Higgs Properties with $H \to ZZ^{(*)} \to 4\ell$ in ATLAS

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on behalf of the ATLAS collaboration

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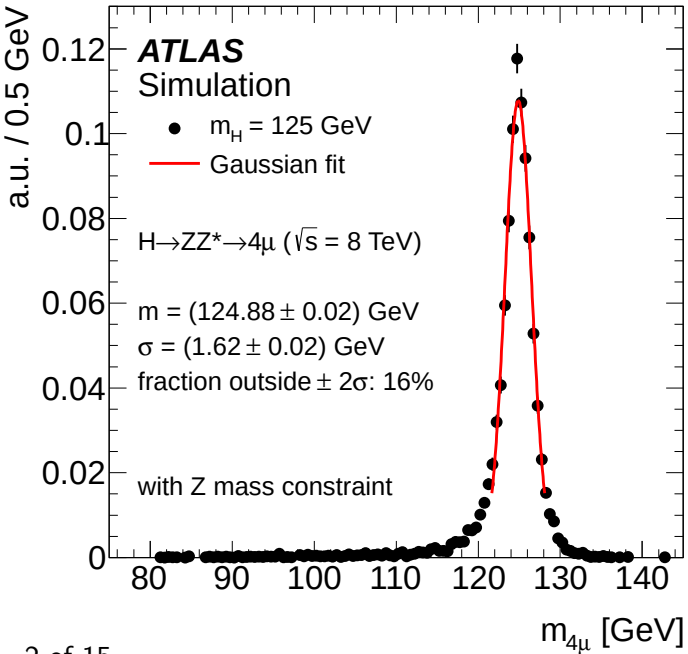
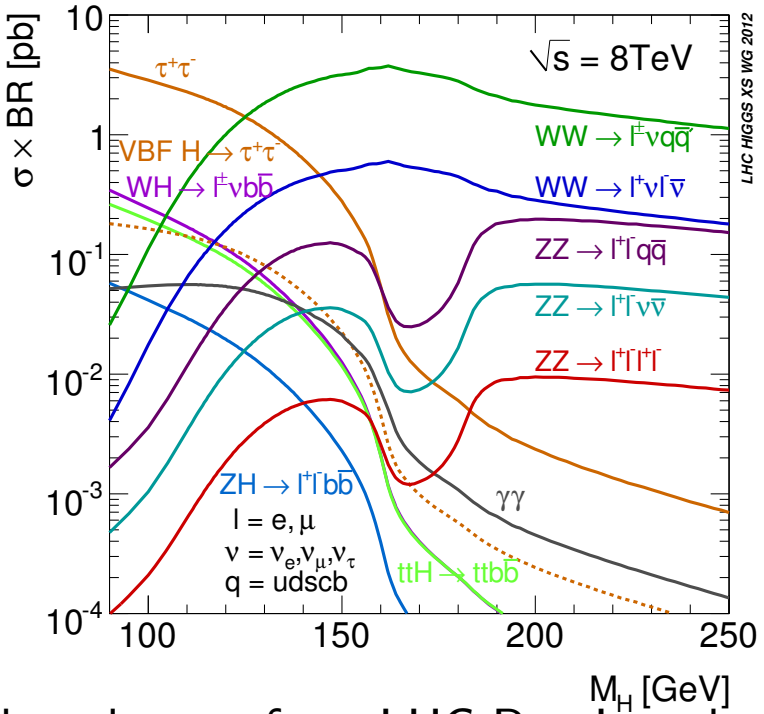
$H \to ZZ^{(*)} \to 4\ell$

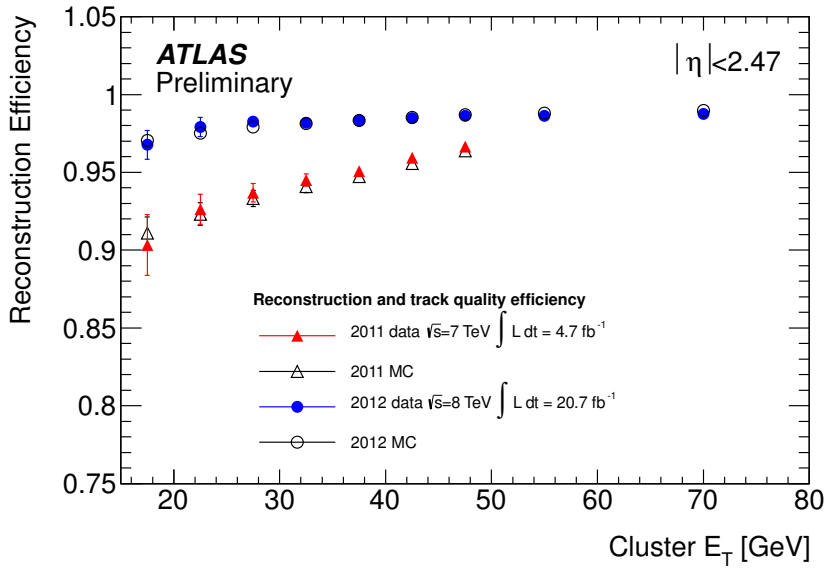
- Following Higgs discovery, emphasis on property measurements
- $H \to ZZ^{(*)} \to 4\ell$ channel, where $\ell = e, \mu$, sensitive to SM Higgs production
  - Fully reconstructed final state
  - Good mass resolution ($\sim$ 1.6-2.4 GeV) and S/B ($\sim$ 1-2)
  - Low branching fraction



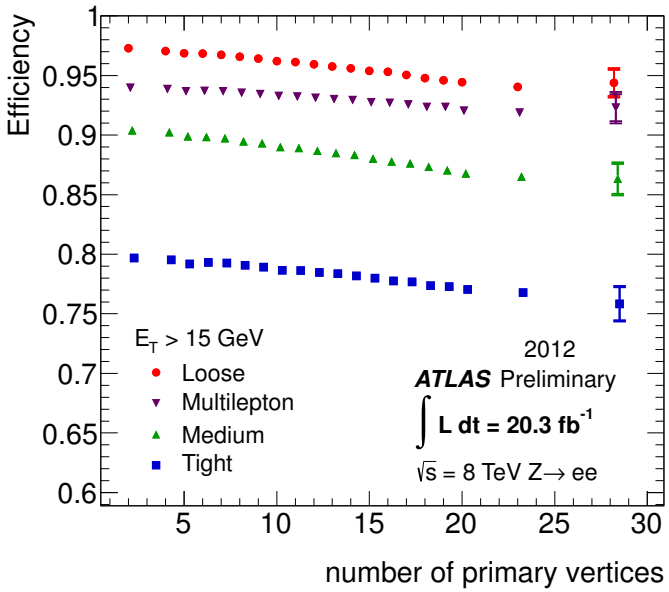


- Complete dataset from LHC Run I used to study mass, rates/couplings and spin-parity
  - 4.6 fb^{-1} at $\sqrt{s} = 7\,TeV$ and 20.7 fb^{-1} at $\sqrt{s} = 8\,TeV$
- Results presented here from *PLB 726 pp.88-119,120-144 (2013)* and *ATLAS-CONF-2013-013*

Lepton Reconstruction and Identification

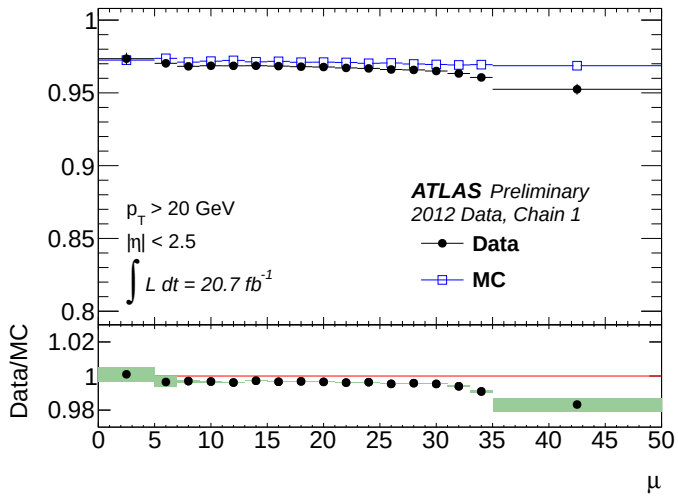


Electron reconstruction efficiency



Electron identification efficiency

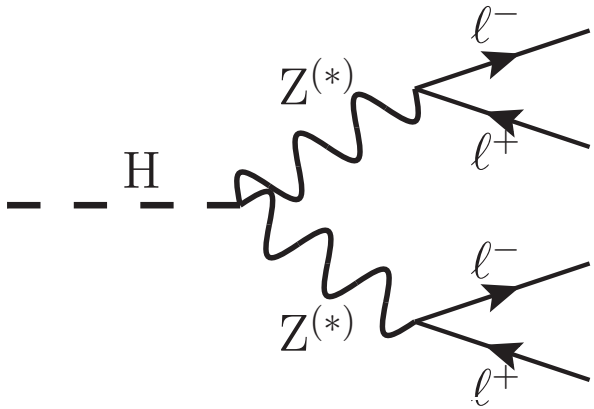
- Electrons
  - Improvements to track pattern recognition and track-cluster matching for 8 TeV run (7 TeV data also processed with improved reconstruction)
  - Also identification requirements tightened to improve background rejection
- Muons
  - Inner Dectector tracks matched with Muon Spectrometer tracks
  - Muon spectrometer only tracks used for $2.5 < |\eta| < 2.7$

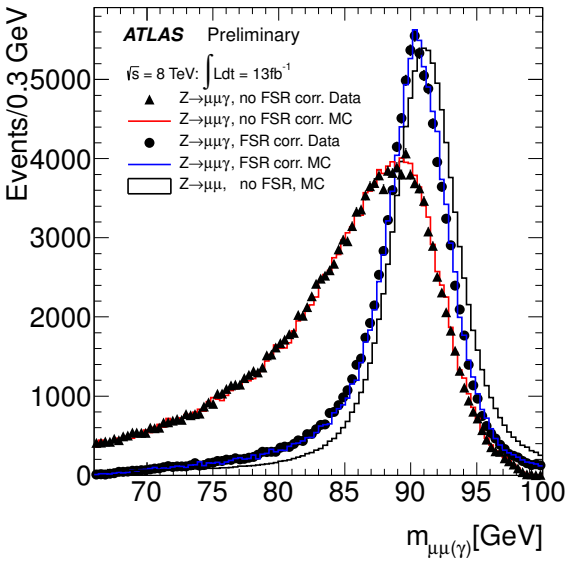


Muon reconstruction efficiency

Event Selection

- Two same-flavour/opposite-sign dilepton pairs
- $p_T^{1,2,3,4} \geq 20$, 15, 10, 7(e)/6(μ) GeV
- Four sub-channels: $4e$, $2e2\mu$, $2\mu2e$, 4μ
- 50 GeV $< m_{12} <$ 106 GeV
- $m_{low}(m_{4\ell}) < m_{34} <$ 115 GeV, where $m_{low} = 12$ GeV $\rightarrow$ 50 GeV, rising linearly for $m_{4\ell} = 140$ GeV $\rightarrow$ 190 GeV





- Selection requirements to suppress reducible backgrounds
  - Tracking and Calorimeter Isolation
  - Impact Parameter (IP) Significance - d_0/σ_{d_0}
    - $d_0/\sigma_{d_0} <$ 3.5 (6.5) for muons (electrons)
- Z mass constraint applied to leading dilepton
- FSR correction to invariant mass for dimuon m_{12} candidates
  - Around 4% of events expected to have a reconstructed FSR photon in 4μ channel

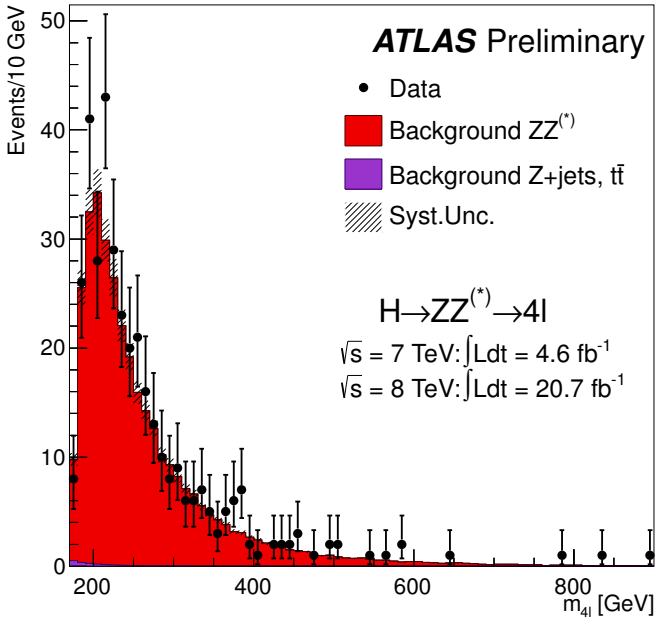
Background Estimation

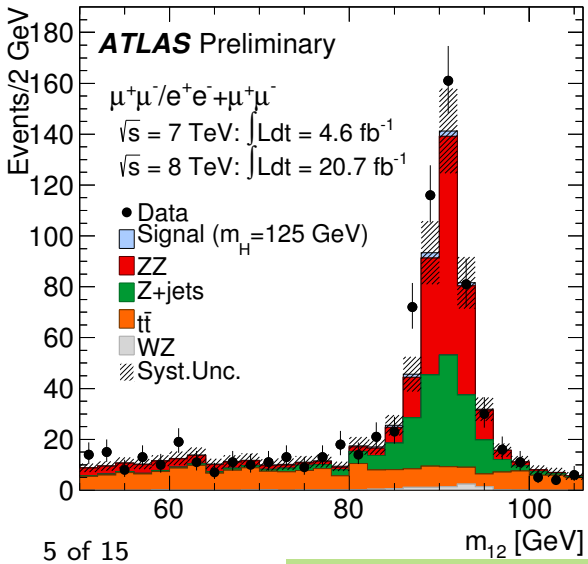
Main background is $ZZ^{(*)}$ production

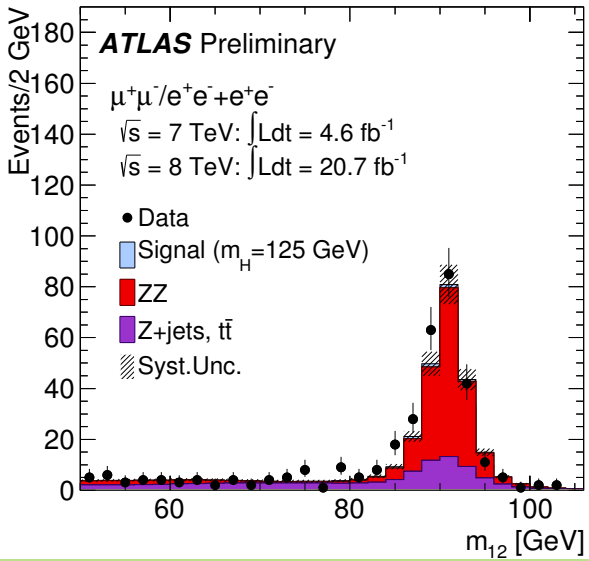
- MC simulation, scaled to theoretical cross section

Reducible backgrounds:

- $Zb\bar{b}$, Z+light jets, $t\bar{t}$
- Estimated using data-driven methods
  - Define background-enriched/signal-depleted control reigions
  - Extrapolate to signal region using transfer factors



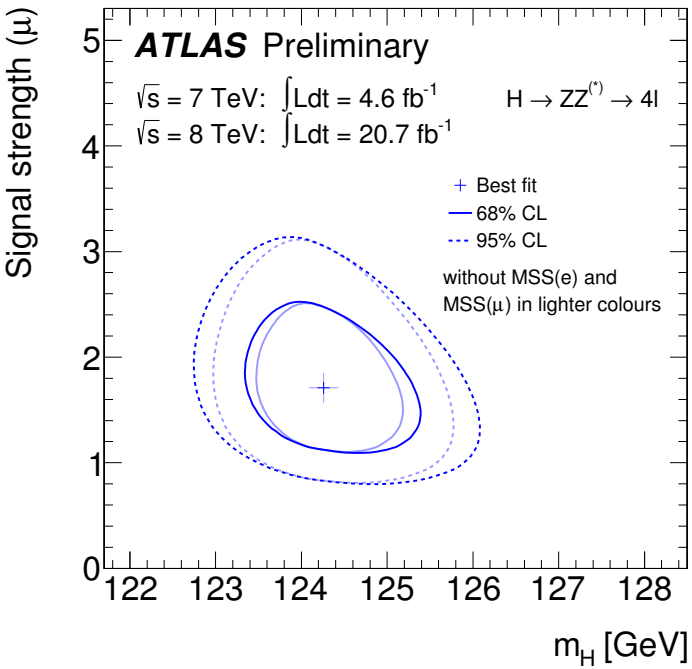


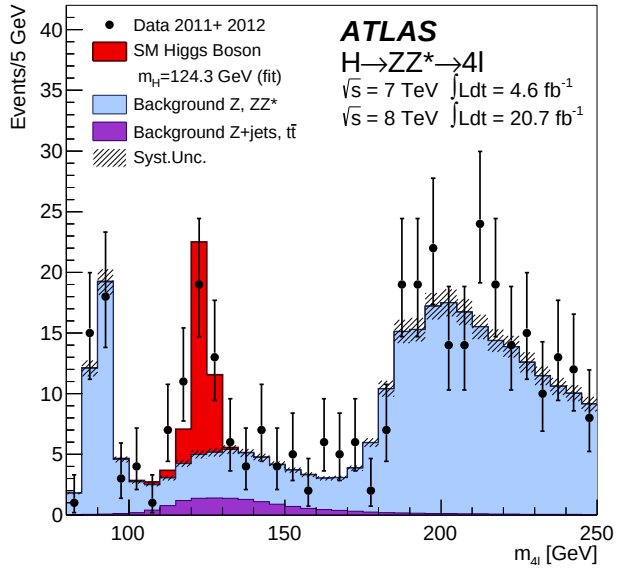


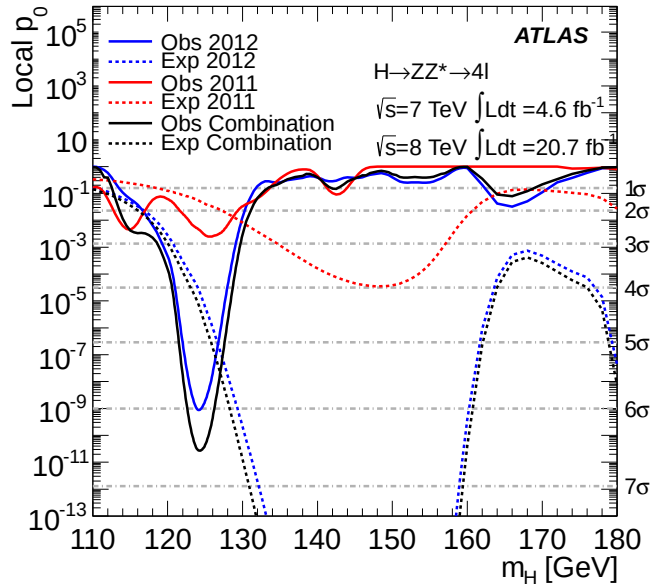
- Estimates agree well with data in control region where isolation and d_0 requirements are removed for subleading pair

Results

- Observe excess of events corresponding to 6.6σ local significance
- Measured mass
  $m_H = 124.3\ ^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(sys)$ GeV
- At this mass, signal strength
  $\mu = \sigma/\sigma_{SM} = 1.7^{+0.5}_{-0.4}$
  - $\mu = 1.5 \pm 0.4$ at ATLAS combined mass measurement $m_H = 125.5$ GeV

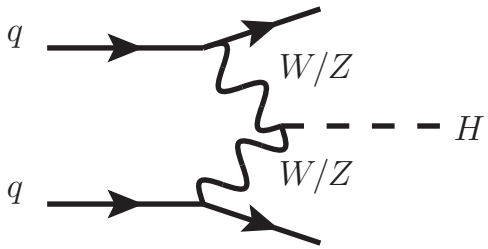




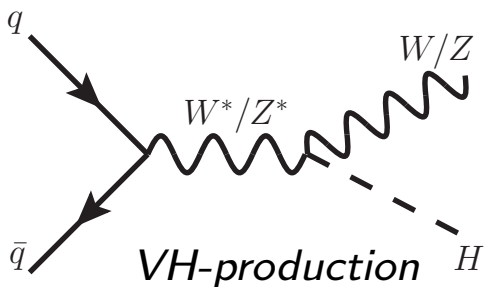


Production Signature Categories

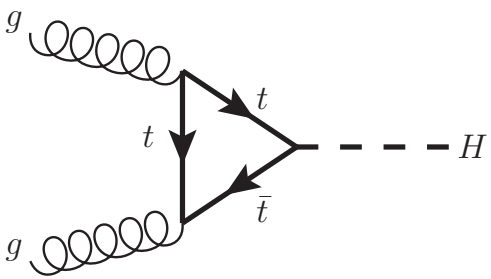
Obtain sensitivity to different production modes by categorizing the candidate 4ℓ events passing selection on slide 4



VBF-production



VH-production



ggF-production

VBF-like category:

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

VH-like category:

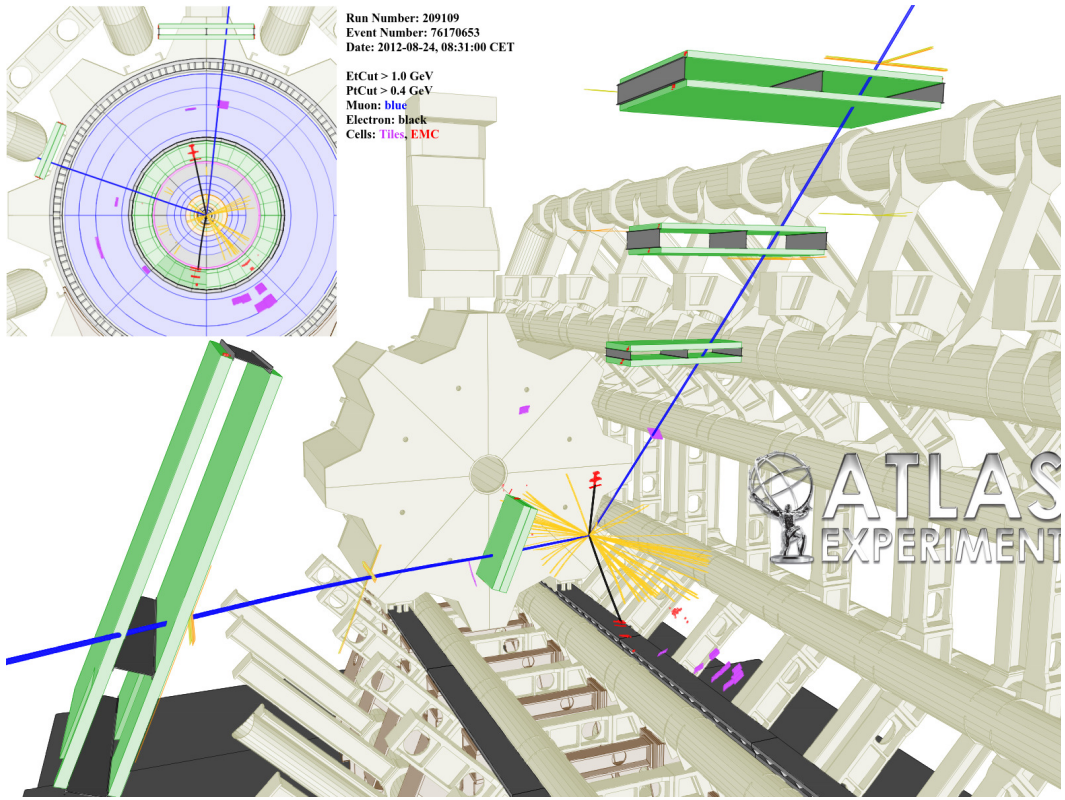
- Additional lepton
- $p_T > 8$ GeV
- Isolation and IP significance

Remaining events are assigned to the ggF-like category

Results - Categories

Of selected events in full mass range: 8 candidates categorised as VBF-like, 1 candidate categorised as VH-like

- One event observed in VBF-like category with mass $m_{4\ell} = 123.5$ GeV
- For $m_H = 125$ GeV, 0.71 ± 0.10 signal events expected for $120 < m_{4\ell} < 130$ GeV
  - S/B $\simeq 5$
- One observed candidate in the VH-like category, $m_{4\ell} = 270.3$ GeV
  - 0.9 ± 0.3 events expected from ZZ* background



Candidate event with $m_{4\ell} = 123.5$ GeV in VBF-like category

Production Rates

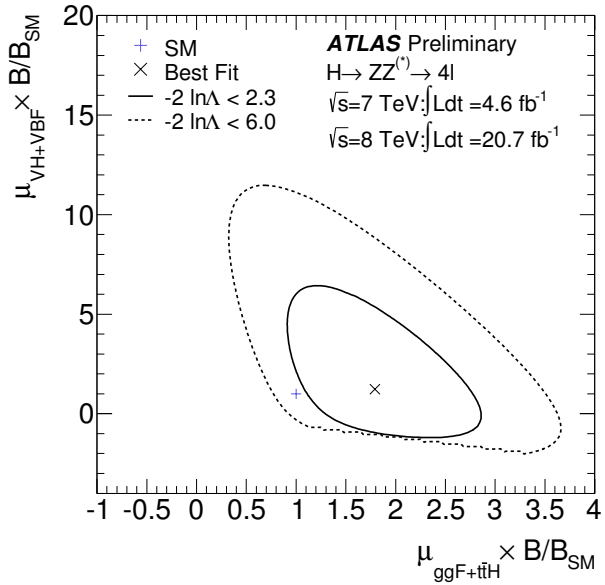
Exploiting categorisation, extend signal strength measurement to measure factors for specific production modes

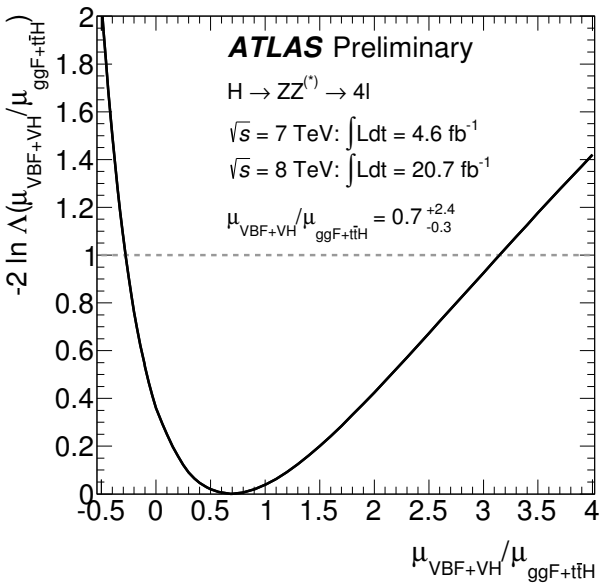
- Group Fermionic(ggF, ttH) and Bosonic(VBF, VH) production mechanisms
  - Branching ratio factor (B/B_{SM}) also included
  - For deviations from SM cannot resolve between production and decay

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

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

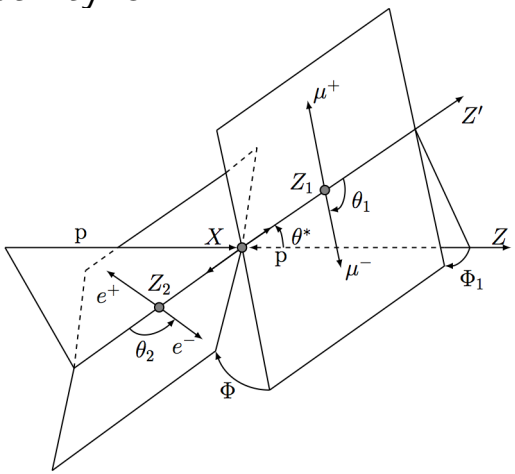
$$\mu_{VBF+VH}/\mu_{ggF+ttH} = 0.7^{+2.4}_{-1.3}$$

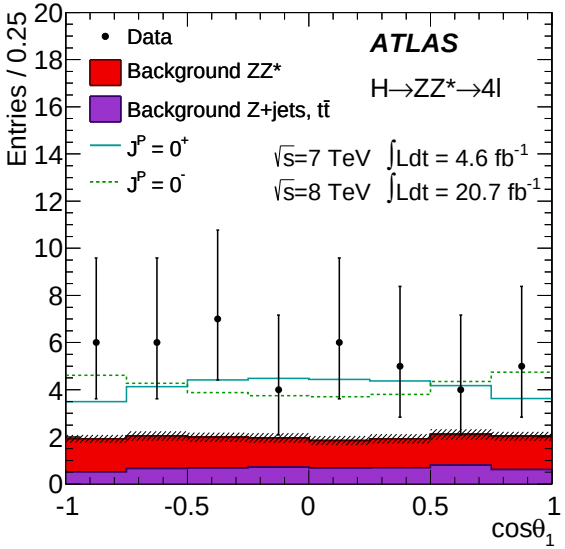




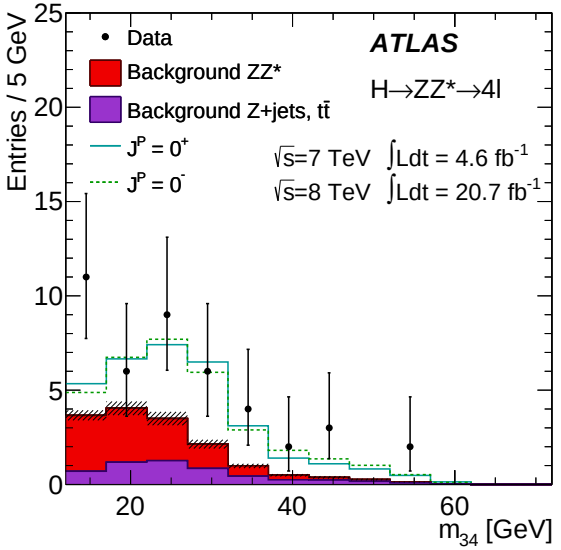
Spin/CP

- In X$\to ZZ^{(*)} \to 4\ell$ decays, m_{Z_1}, m_{Z_2} and the production and decay angles are sensitive to the spin-parity of X



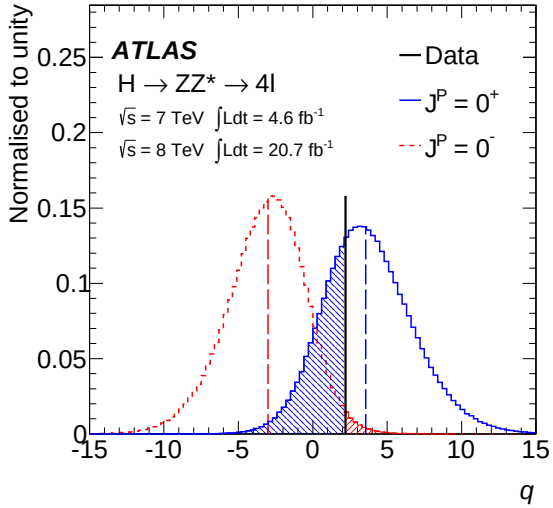


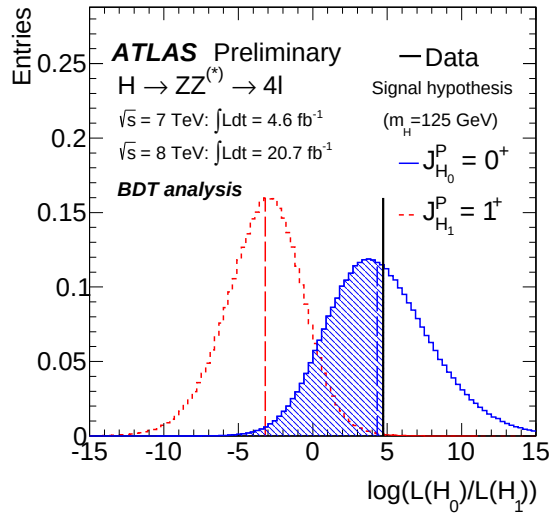
- Construct a discriminant between different hypotheses using two different multivariate techniques:
  - BDT (machine learning)
  - J^P-MELA (use theoretical differential decay rates to construct a matrix element based likelihood ratio)
- Use events in range $115 < m_{4\ell} < 130$ GeV
- Test SM 0^+ hypothesis against alternative hypotheses 0^-, 1^+, 1^-, 2^+_m



Spin/CP

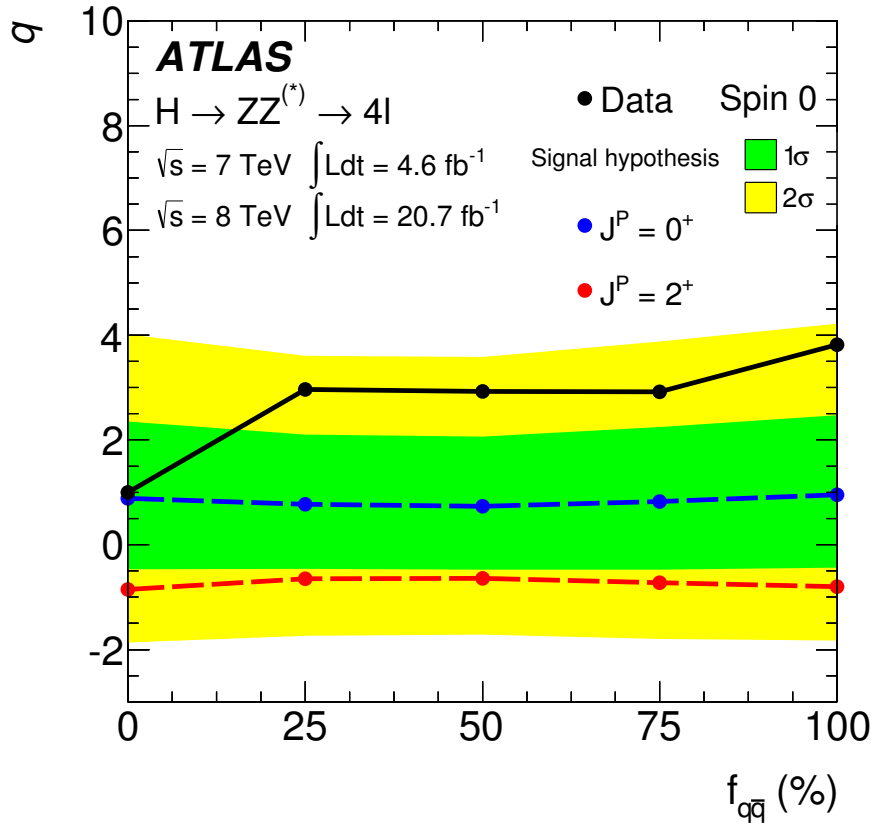
- Test hypotheses using the ratio of profile likelihoods of SM and alternative hypotheses
  - $q = log(\frac{\mathcal{L}(H_0)}{\mathcal{L}(H_1)})$
- The signal strength, μ, is profiled in the fit
  - Separately for each hypothesis
- Observed exclusions in favour of SM 0^+ hypothesis:
  - 0^+ vs 0^- at 97.8% CL_S
  - 0^+ vs 1^- at 94.0% CL_S
  - 0^+ vs 1^+ at 99.8% CL_S





Spin/CP: Spin 2

- For $J^P = 2^+_m$ model:
  - Graviton-like tensor with minimal couplings to SM particles
  - See Phys. Rev. D81 (2010) 075022
  - Production via gg or qq
- Scan fraction of qq production between 0 and 100%
- Sensitivity is stable as a function of $q\bar{q}$ fraction
- Observed exclusion (0^+ vs 2^+_m) at 83.2 CL for 100% ggF produced state



Value of test statistic, q, as a function of the $q\bar{q}$ production fraction, $f_{q\bar{q}}$

Summary

- With a dataset corresponding to 4.6 fb^{-1} at $\sqrt{s} = 7\,TeV$ and 20.7 fb^{-1} at $\sqrt{s} = 8\,TeV$, the Higgs boson is observed in the H$\rightarrow ZZ^{(*)} \rightarrow 4\ell$ channel
  - Excess corresponds to a local significance of 6.6σ
- The best fit mass of the Higgs boson is measured to be $m_H = 124.3\ ^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(sys)$ GeV
- At this mass, the signal strength is $\mu = \sigma/\sigma_{SM} = 1.7^{+0.5}_{-0.4}$
  - $\mu = 1.5 \pm 0.4$ at $m_H = 125$ GeV
- The signal strength for the different production modes are found to be compatible with the SM expectation
  - $\mu_{ggF+ttH} \times B/B_{SM} = 1.8^{+0.8}_{-0.5}$
  - $\mu_{VBF+VH} \times B/B_{SM} = 1.2^{+3.8}_{-1.4}$
- The data is found to favour the SM 0^+ hypothesis, compared with alternative hypotheses tested

Additional material

Couplings

Following recommendations in LHCHXSWG-2012-001, probe benchmark model:

- All fermion couplings modified by single factor k_F
- All massive boson couplings modified by a single factor k_V
- No non-SM contributions to the Higgs total decay width
- The ratio $\lambda_{FV} = k_F / k_V$
  - Assumption on total width is relaxed