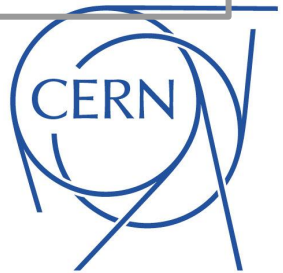
Searches for rare SM and BSM Higgs decays in ATLAS

Adriana Milic

September 20-22, 2021
Higgs Hunting 2021 - Paris, France
On behalf of the ATLAS collaboration

UNIVERSITY OF TORONTO

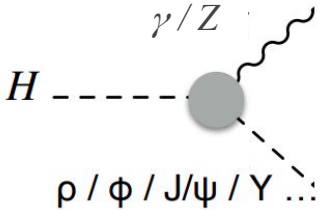


Overview of rare and exotic Higgs decays

- Decays via loops, $H \to Z\gamma$
- Decays to mesons, $H \to M\gamma$
- Direct decays to fermions and bosons

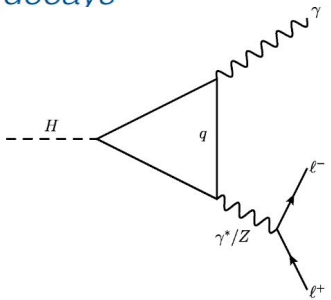
- $H \to aa$, $H \to Za$ decays
- Lepton Flavor Violating (LFV) Higgs decays
- Higgs decays to long-lived particles
- Invisible decays, $BR(H \to invisible) < 9\%$

Rare Higgs decays



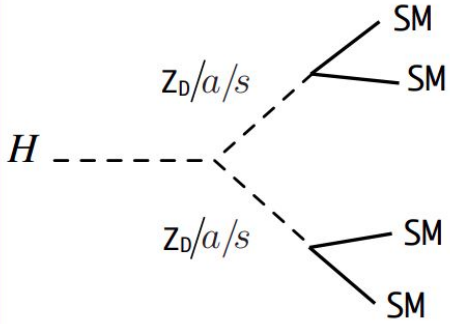
Sensitivity still several orders of magnitude above SM predictions

➡ **Detection would imply BSM!**

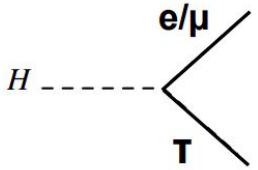


H→ℓℓγ evidence!

Exotic Higgs decays



Lepton flavor violating decays



Analyses covered in this talk

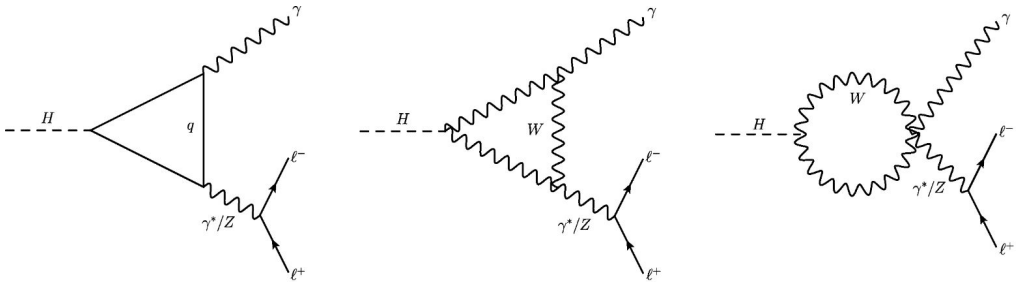
- **Rare Higgs decays**
  - $H \to ll\gamma$
    - Low mass ($m_{ll} < 30\ GeV$)
    - $H \to Z\gamma \to ll\gamma$
- **BSM Higgs decays**
  - $H \to$ *long-lived particles*
  - $H \to aa \to bb\mu\mu$
  - $H \to aa$ summary plots

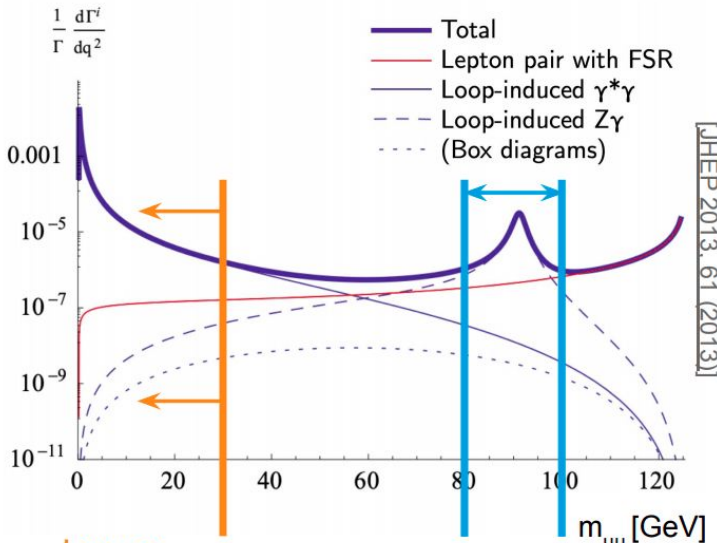
All analyses from 2021 and using 139^{-1} fb!

Rare Higgs decays

$H \to ll\gamma$

- $H \to ll\gamma$ decays explored where $l = e, \mu$
- Analyses separated in
  - Low-mass $m_{ll} < 30$ GeV
  - m_{ll} close to Z peak





Phys. Lett. B 819 (2021) 136412

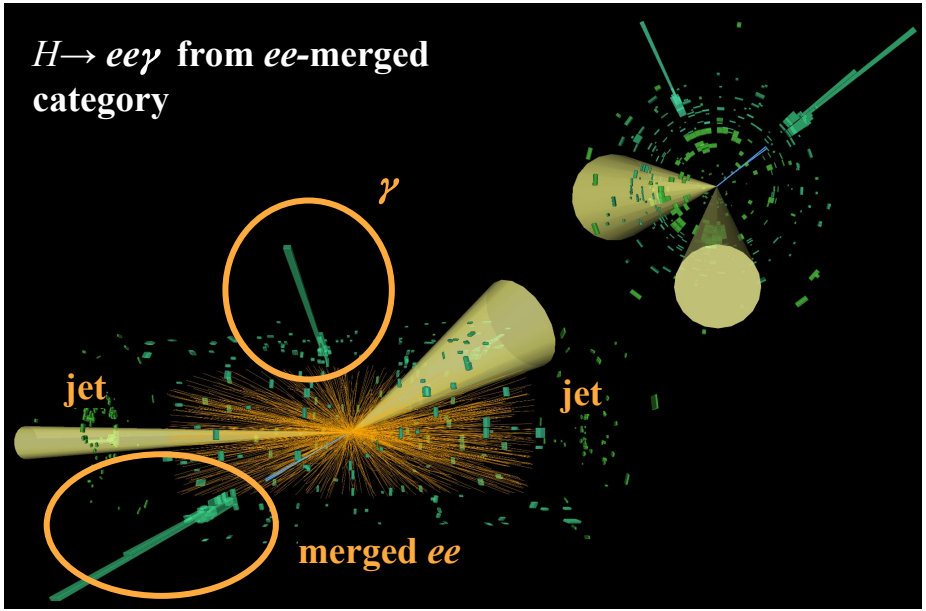
Low m_{ll} $H \to ll\gamma$

- Electron channel experimentally challenging due to **low invariant mass of electron pair and high pair p_T**

➔ Electrons **collimated and merge** in the EM calorimeter

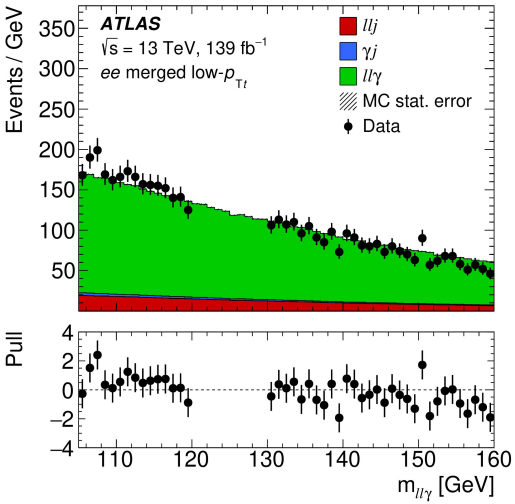
➔ **Special trigger for merged electrons** with relaxed shower shape cuts deployed

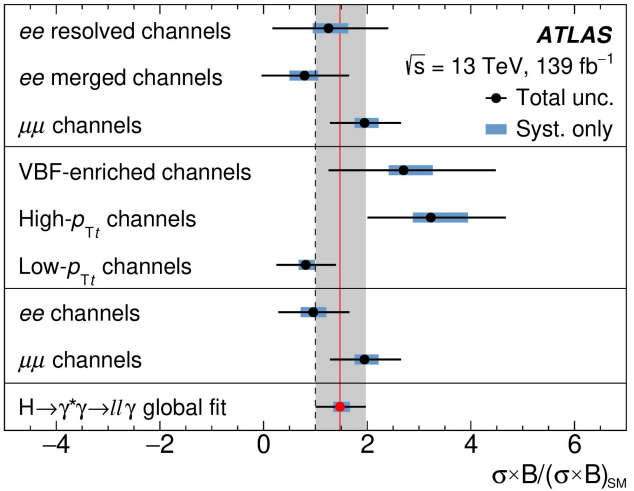
➔ Dedicated **merged electrons calibration** procedure and identification algorithms used



Low m_{ll} $H \to ll\gamma$

- Event categorization based on lepton flavor and topology.
- Background shapes taken from templates and modeled using analytical functions
  - $ll\gamma$ taken from MC
  - $\gamma + jets$ and $ll + jet$ taken from data template.





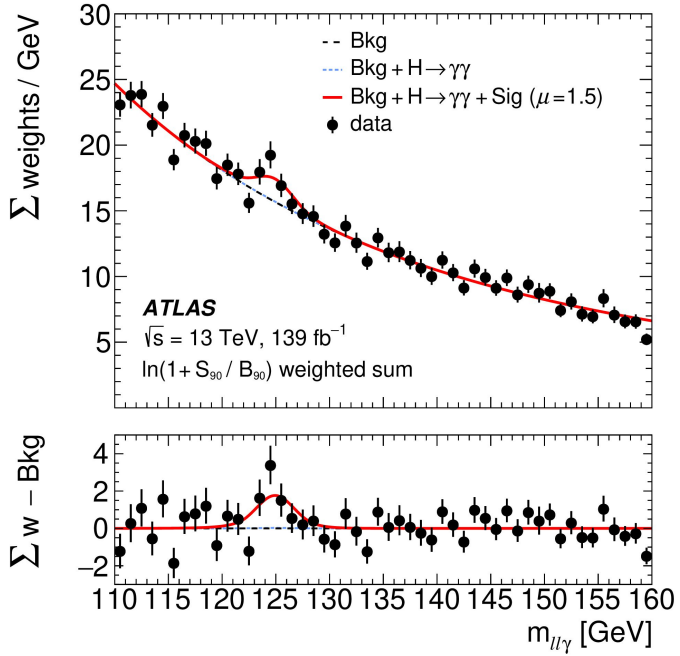
Best-fit values of **signal strength parameters** in fits for the different event categories.

$$\mu = 1.5 \pm 0.5 = 1.5 \pm 0.5\ (\text{stat.})\ ^{+0.2}_{-0.1}\ (\text{syst.})$$

Low m_{ll} $H \to ll\gamma$

- First evidence for $H \to ll\gamma$!
  - 3.2 σ observed, 2.1 σ expected
  - xsec $\times$ BR = $8.7\ ^{2.8}_{-2.7}$ fb

- Search statistically limited (syst. uncertainty 35% of stat. uncertainty)

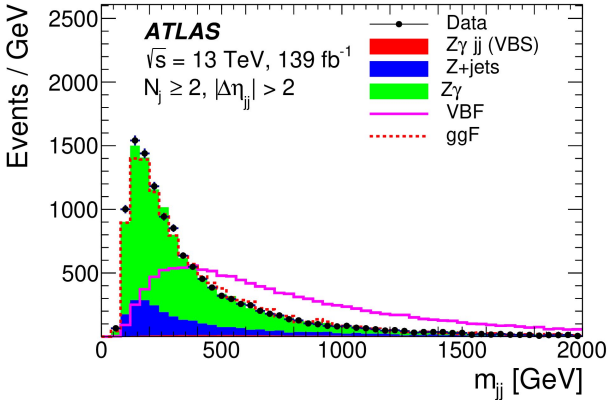


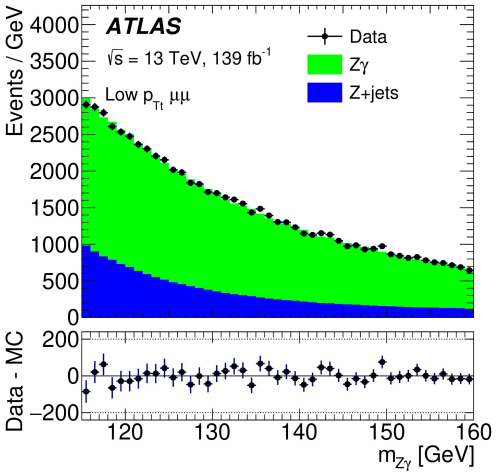
[Phys. Lett. B 819 (2021) 136412]

$H \to Z\gamma \to ll\gamma$

- Event selection
  - Choose events with e^+e^- or $\mu^+\mu^-$ and one γ
  - $80\ GeV < m_{ll} < 101\ GeV$ for Z candidate
  - $105\ GeV < m_{Z\gamma} < 160\ GeV$ for **Higgs** candidate
  - Five cut-based event categories, one **BDT based categorization** of VBF like events

- Fit $m_{ll\gamma}$ with signal + background functions
  - Signal: fit with double-sided crystal ball function
  - Background shape extracted and modeled using analytical functions
    - $Z\gamma$ and $Z\gamma\,jj$ from MC
    - Z+*jets* from data template

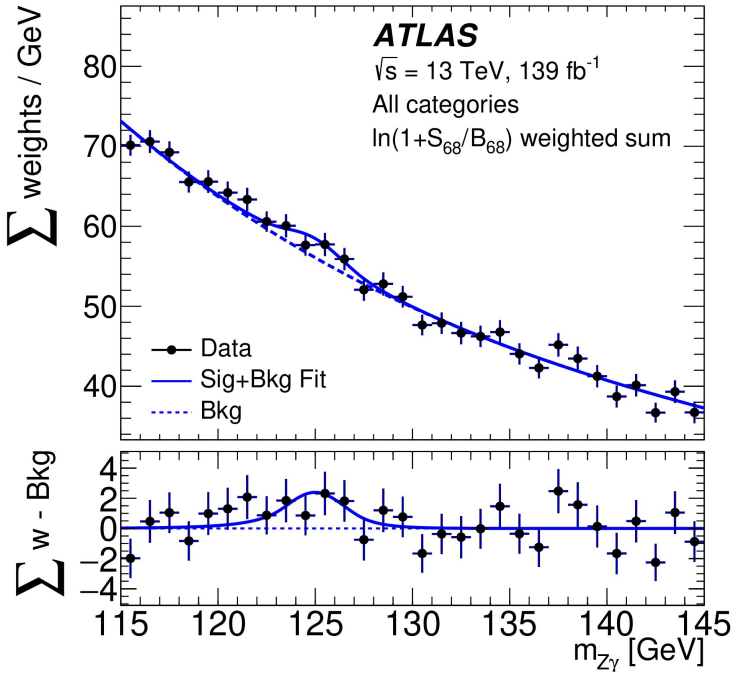




$H \to Z\gamma \to ll\gamma$

- Result is dominated by **statistical uncertainty**
  - **Low BR** and **high irreducible background**
- **2.2 σ** significance observed, **1.2 σ** expected
- Observed 95% CL upper limit on production xsec ***$\sigma(pp \to H)\cdot BR(H \to Z\gamma)$:*** 3.6 × SM (2.6 expected)
- Signal strength:

$$\mathbf{2.0 \pm 0.9}\ (\text{stat.})^{+0.4}_{-0.3}(\text{syst}) = \mathbf{2.0}^{+1.0}_{-0.9}$$

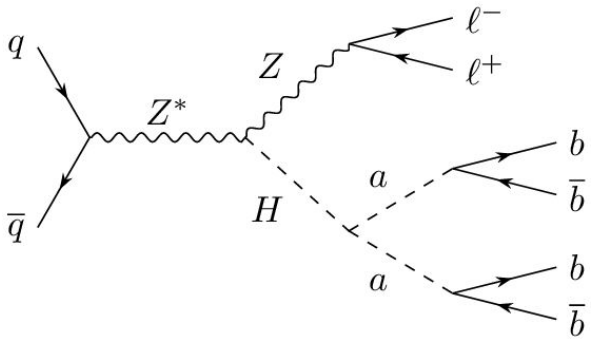


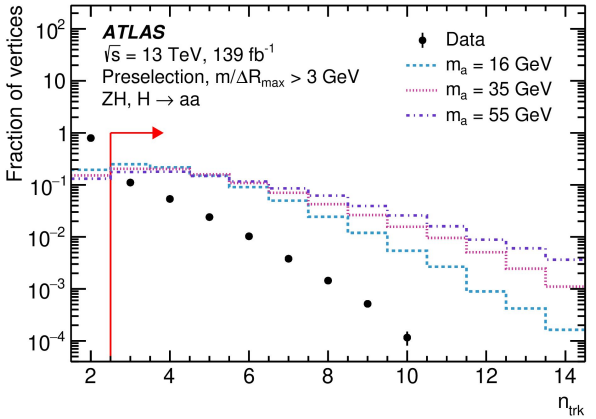
Phys. Lett. B 809 (2020) 135754

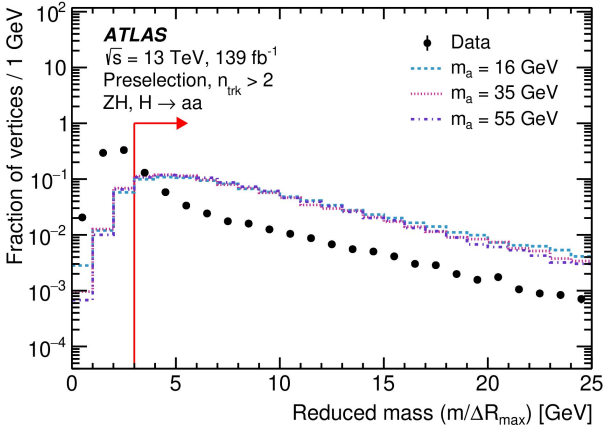
Exotic Higgs decays

$H \rightarrow aa \rightarrow 4b$ (a long-lived)

- **Event selection**
  - At least **two displaced vertices** in inner detector with high mass and track multiplicity
  - **Two leptons** from Z decay
- **Displaced Vertex (DV) reconstruction**
  - Specialized tracking algorithm (LRT) that increases efficiency for particles produced at high radius employed
  - Cutting on two variables to remove background
    - Number of tracks $n_{trk} > 3$ from the DVs
    - Reduced mass $m/\Delta R_{max} > 3$ GeV



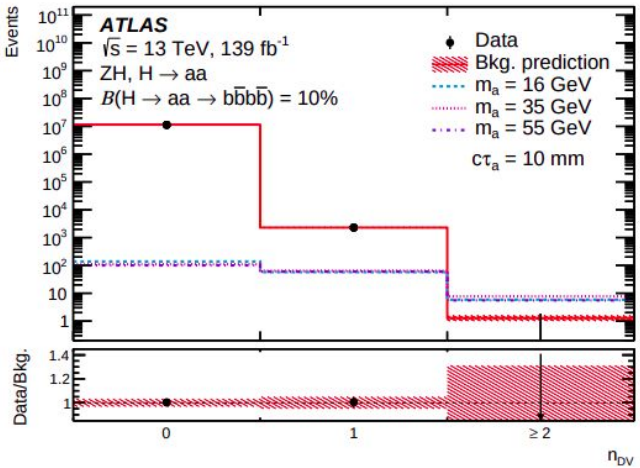


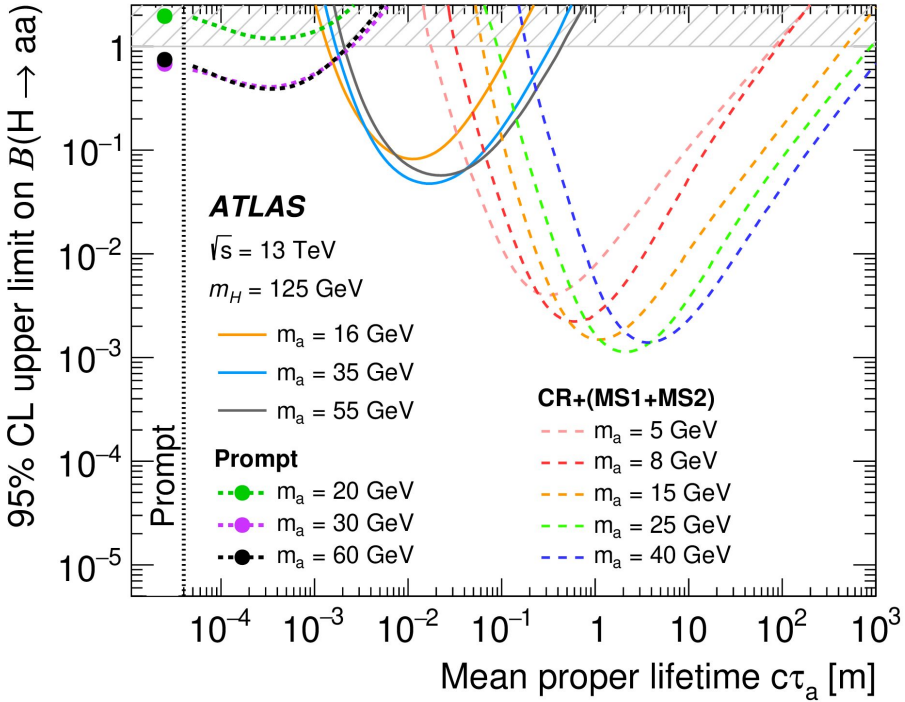


$H \rightarrow aa \rightarrow 4b$ (a long-lived)

- Background estimated from **CR with $n_{DV} < 2$**
  - Extrapolated to SR using the **probability P_{DV} to fake a DV** (depending on jet p_T and b-tagging score)
- No events observed in SR

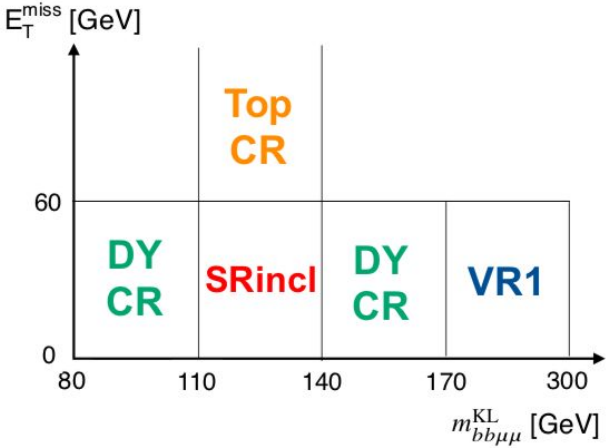
➔ Limits set on ***BR(H →aa →bbbb)***

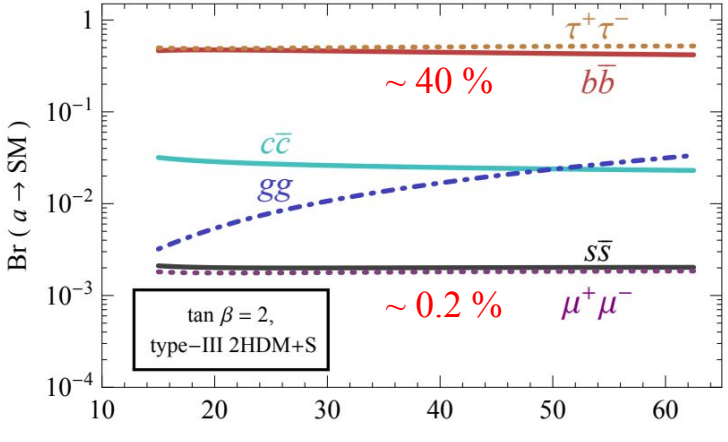


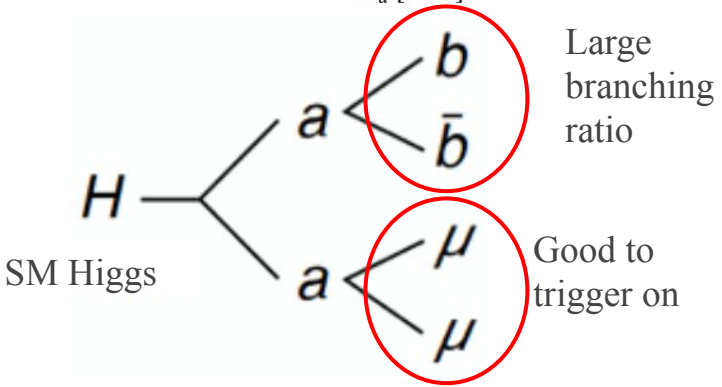


$H \rightarrow aa \rightarrow bb\mu\mu$

- Large BR from ***bb***, clean signature from ***μμ***
- **Main backgrounds**
  - **ttbar:** obtained from simulation.
  - **Drell-Yan:** estimated from data driven method.

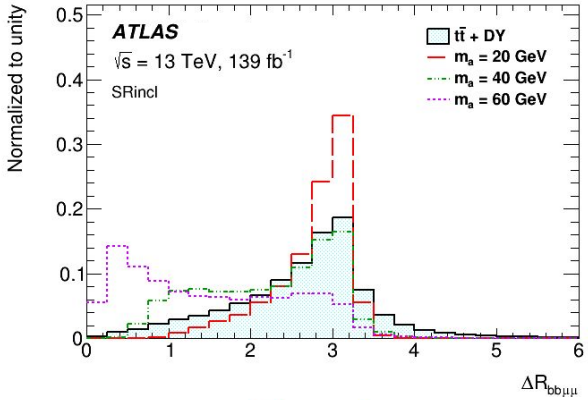


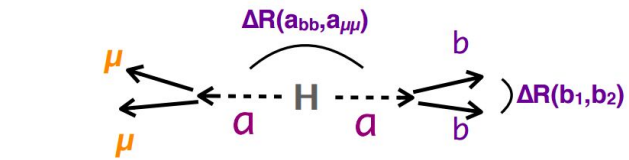




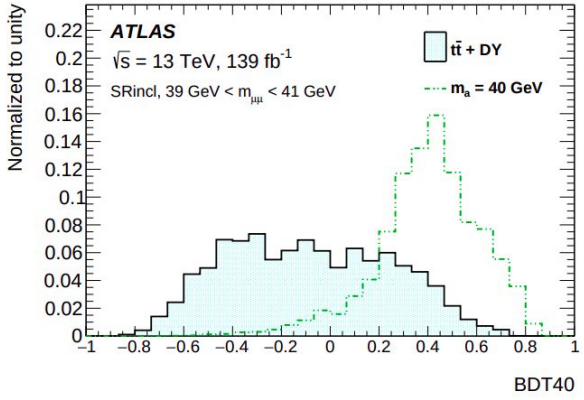
$H \rightarrow aa \rightarrow bb\mu\mu$

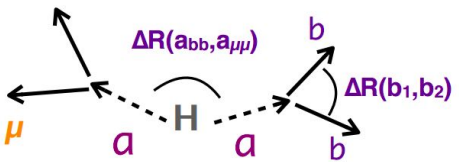
- Train BDTs to separate signal from backgrounds.
- Several input variables go into BDT training.
- Separate BDTs trained for different signals.





low-mass topology

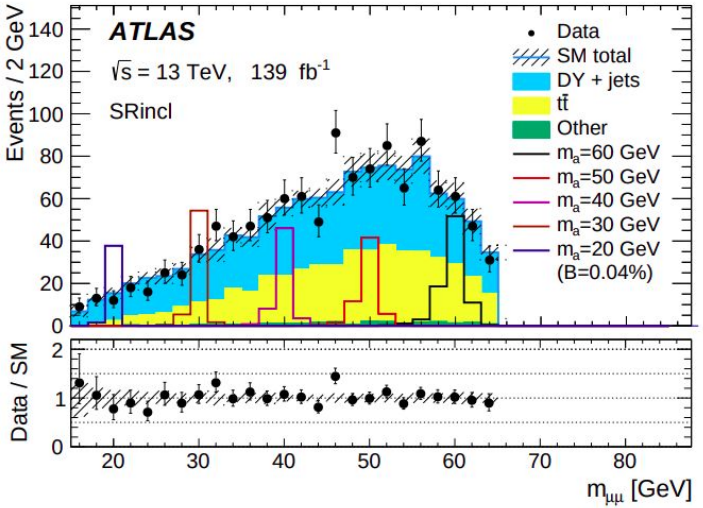




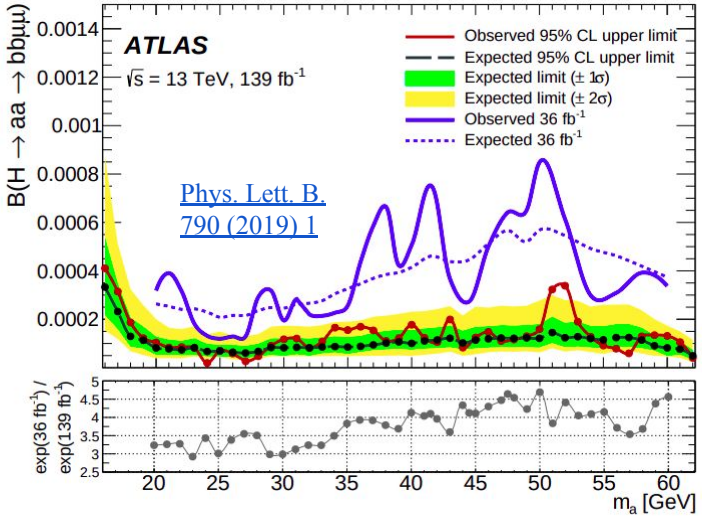
high-mass topology

$H \rightarrow aa \rightarrow bb\mu\mu$

- Looking for **excess in $m_{\mu\mu}$ distribution**.



ATLAS-CONF-2021-009

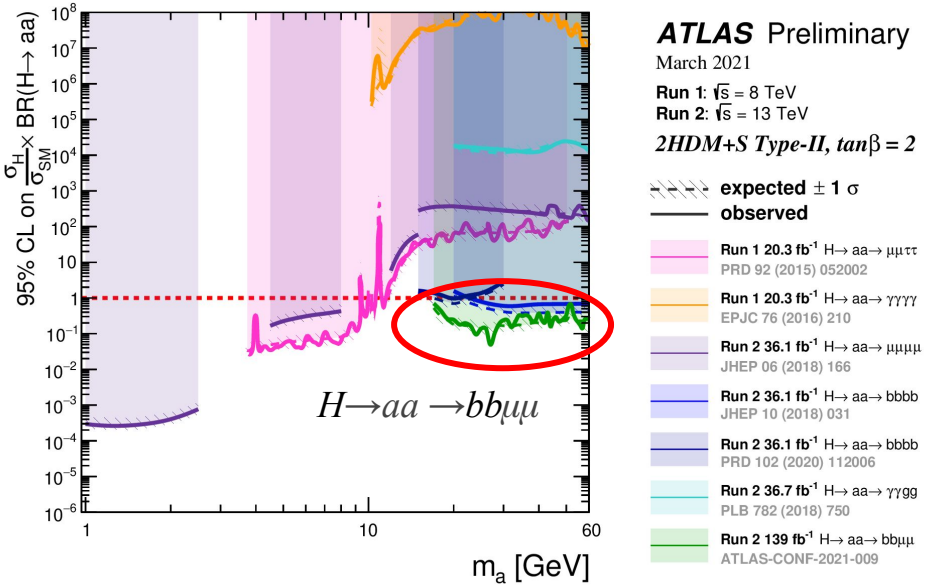


- Limit significantly improved wrt. 36 fb^{-1}
- ➔ Factor ~2 from increased luminosity
- ➔ Factor ~2 from employing BDTs

- Excess of 3.3σ (1.7σ) local (global) observed at m_a=52 GeV

$H \rightarrow aa$ summary plots

- Model independent limits on $BR(H \rightarrow aa \rightarrow xx\ yy)$ (from 1312.4992 & 1802.0215) translated into limits on $BR(H \rightarrow aa)$
- For this plot particular **2HDM + S scenario** that determines $BR(aa \rightarrow xx\ yy)$ was assumed.
- $tan\beta$ = ratio of vacuum expectation values of the 2 Higgs-doublet



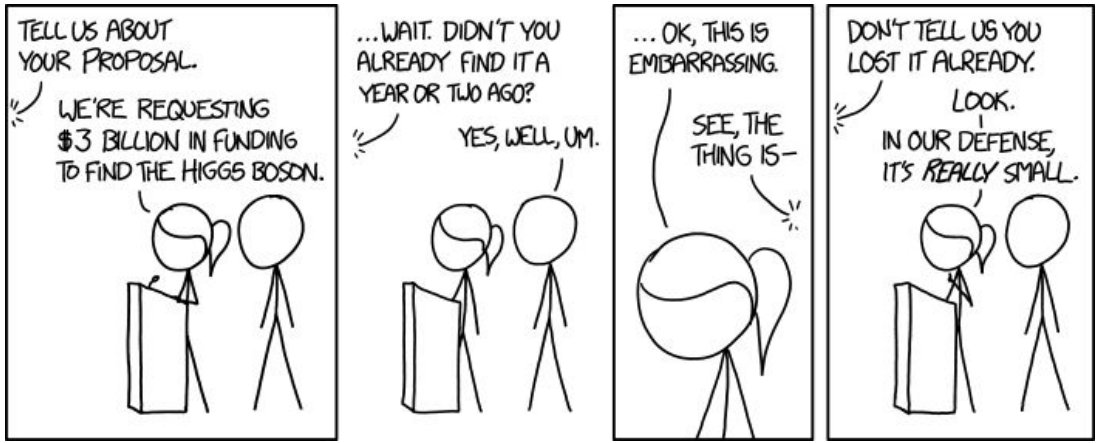
ATL-PHYS-PUB-2021-008

Summary

- With Run 2 data it is possible to start exploring rare Higgs decays.
  - Low m_{ll} $H \rightarrow ll\gamma$ showed first evidence of $H \rightarrow ll\gamma$ decay at 3.2 σ
  - $H \rightarrow Z\gamma \rightarrow ll\gamma$ still very statistically limited

- ***H →aa, H →Za decays***
  - Started exploring **long-lived decays** in this category.
  - $H \rightarrow aa \rightarrow bb\,\mu\mu$ improved limit by factor of 4 (due to higher luminosity and usage of multivariate techniques)
  - No significant excess observed.

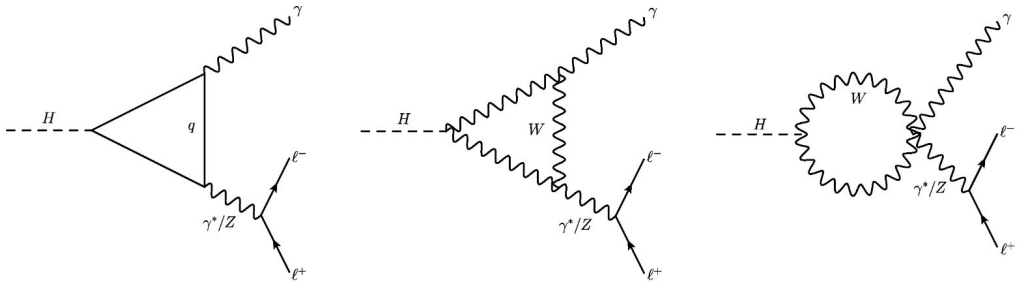
- For Run 3 more data will be available to
  - Probe **Higgs boson properties** more precisely.
  - Search for **BSM couplings**



Backup

$H \rightarrow ll\gamma$

- $BR_{SM}(H \rightarrow Z\gamma) = (1.54 \pm 0.09) \times 10^{-3}$
- Probing this coupling can give a hint to possible extensions of the SM, i.e.
  - The Higgs is a neutral scalar of different origin, or a composite state.
  - There are additional colourless charged scalars, leptons or vector bosons that couple to the Higgs, due to their contributions via loop corrections.
- $\boldsymbol{H \rightarrow ll\gamma}$ dominated by the following diagrams.

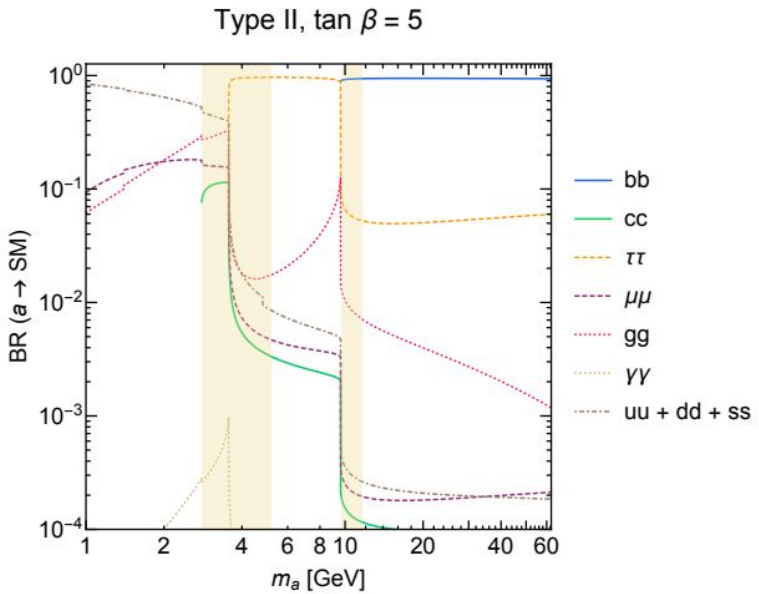


Phys. Lett. B 819 (2021) 136412

2 HDM + S inspired searches

- Mediator is singlet (pseudo)scalar
- Couplings Yukawa-like; proportional to mass

➔ Large BRs to b's and τ's

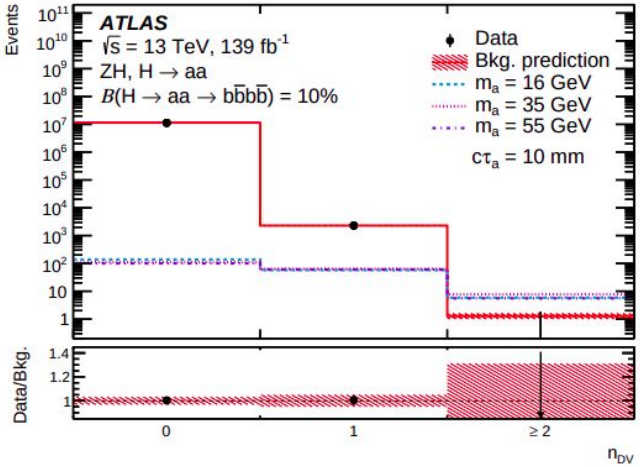


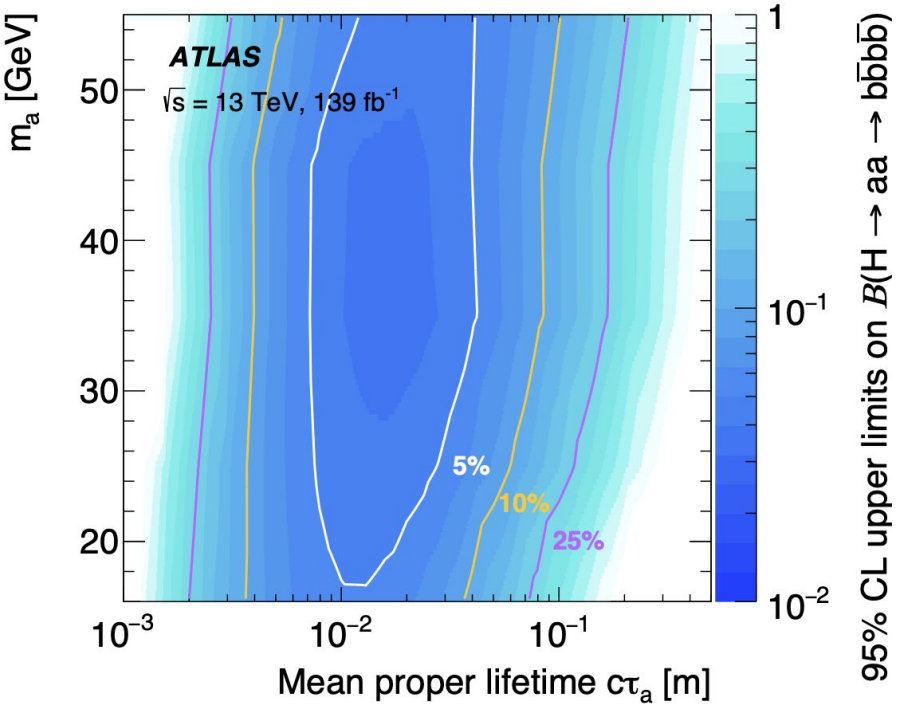
1312.4992

$H \rightarrow aa \rightarrow 4b$ (a long-lived)

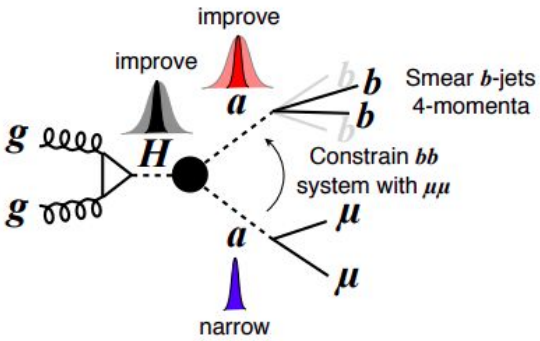
- Background estimated from **CR with $n_{DV} < 2$**
  - Extrapolated to SR using the **probability P_{DV} to fake a DV** (depending on jet p_T and b-tagging score)
- No events observed in SR

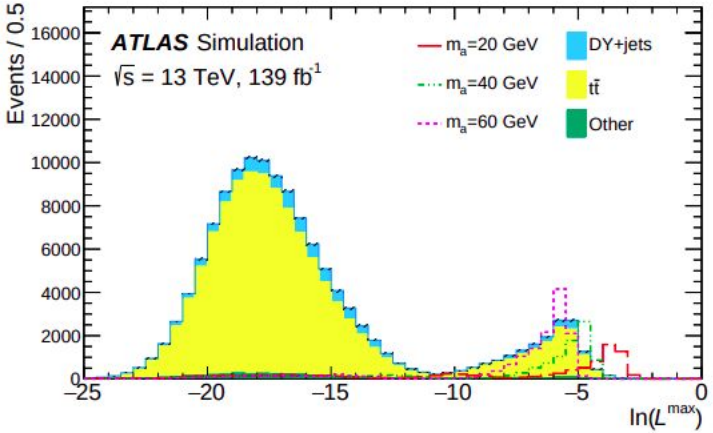
➔ Limits set on ***BR(H →aa →bbbb)***





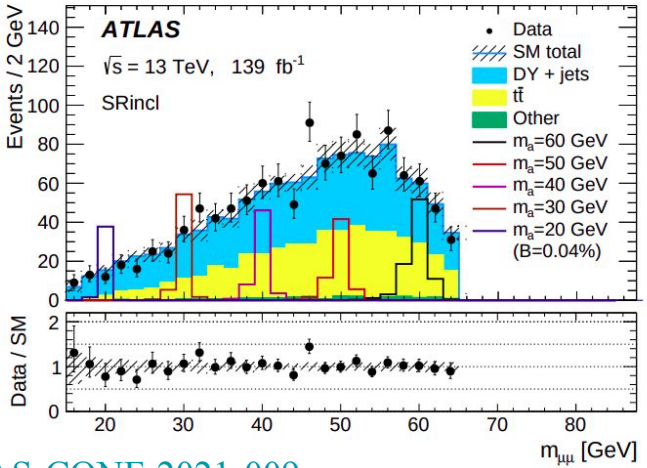
- **Kinematic likelihood (KL) fit**
  - Used to constrain the m_{bb} to the $m_{\mu\mu}$ mass and improve the resolution of the $m_{\mu\mu bb}$ peak.



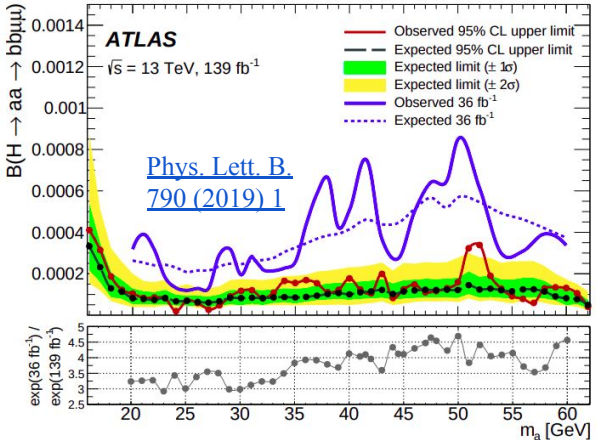


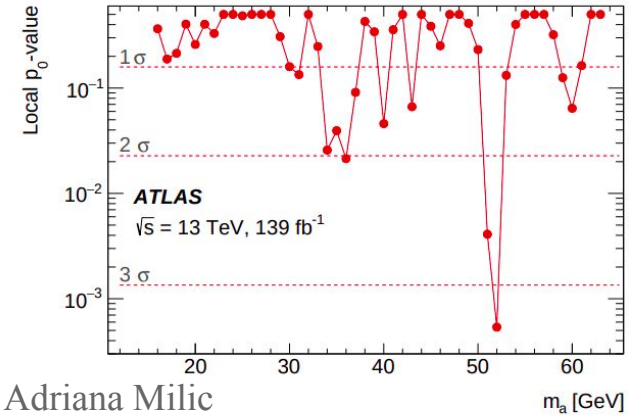
$H \rightarrow aa \rightarrow bb\mu\mu$

- Looking for **excess in $m_{\mu\mu}$ distribution**.
- **Main backgrounds**
  - **ttbar:** obtained from simulation.
  - **Drell-Yan:** estimated from data driven method.



[ATLAS-CONF-2021-009]





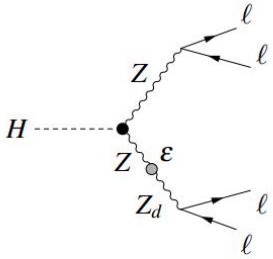
- Limit significantly improved wrt. 36 fb^{-1}
  - → Factor ~2 from increased luminosity
  - → Factor ~2 from employing BDTs
- Excess of 3.3σ (1.7σ) local (global) observed at m_a=52 GeV
- Corresponding to local (global) p_0-value of 0.0005 (0.048)

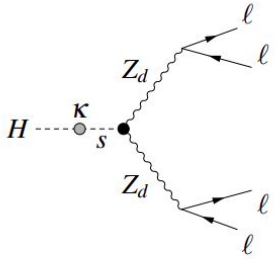
$H \rightarrow XX/ZX \rightarrow llll$

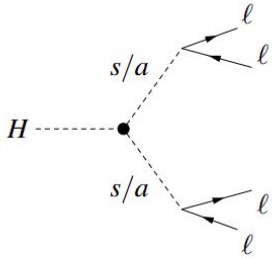
Analysis divided into three channels:

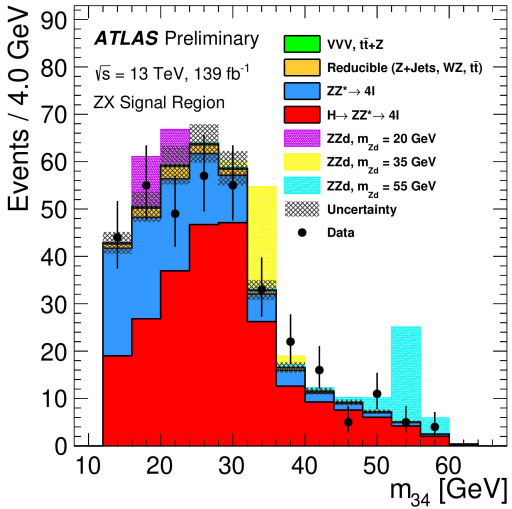
- High-mass (HM): $H \rightarrow XX \rightarrow 4l$ ($15\ \text{GeV} < m_X < 60\ \text{GeV}$)
- Low-mass (LM): $H \rightarrow XX \rightarrow 4\mu$ ($1\ \text{GeV} < m_X < 15\ \text{GeV}$)
- Single Z boson (ZX): $H \rightarrow ZX \rightarrow 4l$ ($15\ \text{GeV} < m_X < 55\ \text{GeV}$).

- Main background contributions:
  - $H \rightarrow ZZ^* \rightarrow 4l$ (~ 72%)
  - $ZZ^* \rightarrow 4l$ (~ 24%)
  - *Z+jets* estimated from data



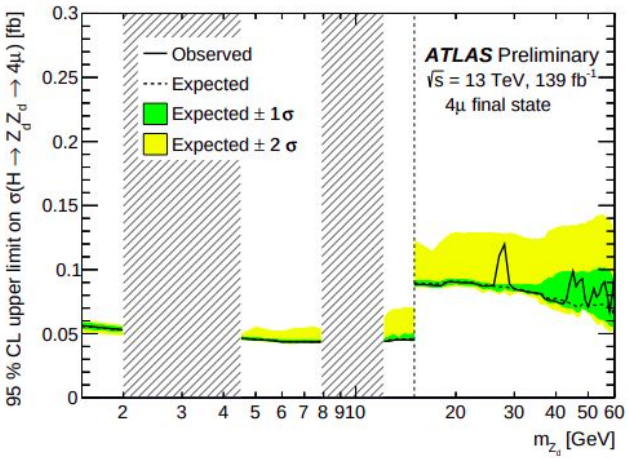




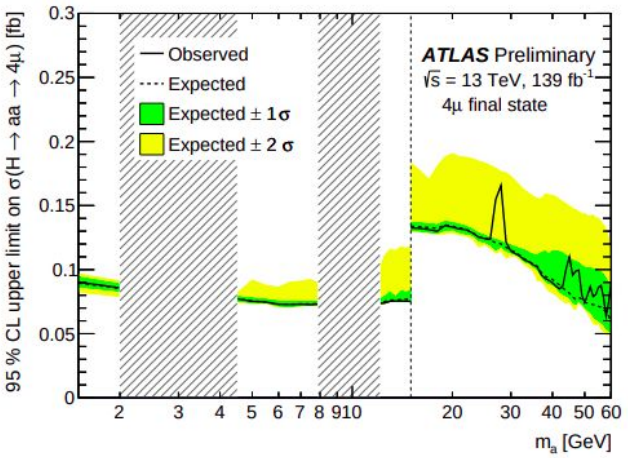


Combined high-mass + low-mass limits on:

$\sigma(H \rightarrow Zd\,Zd \rightarrow 4\mu)$



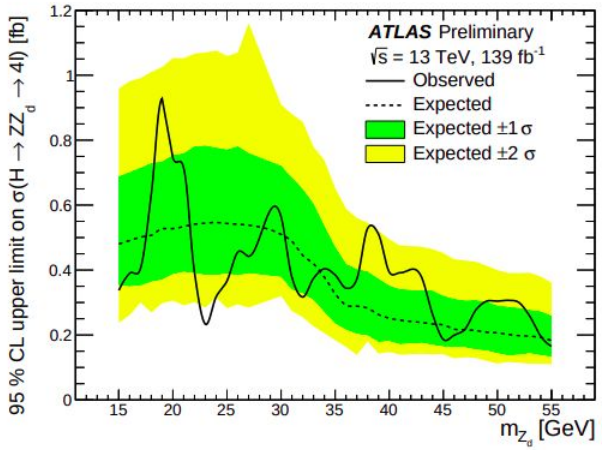
$\sigma(H \rightarrow aa \rightarrow 4\mu)$



UNIVERSITY OF TORONTO

Combined high-mass + low-mass limits on:

$\sigma(H \rightarrow Zd\,Zd \rightarrow 4\mu)$



$\sigma(H \rightarrow aa \rightarrow 4\mu)$