ATLAS Searches for Higgs Boson Decays to BSM Dark-Z Bosons in Four-Lepton Final States

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on behalf of the ATLAS Collaboration
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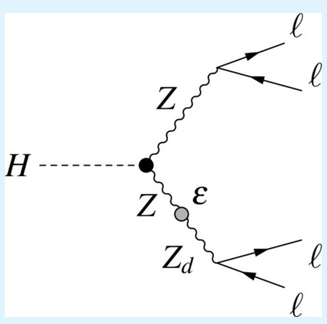
ATLAS-CONF-2021-034

Abstract

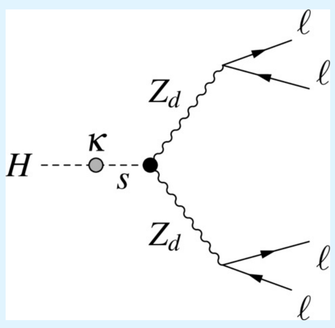
ATLAS searches for a BSM light boson using events where a Higgs boson with mass 125 GeV decays to four leptons are reported. This decay is presumed to occur via an intermediate state which contains one or two on-shell, promptly decaying bosons: H → ZX/XX → 4l, where X is a new dark vector boson Z_d (or a pseudo-scalar a), with an invariant mass between 1 and 60 GeV. These exotic Higgs decays searches use 139 fb^{-1} of p-p collision (Run-2) data at √s=13 TeV collected with the ATLAS detector at the LHC. The results are found to be consistent with SM background predictions and both fiducial model independent limits as well as limits with interpretations in specific benchmark theory models are set.

Introduction & Motivation

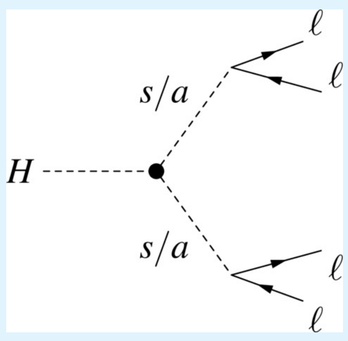
- B(Higgs → BSM) could be as large as $O(10\%)$
- Dark sector interactions could be mediated by a new massive $U(1)$ gauge boson Z_d
- It could couple to SM Higgs via mixing with Z boson or
- Dark sector Higgs S could mix with SM Higgs Boson



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



Dark Higgs S, coupling κ (controls coupling between S and H)



2HDM+S model allow Higgs to couple to a new low mass (pseudo)scalar s (α) states

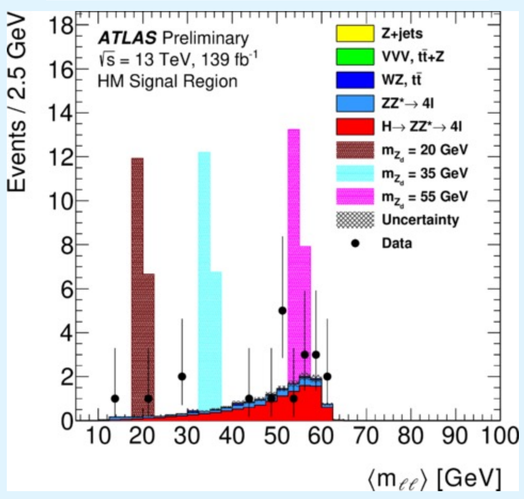
Analysis Overview

- Search for exotic decays of the Higgs in four lepton final states, 3 channels, where ℓ= e, μ
  1. High-mass (HM): H→XX→4ℓ, 15 GeV< m_X < 60 GeV
  2. Low-mass (LM): H →XX →4μ, 1 GeV< m_X < 15 GeV
  3. ZX channel: (ZX) H→ZX→4ℓ, 15 GeV< m_X < 55 GeV
- Select two pairs of prompt Same Flavor Opposite Sign (SFOS) leptons ($|m_{12} - m_Z| < |m_{34} - m_Z|$)
- Four-lepton invariant mass: 115 $GeV < m_{4\ell} <$ 130 GeV

HM Overview

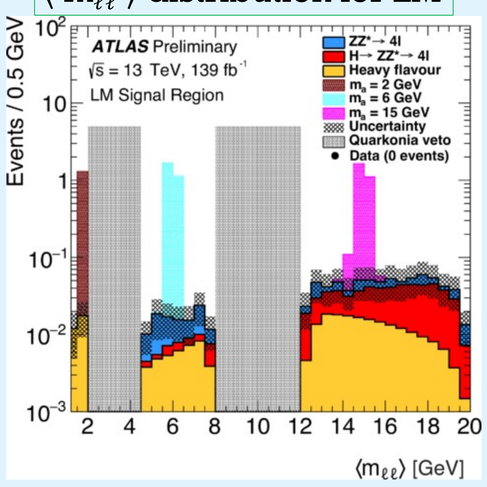
- Similar di-lepton invariant mass:
  - smallest $\Delta m_{\ell\ell} = m_{12} - m_{34}$
- Veto Z bosons (applied also to alternative pairings)
- Veto quarkonia
- Signal region: $m_{34}/m_{12} > 0.85 - 0.1125 f(m_{12})$
- 1D display of signal region: $<m_{\ell\ell}> = 1/2\,(m_{12} + m_{34})$

⟨ $m_{\ell\ell}$ ⟩ distribution for HM



LM Overview

⟨ $m_{\ell\ell}$ ⟩ distribution for LM



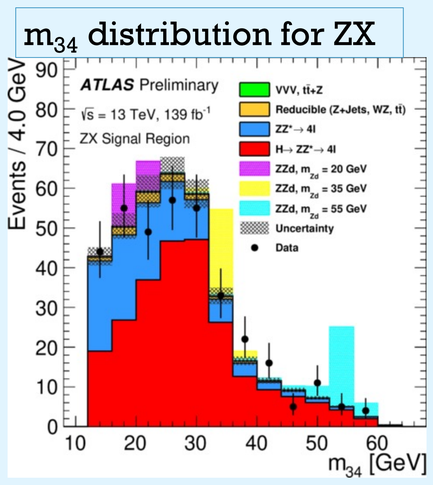
No events observed

- No Z-veto
- Extended quarkonia veto:
  - $m_{\ell\ell} \notin$ [2 GeV,4.4 GeV]
  - $m_{\ell\ell} \notin$ [8 GeV,12 GeV]
- Narrower Higgs mass window:
  - 120 GeV < $m_{4\ell}$ < 130 GeV
- Signal region requirement:
  - $m_{34}/m_{12} > 0.85$

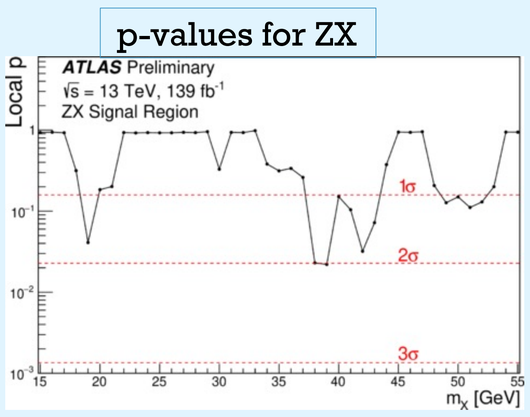
ZX Overview

- Quadruplet ranking (if more than one quadruplet in event):
  - In order 4μ > 2e2μ > 2μ2e > 4e
  - Resolve ambiguities by:
    - smallest $|m_Z - m_{12}|$, smallest $|m_Z - m_{34}|$
- One di-lepton pair m_{12} compatible with Z boson mass
- Signal region: the other di-lepton pair m_{34}
- 50 GeV< m_{12} <106 GeV & 12 GeV < m_{34} < 115 GeV

m_{34} distribution for ZX

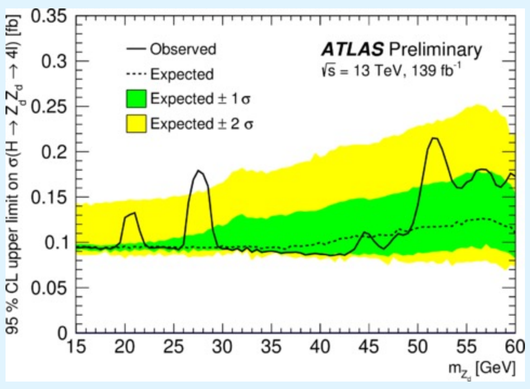


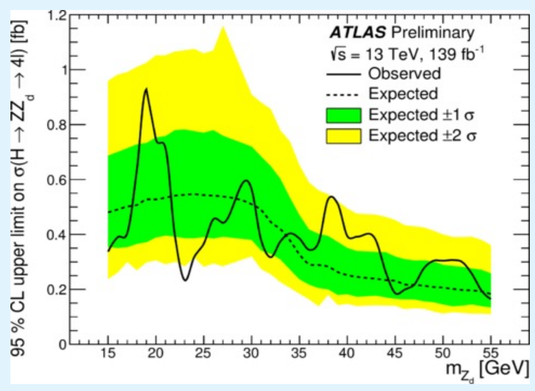
p-values for ZX



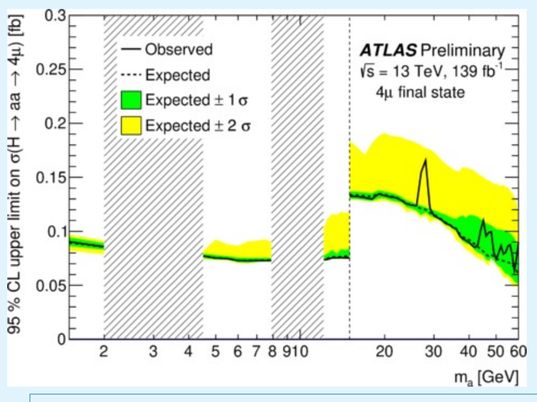
Analysis Results

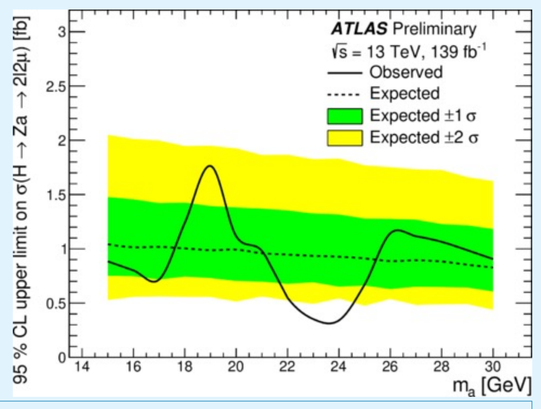
Limits at 95% CL on $\sigma(H \to Z_d Z_d \to 4\ell)$ and $\sigma(H \to ZZ_d \to 4\ell)$



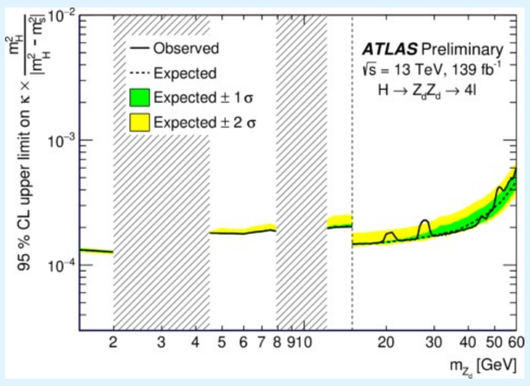


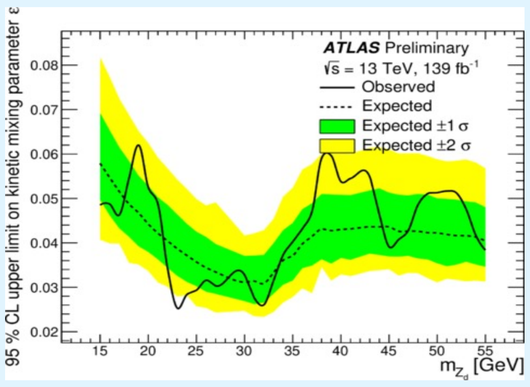
Limits at 95% CL on $\sigma(H \to \alpha\alpha \to 4\mu)$ and $\sigma(H \to Z\alpha \to 2\ell 2\mu)$





Limits on Higgs mixing parameter κ' and Z_d mixing parameter ε





Conclusions

- No significant excess observed above SM background predictions
- Upper limits set on fiducial ($H \to XX$ / ZX) and total cross sections ($H \to Z_d Z_d$ / $ZZ_d \to 4\ell$ and $H \to aa$ / $Za \to 4\mu$)
- Interpretations (HAHM, 2HDM+S) provided on mixing parameters: higgs coupling parameter κ, Z_d kinetic mixing ε, Z-Z_d mass mixing δ

References:
1. JHEP 06 (2018) 166
2. Phys. Rev. D 92 (2015) 092001
3. ATLAS-CONF-2020-027

(1) Affiliation: UTA, Chile

ATLAS SEARCHES FOR HIGGS BOSON DECAYS TO BSM DARK-Z BOSONS IN FOUR-LEPTON FINAL STATES

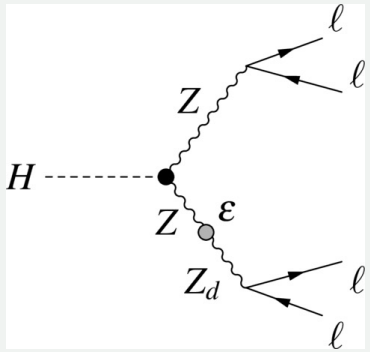
Theodota Lagouri (UTA)

On behalf of the ATLAS Collaboration

ATLAS-CONF-2021-034

INTRODUCTION& MOTIVATION

- B(Higgs → BSM) branching ratio could be as large as $O(10\%)$★
- Dark sector interactions could be mediated by a new massive $U(1)$ gauge boson Z_d
- It could couple to the SM Higgs via mixing with the Z boson or
- Dark sector Higgs S could mix with SM Higgs Boson



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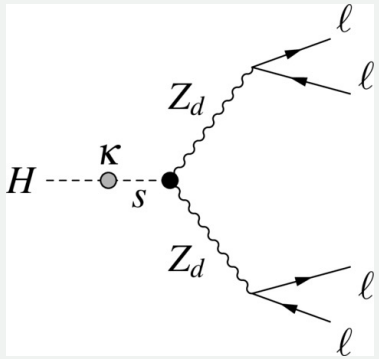

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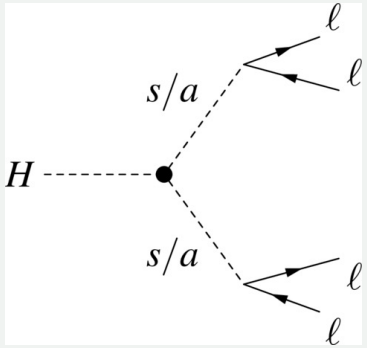


2HDM+S model allow Higgs to couple to new low mass (pseudo)scalar s (α) states

★ATLAS-CONF-2020-027

ANALYSIS OVERVIEW

- ATLAS (Run-2) 139 fb^{-1} data at $\sqrt{s}$=13 TeV analyzed
- Search for exotic decays of the Higgs in four lepton final states, in 3 channels, where ℓ= e, μ:
  1. High-mass (HM): $H \rightarrow XX \rightarrow 4\ell$, 15 GeV< m_X < 60 GeV
  2. Low-mass (LM): $H \rightarrow XX \rightarrow 4\mu$, 1 GeV< m_X < 15 GeV
  3. ZX channel: (ZX) $H \rightarrow ZX \rightarrow 4\ell$, 15 GeV< m_X < 55 GeV
- Select two pairs of prompt Same Flavor Opposite Sign (SFOS) leptons
- Define pairs m_{12} and m_{34} such that $|m_{12} - m_Z| < |m_{34} - m_Z|$
- Four-lepton invariant mass: 115 $GeV < m_{4\ell} <$ 130 GeV compatible with Higgs boson mass

ANALYSIS OVERVIEW - HM

- Similar di-lepton invariant mass:
  - smallest $\Delta m_{\ell\ell} = m_{12} - m_{34}$
- Veto Z bosons:
  - $10\ GeV < m_{12}, m_{34} < 64\ GeV$
  - $5\ GeV < m_{14}, m_{32} < 75\ GeV$ (for same flavor quadruplets)
- Veto quarkonia
- Signal region requirement:
  - $m_{34}/m_{12} > 0.85 - 0.1125 f(m_{12})\star$
- 1D display of signal region:
  - $< m_{\ell\ell} > = 1/2\ (m_{12} + m_{34})$

Backgrounds:

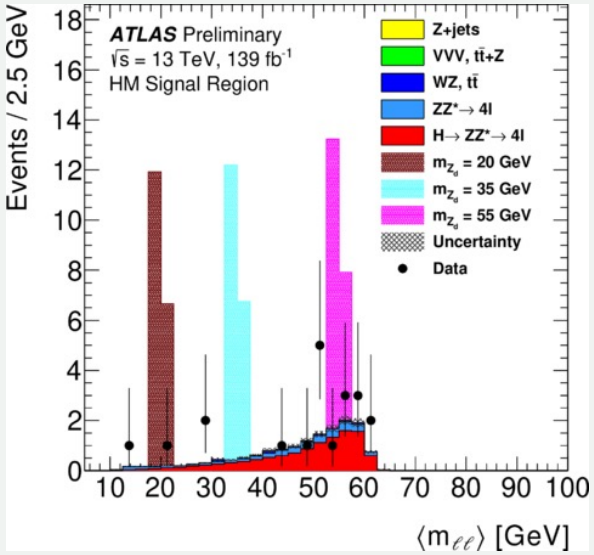
- $H \rightarrow ZZ^* \rightarrow 4\ell$
- $ZZ^\star \rightarrow 4\ell$
- WZ, tt
- VVV, tt+Z

} MC

- Z+jets: data driven (DD)

Process	Yield (±stat. ± syst.)
$H \rightarrow ZZ^* \rightarrow 4\ell$	$11.12 \pm 0.05 \pm 1.02$
$ZZ^* \rightarrow 4\ell$	$3.38 \pm 0.05 \pm 0.25$
$t\bar{t}$	$0.47 \pm 0.13 \pm 0.09$
Z + jets	$0.43 \pm 0.39^{+0.17}_{-0.01}$
$Z + t\bar{t} \rightarrow 4\ell$	$0.09 \pm 0.02 \pm 0.02$
WZ	$0.05 \pm 0.03^{+0.05}_{-0.00}$
VVV/VBS	Negligible
Heavy flavour	Negligible
Total	$15.6 \pm 0.4 \pm 1.2$
Data	20

⟨ $m_{\ell\ell}$ ⟩ distribution for HM



$\sigma(pp \rightarrow H \rightarrow Z_d Z_d \rightarrow 4\ell) = (1/10)\sigma_{SM}(pp \rightarrow H \rightarrow ZZ^\star \rightarrow 4\ell)$

$\star$ $f(m_{12}) \sim 1$ at $m_X = 15$ GeV and 0 for $m_X > 50$ GeV

ANALYSIS OVERVIEW - LM

- No Z-veto:
  - 1.2 GeV < m_{12},m_{34} < 20 GeV
- Extended quarkonia veto:
  - $m_{ll} \notin$ [2 GeV,4.4 GeV]
  - $m_{ll} \notin$ [8 GeV,12 GeV]
- Narrower Higgs mass window:
  - 120 GeV < $m_{4\ell}$< 130 GeV
- Signal region requirement:
  - m_{34} / m_{12} > 0.85

Backgrounds:

- H→ZZ*→4μ
- ZZ* → 4μ
- Heavy Flavor: bb decay

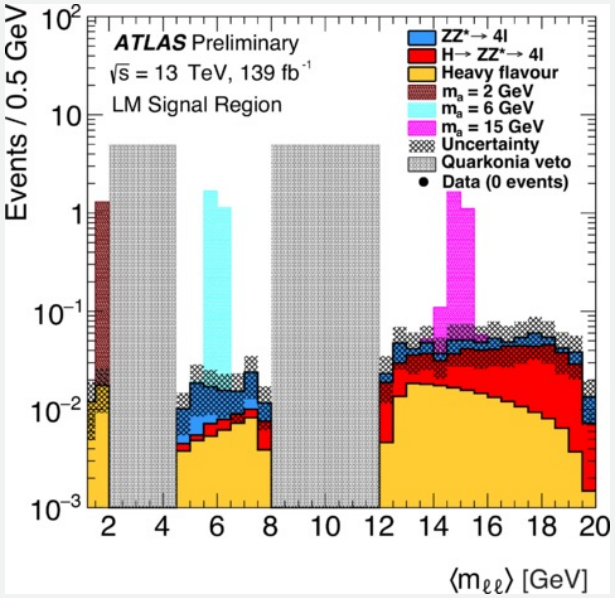
} MC

DD

No events observed in data

Process	Yield (±stat. ± syst.)
$H \to ZZ^* \to 4\mu$	$0.41 \pm 0.01 \pm 0.03$
$ZZ^* \to 4\mu$	$0.22 \pm 0.04 \pm 0.04$
VVV/VBS	Negligible
Heavy flavour	$0.26 \pm 0.09 \pm 0.10$
Total	$0.89 \pm 0.10 \pm 0.11$
Data	0

⟨ $m_{\ell\ell}$ ⟩ distribution for LM



$\sigma(pp \to H \to \alpha\alpha \to 4\mu) = (1/10)\sigma_{SM}(pp \to H \to ZZ^\star \to 4\mu)$

ANALYSIS OVERVIEW - ZX

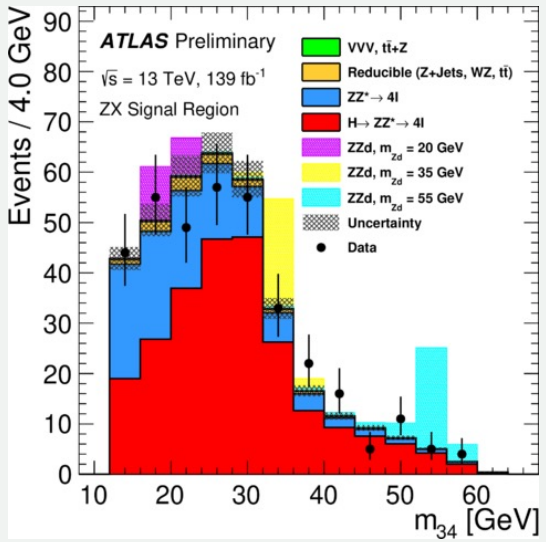
- Quadruplet⋆ ranking (if more than one quadruplet in event):
  - In order $4\mu > 2e2\mu > 2\mu2e > 4e$
  - Resolve ambiguities by:
    - smallest $|m_Z - m_{12}|$
    - smallest $|m_Z - m_{34}|$
- One di-lepton pair m_{12} compatible with Z boson mass m_{12}
- Signal region: the other di-lepton pair invariant mass m_{34}
- 50 GeV < m_{12} < 106 GeV & 12 GeV < m_{34} < 115 GeV
- $m_{14,32} > 5$ GeV ($4e/4\mu$) (alternative pairings allowed)

Backgrounds:

- $H \to ZZ^* \to 4\ell$: MC shape, normalization from fit
- $ZZ^* \to 4\ell$: MC
- Reducible Z+jets, tt: DD
- VVV, tt + Z: MC

Process	Yield (±stat. ± syst.)		
	$2\ell2\mu$	$2\ell2e$	Total
$H \to ZZ^* \to 4\ell$	127.9 ± 0.1 ± 3.6	76.1 ± 0.1 ± 10.2	204.0 ± 0.2 ± 12.4
$ZZ^* \to 4\ell$	70.2 ± 0.2 ± 1.9	33.0 ± 0.2 ± 3.6	103.3 ± 0.3 ± 4.6
Reducible	4.9 ± 0.1 ± 0.3	5.8 ± 0.3 ± 0.6	10.7 ± 0.3 ± 1.0
$VVV, t\bar{t} + Z$	1.1 ± 0.1 ± 0.04	0.7 ± 0.1 ± 0.1	1.8 ± 0.1 ± 0.1
Total	204.1 ± 0.3 ± 5.5	115.6 ± 0.5 ± 13.8	319.7 ± 0.5 ± 17.0
Data	237	119	356

m_{34} distribution for ZX

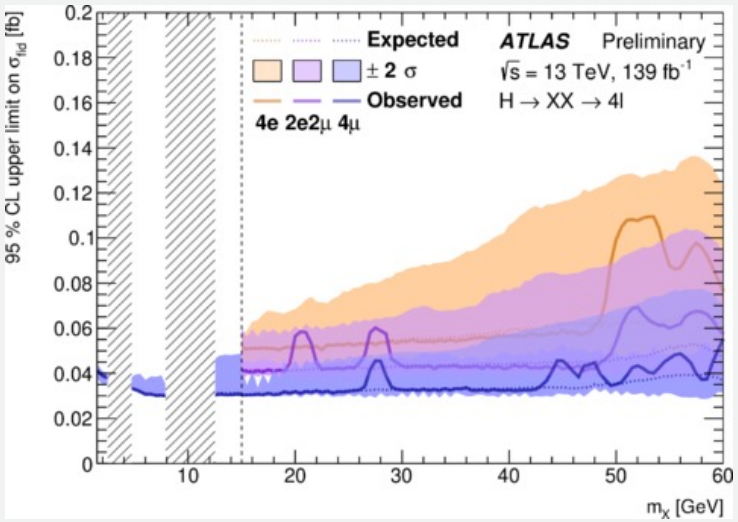


⋆Quadruplet selection similar to SM $H \to ZZ^* \to 4l$ (JHEP **03** (2018) 095)

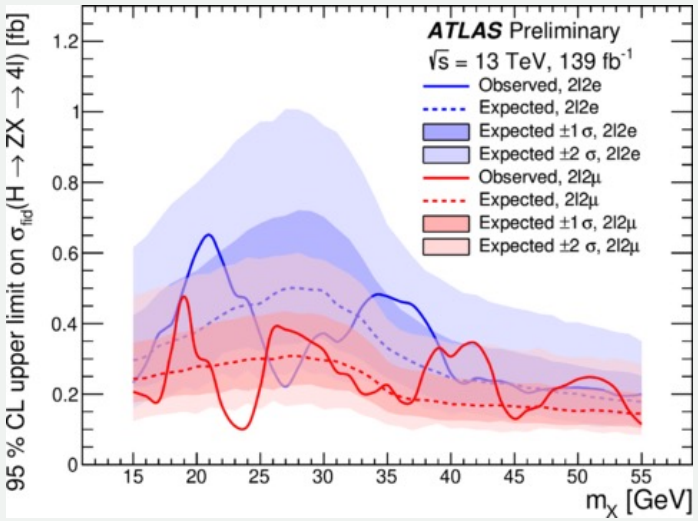
$\sigma(pp \to H \to ZZ_d \to 4\ell) = (1/10)\ \sigma_{SM}(pp \to H \to ZZ^\star \to 4\ell)$

ANALYSIS RESULTS - FIDUCIAL LIMITS

Upper limits at 95% CL on (a) $\sigma_{fid}(H \to Z_d Z_d \to 4\ell)$ and (b) on $\sigma_{fid}(H \to ZZ_d \to 4\ell)$



(a)

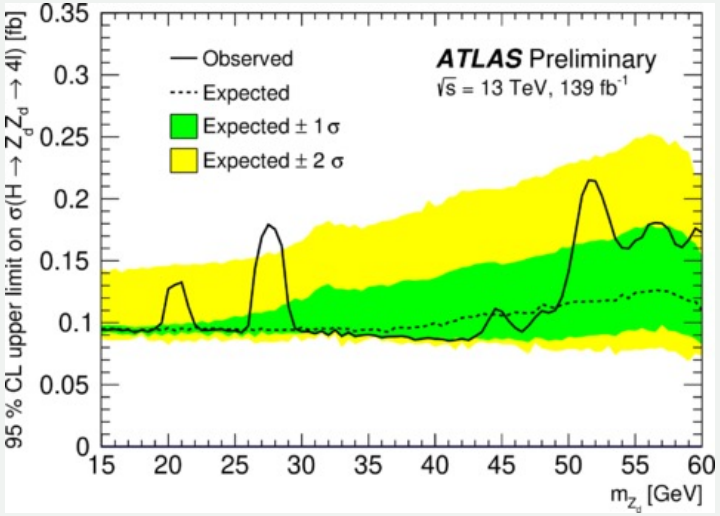


(b)

- The systematic uncertainties for all channels are very small, while the statistical uncertainties are dominant
- No significant excess observed above SM background predictions

ANALYSIS RESULTS – CROSS SECTION LIMITS (1)

Upper limits at 95% CL on (a) $\sigma(H \to Z_d Z_d \to 4\ell)$ and (b) on $\sigma(H \to ZZ_d \to 4\ell)$



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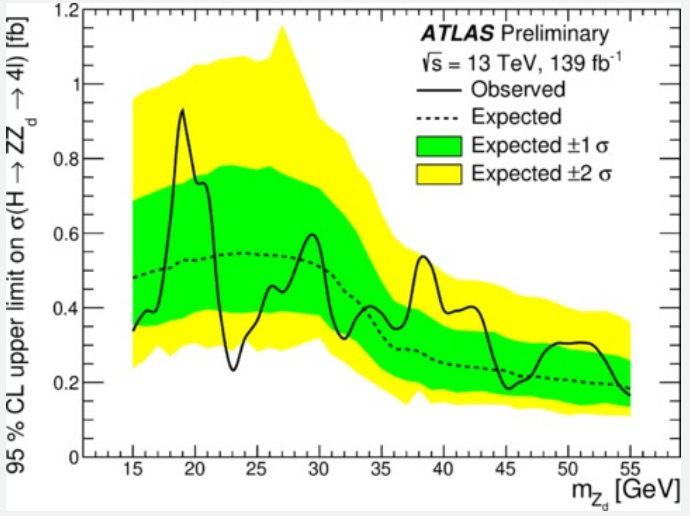
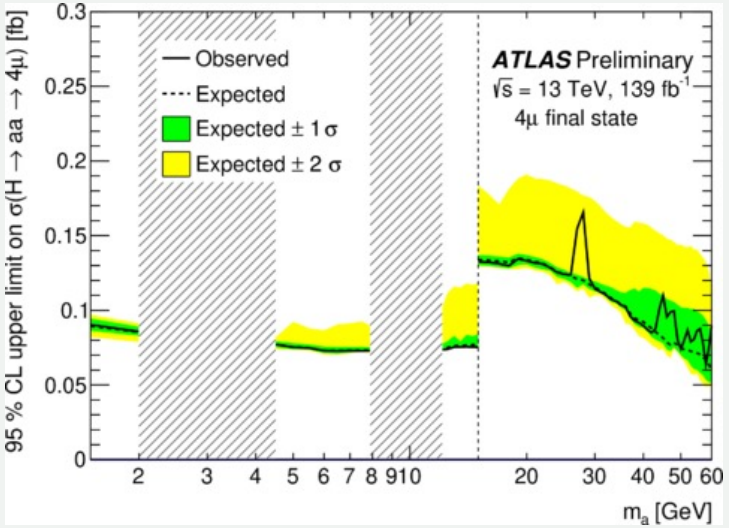


(b)

- Assuming SM Higgs boson production via the gluon-gluon fusion process

ANALYSIS RESULTS – CROSS SECTION LIMITS (2)

Upper limits at 95% CL on (a) $\sigma(H \to \alpha\alpha \to 4\mu)$ and (b) on $\sigma(H \to Z\alpha \to 2\ell 2\mu)$



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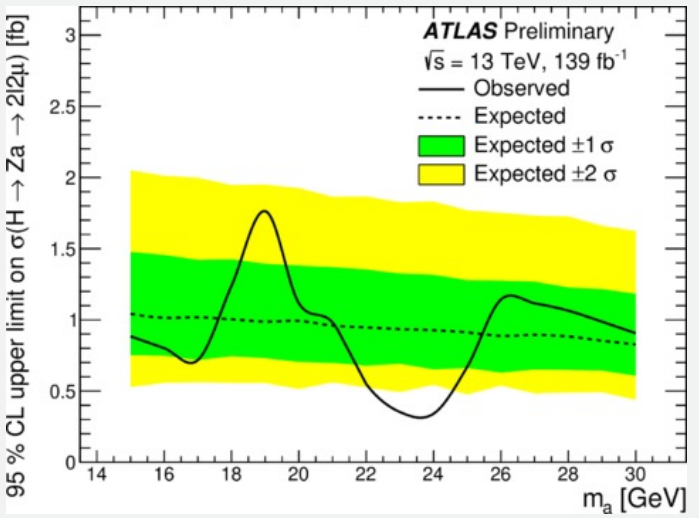
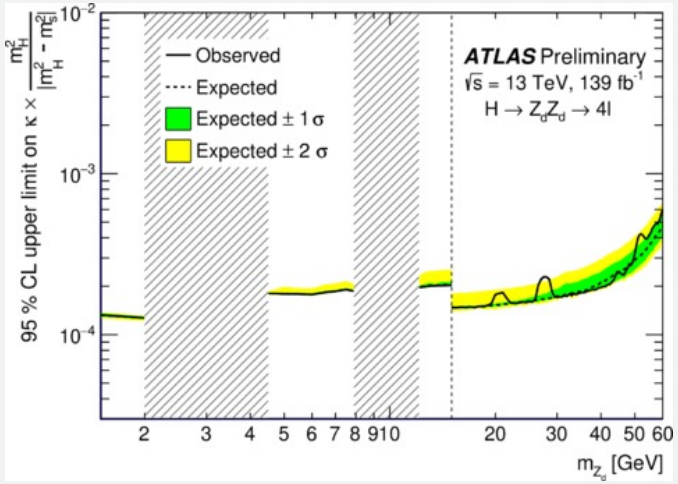


(b)

- Assuming SM Higgs boson production via the gluon-gluon fusion process

ANALYSIS RESULTS – MIXING PARAMETERS LIMITS

Upper limits at 95% on (a) Higgs mixing parameter $\kappa' = \kappa\, m_H^2 / |m_H^2 - m_S^2|$ and
(b) Z_d mixing parameter ε, (c) Z-Z_d mass mixing parameter δ



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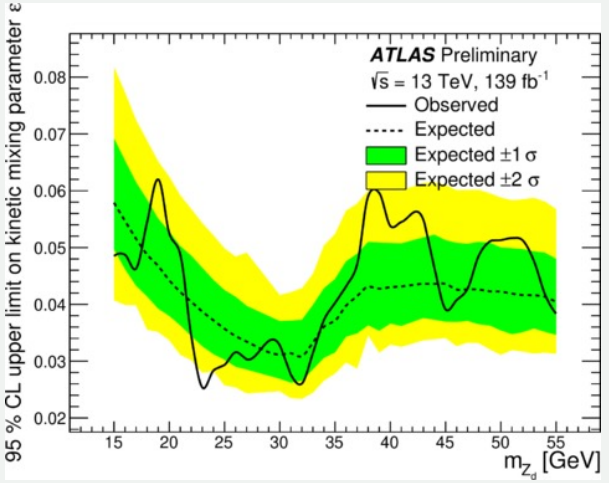
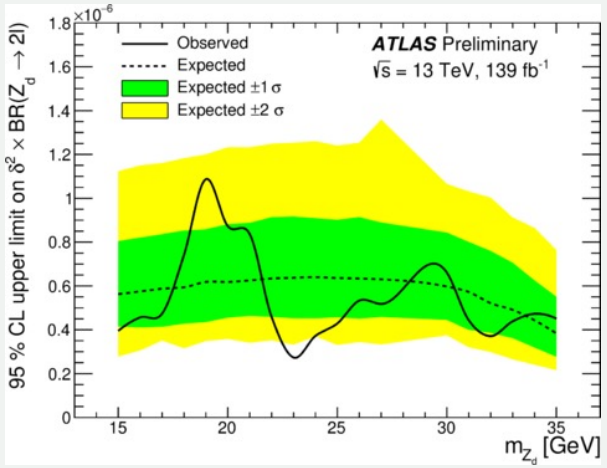


(b)



(c)

CONCLUSIONS

- ATLAS Run-2 139 fb^{-1} data at $\sqrt{s}$=13 TeV analyzed
- No significant excess observed above SM background predictions.
- Results interpreted in terms of exclusion limits.
- Upper limits set on fiducial ($H \rightarrow XX$ / ZX) and total cross sections ($H \rightarrow Z_d Z_d$ / $ZZ_d \rightarrow 4\ell$ and $H \rightarrow aa$ / $Za \rightarrow 4\mu$)
- Interpretations (HAHM, 2HDM+S) provided on mixing parameters: higgs coupling parameter κ, Z_d kinematic mixing ε and Z-Z_d mass mixing δ

References:

1. JHEP 06 (2018) 166
2. Phys. Rev. D 92 (2015) 092001