Search for Higgs boson decays to BSM light bosons in four-lepton events with the ATLAS detector

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on behalf of the ATLAS Collaboration

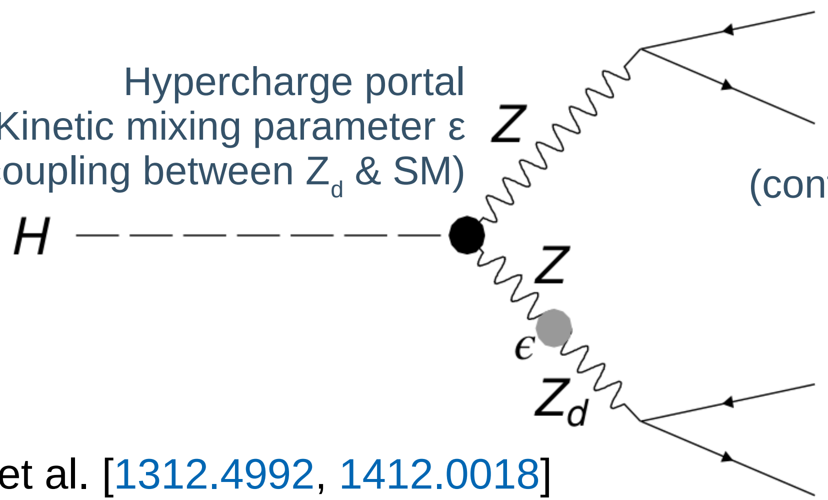
ATLAS EXPERIMENT

University of Victoria

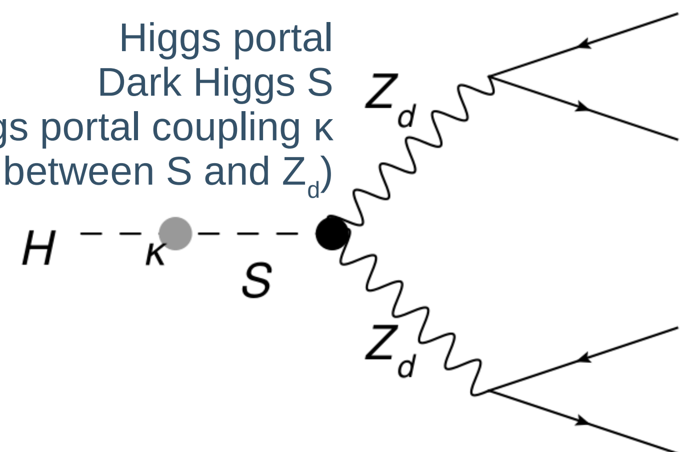
Motivation

- Current measurements allow Higgs to BSM branching ratio to be as large as $\mathcal{O}(30-50\%)$ [1, 2]
- 125 GeV Higgs has a narrow width: $\Gamma_h/m_h \sim \mathcal{O}(10^{-5})$ vs. $\Gamma_Z/m_Z \sim \mathcal{O}(10^{-2})$
  - $\mathrm{Br}(H \to X_{BSM}X_{BSM}) \propto (\Gamma_{BSM})/(\Gamma_{BSM}+\Gamma_{SM})$
  - ➔ Small BSM coupling could open up sizeable decay modes
- New particles could couple to the Higgs and provide a portal to a hidden dark sector or extended Higgs sector
- Addition of U(1) dark gauge symmetry to the SM introduces a new dark vector boson Z_d

Hypercharge portal
Kinetic mixing parameter ε
(controls coupling between Z_d & SM)



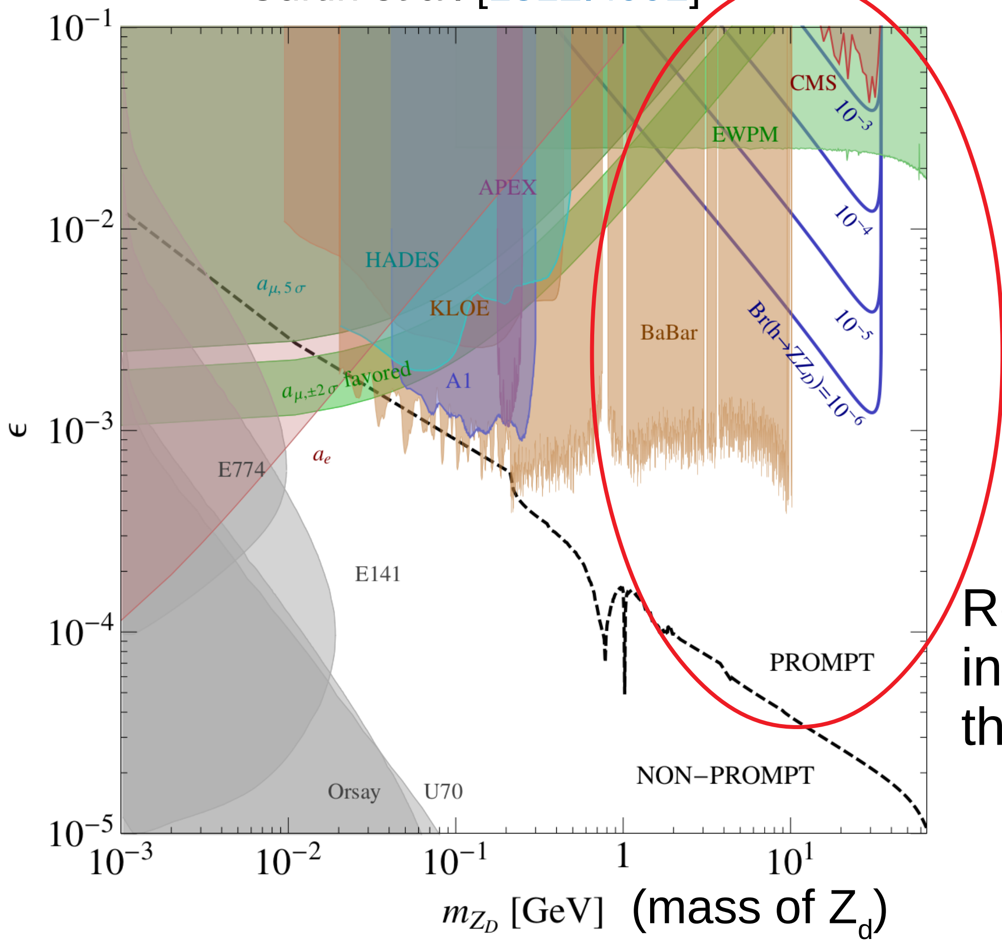
Higgs portal
Dark Higgs S
Higgs portal coupling κ
(controls coupling between S and Z_d)



Curtin et al. [1312.4992, 1412.0018]

Motivation

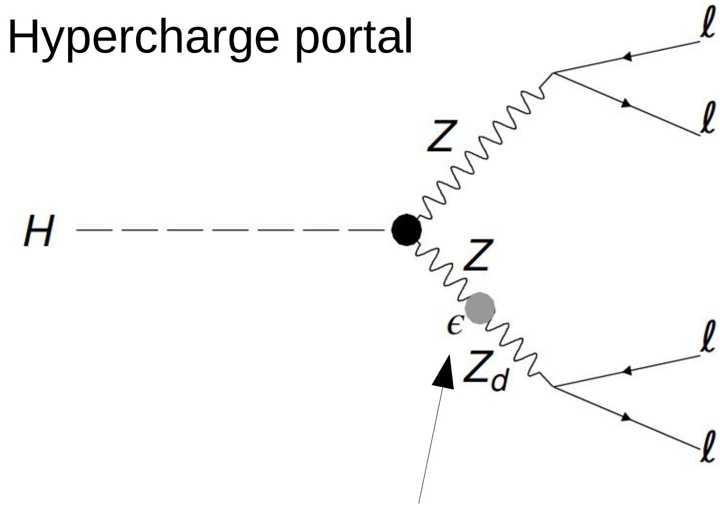
Curtin et al. [1312.4992]



(mass of Z_d)

Region of interest for this search

Hypercharge portal



Kinetic mixing ϵ controls coupling strength between Z_d and SM particles

Objective: Search for 125 GeV Higgs decays to four leptons (*e*, *μ*) via one or two intermediate U(1) dark sector particles Z_d

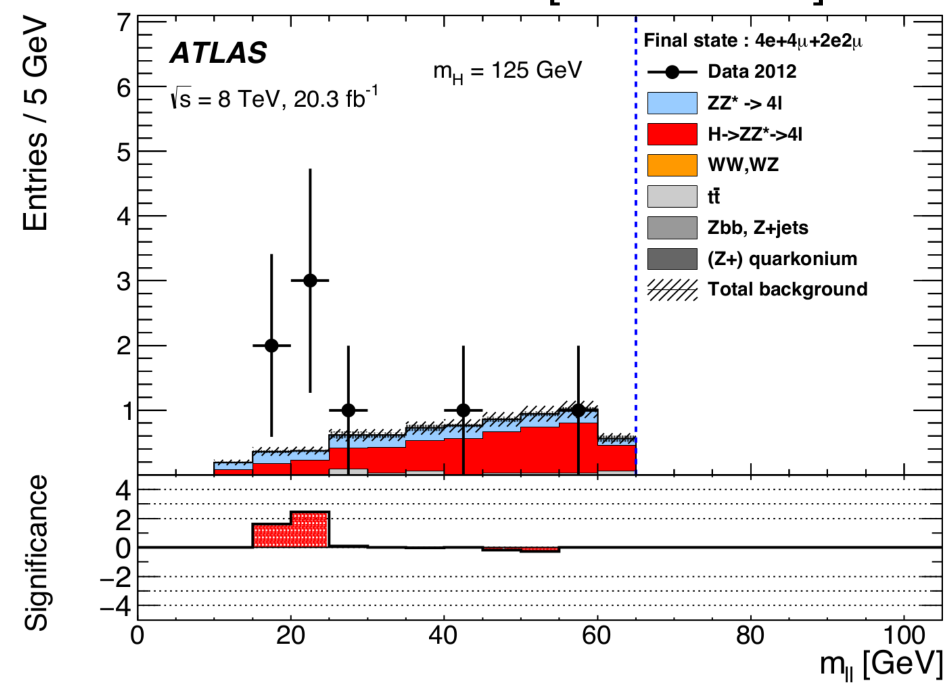
8 TeV 20.3 fb^{-1} analysis

- Two channels: $\ell = e, \mu$

$$H \to Z_d Z_d \to 4\ell \ (15\ \mathrm{GeV} < m_{Z_d} < 60\ \mathrm{GeV})$$
$$H \to Z Z_d \to 4\ell \ (15\ \mathrm{GeV} < m_{Z_d} < 55\ \mathrm{GeV})$$

- $H \to Z_d Z_d \to 4\ell$:
  - Look for four prompt leptons that form two same-flavour (*e*, *μ*) opposite-charge pairs
  - with $m_{4\ell}$ compatible with 125 GeV Higgs
  - with $m_{2\ell}$ of both pairs incompatible with Z
- $H \to Z Z_d \to 4\ell$:
  - with one pair compatible with Z (labelled m_{12})

ATLAS 8 TeV [1505.07645]

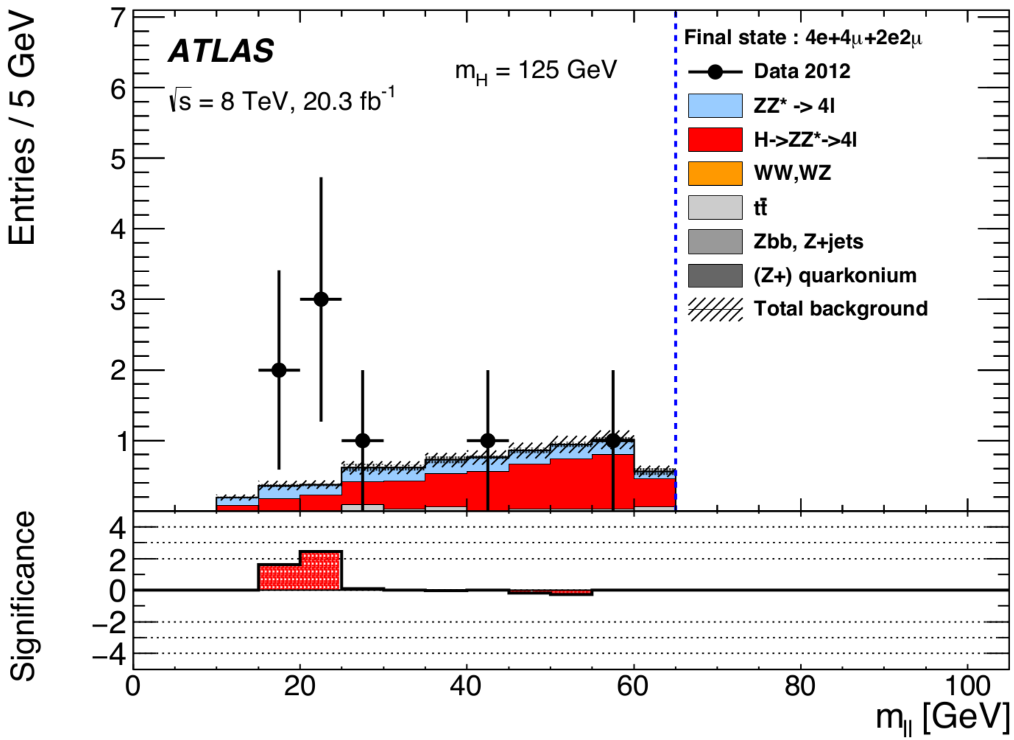


$H \to Z_d Z_d \to 4\ell$ $m_{\ell\ell}$ distribution

(two entries per event corresponding to two lepton pairs in final state)

8 TeV 20.3 fb^{-1} analysis: $Z_d Z_d$ channel

ATLAS 8 TeV [1505.07645]



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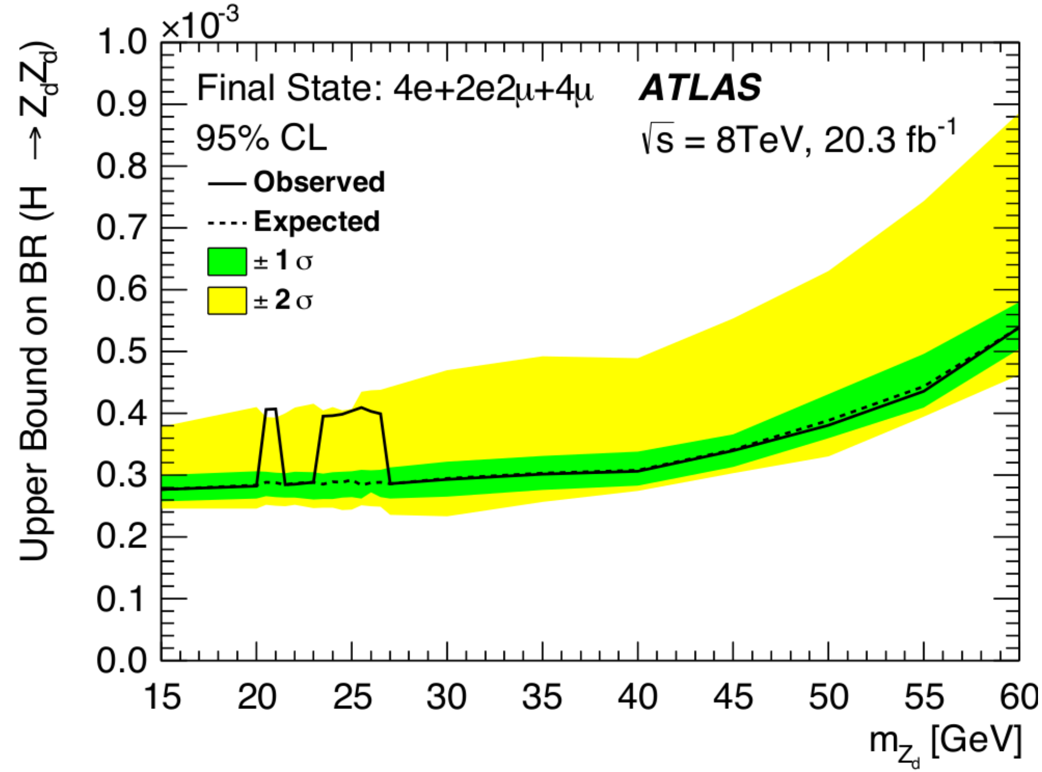
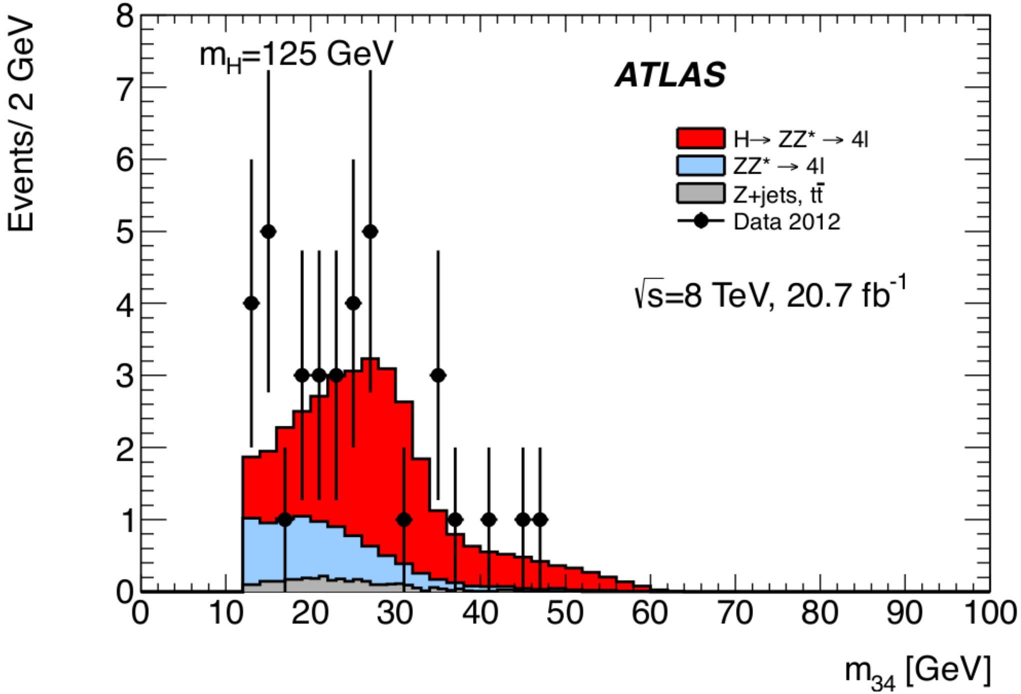
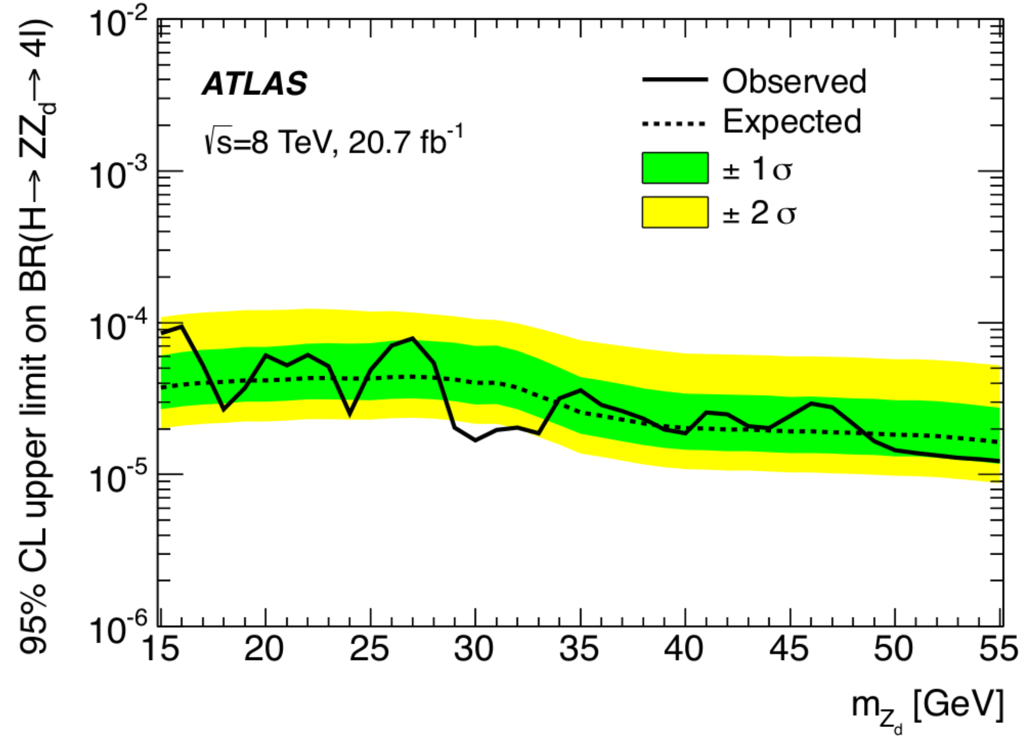


$H \to Z_d Z_d$ branching ratio limit

8 TeV 20.3 fb^{-1} analysis: ZZ_d channel

ATLAS 8 TeV [1505.07645]





$H \to ZZ_d \to 4\ell$ m_{34} distribution

(lepton pair second-closest in mass to m_Z*)*

$H \to ZZ_d \to 4\ell$ branching ratio limit

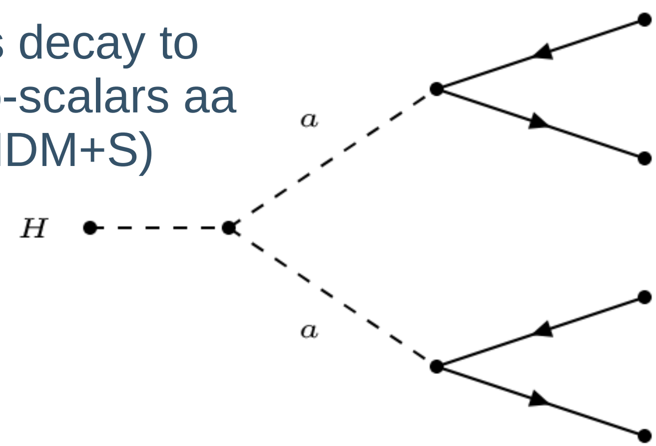
13 TeV 36.1 fb^{-1} analysis

- Expands on 8 TeV analysis with the addition of a low-mass channel and pseudo-scalar benchmark model:

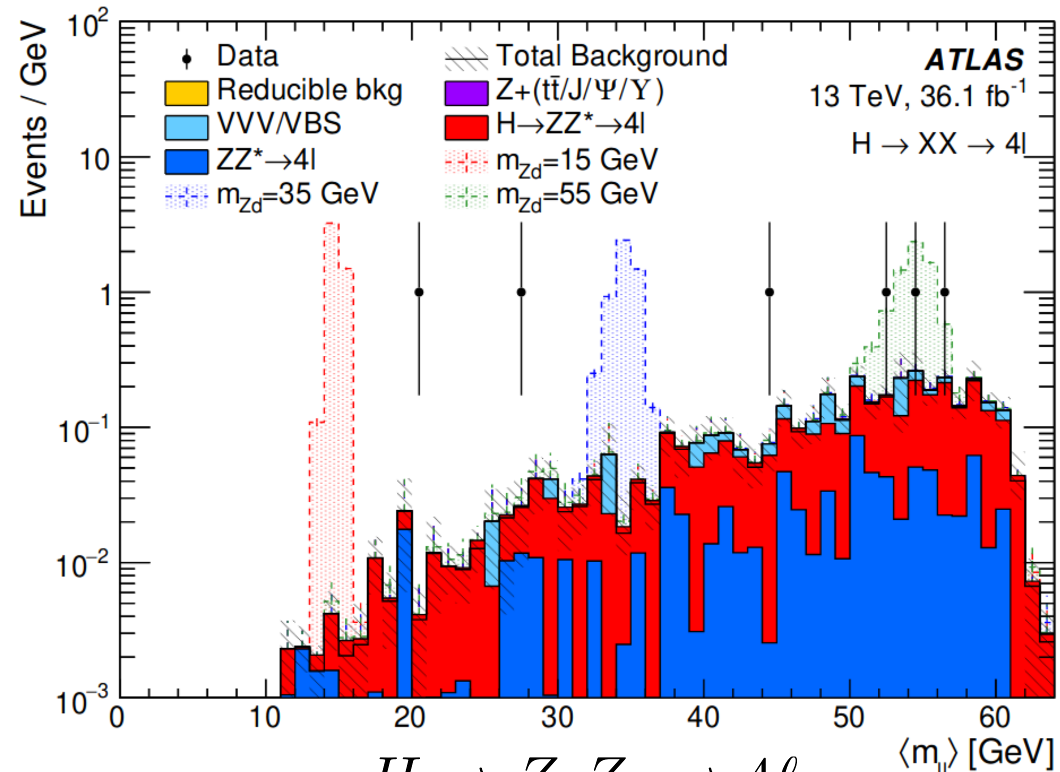
$$H \to XX \to 4\ell \ (15 \text{ GeV} < m_X < 60 \text{ GeV})$$
$$H \to ZX \to 4\ell \ (15 \text{ GeV} < m_X < 55 \text{ GeV})$$
$$H \to XX \to 4\mu \ (1 \text{ GeV} < m_X < 15 \text{ GeV})$$

$$\ell = e, \mu \qquad X = Z_d, a$$

Higgs decay to pseudo-scalars aa (2HDM+S)



[ATLAS 13 TeV 1802.0338]



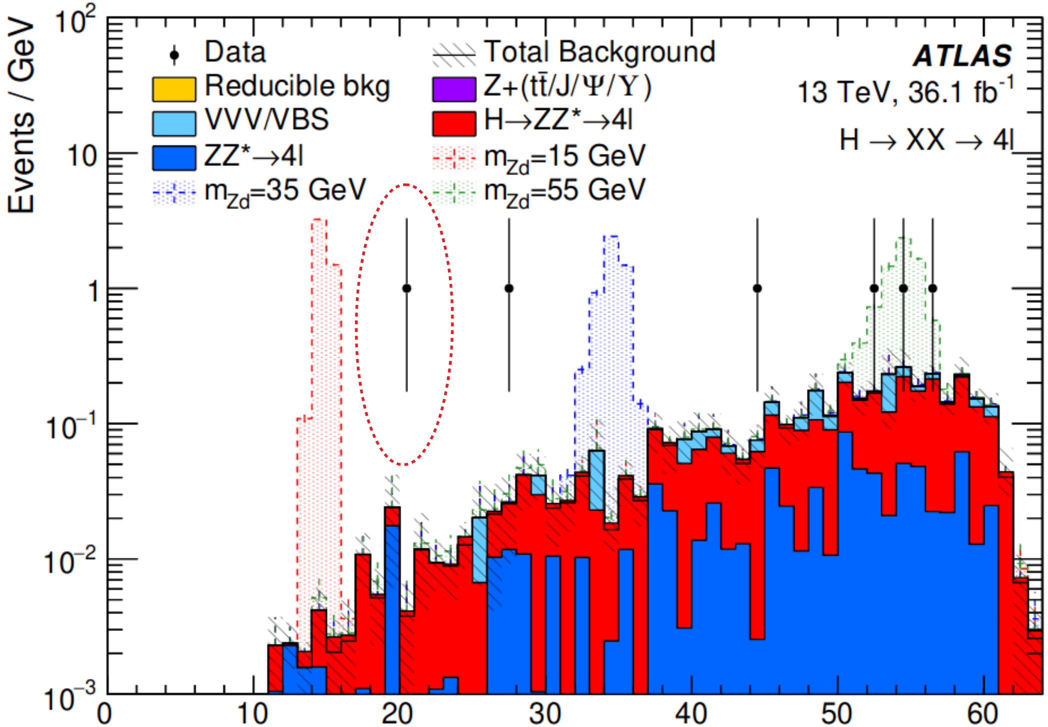
$$H \to Z_d Z_d \to 4\ell$$

Distribution of average dilepton mass

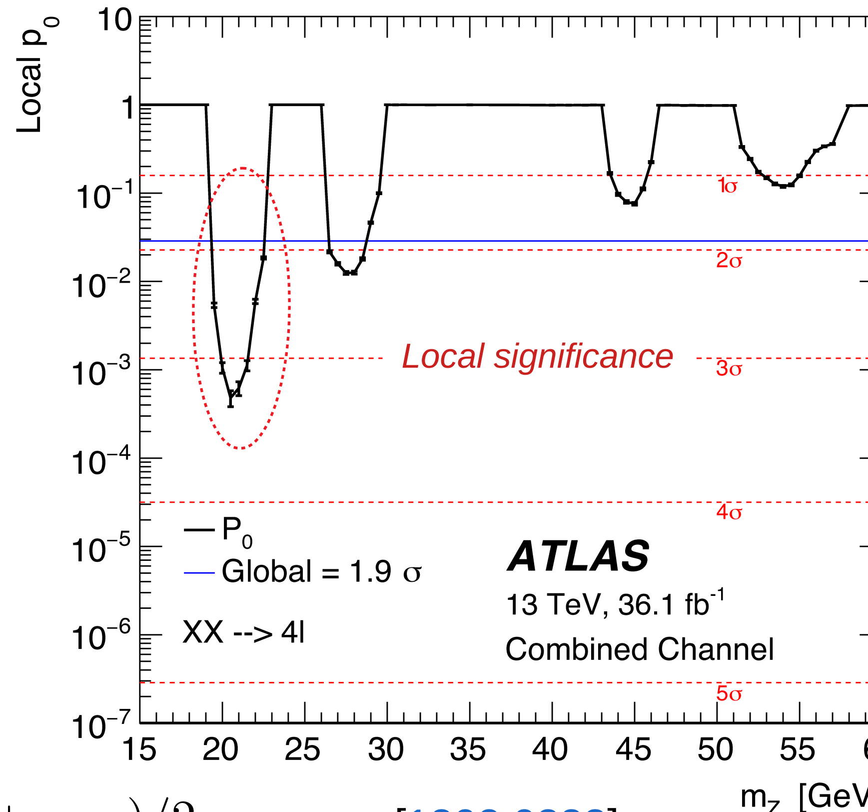
$$\langle m_{\ell\ell} \rangle = (m_{12} + m_{34})/2$$

13 TeV 36.1 fb^{-1} analysis

- Highly constrained signal region dominated by Higgs and ZZ background
- Simulation-driven background estimates
- Event at $\langle m_{\ell\ell}\rangle \approx 20\ \mathrm{GeV}$ corresponds to a local (global) significance of $3.2\ (1.9)\ \sigma$



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



Distribution of average dilepton mass $\langle m_{\ell\ell}\rangle = (m_{12} + m_{34})/2$

[1802.0338]

13 TeV 36.1 fb^{-1} branching ratio limits

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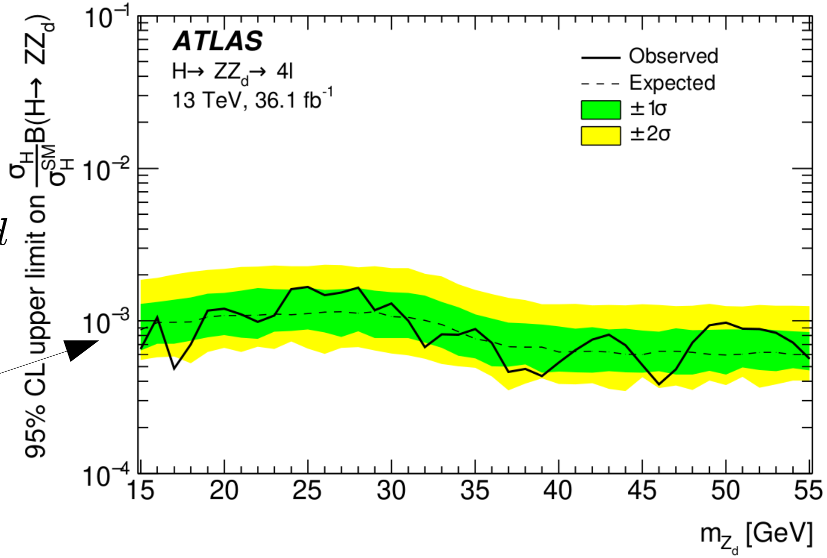
$H \to ZZ_d$

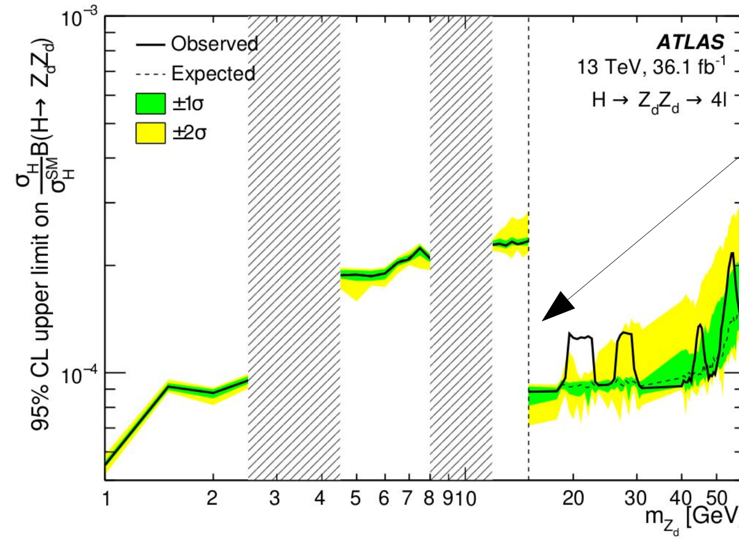
$\mathcal{O}(10^{-3})$



Addition of 4e and 2e2mu states

$H \to Z_d Z_d$

$\mathcal{O}(10^{-4})$



Branching ratio limits for

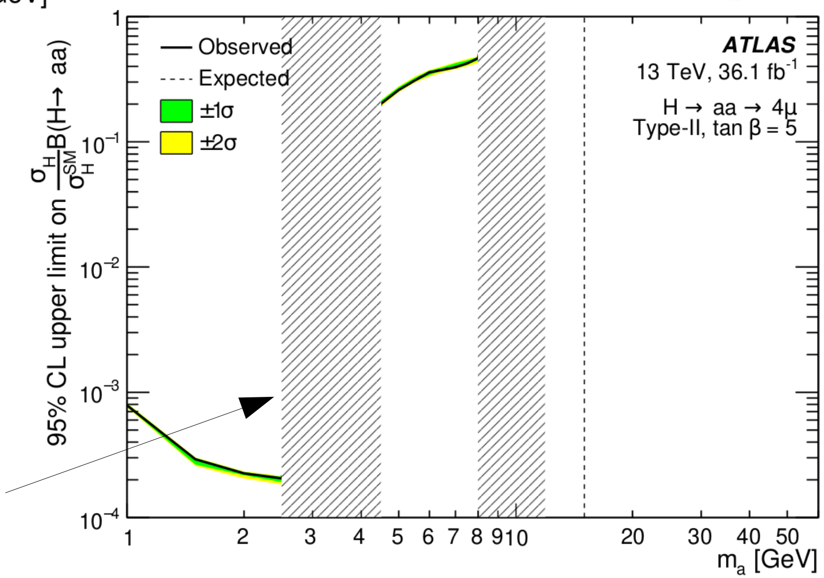
$H \to ZZ_d$ $\quad H \to Z_d Z_d$

$H \to aa$

$\mathcal{O}(10^{-1})$

$H \to aa$

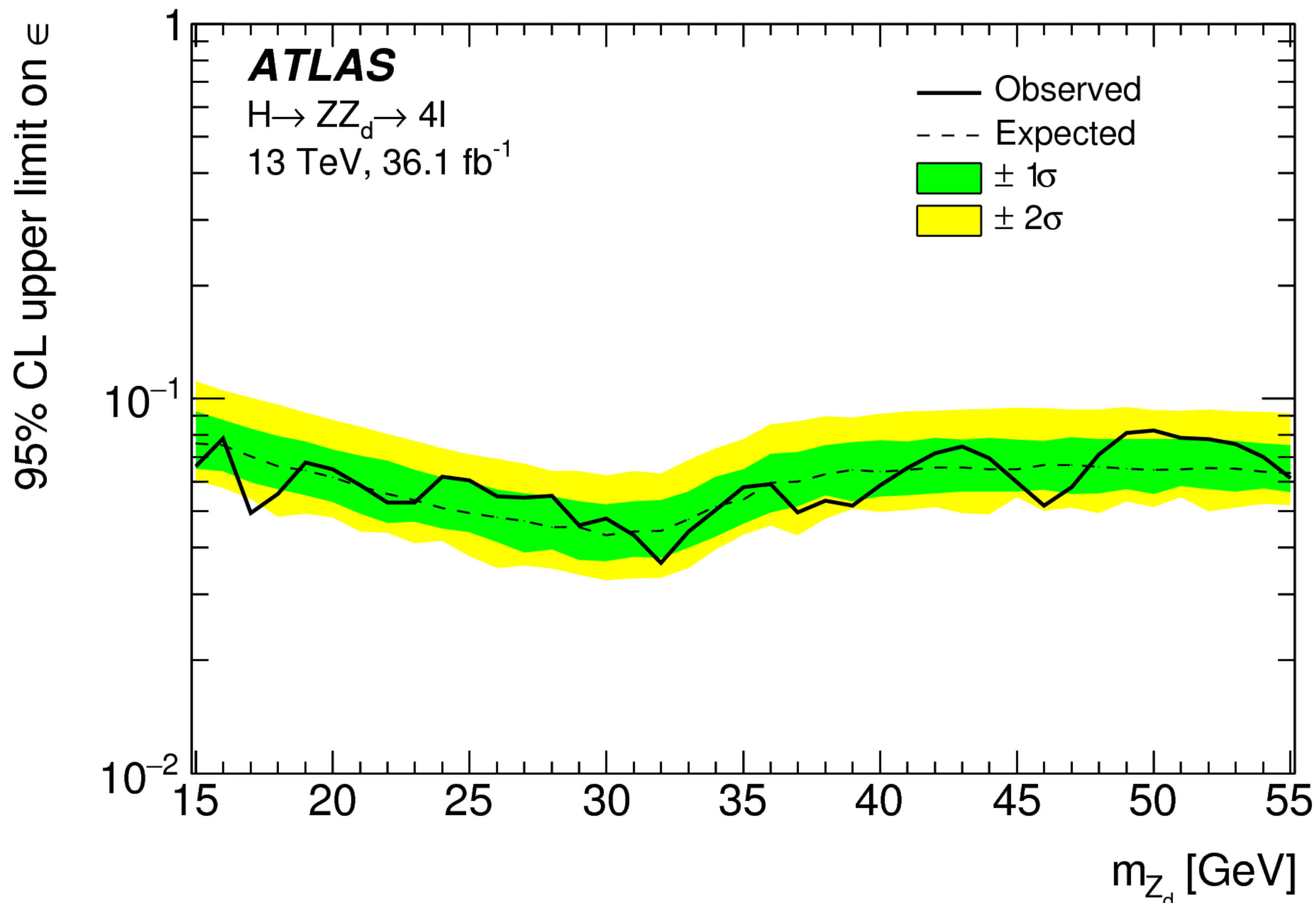
$\mathcal{O}(10^{-3})$



quarkonia veto regions

[1802.0338]

13 TeV 36.1 fb^{-1} limit on kinetic mixing ϵ



Limit on kinetic mixing parameter ϵ

[1802.0338] *set using* $\mathrm{Br}(H \to ZZ_d \to 4\ell)$ *(slide 9) and* $\mathrm{Br}(Z_d \to \ell\ell)$ *from theory [1312.0018]*

Conclusions and current efforts

- Search for 125 GeV Higgs decays to BSM light bosons in four-lepton final states
  - Three channels:

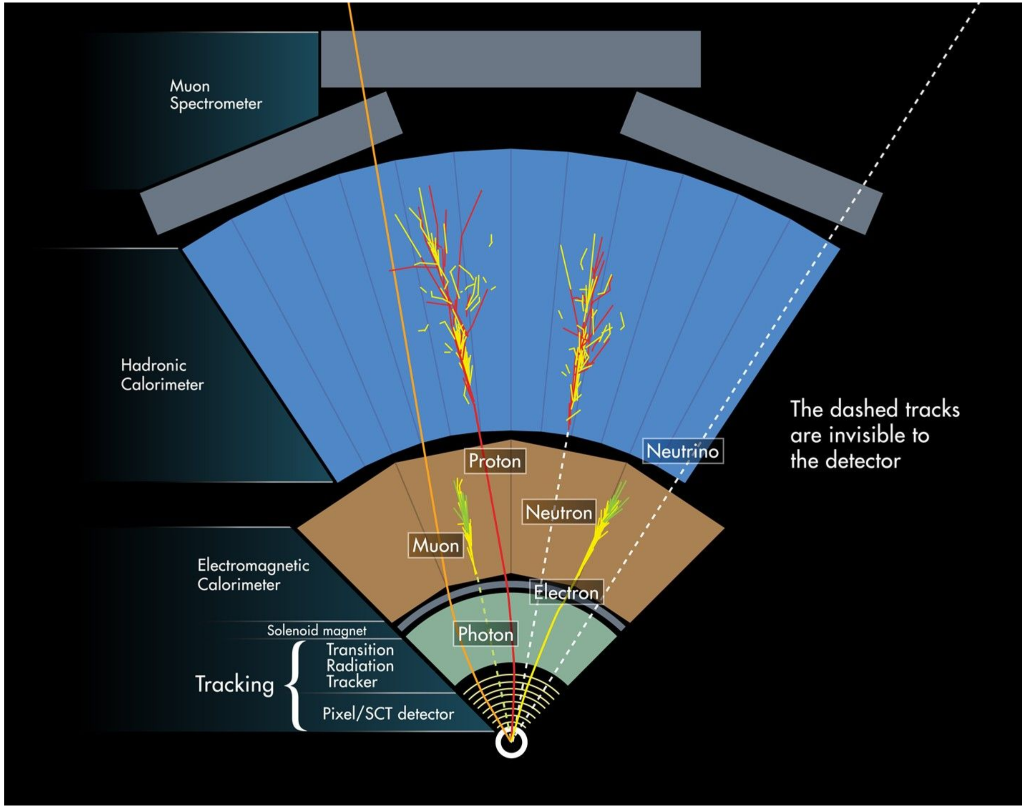
$$H \to XX \to 4\ell \ (15 \text{ GeV} < m_X < 60 \text{ GeV})$$
$$H \to ZX \to 4\ell \ (15 \text{ GeV} < m_X < 55 \text{ GeV})$$
$$H \to XX \to 4\mu \ (1 \text{ GeV} < m_X < 15 \text{ GeV})$$

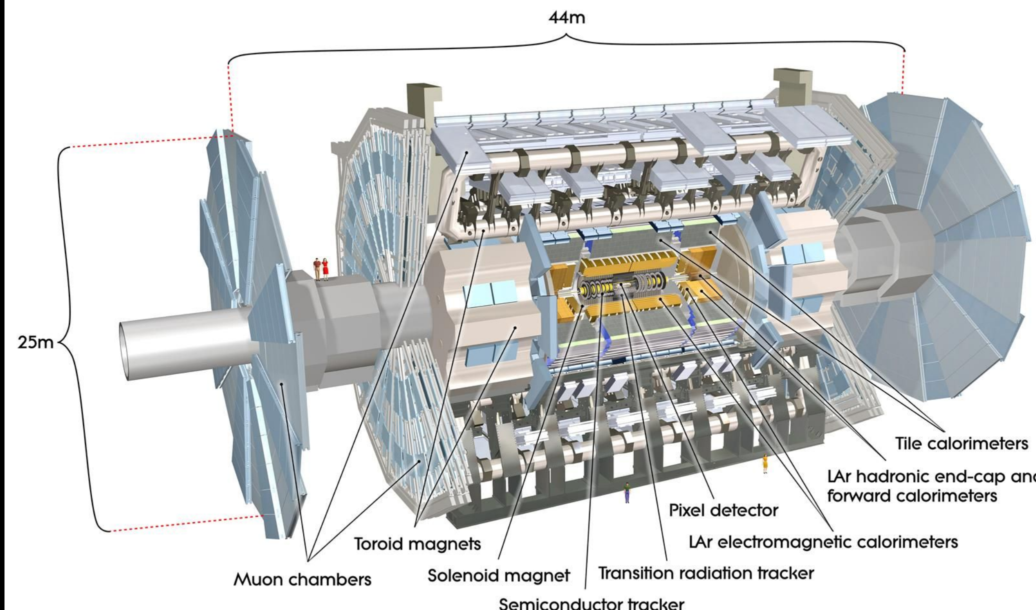
$$\ell = e, \mu$$
$$X = Z_d, a$$

  - No statistically significant excesses in 8 TeV (20.1 fb^{-1}) and 2015-6 13 TeV (36.1 fb^{-1}) results
- Working towards a result encompassing the full 2015-8 dataset (~140 fb^{-1})
- Two new channels:
  - Four tau leptons in final state: $H \to aa \to 4\tau$
  - Scalar progenitor (S < 115 GeV and S > 130 GeV): $S \to Z_d Z_d \to 4\ell$
- Data-driven fake background estimate
- Search for Z_d of different mass: $H \to Z_{d1} Z_{d2} \to 4\ell$
- Possibility of broader Z_d width under consideration

Backup

ATLAS detector





[ATLAS] [ATLAS]

Look for a light resonance in a channel similar to the “golden” channel of the Higgs ($H \to ZZ^* \to 4\ell$)

High-mass analysis selection

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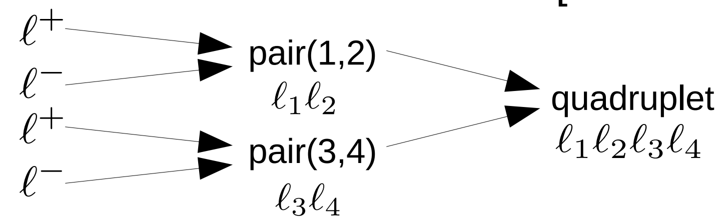
Lepton quadruplet formation and selection

[1802.0338]



- Each lepton must be responsible for firing at least one trigger
- In each event, form quadruplets consisting of two same-flavour opposite sign lepton pairs: “1, 2” & “3, 4”
- Three leading-pT leptons must have pT > 20, 15, and 10 GeV
- ΔR(l, l') > 0.10 (0.20) for all pairings of same-flavour (different-flavour) leptons; $\Delta R \equiv \sqrt{\Delta(\eta)^2 + \Delta(\phi)^2}$

Quadruplet ranking

- Select quadruplet with smallest difference in mass between lepton pairs: $\Delta m_{\ell\ell} \equiv |m_{12} - m_{34}|$

Event selection

- Higgs window: $115 \text{ GeV} < m_{4\ell} < 130 \text{ GeV}$
- Compatibility of lepton pair masses: $m_{34}/m_{12} > 0.85$
- Z veto on lepton pairs: $10 \text{ GeV} < m_{12,34} < 64 \text{ GeV}$
- Additional Z veto on alternative pairings (only for 4e and 4μ quadruplets): $5 \text{ GeV} < m_{14,32} < 75 \text{ GeV}$
- Quarkonia veto: reject event if

$$(m_{J/\Psi} - 0.25 \text{ GeV}) < m_{12,34,14,32} < (m_{\Psi(2S)} + 0.30 \text{ GeV}) \;||\; (m_{\Upsilon(1S)} - 0.70 \text{ GeV}) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75 \text{ GeV})$$

Comparison of high-mass, low-mass, and ZX selections

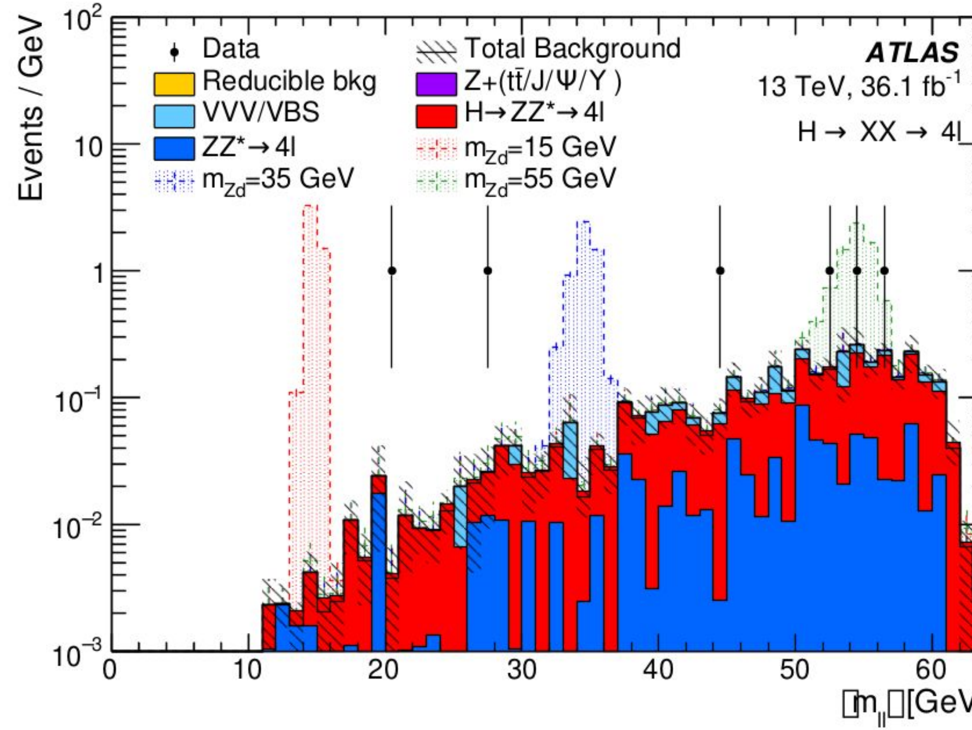
[1802.0338]

<table>
<tr><th></th><th>$H \to ZX \to 4\ell$
(15 GeV $< m_X <$ 55 GeV)</th><th>$H \to XX \to 4\ell$
(15 GeV $< m_X <$ 60 GeV)</th><th>$H \to XX \to 4\mu$
(1 GeV $< m_X <$ 15 GeV)</th></tr>
<tr><td>QUADRUPLET SELECTION</td><td colspan="3">- Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-sign leptons
- Three leading-p_T leptons satisfying $p_T >$ 20 GeV, 15 GeV, 10 GeV
- At least three muons are required to be reconstructed by combining ID and MS tracks in the 4μ channel</td></tr>
<tr><td></td><td>- Select best quadruplet (per channel) to be the one with the (sub)leading dilepton mass (second) closest to the Z mass
- 50 GeV $< m_{12} <$ 106 GeV
- 12 GeV $< m_{34} <$ 115 GeV
- $m_{12,34,14,32} >$ 5 GeV</td><td colspan="2">Leptons in the quadruplet are responsible for firing at least one trigger. In the case of multi-lepton triggers, all leptons of the trigger must match to leptons in the quadruplet</td></tr>
<tr><td></td><td colspan="2">$\Delta R(\ell, \ell') > 0.10$ (0.20) for same-flavour (different-flavour) leptons in the quadruplet</td><td>-</td></tr>
<tr><td>QUADRUPLET RANKING</td><td>Select first surviving quadruplet from channels, in the order: 4μ, $2e2\mu$, $2\mu 2e$, $4e$</td><td colspan="2">Select quadruplet with smallest $\Delta m_{\ell\ell} = \lvert m_{12} - m_{34} \rvert$</td></tr>
<tr><td>EVENT SELECTION</td><td colspan="2">115 GeV $< m_{4\ell} <$ 130 GeV</td><td>120 GeV $< m_{4\ell} <$ 130 GeV</td></tr>
<tr><td></td><td></td><td colspan="2">$m_{34}/m_{12} > 0.85$
Reject event if:
$(m_{J/\Psi} - 0.25\ \text{GeV}) < m_{12,34,14,32} < (m_{\Psi(2S)} + 0.30\ \text{GeV})$, or
$(m_{\Upsilon(1S)} - 0.70\ \text{GeV}) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\ \text{GeV})$</td></tr>
<tr><td></td><td></td><td>10 GeV $< m_{12,34} <$ 64 GeV
$4e$ and 4μ channels:
5 GeV $< m_{14,32} <$ 75 GeV</td><td>0.88 GeV $< m_{12,34} <$ 20 GeV
No restriction on alternative pairing</td></tr>
</table>

Background predictions in high-mass analysis

- All background predictions from simulation
- Dominant backgrounds are $H \to ZZ^*$ and non-resonant ZZ^*:
  - $H \to ZZ^* \to 4\ell$: 63%
  - $ZZ^* \to 4\ell$: 19%
  - Triboson production (VVV): 17%
  - $Z + t\bar{t}$, J/Ψ, or $\Upsilon \to 4\ell$: ~1%
  - Reducible backgrounds (Z + jets, $t\bar{t}$): ~1%

Process	Yield
$ZZ^* \to 4\ell$	0.8 ± 0.1
$H \to ZZ^* \to 4\ell$	2.6 ± 0.3
VVV/VBS	0.51 ± 0.18
$Z + (t\bar{t}/J/\Psi) \to 4\ell$	0.004 ± 0.004
Reducible Background	Negligible
Total	3.9 ± 0.3
Data	6

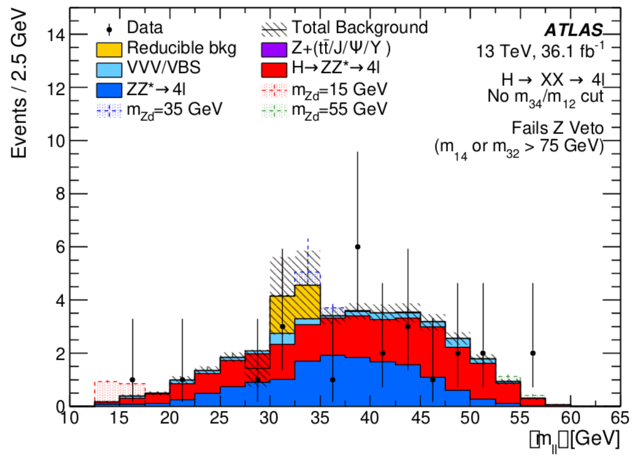


(a) Signal region $\langle m_{\ell\ell} \rangle$ distribution

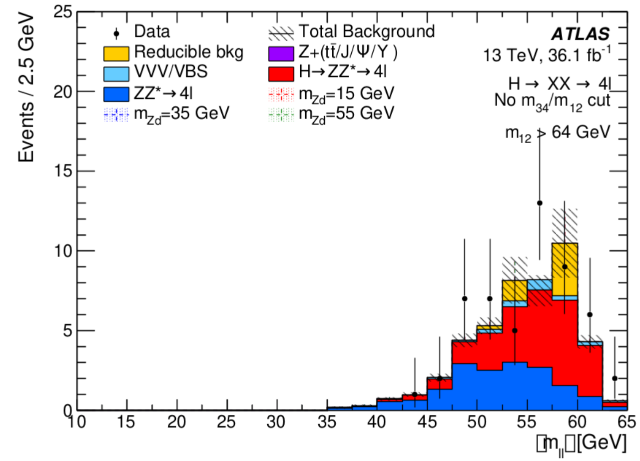
[1802.0338]

Plots from 2015-6 ATLAS result

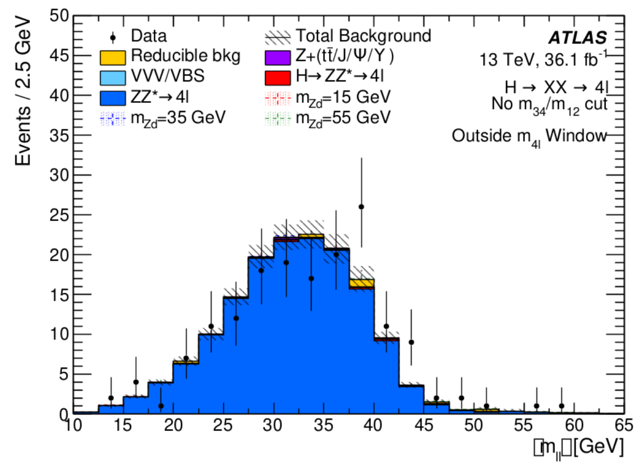
[1802.0338]



(a) VR1



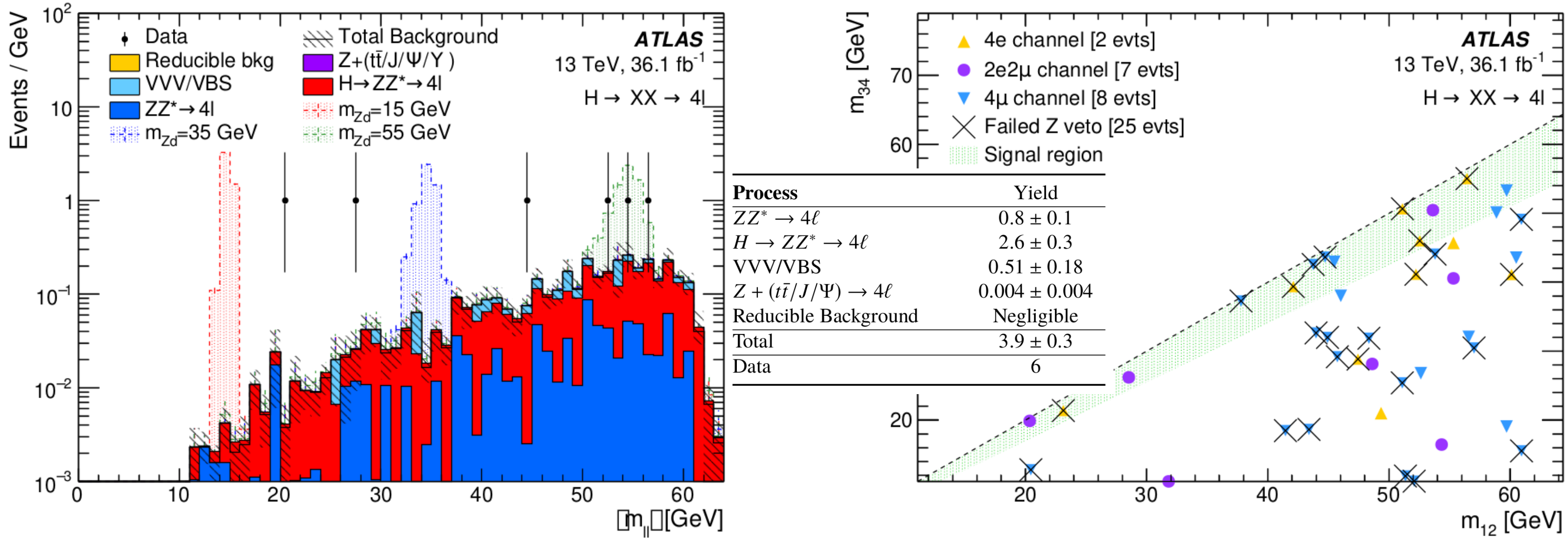
(b) VR2



(c) VR3

Plots from 2015-6 ATLAS result

[1802.0338]



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$H \to ZZ^* \to 4\ell$	2.6 ± 0.3
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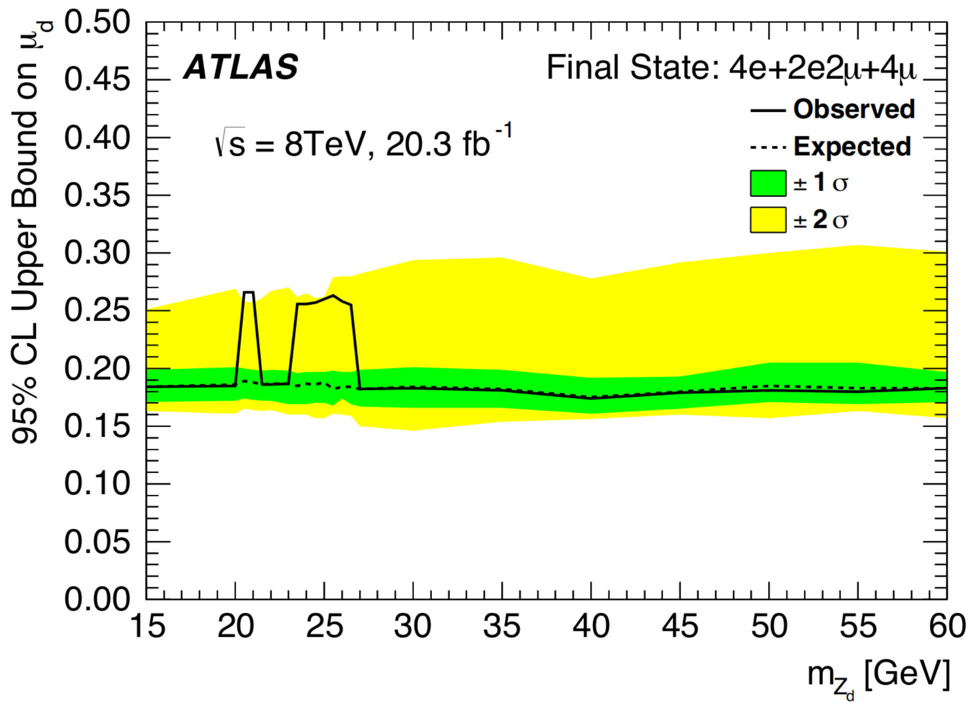
$Z + (t\bar{t}/J/\Psi) \to 4\ell$	0.004 ± 0.004
Reducible Background	Negligible
Total	3.9 ± 0.3
Data	6

(a) Signal region $\langle m_{\ell\ell} \rangle$ distribution

(b) m_{34} vs m_{12} distribution

Figure 4: Distribution of (a) $\langle m_{\ell\ell} \rangle = \frac{1}{2}(m_{12}+m_{34})$ and (b) m_{34} vs m_{12}, for events selected in the $H \to XX \to 4\ell$ ($15 < m_X < 60$ GeV) analysis. The example signal distributions in (a) correspond to the expected yield normalized with $\sigma(pp \to H \to Z_d Z_d \to 4\ell) = \frac{1}{10}\sigma_{\text{SM}}(pp \to H \to ZZ^* \to 4\ell)$. The crossed-through points in (b) fail the *Z Veto*. The events outside the (shaded green) signal region in figure (b) are events that fail the $m_{34}/m_{12} > 0.85$ requirement. The diagonal dashed line marks where $m_{12} = m_{34}$, and in this range of dilepton masses all events will have $m_{34} < m_{12}$.

ATLAS 8 TeV result



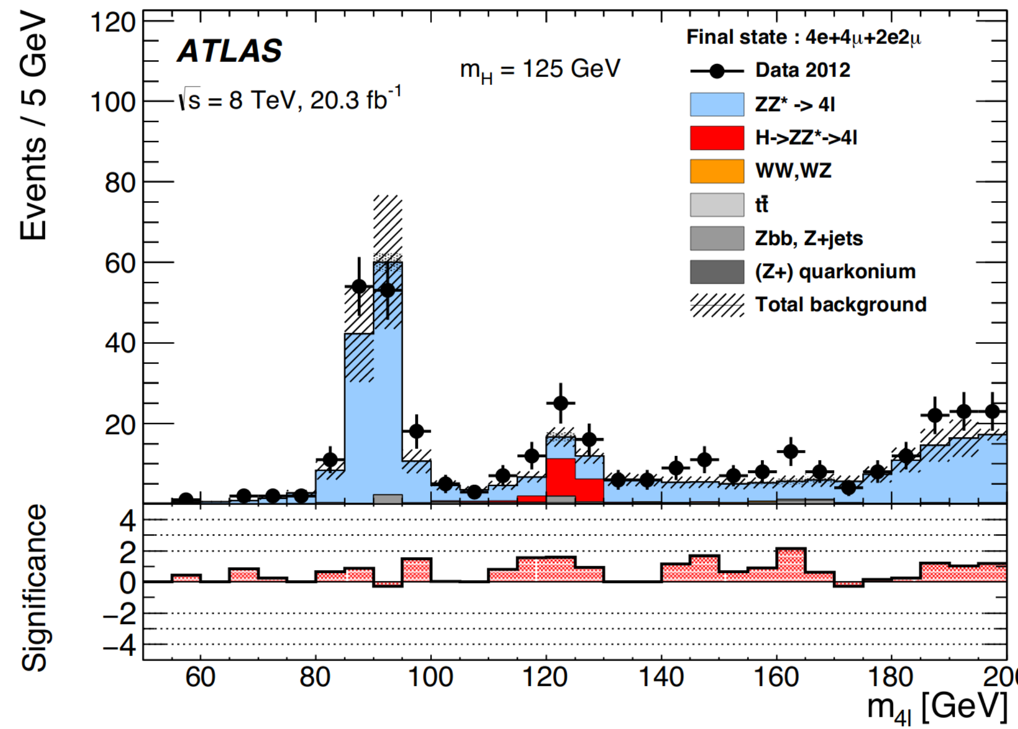


Figure 14: The 95% confidence level upper bound on the signal strength $\mu_d = \frac{\sigma\times BR(H\to Z_dZ_d\to 4\ell)}{[\sigma\times BR(H\to ZZ^*\to 4\ell)]_{SM}}$ of $H \to Z_dZ_d \to 4\ell$ in the combined $4e + 2e2\mu + 4\mu$ final state, for $m_H = 125$ GeV. The $\pm1\sigma$ and $\pm2\sigma$ expected exclusion regions are indicated in green and yellow, respectively.

[1505.07645]