Review of results on Higgs searches from the ATLAS experiment

Camila Rangel Smith

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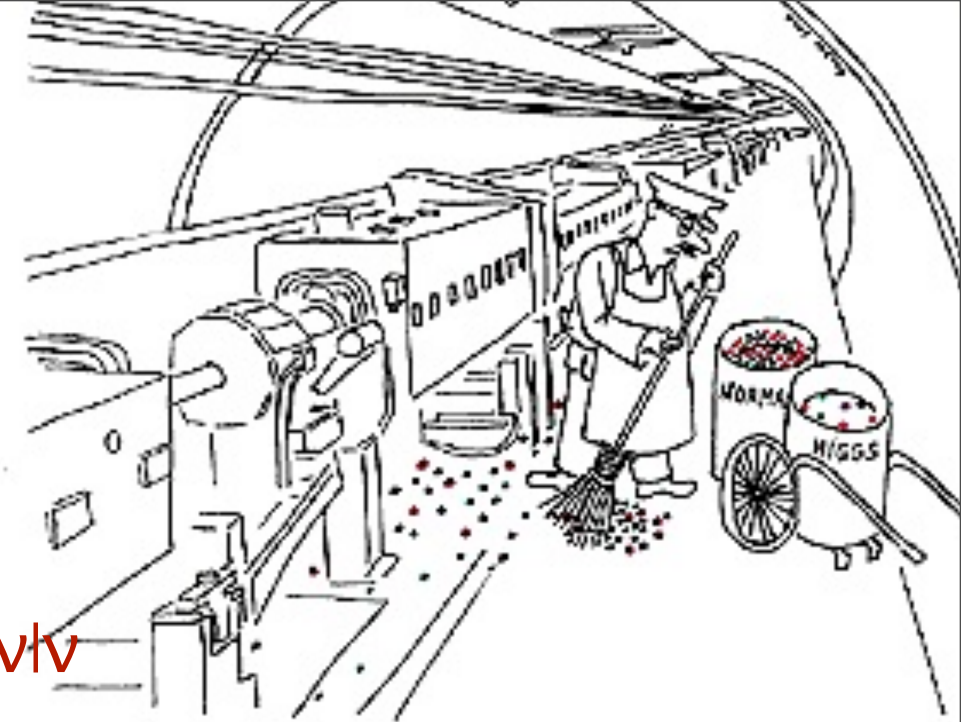
Nobel prize to Englert & Higgs!

"The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Outline



1. Observation of a Higgs boson

$H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow WW \rightarrow l\nu l\nu$

2. Properties measurements:

- Combination of $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$ results:

Mass, signal strength and couplings

Spin and parity

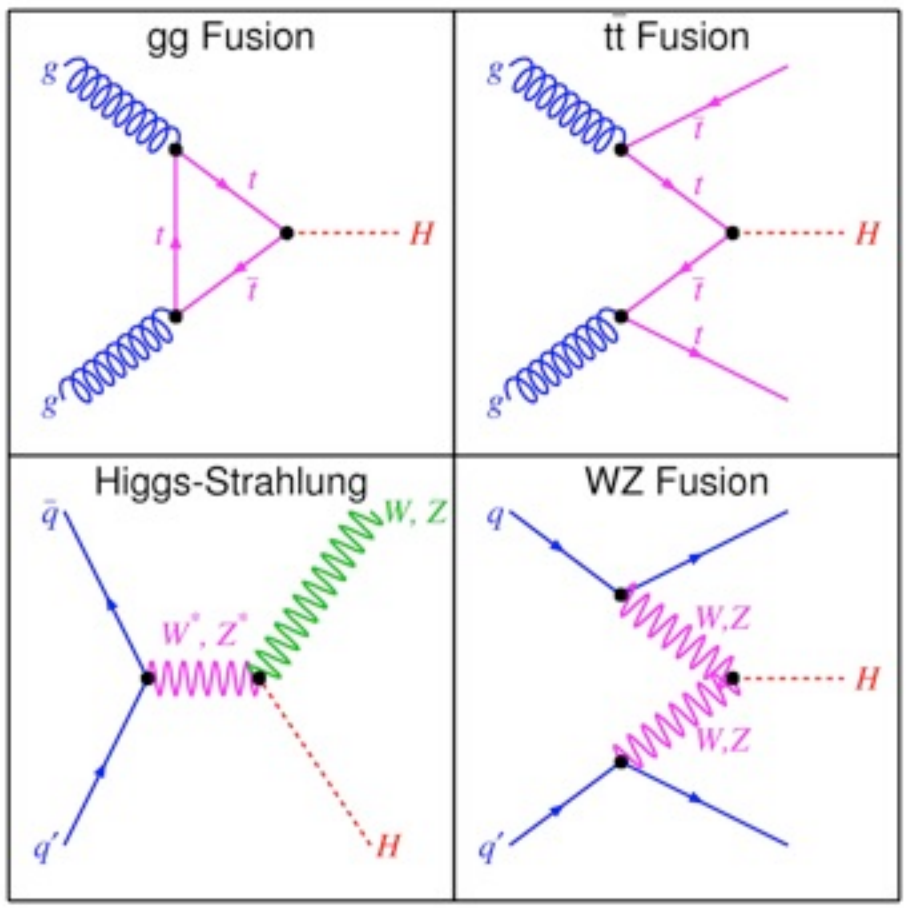
- Differential cross section in the $H \rightarrow \gamma\gamma$ channel

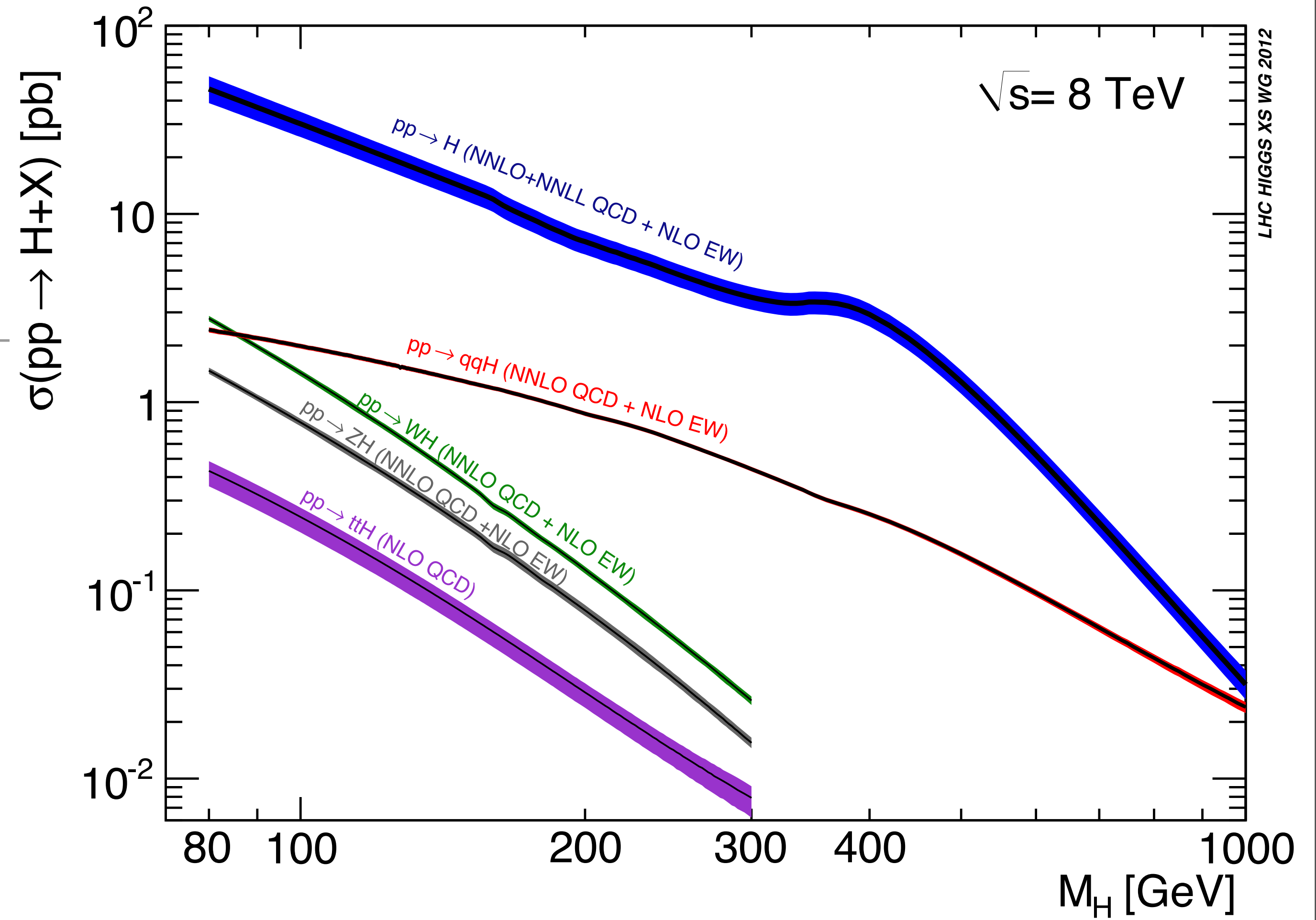
3. Other Higgs boson searches

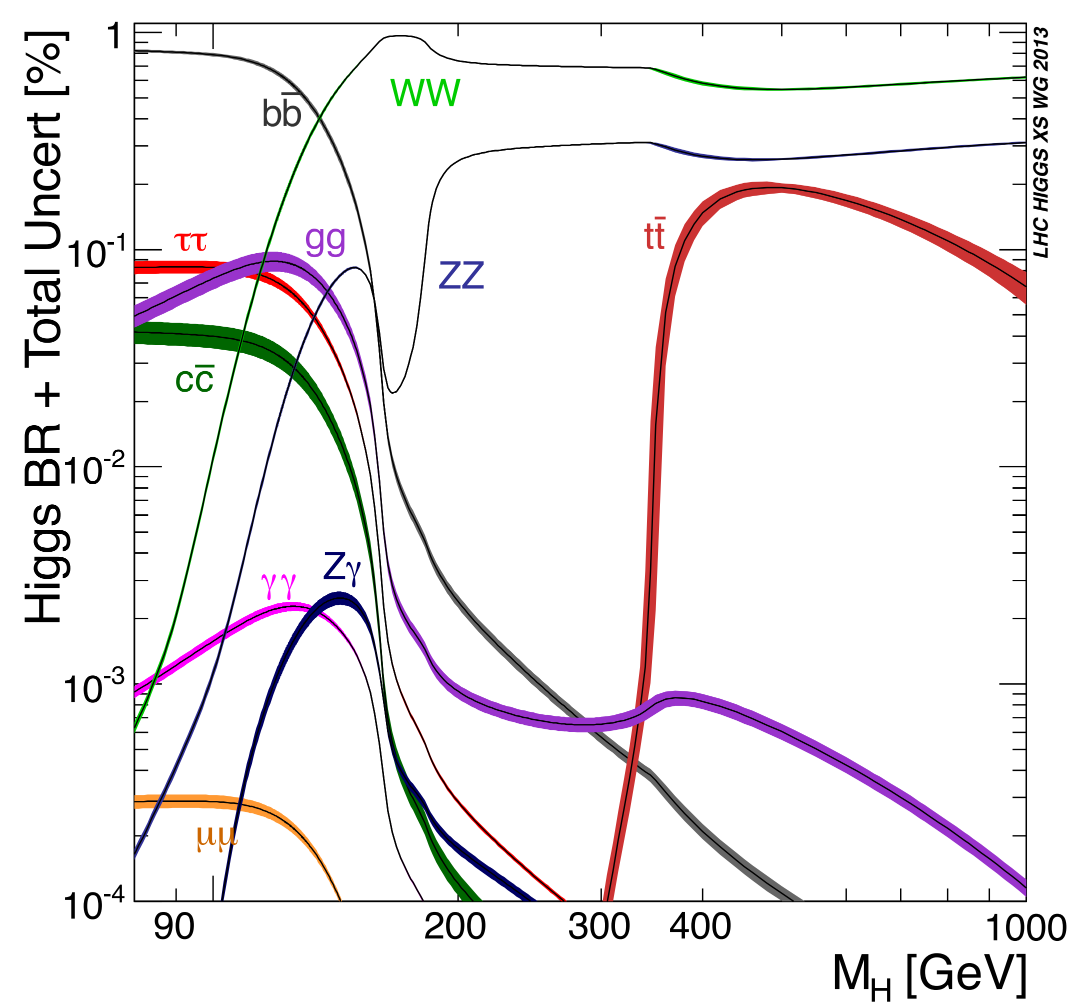
- Higgs into fermions
- Rare decays
- Recent BSM Higgs searches

4. Summary

The Higgs at the LHC





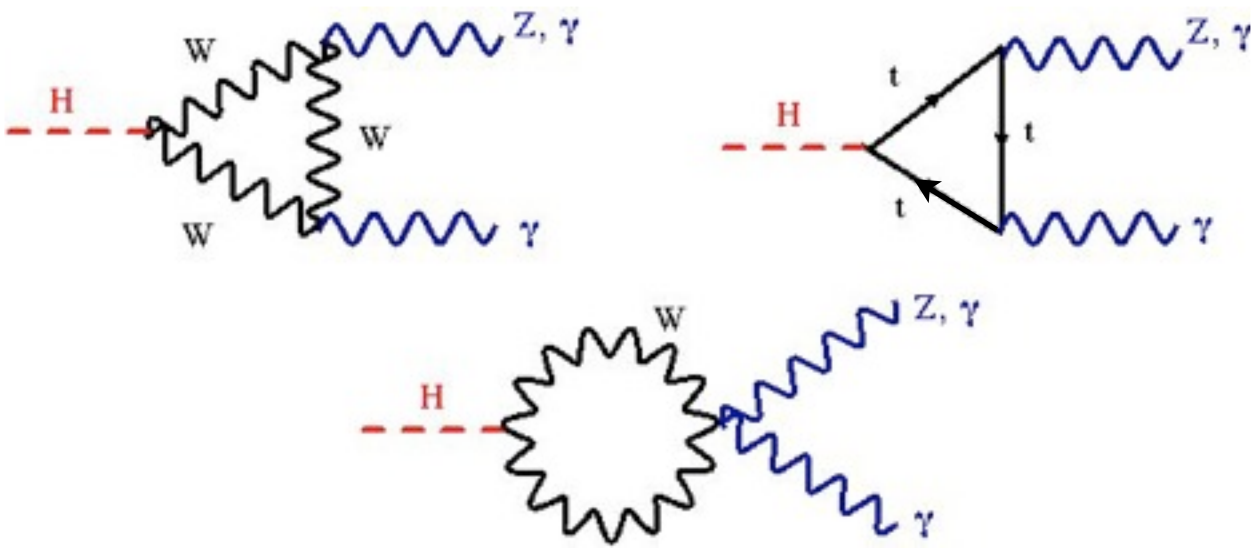


- Main production through gluon fusion (ggF) (mainly proceeds through top quark).
- VBF, WH, ZH and ttH, follow in order.

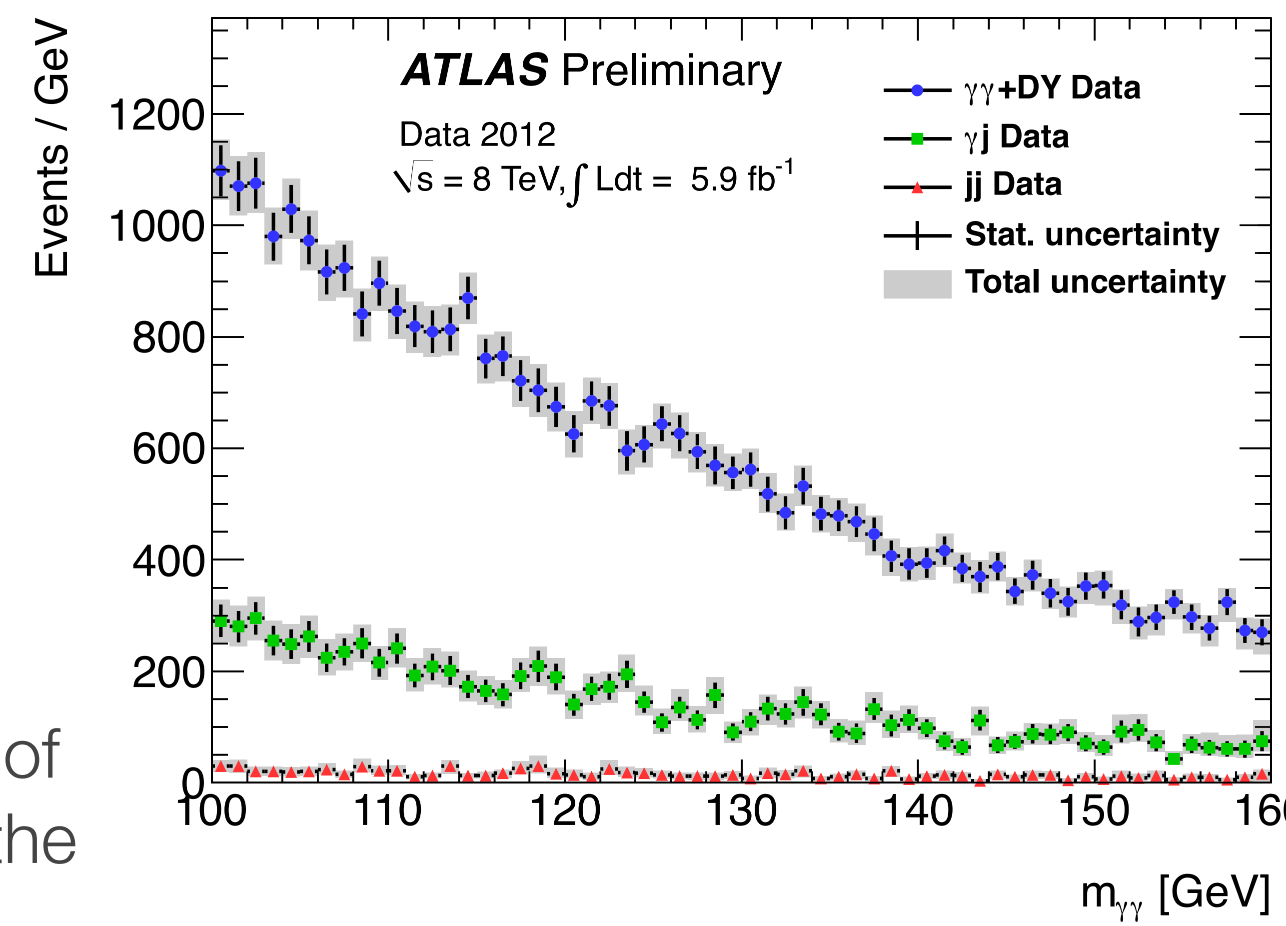
Higgs observation channels

H→γγ channel

- Decay due to W and top loops: Sensitive to Vector boson and top couplings both in production and decay; sensitive to BSM physics



Narrow mγγ resonance searched over a large smooth monotonically decreasing background.



- Despite low BR (0.2%), H→γγ was one of the most promising for Higgs search in the low mass range: clean signature (good mass resolution) to discriminate QCD backgrounds.

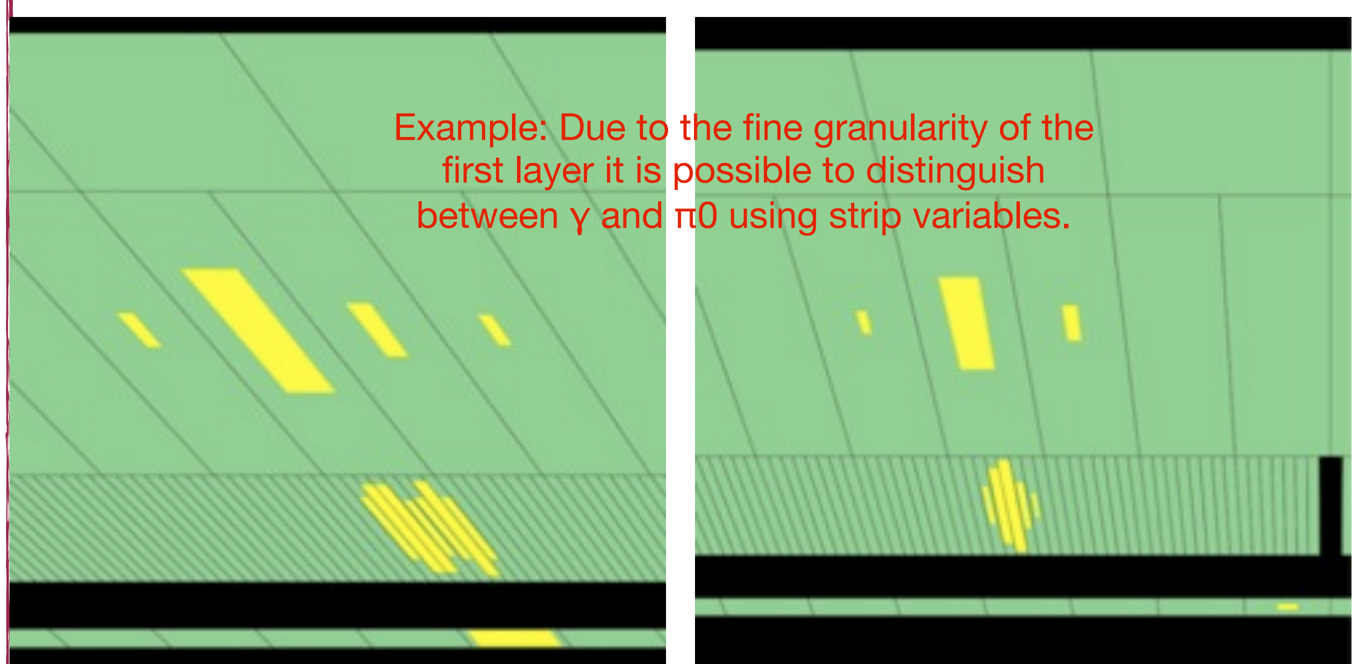
75% irreducible γγ QCD background
25% reducible γj, jj background

H→γγ channel

Selection: 2 tightly identified isolated photons, Pt > 40 / 30 GeV, $|\eta| < 1.37$ or $1.56 < |\eta| < 2.37$

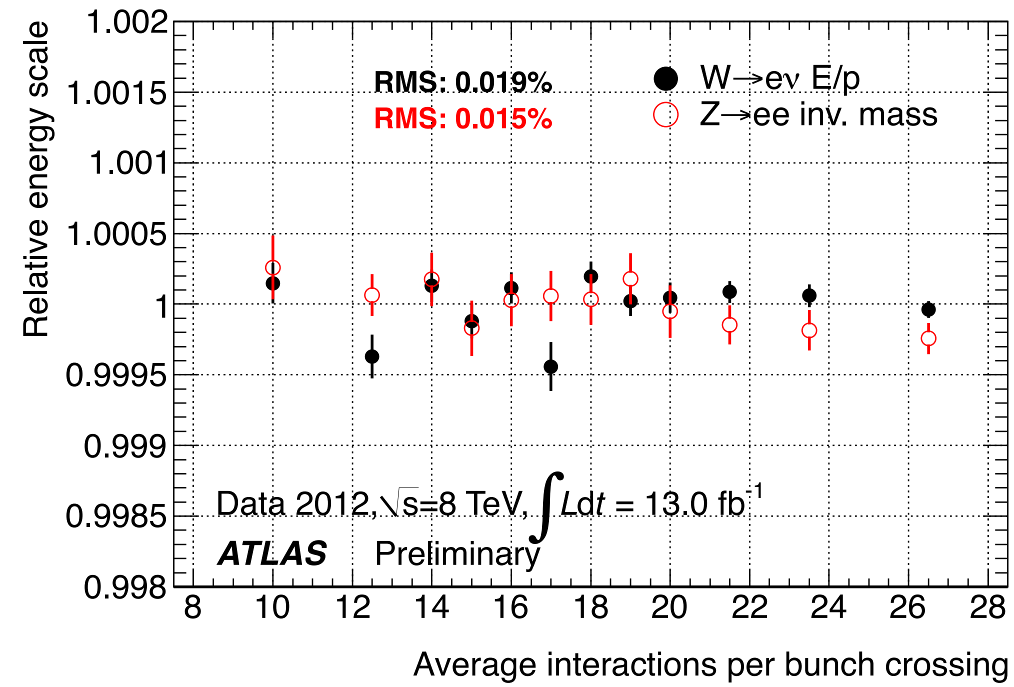
Photon identification:

Cuts on shower shape variables to discriminate isolated photons from QCD jets.



Photon energy reconstruction:

Validated with Z->ee and corrected with MC for e-γ translation effects.



H→γγ: Invariant mass reconstruction

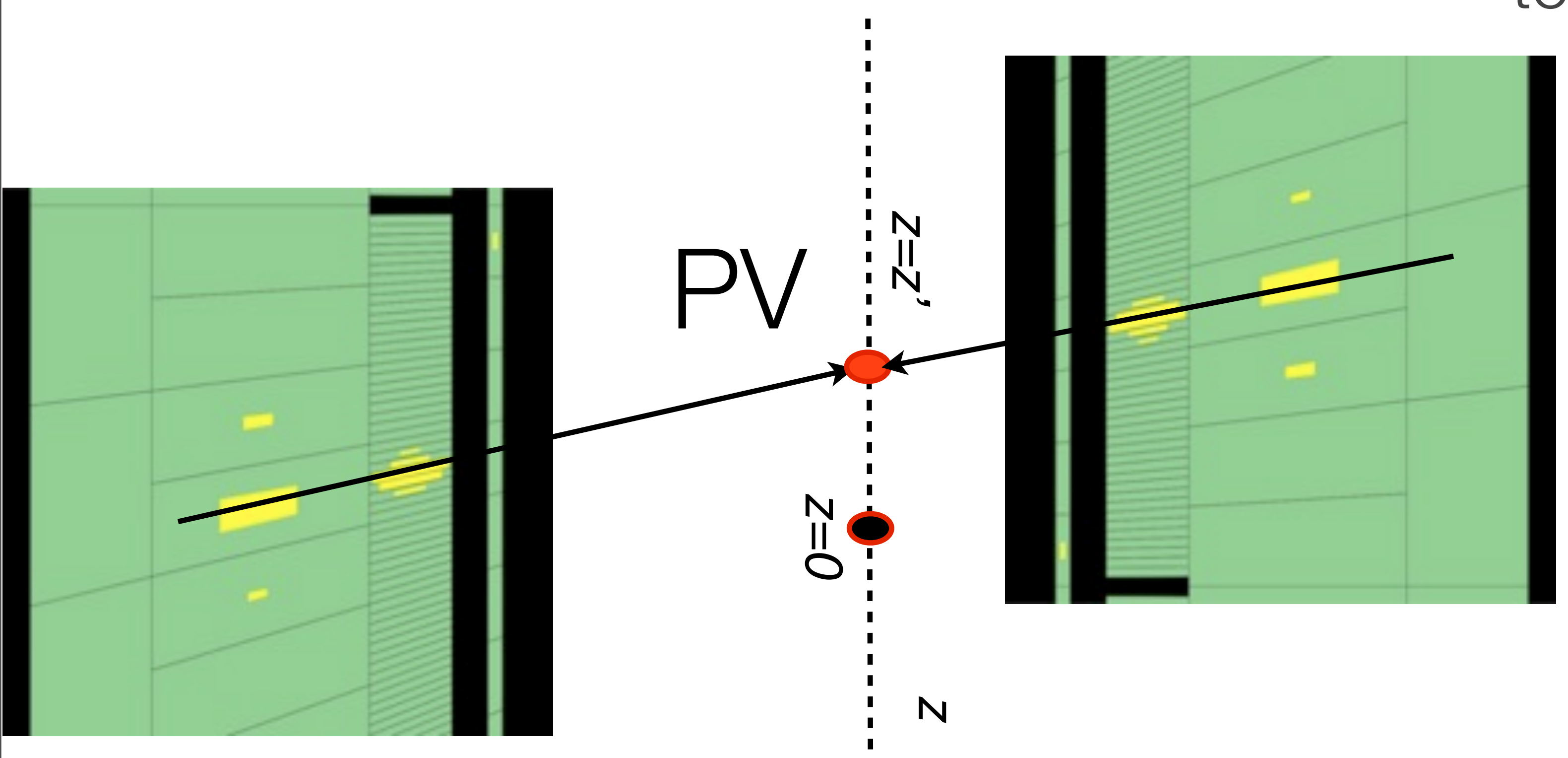
- Evaluated from the following expression:

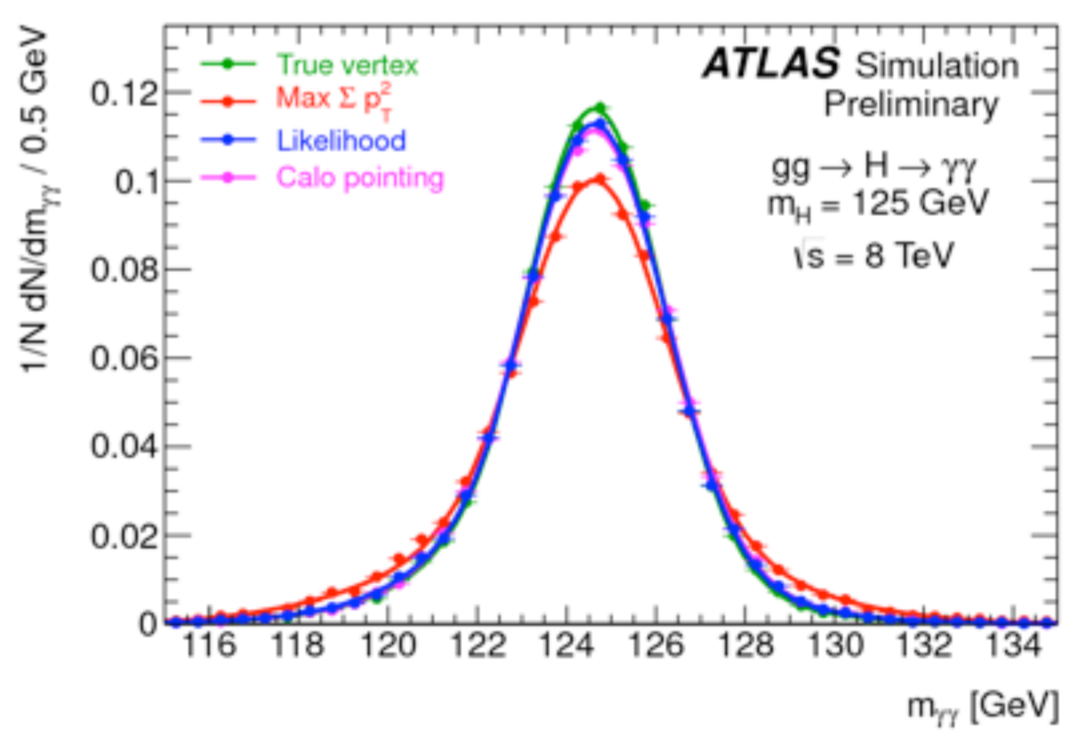
$$M_{\gamma\gamma} = \sqrt{2E_T^1 E_T^2 \left[\cosh(\eta_1 - \eta_2) - \cos(\phi_1 - \phi_2)\right]},$$

Photon η has to be corrected by the PV.

The PV is identified by building a likelihood, which includes:

- Flight direction of the photons (using calo-pointing technique).
- Average beam spot position
- Sum of $|pT|^2$ of the tracks associated to the PV





Inclusive mass resolution ~1.7 GeV.

H→γγ: Results

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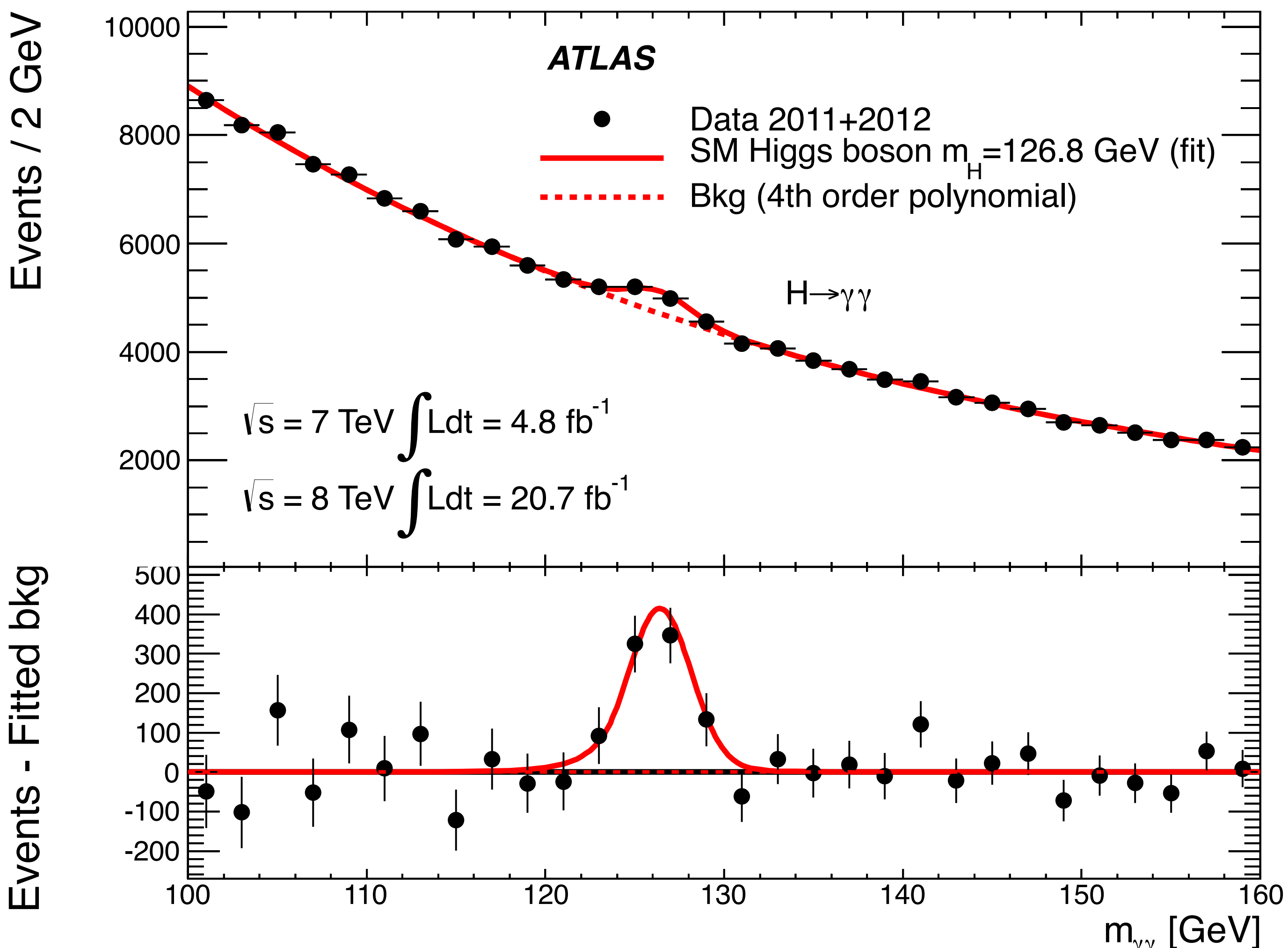
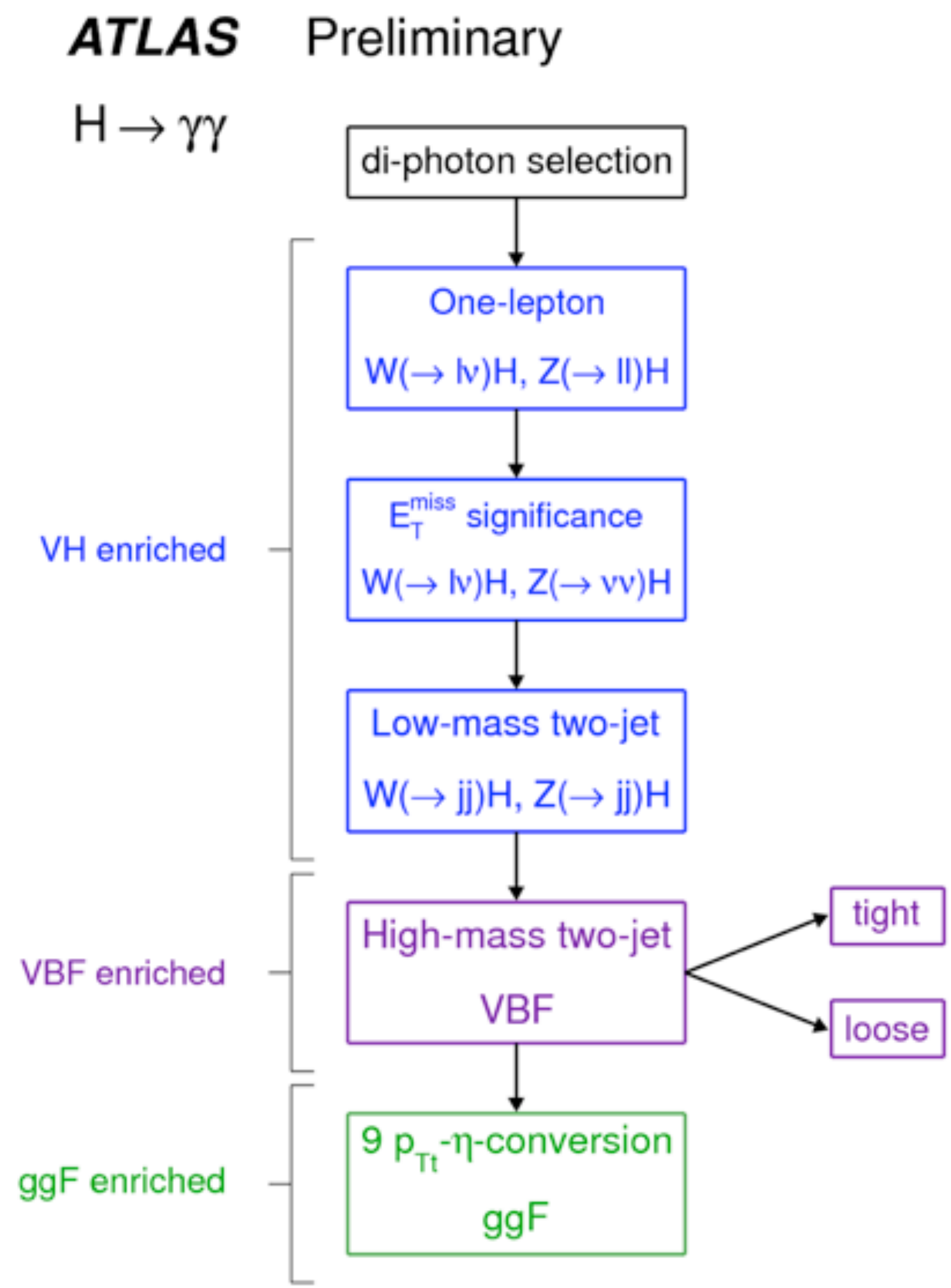
Perform the analysis of the data classifying the events in 14 categories exploiting process signature (VH, VBF or ggF enriched) and differences in mass resolutions.

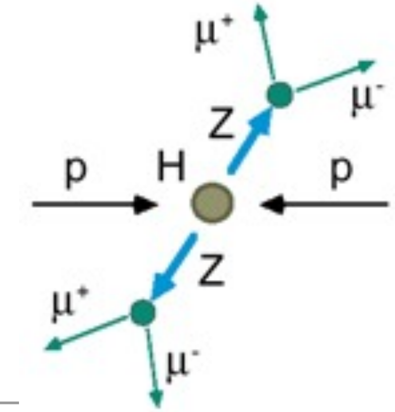




Obs. (Exp.) 7.4σ (4.1σ)

Signal strength μ = 1.55 ± 0.23(stat) ± 0.15 (sys) ± 0.15 (th)

H➞ZZ➞4l channel

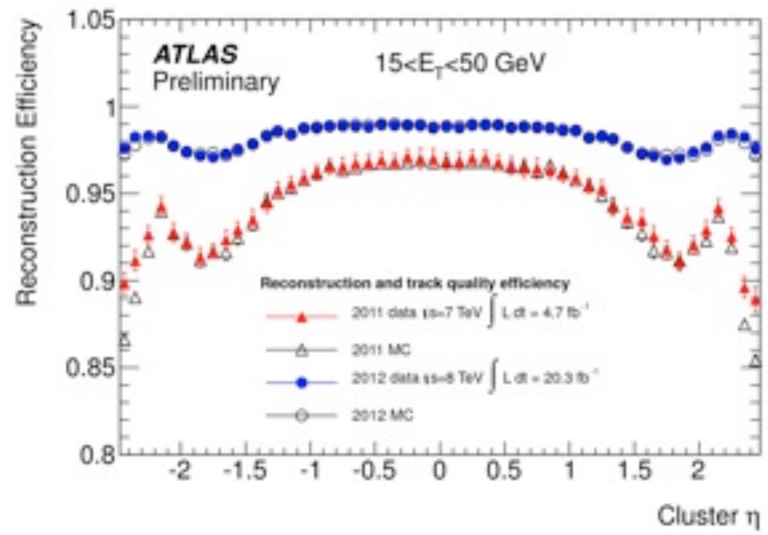


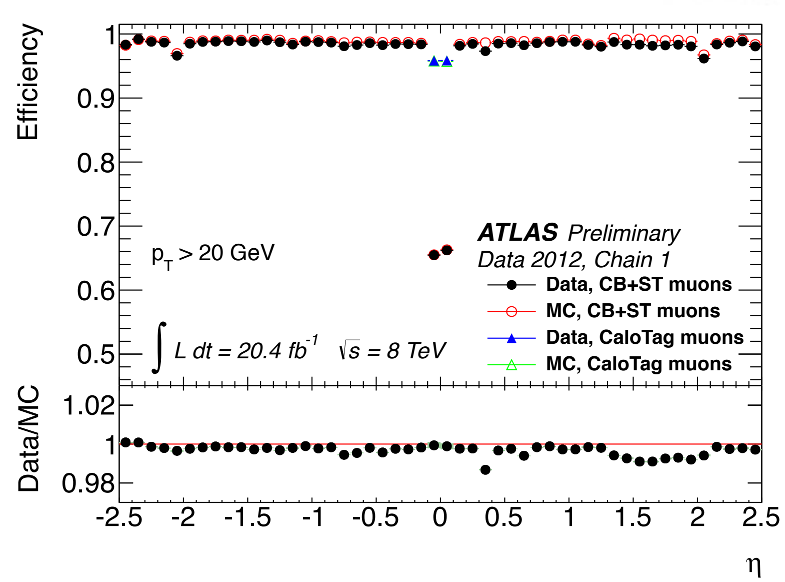
- Events can be fully reconstructed with high efficiency and purity
- Signal/background ratio ~ 1
- However: low σ*BR

Efficiencies:

-Significant improvements of the electron reconstruction efficiency for the 2012 dataset

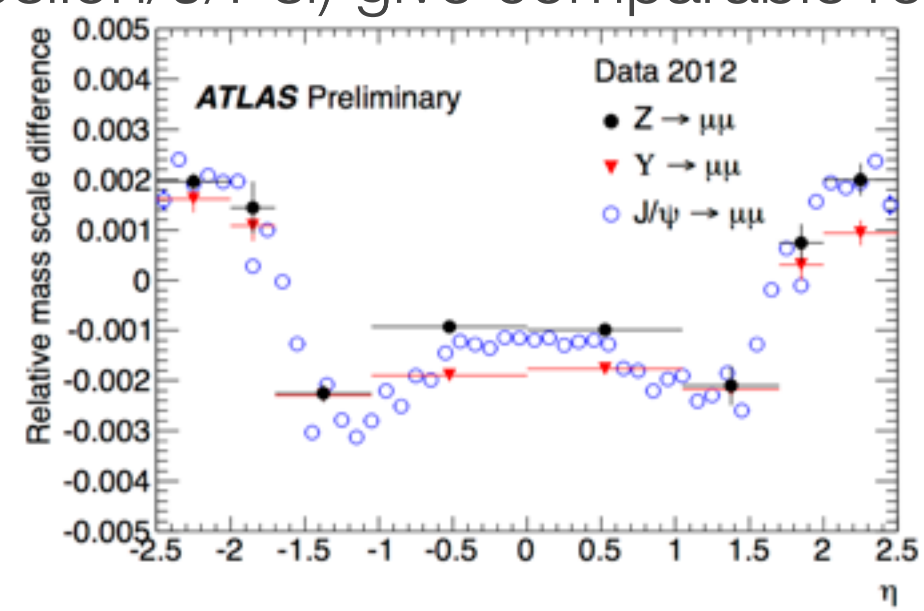
- Very good data/MC agreement for both muons and electrons





Energy scale:

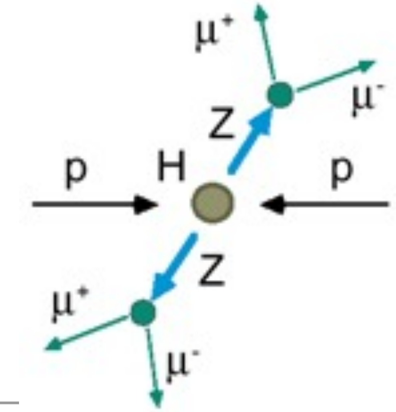
- Muons: Different input objects (Z/W/Upsilon/J/Psi) give comparable results.



- Very stable in time and under pile-up

both for Electrons (shown for H➞γγ) and Muons.

H➞ZZ➞4l: Improvement in the invariant mass



Search for 4 leptons (e,μ): 4e, 2e2μ, 4μ

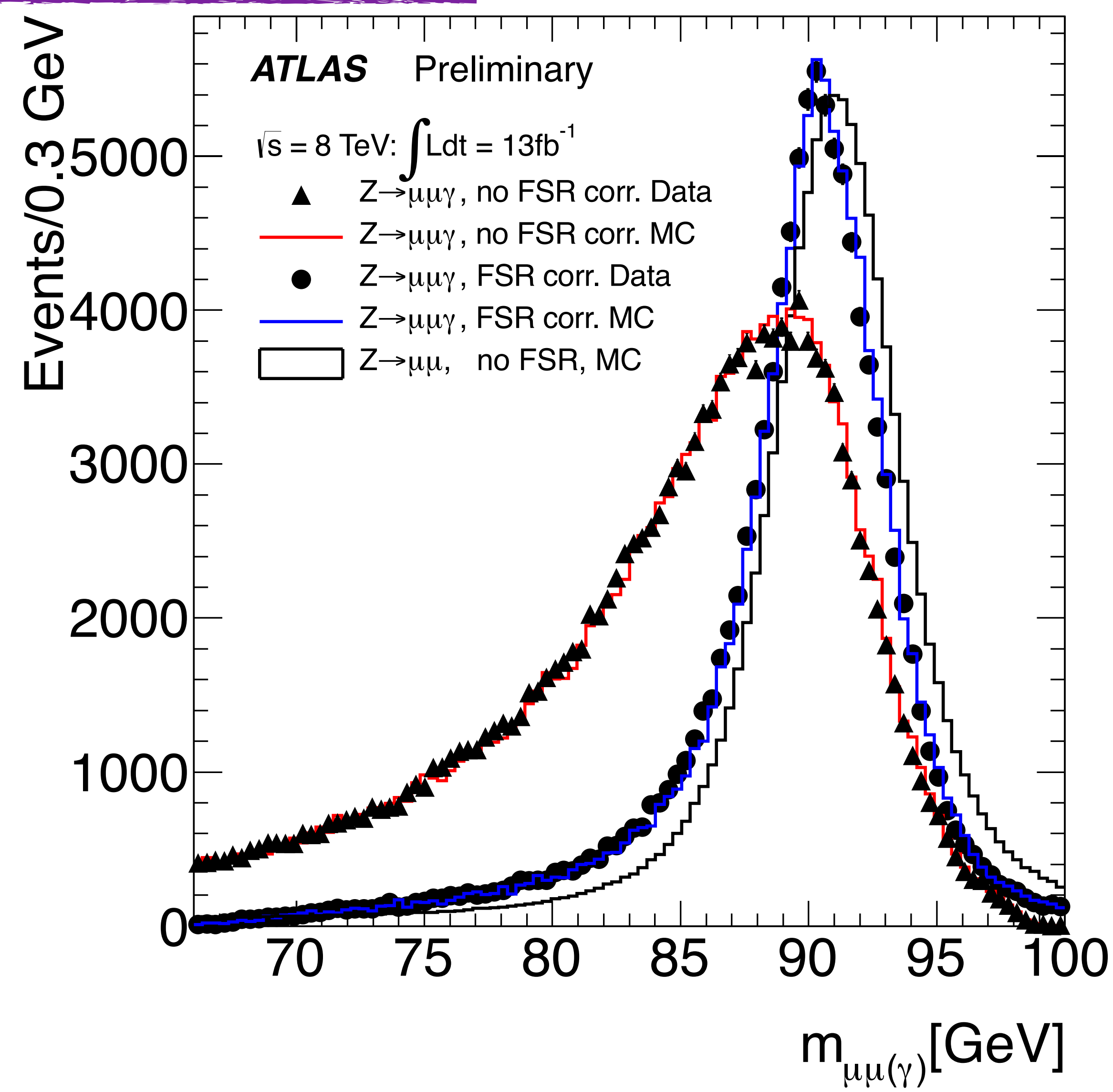
Improvement in the invariant mass:

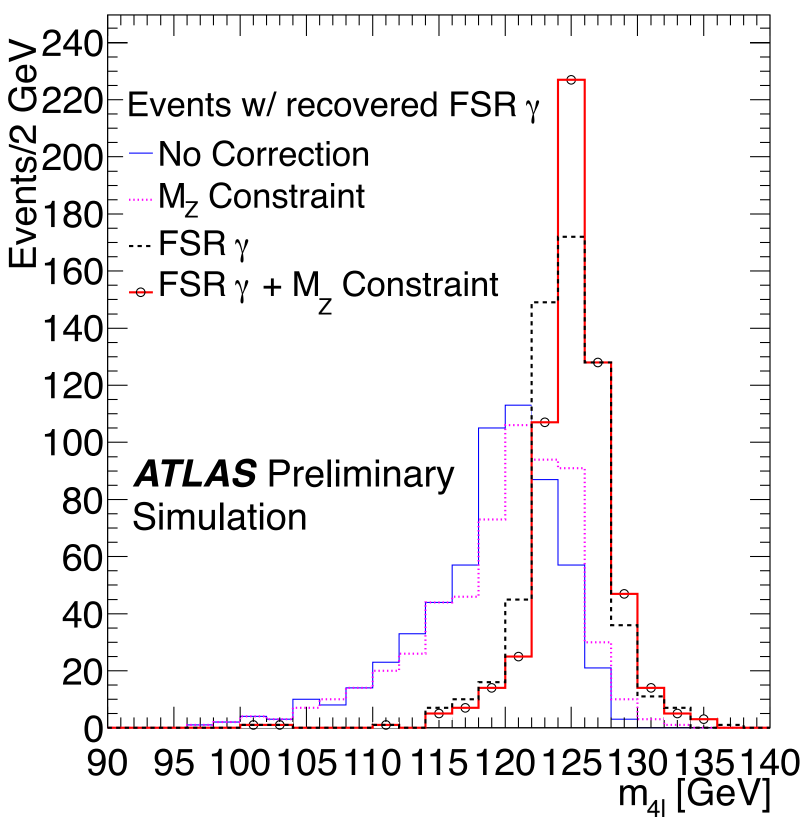
- FSR correction to muon momentum

  Photons with $E_T > 1.3$ GeV

  and $\Delta R_{cluster,\ \mu} < 0.15$

  Affects 4% of the events





- Z-mass constraint on the leading di-lepton (highest pT, opposite sign, same flavour)

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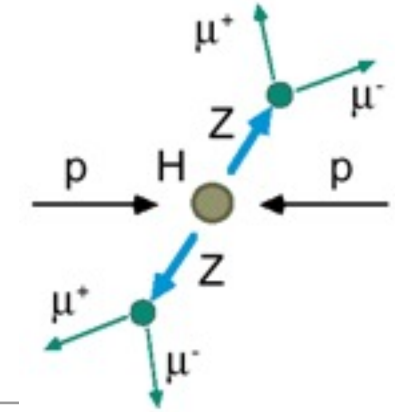
H→ZZ→4l:



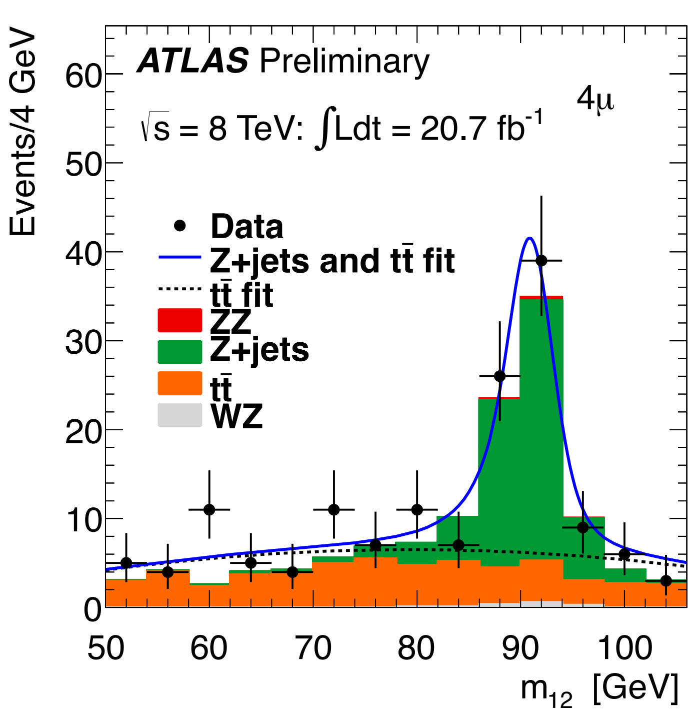
Backgrounds:

Main irreducible background:

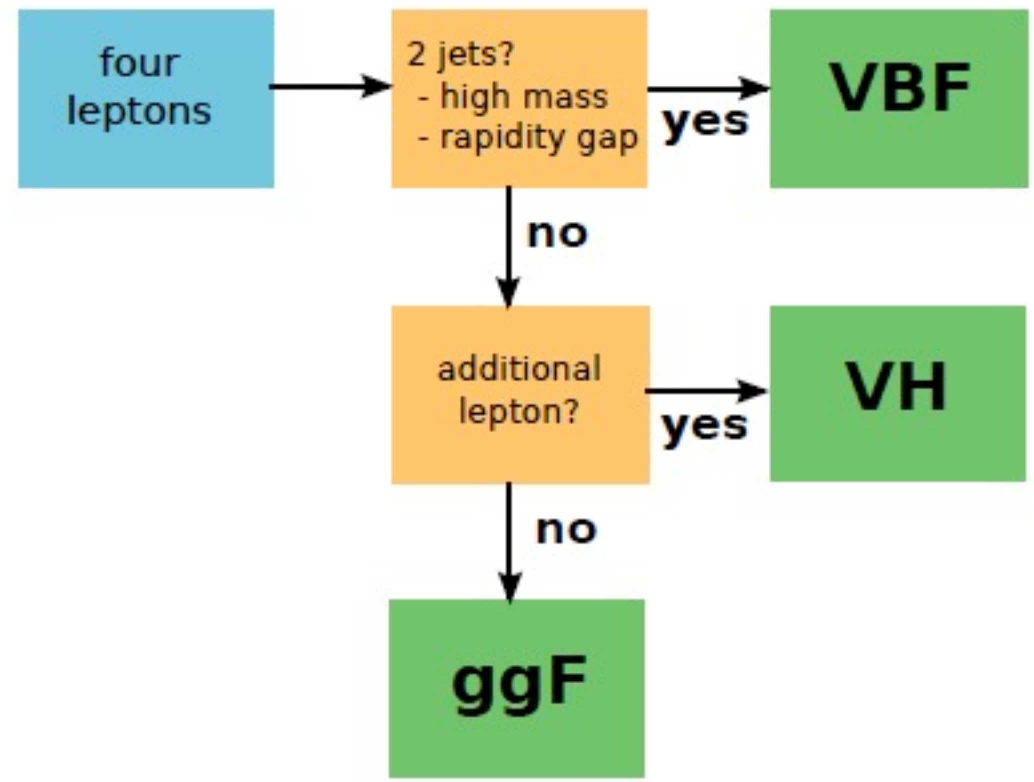
ZZ*, estimated from MC

Reducible background:

Z + jets, ttbar, data-driven methods, transfer factors to extrapolate from control regions to the signal regions from MC and cross-checked with data.



Event Categorisation:



Expected number of signal events in each category +ZZ background events.

category	$gg \to H, q\bar{q}/gg \to t\bar{t}H$	$qq' \to Hqq'$	$q\bar{q} \to W/ZH$	$ZZ^{(*}$
		$\sqrt{s} = 8$ TeV		
ggF-like	13.5	0.79	0.65	320.4
VBF-like	0.28	0.43	0.01	3.58
VH-like	0.06	-	0.14	0.69

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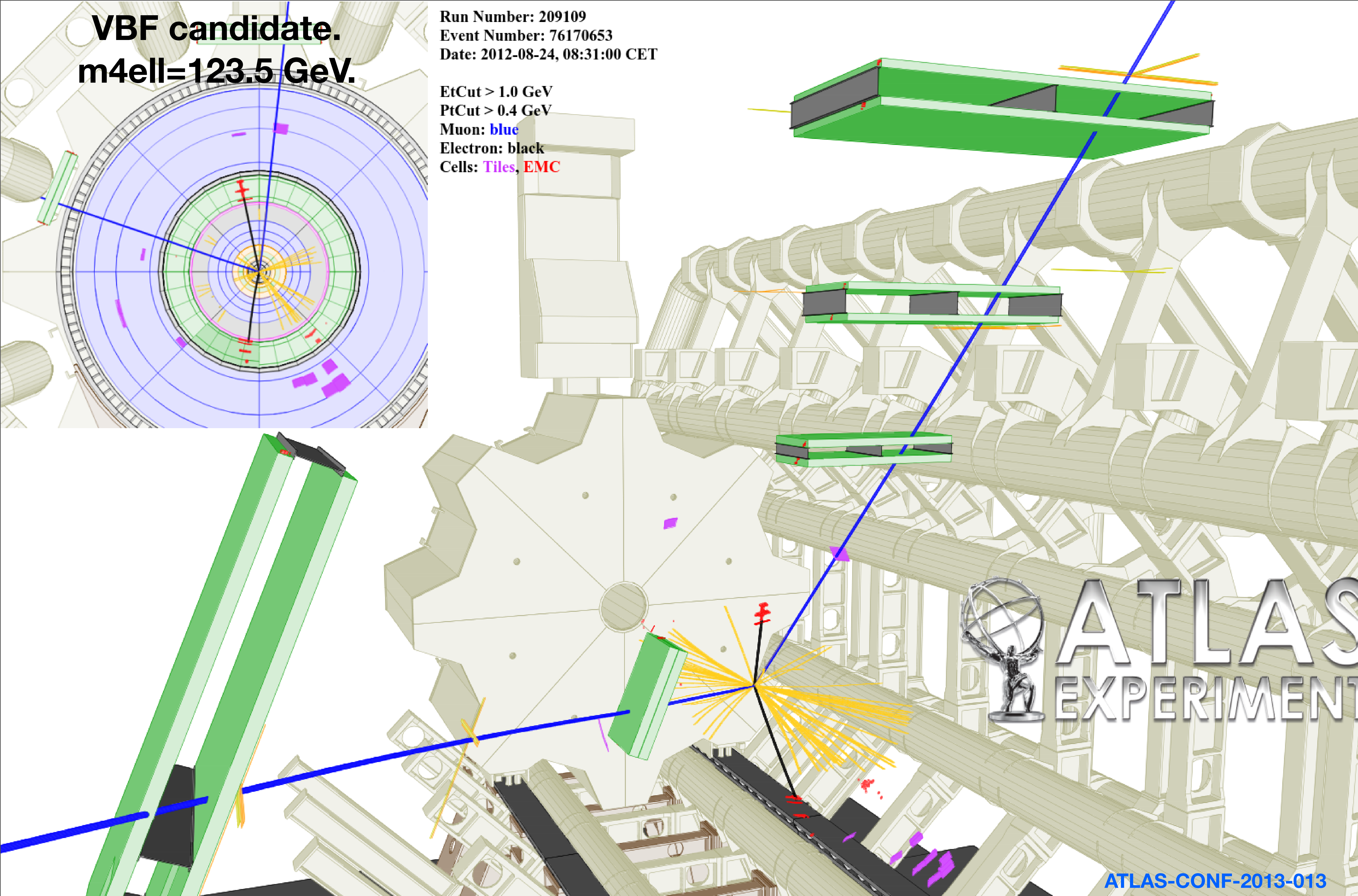

One VBF-like candidate is found in a 5 GeV window around 125 GeV (0.71± 0.10 events expected in VBF category with 60% coming from VBF production).

H→ZZ→4l: Results

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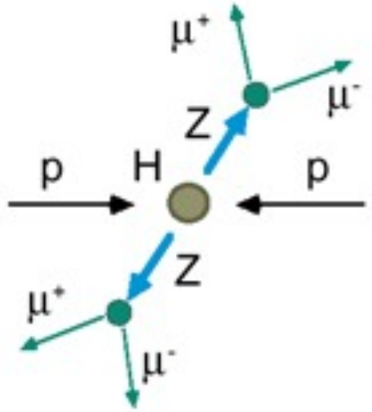
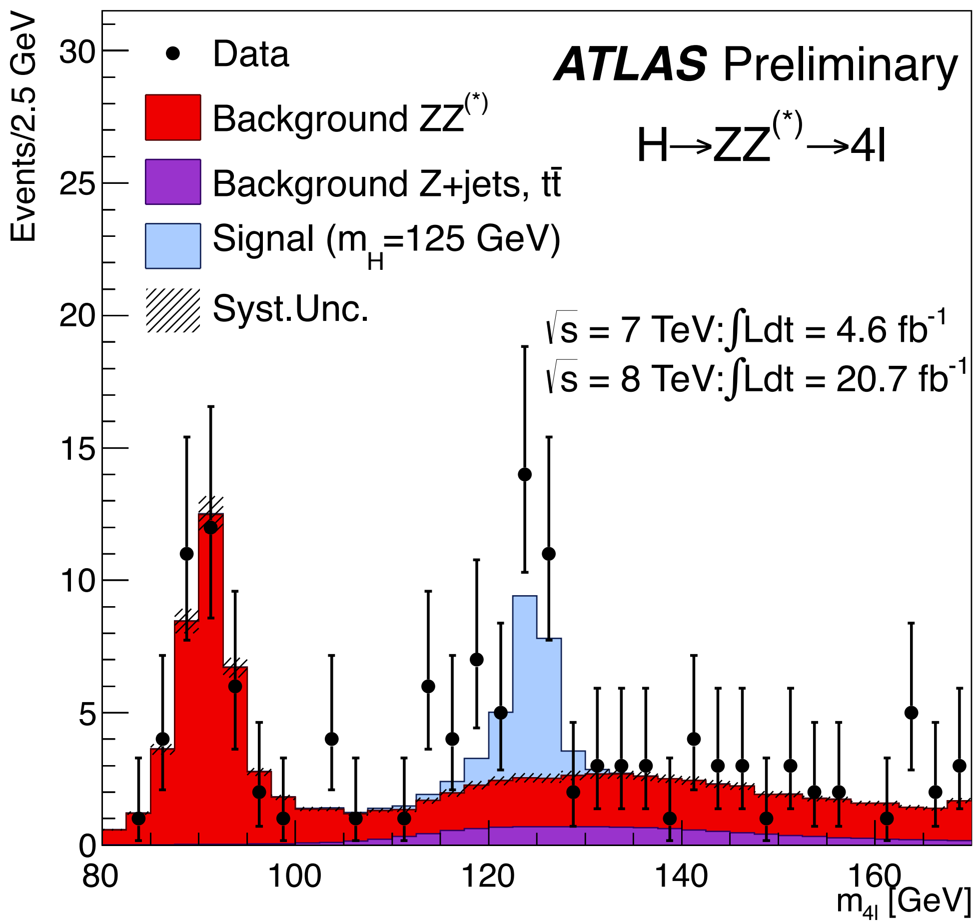
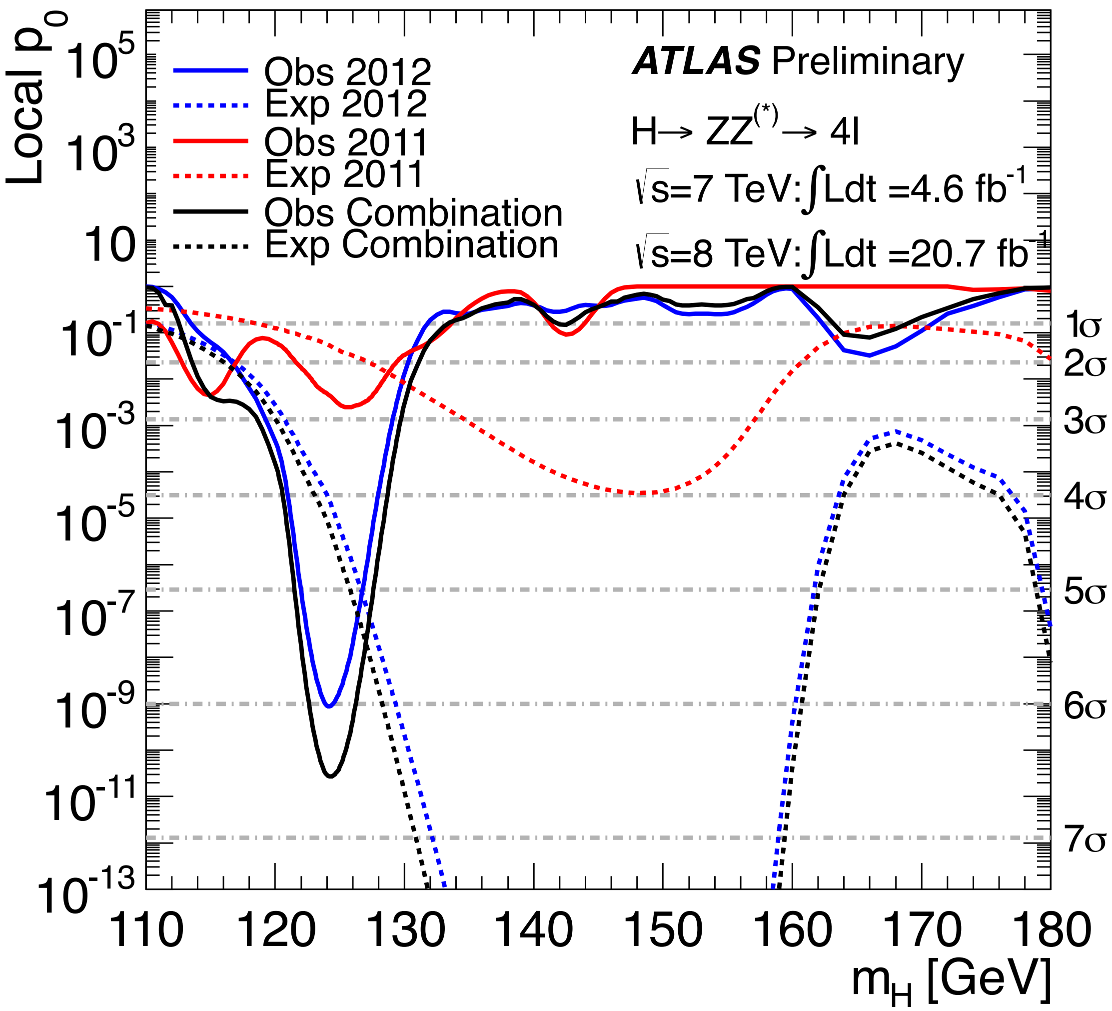


Single channel discovery: 6.6σ (4.4σ) observed (expected) significance

Signal strength: $\mu = 1.7^{+0.5}_{-0.4}$ for mH = 124.3 GeV





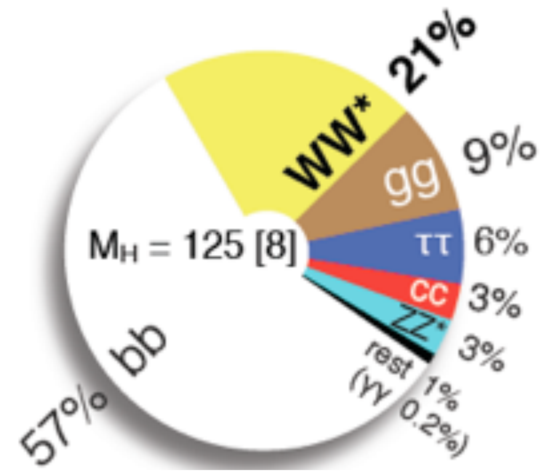
Expected and observed number of signal and background events in a window of 5 GeV around 125 GeV

	Signal	ZZ^*	$Z+$jets, $t\bar{t}$	Observed
4μ	6.3 ± 0.8	2.8 ± 0.1	0.55 ± 0.15	13
$2e2\mu/2\mu2e$	7.0 ± 0.6	3.5 ± 0.1	2.11 ± 0.37	13
$4e$	2.6 ± 0.4	1.2 ± 0.1	1.11 ± 0.28	6

H→WW→lνlν channel

- High production rate (σ x BR ~200 fb) but limited mass resolution and significant backgrounds

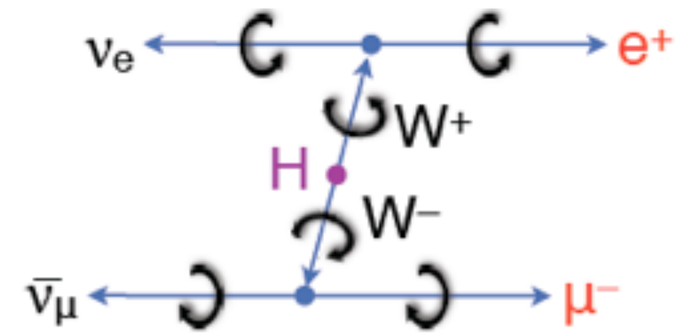
- Sensitivity to the VBF production mode is obtained by adding candidates with Njet ≥ 2:
  - The analysis is divided into Njet = 0, = 1, and ≥ 2.



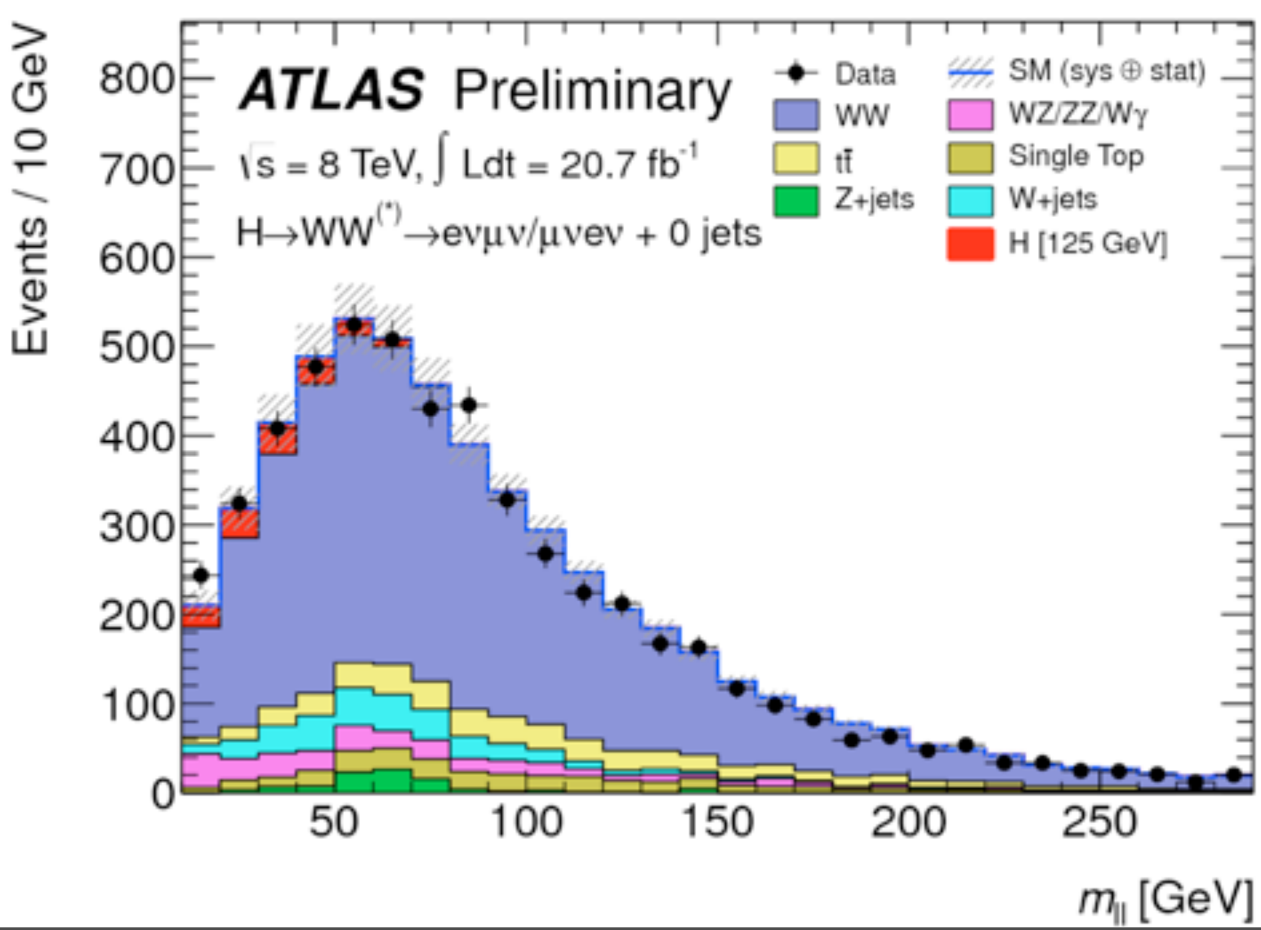
H→WW* →eμ $\nu_e\nu_\mu$

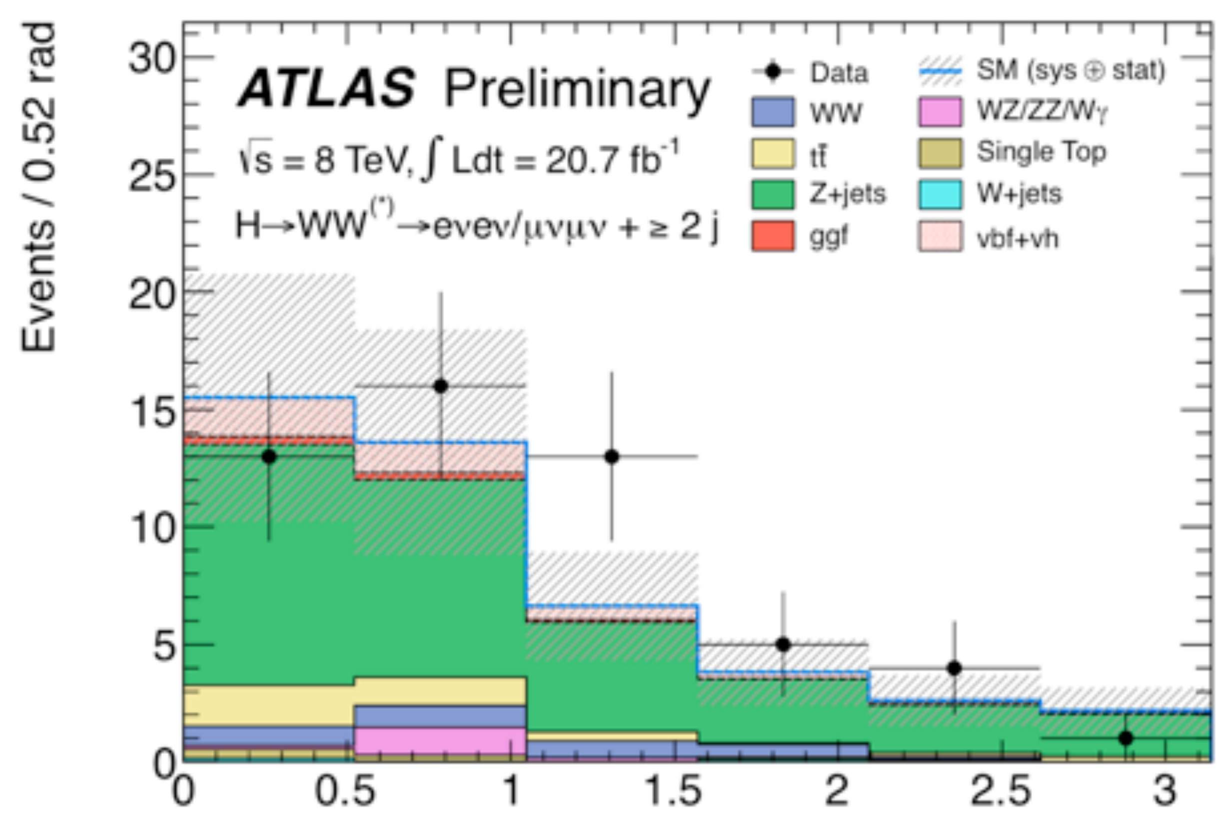
→ee $\nu_e\nu_e$

→μμ $\nu_\mu\nu_\mu$



- Low $M_{\ell\ell}$
- Small $\Delta\phi_{\ell\ell}$
- Large MET





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H→WW→lνlν Backgrounds

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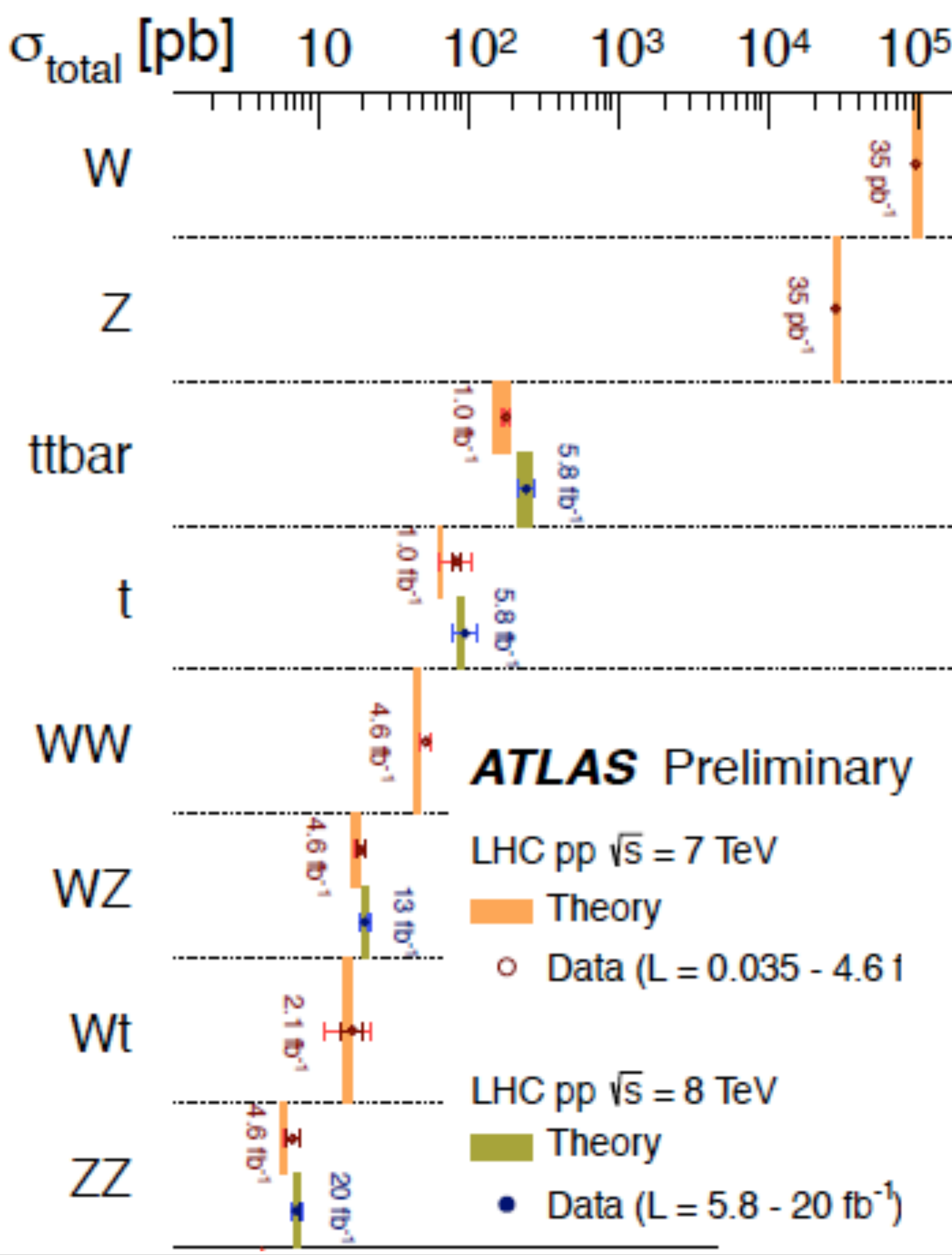
Most backgrounds (WW irreducible, tt, single W, Wt) estimated from data control regions



How it fakes signal		Estimate
$W \to \ell\nu$	Jet fakes ℓ	Data
$Z \to \ell\ell$ $Z \to \tau\tau$	Fake MET Real MET	Data
$t \to b\ell\nu$	Lose b	Data
Irreducible	Large	Data
$WZ \to \ell\nu\ell\ell$	Lose ℓ	MC
$W \to \ell\nu$	Lose b	Data
Irreducible	Small	MC

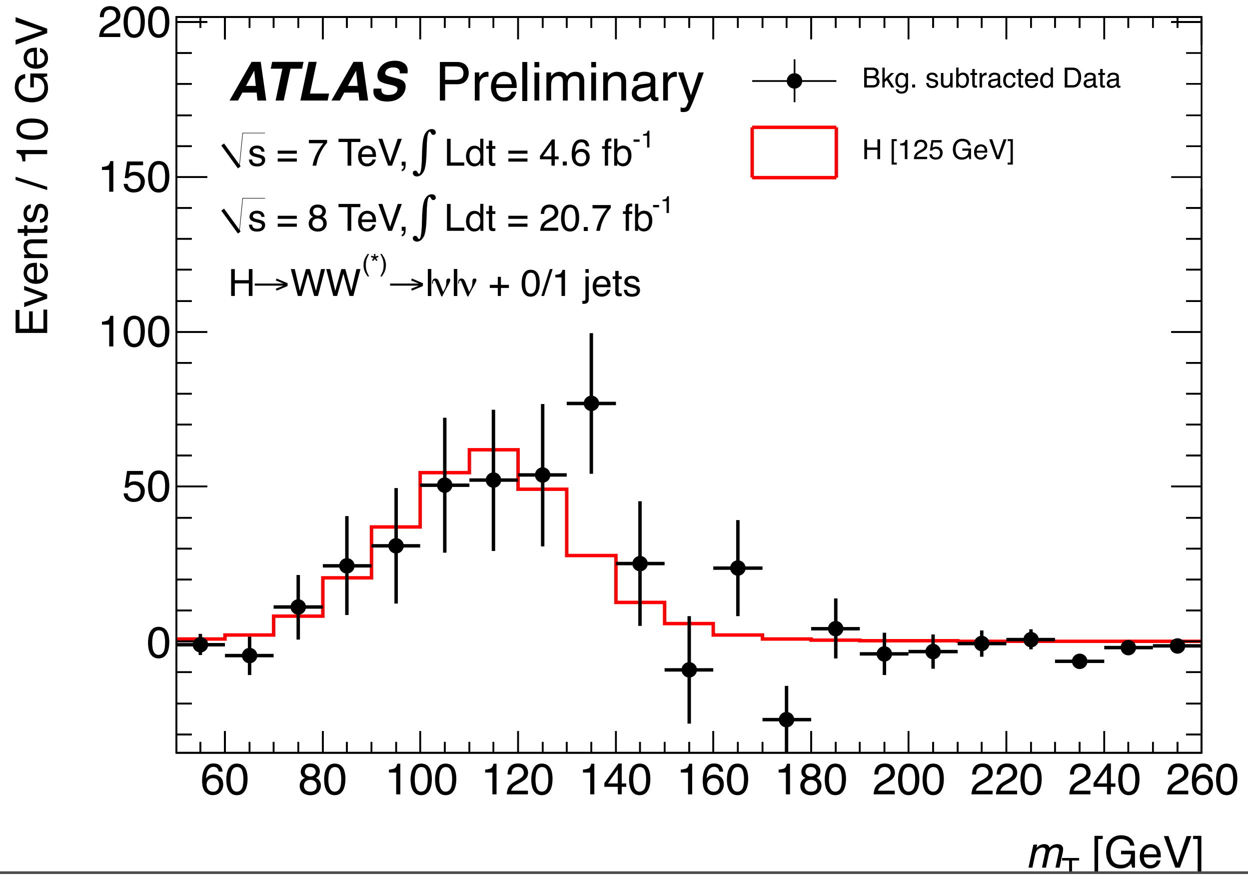
H→WW→lνlν channel
Results

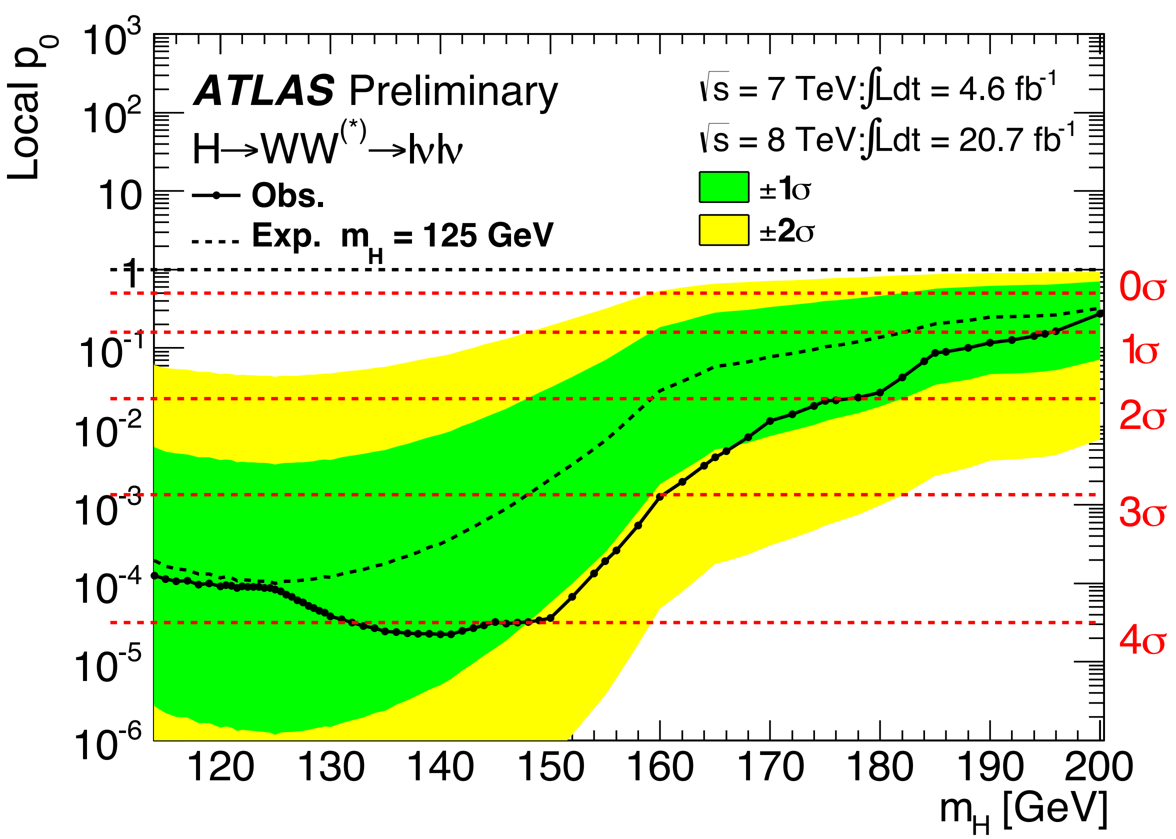
ATLAS-CONF-2013-030

Significance of the signal with mH = 125GeV is 3.7(3.8) expected (observed) standard deviations. With a signal strength:

μ_{obs} = 1.01 ± 0.21 (stat.) ± 0.19 (theo. syst.) ± 0.12 (expt. syst.) ± 0.04 (lumi.)
μ_{obs} = 1.01 ± 0.31.

Results are consistent with the predictions for the Standard Model Higgs boson decaying to a pair of W bosons.





Higgs properties

Mass of the Higgs boson

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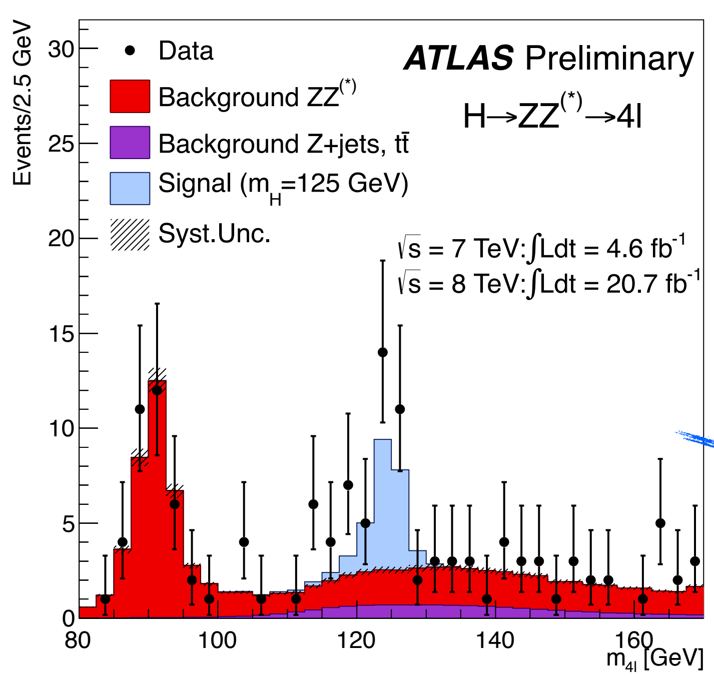
Precise measurement of mH from channels with entirely reconstructed final state and good object resolution:

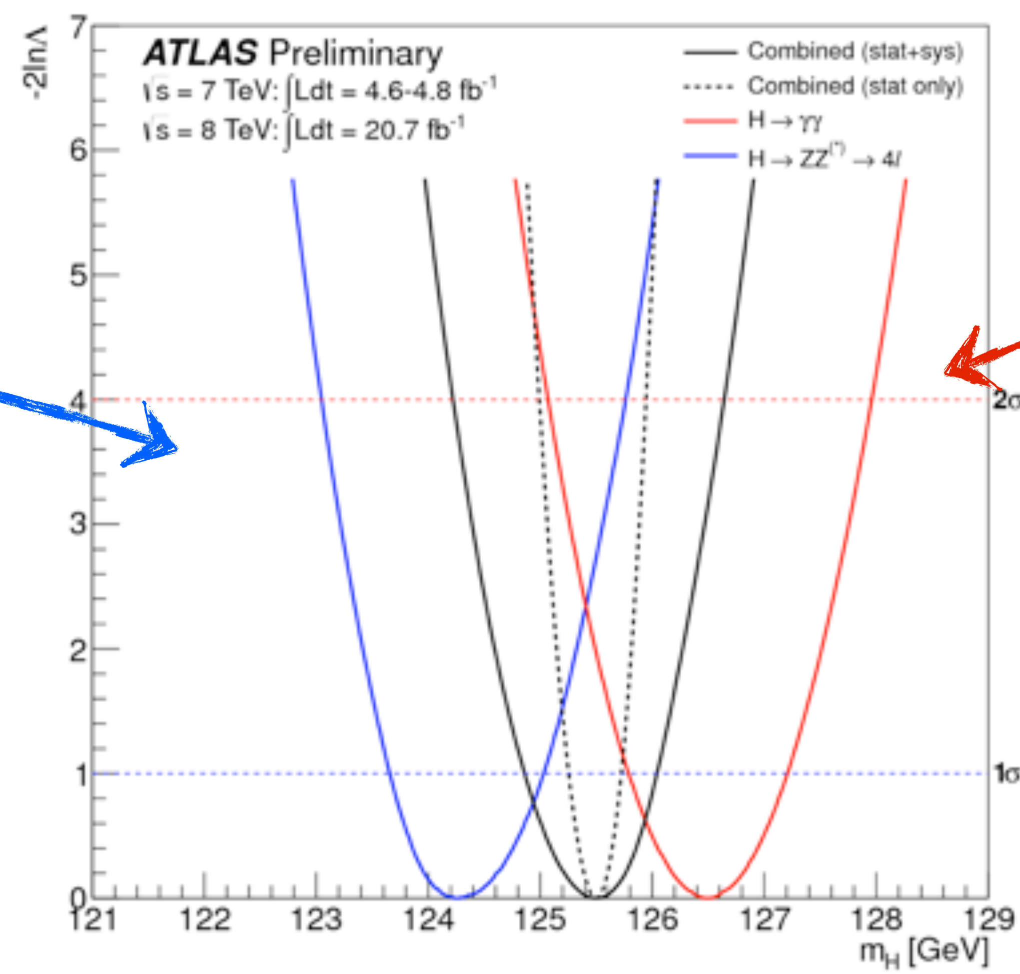
H→γγ, H→ZZ

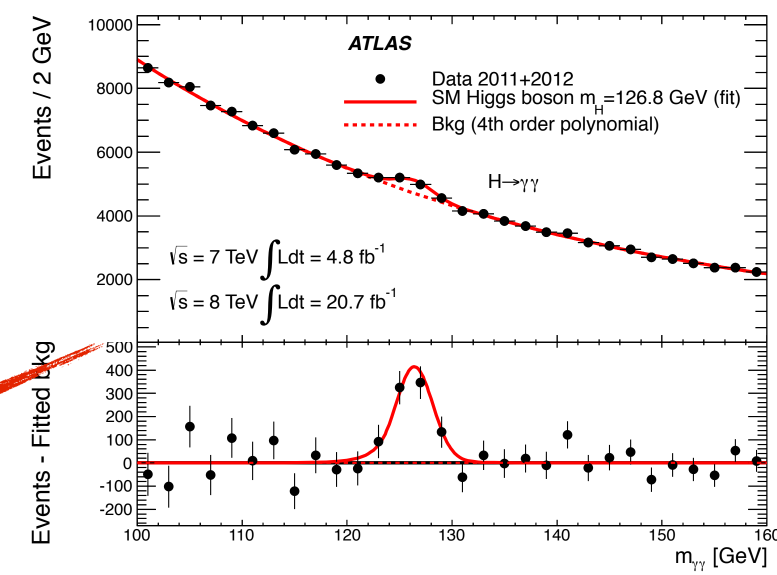
Dominant uncertainties: photon energy scale (H→γγ), lepton energy and momentum scale, statistics ((H→4l))



mH = 124.3 $^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.6}$(sys) GeV

(H→ ZZ(*)→ 4l)





mH = 126.8 ± 0.2(stat) ± 0.7(sys) GeV

(H→γγ)

Combined mass: mH=125.5 ± 0.2(stat) $^{+0.5}_{-0.6}$(sys) GeV

Mass difference 2.4 σ (p-value 1.5%).

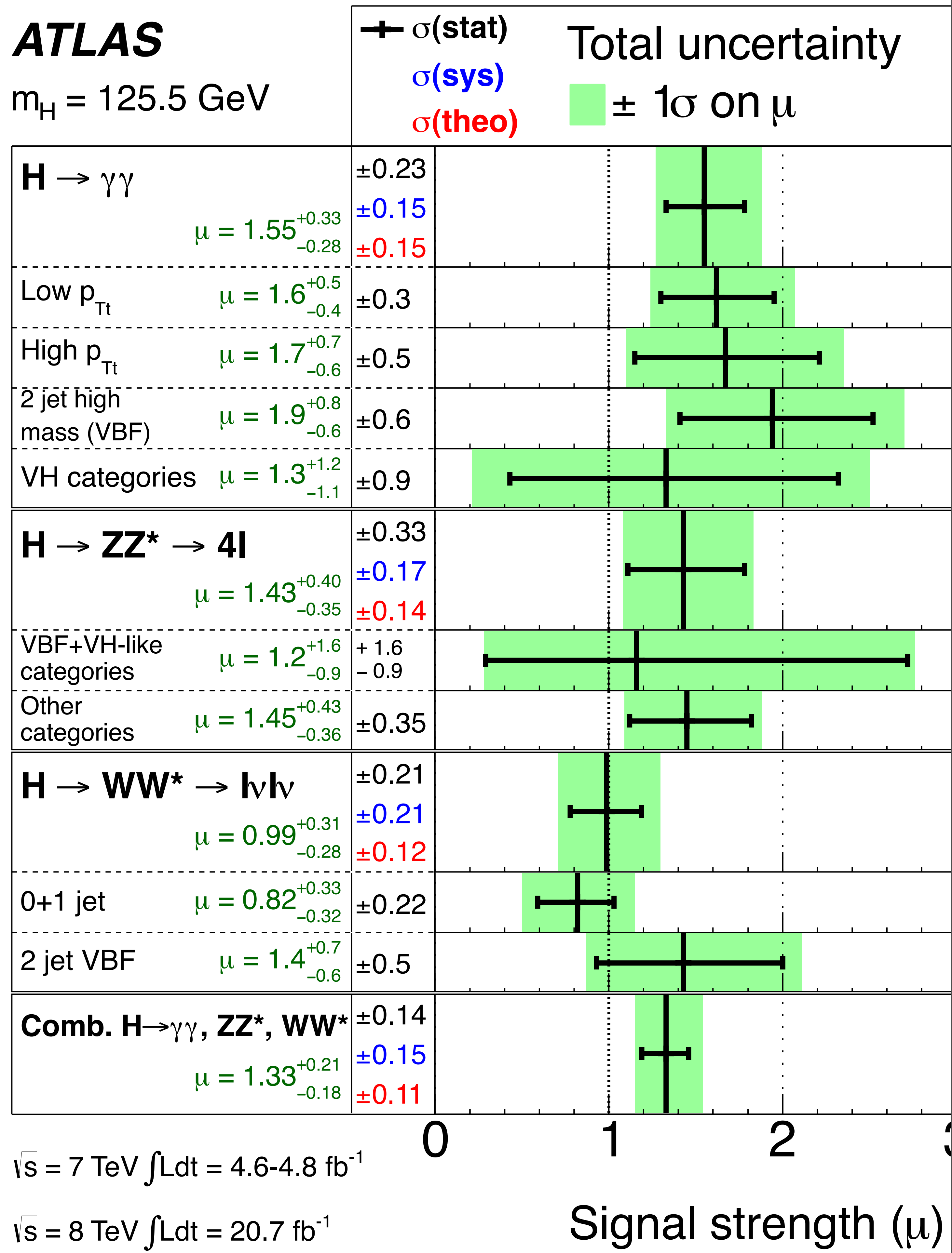
Signal strength

Measure the ratio between observed rate and SM Higgs expectation for **σ** *x BR:*

$$\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$$

where **μ**=1 → SM Higgs

Systematic, statistical and theoretical uncertainties are already comparable.



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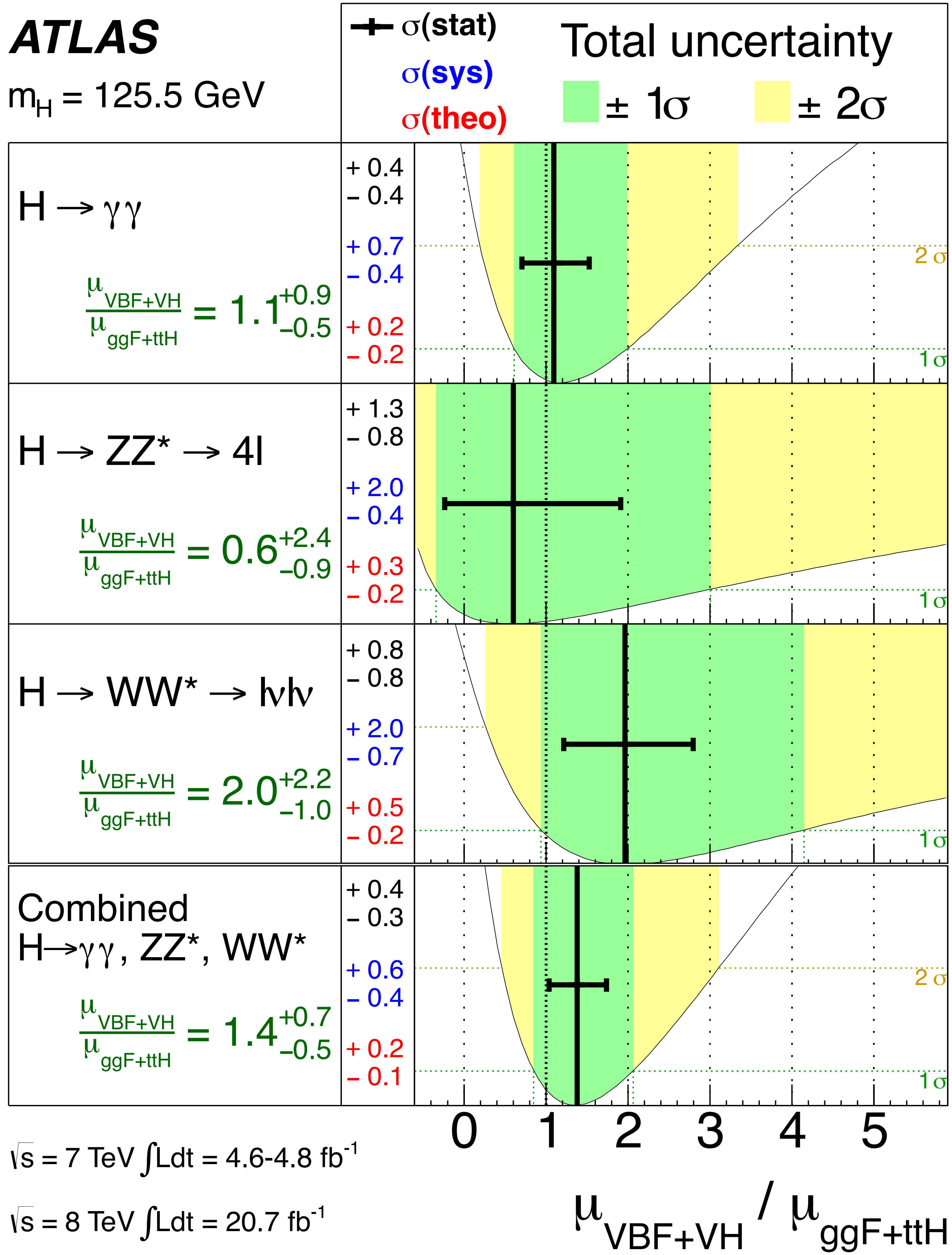
Higgs production modes

Exploiting the categorisations, the signal strength for ggF, VBF, VH and ttH is extracted and combined.

A 3.3σ evidence of VBF production is observed:
All three analysis find a VBF component consistent with the SM expectation



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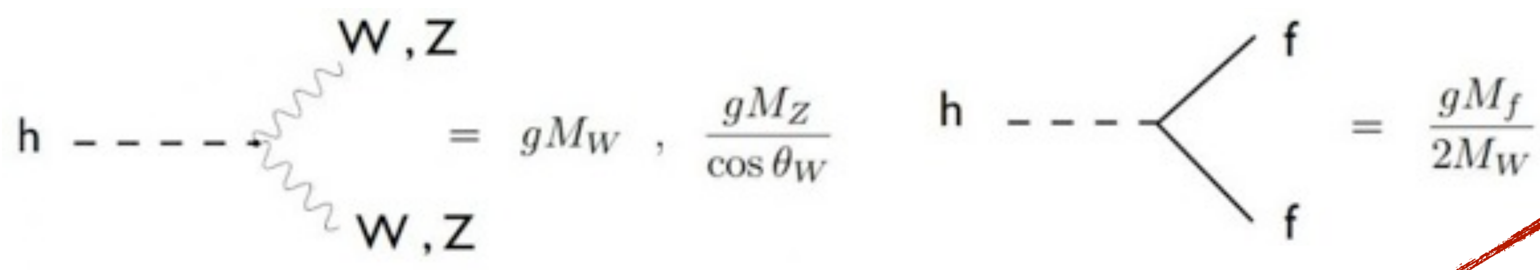
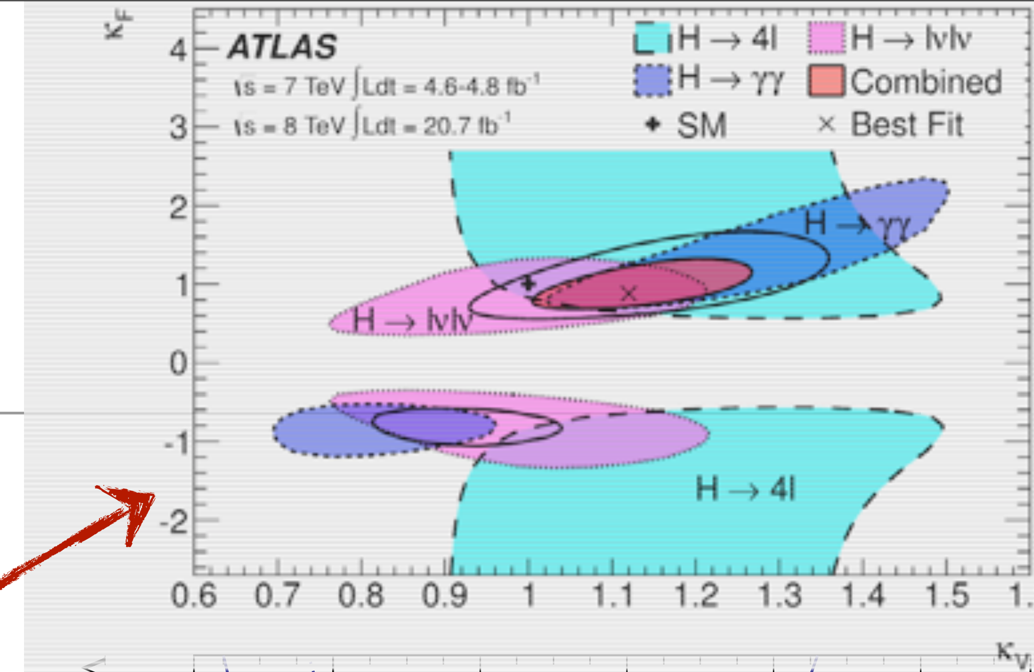
Higgs Couplings



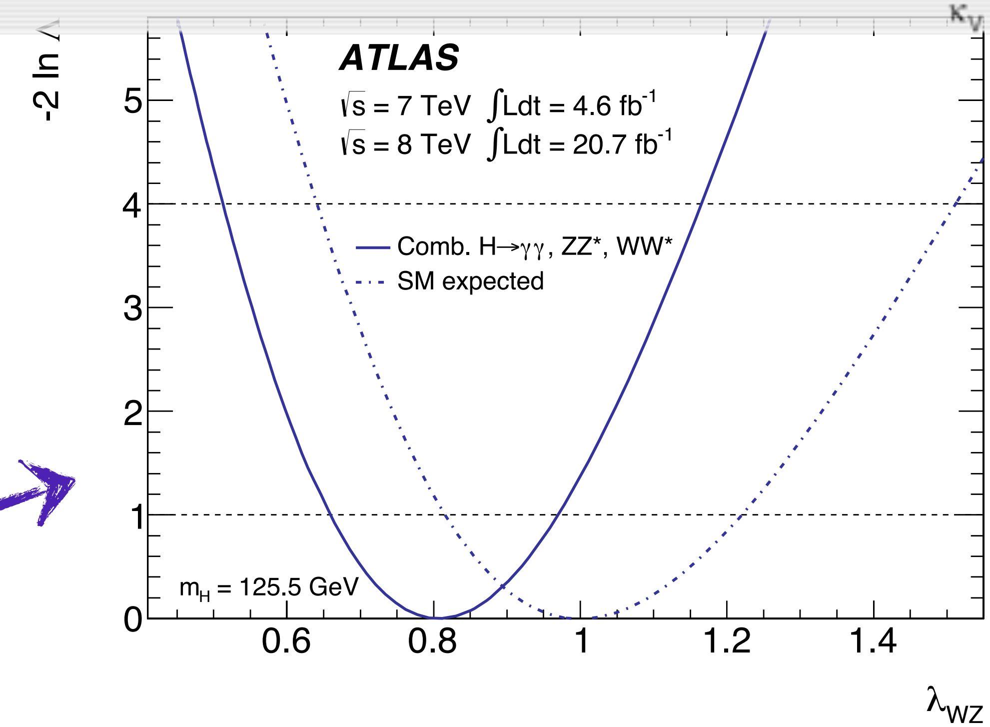
$$= gM_W \,, \quad \frac{gM_Z}{\cos\theta_W} \qquad = \frac{gM_f}{2M_W}$$



Coupling to fermions and bosons: One coupling scale factor for fermions, and one for bosons (assuming custodial symmetry)

κF = 0 (fermiophobic H) excluded at >5σ

2D Compatibility with SM at 12% level

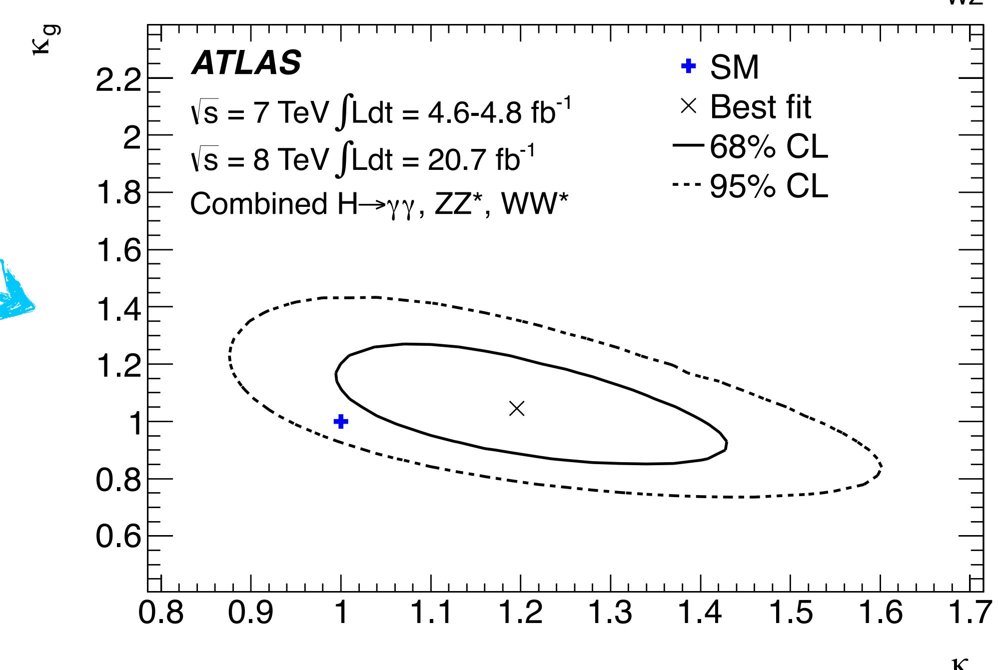


Ratio of couplings to the W and Z bosons

$\lambda_{WZ} = k_W/k_Z$: Test custodial symmetry.

λ = 0.82 ± 0.15

Consistency with SM at 20% level



Constrains on production and decay rates: Test the existence of new heavy particles, that contribute to loop-induced processes (i.e gg→H and H→γγ)

***κg* = 1.04±0.14, κγ = 1.20±0.15.**

2D Compatibility with SM at 14% level

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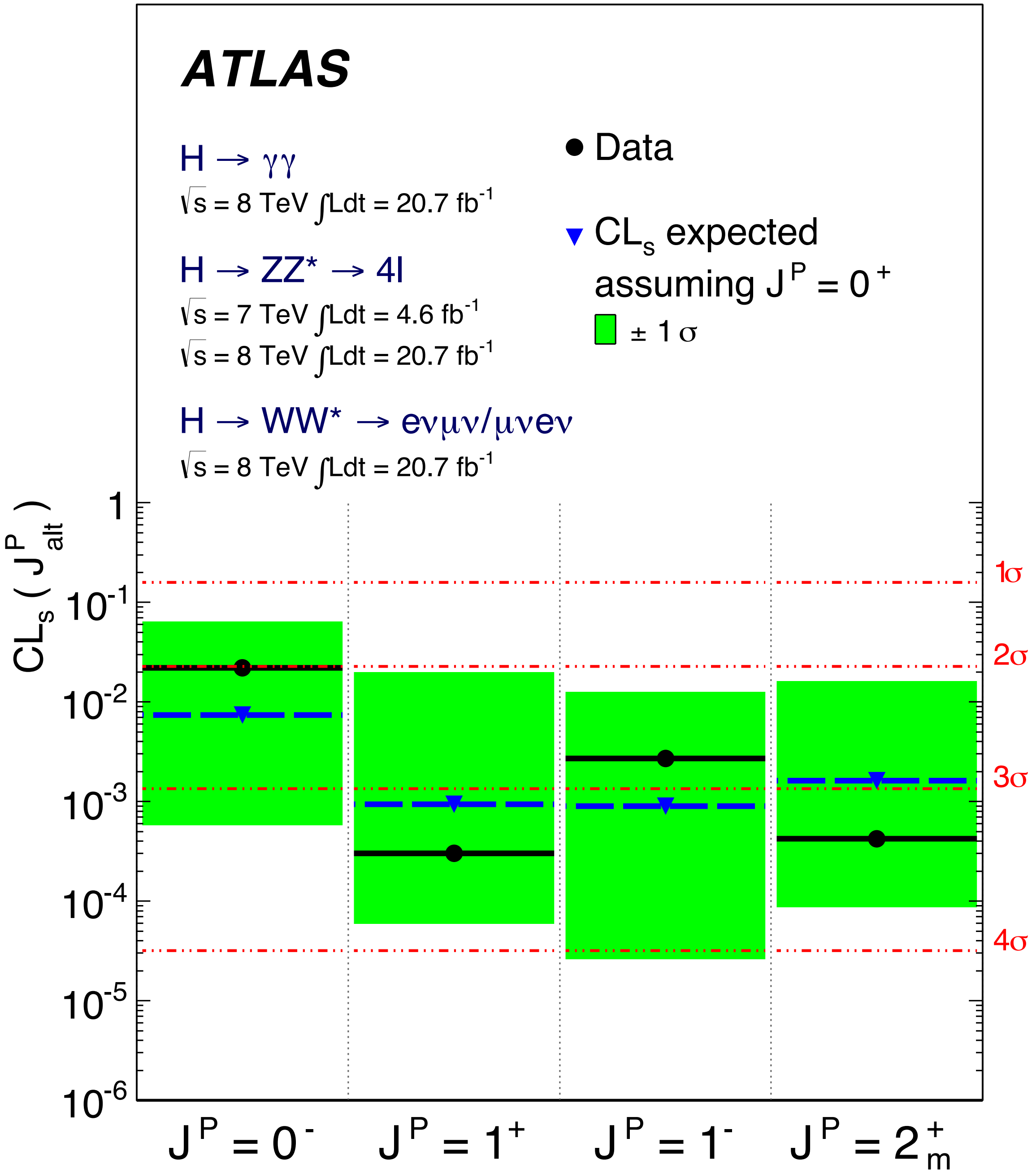
Higgs spin/parity measurement

- Test various options ($J^P=0^-, 0^+, 1^-, 1^+, 2^+$) to verify compatibility with SM hypothesis $J^P = 0+$ using angular and kinematic distributions in:
  - $H \rightarrow \gamma\gamma$ (sensitivity to 2^+, excludes spin 1)
  - $H \rightarrow ZZ^* \rightarrow 4l$ (sensitivity to all spin/parity)
  - $H \rightarrow WW^* \rightarrow l\nu l\nu$ (sensitivity to spin 1/2)



J^P hypo	Exclusion CL	Source	Channel
0^-	97.8%	$H \rightarrow ZZ^* \rightarrow 4l$	ggF only
1^-	99.7%	Combined ZZ^*/WW^*	VBF only
1^+	99.97%	Combined ZZ^*/WW^*	VBF only
2^+	99.9%	Combined $\gamma\gamma/ZZ^*/WW^*$	5 $f_{q\bar{q}}$ points

Combination favours 0^+ hypothesis!

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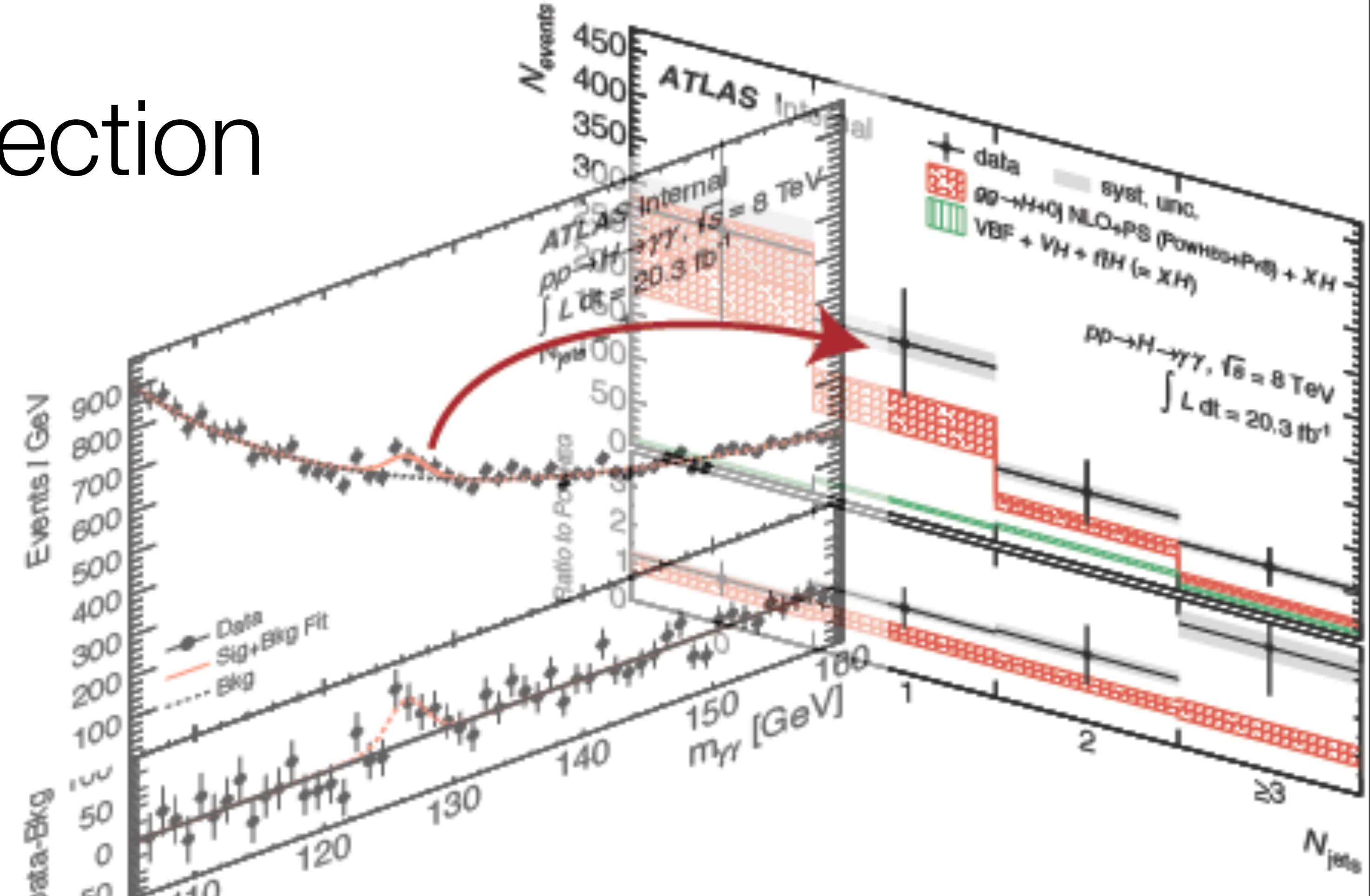
Differential cross-section in the H➛γγ

Define a binning for a variable ($Pt_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, cos(theta)*...):

- For each bin extract yield from fit to $m_{\gamma\gamma}$.
- For each bin, correct for acceptance, efficiency, resolution:"unfolding"



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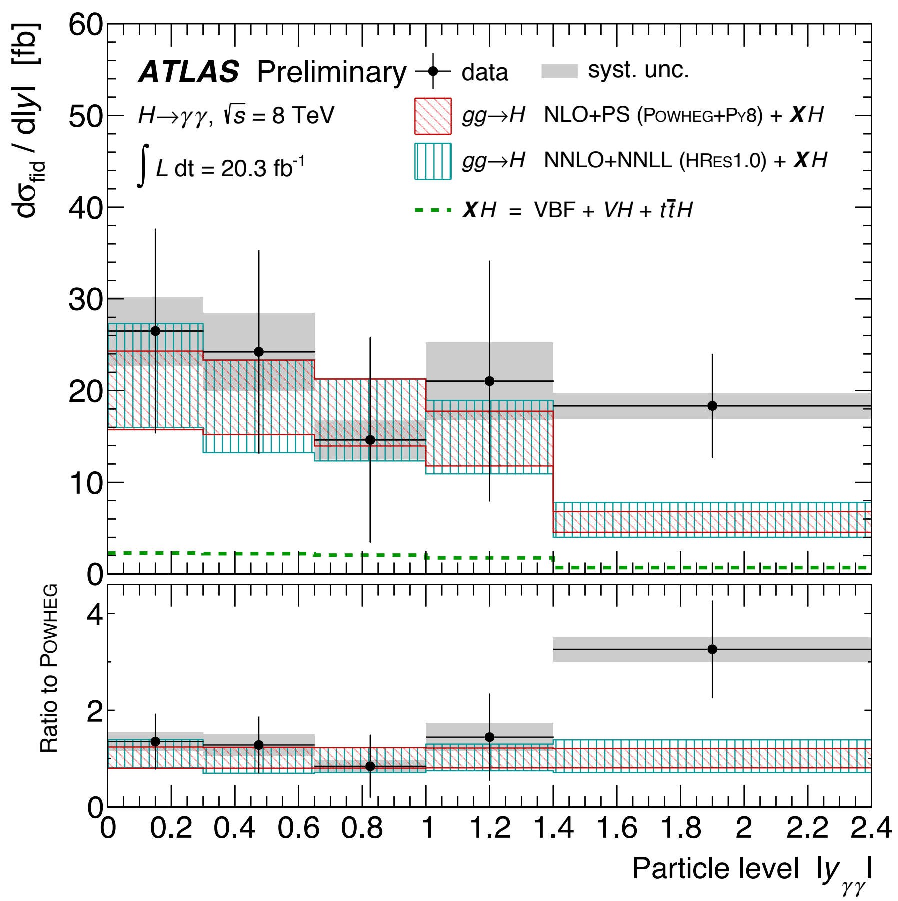
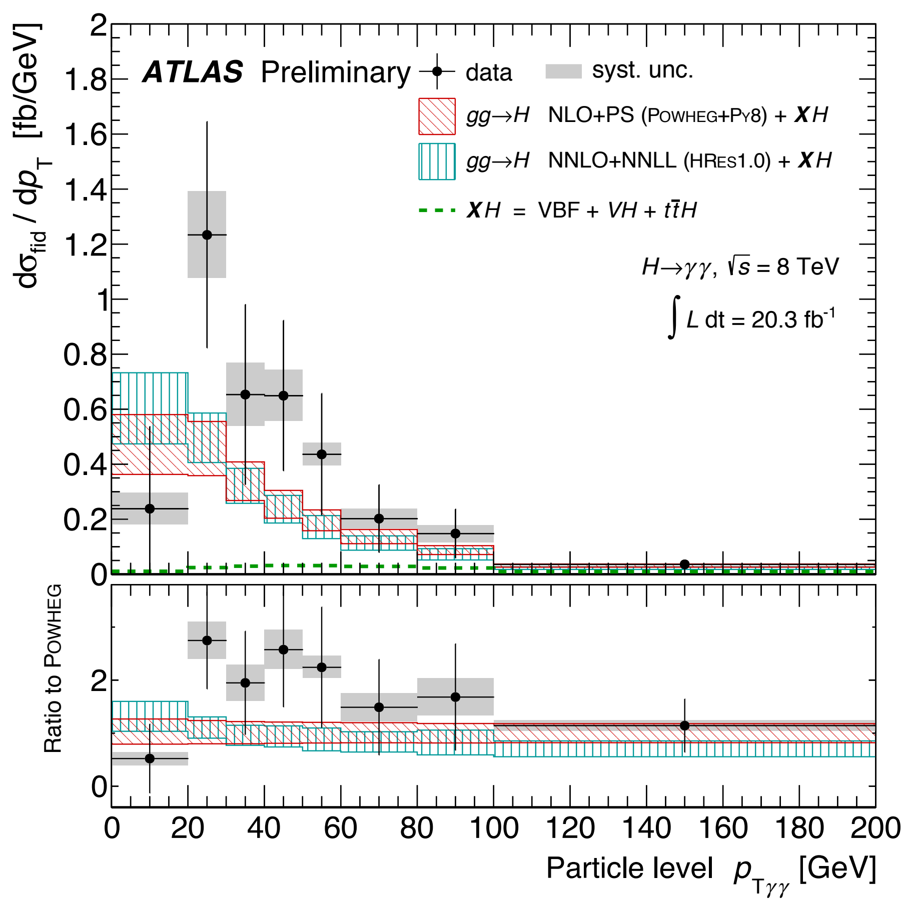
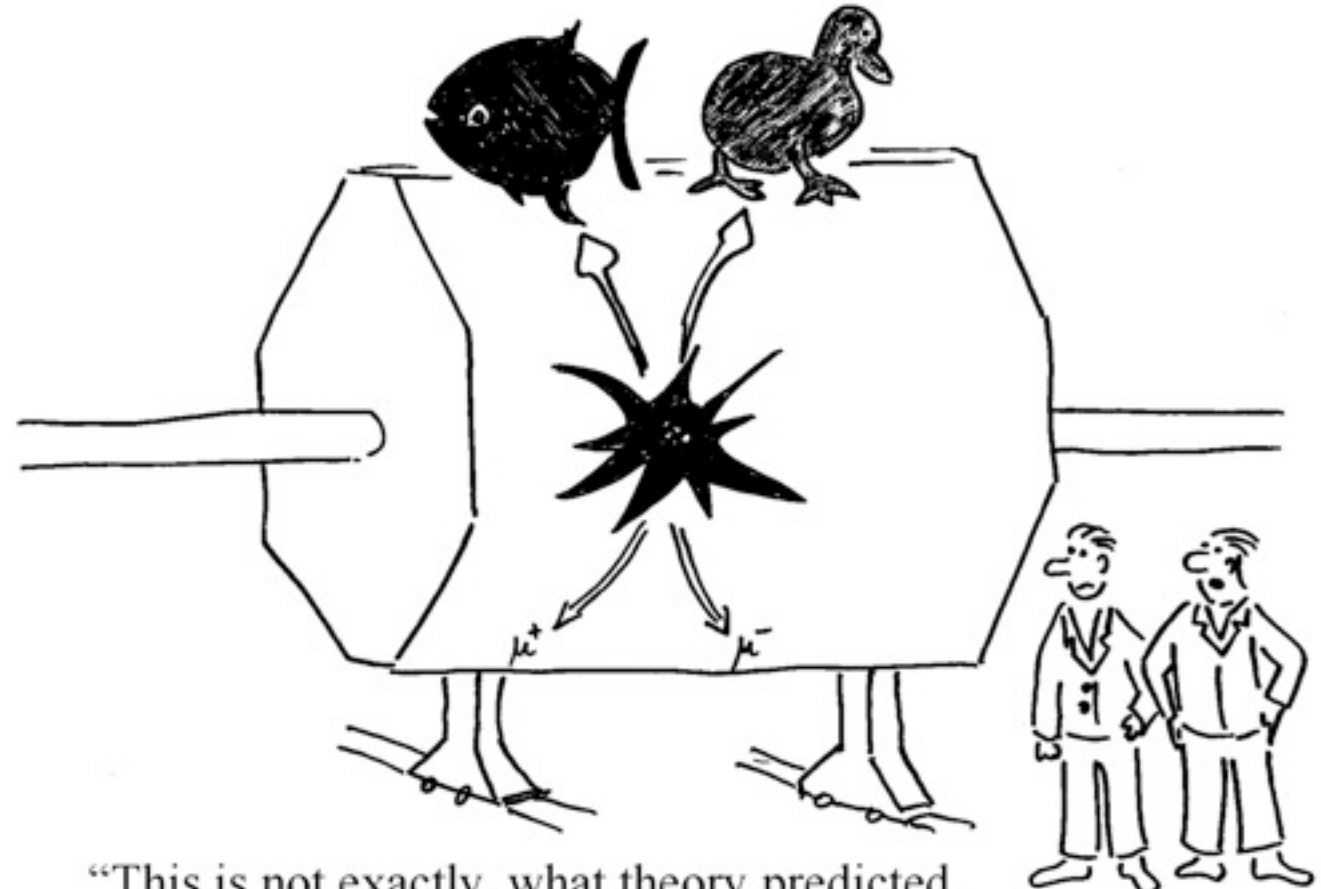




The measured differential cross sections are compared with various theoretical predictions.

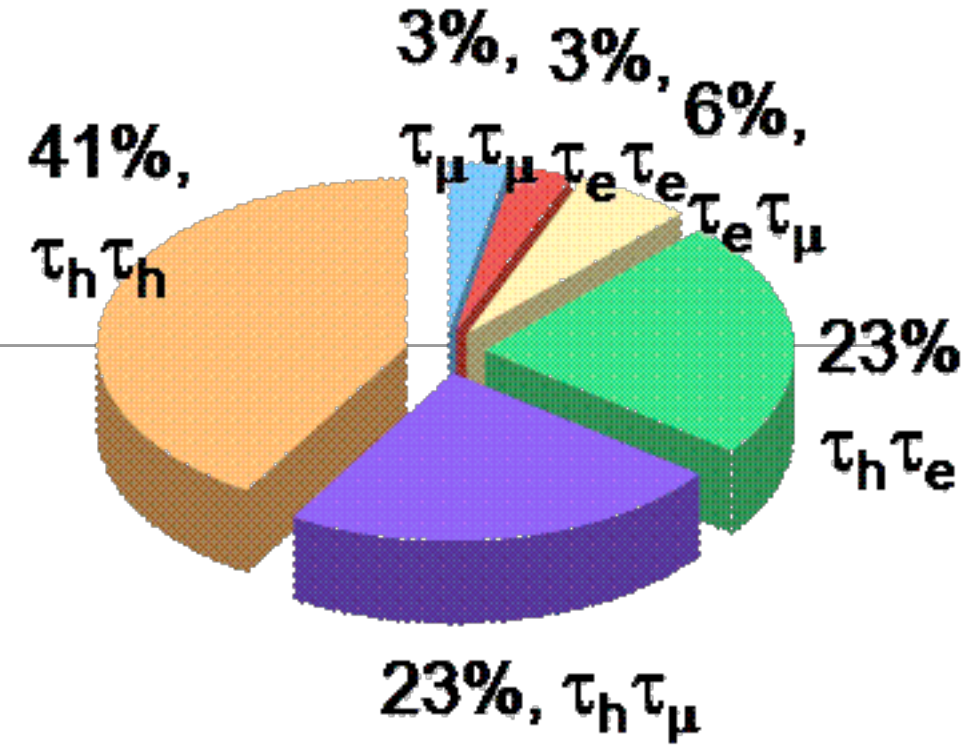
Within the experimental and theoretical uncertainties, no significant deviation from the SM expectation is observed.

Other search channels (SM and BSM)

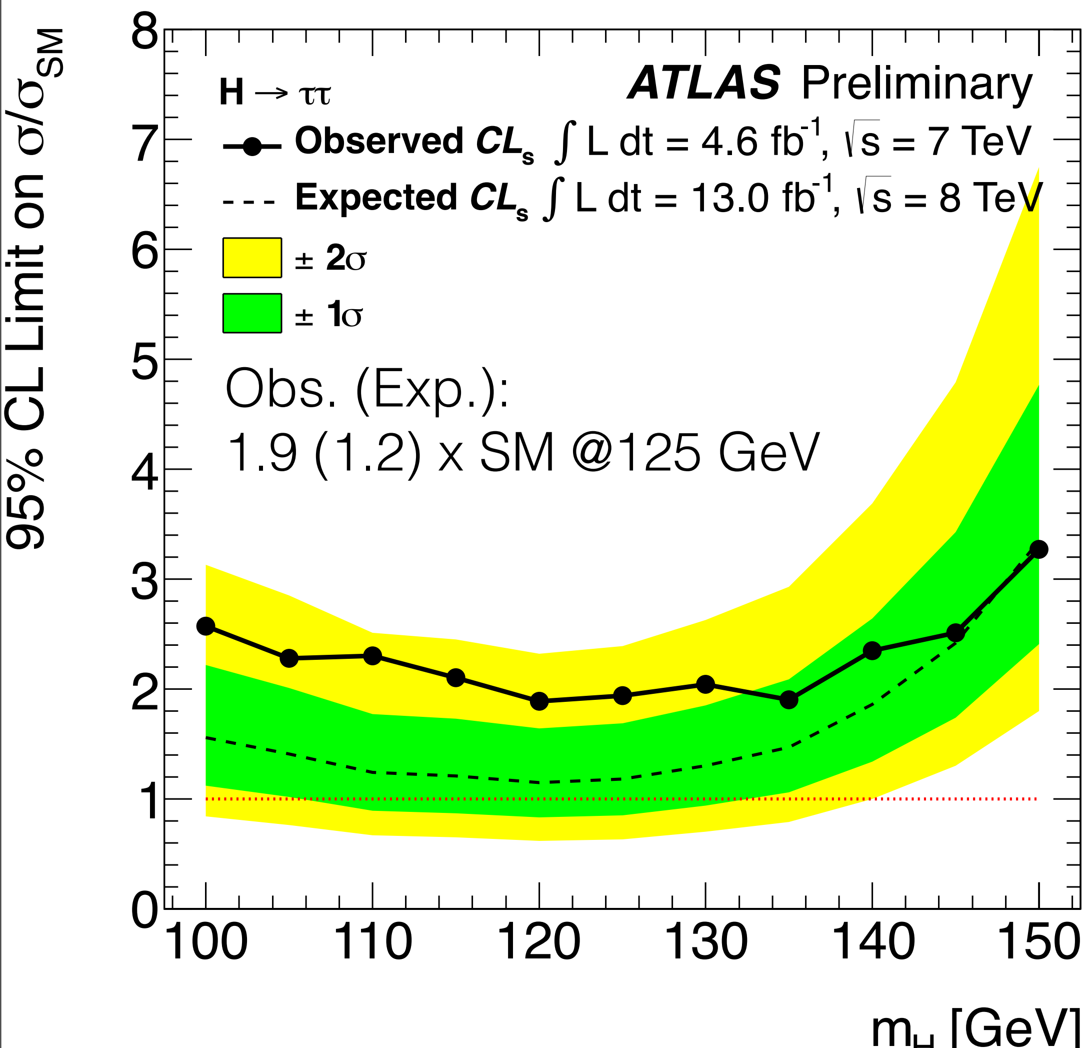


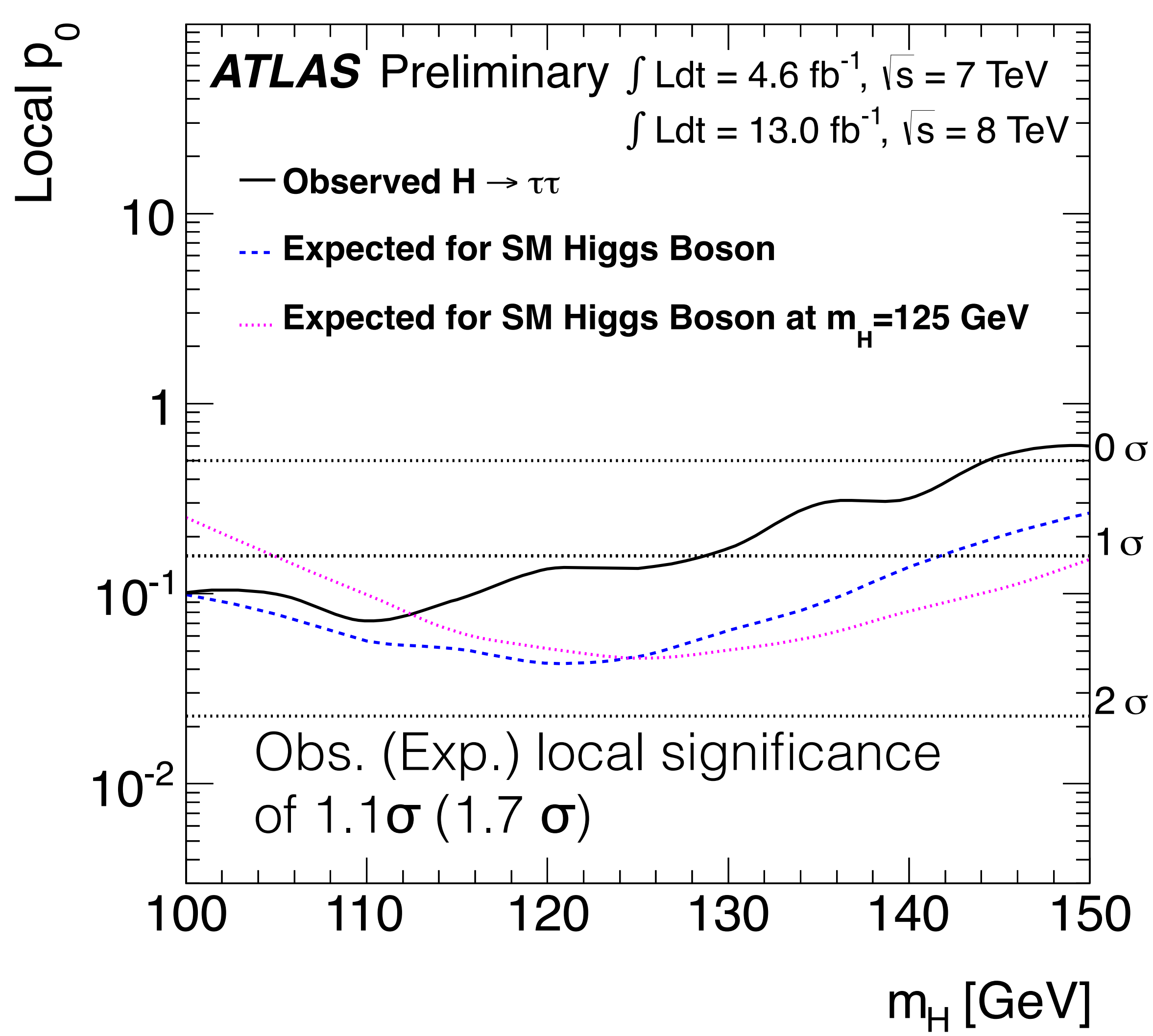
"This is not exactly, what theory predicted for the Higgs decay!"

Decay into fermions $H \rightarrow \tau\tau$



- Search in lep-lep, lep-had and had-had channels
- Each channel affected by different backgrounds
→ cuts optimised separately
- Selected events (in each channel) split in 0, 1, 2 jet case (2 jet case optimised for VBF/VH)



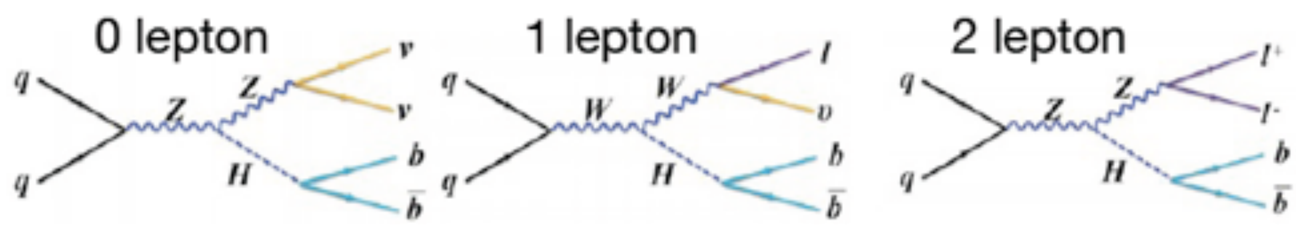


Only 13 fb^{-1} of 8 TeV data. Analysis of full 2012 dataset still ongoing!

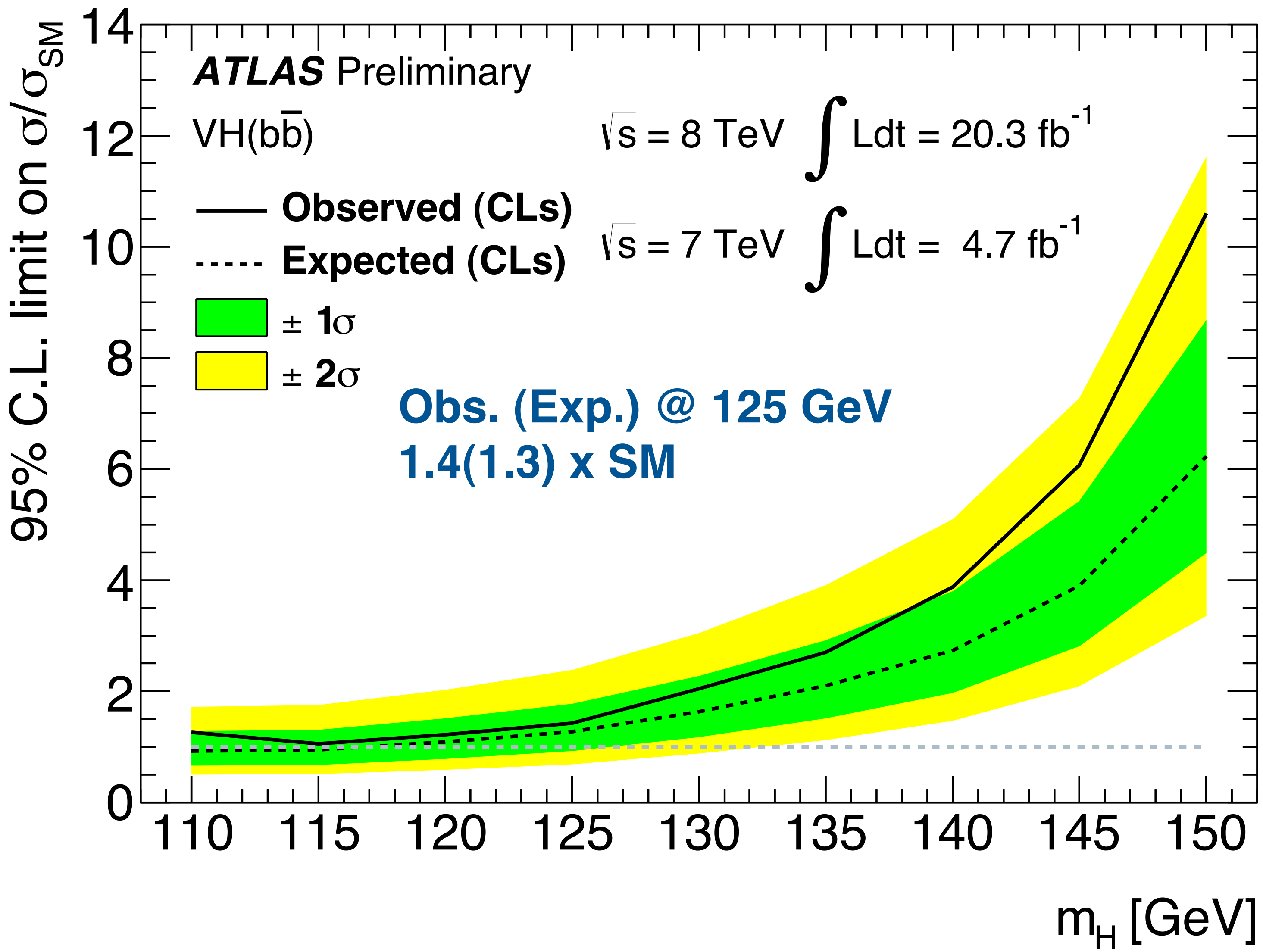
Best fit value of $\mu = 0.7 \pm 0.7$

ATLAS-CONF-2012-160

Decay into fermions VH, H→bb



- High BR (58%) but difficult backgrounds: (WZ, WW, tt, single t, Wt, Wbb, Wcc, Zbb, multijet)
- Categories in different p_T^V to improve sensitivity (0, 90, 120, 160 and 200 GeV)
- Further categorisation used for background estimations from data: number of leptons (0,1,2), number of jets (2,3), number of b-tagged jets (1,2).

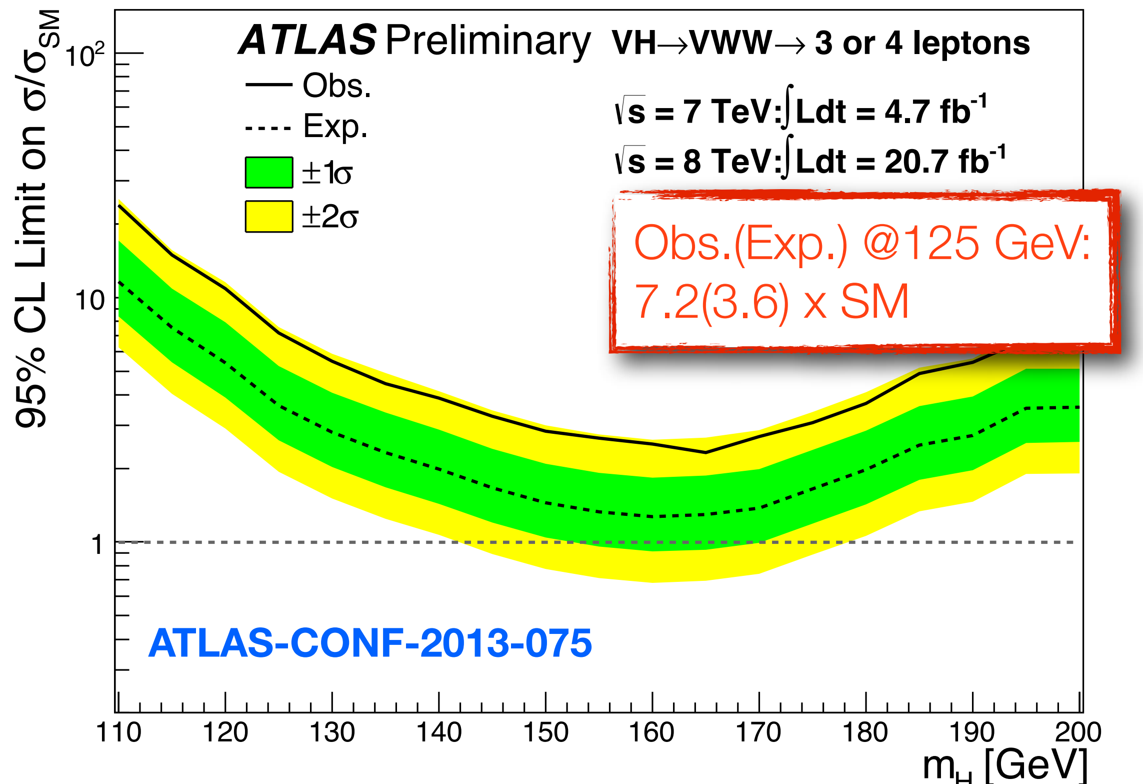


No significant excess observed: data consistent with either SM backgrounds only,and SM backgrounds + Higgs.

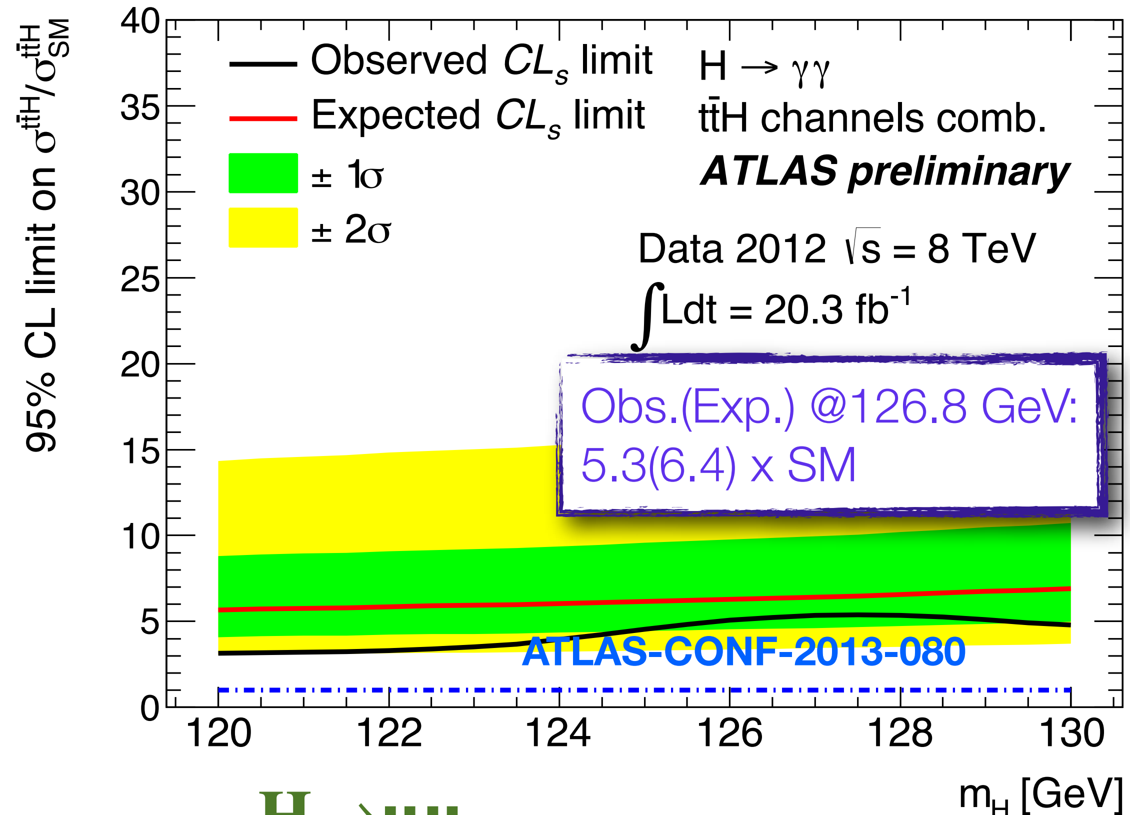
ATLAS-CONF-2012-161

Rare production/decays modes

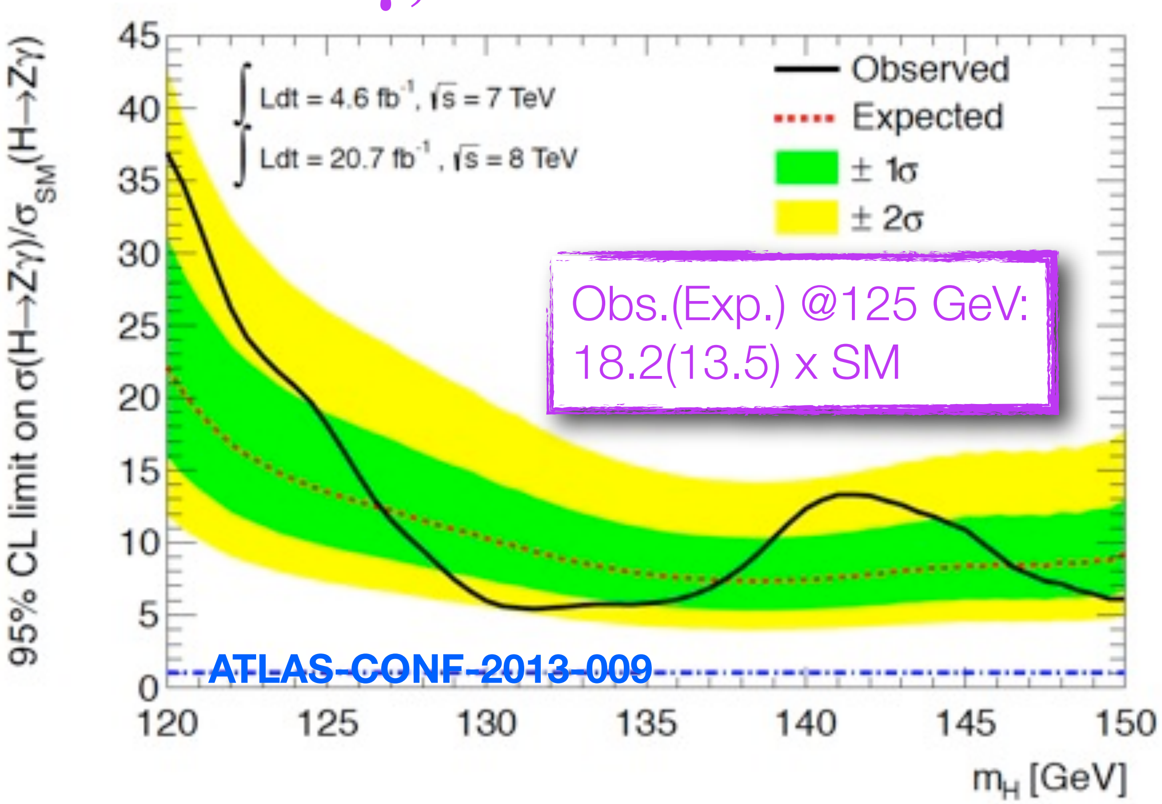
VH, H→ WW(*) (leptonic W decay)



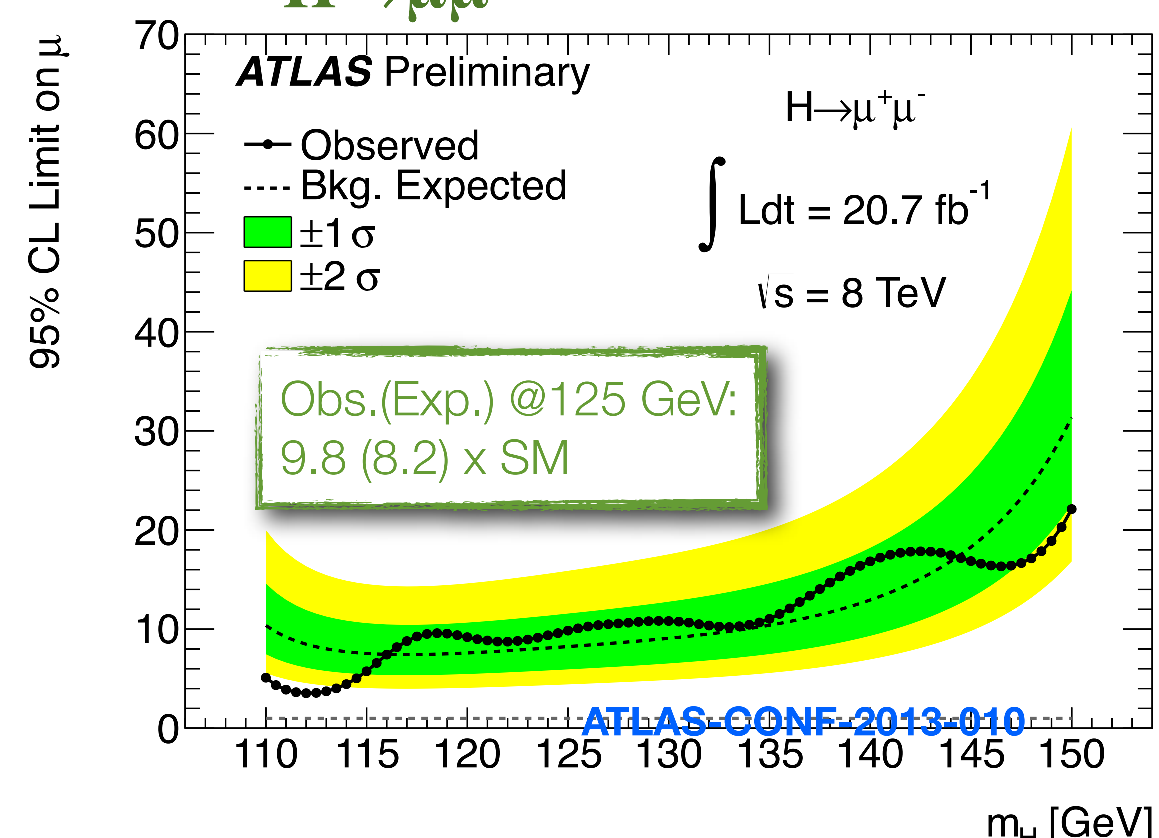
ttH, H→γ γ



H→Zγ, Z→ll



H→μμ

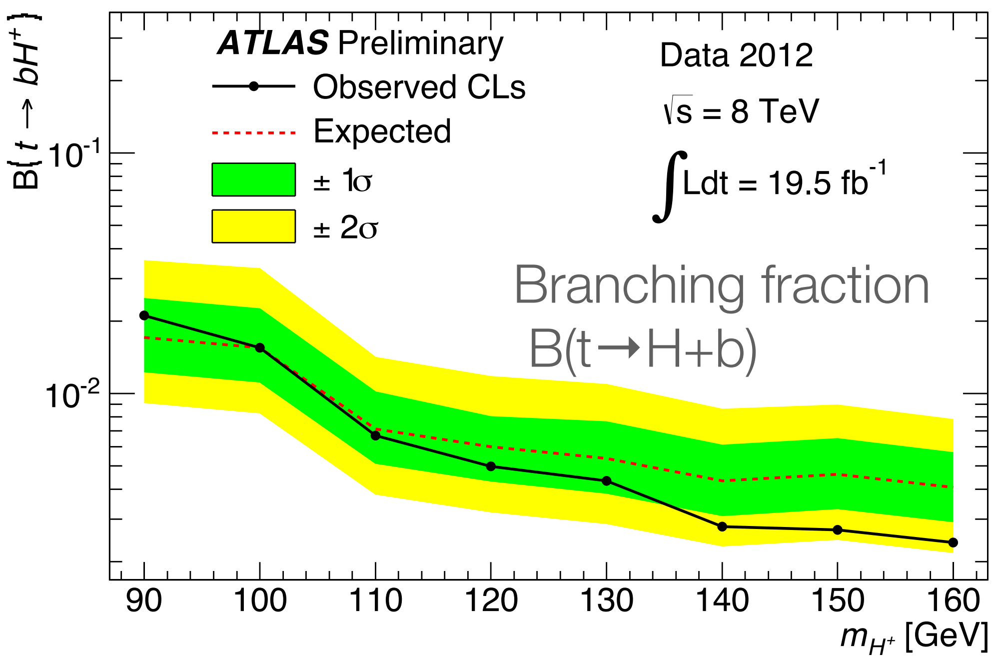


Observation/exclusion sensitivity should be reach in Run II

BSM Higgs -Recent Results

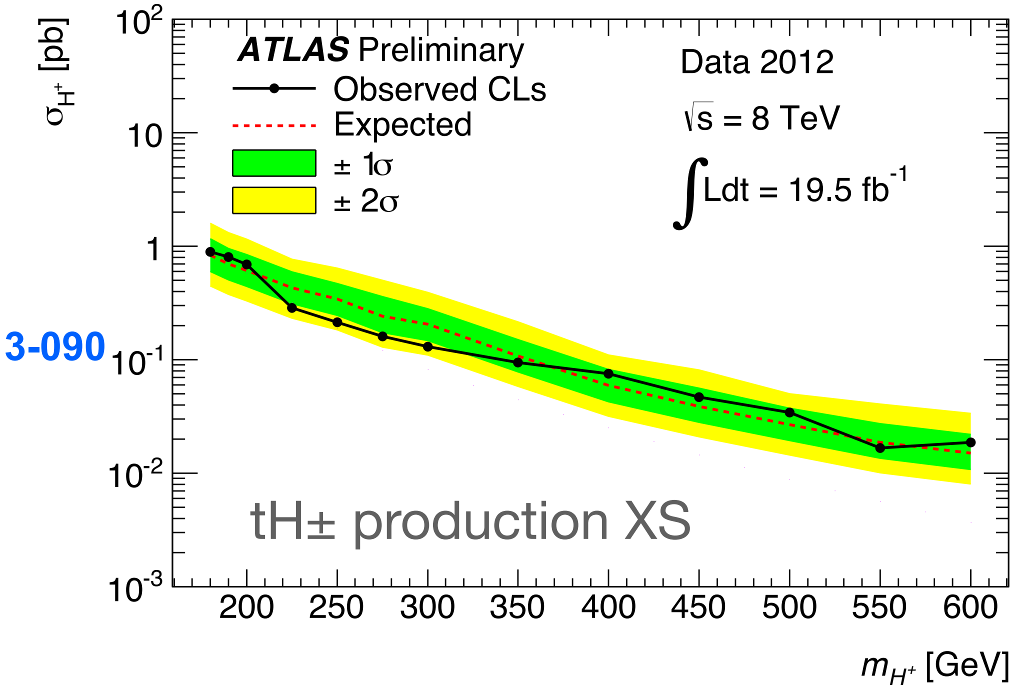
Search for H± → τν + jets (uses the assumption that B(H± → τν = 1.):

Light Higgs (mH± < mt) ttb → H±bWb:

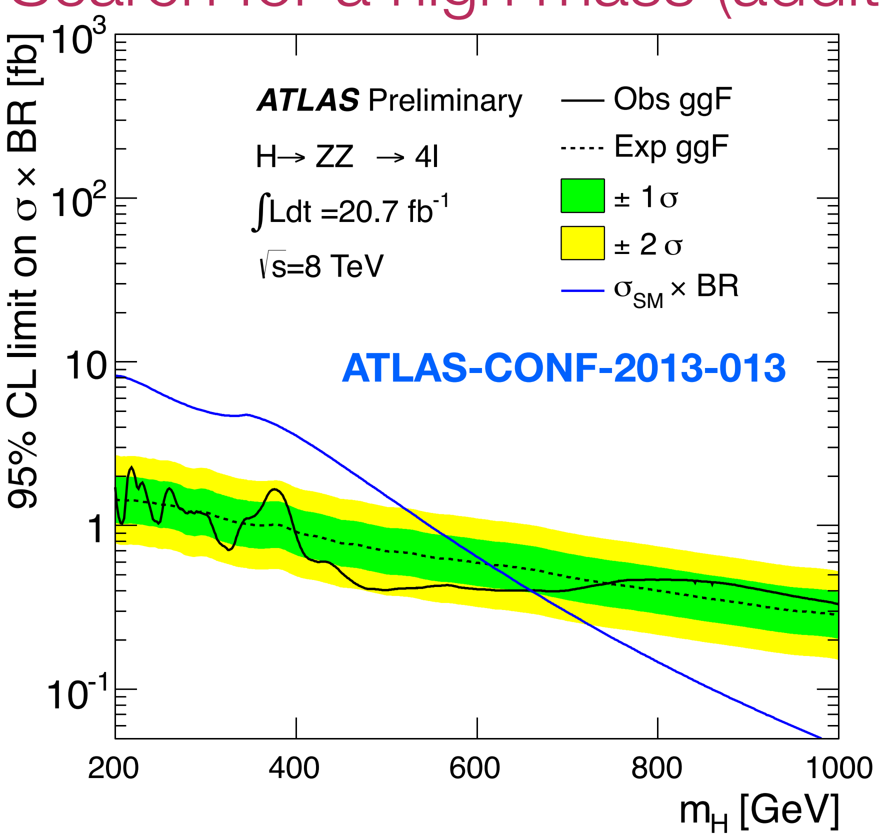


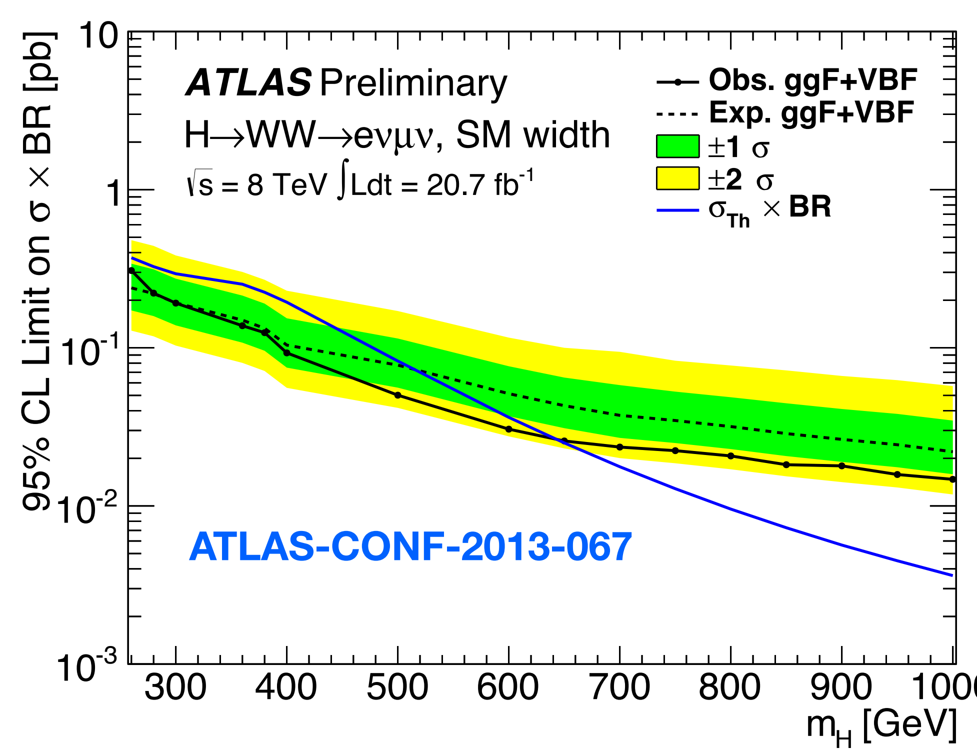
ATLAS-CONF-2013-090

Heavy Higgs (mH± > mt):



Search for a high mass (additional) neutral Higgs in the ZZ and WW decay modes:





Additional SM and BSM Higgs searches

- FCNC in $t \to cH$, $H \to \gamma\gamma$ - upper limit on BR: Obs.(Exp.): 0.83%(0.53%) x SM for 125 GeV at 95% CL [ATLAS-CONF-2013-081]
- $H \to ZZ \to ll\nu\nu$: Excl. 320 - 560 GeV [ATLAS-CONF-2012-016]
- $H \to ZZ \to llqq$: Excl. 300 - 310, 360 - 400 GeV. at 145 GeV 3.5 x SM [ATLAS-CONF-2012-017]
- $H \to WW \to l\nu jj$: at 400 GeV Obs.(Exp.) 2.3(1.6) x SM [ATLAS-CONF-2012-018]
- Higgs in SM with 4th fermion generation: model ruled out [ATLAS-CONF-2011-135]
- Fermiophobic H to diphoton [ATLAS-CONF-2012-013]
- MSSM neutral H [ATLAS-CONF-2012-094]
- NMSSM a1 to $\mu\mu$ [ATLAS-CONF-2011-020]
- NMSSM H to a0a0 to 4γ [ATLAS-CONF-2012-079]

Summary

- LHC-ATLAS Run 1 finished with great success
- After the discovery of the new boson, its properties are being measured. It is looking more like the SM Higgs boson:
  - The combined mass measurement mH=125.5 ± 0.2(stat) $^{+0.5}_{-0.6}$(sys) GeV
  - Combined signal strength μ = 1.3 ± 0.14(stat) ± 0.15 (sys)
  - The spin/parity measurements favour SM $J^P = 0^+$
  - Evidence of VBF production at 3.3σ
  - No direct evidence for fermionic decays yet, but results are consistent with the SM Higgs. Evidence of the coupling to fermions to > 5σ
  - First results on various rare production decay modes and BSM Higgs models.
- ATLAS is preparing for LHC Run II (13/14 TeV and 10^{34} cm $^{-2}$ s $^{-1}$):
  - Rare SM Higgs production/decays should achieve observation sensitivity.
  - More precise measurements to test/challenge the SM predictions
  - Look for surprises... Exciting times ahead, stay tuned!!...

Back-up

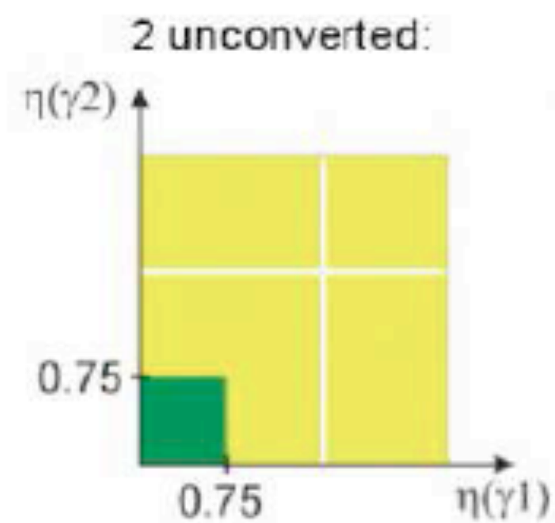
Categories

Both unconverted:

- Central
- Rest

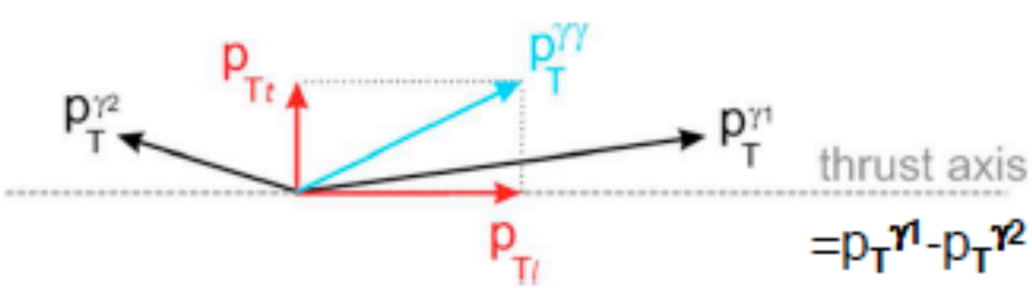
At least one converted:

- Central
- Transition
- Rest

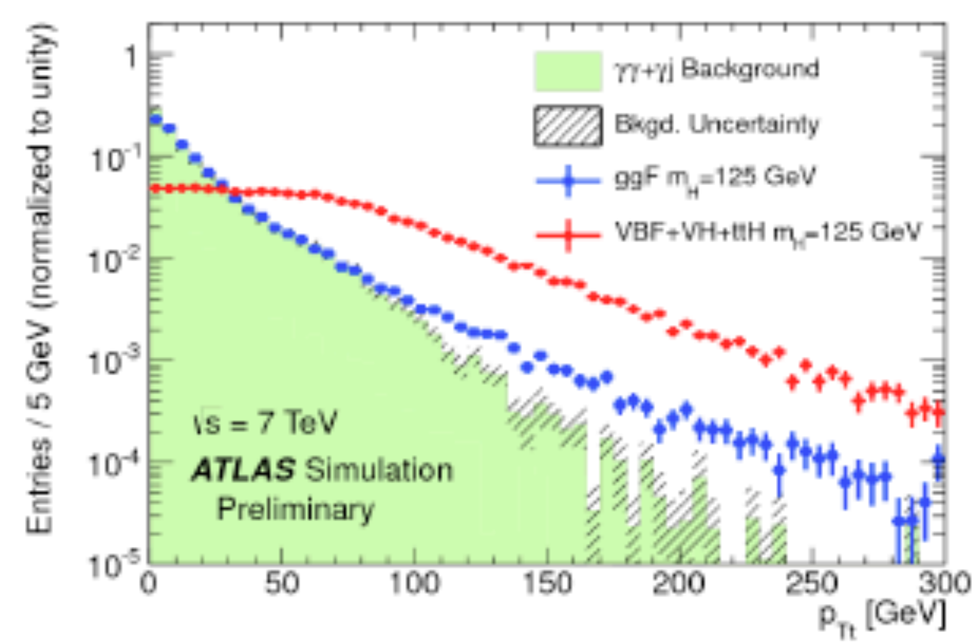


Resolution:

Good
Medium
Poor



Variable p_{Tt} is strongly correlated with diphoton p_T but has better detector resolution and retains a monotically falling invariant mass for background



Higgs to di-photon Uncertainties

Source	Uncertainty (%)
On signal yield	
Photon identification	±2.4
Trigger	±0.5
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

Higgs to 4 leptons
Uncertainties

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

WW Selection

Category	$N_{jet} = 0$	$N_{jet} = 1$	$N_{jet} \geq 2$
Pre-selection	Two isolated leptons ($\ell = e, \mu$) with opposite charge Leptons with $p_T^{lead} > 25$ and $p_T^{sublead} > 15$ $e\mu + \mu e$: $m_{\ell\ell} > 10$ $ee + \mu\mu$: $m_{\ell\ell} > 12$, $\vert m_{\ell\ell} - m_Z \vert > 15$		
Missing transverse momentum and hadronic recoil	$e\mu + \mu e$: $E_{T,rel}^{miss} > 25$ $ee + \mu\mu$: $E_{T,rel}^{miss} > 45$ $ee + \mu\mu$: $p_{T,rel}^{miss} > 45$ $ee + \mu\mu$: $f_{recoil} < 0.05$	$e\mu + \mu e$: $E_{T,rel}^{miss} > 25$ $ee + \mu\mu$: $E_{T,rel}^{miss} > 45$ $ee + \mu\mu$: $p_{T,rel}^{miss} > 45$ $ee + \mu\mu$: $f_{recoil} < 0.2$	$e\mu + \mu e$: $E_T^{miss} > 20$ $ee + \mu\mu$: $E_T^{miss} > 45$ $ee + \mu\mu$: $E_{T,STVF}^{miss} > 35$ -
General selection	- $\vert \Delta\phi_{\ell\ell,MET} \vert > \pi/2$ $p_T^{\ell\ell} > 30$	$N_{b\text{-jet}} = 0$ - $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto	$N_{b\text{-jet}} = 0$ $p_T^{tot} < 45$ $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto
VBF topology	- - - -	- - - -	$m_{jj} > 500$ $\vert \Delta y_{jj} \vert > 2.8$ No jets ($p_T > 20$) in rapidity gap Require both ℓ in rapidity gap
$H \to WW^{(*)} \to \ell\nu\ell\nu$ topology	$m_{\ell\ell} < 50$ $\vert \Delta\phi_{\ell\ell} \vert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_T	$m_{\ell\ell} < 50$ $\vert \Delta\phi_{\ell\ell} \vert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_T	$m_{\ell\ell} < 60$ $\vert \Delta\phi_{\ell\ell} \vert < 1.8$ - Fit m_T

BSM Higgs -Recent Results

Search for $H^{\pm} \rightarrow \tau\nu$ + jets in mass range 180 – 600 GeV
(uses the the assumption that $B(H^{\pm} \rightarrow \tau\nu = 1.)$: