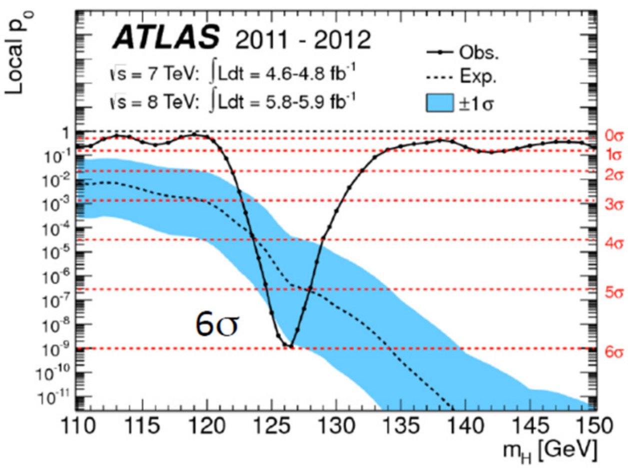
Summary of Higgs Results from ATLAS

Paul Thompson (University of Birmingham)

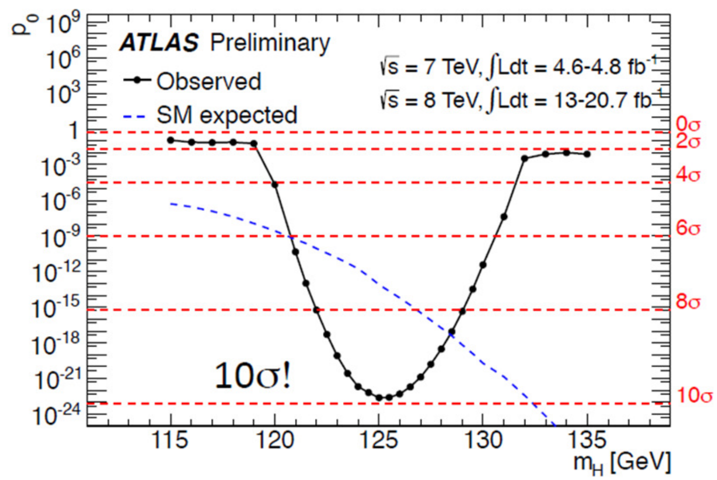
On behalf of the ATLAS Collaboration*

Triggering Discoveries in High Energy Physics

Jammu, September, 2013



July 4th 2012 Discover Higgs-like boson



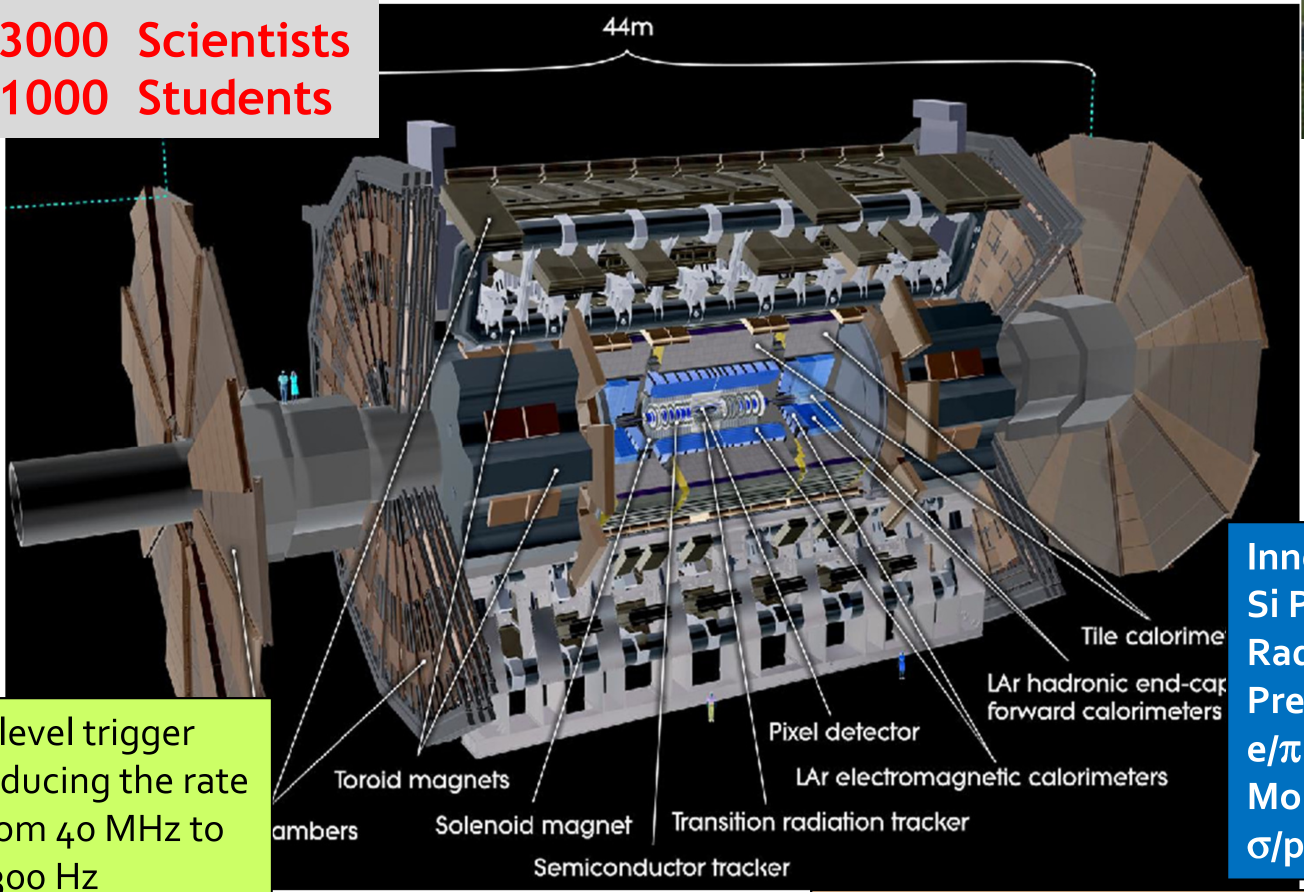
July 2013 SM Higgs boson

* With thanks to Bing Zhou IHSP2013

Muon Spectrometer (|η|<2.7) : air-core toroids with muon chambers (tracking and trigger) to measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

38 Countries
174 Institutions
3000 Scientists
1000 Students

ATLAS Detector



Length : ~ 44 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

Inner Detector (|η|<2.5, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8 \times 10^{-4}\, p_T (\text{GeV}) \oplus 0.015$

3-level trigger reducing the rate from 40 MHz to ~300 Hz

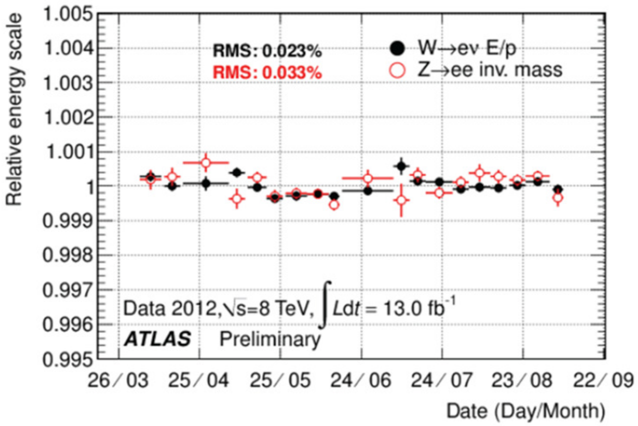
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

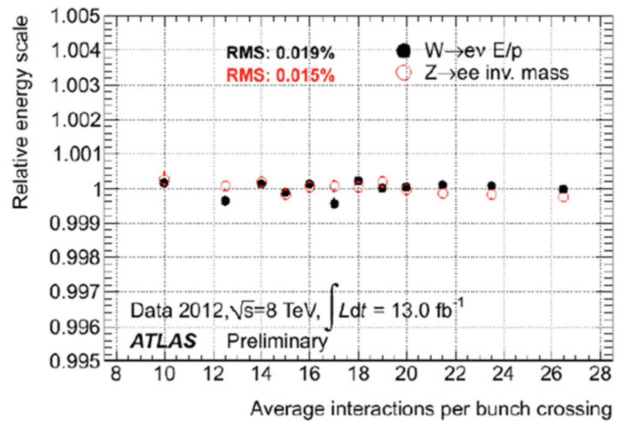
HAD calorimetry (|η|<5): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

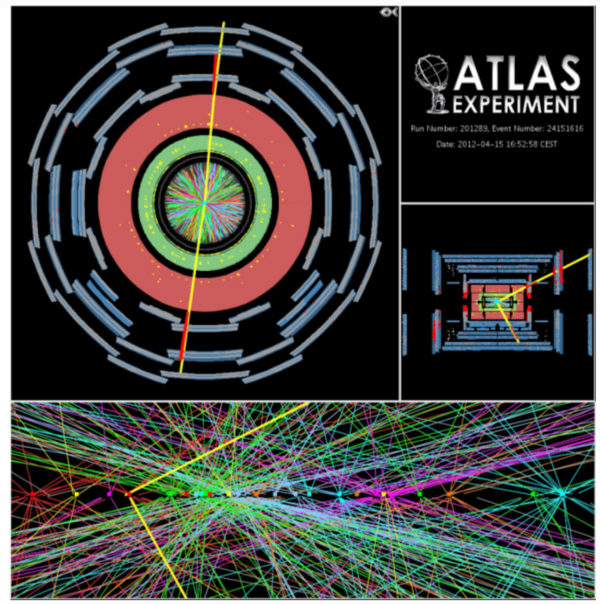
Everything worked!

Electrons

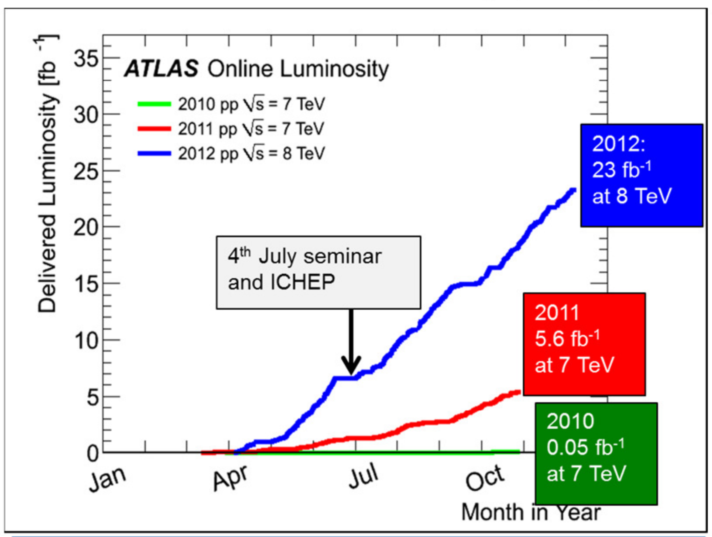
Stability of EM calorimeter response vs time/pile-up better than 0.1%







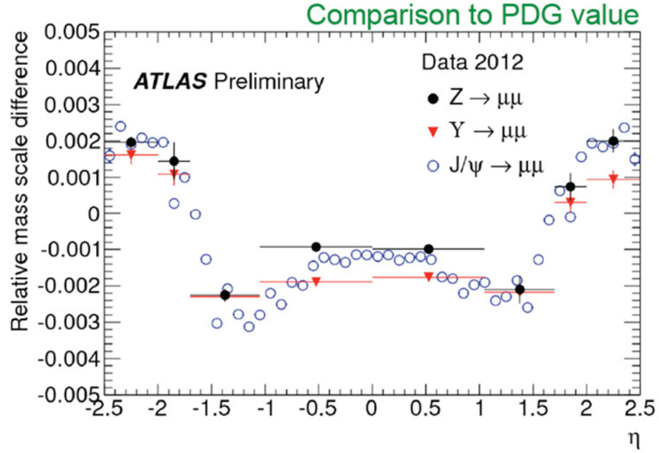
Challenging pile-up

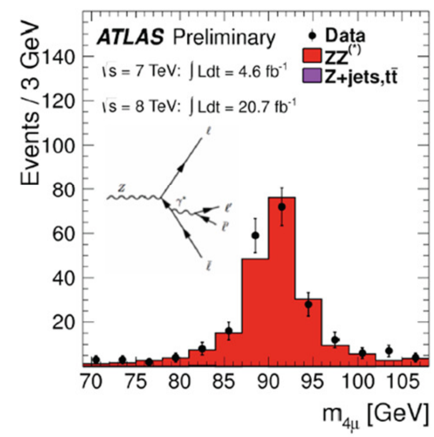


ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.5%										

Muons

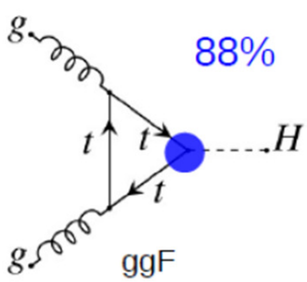
Comparison to PDG value

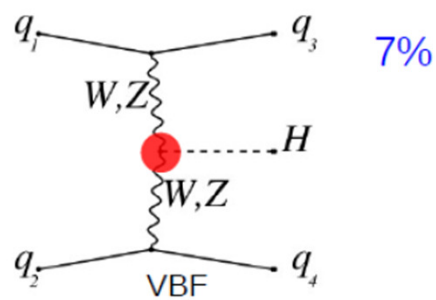


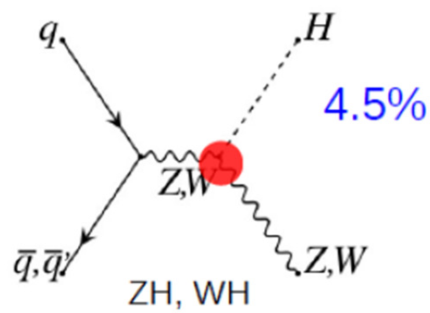


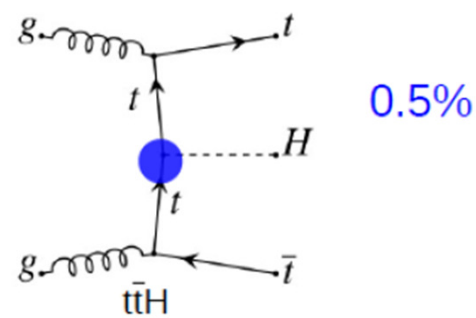
Is the New Boson The SM Higgs?

❖ **Higgs production (m_H = 125 GeV)**

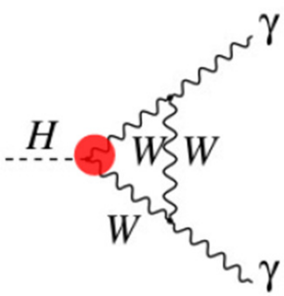


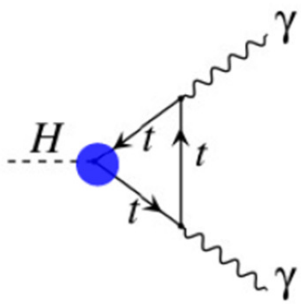


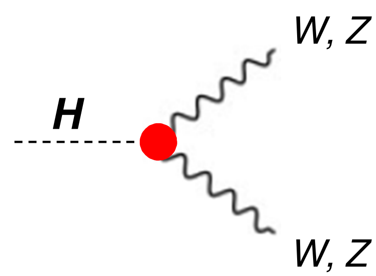


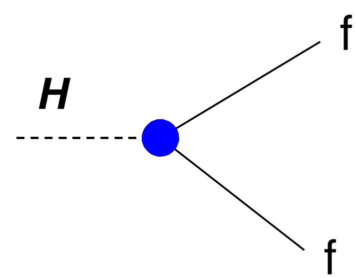


❖ **Higgs decays**









❖ **Couplings (new force!)**

● : fermions

● : vector bosons

g_F (Yukawa coupling) $=\sqrt{2} \times m_F/\nu$

g_V (Gauge coupling) $= 2m_V^2/\nu$

(ν is the vacuum expectation value)

❖ **Spin-Parity**

New -- After the Higgs Discovery

- **$H \rightarrow \gamma\gamma$, ZZ*, WW* analysis updates based on full 2011-2012 dataset (4.6 fb^{-1} @ 7TeV, 20.7 fb^{-1} @ 8TeV)**
- Higgs mass from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$
- Signal strengths ($\mu = \sigma/\sigma_{SM}$)
- Sensitivity to vector boson fusion (VBF)
- Comparison of decay rates
- Couplings
- Spin and parity
- Searches in rare decay modes

New ATLAS Higgs Papers

arXiv:1307.1427 Sub. Phys. Lett. B (Mass, Couplings)
arXiv:1307.1432 Sub. Phys. Lett. B (Spin-parity)

New ATLAS Higgs Pub Notes

ATLAS-CONF-2013-012 ($\gamma\gamma$)

Property measurement:
ATLAS-CONF-2013-013 (ZZ*)
ATLAS-CONF-2013-031 (WW*)
ATLAS-CONF-2013-040 (Spin)
ATLAS-CONF-2013-075 (WW*)
ATLAS-CONF-2013-029 ($\gamma\gamma$)
ATLAS-CONF-2013-079 ($VH \rightarrow bb$)

ATLAS-CONF-2012-160 ($H \rightarrow \tau\tau$)

ATLAS-CONF-2013-009($Z\gamma$)

Searches:
ATLAS-CONF-2013-010($\mu\mu$)
ATLAS-CONF-2013-067(HMH→WW)
ATLAS-CONF-2013-072 (diff σ $H \rightarrow \gamma\gamma$)
ATLAS-CONF-2013-075(VH→WW)
ATLAS-CONF-2013-080(tt +$H \rightarrow \gamma\gamma$)
ATLAS-CONF-2013-081(t→cH)

Update on H→ VV

ZZ*, $\gamma\gamma$, WW*, Zγ

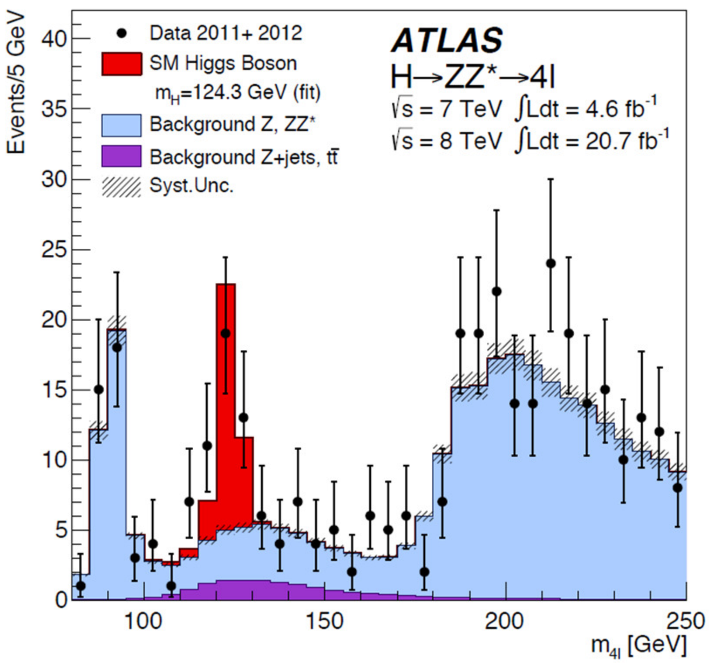
H→ ZZ*→ 4l

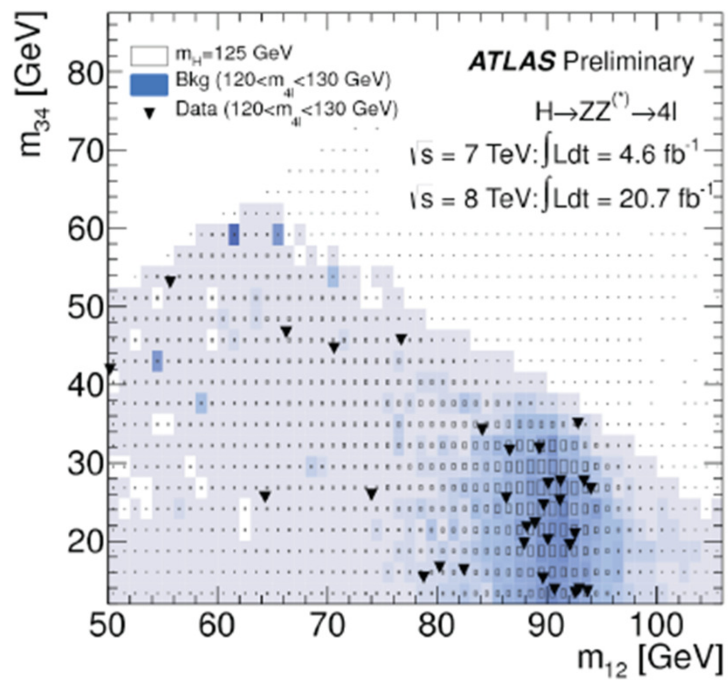
arXiv:1307.1427

BR (H→ZZ*) = 2.63% (M_H= 125 GeV). Total ~65 H→ ZZ*→ 4l events produced at LHC

DataSet	Production	background	Exp. Signal	S/B
~25 fb^{-1}	ggF, (VBF,VH)	ZZ*, Z+X, tt	~16	~1.4

Events in 3 categories: VBF(jets), VH(lepton) and ggF-like (the rest)

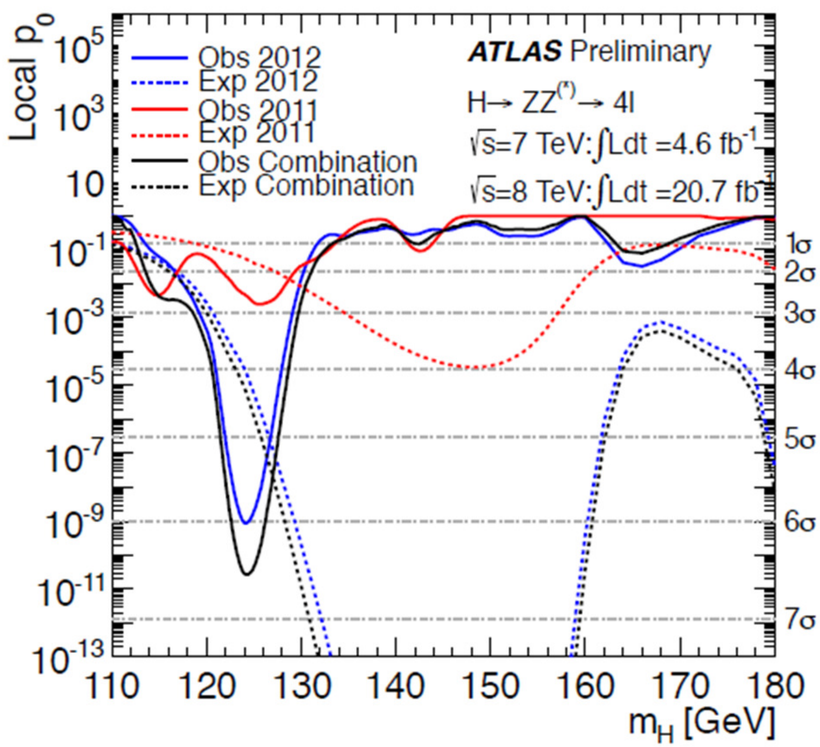


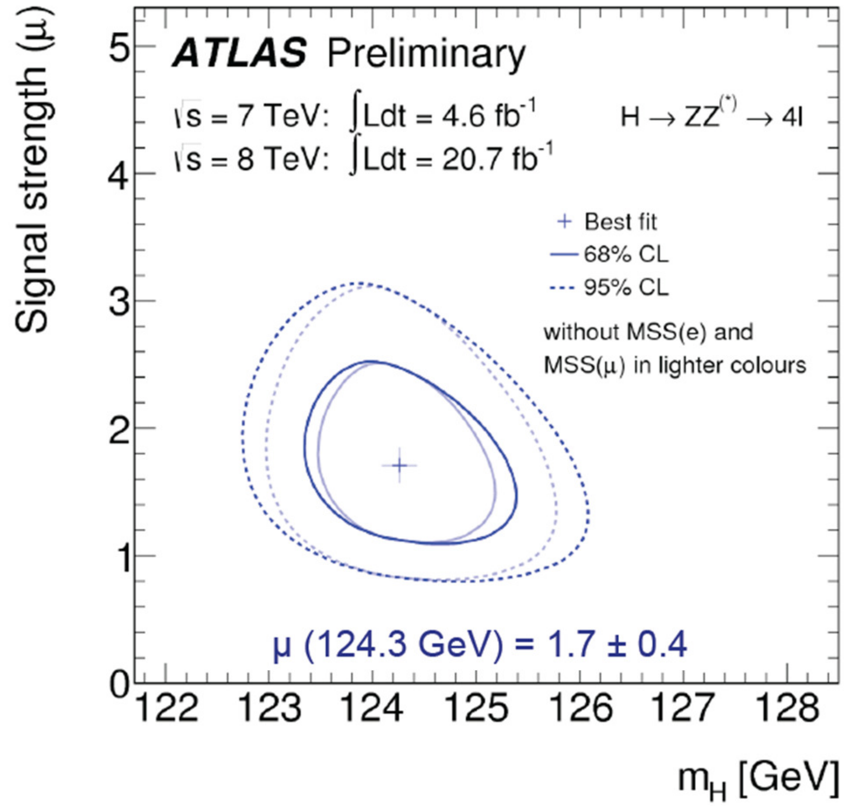


Huge effort on lepton ID efficiencies, and calibration of mass scale for m_{ll} and m_{4l}

H→ ZZ*→ 4l

arXiv:1307.1427





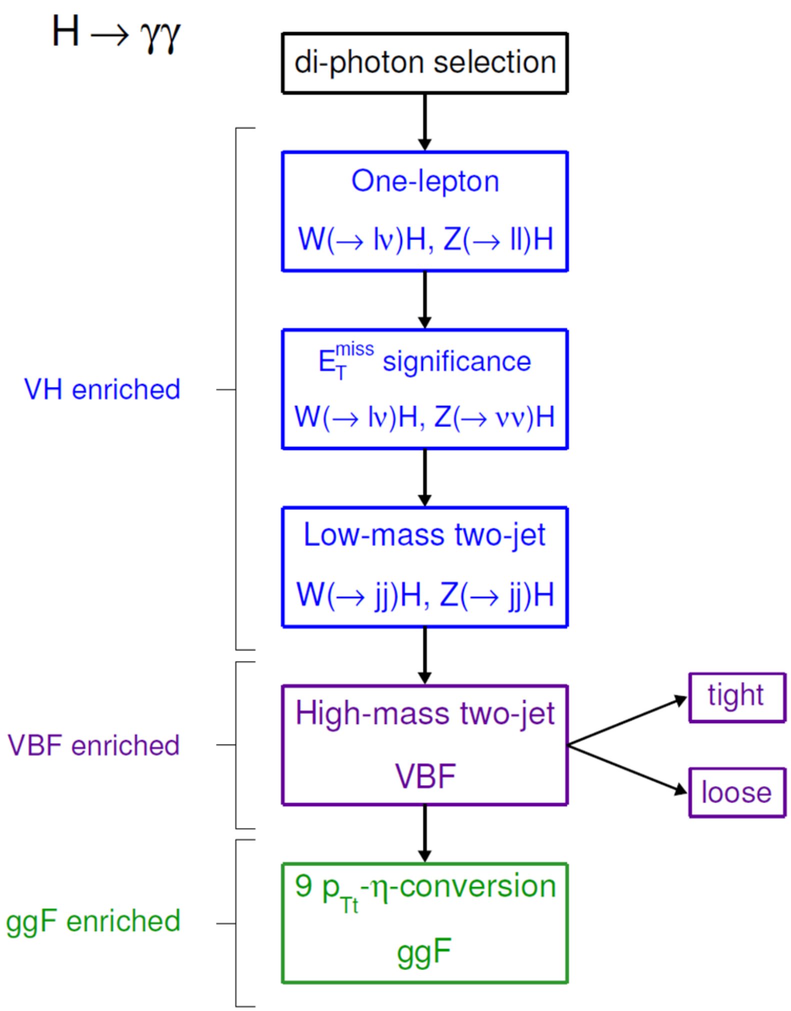
Signal Significance :
6.6σ (4.4σ expected)
Exceeding discovery criteria

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

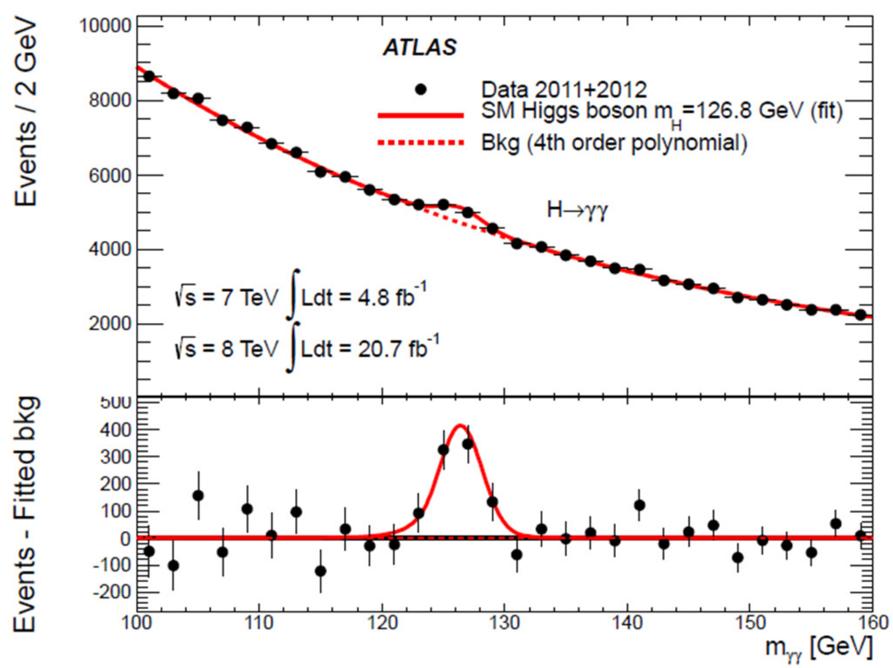
$H \rightarrow \gamma\gamma$

arXiv:1307.1427

Flow-chart of the event categorisation

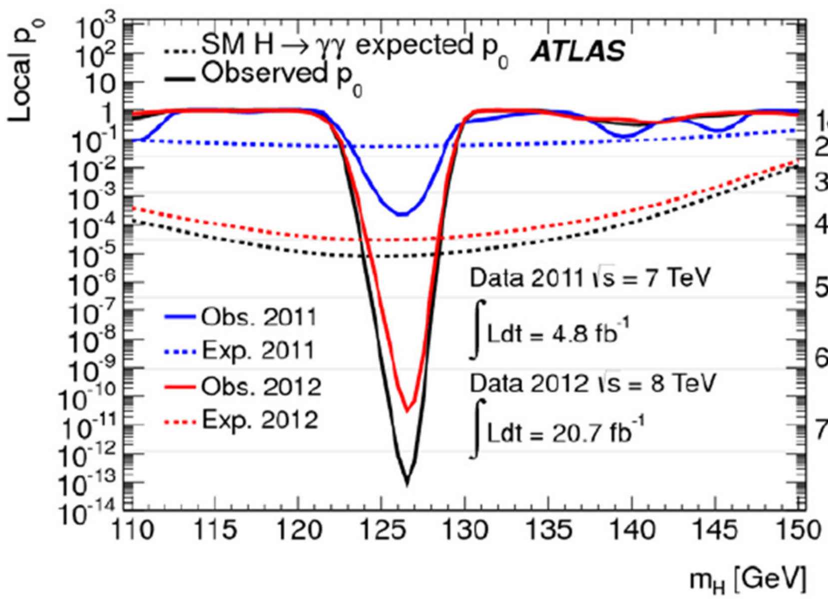


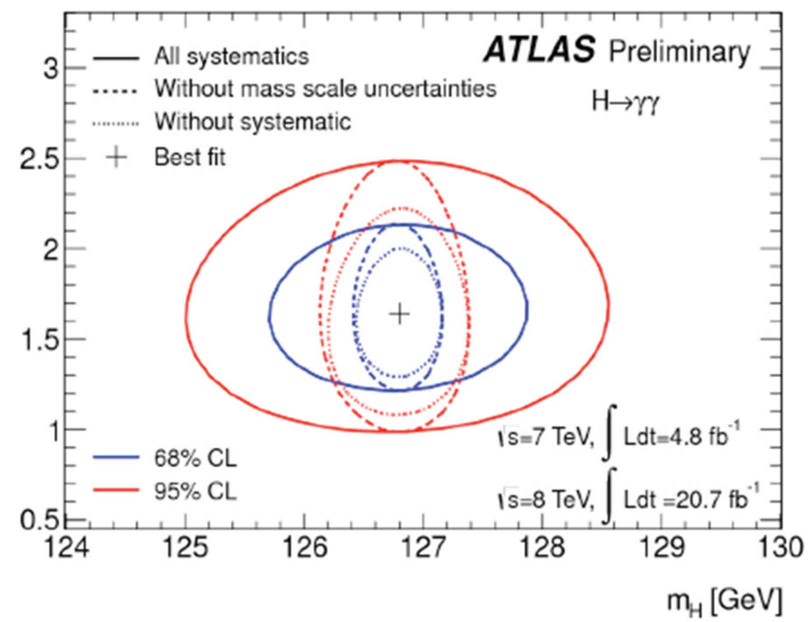
- Simple signature: two high-p_T isolated photons - E_T (γ_1, γ_2) > 40, 30 GeV ($\sqrt{s}$=8 TeV)
- Events divided into **14** categories based on production mode and S/B ratio in different detector region (increase sensitivity, also for coupling measurements)
- Main channel with sensitivity to VBF production



H→ γγ

arXiv:1307.1427





Signal Significance :
7.4σ (4.3σ expected)
Exceeding discovery criteria

Signal strength
μ = 1.57±0.24(stat) ±0.22(syst)
at mass = 126.8 GeV

Obs (√s=8 TeV, m_H^{rec} = 126.8 GeV ±2σ)	Expected purity s/s+b (√s=8 TeV)	Main backgrounds
13931	370/13575 = 2.7%	γγ,γj and jj

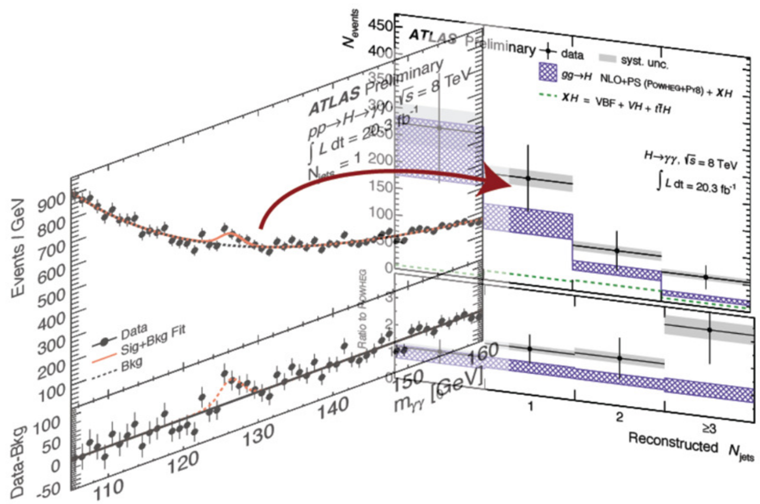
H→ γγ Differential Cross-Sections

ATLAS-CONF-2013-072

Study the kinematic distributions of H→ γγ events

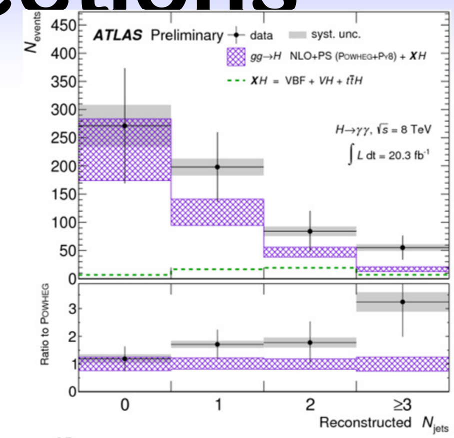
To unfold the experimental measured distributions to particle level distributions (differential dσ/ dx)

	Variable
Inclusive	$p_T^{\gamma\gamma}$
	$\|y^{\gamma\gamma}\|$
	$\|\cos\theta^*\|$
	N_{jets}
	p_T^{j1}
2-jets	$\Delta\varphi_{jj}$
	$p_T^{\gamma\gamma jj}$

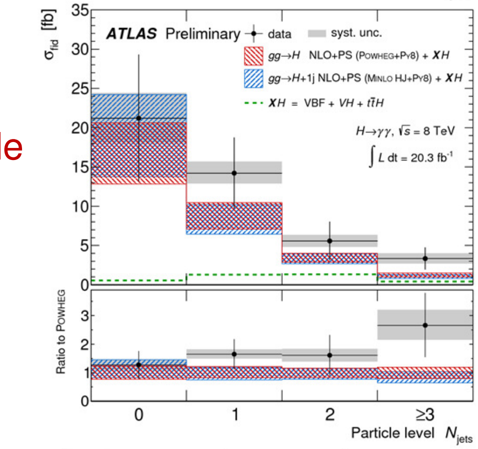


- **Bin events in interesting variables**
- **Background estimations from the mγγ side-band fit in each bin**
- **Estimate the systematics**
- **Background subtraction in each bin**
- **Unfold the reconstructed distributions to truth distributions (→ differential cross-sections)**

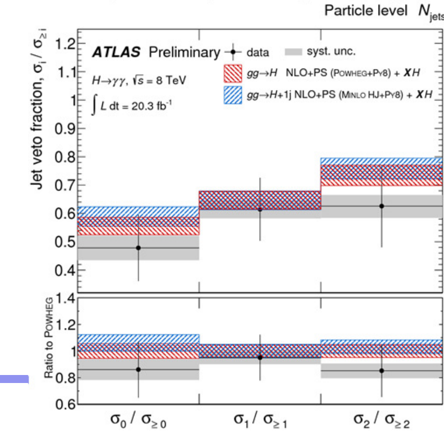
Recon. level



Particle level

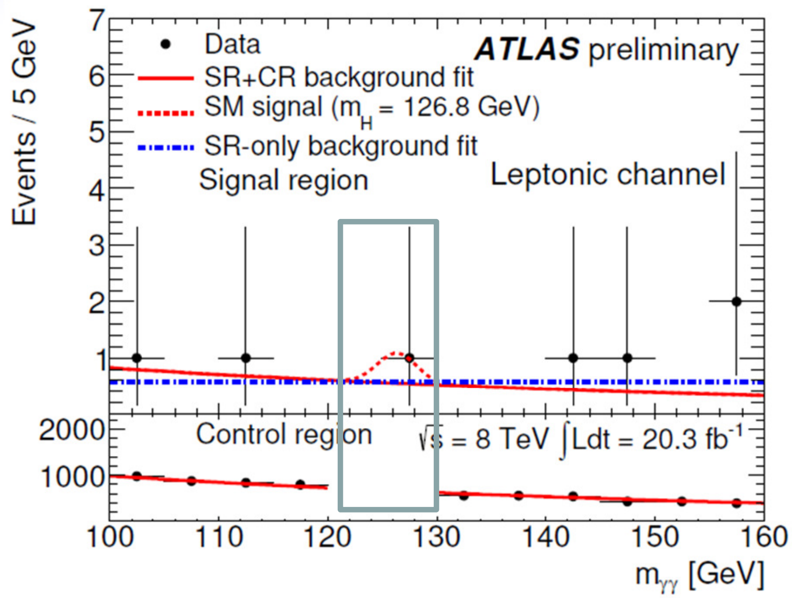


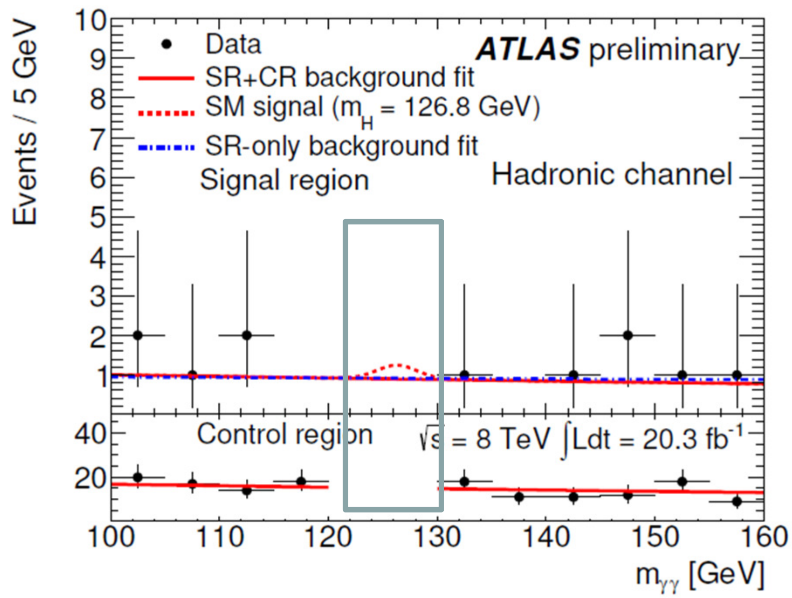
Cross-Section ratio



ttH(→γγ)

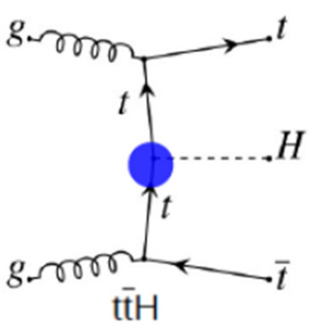
ATLAS-CONF-2013-080



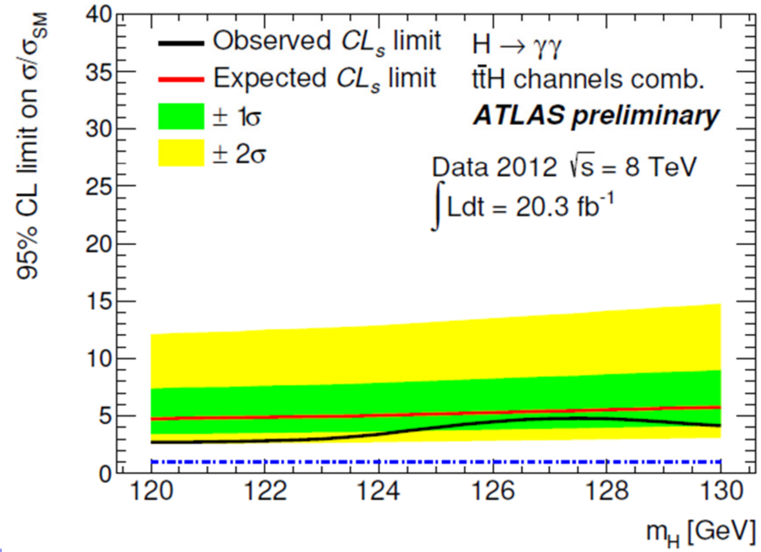


Two analysis categories:

1) Leptonic: $N_{lep} \geq 1$, MET > 20 GeV, $N_b \geq 1$
2) Hadronic: $N_{jet} \geq 6$, $N_b \geq 2$



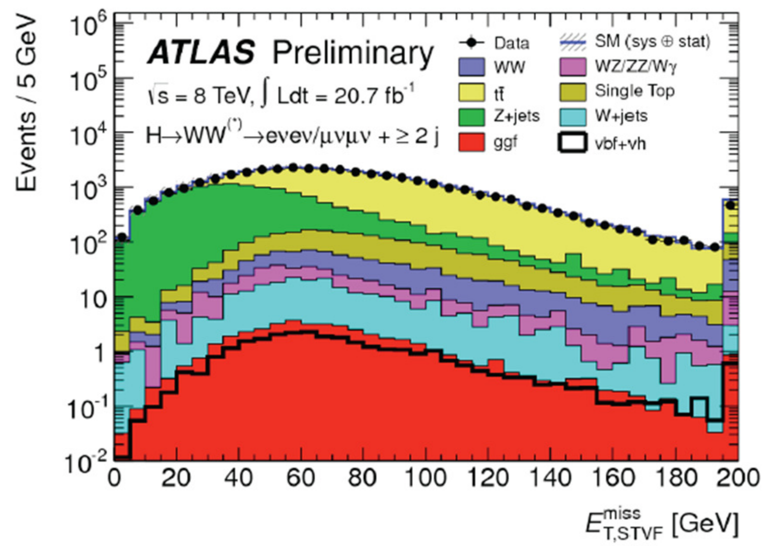
95% CL Limit
(m_H = 126.8 GeV):
$\sigma/\sigma_{SM} < 5.3$

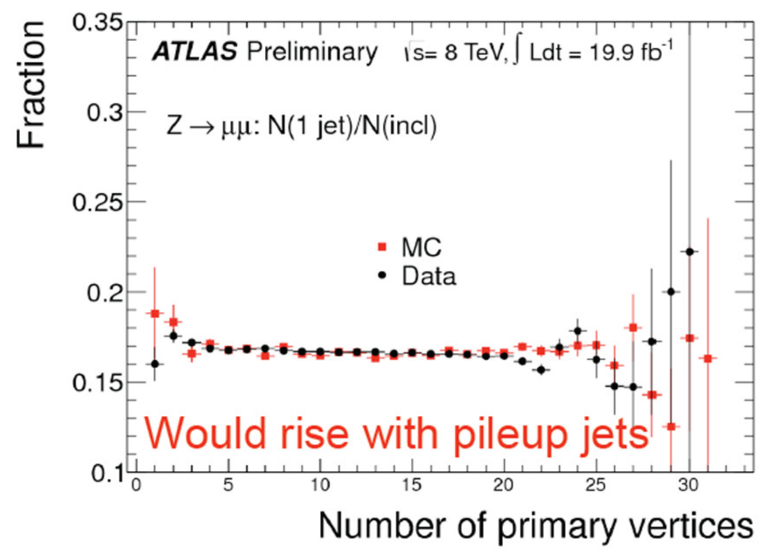


H→WW*→lνlν

arXiv:1307.1427

- ***ee*, *eμ*, *μμ* + 2ν final state: two isolated opposite-sign leptons, large E_T^{miss}**
- **N_{jet} classification (0,1, >= 2 jet) to separate ggF and VBF processes**
- **Main backgrounds: WW, Wt, top, W+jets, Z+jets**
- **~80% of overall significance from eμ channel (large DY background for ee and μμ channels)**
- **Experimental challenge in measurements: E_T^{miss}, Njet (JES)**





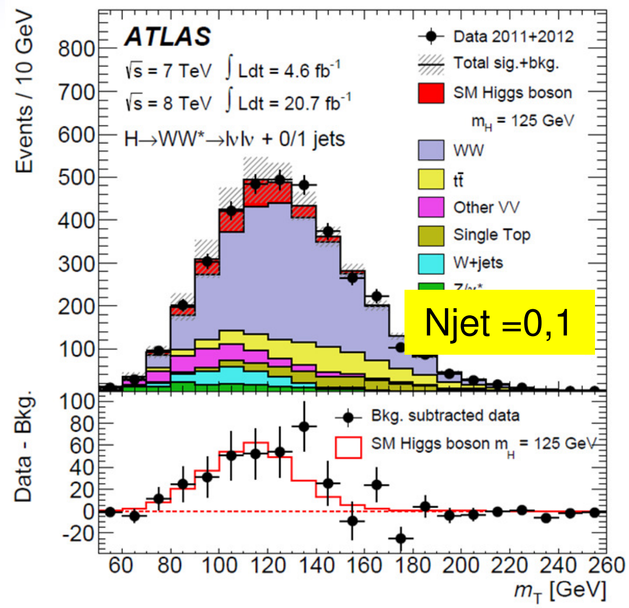
Observed (N_{jet} = 0, 1, >=2) ~25 fb^{-1}	Expected purity s/s+b (√s=8 TeV)
831, 309, 55	**152**/1188 = 12.8%

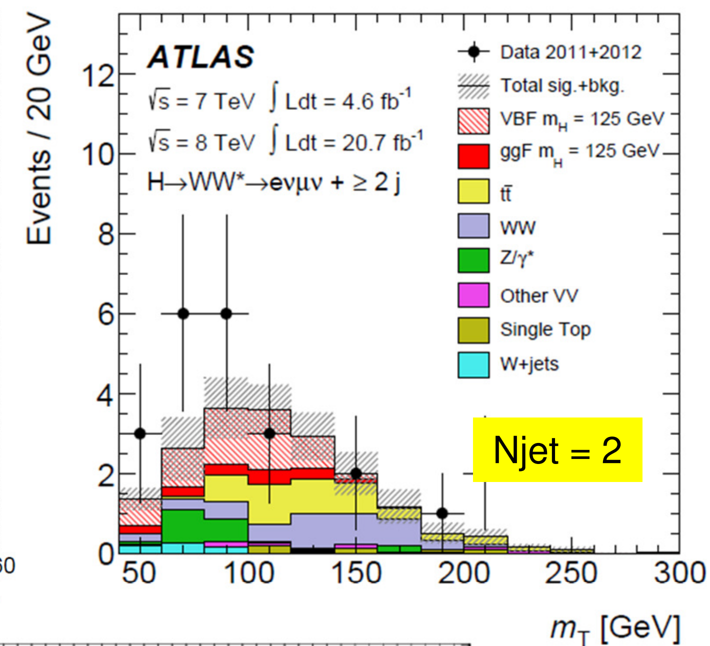
H→WW*→lνlν

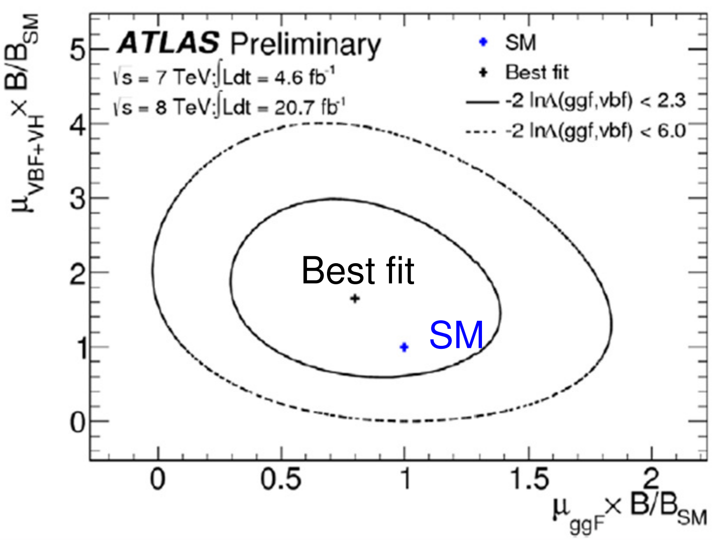
arXiv:1307.1427

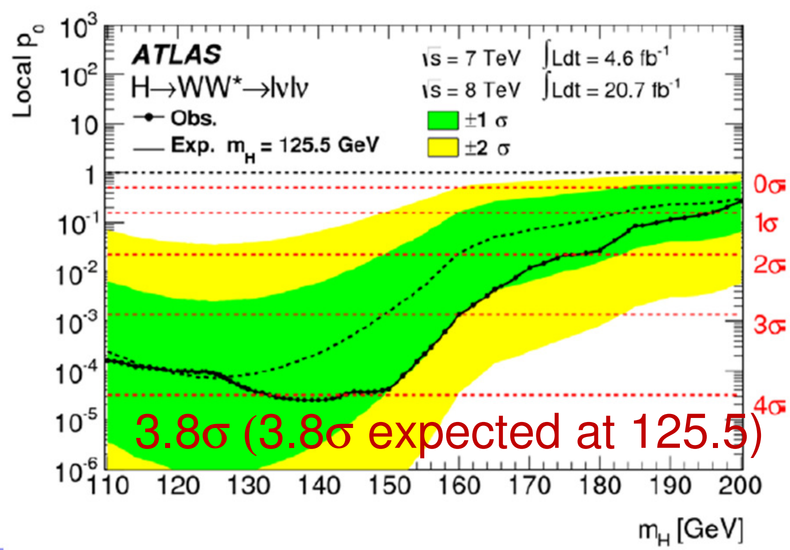
The final discriminant

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









Z/W (→ll/lν) + H (→WW*→lνlν)

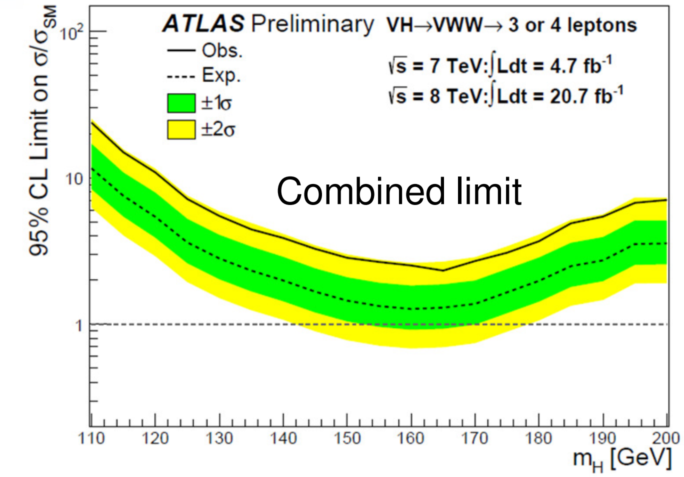
ATLAS-CONF-2013-075

$WH \to WWW^* \to 3\ell + \not{E}_T \quad ZH \to ZWW^* \to 4\ell + \not{E}_T$

Lepton $p_T > 10-25$ GeV, $\not{E}_T^{rel} > 25-40$ GeV

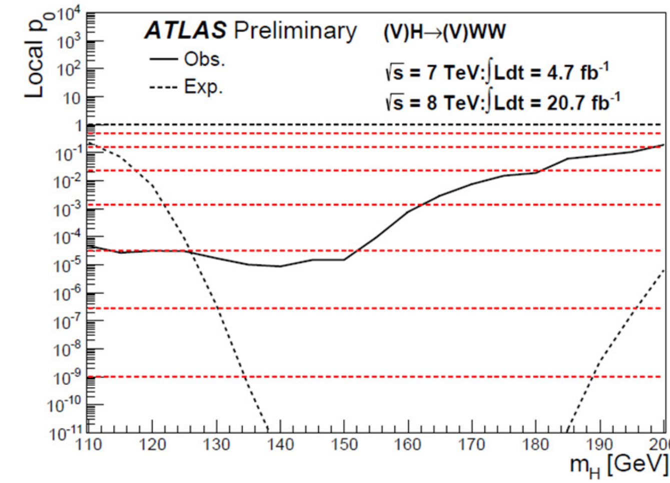
3l analysis Data/MC, Total WWW contribution ~5.1 events

	Data	MC	Data/MC
WZ^* CR	439	438 ± 24	1.00 ± 0.07
ZZ^* CR	244	210 ± 40	1.15 ± 0.23
Z+jets CR	828	860 ± 40	0.96 ± 0.06
Top CR	6	6.2 ± 1.1	1.0 ± 0.4



4l analysis Data/MC, ZWW contribution ~0.6 events

	$Z(H \to WW)$	Data	MC	Data/MC
ZZ CR	0.03 ± 0.00	100	100.00 ± 3.19	1.00 ± 0.10



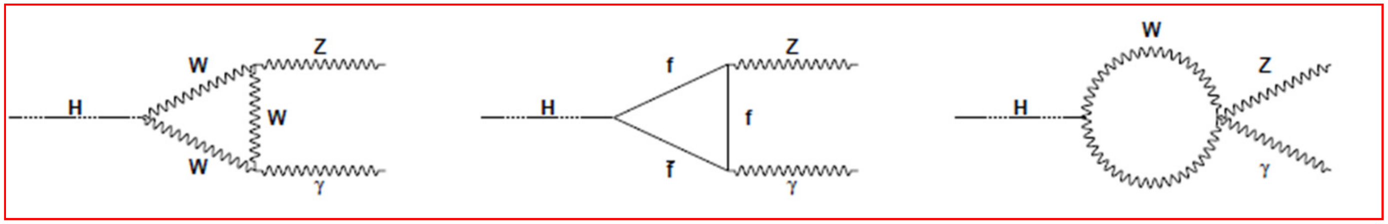
95% C.L. observed (expected) upper limit on the rate/SM at 125 GeV:
7.5 (4.0) for WH and 14.3 (9.6) for ZW

Observed small excess at 125 GeV:
1.7σ (WH→ww), 1.5σ (ZH→WW)

significance (σ)	VH	$H \to WW^{(*)}$ [6]	Combined
expected	0.7	3.7	3.8
observed	2.0	3.8	4.0

H→Zγ → llγ

ATLAS-CONF-2013-009

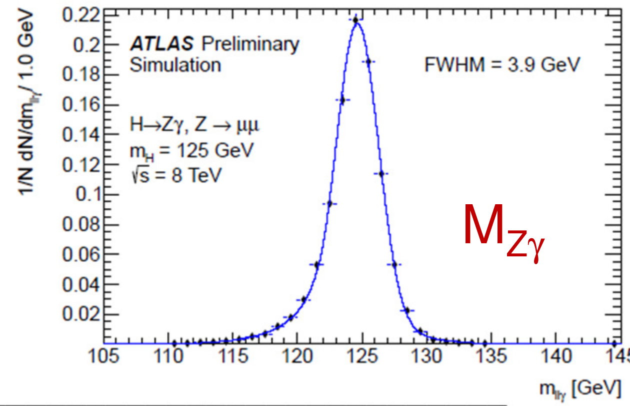


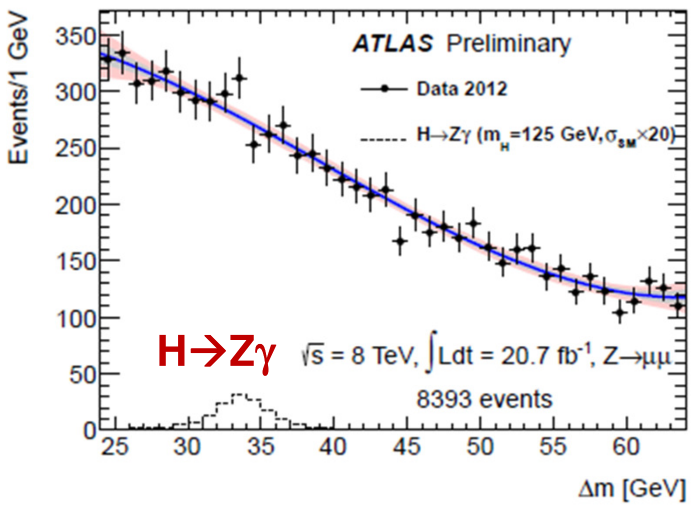
$BR(H \to Z\gamma)$=0.15%

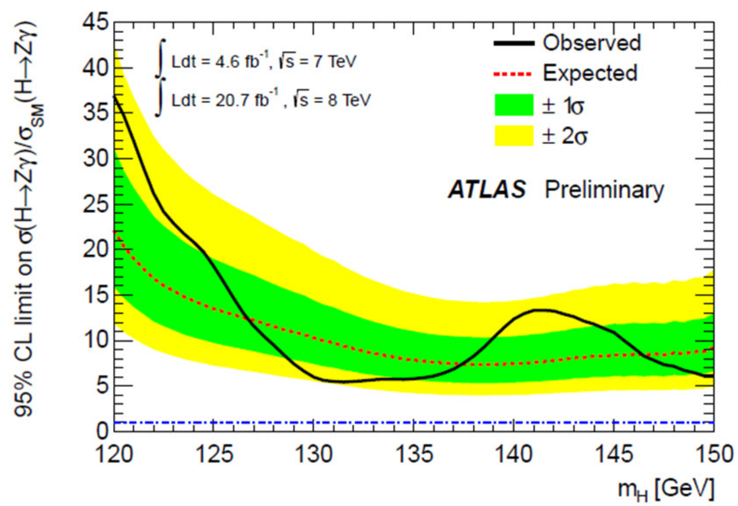
- **H→Zγ** is another high resolution channel
- Sensitive to new particles through loops
- For SM Higgs with mass = 125 GeV:

$$\sigma_H \times Br(H \to Z\gamma \to \ell\ell\gamma) \sim 2.3 \text{ fb}$$

~ 55 events in 2011+2012 dataset







H→ $\tau\tau$, bb, $\mu\mu$

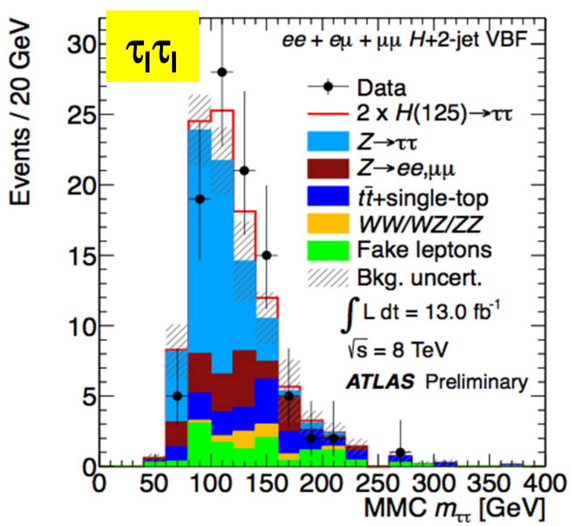
H→ ττ

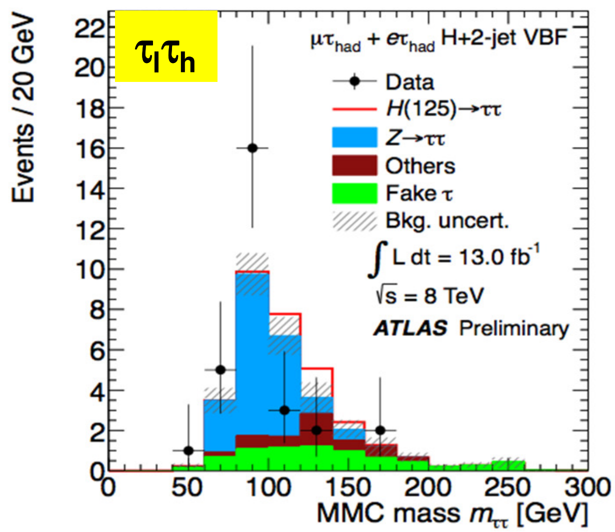
- BR(H→ ττ) = 6.3% (M_H=125 GeV)
- Search in exclusive categories: lep-lep, lep-had, had-had and jets: 0, 1 (boosted or not), 2 (VBF, VH)
- Most powerful channel VBF

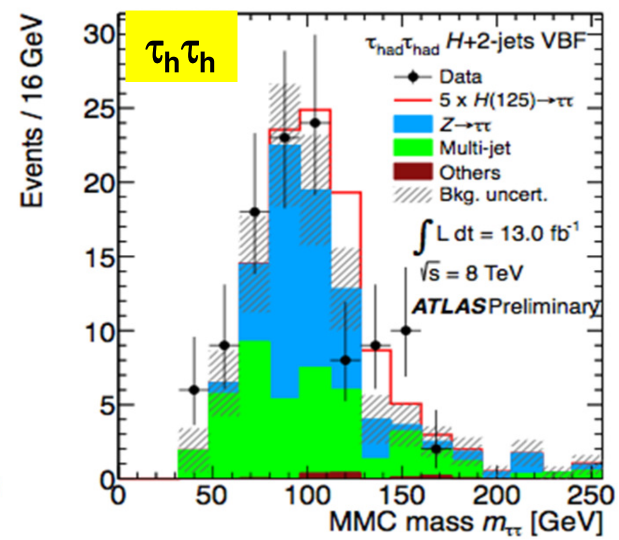
ATLAS-CONF-2012-160

μ(125) = 0.7 ± 0.7
95% CL limit (125): 1.9 [exp: 1.2] × SM
Significance (125): 1.1σ [exp: 1.7σ]

Update will come soon !





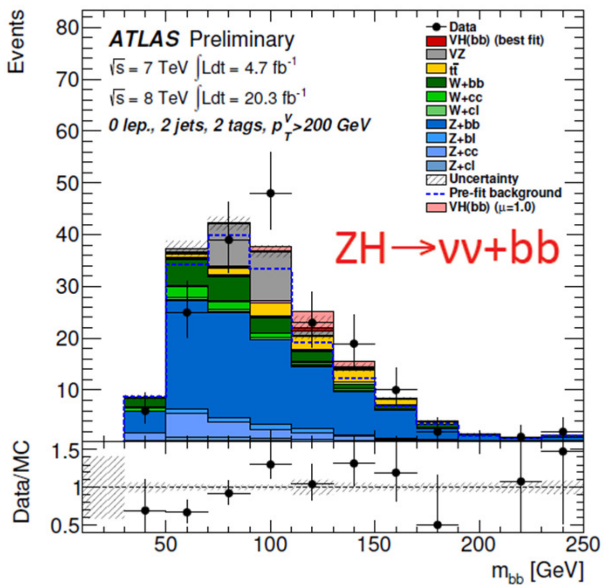


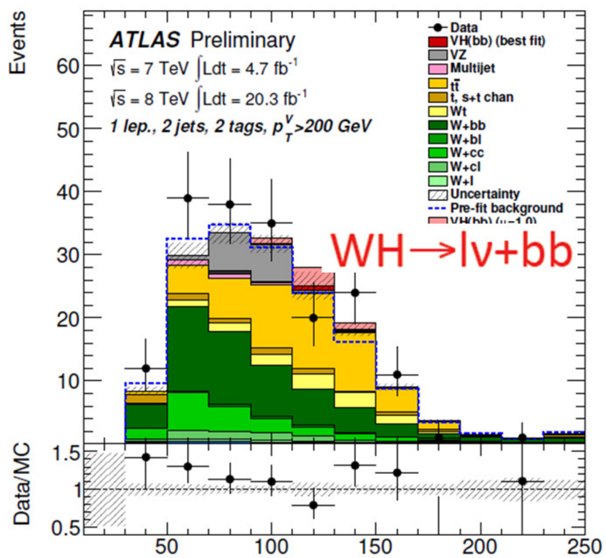
Signal (SM)	Production	7 TeV & 8 TeV	Signal purity s/b	Main backgrounds
~330 (BR=6.3%)	**VBF**, Hgg, VH	4.9 & **13 fb^{-1}**	0.3% - 30%	ZZ, Z+jets, top

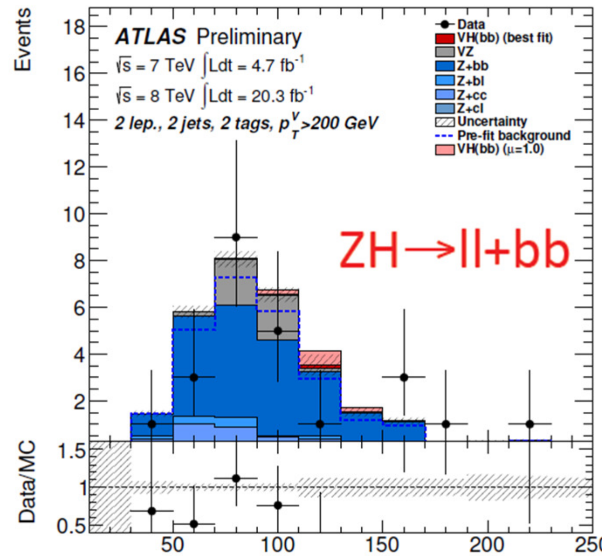
Z/W+H→ bb

ATLAS-CONF-2013-079

Also 7 TeV analysis of tt+H, with H → bb [ATLAS-CONF-2012-135]



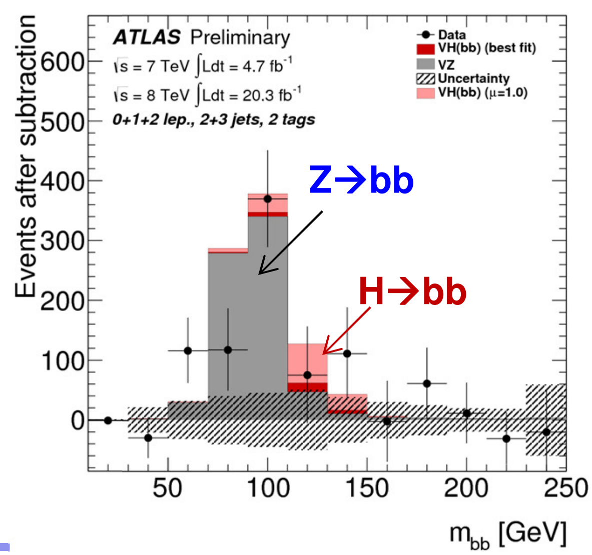


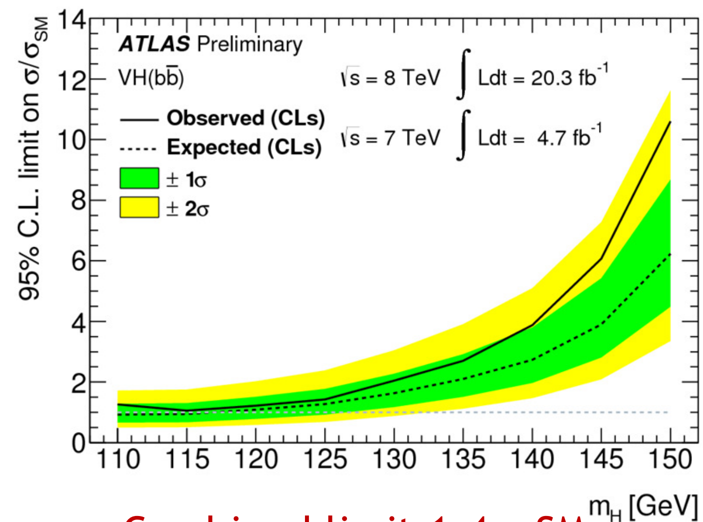


- **BR(H→bb): 57.8%**
- **Large background with fully data-driven**
- **Search for peak in m_{bb} spectra (3 ch)**
- **Validation using VZ(→bb)**

$\mu_{VZ}=0.93\pm0.22$

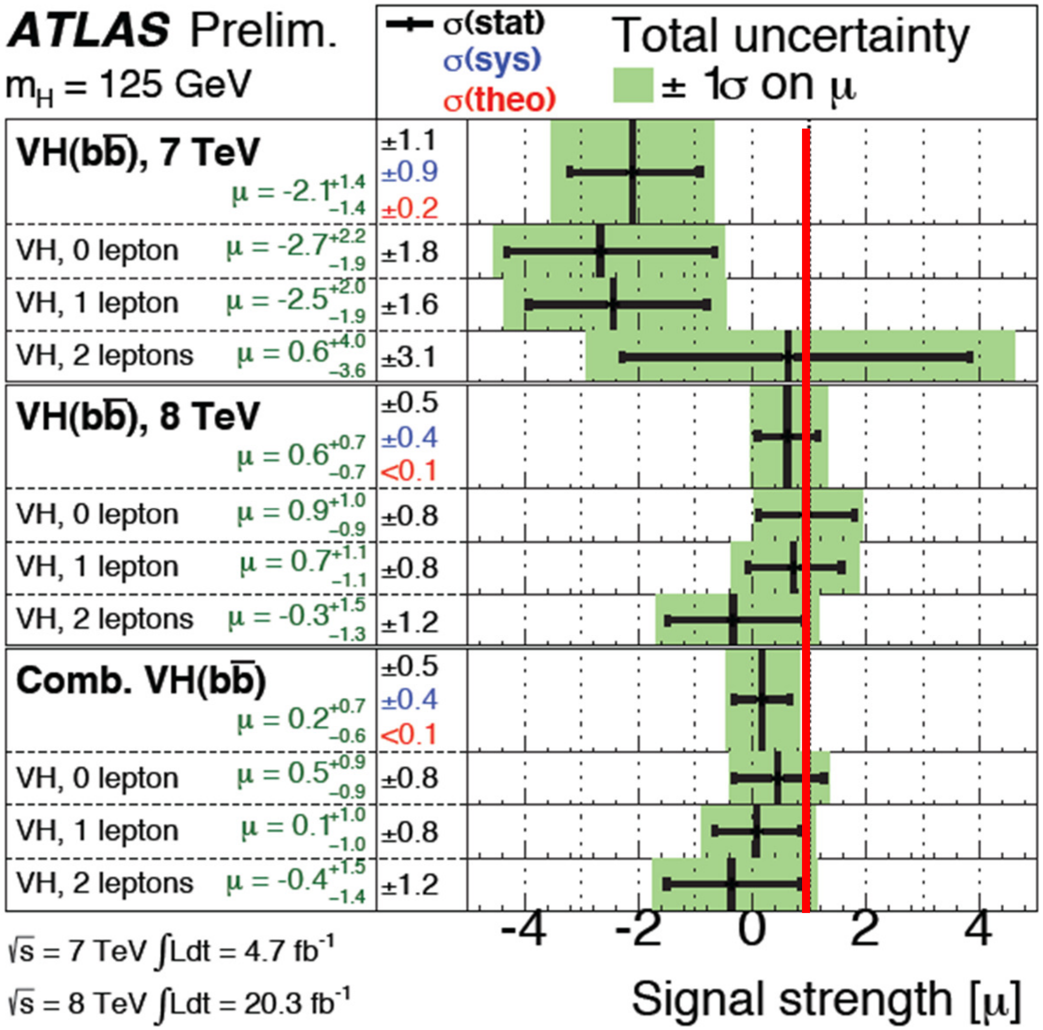
- **Systematic: JES, b-tagging**





Combined limit 1.4 x SM

Signal Strength of H→ bb



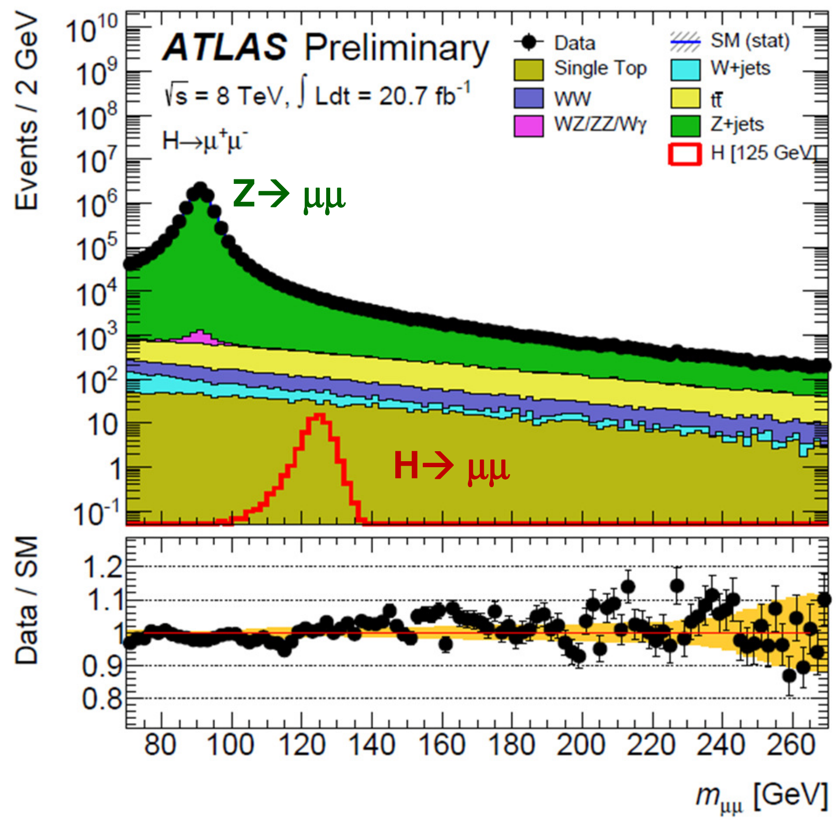
μ (125 GeV) = 0.2 ± 0.5(stat) ± 0.4(syst)

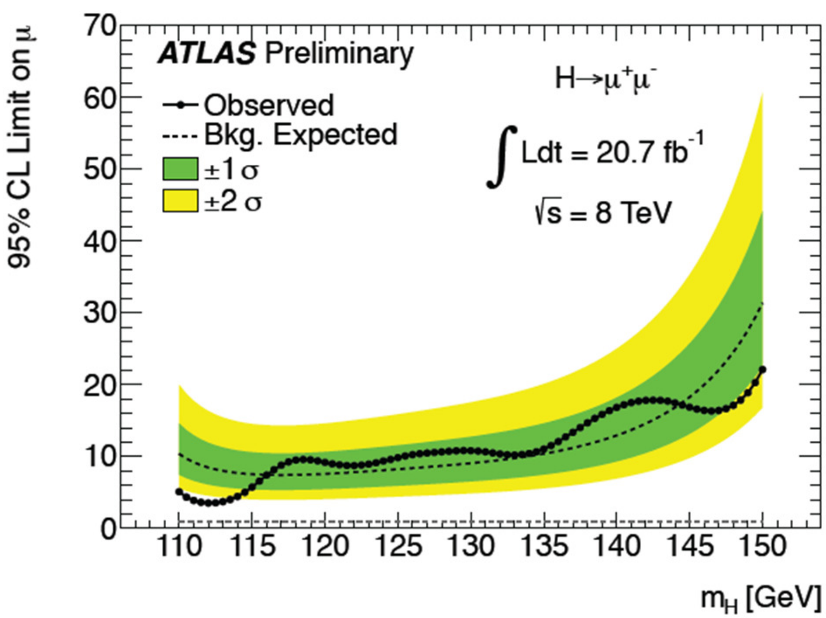
H→ μμ

ATLAS-CONF-2013-010

$$B(H[125] \to \mu\mu) = 2.2 \times 10^{-4}$$

	$\|m_H - m_{\mu\mu}\| \leq 5$ GeV
Signal [125 GeV]	37.7 ± 0.2
WW	250 ± 4
$WZ/ZZ/W\gamma$	30 ± 1
$t\bar{t}$	1374 ± 13
Single Top	151 ± 5
Z+jets	15806 ± 125
W+jets	88 ± 6
Total Bkg.	17697 ± 126
Observed	17442





Search window: 110-150 GeV

MC background predictions are not used in the search (for optimization only)

Properties Measurements: Signal Strength, Mass, Couplings, Spin-Parity

arXiv:1307.1427

Higgs Signal Strength

Signal strength $\mu = \sigma/\sigma_{SM}$

Combination of diboson final states

$H \rightarrow \gamma\gamma$

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

$H \rightarrow WW(*) \rightarrow l\nu l\nu$

measured at combined m_H=125.5 GeV

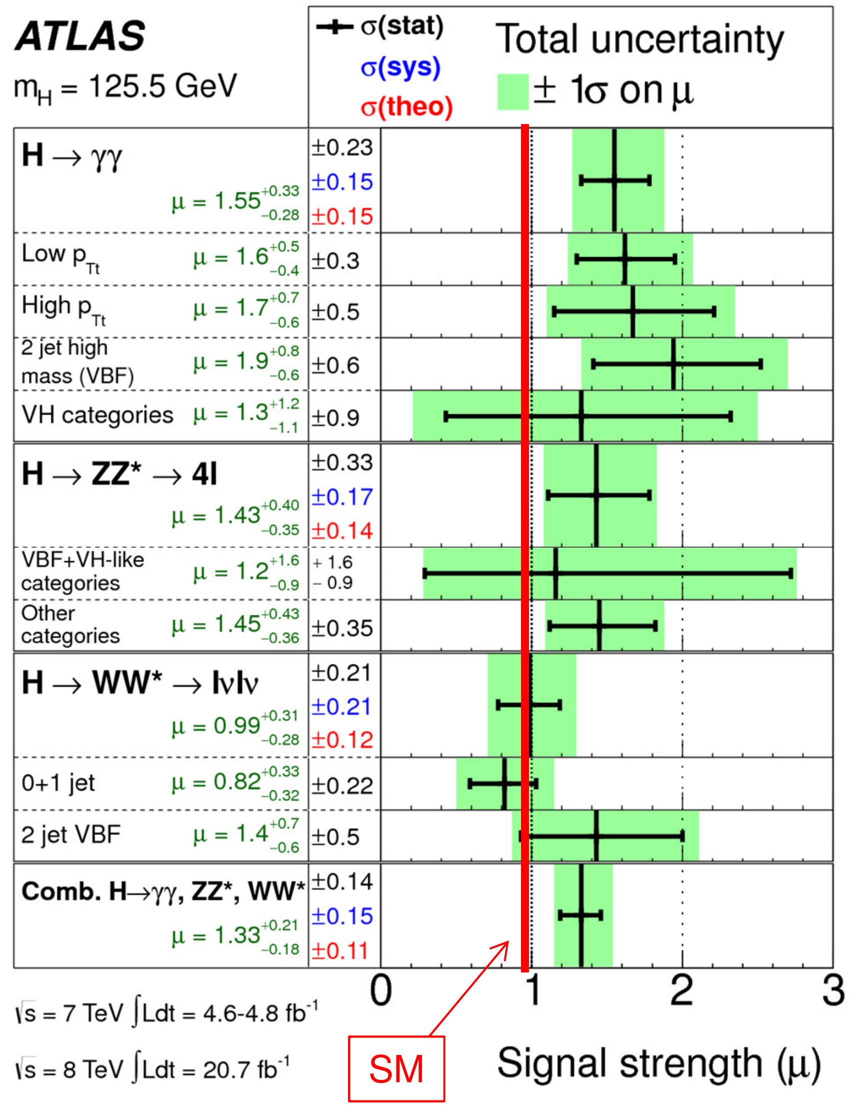
- **Variation due to m_H uncertainty: ±3%**
- **Compatibility with SM (μ=1): 7%**
- **Largest deviation $\mu_{\gamma\gamma}$: 1.9 σ**

Including preliminary μ_{bb}, $\mu_{\tau\tau}$: μ=1.23 ± 0.18

ATLAS also sets preliminary (95%CL) limits:

$H \rightarrow \mu\mu$: μ<9.8 (20.7 fb^{-1})

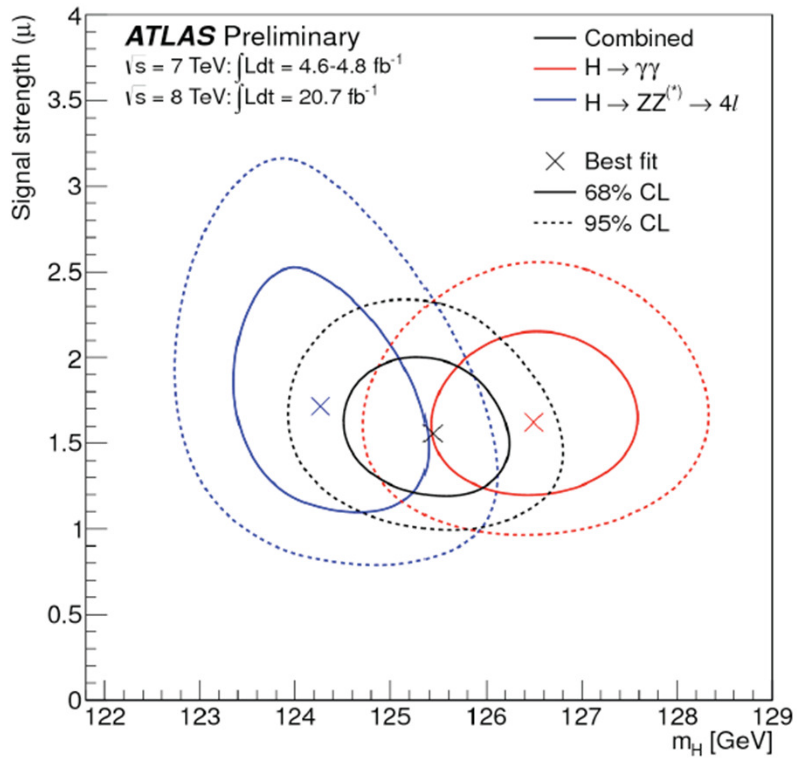
$H \rightarrow Z\gamma$: μ<18.2 (4.6 fb^{-1} + 20.7 fb^{-1})

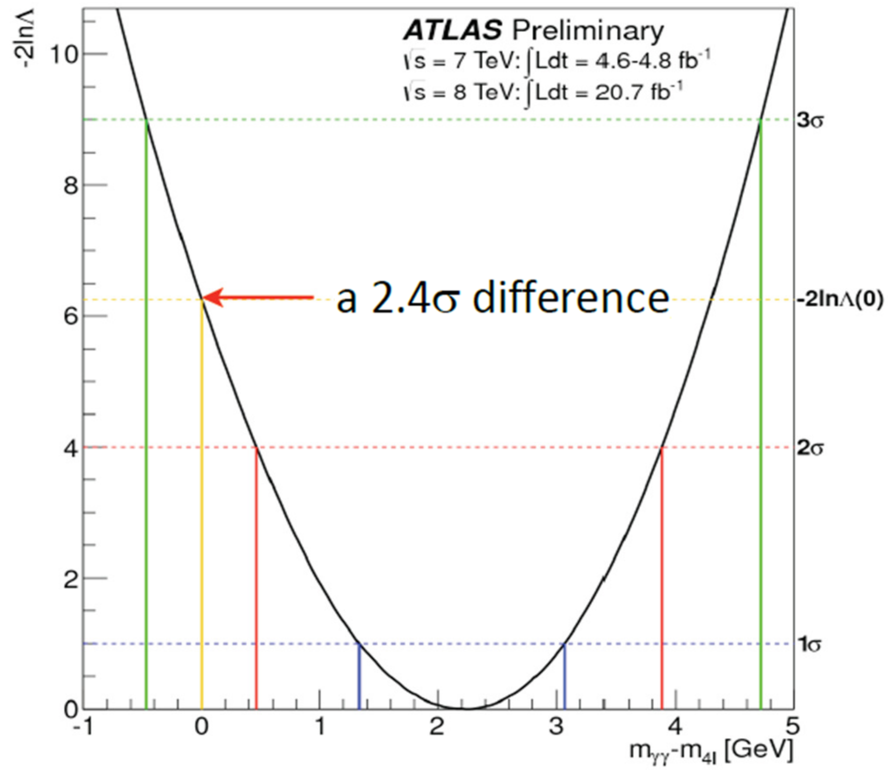


μ = 1.33 ± 0.14 (stat) ± 0.15 (sys) ± 0.11 (theo)

Mass Combination (4l, $\gamma\gamma$)

Combined mass measurement m_H = 125.5 ± 0.2 (stat) ± 0.6 (syst) GeV





$$m_H^{\gamma\gamma} = 126.8 \pm 0.2(stat) \pm 0.7(syst) \text{ GeV}$$

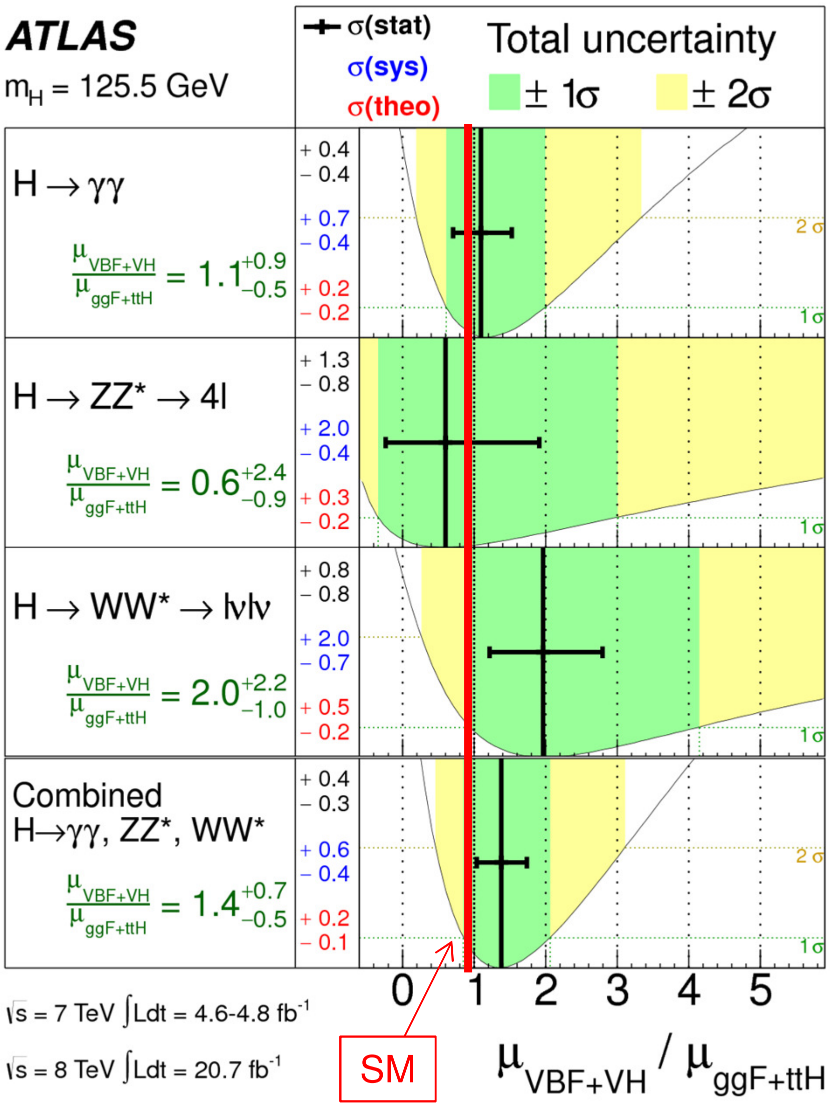
$$m_H^{4\ell} = 124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(syst) \text{ GeV}$$

Two measurements are 2.3 GeV apart:

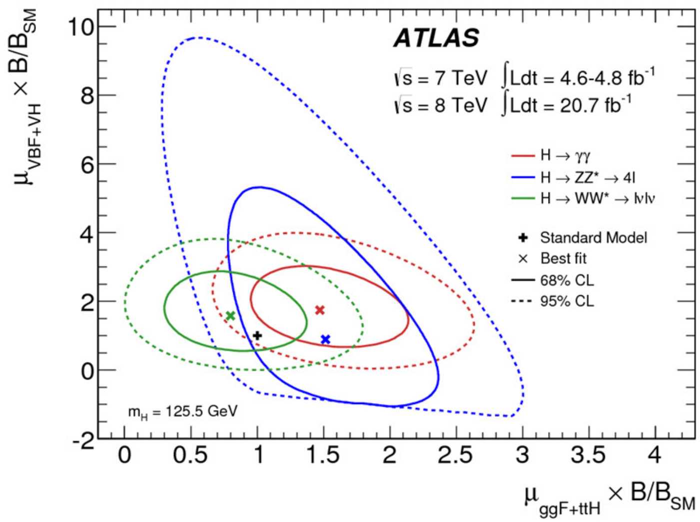
$$\Delta m_H = 2.3^{+0.6}_{-0.7}(stat) \pm 0.6(syst) \text{ GeV}$$

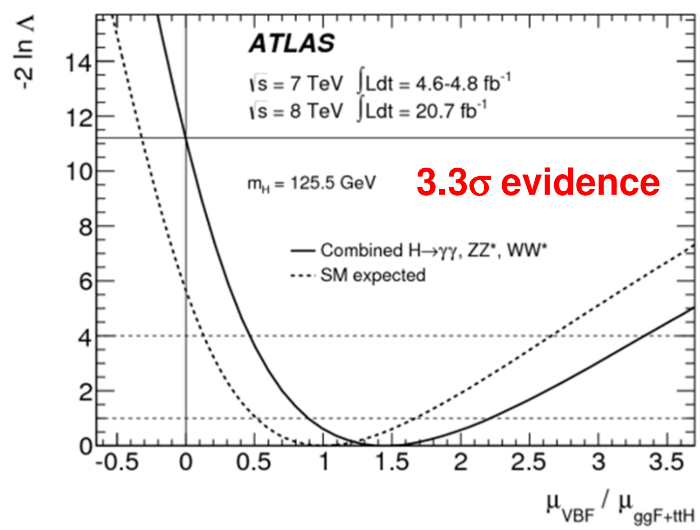
Prob. to observe $\Delta m \geq 2.3$ GeV ~ 1.5% (2.4σ)

VBF vs. ggF Production



μ_{VBF+VH} vs $\mu_{ggF+ttH}$ potentially modified by B/B_{SM}





$\mu_{VBF+VH} / \mu_{ggF+ttH}$ = 1.4+0.4-0.3(stat)+0.6-0.4(sys)

Studies on Spin-Parity

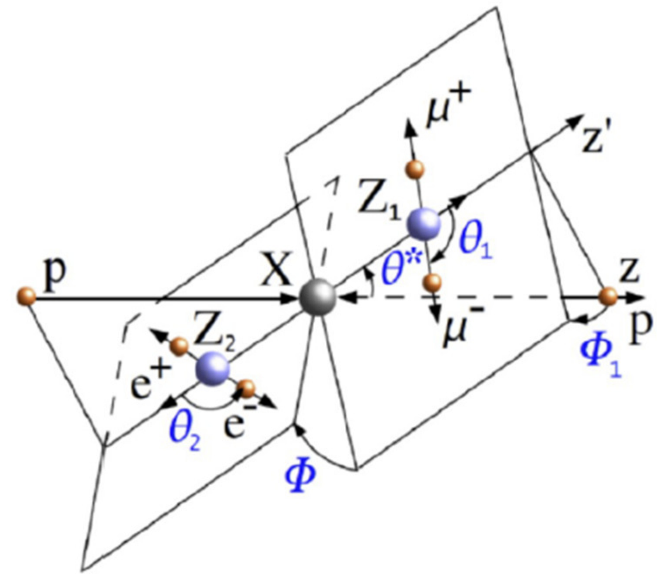
Spin 1 hypothesis strongly disfavored by Landau-Yang theorem, main interest is to test the SM 0^+ hypothesis against 2^+: start with spin 2 tensor with minimal couplings to SM particles (2^+_m)

Spin 2^+_m discrimination is tested for possible mixtures of gluon and quark initiated production

H→ ZZ*→4l analysis is also testing other spin parity states, as 0+ vs 0- etc. with gluon-fusion production

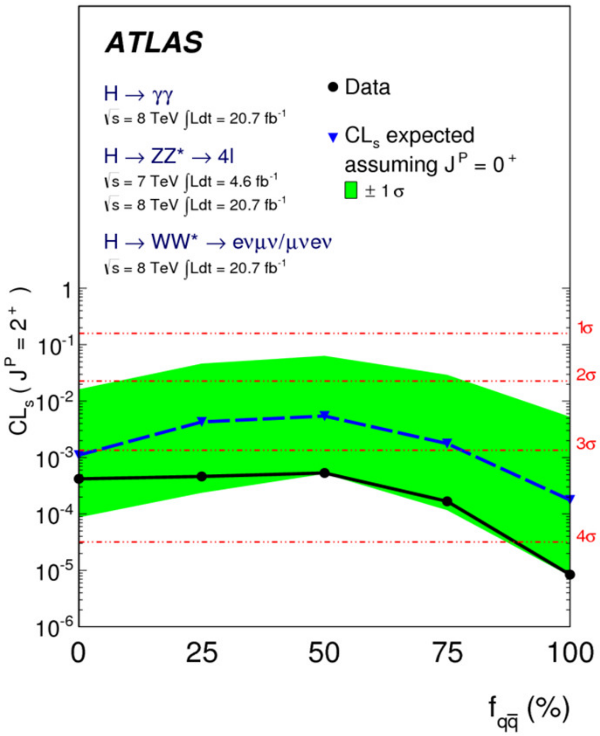
Spin studies in three different decay modes

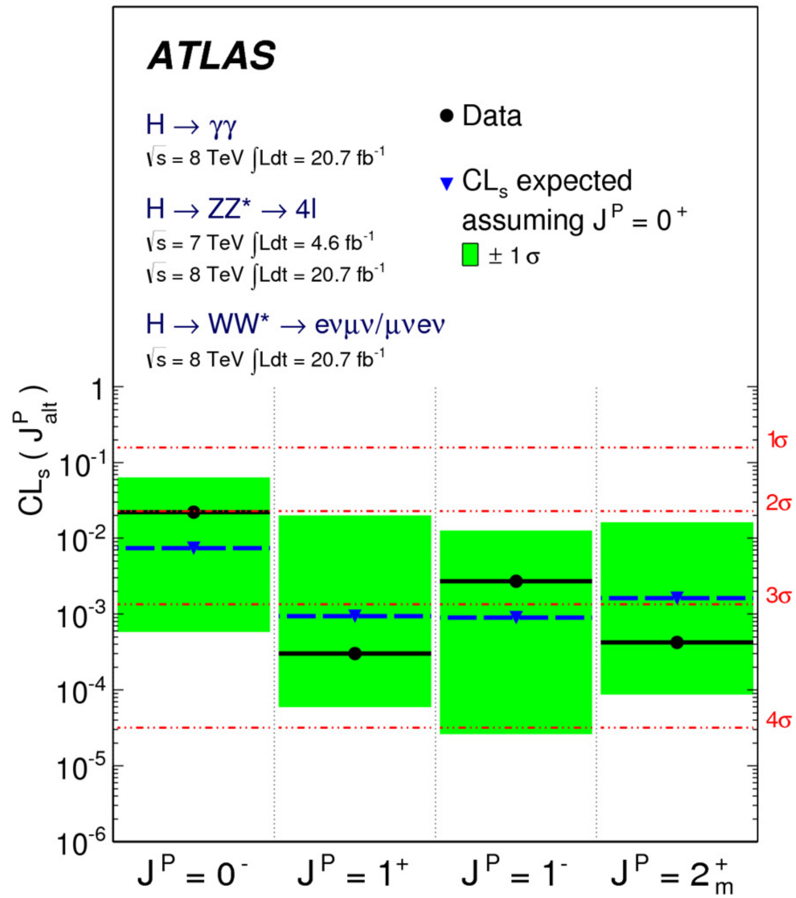
- **H→ γγ**: fully reconstructed, however only production angle θ* available
- **H→ZZ***: fully reconstructed, decay of Z bosons provides full information on the Z decay planes 5 decay angles as shown, and m_{Z1}, and m_{Z2}
- **H→WW***: direct calculation of decay angles not possible, use other kinematic distributions



Combined Spin-Parity Results

- 0^- hypothesis excluded at 97.8% CL in favor of 0^+ by H→ ZZ*→ 4l analysis
- 1^+ and 1^- excluded at 99.7% CL, respectively by WW and ZZ analysis
- 2^+ excluded at 95.2% to 99.96% CL



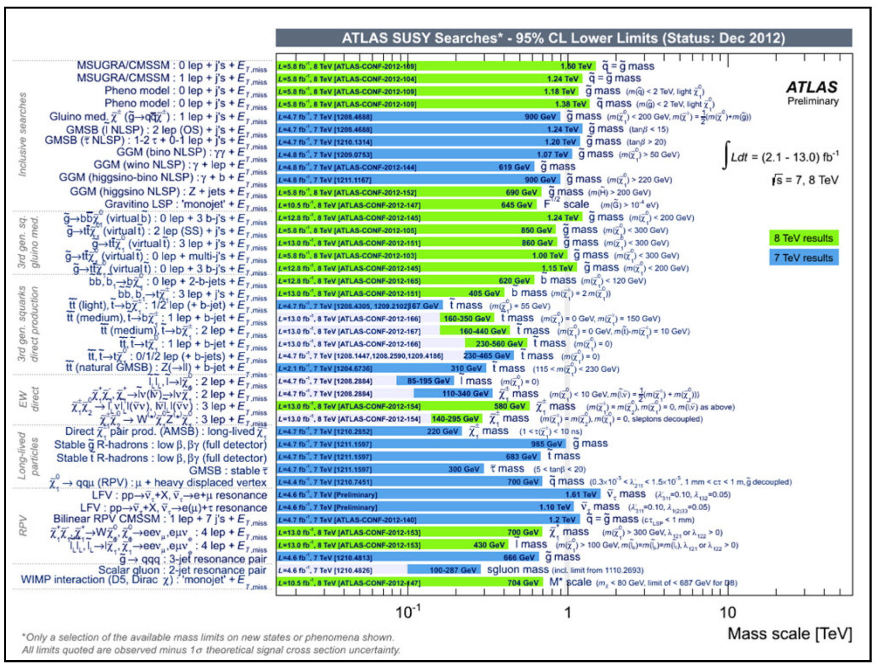


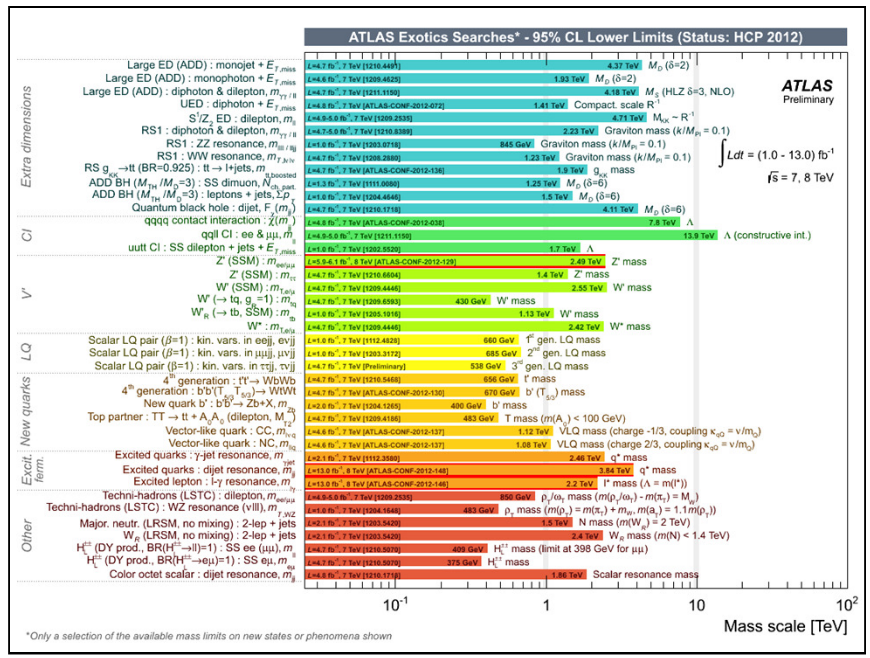
Combine: ZZ ZZ, WW ZZ, WW, γγ

Data favours $J^p = 0^+$ → SM-like Higgs!

What Has Been Learned From LHC Run I

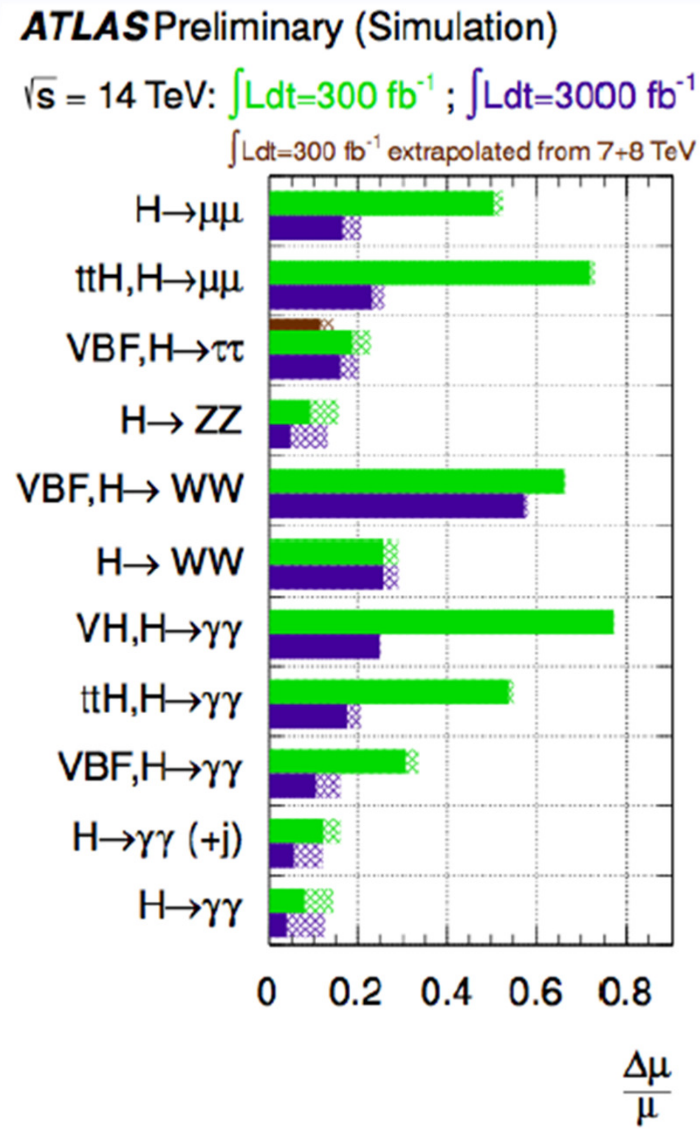
- ❖ **Standard Model gauge sector re-established at the LHC**
- ❖ **Discovered a SM-like Higgs Boson with mass ~ 125 GeV, which couples to Bosons and Fermions – a breakthrough in Standard Model electroweak sector**
- ❖ **No other new physics has been observed in data**





Exciting Physics in Run II, III

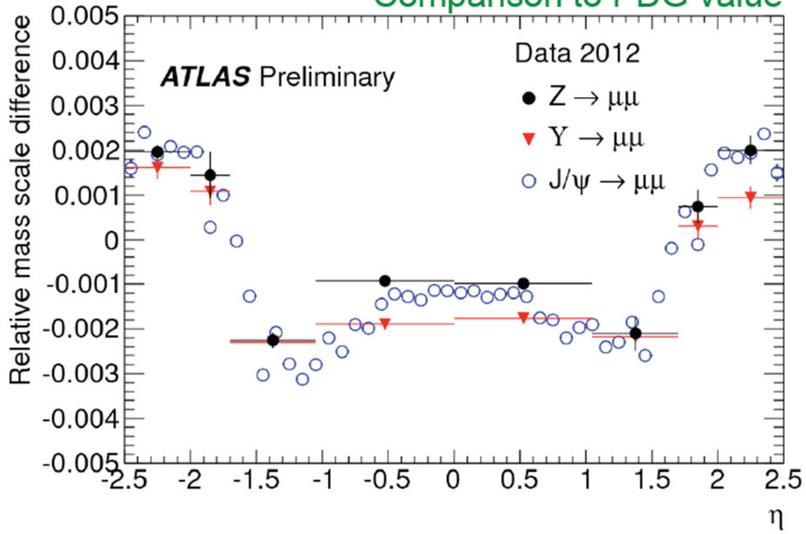
- **LHC Run II, II: 14 TeV; 300 fb^{-1}, 3000 fb^{-1}**
- **Precision Higgs physics**
  - Establish fermion decay signals
  - Precision coupling measurements
  - Observe rare decay modes, including Higgs self interactions
- **Study of vector boson scattering** – key processes to connect EWSB
- **Continue to search for BSM Higgs** – if there are more scalar particles?
- **Dark Matter signature?**
- **Supersymmetry** (still highly motivated)
  - Weakly produced new physics
  - Significantly increase chargino-neutralino mass sensitivity from ~350 GeV to ~ 1TeV
- **Explore unknown at 14 TeV!**



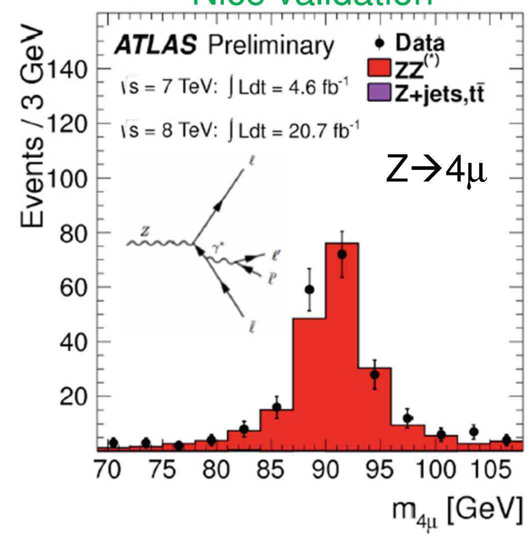
Spare slides

Lepton Energy/Momentum Calibration

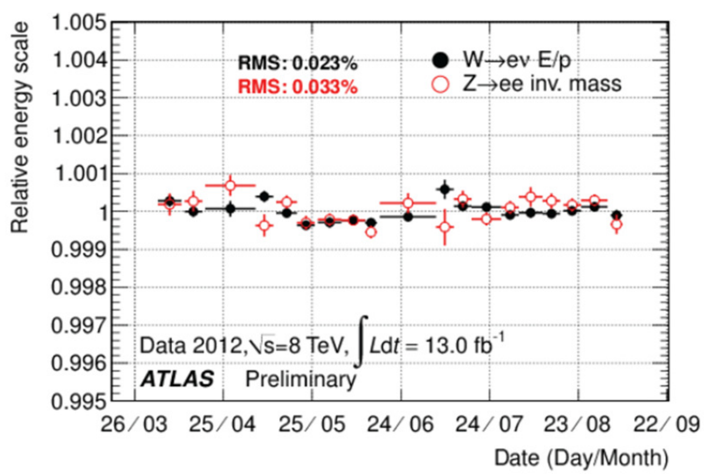
Comparison to PDG value

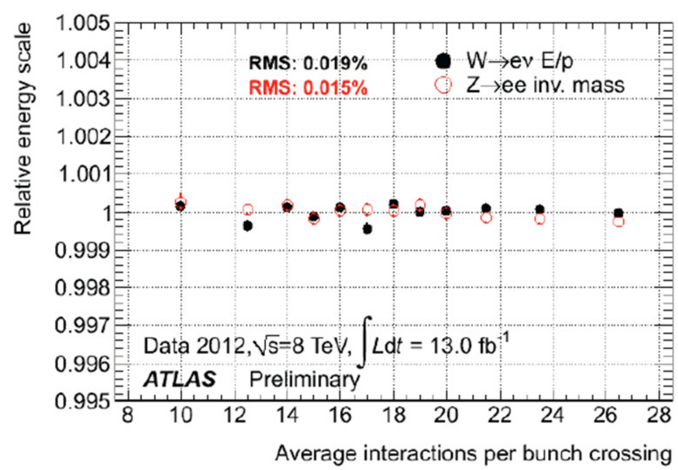


Nice validation



Stability of EM calorimeter response vs time/pile-up better than 0.1%

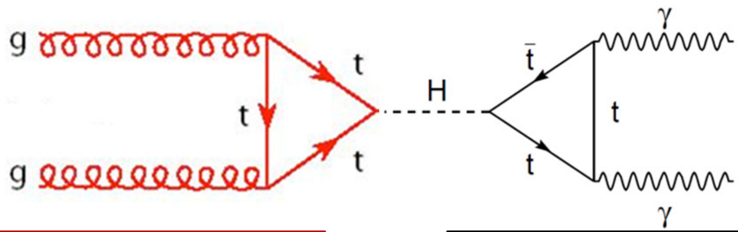




Constraints on BSM Loops

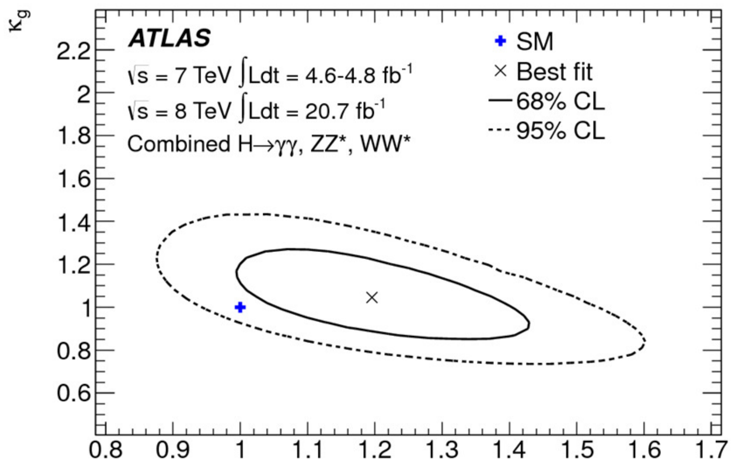
New heavy particles may contribute to loops

- Introduce effective κ_g, κ_γ to allow heavy BSM particles contribute to the loops
- Tree-level couplings: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau$ etc set to 1
  - Absorb all difference into loop couplings
  - Indirectly fixed normalization of Higgs width

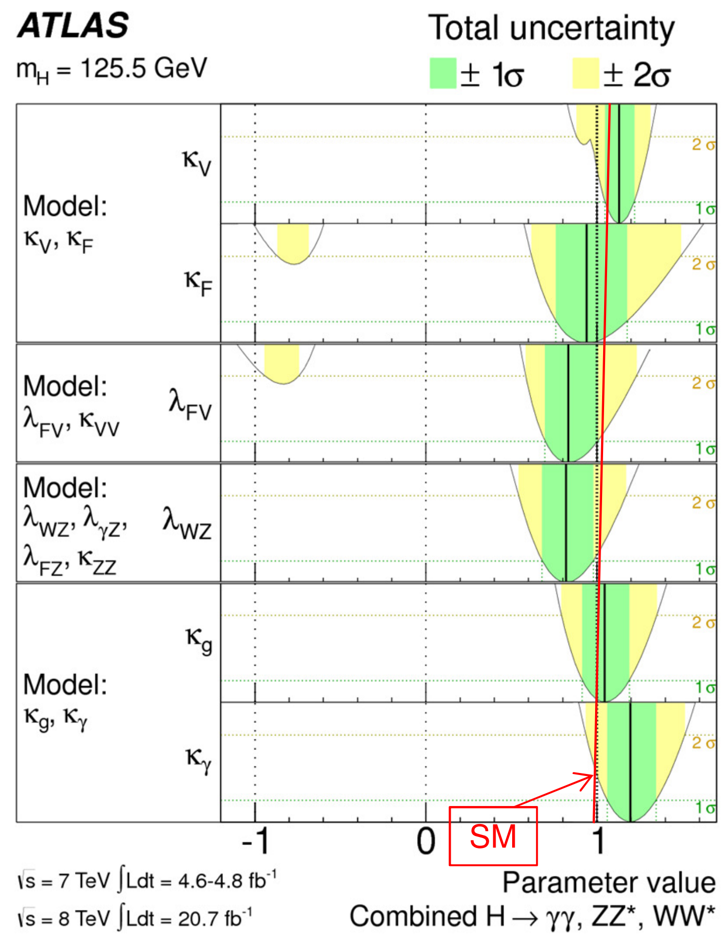


κ_g =1.04 ± 0.14

κ_γ =1.20 ± 0.15



2D Compatibility with SM: 14%



Couplings tested for anomalies w.r.t. fermion and boson, W/Z and vertex loop contributions at ±10-15% precision

Limit on Invisible Decay BR_{inv}

- Consider effective loop couplings: κ_γ, κ_g
- Fix the SM Higgs couplings for κ_V and κ_f
- Define the invisible branching ratio BR_{inv}

$\Gamma_H = \Gamma_{SM} + \Gamma_{inv}$ $\quad BR_{inv} = \Gamma_{inv}/\Gamma_H$

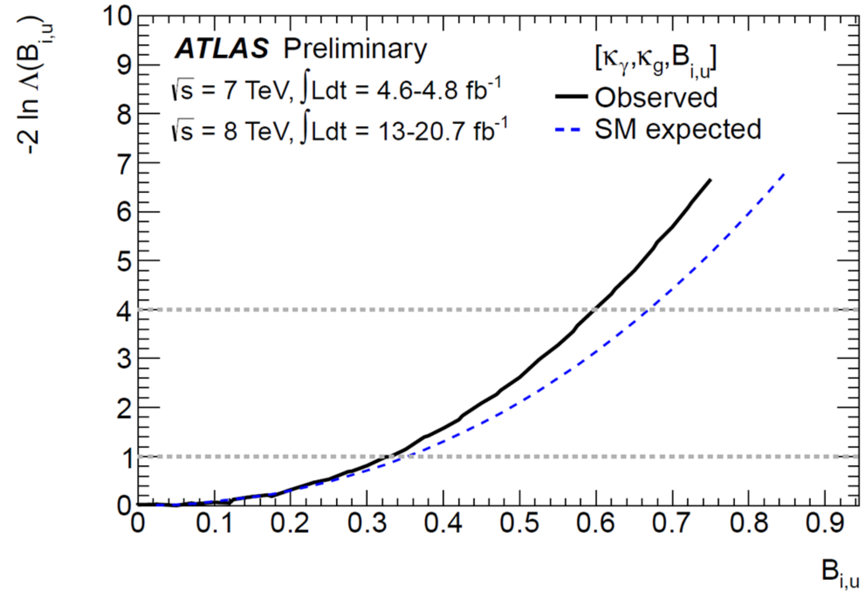
Parameterization on modified Higgs width:

$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{inv.,undet.})}\Gamma_H^{SM}$$

- Three fitted parameters:

κ_γ, κ_g + BR_{inv}

ATLAS-CONF-2013-34

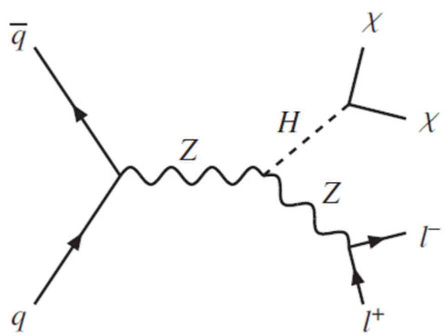


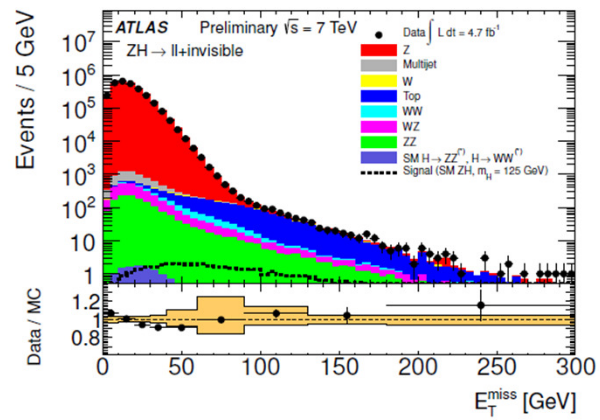
$BR_{inv} < 58\%$ at 95% C.L.

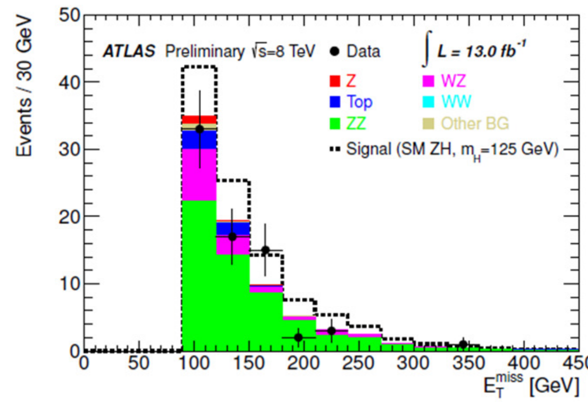
$$\kappa_g = 1.08^{+0.32}_{-0.14}$$
$$\kappa_\gamma = 1.24^{+0.16}_{-0.14}$$

Direct Search For Invisible Higgs

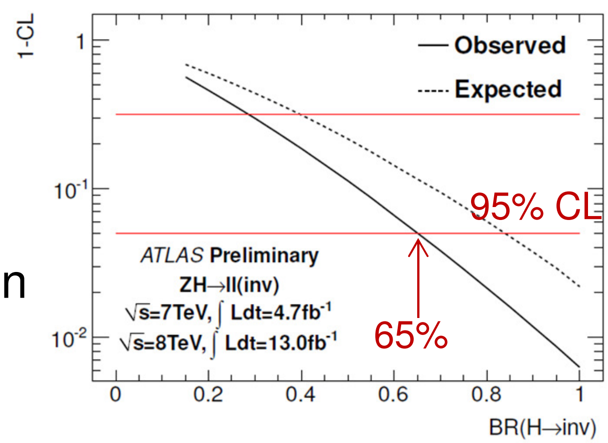
ATLAS-CONF-2013-011

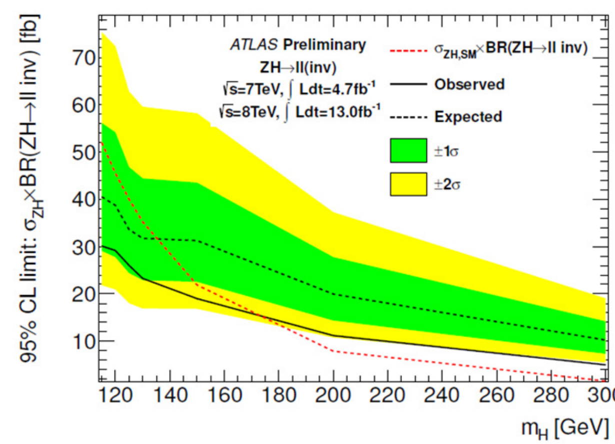






Signature:
$Z(\rightarrow ll)$ + invisible (E_T^{miss})





Select events

- $Z \rightarrow ll$
- Large missing ET
- Recoiling against Z boson

Results

No excess of events over wide mass range

BR limit (m_H= 125 GeV) :

BR_{inv} < 65% at 95% CL

σxBR limit:

10 – 30 fb (115 – 300 GeV)

Search for *t→ cH*

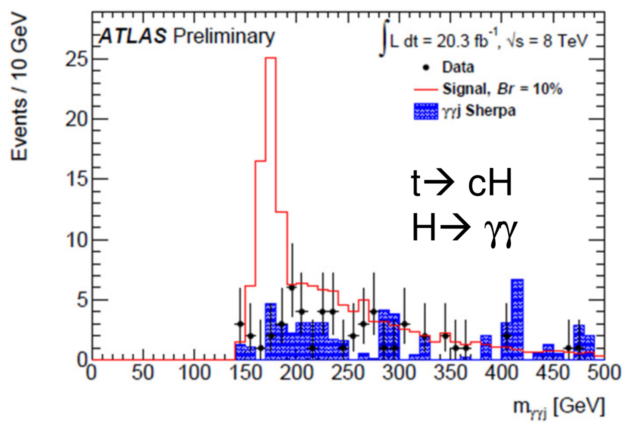
ATLAS-CONF-2013-081

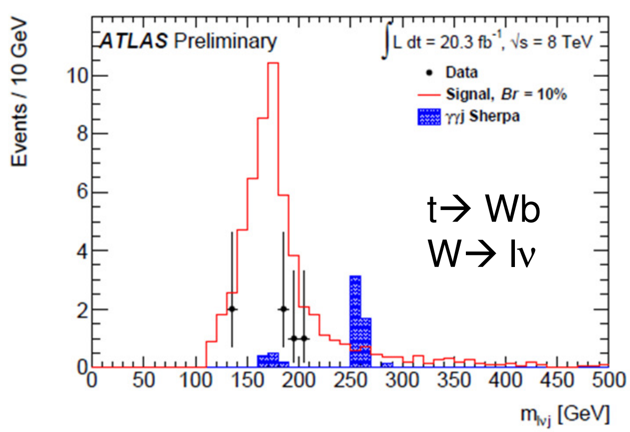
$$\Gamma_{t\to cH} = \frac{\alpha}{32 s_W^2} g_{tcH}^2 m_t \left(1 - \frac{m_H^2}{m_t^2}\right)^2$$

$$\Gamma_{t\to bW} = \frac{\alpha}{16 s_W^2} |V_{tb}|^2 \frac{m_t^3}{m_W^2} \left(1 - 3x^4 + 2x^6\right)$$

$$x = m_W / m_t$$

Benchmark model:tt → (Wb) + (cH)





Models

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

Expected event yield for BR(t→cH) = 1%

Channel	Hadronic 7 TeV	Hadronic 8 TeV	Leptonic 8 TeV
tt cross section (pb)	172^{+7}_{-8}	246^{+9}_{-11}	
$H \to \gamma\gamma$ branching ratio (‰)		2.28±0.12	
Signal efficiency (%)	4.34	4.13	1.29
Stat. uncertainty (%)	0.12	0.14	0.06
Expected events for 1% *tcH Br*	1.58	9.30	2.91
Uncertainty (not incl. exp. syst.)	±0.12	(+0.65,−0.72)	(+0.24,−0.27)

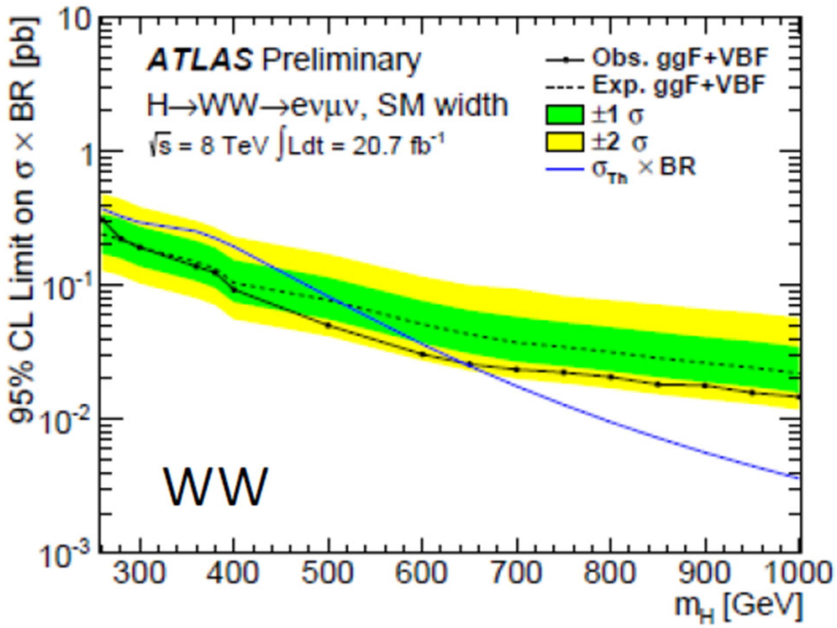
ATLAS FCNC limit:
t → cH(γγ): **BR(t→cH) < 0.8%** @ 95% CL (exp. 0.5%)

Search for High Mass H→ ZZ, WW

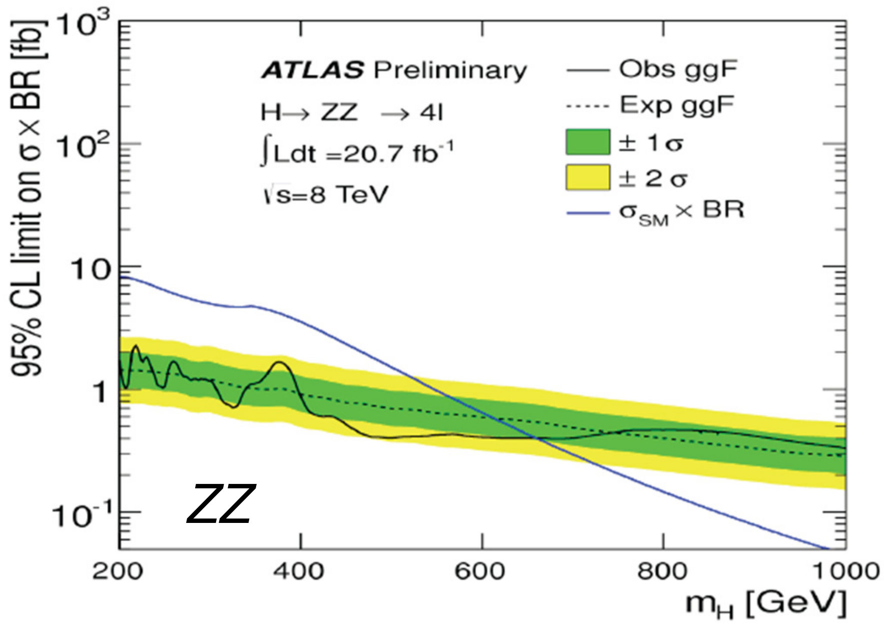
ATLAS-CONF-2013-067

Extend the Higgs search to high mass assume SM-like width, and decay to

WW→ lνlν*

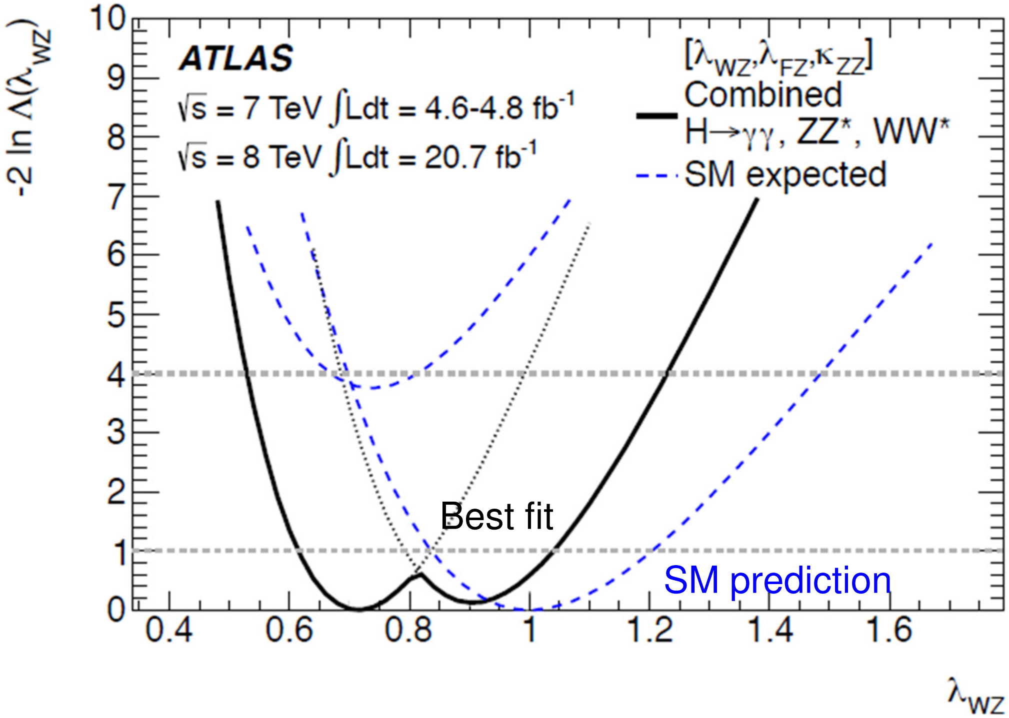


ZZ→ 4l*



95% C.L. exclusion of a SM-like heavy Higgs up to ~ 650 GeV

W vs Z Coupling (custodial symmetry)



λ_{WZ} consistent with SM

$$\lambda_{WZ} = 0.82 \pm 0.15$$

Indirect indication "Higgs-like" boson is EW doublet (since λ_{WZ} = 0.5 for triplet)

Ratio of W/Z couplings (λ_{WZ}), with:

- Fermion couplings grouped together
- Total width left free
- Extra degree to allow to absorb deviation from the SM in the H → γγ loop

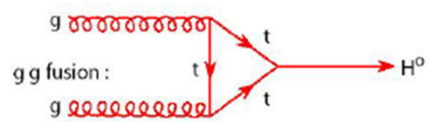
λ_{WZ} consistent with the SM

Coupling Measurements

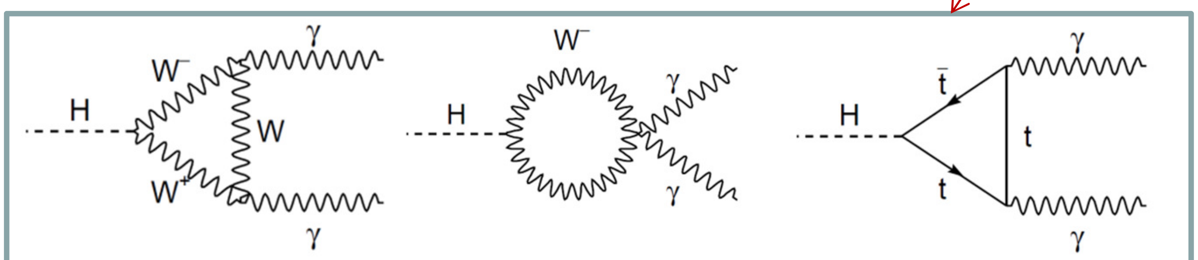
Coupling strengths κ_i & ratio: $\kappa_F = g_F/g_{F,SM}$, $\kappa_V = g_V/g_{V,SM}$, $\lambda_{ij} = \kappa_i/\kappa_j$

Model	Probed couplings	Parameters of interest	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H	Example: $gg \to H \to \gamma\gamma$
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√	$\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)/\kappa_H^2(\kappa_F, \kappa_V)$
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-	$\kappa_{VV}^2 \cdot \lambda_{FV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, \lambda_{FV}, \lambda_{FV}, 1)$
3	Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	√	√	√	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{WZ})$
4		$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$	-	√	√	-	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \lambda_{\gamma Z}^2$
5	Vertex loops	κ_g, κ_γ	=1	=1	-	-	√	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g, \kappa_\gamma)$

Example $H \to \gamma\gamma$



$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$



κ_g , κ_γ: loop coupling scale factors

κ_H is the total Higgs width scale factor

$$\kappa_\gamma^2 = |1.28\,\kappa_W - 0.28\,\kappa_t + \ldots|^2$$

Vector vs Fermion Couplings

2-parameter benchmark model:

$\kappa_V = \kappa_W = \kappa_Z$ (>0)

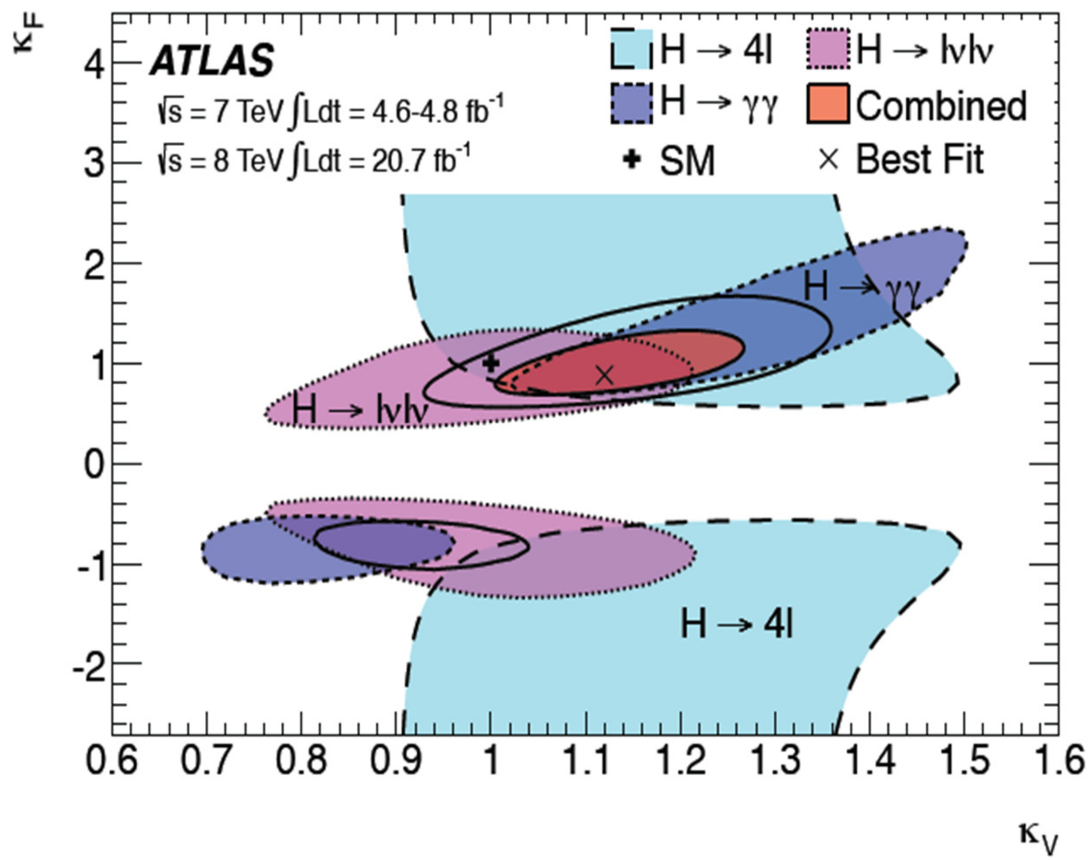
$\kappa_F = \kappa_t = \kappa_b = \kappa_c = \kappa_\tau = \kappa_g$

(Gluon coupling are related to top, b, and their interference in tree level loop diagrams)

Assume no BSM contributions to loops: gg→ H and H→γγ, and no BSM decays (no invisible decays)

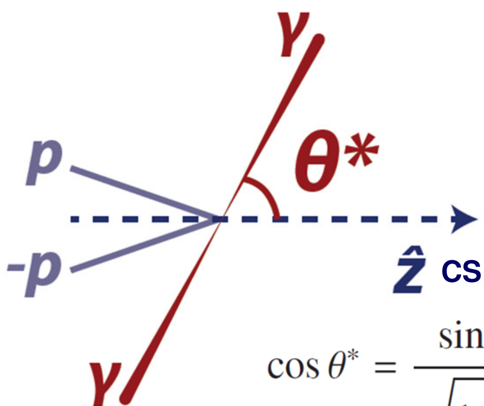
- **$\kappa_F = 0$ is excluded (>5σ)**

Double minimum from interference between vector(W) and fermion(top) in H→γγ



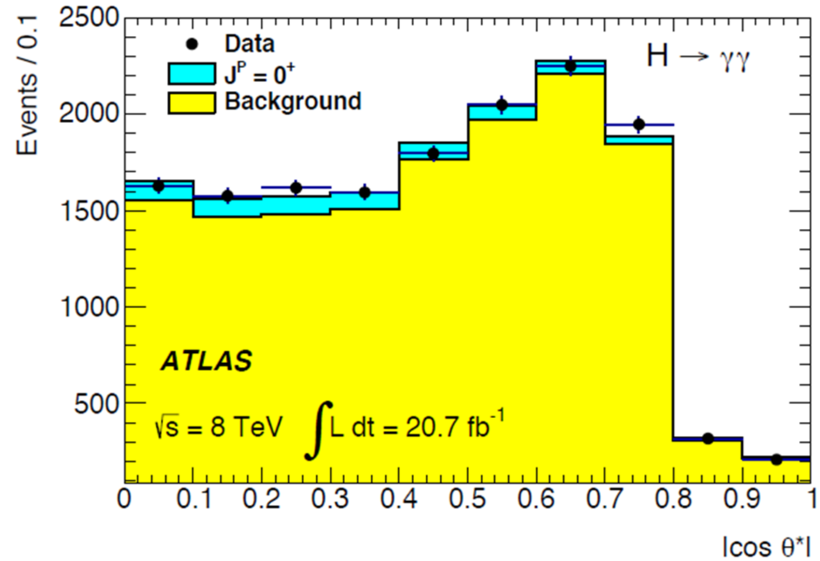
Spin Analysis with H→ γγ

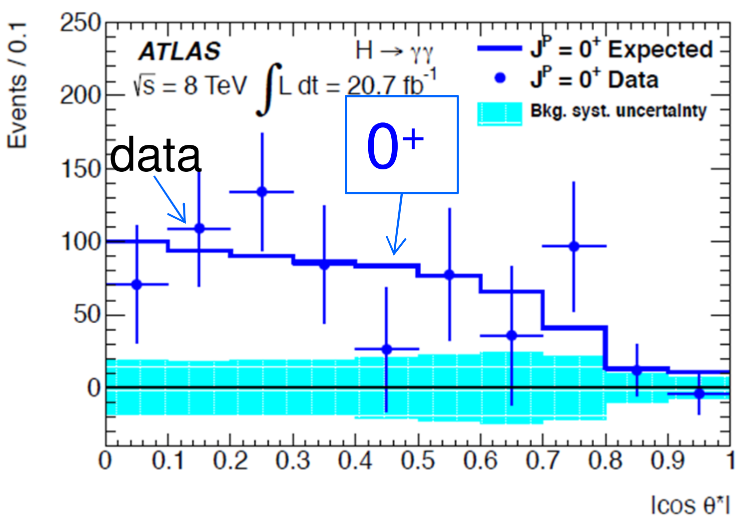
Polar angle θ^* of the photon decay in Collines-Soper frame, along with $m_{\gamma\gamma}$

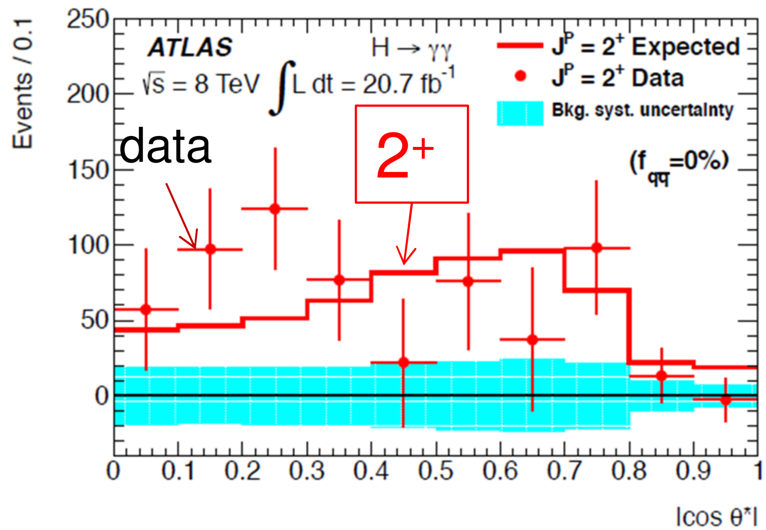


Z_{CS} bisects angle between the momenta of colliding hadrons

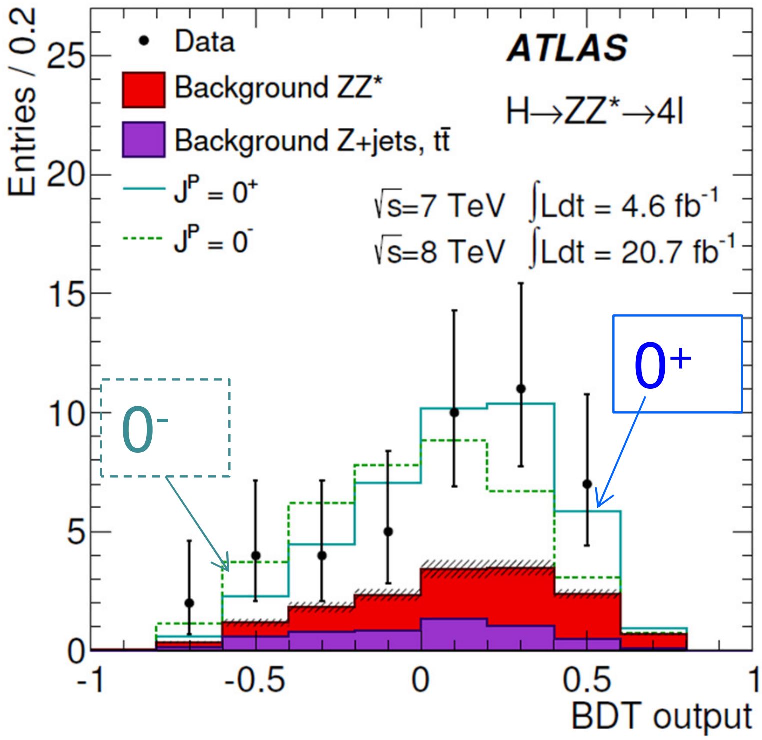
$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

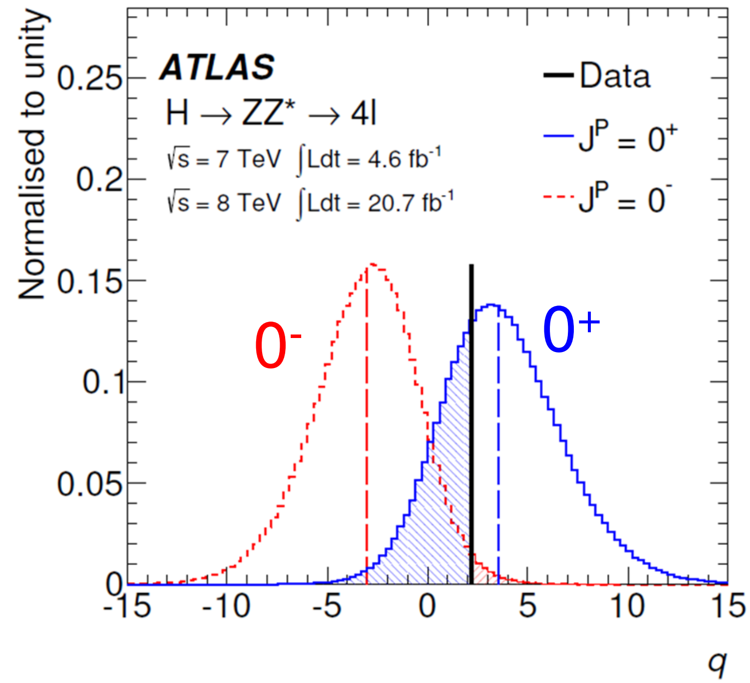






Spin Analysis with H→ ZZ*→ 4l





BDT analysis variables:

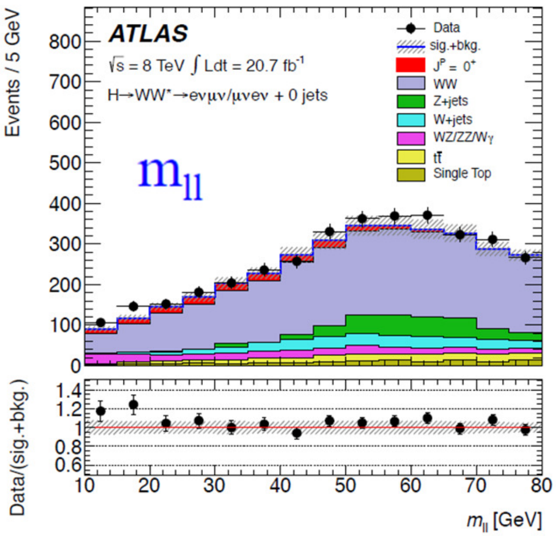
m_{Z1}, m_{Z2} from Higgs --> ZZ* →4l
+ production and decay angles

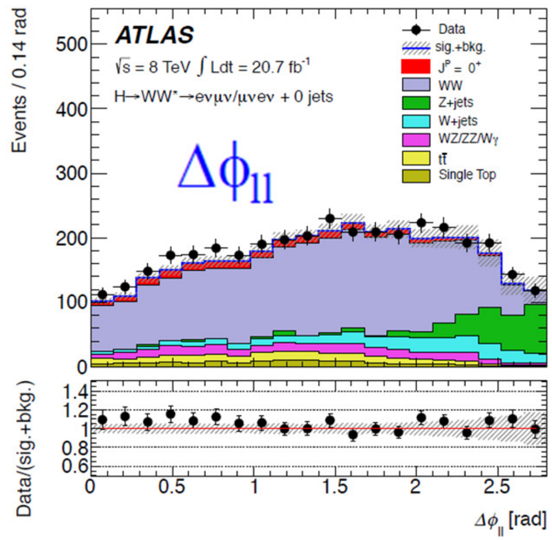
Exclusion **(1-CL_s):**

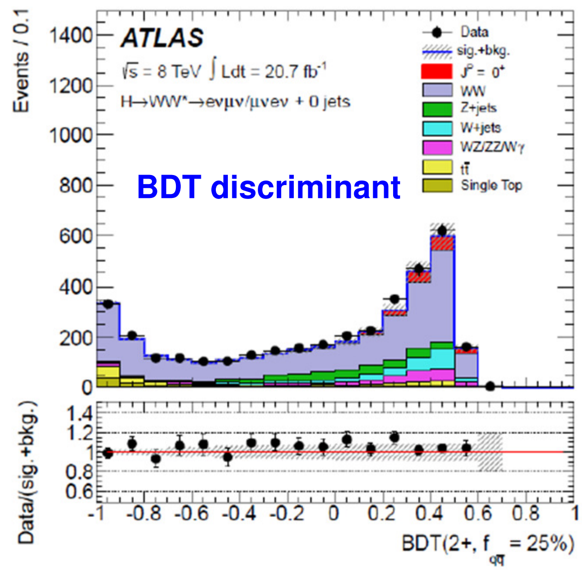
Observed 0^- exclusion 97.8%
Observed 1^+ exclusion 99.8%

		BDT analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060
2^+_m	p_0	0.092	0.079	0.53	0.168
2^-	p_0	0.0053	0.25	0.034	0.258

Spin Analysis With H→ WW*

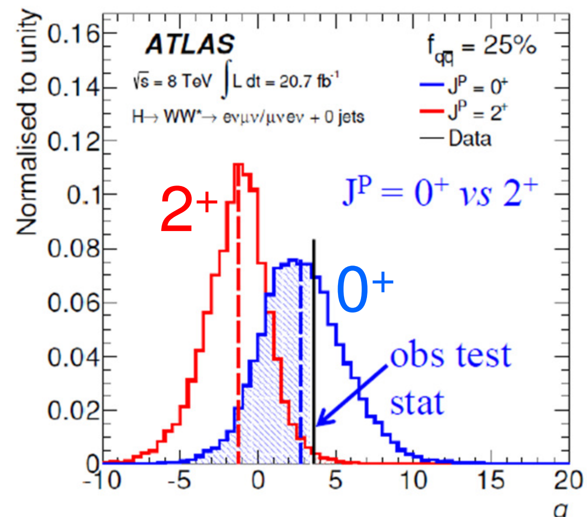






$J^P = 0^+ \; vs \; 2^+$

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.013	$3.6 \cdot 10^{-4}$	0.541	$1.7 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$
75%	0.028	0.003	0.586	0.001	0.003
50%	0.042	0.009	0.616	0.003	0.008
25%	0.048	0.019	0.622	0.008	0.020
0%	0.086	0.054	0.731	0.013	0.048



Exclusion **(1-CL$_s$):**
Observed 2+ (qq=100%) exclusion 99.96%
Observed 2+ (qq = 0%) exclusion 95.2%

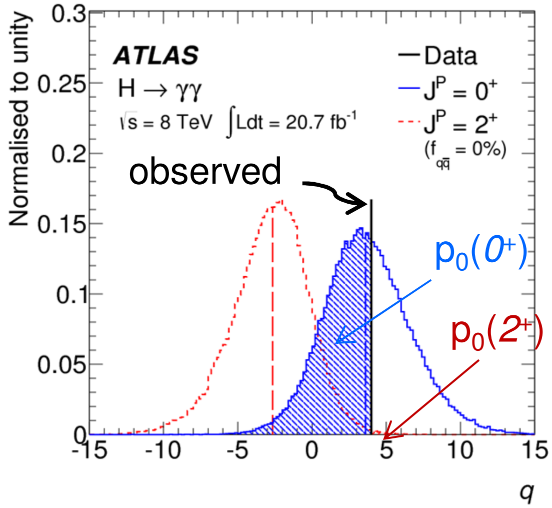
2^+ Hypothesis Exclusion

Method

- Binned likelihood using discriminants
  e.g. $\mathbf{m}_{\gamma\gamma}$ and |**cos** θ*|
- Poisson probability given a signal ***S*** scaled by strength μ and background ***B*** with nuisance parameters θ and constraints from auxiliary
- measurements *A* for each channel
  Ratio of likelihoods test statistic
  $$q = \log(\mathcal{L}(0^+)/\mathcal{L}(J^P_{alt}))$$
  with μ fixed for a given J^P
- **Exclusion using (1 - CL_S)**
  $$CL_S = p_0(J^P_{alt}) / (1-p_0(0^+))$$

$$\mathcal{L}(J^P, \mu, \theta) = \prod_j^{N_{\text{chann.}}} \prod_i^{N_{\text{bins}}} P(N_{i,j} \mid \mu_j \cdot S_{i,j}^{(J^P)}(\theta) + B_{i,j}(\theta)) \times \mathcal{A}_j(\theta)$$

Observed 2^+ exclusion 99.3% (1-CL_S)



$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.148	0.135	0.798	0.025	0.124
75%	0.319	0.305	0.902	0.033	0.337
50%	0.198	0.187	0.708	0.076	0.260
25%	0.052	0.039	0.609	0.021	0.054
0%	0.012	0.005	0.588	0.003	0.007