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

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On the behalf of the ATLAS Collaboration

January 14, 2020

ATLAS EXPERIMENT

Outline

1. Context and Objectives
2. Analysis overview Run2
3. Event Selection Run2
4. Background estimates and uncertainties
5. Run1 Results
6. Run2 Results
7. Conclusion

Context and Objectives

- **Standard Model (SM) deficiencies**
  - Many free parameters, (anti)matter paradox, hierarchy problem, strong CP problem, no gravity, no DE or DM...
  - Explanation of astrophysical observations of positron excesses

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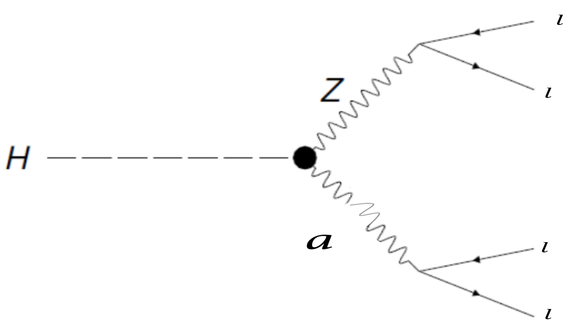
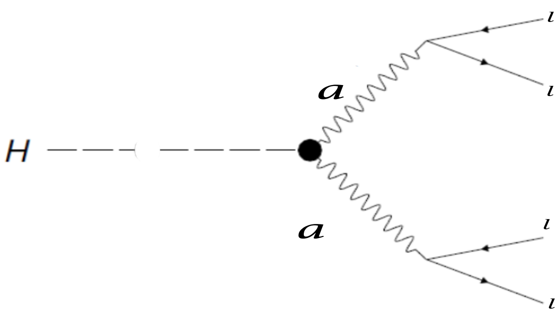
  - Many free parameters, (anti)matter paradox, hierarchy problem, strong CP problem, no gravity, no DE or DM...
  - Explanation of astrophysical observations of positron excesses

- **2 BSM Bench mark models considered**

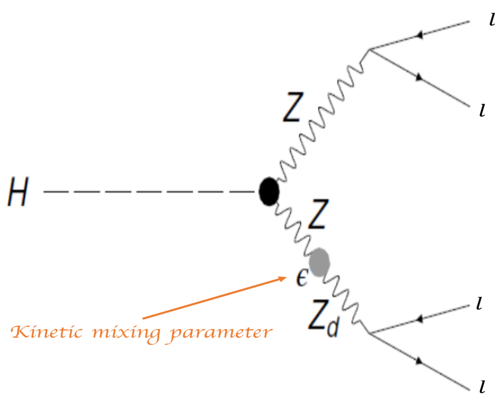
  → **2HDM+S** Curtin et al. (Phys.Rev.D90,075004(2014).), H. Davoudiasl et al Phys.Rev.D88.1(2013)015022
  - It predicts the decay of the Higgs boson to 1 or 2 pseudo-scalar a.
  - Only $a \to \mu\mu$ is considered and it's determined by Yukawa couplings of a to fermions.

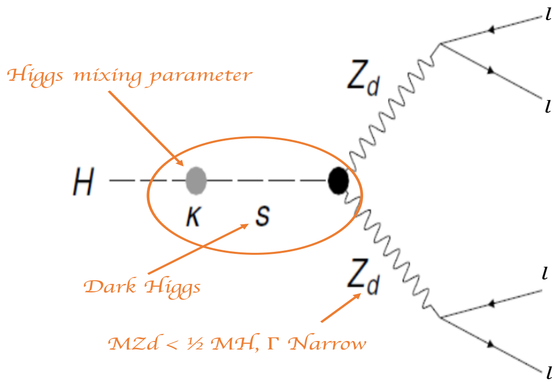




Context and Objectives

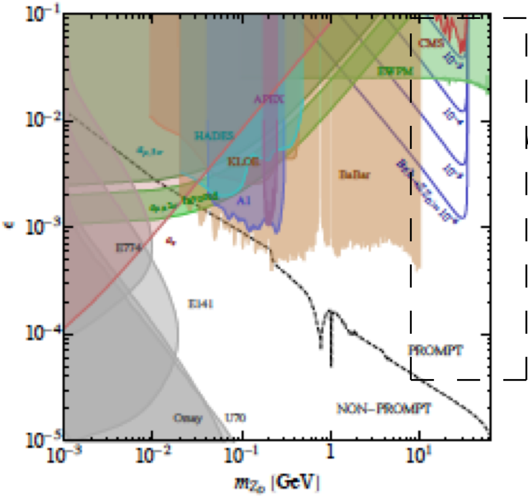
- **HAHM** (Hidden Abelian Higgs Model) → Curtin et al. (Phys.Rev.D90,075004(2014).), H. Davoudiasl et al Phys.Rev.D88.1(2013)015022
  - introduce an additional U(1) dark gauge symmetry mediated by a dark gauge boson Z_d
  - Z_d interacts with the SM through kinetic mixing with the hypercharge gauge boson (→ kinetic mixing parameter ϵ)
  - Dark Higgs mechanism could spontaneously break the U(1) dark gauge symmetry (→ mixing between SM Higgs and dark Higgs → mixing parameter κ)
  - Mass-mixing between the SM Z boson and Z_d through mass mixing parameter δ





Context and objectives

Region of interest



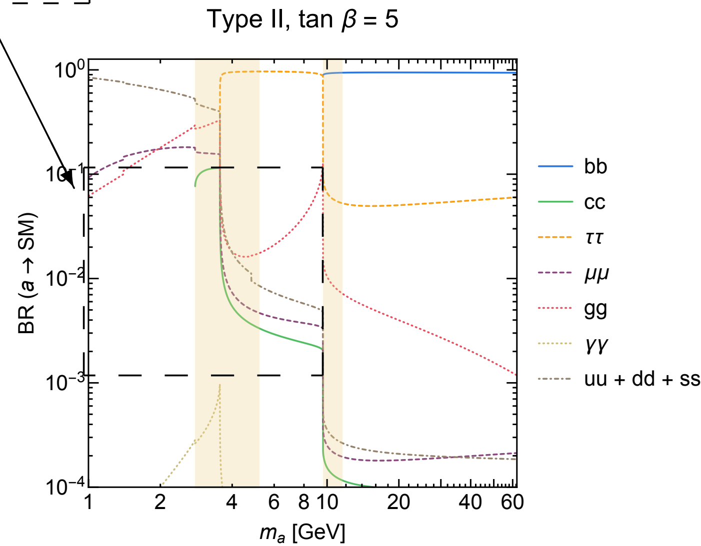


Figure 1: Constraint on ϵ, m_{Z_d} for pure kinematic mixing for $m_{Z_d} \sim MeV - 10\,GeV$

Figure 2: BR of a singlet-like pseudoscalar in the 2HDM+S for Type II Yukawa couplings.

Curtin et al. (Phys.Rev.D90,075004(2014).), H. Davoudiasl et al Phys.Rev.D88.1(2013)015022, H. Davoudiasl et al Phys.Rev.D85(2012)115019, S. Gopalakrishna, S. Jung and J. D. Wells, Phys.Rev.D78(2008)055002

Analysis overview in Run 2

3 analyses are covered: $X = Z_d/a$

channels of the analysis			
channels	decay mode	X range in GeV	final state
high mass	$H \to XX \to 4l$	$[15, 60]$	$4e, 4\mu, 2e2\mu$
ZX	$H \to ZX \to 4l$	$[15, 55]$	$4e, 4\mu, 2e2\mu, 2\mu 2e$
low mass	$H \to XX \to 4l$	$[1, 15]$	4μ

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Labeling (same as Run 1)

m_{12} is the invariant mass of the dilepton that is closer to the (SM) Z boson mass, and m_{34} is the invariant mass of the other dilepton in the quadruplet.
In the case of quadruplets formed from 4e or 4μ, alternate pairings of same-flavour opposite-sign (SFOS) leptons can be formed, they are denoted m_{14} and m_{23}

Event Selection in Run 2

<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 rowspan="3">4l selection</td><td colspan="3">- Require at least one SFOS quadruplet
- Three leading-pt leptons satisfying $pt >$ 20 GeV, 15 GeV, 10 GeV
- 3μ required to be reconstructed by combining ID and MS tracks</td></tr>
<tr><td>- The best quadruplet is required to have:

- $50\,GeV < m_{12} < 106\,GeV$
- $12\,GeV < m_{34} < 115\,GeV$
- $m_{12,34,14,32} >$ 5 GeV</td><td colspan="2">each lepton should fire at least 1 trigger.
In the case of multi-lepton triggers, all leptons of the trigger must match to leptons in the quadruplet</td></tr>
<tr><td colspan="2">$\Delta R(l,l') > 0.10$ (0.20) for same-flavour (different-flavour) leptons in the quadruplet</td><td>-</td></tr>
<tr><td>4l ranking</td><td>Select first surviving quadruplet from channels, in the order: 4μ, $2e2\mu$, $2\mu2e$, $4e$</td><td colspan="2">Select quadruplet with smallest $\mathbf{\Delta m_{\ell\ell} = \lvert m_{12} - m_{34} \rvert}$</td></tr>
<tr><td rowspan="3">Event selection</td><td colspan="2">$\mathbf{115\,GeV < m_{4\ell} < 130\,GeV}$</td><td>$\mathbf{120\,GeV < m_{4\ell} < 130\,GeV}$</td></tr>
<tr><td rowspan="2"></td><td colspan="2">$\mathbf{m_{34}/m_{12} > 0.85}$
Reject event if:
$(m_{J/\Psi} - 0.25\,GeV) < m_{12,34,14,32} < (m_{\Psi(2S)} + 0.30\,GeV)$, or
$(m_{\Upsilon(1S)} - 0.70\,GeV) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\,GeV)$</td></tr>
<tr><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>

Signal Generation in Run2

- Same as Run 1 for high mass and ZX channel
- For low mass: Higgs boson was produced using PowHeg- Box and CT10 NLO PDFs then replaced by a Higgs boson for 2HDM+S model

Backgrounds estimates and uncertainties

Dominant background

- $H \to ZZ^* \to 4l$
- Non resonant SM ZZ^*

Sub-dominant background

- WZ, ZZ dibosons processes
- J/ψ and Υ
- $t\bar{t}$ and Z+ Jet (cross check by data driven method, for high mass)
- heavy flavor (for low mass region)

- For high and low mass region: most of them are cross checked in regions orthogonal to the signal region
- For $H \to ZX \to 4l$: estimation is done from simulation and normalised with the theoretical calculations of their cross-section

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Uncertainties

- Data driven bkg uncertainty is $\to$ up to 65%
- Statistical uncertainty
- Systematic uncertainties from: detector, theory $\to$ up to 10%

$H \to ZX \to 4l$ Run 1 results

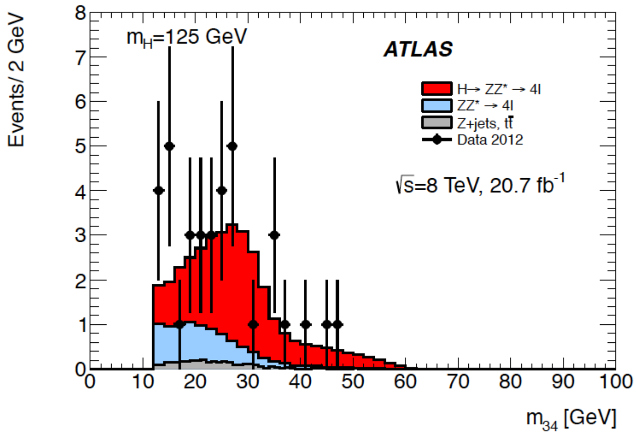

Figure 3: m_{34} distribution.

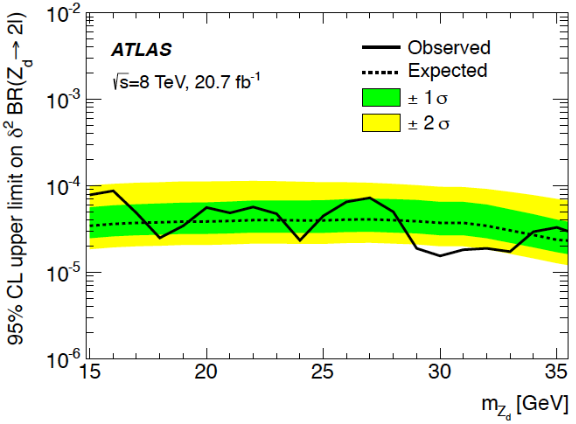

Figure 4: upper limits on δ vs m_{Zd}

channel	ZZ^*	$t\bar{t} + Z + jets$	Sum	Observed	$H \to 4l$
4μ	$3.1 \pm 0.02 \pm 04$	$0.6 \pm 0.04 \pm 0.2$	$3.7 \pm 0.04 \pm 0.6$	12	$8.3 \pm 0.04 \pm 0.6$
$4e$	$1.3 \pm 0.02 \pm 0.5$	$0.8 \pm 0.07 \pm 0.4$	$2.1 \pm 0.07 \pm 0.9$	9	$6.9 \pm 0.07 \pm 0.9$
$2\mu 2e$	$1.4 \pm 0.01 \pm 0.3$	$1.2 \pm 0.10 \pm 0.4$	$2.6 \pm 0.10 \pm 0.6$	7	$4.4 \pm 0.10 \pm 0.6$
$2e2\mu$	$2.1 \pm 0.02 \pm 0.3$	$0.6 \pm 0.04 \pm 0.2$	$2.7 \pm 0.10 \pm 0.5$	8	$5.3 \pm 0.04 \pm 0.5$
all	$7.8 \pm 0.04 \pm 1.2$	$3.2 \pm 0.1 \pm 1.0$	$11.1 \pm 0.1 \pm 1.8$	36	$24.9 \pm 0.1 \pm 1.8$

Table 1: Expected and observed of events at $20.1 fb^{-1}$, The uncertainties are statistical and systematic respectively.

$H \to XX \to 4l$ Run 1 results

Process	$4e$	4μ	$2e2\mu$
$H \to ZZ^* \to 4\ell$	$(1.5 \pm 0.3 \pm 0.2) \times 10^{-2}$	$(1.0 \pm 0.3 \pm 0.3) \times 10^{-2}$	$(2.9 \pm 1.0 \pm 2.0) \times 10^{-3}$
$ZZ^* \to 4\ell$	$(7.1 \pm 3.6 \pm 0.5) \times 10^{-4}$	$(8.4 \pm 3.8 \pm 0.5) \times 10^{-3}$	$(9.1 \pm 3.6 \pm 0.6) \times 10^{-3}$
WW, WZ	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$
$t\bar{t}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$
$Zbb, Z + jets$	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$
$ZJ/\Psi, Z\Upsilon$	$< 2.3 \times 10^{-2}$	$< 2.3 \times 10^{-2}$	$< 2.3 \times 10^{-2}$
Total background	$< 5.6 \times 10^{-2}$	$< 5.9 \times 10^{-2}$	$< 5.3 \times 10^{-2}$
Data	1	0	0

Table 2: Expected and observed events for mass $m_{Zd} = 25\,GeV$

Process	$4e$	4μ	$2e2\mu$
$H \to ZZ^* \to 4\ell$	$(1.2 \pm 0.3 \pm 0.2) \times 10^{-2}$	$(5.8 \pm 2.0 \pm 2.0) \times 10^{-3}$	$(2.6 \pm 1.0 \pm .2) \times 10^{-3}$
$ZZ^* \to 4\ell$	$(3.5 \pm 2.0 \pm 0.2) \times 10^{-3}$	$(4.1 \pm 2.7 \pm 0.2) \times 10^{-3}$	$(2.0 \pm 0.6 \pm 0.1) \times 10^{-3}$
WW, WZ	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$
$t\bar{t}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$
$Zbb, Z + jets$	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$
$ZJ/\Psi, Z\Upsilon$	$< 2.3 \times 10^{-2}$	$< 2.3 \times 10^{-2}$	$< 2.3 \times 10^{-2}$
Total background	$< 5.3 \times 10^{-2}$	$< 5.1 \times 10^{-2}$	$< 6.4 \times 10^{-2}$
Data	1	0	0

Table 3: Expected and observed events for mass $m_{Zd} = 20.5\,GeV$

$H \to XX \to 4l$ Run1 results

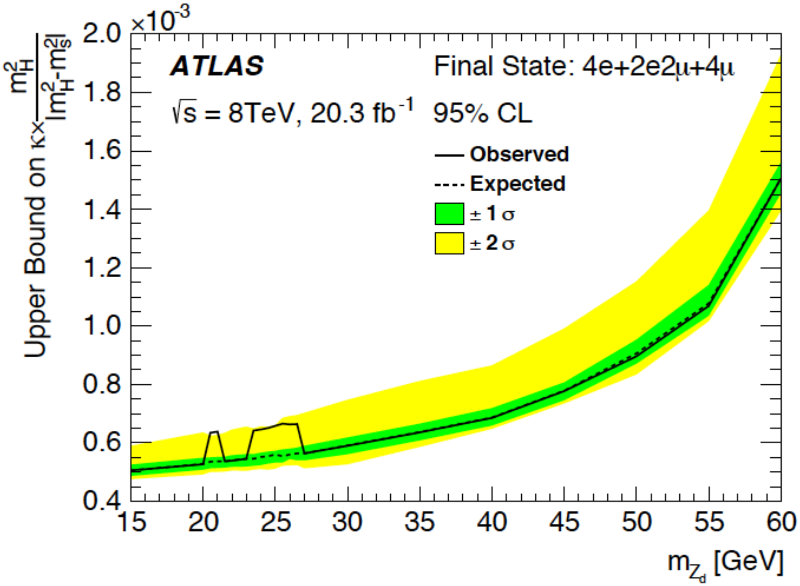

Figure 5: upper limits on κ vs m_{Zd}

$$\kappa^2 = \Gamma(H \to Z_d Z_d) \frac{32\pi m_h^5}{v^2[(m_h^2 - 2m_{Z_d}^2)^2 - 8(m_h^2 - m_{Z_d}^2)m_{Z_d}^2]} \frac{1}{\sqrt{1 - \frac{4m_{Z_d}^2}{m_h^2}}}$$

$$\kappa' = \kappa \times \frac{m_H^2}{|m_H^2 - m_S^2|}$$

$H \to ZX/XX \to 4l$ analysis Run1 $\to$ Run2

Factors that are expected to lead to an improvement in the Run 2 result

- The Higgs production cross section in Run 2 (13 TeV) > Run 1 (8 TeV) 43.92 pb vs 19.3 pb
- The Luminosity in Run 2 (36.1 fb^{-1}) > Run 1 (20.3 fb^{-1})
- Improvement in the Analysis code, at various levels
- Optimization of the signal region cut.
- Exploration of the low mass region ($m_X < 15$ GeV).
- Improvement expected in the limit setting.

$H \to ZX \to 4l$ Run2 results

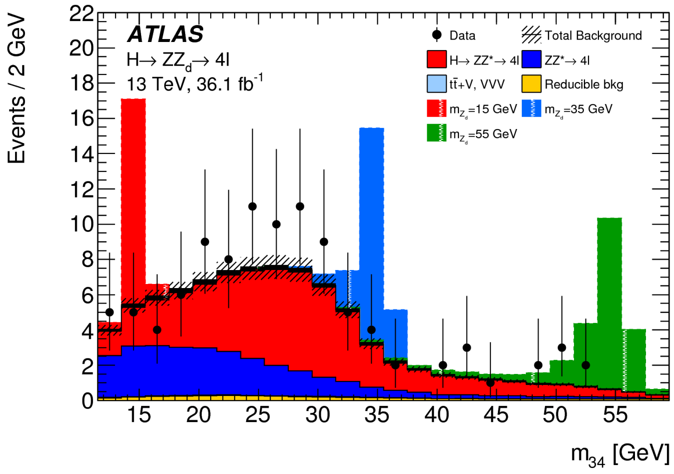

Figure 6: m_{34} in the mass range m4ℓ in [115,130] GeV.

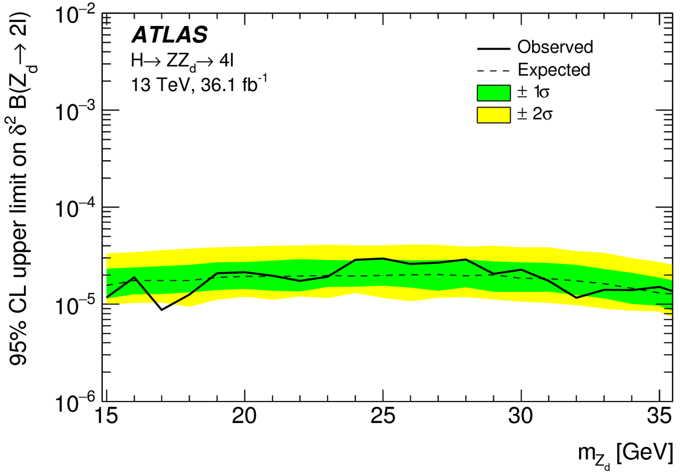

Figure 7: upper limits on δ vs m_{Zd}

- Some excesses are observed but not statistically significant

Process	$2\ell 2\mu$	$2\ell 2e$	Total
$H \to ZZ^* \to 4\ell$	34.3 ± 3.6	21.4 ± 3.0	55.7 ± 6.3
$ZZ^* \to 4\ell$	16.9 ± 1.2	9.0 ± 1.1	25.9 ± 2.0
Reducible background	2.1 ± 0.6	2.7 ± 0.7	4.8 ± 1.1
VVV, $t\bar{t} + V$	0.20 ± 0.05	0.20 ± 0.04	0.40 ± 0.06
Total expected	53.5 ± 4.3	33.3 ± 3.4	86.8 ± 7.5
Observed	65	37	102

Table 4: Expected and observed of events at $36.1 fb^{-1}$

$H \to XX \to 4l$ high mass Run2 results

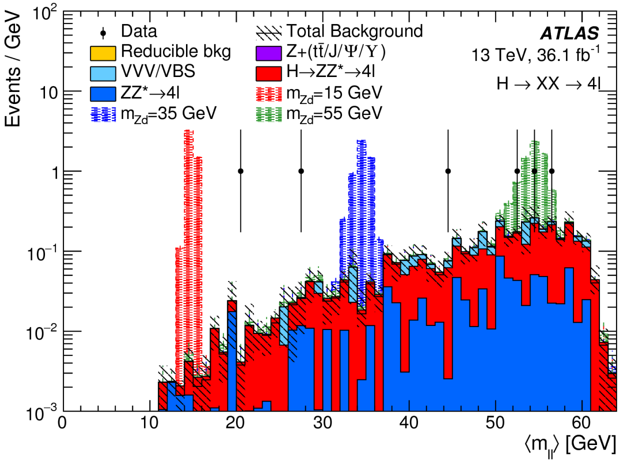

Figure 8: m_{34} in the mass range m4ℓ in [115,130] GeV.

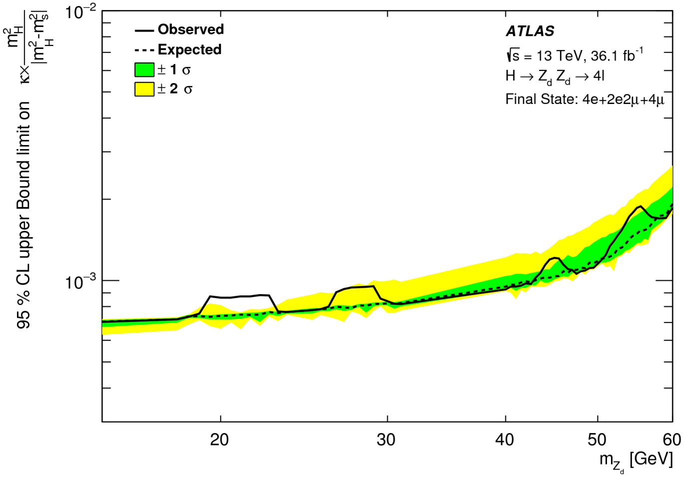

Figure 9: upper limits on κ vs m_{Zd}

- Some excesses are observed but not statistically significant

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

Table 5: Expected and observed of events at $36.1 fb^-1$

$H \to XX \to 4l$ low mass Run2 results

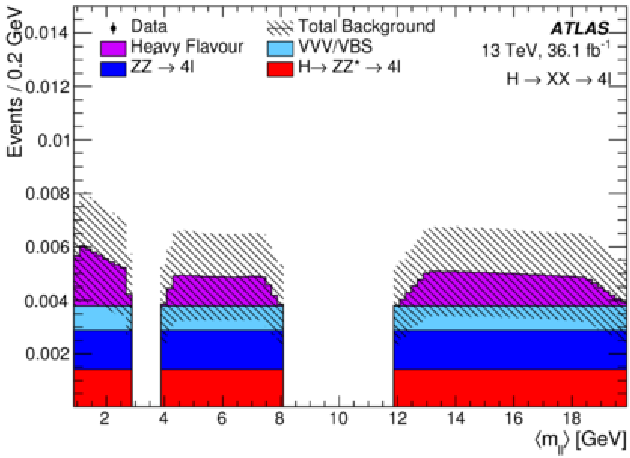

Figure 10: m_{34} in the mass range m4ℓ in [120,130] GeV.

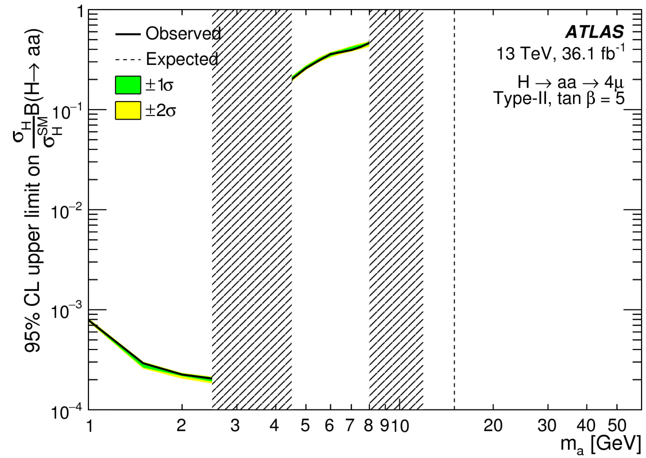

Figure 11: upper limits on BR vs m_{Zd}

- No excess is observed for the low mass region

Process	Yield
$ZZ^* \to 4l$	0.10 ± 0.01
$H \to ZZ* \to 4l$	0.1 ± 0.1
VVV/VBS	0.06 ± 0.03
Heavy flavour	0.07 ± 0.04
Total	0.4 ± 0.1
Data	0

Table 6: Expected and observed events at $36.1 fb^{-1}$

Conclusion

1. **Summary**

- Search for light BSM boson in 4l channel is performed.
- Data is mostly consistent with expected background.
- Upper limits on branching ratio (benchmark model) is set at 95% CL.
- Run1 paper `https://arxiv.org/abs/1505.07645`
- Run2 paper `https://arxiv.org/abs/1802.03388`

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1 Summary

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2 Plan

- Research to heavier progenitor scalar
- Making use of a more sensitive variable
- Improving background estimation
- exploring 4τ channel in low mass region

Backup

Interpretation: fiducial cross-section

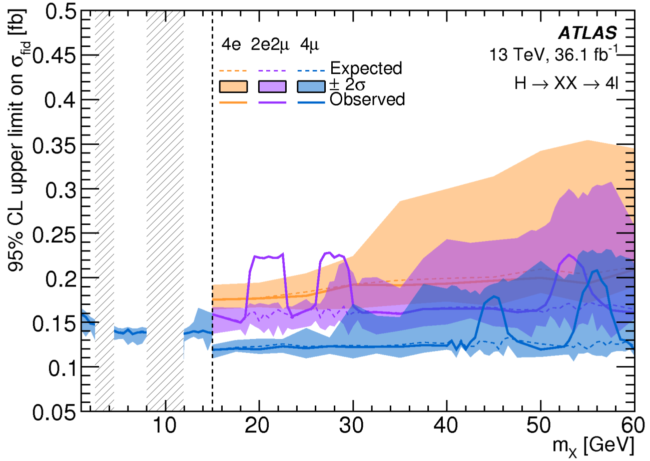


Figure 12: Upper limits at 95% CL on fiducial cross-sections for the $H \to XX \to 4l$ process

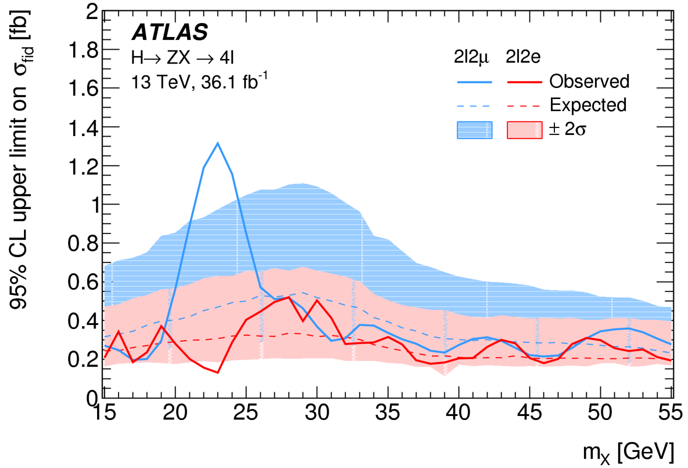


Figure 13: Upper limit at 95% CL on the fiducial cross-sections for the $H \to ZX$ process.

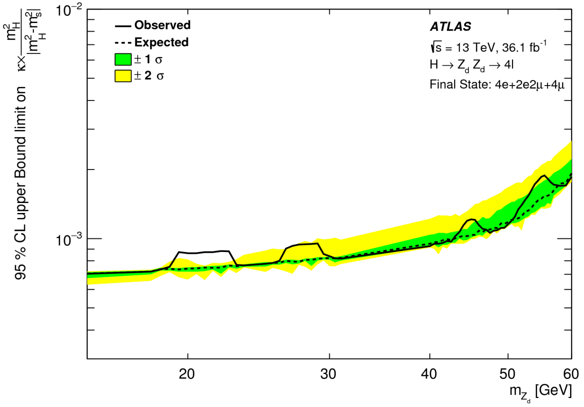


Figure 14: Upper limits at 95% CL on fiducial cross-sections for the $H \to ZX \to 4l$ process

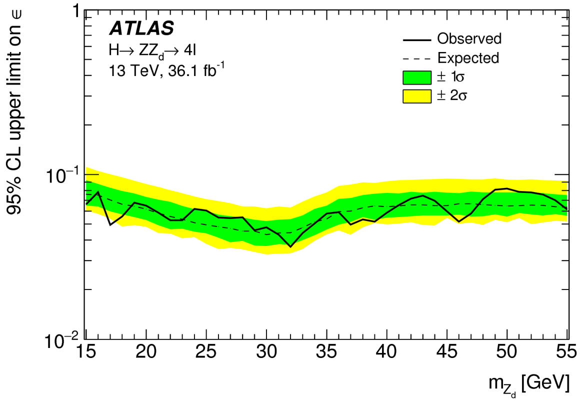


Figure 15: Upper limit at 95% CL on the branching ratio for the $H \to ZZ_d$ process.

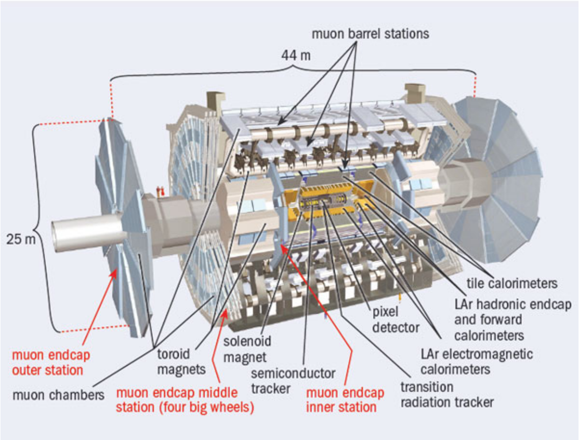
$$\kappa^2 = \Gamma(H \to Z_d Z_d) \frac{32\pi m_h^5}{v^2[(m_h^2 - 2m_{Z_d}^2)^2 - 8(m_h^2 - m_{Z_d}^2)m_{Z_d}^2]} \frac{1}{\sqrt{1 - \frac{4m_{Z_d}^2}{m_h^2}}}$$

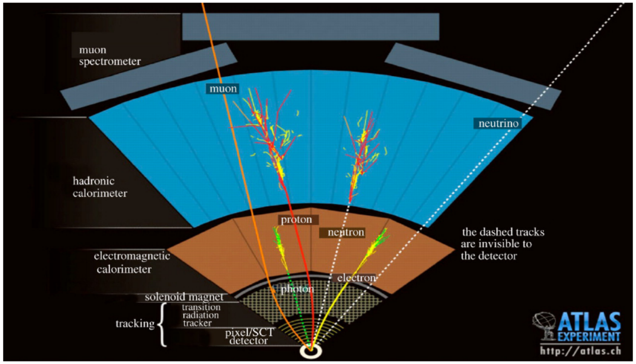
$$\kappa' = \kappa \times \frac{m_H^2}{|m_H^2 - m_S^2|}$$

$H \to ZZ_d \to 4\ell$ Strategy

- Sample of selected 4ℓ events is used, with $115 < m_{4\ell} < 130$ GeV
- The $H \to 4\ell$ yield denoted $n(H \to 4\ell)$ is determined by subtracting the relevant backgrounds from the 4ℓ sample: $n(H \to 4\ell) = n(4\ell) - n(ZZ^*) - n(t\bar{t}) - n(Z + jets)$.
- A template fit of the m_{34} distribution, using histogram-based templates of the $H \to ZZ_d \to 4\ell$ signal and backgrounds.
- m_{34} mass spectrum is extracted to test for a local excess consistent with the decay of a narrow Zd resonance.
- In the absence of any significant local excess, the search can be used to constrain a relative branching ratio R_B, defined as: $R_B = \frac{BR(H \to ZZ_d \to 4\ell)}{BR(H \to 4\ell)} = \frac{BR(H \to ZZ_d \to 4\ell)}{BR(H \to ZZ_d \to 4\ell) + BR(H \to ZZ^* \to 4\ell)}$
- A likelihood function is defined as: $\mathcal{L}(\rho, \mu_H, \nu) = \prod_{i=1}^{N_{bins}} \mathcal{P}(n_i^{obs} | n_i^{exp}) = \prod_{i=1}^{N_{bins}} \mathcal{P}(n_i^{obs} | \mu_H \times (n_i^{Z^*} + \rho \times n_i^{Z_d}) + b_i(\nu))$
- $R_B = \frac{\rho}{\rho + C}$

ATLAS Detector





- Tracking System
  - → reconstruct charged particles trajectories
- Thin superconducting solenoid
  - → to compute particles impulsion
- electromagnetic calorimeter
  - → measure electromagnetic energy deposited by e^- and γ
- muon system
  - → designed to identify and reconstruct muons
- trigger system
  - → choose either to keep or not events
- hadronic calorimeters
  - → measure hadronic energy deposited by hadronic system
- Detector surrounded by Magnetic

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m_{12} is the invariant mass of the dilepton that is closer to the (SM) Z boson mass, and m_{34} is the invariant mass of the other dilepton in the quadruplet.
In the case of quadruplets formed from 4e or 4μ, alternate pairings of same-flavour opposite-sign (SFOS) leptons can be formed, they are denoted m_{14} and m_{23}

Event Selection in Run1

	$H \to ZX \to 4\ell$ ($15\,GeV < m_X < 55\,GeV$)	$H \to XX \to 4\ell$ ($15\,GeV < m_X < 60\,GeV$)
4l selection	- Require at least one SFOS quadruplet - Three leading-pt leptons satisfying $pt >$ 20 GeV, 15 GeV, 10 GeV - 3μ required to be reconstructed by combining ID and MS tracks	
	- The best quadruplet is required to have: - $50\,GeV < m_{12} < 106\,GeV$ - $12\,GeV < m_{34} < 115\,GeV$ - $m_{12,34,14,32} > 5$ GeV	each lepton should fire at least 1 trigger. In the case of multi-lepton triggers, all leptons of the trigger must match to leptons in the quadruplet
	$\Delta R(l, l') > 0.10$ (0.20) for same-flavour (different-flavour) leptons in the quadruplet	
4l ranking	Select first surviving quadruplet from channels, in the order: 4μ, $2e2\mu$, $2\mu 2e$, $4e$	Select quadruplet with smallest $\Delta m_{\ell\ell} = \|m_{12} - m_{34}\|$
Event selection	(Higgs window cut) $115\,GeV < m_{4\ell} < 130\,GeV$	
		(Z veto cut) $\|m_{12,34} - m_Z\| < 10\,GeV$ (Loose SR cut) $m_{12} < m_H/2$ and $m_{34} < m_H/2$ GeV Reject event if: m_{12} and $m_{34} < 12$ GeV (suppress J/Ψ and Υ)
		(Tight SR cut) $\|m_{Zd} - m_{12}\| < \delta m$ and $\|m_{Zd} - m_{34}\| < \delta m$ $\delta m = 5/3/4.5$ for $4e/4\mu/2e2\mu$

Signal generation

$H \to ZX \to 4l$ and $H \to XX \to 4l$ (high mass)

- Higgs boson is produced in gluon-gluon fusion mode (ggF) using HAHM model, with $M_H = 125\,GeV$
- MadGraph5_aMC@NLO and NNPDF23 are used as event generator
- Pythia8 was used for modeling of the parton shower, hadronisation and underlying event.
- The model parameters ϵ and κ were adjusted so that only $H \to ZX \to 4l$ ($\epsilon >> \kappa$) or $H \to XX \to 4l$ ($\epsilon << \kappa$) decays were generated

Backgrounds estimates and uncertainties

Dominant background

- $H \to ZZ^* \to 4l$
- Non resonant SM ZZ^*

Sub-dominant background

- WZ, ZZ dibosons processes
- J/ψ and Υ
- $t\bar{t}$ and Z+ Jet (cross check by data driven method, for ZX channel)

- For $H \to XX \to 4l$: estimation is done from simulation and normalised with the theoretical calculations of their cross-section

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Uncertainties

- Data driven bkg uncertainty is $\to$ up to 65%
- Statistical uncertainty
- Systematic uncertainties from: detector, theory $\to$ up to 10%

P value for High mass result

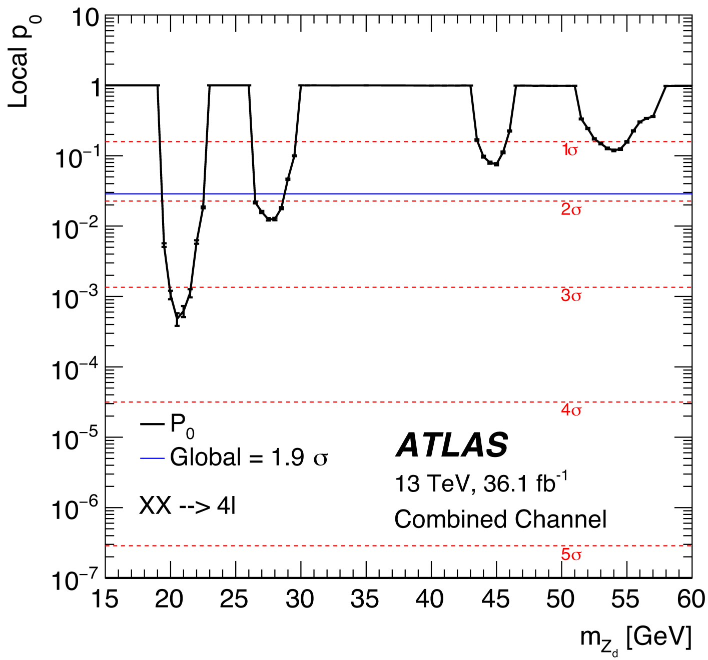

Figure 16: Observed local p-values under the background-only hypothesis