Higgs Physics in ATLAS

Summer School and Workshop on the Standard Model and Beyond

Corfu, Greece 9/2014

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on behalf of the ATLAS Collaboration

ATLAS EXPERIMENT
http://atlas.ch

European Union
European Social Fund
OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
investing in knowledge society
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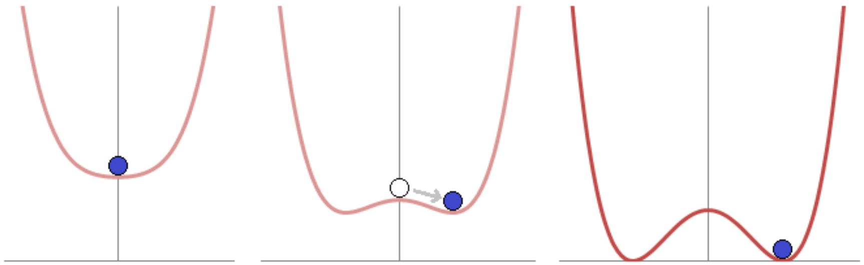
Contents

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Despite SM being extremely successful,

- *Renormalisability*
- *Mass of particles*

Mechanism of spontaneous electroweak symmetry breaking



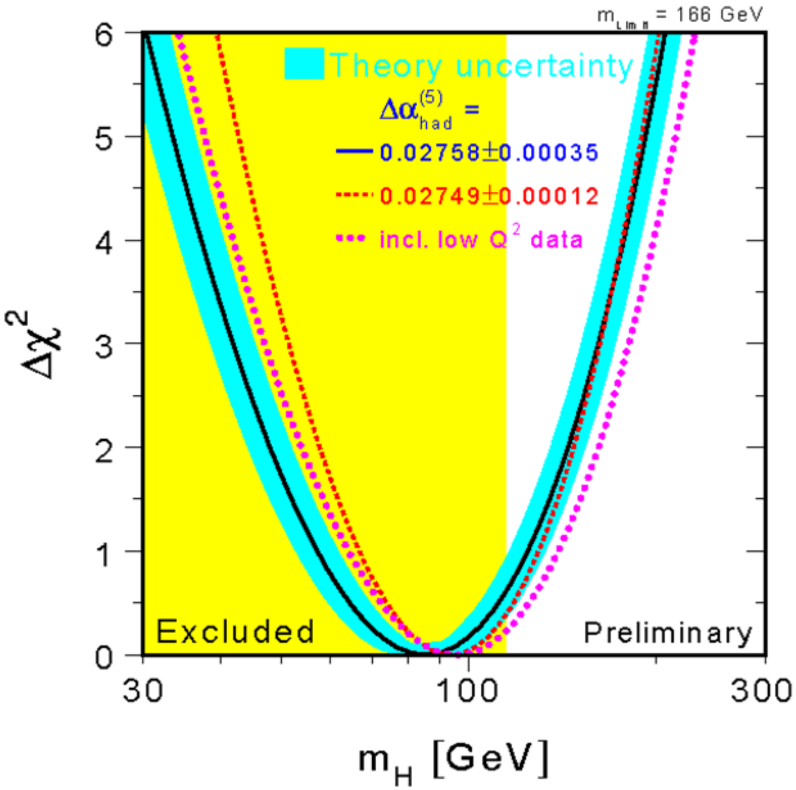
Presence of Higgs Boson

Before the start of LHC

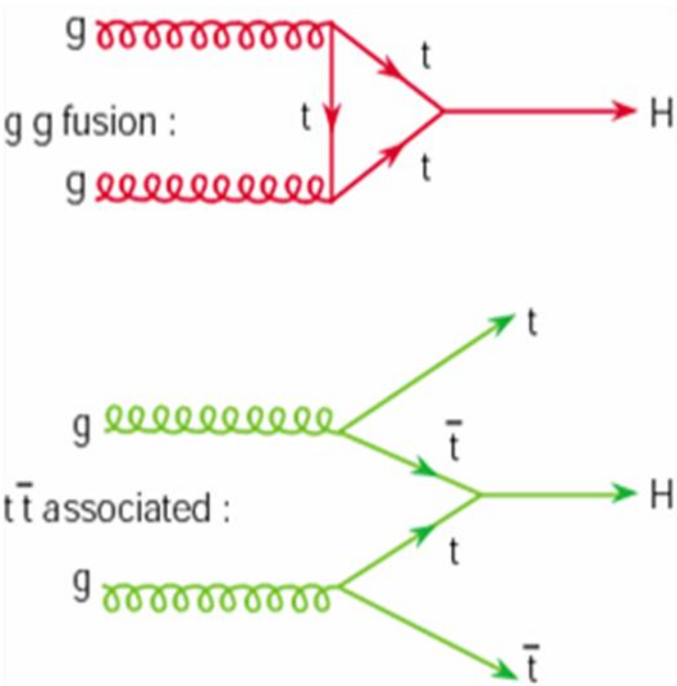
Direct searches at LEP and Tevatron

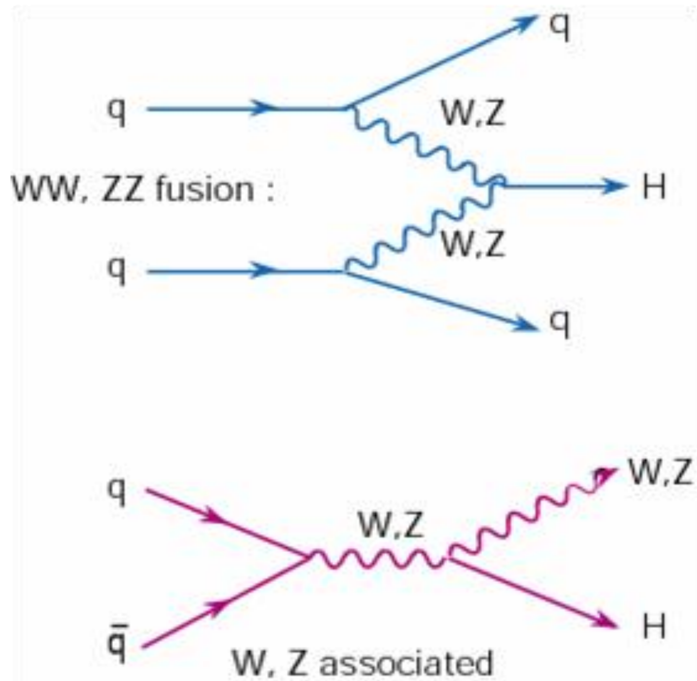
→ **m_H>114.4 GeV @ 95%CL**

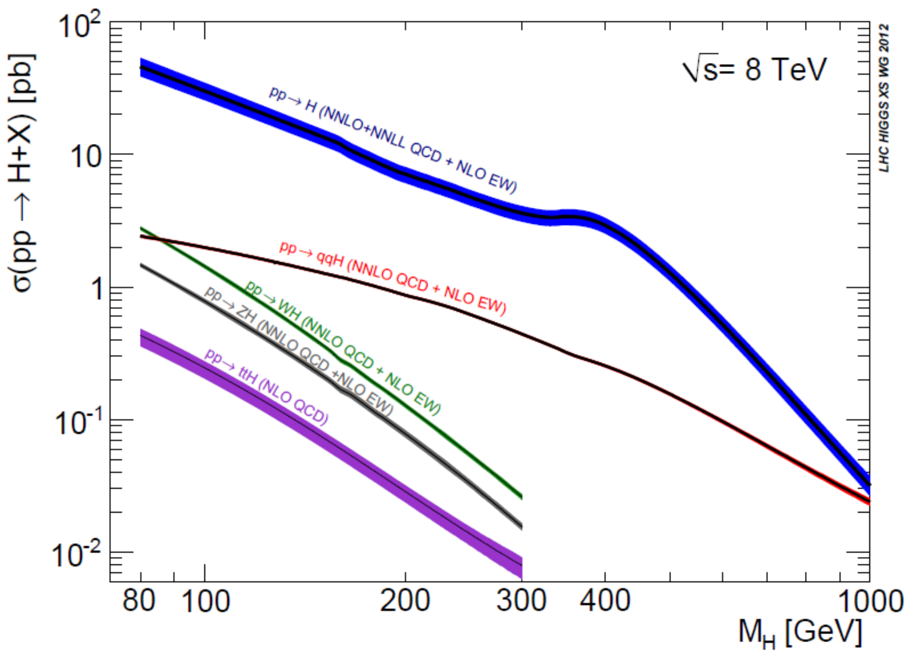
Global fit of all available electroweak data

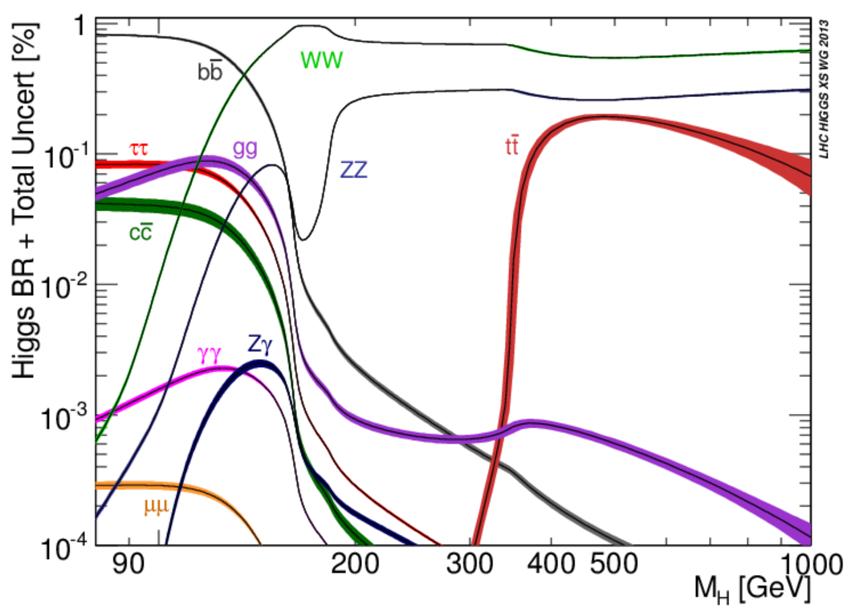


Higgs physics in ATLAS: Introduction - Higgs production at LHC



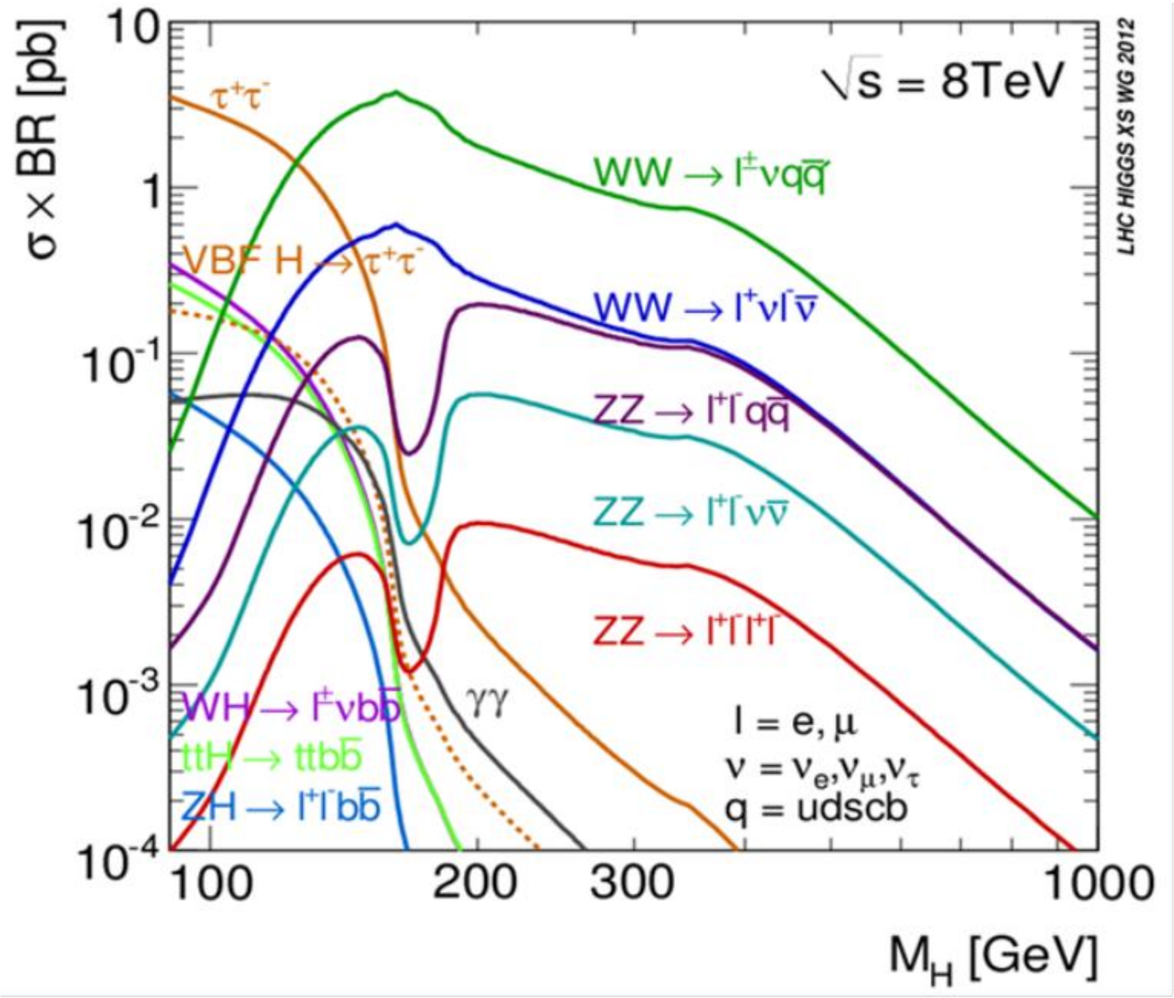




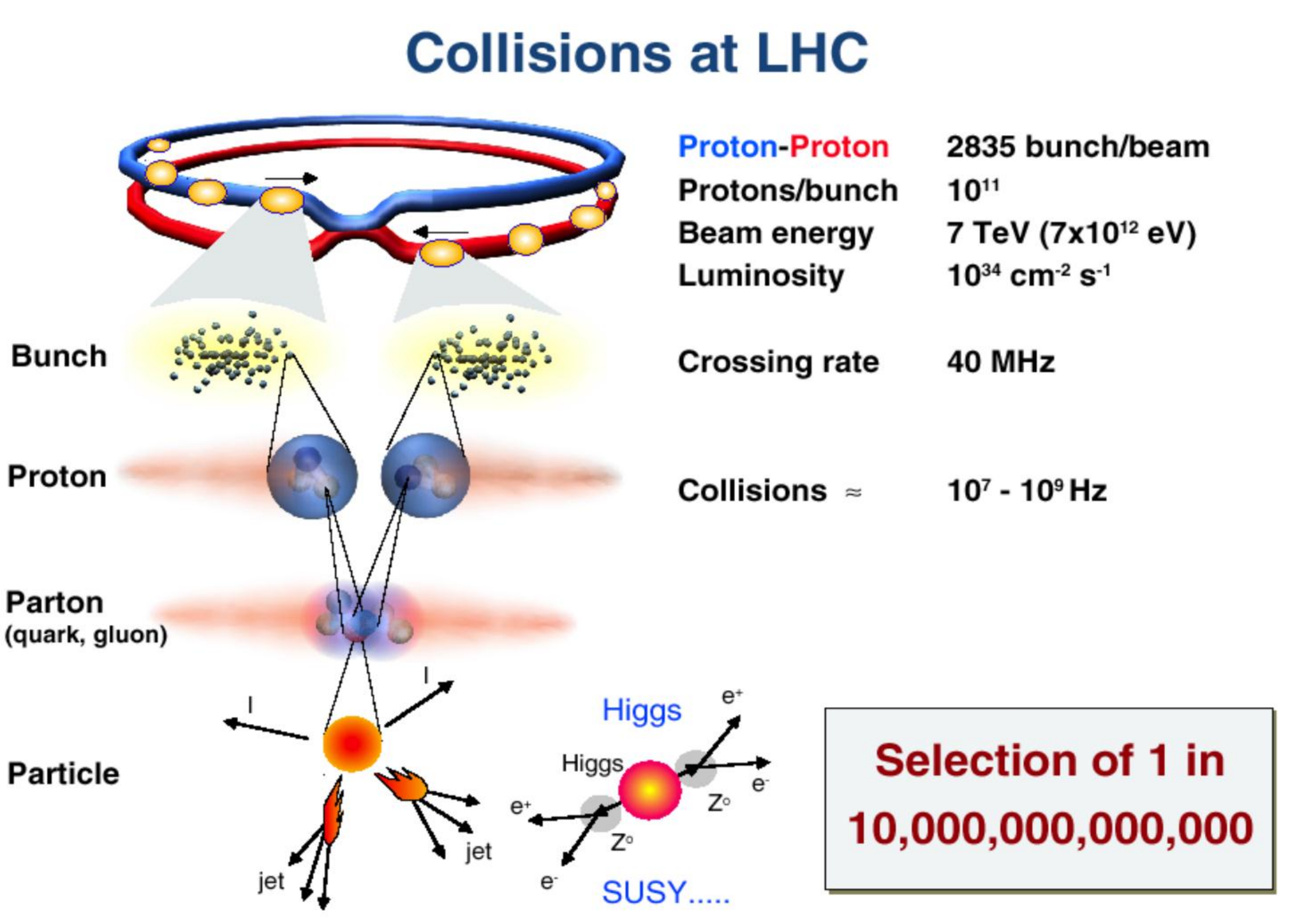


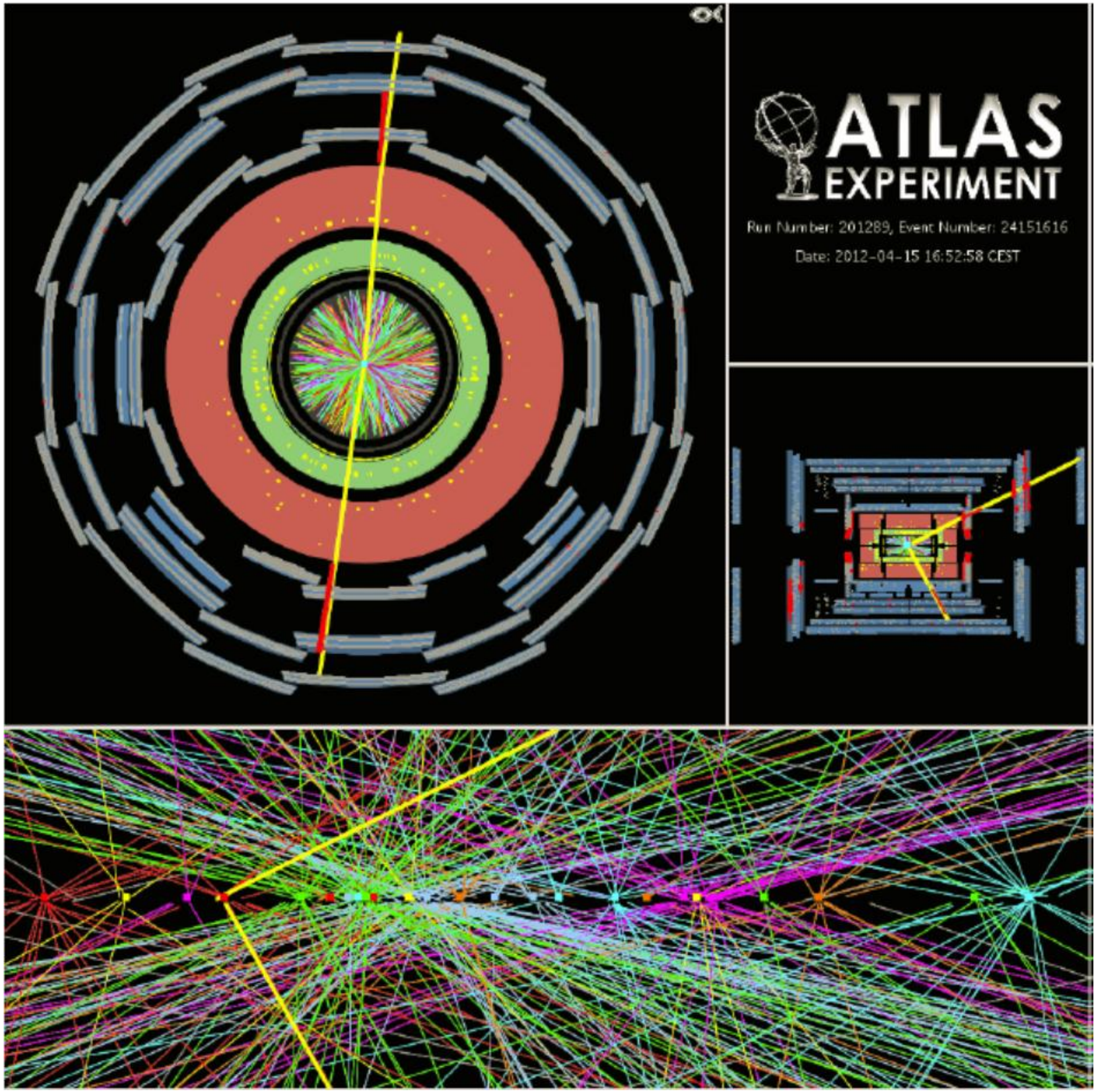
m_H 125 GeV @ 8TeV		
Prod. mechanism	Cross section [pb]	Percentage [%]
ggF	19.3	87
VBF	1.6	7
WH	0.7	3
ZH	0.4	2
tt(bb)H	0.3	1

Some of the decays though, suffer from huge backgrounds (i.e. bbar) and cannot be searched for in the bare ggF production mode.



√s = 8TeV
LHC HIGGS XS WG 2012
σ × BR [pb]
M_H [GeV]
WW → l±νqq̄
WW → l+νl-ν̄
ZZ → l+l-qq̄
ZZ → l+l-νν̄
ZZ → l+l-l+l-
τ+τ-
VBF H → τ+τ-
γγ
WH → l±νbb̄
ttH → ttbb̄
ZH → l+l-bb̄
l = e, μ
ν = νe,νμ,ντ
q = udscb
10
1
10-1
10-2
10-3
10-4
100
200
300
1000

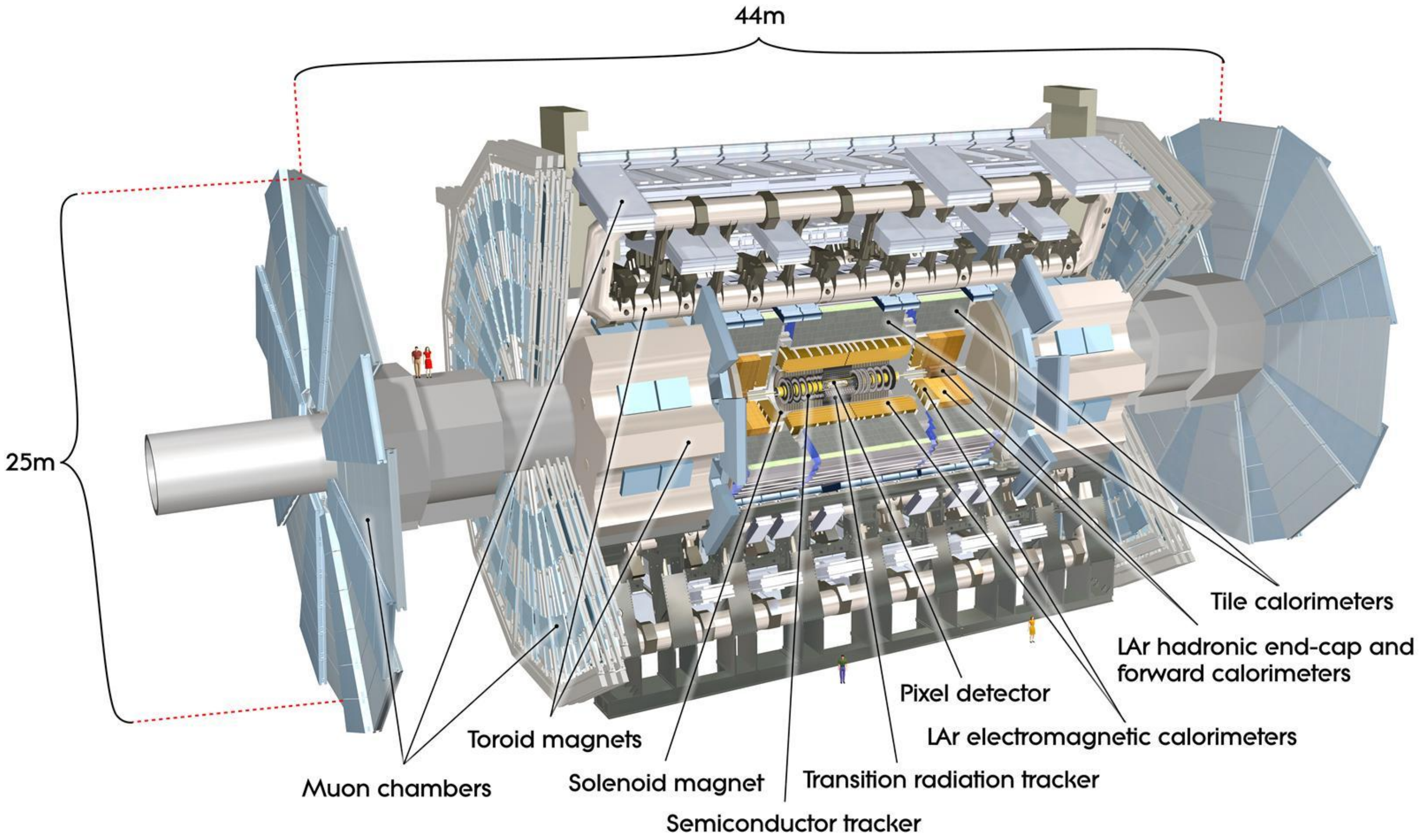

Collisions at LHC
Proton-Proton 2835 bunch/beam
Protons/bunch 10^{11}
Beam energy 7 TeV ($7x10^{12}$ eV)
Luminosity 10^{34} cm^{-2} s^{-1}
Crossing rate 40 MHz
Collisions ≈ 10^7 - 10^9 Hz
Bunch
Proton
Parton
(quark, gluon)
Particle
l
l
jet
jet
Higgs
Higgs
e^+
e^-
Z^o
e^+
Z^o
e^-
SUSY.....
Selection of 1 in
10,000,000,000,000



pile-up

Additional interactions per bunch crossing apart from the primary

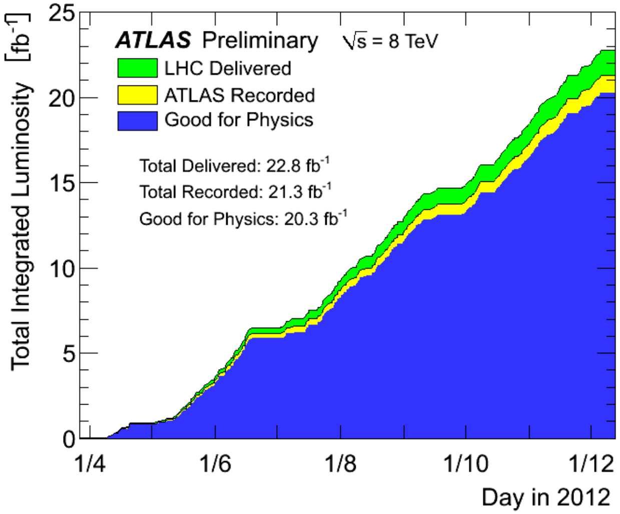
Higgs physics in ATLAS: The Detector

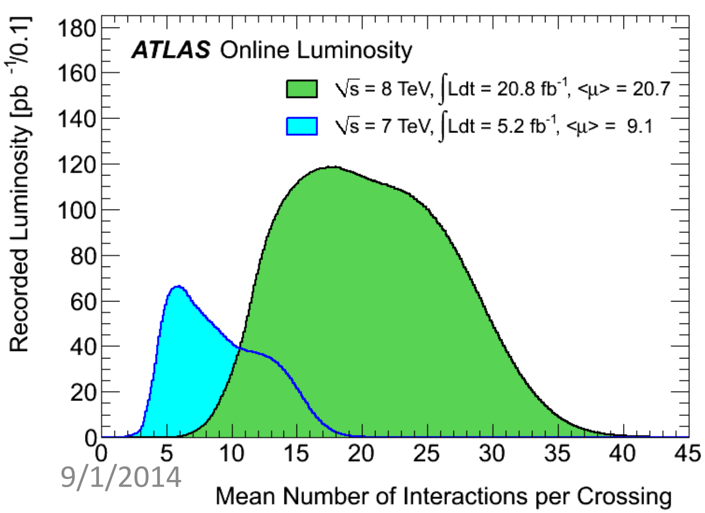


Excellent ATLAS performance in harsh conditions

95% of recorded events (90% of delivered events) available for analysis

- 4.57 fb-1 @ √s = 7 TeV (2011)
- 20.3 fb-1 @ √s = 8 TeV (2012)





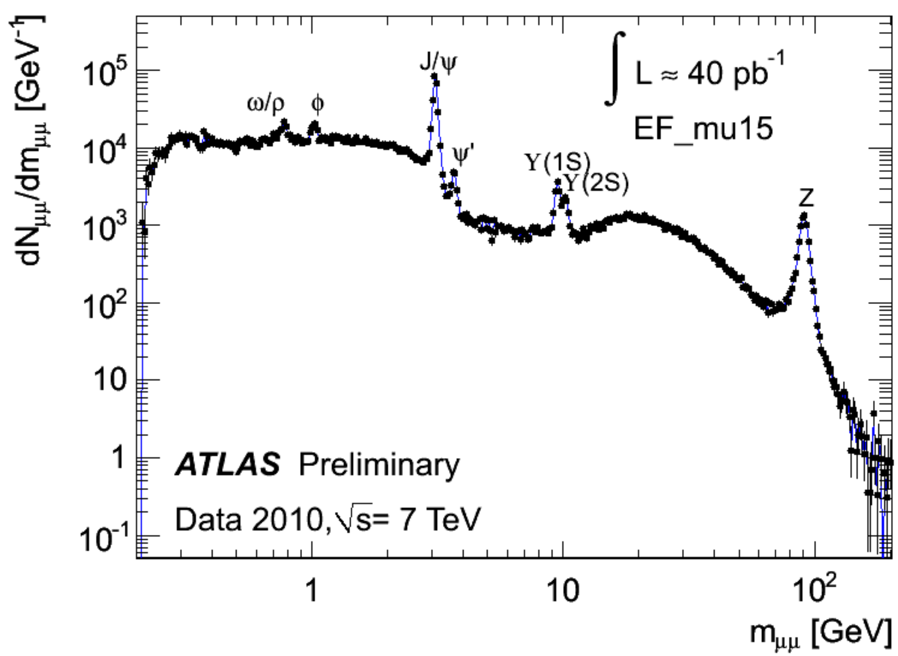
Standard candles are used to calibrate the detector

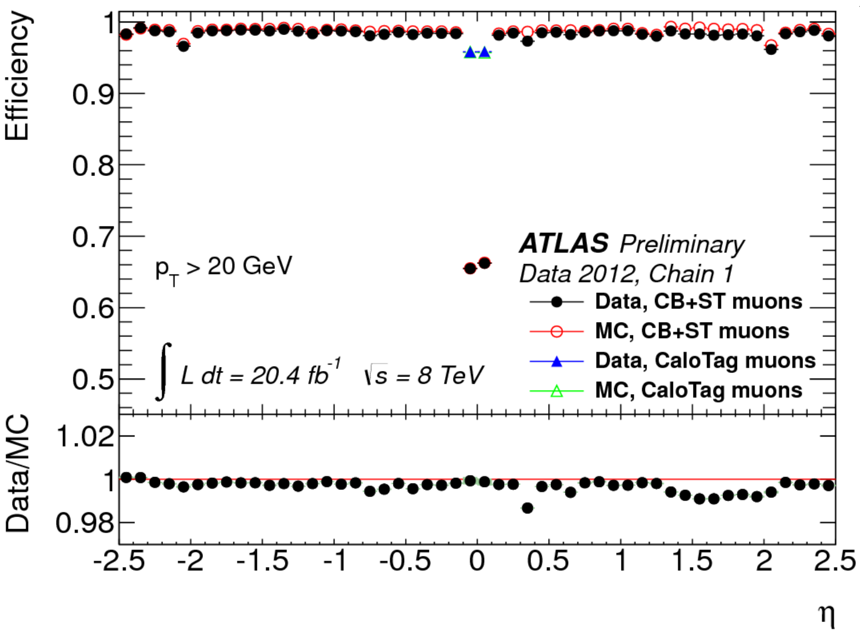
$9\times10^6\ Z\rightarrow\mu^+\mu^-$, $6\times10^6\ J/\psi\rightarrow\mu^+\mu^-$

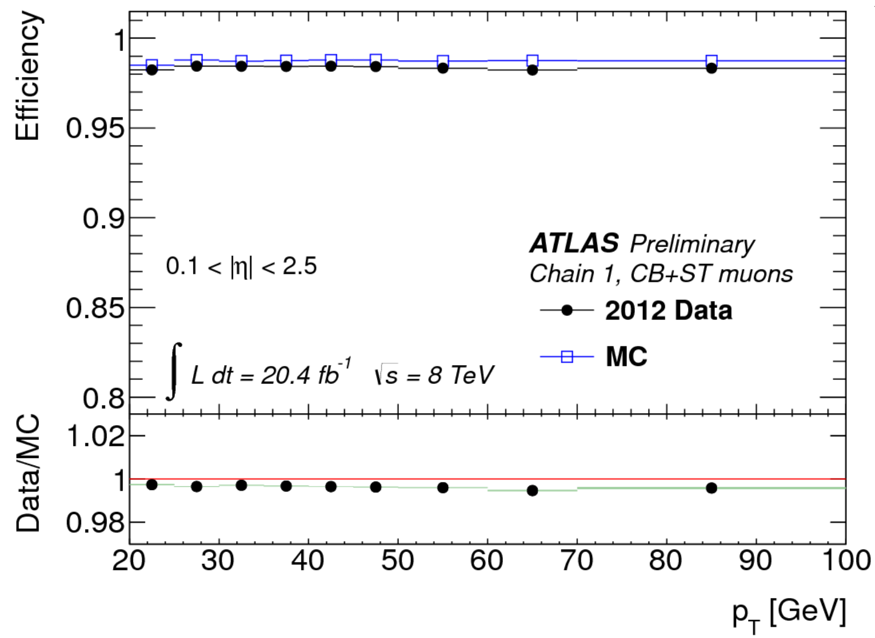
$6.6\times10^6\ Z\rightarrow e^+e^-$, $0.3\times10^6\ J/\psi\rightarrow e^+e^-$, $0.2\times10^6\ Z\rightarrow l^+l^-\gamma$

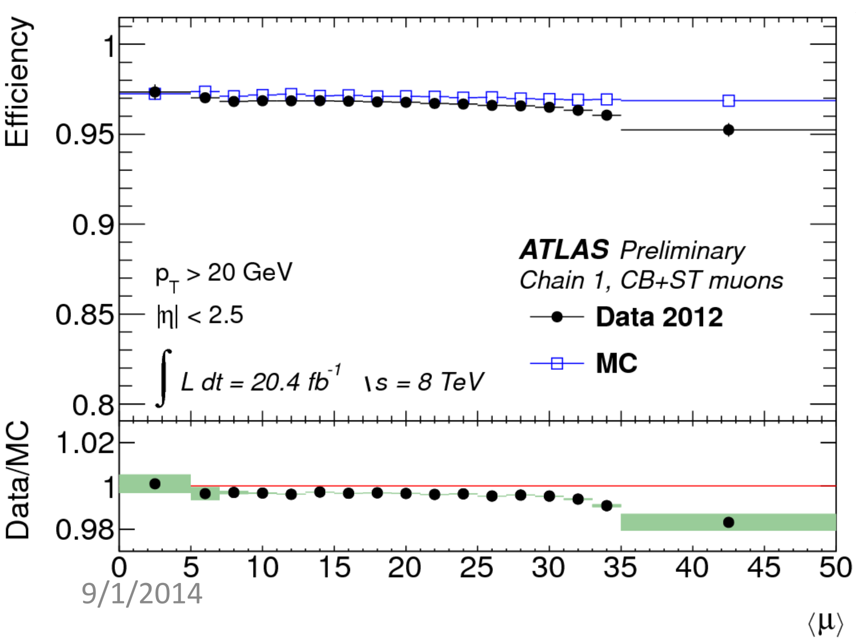
used for detector calibration

Run I corresponds >600 times the luminosity of the plot





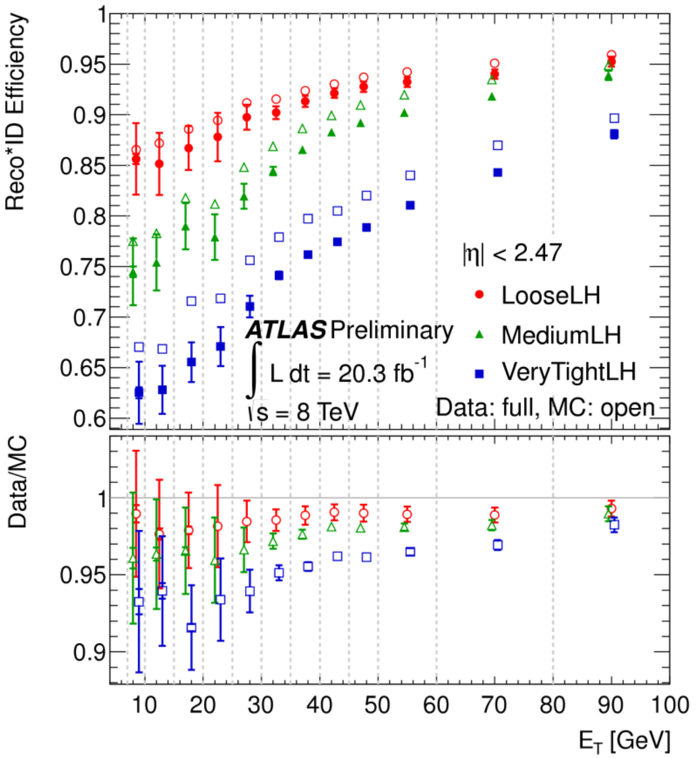


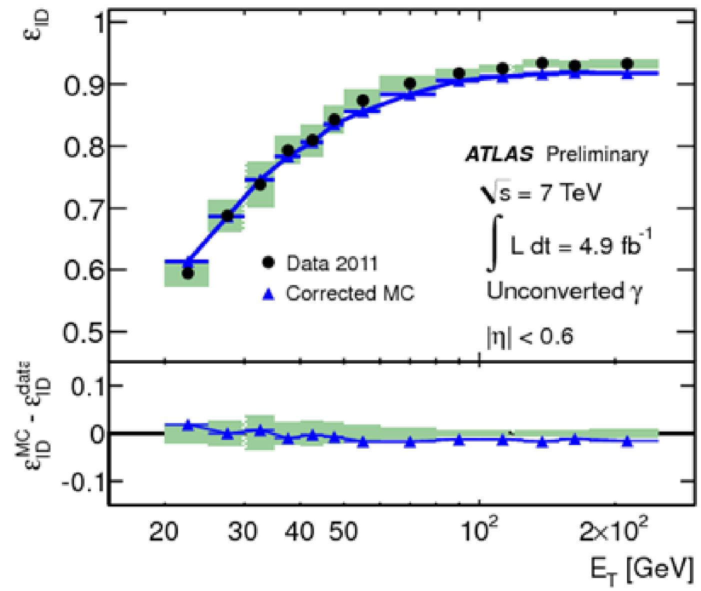


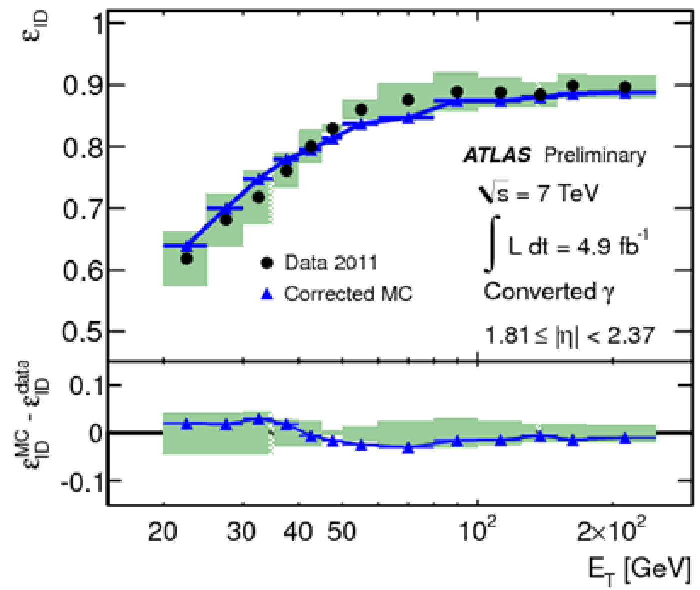
measure of pile-up

ATLAS-CONF-2014-032

ATLAS-CONF-2012-123







Channels studied in the context of SM Higgs Boson search:

- Bosonic Decays:

H → ZZ(*)→4l
H→ γγ
H→ WW(*) → lνlν
H→ Zγ

- Fermionic Decays:

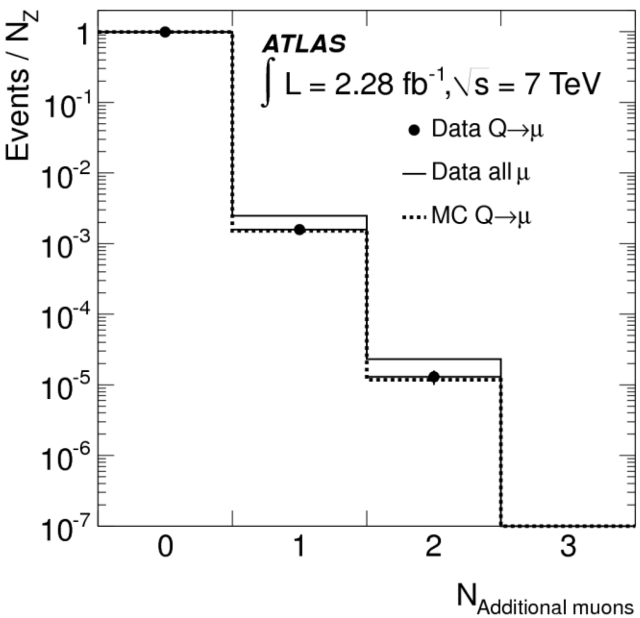
H → ττ (VBF, boosted)
VH→ Vbb, ttH→ttbb
H → μμ

- Sensitive mostly to high masses:

H→ZZ →llqq
H→ZZ → llνν
H→WW→ lνqq

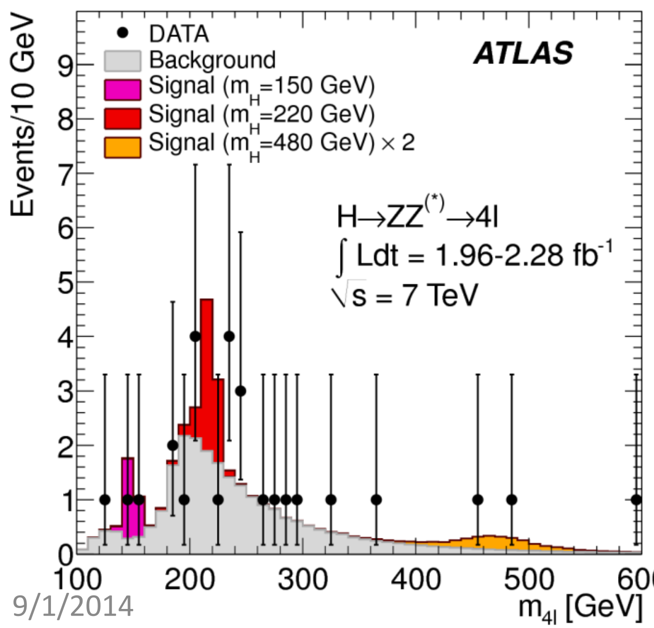
- **Four Isolated leptons**
- Narrow resonance on top of small background

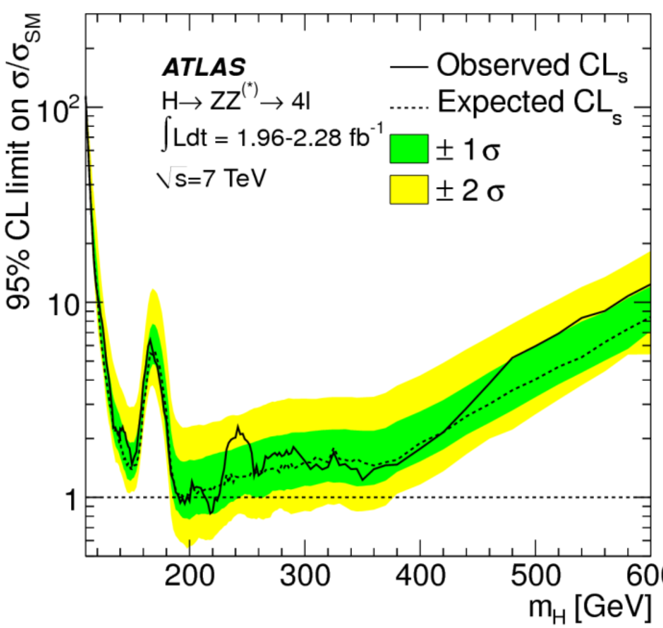
Background Composition: ZZ(*) - Z+jets, ttbar



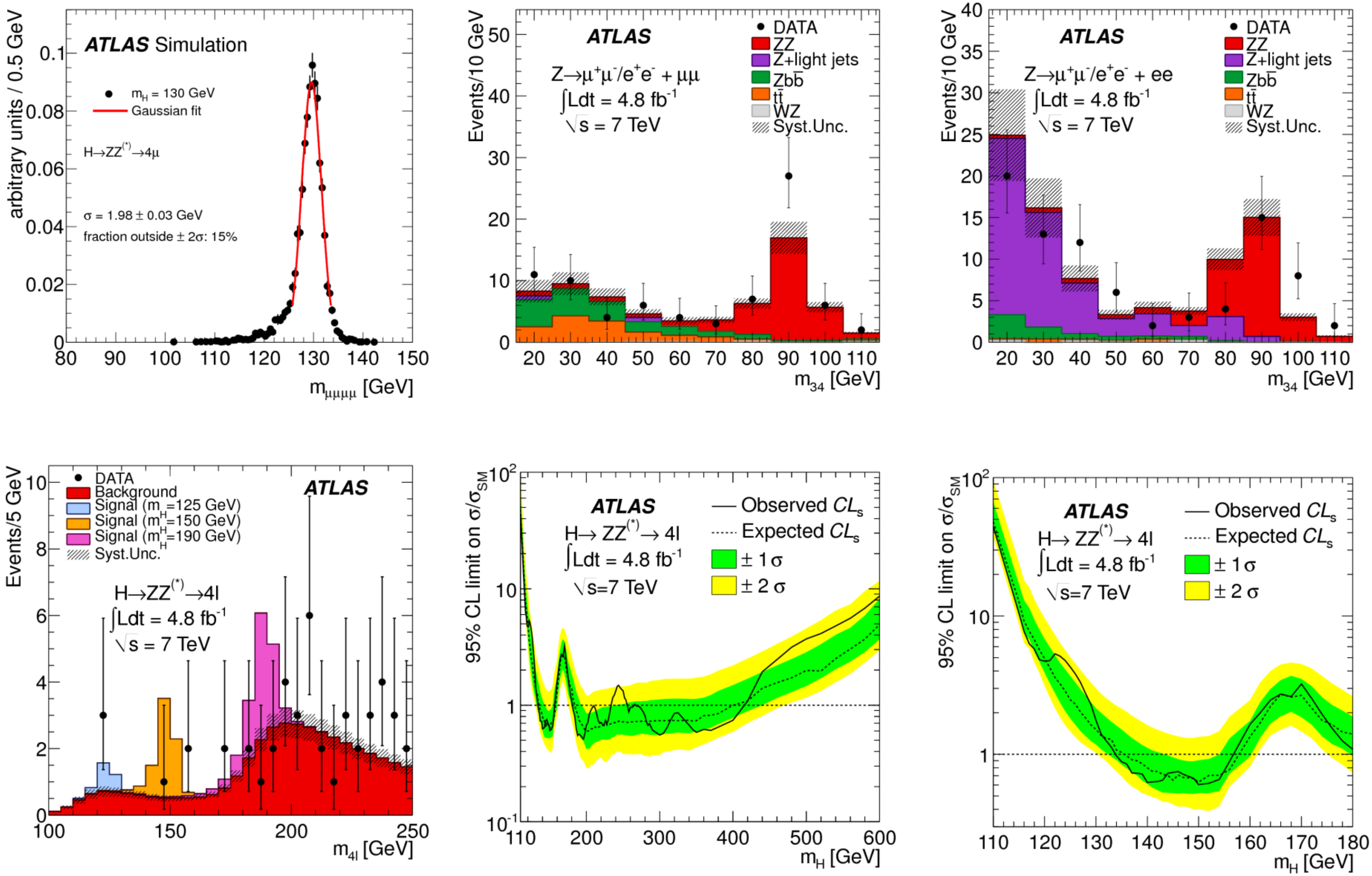
First data were used to:

- Estimate lepton reco/id efficiencies
- Define methods to control the reducible backgrounds
- Estimate the efficiency of the selection criteria
- Investigate high sensitivity regions

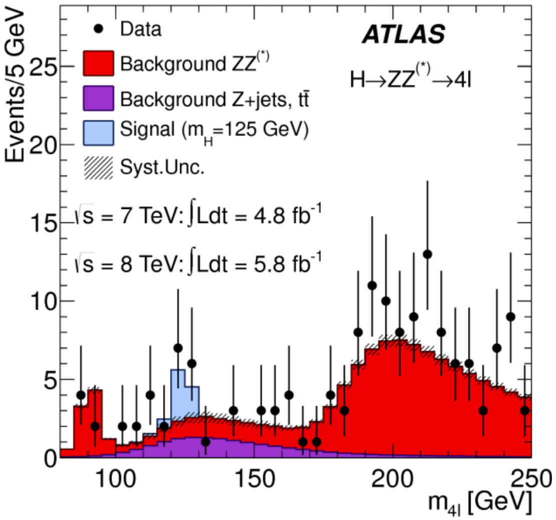


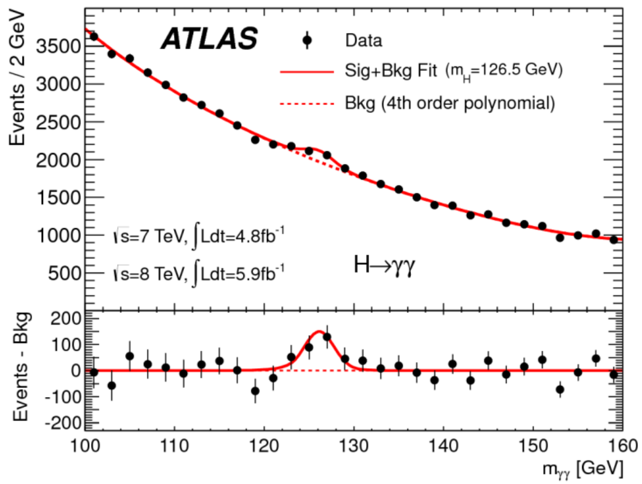


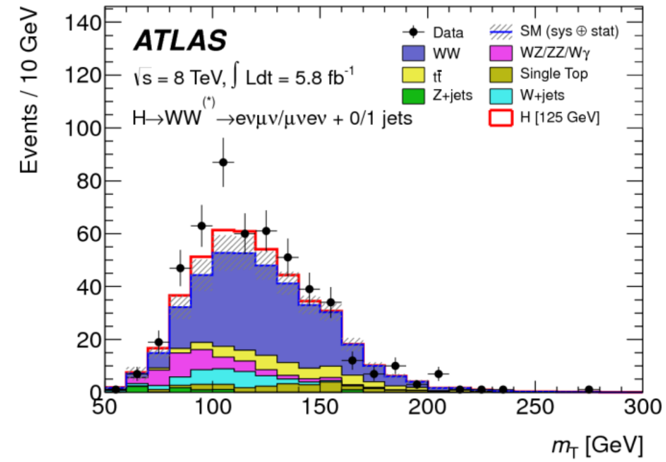
Higgs physics in ATLAS: *H→ZZ(*)→4l* - *Mid days* *Phys.Lett. B710 (2012) 383-402*

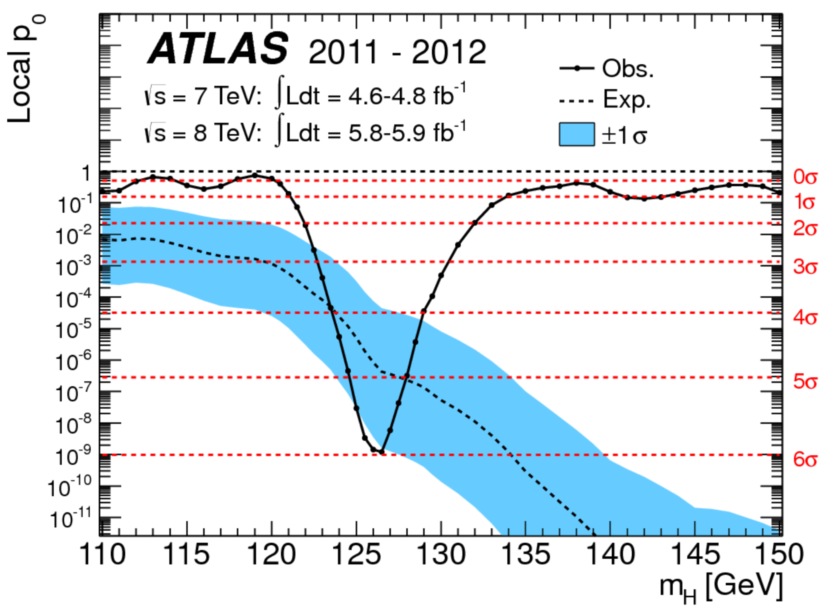


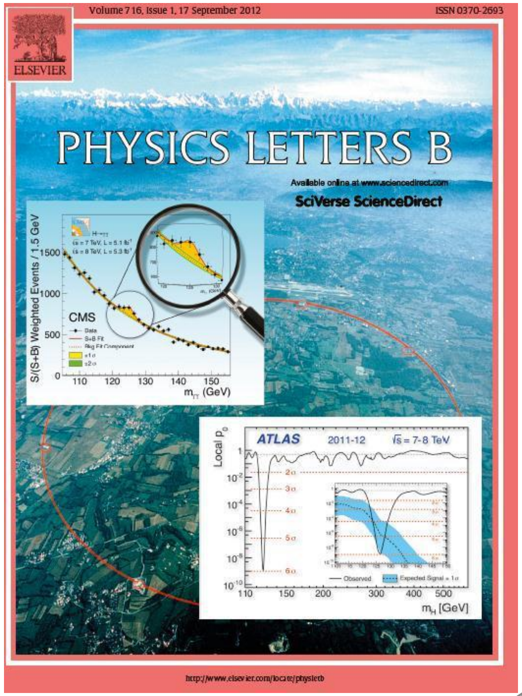
Higgs physics in ATLAS: ***The discovery*** *Phys. Lett. B 716 (2012) 1-29*











Trigger (eff 97-100%):

Single lepton 24 GeV

Di-lepton 12-12 (13-13, 18-8) GeV

e-mu 12-8 GeV

Selection:

2 SFOS lepton pairs

p_T> 20,15,10,7(6) GeV

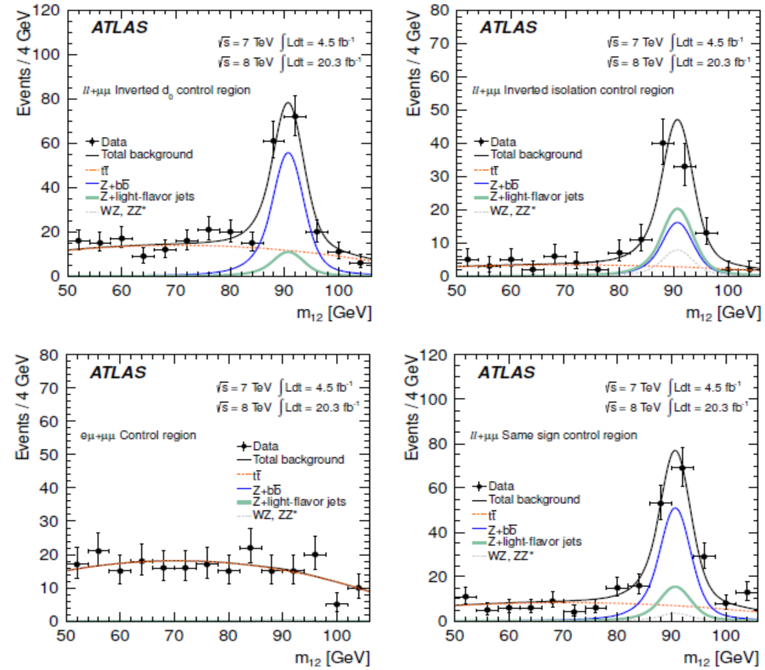
50 < m_{12}< 106 GeV, 12-50 < m_{34}< 115 GeV

Isolation - Originate from the primary vertex

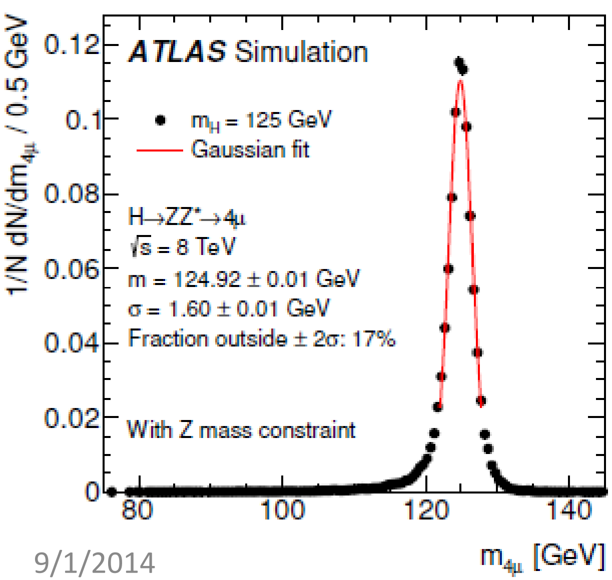
Efficiency: 39-27-20 %

Categorization: lepton flavour

Data driven background estimation



Excellent mass resolution



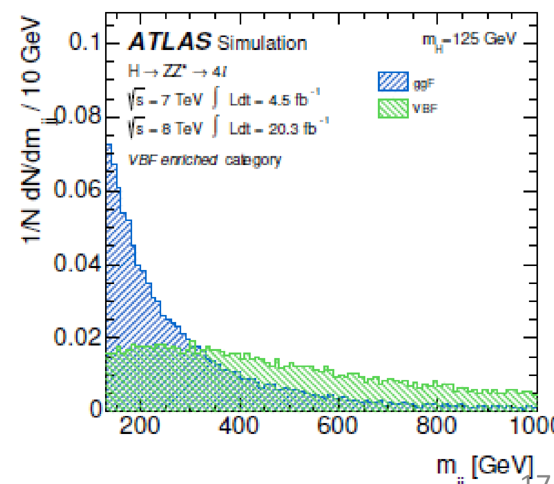
Use of BDT:

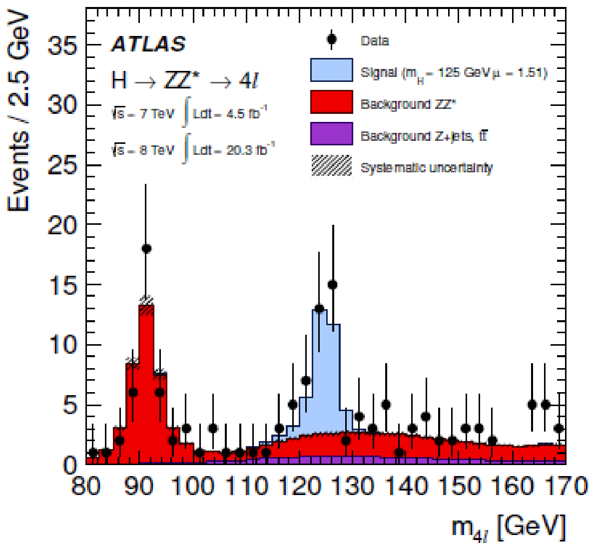
- for background rejection

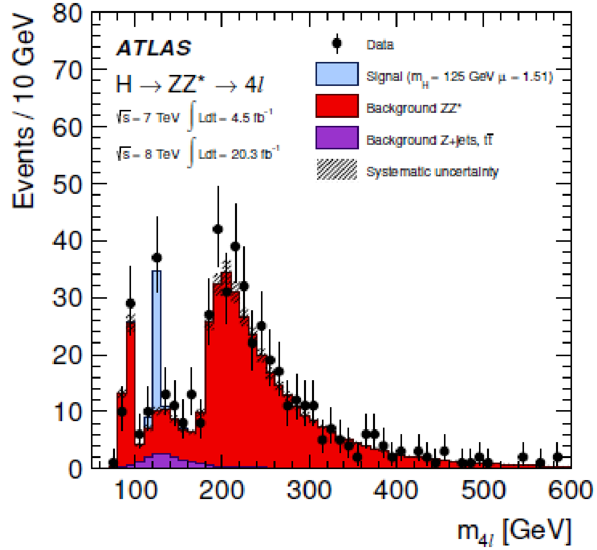
ME,P_T^{4l},η^{4l}

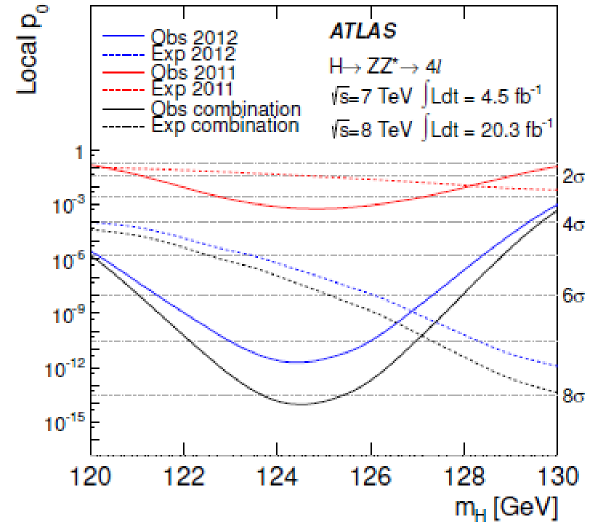
- for categorization

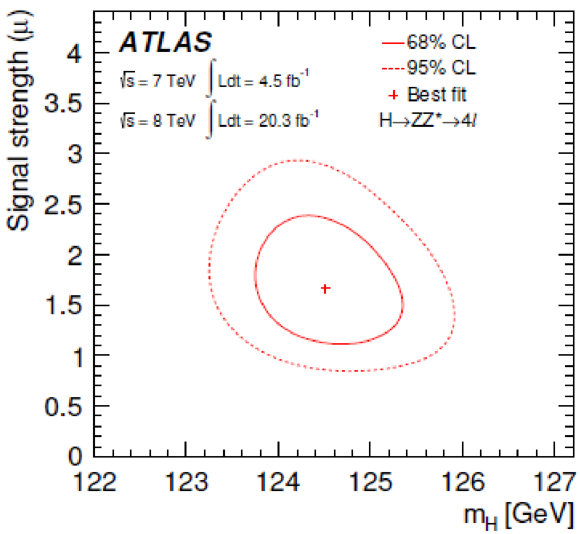
m_{jj}, $\Delta\eta_{jj}$, p_T^{j1}, p_T^{j2}, η^{j1}











Mass

$$m_H = 124.51 \pm 0.52(stat) \pm 0.06(syst)$$

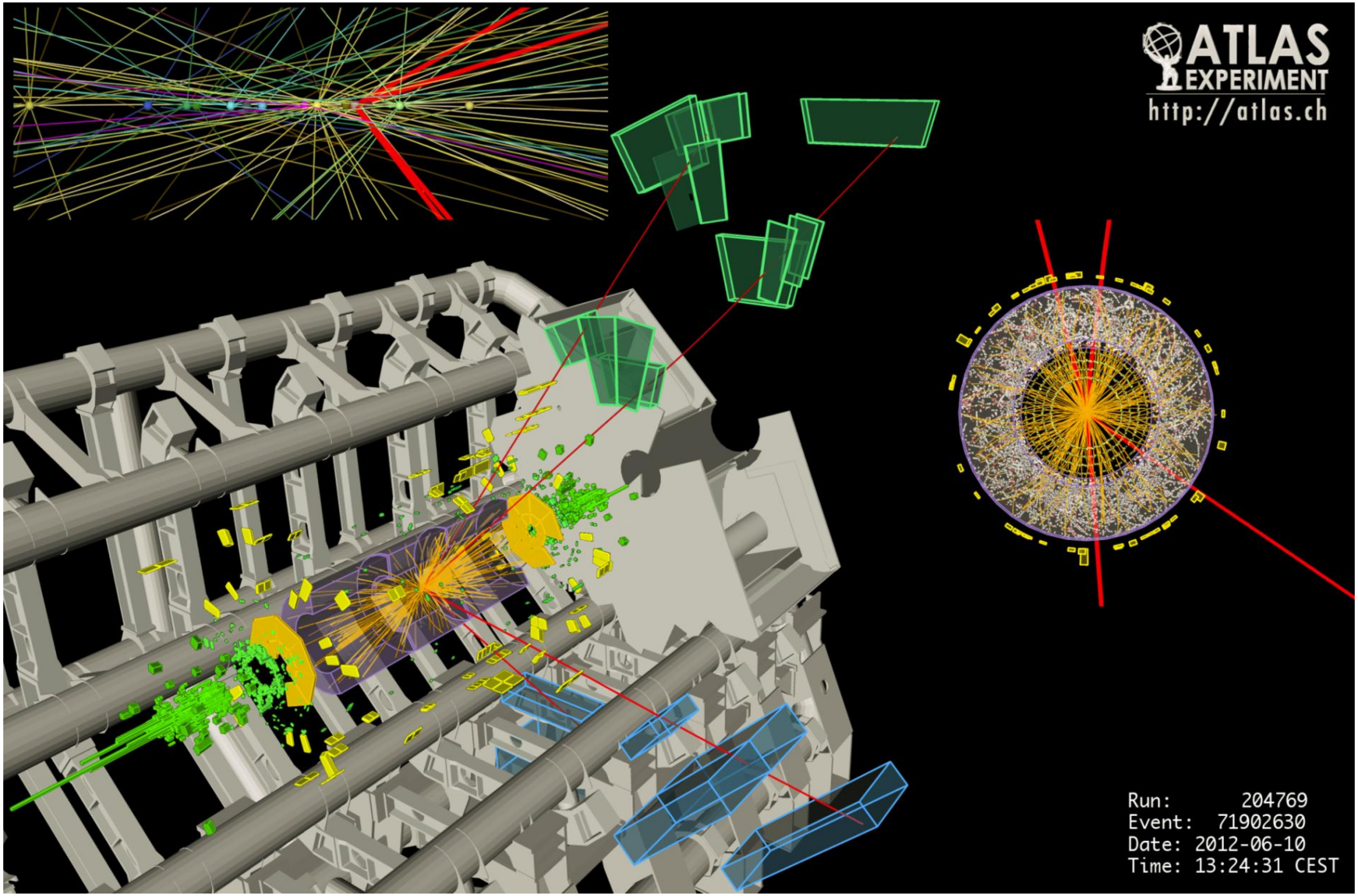
Signal strength at combined mass

$$\mu = 1.44^{+0.34}_{-0.31}(stat)^{+0.21}_{-0.11}(syst)$$

Signal Strength:
Observed signal rate / Expected SM rate

Higgs physics in ATLAS: *H→ZZ(*)→4l*

$$H \rightarrow ZZ(*) \rightarrow 4\mu$$



- **Two isolated photons**
- Narrow resonance on top of a continuous background

Background Composition:

Irreducible γγ continuum(~77%)

Reducible γ-jet(~20%), jet-jet(~3%)

Trigger (eff >99%):

Diphoton 35-25 GeV

Selection (eff 30-40%):

Two photons $E_T/m_{\gamma\gamma} \geq 0.35, 0.25$

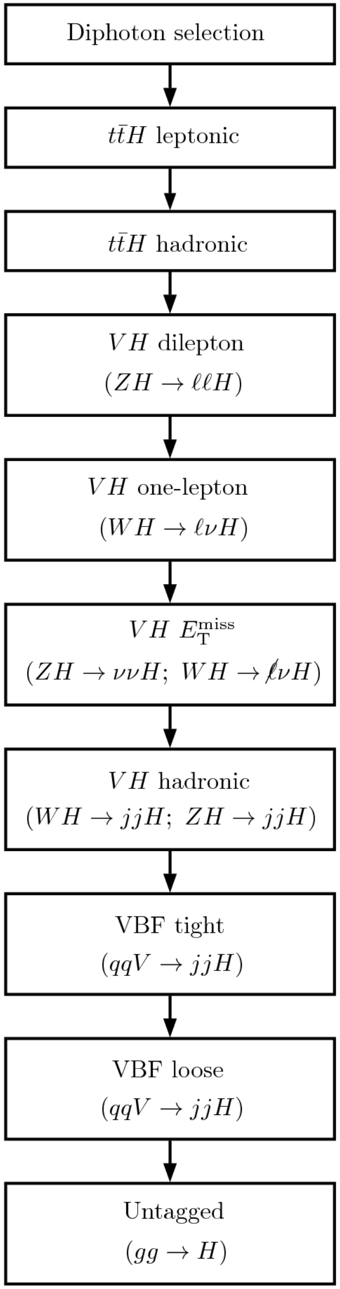
Isolation , Photon pointing

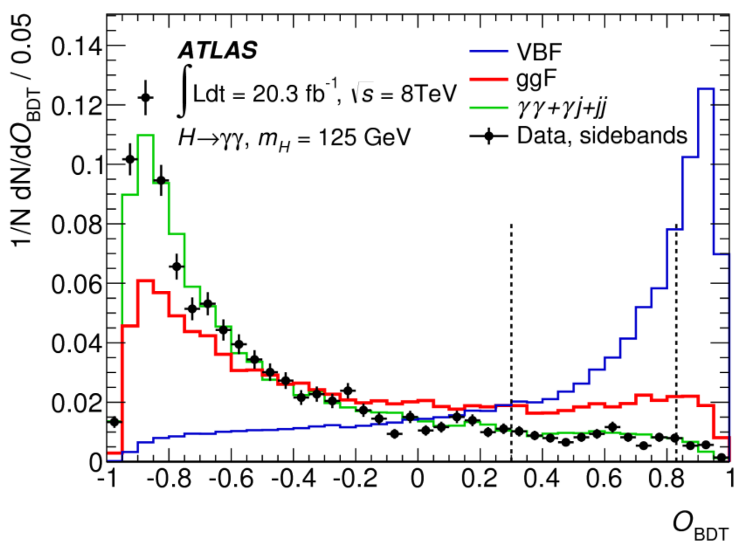
Categorization:

Converted – Unconverted

η region, E_T region

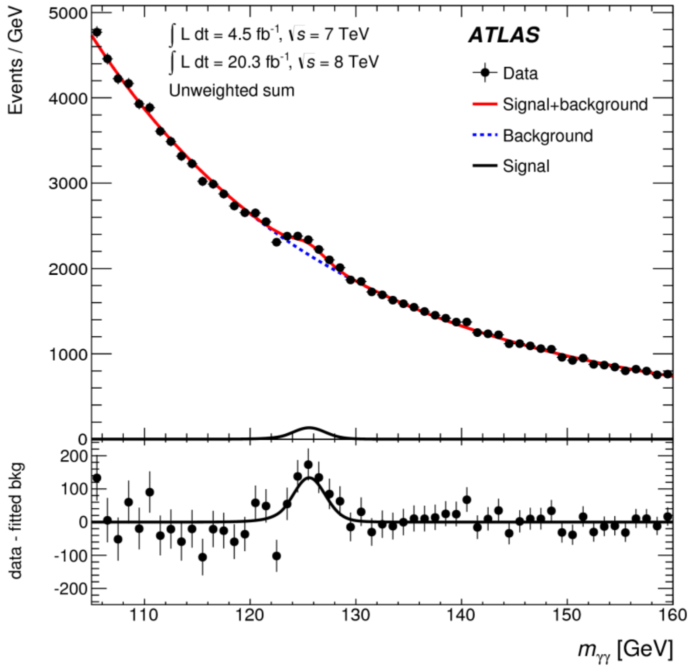
Further Categorization for production modes

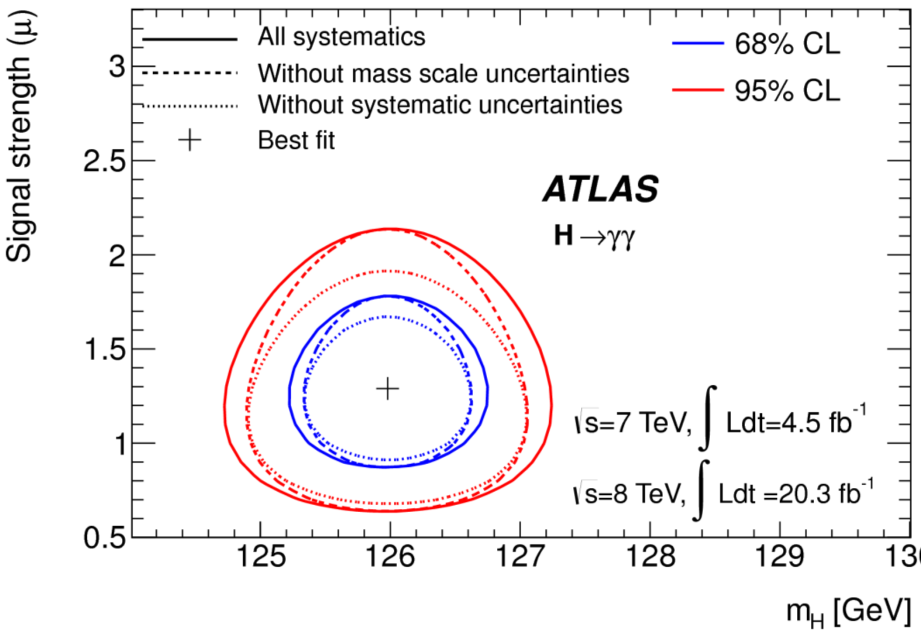


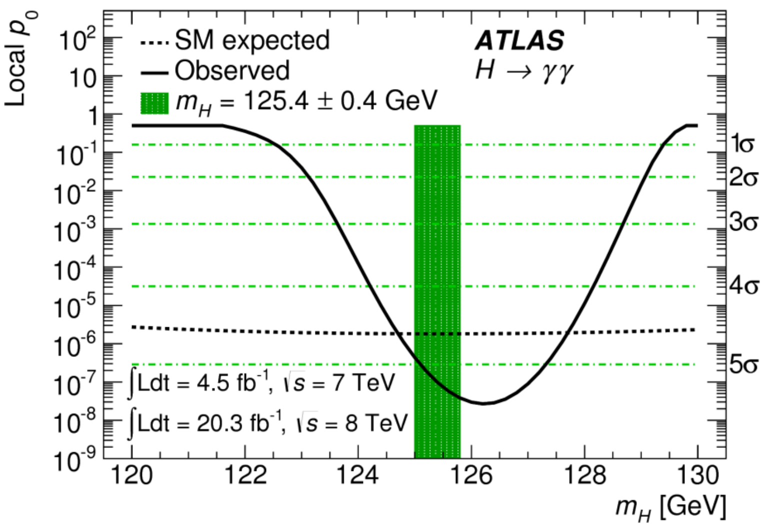


Higgs physics in ATLAS: $H \rightarrow \gamma\gamma$

arXiv:1406.3827, arXiv:1408.7084







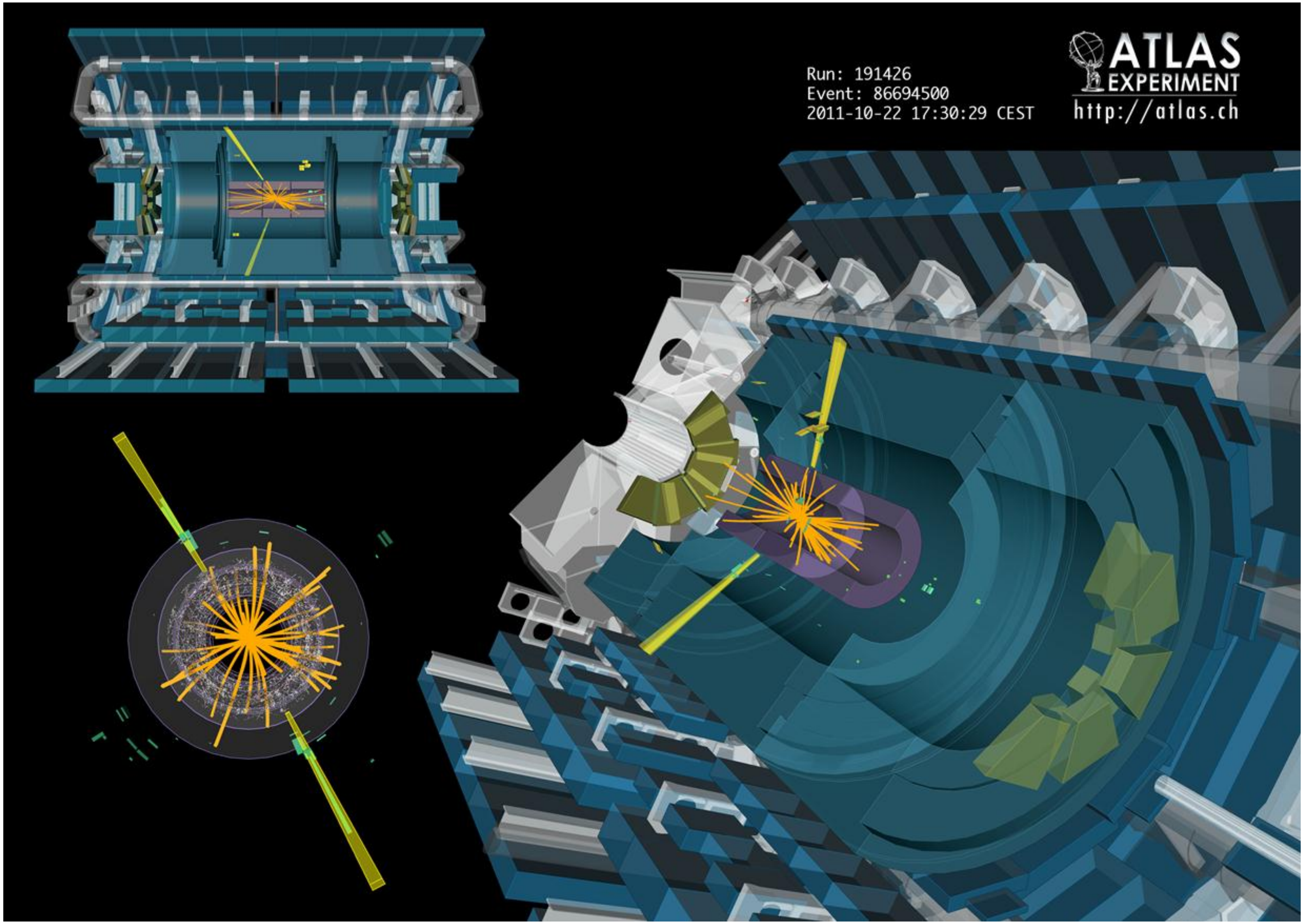
Mass

$$m_H = 125.98 \pm 0.42(stat) \pm 0.28(syst)$$

Signal strength

$$\mu = 1.17 \pm 0.23(stat)^{+0.10}_{-0.08}(syst)^{+0.12}_{-0.08}(theory)$$

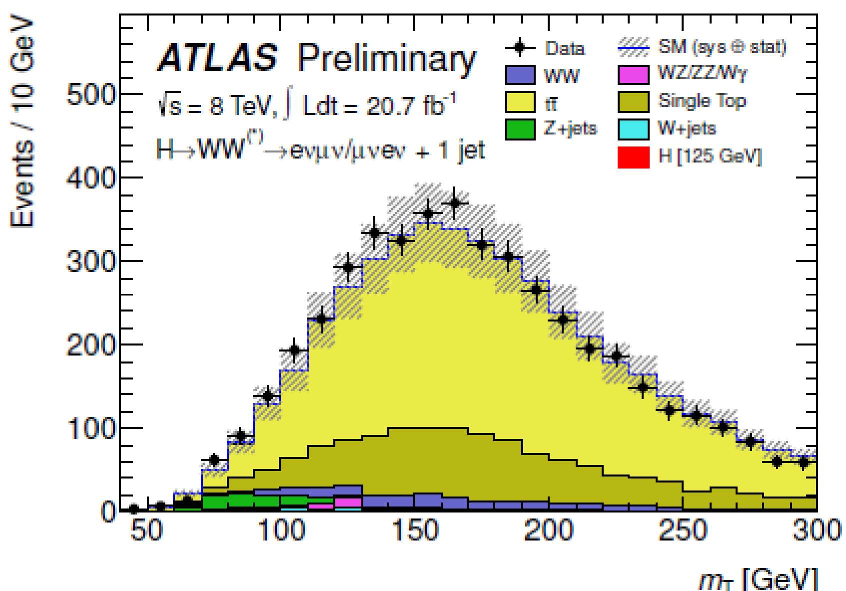
$$H \to \gamma\gamma$$

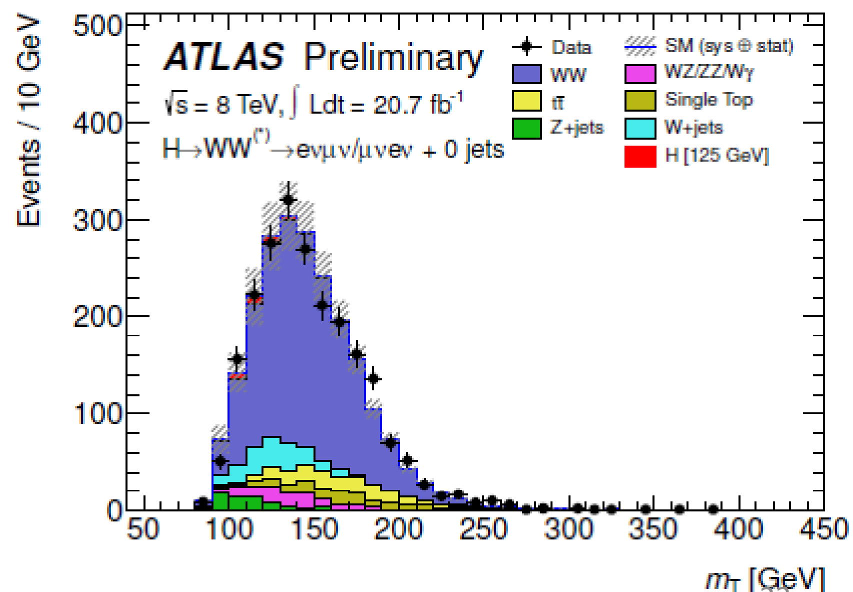


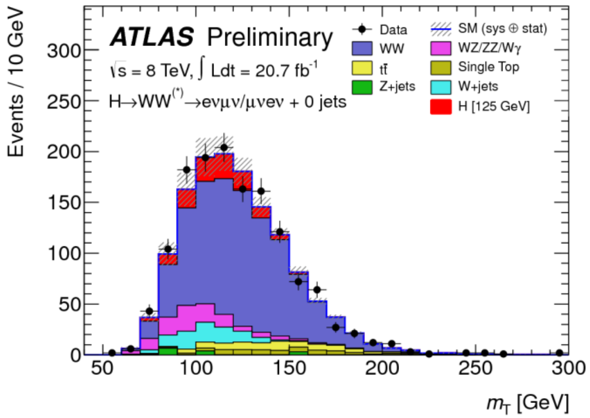
- **Two isolated leptons + Missing E_T**
- Full reconstruction not possible
  but excellent rate

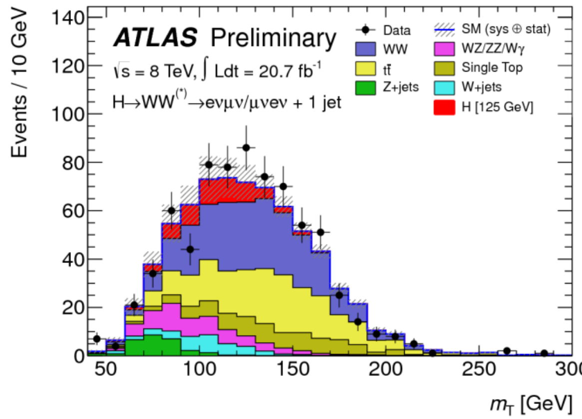
Background Composition:
WW, ttbar, Drell-Yan, W+jets

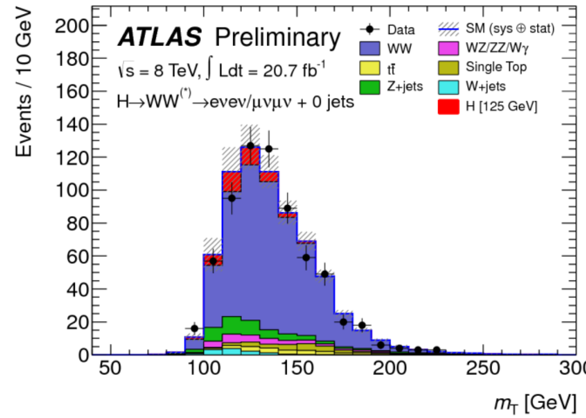
Trigger: As in H→ZZ→4l
Selection: 2 OS isolated leptons p_T> 25,15 GeV
Large missing E_T (>20 GeV) criteria on $\Delta\phi_{ll}$, m_{ll}, p_{Tll}
Categorization: Number of jets – lepton flavour – m_{ll}
Discriminant: $\mathbf{m_T}$

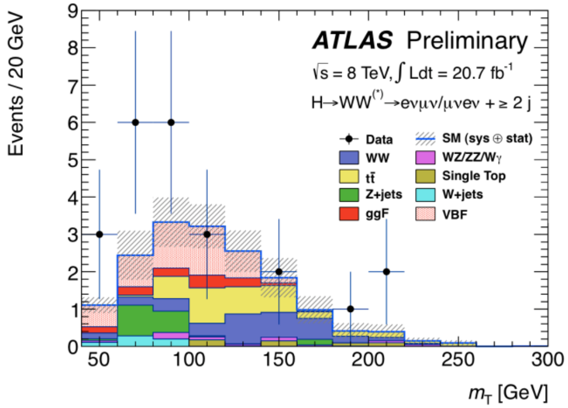


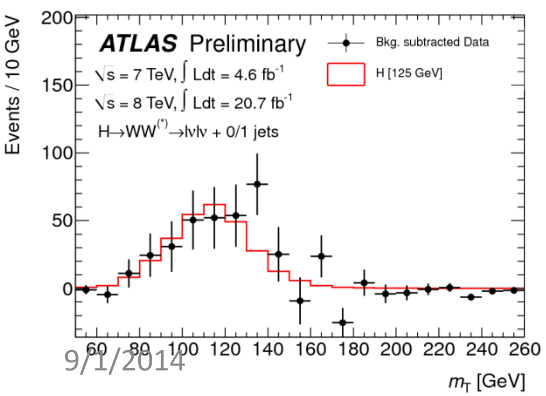


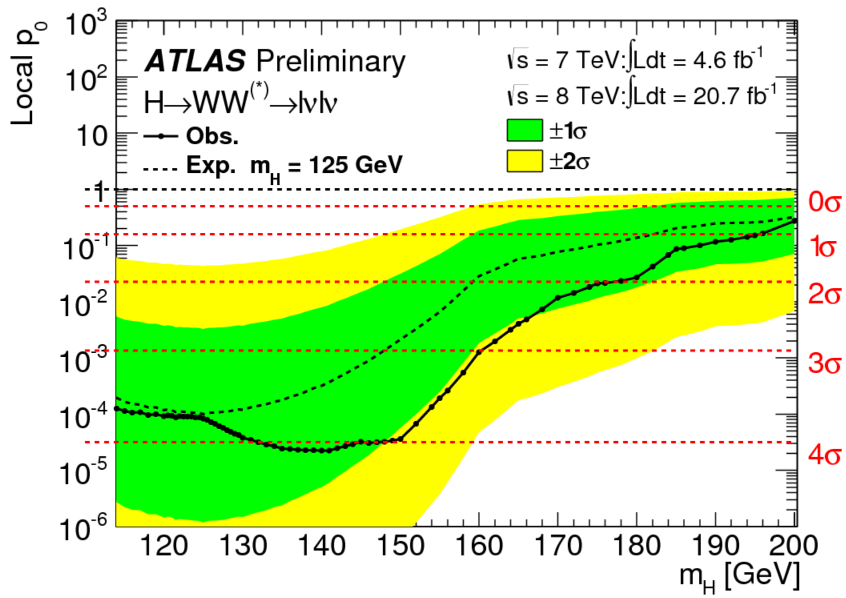








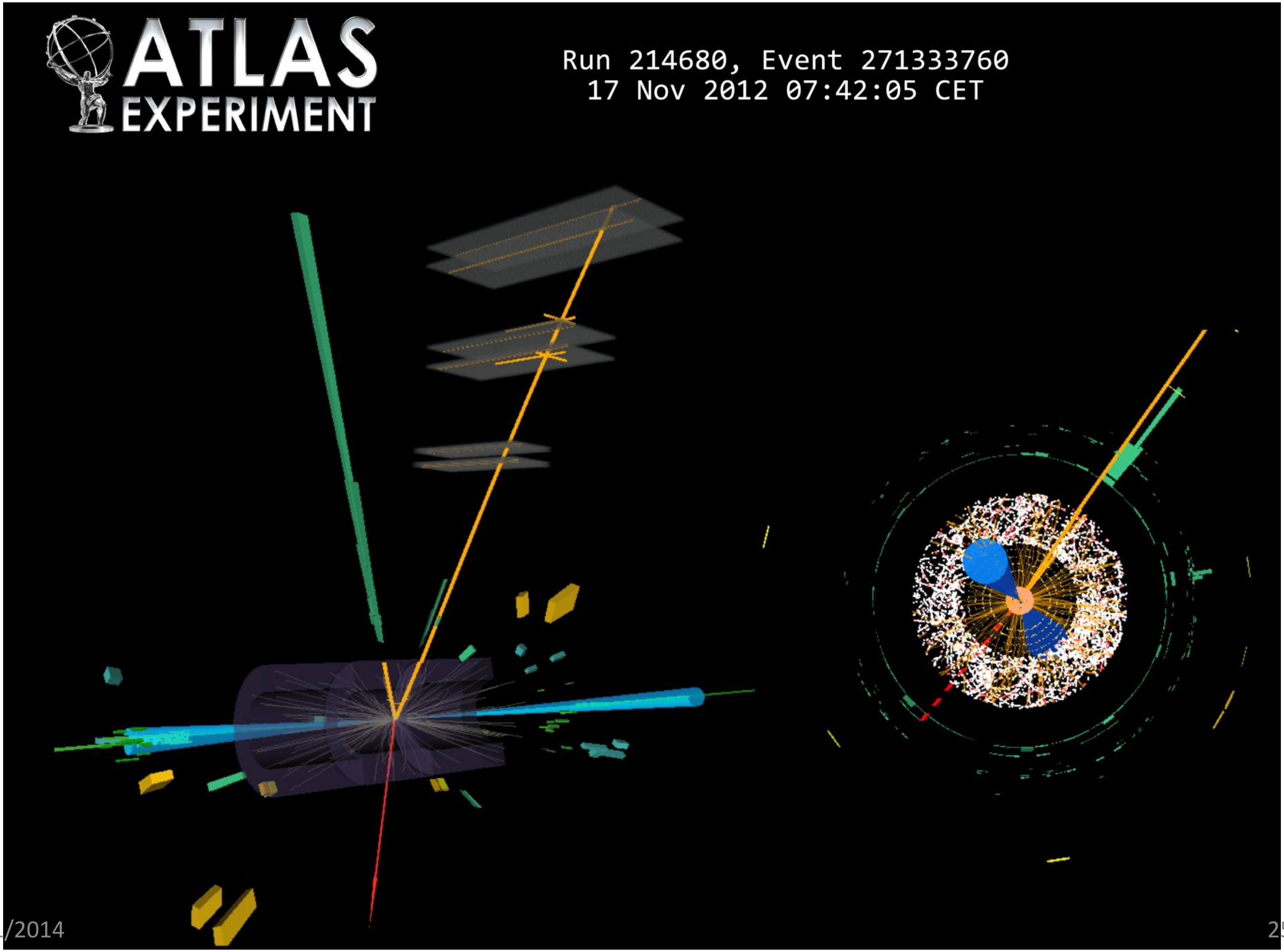




Signal strength

$$\mu = 1.01 \pm 0.21(stat) \pm 0.19(th.syst) \pm 0.12(ex.syst)$$

$$H \to \mu\nu\, e\nu$$

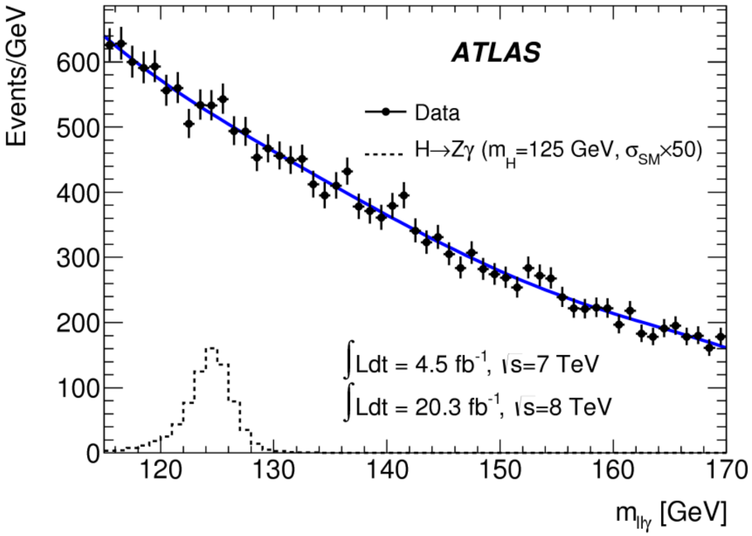

ATLAS
EXPERIMENT
Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET

- **Two isolated leptons + photon**
- Narrow resonance on top of

a continuous background

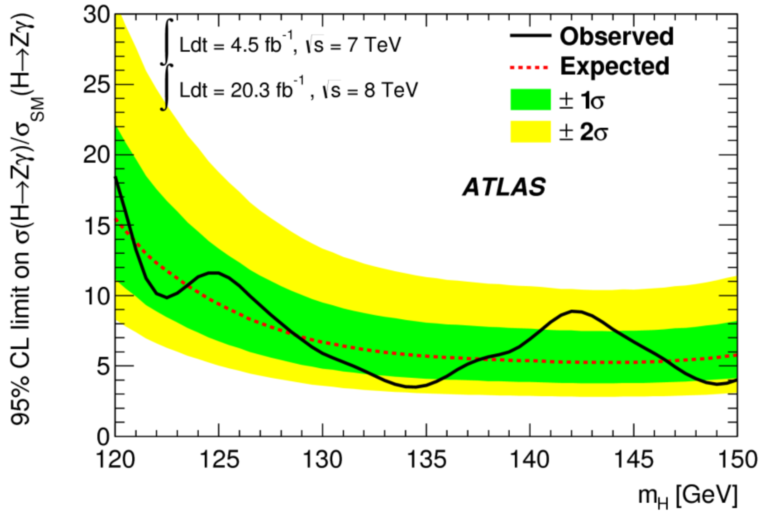
Background Composition:

Z+γ, Z+jets



Selection:

Well reconstructed Z candidates (±10 GeV from the Z pole) accompanied by a photon (E_T > 15 GeV)



- **2 b-jets + ll or lν or νν**
- Broad peak (σ≈10%)

Background Composition:

W+jets, Z+jets, top, diboson

Trigger:

Single lepton, di-lepton, missing E_T

Selection:

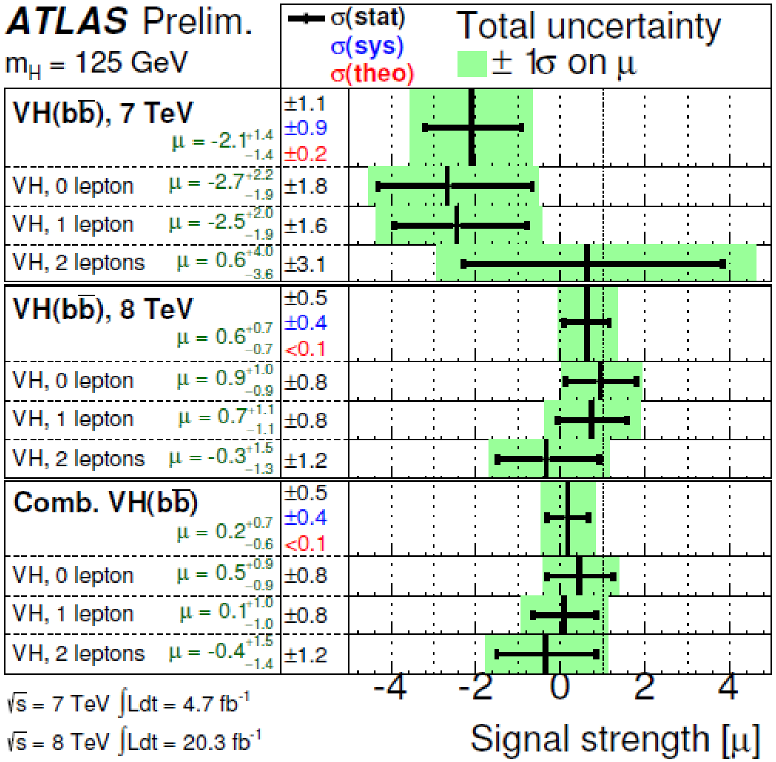
leptons (p_T>25 GeV) 0, 1 or 2 and E_T^{miss} requirement accordingly

Isolation

Two jets b-tagged, p_T> 45,20 GeV

Categorization:

According to V decay, # of jets, p_T^V

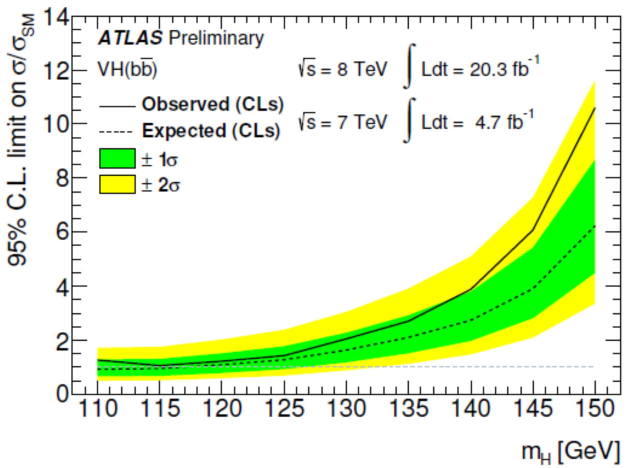


Analysis results on VZ(Z→bb)

μ_{VZ}**=0.9±0.2**

Signal strength

$$\mu = 0.2 \pm 0.5(stat) \pm 0.4(syst)$$



Higgs physics in ATLAS: tt*H*→ *ttbb*

ATLAS-CONF-2014-011

- **4 b-jets + lνlν or lν**
- Broad peak (σ≈10%)

Background Composition:

Mainly ttbar

Trigger:

Single lepton

Selection:

1 or 2 leptons p_T>25(15) GeV

Isolation

>=2 jets b-tagged, p_T> 25 GeV

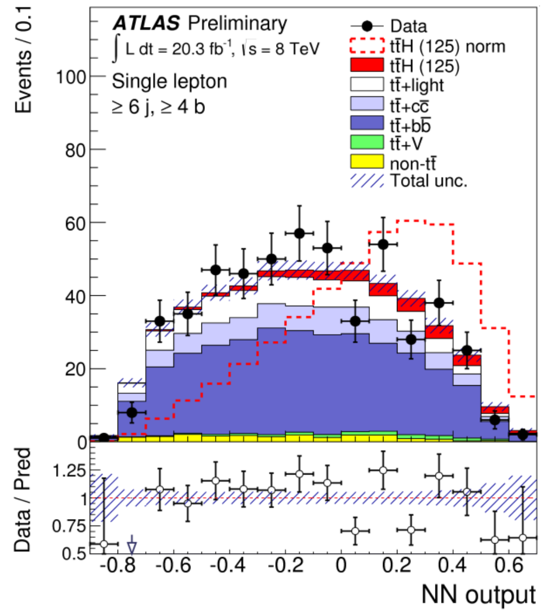
Categorization:

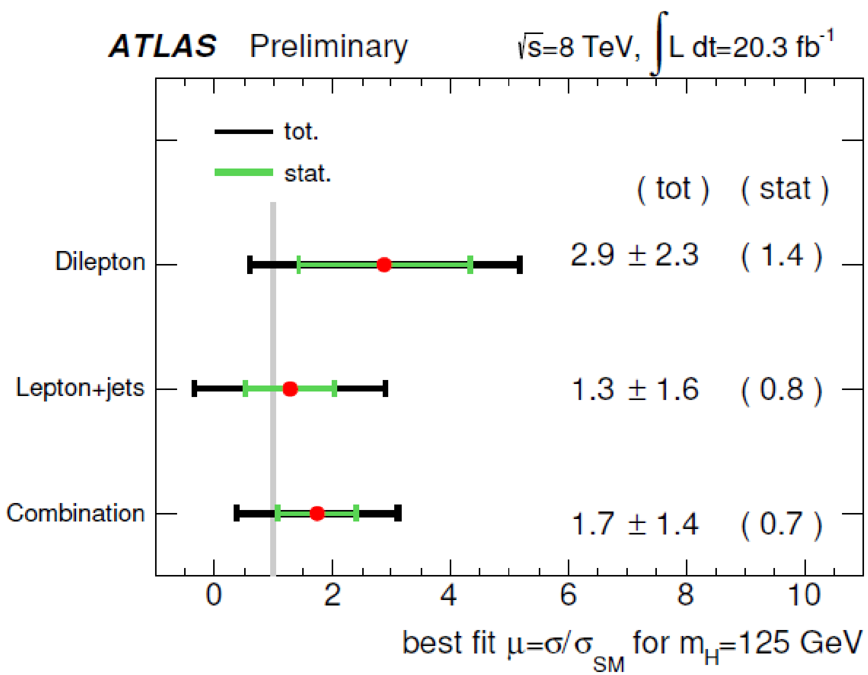
According to

# of jets, # b-tagged jets

Some are SR, other CR

Discriminant 3-layer NN





- **Two isolated taus, two jets**
- Full reconstruction not possible

Background Composition:

Z→ττ, Z→ll, W+jets, top, diboson

Trigger:

Single lepton, di-lepton, tau-had

Selection:

p_T^e>15 GeV, p_T^μ>10 GeV

BDT tau, p_T^τ>20 GeV (eff 55-60%)

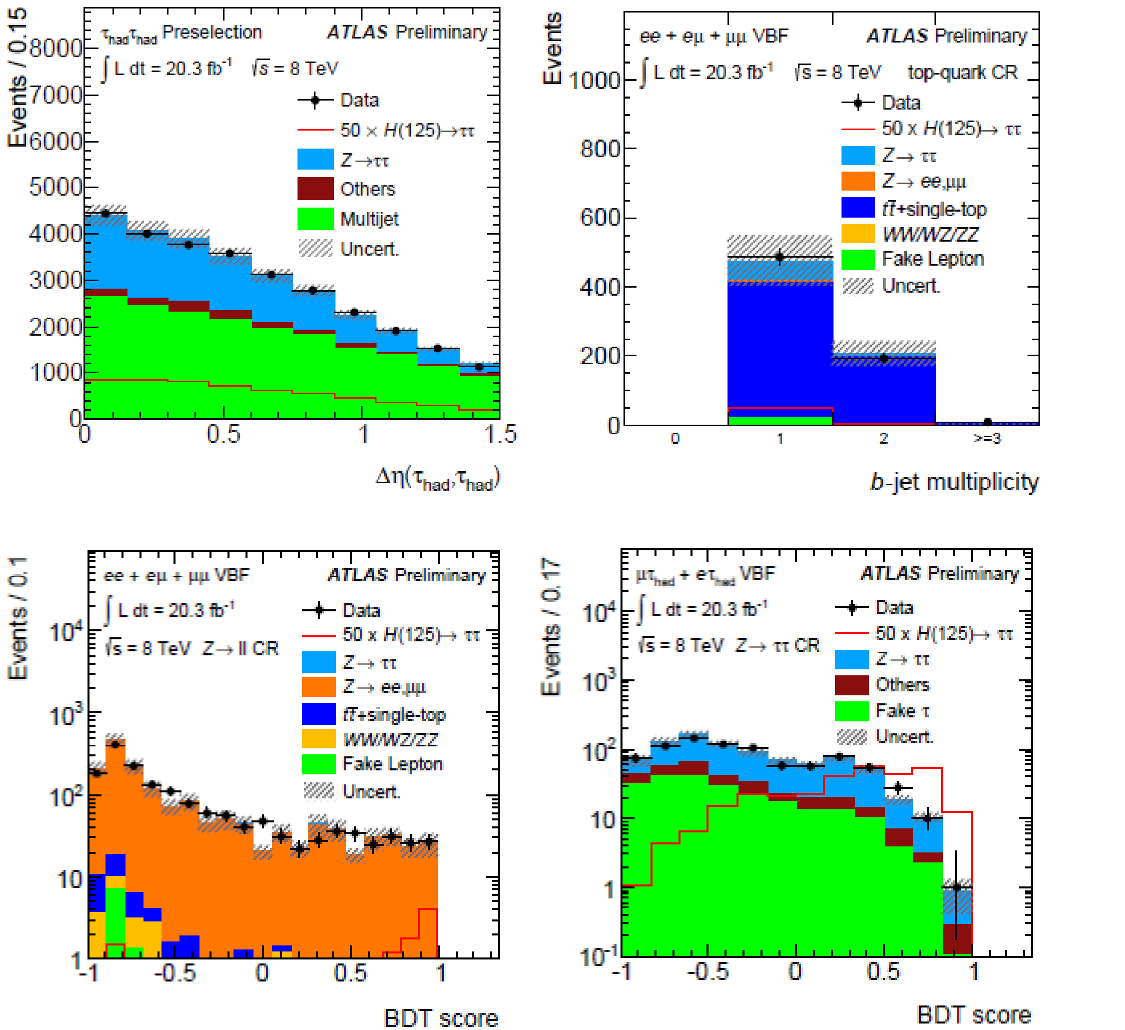
E^T_{mis}>20 – 40 GeV, p_T^{jet}> 30 GeV

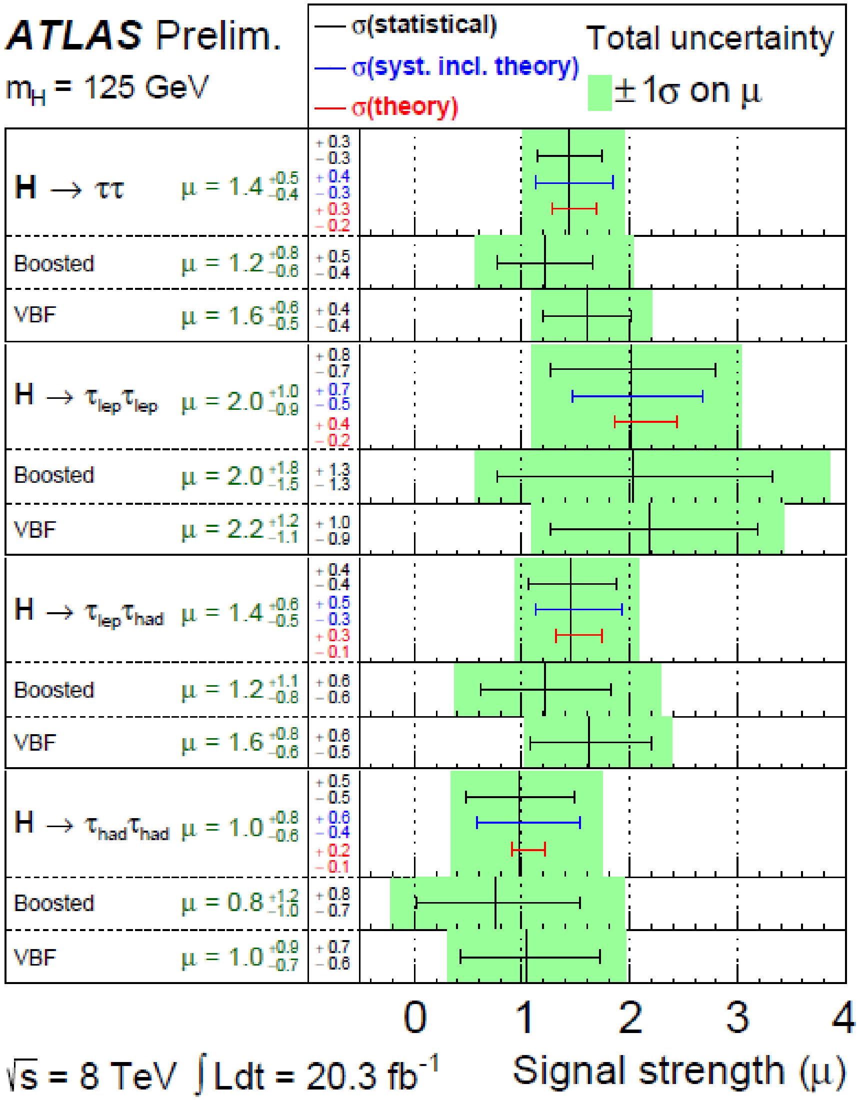
Categorization (BDT for each):

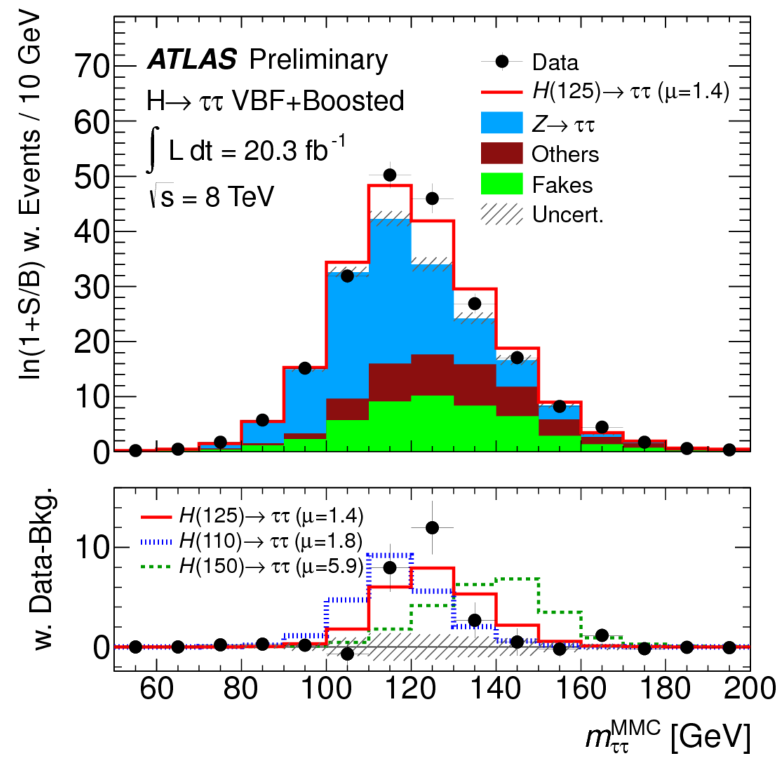
τ decay (ll,lh,hh)

jet config (VBF, Boosted)

Z→ττ τ-embedded Z→μμ



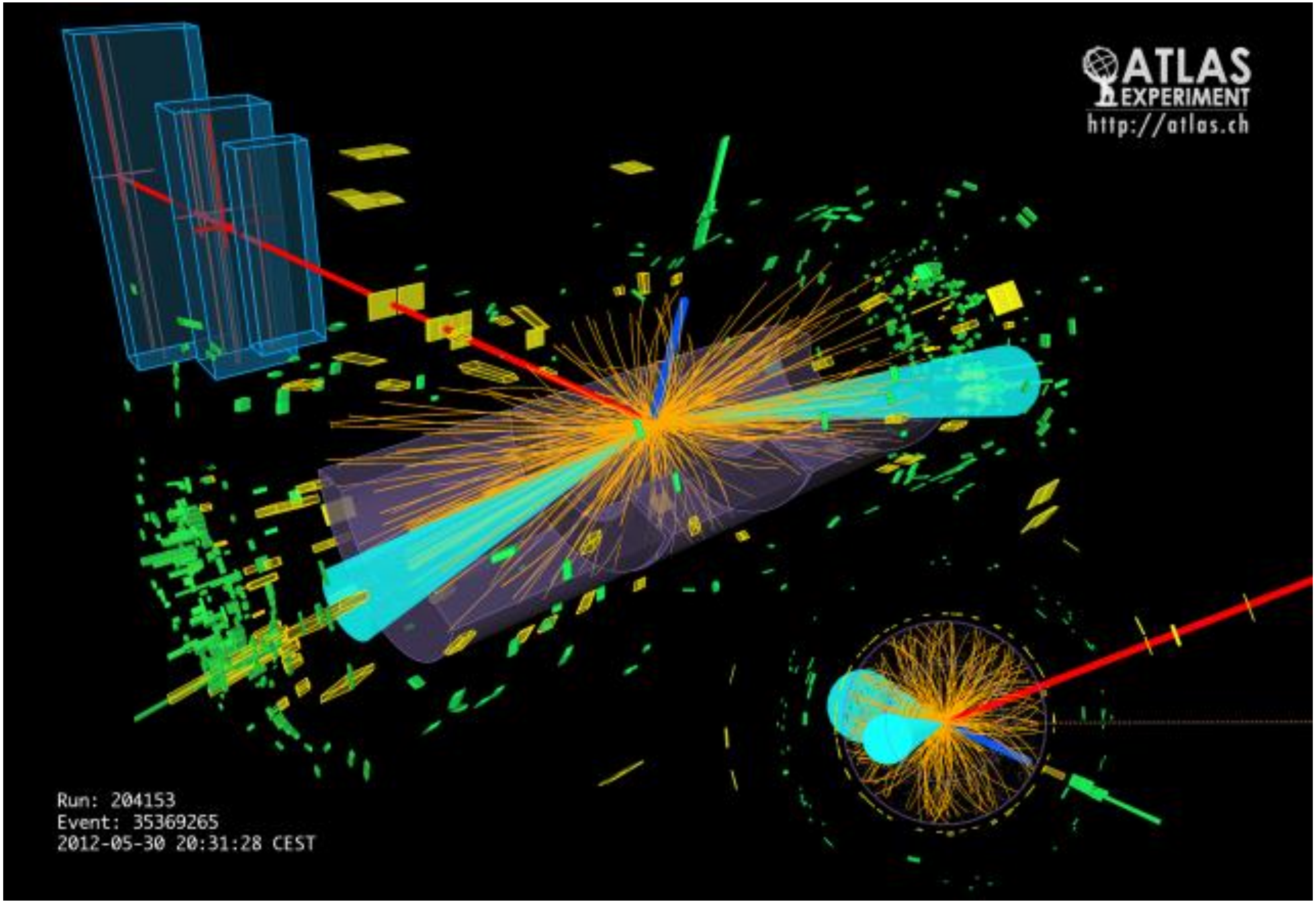




Signal strength

$$\mu = 1.43^{+0.31}_{-0.29}(stat)^{+0.41}_{-0.30}(syst)$$

$$H \to \tau^+\tau^-$$


ATLAS
EXPERIMENT
http://atlas.ch
Run: 204153
Event: 35369265
2012-05-30 20:31:28 CEST

- **Two isolated muons**
- Narrow resonance on top of DY

Background Composition:

Mainly DY

Trigger:

Single muon 24 GeV

Di-muon 13-13, 18-8 GeV

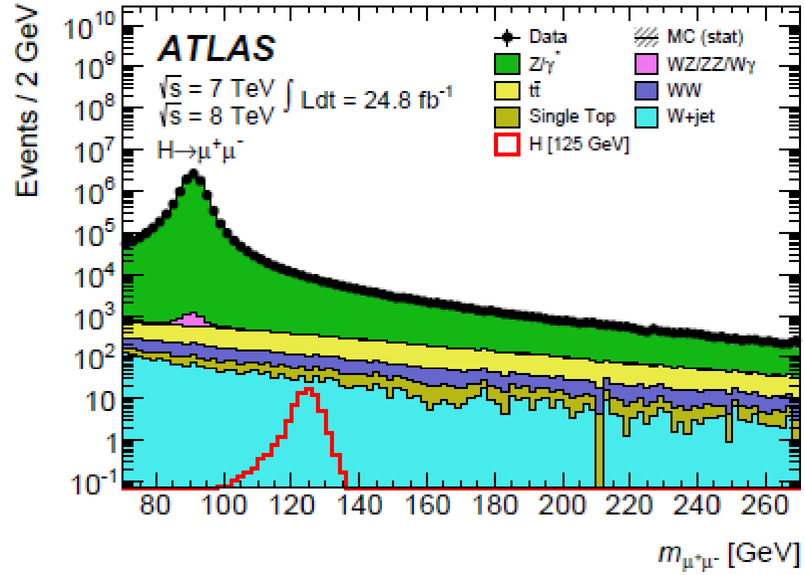
Selection:

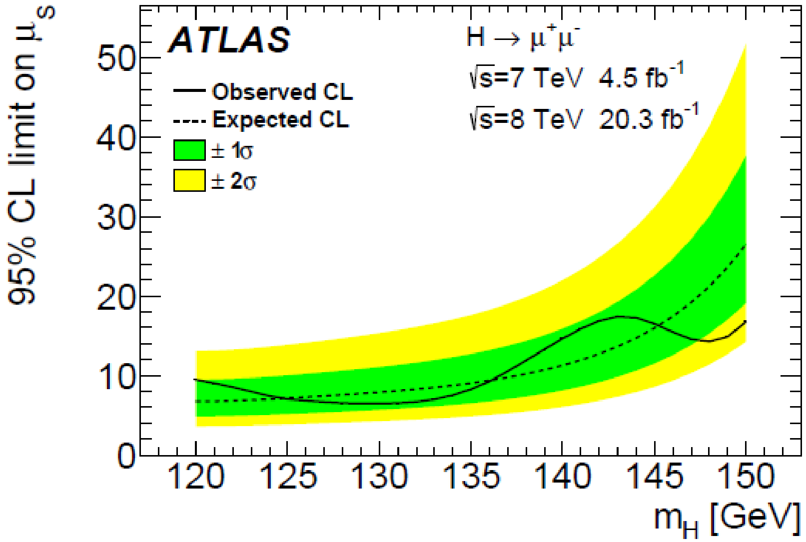
2 isolated muons p_T>25 (15) GeV

Categorization:

$p_T^{\mu\mu}$, η^{μ}, VBF

BR(H→μμ)<1.5x10^{-3} @ 95% CL

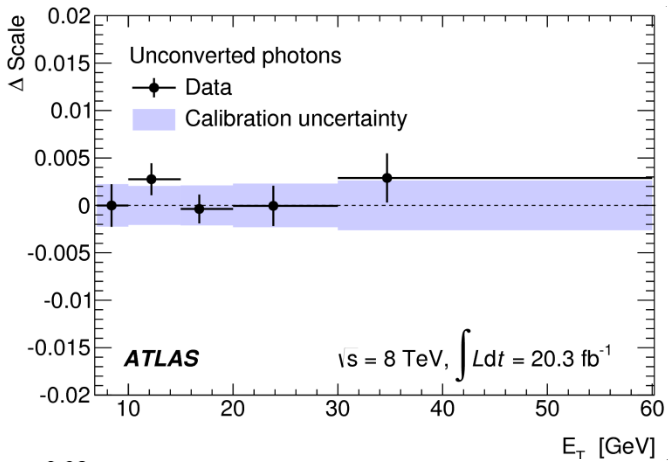


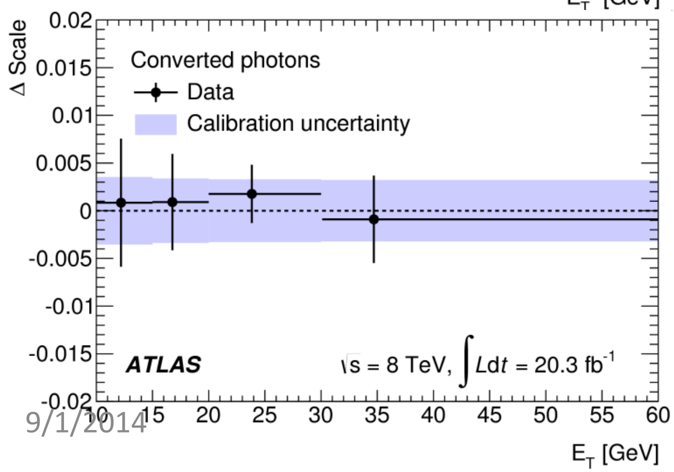


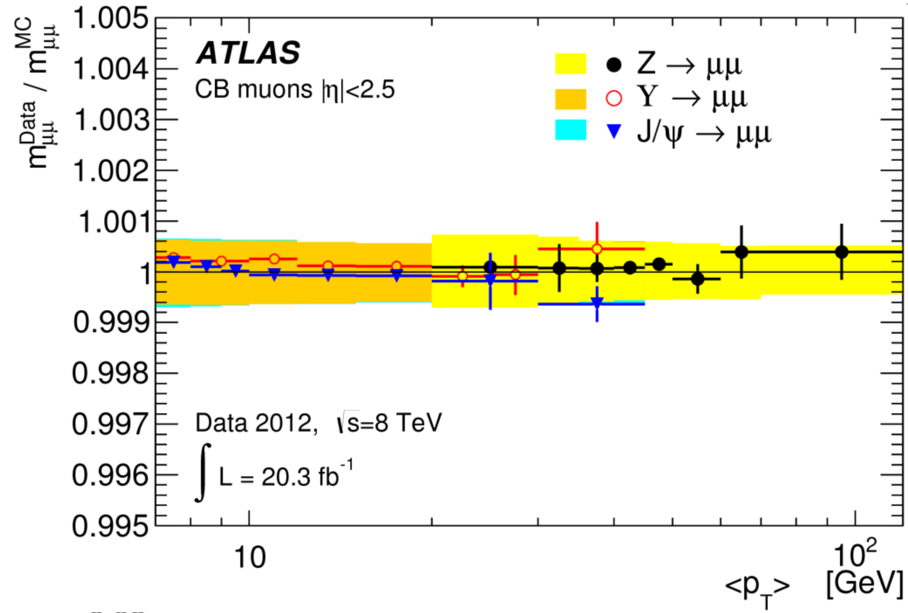
Several Improvements:

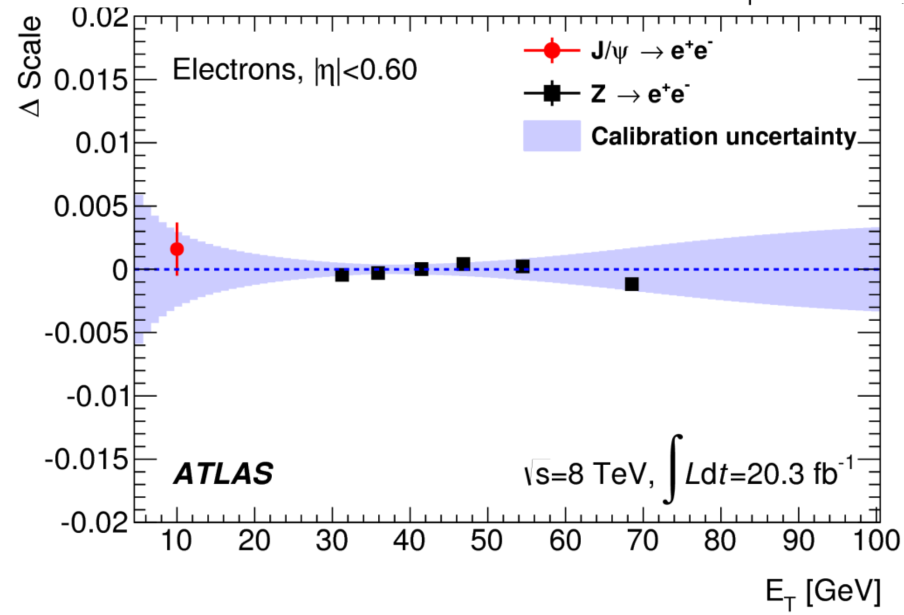
- analyses
- muon momentum scale (uncert)
- electron – photon energy scale (improved calibration and uncert)

arXiv:1407.5063

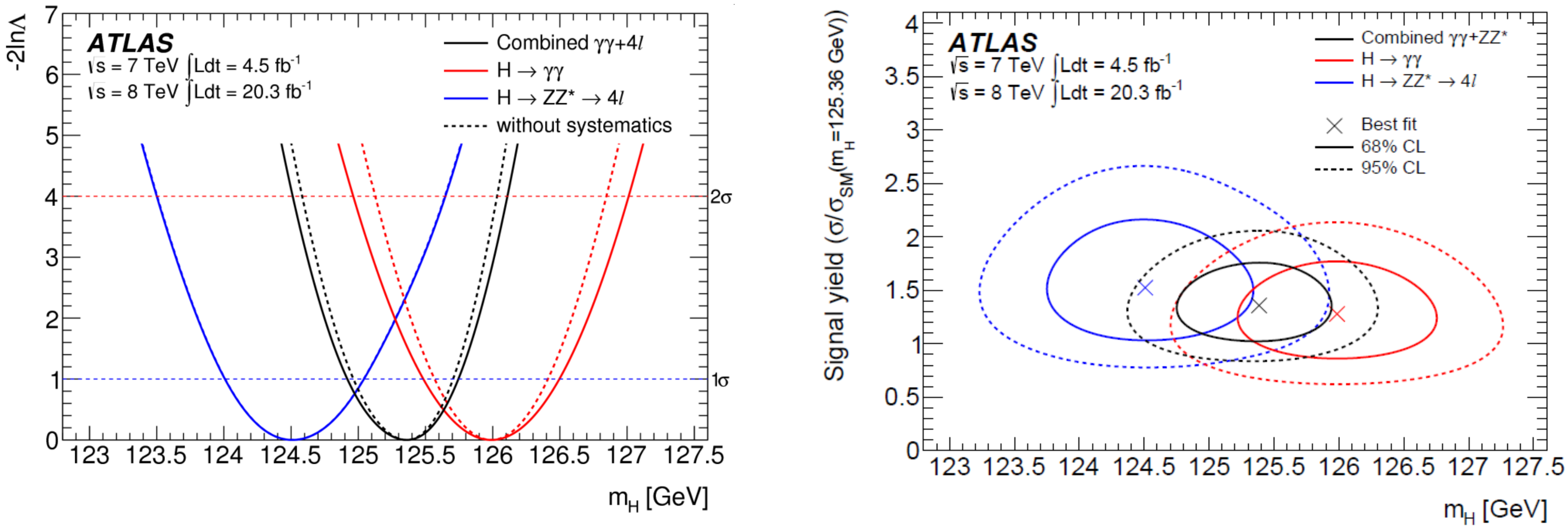




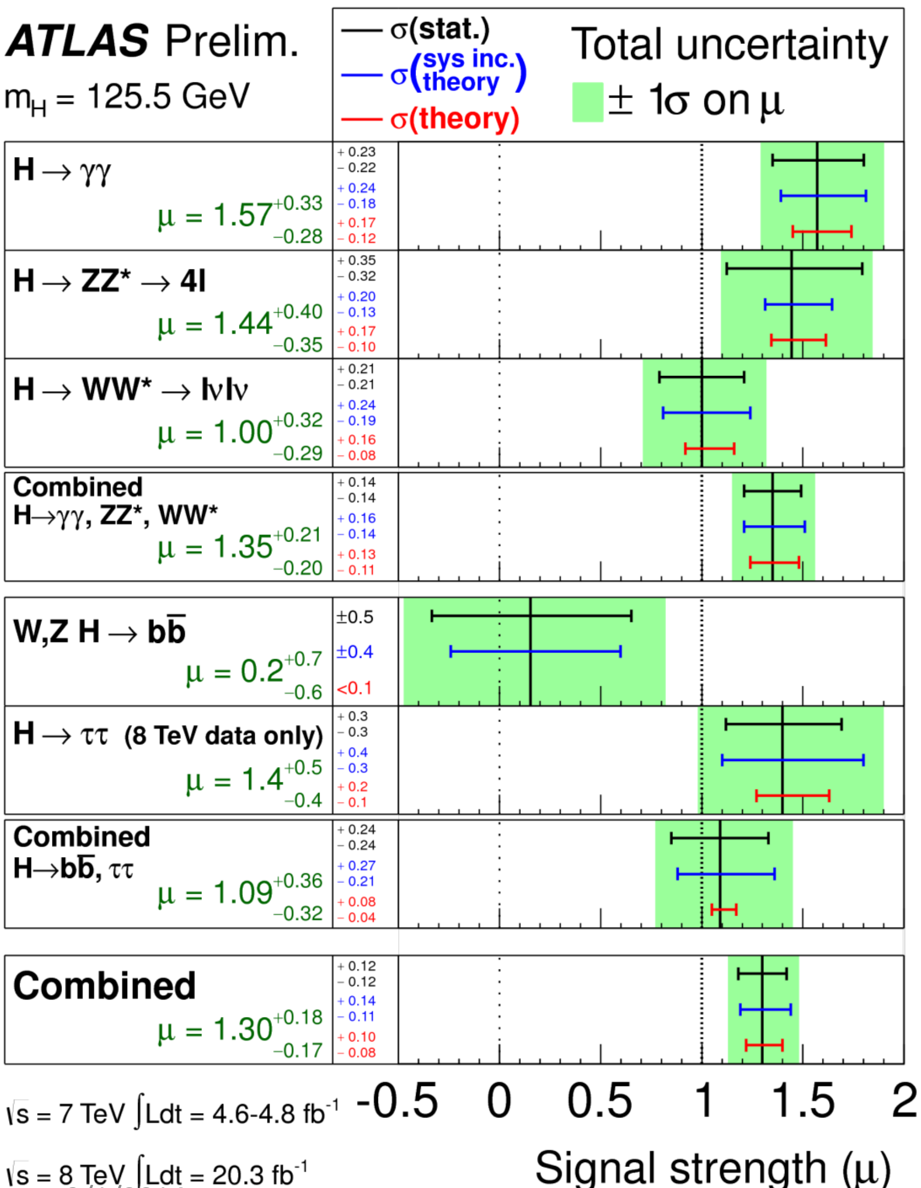




Resolution: **γγ: ~1.7 GeV, 4l: 1.6-2.2 GeV**



$$m_H = 125.36 \pm 0.37(stat) \pm 0.18(syst)$$

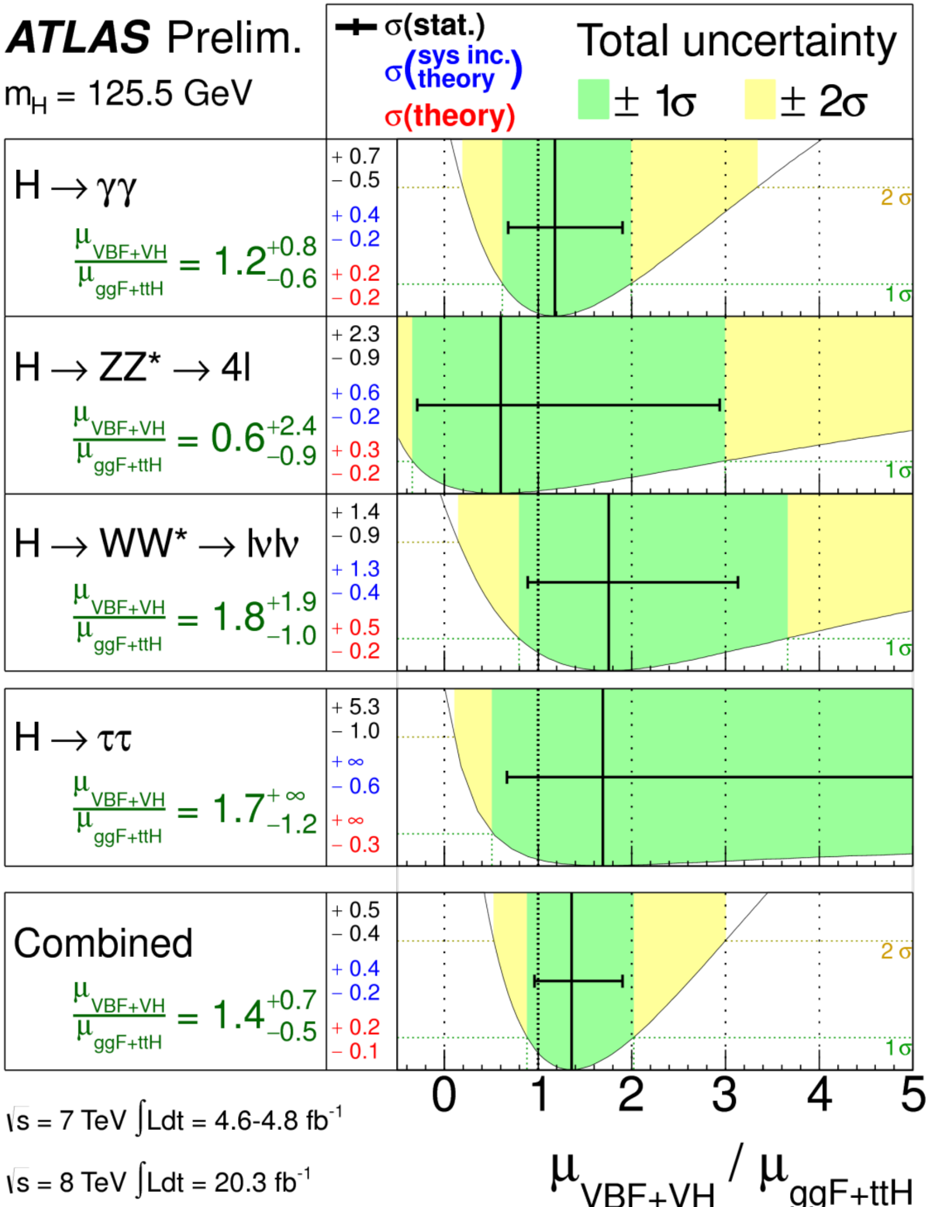


To be updated soon…

$$\mu = 1.30 \pm 0.12(stat)^{+0.14}_{-0.11}(syst)$$

$$\mu^{bb\tau\tau} = 1.09 \pm 0.24(stat)^{+0.27}_{-0.21}(syst)$$

3.7σ evidence for fermionic couplings

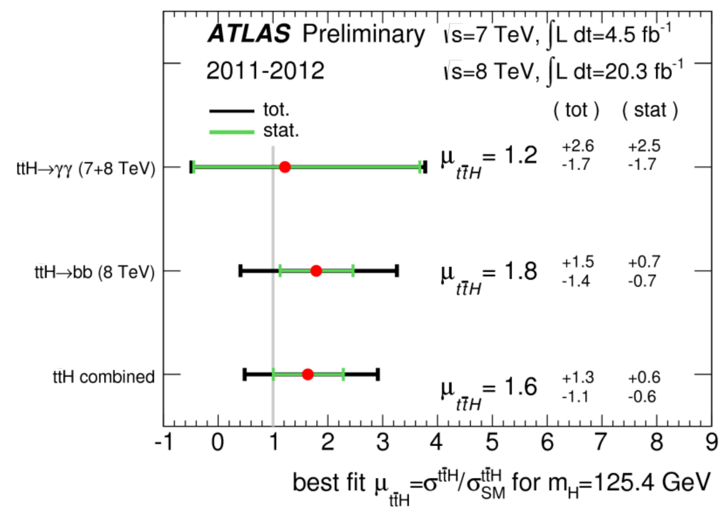


To be updated soon…

$$\mu_{VBF}/\mu_{ggF+ttH} = 1.4^{+0.5}_{-0.4}(stat)^{+0.4}_{-0.3}(syst)$$

4.1σ evidence for VBF production

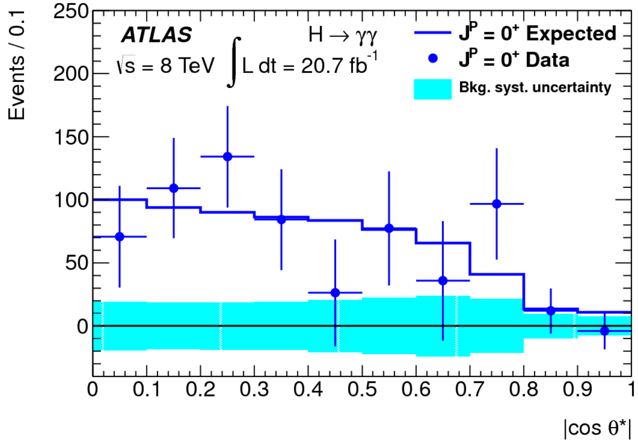
ttH (H→bb,H→γγ)

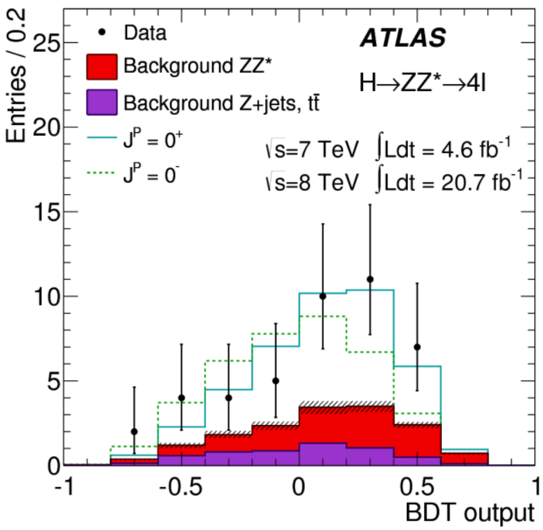


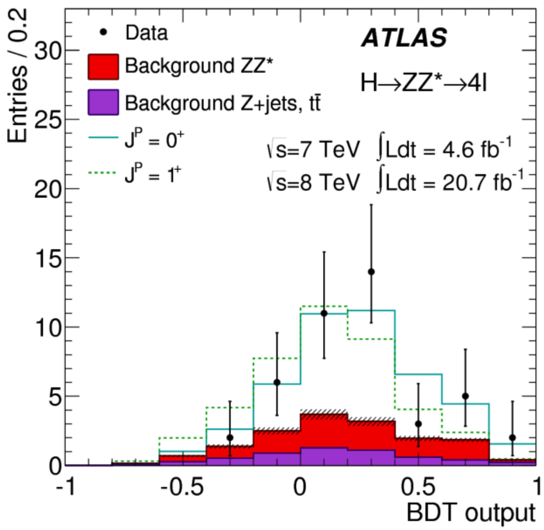
ATLAS-CONF-2014-043

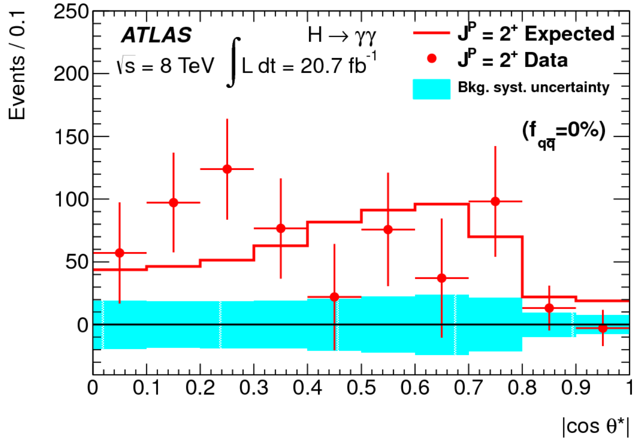
 Phys. Lett. B 726 (2013) 120-144

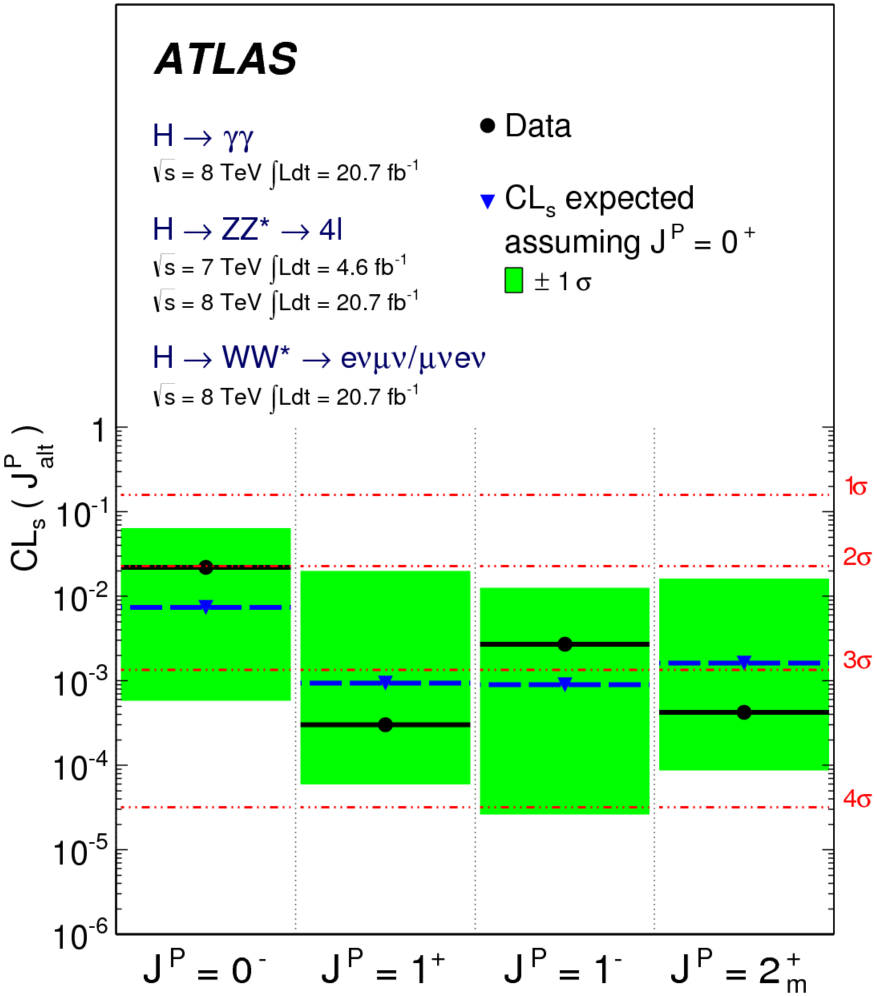
Channel	Discriminants
H→ZZ*→4l	BDT: five production/decay angles
H→γγ	|cosθ*| the polar angle between γγ at their rest frame
H→WW*→lνlν	BDT: m_{ll}, p_T^{ll}, $\Delta\phi_{ll}$, m_T







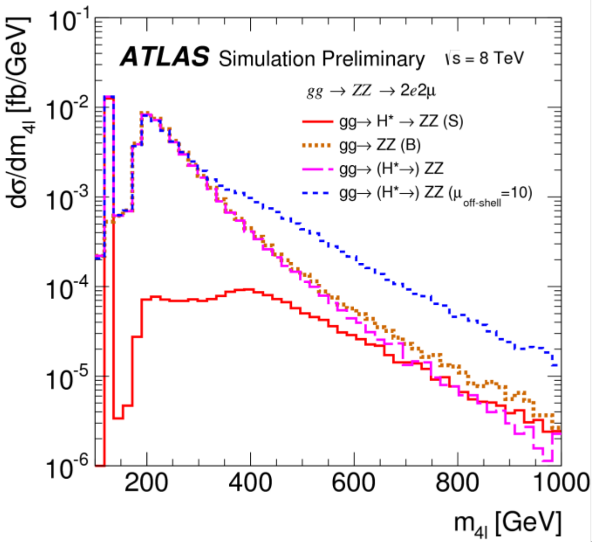


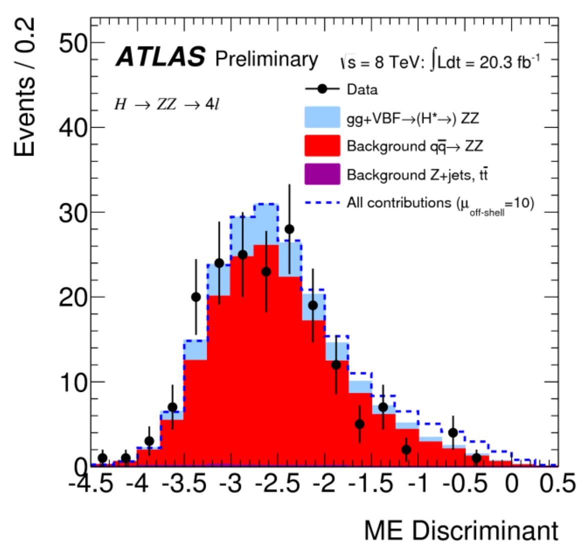


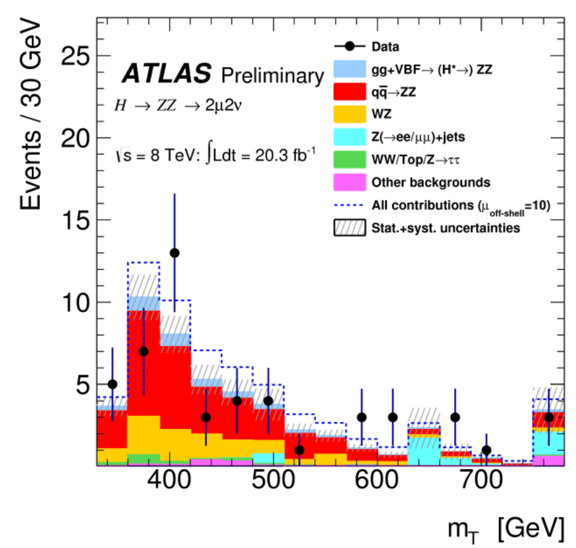
Data favors the SM JP=0+

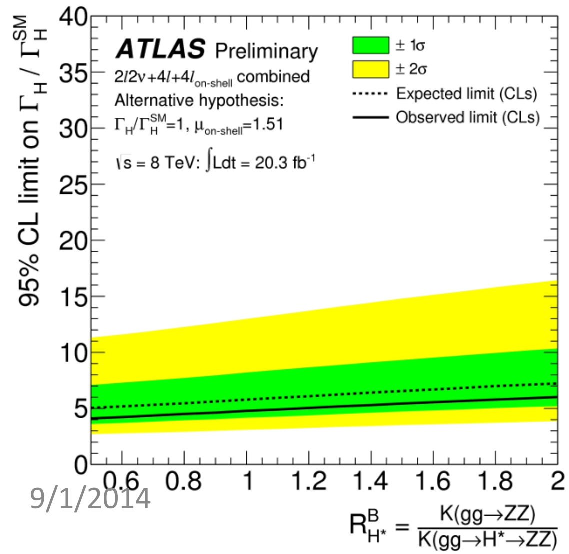
- **0^-** is excluded at **97.8% CL** (H→ZZ(*)→4l)
- **1^+** and **1^-** are excluded at **99.7%** CL (H→ZZ(*)→4l and H→WW(*)→lνlνl)
- **2^+_m** is excluded at >**99.9% CL** (H→ZZ(*)→4l, H→γγ, H→WW(*)→lνlν)

- Sizeable negative interference gg→H→ZZ and gg→ZZ
- Interference proportional $\sqrt{\mu_{\text{off-shell}}}$
- ZZ→4l (cut-based and MVA) and ZZ→2l2ν (cut-based) channels used









$R^B_{H^*}$	Observed 0.5	1.0	2.0	Median expected 0.5	1.0	2.0	Alternative hypothesis
$\mu_{\text{off-shell}}$	5.6	**6.7**	9.0	6.6	**7.9**	10.7	$R^B_{H^*}=1,\ \mu_{\text{off-shell}}=1$
Γ_H/Γ_H^{SM}	4.1	**4.8**	6.0	5.0	**5.8**	7.2	$R^B_{H^*}=1,\ \Gamma_H/\Gamma_H^{SM}=1,\ \mu_{\text{on-shell}}=1.51$
Γ_H/Γ_H^{SM}	4.8	**5.7**	7.7	7.0	**8.5**	12.0	$R^B_{H^*}=1,\ \Gamma_H/\Gamma_H^{SM}=1,\ \mu_{\text{on-shell}}=1$

- **Z→ll + Missing E_T**

Background Composition:

ZZ, WZ, WW

Trigger:

Single lepton, di-lepton

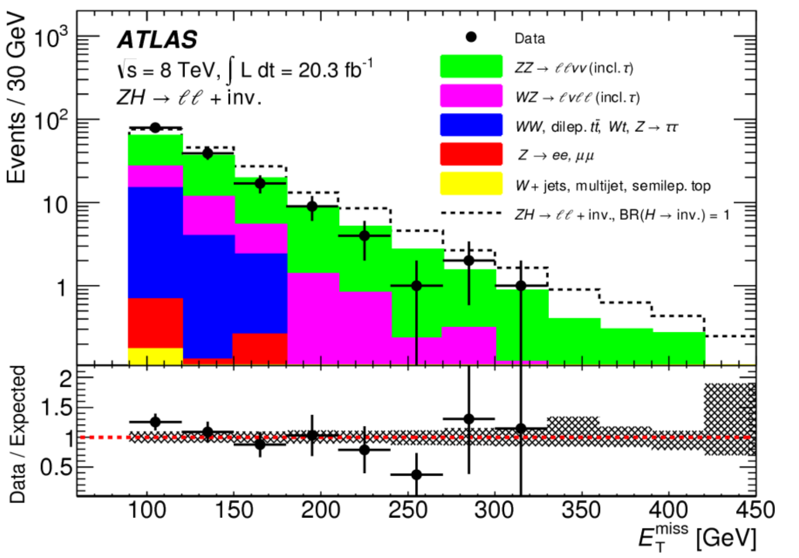
Selection:

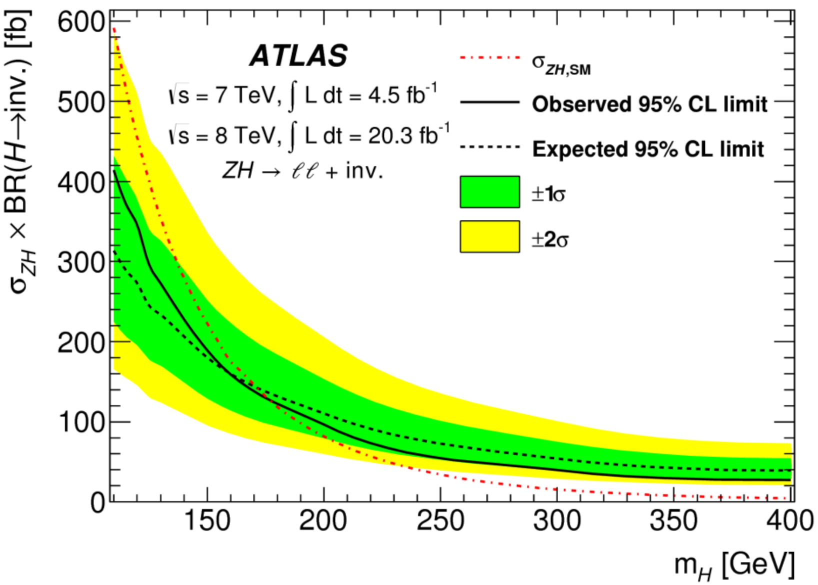
2 SFOS leptons (p_T>20 GeV)

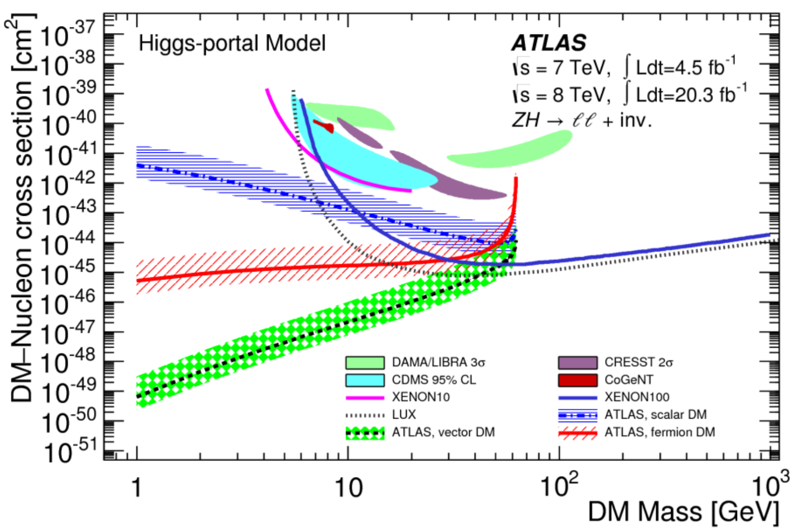
Isolation, 76< m_{ll} <106 GeV

$\Delta\phi_{ll}$, $\Delta\phi(ll, E^T_{miss})$

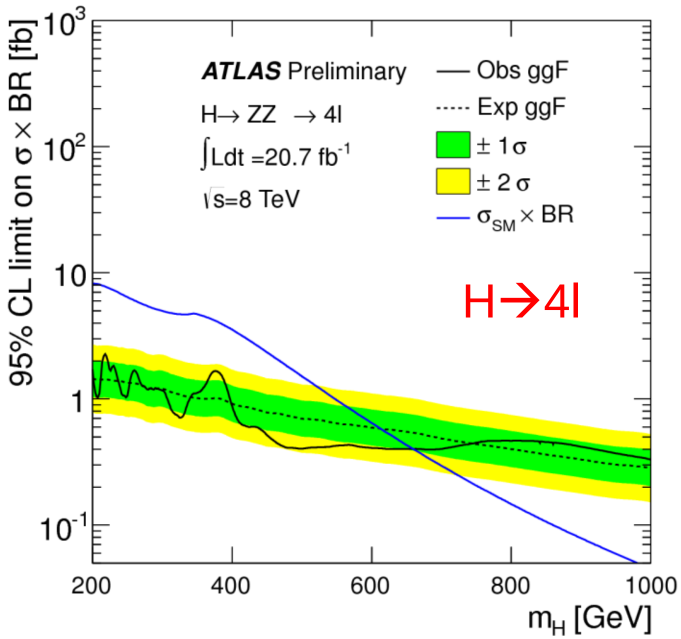
Discriminant: E_T^{miss}

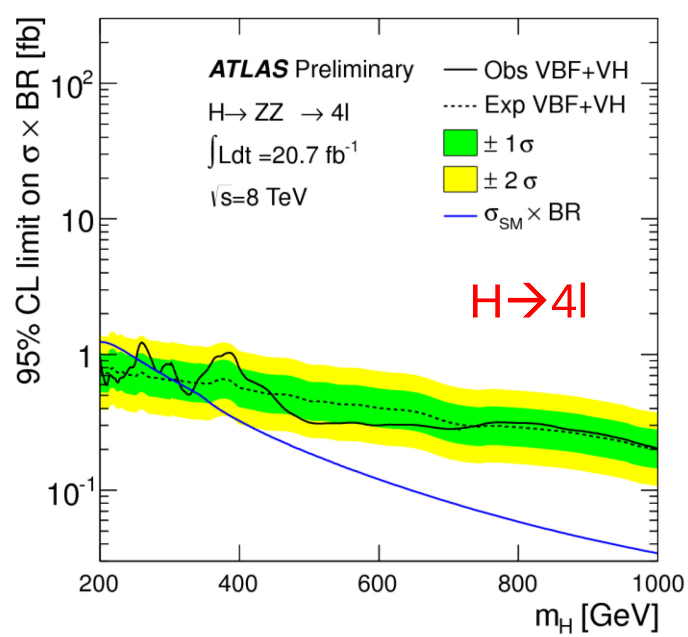


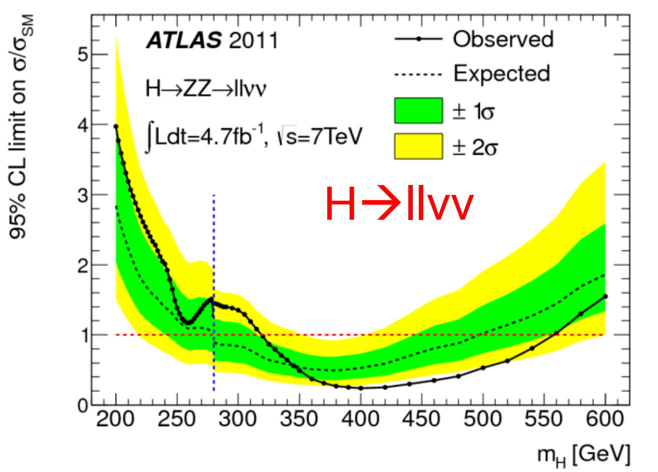


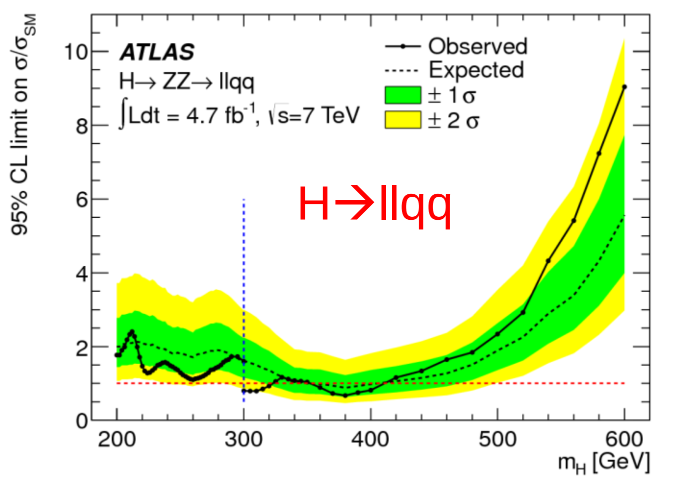


Higgs physics in ATLAS: Search for other Higgs-like bosons *Phys.Lett. B 717 (2012) 70-88, Phys.Lett. B 717 (2012) 29-48 , arXiv:1407.6583, ATLAS-CONF-2013-012, ATLAS-CONF-2013-067*

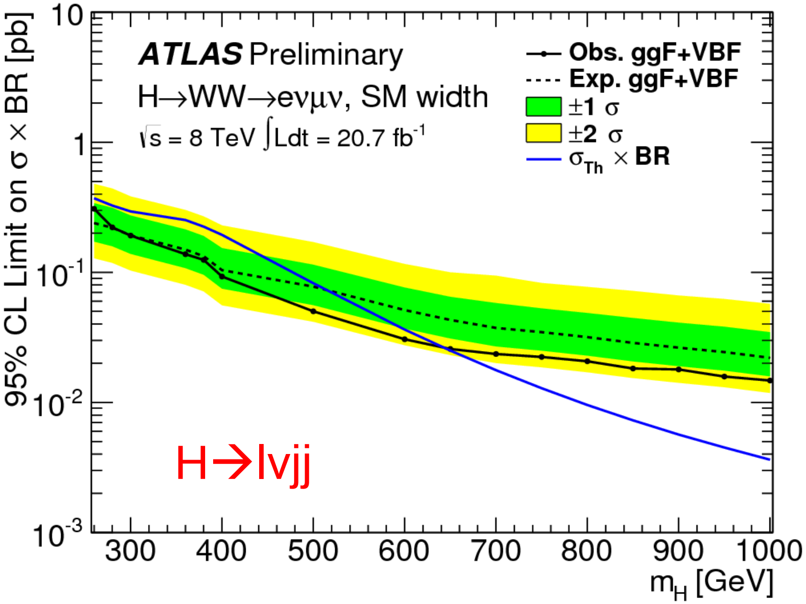


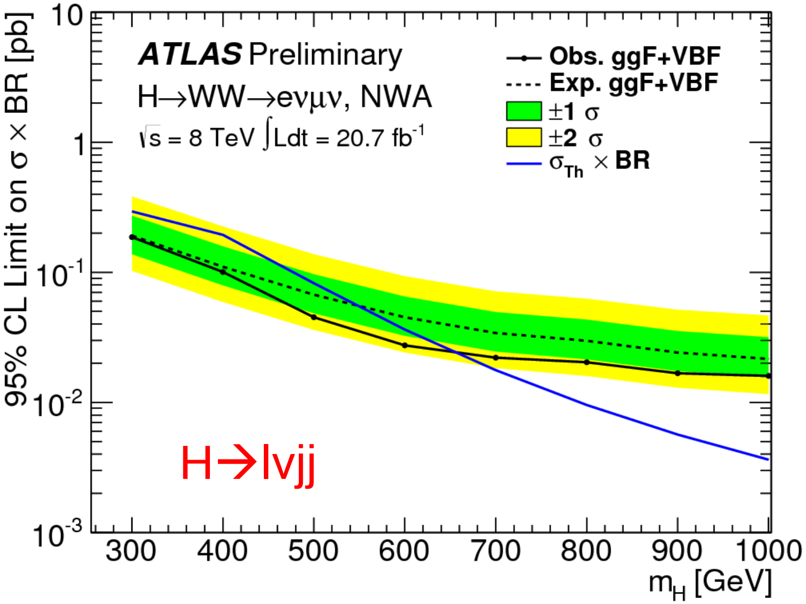


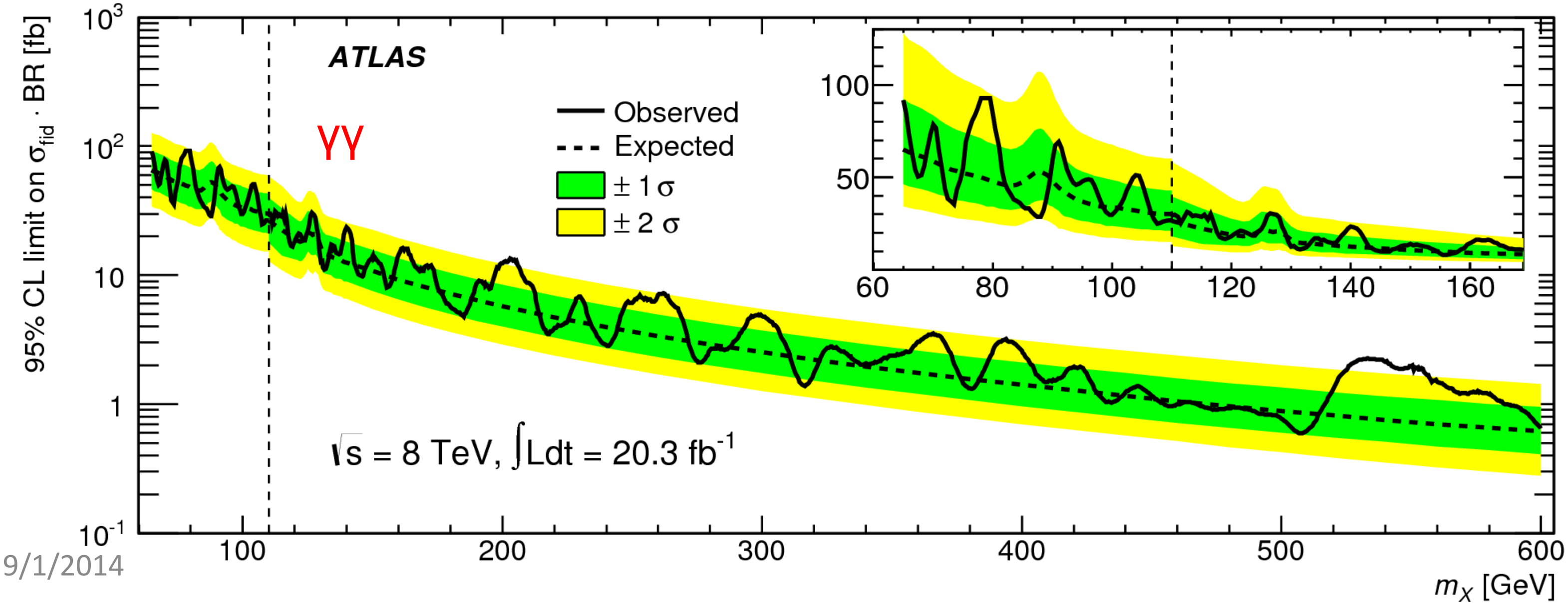




Higgs physics in ATLAS: Search for other Higgs-like bosons *Phys.Lett. B 717 (2012) 70-88, Phys.Lett. B 717 (2012) 29-48 , arXiv:1407.6583, ATLAS-CONF-2013-012, ATLAS-CONF-2013-067*

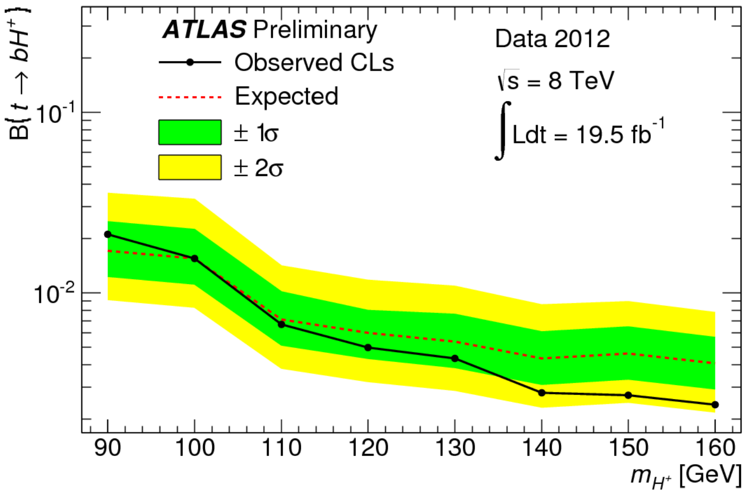




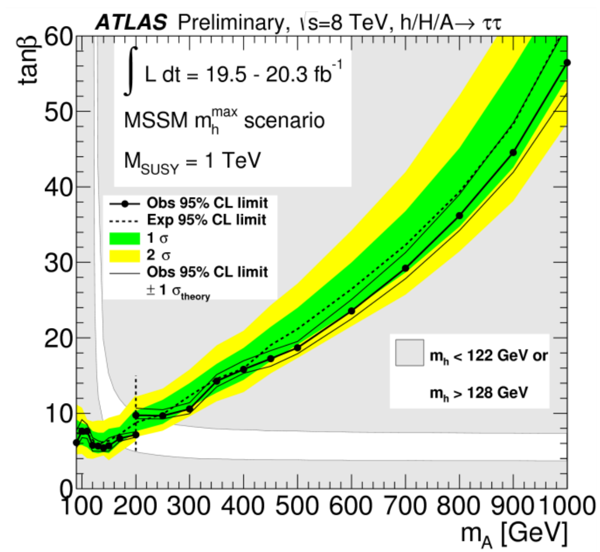


Phys.Rev. D 89, 032002 (2014), ATLAS-CONF-2013-090
ATLAS-CONF-2013-090, Eur. Phys. J. C, 73 6 (2013) 2465

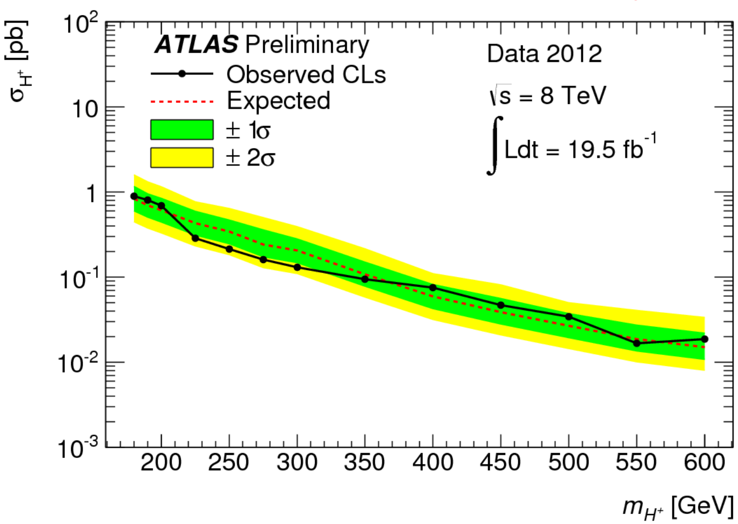
$t\bar{t} \rightarrow H^+ bW^- \bar{b} \rightarrow [\tau^+ \nu_\tau b][q\bar{q}\bar{b}]$



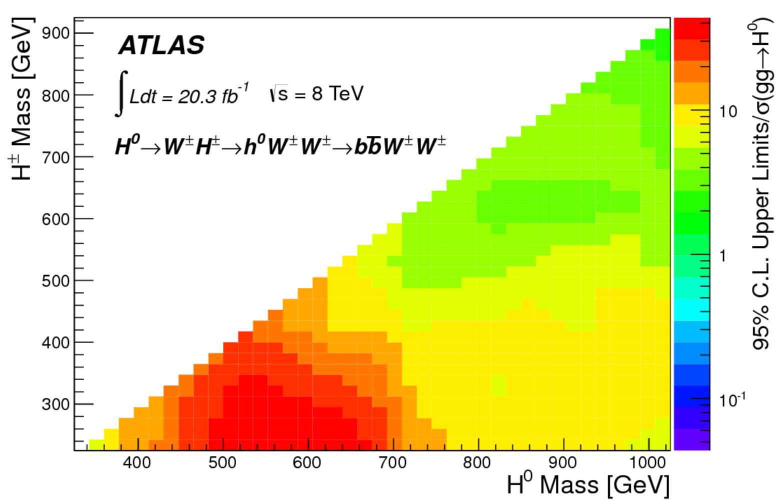
$H,A,h \rightarrow \tau^+\tau^-, \mu^+\mu^-$



$t\bar{b}(b)H^+ \rightarrow [q\bar{q}\bar{b}](b)[\tau^+\nu_\tau]$



$H^0 \rightarrow W^- H^+ \rightarrow h^0 W^+ W^- \rightarrow b\bar{b} W^+ W^-$



Summary

Run-1

- **Discovery of a new Higgs-like boson**
- **All studies up to now show consistency with the SM Higgs boson**
- **ATLAS Run-1 Higgs studies (a huge amount of effort) being finalized (concerning both SM and BSM results)**

Run-2

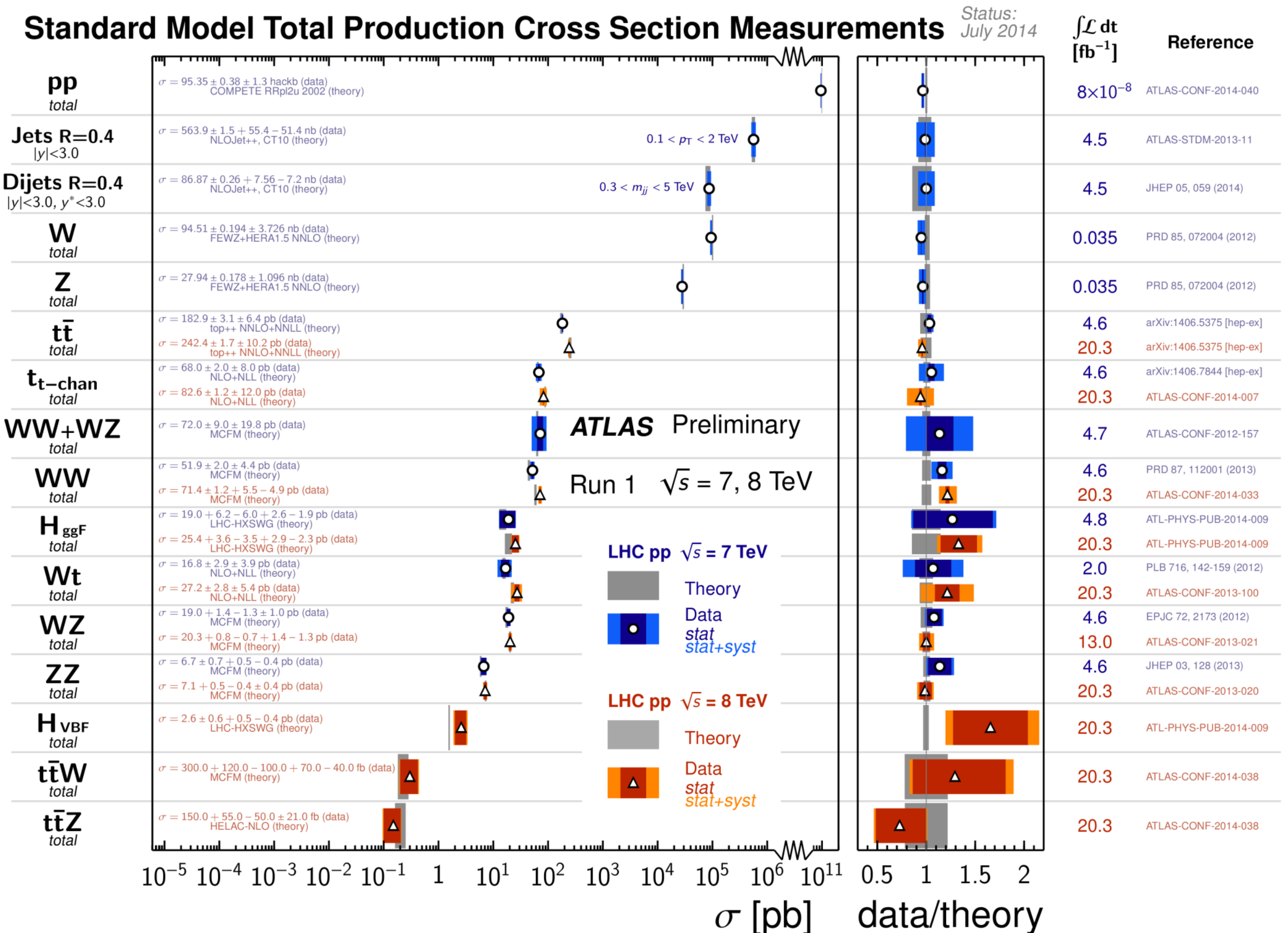
- **with ~2.5 times higher cross sections**
- **Will give the opportunity for more precise measurements**
- **Study more rare channels**
- **… and may offer a new discovery**

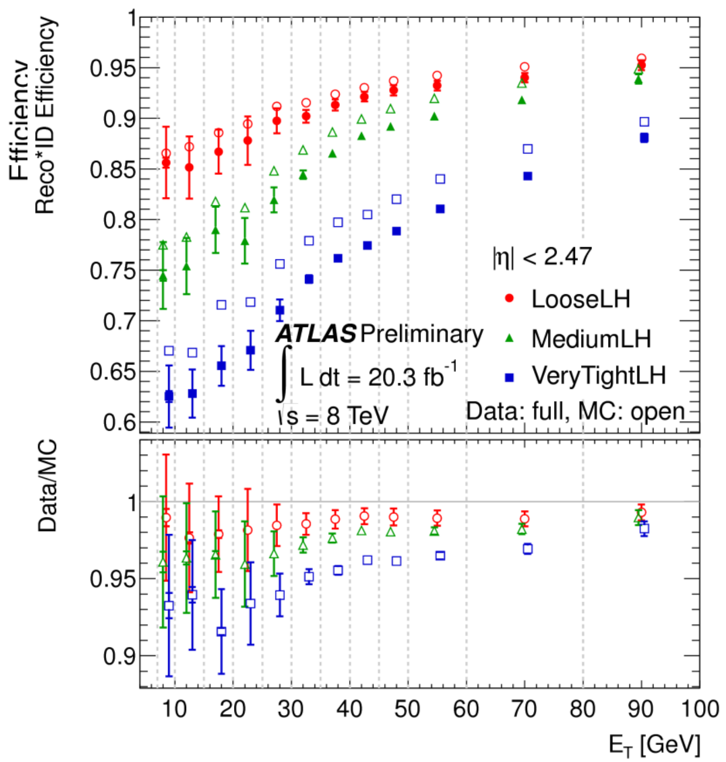
European Union
European Social Fund
OPERATIONAL PROGRAMME
EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION & RELIGIOUS AFFAIRS
MANAGING AUTHORITY
Co-financed by Greece and the European Union
NSRF 2007-2013
programme for development
EUROPEAN SOCIAL FUND

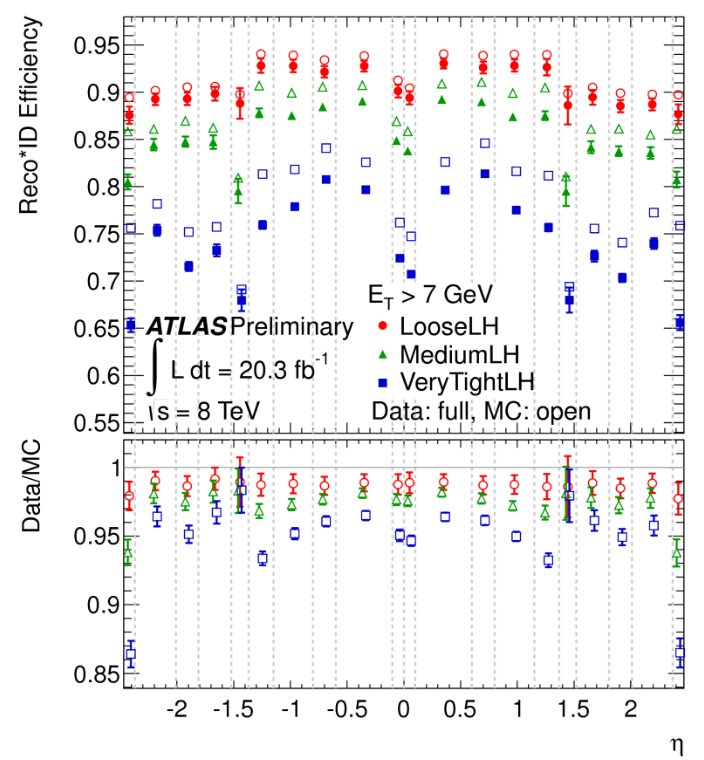
This research has been co-financed by the European Union (European Social Fund - ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: THALES. Investing in knowledge society through the European Social Fund.

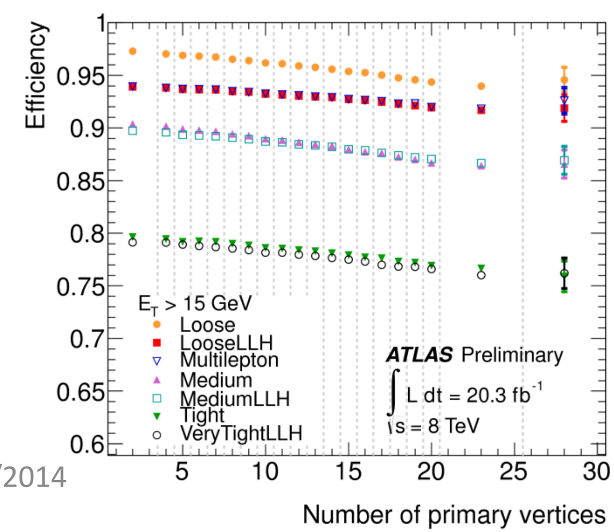
Back up slides

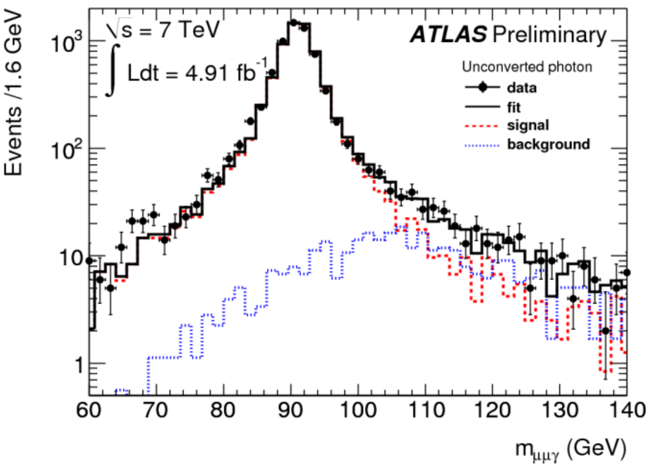
Higgs physics in ATLAS: SM measurements

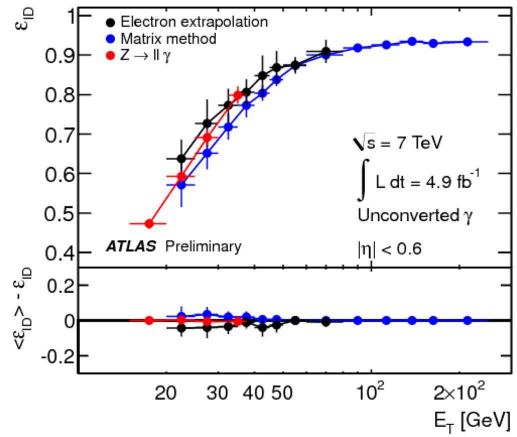


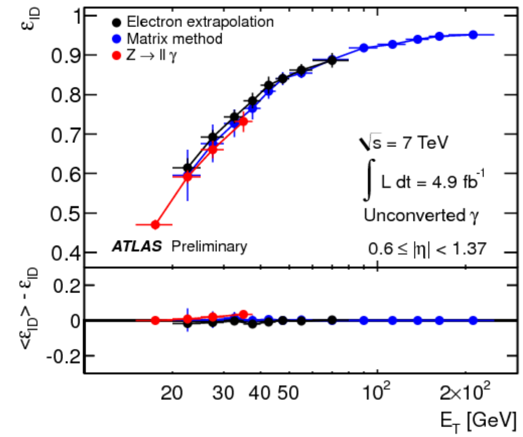

Reco*ID Efficiency
Data/MC
|η| < 2.47
LooseLH
MediumLH
VeryTightLH
ATLAS Preliminary
∫ L dt = 20.3 fb⁻¹
√s = 8 TeV
Data: full, MC: open
E_T [GeV]

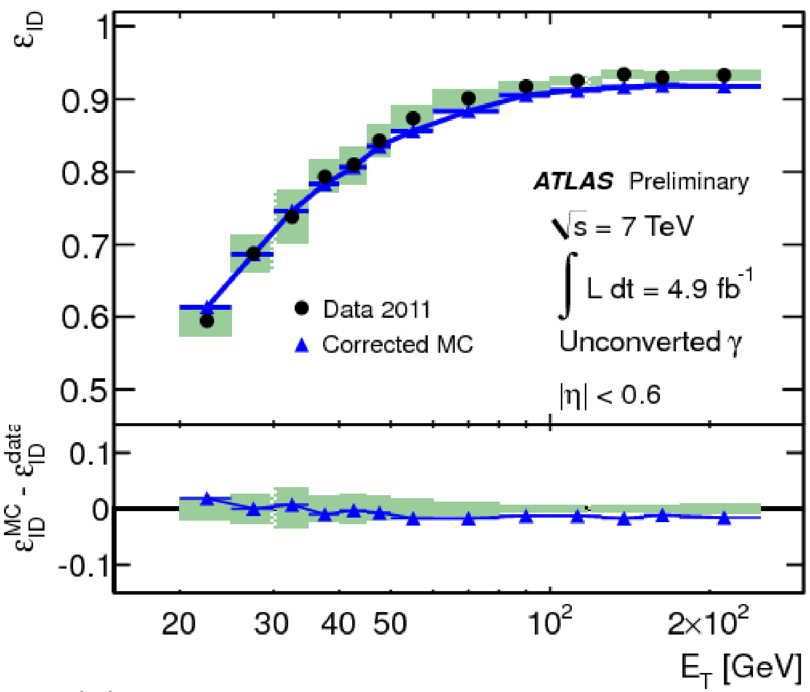

Reco*ID Efficiency
Data/MC
E_T > 7 GeV
ATLAS Preliminary
LooseLH
MediumLH
VeryTightLH
∫ L dt = 20.3 fb⁻¹
√s = 8 TeV
Data: full, MC: open
η

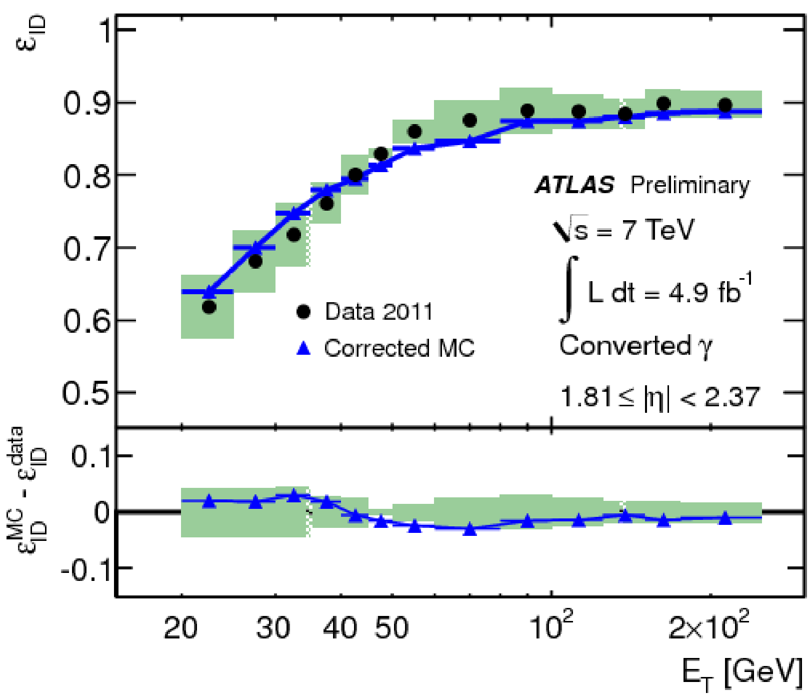

Efficiency
E_T > 15 GeV
Loose
LooseLLH
Multilepton
Medium
MediumLLH
Tight
VeryTightLLH
ATLAS Preliminary
∫ L dt = 20.3 fb⁻¹
√s = 8 TeV
Number of primary vertices


$\sqrt{s}$ = 7 TeV
$\int$ Ldt = 4.91 fb^{-1}
ATLAS Preliminary
Unconverted photon
data
fit
signal
background
Events /1.6 GeV
$m_{\mu\mu\gamma}$ (GeV)


Electron extrapolation
Matrix method
$Z \to ll\gamma$
$\sqrt{s}$ = 7 TeV
$\int$ L dt = 4.9 fb^{-1}
Unconverted γ
ATLAS Preliminary
$|\eta| < 0.6$
ε_{ID}
$<\varepsilon_{ID}> - \varepsilon_{ID}$
E_T [GeV]


Electron extrapolation
Matrix method
$Z \to ll\gamma$
$\sqrt{s}$ = 7 TeV
$\int$ L dt = 4.9 fb^{-1}
Unconverted γ
ATLAS Preliminary
$0.6 \leq |\eta| < 1.37$
ε_{ID}
$<\varepsilon_{ID}> - \varepsilon_{ID}$
E_T [GeV]


ATLAS Preliminary
$\sqrt{s}$ = 7 TeV
$\int$ L dt = 4.9 fb^{-1}
Data 2011
Corrected MC
Unconverted γ
$|\eta| < 0.6$
ε_{ID}
$\varepsilon_{ID}^{MC} - \varepsilon_{ID}^{data}$
E_T [GeV]


ATLAS Preliminary
$\sqrt{s}$ = 7 TeV
$\int$ L dt = 4.9 fb^{-1}
Data 2011
Corrected MC
Converted γ
$1.81 \leq |\eta| < 2.37$
ε_{ID}
$\varepsilon_{ID}^{MC} - \varepsilon_{ID}^{data}$
E_T [GeV]

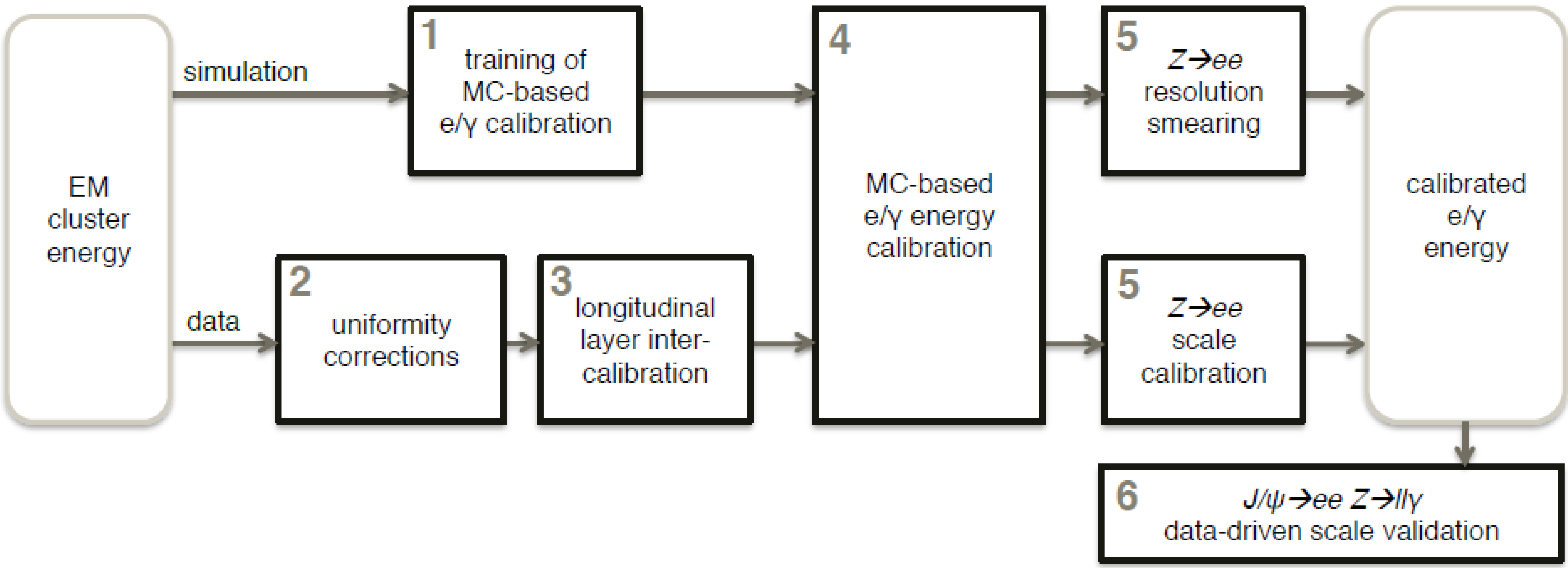
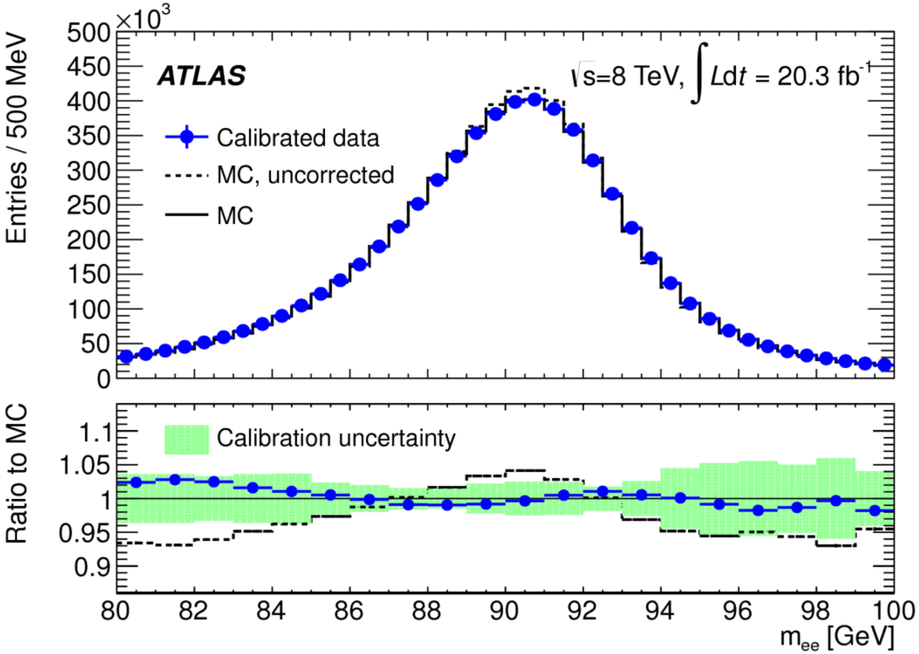
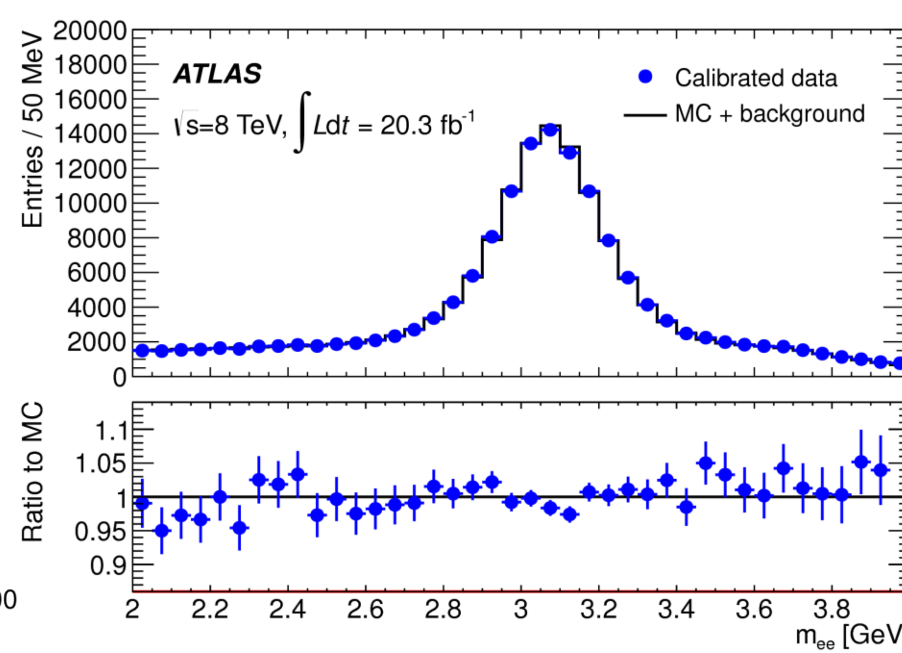
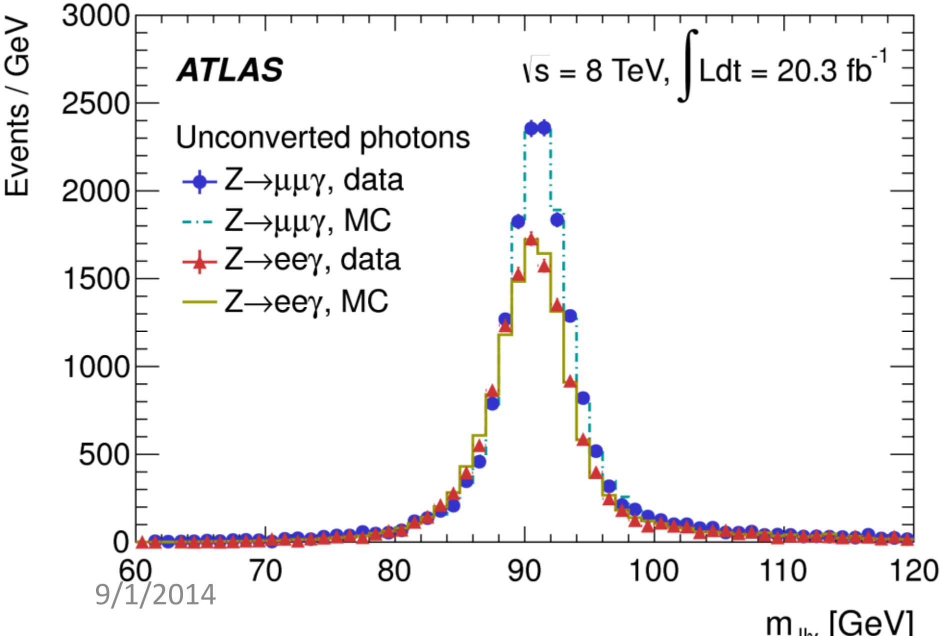
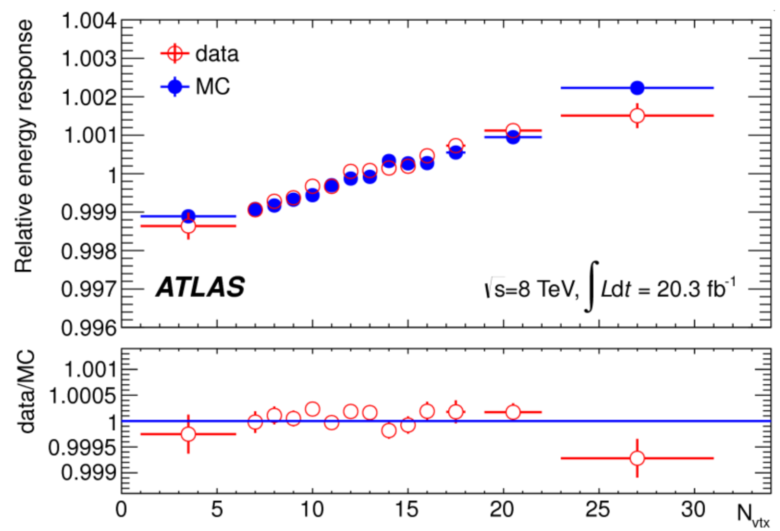


Fig. 1 Schematic overview of the procedure used to calibrate the energy response of electrons and photons in ATLAS.

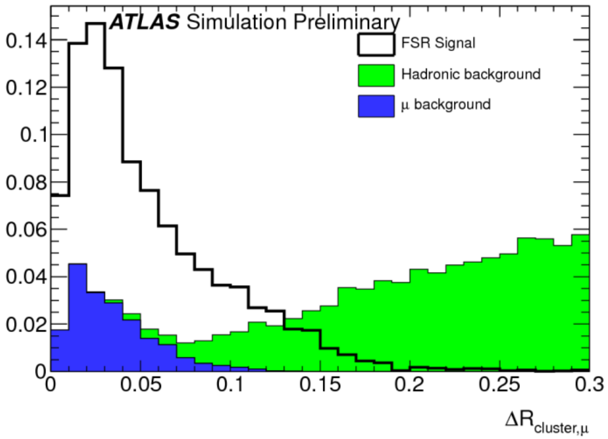

ATLAS
√s=8 TeV, ∫Ldt = 20.3 fb-1
Calibrated data
MC, uncorrected
MC
Entries / 500 MeV
×10^3
Calibration uncertainty
Ratio to MC
m_ee [GeV]

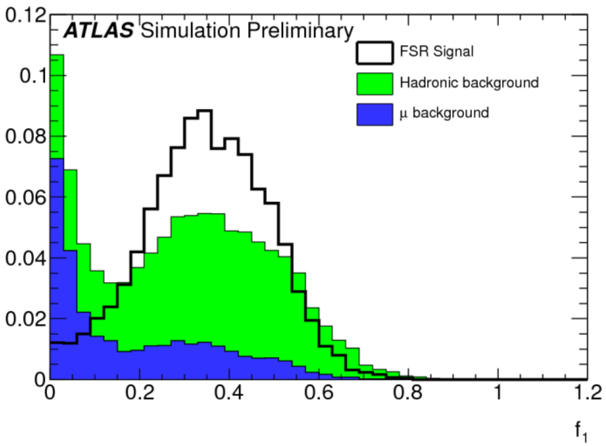

ATLAS
√s=8 TeV, ∫Ldt = 20.3 fb-1
Calibrated data
MC + background
Entries / 50 MeV
Ratio to MC
m_ee [GeV]

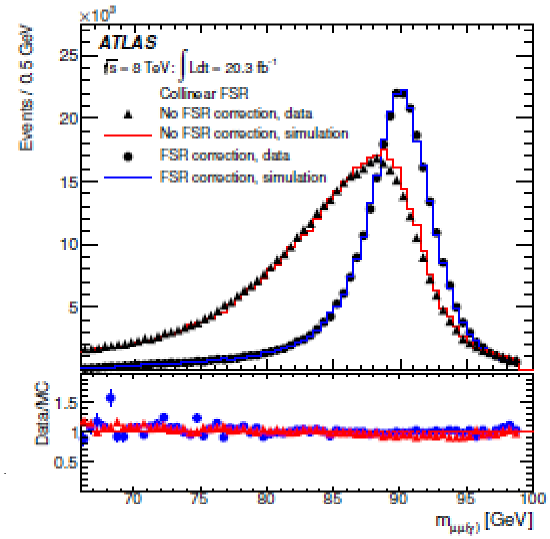

ATLAS
√s = 8 TeV, ∫Ldt = 20.3 fb-1
Unconverted photons
Z→μμγ, data
Z→μμγ, MC
Z→eeγ, data
Z→eeγ, MC
Events / GeV
m_llγ [GeV]

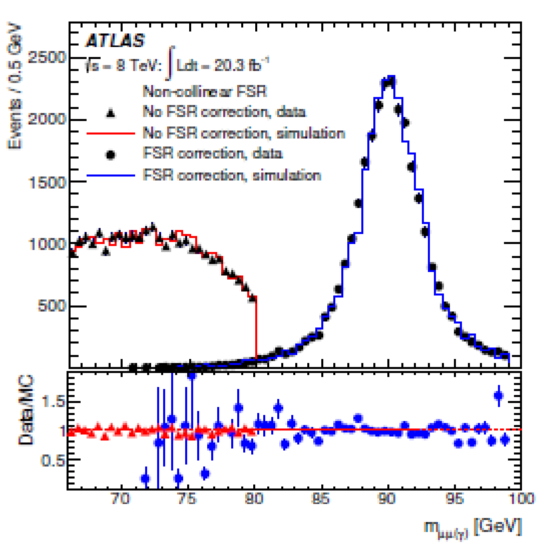

data
MC
ATLAS
√s=8 TeV, ∫Ldt = 20.3 fb-1
Relative energy response
data/MC
N_vtx

FSR recovery in Z→ll events



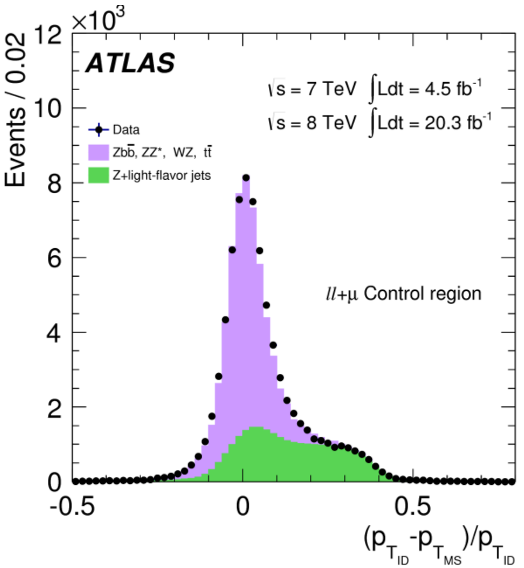


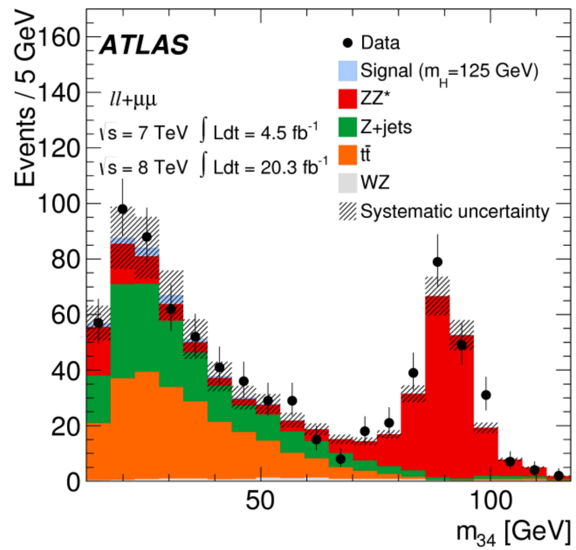


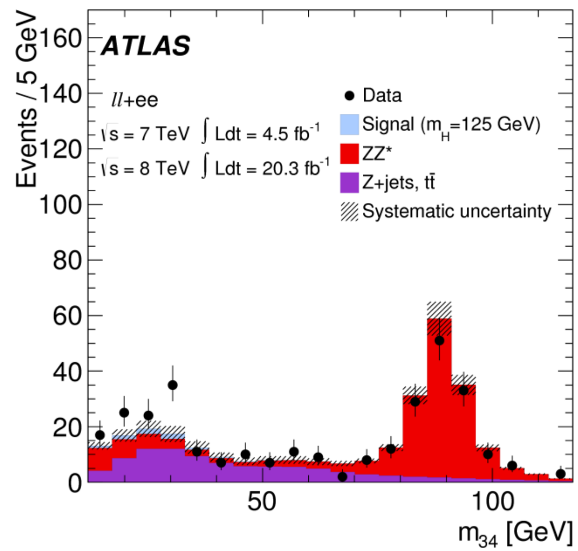


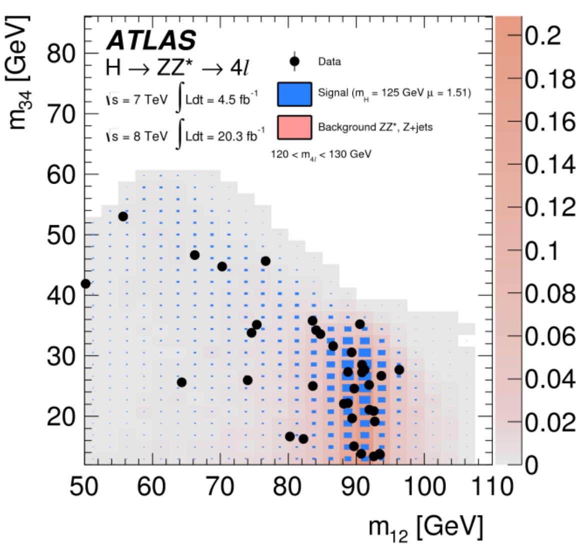
Collinear FSR ε ~ 75%, p ~ 85%
Non-collinear FSR ε ~ 60%, p ~ 95%

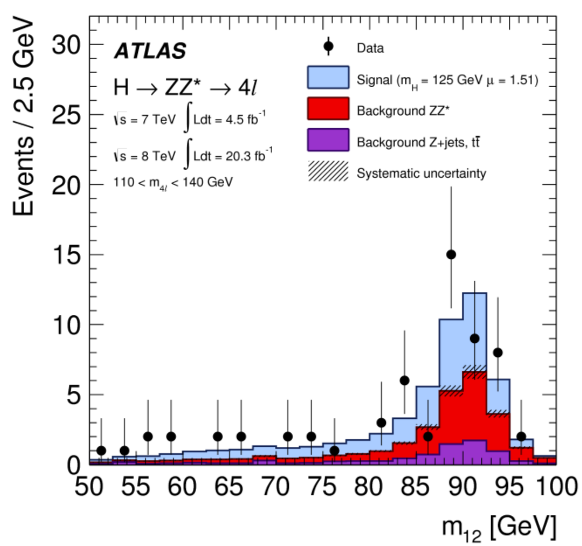
Higgs physics in ATLAS: *H→ZZ(*)→4l* *arXiv:1408.5191*

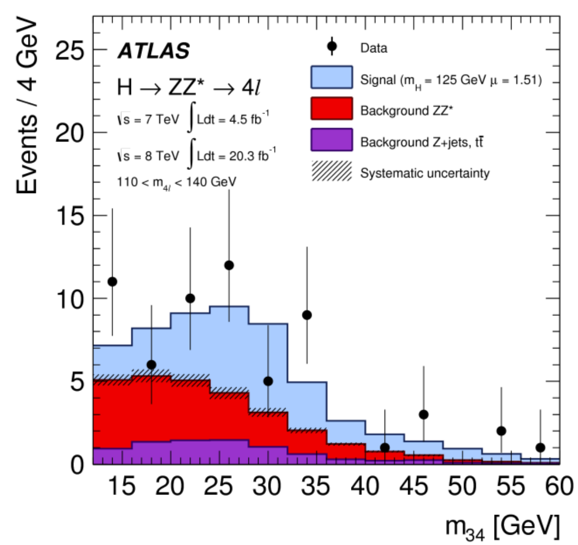


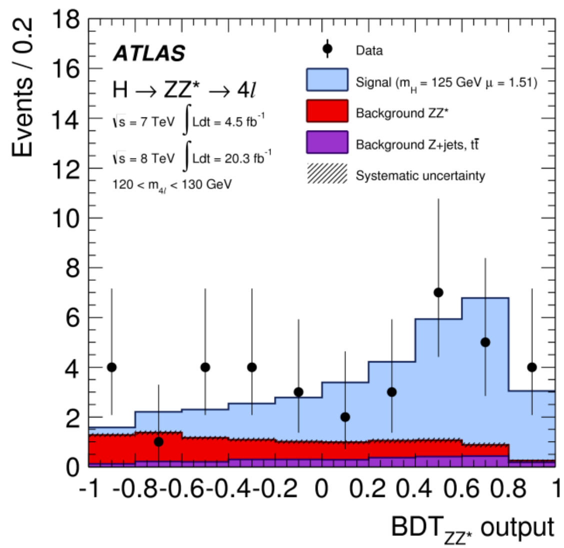


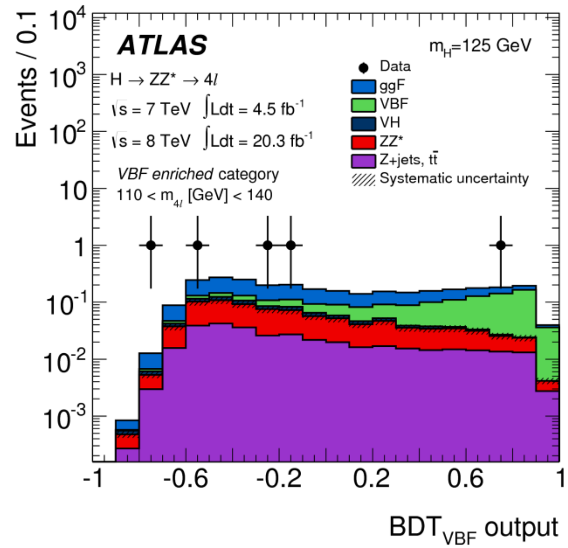


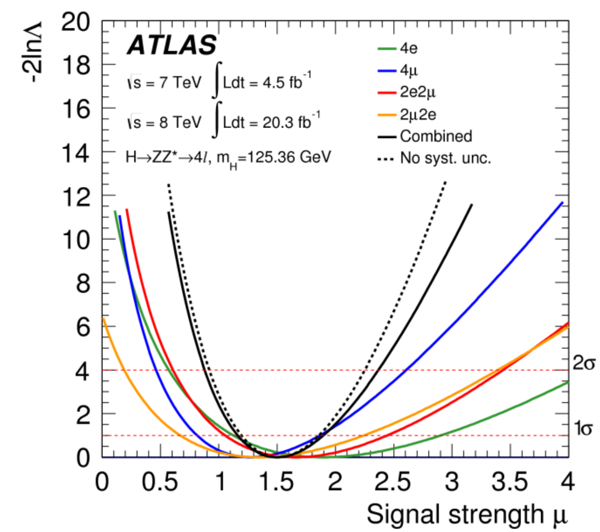


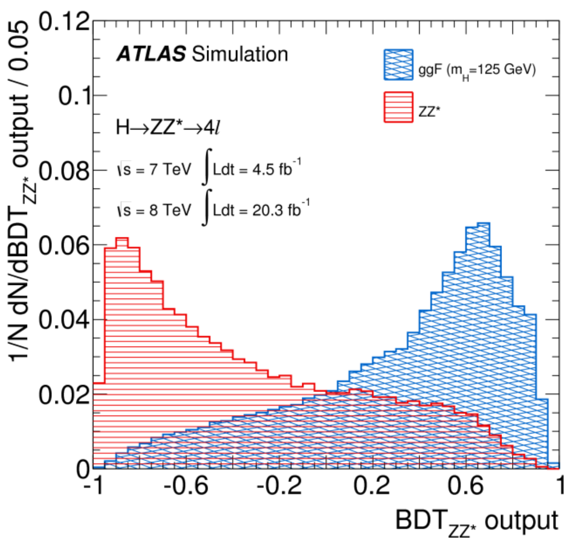


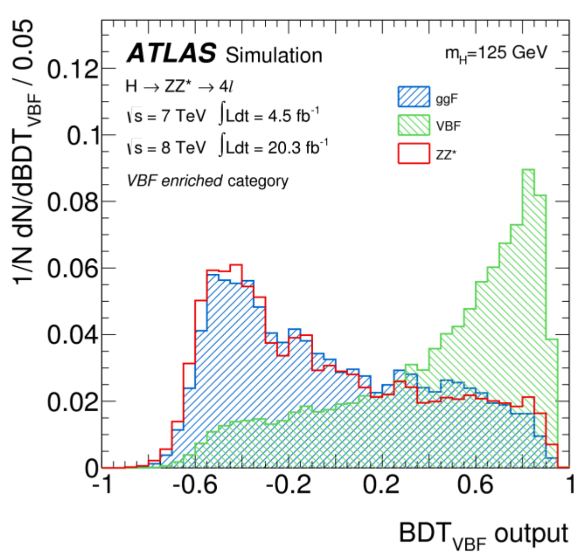


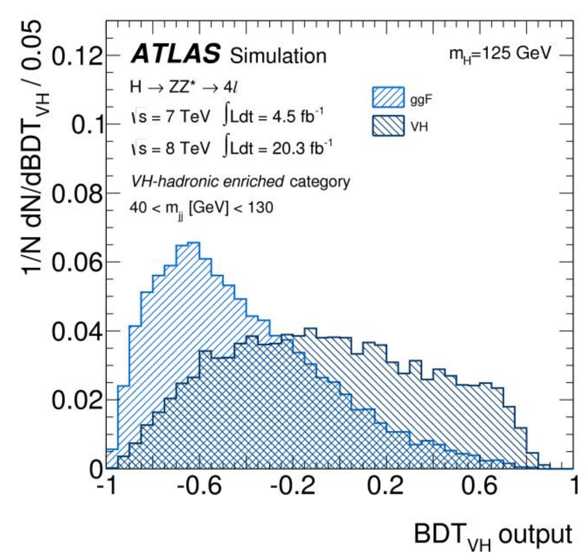

ATLAS
H → ZZ* → 4l
√s = 7 TeV ∫Ldt = 4.5 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
120 < m4l < 130 GeV
Data
Signal (mH = 125 GeV μ = 1.51)
Background ZZ*
Background Z+jets, tt̄
Systematic uncertainty
Events / 0.2
BDTZZ* output


ATLAS
mH=125 GeV
H → ZZ* → 4l
√s = 7 TeV ∫Ldt = 4.5 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
VBF enriched category
110 < m4l [GeV] < 140
Data
ggF
VBF
VH
ZZ*
Z+jets, tt̄
Systematic uncertainty
Events / 0.1
BDTVBF output


ATLAS
√s = 7 TeV ∫Ldt = 4.5 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
H→ZZ*→4l, mH=125.36 GeV
4e
4μ
2e2μ
2μ2e
Combined
No syst. unc.
2σ
1σ
-2lnΛ
Signal strength μ

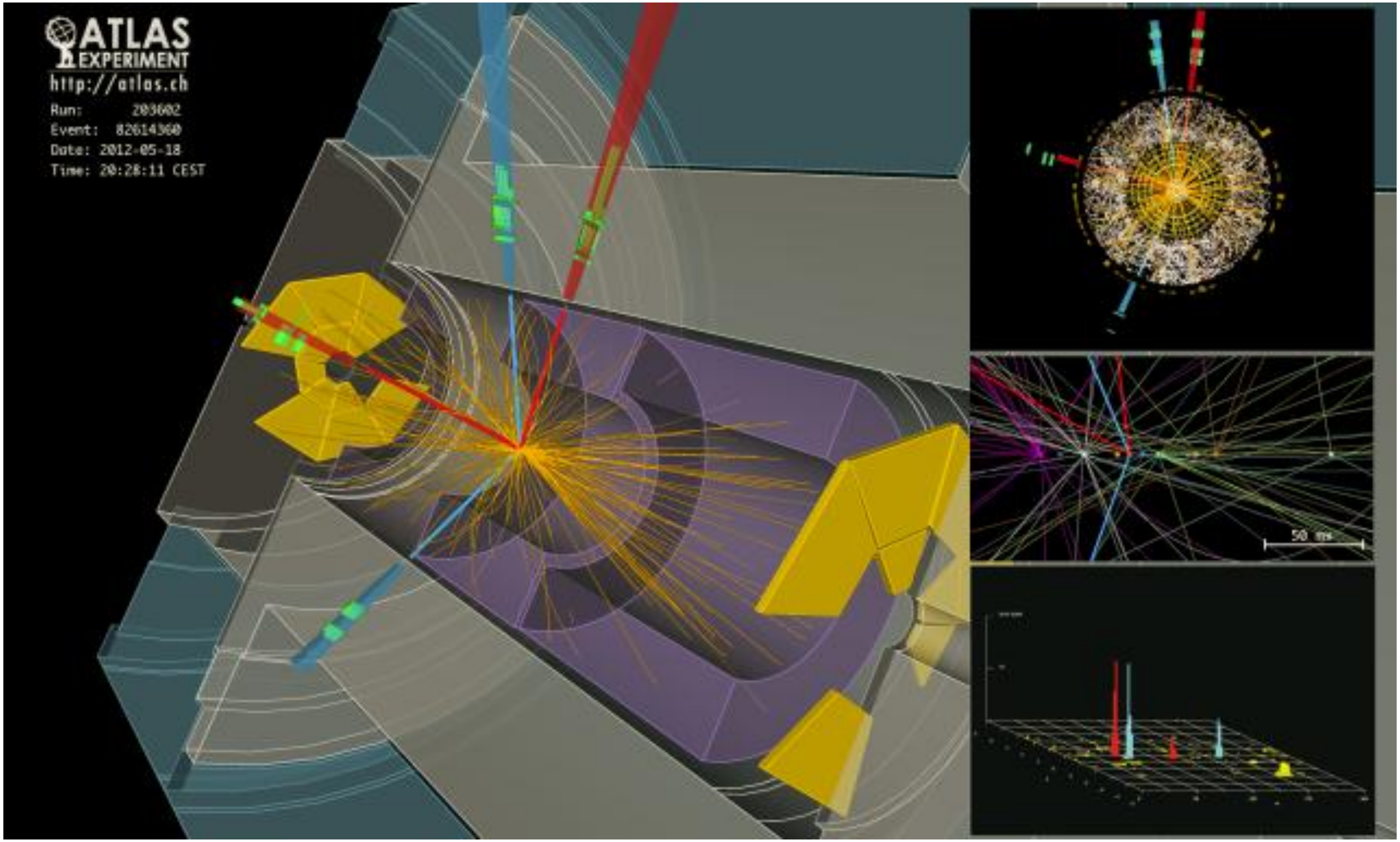

ATLAS Simulation
H→ZZ*→4l
√s = 7 TeV ∫Ldt = 4.5 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
ggF (mH=125 GeV)
ZZ*
1/N dN/dBDTZZ* output / 0.05
BDTZZ* output


ATLAS Simulation
mH=125 GeV
H → ZZ* → 4l
√s = 7 TeV ∫Ldt = 4.5 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
VBF enriched category
ggF
VBF
ZZ*
1/N dN/dBDTVBF / 0.05
BDTVBF output

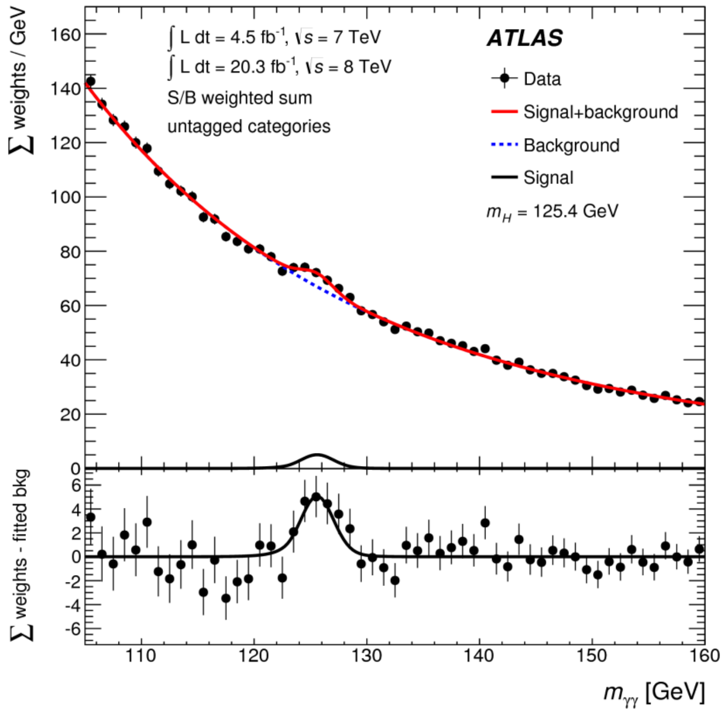

ATLAS Simulation
mH=125 GeV
H → ZZ* → 4l
√s = 7 TeV ∫Ldt = 4.5 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
VH-hadronic enriched category
40 < mjj [GeV] < 130
ggF
VH
1/N dN/dBDTVH / 0.05
BDTVH output

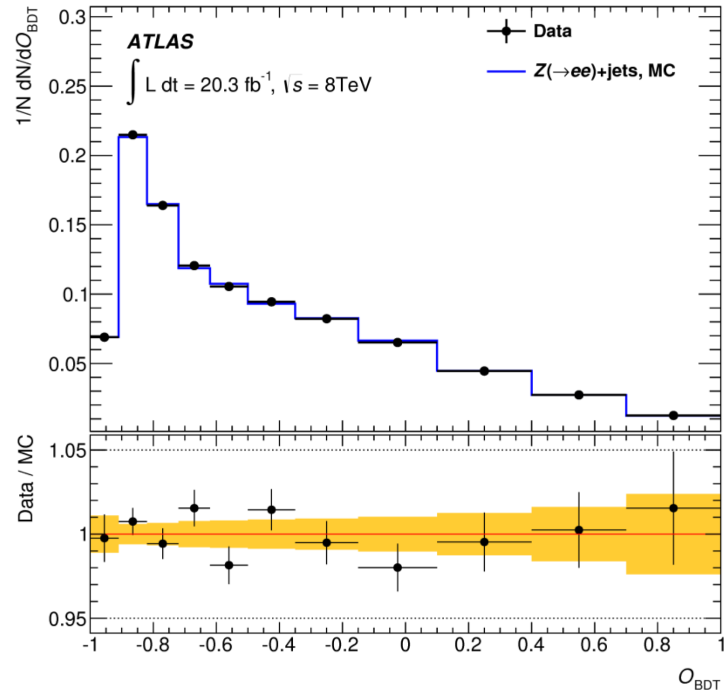
Higgs physics in ATLAS: *H→ZZ(*)→4l*

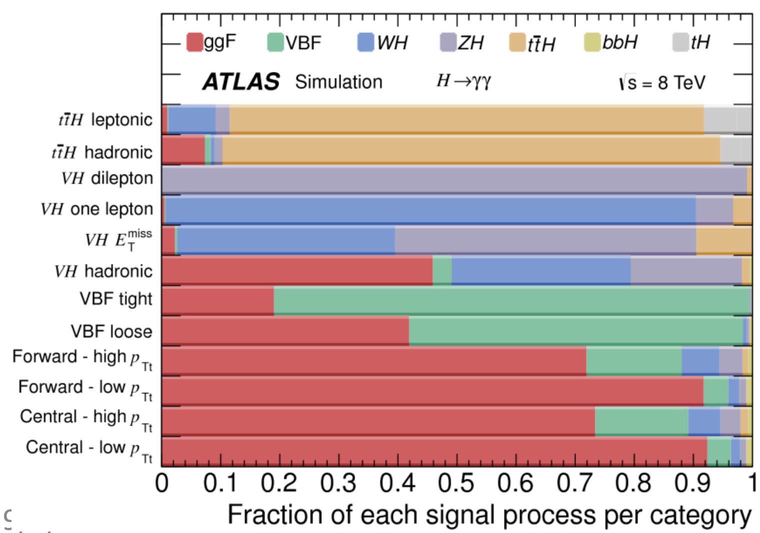
$$H \to ZZ(*) \to 4e$$

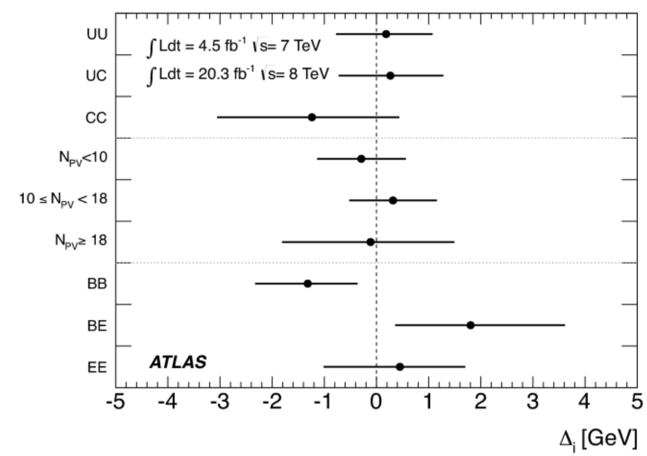


Higgs physics in ATLAS: *H→γγ* — *arXiv:1408.7084, arXiv:1406.3827*

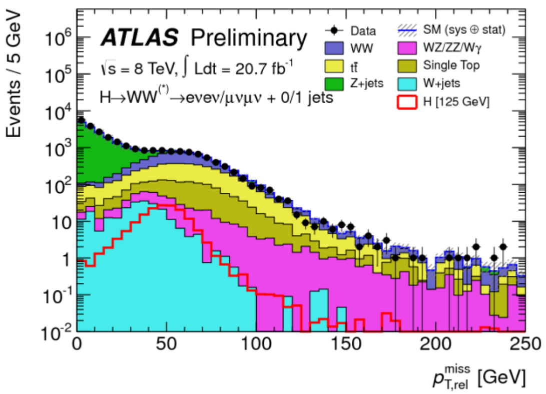


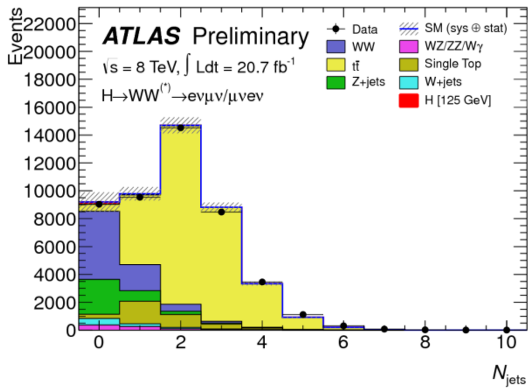


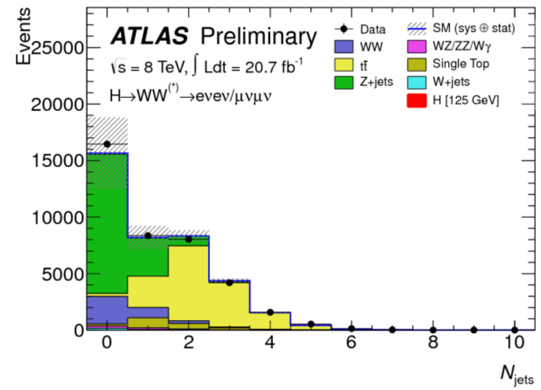




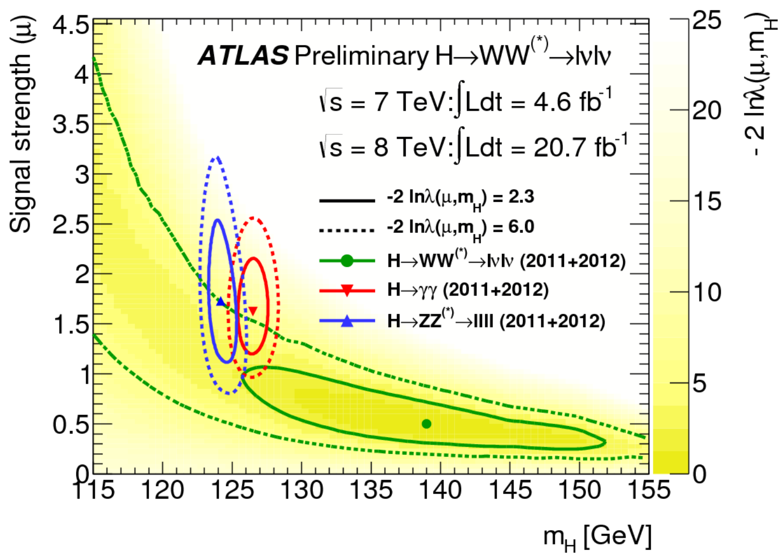
Samples of distributions at pre-selection level







2D signal strengths



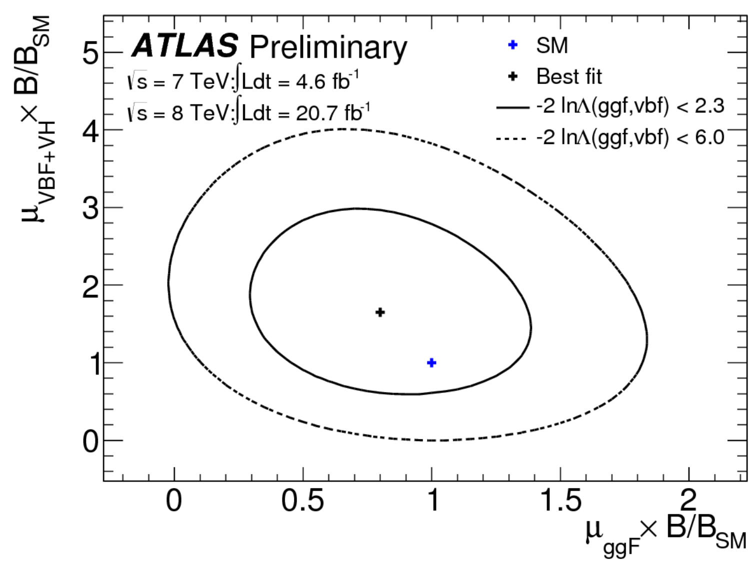
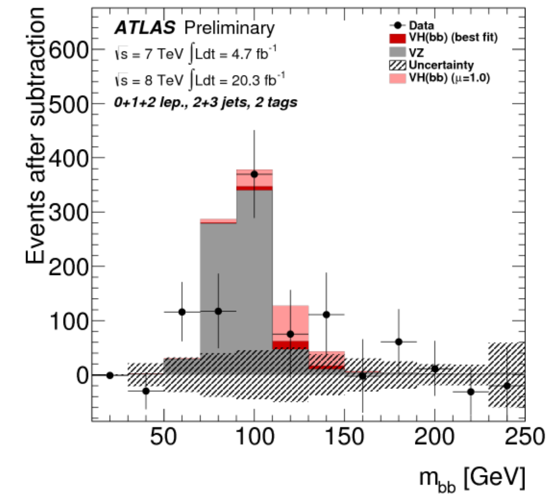
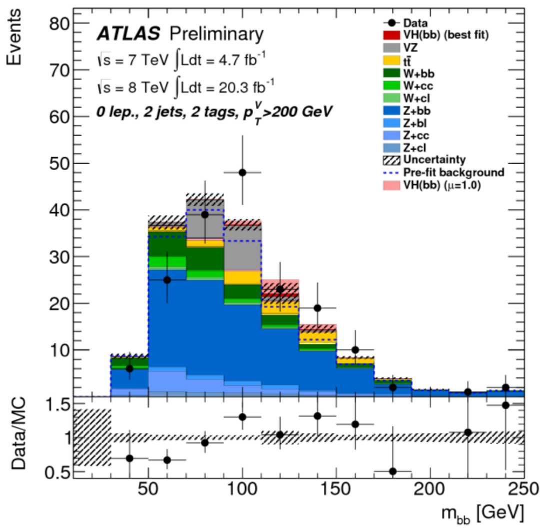


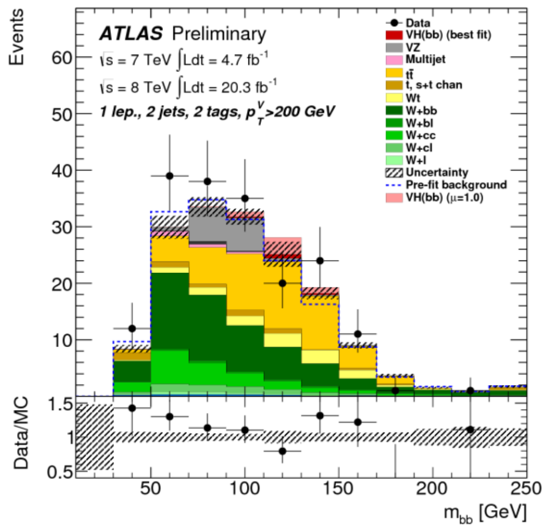
Table 1: The basic event selection for the three channels.

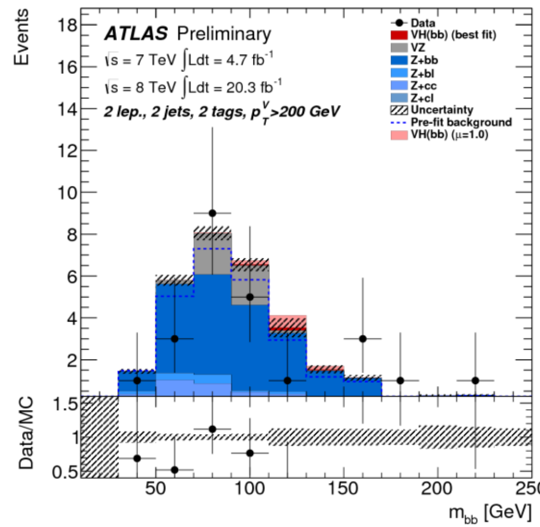
Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_T^{\mathrm{jet}_1} > 45$ GeV $p_T^{\mathrm{jet}_2} > 20$ GeV $+ \leq 1$ extra jets		
Missing E_T	$E_T^{\mathrm{miss}} > 120$ GeV $p_T^{\mathrm{miss}} > 30$ GeV $\Delta\phi(E_T^{\mathrm{miss}}, p_T^{\mathrm{miss}}) < \pi/2$ $\min[\Delta\phi(E_T^{\mathrm{miss}}, \mathrm{jet})] > 1.5$ $\Delta\phi(E_T^{\mathrm{miss}}, b\bar{b}) > 2.8$	$E_T^{\mathrm{miss}} > 25$ Gev	$E_T^{\mathrm{miss}} < 60$ GeV
Vector Boson	-	$m_T^W < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV



Samples of m_{bb} distributions for the different categories





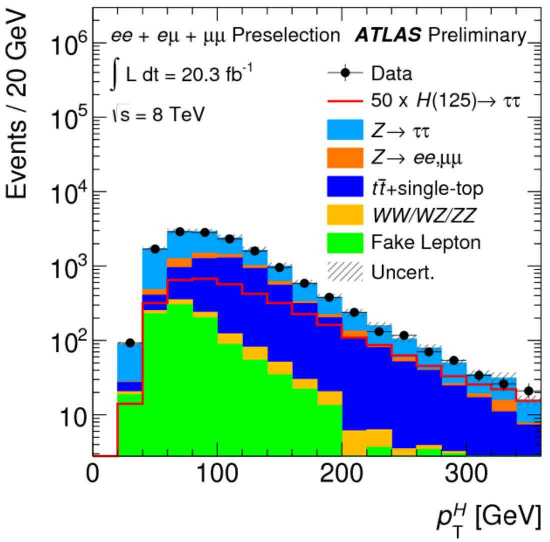


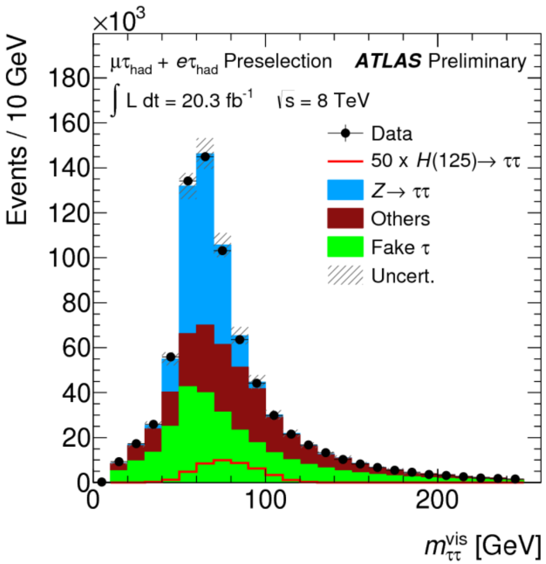
- **Two isolated taus**
- Full reconstruction not possible

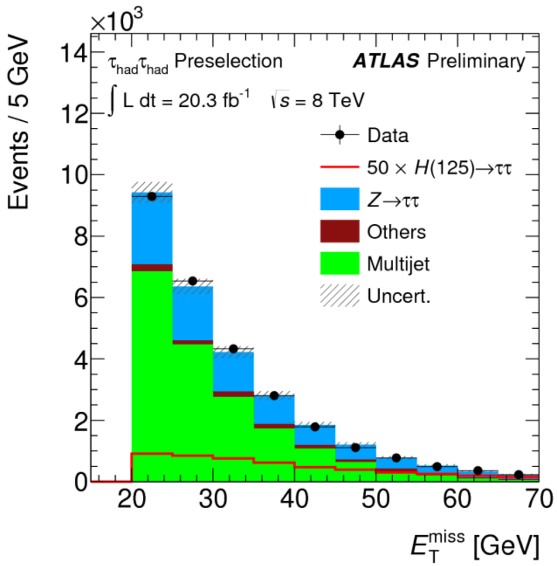
Background Composition:

Z→ττ, Z→ll, W+jets, top, diboson

Samples of kinematic distributions for different categories







Trigger	p_T threshold(s) [GeV]	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
Electron	24	•	•	
Muon	24		•	
Di-electron	12 ; 12	•		
Di-muon	18 ; 8	•		
Electron + Muon	12 ; 8	•		
Electron + τ_{had}	18 ; 20		•	
Muon + τ_{had}	15 ; 20		•	
Di-τ_{had}	29 ; 20			•

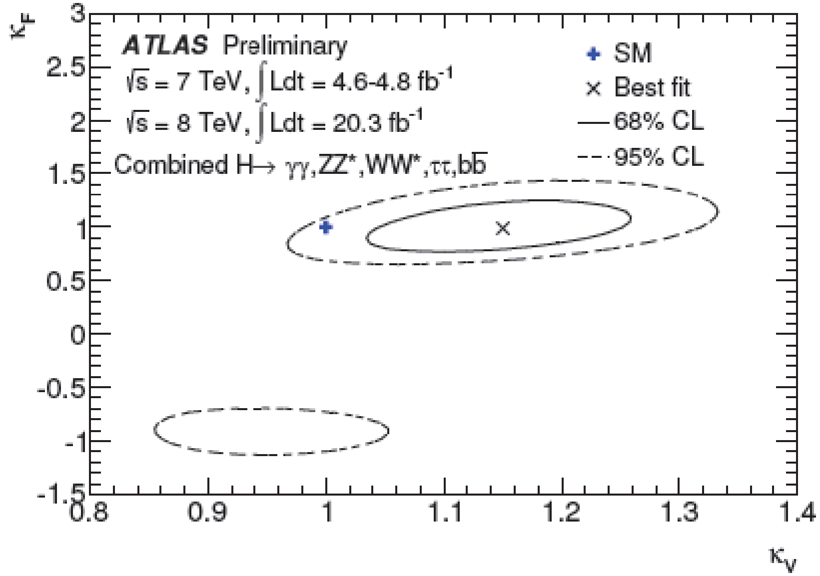
Category	Selection	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
VBF	$p_T(j_1)$ (GeV)	40	50	50
	$p_T(j_2)$ (GeV)	30	30	30/35
	$\Delta\eta(j_1, j_2)$	2.2	3.0	2.0
	b−jet veto for jet p_T (GeV)	25	30	-
	p_T^H (GeV)	-	-	40
Boosted	$p_T(j_1)$ (GeV)	40	-	-
	p_T^H (GeV)	100	100	100
	b−jet veto for jet p_T (GeV)	25	30	-

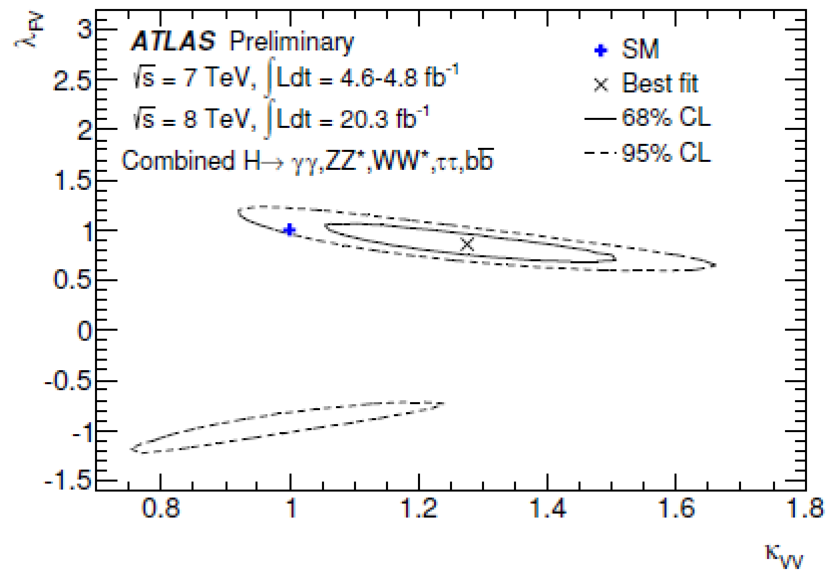
Variable	VBF			Boosted		
	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
$m_{\tau\tau}^{MMC}$	•	•	•	•	•	•
$\Delta R(\tau, \tau)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1, j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
p_T^{Total}		•	•			
sum p_T					•	•
$p_T(\tau_1)/p_T(\tau_2)$					•	•
$E_T^{miss}\phi$ centrality		•	•	•	•	•
$x_{\tau 1}$ and $x_{\tau 2}$						•
$m_{\tau\tau, j_1}$				•		
m_{ℓ_1, ℓ_2}				•		
$\Delta\phi_{\ell_1, \ell_2}$				•		
sphericity				•		
$p_T^{\ell_1}$				•		
$p_T^{j_1}$				•		
$E_T^{miss}/p_T^{\ell_2}$				•		
m_T		•			•	
$\min(\Delta\eta_{\ell_1\ell_2, jets})$	•					
j_3 η centrality	•					
$\ell_1 \times \ell_2$ η centrality	•					
ℓ η centrality		•				
$\tau_{1,2}$ η centrality			•			

Variable	Definition
Centrality	Sum of the p_T divided by sum of the E for all jets and the lepton
H1	Second Fox-Wolfram moment computed using all jets and the lepton
$m_{bb}^{\min \Delta R}$	Mass of the combination of two b-tagged jets with the smallest ΔR
N_{40}^{jet}	Number of jets with $p_T \geq 40$ GeV
ΔR_{bb}^{avg}	Average ΔR for all b-tagged jet pairs
$m_{jj}^{\max p_T}$	Mass of the combination of any two jets with the largest vector sum p_T
$\text{Aplanarity}_{b-jet}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor built with only b-tagged jets
H_T^{had}	Scalar sum of jet p_T
$m_{jj}^{\min \Delta R}$	Mass of the combination of any two jets with the smallest ΔR
$\Delta R_{lep-bb}^{\min \Delta R}$	ΔR between the lepton and the combination of two b-tagged jets with the smallest ΔR
$m_{bj}^{\min \Delta R}$	Mass of the combination of a b-tagged jet and any jet with the smallest ΔR
$m_{bj}^{\max p_T}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_T
$m_{uu}^{\min \Delta R}$	Mass of the combination of two untagged jets with the smallest ΔR
p_T^{jet5}	Fifth leading jet p_T
$\Delta R_{bb}^{\max p_T}$	ΔR between two b-tagged jets with the largest vector sum p_T
$m_{bb}^{\max m}$	Mass of the combination of two b-tagged jets with the largest invariant mass
$p_{T,uu}^{\min \Delta R}$	Scalar sum of the p_T's of the pair of untagged jets with the smallest ΔR
m_{jjj}	Mass of the jet triplet with the largest vector sum p_T
$\Delta R_{uu}^{\min \Delta R}$	Minimum ΔR between two untagged jets
$m_{bb}^{\max p_T}$	Mass of the combination of two b-tagged jets with the largest vector sum p_T

Table 4: List of variables used in the NN in the single lepton channel in at least one region. From the list, 10 variables are chosen in each region.

Systematic	Uncertainty on m_H [MeV]
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr cell non-linearity (layer 2)	60
LAr cell non-linearity (layer 1)	30
LAr layer calibration (barrel)	50
Lateral shower shape (conv)	50
Lateral shower shape (unconv)	40
Presampler energy scale (barrel)	20
ID material model ($\|\eta\| < 1.1$)	50
$H \to \gamma\gamma$ background model (unconv rest low p_{Tt})	40
$Z \to ee$ calibration	50
Primary vertex effect on mass scale	20
Muon momentum scale	10
Remaining systematic uncertainties	70
Total	180





$$\kappa_V = 1.15 \pm 0.08$$

$$\kappa_F = 0.99^{+0.17}_{-0.15}$$

$$\lambda_{FV} = 0.86^{+0.14}_{-0.12}$$

$$\kappa_{VV} = 1.28^{+0.16}_{-0.15}$$

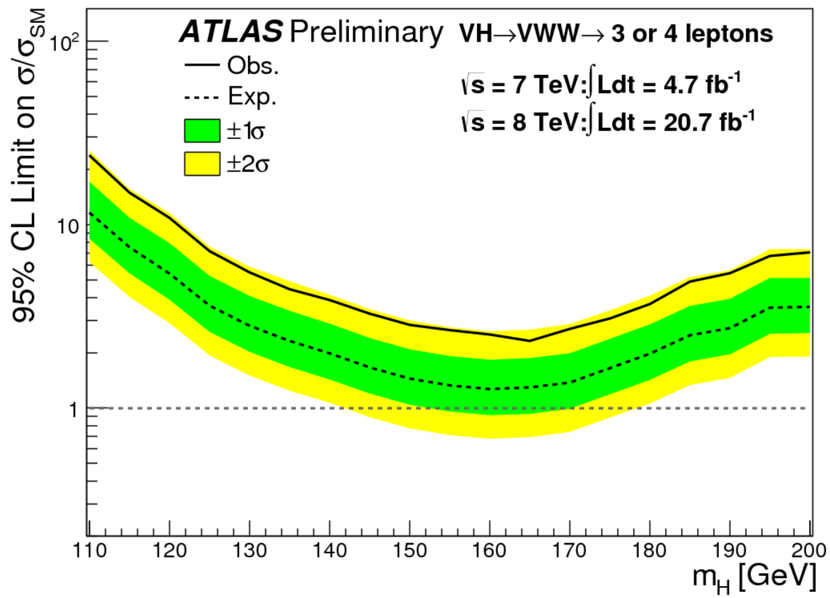
Model		Coupling Parameter	Description	Measurement
1	MCHM4, EW singlet	μ_h	Overall signal strength	$1.30^{+0.18}_{-0.17}$
		$\kappa = \sqrt{\mu_h}$	Universal coupling	$1.14^{+0.09}_{-0.08}$
2	MCHM5, 2HDM Type I	κ_V	Vector boson (W, Z) coupling	1.15 ± 0.08
		κ_F	Fermion $(t, b, \tau, \ldots)$ coupling	$0.99^{+0.17}_{-0.15}$
3	2HDM Type II, MSSM	$\lambda_{Vu} = \kappa_V/\kappa_u$	Ratio of vector boson & up-type fermion $(t, c, \ldots)$ couplings	$1.21^{+0.24}_{-0.26}$
		$\kappa_{uu} = \kappa_u^2/\kappa_h$	Ratio of squared up-type fermion coupling & total width scale factor	$0.86^{+0.41}_{-0.21}$
		$\lambda_{du} = \kappa_d/\kappa_u$	Ratio of down-type fermion $(b, \tau, \ldots)$ & up-type fermion couplings	$[-1.24, -0.81] \cup [0.78, 1.15]$
4	2HDM Type III	$\lambda_{Vq} = \kappa_V/\kappa_q$	Ratio of vector boson & quark $(t, b, \ldots)$ couplings	$1.27^{+0.23}_{-0.20}$
		$\kappa_{qq} = \kappa_q^2/\kappa_h$	Ratio of squared quark coupling & total width scale factor	$0.82^{+0.23}_{-0.19}$
		$\lambda_{lq} = \kappa_l/\kappa_q$	Ratio of lepton (τ, μ, e) & quark couplings	$[-1.48, -0.99] \cup [0.99, 1.50]$
5	Mass scaling parametrization	κ_Z	Z boson coupling	$0.95^{+0.24}_{-0.19}$
		κ_W	W boson coupling	$0.68^{+0.30}_{-0.14}$
		κ_t	t quark coupling	$[-0.80, -0.50] \cup [0.61, 0.80]$
		κ_b	b quark coupling	$[-0.7, 0.7]$
		κ_τ	τ lepton coupling	$[-1.15, -0.67] \cup [0.67, 1.14]$
6	Higgs portal (without $Zh \to \ell\ell + E_T^{miss}$)	κ_g	Gluon effective coupling	$1.00^{+0.23}_{-0.16}$
		κ_γ	Photon effective coupling	$1.17^{+0.16}_{-0.13}$
		BR_i	Invisible branching ratio	$-0.16^{+0.29}_{-0.30}$
7	Higgs portal (with $Zh \to \ell\ell + E_T^{miss}$)	κ_g	Gluon effective coupling	–
		κ_γ	Photon effective coupling	–
		BR_i	Invisible branching ratio	-0.02 ± 0.20

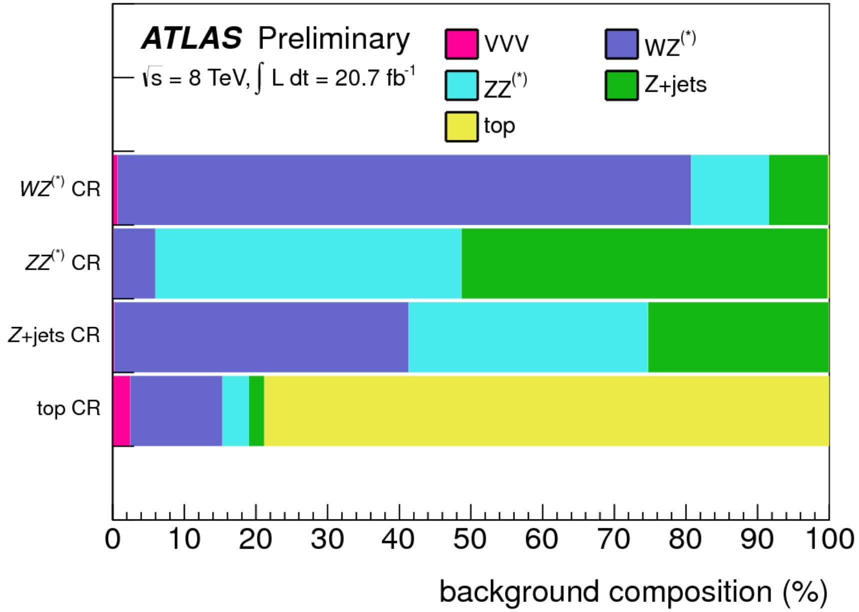
Selection:

3 or 4 isolated lepton
p_T> 25 (leading), 15 GeV
E_T^{miss}> 25 (40) GeV
b-jet veto
di-lepton mass cut $|m_{ll}-m_Z|$>25 GeV
ΔR_{l0l1}< 2

Categorization:

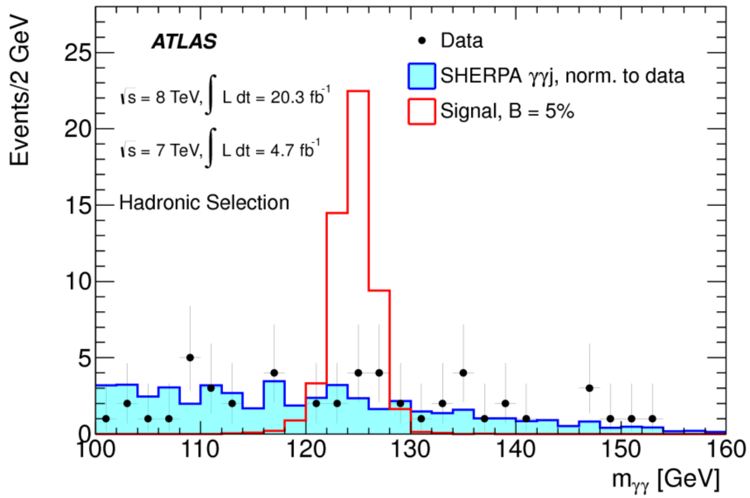
Z-enriched or depleted

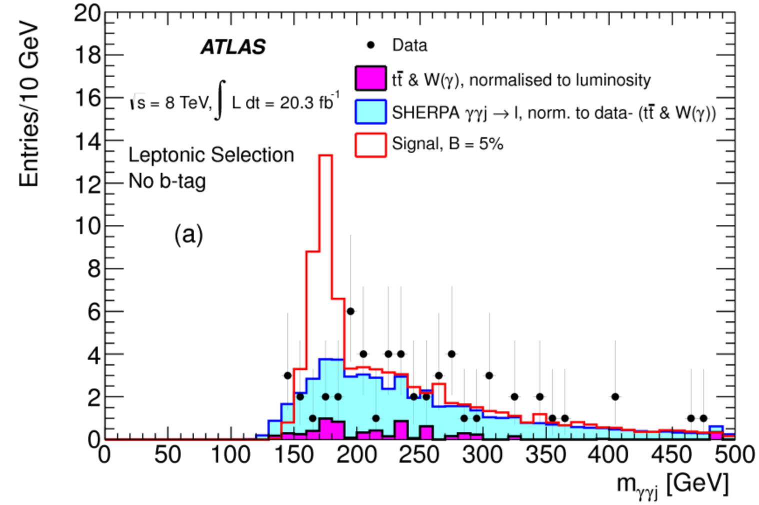


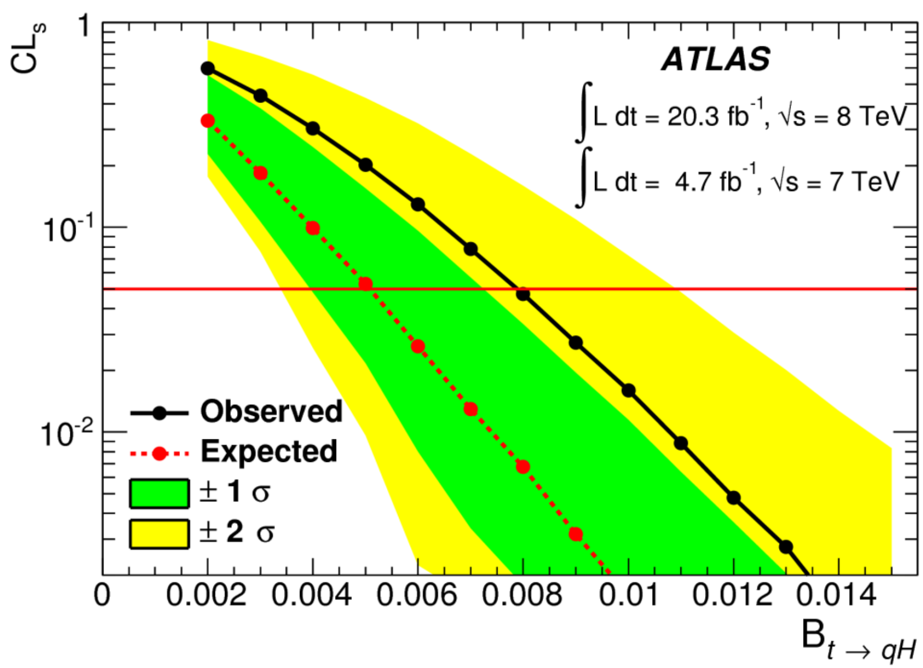


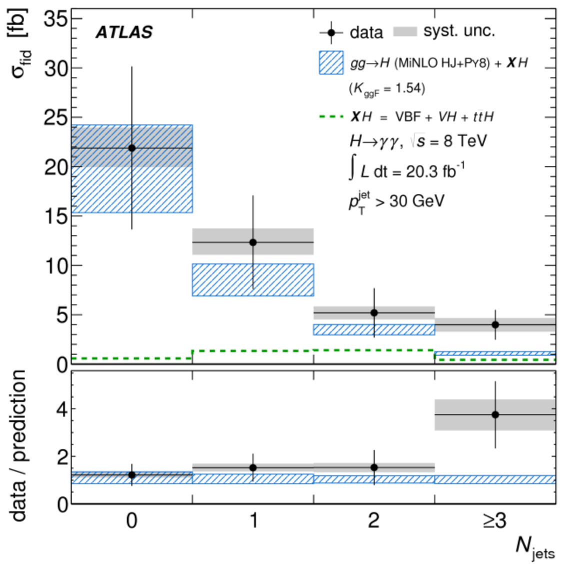
Signal strength

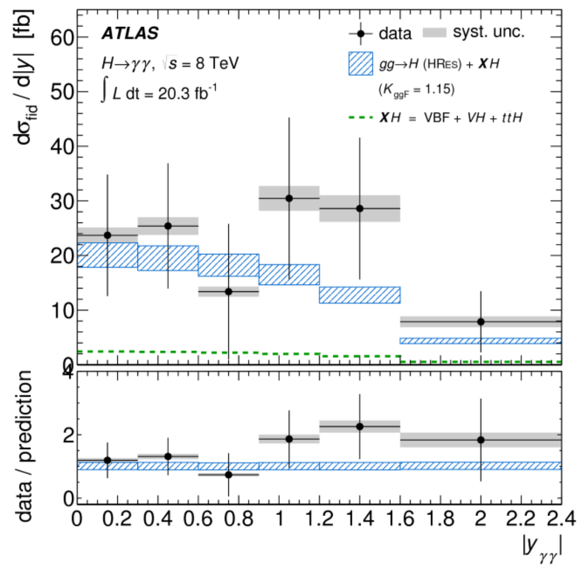
$$\mu = 3.7^{+1.9}_{-2.0}$$

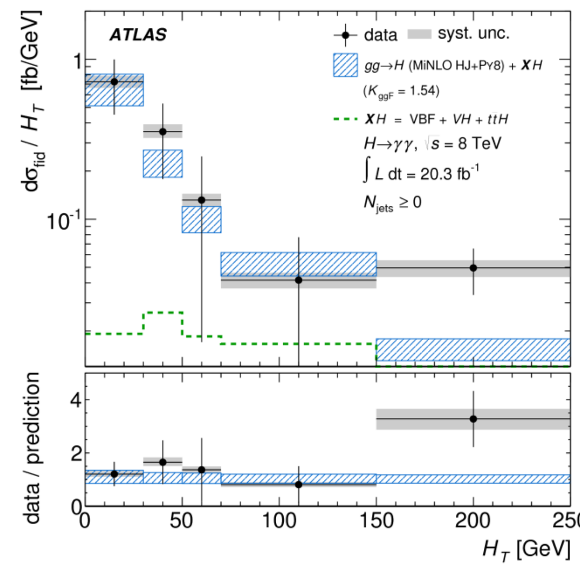

ATLAS
√s = 8 TeV, ∫ L dt = 20.3 fb⁻¹
√s = 7 TeV, ∫ L dt = 4.7 fb⁻¹
Hadronic Selection
Data
SHERPA γγj, norm. to data
Signal, B = 5%
Events/2 GeV
$m_{\gamma\gamma}$ [GeV]


ATLAS
√s = 8 TeV, ∫ L dt = 20.3 fb⁻¹
Leptonic Selection
No b-tag
(a)
Data
$t\bar{t}$ & W(γ), normalised to luminosity
SHERPA γγj → l, norm. to data- ($t\bar{t}$ & W(γ))
Signal, B = 5%
Entries/10 GeV
$m_{\gamma\gamma j}$ [GeV]

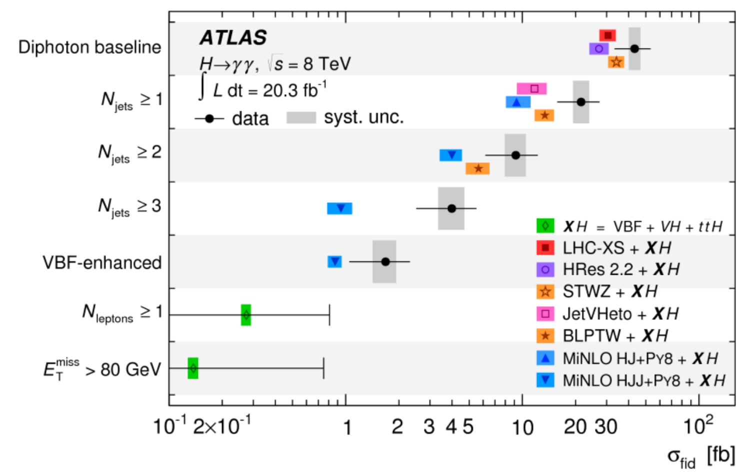

ATLAS
∫ L dt = 20.3 fb⁻¹, √s = 8 TeV
∫ L dt = 4.7 fb⁻¹, √s = 7 TeV
Observed
Expected
± 1 σ
± 2 σ
CL_s
$B_{t \to qH}$

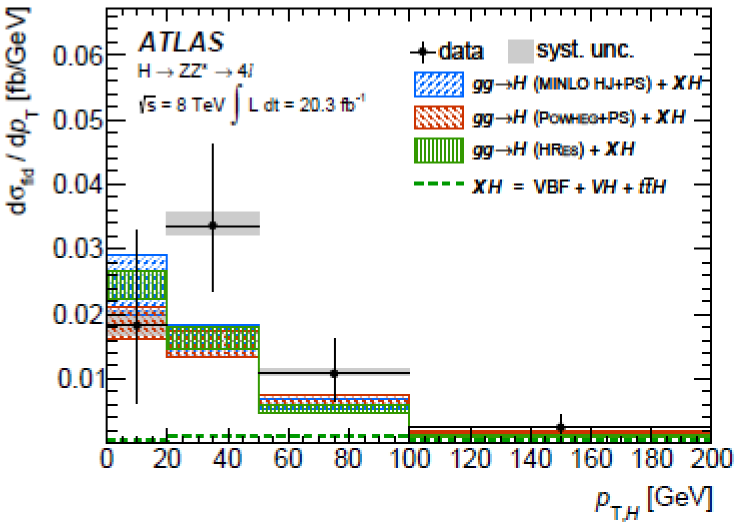


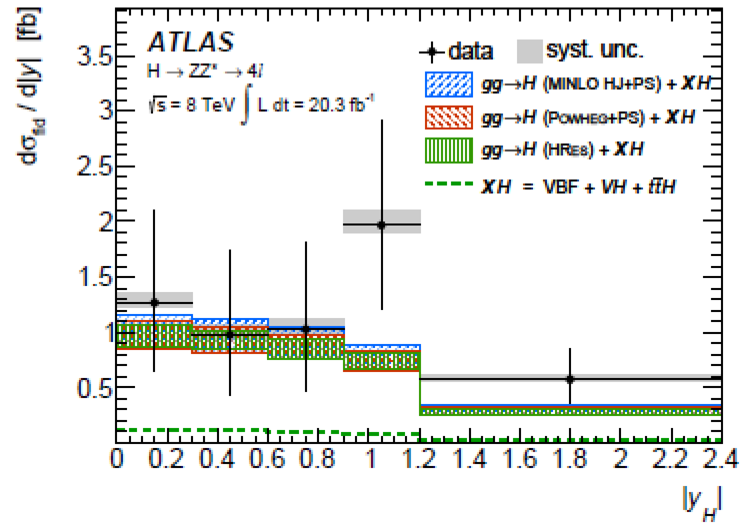




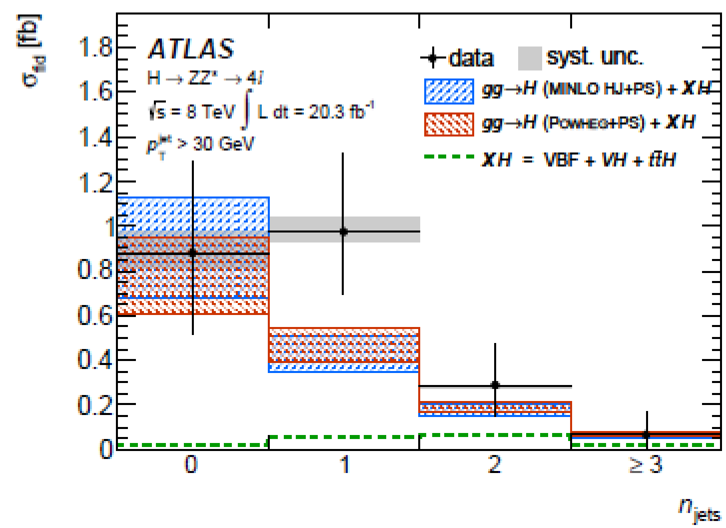
Source	Uncertainty on fiducial cross section (%)				
	Baseline	$N_{\text{jets}} \geq 1$	$N_{\text{jets}} \geq 2$	$N_{\text{jets}} \geq 3$	VBF-enhanced
Signal extraction (stat.)	± 22	± 25	± 30	± 33	± 34
Signal extraction (syst.)	± 6.5	± 7.4	± 7.1	± 6.5	± 9.0
Photon efficiency	± 1.5	± 2.1	± 3.1	± 4.2	± 2.3
Jet energy scale/resolution	-	$^{+6.2}_{-5.8}$	$^{+11}_{-10}$	$^{+15}_{-13}$	$^{+12}_{-11}$
JVF/pileup-jet	-	± 1.3	± 2.2	± 3.3	± 0.5
Theoretical modelling	$^{+3.3}_{-1.0}$	$^{+5.0}_{-2.6}$	± 4.1	$^{+6.3}_{-4.9}$	$^{+2.2}_{-3.2}$
Luminosity	± 2.8	± 2.8	± 2.8	± 2.8	± 2.8

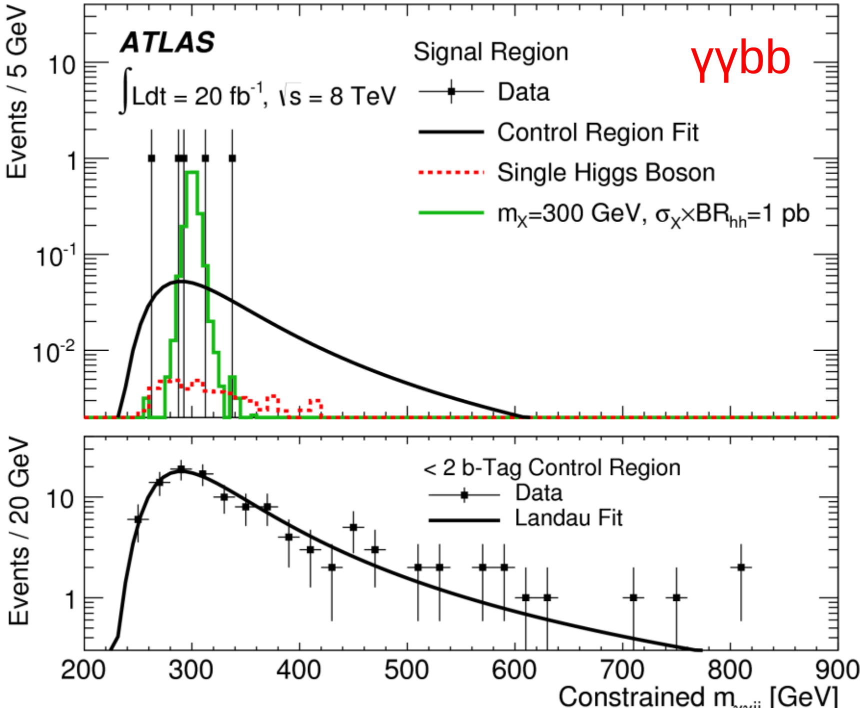


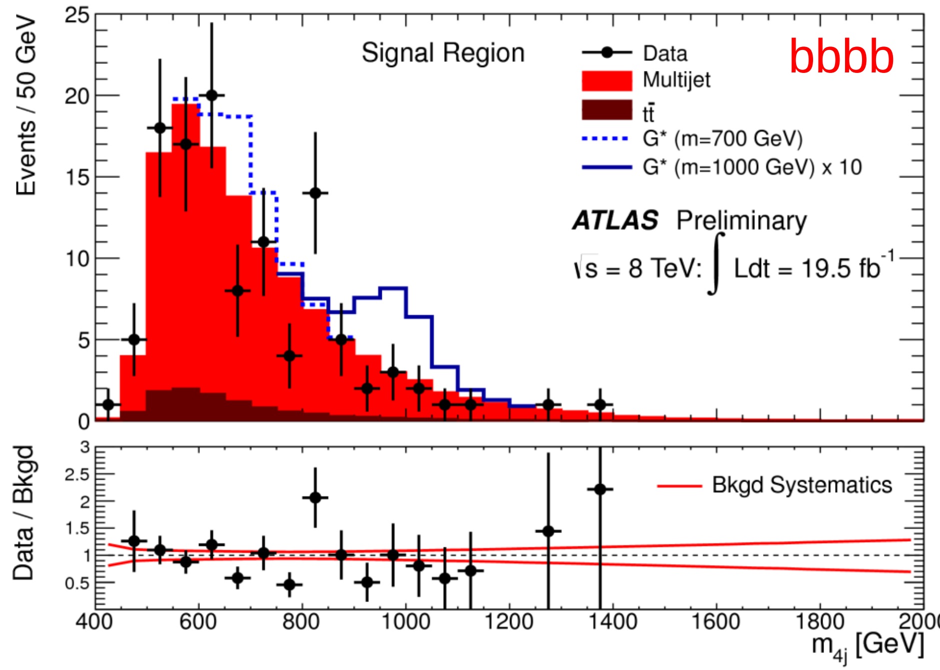


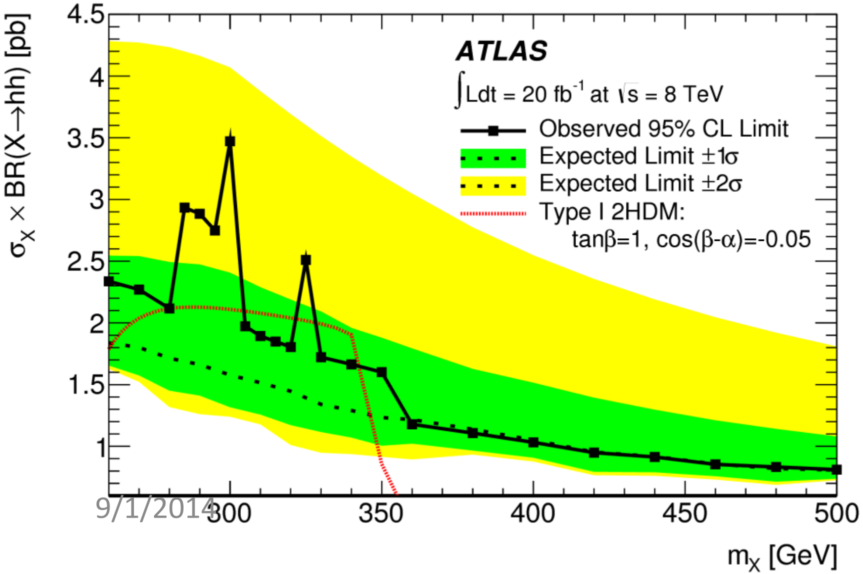


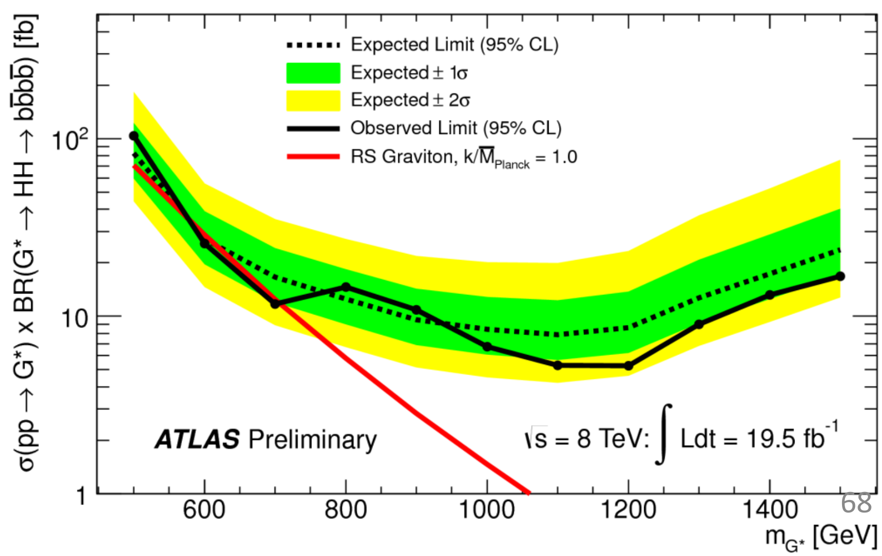
Systematic Uncertainties (%)	
Background	
Luminosity	1.4–2.3
Reducible background	1.6–34
Experimental, leptons	1.3–2.3
PDF/scale	3.0–24
Correction factors/conversion to σ	
Luminosity	2.8
Experimental, leptons	2.1–2.6
Experimental, jets	2.7–13
Production process	0.1–15
Higgs boson mass	0.4–2.7




γγbb
ATLAS
∫Ldt = 20 fb^-1, √s = 8 TeV
Signal Region
Data
Control Region Fit
Single Higgs Boson
m_X=300 GeV, σ_X×BR_hh=1 pb
Events / 5 GeV
< 2 b-Tag Control Region
Data
Landau Fit
Events / 20 GeV
Constrained m_γγjj [GeV]


bbbb
Signal Region
Data
Multijet
tt̄
G* (m=700 GeV)
G* (m=1000 GeV) x 10
ATLAS Preliminary
√s = 8 TeV: ∫ Ldt = 19.5 fb^-1
Events / 50 GeV
Data / Bkgd
Bkgd Systematics
m_4j [GeV]


ATLAS
∫Ldt = 20 fb^-1 at √s = 8 TeV
Observed 95% CL Limit
Expected Limit ±1σ
Expected Limit ±2σ
Type I 2HDM:
tanβ=1, cos(β-α)=-0.05
σ_X × BR(X→hh) [pb]
m_X [GeV]


Expected Limit (95% CL)
Expected ± 1σ
Expected ± 2σ
Observed Limit (95% CL)
RS Graviton, k/M̄_Planck = 1.0
ATLAS Preliminary
√s = 8 TeV: ∫ Ldt = 19.5 fb^-1
σ(pp → G*) x BR(G* → HH → bb̄bb̄) [fb]
m_G* [GeV]