV	• m_T <50 GeV
• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 1.6$	• $\sum \Delta\phi < 2.8$	–
–	–	• b-tagged jet veto	• b-tagged jet veto
1 Jet Category	0 Jet Category	1 Jet Category	0 Jet Category
▹ ≥ 1 jet, p_T >25 GeV	▹ 0 jets p_T >25 GeV	▹ ≥ 1 jet, p_T >30 GeV	▹ 0 jets p_T >30 GeV
▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV	▹ E_T^{miss} >20 GeV
▹ Fails VBF, Boosted	▹ Fails Boosted	▹ Fails VBF, Boosted	▹ Fails Boosted
• m_T <50 GeV	• m_T <30 GeV	• m_T <50 GeV	• m_T <30 GeV
• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$	• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$
–	• $p_T^{\ell} - p_T^{\tau} < 0$	–	• $p_T^{\ell} - p_T^{\tau} < 0$

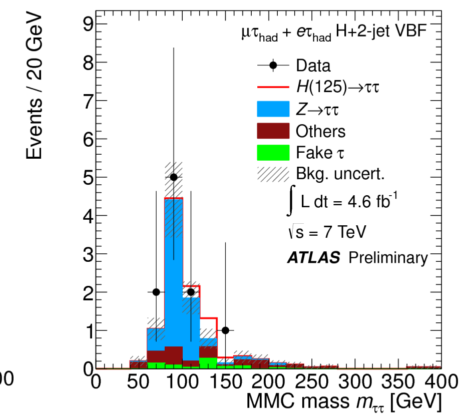
$H \rightarrow \tau_{lep}\tau_{had}$: background estimation

- Non-VBF categories:
- $Z \rightarrow \tau\tau$: embedding procedure
- multi-jet: data
  - same sign (lepton-τ) vs opposite signe
- W + jets: from MC
  - scale factors: control region (m_T > 70 GeV)
- top: from MC
  - scale factors: control region (b-tagged, invert m_T)
- VBF categories: high statistics MC samples
- Summary for 8 TeV:









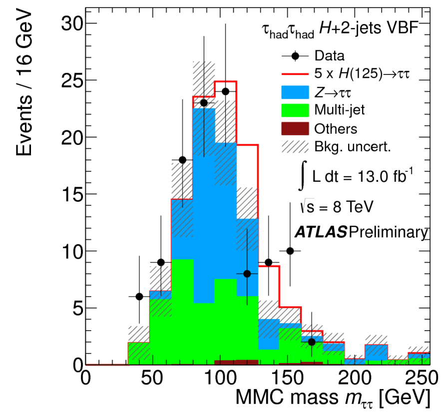
Process	Events		Events	
	0-Jet	1-Jet	Boosted	VBF
$gg \rightarrow H$ (125 GeV)	4.6 ± 0.2 ± 1.2	6.4 ± 0.2 ± 1.3	4.1 ± 0.1 ± 1.0	0.17 ± 0.03 ± 0.06
VBF H (125 GeV)	0.04 ± 0.00 ± 0.01	1.35 ± 0.03 ± 0.12	1.52 ± 0.03 ± 0.13	0.87 ± 0.02 ± 0.15
VH (125 GeV)	0.03 ± 0.01 ± 0.00	0.67 ± 0.04 ± 0.06	0.86 ± 0.04 ± 0.08	<0.001
$Z/\gamma^* \rightarrow \tau\tau$ † SS)	$(0.88 \pm 0.01 \pm 0.17)\times10^3$	$(1.20 \pm 0.02 \pm 0.17)\times10^3$	$(0.70 \pm 0.02 \pm 0.10)\times10^3$	6.5 ± 0.6 ± 1.5
Diboson †	2.3 ± 0.3 ± 0.4	9.1 ± 1.2 ± 0.8	8.4 ± 0.7 ± 0.8	0.12 ± 0.06 ± 0.03
$Z/\gamma^* \rightarrow \ell\ell$ †	10 ± 3 ± 2	13 ± 3 ± 4	3.7 ± 1.3 ± 1.0	0.8 ± 0.3 ± 1.0
Top †	0.5 ± 0.2 ± 0.1	92 ± 3 ± 14	52 ± 2 ± 9	1.2 ± 0.3 ± 0.1
W boson + jets (OS-SS)	65 ± 11 ± 6	$(0.15 \pm 0.02 \pm 0.02)\times10^3$	41 ± 7 ± 8	–
Same sign data	60 ± 8 ± 3	$(0.31 \pm 0.02 \pm 0.02))\times10^3$	90 ± 10 ± 5	–
Fake-$\tau_{had\text{-}vis}$ backgrounds			–	0.8 ± 0.2 ± 0.4
Total background	$(1.01 \pm 0.02 \pm 0.17)\times10^3$	$(1.78 \pm 0.03 \pm 0.18)\times10^3$	$(0.90 \pm 0.02 \pm 0.10)\times10^3$	9.5 ± 0.8 ± 1.9
Observed data	958	1701	834	10

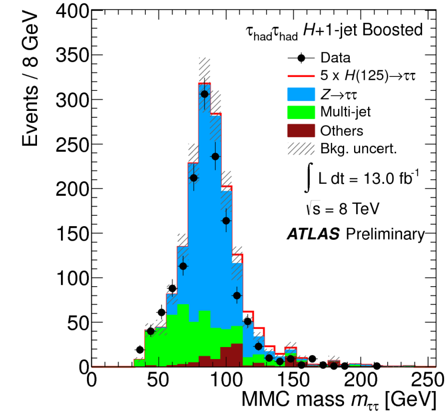
$H \rightarrow \tau_{had}\tau_{had}$: selection

Cut	Description
Preselection	No muons or electrons in the event
	Exactly 2 medium τ_{had} candidates matched with the trigger objects
	At least 1 of the τ_{had} candidates identified as tight
	Both τ_{had} candidates are from the same primary vertex
	Leading $\tau_{\text{had-vis}}$ $p_T > 40$ GeV and sub-leading $\tau_{\text{had-vis}}$ $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
	τ_{had} candidates have opposite charge and 1- or 3-tracks
	$0.8 < \Delta R(\tau_1, \tau_2) < 2.8$
	$\Delta\eta(\tau, \tau) < 1.5$
	if $E_{\text{T}}^{\text{miss}}$ vector is not pointing in between the two taus, $\min\left\{\Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_1), \Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_2)\right\} < 0.2\pi$
VBF	At least two tagging jets, j_1, j_2, leading tagging jet with $p_{\text{T}} > 50$ GeV
	$\eta_{j1} \times \eta_{j2} < 0$, $\Delta\eta_{jj} > 2.6$ and invariant mass $m_{jj} > 350$ GeV
	$\min(\eta_{j1}, \eta_{j2}) < \eta_{\tau 1}, \eta_{\tau 2} < \max(\eta_{j1}, \eta_{j2})$
	$E_{\text{T}}^{\text{miss}} > 20$ GeV
Boosted	Fails VBF
	At least one tagging jet with $p_{\text{T}} > 70(50)$ GeV in the 8(7) TeV dataset
	$\Delta R(\tau_1, \tau_2) < 1.9$
	$E_{\text{T}}^{\text{miss}} > 20$ GeV
	if $E_{\text{T}}^{\text{miss}}$ vector is not pointing in between the two taus, $\min\left\{\Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_1), \Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_2)\right\} < 0.1\pi$.

$H \to \tau_{had}\tau_{had}$: background estimation

- $Z \to \tau\tau$: embedding procedure
- multi-jet: data
  - looser τ selection
- top, $Z \to ee$, $\mu\mu$, Z+jets: from MC
  - scale factors from control regions





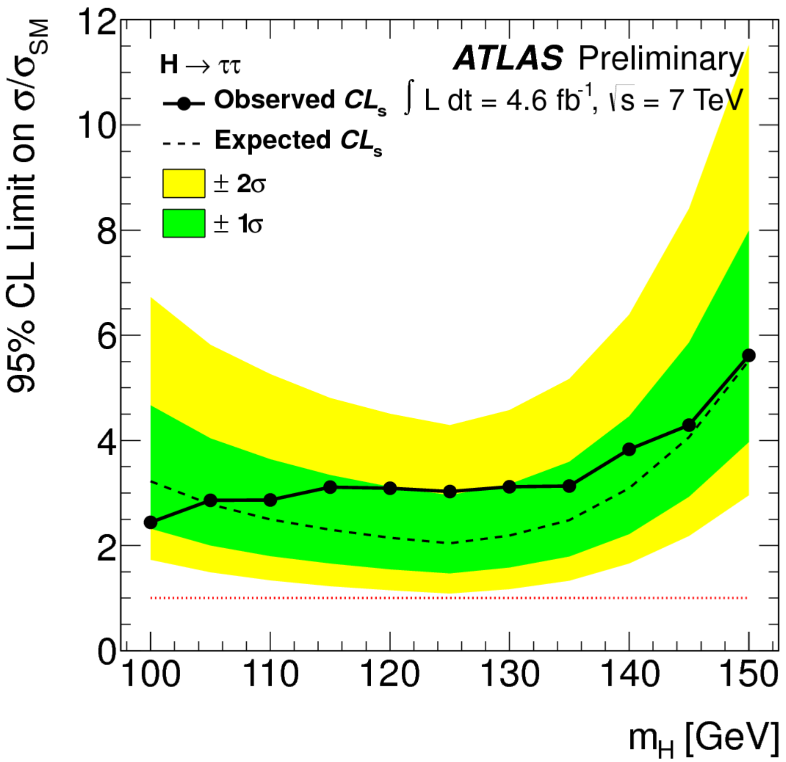
$H \to \tau_{had}\tau_{had}$	7 TeV analysis (4.6 fb^{-1})		8 TeV analysis (13.0 fb^{-1})	
	VBF category	Boosted category	VBF category	Boosted category
$gg \to H$ (125 GeV)	0.36 ± 0.06 ± 0.12	2.4 ± 0.2 ± 0.7	1.0 ± 0.1 ± 0.3	8.2 ± 0.4 ± 1.8
VBF H (125 GeV)	1.12 ± 0.04 ± 0.18	0.68 ± 0.03 ± 0.07	3.01 ± 0.09 ± 0.48	1.98 ± 0.07 ± 0.30
VH (125 GeV)	<0.02	0.61 ± 0.05 ± 0.06	<0.05	1.4 ± 0.2 ± 0.2
$Z/\gamma^* \to \tau\tau$ embedded	20 ± 2 ± 3	392 ± 9 ± 12	50 ± 4 ± 6	1080 ± 20 ± 110
W/Z boson+jets	1.5 ± 0.7 ± 0.4	5 ± 1 ± 1	0.4 ± 0.4	90 ± 20 ± 30
Top	1.0 ± 0.2 ± 0.2	3.0 ± 0.3 ± 0.5	1.4 ± 1.0	21 ± 3 ± 5
Diboson	0.10 ± 0.07 ± 0.02	4.4 ± 0.6 ± 0.7	<0.01	<0.5
Multijet	10.2 ± 0.9 ± 5.0	156 ± 6 ± 30	44 ± 5 ± 7	420 ± 20 ± 60
Total background	32.5 ± 2.2 ± 5.9	561 ± 11 ± 32	96 ± 6 ± 9	1607 ± 37 ± 130
Observed data	38	535	110	1435

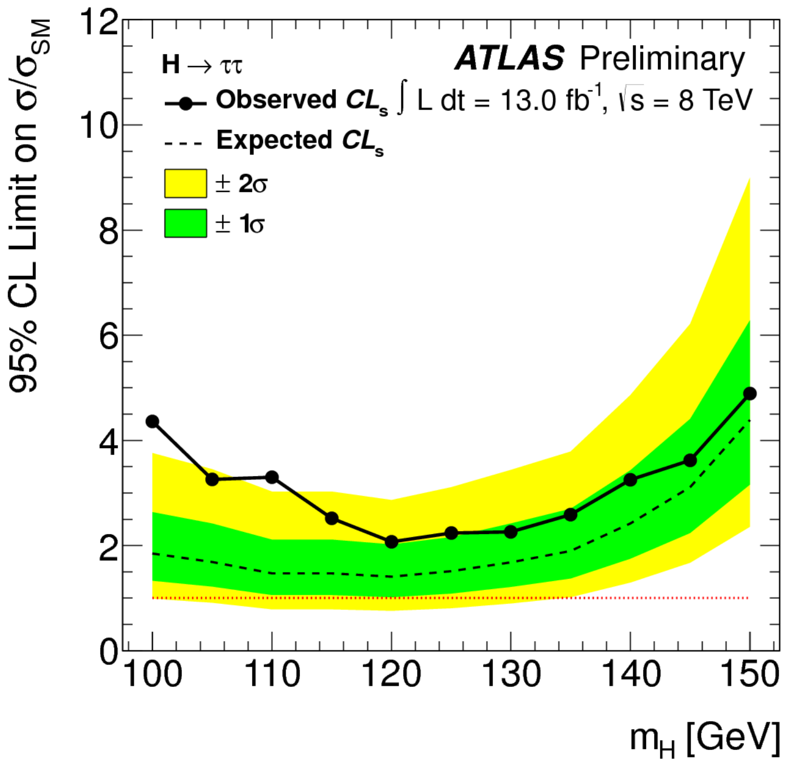
H→ττ: systematic uncertainties

Uncertainty	$H \to \tau_{lep}\tau_{lep}$	$H \to \tau_{lep}\tau_{had}$	$H \to \tau_{had}\tau_{had}$
$Z \to \tau^+\tau^-$			
Embedding	1–4% (S)	2–4% (S)	1–4% (S)
Tau Energy Scale	–	4–15% (S)	3–8% (S)
Tau Identification	–	4–5%	1–2%
Trigger Efficiency	2–4%	2–5%	2–4%
Normalisation	5%	4% (non-VBF), 16% (VBF)	9–10%
Signal			
Jet Energy Scale	1–5% (S)	3–9% (S)	2–4% (S)
Tau Energy Scale	–	2–9% (S)	4–6% (S)
Tau Identification	–	4–5%	10%
Theory	8–28%	18–23%	3–20%
Trigger Efficiency	small	small	5%

H→ττ: results (1)

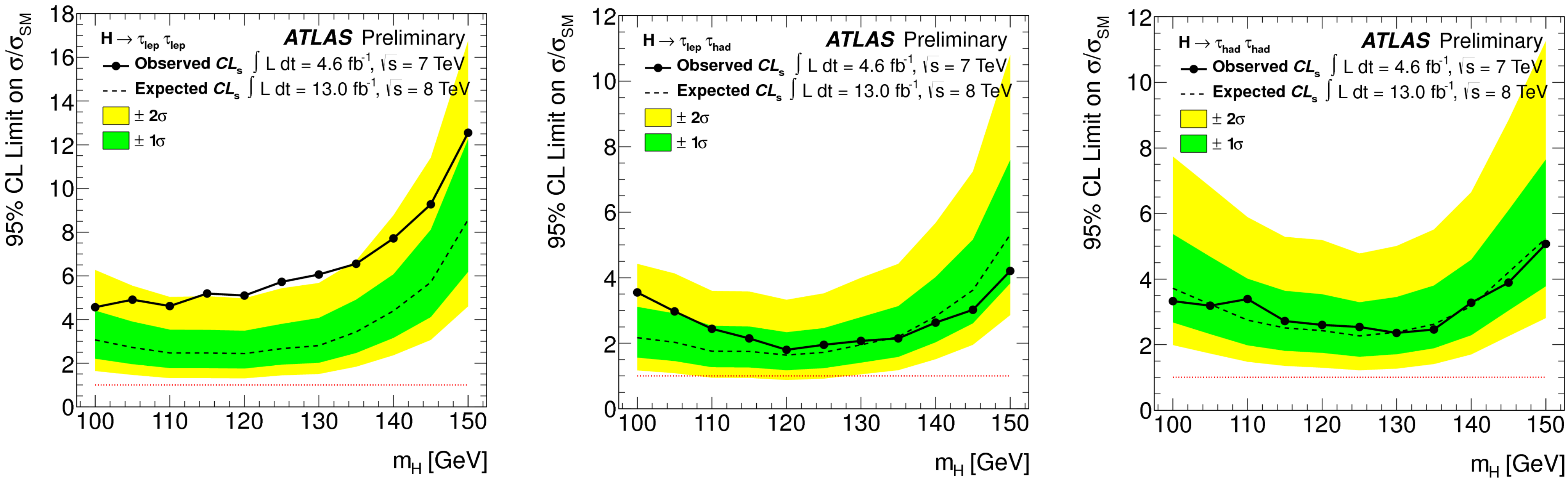
- 7 TeV vs 8 TeV:





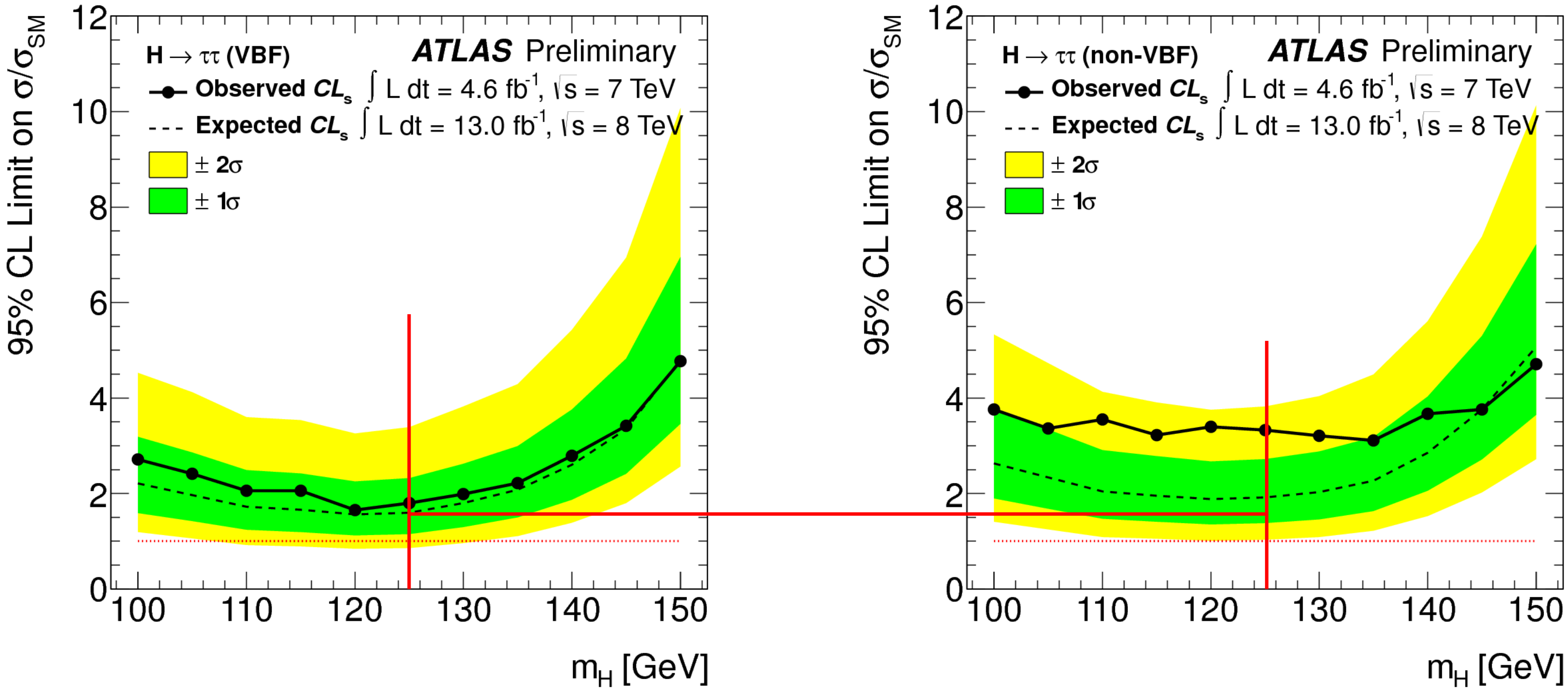
H→ττ: results (2)

- For 3 channels:



H→ττ: results (3)

- VBF vs non-VBF:



$H \rightarrow b\bar{b}$: selection

Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV $+ \leq 1$ extra jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV + 0 extra jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV -
Missing E_T	$E_T^{miss} > 120$ GeV $p_T^{miss} > 30$ GeV $\Delta\phi(E_T^{miss}, p_T^{miss}) < \pi/2$ Min$[\Delta\phi(E_T^{miss}, \text{jet})] > 1.5$ $\Delta\phi(E_T^{miss}, b\bar{b}) > 2.8$	-	$E_T^{miss} < 60$ GeV
Vector Boson	-	$m_T^W < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

0-lepton channel			
E_T^{miss} (GeV)	120-160	160-200	>200
$\Delta R(b, \bar{b})$	0.7-1.9	0.7-1.7	<1.5

1-lepton channel					
p_T^W (GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b, \bar{b})$	>0.7			0.7-1.6	<1.4
E_T^{miss} (GeV)	> 25				> 50
m_T^W (GeV)	> 40			-	

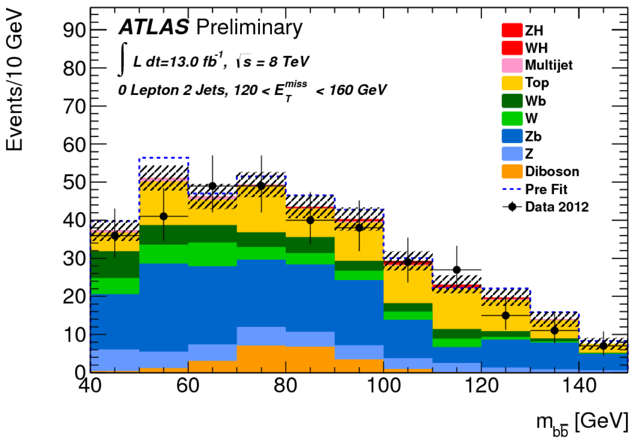
2-lepton channel					
p_T^Z (GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b, \bar{b})$	>0.7			0.7-1.8	<1.6

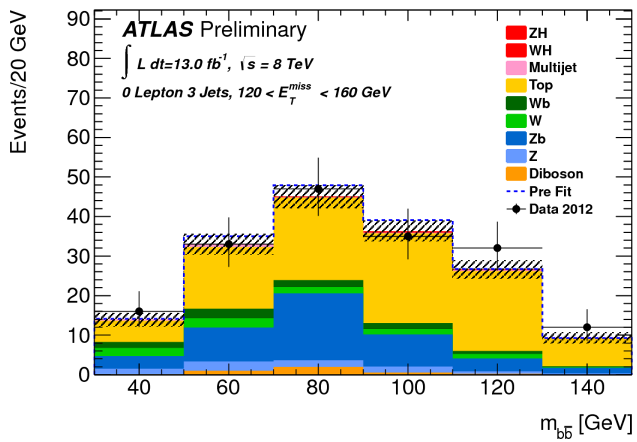
$H\rightarrow b\bar{b}$: background estimation

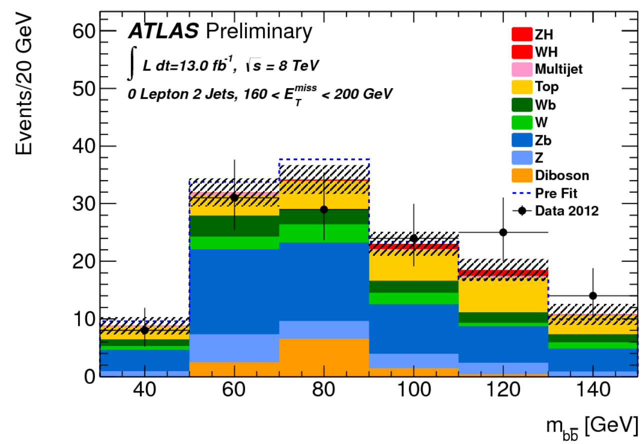
- Di-boson:
  - shape from MC
  - resonant background normalisation
- top, W/Z + jets
  - shape from MC
  - normalised to data (control regions)
- multijet:
  - from data

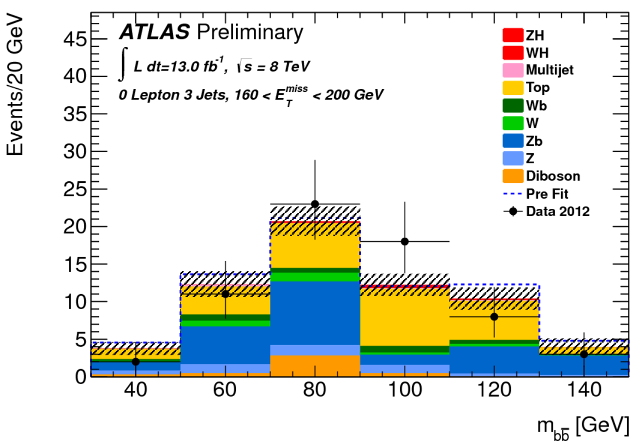
	0-lepton, 2 jet			0-lepton, 3 jet			1-lepton					2-lepton				
Bin	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]						p_{T}^{W}[GeV]					p_{T}^{Z}[GeV]				
	120-160	160-200	>200	120-160	160-200	>200	0-50	50-100	100-150	150-200	> 200	0-50	50-100	100-150	150-200	>200
ZH	2.9	2.1	2.6	0.8	0.8	1.1	0.3	0.4	0.1	0.0	0.0	4.7	6.8	4.0	1.5	1.4
WH	0.8	0.4	0.4	0.2	0.2	0.2	10.6	12.9	7.5	3.6	3.6	0.0	0.0	0.0	0.0	0.0
Top	89	25	8	92	25	10	1440	2276	1120	147	43	230	310	84	3	0
$W+c$,light	30	10	5	9	3	2	580	585	209	36	17	0	0	0	0	0
$W+b$	35	13	13	8	3	2	770	778	288	77	64	0	0	0	0	0
$Z+c$,light	35	14	14	8	5	8	17	17	4	1	0	201	230	91	12	15
$Z+b$	144	51	43	41	22	16	50	63	13	5	1	1010	1180	469	75	51
Diboson	23	11	10	4	4	3	53	59	23	13	7	37	39	16	6	4
Multijet	3	1	1	1	1	0	890	522	68	14	3	12	3	0	0	0
Total Bkg.	361	127	98	164	63	42	3810	4310	1730	297	138	1500	1770	665	97	72
	± 29	± 11	± 12	± 13	± 8	± 5	± 150	± 86	± 90	± 27	± 14	± 90	± 110	± 47	± 12	± 12
Data	342	131	90	175	65	32	3821	4301	1697	297	132	1485	1773	657	100	69

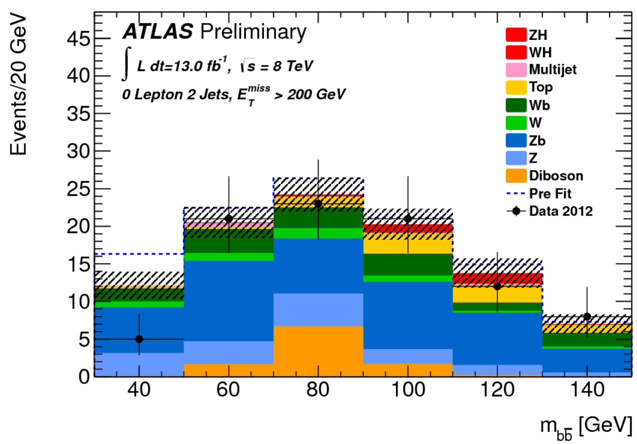
H→b$\bar{b}$: 0 lepton

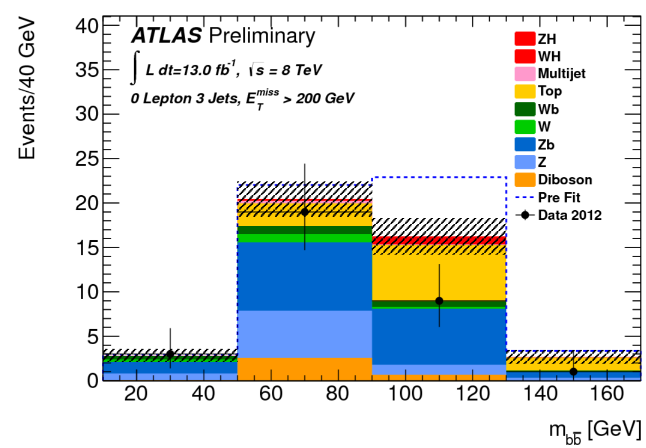




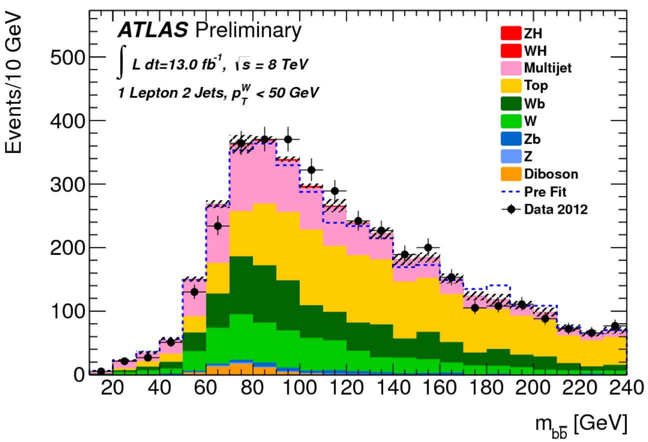


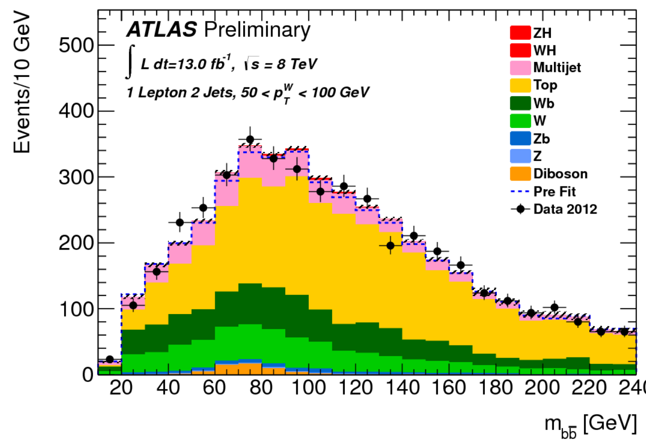


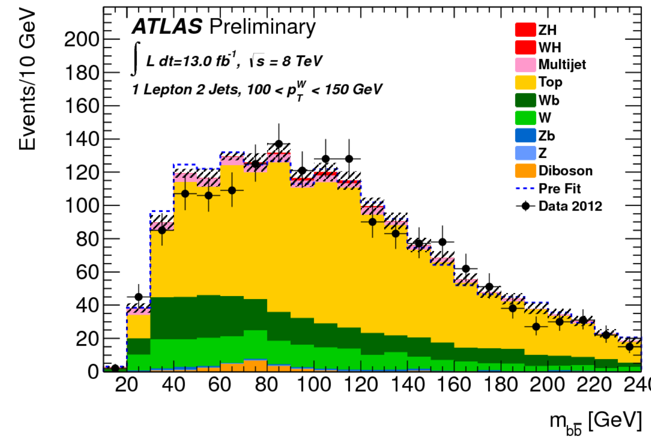


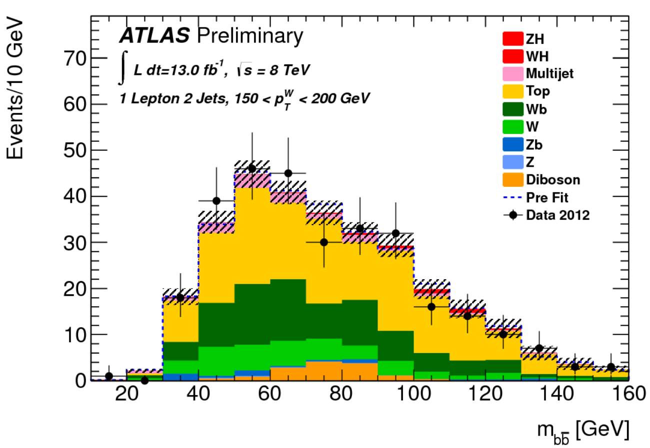


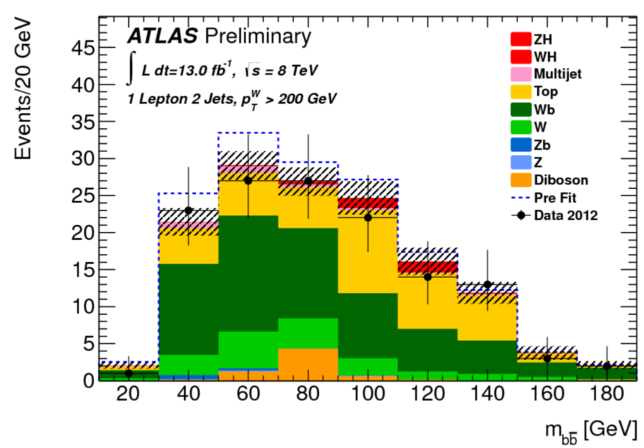
H→b$\bar{b}$: 1 lepton



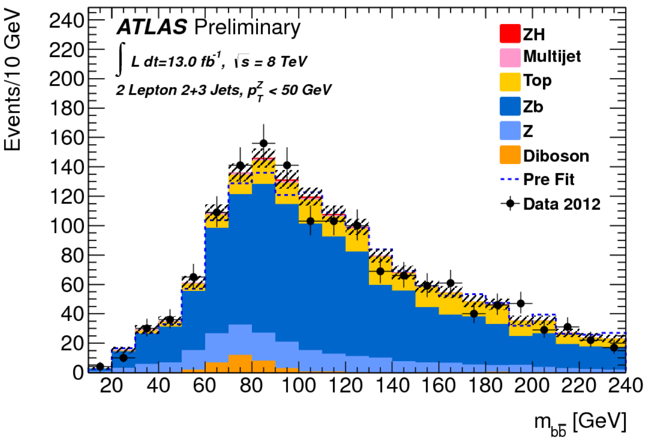


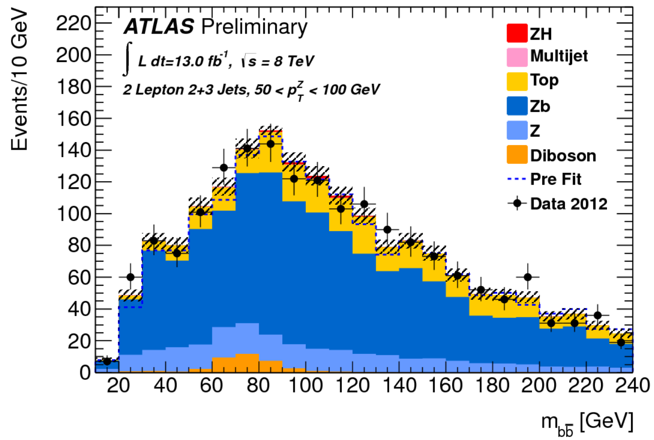


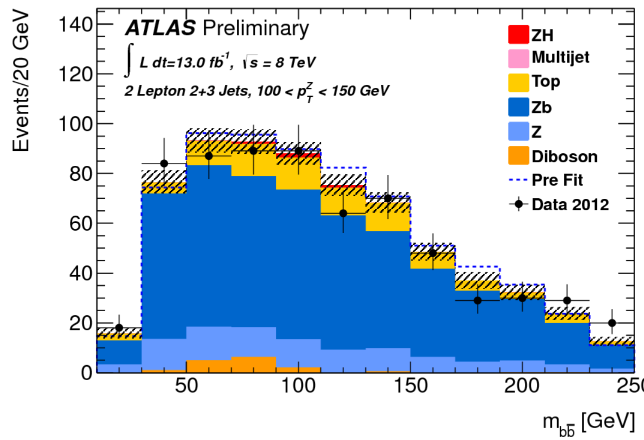


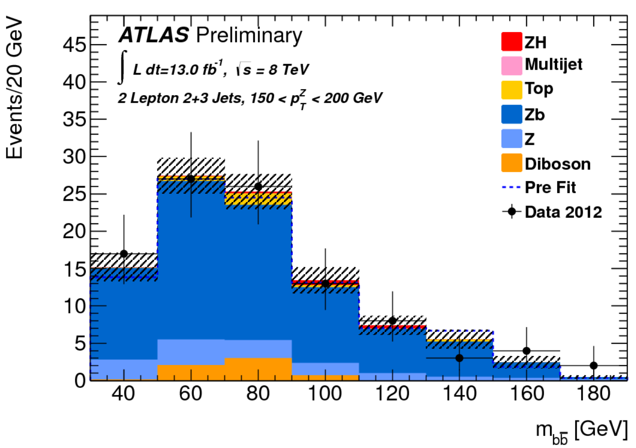


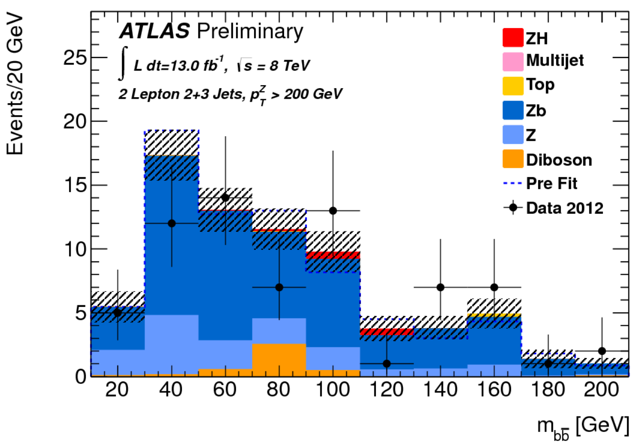
H→b$\bar{b}$: 2 leptons





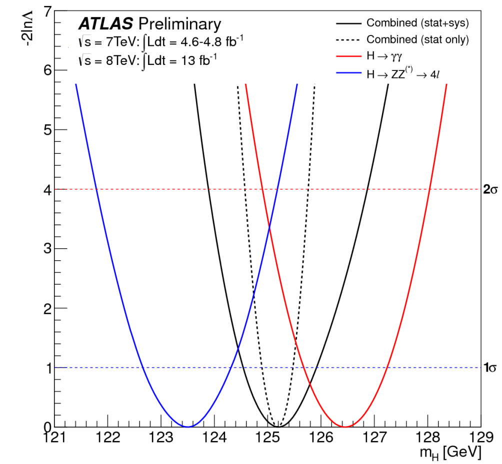




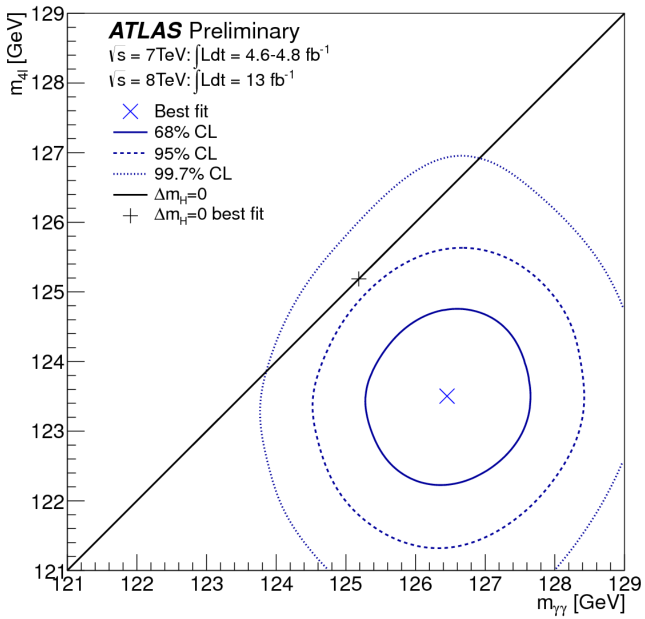


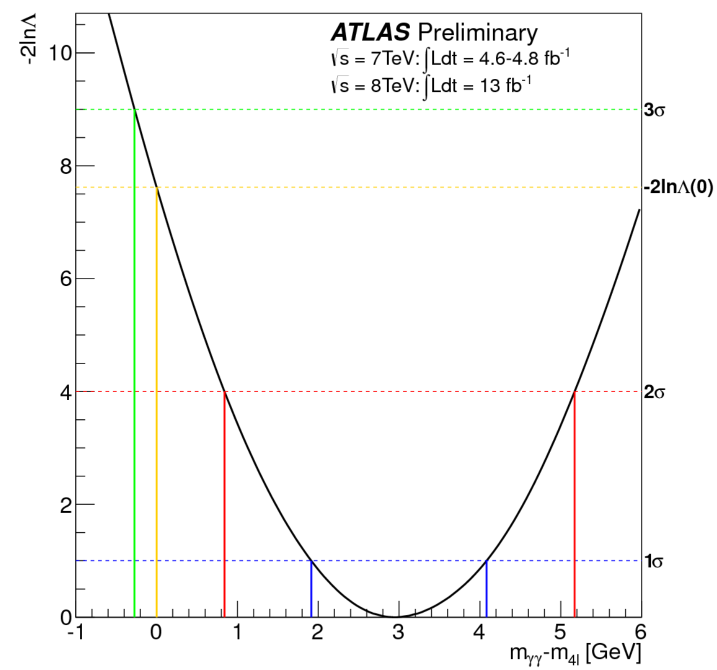
Mass

- H → ZZ*: 123.5 ± 0.8 (stat) ± 0.3 (syst) GeV
- H → γγ: 126.6 ± 0.3 (stat) ± 0.7 (syst) GeV



- $m_H^{\gamma\gamma}$ and m_H^{4l} varied independently:
  - almost uncorrelated

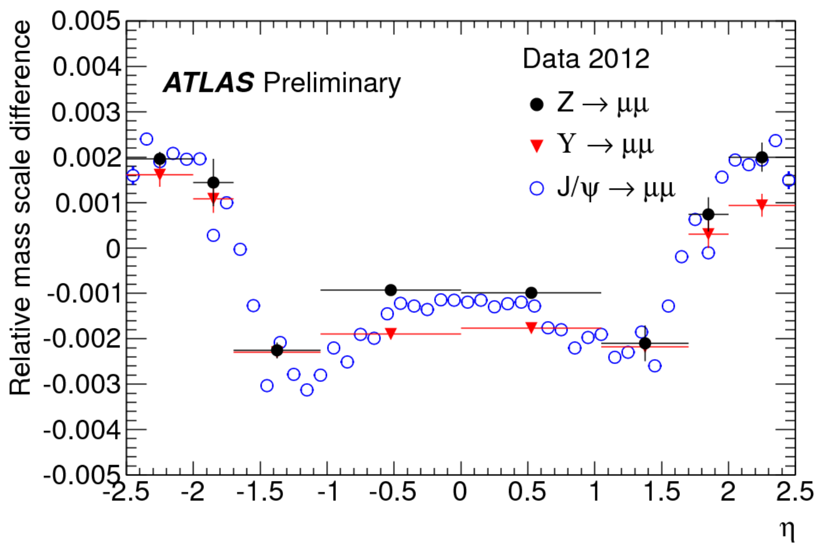




- likelihood for $\Delta m_H = m_H^{\gamma\gamma} - m_H^{4l}$
  - m_H profiled

Mass: H→ZZ*→4l

- Dominated by 4μ channel
- Mass scale systematics
  - absolute energy scale (from Z): 0.4%
  - low E_T electrons: 0.2%
  - muon momentum scale: 0.2%
- Checks:
  - mass measurement with ID tracks alone
  - bkg unconstrained
  - Z mass constraint on m_{12}
- More checks:
  - check of kinematic distributions
  - scale measurement with ID or MS tracks only
  - FSR: data/MC agreement to 0.1%
  - event-by-event errors



Mass: H→γγ

- Uncertainties:
  - absolute energy scale (Z→ee): 0.3%
  - material before calo: 0.3%
  - relative calibration of calo layers: 0.2 and 0.1%
  - difference in lateral shower-shape photons-electrons: 0.1%
  - read-out electronic gain: 0.15%

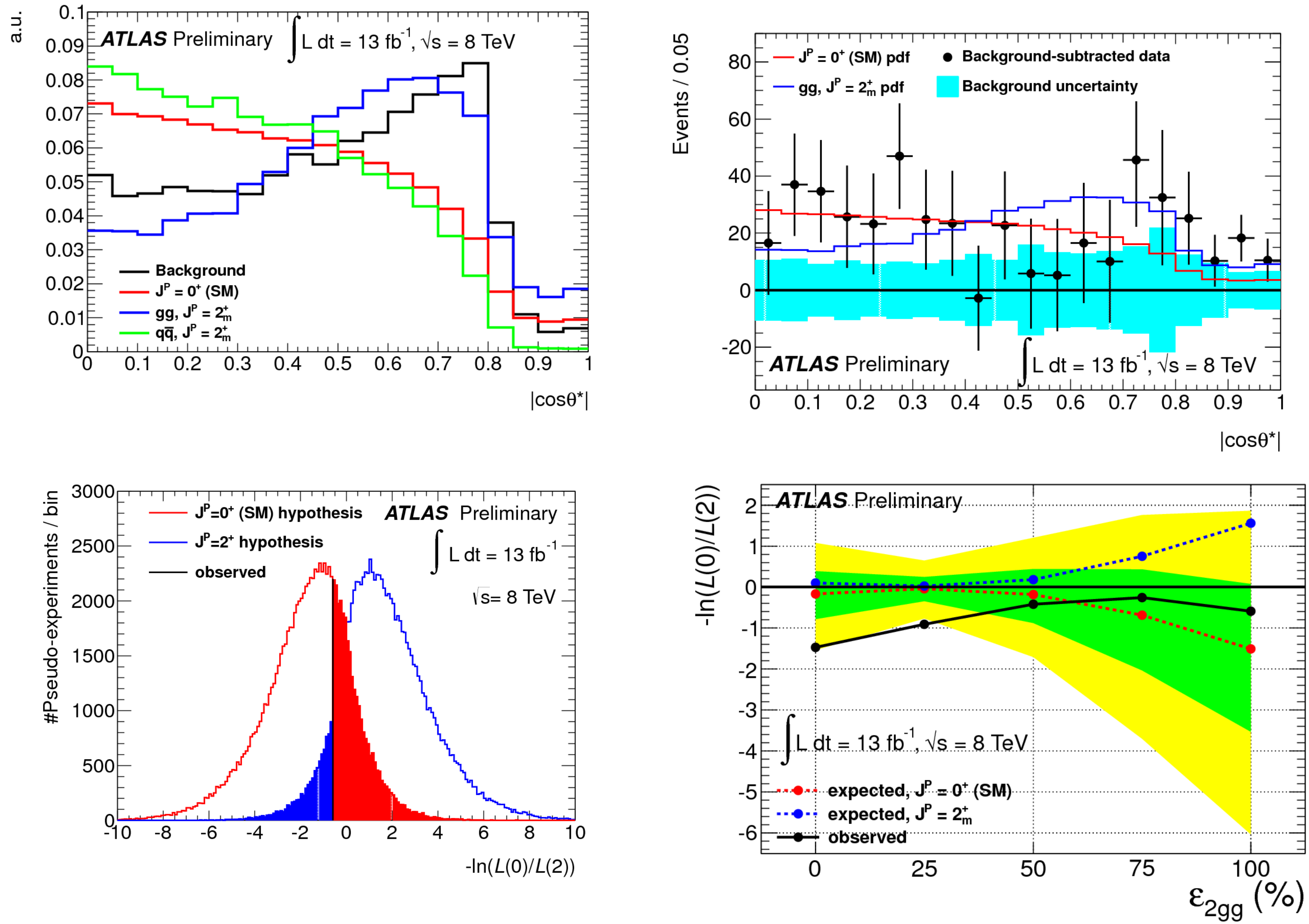
- More uncertainties:
  - converted photons: data/MC diff: 0.13%
  - background modelling: 0.1%
  - stability with mass resolution: 0.15%
  -

Spin 2 model

$$
\begin{aligned}
A(X \to VV) = \Lambda^{-1} \Bigg[& 2g_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\alpha} \\
& + g_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha} \right) + g_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta} \\
& + m_V^2 \left(2g_5 t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\
& + g_8 \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + g_9 t_{\mu\alpha} \tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma \\
& + \frac{g_{10} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q \epsilon_2^*) + \epsilon_2^{*\nu} (q \epsilon_1^*) \right) \Bigg],
\end{aligned}
$$

- General interaction of spin-2 particle with gauge bosons pair: 10 independent tensor couplings
  - excluding generic spin-2 model is impossible
  - start with model with minimal couplings (g1=g5=1)
  - two production modes allowed: gg and qqbar
  - study 5 different gg fractions from 0% to 100%

H→γγ: Spin



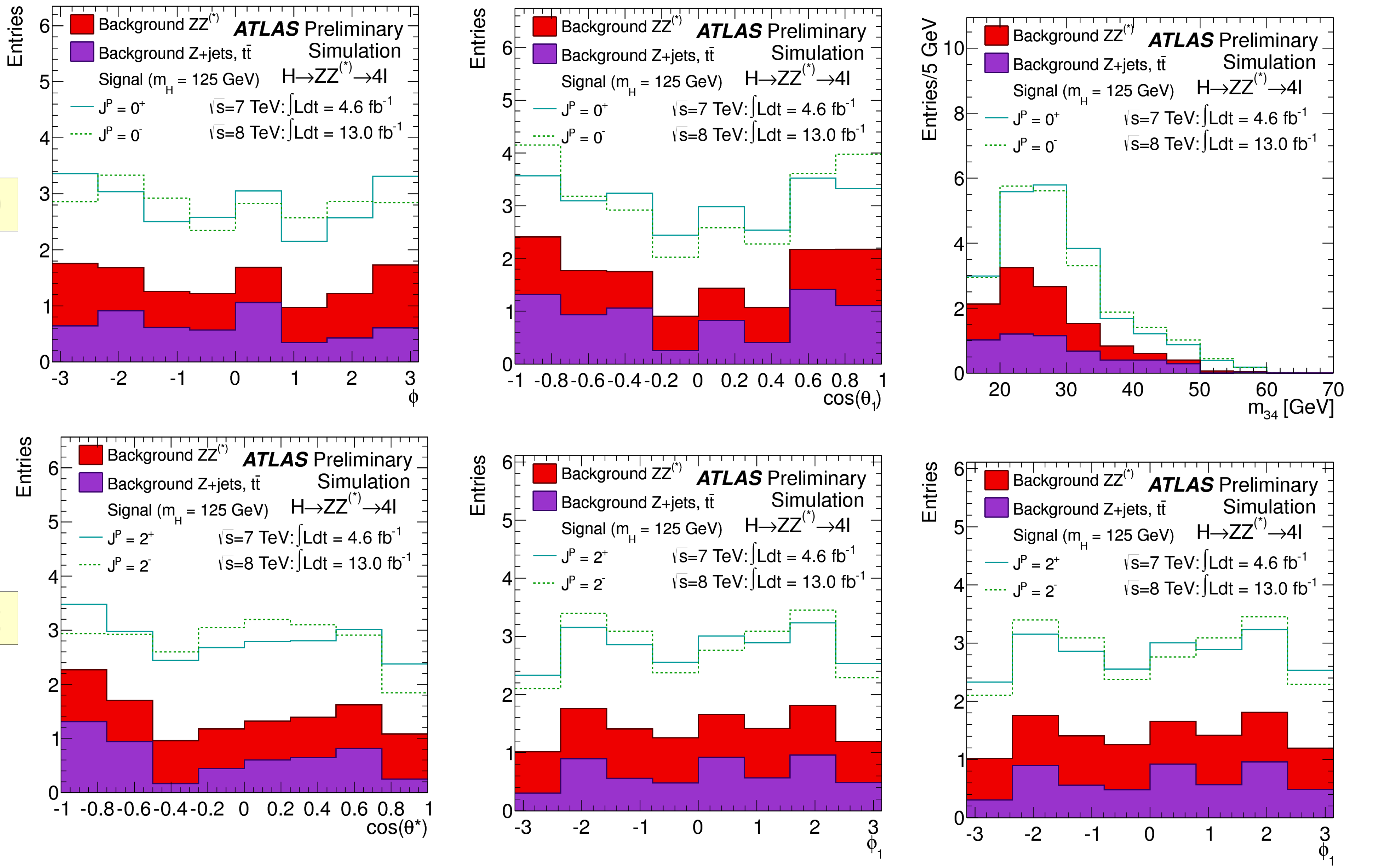
ATLAS Preliminary
∫L dt = 13 fb-1, √s = 8 TeV
a.u.
|cosθ*|
Background
JP = 0+ (SM)
gg, JP = 2+m
qq̄, JP = 2+m
Events / 0.05
JP = 0+ (SM) pdf
gg, JP = 2+m pdf
Background-subtracted data
Background uncertainty
#Pseudo-experiments / bin
JP=0+ (SM) hypothesis
JP=2+ hypothesis
observed
-ln(L(0)/L(2))
expected, JP = 0+ (SM)
expected, JP = 2+m
observed
ε2gg (%)

H→ZZ*→4l: Spin (1)

- Input variables:

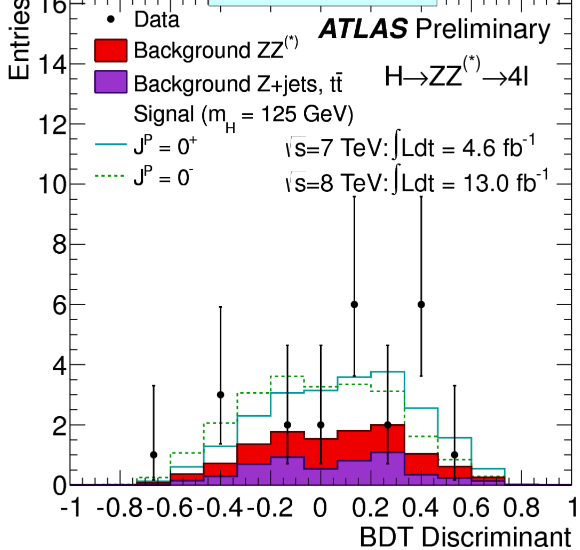
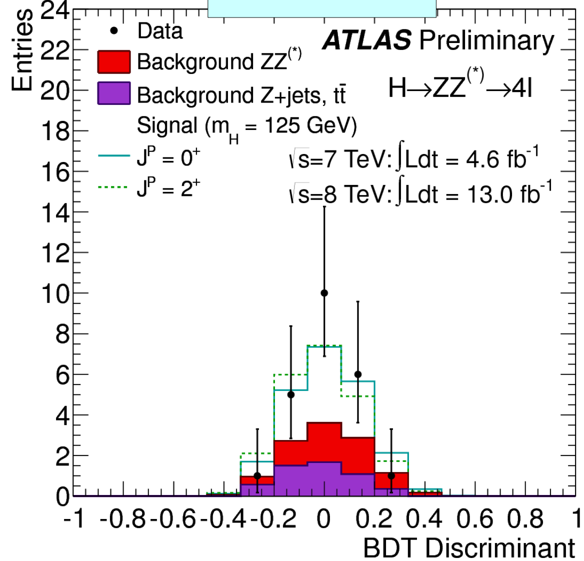
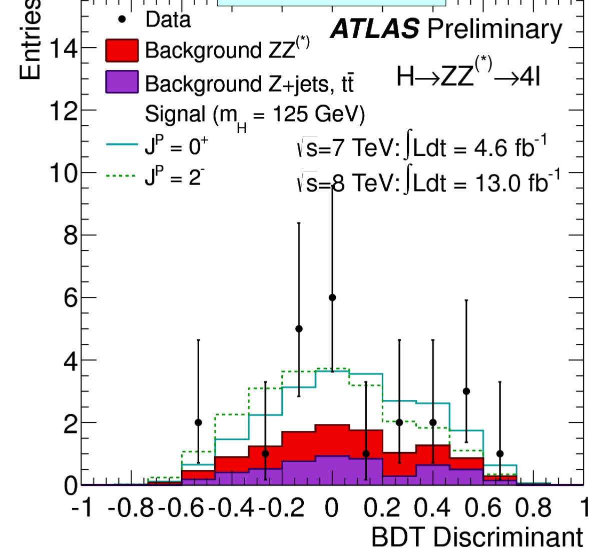
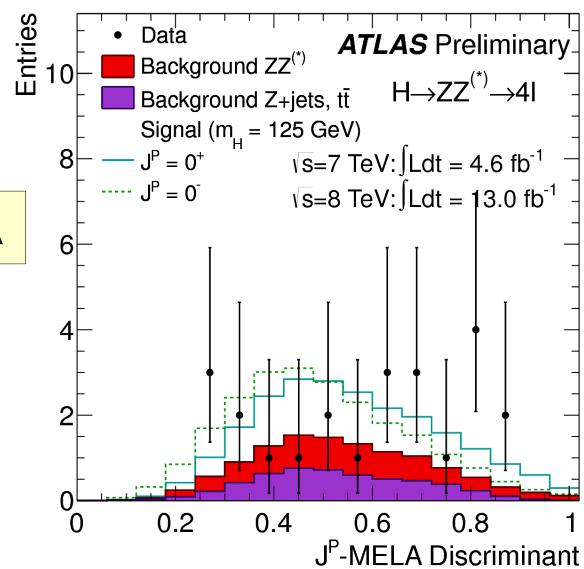
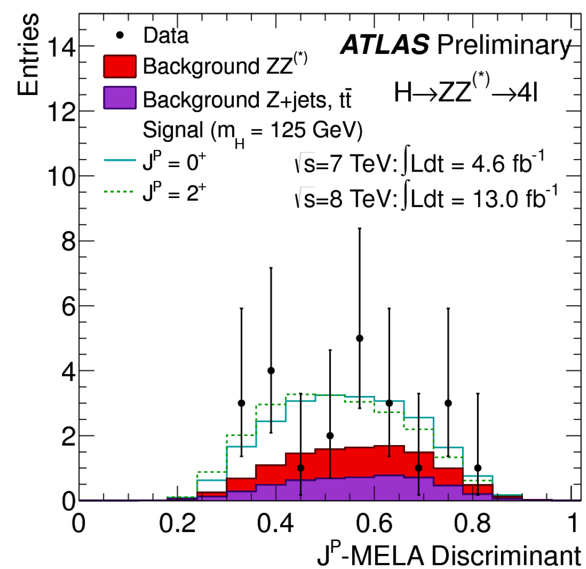
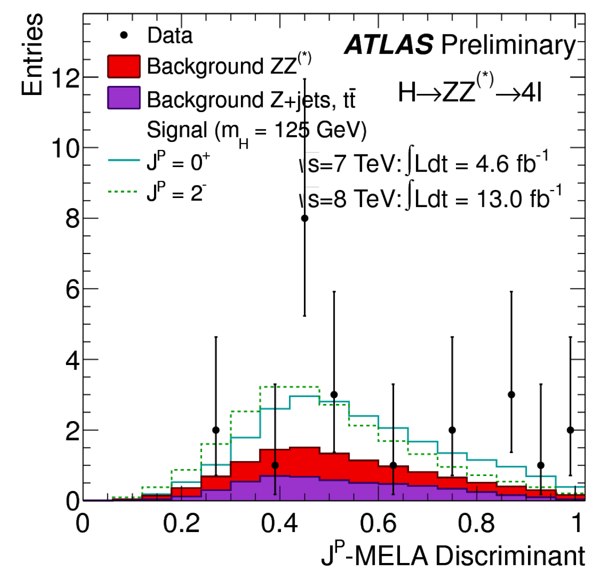
spin 0

spin 2



H→ZZ*→4l: Spin (3)

- Discriminants:

	0+ vs 0-	0+ vs 2+	0+ vs 2-
BDT			
J^P-MELA			

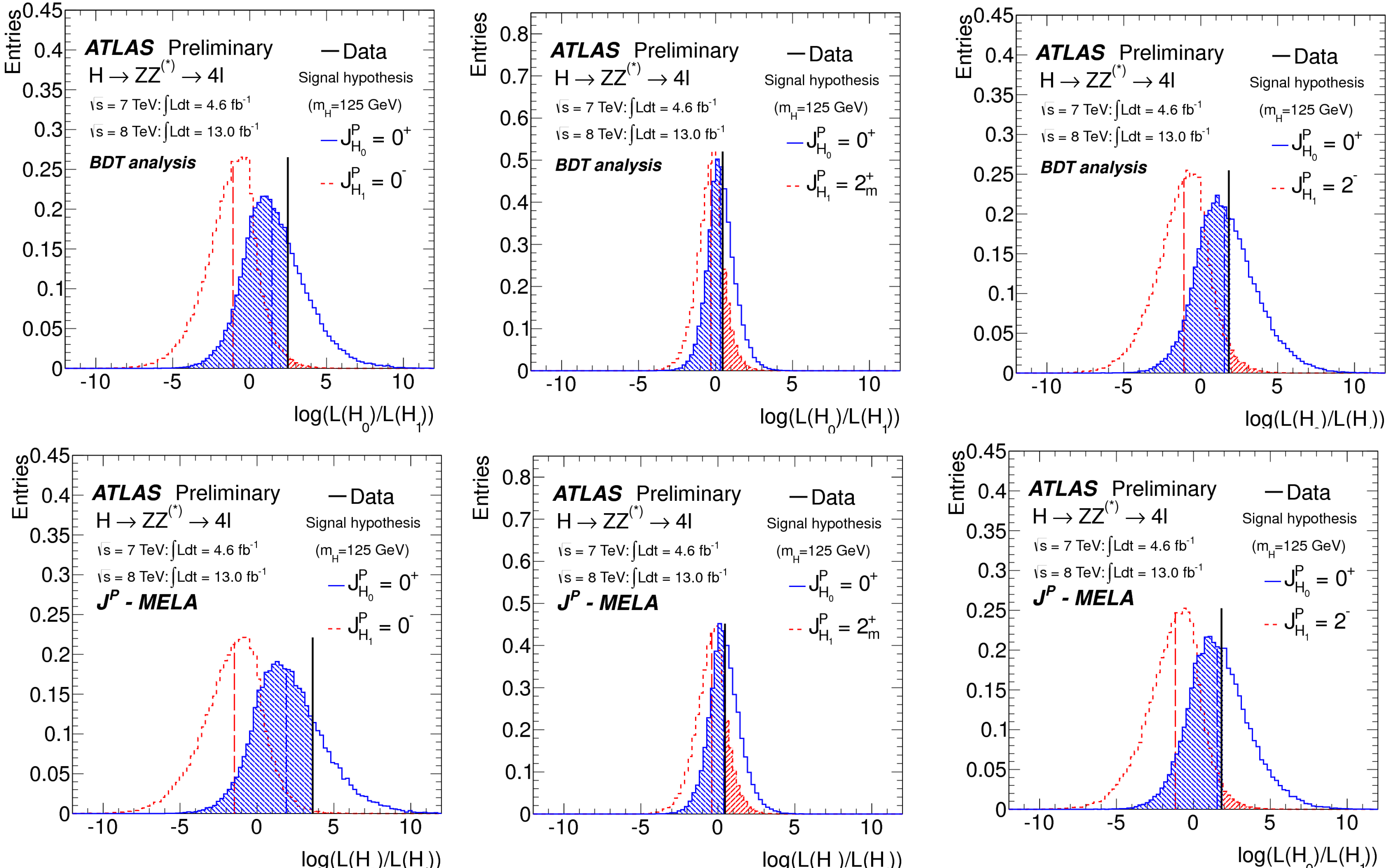
H→ZZ*→4l: Spin (2)

- Results:

0+ vs 0- | 0+ vs 2+ | 0+ vs 2-

BDT

J^P-MELA



H→ZZ*→4l: Spin (4)

- Discriminants:

	0+ vs 0-			0+ vs 2+			0+ vs 2-		
	Tested J^P hypotheses for an assumed 0^+								
	0^-			2^+_m			2^-		
	expected	observed	obs 0^+	expected	observed	obs 0^+	expected	observed	obs 0^+
	BDT analysis								
BDT p_0-value	0.041	0.011	0.69	0.20	0.16	0.57	0.046	0.029	0.56
BDT σ	1.7	2.3	-0.50	0.84	0.99	-0.18	1.7	1.9	-0.15
	J^P-MELA analysis								
J^P-MELA p_0-value	0.031	0.0028	0.76	0.18	0.17	0.53	0.04	0.025	0.56
J^P-MELA σ	1.9	2.7	-0.72	0.91	0.97	-0.08	1.7	2.0	-0.15