Searches for exotics decays of the Higgs and Z bosons with the ATLAS detector

Daniela Paredes

On behalf of ATLAS Collaboration

University of Hong Kong

LHC Days 2022

Split (Croatia), October 03, 2022

Introduction

1. SM Higgs boson can be used as a portal to look for BSM physics
   - Current constraints allows for a $\mathcal{B}(H \rightarrow \text{invisible}) < 13\%$: *Nature (2022)*
   - Many BSM theories allow for exotic decays of the Higgs boson to Long Live Particles (LLPs).

2. BSM physics can also be found by looking at Z decays or in lepton-flavour-violation (LFV).

Presenting here the latest results about the subject:

Exotic Higgs decays to LLPs using displaced vertices (DVs):

- In the inner detector (ID): *JHEP 11 (2021) 229*
- In the calorimeter: *JHEP 06 (2022) 005*
- In the muon spectrometer (MS): *Phys. Rev. D 106, (2022) 032005*
- In the calorimeter and/or MS: *arXiv:2206.12181*

Higgs decays to dark photons: *ATLAS-CONF-2022-064*

LFV in Higgs decays: *ATLAS-CONF-2022-060*

Exotic Z decays: *ATLAS-CONF-2022-041*

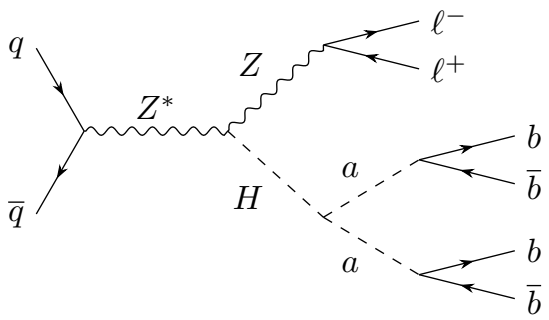
Higgs decays with displaced vertices in the ID (I)

JHEP 11 (2021) 229

1 **Signal:** ZH, $H \to aa \to b\bar{b}b\bar{b}$

$\to$ *$Z \to \ell\ell$ provides highly efficient trigger objects.*

$\to$ *a decays within the ID.*



2 **Background:**

- Interaction between SM particles with the detector.
- Secondary vertices originating from SM processes (i.e. $K_S^0 \to \pi^+\pi^-$).
- Vertices with random track crossings.

$\to$ *Estimated with data-driven techniques using a CR.*

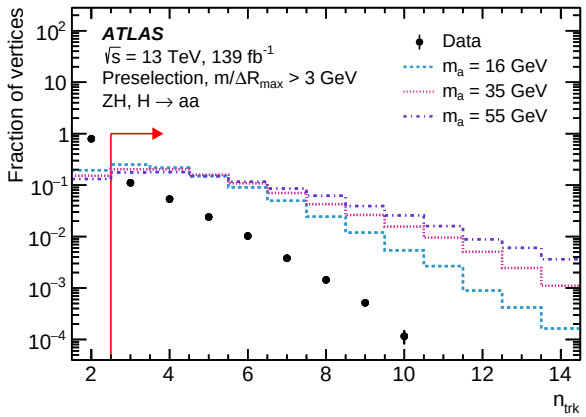
3 **SR:**

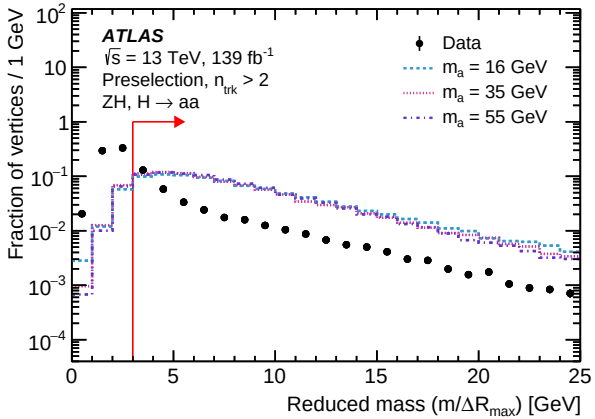
- Two opposite-sign, same flavour leptons with $m_{\ell\ell} \in [66, 116]$ GeV
- $\geq$ 2 jets.
- $\geq$ 2 DVs

$\to$ *DVs reconstructed from ID tracks.*

Selection type	Requirement
Track pruning	$\lvert d_0^{\mathrm{DV}}\rvert < 0.8$ mm $\lvert z_0^{\mathrm{DV}}\rvert < 1.2$ mm $\sigma(d_0^{\mathrm{DV}}) < 0.1$ mm $\sigma(z_0^{\mathrm{DV}}) < 0.2$ mm
Vertex preselection	$\chi^2/n_{\mathrm{DoF}} < 5$ $r < 300$ mm $\lvert z\rvert < 300$ mm pass material veto
Vertex selection	$n_{\mathrm{trk}} > 2$ $m/\Delta R_{\mathrm{max}} > 3$ GeV $r/\sigma(r) > 100$ $\max(\lvert d_0\rvert) > 3$ mm $\Delta R_{\mathrm{jet}} < 0.6$

Vertex selection criteria

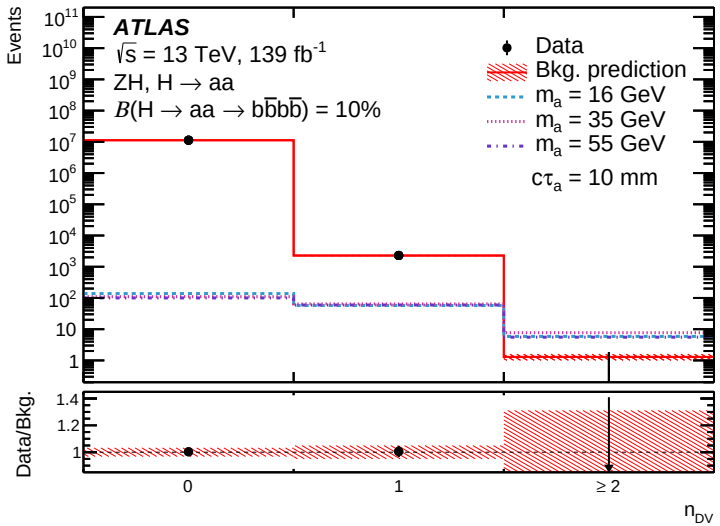


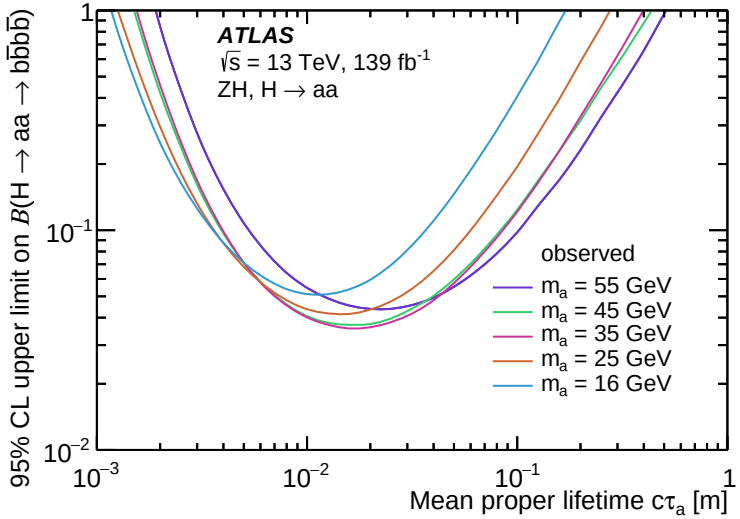


Higgs decays with displaced vertices in the ID (II)

JHEP 11 (2021) 229

- No excess of events has been observed.
- Upper limits on the $\mathcal{B}(H \to aa \to b\bar{b}b\bar{b})$ as a function of $c\tau_a$ have been computed.

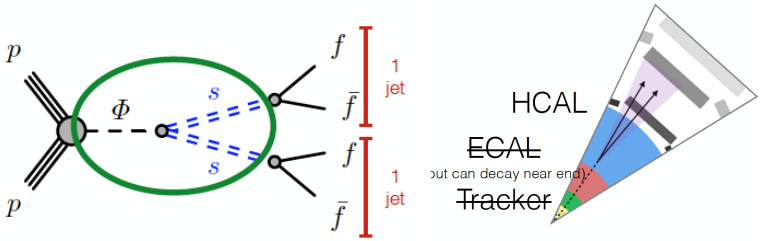




Strongest limits exclude $\mathcal{B}(H \to aa \to b\bar{b}b\bar{b}) > 4\%$ for $c\tau_a \approx 10 - 20$ mm

Higgs decays with displaced jets in the calorimeter (I)

JHEP 06 (2022) 005



1 **Signal:** $\Phi \to ss \to f\bar{f}f'\bar{f}'$ ($m_\Phi \in [60, 1000]$ GeV)

- Φ could be the SM Higgs boson.

→ Signal objects are narrow jets with no collinear tracks, depositing majority of energy in HCAL.

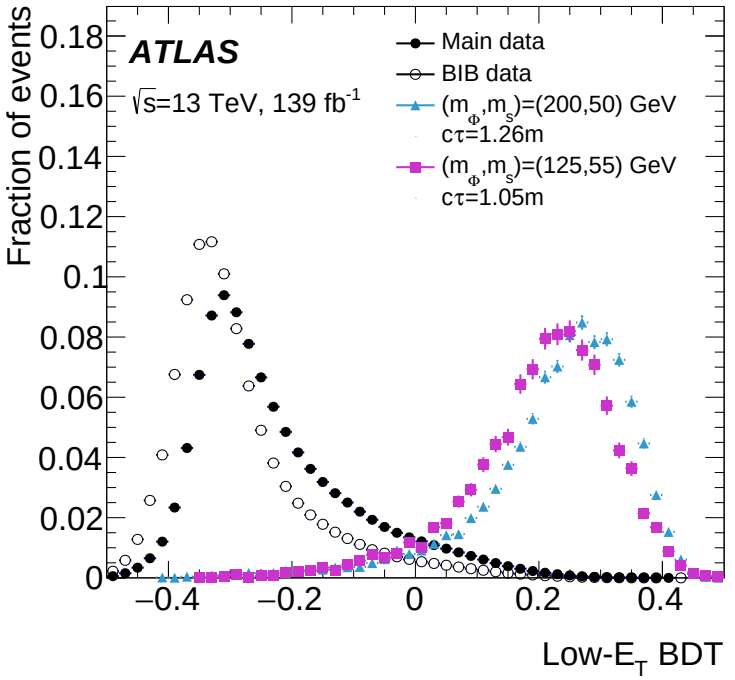
2 **Background:** SM multijet, beam induced background (BIB), cosmic rays.

→ Estimated using the ABCD method after the low-E_T selection.

3 **Signal vs Background discrimination:**

- low-E_T NN: per-jet NN trained to tag jets as signal, BIB and SM multijet.
- low-E_T BDT: per-event BDT trained to discriminate signal against background.

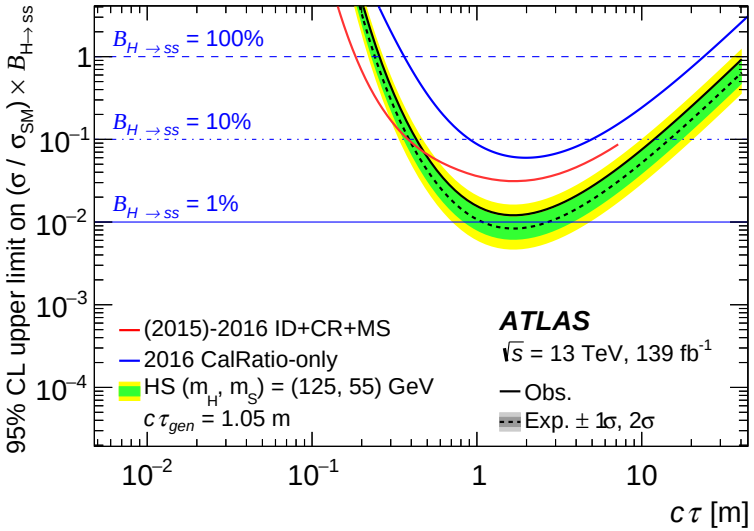
Training done after preselection: CalRatio trigger, $\geq$ 2 jets, $\sum \Delta R_{min} > 0.5$

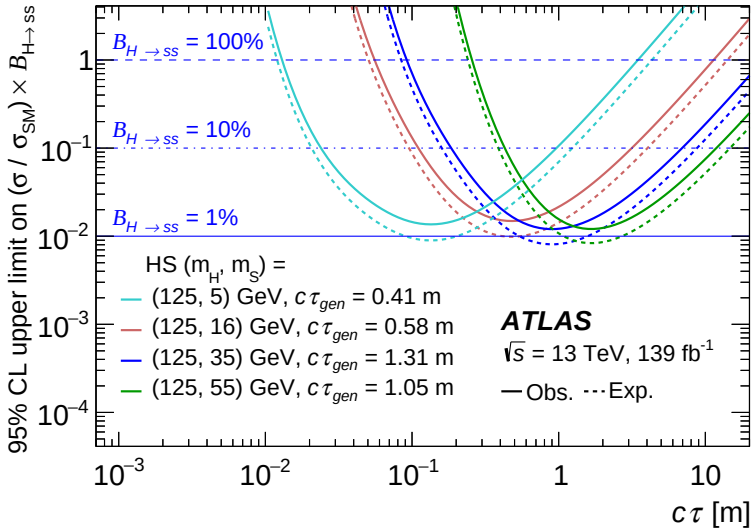


Higgs decays with displaced jets in the calorimeter (II)

JHEP 06 (2022) 005

- No significant excess of events has been observed.
- Upper limits on the $\mathcal{B}(H \to ss)$ as a function of $c\tau$ have been computed.





$\mathcal{B}(H \to ss) > 5\%$ are excluded for $c\tau$ between ∼30 mm and ∼9 m

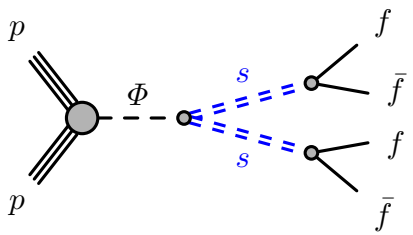
Higgs decays with displaced vertex in the MS (I)

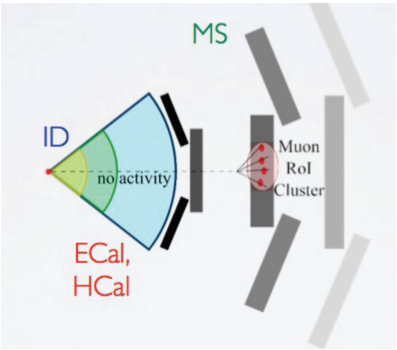
Phys. Rev. D 106, (2022) 032005

1 **Signal:** $\Phi \rightarrow ss \rightarrow f\bar{f}f'\bar{f}'$ ($m_\Phi \in [60, 1000]$ GeV)

- Φ could be the SM Higgs boson.

→ *Signal objects are narrow jets in the MS.*





2 **Background:** Punch-through jets, SM multijet, noncolission (electronic noise in the MDT and RPC/TGC chambers, cosmic-ray muons, and BIB).

→ *Estimated with data-driven techniques in a CR.*

3 **SR:** $\geq$ 2 DVs

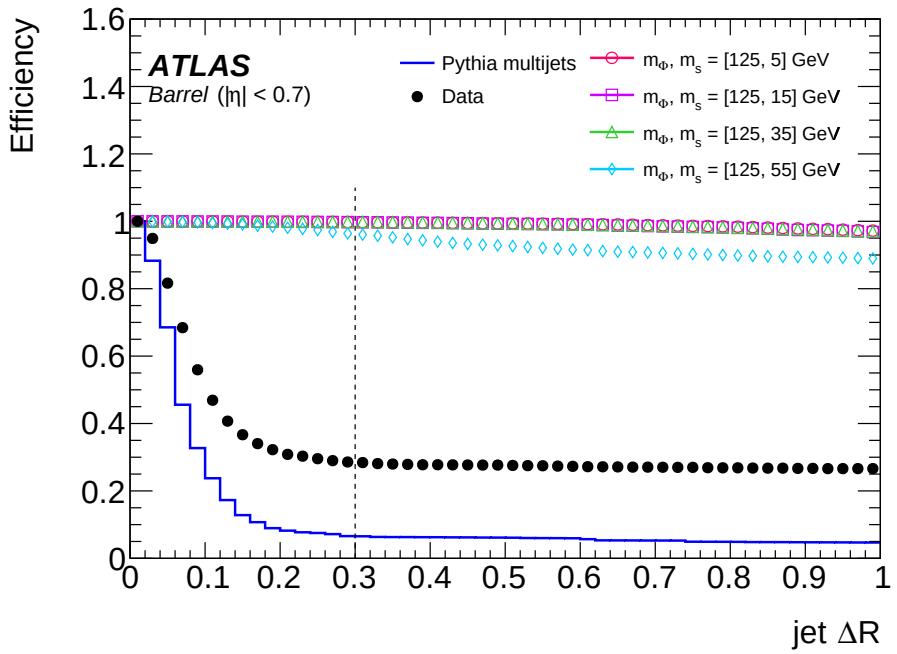
Event passes data quality requirements and Muon RoI Cluster trigger
Event has a PV with at least two tracks with $p_T > 500$ MeV
Event has at least one MS DV
MS DV is matched to the triggering muon-RoI cluster (ΔR(DV, RoI cluster) < 0.4) In the case of two muon-RoI clusters, the second vertex must be matched to the second cluster
$300 \leq n_{MDT} < 3000$

Barrel	*Endcaps*
MS DV with $\lvert\eta_{vx}\rvert < 0.7$ MS DV with 3 m $< L_{xy} <$ 8 m $n_{RPC} \geq 250$	MS DV with $1.3 < \lvert\eta_{vx}\rvert < 2.5$ MS DV with $L_{xy} <$ 10 m and 5 m $< \lvert L_z\rvert <$ 15 m $n_{TGC} \geq 250$

Baseline selection

Isolation requirements	Barrel	Endcaps
Isolation from high-p_T tracks ($p_T > 5$ GeV)	$\Delta R > 0.3$	$\Delta R > 0.6$
Isolation from low-p_T tracks ($\Sigma p_T(\Delta R < 0.2)$)	$\Sigma p_T < 10$ GeV	$\Sigma p_T < 10$ GeV
Isolation from jets	$\Delta R > 0.3$	$\Delta R > 0.6$

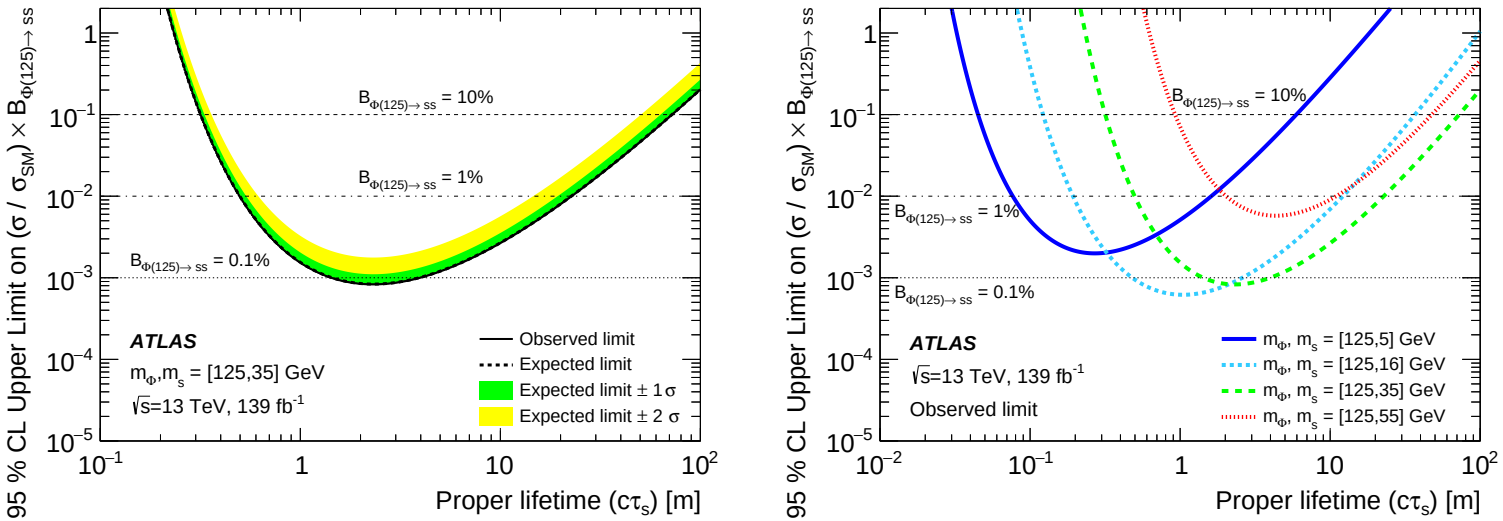
Vertex Isolation



Higgs decays with displaced vertex in the MS (II)

Phys. Rev. D 106, (2022) 032005

- No observed events for 0.32 ± 0.05 expected background.
- Upper limits on the $\mathcal{B}(H \to ss)$ as a function of $c\tau_s$ have been computed.



$\mathcal{B}(H \to ss) > 1\%$ are excluded for $c\tau_s$ between ∼10 cm and ∼20 m

Exotic Higgs decays in the calorimeter and MS (I)

arXiv:2206.12181

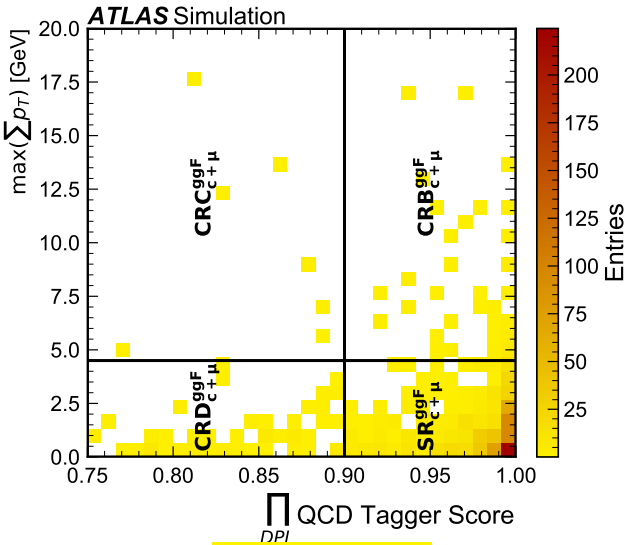
1 Signal:

- FRVZ: $H \to f_d f_d \to 2\gamma_d + X$
- HAHM: $H \to 2\gamma_d$

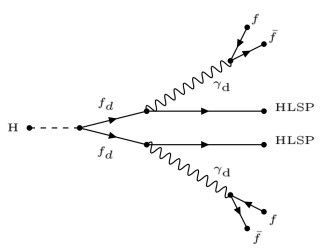
→ Signal objects are collimated jets in the hadronic calorimeter (caloDPJs) or the MS (μDPJs).

2 Background: Punch-through jets, SM multijet, noncolission (electronic noise in the MDT and RPC/TGC chambers, cosmic-ray muons, and BIB).

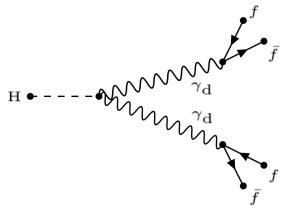
→ Estimated used the ABDC method.



FRVZ signal



FRVZ



HAHM

Requirement / Region	$SR^{ggF}_{2\mu}$	SR^{ggF}_{2c}	$SR^{ggF}_{c+\mu}$
Number of μDPJs	2	0	1
Number of caloDPJs	0	2	1
Tri-muon MS-only trigger	yes	-	-
Muon narrow-scan trigger	yes	-	yes
CalRatio trigger	-	yes	-
$\lvert\Delta t_{\text{caloDPJs}}\rvert$ [ns]	-	< 2.5	-
caloDPJ JVT	-	< 0.4	-
$\Delta\phi_{\text{DPJ}}$	$> \pi/5$	$> \pi/5$	$> \pi/5$
BIB tagger score	-	> 0.2	> 0.2
$\max(\sum p_{\text{T}})$ [GeV]	< 4.5	< 4.5	< 4.5
$\prod$ QCD tagger	-	> 0.95	> 0.9

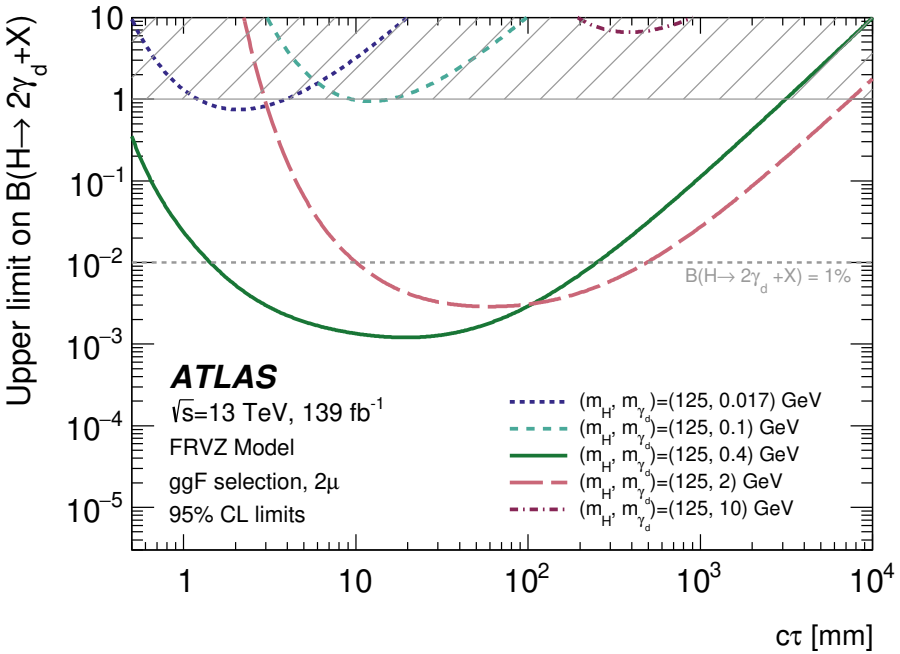
ggF selection

3 SRs: designed to target the *ggF* and *WH* production modes.

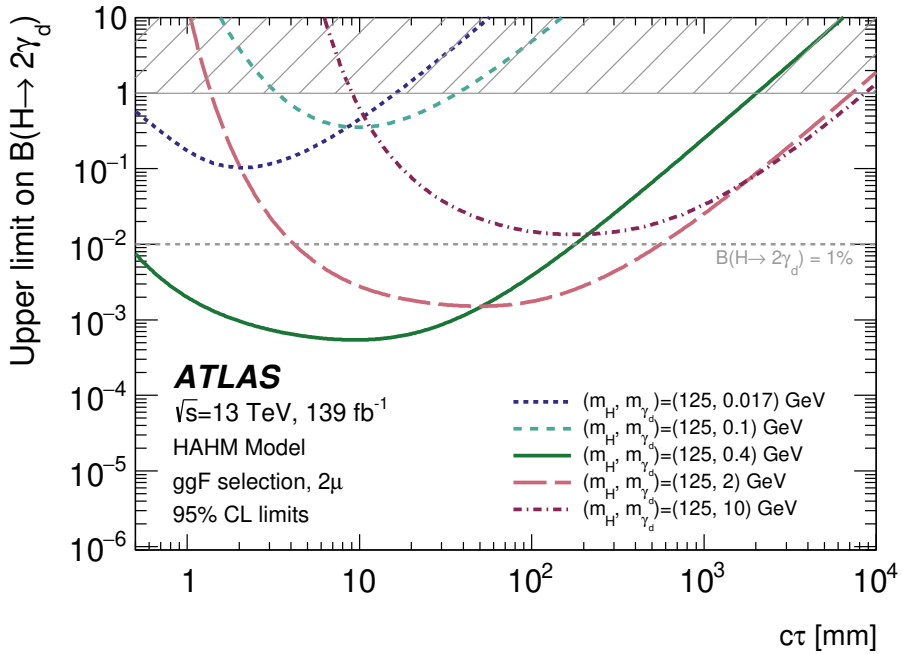
Exotic Higgs decays in the calorimeter and MS (II)

arXiv:2206.12181

- No significant excess of events has been observed.
- Upper limits on the $\mathcal{B}(H \to 2\gamma_d)$ as a function of $c\tau$ have been computed.



FRVZ model

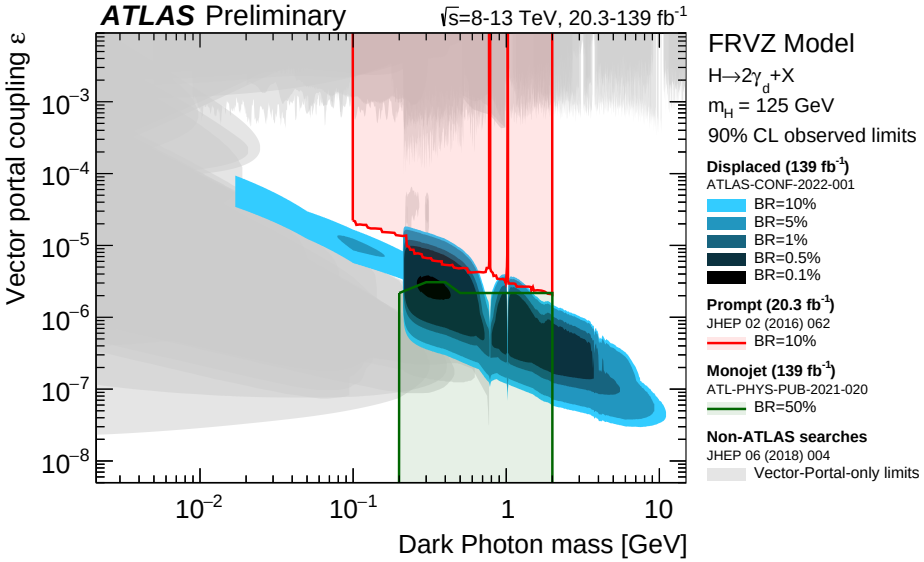


HAHM model

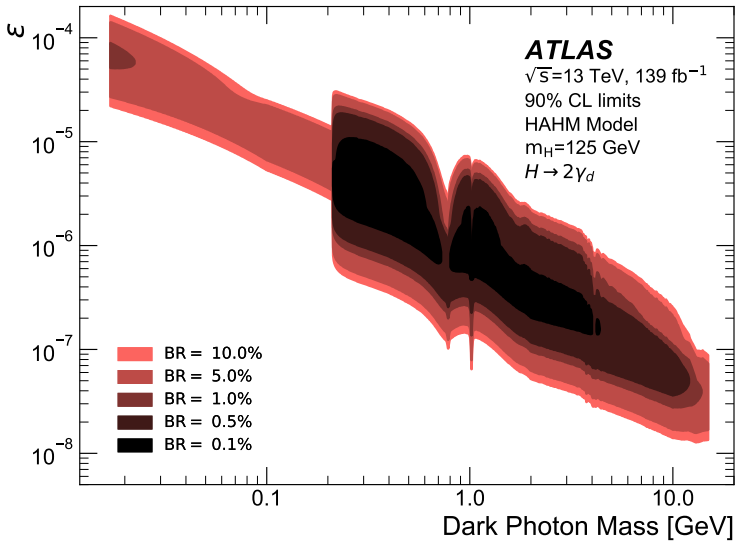
$\mathcal{B}(H \to 2\gamma_d) > 1\%$ excluded for $m_{\gamma_d} \in [0.4, 2]$ GeV and $c\tau \in [10, 250]$ mm

Interpretation in the ϵ vs dark photon mass plane

arXiv:2206.12181



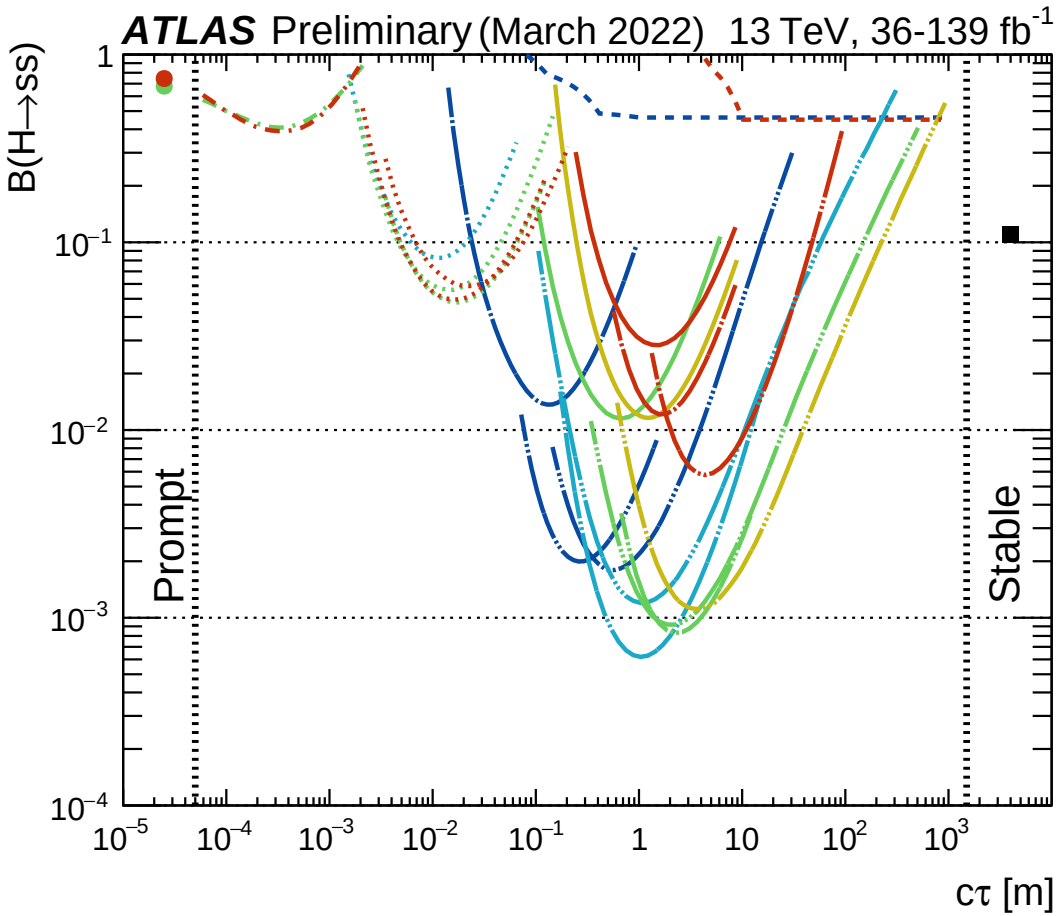
FRVZ model



HAHM model

Exotics Higgs decays: comparison of different searches (I)

ATL-PHYS-PUB-2022-007



Hidden Sector, m_H = 125 GeV
Selected **ATLAS** results
95% CL observed limits

Searches:

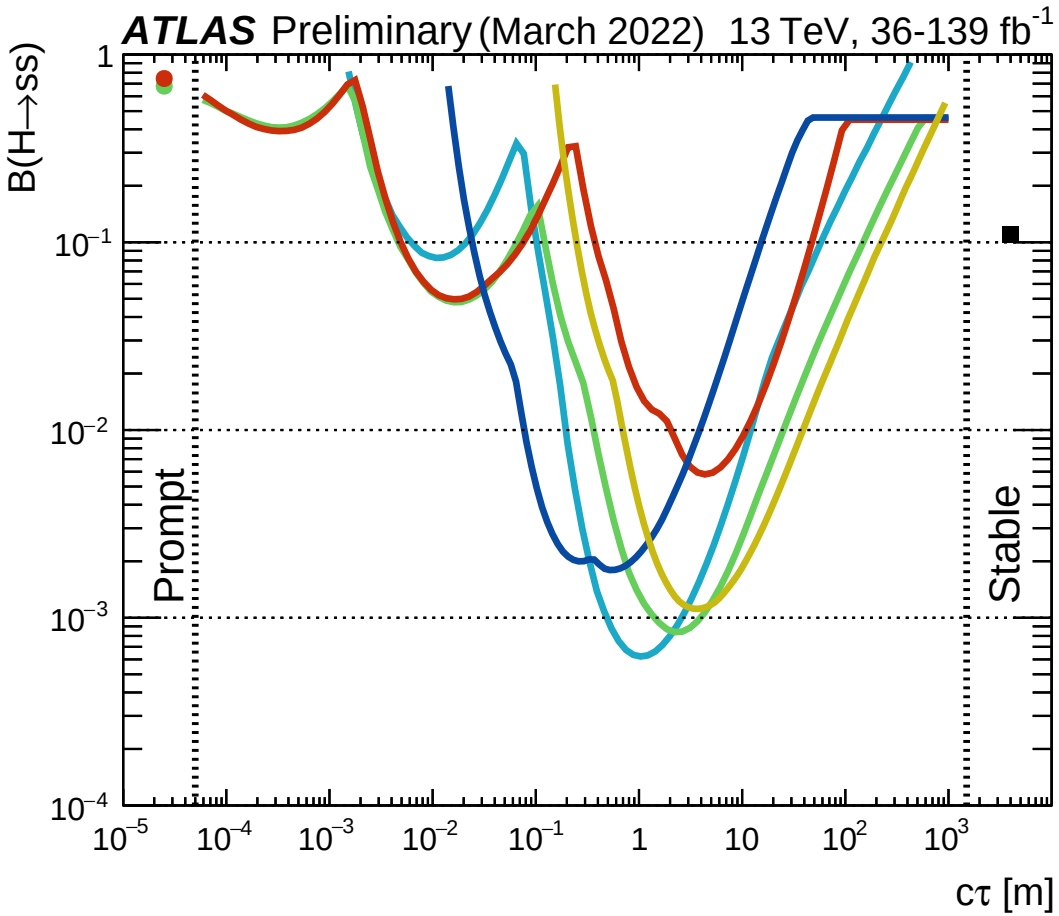
- **Muon System (2 Vtx Only), 139 fb^{-1}**
  arXiv:2203.00587
- **Muon System (1 Vtx + 2 Vtx), 36 fb^{-1}**
  Phys. Rev. D 99 (2019) 052005
- **Calorimeter, 139 fb^{-1}**
  arXiv:2203.01009
- **Tracker+Muon System, 36 fb^{-1}**
  Phys. Rev. D 101 (2020) 052013
- **Tracker (LRT), 139 fb^{-1}**
  JHEP 11 (2021) 229
- **Tracker (b-tag), 36 fb^{-1}**
  JHEP 10 (2018) 031
- **Monojet, 139 fb^{-1}**
  ATL-PHYS-PUB-2021-020
- **H→ inv, 7-8-13 TeV combination**
  ATLAS-CONF-2020-052

LLP masses:

5-8 GeV | 15-20 GeV | 25-35 GeV
40 GeV | 45-60 GeV | Any

Exotics Higgs decays: comparison of different searches (II)

ATL-PHYS-PUB-2022-007



Hidden Sector, m_H = 125 GeV

Selected *ATLAS* results

95% CL observed limits

Contributing searches:

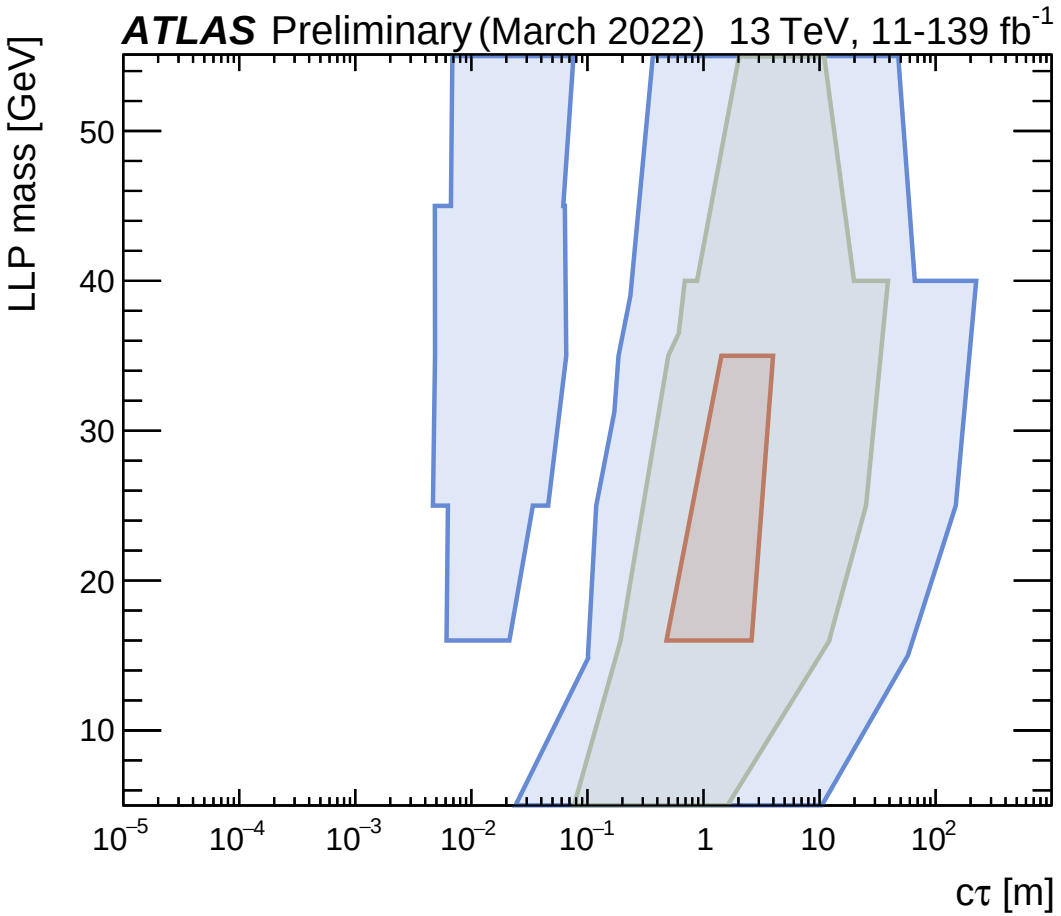
- **Muon System (2 Vtx Only), 139 fb^{-1}**
  arXiv:2203.00587
- **Muon System (1 Vtx + 2 Vtx), 36 fb^{-1}**
  Phys. Rev. D 99 (2019) 052005
- **Calorimeter, 139 fb^{-1}**
  arXiv:2203.01009
- **Tracker+Muon System, 36 fb^{-1}**
  Phys. Rev. D 101 (2020) 052013
- **Tracker (LRT), 139 fb^{-1}**
  JHEP 11 (2021) 229
- ● **Tracker (b-tag), 36 fb^{-1}**
  JHEP 10 (2018) 031
- **Monojet, 139 fb^{-1}**
  ATL-PHYS-PUB-2021-020
- ■ **H→ inv, 7-8-13 TeV combination**
  ATLAS-CONF-2020-052

LLP masses:

5-8 GeV | 15-20 GeV | 25-35 GeV | 40 GeV | 45-60 GeV | Any

Exotics Higgs decays: comparison of different searches (III)

ATL-PHYS-PUB-2022-007



Hidden Sector, m_H = 125 GeV
95% CL observed limits
from all *ATLAS* results

B(H→ss) = 10%

B(H→ss) = 1%

B(H→ss) = 0.1%

Contributing searches:

Muon System (2 Vtx Only), 139 fb^{-1}
arXiv:2203.00587
Muon System (1 Vtx + 2 Vtx), 36 fb^{-1}
Phys. Rev. D 99 (2019) 052005
Calorimeter, 139 fb^{-1}
arXiv:2203.01009
Calorimeter, 11 fb^{-1}
Eur. Phys. J. C 79 (2019) 481
Tracker+Muon System, 36 fb^{-1}
Phys. Rev. D 101 (2020) 052013
Tracker (LRT), 139 fb^{-1}
JHEP 11 (2021) 229

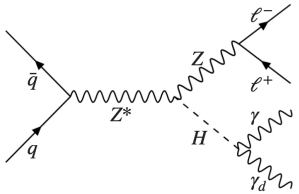
Higgs decays to dark photons

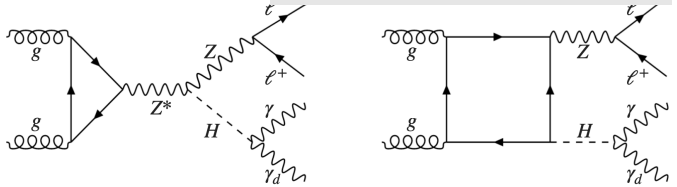
ATLAS-CONF-2022-064

1 Signal: ZH, $H \to \gamma\gamma_d$

$\to Z \to \ell^+\ell^-$

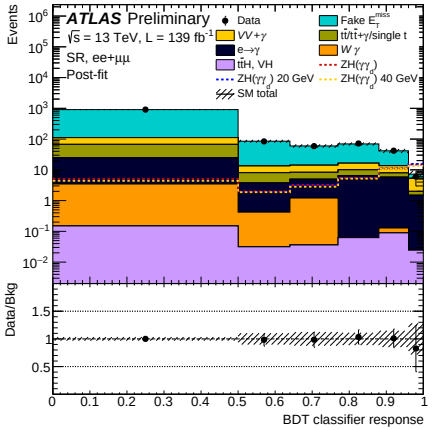
$\to$ *Undetected* γ_d.





2 Background:

- $VV\gamma$: Normalised in a CR.
- Fake $E_{\mathrm{T}}^{\mathrm{miss}}$, fake photons: Estimated from data-driven techniques.
- $tW\gamma$, $t\bar{t}\gamma$, $t\bar{t}$, single-top, $W\gamma$, $t\bar{t}H(\to Z\gamma)$, $VH(\to Z\gamma)$: taken from MC.

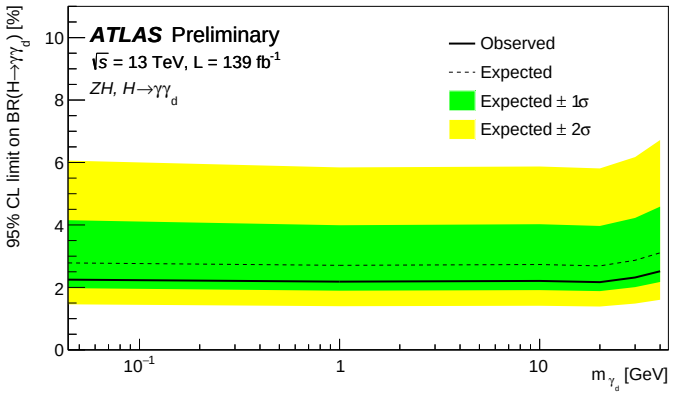


3 Analysis strategy:

- Target the signature final state: $\ell^+\ell^- + \gamma + E_{\mathrm{T}}^{\mathrm{miss}}$
- Use BDT to discriminate signal against background.

4 Result:

- No significance excess of events has been observed.
- Massless photon: $\mathcal{B}(H \to \gamma\gamma_d) > 2.3\%$ is excluded.



→ *CMS result:* $\mathcal{B}(H \to \gamma\gamma_d) > 4.6\%$ *JHEP10(2019)139*

ATLAS improves by a factor of 2 the results from CMS

LFV decays of the Higgs boson into $e\tau$ and $\mu\tau$ (I)

[ATLAS-CONF-2022-060]

1 Signal: $H \to e\tau$ and $H \to \mu\tau$

2 Background:

- $Z \to \tau\tau$, top-quark: normalised in a CR.
- Other prompt: taken from MC.
- Misidentified: Estimated from data-driven techniques.

3 Analysis strategy:

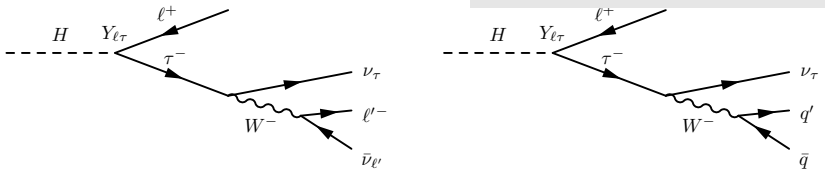
- Signal regions defined according to the τ decay mode and the Higgs production mode:

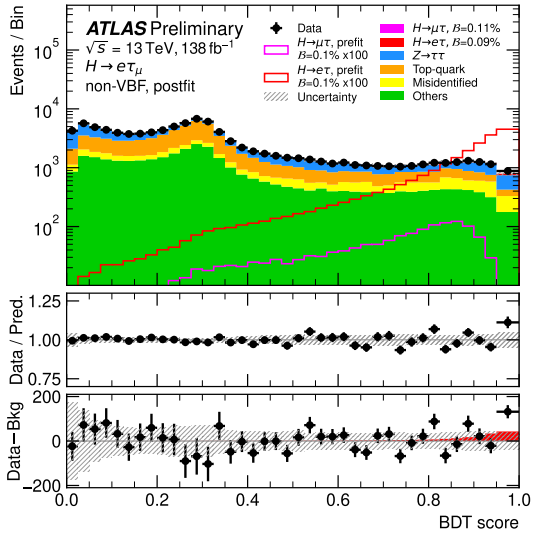
  $\tau \to \ell' \nu\bar{\nu}$, $\tau \to$ *hadrons* $+ \nu$, *VBF and non-VBF.*

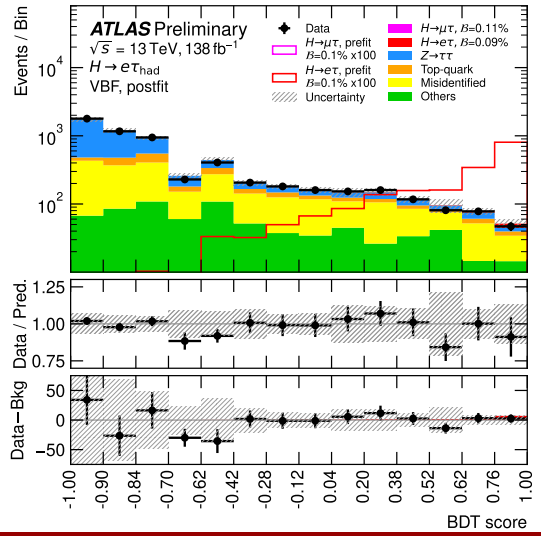
- Use BDTs to separate signal from background.
- $\mathcal{B}(H \to e\tau)$ and $\mathcal{B}(H \to \mu\tau)$ are fitted simultaneously using the BDT score in the SRs and the event yield in the CRs.

4 Result:

- No significant excess of events has been observed.

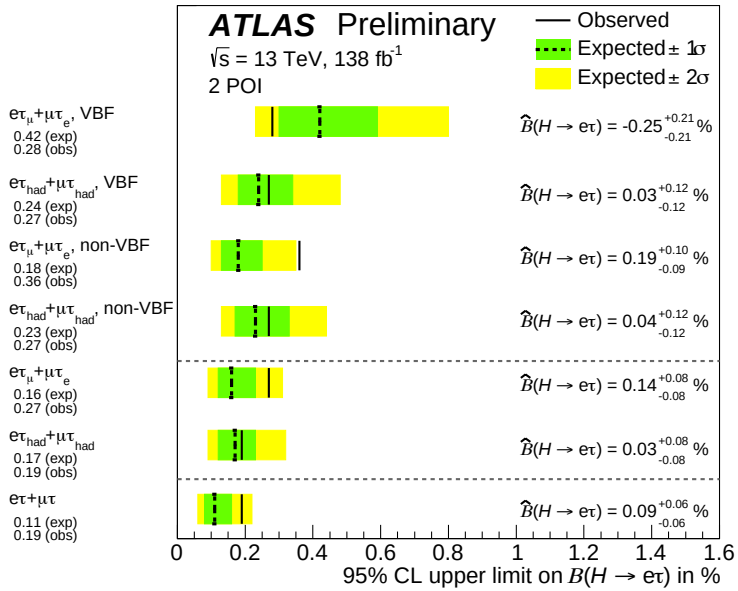


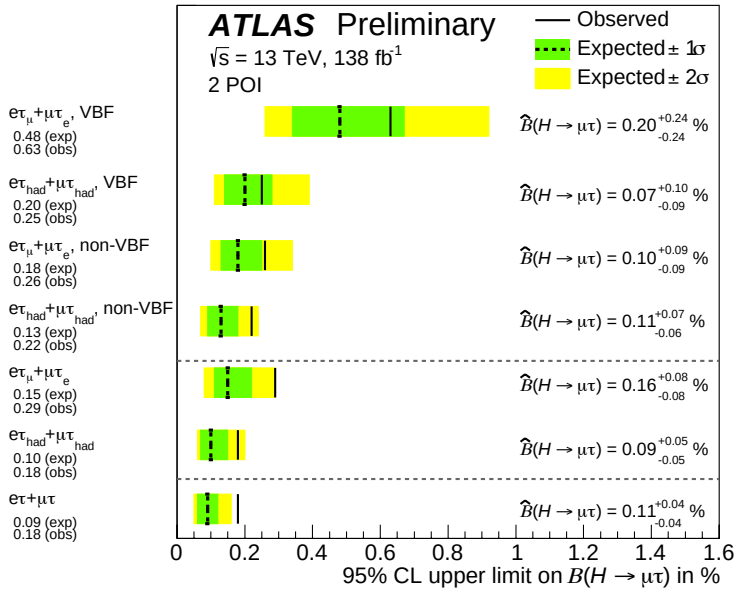


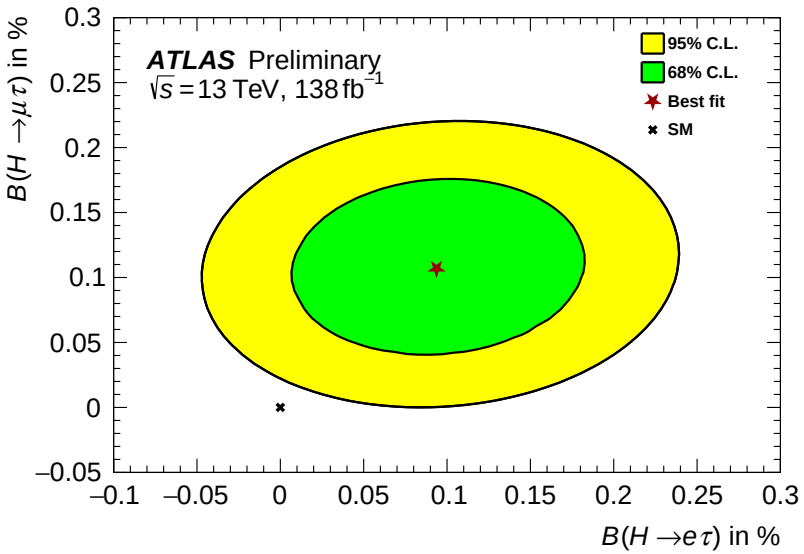


LFV decays of the Higgs boson into $e\tau$ and $\mu\tau$ (II)

ATLAS-CONF-2022-060







- Results improved by a factor of up to 2.4 (1.5) the limits for $H \to e\tau$ ($H \to \mu\tau$) decay from previous ATLAS results (*Phys. Lett. B 800 (2020) 135069*).
- Expected sensitivity for $H \to e\tau$ ($H \to \mu\tau$) signal improved by a factor of about 3.1 (4.1).

Results compatible with the SM within 2.2σ

Exotics decays of the Z boson (I)

[ATLAS-CONF-2022-041]

1 Signal: $pp \to Z'\mu\mu \to 4\mu$

$\to$ *Can address the observed muon $g-2$ anomanly*

2 Background:

- SM $Z(Z^*)$: normalised in a CR.
- Other SM prompt: taken from MC.
- Reducible: Estimated from data-driven techniques.

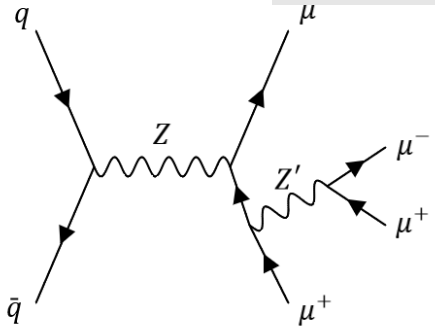
3 Analysis strategy:

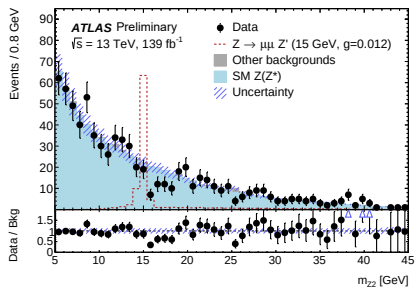
- Select events with 4μ, $m_{4\mu} \in [80, 180]$ GeV, excluding $m_{4\mu} \in [110, 130]$ GeV.
- Use a deep learning approach to separate signal from background.
- *m_{Z1} and m_{Z2} are scanned looking for an excess.*

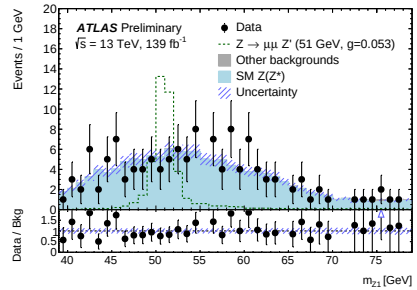
  $\to$ m_{Z1} for $m_{Z'} > 42$ GeV, m_{Z2} for $m_{Z'} < 42$ GeV.

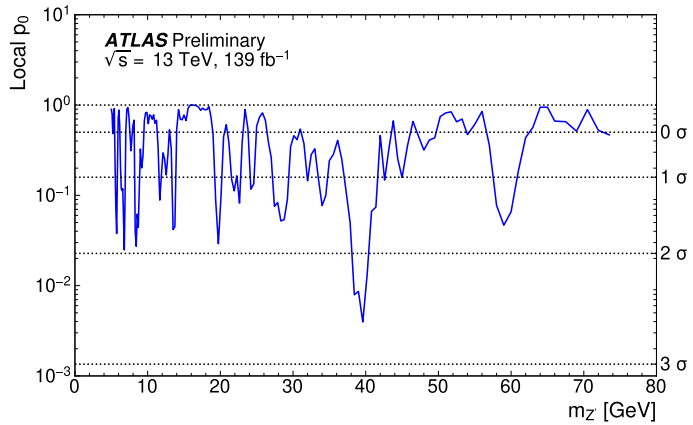
4 Result:

- No significant excess of events has been observed.





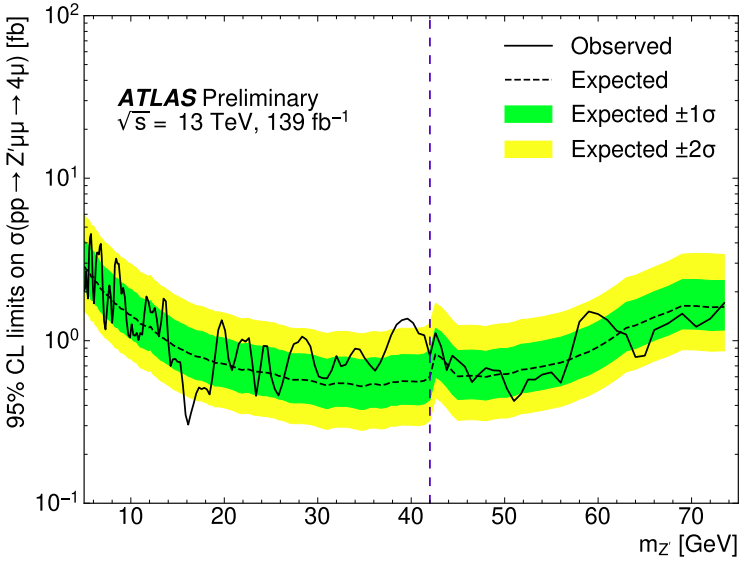


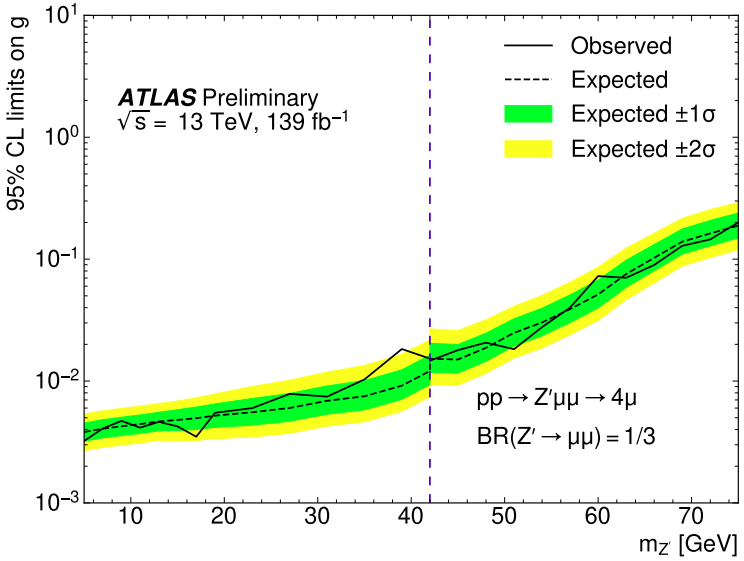


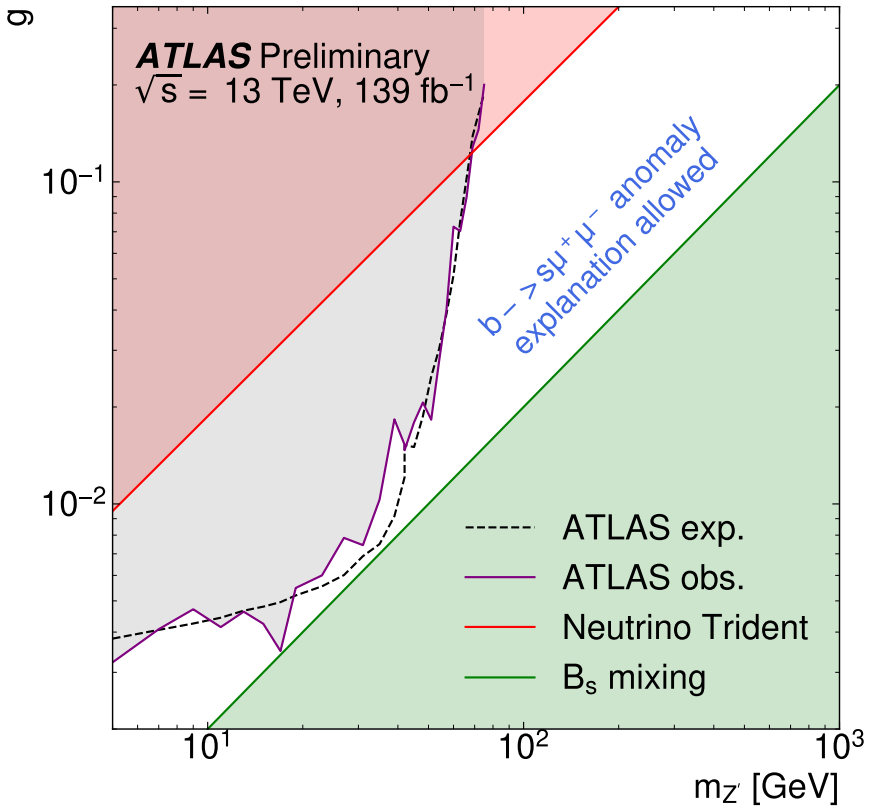
Highest local significance 2.65σ (global: 0.52σ)

Exotics decays of the Z boson (II)

ATLAS-CONF-2022-041







Gap allowed to explain the LHCb $b \to s\mu^+\mu^-$ anomaly largely excluded by ATLAS

Summary

- ATLAS searches for LLP from Higgs boson decays are complementary

  $\rightarrow$ *Together, they provide coverage of $c\tau$ values extending from effectively prompt to $\sim$ 200 m*

- No evidence for exotic decays of the Higgs and Z boson has been found.

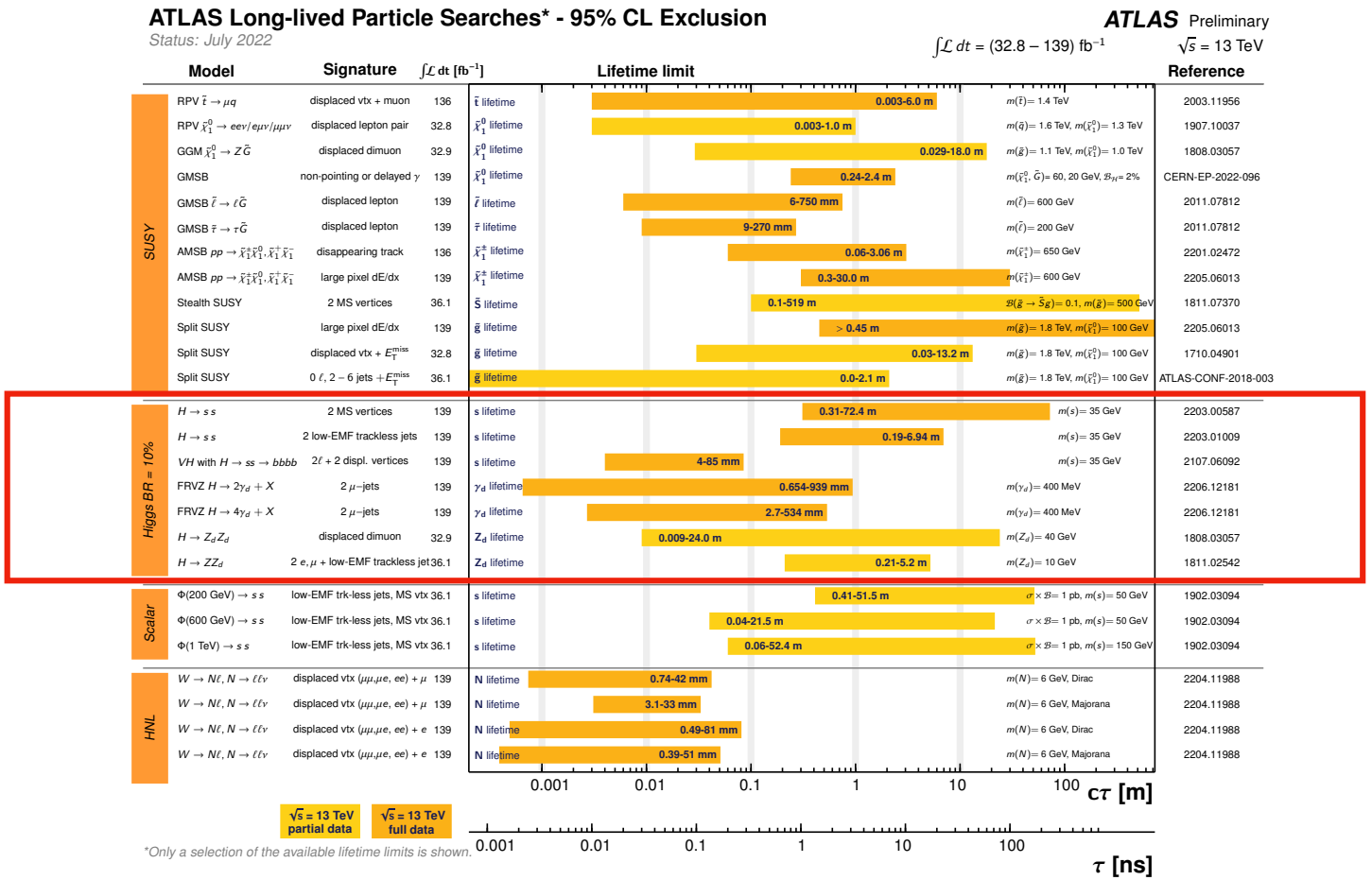
- Sensitivity has improved significantly with respect to the latest results due to the enlarged dataset and new analysis techniques.

- Still a lot of work to be done...

Waiting for more data from the LHC Run 3!

BACKUP

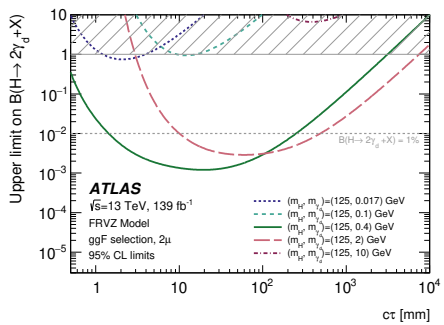
Summary of LLP lifetimes from exotic Higgs decays excluded at the 95% CL

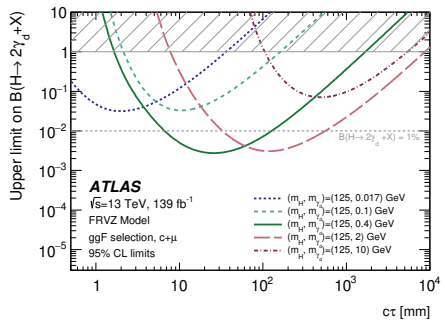


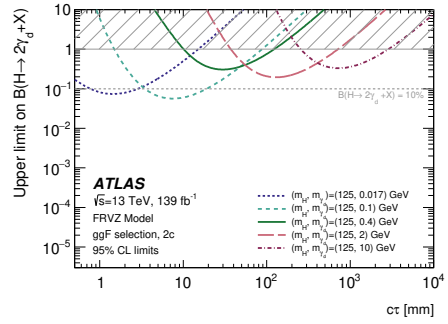
Exotics Higgs decays in the calorimeter and MS

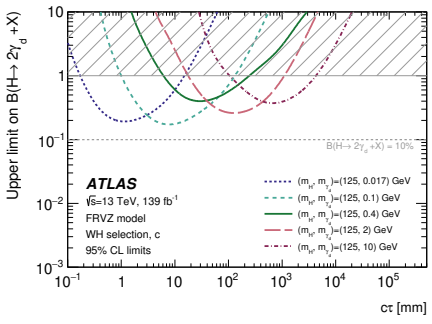
- No significant excess of events has been observed.
- Upper limits on the $\mathcal{B}(H \to 2\gamma_d)$ as a function of $c\tau$ have been computed.

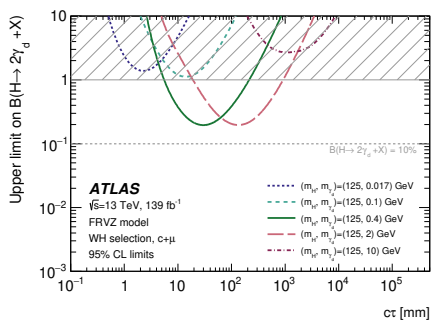
FRVZ

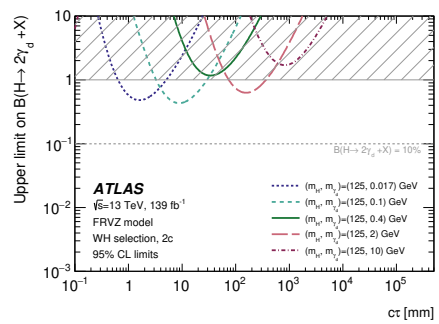












HAHM