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

Diallo Boye

African School of Physics 2023 (George-SA)

September 28, 2023

Outline

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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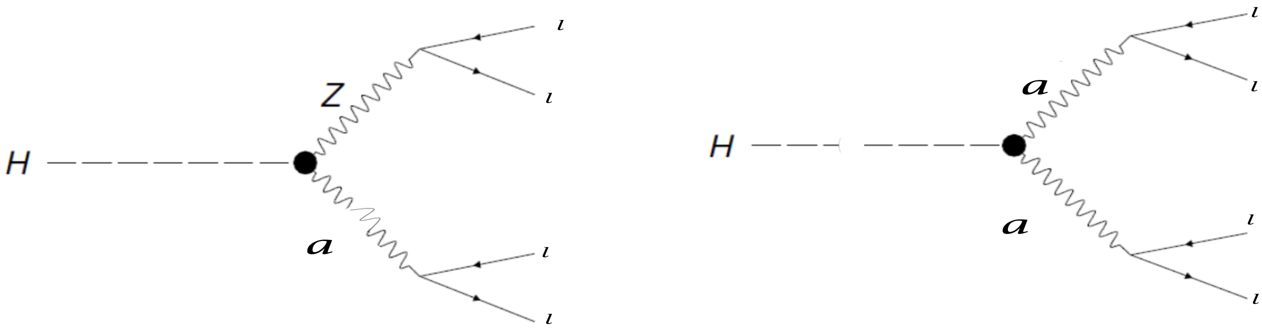
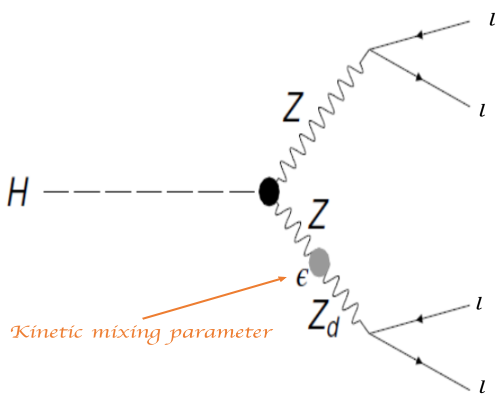
- **2 BSM Bench mark model considered**

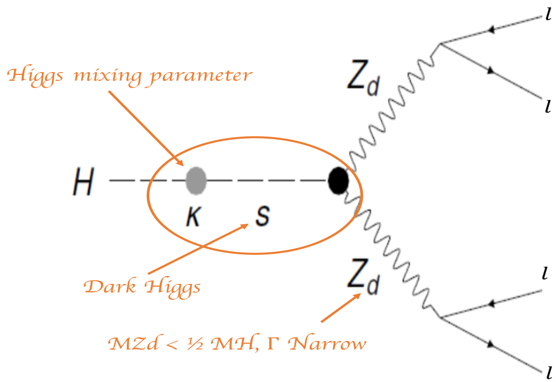
  → **2HDM+S** Curtin et al. (Phys.Rev.D90,075004(2014).), H. Davoudiasl et al Phys.Rev.D88.1(2013)015022
  - It predicts the decay of the Higgs boson to 1 or 2 pseudoscalar a which is the lightest of the higgs boson.
  - Only $a \to \mu\mu$ is considered and it's determined by Yukawa couplings of a to 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 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 Higss → mixing parameter κ)
  - Mass-mixing between the SM Z boson and Z_d through mass mixing parameter δ





Context and objectif

Region of interest

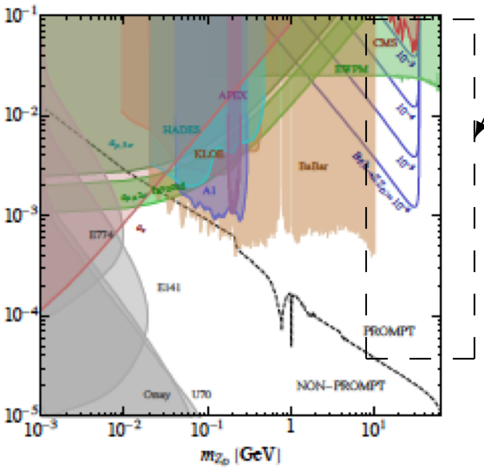


Figure 1: Constraint on ϵ, m_{Z_d} for pure kinematic mixing for $m_{Z_d} \sim MeV - 10\, GeV$

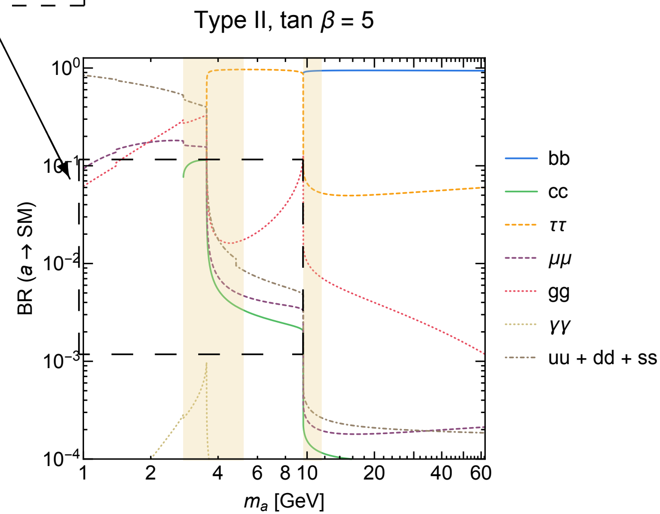
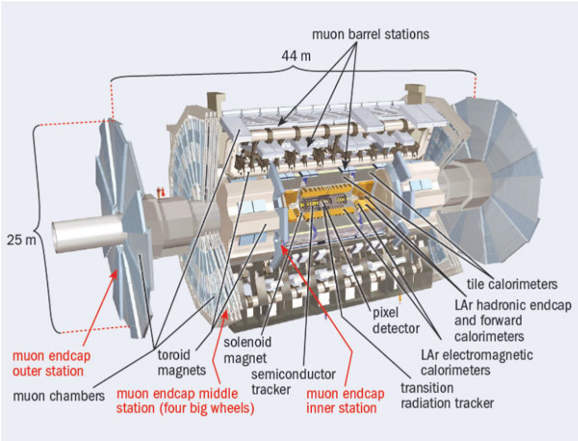
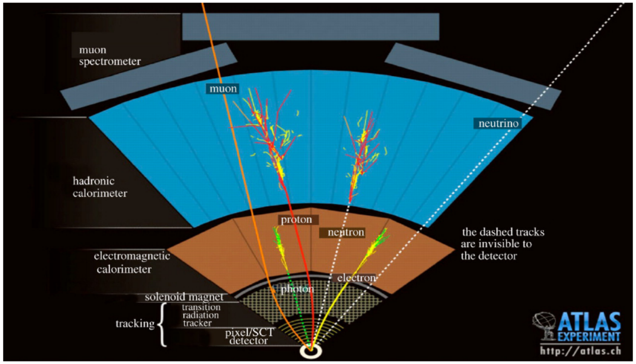


Figure 2: BR of a singlet-like pseudoscalar in the 2HDM+S for Type II Yukawa couplings.

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,

ATLAS Dectector





- 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

Analysis overview

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	$H \to ZX \to 4l$	$[15, 55]$	$4e, 4\mu, 2e2\mu, 2\mu2e$
low mass	$H \to XX \to 4l$	$[1, 15]$	4μ

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Labeling

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

	$H \to ZX \to 4\ell$ $(15\,GeV < m_X < 55\,GeV)$	$H \to XX \to 4\ell$ $(15\,GeV < m_X < 60\,GeV)$	$H \to XX \to 4\mu$ $(1\,GeV < m_X < 15\,GeV)$
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 $\mathbf{\Delta m_{\ell\ell} = \|m_{12} - m_{34}\|}$	
Event selection	$\mathbf{115\,GeV < m_{4\ell} < 130\,GeV}$		$\mathbf{120\,GeV < m_{4\ell} < 130\,GeV}$
		$\mathbf{m_{34} > 0.85 \times m_{12} - 0.1125 f(m_{12}) \times m_{12}}$ Reject event if: $(m_{J/\Psi} - 0.25\,GeV) < m_{12,34,14,32} < (m_{\Psi(2S)} + 0.30\,GeV)$, or $(m_{\Upsilon(1S)} - 0.70\,GeV) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\,GeV)$	
		$10\,GeV < m_{12,34} < 64\,GeV$ $4e$ and 4μ channels: $5\,GeV < m_{14,32} < 75\,GeV$	$0.88\,GeV < m_{12,34} < 20$ GeV No restriction on alternative pairing

Note

- $f(m_{12})$ is the modulated function defined for the re-optimization of the SR. It's detailed in backup.

Backgrounds estimates and uncertainties

Dominant background

- $H \rightarrow ZZ^* \rightarrow 4l$
- 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 $H \rightarrow ZX \rightarrow 4l$: 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%

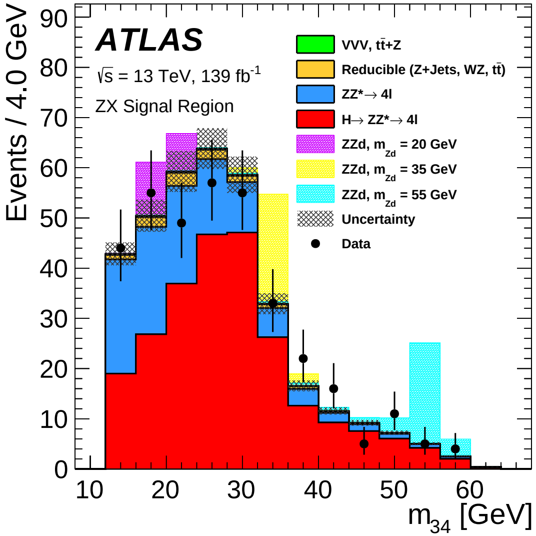


Figure 3: m_{34} distribution.

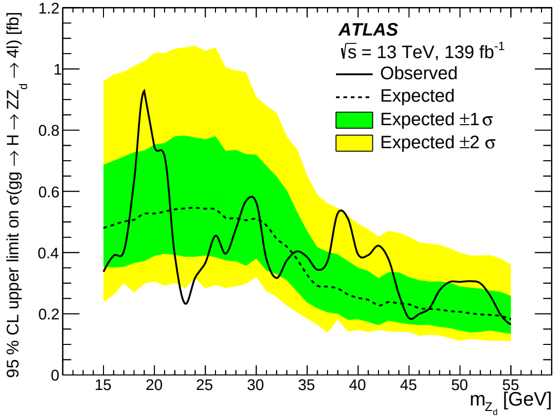
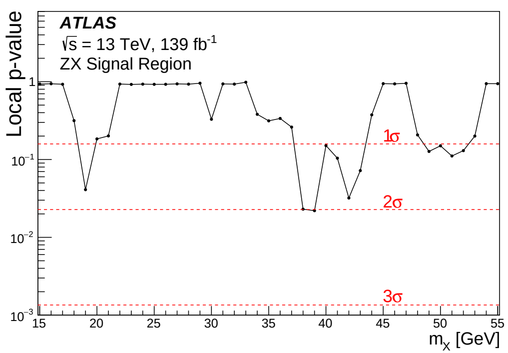


Figure 4: upper limits on cross-section



- No significant excess is observed above SM background predictions. Therefore, the results are interpreted in terms of exclusion limits.

$H \to XX \to 4l$ full run2

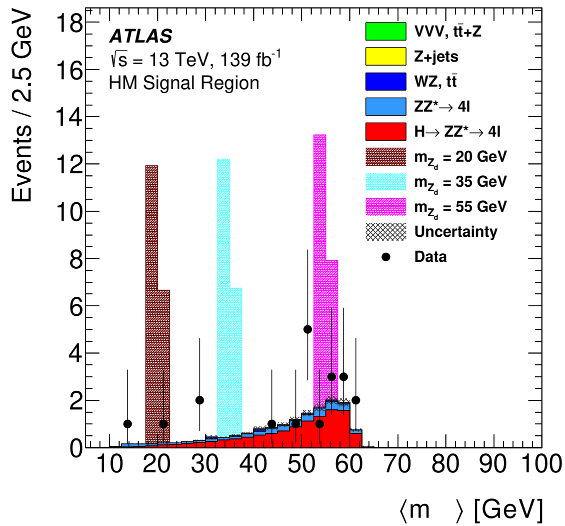


Figure 6: $\langle m \rangle_{\ell\ell}$ distribution.

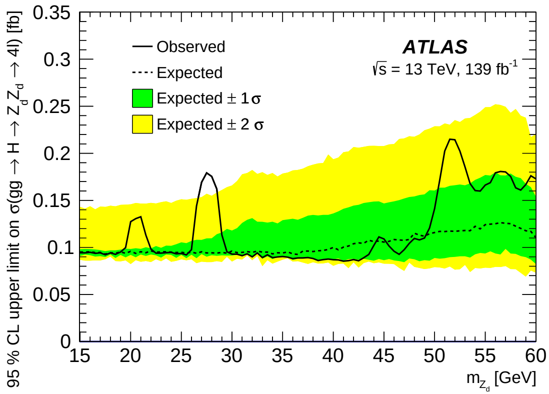
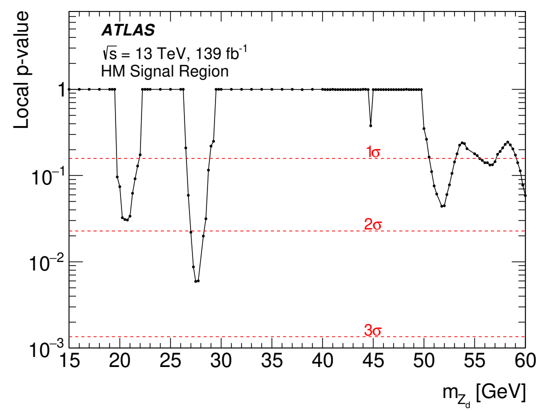


Figure 7: upper limits on cross-section



- No significant excess is observed above SM background predictions.
- Most significant excess corresponds to a local significance of 2.5σ at $m_{Z_d} = 28$ GeV.

$H \to aa \to 4l$ full run2

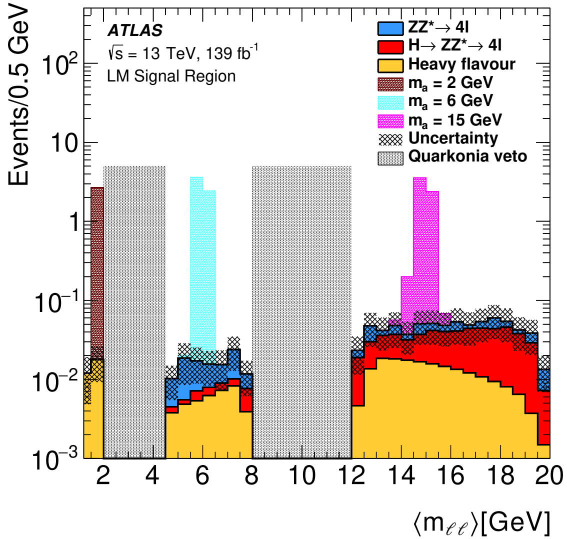


Figure 9: m_{34} distribution.

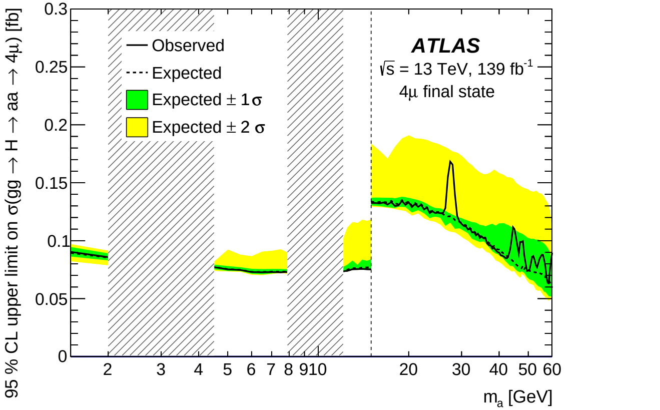


Figure 10: upper limits on cross-section

- No significant excess is observed above SM background predictions. Therefore, the results are interpreted in terms of exclusion limits.

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.**
- **This analysis has been carried out in Run 1, Run 2 already:**
  - Run1 paper https://arxiv.org/abs/1505.07645
  - Run2 paper https://arxiv.org/abs/1802.03388
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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

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

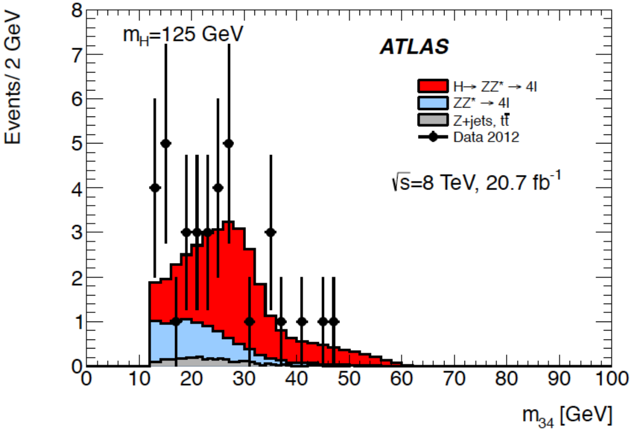


Figure 11: m_{34} distribution.

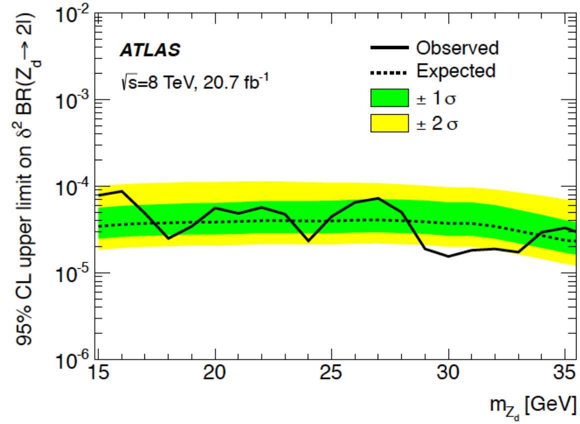


Figure 12: upper limits on δ vs m_{Zd}

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

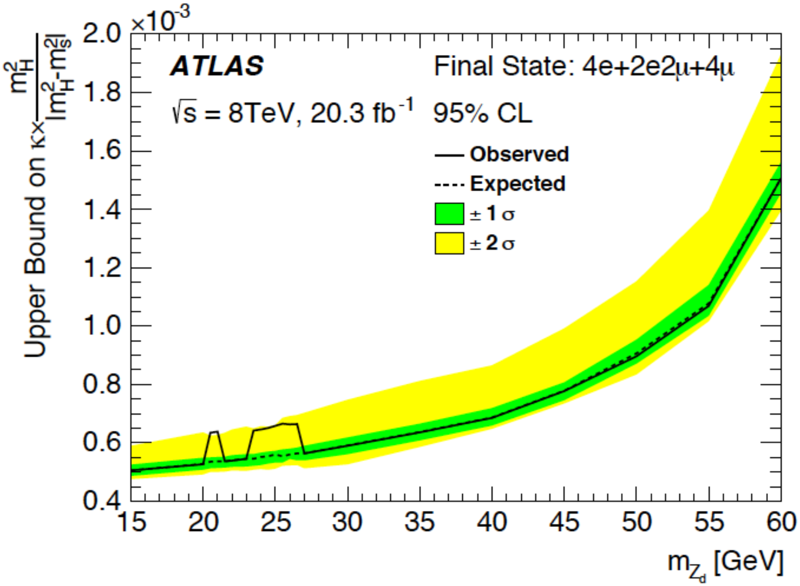


Figure 13: upper limits on κ vs m_{Zd}

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

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

$H \to ZX/XX \to 4l$ 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

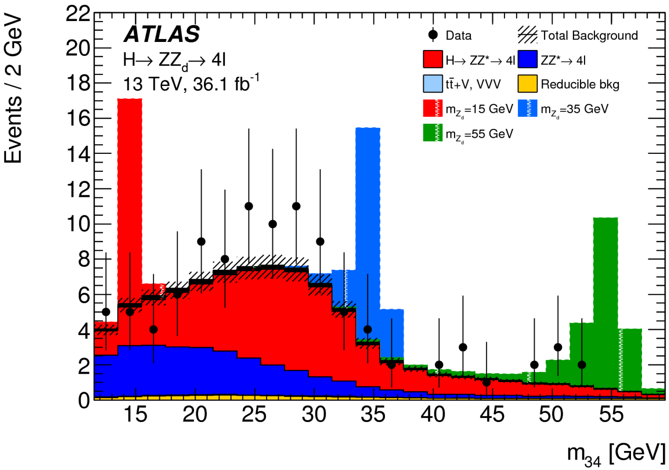


Figure 14: m_{34} in the mass range m4ℓ in [115,130] GeV.

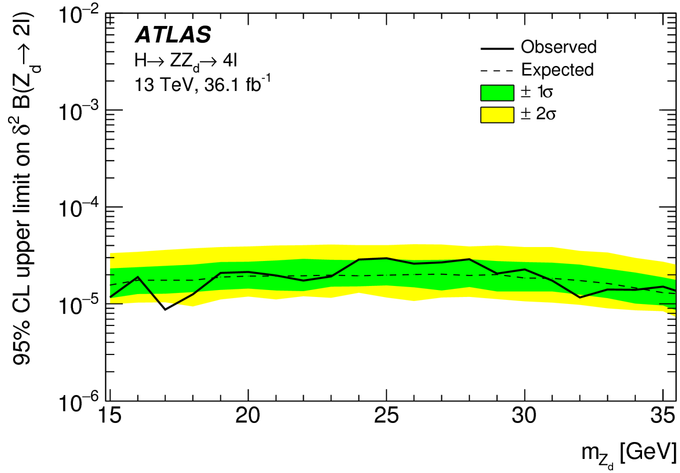


Figure 15: upper limits on δ vs m_{Zd}

- 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

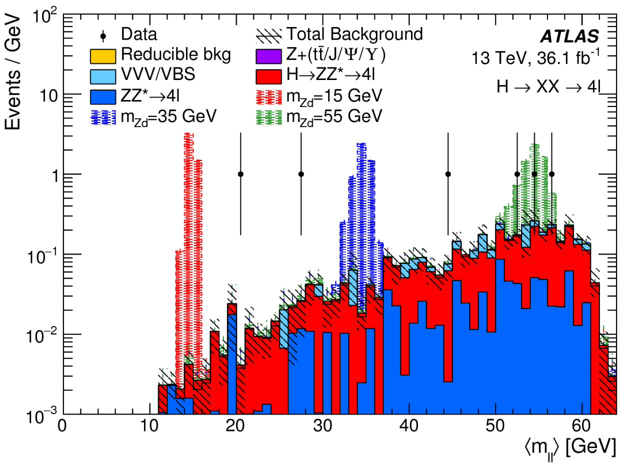


Figure 16: m_{34} in the mass range m4ℓ in [115,130] GeV.

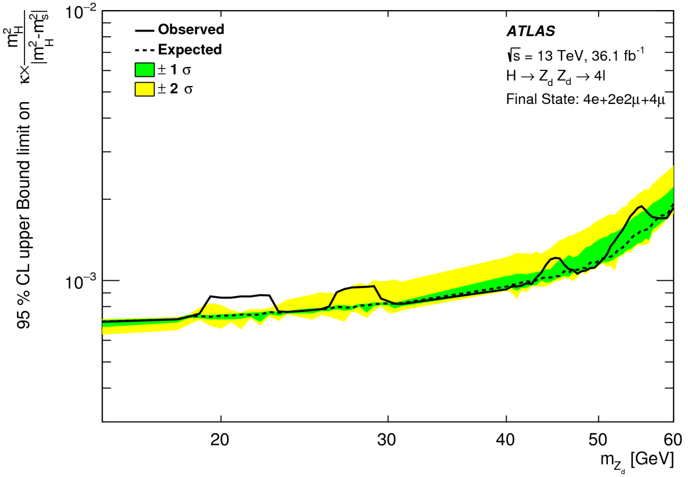


Figure 17: upper limits on κ vs m_{Zd}

- 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

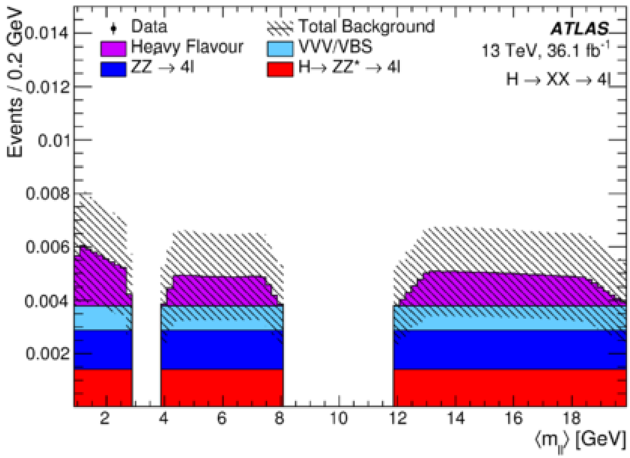


Figure 18: m_{34} in the mass range m4ℓ in [120,130] GeV.

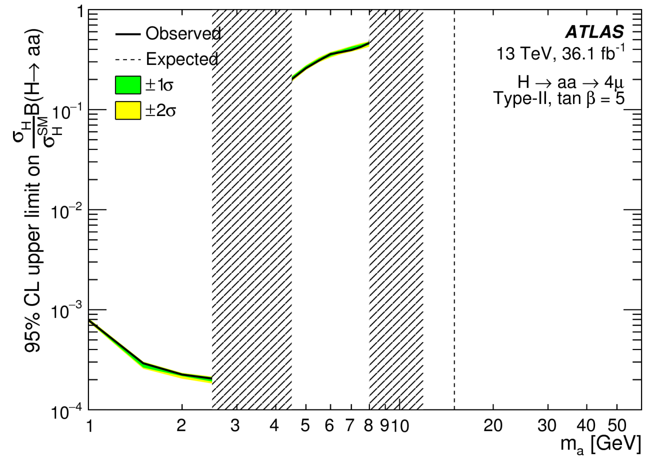


Figure 19: upper limits on BR vs m_{Zd}

- 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 $36.1 fb^{-1}$

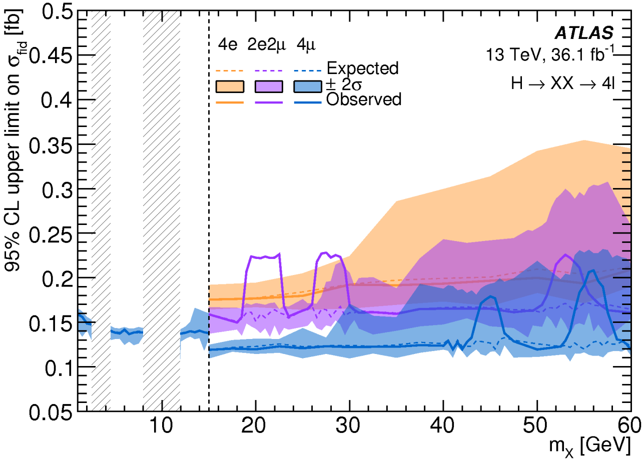


Figure 20: Upper limits at 95% CL on fiducial cross-sections for the $H \to XX \to 4l$ process

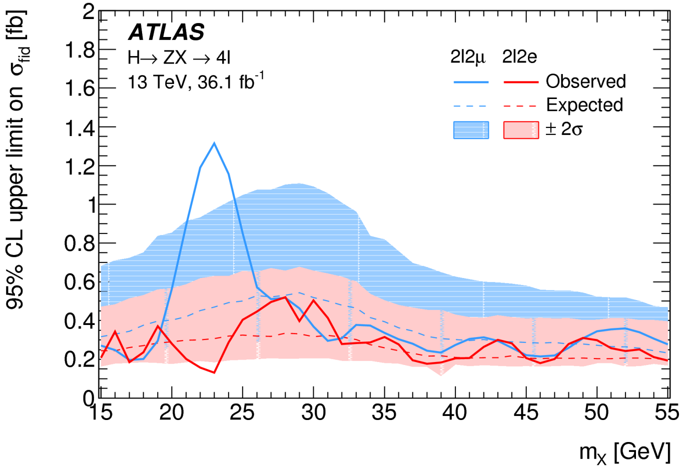


Figure 21: Upper limit at 95% CL on the fiducial cross-sections for the $H \to ZX$ process.

Interpretation: κ and ϵ parameter

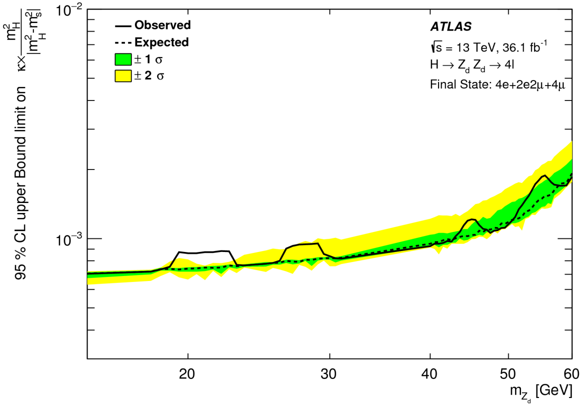


Figure 22: Upper limits at 95% CL on fiducial cross-sections for the $H \to ZX \to 4l$ process

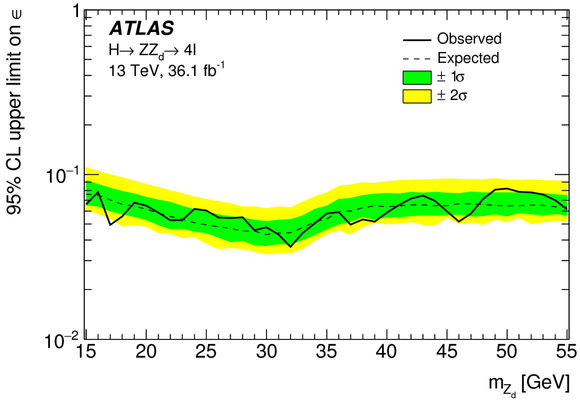


Figure 23: Upper limit at 95% CL on the branching ratio for the $H \to ZZ_d$ process.

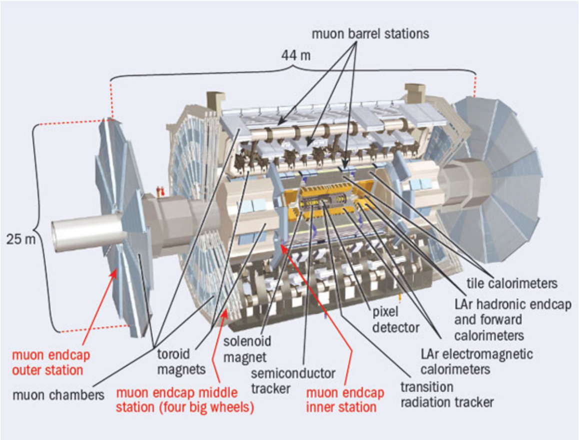
$$\kappa^2 = \Gamma(H \to Z_d Z_d) \frac{32\pi m_h^5}{v^2[(m_h^2 - 2m_{Z_d}^2)^2 - 8(m_h^2 - m_{Z_d}^2)m_{Z_d}^2]} \frac{1}{\sqrt{1 - \frac{4m_{Z_d}^2}{m_h^2}}}$$

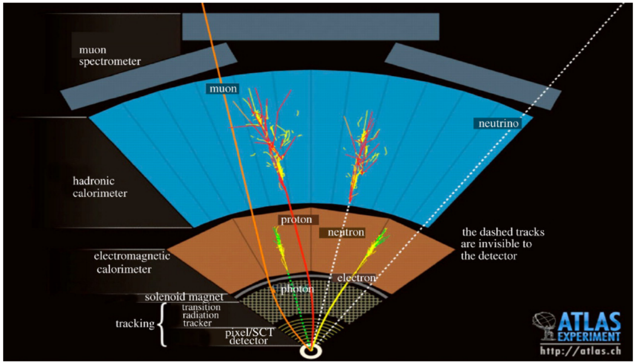
$$\kappa' = \kappa \times \frac{m_H^2}{|m_H^2 - m_S^2|}$$

$H \to ZZ_d \to 4\ell$ 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

Analysis overview in Run1

2 channels are covered: $X = Z_d$

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	$H \to ZX \to 4l$	$[15, 55]$	$4e, 4\mu, 2e2\mu, 2\mu2e$

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Labeling

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 $\Delta m_{\ell\ell} = \lvert m_{12} - m_{34} \rvert$
Event selection	(Higgs window cut) $115\,GeV < m_{4\ell} < 130\,GeV$	
		(Z veto cut)$\lvert m_{12,34} - m_Z \rvert < 10\,GeV$ (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) $\lvert m_{Zd} - m_{12} \rvert < \delta m$ and $\lvert m_{Zd} - m_{34} \rvert < \delta m$ $\delta m = 5/3/4.5$ 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

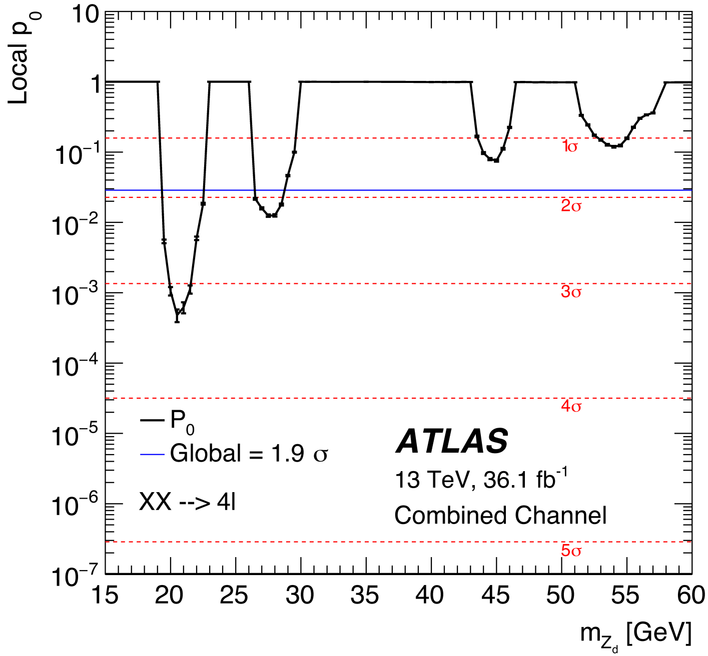

Figure 24: Observed local p-values under the background-only hypothesis