Search for exotic and rare decays of the Higgs boson with the ATLAS detector

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Rare decays

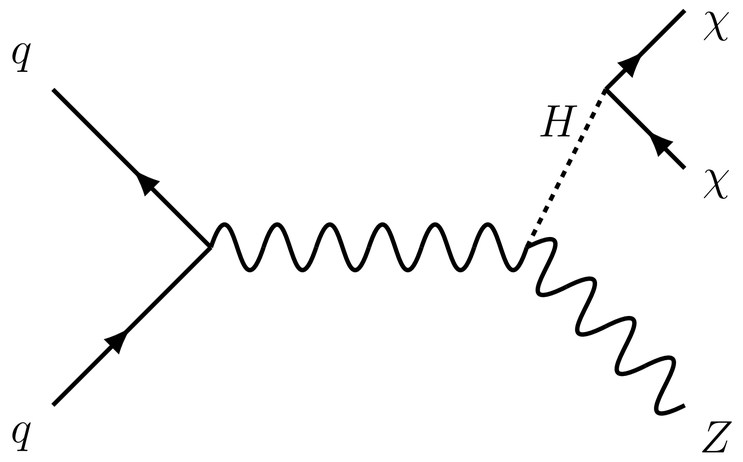
- Higgs couplings to 1st and 2nd generation need to be measured to confirm the Standard Model (SM)
  - H → ee, μμ etc.
- Rare and invisible decay Standard Model (SM) branching ratios are tiny.
  - any significant deviation from SM could indicate new physics.
  - H → Zγ, Meson+γ, etc.; H → invisible
- New results on
  - ZH, Z → ll and H → invisible (Z(ll)Hinv).
  - With full data set (139 fb^{-1}) from 13 TeV pp collisions.

Exotic decays

- Many Beyond the Standard Model (BSM) Theories predicts exotic decays of Higgs boson.
- Two Higgs Doublet Model (2HDM) + S (singlet).
  - 5 Higgs bosons: scalar (H), pseudoscalar (a), heavy scalar, two charged.
- Dark matter motivated: Dark sector.
  - Dark Higgs, dark photon, dark Z (Z_d), etc.
- New results with full data set (139 fb^{-1}) from 13 TeV pp collisions:
  - $H \rightarrow aa \rightarrow bb\mu\mu$
  - $H \rightarrow aa \rightarrow 4\mu$
  - $H \rightarrow ZZ_d \rightarrow 4l$
  - $H \rightarrow Z_dZ_d \rightarrow 4l$

Z(ll)Hinv

ATLAS-CONF-2021-029

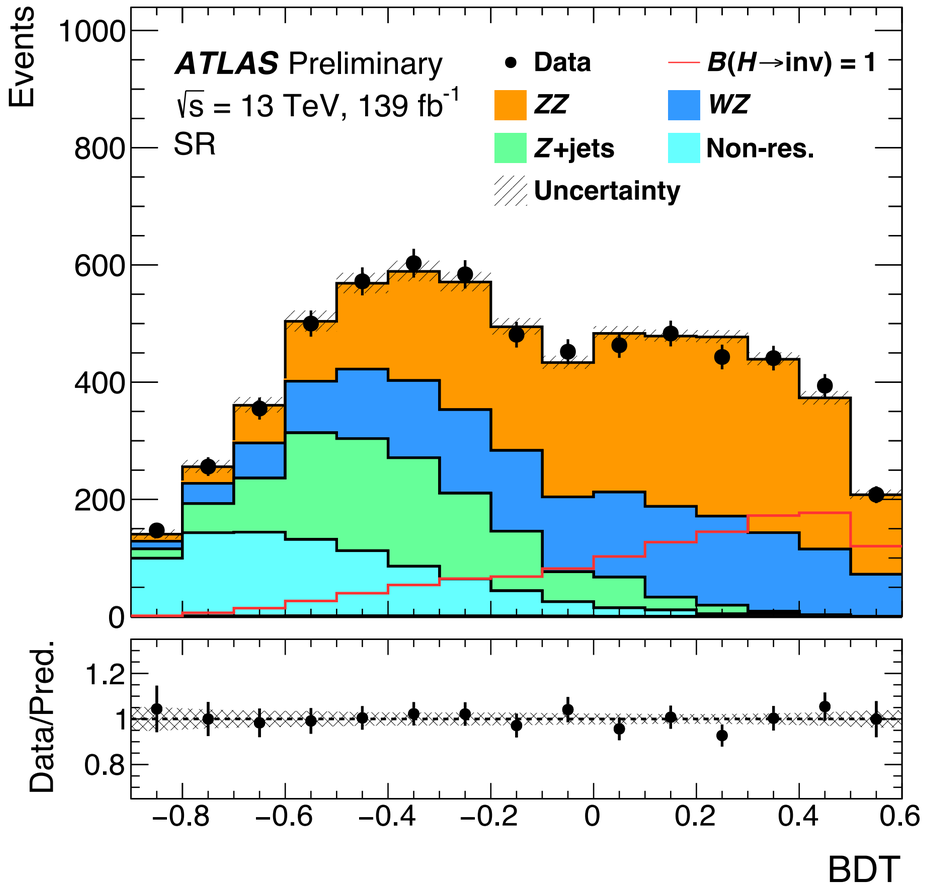


- Associated production of Higgs : ZH
- Z decays to 2 leptons (electrons or muons): clean channel

- SM Hinv decay BR(H → ZZ → 4ν) = 0.1 %.
- Current best limit on invisible decay from ATLAS:
  - BR < 11 % (ATLAS-CONF-2020-052)
  - Combination of VBF H and ttH results.

Z(ll)Hinv: Method

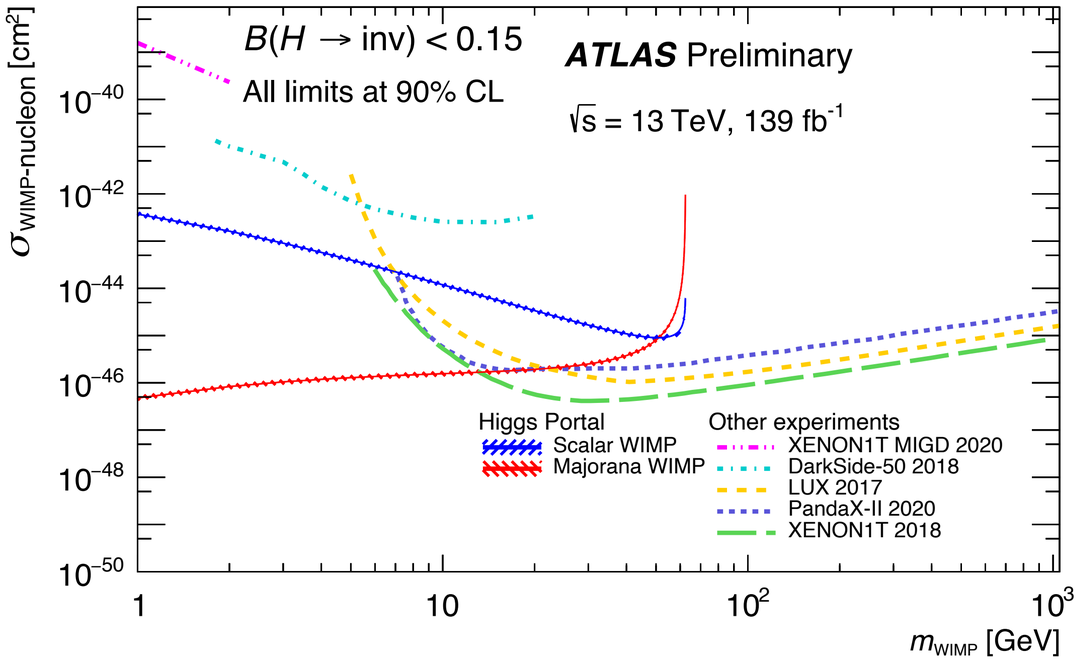
- Event selection.
  - Electron and muon triggers.
  - Two isolated leptons with p_T > 30, 20 GeV.
  - Z mass window: 76 GeV < lepton pair mass < 106 GeV.
  - Missing transverse momentum (MET) > 90 GeV.
  - MET significance > 9.
- Background estimation.
  - ZZ : 4 lepton control region.
  - WZ: 3 lepton control region.
  - Non-resonant (ttbar, WW etc.): eμ control region.
  - Z+jets: simulation.
- BDT (Boosted Decision Tree) score is used as a discriminant variable.
- Systematic limited: ZZ modeling uncertainty is the largest.



Z(ll)Hinv: Results

- BR limit: BR < 18 % (both observed and expected).
- 45 % improvement from previous result.
- Significant contribution to the next combined limit with VBF H and ttH.

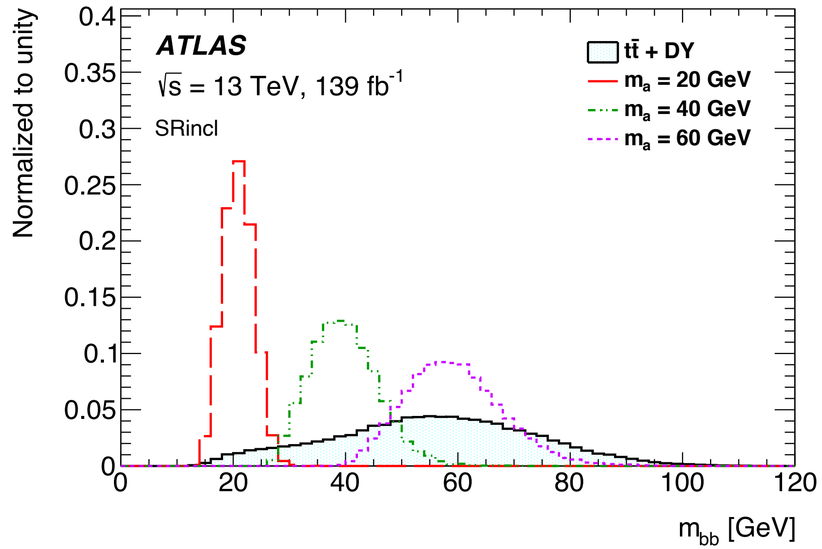
- Compared with dark matter direct detection experiments.
- Using a Higgs portal model.



H → aa → bbμμ : Selection

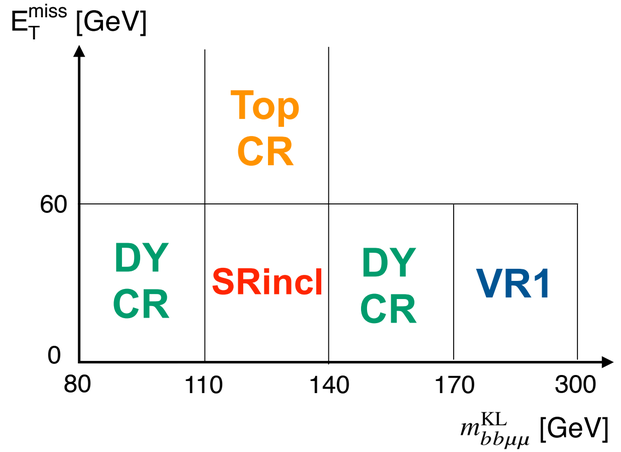
arXiv:2110.00313

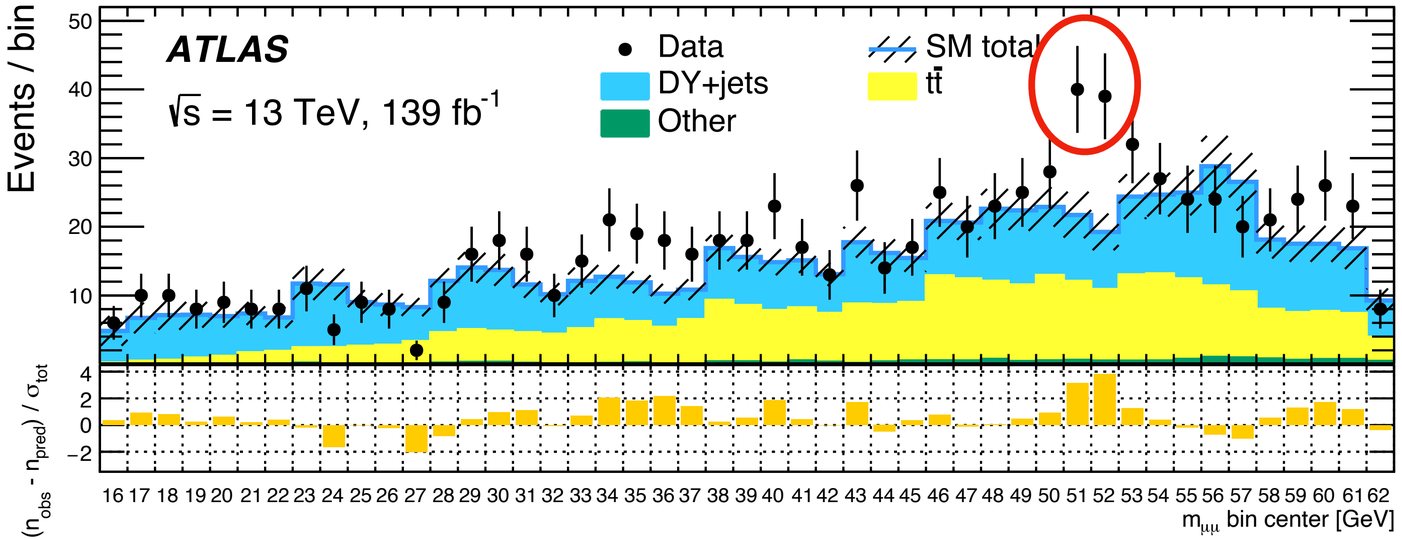
- Event selection
  - Muon triggers.
  - Two isolated muons with p_T > 15, 5 GeV.
  - Two b-tagged jets with p_T > 20 GeV.
  - b pair mass is close to muon pair mass.
    - A kinematic fit was used to achieve this.
  - Higgs window: 110 GeV < bbμμ mass < 140 GeV.
  - Low missing transverse momentum (MET) < 60 GeV.
  - BDT (Boosted Decision Tree) cut was used to reduce backgrounds.
  - 15 GeV < muon pair mass < 65 GeV.



H → aa → bbμμ : Backgrounds

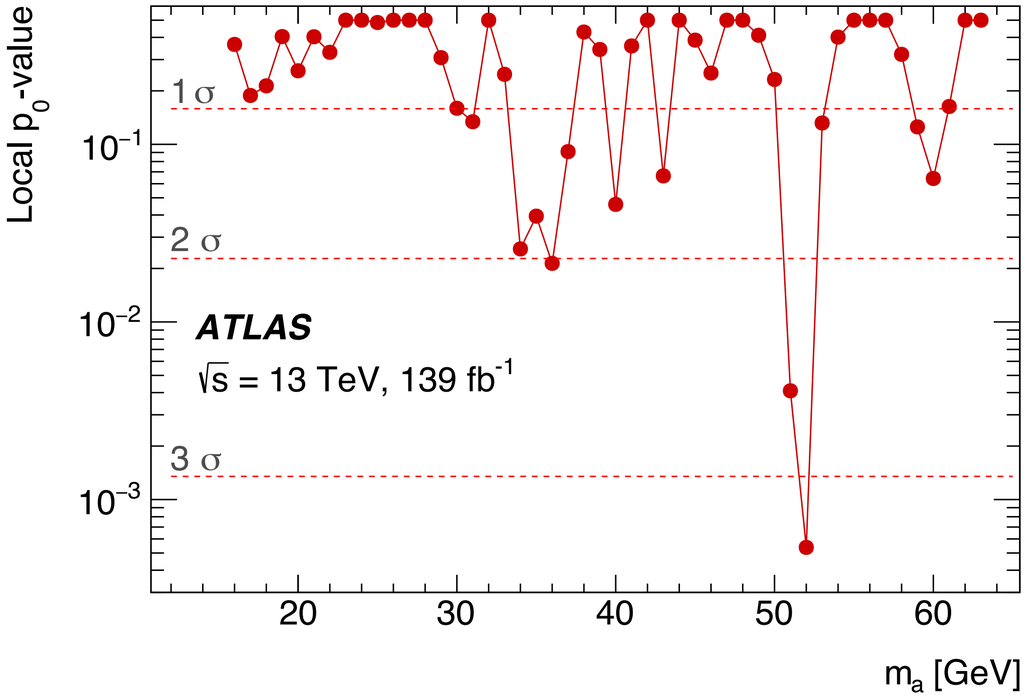
- Backgrounds
  - DY (Drell-Yan) dimuon + jets:
    - bbμμ mass side bands control region.
    - Distribution shapes are from data templates with 0 b-jets.
  - ttbar:
    - High-MET control region
    - Distribution shapes are from simulation.
  - Other (diboson, single-top etc.):
    - Simulation.





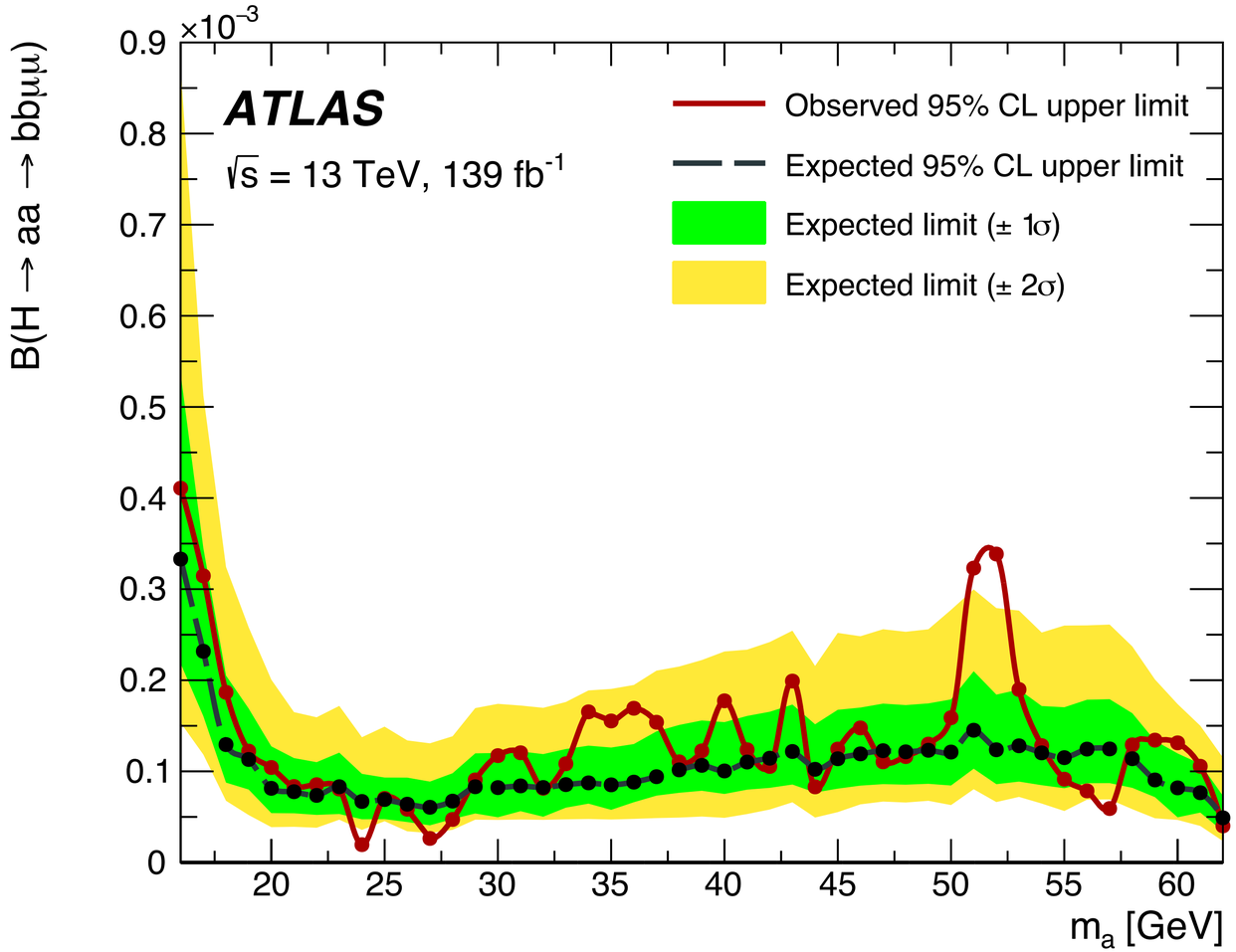
H → aa → bbμμ : Results

- Dominant systematic uncertainties.
  - DY background: BDT selection and normalization.
  - Signal : b-tagging and jet energy related uncertainties.
- Overall data are compatible with the SM background.
  - The data excess at 52 GeV is local 3.3 σ, global 1.7 σ.



H → aa → bbμμ : Limits

- Limits on B(H → aa → bbμμ).
- Factor 2 - 5 improvement from the previous analysis.
  - Larger data set (factor ~2).
  - Use of BDT (factor ~2).



H → aa → 4μ

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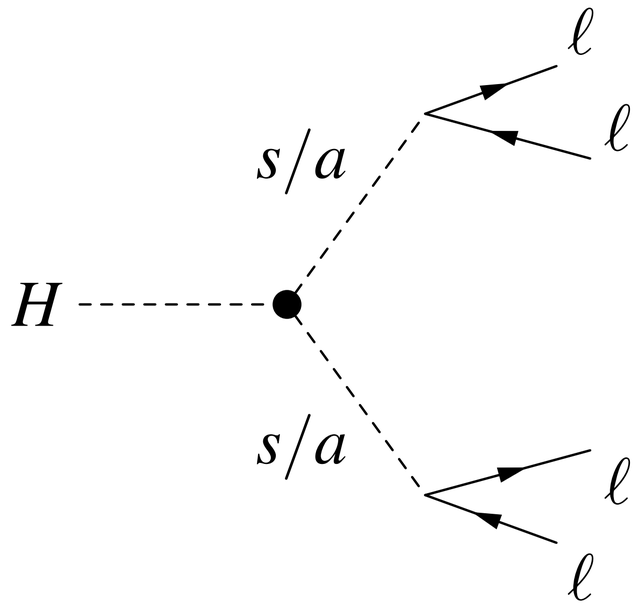
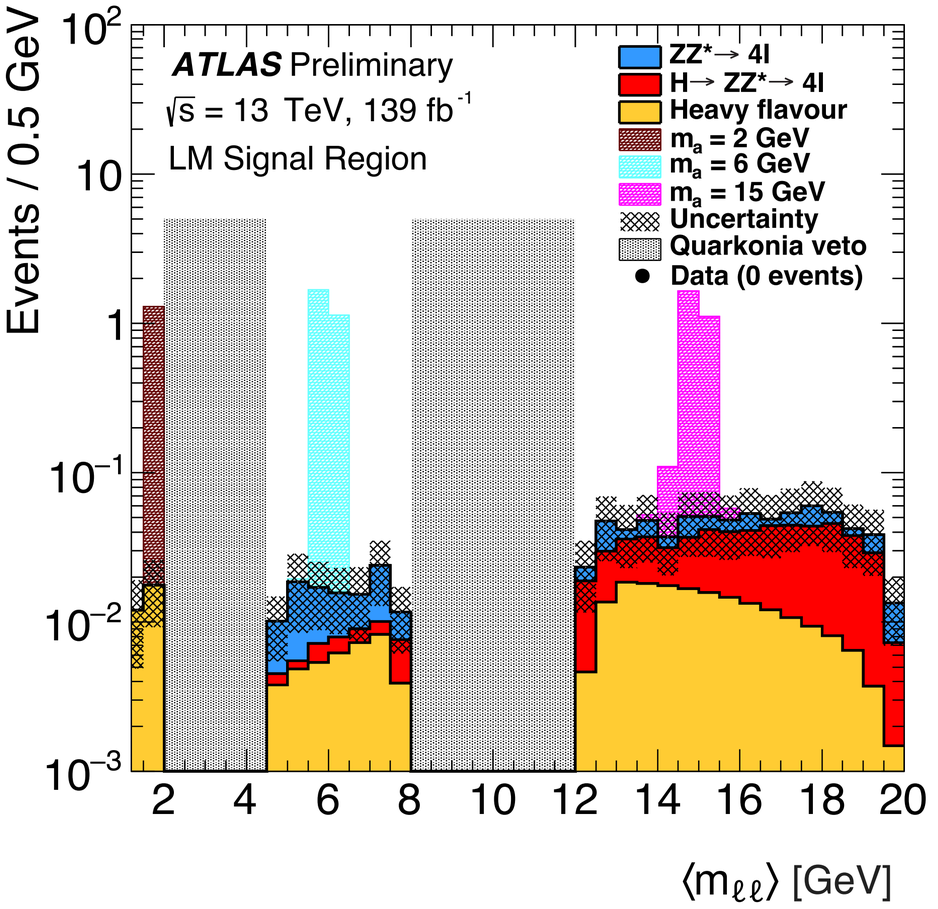


- Event selection
  - Muon triggers.
  - 4 or more isolated muons with p_T > 20, 15, 10, 5 GeV.
  - Selection of 2 pairs: m_{12} and m_{34}.
    - $m_{12} > m_{34}$.
    - Smallest $|m_{12} - m_{34}|$.
  - Higgs mass window: 120 GeV < $m_{4\mu}$ < 130 GeV.
  - heavy-flavor/quarkonia vetos.
  - $m_{12} \sim m_{34}$: $m_{34}/m_{12} > 0.85$
  - 1.2 GeV < m_{12} and m_{34} < 15 GeV.

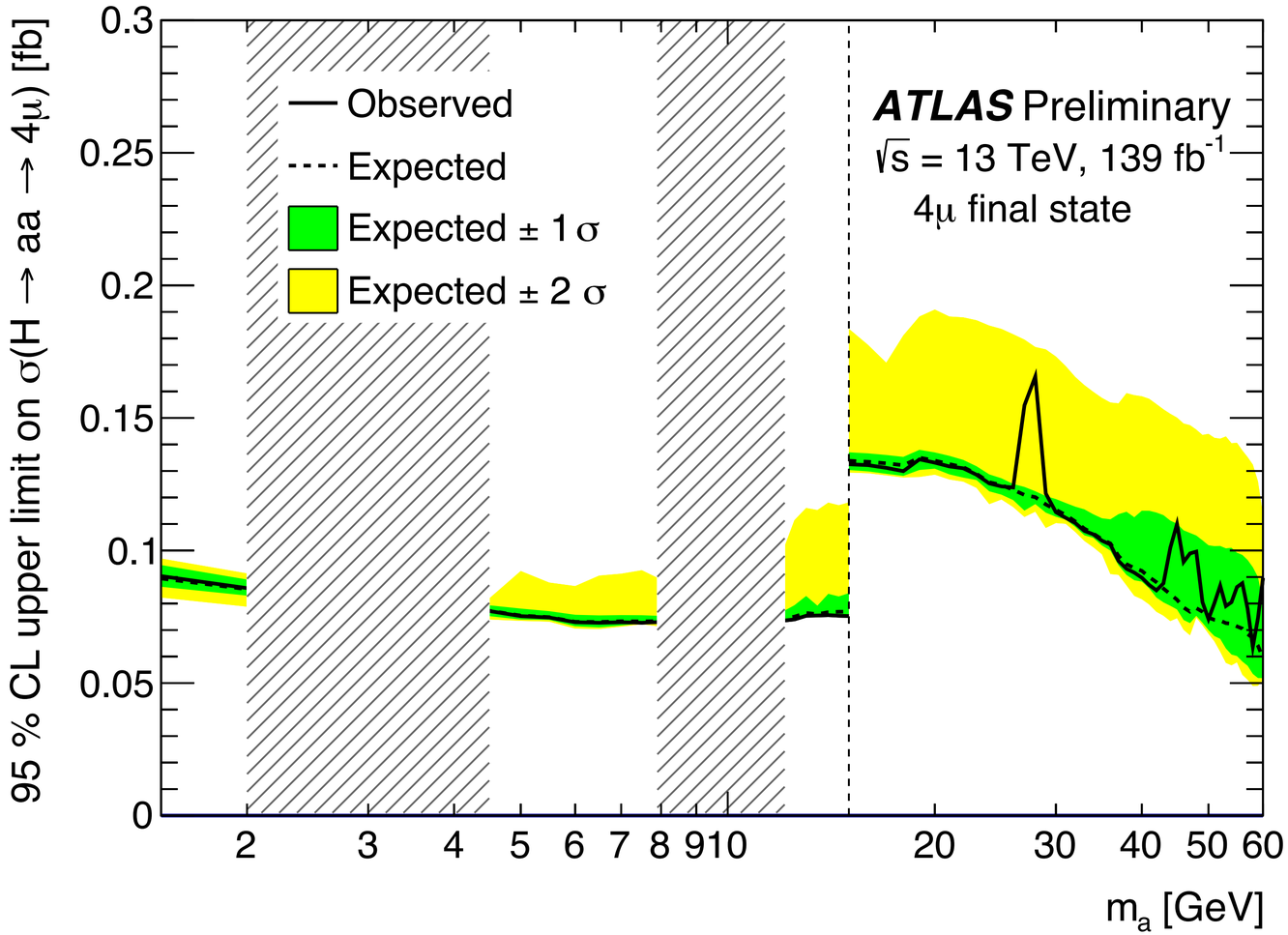
H → aa → 4μ: Backgrounds

- Backgrounds: simulation.
  - ZZ* → 4μ: simulation.
  - H → ZZ* → 4μ: simulation.
  - Non-prompt leptons from heavy flavour hadrons: data-driven method.
- Statistics limited.



H → aa → 4μ: Limits

- Limits on σ(H → aa → 4μ)
- Factor ~3 improvement from previous results.



H → aa Summary

- Model independent limits.
- 4μ and bbμμ are the two strongest limits.
- The 4μ in the plot is previous one.

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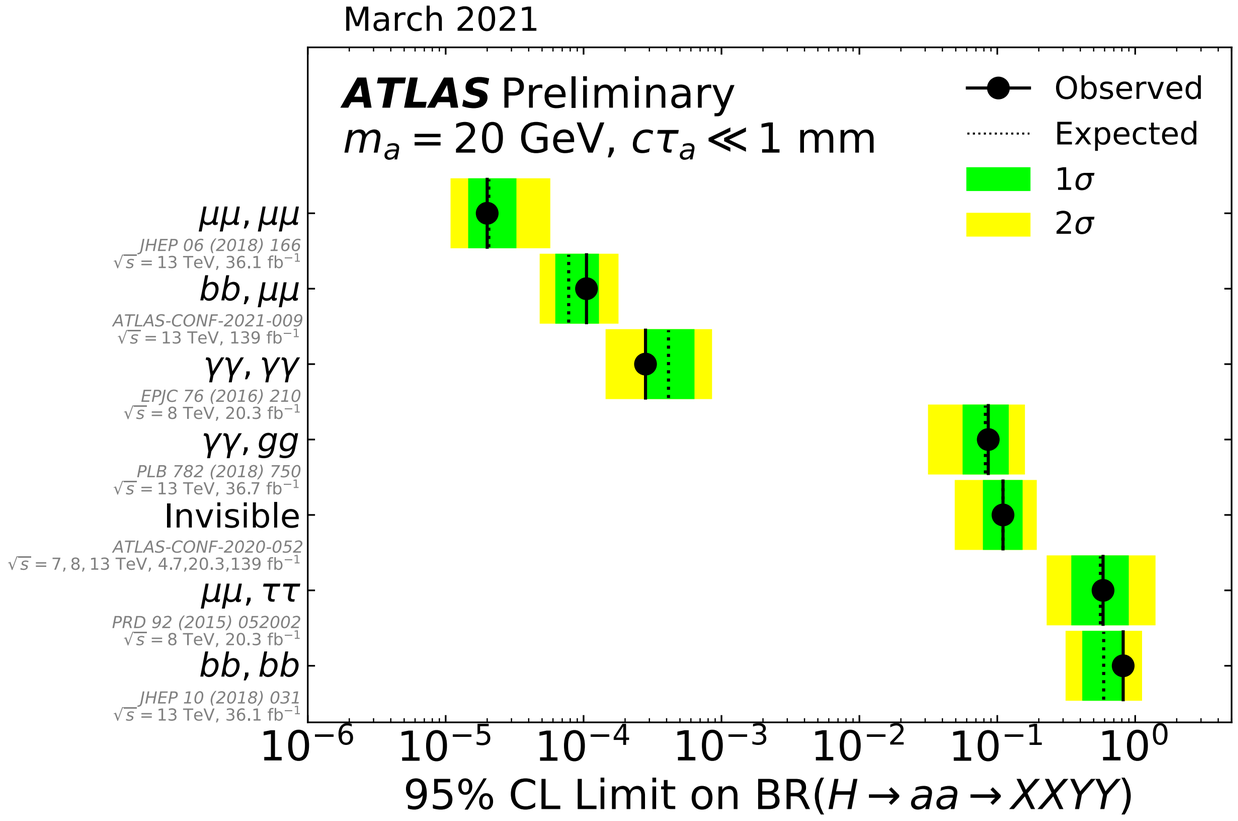
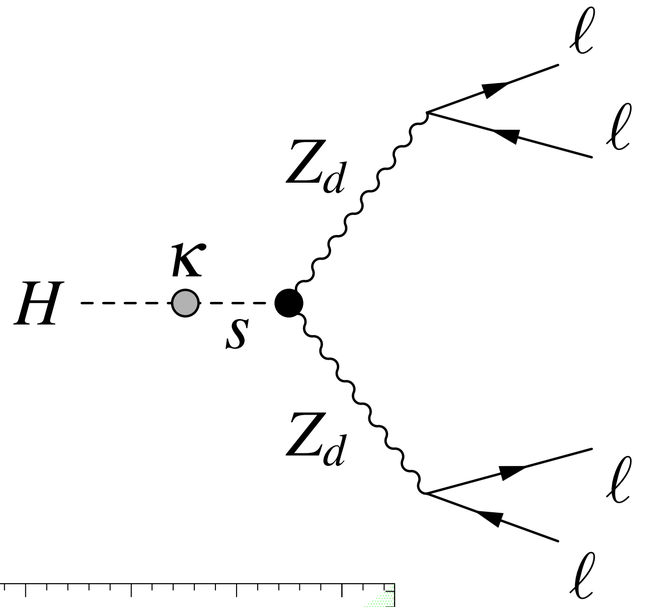
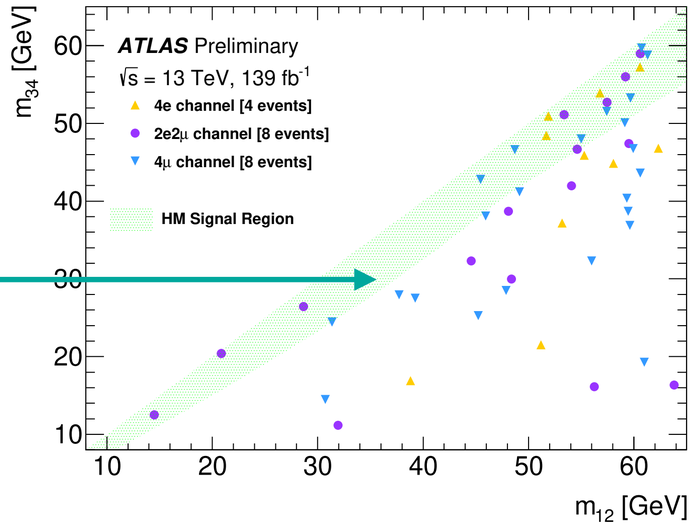


$H \rightarrow Z_d Z_d \rightarrow 4l$

ATLAS-CONF-2021-034

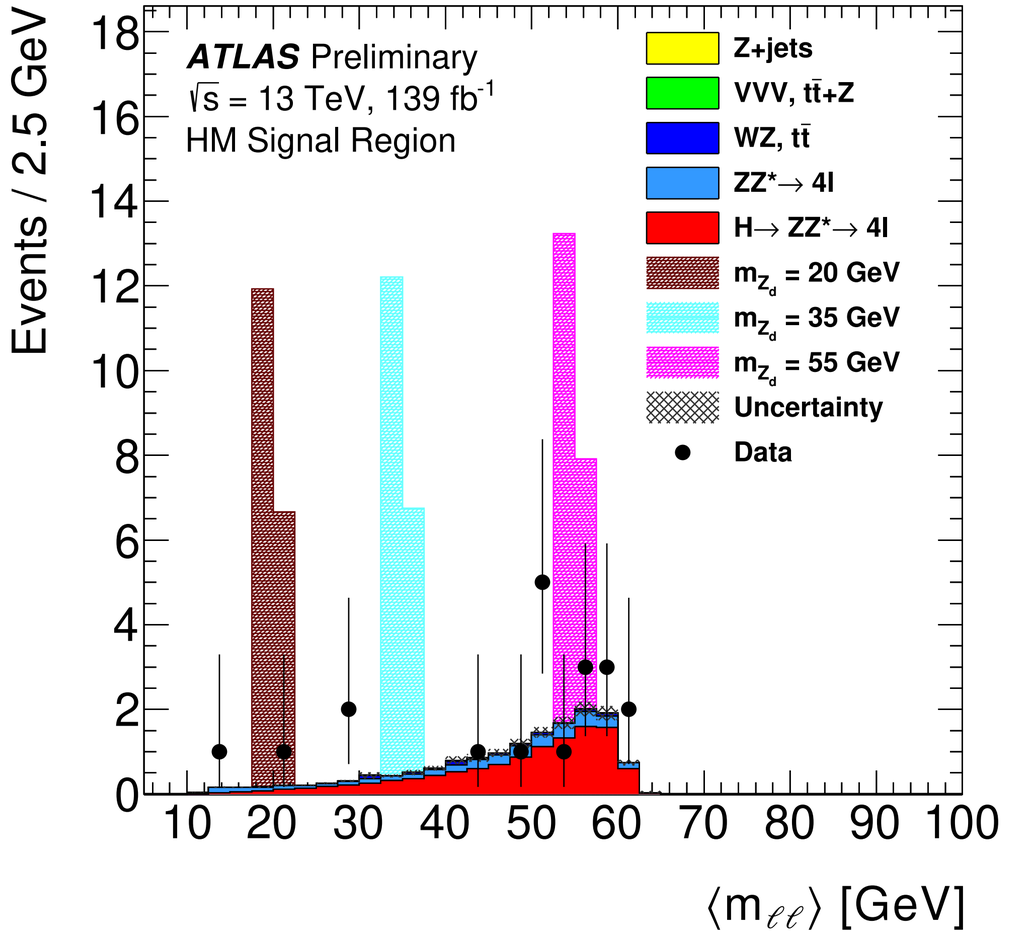
- Model
  - Z_d : dark Z, s: dark scalar
  - κ: Higgs and dark scalar mixing constant.
- Event selection (almost identical to $H \rightarrow aa \rightarrow 4\mu$)
  - Electron and muon triggers.
  - 4 or more isolated leptons with $p_T > 20, 15, 10, 5$ GeV.
  - Selection of 2 pairs: m_{12} and m_{34}.
    - m_{12} is closer to Z mass.
    - Smallest $|m_{12} - m_{34}|$.
  - Higgs mass window: $115 \text{ GeV} < m_{4\mu} < 130 \text{ GeV}$
  - Z vito. Quarkonia vito.
  - $m_{12} \sim m_{34}$: $m_{34}/m_{12} > 0.85 - 0.1125\, f(m_{12})$.
  - $15 \text{ GeV} < m_{12}$ and $m_{34} < 60$ GeV.





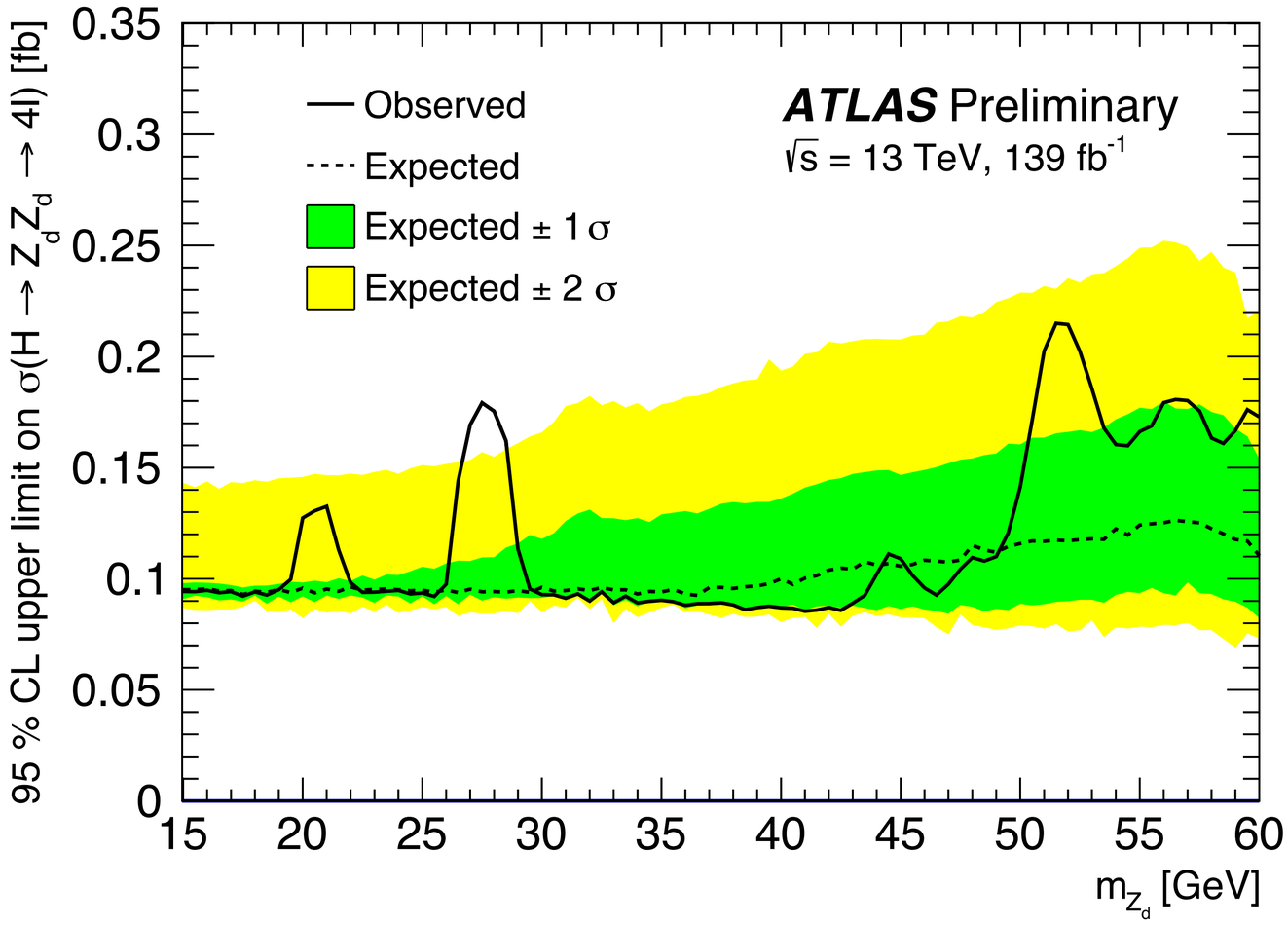
$H \rightarrow Z_d Z_d \rightarrow 4l$: Background

- Backgrounds: simulation.
  - $ZZ^* \rightarrow 4l$: simulation.
  - $H \rightarrow ZZ^* \rightarrow 4l$: simulation.
  - Z+jets: data-driven fake factor method.
  - Other small backgrounds: simulation.
- Statistics limited.
- Excess at 28 GeV:
  - local significance 2.5 σ.



$H \rightarrow Z_d Z_d \rightarrow 4l$: Limits

- Limits on $\sigma(H \rightarrow Z_d Z_d \rightarrow 4l)$
- Factor ~5 improvement from previous results.



$H \rightarrow ZZ_d \rightarrow 4l$

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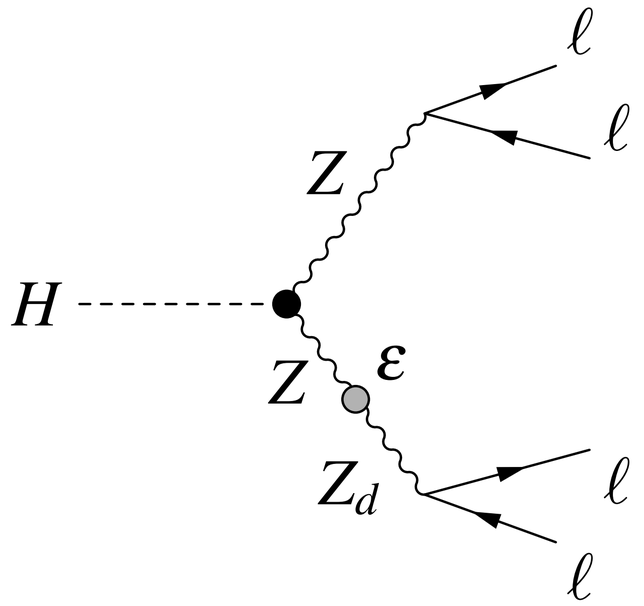
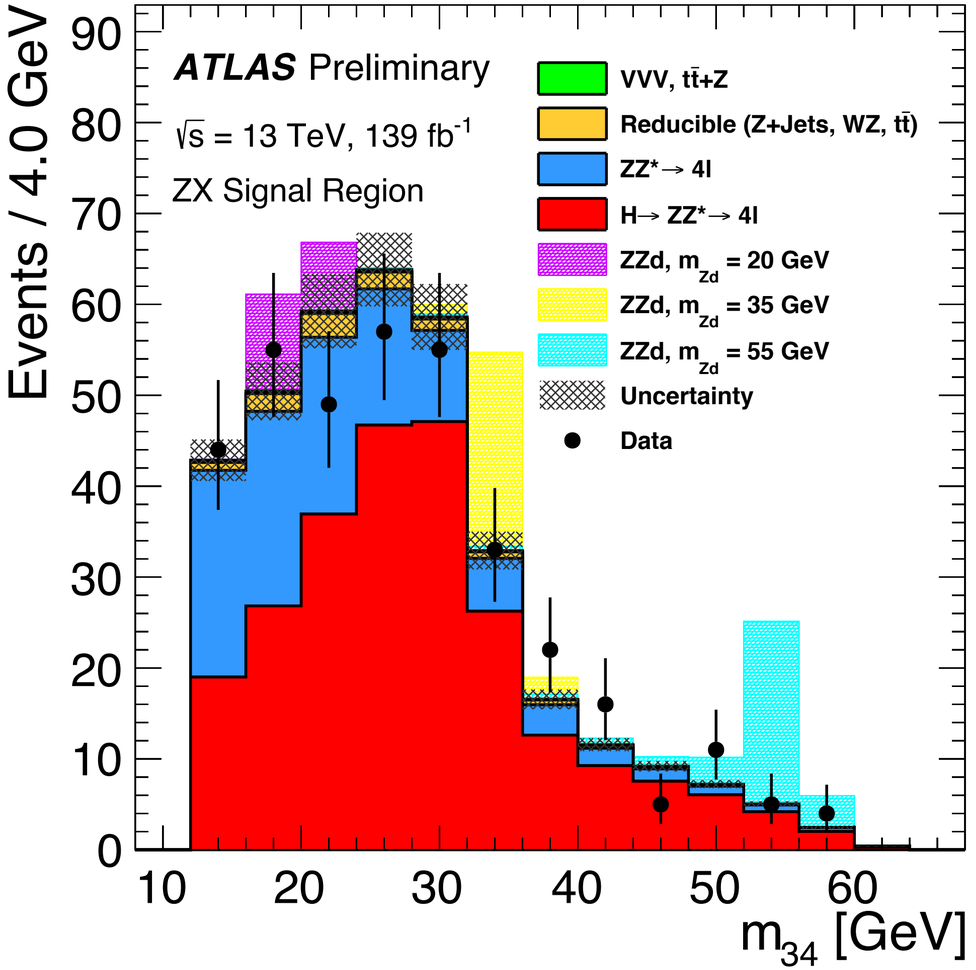


- Model
  - Z_d : dark Z,
  - ε: Z and Z_d mixing constant.
- Event selection (similar to $H \rightarrow aa \rightarrow 4\mu$)
  - Electron and muon triggers.
  - 4 or more isolated leptons with $p_T > 20, 15, 10, 5$ GeV.
  - Z candidate: smallest $|m_Z - m_{12}|$.
  - Higgs mass window: 115 GeV $< m_{4\mu} <$ 130 GeV.
  - 15 GeV $< m_{34} <$ 55 GeV.

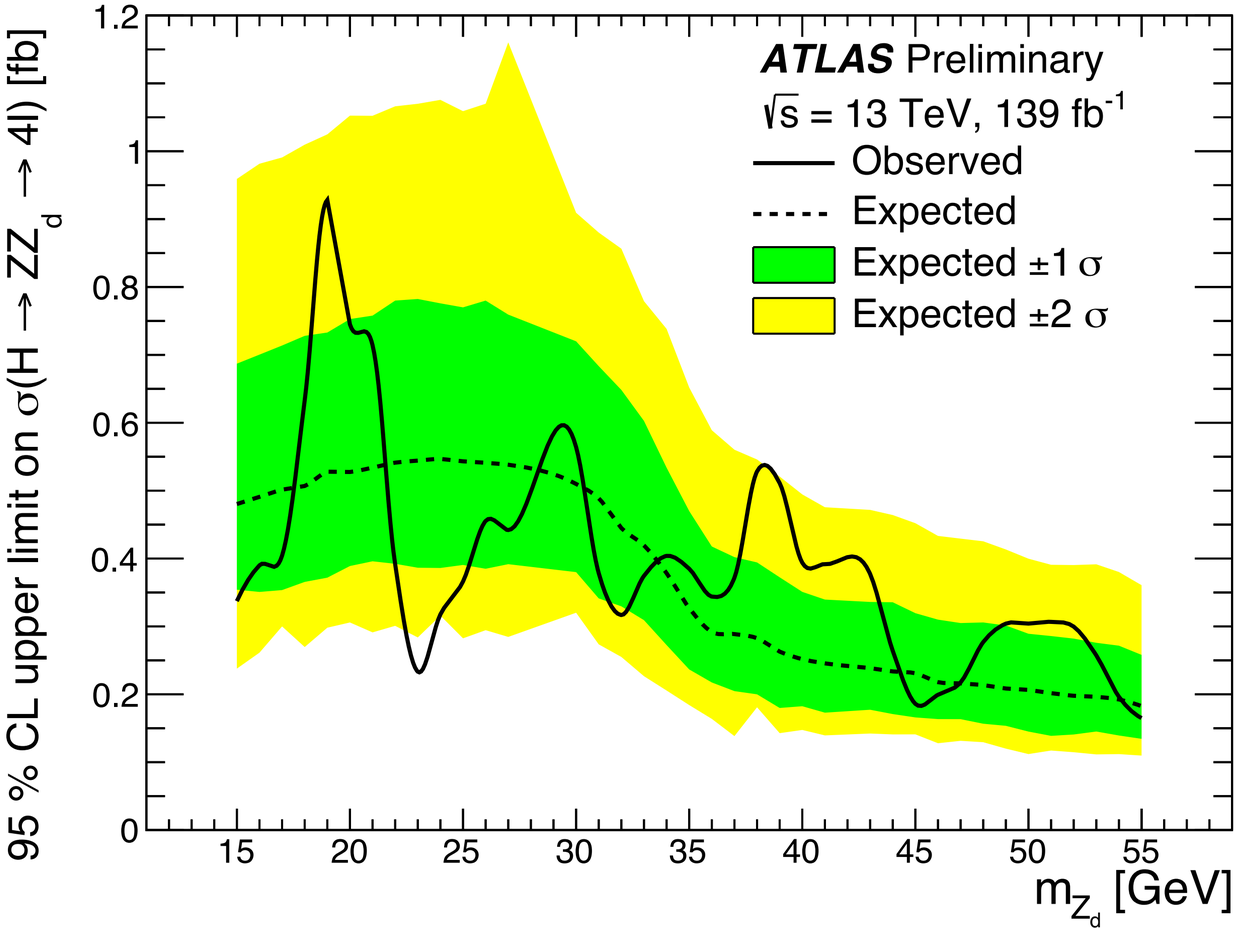
$H \rightarrow ZZ_d \rightarrow 4l$: Background

- Backgrounds: simulation.
  - $ZZ^* \rightarrow 4l$: simulation.
  - $H \rightarrow ZZ^* \rightarrow 4l$: simulation.
  - Other small backgrounds:
    - Triboson, ttV: simulation
    - Reducible (Z+jets etc): data-driven method.
- Statistics limited.



$H \rightarrow ZZ_d \rightarrow 4l$: Limits

- Limits on $\sigma(H \rightarrow ZZ_d \rightarrow 4l)$
- Significant improvement from previous results.



Conclusions

- New results for rare and exotic Higgs decay are presented.
  - ZH, Z → ll and H → invisible.
  - H → aa → bbμμ
  - H → aa → 4μ
  - H → ZZ_d → 4*l*
  - H → Z_dZ_d → 4*l*
- All new results are with full data set (139 fb^{-1}) from 13 TeV pp collisions.
- No evidence for BSM physics was observed ==> limits are set.
- Limits are improved, providing important new constraints in the Higgs sector .
- Need more data to find new physics.

Reference

- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-029/
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2020-052/
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-036/
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2021-03/
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-008/
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-034/

Backup: Limits on 2HDM+a (pseudoscalar mediator) dark matter model

ATLAS-CONF-2021-036

- The same results are used to set limit on dark matter models.
- Dominant contribution in the limits on 2HDM+a dark matter model