Study of the properties of the Higgs-like Boson in the H$\rightarrow ZZ^{(*)} \rightarrow 4\ell$ decay channel with the ATLAS detector

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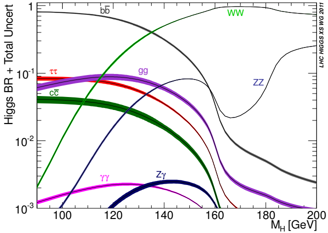
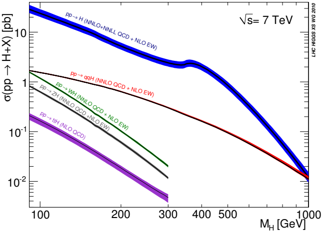
H$\rightarrow ZZ^{(*)} \rightarrow 4\ell$

- Following discovery of particle, measurement of its properties important in the determination of its nature

- H$\rightarrow ZZ^{(*)} \rightarrow 4\ell$ channel, where $\ell = e, \mu$, is sensitive to SM Higgs production
  - Good mass resolution and S/B. However low branching fraction makes analysis challenging



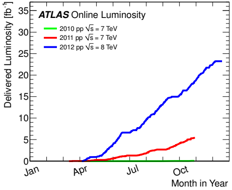


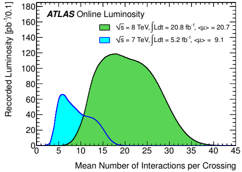
- Complete dataset from first LHC run used (ATLAS-CONF-2013-013) to study mass, rates, couplings and spin-parity

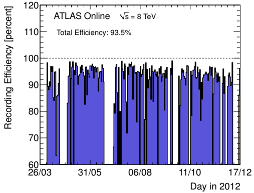
- Results presented here, with emphasis on the measurement of the coupling properties

ATLAS Detector Performance

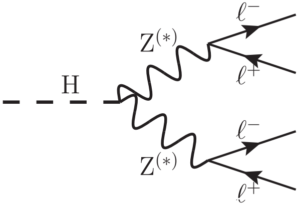
- Excellent performance of LHC and ATLAS detector has made Higgs discovery possible
- 4.6 fb^{-1} and 20.7 fb^{-1} of data collected in 2011 and 2012 respectively
- Peak stable luminosity 7.73×10^{33} cm^2 s^-1
- Operating with levels of pileup exceeding design specifications
- Data-taking efficiency high and stable







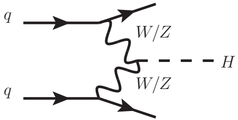
Event Selection

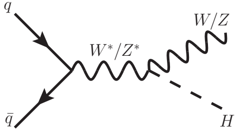


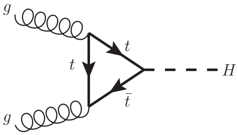
- Two same-flavour/opposite-sign dilepton pairs
- $p_T^{1,2,3,4} = 20, 15, 10, 7(6)$ GeV for e(μ)
- Four sub-channels: $4e$, $2e2\mu$, $2\mu 2e$, 4μ
- 50 GeV $< m_{12} <$ 106 GeV
- $m_{low}(m_{4\ell}) < m_{34} <$ 115 GeV, where $m_{low} = 12$ GeV for (for $m_{4\ell} < 140$ GeV) and $m_{low} = 50$ GeV for (for $m_{4\ell} > 190$ GeV)
- Tracking and Calorimeter Isolation
- Impact Parameter Significance - d_0/σ_{d_0}
- Z mass constraint applied to leading dilepton
  - See talk by Andrew Daniells
- FSR correction to invariant mass for di-muon m_{12} candidates
  - See poster by Kerry Parker

Production Signature Categories

Obtain sensitivity to different production modes by categorizing the candidate 4ℓ events







VBF-like category:

- At least 2 jets
  - $p_T > 25$ (30) GeV for $|\eta| < 2.5$ (4.5)
- $\Delta\eta_{jj} > 3.0$
- $m_{jj} > 350$ GeV

VH-like category:

- Additional lepton
- $p_T > 8$ GeV
- Isolation and I.P. significance

Remaining events are assigned to the ggF-like category

Background Estimation

Main background is $ZZ^{(*)}$ production

- Monte Carlo (MC) simulation, scaled to theoretical cross section and constrained during fit to the data

Reducible backgrounds:

- $Zb\bar{b}$, Z+light jets, $t\bar{t}$
- Suppressed by isolation, d_0 cuts
- Estimated using data-driven methods

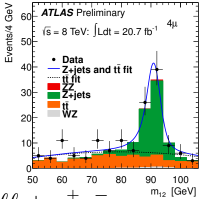
Main background in each sub-channel determined by flavour of subleading lepton pair:

- $\ell\ell + \mu^+\mu^-$: $Zb\bar{b}$, Z+light jets, $t\bar{t}$
- $\ell\ell + e^+e^-$: $Z+$ jets

General approach:

- Define background-enriched/signal-depleted control reigions (CR)
- Extrapolate to signal region using transfer factors (calculated using MC, verified using data)

Background Estimation

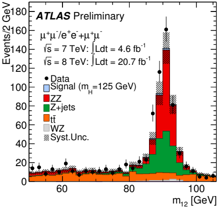


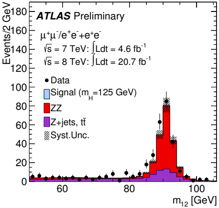
$\ell\ell + \mu^+\mu^-$:

- Z+jets, $t\bar{t}$ contributions estimated simultaneously by fitting m_{12} distribution
- Use CR where isolation and d_0 requirements relaxed for subleading lepton pair and one of these fails d_0 or isolation cut

$\ell\ell + e^+e^-$:

- Background estimated using CR where electron identification relaxed for subleading pair
- Background composition studied by classifying electron candidates as electron-like or fake-like using reconstruction-based discriminating variables

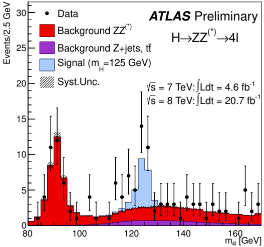


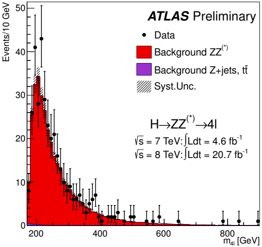


- Agreement good in relaxed CR where isolation and d_0 requirements are relaxed for subleading pair
  - Reducible backgrounds are normalised to data-driven estimates

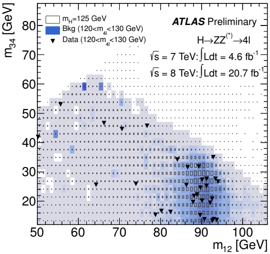
Results - Mass Distributions

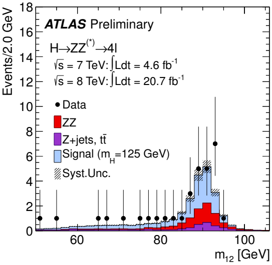
After full selection, an excess of events over background is observed in the region around $m_{4\ell} = 125$ GeV

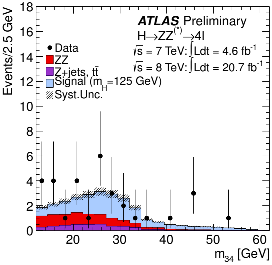




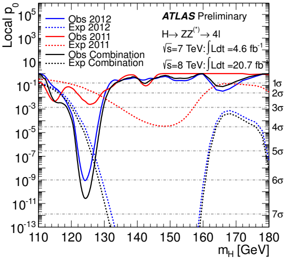
The distribution of events is consistent with expectation for an SM Higgs Boson

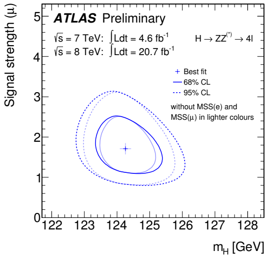






Results - Mass and Signal Strength Measurements



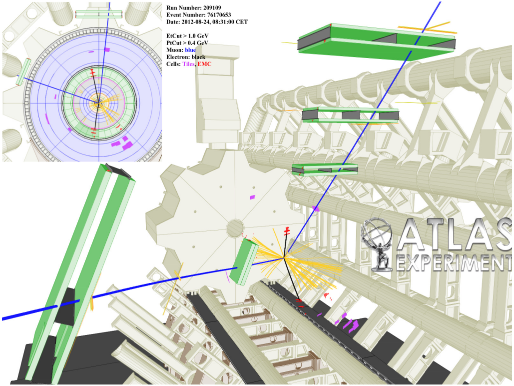


- The observed minimum p_0 is at $m_H = 124.3$ GeV and corresponds to a significance of 6.6σ
- The best fit mass value is $m_H = 124.3\ ^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(stat)$ GeV
- At this mass, the signal strength $\mu = \sigma/\sigma_{SM}$ is $\mu = 1.7^{+0.5}_{-0.4}$
  - See also talks by Karoline Selbach and Andrew Daniells

Results - Categories

In full mass range: 8 candidates in VBF-like category, 1 in VH-like category

- In VBF-like category one event is observed in range 120 GeV $< m_{4\ell} <$ 130 GeV with mass $m_{4\ell} = 123.5$ GeV
- For $m_H = 125$ GeV, 0.71 ± 0.10 events are expected in this range
  - The S/B in this region is around 5.
- One observed candidate in the VH-like category, with a mass of 270.3 GeV
  - 0.9 ± 0.3 ZZ^* events expected



Couplings

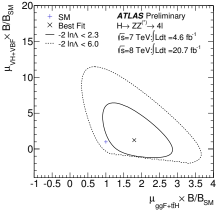
Exploiting categorisation, extend signal strength measurement to measure factors for specific production modes

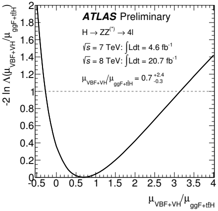
- Group Fermionic(ggF, ttH) and Bosonic(VBF, VH) production mechanisms

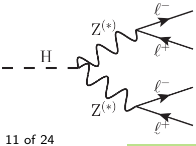
$$\mu_{ggF+ttH} \times B/B_{SM} = 1.8^{+0.8}_{-0.5}$$
$$\mu_{VBF+VH} \times B/B_{SM} = 1.2^{+3.8}_{-1.4}$$

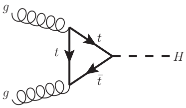
- By measuring the ratio, $\mu_{VBF+VH}/\mu_{ggF+ttH}$, the dependence on the branching ratio cancels out

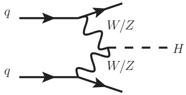
$$\mu_{VBF+VH}/\mu_{ggF+ttH} = 0.7^{+2.4}_{-1.3}$$

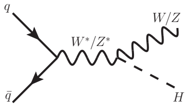








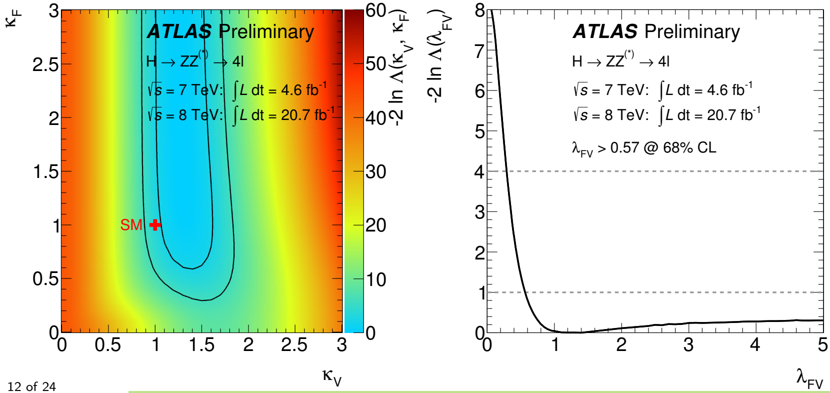




Couplings

Following the prescription used in ATLAS-CONF-2012-127, a benchmark model is probed where:

- All fermions are modified by a single factor k_F
- All massive bosons are modified by a single factor k_V
- No non-SM contributions to the Higgs total decay width
- The ratio $\lambda_{FV} = k_F/k_V$



Summary

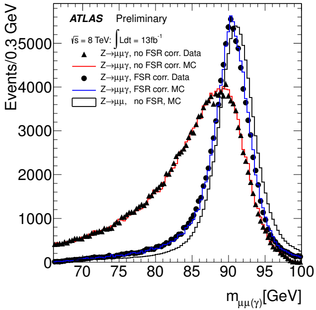
- With a dataset corresponding to 4.6 fb^{-1} at $\sqrt{s} = 7\,TeV$ and 20.7 fb^{-1} at $\sqrt{s} = 8\,TeV$, an excess of events above background is observed in the H$\rightarrow ZZ^{(*)} \rightarrow 4\ell$ channel with a local significance corresponding to 6.6σ
- The overall S/B for the analysis is 1.4
  - Reducible backgrounds from data-driven methods
- The excess is interpreted as the discovery of an SM-like Higgs Boson
  - The best fit mass is $m_H = 124.3\ ^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}$ GeV.
  - At this mass, the signal strength is $\mu = 1.7^{+0.5}_{-0.4}$
  - At 125.5 GeV, the signal strength is $\mu = 1.5^{\pm 0.4}$
- For the first time in this channel, the events have been categorised to probe the couplings of the new particle
  - A VBF-like candidate has been found at 123.5 GeV
  - The signal strength for the different production modes, grouped as Fermionic(ggF, ttH) and Bosonic(VBF, VH), have been measured
    - $\mu_{ggF+ttH} \times B/B_{SM} = 1.8^{+0.8}_{-0.5}$
    - $\mu_{VBF+VH} \times B/B_{SM} = 1.2^{+3.8}_{-1.4}$

Additional material

FSR-recovery

In 4ℓ candidates where the leading dilepton is muonic, the effect on the invariant mass due to the Final State Radiation(FSR) of photons is corrected for

- Di-muon m_{12} candidates with 66 GeV $< m_{12} <$ 89 GeV are corrected for FSR by including in the invariant mass any reconstructed photon with $E_T > 1$ GeV lying close ($\Delta R < 0.08$ to $\Delta R < 0.08$ depending on E_T^{γ}) to one of the muon tracks
- From MC, around 4% of H$\rightarrow ZZ^{(*)} \rightarrow 4\mu$ events are expected to be corrected. The correction is expected to have 70% efficiency and 85% purity
- Of the 225 observed 4μ events, the correction is applied to 7. One of these is in the mass range 120 GeV $< m_{4\ell} <$ 130 GeV



Detailed studies about the reconstruction of FSR photons can be found in ATLAS-CONF-2012-143

Jet selection Requirements

Jets are reconstructed from topological clusters using the anti-k_t algorithm with a distance parameter $R = 0.4$

- Jets are required to have $p_T > 25$ (30) GeV for $|\eta| < 2.5$ (4.5)
- Jets which overlap with electrons within $\Delta R < 0.2$ are removed
- To reduce the background due to pileup jets, jets within the inner detector acceptance ($|\eta| < 2.47$) are required to have $>$50% of the sum of the scalar p_T of their associated tracks coming from the primary vertex

Summary of reducible background expectations

Summary of the estimated numbers of $Z + \mathrm{jets}$ and $t\bar{t}$ background events for the $\sqrt{s} = 8$ TeV and $\sqrt{s} = 7$ TeV data after the full selection. Sub-leading same sign full analysis event counts are given only for $m_{4\ell} < 160$ GeV to avoid contamination from $ZZ^{(*)}$ with an incorrect charge measurement. The "†" indicates the estimates used for the background normalisation.

method	estimate at $\sqrt{s} = 8$	estimate at $\sqrt{s} = 7$ TeV
	4μ	4μ
m_{12} fit: $Z + \mathrm{jets}$ contribution	$2.4 \pm 0.5 \pm 0.6^{\dagger}$	$0.22 \pm 0.07 \pm 0.02^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.14 \pm 0.03 \pm 0.03^{\dagger}$	$0.03 \pm 0.01 \pm 0.01^{\dagger}$
$t\bar{t}$ from $e\mu + \mu\mu$	$0.10 \pm 0.05 \pm 0.004$	-
	$2e2\mu$	$2e2\mu$
m_{12} fit: $Z + \mathrm{jets}$ contribution	$2.5 \pm 0.5 \pm 0.6^{\dagger}$	$0.19 \pm 0.06 \pm 0.02^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.10 \pm 0.02 \pm 0.02^{\dagger}$	$0.03 \pm 0.01 \pm 0.01^{\dagger}$
$t\bar{t}$ from $e\mu + \mu\mu$	$0.12 \pm 0.07 \pm 0.005$	-
	$2\mu 2e$	$2\mu 2e$
$\ell\ell + e^{\pm}e^{\mp}$ relaxed cuts	$5.2 \pm 0.4 \pm 0.5^{\dagger}$	$1.8 \pm 0.3 \pm 0.4$
$\ell\ell + e^{\pm}e^{\mp}$ inverted cuts	$3.9 \pm 0.4 \pm 0.6$	-
$3\ell + \ell$ (same-sign)	$4.3 \pm 0.6 \pm 0.5$	$2.8 \pm 0.4 \pm 0.5^{\dagger}$
sub-leading same sign full analysis events	4	0
	$4e$	$4e$
$\ell\ell + e^{\pm}e^{\mp}$ relaxed cuts	$3.2 \pm 0.5 \pm 0.4^{\dagger}$	$1.4 \pm 0.3 \pm 0.4$
$\ell\ell + e^{\pm}e^{\mp}$ inverted cuts	$3.6 \pm 0.6 \pm 0.6$	-
$3\ell + \ell$ (same-sign)	$4.2 \pm 0.5 \pm 0.5$	$2.5 \pm 0.3 \pm 0.5^{\dagger}$
sub-leading same sign full analysis events	3	2

Categories - Additional information

The expected numbers of events in each category for each signal production mechanism at m_H =125 GeV and the $ZZ^{(*)}$ background, for $m_{4\ell} > 100$ GeV.

category	$gg \to H, q\bar{q}/gg \to t\bar{t}H$	$qq' \to Hqq'$	$q\bar{q} \to W/ZH$	$ZZ^{(*)}$
		$\sqrt{s} = 8$ TeV		
ggF-like	13.5	0.79	0.65	320.4
VBF-like	0.28	0.43	0.01	3.58
VH-like	0.06	-	0.14	0.69
		$\sqrt{s} = 7$ TeV		
ggF-like	2.20	0.14	0.11	57.5
VBF-like	0.03	0.06	-	0.44
VH-like	0.01	-	0.03	0.25

Systematic uncertainties on the yields contributing to the VBF-like category expressed in percent on the yields due to each contribution. The uncertainty in the ggF contamination due to the QCD scale is included in the theory cross section uncertainty.

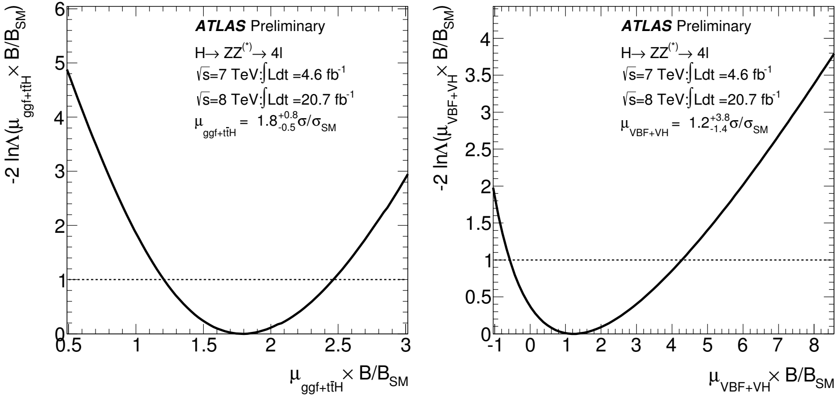
process	$gg \to H, q\bar{q}/gg \to t\bar{t}H$	$qq' \to Hqq'$	$q\bar{q} \to W/ZH$	$ZZ^{(*)}$
theory cross section	21%	4%	4%	35%
underlying event	19%	4%	-	-
jet energy scale	14%	10%	10%	10%
total	32%	11%	11%	36%

Expected and Observed Events

The numbers of expected signal events for the m_H=125 GeV hypothesis and background events together with the numbers of observed events, in a window of $\pm$5 GeV around 125 GeV

	total signal full mass range	signal	$ZZ^{(*)}$	$Z + \text{jets}, t\bar{t}$	S/B	expected	observed
		$\sqrt{s} = 8$ TeV and $\sqrt{s} = 7$ TeV					
4μ	6.8 ± 0.8	6.3 ± 0.8	2.8 ± 0.1	0.55 ± 0.15	1.9	9.6 ± 1.0	13
$2\mu 2e$	3.4 ± 0.5	3.0 ± 0.4	1.4 ± 0.1	1.56 ± 0.33	1.0	6.0 ± 0.8	5
$2e2\mu$	4.7 ± 0.6	4.0 ± 0.5	2.1 ± 0.1	0.55 ± 0.17	1.5	6.6 ± 0.8	8
$4e$	3.3 ± 0.5	2.6 ± 0.4	1.2 ± 0.1	1.11 ± 0.28	1.1	4.9 ± 0.8	6
total	18.2 ± 2.4	15.9 ± 2.1	7.4 ± 0.4	3.74 ± 0.93	1.4	27.1 ± 3.4	32

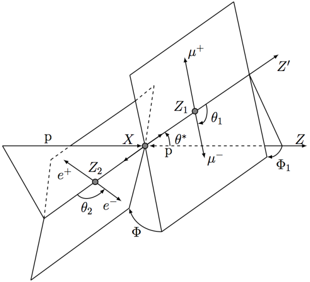
Couplings



1D likelihood scans of μ_{VBF+VH} and $\mu_{ggF+ttH}$

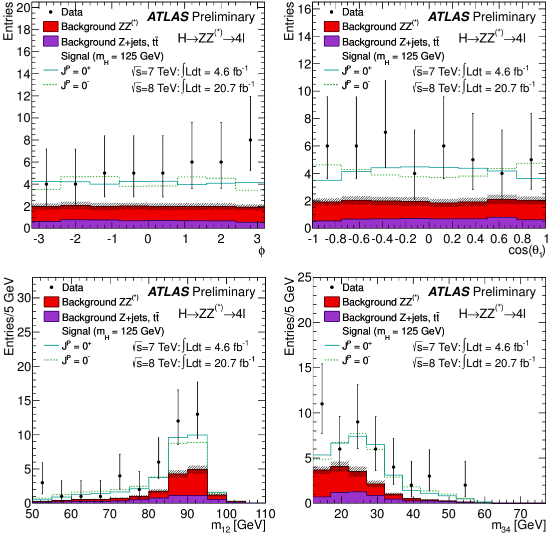
Spin/CP

- In X$\rightarrow ZZ^{(*)} \rightarrow 4\ell$ decays the masses of the Z bosons and the production and decay angles are are sensitive to the spin and parity of the decaying particle
- Using events in the range 115 GeV $< m_H <$ 130 GeV, different spin-parity hypotheses are tested



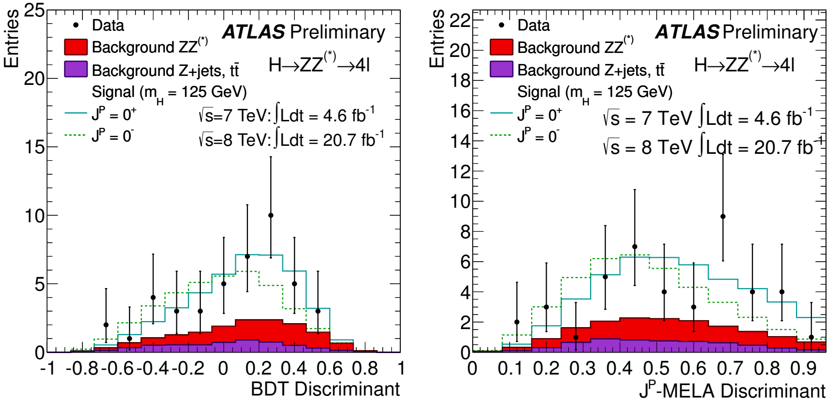
- Two different approaches are used to construct a discriminant between the different hypotheses:
  - A Boosted Decision Tree (BDT) in a multivariate analysis
  - J^P-MELA, which uses the theoretical differential decay rates for the sensitive observables to construct a matrix element based likelihood ratio
- Hypotheses are tested using the ratio of profile likelihoods as a test statistic
- In each case the 0^+ hypothesis is preferred

Spin/CP



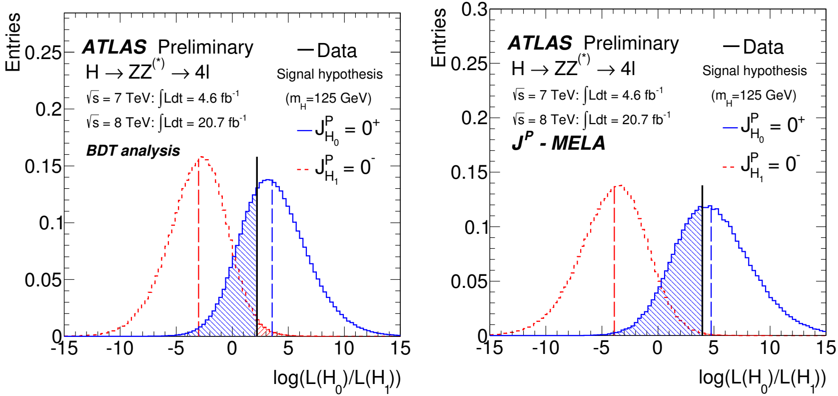
Distributions in data and MC of spin parity sensitive observables in the mass range
115 GeV $< m_{4\ell} <$ 130 GeV
after the full selection

Spin/CP



- The distributions in data and MC for the BDT and J^P -MELA discriminants for the 0^+ hypothesis vs 0^- in the mass range 115 GeV $< m_4\ell <$ 130 GeV

Spin/CP



- Distributions of the log-likelihood ratio generated with MC pseudo-experiments assuming the 0^+ hypothesis and testing 0^-
- The log-likelihood value observed in the data is indicated by the solid vertical line
- The shaded areas correspond to the observed p_0 values, representing the compatibility with the tested and assumed hypotheses