Higgs production and couplings with the ATLAS detector

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Outline

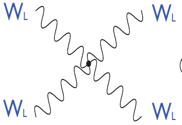
- Higgs is neccesary
- Cross-sections and branching ratios
- ATLAS detector and integrated luminosity
- Production and couplings
  - $H \to \gamma\gamma$
  - $H \to ZZ \to 4l$
  - $H \to WW \to l\nu l\nu$
- Spin-parity determination
- Searches for $H \to b\bar{b}, \tau^+\tau^-, \mu^+\mu^-$
- Search for $H^+ \to c\bar{s}$
- Summary and outlook

Higgs is neccesary

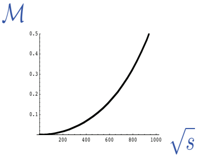
What makes the Higgs special...

Without a Higgs, the states W_L, Z_L **spoil** the nice calculability power of gauge theories

a)

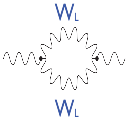


$$\propto \frac{s}{v^2}$$



Unitarity is lost at high-energies

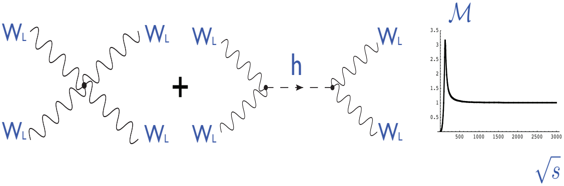
b)

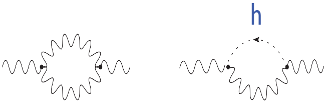


Loops are not finite!

Do not allow for precision calculations

With the Higgs **calculability** is recovered:



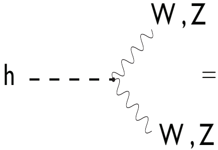


Finite results!

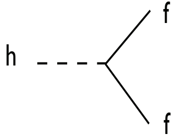
Back to the prediction era!

Higgs is neccesary

To do this job, the Higgs couplings must take a particular value:



$$= gM_W \quad , \quad \frac{gM_Z}{\cos\theta_W}$$

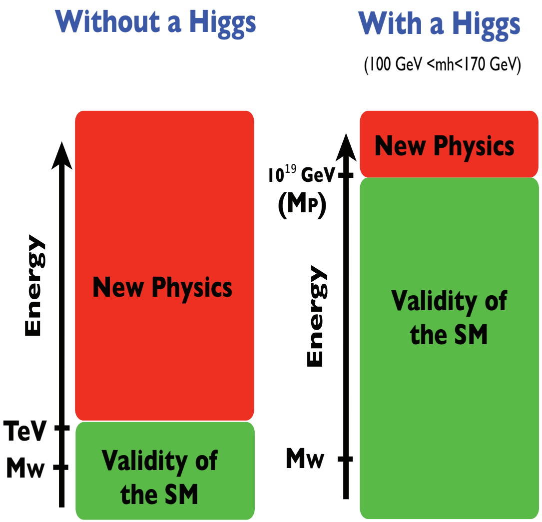


$$= \frac{gM_f}{2M_W}$$

The couplings must be **exactly** these ones (at tree-level) to make the SM a **consistent** theory

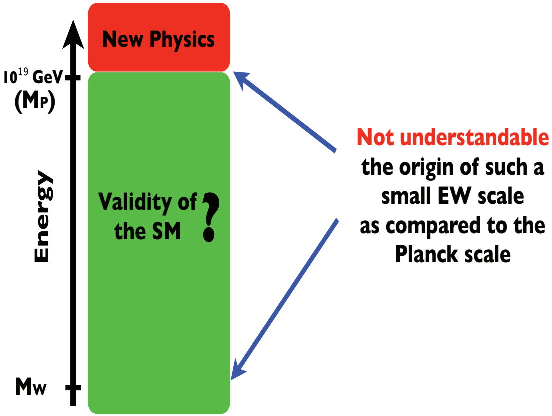
Otherwise this is **NOT** a Higgs = **"Impostor"**

Higgs is neccesary



Higgs is neccesary

Although consistent, we think (and hope) the SM is not the full story



Possibilities that theorists envisage to tackle this problem:

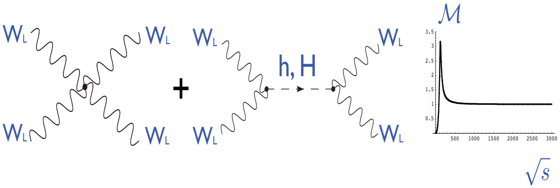
1) Keep the Higgs elementary, but protect it by symmetries: **Supersymmetry**

2) The Higgs is not elementary: **Composite Higgs**

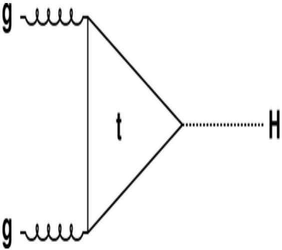
➥ Both imply **changes** in the Higgs sector

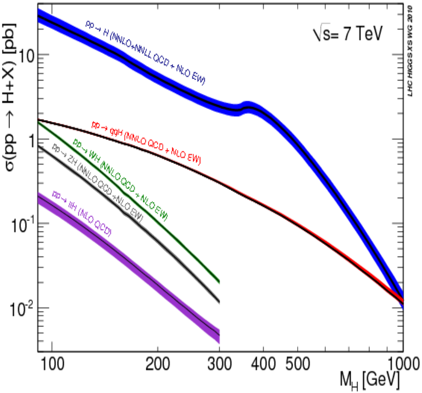
Supersymmetry = MSSM

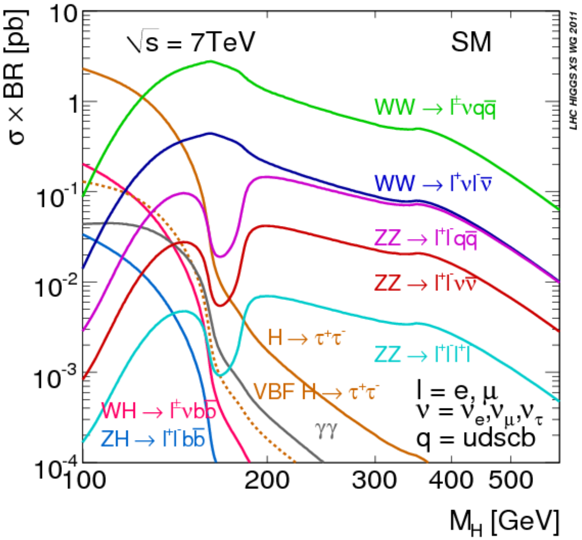
For consistency, an **extra Higgs** (doublet) is needed, sharing the "duties" of the SM Higgs



$$g_{hWW}^{2} + g_{HWW}^{2} = g_{hWW}^{SM\,2} \quad \Rightarrow \quad g_{hWW}, g_{HWW} < g_{hWW}^{SM}$$

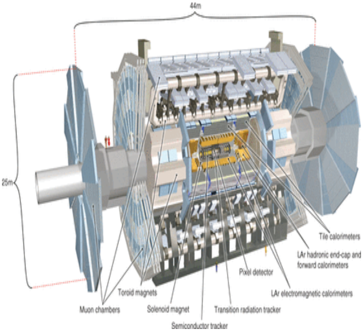

g
g
t
H


σ(pp → H+X) [pb]
10
1
10^{-1}
10^{-2}
100
200
300
400
500
1000
M_H [GeV]
$\sqrt{s}$= 7 TeV
LHC HIGGS XS WG 2010
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)



√s = 7TeV
SM
WW → l⁺νqq̄
WW → l⁺νl⁻ν̄
ZZ → l⁺l⁻qq̄
ZZ → l⁺l⁻νν̄
H → τ⁺τ⁻
ZZ → l⁺l⁻l⁺l⁻
VBF H → τ⁺τ⁻
γγ
WH → l⁺νbb̄
ZH → l⁺l⁻bb̄
l = e, μ
ν = νe,νμ,ντ
q = udscb
σ × BR [pb]
MH [GeV]
LHC HIGGS XS WG 2011
10
1
10-1
10-2
10-3
10-4
100
200
300
400
500

Cross section (pb) at $\sqrt{s}$=8 (7) TeV		Branching ratio (relative uncertainty)	
ggF	19.52 (15.32)	$H \to WW^* \to \ell\nu\ell\nu$	0.01 (± 5%)
VBF	1.58 (1.22)	$H \to \gamma\gamma$	2.28×10^{-3} (± 5%)
WH	0.70 (0.57)	$H \to ZZ^* \to 4\ell$	1.25×10^{-4} (± 5%)
ZH	0.39 (0.31)		
$t\bar{t}H$	0.13 (0.09)		
Total	22.32 (17.51)		


44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

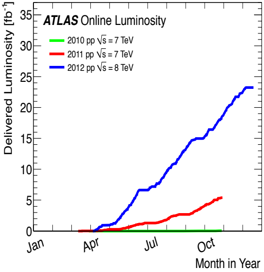
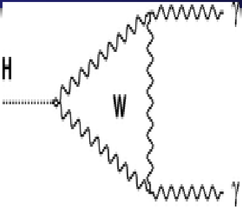

ATLAS Online Luminosity
2010 pp √s = 7 TeV
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
Delivered Luminosity [fb⁻¹]
35
30
25
20
15
10
5
0
Jan
Apr
Jul
Oct
Month in Year

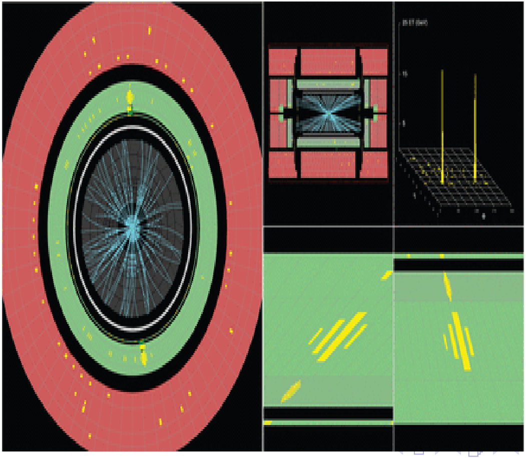
Table 1: Main sources of experimental uncertainty, and of theoretical uncertainty on the signal yield, common to the three channels considered in this study. Theoretical uncertainties are given for a SM Higgs boson of mass m_H = 125 GeV and are taken from Refs. [14–16]. "QCD scale" indicates (here and throughout this paper) QCD renormalisation and factorisation scales and "PDFs" indicates parton distribution functions. The ranges for the experimental uncertainties cover the variations with p_T and η.

Source (experimental)	Uncertainty (%)
Luminosity	±1.8 (2011), ±3.6 (2012)
Electron efficiency	±2–5
Jet energy scale	±1–5
Jet energy resolution	±2–40
Source (theory)	**Uncertainty (%)**
QCD scale	±8 (ggF), ±1(VBF, VH), $^{+4}_{-9}$ (ttH)
PDFs + α_s	±8 (ggF, ttH), ±4 (VBF, VH)

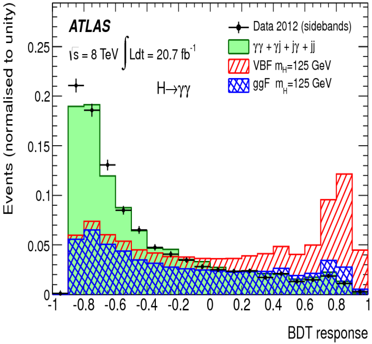
Table 2: Event generators used to model the signal and the main background processes. "PYTHIA" indicates that PYTHIA6 [31] and PYTHIA8 [32] are used for the simulations of 7 TeV and 8 TeV data, respectively.

Process	Generator
ggF, VBF	POWHEG [33, 34]+PYTHIA
$WH, ZH, t\bar{t}H$	PYTHIA
$H \to ZZ^* \to 4\ell$ decay	PROPHECY4f [35, 36]
W+jets, Z/γ^*+jets	ALPGEN [37]+HERWIG [38], POWHEG+PYTHIA, SHERPA [39]
$t\bar{t}, tW, tb$	MC@NLO [40]+HERWIG
tqb	AcerMC [41]+PYTHIA6
$q\bar{q} \to WW$	POWHEG+PYTHIA6
$gg \to WW$	gg2WW [42, 43]+HERWIG
$q\bar{q} \to ZZ^*$	POWHEG [44]+PYTHIA
$gg \to ZZ^*$	gg2ZZ [43, 45]+HERWIG
WZ	MadGraph [46, 47]+PYTHIA6, HERWIG
$W\gamma$+jets	ALPGEN+HERWIG
$W\gamma^*$	MadGraph [48]+PYTHIA6 for $m_{\gamma^*} < 7$ GeV
	POWHEG+PYTHIA for $m_{\gamma^*} > 7$ GeV
$q\bar{q}/gg \to \gamma\gamma$	SHERPA

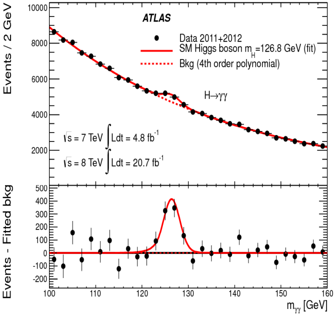

H
W
γ
γ



This channel is particularly sensitive to physics BSM
Di-photon trigger with E_T threshold above 20 GeV at 7 TeV $\rightarrow \epsilon > 99\%$
Event selection: two **high pt isolated photons** with $100 < m_{\gamma\gamma} < 160$ GeV$\rightarrow$ event categories. Shows first evidence for VBF contribution
Main background: $\gamma\gamma$ continuum, plus smaller $\gamma + jet$ and di-jet production



Category	N_D	N_B	N_S	ggF	VBF	WH	ZH	$t\bar{t}H$
Untagged	14248	13582	350	320	19	7.0	4.2	1.0
Loose high-mass two-jet	41	28	5.0	2.3	2.7	< 0.1	< 0.1	< 0.1
Tight high-mass two-jet	23	13	7.7	1.8	5.9	< 0.1	< 0.1	< 0.1
Low-mass two-jet	19	21	3.1	1.5	< 0.1	0.92	0.54	< 0.1
E_T^{miss} significance	8	4	1.2	< 0.1	< 0.1	0.43	0.57	0.14
Lepton	20	12	2.7	< 0.1	< 0.1	1.7	0.41	0.50
All categories (inclusive)	13931	13205	370	330	27	10	5.8	1.7

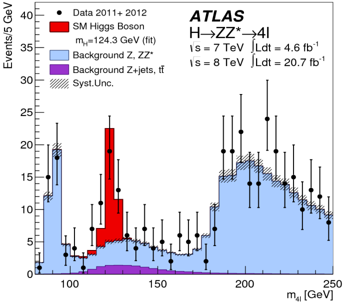


$$m_H = 126.8 \pm 0.2(stat) \pm 0.7(syst)GeV \quad (1)$$

Significance of observed peak is 7.4σ with 4.3σ expected from SM

Small branching ratio but large signal to background ratio → coupling to Z bosons. Select **two pairs of same-flavour opposite-charge, isolated leptons**
Main backgrounds: ZZ^* continuum, $t\bar{t}$ and $Z + b\bar{b}$ production
Three categories: VBF, VH and ggF

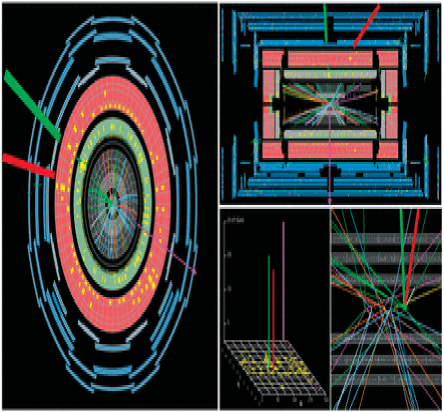
	Signal	ZZ^*	$Z + \text{jets}, t\bar{t}$	Observed
4μ	6.3±0.8	2.8±0.1	0.55±0.15	13
$2e2\mu/2\mu2e$	7.0±0.6	3.5±0.1	2.11±0.37	13
$4e$	2.6±0.4	1.2±0.1	1.11±0.28	6



$$m_H = 124.3 \pm 0.6(stat) \pm 0.5(syst) GeV \quad (2)$$

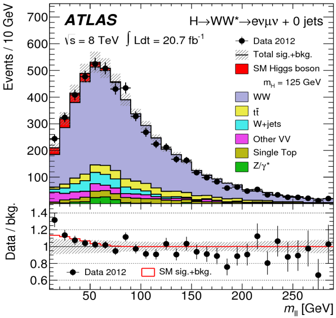
Significance of observed peak is 6.6σ with 4.4σ expected from SM

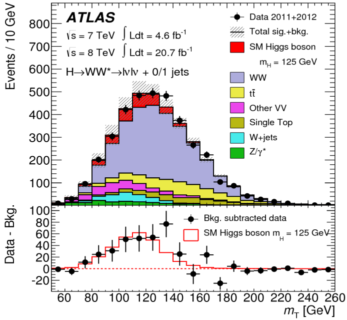
Higgs $\rightarrow WW \rightarrow l\nu l\nu$

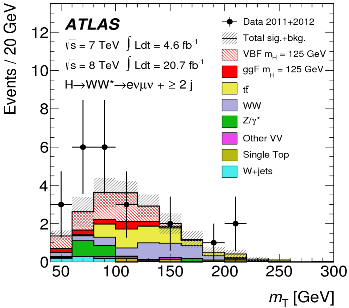


This decay mode is sensitive to Higgs coupling to W bosons. Large rate but no mass peak reconstruction is possible. Requires **two opposite-charge isolated leptons + missing** E_T. Dominant backgrounds are: WW, $t\bar{t}$, Wt, Drell-Yan. Events are classified according to associated jet multiplicity thus allowing background control and extraction of ggF and VBF strengths

	$N_{jet}=0$	$N_{jet}=1$	$N_{jet}\geq 2$
Observed	831	309	55
Signal	100 ± 21	41 ± 14	10.9 ± 1.4
Total background	739 ± 39	261 ± 28	36 ± 4
WW	551 ± 41	108 ± 40	4.1 ± 1.5
Other VV	58 ± 8	27 ± 6	1.9 ± 0.4
Top-quark	39 ± 5	95 ± 28	5.4 ± 2.1
Z+jets	30 ± 10	12 ± 6	22 ± 3
W+jets	61 ± 21	20 ± 5	0.7 ± 0.2







No precise mass determination is possible.
Observed significance for $m_H = 125.5 GeV$ is 3.8σ with 3.8σ expected in SM

Hypothesis testing and confidence intervals based on the profile likelihood ratio $\Lambda(\alpha)$.

The latter depends on parameters of interest, α, such as : m_H, production strengths relative to SM μ, coupling strengths κ, ratios of coupling strengths λ, as well as on nuisance parameters denoted by θ.

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\hat{\theta}}(\alpha))}{L(\hat{\alpha}, \hat{\theta})} \tag{3}$$

Likelihood functions are built using sums of signal and background probability density functions in the discriminating variables: $m_{\gamma\gamma}, m_{4l}, m_T$.

Single circumflex: unconditional maximum likelihood estimate of a parameter

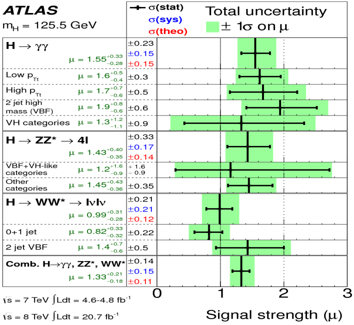
Double circumflex: conditional maximum likelihood estimate for given fixed values of the parameter of interest α

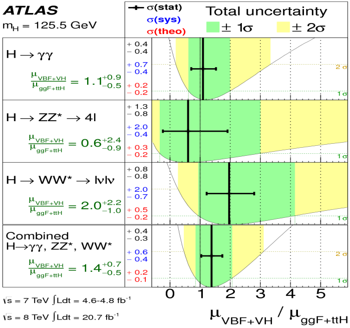
Systematic uncertainties and their correlations are modelled by introducing nuisance parameters

$$Combined\ \ mass\ \ :\ \ m_H = 125.5 \pm 0.2(stat) \pm 0.6(syst)GeV \tag{4}$$

$$Production\ strength\ \ :\ \ \mu = 1.33 \pm 0.14(stat) \pm 0.15(syst)GeV \tag{5}$$

$$\frac{\mu_{VBF}}{\mu_{ggF+ttH}} = 1.4 \pm 0.4(stat) \pm 0.5(syst)GeV \tag{6}$$

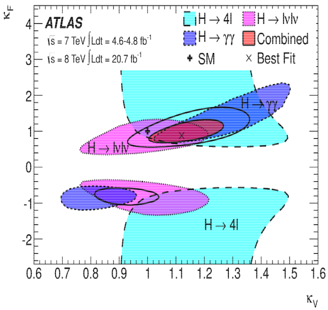




Assumptions:

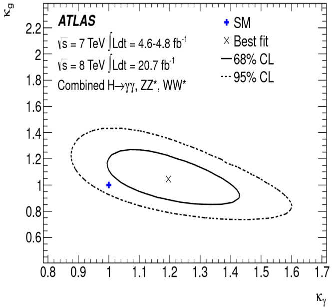
- Signals observed in various channels originate from a single resonance
- Width of Higgs boson is narrow : $\sigma B(i \to H \to j) = \frac{\sigma_i \Gamma_f}{\Gamma_H}$
- Only modifications of coupling strengths are considered without changing SM Lagrangian

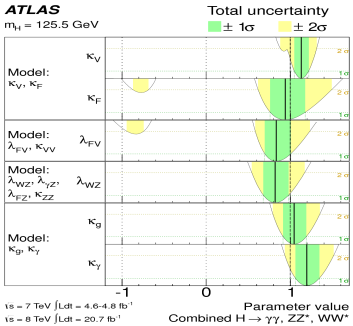
$$\kappa_F : [0.76, 1.18] \quad \kappa_V : [1.05, 1.22] \tag{7}$$



BSM scenarios predict new heavy particles with potential contributions to loop induced processes such as $gg \to H$ and $H \to \gamma\gamma$. Efective scale factors κ_g and κ_γ are fitted to be:

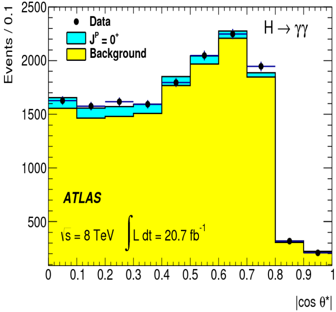
$$\kappa_g = 1.04 \pm 0.14 \qquad \kappa_\gamma = 1.20 \pm 0.15 \tag{8}$$



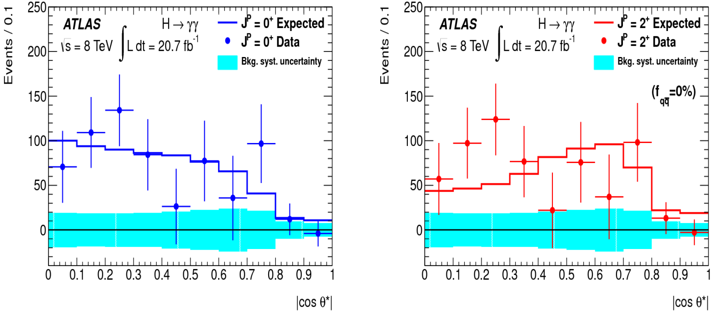


Measure polar angle, θ^*, distribution of the photons in the resonance rest frame
Large background whose distributions in $|cos\theta^*|$ lies between $J^P = 0^+$ and $J^P = 2^+$ from $gg \to \gamma\gamma$
Likelihood fits to $m_{\gamma\gamma}$ and $|cos\theta^*|$ with $105 < m_{\gamma\gamma} < 160 GeV$
SR: $122 < m_{\gamma\gamma} < 130 GeV$ with 14977 events see figure below
CR : $105 < m_{\gamma\gamma} < 122 GeV$ and $130 < m_{\gamma\gamma} < 160 GeV$ with 14300 events

Expected SM Higgs boson signal: 370 events

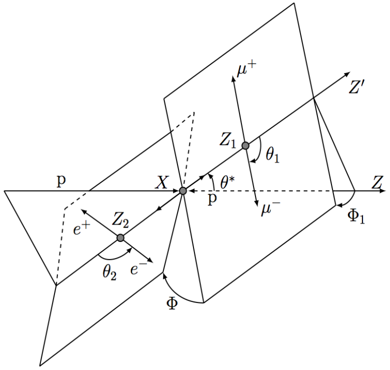


Polar angle distribution in the signal region after background subtraction compared to $J^P = 0^+, 2^+$

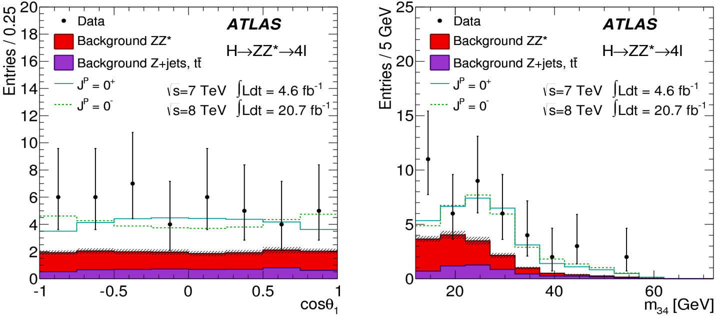


Higgs is $J^P = 0^+$: $H \to ZZ^* \to 4l$

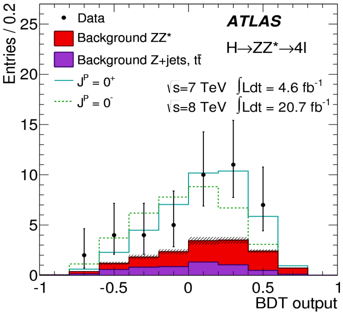
Select events with $115 GeV < m_{4l} < 130 GeV$ and measure m_{12}, m_{34} and five angles as illustrated below: 43 events with expected background of 16. Variables are fed into a BDT algorithm designed to distinguish between $J^P = 0^+$ and $J^P = 0^-, 1^+, 1^-, 2^+, 2^-$.

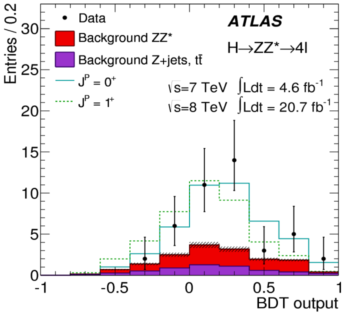


Higgs is $J^P = 0^+$: $H \to ZZ^* \to 4l$



Higgs is $J^P = 0^+$: $H \to ZZ^* \to 4l$





$J^P = 0^+$ vs $J^P = 0^-$: $H \to ZZ^* \to 4l$

$J^P = 0^-$ excluded at 97.8% CL

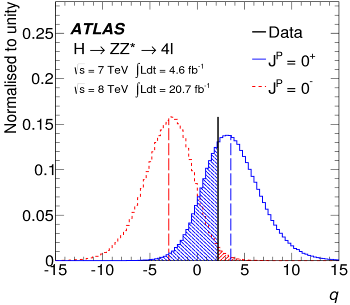
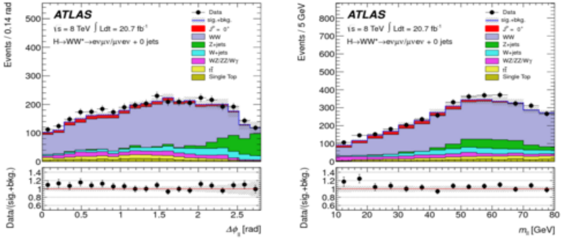


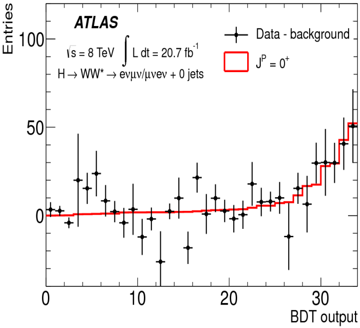
Table 1: Summary of results for the 0^+ versus 0^- test in the $H \to ZZ^*$ channel. The expected p_0-values for rejecting the 0^+ and 0^- hypotheses (assuming the alternative hypothesis) are shown in the second and third columns. The fourth and fifth columns show the observed p_0-values, while the CL_s value for excluding the 0^- hypothesis is given in the last column.

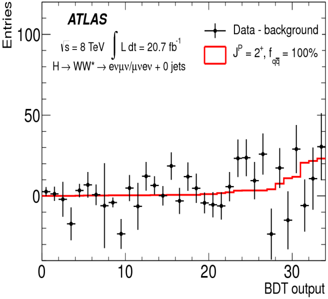
Channel	0^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 0^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 0^-)$	$CL_s(J^P = 0^-)$
$H \to ZZ^*$	$1.5 \cdot 10^{-3}$	$3.7 \cdot 10^{-3}$	0.31	0.015	0.022

Select dilepton events with $m_{ll} < 80GeV$, $p_T^{ll} > 20GeV$ and $\Delta\Phi_{ll} < 2.8$ with no additional jets above $p_T = 30GeV$: 3615 events with 170 (3300) expected from SM Higgs (resp. Background processes)
These variables together with transverse mass,m_T, of the dilepton and the missing momentum system, are fed into a BDT algorithm to distinguish between $J^P = 0^+$ and alternative hypothesis.



BDT outputs after background subtraction





$J^P = 1^\pm$ excluded at 99.7% CL

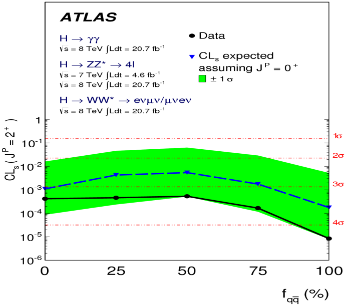
Table 2: Summary of results for the $J^P = 0^+$ versus 1^+ test in the $H \to ZZ^*$ and $H \to WW^*$ channels, as well as their combination. The expected p_0-values for rejecting the $J^P = 0^+$ and 1^+ hypotheses (assuming the alternative hypothesis) are shown in the second and third columns. The fourth and fifth columns show the observed p_0-values, while the CL_s values for excluding the 1^+ hypothesis are given in the last column.

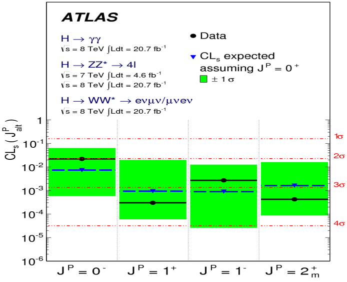
Channel	1^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^+)$	$CL_s(J^P = 1^+)$
$H \to ZZ^*$	$4.6 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	0.55	$1.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
$H \to WW^*$	0.11	0.08	0.70	0.02	0.08
Combination	$2.7 \cdot 10^{-3}$	$4.7 \cdot 10^{-4}$	0.62	$1.2 \cdot 10^{-4}$	$3.0 \cdot 10^{-4}$

Table 3: Summary of results for the $J^P = 0^+$ versus 1^- test in the $H \to ZZ^*$ and $H \to WW^*$ channels, as well as their combination. The expected p_0-values for rejecting the $J^P = 0^+$ and 1^- hypotheses (assuming the alternative hypothesis) are shown in the second and third columns. The fourth and fifth columns show the observed p_0-values, while the CL_s values for excluding the 1^- hypothesis are given in the last column.

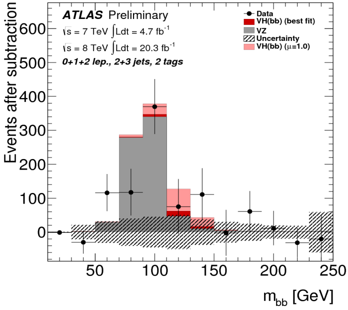
Channel	1^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^-)$	$CL_s(J^P = 1^-)$
$H \to ZZ^*$	$0.9 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$	0.15	0.051	0.060
$H \to WW^*$	0.06	0.02	0.66	0.006	0.017
Combination	$1.4 \cdot 10^{-3}$	$3.6 \cdot 10^{-4}$	0.33	$1.8 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$

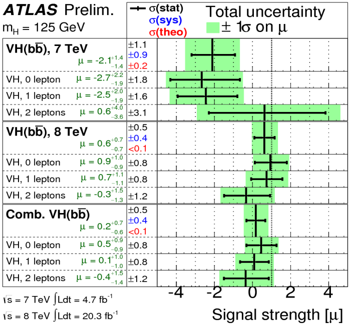
$J^P = 2^+$ excluded at above 95% CL

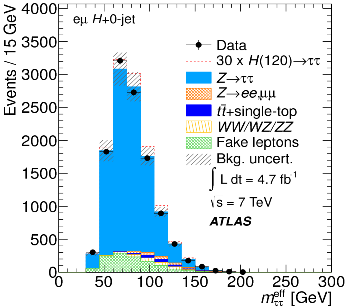


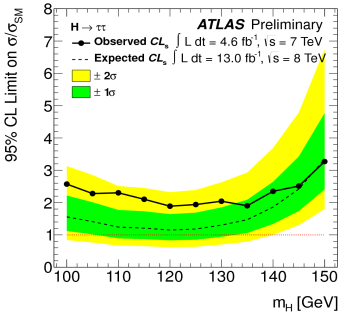


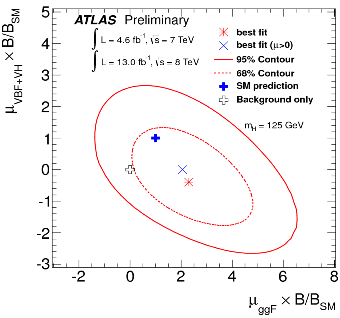
With $V = Z \to \nu\nu, ll$ (0-lepton, 2-lepton mode) or $V = W \to l\nu$ 1-lepton mode
Signal strength fitted to be : $\mu = 0.2 \pm 0.5(stat.) \pm 0.4(syst.)$.

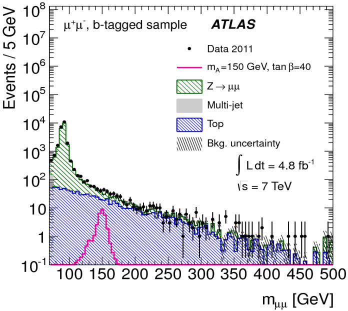




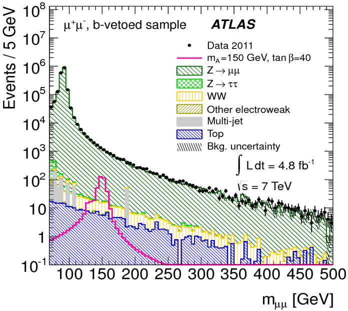

eμ H+0-jet
Data
30 x H(120)→ττ
Z→ττ
Z→ee,μμ
tt̄+single-top
WW/WZ/ZZ
Fake leptons
Bkg. uncert.
∫ L dt = 4.7 fb-1
√s = 7 TeV
ATLAS
Events / 15 GeV
m_ττ^eff [GeV]
ee + eμ + μμ H+1-jet
10 x H(120)→ττ
Events / 20 GeV
Collinear mass m_ττ [GeV]


ATLAS Preliminary
H → ττ
Observed CLs ∫ L dt = 4.6 fb-1, √s = 7 TeV
Expected CLs ∫ L dt = 13.0 fb-1, √s = 8 TeV
± 2σ
± 1σ
95% CL Limit on σ/σSM
mH [GeV]

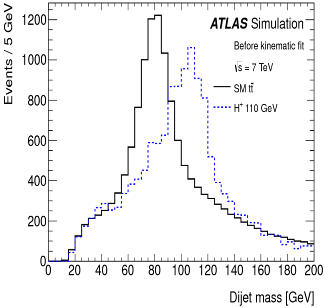

ATLAS Preliminary
∫ L = 4.6 fb-1, √s = 7 TeV
∫ L = 13.0 fb-1, √s = 8 TeV
best fit
best fit (μ>0)
95% Contour
68% Contour
SM prediction
Background only
mH = 125 GeV
μVBF+VH × B/BSM
μggF × B/BSM

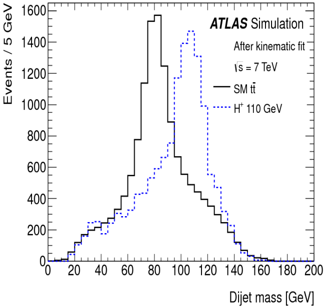


μ+μ-, b-tagged sample
ATLAS
Data 2011
m_A=150 GeV, tan β=40
Z → μμ
Multi-jet
Top
Bkg. uncertainty
∫ L dt = 4.8 fb-1
√s = 7 TeV
Events / 5 GeV
m_μμ [GeV]

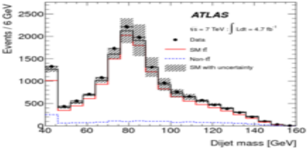


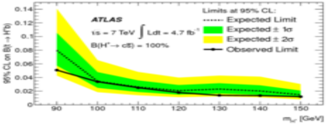
μ+μ-, b-vetoed sample
ATLAS
Data 2011
m_A=150 GeV, tan β=40
Z → μμ
Z → ττ
WW
Other electroweak
Multi-jet
Top
Bkg. uncertainty
∫ L dt = 4.8 fb-1
√s = 7 TeV
Events / 5 GeV
m_μμ [GeV]


ATLAS Simulation
Before kinematic fit
√s = 7 TeV
SM tt̄
H+ 110 GeV
Events / 5 GeV
Dijet mass [GeV]
0
200
400
600
800
1000
1200
0
20
40
60
80
100
120
140
160
180
200


ATLAS Simulation
After kinematic fit
√s = 7 TeV
SM tt̄
H+ 110 GeV
Events / 5 GeV
Dijet mass [GeV]
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180
200

Charged Higgs searches





Summary and Outlook

- Production and coupling strengths in agreement with SM expectations
- $J^P = 0^+$ favoured
- No signs of H^+
- Looking forward to running at 13 TeV, $H \to \tau\tau, b\bar{b}$?