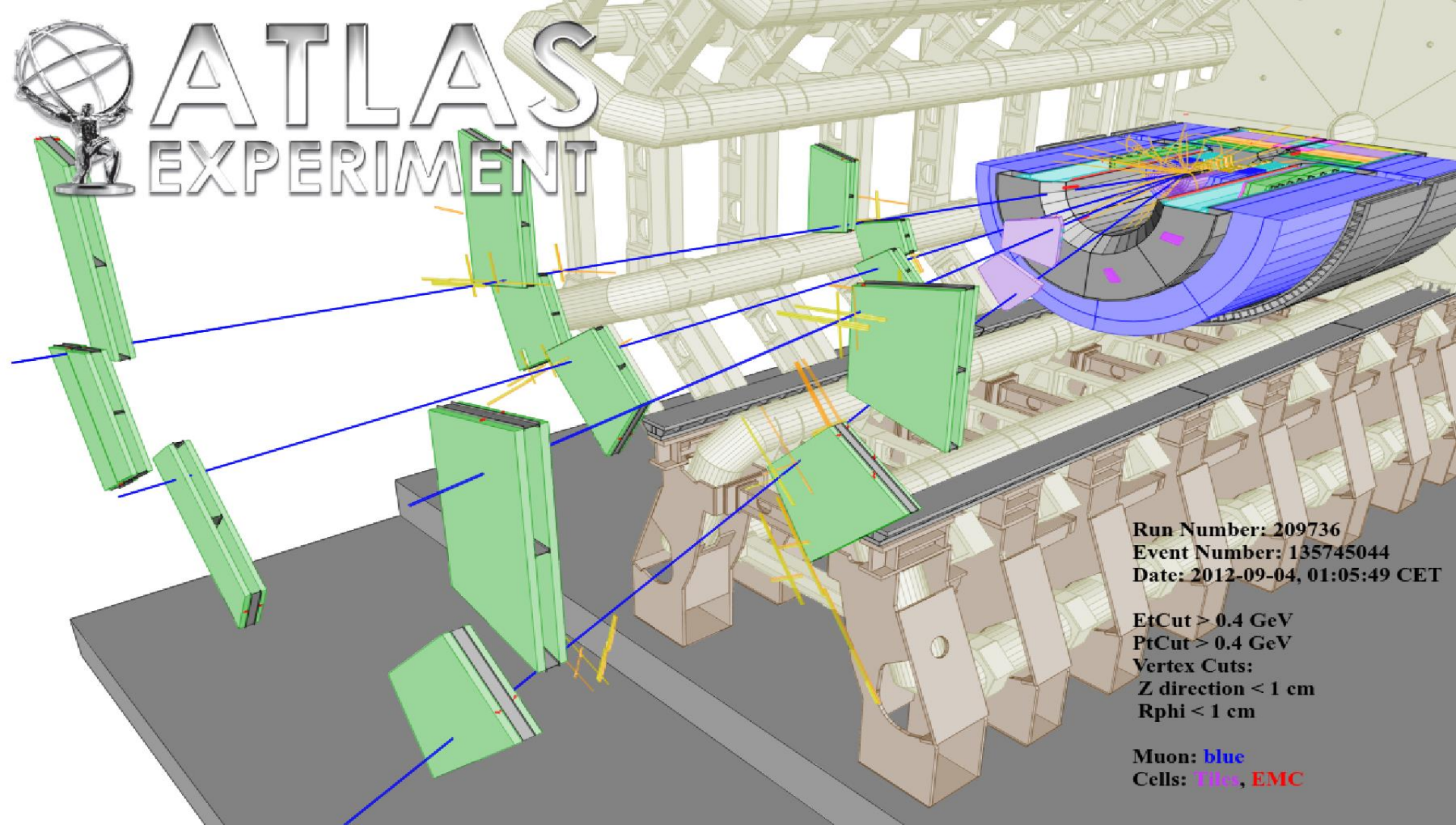


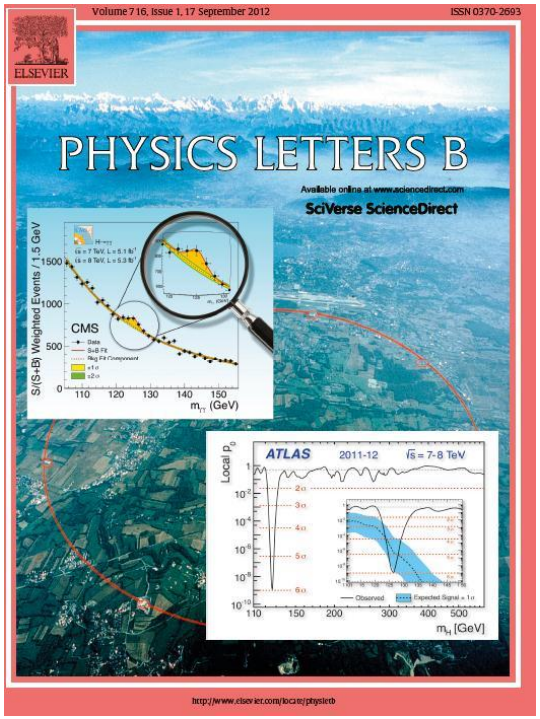
Higgs discovery status from ATLAS

Kalliopi Iordanidou
University of Athens and Brookhaven National Laboratory

on behalf of the ATLAS Collaboration

Excited QCD 2014
Sarajevo, 2-8 February 2014

Introduction



After the discovery a number of questions need to addressed

Are there any more Higgses?

→Mass measurement

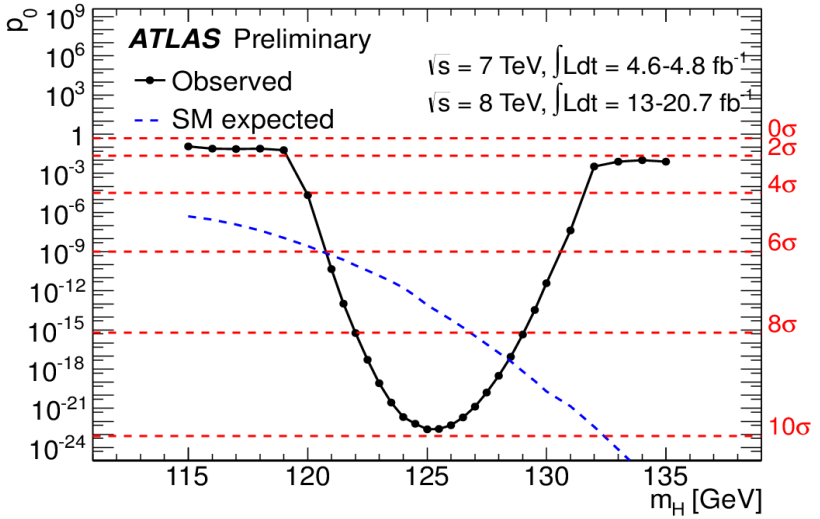
→ Signal strength

→ Spin and parity

→ Couplings to fermions/bosons

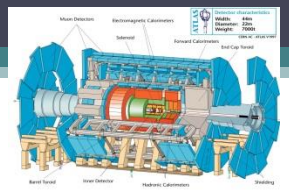
→ Production mechanisms

"Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC"
[Phys. Lett . B 716 (2012) 1-29]
4th July 2012



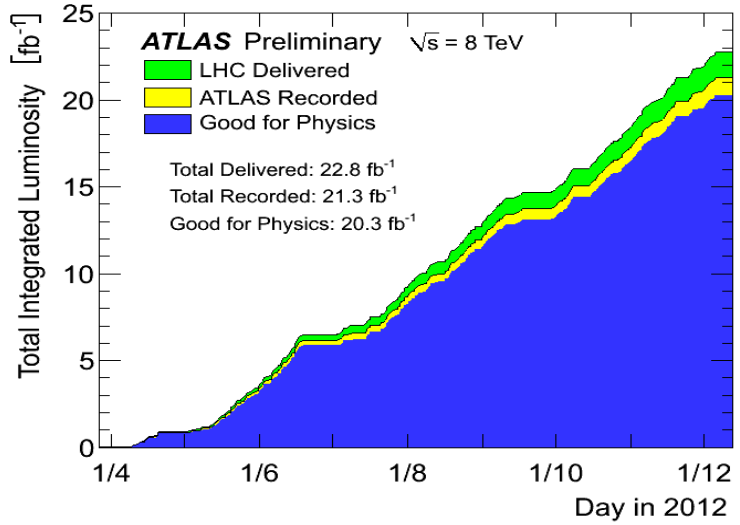
Latest ATLAS Higgs Results:

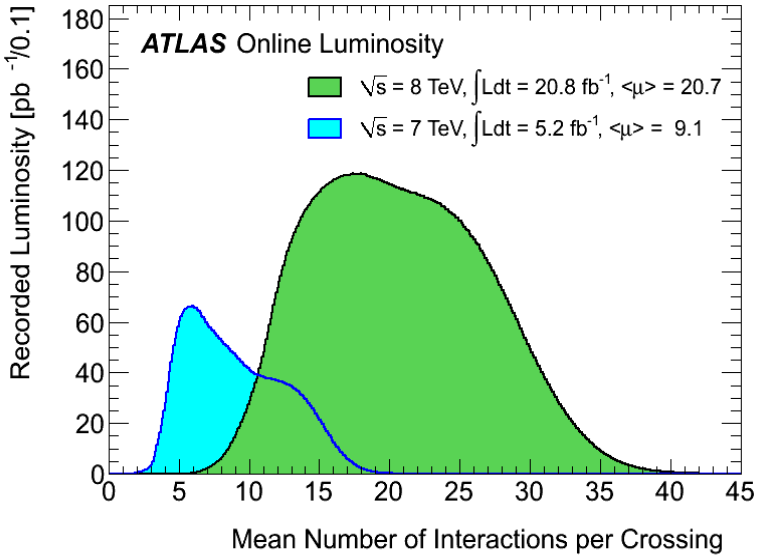
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults



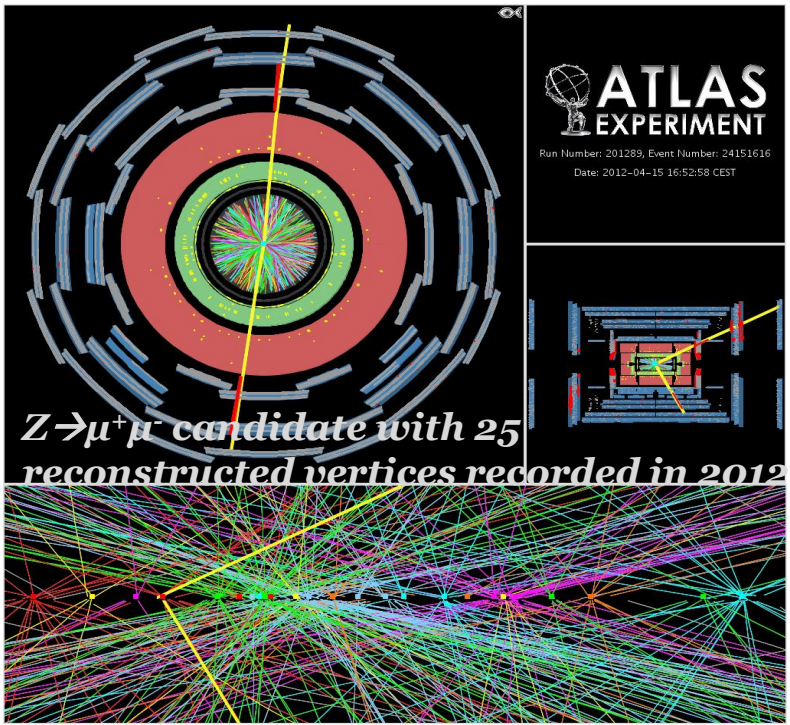
ATLAS at the Large Hadron Collider

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

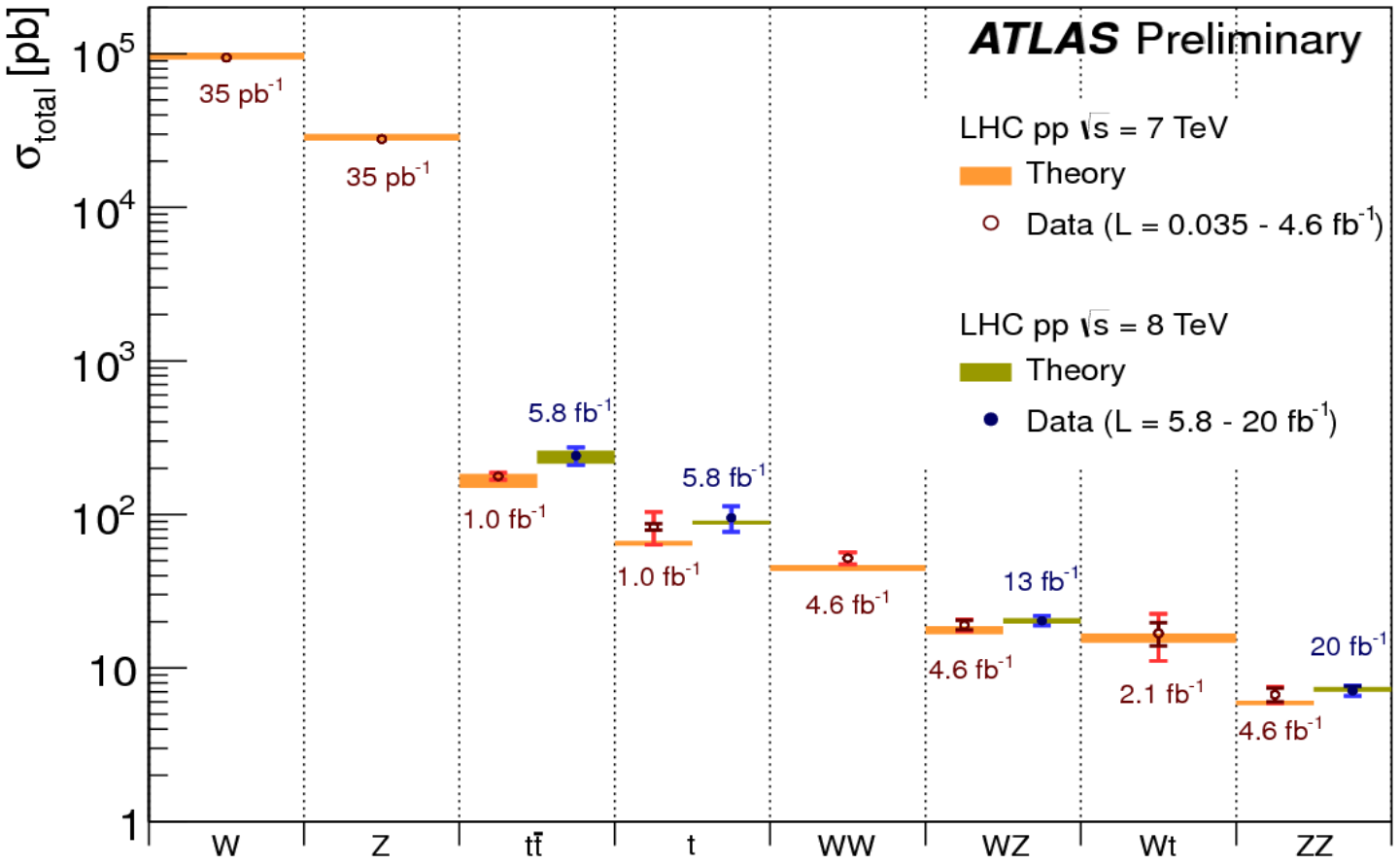




- LHC started its high energy *pp* collisions in 2010
- Excellent ATLAS performance in harsh conditions:
  - 4.57 fb^{-1} @$\sqrt{s}$ = 7 TeV (2011)
  - 20.3 fb^{-1} @ $\sqrt{s}$ = 8 TeV (2012)
- Run I period: 2010 - 2012



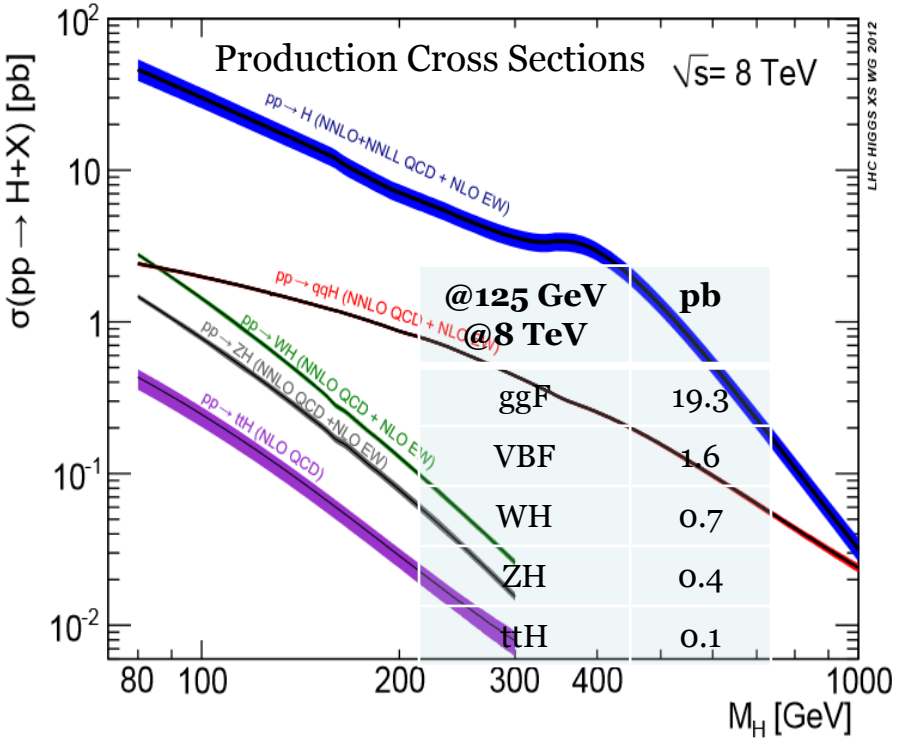
Testing the SM @ ATLAS



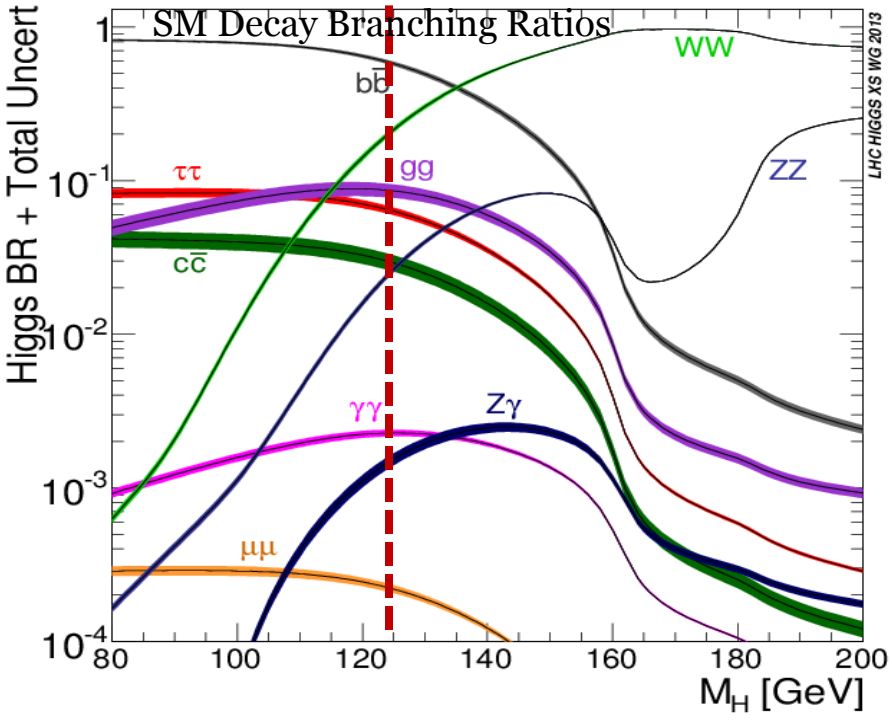
Precision tests of the SM → All the results are consistent with the theory predictions

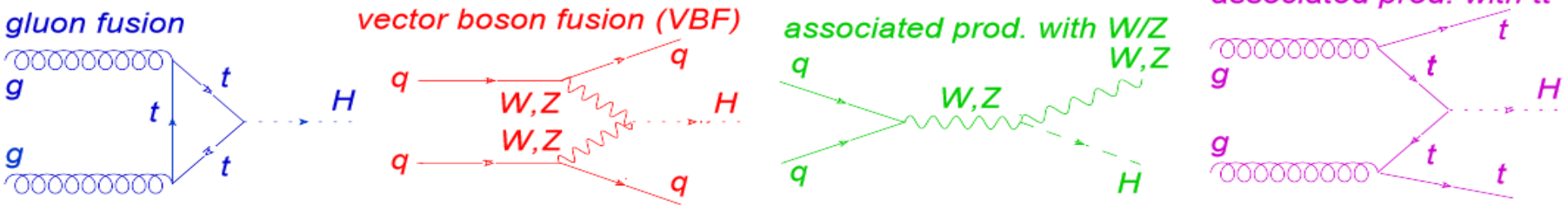
LHC Higgs Cross Sections:
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

Higgs Boson Production @LHC



@125 GeV @8 TeV	pb
ggF	19.3
VBF	1.6
WH	0.7
ZH	0.4
ttH	0.1



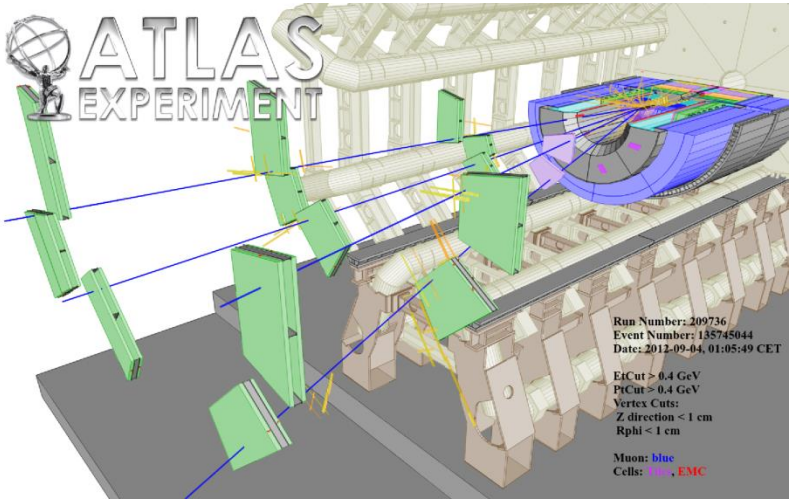


Outline Higgs Decay Searches

- Channels studied in the context of SM Higgs Boson search:
  - Bosonic Decays:
    - $H \rightarrow ZZ(*) \rightarrow 4l$
    - $H \rightarrow \gamma\gamma$
    - $H \rightarrow WW(*) \rightarrow lvlv$
    - $H \rightarrow Z/\gamma$
  - Devoted to High Mass Studies ($H \rightarrow ZZ(*) \rightarrow llqq$, $H \rightarrow ZZ(*) \rightarrow llvv$, $H \rightarrow WW(*) \rightarrow lvqq$, $H \rightarrow ZZ(*) \rightarrow ll\tau\tau$)
  - Fermionic Decays
    - $H \rightarrow bb$
    - $H \rightarrow \tau\tau$
    - $H \rightarrow \mu\mu$
- BSM scenarios

H→ZZ(*)→4l

- "Golden Channel"
- **Four isolated leptons originated from primary vertex**
- Narrow resonance on top of a smooth background
- Background Composition:
  - *Irreducible ZZ**
  - *Reducible Zbb, Zlight, ttbar*



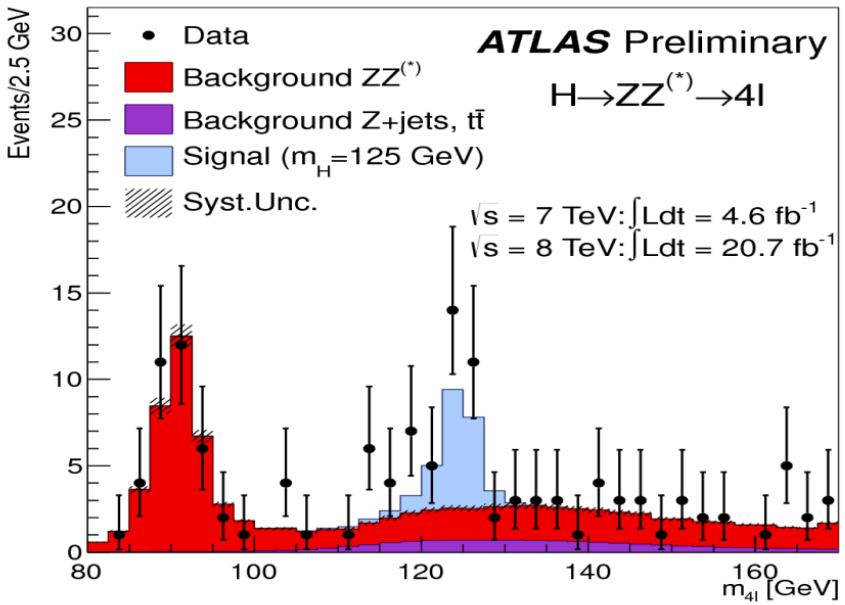
Combined 7 TeV & 8 TeV:
Expected SM Significance: 4.4 σ
Observed Significance: 6.6 σ

Mass Measurement:

$$124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(syst)\ GeV$$

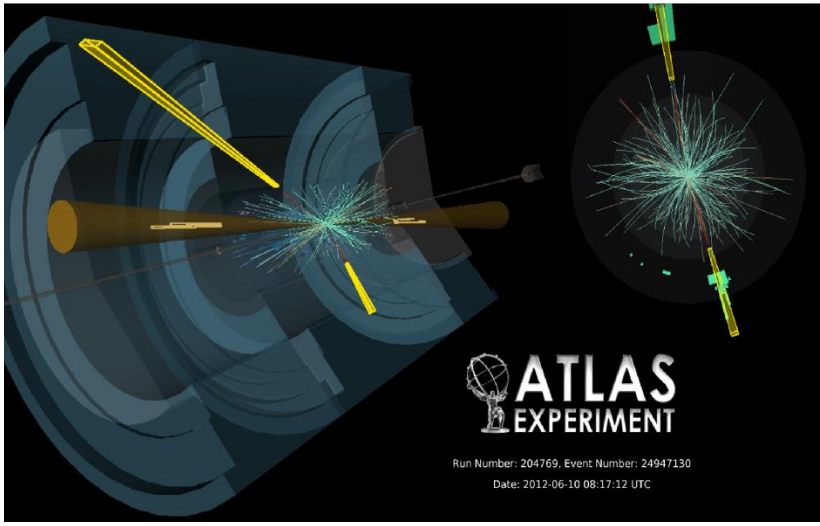
Signal Strength:

$$1.7^{+0.5}_{-0.4}$$



H→ γγ

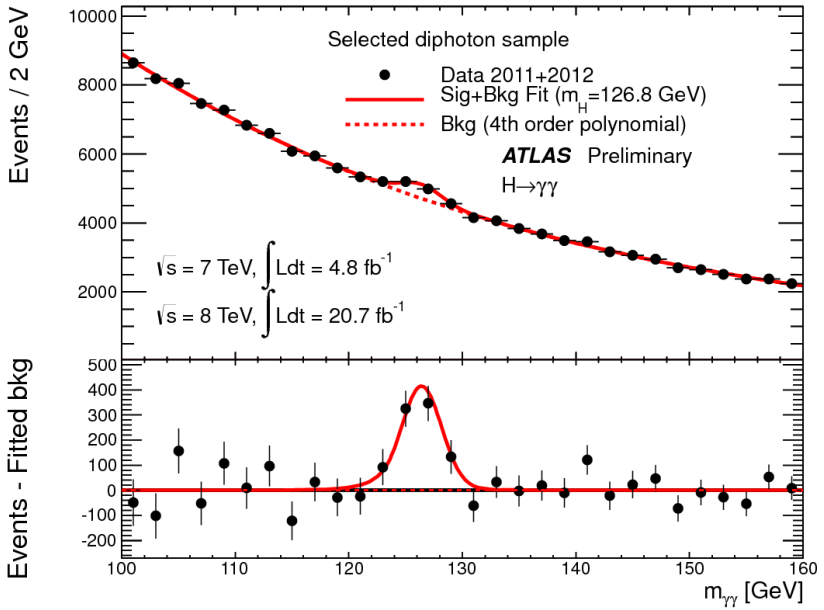
- **Two isolated photons**
- Narrow resonance on top of a continuous background
- Background Composition:
  - *Irreducible γγ continuum(~82%)*
  - *Reducible γ-jet(~15%), jet-jet(~3%)*



Combined 7 TeV & 8 TeV:
Expected SM Significance: 4.1 σ
Observed Significance: 7.4 σ

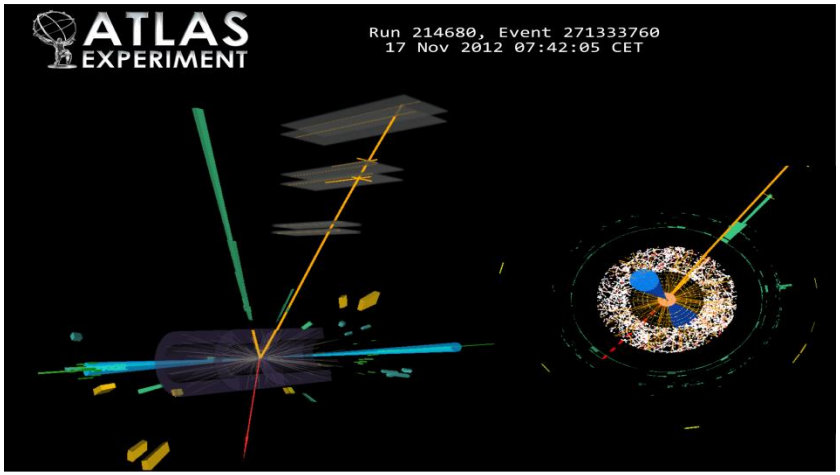
Mass Measurement:
126.8 ± 0.2(stat) ± 0.7(syst) GeV

Signal Strength:
$1.65^{+0.24}_{-0.24}(stat)^{+0.25}_{-0.18}(syst)$



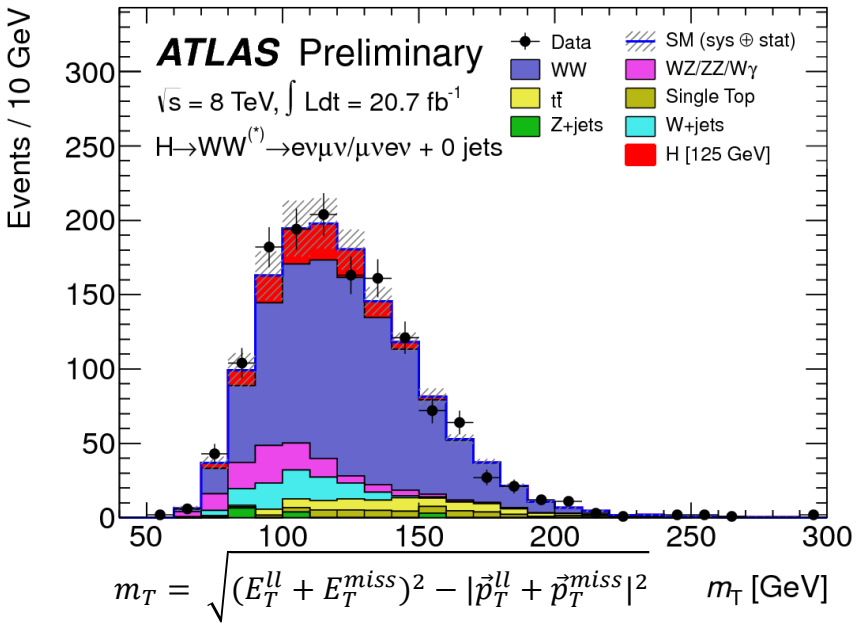
H→WW(*)→lνlν

- Large production rate and clear signature, no full mass reconstruction possible due to 2ν
- **Dilepton candidates discriminated by the transverse mass (m_T) and $\Delta\varphi(l_1,l_2)$, vetoed for Z and DY**
- Background Composition:
  WW, ttbar, W+jets



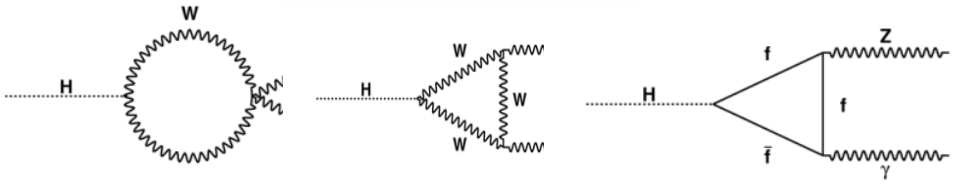
Combined 7 TeV & 8 TeV:
Expected SM Significance: 3.7 σ
Observed Significance: 3.8 σ

Signal Strength:
1.01 ± 0.31

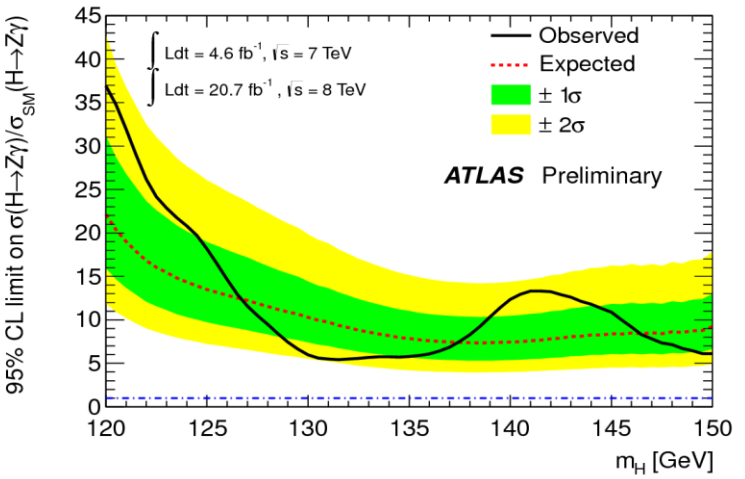


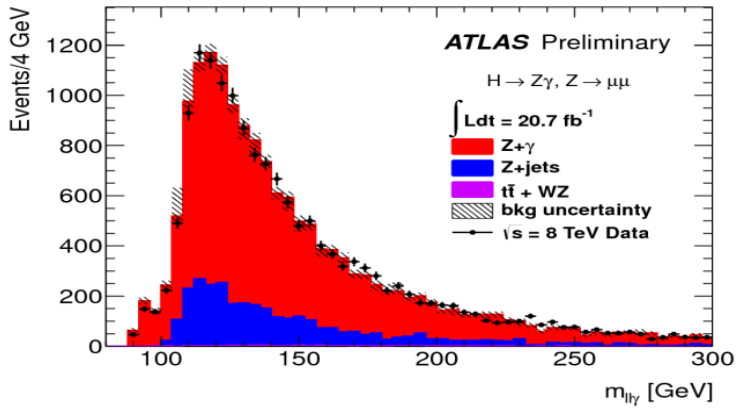
H→Z/γ

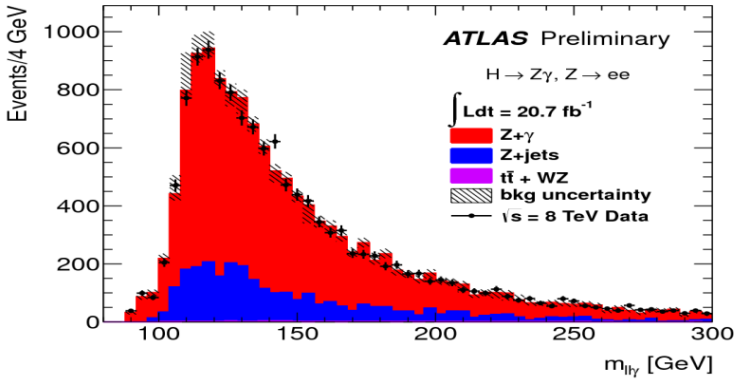
- Decay rate can provide insight into models beyond the SM
- Total cross section 1.8(2.3) fb @$\sqrt{s}$ = 7(8) TeV (including $Z \rightarrow l^+l^-$ cross section)
- **Well reconstructed Z candidates (±10 GeV from the Z pole) accompanied by a photon (E_T > 15 GeV)**
- Background Composition:
  mainly Z+γ and Z+jets



No significant deviation from the SM prediction was observed

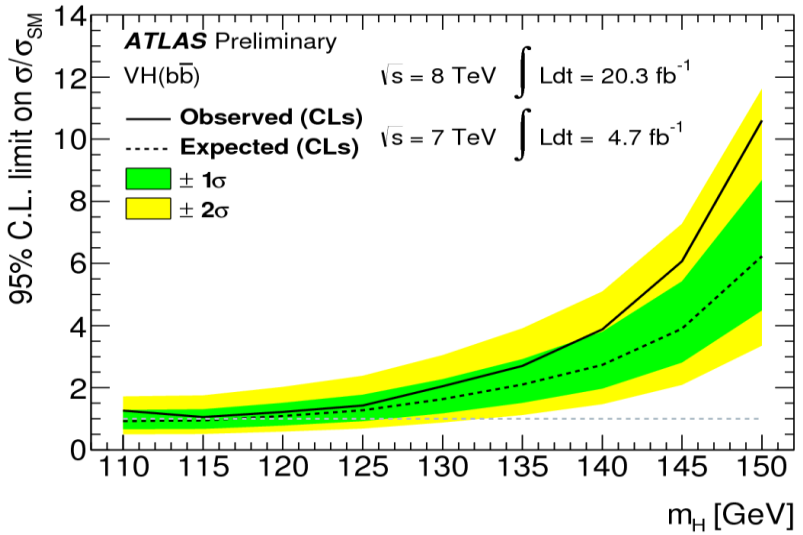






H→bb

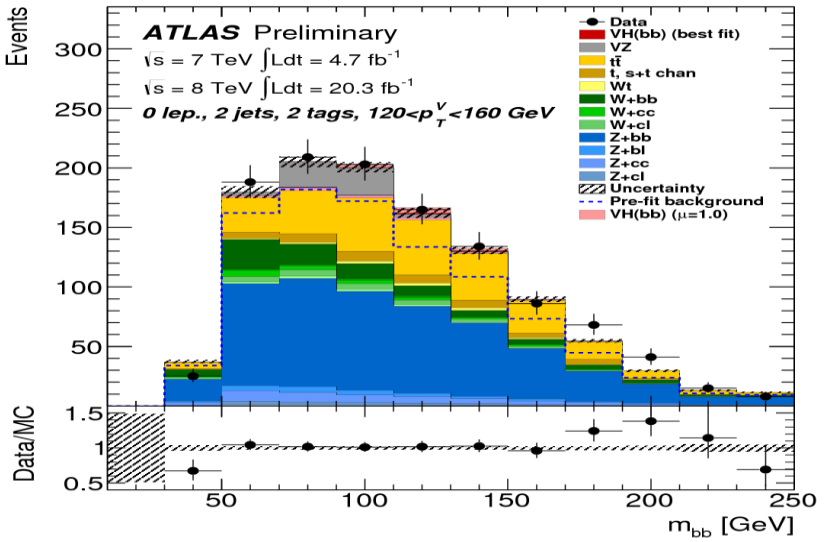
- High BR and can provide direct constraint to Higgs coupling to quarks/fermions
- **Associated VH production: W(lv)H→bb, Z(vv or ll)H→bb**
- Require two b-jets and classify according to missing E_T, $P_T(v)$, discriminate according to m_{bb}
- Background Composition:
  High jet background



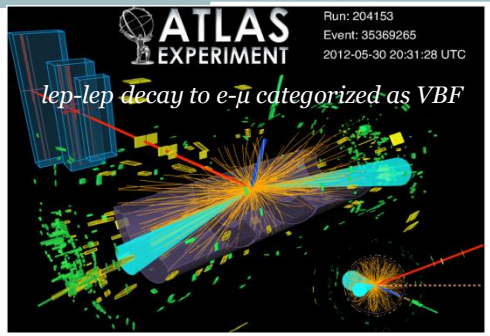
No Significant Excess is Observed

Signal Strength:

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



H→ ττ

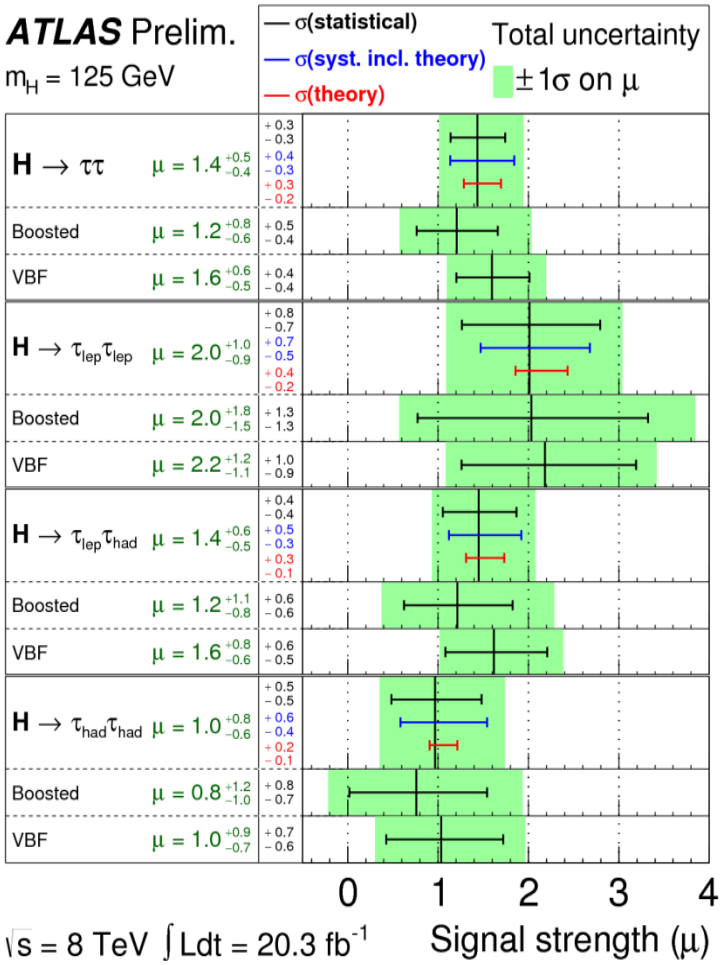


- Sample analyzed: $\int L = 20.3\ \text{fb}^{-1}$ @$\sqrt{s} = 8$ TeV
- Important for the H decays to fermions/leptons
- **Split events according to τ decay and discriminate with $m_{\tau\tau}$, E_T^{miss}, p_T^H, $\Delta\eta_{jj}$**
- Background Composition:
  mainly $Z/\gamma^* \rightarrow \tau^+\tau^-$ and $Z \rightarrow ll$, ttbar+single top, WW, WZ, ZZ
- Exploit Signal Sensitive Topologies
  - VBF: *presence of two jets with a large pseudorapidity separation*
  - Boosted: *from ggF (failing the VBF)*

Results compatible with the Standard Model

Observed Strength:

$$1.4 \pm 0.3(stat)^{+0.4}_{-0.3}(syst)$$

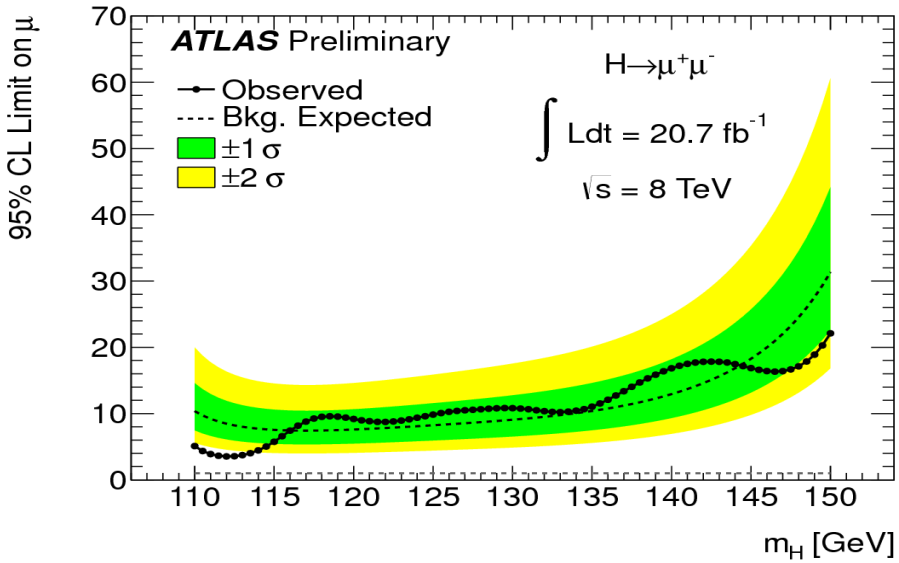


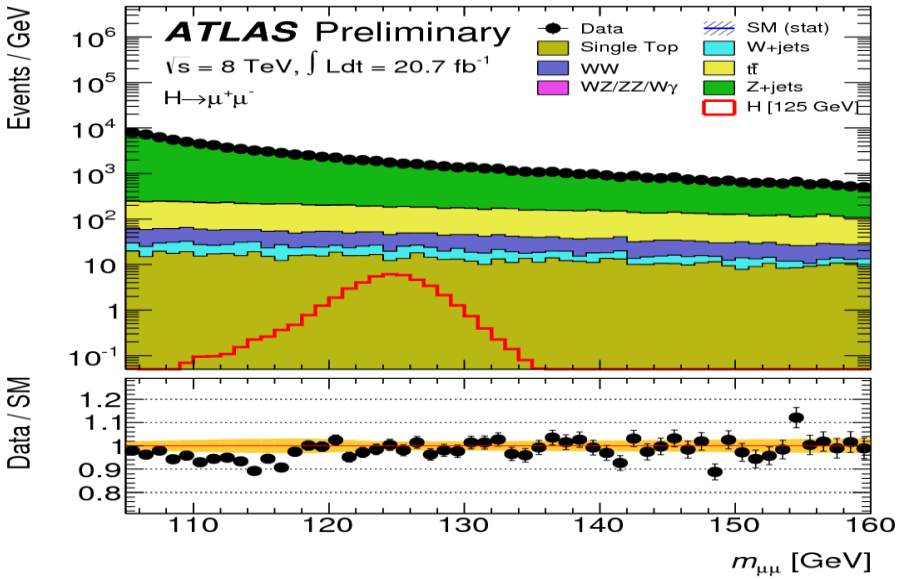
H→μ⁺μ⁻

- The only channel where the Higgs coupling to second generation fermions can be measured at the LHC. Small BR and high background.
- Sample analyzed: @$\sqrt{s}$ = 8 TeV data
- **Isolated muons originating from the primary vertex**
- Background Composition:
  mainly $Z/\gamma^* \rightarrow \mu^+\mu^-$

The observed data is consistent with the expectation from the SM backgrounds.

No evidence of a signal is observed





What are the properties of the discovered boson?

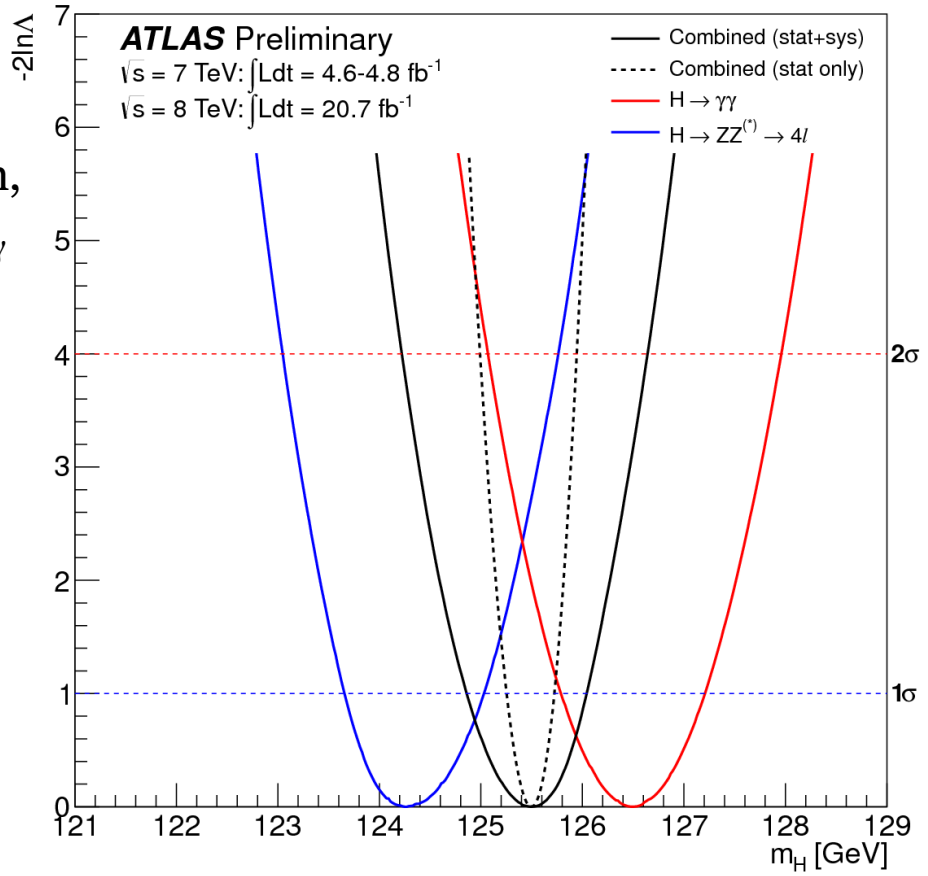
Is it the SM Higgs?

Are there hints for BSM?

Mass Measurement

Combining the H→ZZ(*)→4l and H→γγ

The profile likelihood ratio -2ln $\Lambda(m_H)$ as a function of mH for the H→γγ and H→ZZ*→4l channels and their combination, obtained by allowing the signal strengths $\mu_{\gamma\gamma}$ and μ_{4l} to vary independently.



H→ZZ*→4l: $124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})$ GeV

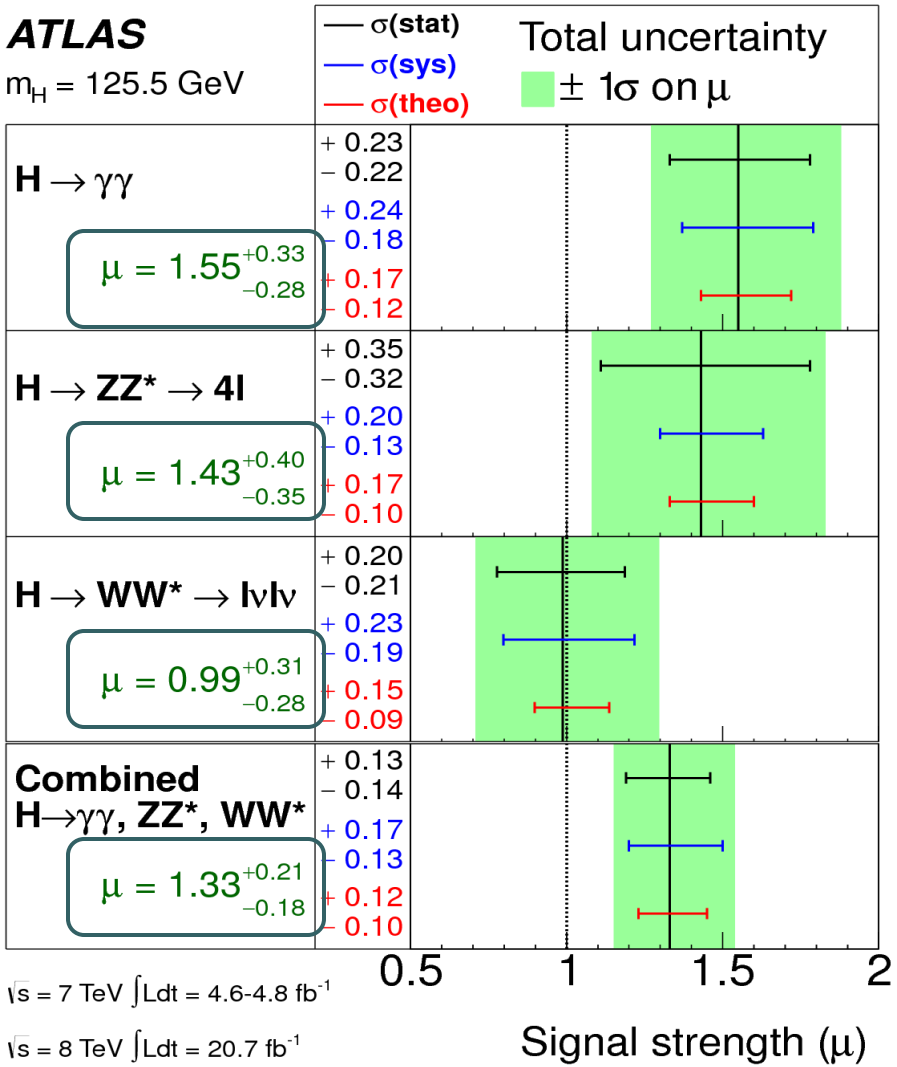
H→γγ: $126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})$ GeV

Combined: $125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{syst})$ GeV

Signal Strength

Compatibility of the observed rate with the SM

To measure the Higgs boson production strength, the parameter μ is determined from a fit to the data using the profile likelihood ratio Λ(μ) for a fixed mass hypothesis corresponding to the measured value m_H =125.5 GeV

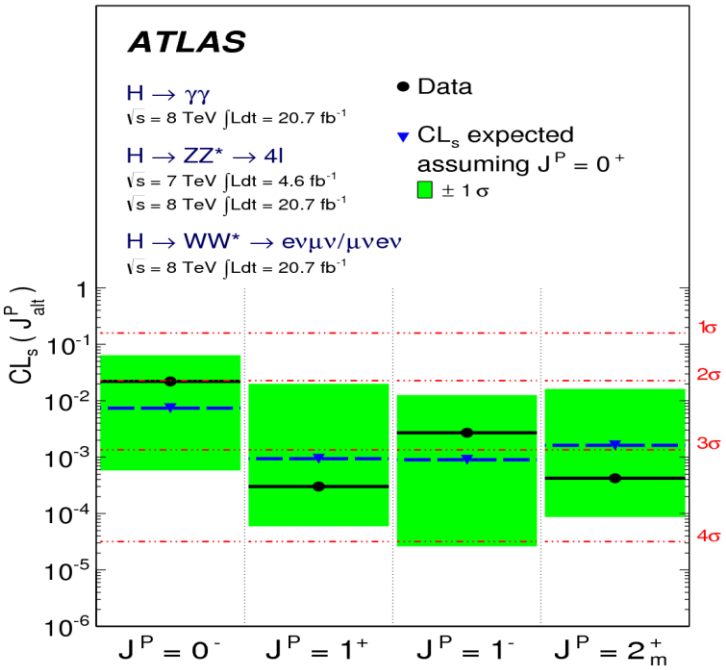


Theory uncertainty from :QCD scale, PDF and BR

Spin / CP Properties

- **SM Higgs has $J^P = 0^+$**
- Observed decay channels (bosonic) imply integer spin. H→γγ decay excludes spin-1 hypothesis (Landau-Yang theorem)
- Analyses are channel dependent

Channel	Discriminants
H→ZZ*→4l	BDT, five production/decay angles
H→γγ	$\|\cos\theta^*\|$, where θ^* is the polar angle between γγ wrt rest frame
H→WW*→lνlν	BDT, m_{ll}, p_T^{ll}, $\Delta\varphi_{ll}$, m_T

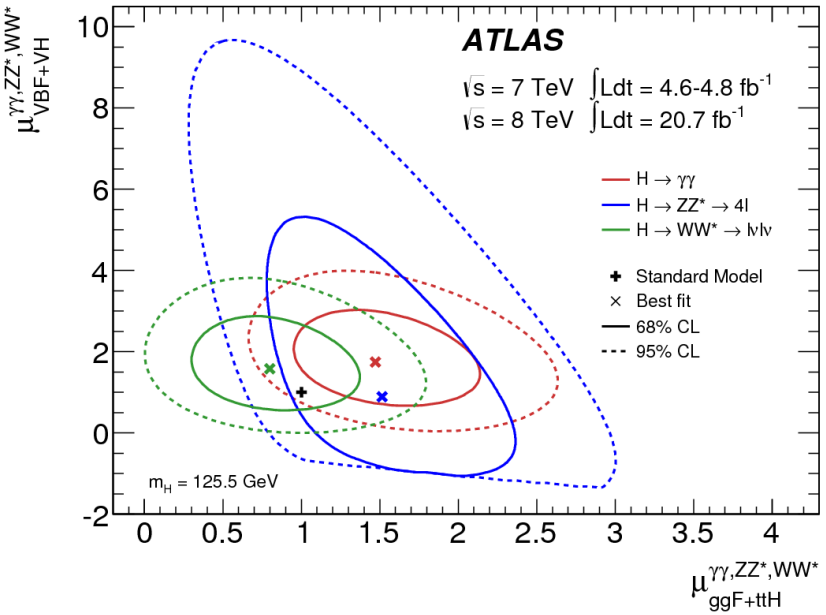


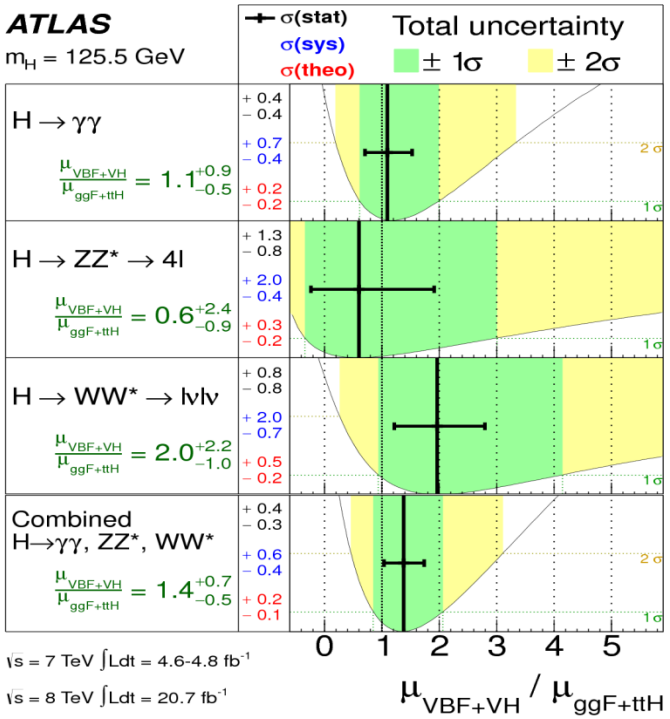
- **Data favors the SM $J^P=0^+$**
- *The 0^- is rejected at 97.8% CL (H→ZZ(*)→4l)*
- *The 1^+ and 1^- are rejected with a CL of at least 99.7% (combining H→ZZ(*)→4l and H→WW(*)→lνlν)*
- *The graviton-inspired $J^P=2^+$ model is excluded at more than 99.9% CL (combining the H→ZZ(*)→4l, H→γγ, H→WW(*)→lνlν)*

Production Mechanisms

Production Characteristics:

- **VBF**: *two jets in opposite hemisphere*
- **VH**: *H candidate + W/Z candidate*
- **ttH**: *b-jets stemming from top quark decays*
- **ggF**: *if none of the above*



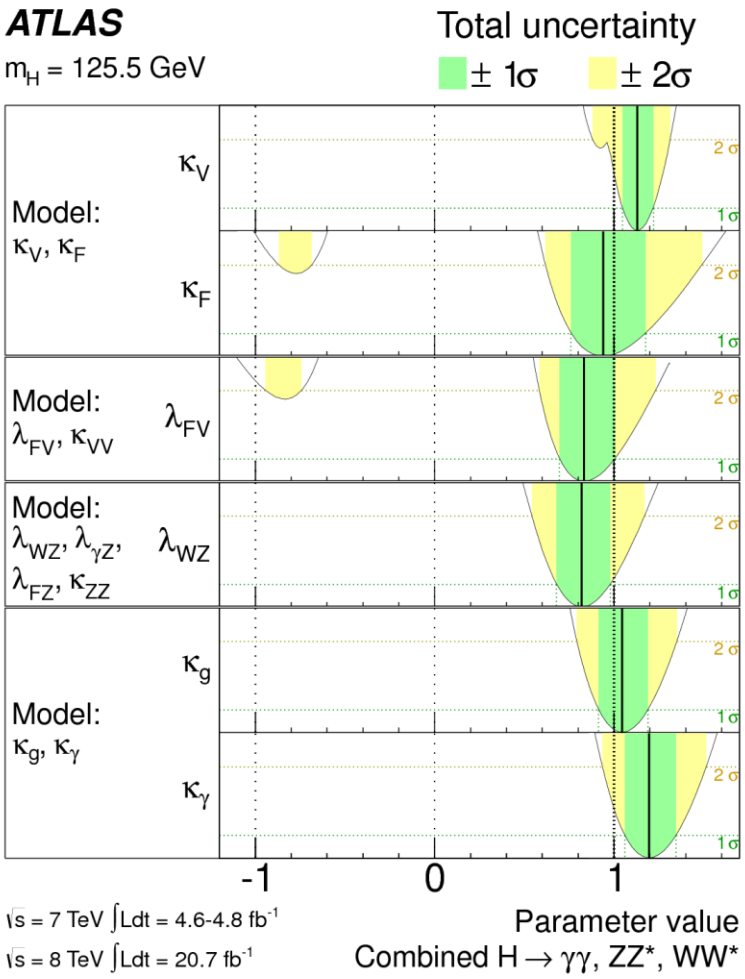


$\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.4^{+0.4}_{-0.3}(stat)^{+0.6}_{-0.4}(syst)$ in agreement with the SM

3.3 σ evidence in the VBF production (when μ_{VH} is profiled and not treated together with μ_{VBF})

The sharp lower edge of the H→ZZ(*)→ 4l contours is due to the small number of events in this channel and the requirement of a positive pdf

Coupling Strength Studies



$\sigma^*BR(ii \rightarrow H \rightarrow ff) = \frac{\sigma_i \Gamma_f}{\Gamma_H}$, $\quad \mu = \frac{\sigma_{obs}}{\sigma_{SM}} = \frac{k_i^2 k_f^2}{k_H^2}$

k is a scale factor for a SM coupling

$\lambda_{XY} = k_X/k_Y$

Several models can be tested:

- *Couplings to fermions and bosons*
- *Custodial symmetry* (in the SM $\lambda_{W/Z} = k_W/k_Z=1$)
- *Production and decay loops constrains* (testing for BSM heavy particles)

No significant deviation from the SM prediction is observed

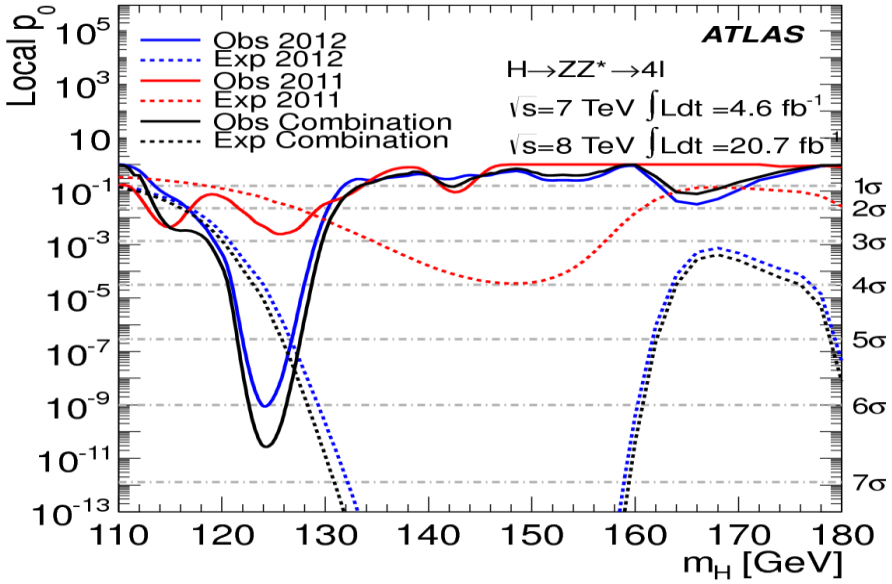
Summary

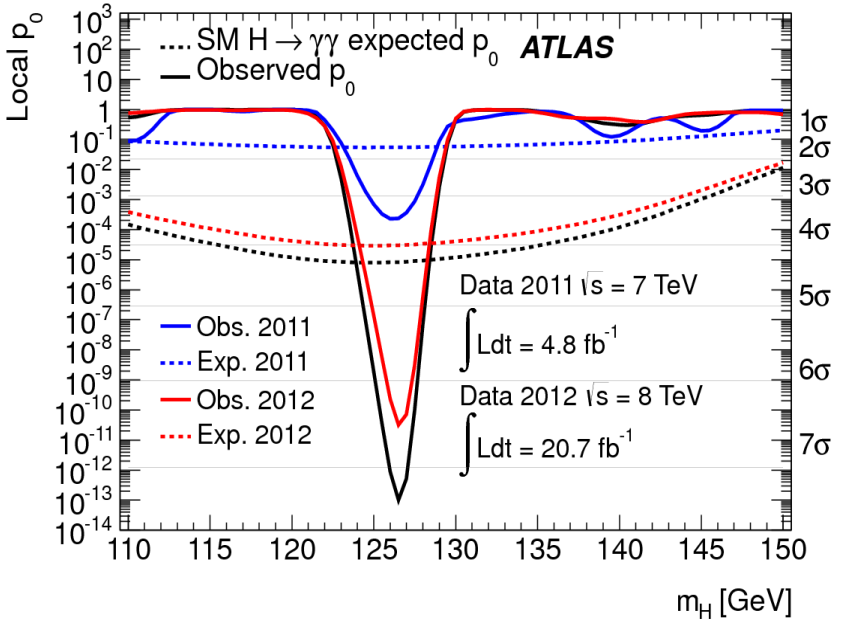
- Run I of the LHC delivered a significant amount of data, allowing the discovery of the Higgs Boson
- The current observations are consistent with the Standard Model predictions and no new physics sign found
- Final results from Run I will come soon and Run II will challenge the Standard Model predictions with more precise measurements

the discovery was just the beginning!

Back - up Slides

Local p_0 value





p_0 is the probability of obtaining a result as signal like if no signal is present

Systematics

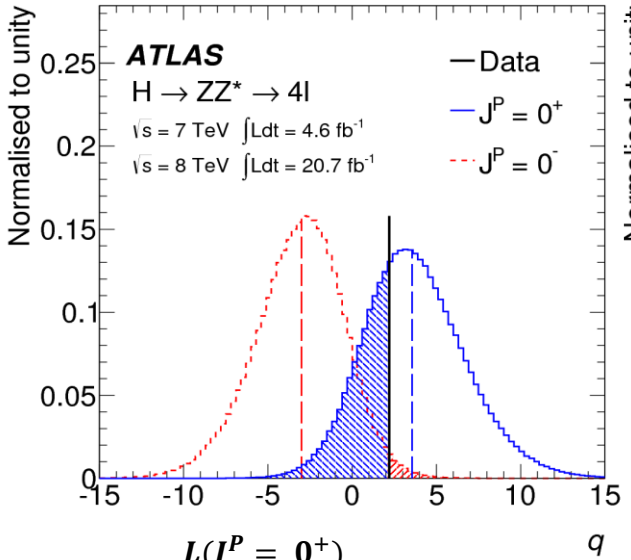
Table 4: For $m_H = 125$ GeV and the 8 TeV data analysis, the impact of the main sources of systematic uncertainty specific to the $H \to \gamma\gamma$ channel on the signal yield, event migration between categories and mass measurement and resolution. Uncertainties common to all channels are listed in Table 1. The ± and ∓ signs indicate anticorrelations between categories. H→γγ

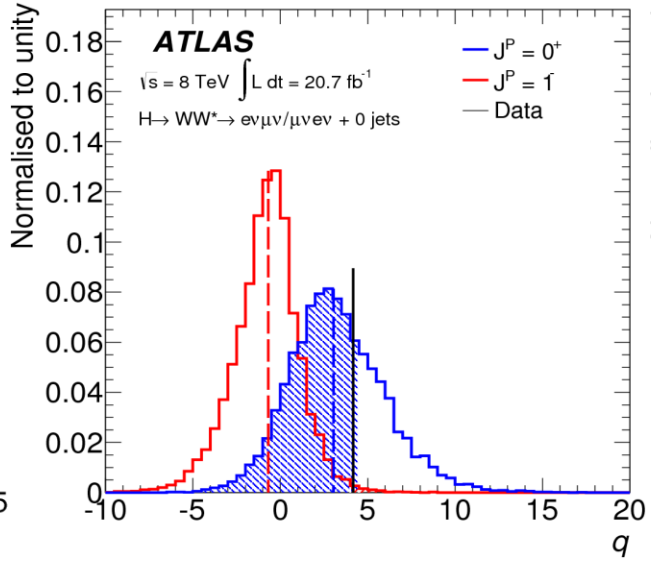
Source	Uncertainty (%)
	on signal yield
Trigger	±0.5
Photon identification	±2.4
Isolation	±1.0
Photon energy scale	±0.25
ggF (theory), tight high-mass two-jet cat.	±48
ggF (theory), loose high-mass two-jet cat.	±28
ggF (theory), low-mass two-jet cat.	±30
Impact of background modelling	±(2 – 14), cat.-dependent
	on category population (migration)
Material modelling	−4 (unconv), +3.5 (conv)
p_T modelling	±1 (low-p_{Tt}), ∓(9 – 12) (high-p_{Tt}, jets), ±(2 – 4) (lepton, E_T^{miss})
$\Delta\phi_{\gamma\gamma,jj}$, η^* modelling in ggF	±(9 – 12), ±(6 – 8)
Jet energy scale and resolution	±(7 – 12) (jets), ∓(0 – 1) (others)
Underlying event two-jet cat.	±4 (high-mass tight), ±8 (high-mass loose), ±12 (low-mass)
E_T^{miss}	±4 (E_T^{miss} category)
	on mass scale and resolution
Mass measurement	±0.6, cat.-dependent
Signal mass resolution	±(14 – 23), cat.-dependent

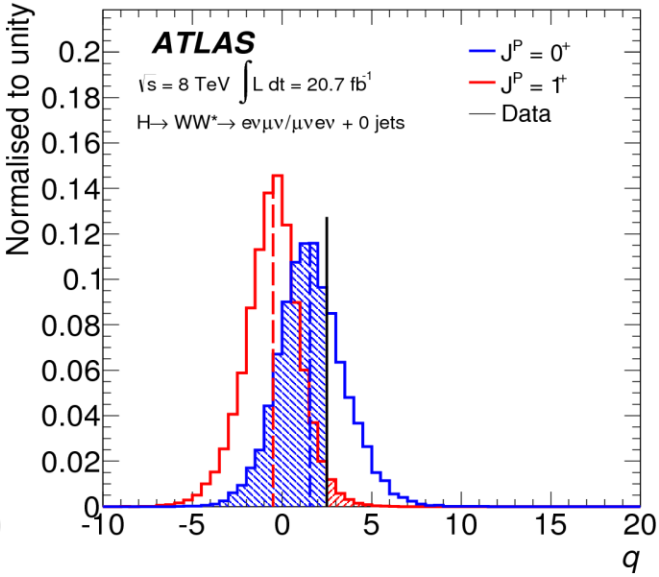
Table 6: For $m_H = 125$ GeV and the 8 TeV data analysis, the impact of the main sources of systematic uncertainty specific to the $H \to ZZ^*$ channel on the signal yield, estimated reducible background, event migration between categories and mass measurement. Uncertainties common to all channels are listed in Table 1. H→ZZ(*)→4l

Source	Uncertainty (%)			
Signal yield	4μ	$2\mu 2e$	$2e2\mu$	$4e$
Muon reconstruction and identification	±0.8	±0.4	±0.4	-
Electron reconstruction and identification	-	±8.7	±2.4	±9.4
Reducible background (inclusive analysis)	±24	±10	±23	±13
Migration between categories				
ggF/VBF/VH contributions to VBF–like cat.		±32/11/11		
ZZ^* contribution to VBF–like cat.		±36		
ggF/VBF/VH contributions to VH–like cat.		±15/5/6		
ZZ^* contribution to VH–like cat.		±30		
Mass measurement	4μ	$2\mu 2e$	$2e2\mu$	$4e$
Lepton energy and momentum scale	±0.2	±0.2	±0.3	±0.4

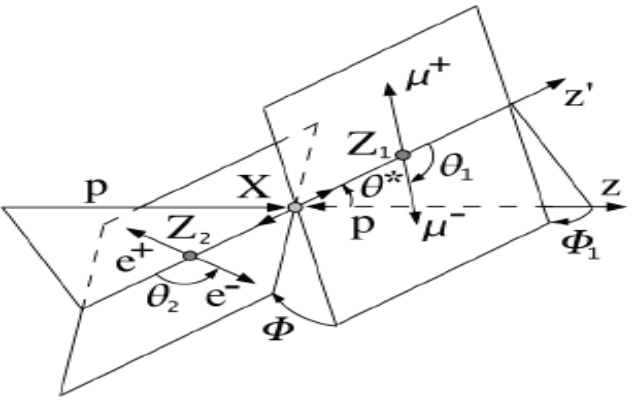
Spin & Parity

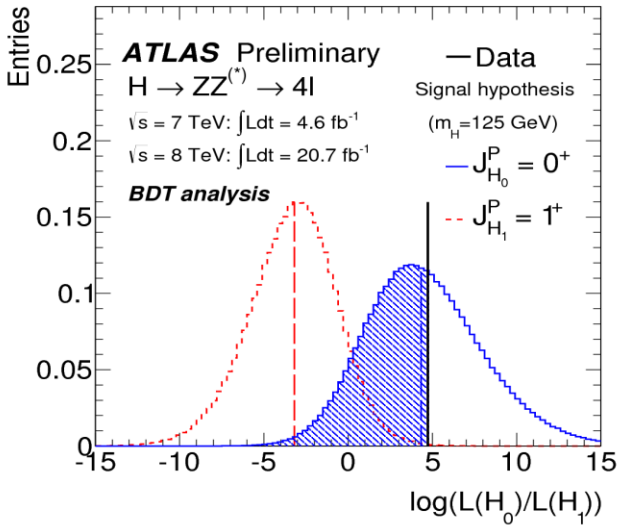


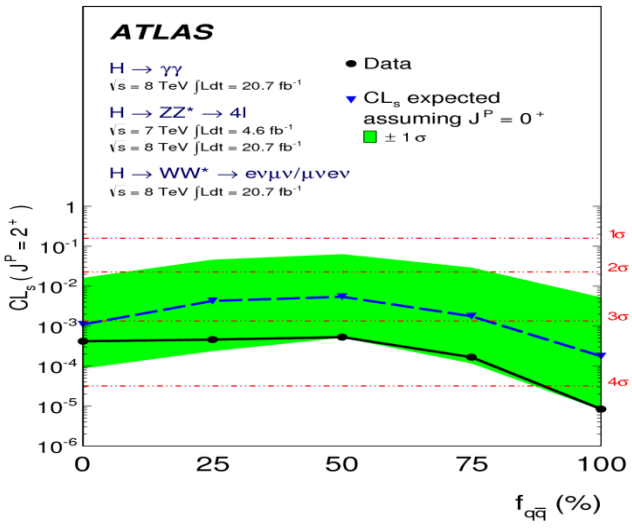




$$q = \log \frac{L(J^P = 0^+)}{L(J^P \neq 0^+)}$$







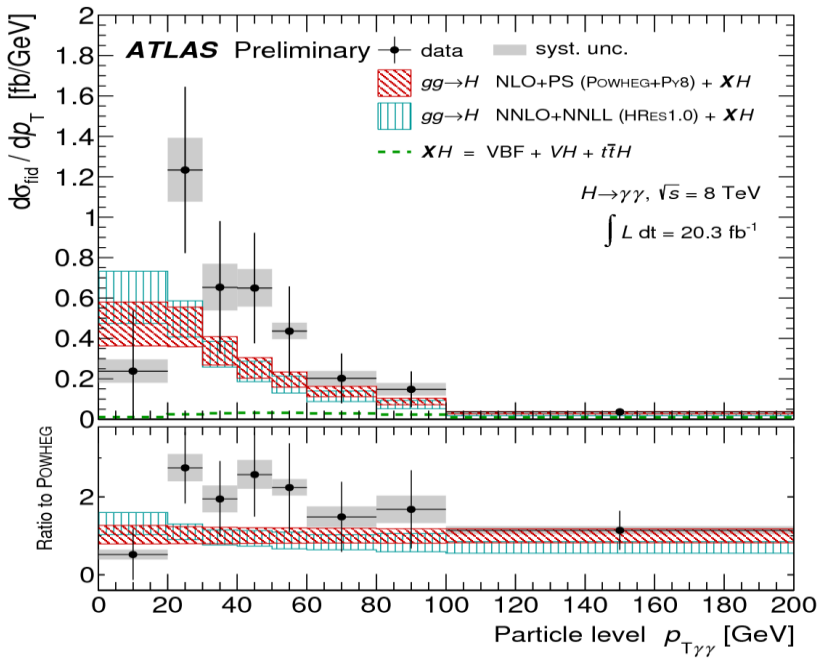
Differential Cross Section (H→γγ)

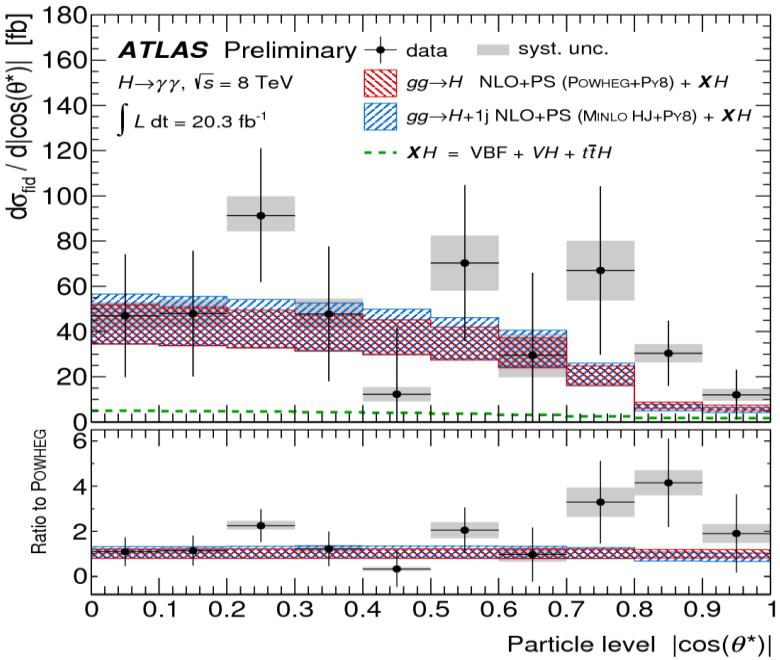
- Observables: *$p_T^{\gamma\gamma}$ and rapidity $|y^{\gamma\gamma}|$ of the Higgs boson, the helicity angle $|\cos\theta^*|$ between γ's, N_{jets}, leading jet p_T, the azimuthal angle between leading-subleading jet $\Delta\varphi_{jj}$, $P_T^{\gamma\gamma jj}$*

- The variables presented describe the fundamental kinematic properties of the Higgs boson, probe its spin and parity, and test the theoretical description of QCD in its production

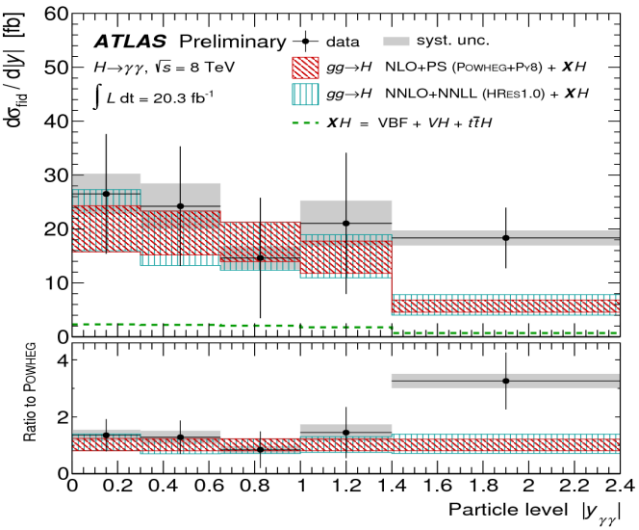
- **Unbinned fit of the diphoton invariant mass is performed simultaneously in all bins**, for each observable

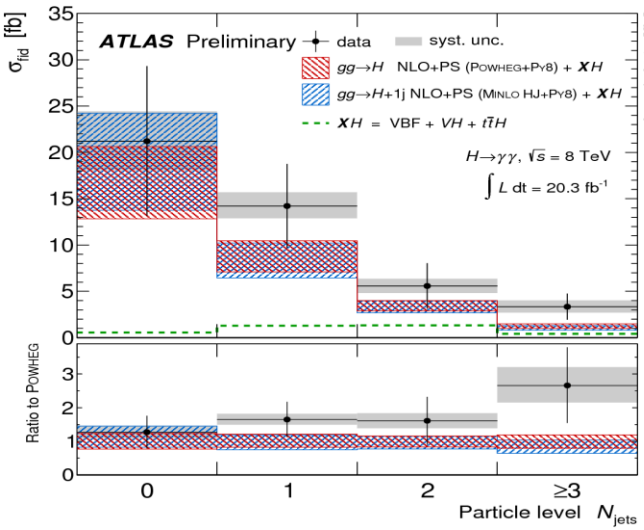
- Within the uncertainties, no significant deviation from the SM expectation is observed

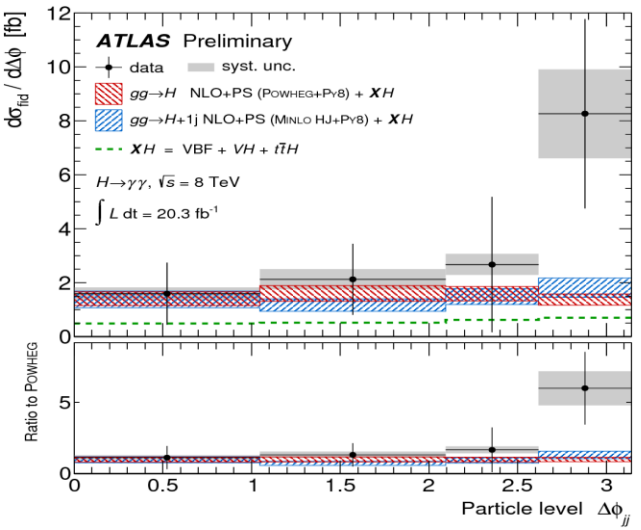


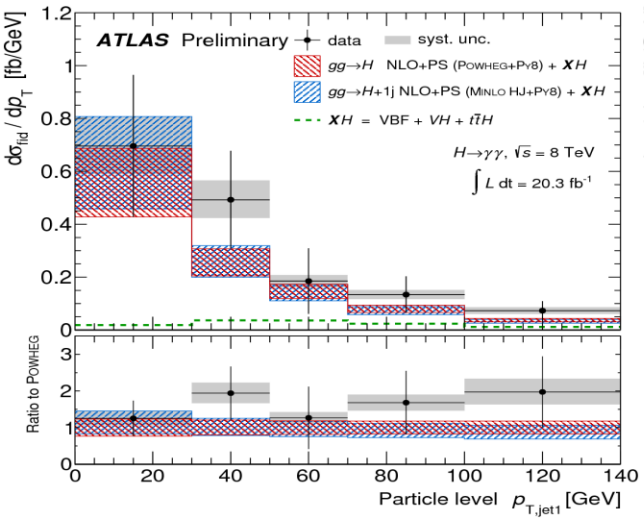


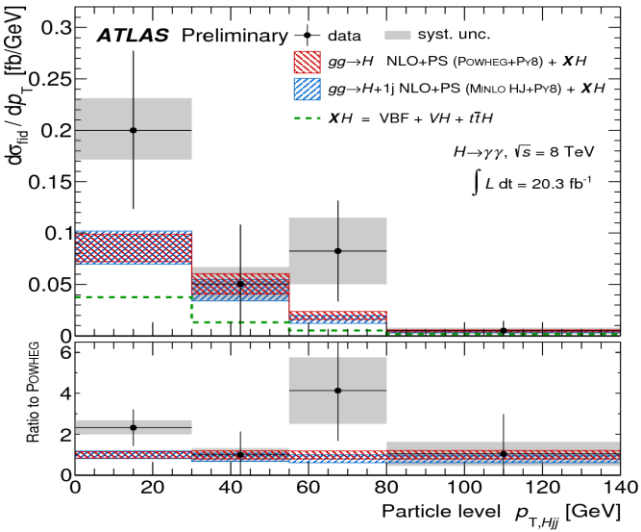
H→γγ Differential Cross Section



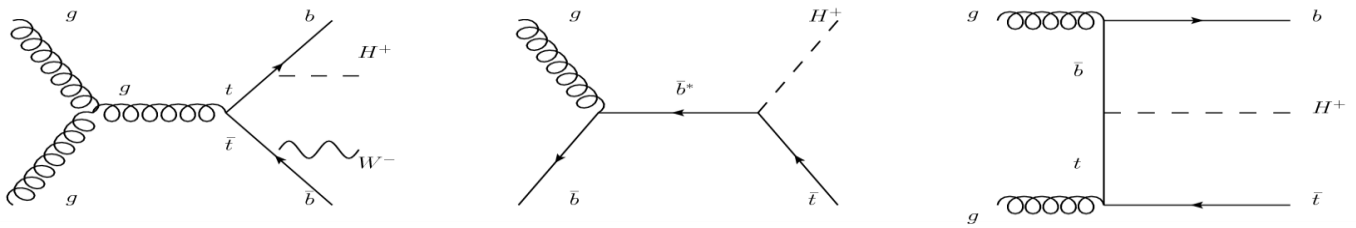








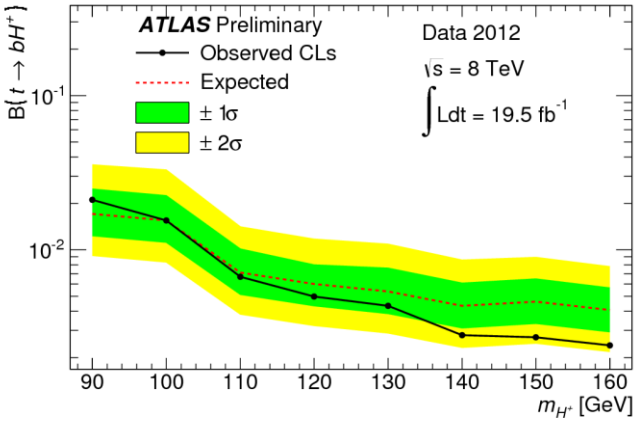
$H^{\pm} \rightarrow \tau^{\pm}$+jets

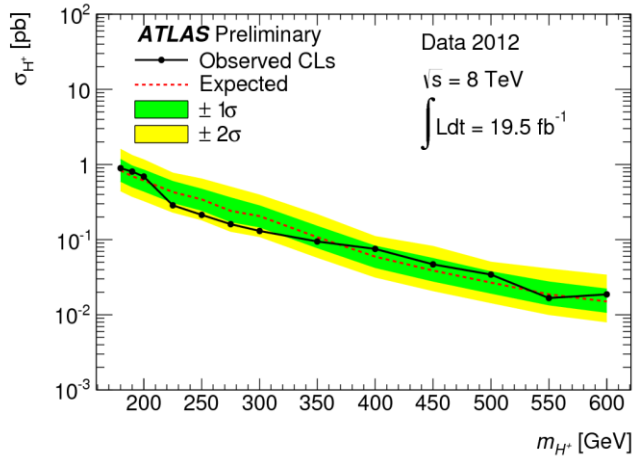


- $H^{\pm}$ bosons are predicted by several non-minimal Higgs scenarios **beyond the SM**, ex. models containing Higgs triplets , 2HDM
- <u>Events selected</u>: large number of jets , at least one tagged, large E_T^{miss},discriminant

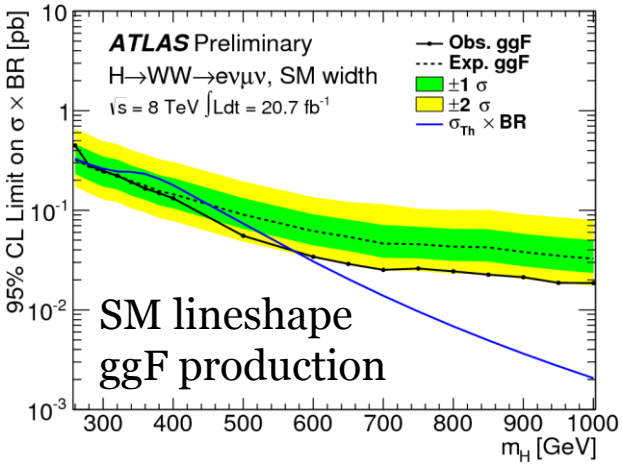
$$m_T = \sqrt{2p_T^{\tau} E_T^{miss}(1 - cos\Delta\varphi_{\tau,miss})}$$

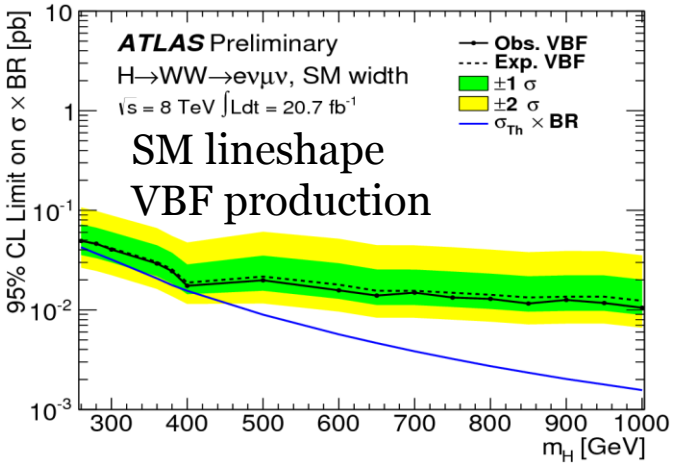
Results consistent with the SM

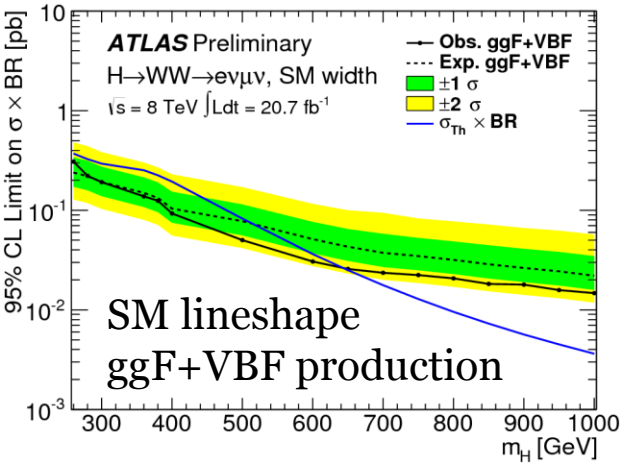




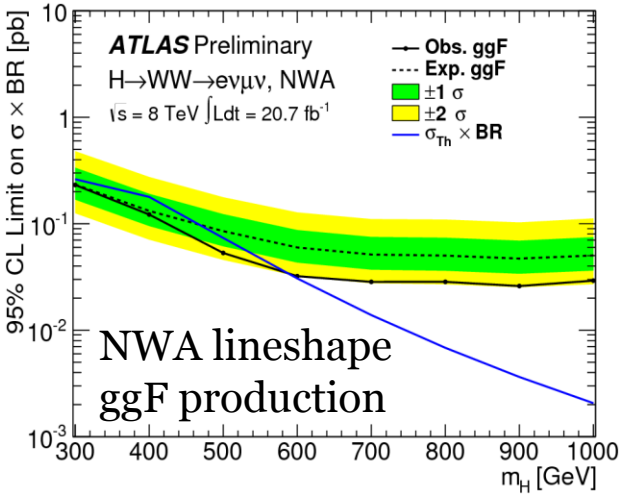
High Mass H→WW→lνlν

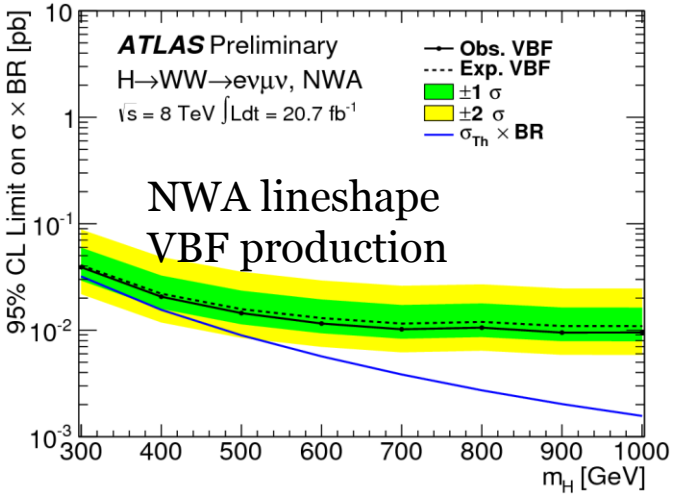


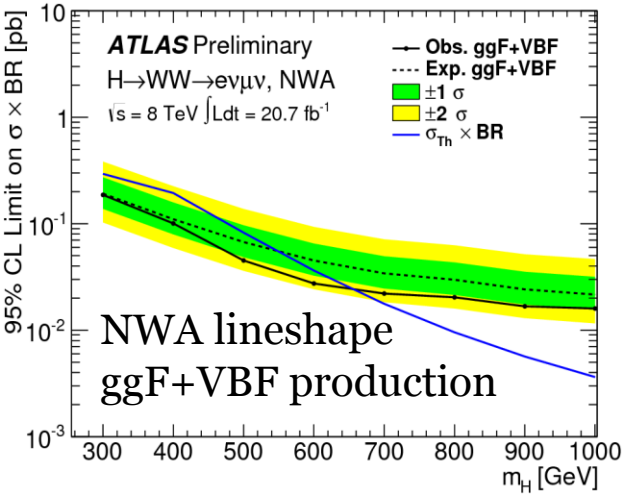




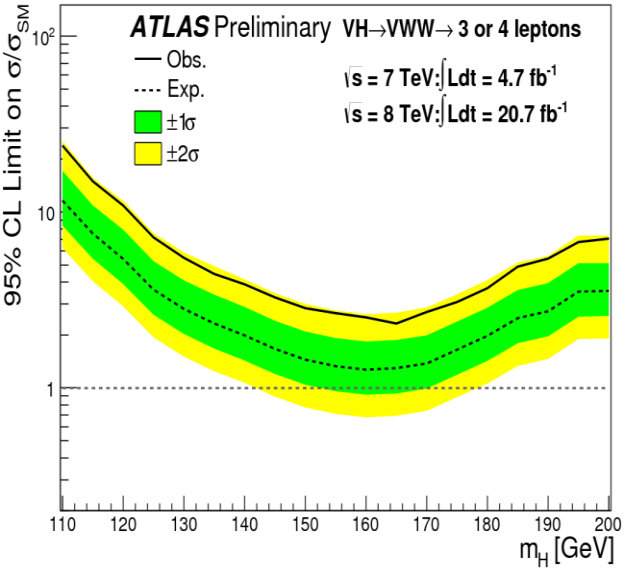
Narrow Width Approximation (NWA): 1 GeV wide Breit-Wigner lineshape

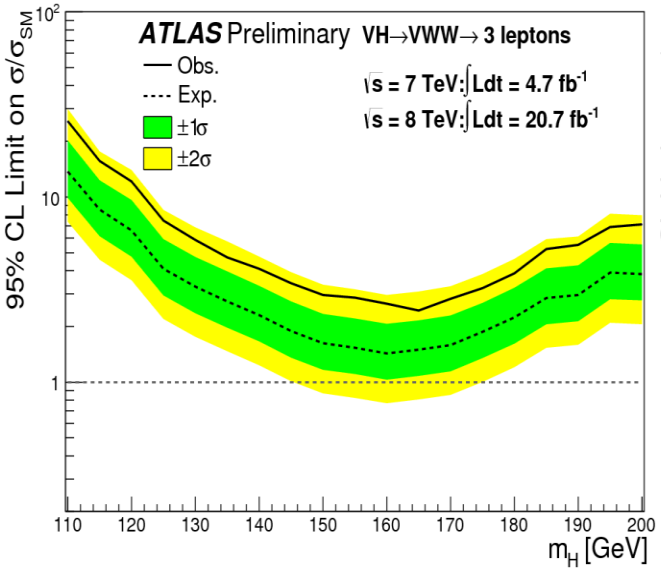


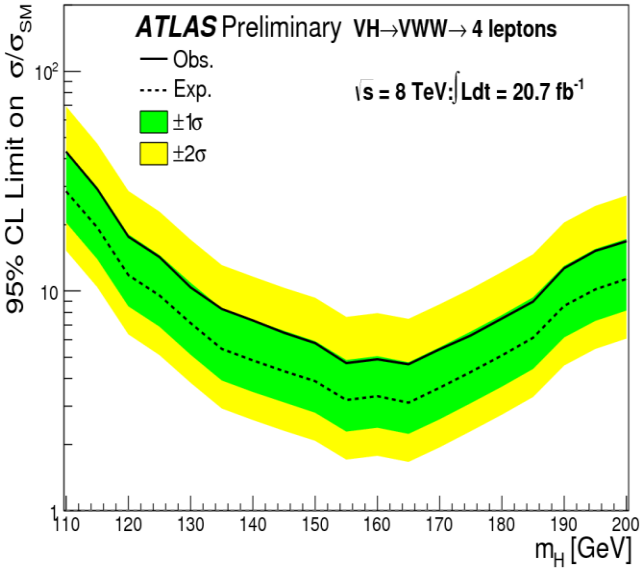




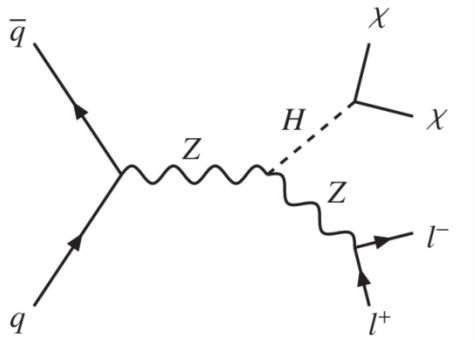
WH→WWW(*)→lνlνlν & ZH→ZWW(*)→lllνlν





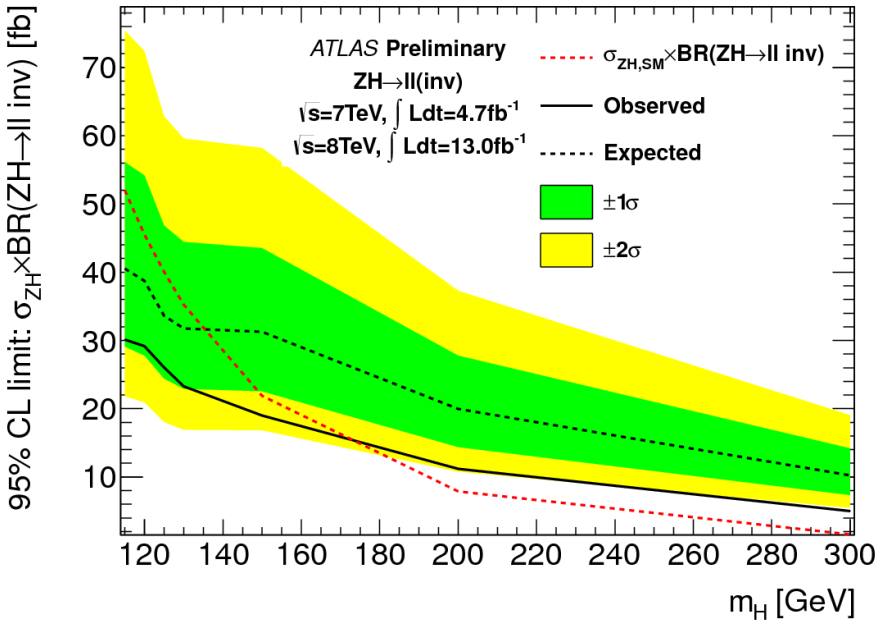


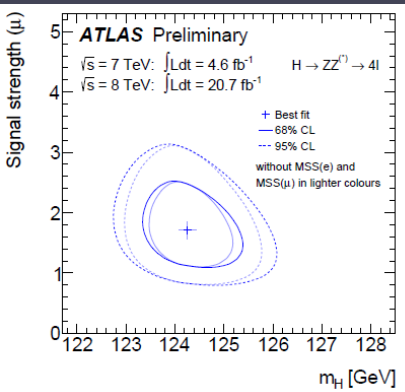
ZH Invisible



- Some SM extensions allow decay to stable or long-lived particles that interact with the Higgs boson
- **Search for excess in the ll+MET**
- Background: *ZZ→llvv, WW, ttbar, Wt, inclusive Z or W, SM H→ZZ(*)→llvv and H→WW(*)*
- This measurement is sensitive to enhancements of the invisible branching fraction, ex. decays to dark matter particles

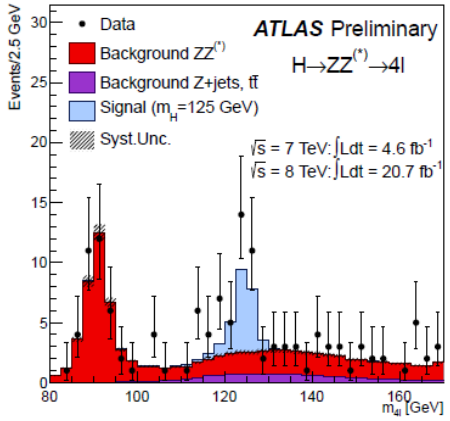
No deviation from the SM is observed

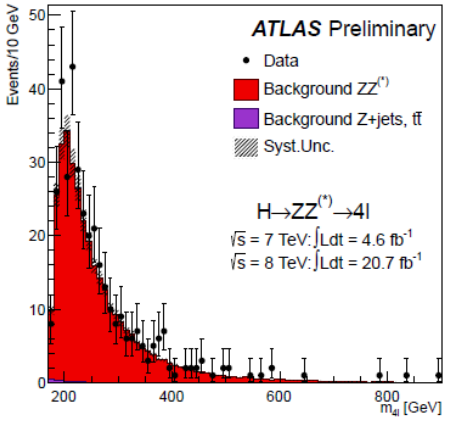




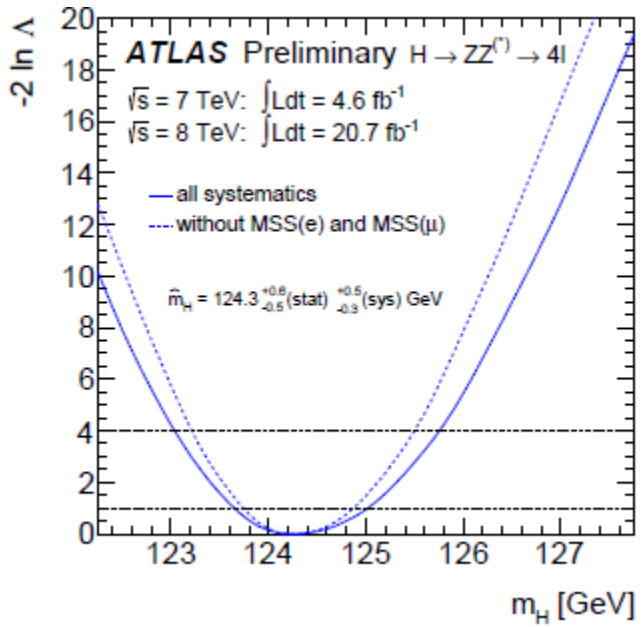
H→ZZ(*)→4l

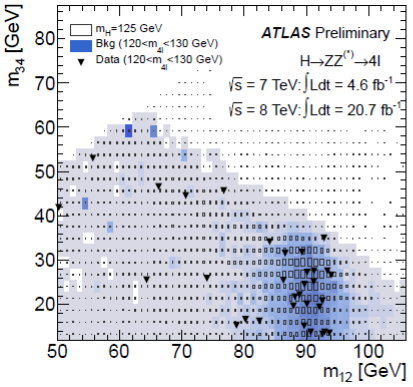
The mass distributions are described using smooth, non-parametric, unbinned estimates of the relevant probability density functions obtained from the simulations. The form of the background varied from the nominal to allow shape systematics.

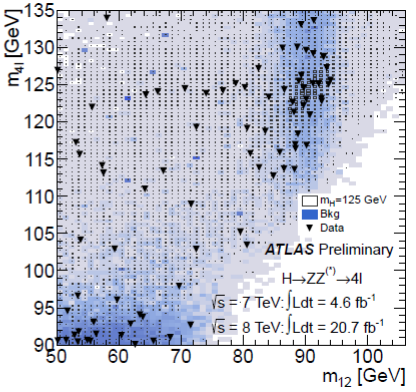




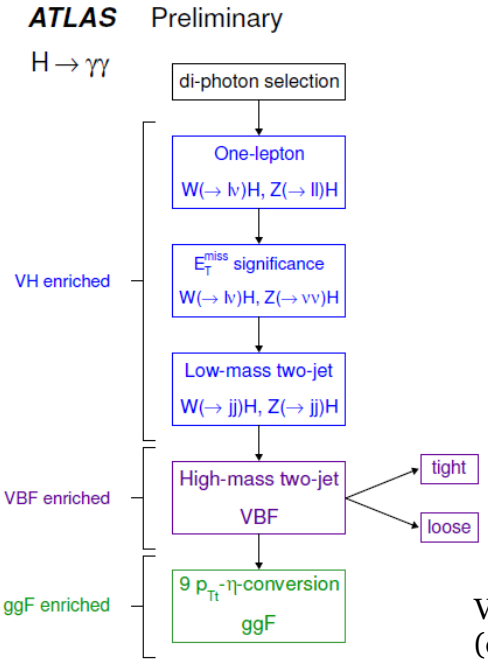
data set	observed			expected	
	min p_0	significance $[\sigma]$	$m_H(p_0)$	min $p_0(m_H)$	significance $[\sigma]$
$\sqrt{s} = 7$ TeV	2.5×10^{-3}	2.8	125.6 GeV	3.5×10^{-2}	1.8
$\sqrt{s} = 8$ TeV	8.8×10^{-10}	6.0	124.1 GeV	2.8×10^{-5}	4.0
combined	2.7×10^{-11}	6.6	124.3 GeV	5.7×10^{-6}	4.4

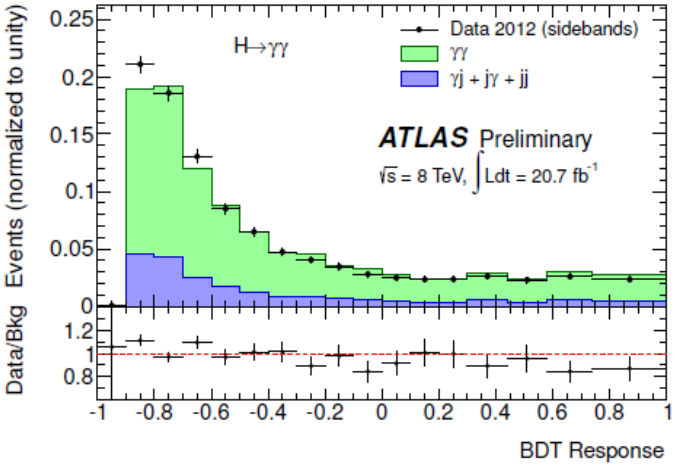


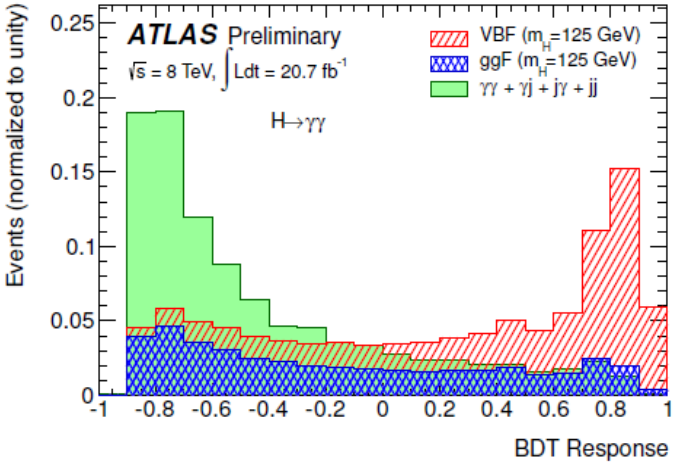




H→γγ

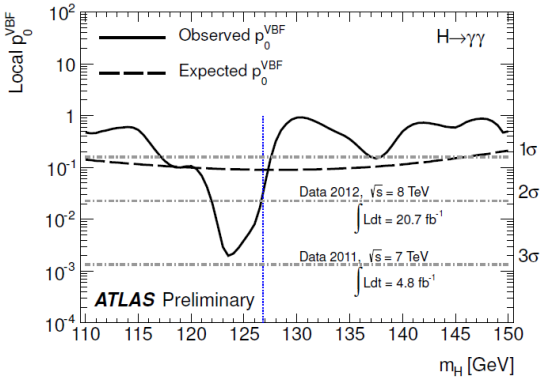


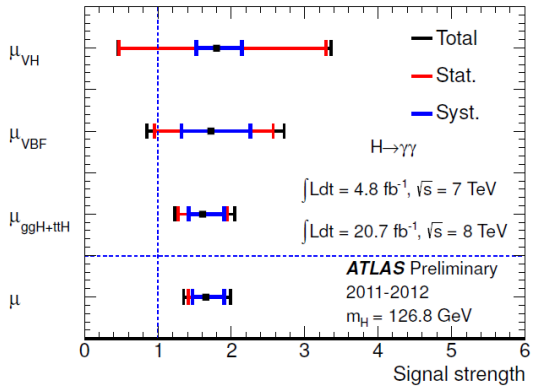




VBF BDT response to the data in the signal sidebands (excluding 120-130 GeV region) and to the expected background after selection cuts, normalized to unit

- The invariant mass distribution of the background is parameterized with analytic functions
- The main sources of uncertainties on the mass measurement arise from the extrapolation of the photon energy scale from the Z→e⁺e- electron energy scale (0.3%), the material modeling (0.3%) and the presampler energy scale (0.1%). Total 0.45% (0.6 GeV).



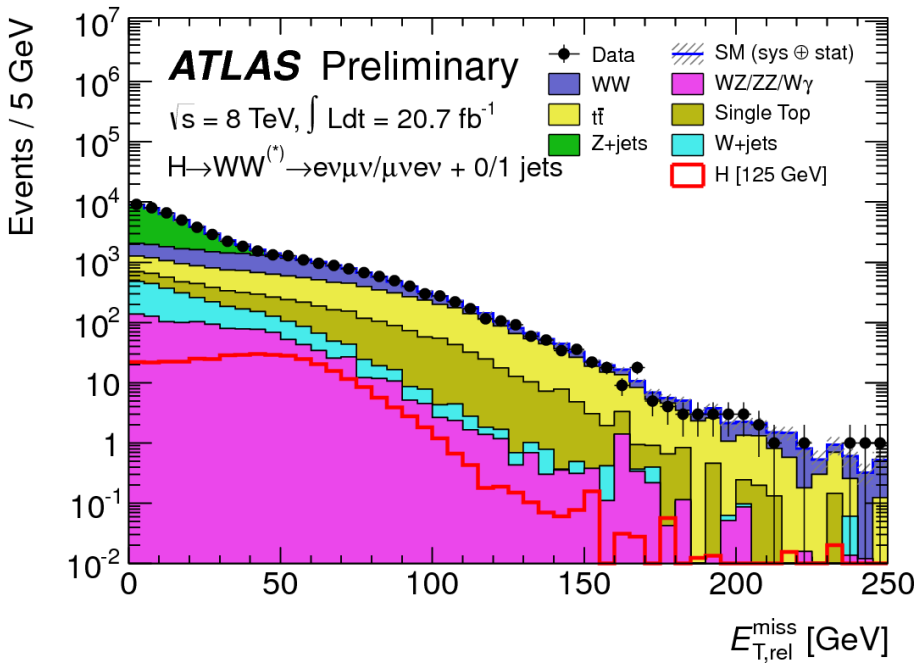


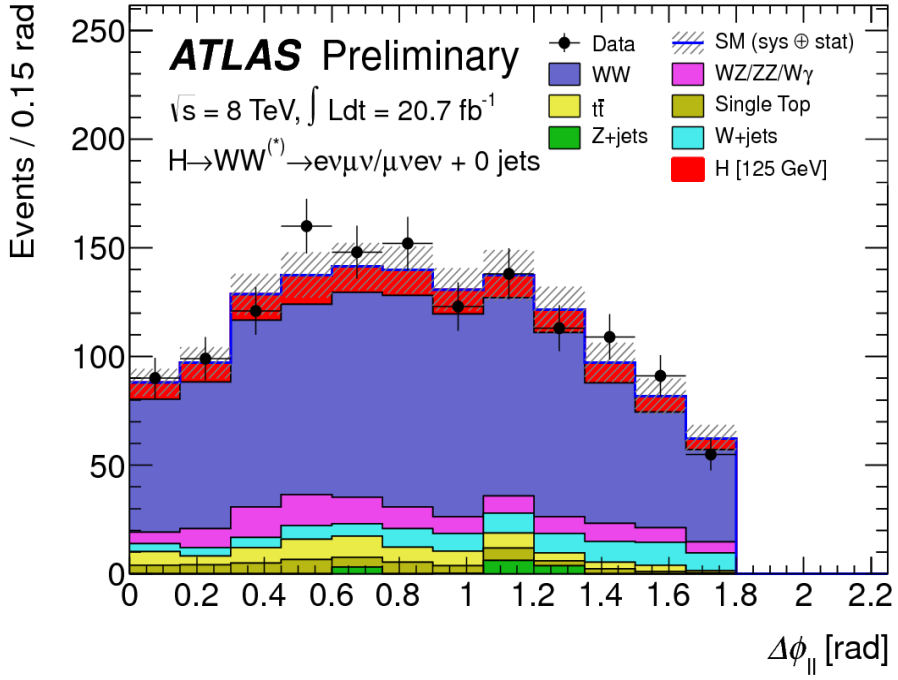
$$\mu_{\mathrm{ggF+ttH}} \times B/B_{\mathrm{SM}} = 1.6^{+0.3}_{-0.3}(\mathrm{stat})^{+0.3}_{-0.2}(\mathrm{syst})$$

$$\mu_{\mathrm{VBF}} \times B/B_{\mathrm{SM}} = 1.7^{+0.8}_{-0.8}(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})$$

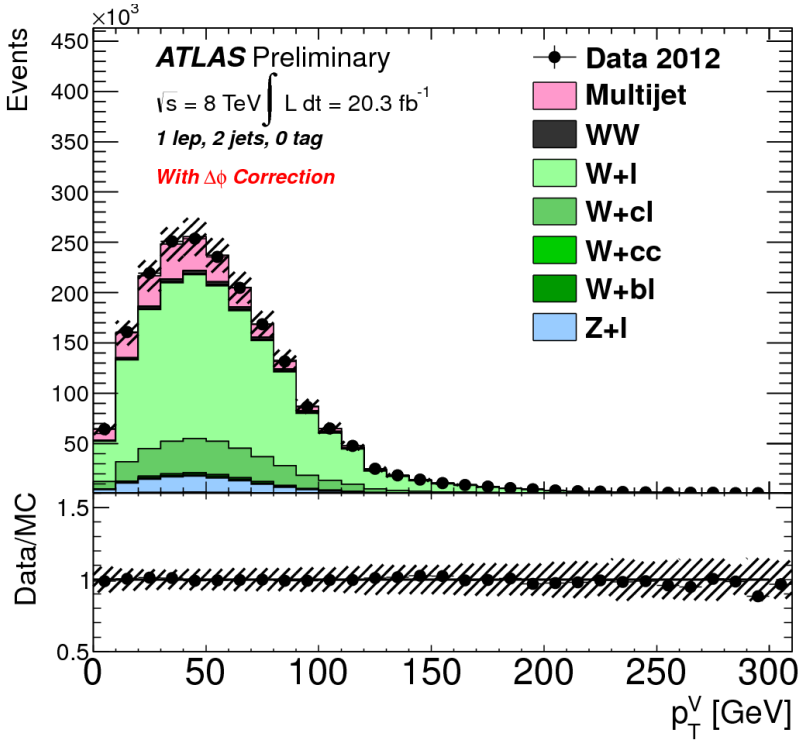
$$\mu_{\mathrm{VH}} \times B/B_{\mathrm{SM}} = 1.8^{+1.5}_{-1.3}(\mathrm{stat})^{+0.3}_{-0.3}(\mathrm{syst})$$

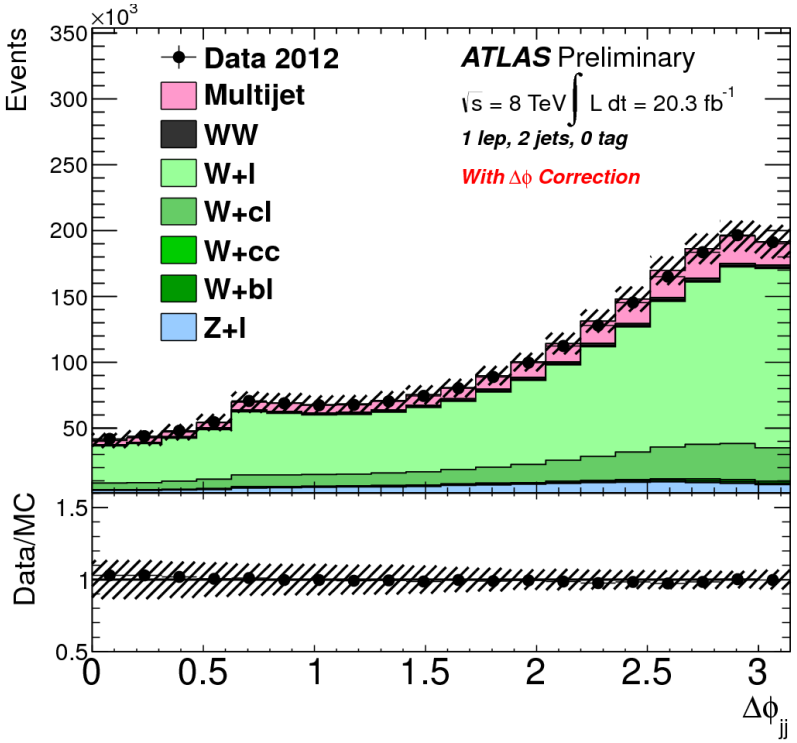
H→WW(*)→lνlν


ATLAS Preliminary
√s = 8 TeV, ∫ Ldt = 20.7 fb-1
H→WW(*)→eνμν/μνeν + 0/1 jets
Data
WW
tt̄
Z+jets
SM (sys ⊕ stat)
WZ/ZZ/Wγ
Single Top
W+jets
H [125 GeV]
Events / 5 GeV
E^miss_T,rel [GeV]


ATLAS Preliminary
√s = 8 TeV, ∫ Ldt = 20.7 fb-1
H→WW(*)→eνμν/μνeν + 0 jets
Data
WW
tt̄
Z+jets
SM (sys ⊕ stat)
WZ/ZZ/Wγ
Single Top
W+jets
H [125 GeV]
Events / 0.15 rad
Δφ_ll [rad]

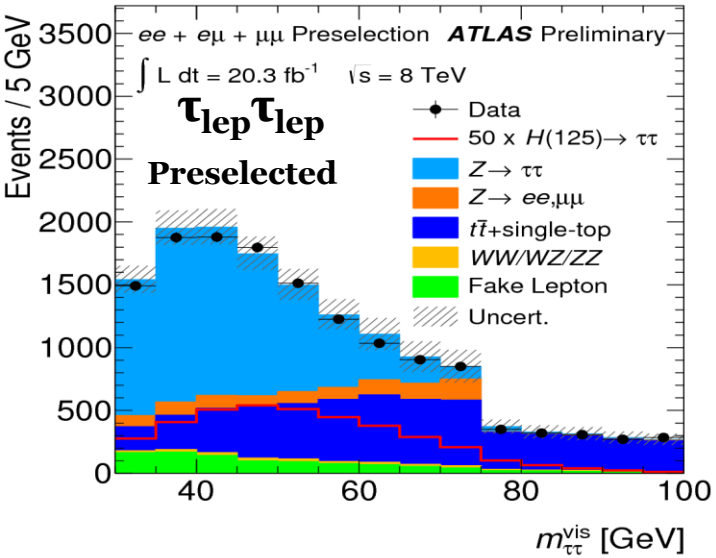
H→bb

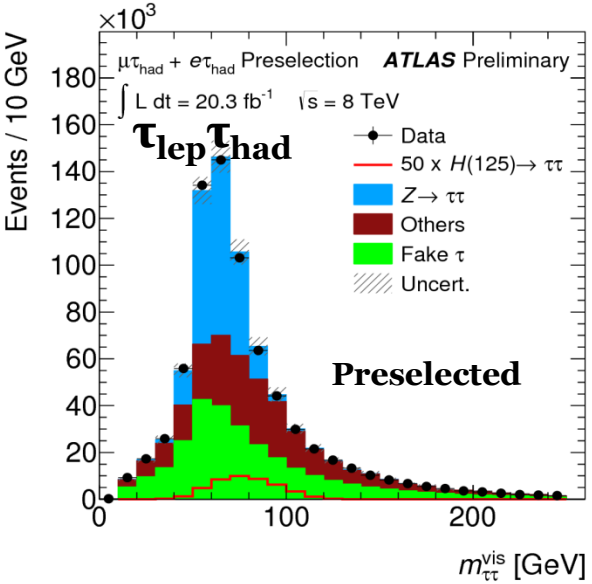


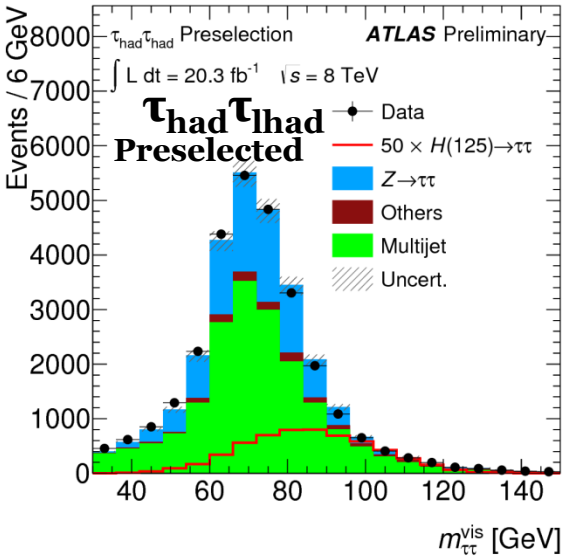


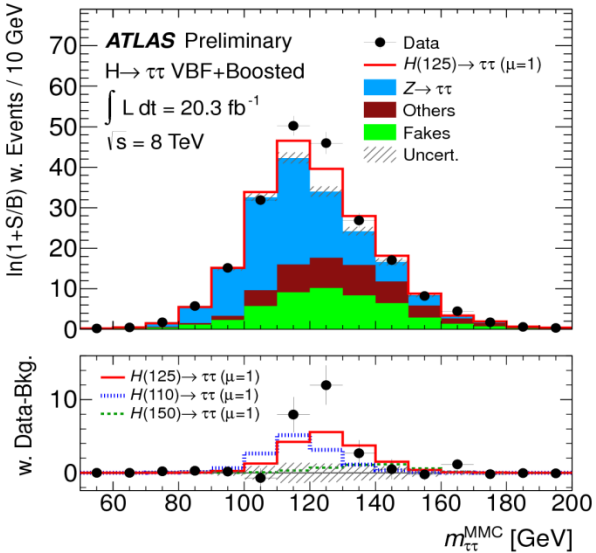
Reweighted by a simple linear function

H→ττ


ee + eμ + μμ Preselection ATLAS Preliminary
∫ L dt = 20.3 fb-1 √s = 8 TeV
τlepτlep
Preselected
Data
50 × H(125)→ ττ
Z→ ττ
Z→ ee,μμ
tt̄+single-top
WW/WZ/ZZ
Fake Lepton
Uncert.
Events / 5 GeV
m_ττ^vis [GeV]

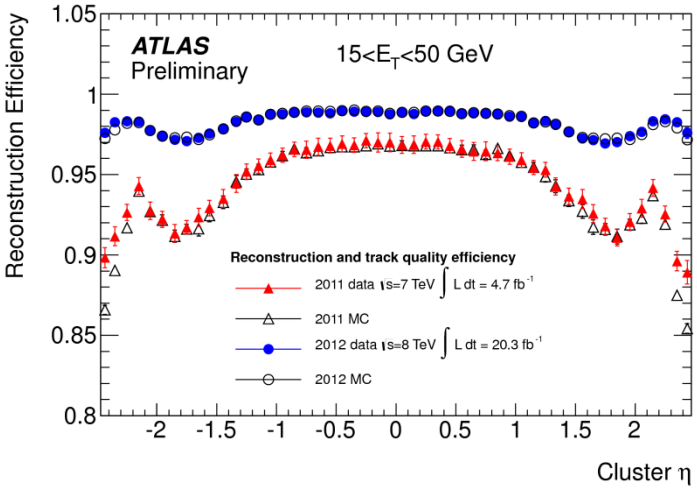

μτhad + eτhad Preselection ATLAS Preliminary
∫ L dt = 20.3 fb-1 √s = 8 TeV
τlepτhad
Preselected
Data
50 × H(125)→ ττ
Z→ ττ
Others
Fake τ
Uncert.
×10^3
Events / 10 GeV
m_ττ^vis [GeV]

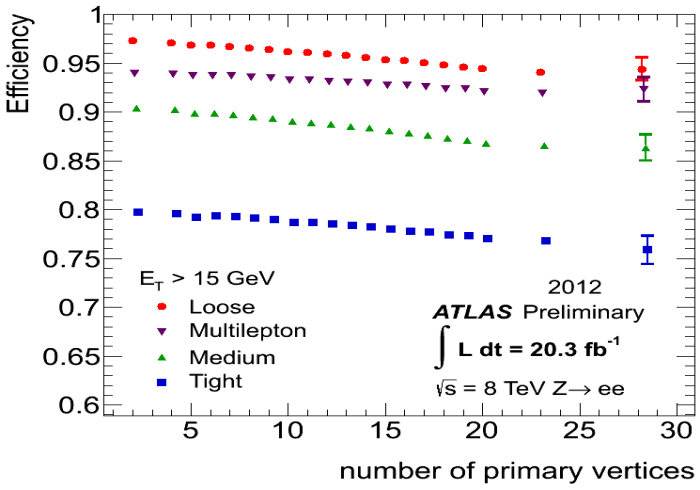

τhadτhad Preselection ATLAS Preliminary
∫ L dt = 20.3 fb-1 √s = 8 TeV
τhadτlhad
Preselected
Data
50 × H(125)→ττ
Z→ττ
Others
Multijet
Uncert.
Events / 6 GeV
m_ττ^vis [GeV]


ATLAS Preliminary
H→ ττ VBF+Boosted
∫ L dt = 20.3 fb-1
√s = 8 TeV
Data
H(125)→ ττ (μ=1)
Z→ ττ
Others
Fakes
Uncert.
ln(1+S/B) w. Events / 10 GeV
H(125)→ ττ (μ=1)
H(110)→ ττ (μ=1)
H(150)→ ττ (μ=1)
w. Data-Bkg.
m_ττ^MMC [GeV]

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Combined_Performance_Groups_Simu

Electrons

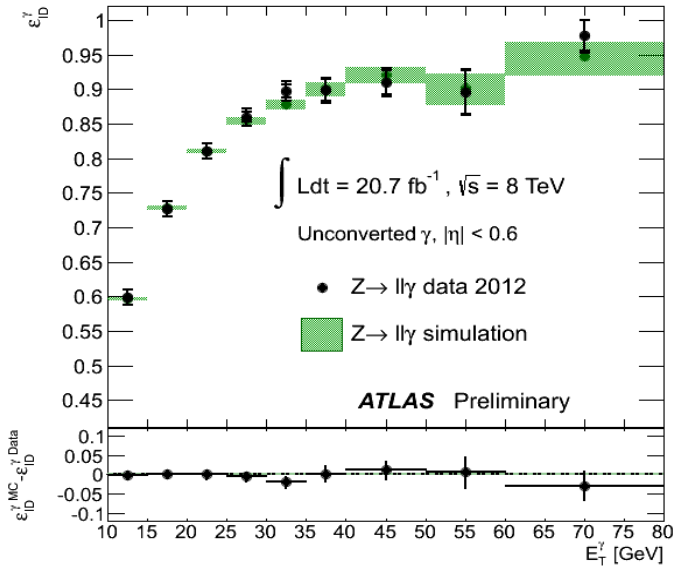


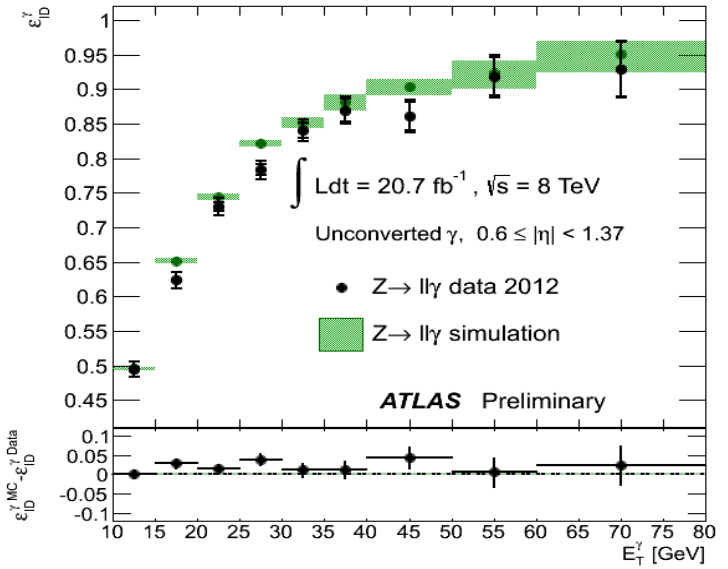


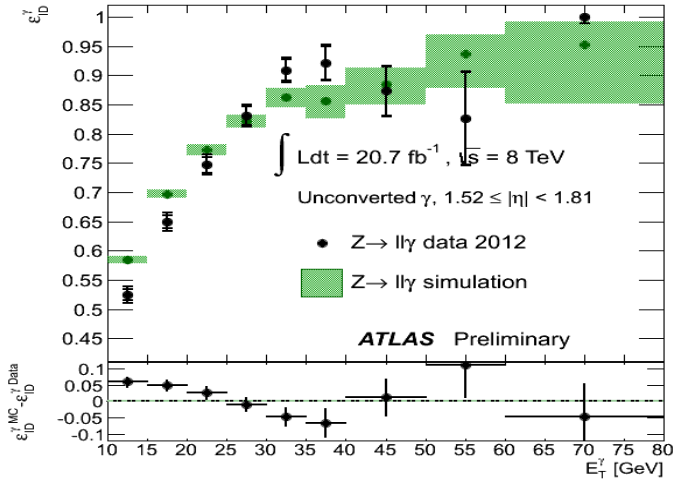
Extracted efficiencies using the tag and probe method

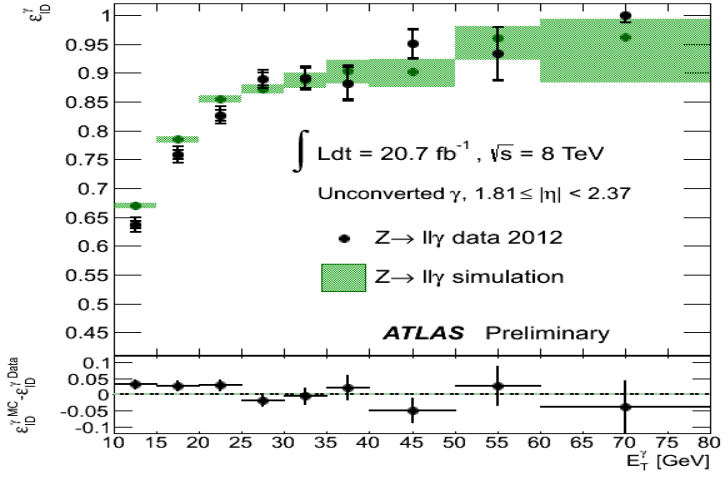
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Combined_Performance_Groups_Simu

Photons









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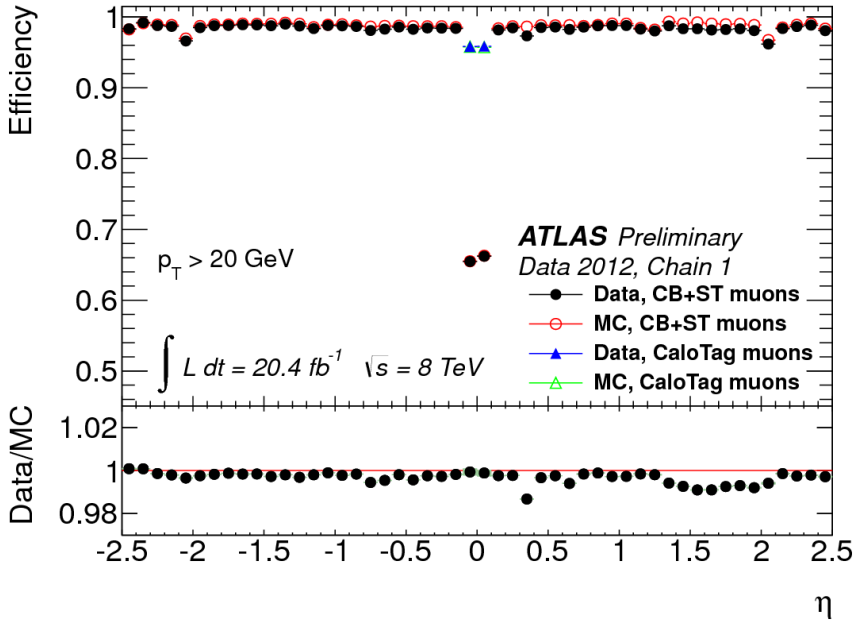

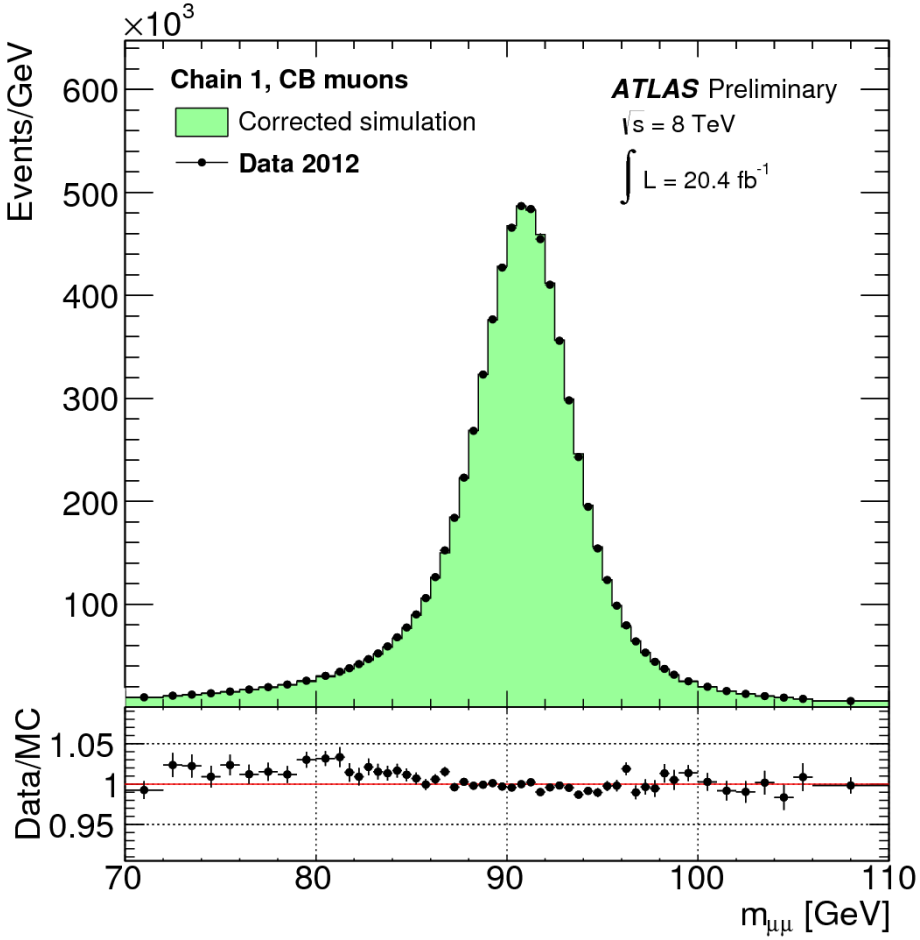

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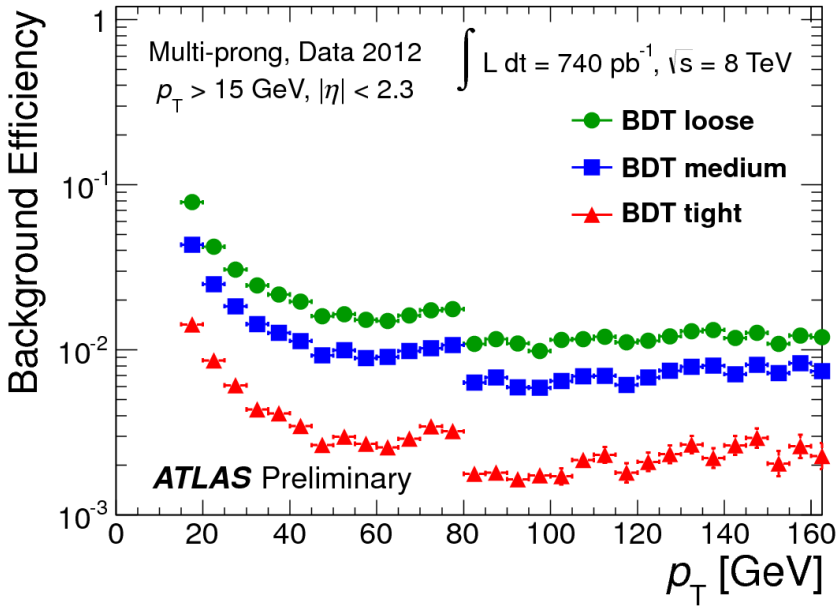

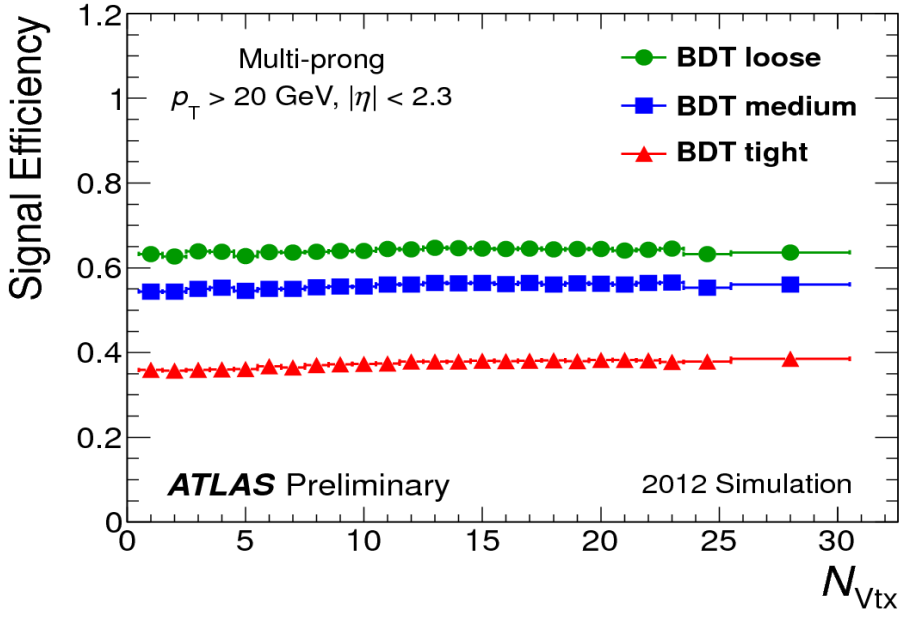

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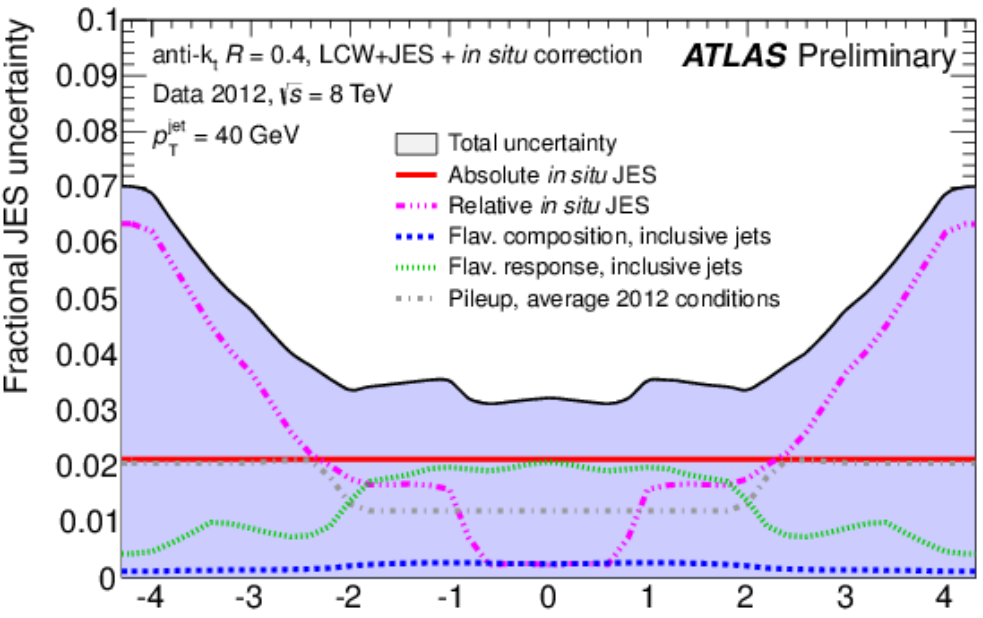
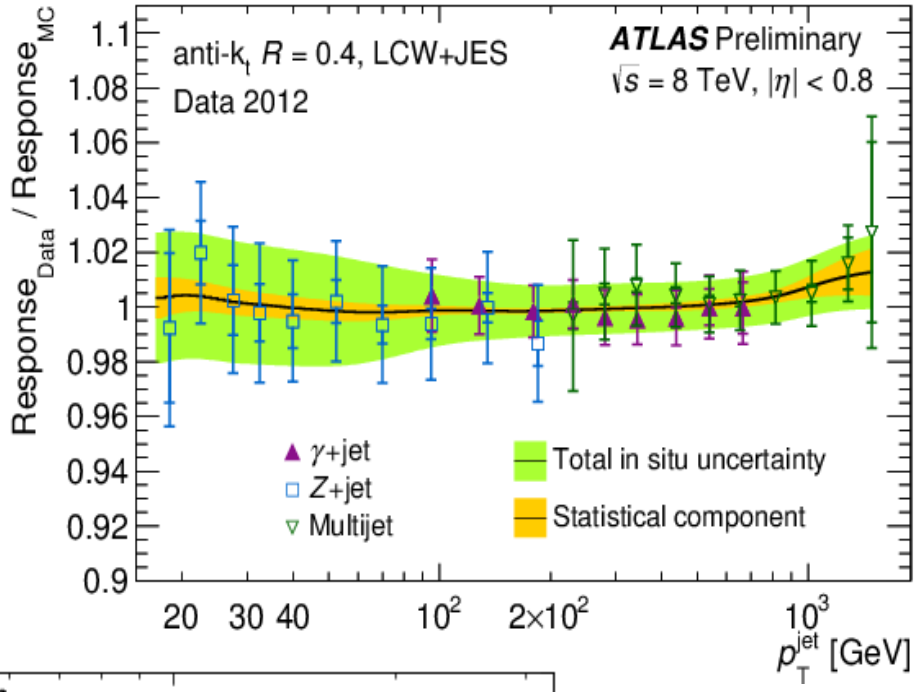
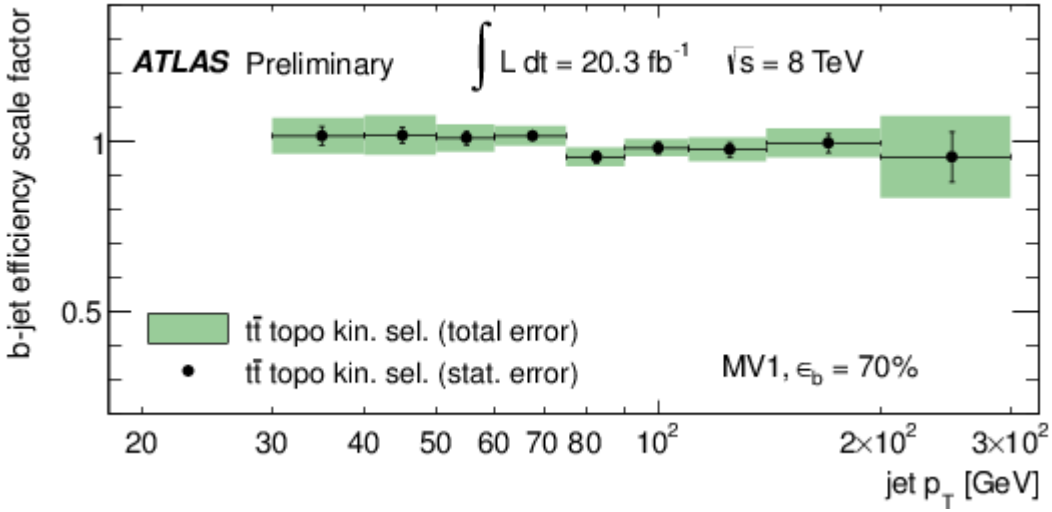
Jets







LCW: local cluster reweighting