

**Recent ATLAS results on Higgs decays to  $\gamma\gamma$ /ZZ/WW**  
International Symposium on Higgs Physics 2013

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on behalf of the ATLAS Collaboration



**06-08-2013**

## Introduction

- new particle with mass about 125 GeV discovered in July 2012 by both ATLAS and CMS
- since then, several analysis improvements have been made and larger data samples have been collected to study **the Higgs**
  - targeted analysis of *Higgs production modes*
  - allows for detailed *Higgs properties measurements*
- this presentation will focus on **new ATLAS results from the di-boson decay modes** since Ref [1]
  - changes w.r.t. discovery analysis denoted with 

# Outline

## 1 Introduction

- data samples
- basic observables in all channels

## 2 Higgs production (rate, and couplings)

- overall rate measurement
- vector boson fusion (VBF) production
- couplings determination
- mass

## 3 Higgs quantum properties

- spin
- parity



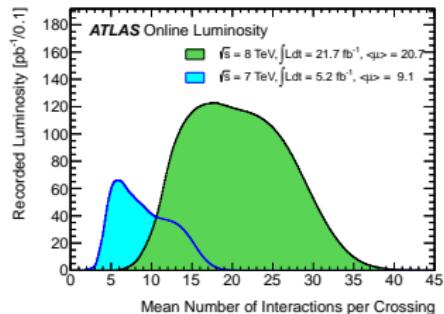
for each channel, and combined

## Further references:

- *Higgs boson production and couplings in diboson final states:* [arXiv:1307.1427](https://arxiv.org/abs/1307.1427) (submitted to Phys. Letters B)
- *Evidence for the spin-0 nature of the Higgs boson:* [arXiv:1307.1432](https://arxiv.org/abs/1307.1432) (submitted to Phys. Letters B)

# Event Reconstruction

- collected  $\sim 4.7 \text{ fb}^{-1}$  in 2011 at 7 TeV,  
 $20.7 \text{ fb}^{-1}$  in 2012 at 8 TeV (**much higher pileup**)

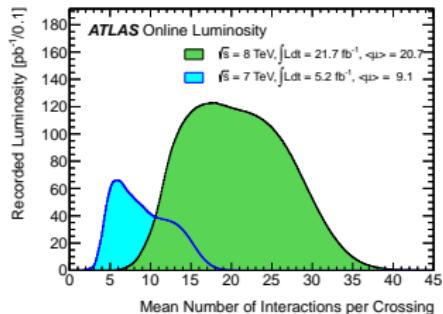


## Leptons

- muons from matched tracks in muon spectrometer (MS) to inner tracker (use only MS in  $2.5 < |\eta| < 2.7$ )
  - calorimeter-tagged and standalone used in  $Z Z \rightarrow 4\ell$
- electrons reconstructed from tracks matched to clusters
  - select based on cluster shapes in electromagnetic (EM) calorimeter, hadronic leakage
- determine efficiencies and energy/momentum scale & resolution using  $Z \rightarrow ll$ ,  $W \rightarrow l\nu$  and  $J/\psi \rightarrow ll$  samples
- uncertainties  $\lesssim 1\%$  except electron efficiency ( $2 - 5\%$  depending on  $\eta$ )

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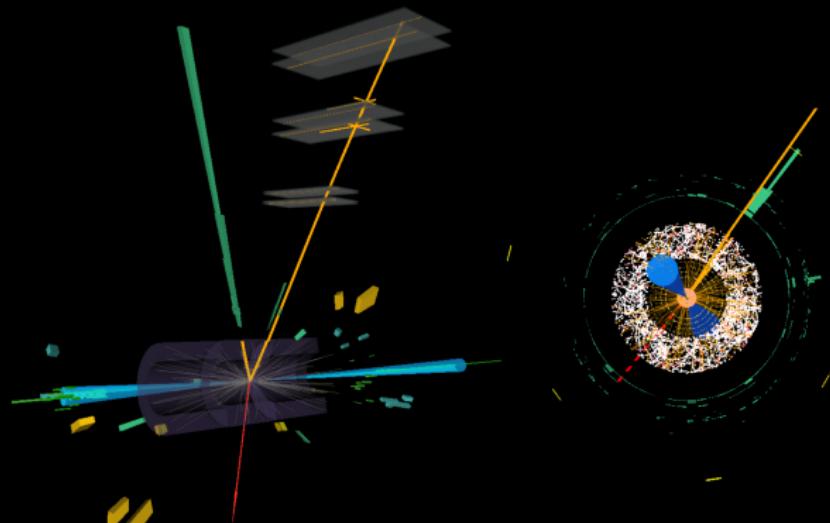
$H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$  candidate event ( $e\mu$  channel)

+ 21.7  $\text{fb}^{-1}$ ,  $\langle\mu\rangle = 20.7$   
+ 5.2  $\text{fb}^{-1}$ ,  $\langle\mu\rangle = 9.1$

- collect  
20.7 fb<sup>-1</sup>  
pileup



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



tracker

sing

on  $\eta$ )

## Event Reconstruction

### Photons

- isolated EM clusters, identified using shower shape variables
  - use track or calorimeter isolation cone  $\Delta R < 0.2$  or  $0.4$
- converted (two matched tracks, or single with no inner layer hit) and un-converted photon categories utilised

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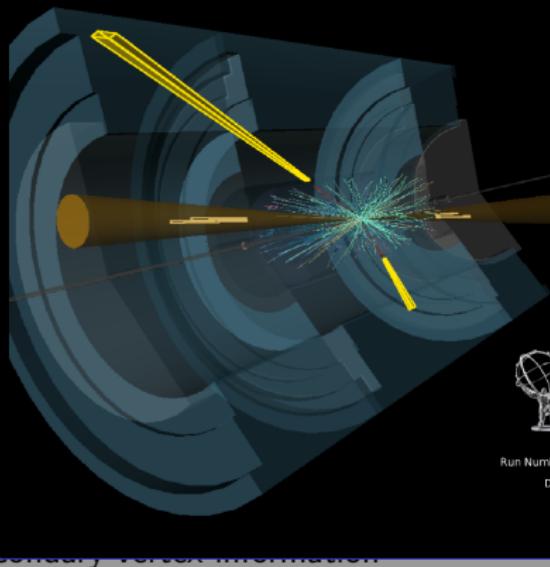
### Jets

- reconstructed with  $R = 0.4$  anti- $k_T$  algorithm
  - inputs noise-suppressed topological clusters
- $p_T > 25$  (30) GeV in central (forward,  $2.4 \leq |\eta| \leq 4.5$ ) region, jet vertex fraction (JVF) to suppress pileup jets
- correct for pileup based on  $N_{PV}$  and event energy density  $\rho$ , jet area  $A$
- $b$ -tagging using NN-based combination of impact parameter and secondary vertex information

# Event Reconstruction

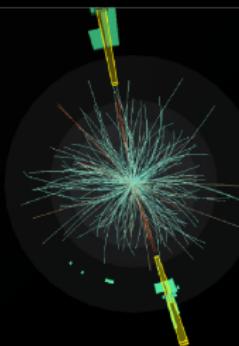
## Photons

- isolated photons
- conversion vertices
- unassociated photons



## Jets

- reconstructed jets
- $p_T$  flow frames
- combined jets
- $b$ -tagged jets
- secondary vertex information



Run Number: 204769, Event Number: 24947130

Date: 2012-06-10 08:17:12 UTC

and

vertex

area A

## Higgs Rate, Mass and Couplings

## Sample Selection

- diphoton trigger  $E_T > 20/20$  ( $35/25$ ) GeV for leading/sub-leading photon in 7 TeV (8 TeV)
- offline  $E_T > 40/30$  GeV, exclude transition region ( $1.37 \leq |\eta| \leq 1.56$ )
  - **except for** spin analysis uses  $p_T > 0.35 m_{\gamma\gamma}$  for leading,  $p_T > 0.25 m_{\gamma\gamma}$  for sub-leading<sup>a</sup>
- select events with  $100 < m_{\gamma\gamma} < 160$

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<sup>a</sup>Note: reduces correlation between  $m_{\gamma\gamma}$  and  $\cos\theta^*$  used in *spin analysis*

## Analysis Categories

$\geq 1$  Leptons (8 TeV): 

- targets  $VH$  production,  $W \rightarrow \ell\nu$  or  $Z \rightarrow \ell\ell$

Large  $E_T^{\text{miss}}$  (8 TeV):

- targets  $VH$ , with  $W \rightarrow \ell\nu$  or  $Z \rightarrow \nu\nu$
- $S(E_T^{\text{miss}}) = E_T^{\text{miss}}/\sigma > 5$ , where  $\sigma \sim 0.7 \text{ GeV}^{1/2} \sqrt{\sum E_T}$

2-jet (low mass) (8 TeV):

- $60 < m_{jj} < 110 \text{ GeV}$  targets  $VH$  production,  $V \rightarrow ff'$ 
  - $|\Delta\eta(\gamma\gamma, jj)| < 1$ ,  $p_{T,t} > 70$  to reduce ggF contribution

2-jet (high mass) (7/8 TeV):

- high  $m_{jj}$ , large rapidity gap targets VBF production
- 8 TeV: cut on BDT trained w/ jet  $\eta$ 's,  $\Delta\eta_{jj}$ ,  $n_{\gamma\gamma} - \bar{n}_j$ , min  $\Delta R(j, \gamma)$ ,  $\Delta\phi(\gamma\gamma, jj)$
- 7 TeV: select events with  $m_{jj} > 400$ ,  $|\Delta\eta_{jj}| > 2.8$  and  $\Delta\phi(\gamma\gamma, jj) > 2.8$

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- 8 TeV: **NEW** cut on BDT trained w/ jet  $\eta$ 's,  $\Delta\eta_{jj}$ ,  $n_{\gamma\gamma} - \bar{n}_j$ ,  $\min \Delta R(j, \gamma)$ ,  $\Delta\phi(\gamma\gamma, jj)$
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Untagged:

	central ( $ \eta  < 0.75$ )		transition ( $1.3 <  \eta  < 1.75$ )		other ( $0.75 <  \eta  < 1.3$ , $1.75 <  \eta  < 2.37$ )	
$\geq 1$ conversions	$p_{T,t} < 60$	$p_{T,t} > 60$	all $p_{T,t}$		$p_{T,t} < 60$	$p_{T,t} > 60$
unconverted	$p_{T,t} < 60$	$p_{T,t} > 60$	$p_{T,t} < 60$		$p_{T,t} > 60$	

# Analysis Categories

$\geq 1$  Leptons (8 TeV):

- target
- Expected signal composition in  $H \rightarrow \gamma\gamma$  categories

Large  $E_T$

- target

- $S(1)$

2-jet (loose)

- 60

- 100

2-jet (high)

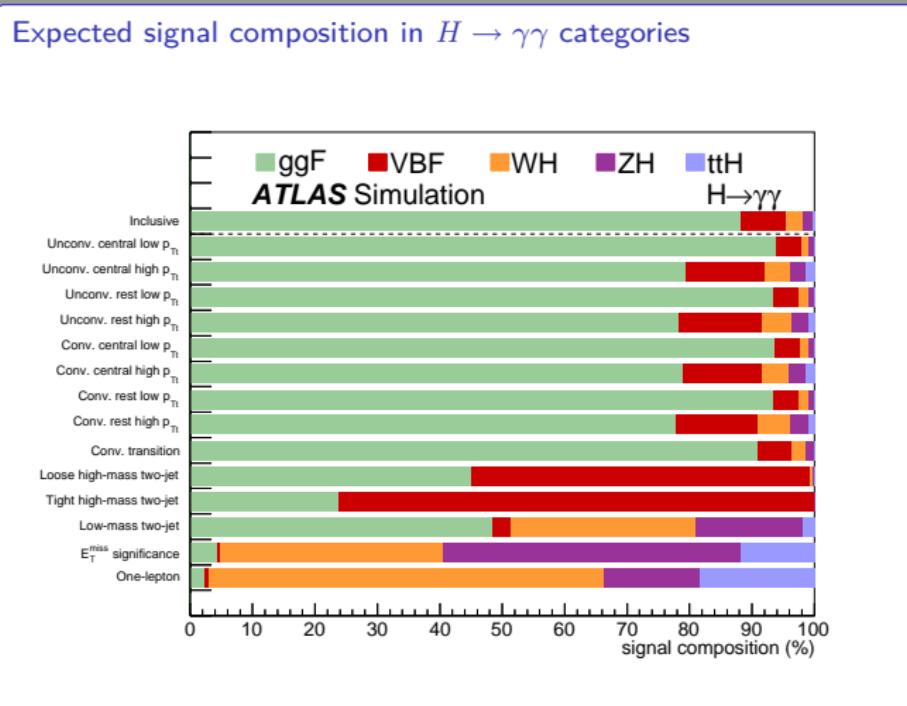
- high

- 8 TeV

- $\Delta\phi$

- 7 TeV

Untagged



$\geq 1$  conversions

$p_{T,t} < 60$     $p_{T,t} > 60$

all  $p_{T,t}$

$p_{T,t} < 60$

$p_{T,t} > 60$

unconverted

$p_{T,t} < 60$     $p_{T,t} > 60$

$p_{T,t} < 60$

$p_{T,t} > 60$

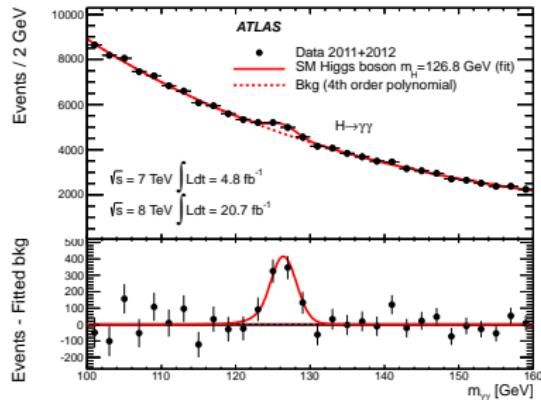
## Signal Yield

- background from fits in  $m_{\gamma\gamma}$  sidebands
- dominant uncertainty on signal yield  
reduced **by factor of 4** to  $\sim 2\%$ 
  - larger data sample and analysis  
improvements to set  $\gamma$  scale
- detailed list of systematic uncertainties  
can be found in [extra material](#)

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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
$E_T^{\text{miss}}$ 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



- combined observed  $Z_0 = 7.4\sigma$ , compared to  $4.3\sigma$  expected
  - *discovery-level signal in just this channel*

## Sample Selection

- largely unchanged w.r.t. discovery analysis, see Ref [1]
  - tighten electron ID
  - constrained fit to  $Z$  mass to improve  $m_{4\ell}$  resolution
  - inclusion of FSR photons within  $\Delta R \lesssim 0.15$  of muon
- select four leptons ( $p_T > 20/15/10/6 - 7$ )
  - include  $\leq 1$  calorimeter-tagged muon in  $|\eta| < 0.1$  or standalone muon
- quadruplets satisfy  $50 < m_{12} < 106$  GeV,  $m_{\min} < m_{34} < 115$  GeV<sup>a</sup>
  - $m_{12}$  is mass closest to  $m_Z$ ,  $m_{34}$  is the other pair mass
- selection efficiency ranges between 19% ( $4e$ ) and 39% ( $4\mu$ )
- suppress  $t\bar{t}$ ,  $Z$ +jets with impact parameter significance cut  $|d_0|/\sigma < 3.5$  (6.5) for muons (electrons)

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<sup>a</sup>Note:  $m_{\min}$  ranges from 12 to 50 depending on  $m_{4\ell}$ , select one with minimal  $|m_{34} - m_Z|$

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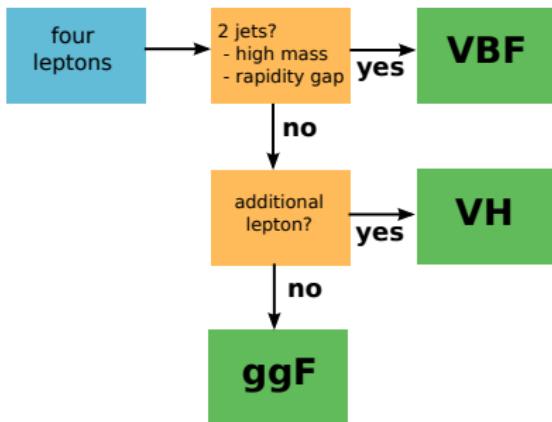
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## Analysis Categories NEW



- new categories added to enhance VBF and VH sensitivity
  - 1  $\Delta\eta_{jj} > 3$  &  $m_{jj} > 350$  GeV  $\rightarrow$  **VBF**
  - 2 !VBF & additional lepton w/  $p_T > 8$  GeV  $\rightarrow$  **VH**
  - 3 !VBF & !VH  $\rightarrow$  **ggF**
- $S/B$  is significantly enhanced for VH and VBF categories w.r.t. inclusive (ggF)

## Background & Signal Yield

- use NLO simulation for irreducible background  $ZZ$
- $\ell\ell + \mu\mu$ : non-isolated muon sample for  $Z + bb$  and  $t\bar{t}$  backgrounds<sup>a</sup>
- relax electron cuts to determine  $\ell\ell + ee$  fakes background

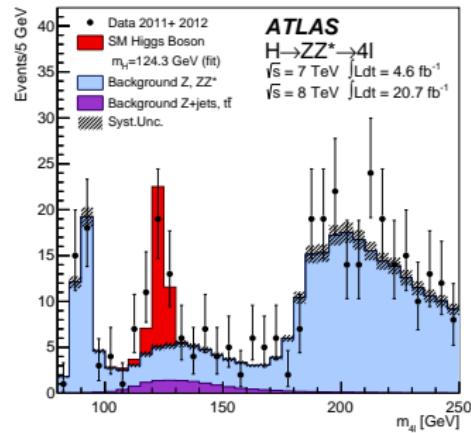
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<sup>a</sup> fit  $m_{12}$  distribution

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- relax electron cuts to determine  $\ell\ell + ee$  fakes background
- largest uncertainties on fitted signal arise from electron efficiencies and  $Z + bb$  background estimate
- maximal deviation is  $Z_0 = 6.6\sigma$  ( $4.4\sigma$  expected) at  $m_H = 124.3$  GeV
  - also clear signal in just this channel

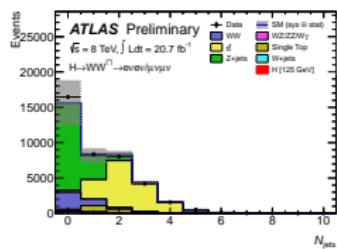
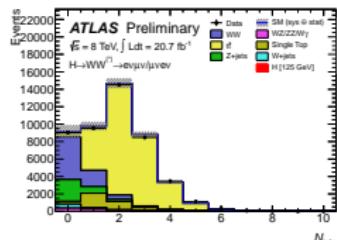
	Signal	$ZZ^*$	$Z + \text{jets}, t\bar{t}$	Observed
$4\mu$	$6.3 \pm 0.8$	$2.8 \pm 0.1$	$0.55 \pm 0.15$	13
$2e2\mu/2\mu2e$	$7.0 \pm 0.6$	$3.5 \pm 0.1$	$2.11 \pm 0.37$	13
$4e$	$2.6 \pm 0.4$	$1.2 \pm 0.1$	$1.11 \pm 0.28$	6



<sup>a</sup>fit  $m_{12}$  distribution

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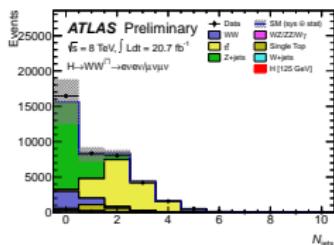
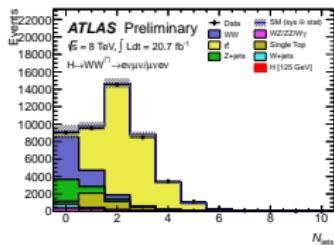
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## Sample Selection

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- motivates quite varied selections based on lepton flavor and jet multiplicity

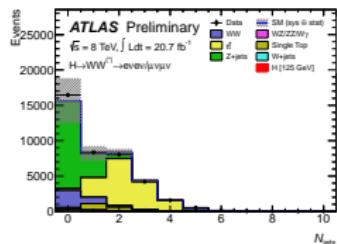
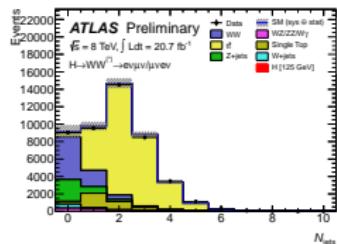
	$e\mu + \mu e$	$ee + \mu\mu$
$N_j = 0$	$m_{\ell\ell} > 10$ GeV $E_{T,\text{rel}}^{\text{miss}} > 25$ GeV	$m_{\ell\ell} > 12,  m_{\ell\ell} - m_Z  > 15$ GeV $E_{T,\text{rel}}^{\text{miss}} > 45$ GeV, $p_{T,\text{rel}}^{\text{miss}} > 45$ GeV $f_{\text{recoil}} < 0.05$ $\Delta\phi_{\ell\ell, E_T^{\text{miss}}} > \pi/2$ $p_T^{\ell\ell} > 30$
$N_j = 1$	$m_{\ell\ell} > 10$ GeV $E_{T,\text{rel}}^{\text{miss}} > 25$ GeV $ m_{\tau\tau} - m_Z  > 25$	$m_{\ell\ell} > 12,  m_{\ell\ell} - m_Z  > 15$ GeV $E_{T,\text{rel}}^{\text{miss}} > 45$ GeV, $p_{T,\text{rel}}^{\text{miss}} > 45$ GeV $f_{\text{recoil}} < 0.2$ $N_{b-\text{tag}} = 0$
$N_j \geq 2$	$m_{\ell\ell} > 10$ GeV $E_T^{\text{miss}} > 20$ GeV	$m_{\ell\ell} > 12,  m_{\ell\ell} - m_Z  > 15$ GeV $E_T^{\text{miss}} > 45$ GeV, $E_{T,\text{STVF}}^{\text{miss}} > 35$ GeV $m_{jj} > 500$ GeV, $\Delta y_{jj} > 2.8$ central jet, outer lepton veto $p_T^{\text{tot}} < 45$ GeV, $N_{b-\text{tag}} = 0$



## Sample Selection

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- motivates quite varied selections based on lepton flavor and jet multiplicity

	$e\mu + \mu e$	$ee + \mu\mu$
$N_j = 0$	$m_{\ell\ell} > 10$ GeV $E_{T,\text{rel}}^{\text{miss}} > 25$ GeV	$m_{\ell\ell} > 12,  m_{\ell\ell} - m_Z  > 15$ GeV $E_{T,\text{rel}}^{\text{miss}} > 45$ GeV, $p_{T,\text{rel}}^{\text{miss}} > 45$ GeV $f_{\text{recoil}} < 0.05$ $\Delta\phi_{\ell\ell, E_T^{\text{miss}}} > \pi/2$ $p_T^{\ell\ell} > 30$
$N_j = 1$	$m_{\ell\ell} > 10$ GeV $E_{T,\text{rel}}^{\text{miss}} > 25$ GeV $ m_{\tau\tau} - m_Z  > 25$	$m_{\ell\ell} > 12,  m_{\ell\ell} - m_Z  > 15$ GeV $E_{T,\text{rel}}^{\text{miss}} > 45$ GeV, $p_{T,\text{rel}}^{\text{miss}} > 45$ GeV $f_{\text{recoil}} < 0.2$ $N_{b-\text{tag}} = 0$
$N_j \geq 2$	$m_{\ell\ell} > 10$ GeV $E_T^{\text{miss}} > 20$ GeV	$m_{\ell\ell} > 12,  m_{\ell\ell} - m_Z  > 15$ GeV $E_T^{\text{miss}} > 45$ GeV, $E_{T,STVF}^{\text{miss}} > 35$ GeV $m_{jj} > 500$ GeV, $\Delta y_{jj} > 2.8$ central jet, outer lepton veto $p_T^{\text{tot}} < 45$ GeV, $N_{b-\text{tag}} = 0$



- exploit spin-0 nature of SM Higgs with  $\Delta\phi_{\ell\ell} < 1.8$ ,  $m_{\ell\ell} < 50$  cuts<sup>a</sup>
- $m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\mathbf{p}_T^{\text{miss}} + \mathbf{E}_T^{\text{miss}}|^2}$  is discriminating variable in all channels
- ratio of VBF to ggF yield in 0/1/2-jet is 2/12/81%

<sup>a</sup>Note:  $m_{\ell\ell} < 60$  GeV for  $N_j \geq 2$

## Background Estimation

### Legend:

Process
$Z^{(*)}Z^{(*)} \rightarrow 4l$
$W(Z/\gamma^*)$ , $W\gamma$
$WW$
$t\bar{t}$
single top
$Z/\gamma^*$ (+ jets)
$W+$ jets

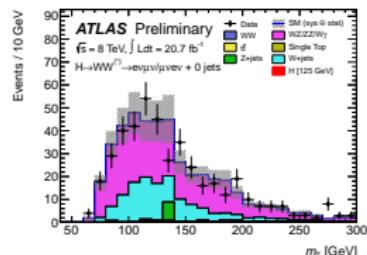
- prediction from simulation
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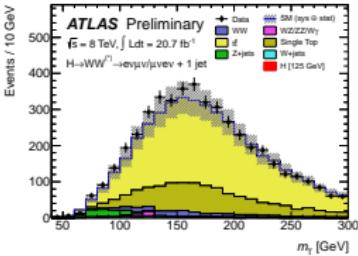
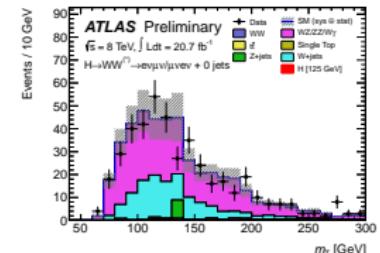
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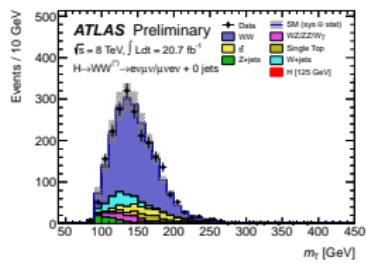
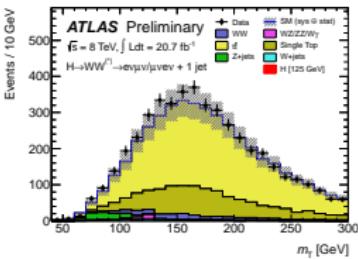
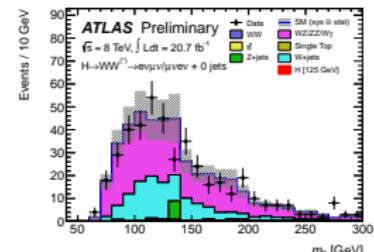
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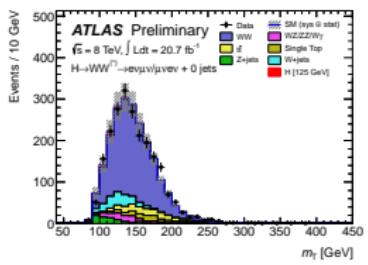
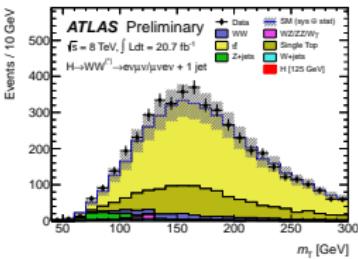
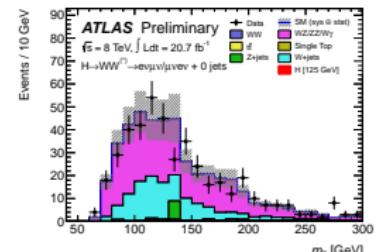
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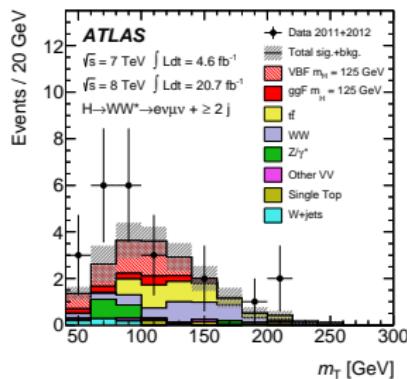
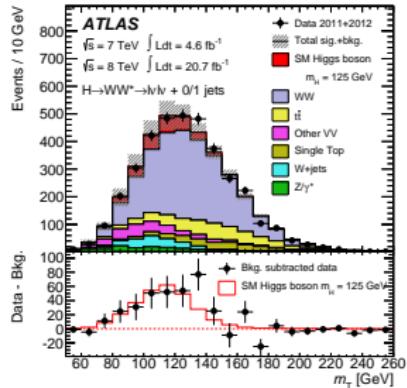


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# Signal Yield

- largest systematic uncertainties are theoretical (QCD scale, parton shower modeling)
- dominant experimental uncertainty is jet energy scale/resolution,  $b$ -tagging

	$N_j = 0$	$N_j = 1$	$N_j \geq 2$
Observed	831	309	55
Signal	$100 \pm 21$	$41 \pm 14$	$10.9 \pm 1.4$
Total background	$739 \pm 39$	$261 \pm 28$	$36 \pm 4$
$WW$	$551 \pm 41$	$108 \pm 40$	$4.1 \pm 1.5$
<i>Other VV</i>	$58 \pm 8$	$27 \pm 6$	$1.9 \pm 0.4$
Top-quark	$39 \pm 5$	$95 \pm 28$	$5.4 \pm 2.1$
$Z+jets$	$30 \pm 10$	$12 \pm 6$	$22 \pm 3$
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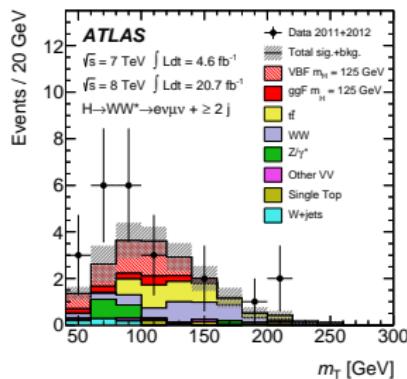
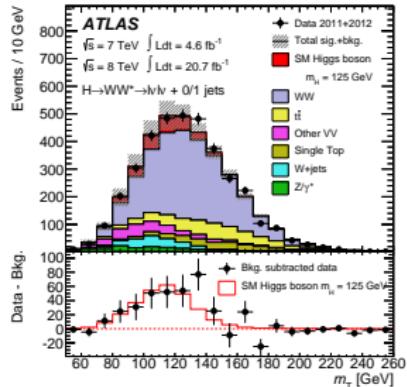


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- maximal observed  $Z_0$  is  $4.1\sigma$  for  $m_H = 140$  GeV
- at  $m_H = 125$  GeV,  $Z_0 = 3.8\sigma$  (obs. & exp.)

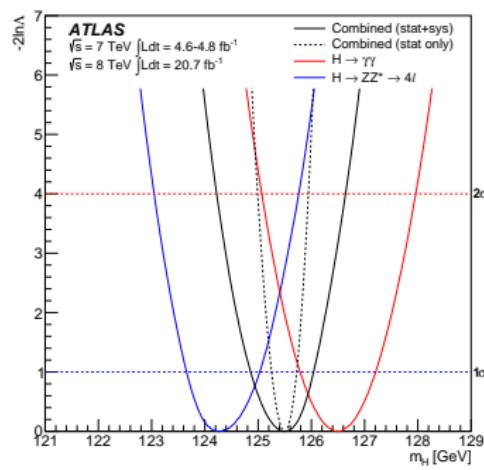


## Mass Measurement

- mass measurement is performed in  $ZZ \rightarrow 4\ell$  and  $\gamma\gamma$  channels
- allow the signal strengths  $\mu_{4\ell}$ ,  $\mu_{\gamma\gamma}$  to float
  - best overall  $m_H = 125.5 \pm 0.2 \text{ (stat)}^{+0.5}_{-0.6} \text{ (sys) GeV}$
  - combination shifts  $e/\gamma$  energy scale slightly, reduces  $m_{\gamma\gamma}$  compared to standalone

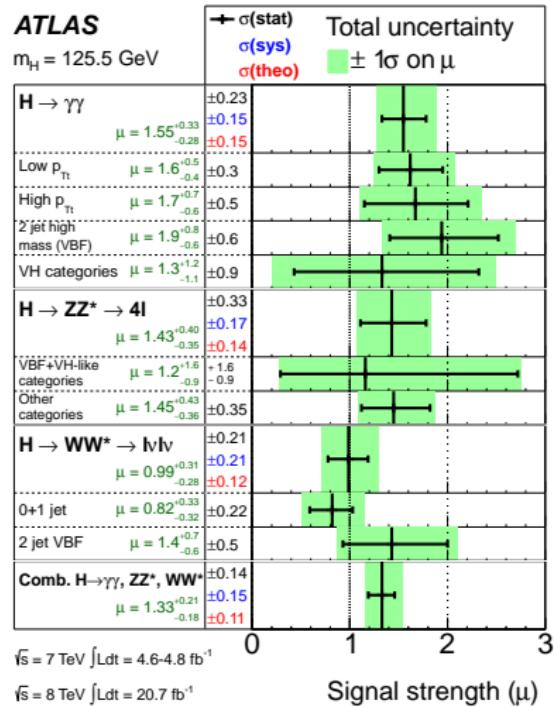
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  - combination shifts  $e/\gamma$  energy scale slightly, reduces  $m_{\gamma\gamma}$  compared to standalone
- consistency of  $\gamma\gamma$  and  $ZZ$  masses is at the 1.5% level
 
$$\Delta m_H = 2.3^{+0.6}_{-0.7} \text{ (stat)} \pm 0.6 \text{ (sys) GeV}$$
- many cross-checks performed, dedicated sub-group
- investigate systematics on  $e/\gamma$  scales with  $Z, Z\gamma, J/\psi$  samples
- estimate effect of non-Gaussian behaviour for largest systematic uncertainties ( $e/\gamma$  scale, lepton ID), then consistency is at 8%



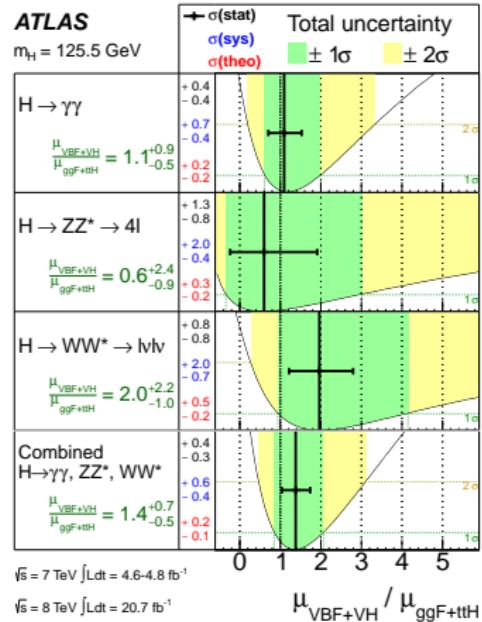
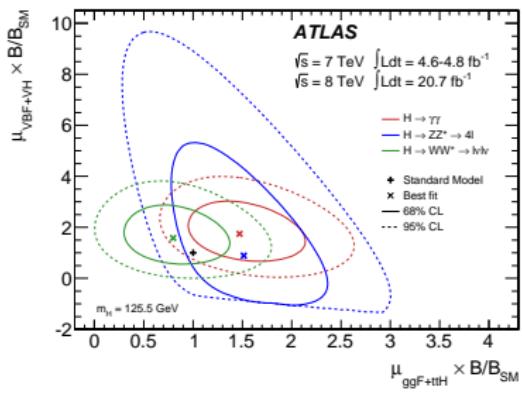
# Combined Signal Yield

- use best-fit mass hypothesis  $m_H = 125.5$  GeV maximum likelihood fit
- $\mu = 1.33 \pm 0.14 \text{ (stat)} \pm 0.15 \text{ (sys)}$ 
  - consistent with SM  $\mu = 1$  at  $\sim 7\%$  level
  - largest deviation in  $H \rightarrow \gamma\gamma$  at  $1.9\sigma$
- including  $H \rightarrow bb$  and  $H \rightarrow \tau\tau$  partial dataset, reduce to  $\mu = 1.23 \pm 0.18$



# VBF Production

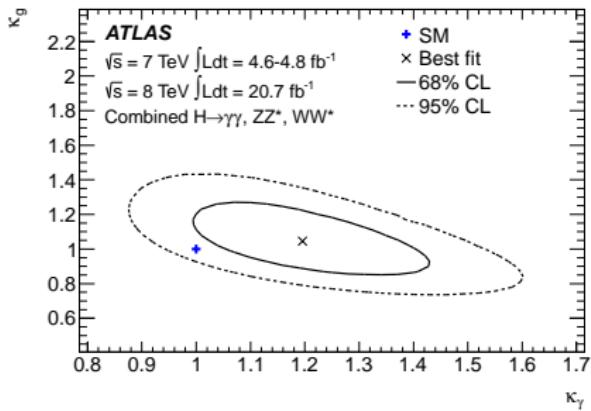
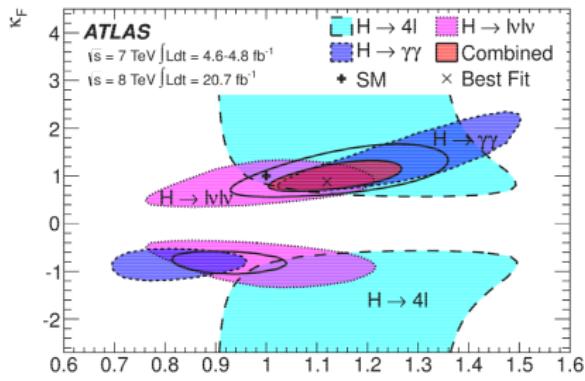
- targetted analysis categories used to improve measurement of production modes
- combine VH+VBF and ggF+ttH production



- evidence for VBF production at  $3.3\sigma$  level
- best-fit VBF to ggF+ttH ratio is  $1.4^{+0.4}_{-0.3}(\text{stat})^{+0.6}_{-0.4}(\text{sys})$

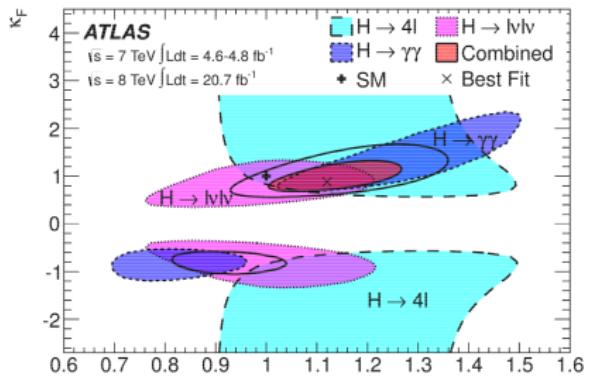
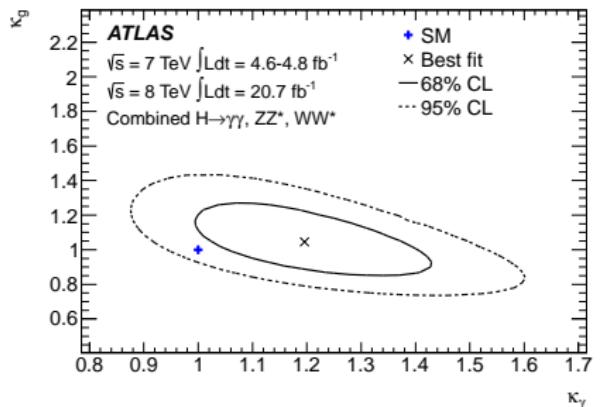
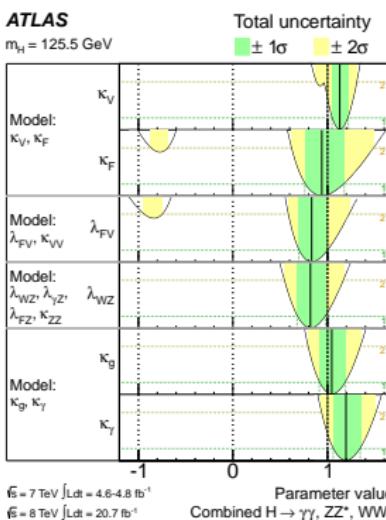
# Couplings

- profile coupling factors  $\kappa$  (scale SM  $\sigma$  and  $\Gamma$ )
- various scenarios considered (see Ref [2] for more details)
  - 1 assuming single  $\kappa_F$  and  $\kappa_V$ , compatible with SM  $\kappa = 1$  at 12% level
  - 2  $gg \rightarrow H \rightarrow \gamma\gamma$  production and decay factors  $\kappa_g, \kappa_\gamma$



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  - 3 ...

 $\kappa_V$  $\kappa_\gamma$ 

**Higgs quantum numbers: spin and parity**

## Motivation

- motivation is to fully characterize the new Higgs particle (“is it really **the** SM Higgs?”)
- decay to bosons with no net charge → **it is a neutral boson**
- observation in  $\gamma\gamma$  channel **disfavors**<sup>1</sup>  $J = 1$

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- spin and parity is manifest in angular decay characteristics and the momenta of the decay particles
  - precise kinematic shape fits to discriminate spin/CP hypotheses

---

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## Models

Ref. [2] describes general production and decay of a boson w/ various  $J^P$

- specific models identified and tested in 8 TeV data
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- for  $J^P = 2^+$ , the most general amplitude of the decay to vector bosons has complex coupling constants  $g_{1..10}$  :
- test minimal graviton-inspired model with  $g_1 = g_5 = 1$  (all other  $g$ 's are 0)
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- $0^+$  is the SM Higgs boson POWHEG + PYTHIA8/HqT

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## Statistical Analysis

- binned likelihood with a single parameter of interest to test both different hypotheses

$$\mathcal{L}(\epsilon, \mu, \vec{\theta}) = \prod_i^{N_{bins}} P\left(\underbrace{N_i}_{\text{observed}} \mid \mu, \left( \underbrace{\epsilon S_{0+,i}(\vec{\theta}) + (1 - \epsilon) S_{JP_{\text{alt}},i}(\vec{\theta})}_{\text{signal prediction}} \right) + \underbrace{b_i(\vec{\theta})}_{\text{background}} \right) \times \prod_j^{N_{sys}} \underbrace{\mathcal{A}(\tilde{\theta}_j | \theta_j)}_{\text{constraints}}$$

- $\epsilon = 0$  implies  $0^-, 1^\pm$ , or  $2^+$  particle and  $\epsilon = 1$  implies SM  $0^+$

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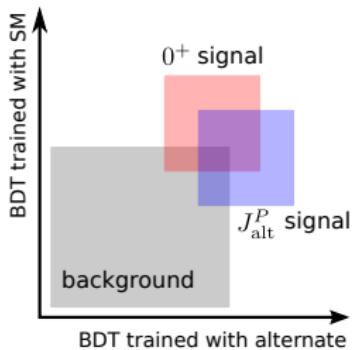
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- $\epsilon = 0$  implies  $0^-, 1^\pm$ , or  $2^+$  particle and  $\epsilon = 1$  implies SM  $0^+$
- **Note:** the cross-section for  $J_{alt}^P$  is arbitrary, so signal yield is profiled
  - the signal strength parameter  $\mu$  is treated a nuisance parameter
  - this means that uncertainties on the  $0^+$  cross-section are irrelevant
- test statistic is ratio of profiled likelihoods for  $J_{alt}^P$  and  $0^+$  hypotheses:

$$q = \log \frac{\mathcal{L}(H_{0+})}{\mathcal{L}(H_{J_{alt}^P})} = \log \frac{\mathcal{L}(\epsilon = 1, \hat{\mu}_{\epsilon=1}, \hat{\theta}_{\epsilon=1})}{\mathcal{L}(\epsilon = 0, \hat{\mu}_{\epsilon=0}, \hat{\theta}_{\epsilon=0})}$$

$$H \rightarrow WW \rightarrow \ell\nu\ell\nu$$

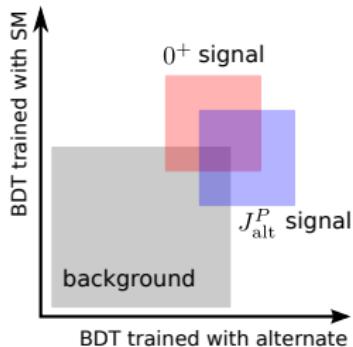
- $0^+$  and  $2_m^+, 1^\pm$  hypotheses are tested using a two-dimensional shape fit
- the discriminants used in the fit are outputs of two different boosted decision trees,  $BDT_{0^+}$  and  $BDT_{2_m^+/1^\pm}$ 
  - trained to separate  $0^+$  or  $2_m^+/1^\pm$  events from background (same background model in both cases)
  - note that  $BDT_{2_m^+}$  is retrained for each  $f_{q\bar{q}}$  fraction
  - use  $m_{\ell\ell}$ ,  $p_T^{\ell\ell}$ ,  $\Delta\phi_{\ell\ell}$  and  $m_T$  input variables



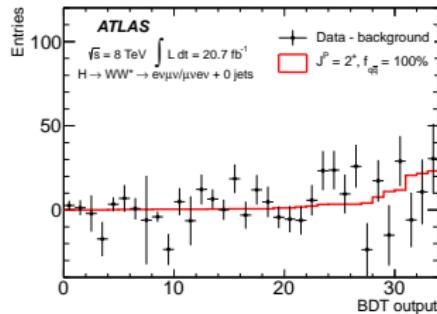
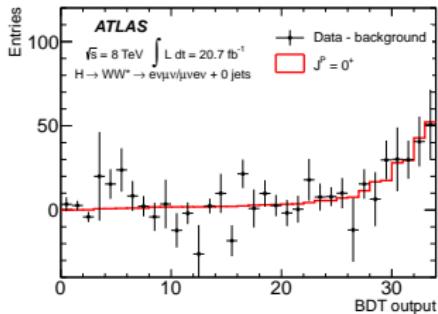
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  - use  $m_{\ell\ell}$ ,  $p_T^{\ell\ell}$ ,  $\Delta\phi_{\ell\ell}$  and  $m_T$  input variables
- selection cuts loosened w.r.t. nominal analysis
  - use 0-jet  $e\mu + \mu e$  channel only

Variable	Spin analysis	Rate analysis
common $e\mu/\mu e$ lepton selection		
$p_T^{\ell\ell}$	$> 20$ GeV	$> 30$ GeV
$m_{\ell\ell}$	$< 80$ GeV	$< 50$ GeV
$\Delta\phi_{\ell\ell}$	$< 2.8$	$< 1.8$



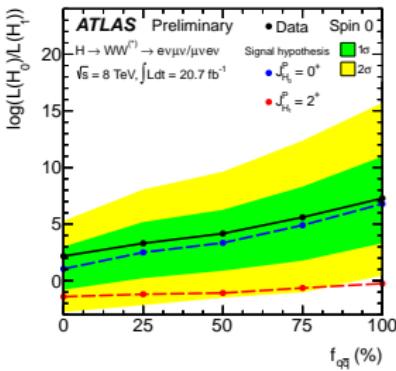
- 0<sup>+</sup> two
- the different BD



Final  
J<sup>P</sup><sub>alt</sub> signal  
with alternate

- $J_{\text{alt}}^P = 1^+(1^-)$  excluded at 92% (98%) CL
- $2_m^+$  is excluded at 95 - 99% CL (depending on  $f_{q\bar{q}}$ )

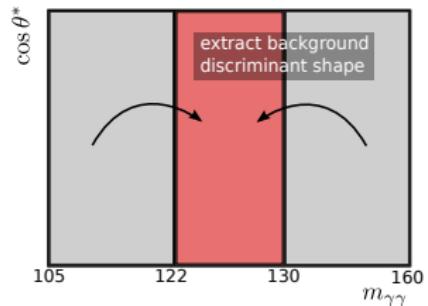
- So



$$H \rightarrow \gamma\gamma$$

- compare  $0^+$  to  $J_{\text{alt}}^P = 2_m^+$  hypothesis
- use polar angle as discriminating variable in 2D fit with  $m_{\gamma\gamma}$

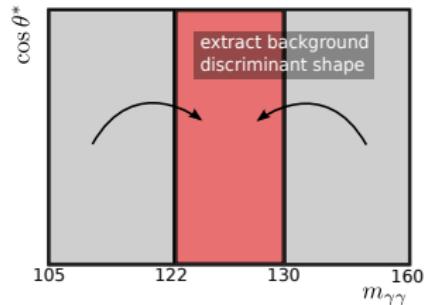
$$\cos \theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(\frac{p_T^{\gamma\gamma}}{m_{\gamma\gamma}}\right)^2}} \cdot \frac{2p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$



$$H \rightarrow \gamma\gamma$$

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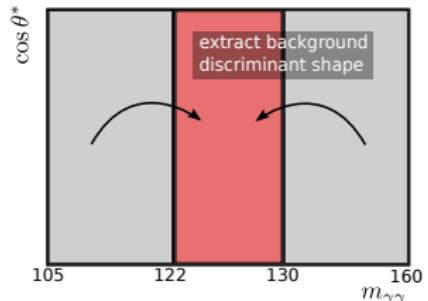
### Systematic uncertainties

- $p_T$  spectrum for  $2_m^+ gg$ , reweighted to  $0^+$
- correlation between  $\cos \theta^*$  and  $m_{\gamma\gamma}$

$$H \rightarrow \gamma\gamma$$

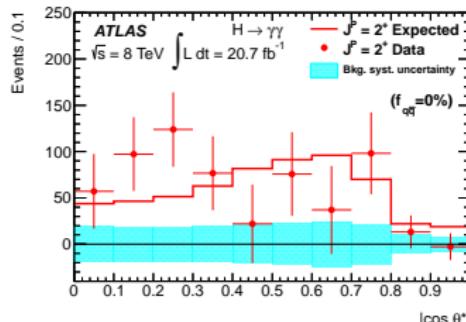
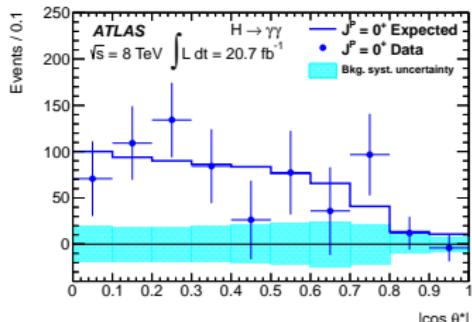
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## Systematic uncertainties

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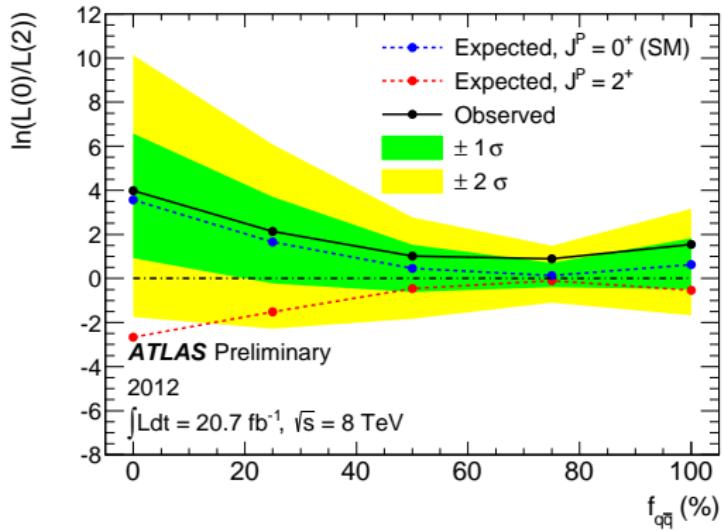
$H \rightarrow \gamma\gamma$ 

- compare
- use polarizations in 2D

### Systematic uncertainties

- $p_T$  selection
- corrections

Events / 0.1

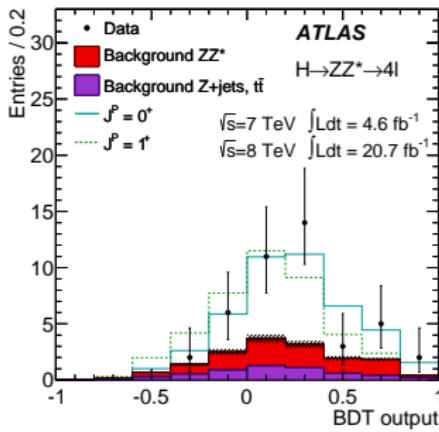
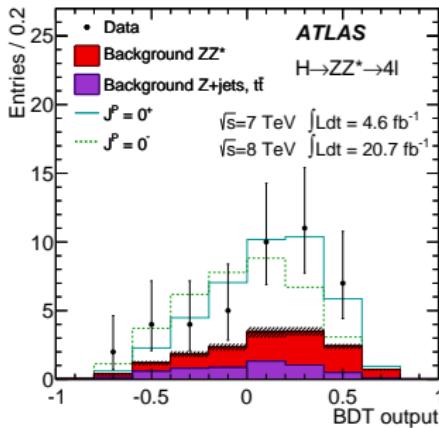


- $\gamma\gamma$  and  $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$  have different sensitivities versus  $f_{q\bar{q}}$ 
  - b/c helicity combinations are different for  $H \rightarrow \gamma\gamma$  and  $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$
  - backgrounds behave differently in both channels

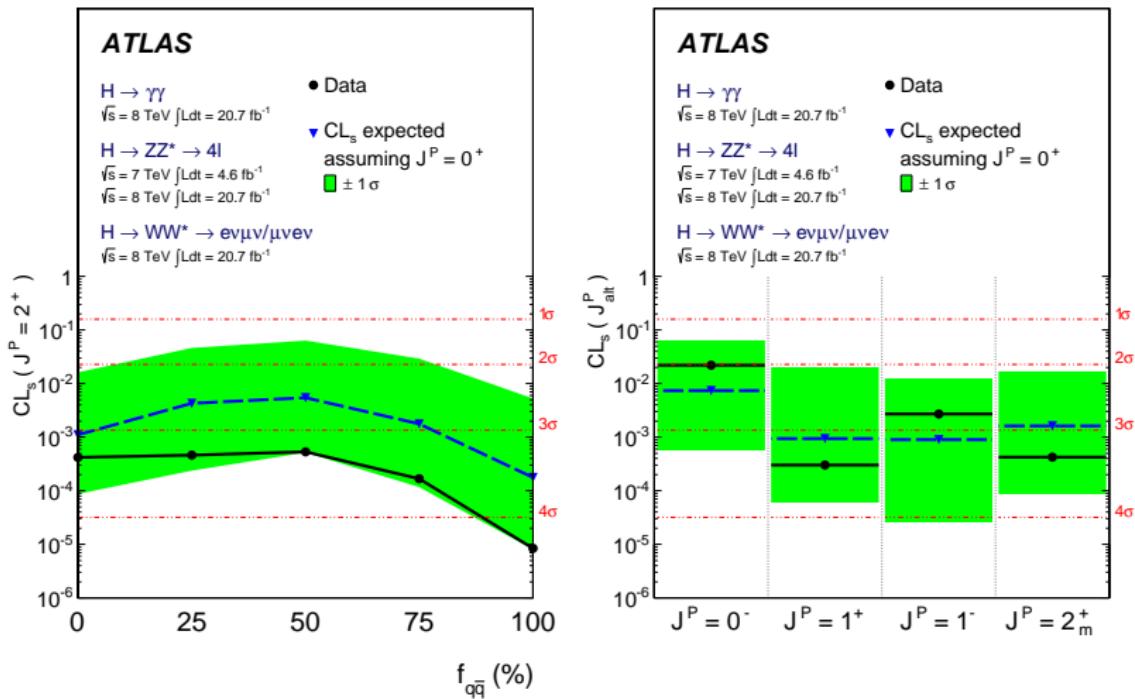
 $|\cos \theta^*|$  $|\cos \theta^*|$

$$H \rightarrow ZZ \rightarrow 4\ell$$

- select candidate events in  $115 < m_{4\ell} < 130$ 
  - split analysis into 115-121 and 127-130 GeV (low  $S/B$ ) and 121-127 GeV
- powerful channel b/c can fully reconstruct the decay, readily test many hypotheses
- train separate BDT for each of  $J_{\text{alt}}^P = 0^-, 1^\pm, 2_m^+$  hypotheses
- matrix element based discriminant yielded compatible results
- data favors  $0^+$  over all alternatives,  $0^-$  excluded at 98%



## Combined



- data clearly favor the SM Higgs quantum numbers over the alternative models considered
  - alternatives models are rejected at 97.8 - 99.7% CL

## Conlusions

- data collected at ATLAS with LHC Run I exploited for **detailed studies of Higgs properties**
  - rate, couplings, mass, spin & CP
- everything compatible **the Standard Model** Higgs
  - *of course, still room for BSM scenarios*
- looking forward to ATLAS updates on fermionic decay modes, final improvements to bosonic decays

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- looking forward to ATLAS updates on fermionic decay modes, final improvements to bosonic decays
- ... finally, need to prepare for Run II and more precise measurements

## **Extra Material**

# Monte Carlo Simulations

Process	Generator
ggF, VBF	POWHEG +PYTHIA
$WH, ZH, t\bar{t}H$	PYTHIA
$H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ decay	PROPHECY4f
$W+$ jets, $Z/\gamma^*+$ jets	ALPGEN + HERWIG , POWHEG + PYTHIA, SHERPA
$t\bar{t}, tW, tb$	MC@NLO + HERWIG
$tqb$	AcerMC + PYTHIA6
$q\bar{q} \rightarrow WW$	POWHEG + PYTHIA6
$gg \rightarrow WW$	gg2WW + HERWIG
$q\bar{q} \rightarrow ZZ^*$	POWHEG + PYTHIA
$gg \rightarrow ZZ^*$	gg2ZZ + HERWIG
$WZ$	MadGraph + PYTHIA6, HERWIG
$W\gamma+$ jets	ALPGEN + HERWIG
$W\gamma^*$	MadGraph + PYTHIA6 for $m_{\gamma^*} < 7$ GeV POWHEG + PYTHIA for $m_{\gamma^*} > 7$ GeV
$q\bar{q}/gg \rightarrow \gamma\gamma$	SHERPA

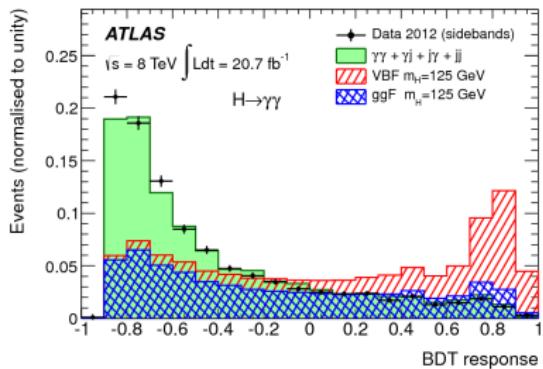
Note on  $\gamma\gamma$  Vertexing

- use fine calorimeter granularity to “point” back to production vertex
  - utilise vertex for converted photons
- combine in neural network with
  - $\sum p_T^2$  (8 TeV analysis)
  - $\sum p_T, \Delta\phi(\gamma\gamma, \mathbf{p}_T)$  (7 TeV analysis)
- vertexing performance from  $Z \rightarrow ee$  events by removing electron tracks

## Systematic Uncertainties in $H \rightarrow \gamma\gamma$

**Table:** Leading systematic uncertainties on the total signal and background yields for the  $H \rightarrow \gamma\gamma$  analysis.

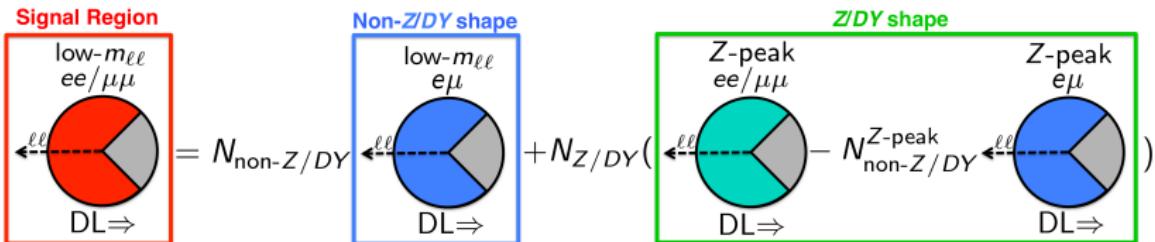
Source	Uncertainty (%)
on signal yield	
Photon identification	$\pm 2.4$
Trigger	$\pm 0.5$
Isolation	$\pm 1.0$
Photon energy scale	$\pm 0.25$
ggF (theory), tight high-mass two-jet cat.	$\pm 48$
ggF (theory), loose high-mass two-jet cat.	$\pm 28$
ggF (theory), low-mass two-jet cat.	$\pm 30$
Impact of background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

$H \rightarrow \gamma\gamma + 2j$  BDT Validation

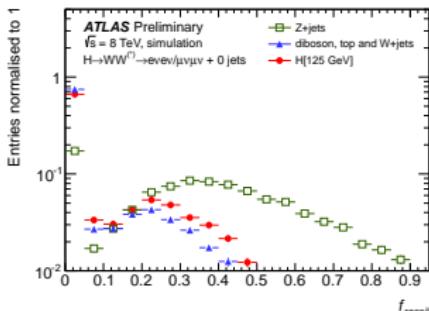
Distribution of the VBF BDT response after applying the selection of the inclusive analysis and requiring in addition the presence of two jets with  $|\Delta\eta_{jj}| > 2$  and  $|\eta^*| < 5$ .

$f_{\text{recoil}}$  Selection

$$f_{\text{recoil}} = \frac{\left| \sum_{\text{jets with } p_T > 10 \text{ GeV}} |\text{JVF}| \times \vec{p}_T^{\text{jet}} \right|}{p_T^{\ell\ell}}$$



$$\epsilon^{\text{DY}} = \frac{N 0_{\text{same flavour}}^{\text{Z-peak}} - \epsilon_{Z\text{-peak}}^{\text{non-DY}} \times N(\text{non-DY})_{\text{same flavour}}^{\text{Z-peak}}}{N_{\text{same flavour}}^{\text{Z-peak}} - N(\text{non-DY})_{\text{same flavour}}^{\text{Z-peak}}}$$



# Systematic Uncertainties in $H \rightarrow WW \rightarrow \ell\nu\ell\nu$

**Table:** Leading systematic uncertainties on the total signal and background yields for the 8 TeV  $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$  analysis.

Source	$N_j = 0$	$N_j = 1$	$N_j \geq 2$
Theoretical uncertainties on total signal yield (%)			
QCD scale for ggF, $N_j \geq 0$	+13	-	-
QCD scale for ggF, $N_j \geq 1$	+10	-27	-
QCD scale for ggF, $N_j \geq 2$	-	-15	+4
QCD scale for ggF, $N_j \geq 3$	-	-	+4
Parton shower and underlying event	+3	-10	$\pm 5$
QCD scale (acceptance)	+4	+4	$\pm 3$
Experimental uncertainties on total signal yield (%)			
Jet energy scale and resolution	5	2	6
Uncertainties on total background yield (%)			
Jet energy scale and resolution	2	3	7
$WW$ transfer factors (theory)	$\pm 1$	$\pm 2$	$\pm 4$
$b$ -tagging efficiency	-	+7	+2
$f_{\text{recoil}}$ efficiency	$\pm 4$	$\pm 2$	-