

# 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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**Recent Developments on High Energy Physics and Cosmology**

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## 1 Introduction

2  $H \rightarrow ZZ_d \rightarrow 4\ell$

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

## 4 Summary

## 1 Introduction

- Motivation
- Signal / Background / Data

## 2 $H \rightarrow ZZ_d \rightarrow 4\ell$

- Search strategy
- Systematic uncertainties
- Results

## 3 $H \rightarrow Z_d Z_d \rightarrow 4\ell$

- Search strategy
- Signal Region
- Data/background comparison in the loose SR
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## 4 Summary

# 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  $\epsilon$**  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  $\kappa$**  leading to a new Higgs doublet.

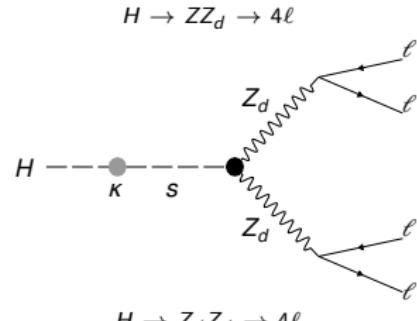
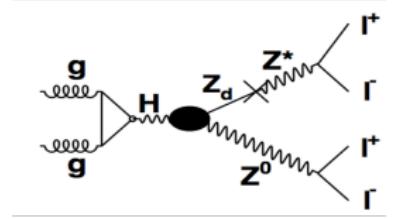
→ motivated by DM searches (see arXiv:1312.4992).

## 2 Dark sector can be inferred from:

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

⇒ Open possibilities such as

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



→ 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:

- $H \rightarrow ZZ^* \rightarrow 4\ell$  (Higgs coming from ggF, VBF, WH, ZH and  $t\bar{t}H$ ),  $ZZ^* \rightarrow 4\ell$ ,  $WW/WZ$   
 ⇒ Obtained from simulation and normalized from theory.
- $Z + jets, t\bar{t}$   
 ⇒ Estimated from data.
- $J/\psi$  and  $\Upsilon$   
 ⇒ Obtained from simulation and normalized using the ATLAS measurements.

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

⇒ Only electrons and muons are used.

All results from [ATLAS-CONF-2015-003](#)

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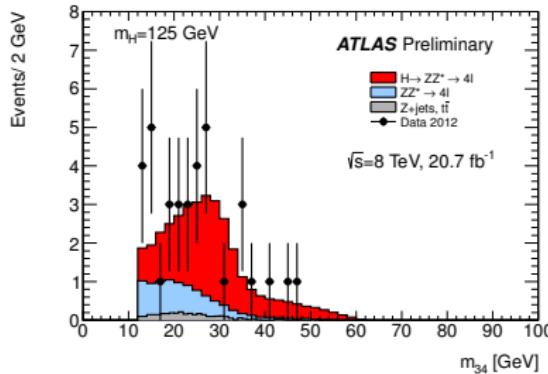
# Search strategy

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

- $m_{12}$ : Invariant mass of the opposite-sign, same-flavor pair with a mass closest to the  $Z$  boson  
 $\Rightarrow m_{12} \in [50, 106]$  GeV
- $m_{34}$ : Remaining invariant mass of the remaining dilepton pair  $\Rightarrow m_{34} \in [12, 115]$  GeV.

Events are required to have  $m_{4\ell} \in [115, 130]$  GeV.

## 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 | = ↻ 🔍 ↵

# Search strategy

- The search is used to constraint the relative branching ratio:

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

- A likelihood function  $\mathcal{L}$  is used to obtain a measurement of  $R_B$

$$\begin{aligned} \mathcal{L}(\rho, \mu_H, \nu) &= \prod_{i=0}^{Nbins-1} \mathcal{P}(n_i^{\text{obs}} | n_i^{\text{exp}}) \\ &= \prod_{i=0}^{Nbins-1} \mathcal{P}(n_i^{\text{obs}} | \mu_H \times (n_i^{Z^*} + \rho \times n_i^{Z_d}) + b_i(\nu)) \end{aligned} \quad (1)$$

$\mu_H$  : normalization of  $H \rightarrow ZZ^* \rightarrow 4\ell$

$\rho$  : parameter of interests related to  $H \rightarrow ZZ_d \rightarrow 4\ell$  normalization

$\rho \times \mu_H$  : normalization of  $H \rightarrow ZZ_d \rightarrow 4\ell$

$\nu$  : systematic uncertainties on the background

Upper bound on  $\rho$  obtained from the binned likelihood fit to data.

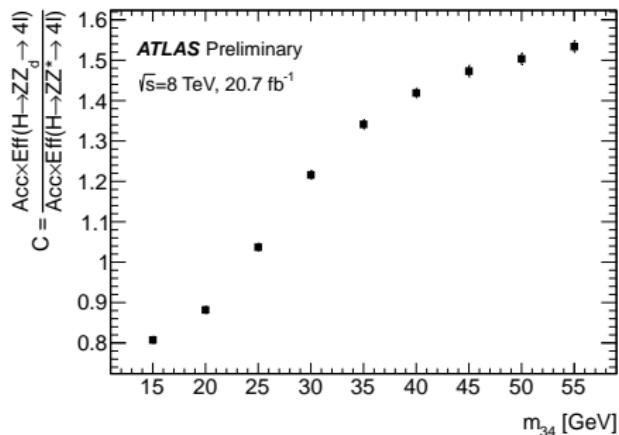
# Search strategy

- $\rho$  is used to obtain  $R_B$ :

$$\begin{aligned} R_B &= \frac{\rho \times \mu_H \times N}{\rho \times \mu_H \times N + C \times \mu_H \times N} \\ &= \frac{\rho}{\rho + C} \end{aligned} \quad (2)$$

where  $C$ :

$$C = \frac{\mathcal{A}_{ZZ_d} \times \varepsilon_{ZZ_d}}{\mathcal{A}_{ZZ^*} \times \varepsilon_{ZZ^*}}. \quad (3)$$



# Systematic uncertainties

Systematic Uncertainties (%)				
Source	$4\mu$	$4e$	$2\mu 2e$	$2e 2\mu$
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 $Z + \text{jet}$	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 $\alpha_s$ )	4.0	4.0	4.0	4.0
$ZZ^*$ (gg/PDFs and $\alpha_s$ )	8.0	8.0	8.0	8.0

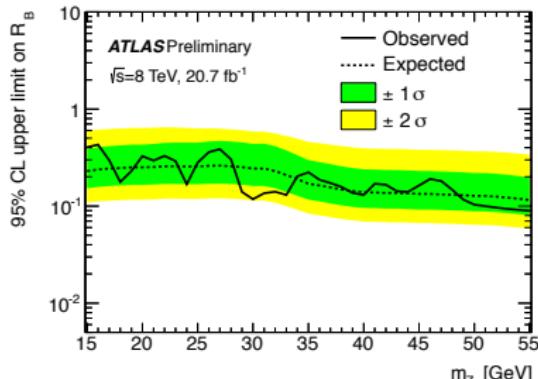
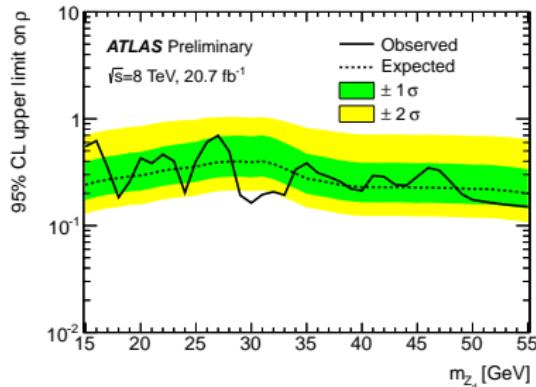
Table 3: The relative systematic uncertainties in the  $H \rightarrow ZZ_d \rightarrow 4\ell$  search.

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

Upper limits computed at 95% CL in terms of:

- The relative branching ratio

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



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

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

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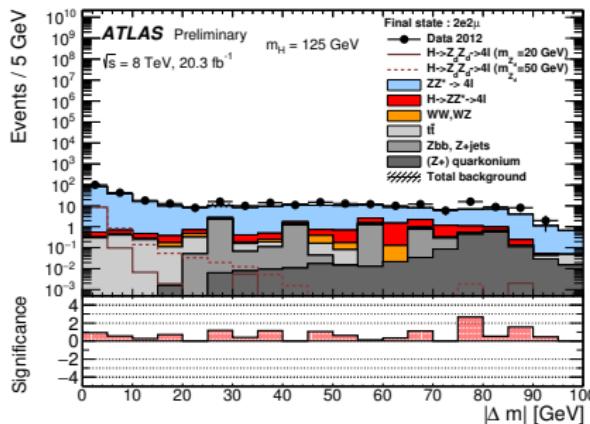
## 4 Summary

# Search strategy

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  $|\Delta m| = |m_{12} - m_{34}|$ .

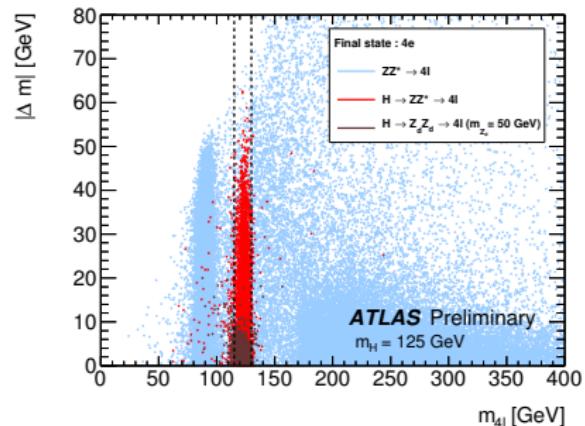
⇒  $m_{\ell\ell}$  has to be consistent with the detector resolution (the two  $Z_d$  have the same mass).



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

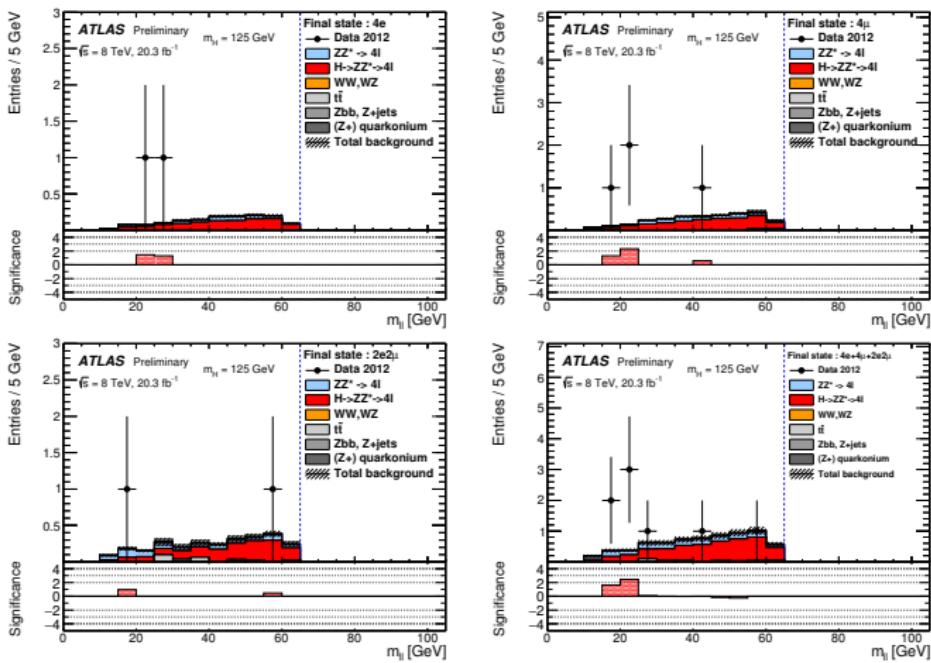
# Signal Region

- 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  $m_{\ell\ell} < m_H/2 \rightarrow$  loose Signal Region.
- 4  $|m_{Z_d} - m_{\ell\ell}| < \delta m$   
 $\Rightarrow \delta m = 5/3/4.5$  GeV for  $4e/4\mu/2e2\mu$  channel.

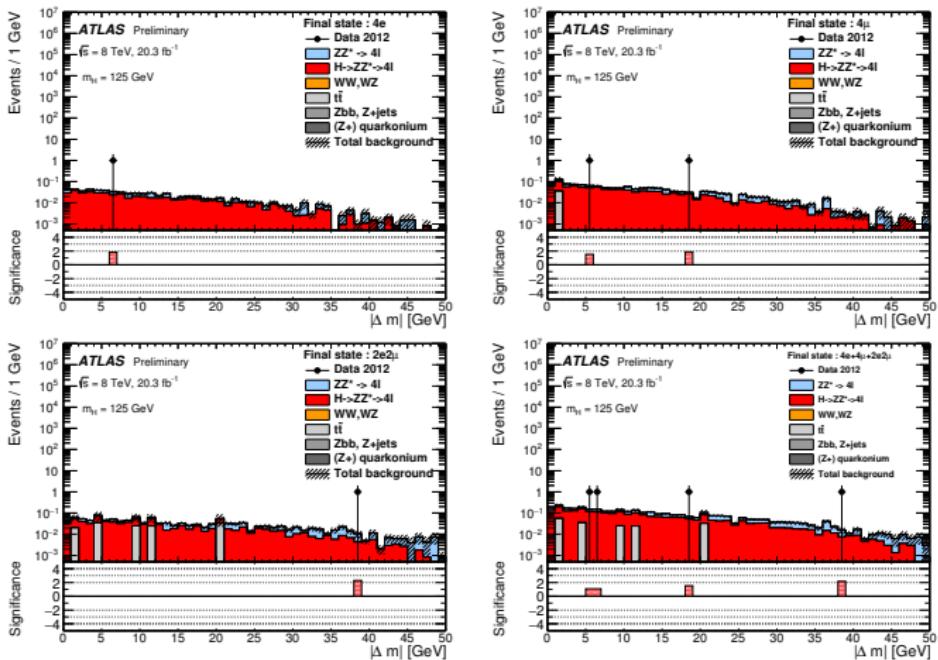


$ZZ \rightarrow 4\ell$ ,  $H \rightarrow ZZ^* \rightarrow 4\ell$  and  $H \rightarrow Z_dZ_d \rightarrow 4\ell$   
 $(m_{Z_d} = 50$  GeV)

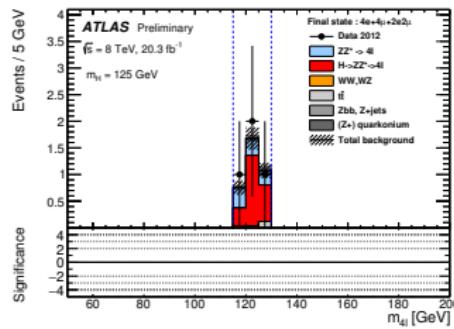
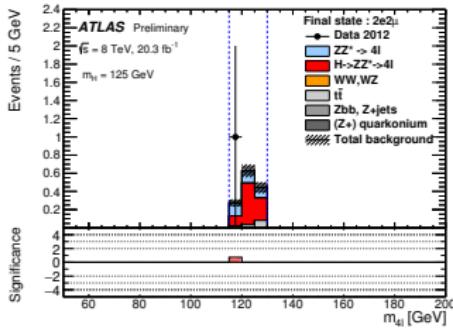
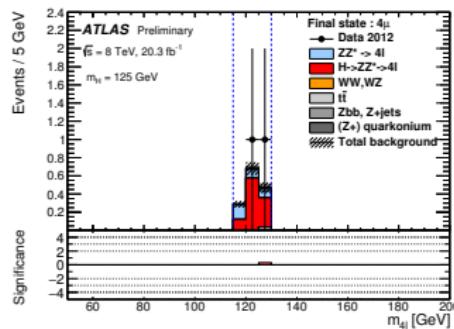
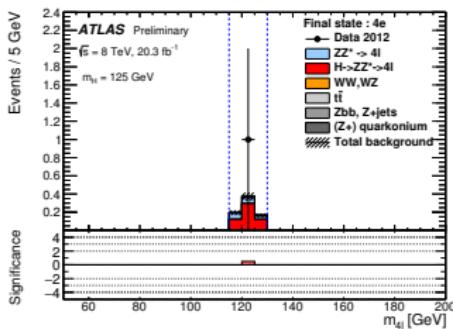
# Data/background comparison in the loose SR: $m_{\ell\ell}$



# Data/background comparison in the loose SR: $|\Delta m|$



# Data/background comparison in the loose SR: $m_{4\ell}$



# Systematic uncertainties: $H \rightarrow Z_dZ_d \rightarrow 4\ell$

Source	Systematic Uncertainties (%)		
	$4\mu$	$4e$	$2e2\mu$
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 $\alpha_S$	7.5	7.5	7.5
$ZZ^*$ Normalization	5.0	5.0	5.0

Table 4: The relative systematic uncertainties in the  $H \rightarrow Z_dZ_d \rightarrow 4\ell$  search.

# Number of events in the Signal Region

Process	4e	4μ	2e2μ
$H \rightarrow Z_d Z_d \rightarrow 4\ell$ ( $m_{Z_d} = 25$ 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) $H \rightarrow ZZ^* \rightarrow 4\ell$	$(1.3 \pm 0.3 \pm 0.2) \times 10^{-2}$	$(0.9 \pm 0.3 \pm 0.3) \times 10^{-2}$	$(0.2 \pm 0.1 \pm 0.2) \times 10^{-2}$
(VBF) $H \rightarrow ZZ^* \rightarrow 4\ell$	$(10.0 \pm 2.0 \pm 0.7) \times 10^{-4}$	$(8.4 \pm 2.3 \pm 0.4) \times 10^{-4}$	$(5.1 \pm 1.7 \pm 0.2) \times 10^{-4}$
(W) $H \rightarrow ZZ^* \rightarrow 4\ell$	$(8.4 \pm 2.1 \pm 0.8) \times 10^{-4}$	$(2.2 \pm 1.1 \pm 0.1) \times 10^{-4}$	$(2 \pm 1 \pm 0.1) \times 10^{-4}$
(Z) $H \rightarrow ZZ^* \rightarrow 4\ell$	$(2.8 \pm 1.0 \pm 0.2) \times 10^{-4}$	$(9.8 \pm 5.6 \pm 0.5) \times 10^{-5}$	$(18 \pm 7 \pm 1) \times 10^{-5}$
(t̄t) $H \rightarrow ZZ^* \rightarrow 4\ell$	$(5.6 \pm 2.0 \pm 0.6) \times 10^{-5}$	$(3.8 \pm 1.7 \pm 0.4) \times 10^{-5}$	$(4.7 \pm 1.9 \pm 0.5) \times 10^{-5}$
$ZZ^* \rightarrow 4\ell$	$(7.1 \pm 3.6 \pm 0.5) \times 10^{-4}$	$(8.4 \pm 3.8 \pm 0.5) \times 10^{-3}$	$(9.1 \pm 3.6 \pm 0.6) \times 10^{-3}$
WW, WZ	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$
t̄t	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$
Zbb, Z+jets	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$
ZJ/ψ and ZT	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$
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
$H \rightarrow Z_d Z_d \rightarrow 4\ell$ ( $m_{Z_d} = 20.5$ 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) $H \rightarrow ZZ^* \rightarrow 4\ell$	$(1.1 \pm 0.3 \pm 0.2) \times 10^{-2}$	$(0.5 \pm 0.2 \pm 0.2) \times 10^{-2}$	$(0.2 \pm 0.1 \pm 0.02) \times 10^{-2}$
(VBF) $H \rightarrow ZZ^* \rightarrow 4\ell$	$(5.8 \pm 1.8 \pm 0.4) \times 10^{-4}$	$(6.3 \pm 2.0 \pm 0.3) \times 10^{-4}$	$(3.6 \pm 1.5 \pm 0.1) \times 10^{-4}$
(W) $H \rightarrow ZZ^* \rightarrow 4\ell$	$(3.3 \pm 1.2 \pm 0.3) \times 10^{-4}$	$(1.0 \pm 1.0 \pm 0.0) \times 10^{-6}$	$(9.4 \pm 6.7 \pm 0.5) \times 10^{-5}$
(Z) $H \rightarrow ZZ^* \rightarrow 4\ell$	$(2.4 \pm 0.9 \pm 0.2) \times 10^{-4}$	$(1.6 \pm 0.7 \pm 0.1) \times 10^{-4}$	$(1.1 \pm 0.6 \pm 0.1) \times 10^{-4}$
(t̄t) $H \rightarrow ZZ^* \rightarrow 4\ell$	$(4.1 \pm 1.9 \pm 0.4) \times 10^{-5}$	$(4.4 \pm 2.1 \pm 0.5) \times 10^{-5}$	$(4.0 \pm 1.6 \pm 0.4) \times 10^{-5}$
$ZZ^* \rightarrow 4\ell$	$(3.5 \pm 2.0 \pm 0.2) \times 10^{-3}$	$(4.1 \pm 2.7 \pm 0.2) \times 10^{-3}$	$(2.0 \pm 0.6 \pm 0.1) \times 10^{-2}$
WW, WZ	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$
t̄t	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$
Zbb, Z+jets	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$
ZJ/ψ and ZT	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$
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

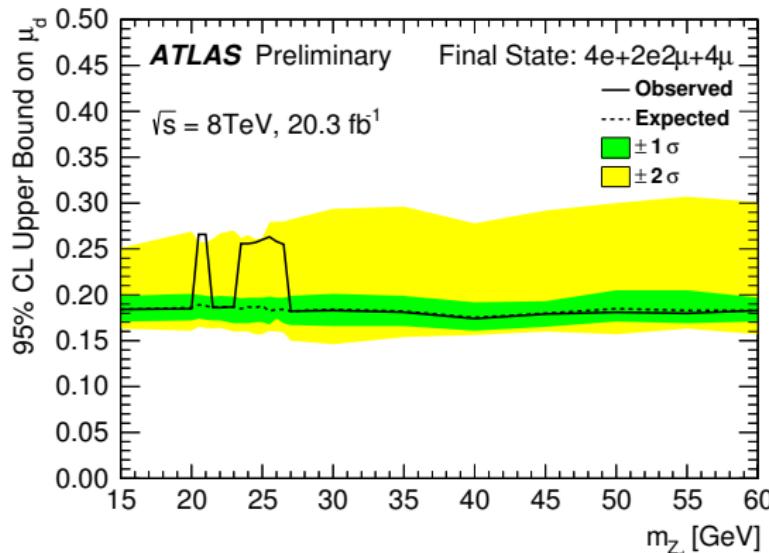
The expected and observed numbers of events in the signal region for each of the three final states, for the hypothesized mass  $m_{Z_d} = 25$  GeV and 20.5 GeV

- 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.

# Limit setting

Upper limits computed at 95% CL in terms of:

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



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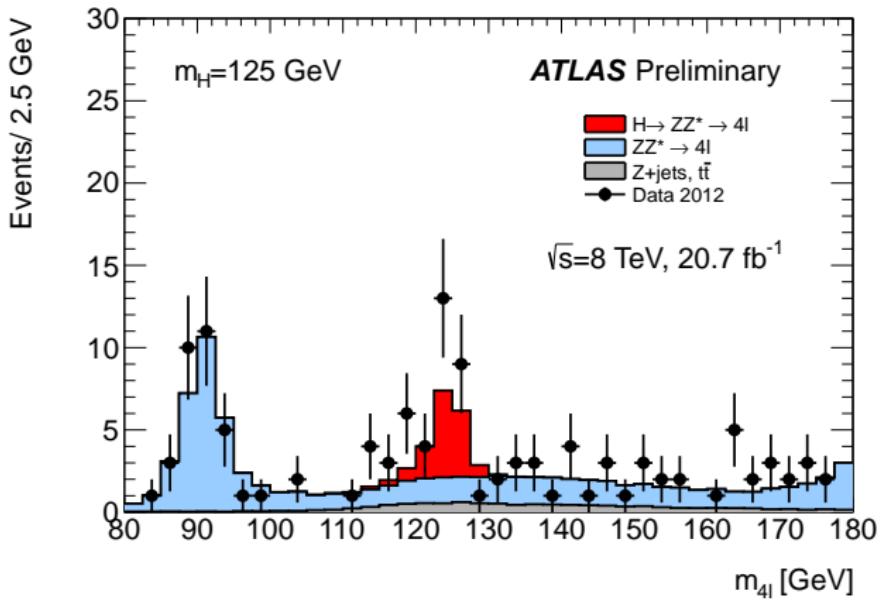
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# Summary

- 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  $\mu_d$  as a function of the dark vector boson mass  $m_{Z_d}$ .

# BACKUP



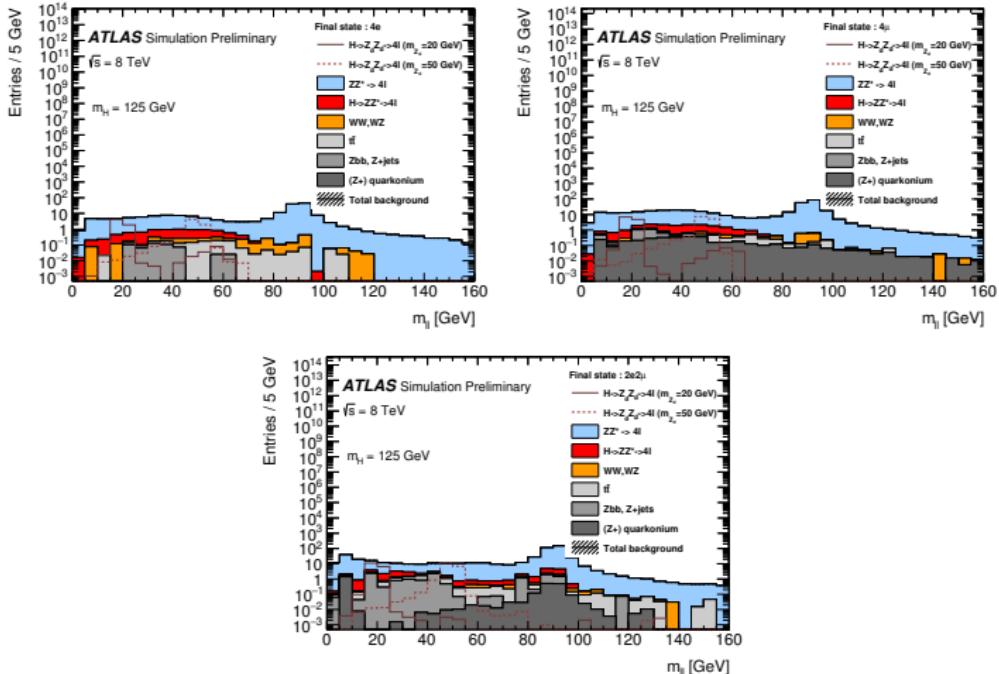
The four-lepton mass distribution for the combination of four lepton final states. This distribution is from the four-lepton mass range between 80 and 180 GeV.

Channel	$ZZ^*$	$t\bar{t} + Z + \text{jets}$	All backgrounds	Observed	$H \rightarrow 4\ell$
$4\mu$	$3.1 \pm 1.8$	$0.6 \pm 0.8$	$3.7 \pm 1.9$	12	$8.3 \pm 1.9$
$4e$	$1.3 \pm 1.1$	$0.8 \pm 0.9$	$2.1 \pm 1.4$	9	$6.9 \pm 1.4$
$2\mu 2e$	$1.4 \pm 1.2$	$1.2 \pm 1.1$	$2.6 \pm 1.6$	7	$4.4 \pm 1.6$
$2e 2\mu$	$2.1 \pm 1.5$	$0.6 \pm 0.8$	$2.7 \pm 1.7$	8	$5.3 \pm 1.7$
all	$7.8 \pm 2.8$	$3.2 \pm 1.8$	$11.1 \pm 3.3$	36	$24.9 \pm 3.3$

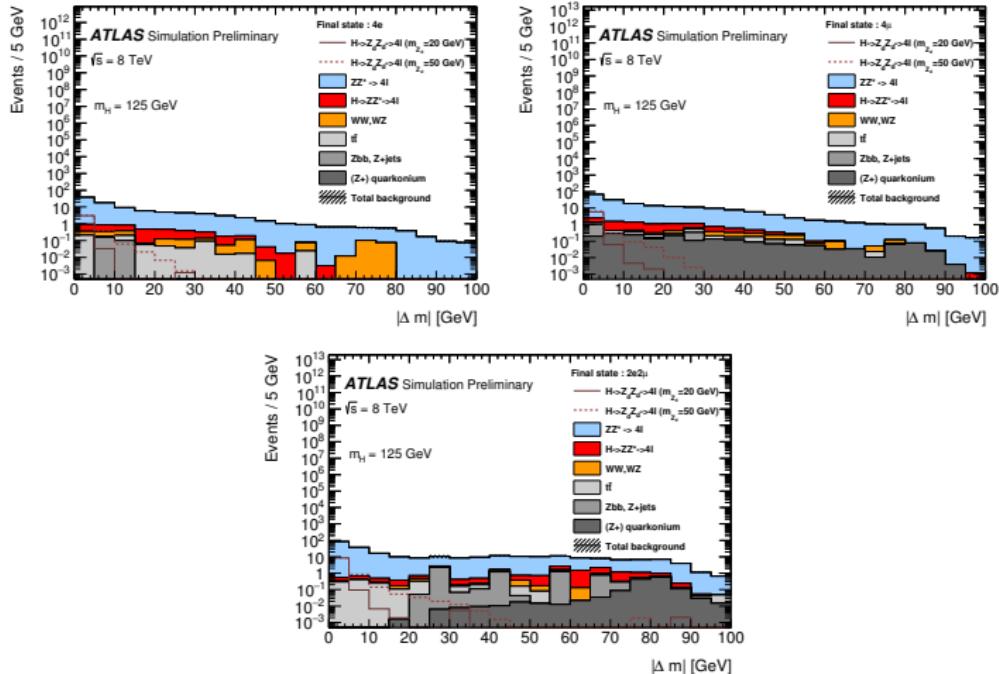
The estimated pre-fit event yields for the  $4\ell$  sample



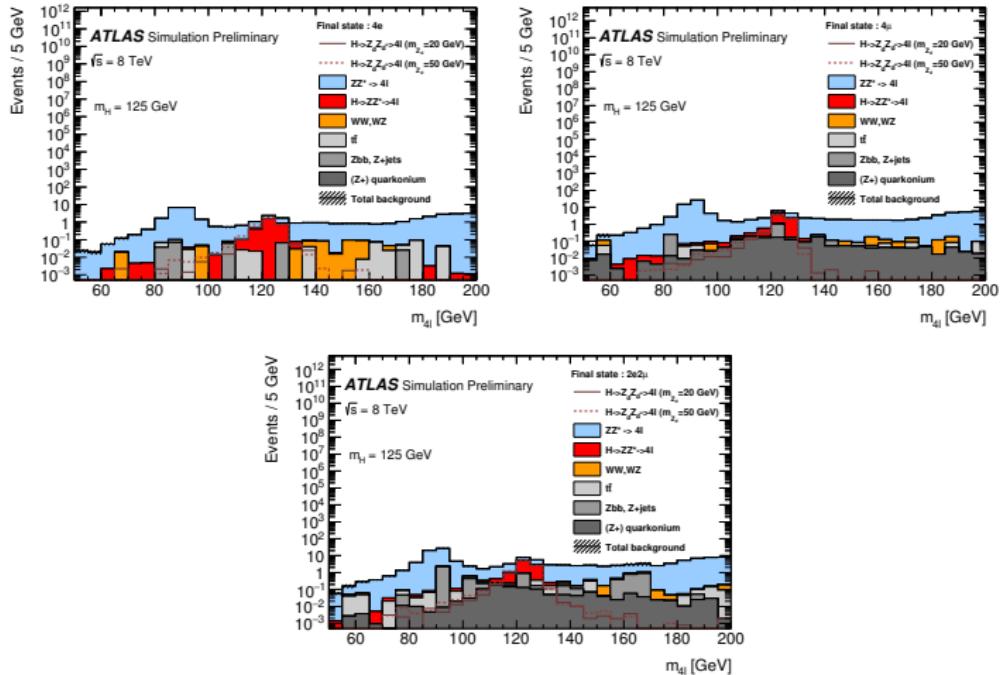
# Discriminant variables after event preselection: $m_{\ell\ell}$



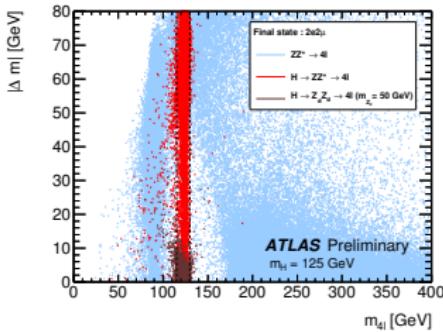
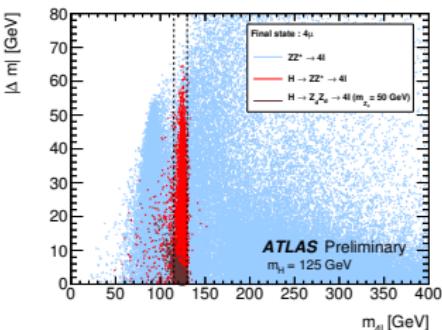
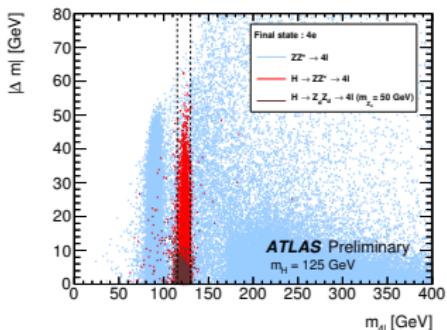
# Discriminant variables after event preselection: $\Delta m$



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

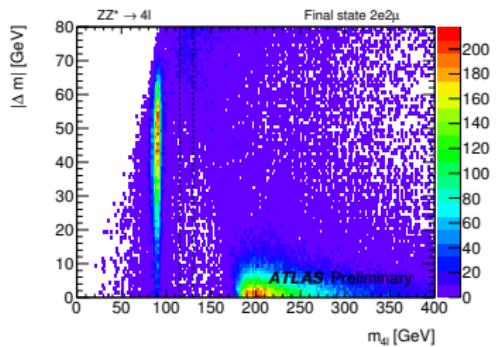
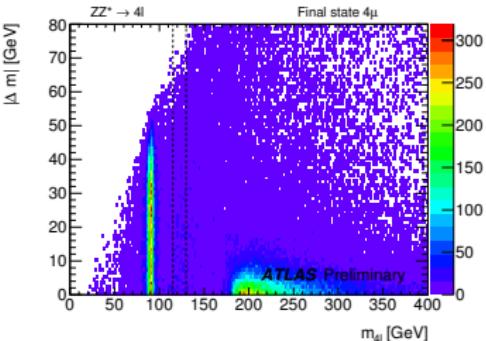
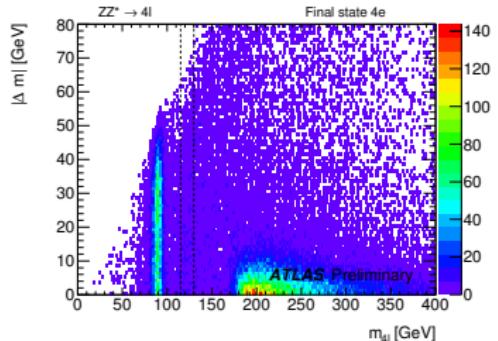


# Signal region

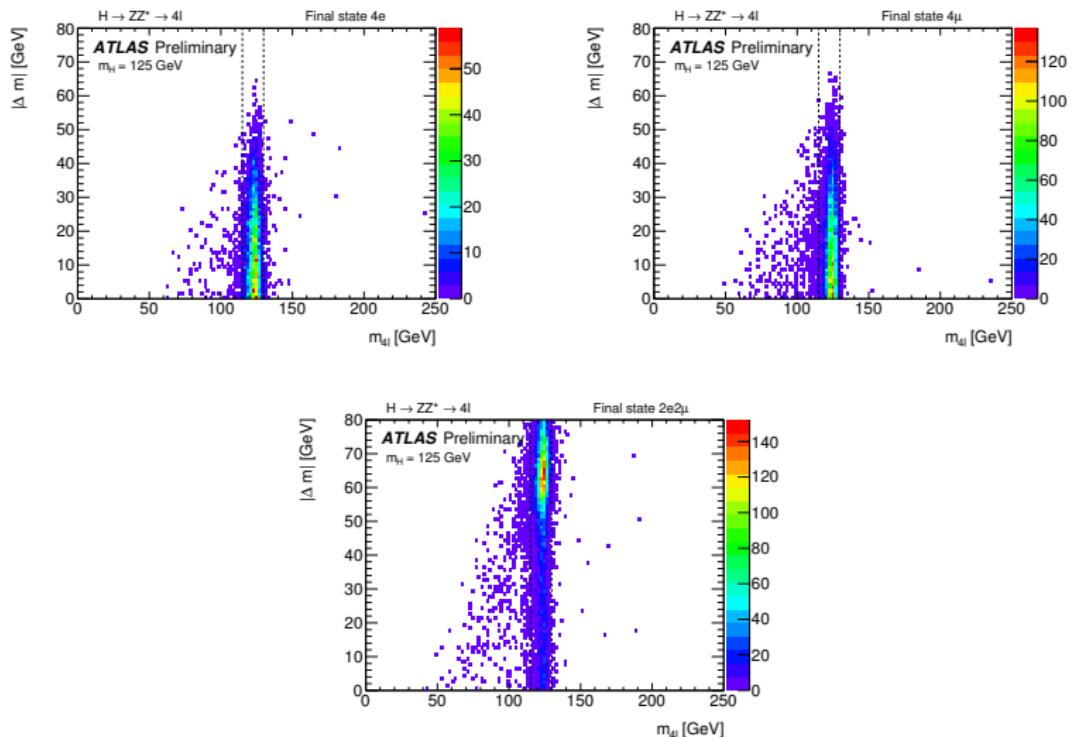


$ZZ \rightarrow 4\ell$ ,  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$  and  $H \rightarrow Z_d Z_d \rightarrow 4\ell$  ( $m_{Z_d} = 50 \text{ GeV}$ )

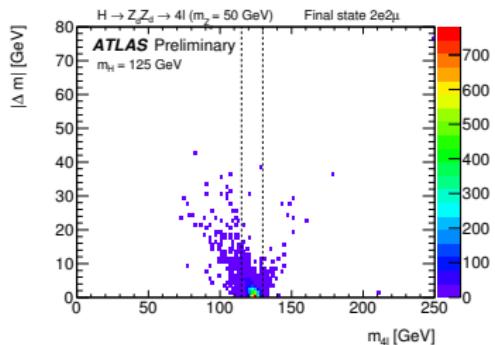
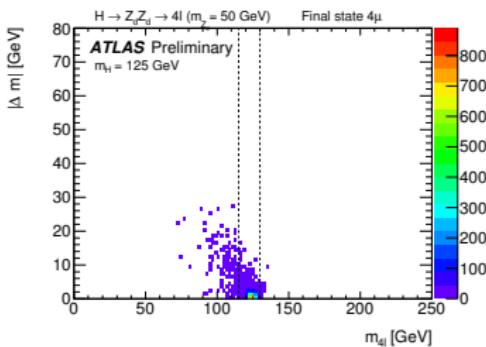
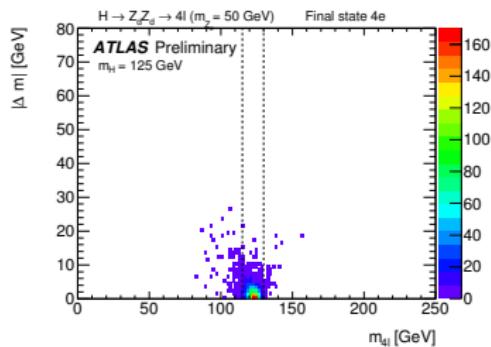
# Density of events for $ZZ^* \rightarrow 4\ell$



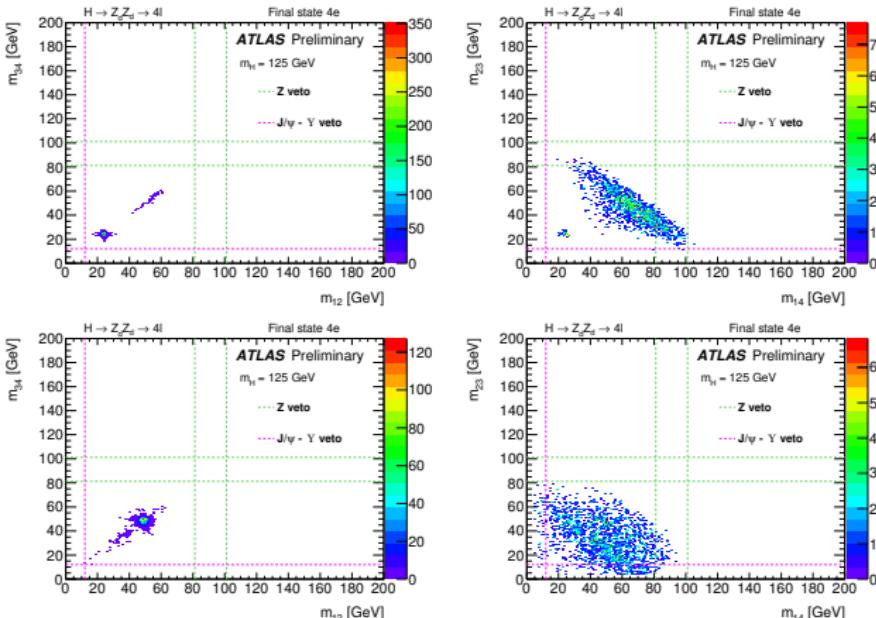
# Density of events for $H \rightarrow ZZ^* \rightarrow 4\ell$



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

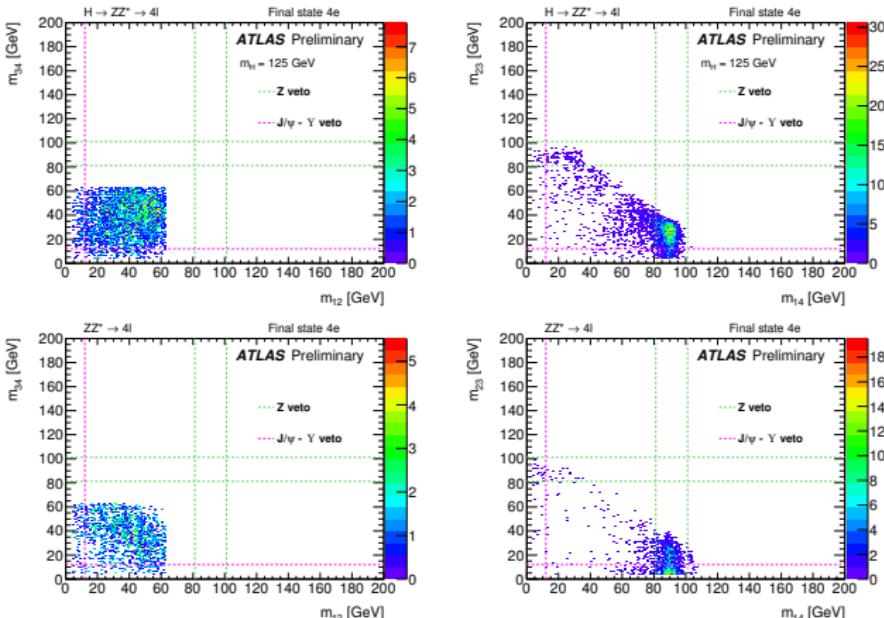


# Impact of the $Z$ and $J/\psi - \gamma$ vetoes: 4e



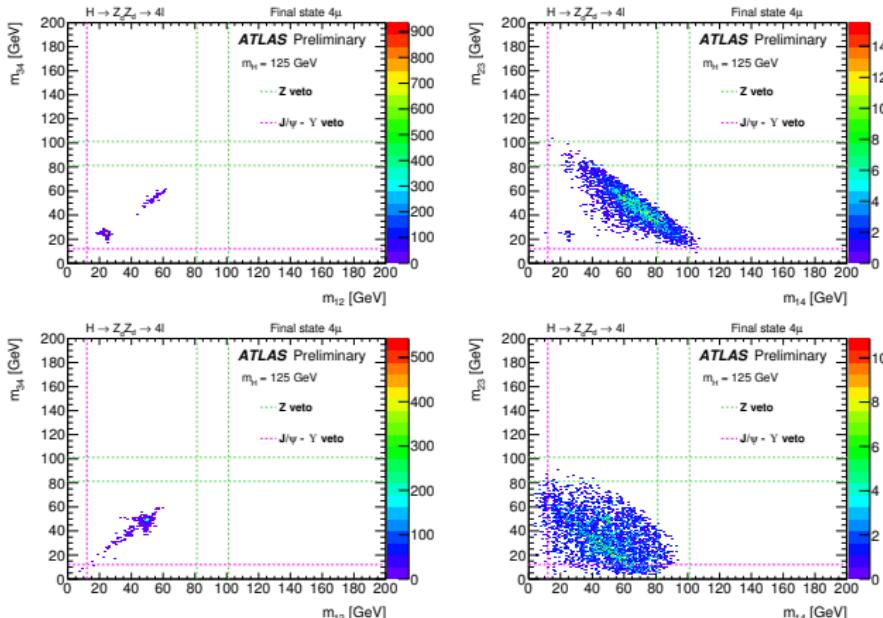
First pair invariant mass ( $m_{12}$ ) as a function of the second pair invariant mass ( $m_{34}$ ) (left) and first alternative pair invariant mass ( $m_{14}$ ) as a function of the second alternative pair invariant mass ( $m_{23}$ ) (right), for two signal samples (top :  $m_{Z_d} = 20$  GeV, bottom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

# Impact of the $Z$ and $J/\psi - \gamma$ vetoes: 4e



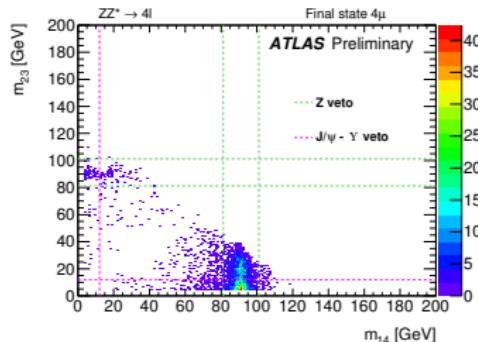
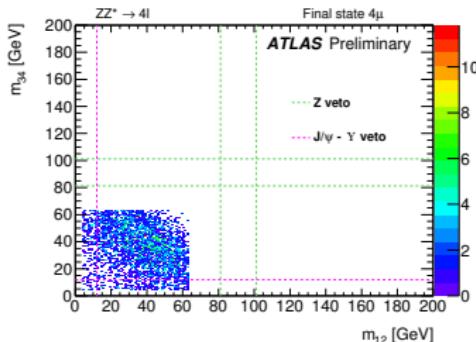
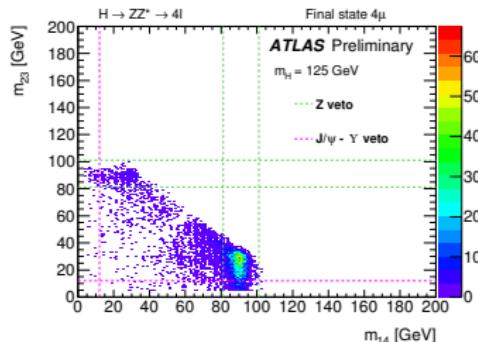
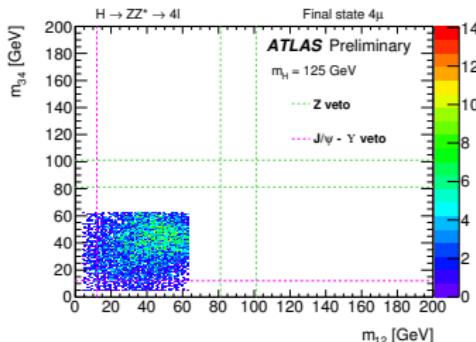
First pair invariant mass ( $m_{12}$ ) as a function of the second pair invariant mass ( $m_{34}$ ) (left) and first alternative pair invariant mass ( $m_{14}$ ) as a function of the second alternative pair invariant mass ( $m_{23}$ ) (right), for the two main background samples (top :  $H \rightarrow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

# Impact of the $Z$ and $J/\psi - \gamma$ vetoes: $4\mu$



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 $J/\psi - \gamma$ vetoes: $4\mu$

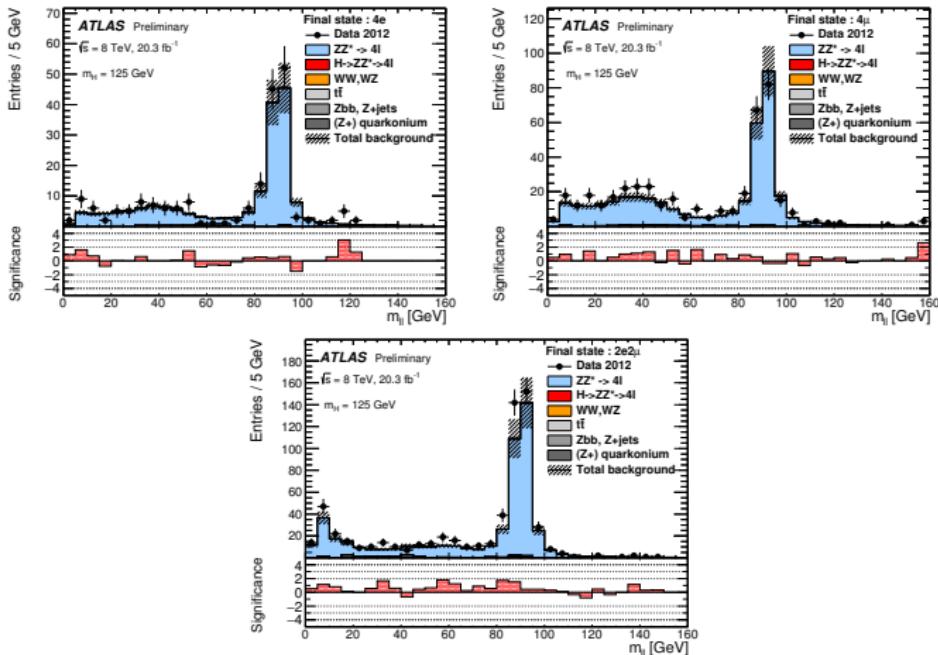


# Background validation: Control Region (CR)

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

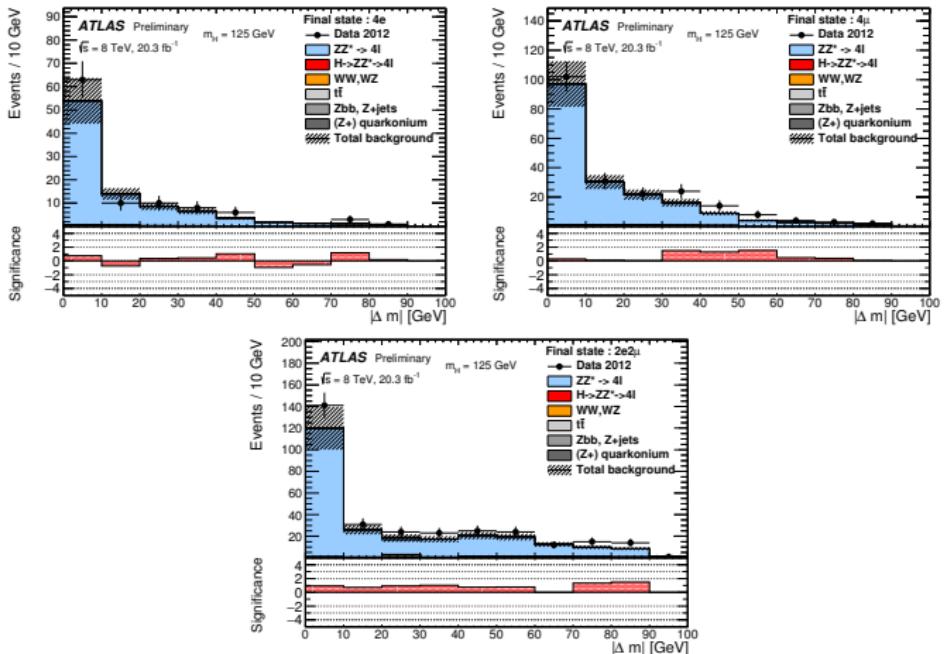
\*Reminder: SR is defined by  $m_{4\ell} \in (115, 130)$  GeV.

# CR: 1) $m_{2\ell}$



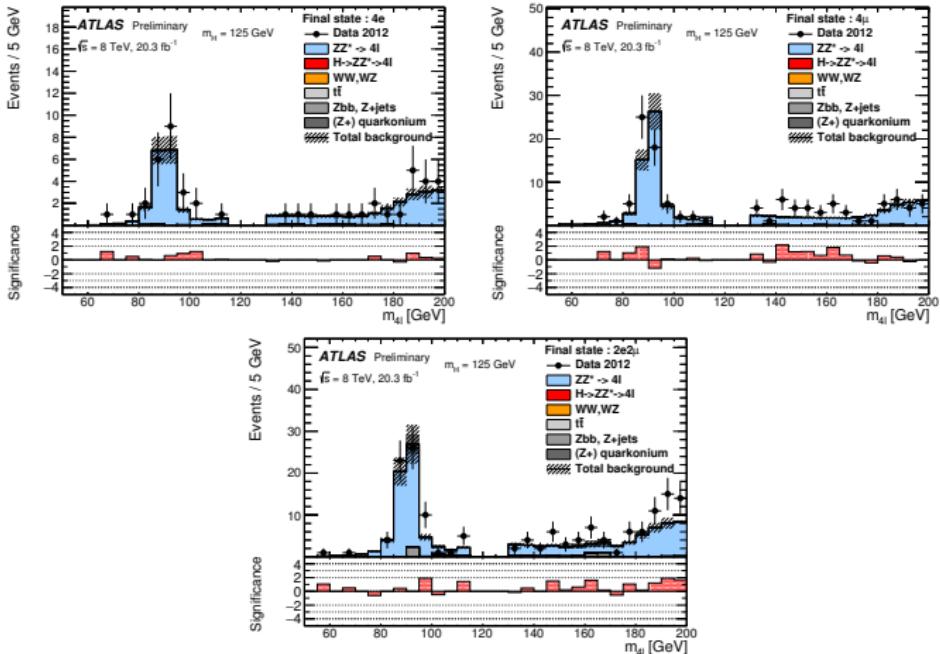
Overall agreement is good

## CR: 2) $\Delta m$



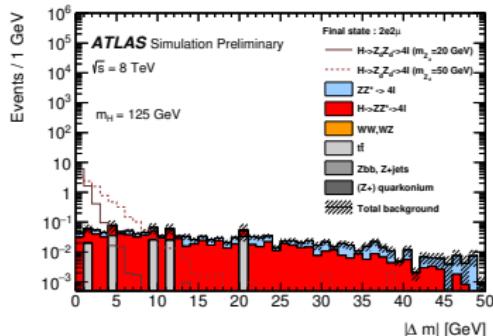
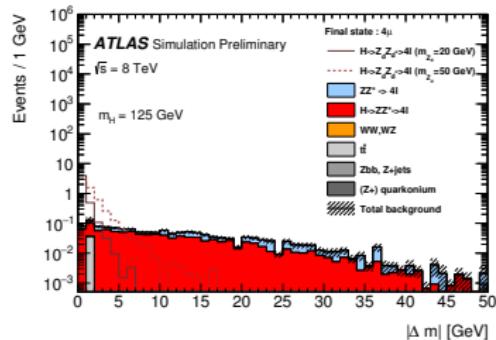
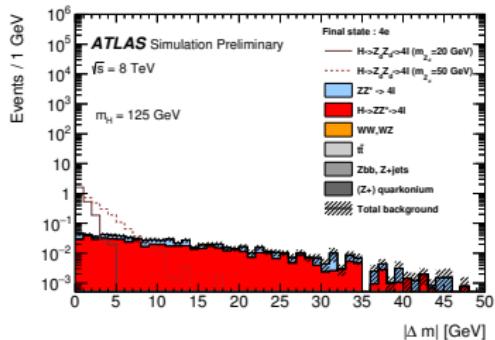
Overall agreement is good

# CR: 3) $m_{4\ell}$



Overall agreement is good

# Distribution of $\Delta m$ in the loose signal region



# Data/background comparison at the IP level

