Search for new light gauge bosons in Higgs boson decays to four-lepton events at $\sqrt{s} = 8$ TeV with the ATLAS detector

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Rencontres de Moriond: EW Interactions and Unified Theories

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Motivation

Some BSM theories include **dark sector states** that use the Higgs boson as a portal to look for New Physics.

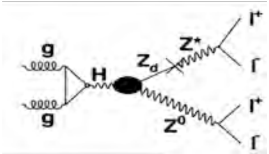
1 Models add a $U(1)_d$ gauge symmetry which introduces:

- New gauge field Z_d with kinetic mixing ϵ with the hypercharge gauge boson

  Z_d : BSM light gauge boson or Dark Z that couples to the dark charge of the new sector.

- Additional Higgs with mass mixing κ leading to a new Higgs doublet.

$\rightarrow$ **motivated by DM searches (see arXiv:1312.4992).**



$H \rightarrow ZZ_d \rightarrow 4\ell$

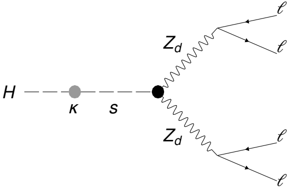
2 Dark sector can be inferred from:

- Deviations from the SM-predicted rates.
- Decays through exotic intermediate states.

$\Rightarrow$ Open possibilities such as

a) $H \rightarrow ZZ_d \rightarrow 4\ell$: $\epsilon \gg \kappa$

b) $H \rightarrow Z_d Z_d \rightarrow 4\ell$: $\kappa \gg \epsilon$.



$H \rightarrow Z_d Z_d \rightarrow 4\ell$

$\rightarrow$ Analyses based on the $H \rightarrow ZZ^* \rightarrow 4\ell$ measurement (arXiv:1307.1427)

Signal / Background / Data

1 Signal generation:

- Only gluon fusion for Higgs production is considered.
- Hidden Abelian Higgs Model is used as a benchmark (**arXiv:0801.3456**)
- $m_{Z_d} \in [15, 60]$ GeV.

2 Background processes:

- $H \to ZZ^* \to 4\ell$ (**Higgs coming from ggF, VBF, WH, ZH and $t\bar{t}H$**), $ZZ^* \to 4\ell$, WW/WZ
  $\Rightarrow$ Obtained from simulation and normalized from theory.

- $Z + jets$, $t\bar{t}$
  $\Rightarrow$ Estimated from data.

- J/ψ and Υ
  $\Rightarrow$ Obtained from simulation and normalized using the ATLAS measurements.

3 Data: ~ 20 fb^{-1} @ $\sqrt{s} = 8$ TeV.

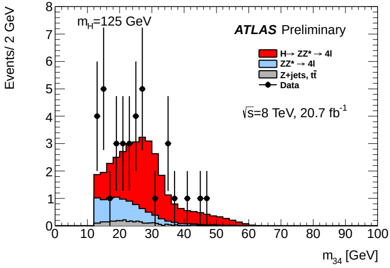
$\Rightarrow$ Only electrons and muons are used.

All results from ATLAS-CONF-2015-003

1 Four final states considered: $4e$, 4μ, $2e2\mu$ and $2\mu2e$:

- m_{12}: Invariant mass of the opposite-sign, same-flavor pair with a mass closest to the Z boson.
- m_{34}: Remaining invariant mass of the remaining dilepton pair.

2 Search for narrow peak or excess above the backgrounds in m_{34} mass distribution.



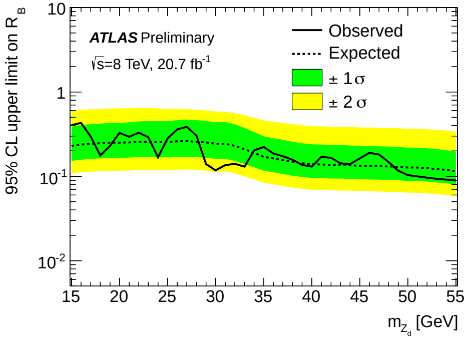
The m_{34} distribution of the data and the expected backgrounds corresponding to $115 < m_{4\ell} < 130$ GeV

a) $H \rightarrow ZZ_d \rightarrow 4\ell$: Results

Upper limits computed at 95% CL in terms of:

- The **relative branching ratio**

$$R_B = \frac{BR(H \rightarrow ZZ_d \rightarrow 4\ell)}{BR(H \rightarrow 4\ell)^*} = \frac{BR(H \rightarrow ZZ_d \rightarrow 4\ell)}{BR(H \rightarrow ZZ_d \rightarrow 4\ell) + BR(H \rightarrow ZZ^* \rightarrow 4\ell)}$$



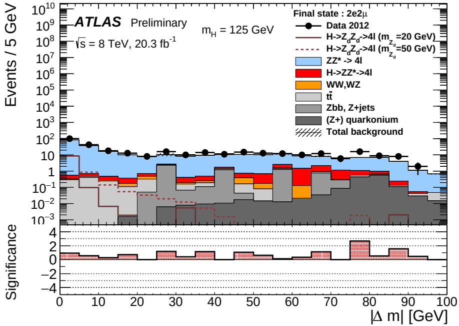
$\Rightarrow R_B > 0.4$ the entire mass range is excluded

$\Rightarrow R_B < 0.09$ no m_{Z_d} is excluded

Events with at least 4 leptons containing 2 same-flavor opposite-sign leptons (SFOS) are used

- $m_{12(34)}$: Invariant mass of the first (second) SFOS pair.
- Keep only quadruplets with minimum $|\Delta m| = |m_{12} - m_{34}|$.

$\Rightarrow$ $m_{\ell\ell}$ has to be consistent with the detector resolution (the two Z_d have the same mass).

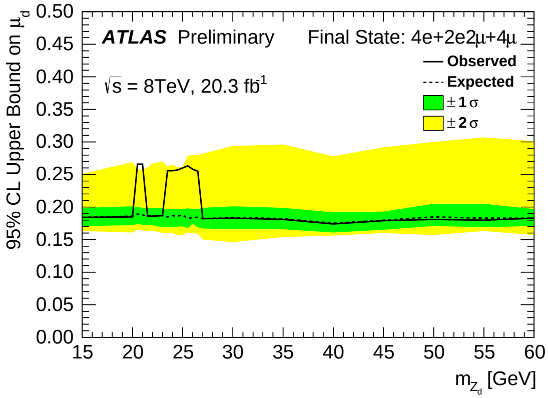


Absolute mass difference, $|\Delta m|$, in the $2e2\mu$ channel, after the impact parameter significance requirements

b) $H \to Z_d Z_d \to 4\ell$: Results

Upper limits computed at 95% CL in terms of:

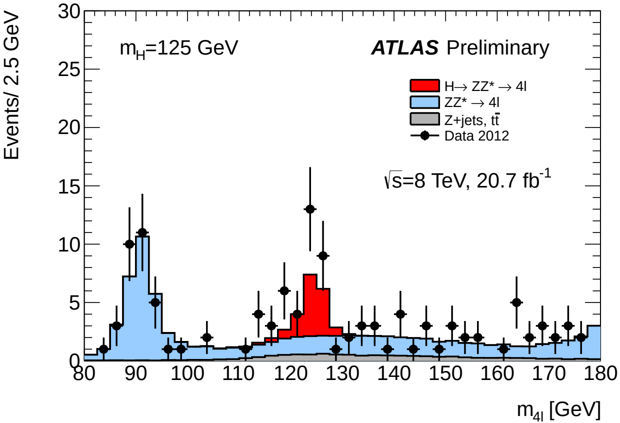
- **Signal strength** $\mu_d = \frac{\sigma \times BR(H \to Z_d Z_d \to 4\ell)}{[\sigma \times BR(H \to ZZ^* \to 4\ell)]_{SM}}$



Summary

1. A search for exotic decays of the Higgs boson in four-lepton events has been presented.
2. No excess of events has been found.
3. Upper limits at 95% CL have been set on the relative branching ratios R_B and μ_d as a function of the dark vector boson mass m_{Z_d}.

BACKUP



The four-lepton mass distribution for the combination of four lepton final states. This distribution is from the four-lepton mass range between 80 and 180 GeV.

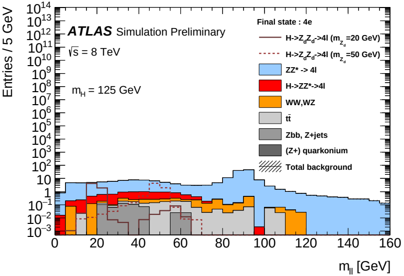
Systematic uncertainties: $H \to ZZd \to 4\ell$

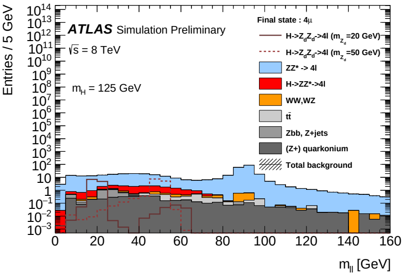
Systematic Uncertainties (%)				
Source	4μ	$4e$	$2\mu 2e$	$2e2\mu$
Electron Identification	–	9.4	8.7	2.4
Electron Energy Scale	–	0.4	–	0.2
Muon Identification	0.8	–	0.4	0.7
Muon Momentum Scale	0.2	–	0.1	–
Luminosity	3.6	3.6	3.6	3.6
$t\bar{t}$ and Z+jet	25.0	25.0	25.0	25.0
ZZ^* (QCD scale)	5.0	5.0	5.0	5.0
ZZ^* ($q\bar{q}$/PDFs and α_s)	4.0	4.0	4.0	4.0
ZZ^* (gg/PDFs and α_s)	8.0	8.0	8.0	8.0

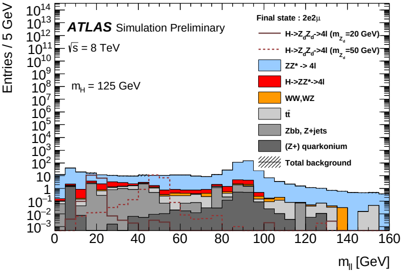
Table 3: The relative systematic uncertainties in the $H \to ZZ_d \to 4\ell$ search.

$$H \to Z_d Z_d \to 4\ell$$

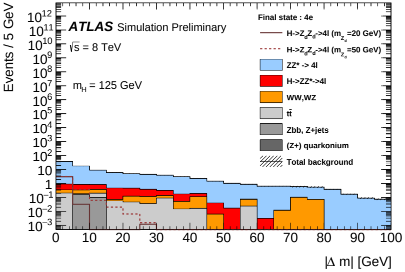
Discriminant variables after event preselection: $m_{\ell\ell}$

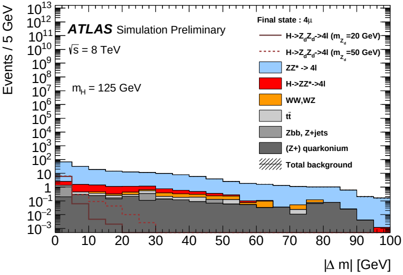


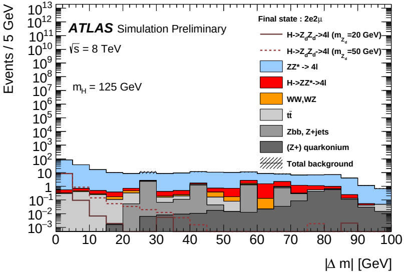




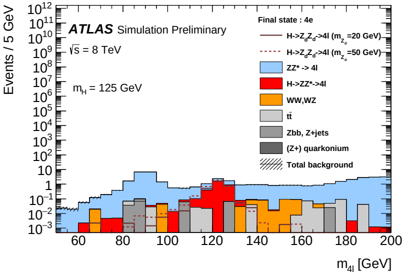
Discriminant variables after event preselection: Δm

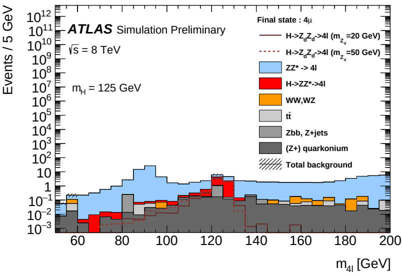


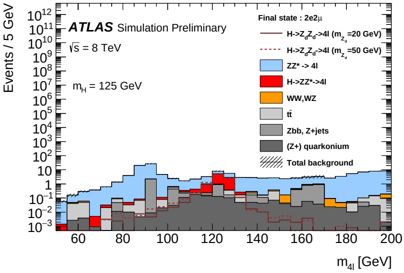




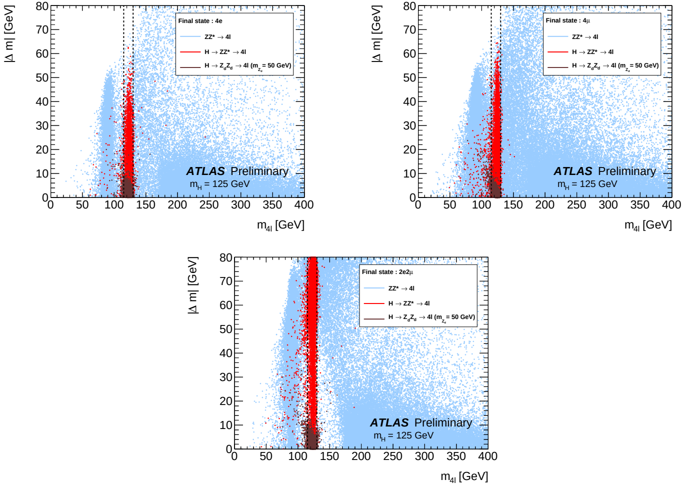
Discriminant variables after event preselection: $m_{4\ell}$





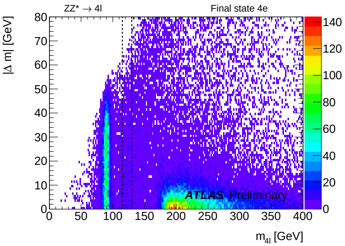


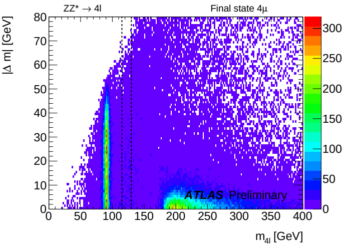
Signal region

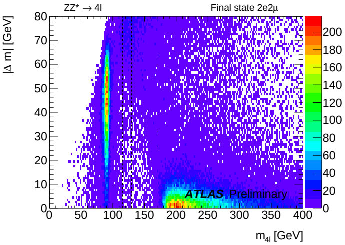


$ZZ \to 4\ell$, $H \to ZZ^{(*)} \to 4\ell$ and $H \to Z_d Z_d \to 4\ell$ $(m_{Z_d} = 50$ GeV)

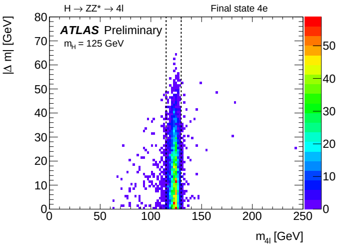
Density of events for $ZZ^* \to 4\ell$

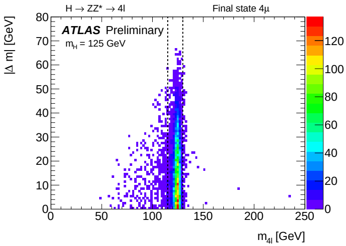


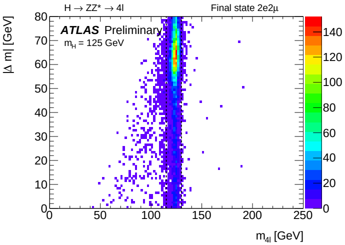




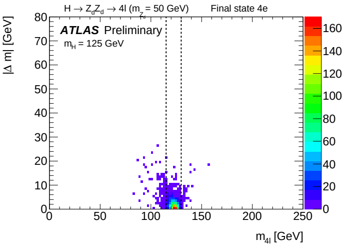
Density of events for $H \to ZZ^* \to 4\ell$

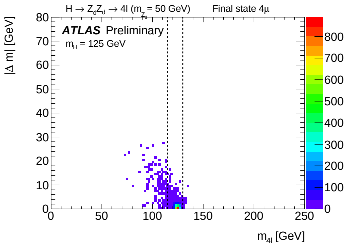


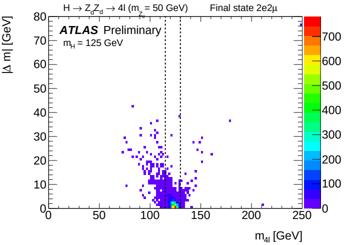




Density of events for signal ($m_{Z_d} = 50$ GeV)

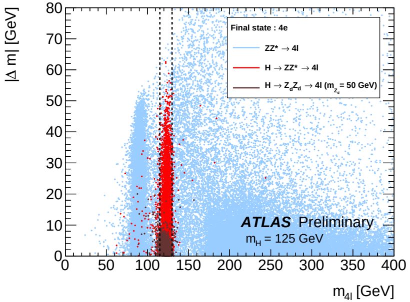




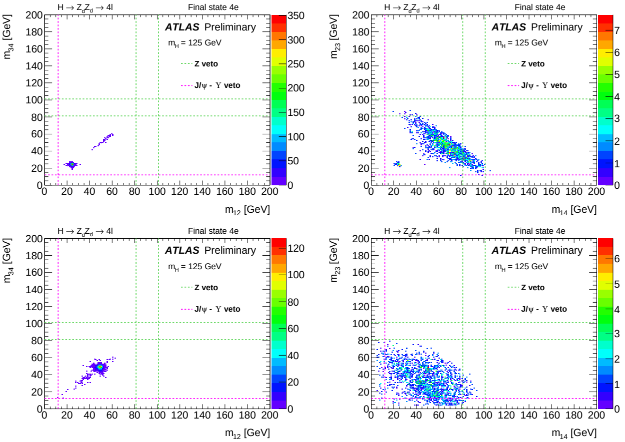


Signal region

1. $115 < m_{4\ell} < 130$ GeV
   $\Rightarrow$ **Remove a lot of ZZ events.**
2. Z and $J/\psi - \Upsilon$ vetoes ($|m_{2\ell} - m_Z| < 10$ GeV and $m_{2\ell} < 12$ GeV) on **all** SFOS pairs
   $\Rightarrow$ **Remove events with a Z on-shell or low-mass resonances.**
3. $m_{\ell\ell} < 63$ GeV $\rightarrow$ **loose Signal Region.**
4. $|m_{Z_d} - m_{2\ell}| < \delta m$
   $\Rightarrow$ $\delta m = 5/3/4.5$ **GeV for** $4e/4\mu/2e2\mu$ **channel.**

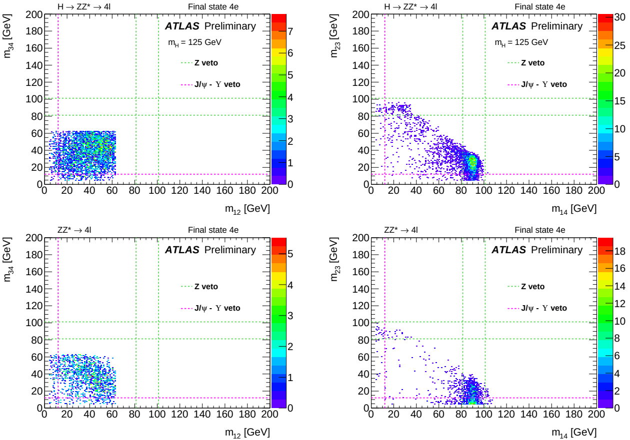


$ZZ \rightarrow 4\ell$, $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ and $H \rightarrow Z_d Z_d \rightarrow 4\ell$ ($m_{Z_d} = 50$ GeV)



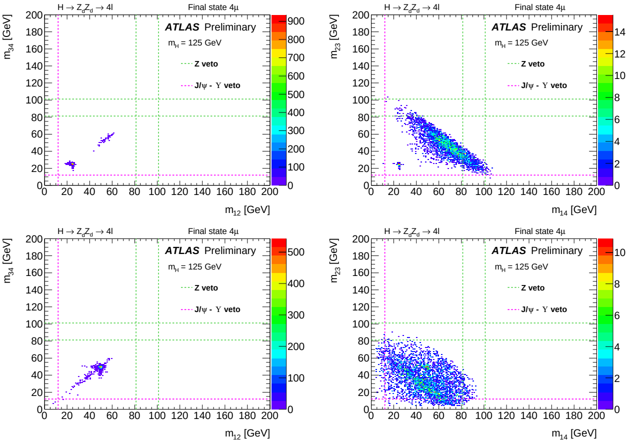
First pair invariant mass (m_{12}) as a function of the second pair invariant mass (m_{34}) (left) and first alternative pair invariant mass (m_{14}) as a function of the second alternative pair invariant mass (m_{23}) (right), for two signal samples (top : $m_{Z_d} = 20$ GeV, bottom : $m_{Z_d} = 50$ GeV).

Impact of the Z and $J/\Psi - \Upsilon$ vetoes: $4e$



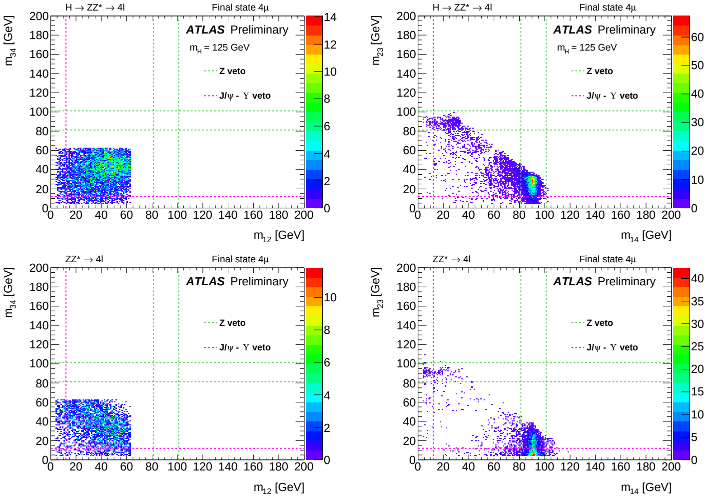
First pair invariant mass (m_{12}) as a function of the second pair invariant mass (m_{34}) (left) and first alternative pair invariant mass (m_{14}) as a function of the second alternative pair invariant mass (m_{23}) (right), for the two main background samples (top : $H \to ZZ^* \to 4\ell$, bottom : $ZZ^* \to 4\ell$).

Impact of the Z and $J/\Psi - \Upsilon$ vetoes: 4μ



First pair invariant mass (m_{12}) as a function of the second pair invariant mass (m_{34}) (left) and first alternative pair invariant mass (m_{14}) as a function of the second alternative pair invariant mass (m_{23}) (right), for two signal samples (top : $m_{Z_d} = 20$ GeV, bottom : $m_{Z_d} = 50$ GeV).

Impact of the Z and $J/\Psi - \Upsilon$ vetoes: 4μ

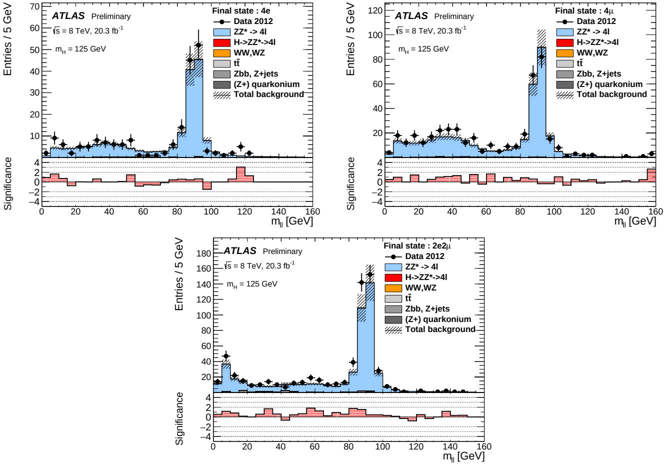


First pair invariant mass (m_{12}) as a function of the second pair invariant mass (m_{34}) (left) and first alternative pair invariant mass (m_{14}) as a function of the second alternative pair invariant mass (m_{23}) (right), for the two main background samples (top : $H \to ZZ^* \to 4\ell$, bottom : $ZZ^* \to 4\ell$).

Background validation: Control Region (CR)

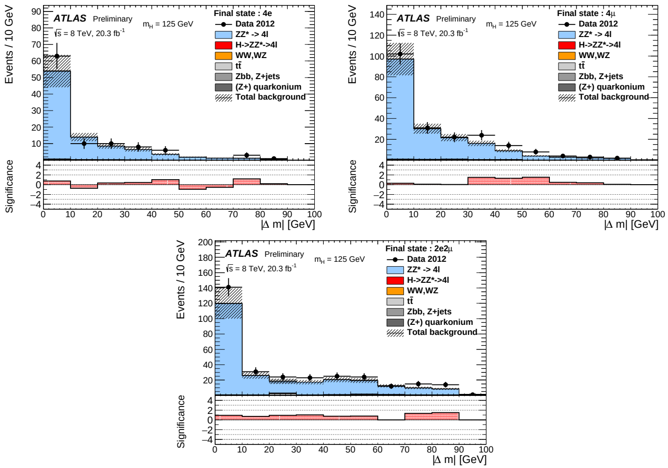
- Event preselection (events are selected at the IP level).
- $m_{4\ell} \notin (115, 130)$ GeV.

***Reminder: SR is defined by $m_{4\ell} \in (115, 130)$ GeV.**

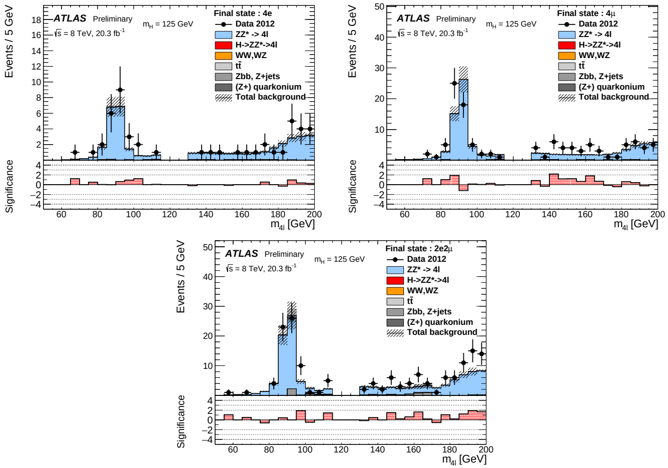


Overall agreement is good

CR: 2) Δm

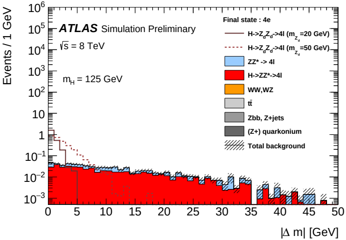


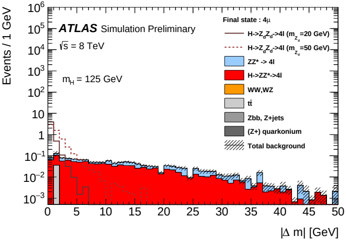
Overall agreement is good

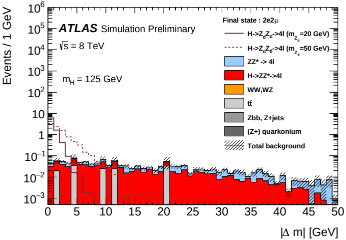


Overall agreement is good

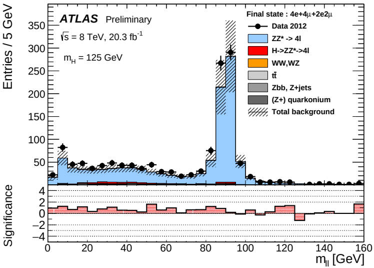
Distribution of Δm in the loose signal region

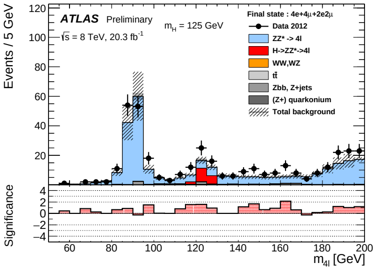




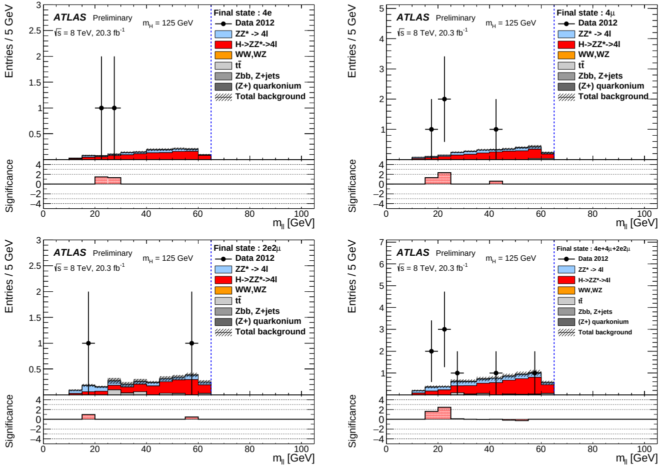


Data/background comparison at the IP level

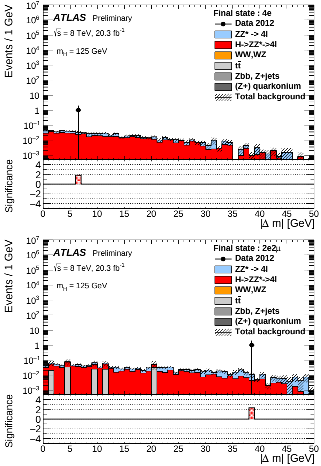




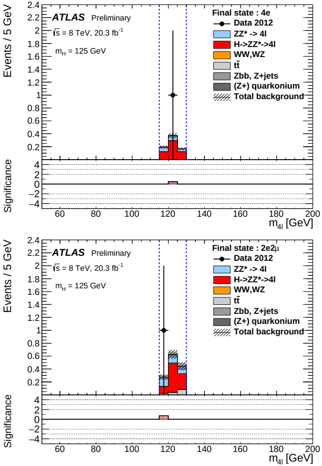
Data/background comparison in the loose SR



Data/background comparison in the loose SR



Data/background comparison in the loose SR



Number of events in the Signal Region

Process	$4e$	4μ	$2e2\mu$
$H \to Z_d Z_d \to 4\ell$ (m_{Z_d} = 25 GeV)	$2.38 \pm 0.07 \pm 0.30$	$4.71 \pm 0.10 \pm 0.52$	$8.01 \pm 0.12 \pm 0.93$
(ggF)$H \to ZZ^* \to 4\ell$	$(1.3 \pm 0.3 \pm 0.2) \times 10^{-2}$	$(0.9 \pm 0.3 \pm 0.3) \times 10^{-2}$	$(0.2 \pm 0.1 \pm 0.2) \times 10^{-2}$
(VBF)$H \to ZZ^* \to 4\ell$	$(10.0 \pm 2.0 \pm 0.7) \times 10^{-4}$	$(8.4 \pm 2.3 \pm 0.4) \times 10^{-4}$	$(5.1 \pm 1.7 \pm 0.2) \times 10^{-4}$
(W)$H \to ZZ^* \to 4\ell$	$(8.4 \pm 2.1 \pm 0.8) \times 10^{-4}$	$(2.2 \pm 1.1 \pm 0.1) \times 10^{-4}$	$(2 \pm 1 \pm 0.1) \times 10^{-4}$
(Z)$H \to ZZ^* \to 4\ell$	$(2.8 \pm 1.0 \pm 0.2) \times 10^{-4}$	$(9.8 \pm 5.6 \pm 0.5) \times 10^{-5}$	$(18 \pm 7 \pm 1) \times 10^{-5}$
$(t\bar{t})H \to ZZ^* \to 4\ell$	$(5.6 \pm 2.0 \pm 0.6) \times 10^{-5}$	$(3.8 \pm 1.7 \pm 0.4) \times 10^{-5}$	$(4.7 \pm 1.9 \pm 0.5) \times 10^{-5}$
$ZZ^* \to 4\ell$	$(7.1 \pm 3.6 \pm 0.5) \times 10^{-4}$	$(8.4 \pm 3.8 \pm 0.5) \times 10^{-3}$	$(9.1 \pm 3.6 \pm 0.6) \times 10^{-3}$
WW, WZ	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$
$t\bar{t}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$
Zbb, Z+jets	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$
ZJ/ψ and $Z\Upsilon$	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$
Total background	$(1.6 \pm 3.1 \pm 0.2) \times 10^{-2}$	$(1.9 \pm 3.1 \pm 0.3) \times 10^{-2}$	$(1.2 \pm 3.1 \pm 0.1) \times 10^{-2}$
Data	1	0	0
$H \to Z_d Z_d \to 4\ell$ (m_{Z_d} = 20.5 GeV)	$2.32 \pm 0.07 \pm 0.30$	$4.50 \pm 0.10 \pm 0.50$	$8.27 \pm 0.10 \pm 0.96$
(ggF)$H \to ZZ^* \to 4\ell$	$(1.1 \pm 0.3 \pm 0.2) \times 10^{-2}$	$(0.5 \pm 0.2 \pm 0.2) \times 10^{-2}$	$(0.2 \pm 0.1 \pm 0.02) \times 10^{-2}$
(VBF)$H \to ZZ^* \to 4\ell$	$(5.8 \pm 1.8 \pm 0.4) \times 10^{-4}$	$(6.3 \pm 2.0 \pm 0.3) \times 10^{-4}$	$(3.6 \pm 1.5 \pm 0.1) \times 10^{-4}$
(W)$H \to ZZ^* \to 4\ell$	$(3.3 \pm 1.2 \pm 0.3) \times 10^{-4}$	$(1.0 \pm 1.0 \pm 0.0) \times 10^{-6}$	$(9.4 \pm 6.7 \pm 0.5) \times 10^{-5}$
(Z)$H \to ZZ^* \to 4\ell$	$(2.4 \pm 0.9 \pm 0.2) \times 10^{-4}$	$(1.6 \pm 0.7 \pm 0.1) \times 10^{-4}$	$(1.1 \pm 0.6 \pm 0.1) \times 10^{-4}$
$(t\bar{t})H \to ZZ^* \to 4\ell$	$(4.1 \pm 1.9 \pm 0.4) \times 10^{-5}$	$(4.4 \pm 2.1 \pm 0.5) \times 10^{-5}$	$(4.0 \pm 1.6 \pm 0.4) \times 10^{-5}$
$ZZ^* \to 4\ell$	$(3.5 \pm 2.0 \pm 0.2) \times 10^{-3}$	$(4.1 \pm 2.7 \pm 0.2) \times 10^{-3}$	$(2.0 \pm 0.6 \pm 0.1) \times 10^{-2}$
WW, WZ	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$
$t\bar{t}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$
Zbb, Z+jets	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$
ZJ/ψ and $Z\Upsilon$	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$
Total background	$(1.6 \pm 3.1 \pm 0.2) \times 10^{-2}$	$(1.0 \pm 3.1 \pm 0.2) \times 10^{-2}$	$(2.6 \pm 3.1 \pm 0.1) \times 10^{-2}$
Data	0	1	0

The expected and observed numbers of events in the tight signal region for each of the three final states, for the hypothesized mass $m_{Z_d} = 25$ GeV and 20.5 GeV. Statistical and systematic uncertainties are given respectively for the signal and the background expectations. One event in data passes all the selections in the $4e$ channel and is consistent with $23.5 \leq m_{Z_d} \leq 26.5$ GeV. One other in data passes all the selections in the 4μ channel and is consistent with $20.5 \leq m_{Z_d} \leq 21.0$ GeV.

Systematic uncertainties: $H \to Z_d Z_d \to 4\ell$

Systematic Uncertainties (%)			
Source	4μ	4e	$2e2\mu$
Electron Identification	–	6.7	3.2
Electron Energy Scale	–	0.8	0.3
Muon Identification	2.6	–	1.3
Muon Momentum Scale	0.1	–	0.1
Luminosity	2.8	2.8	2.8
ggF QCD	7.8	7.8	7.8
ggF PDFs and α_S	7.5	7.5	7.5
ZZ^* Normalization	5.0	5.0	5.0

Table 4: The relative systematic uncertainties in the $H \to Z_d Z_d \to 4\ell$ search.