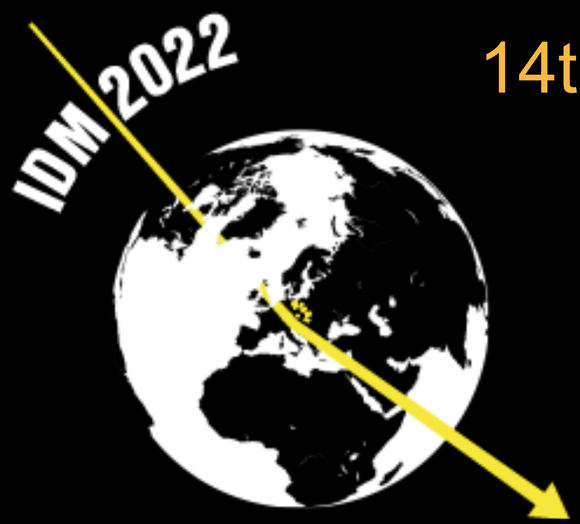
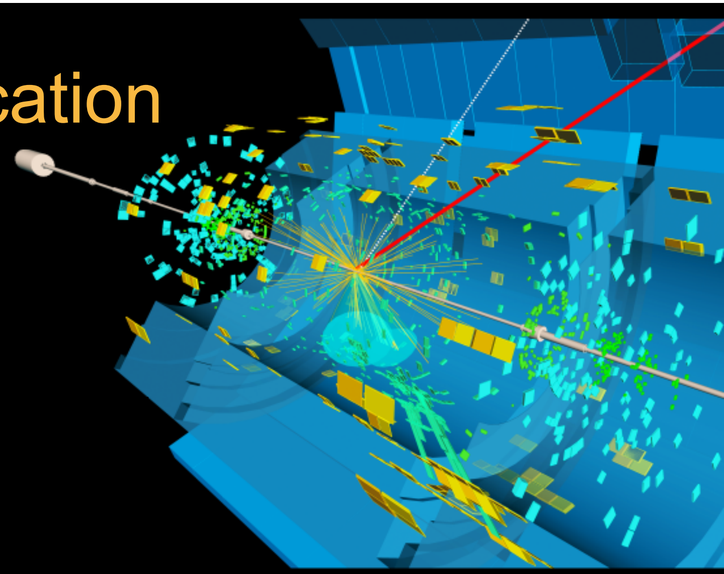
Searches for exotic decays of the Higgs boson as a window to the dark sector with the ATLAS detector



14th International Conference on Identification of Dark Matter

Victoria Sánchez Sebastián
on behalf of the ALTAS Collaboration

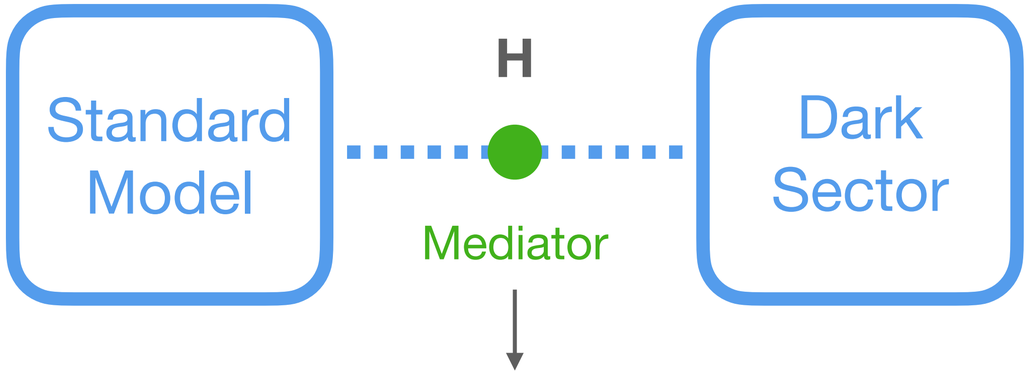
21st July 2022



Introduction

- Dark Matter (DM) can be part of a hidden sector whose interactions with visible matter are not completely decoupled
- Higgs boson could be the portal to DM: full Run 2 (2015-2018) results set a 95% CL upper limit of **15%** on the BSM contribution to the branching ratio for **H→undetected modes** [1]

  ➡ Exotic decays of Higgs boson remain a high priority
- Biased summary of newest ATLAS results highlighted in this talk (all full Run 2, $\sqrt{s} = 13$ TeV), **prompt** and **non-prompt decays** included



Non-gravitational interaction between dark matter and ordinary matter

Extended Higgs sectors predicted by many theories of beyond the Standard Model (BSM) physics: naturalness, axions, SUSY, DM …

[1] ATLAS-CONF-2021-053

Prompt searches

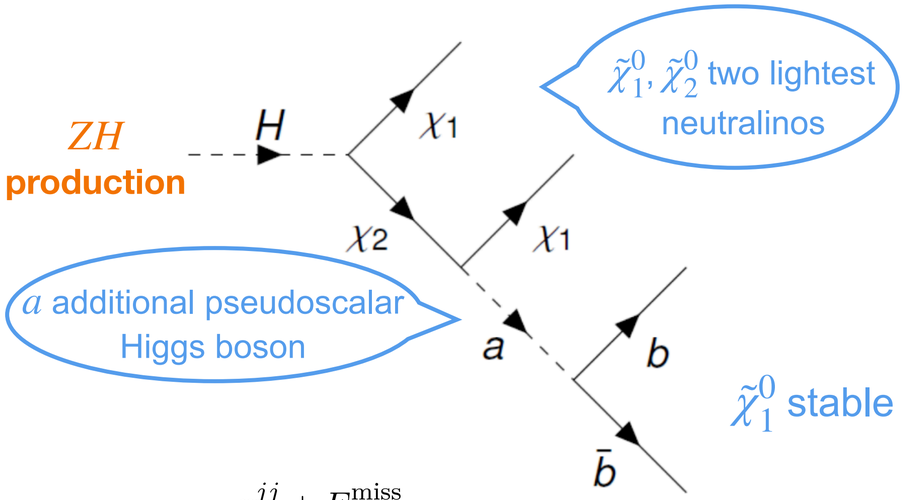
- Higgs to $bb + E_T^{miss}$
- Higgs to $b\bar{b} + \mu\mu$
- Higgs to 4 leptons:
  - $H \rightarrow XX \rightarrow 4l$
  - $H \rightarrow XZ \rightarrow 4l$

- Other recent results

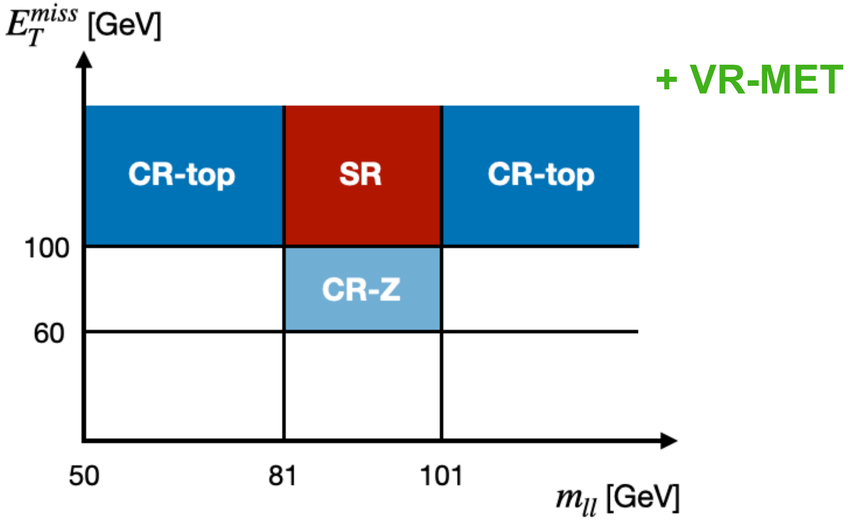
Higgs to $bb + E_T^{miss}$

JHEP 01 (2022) 063

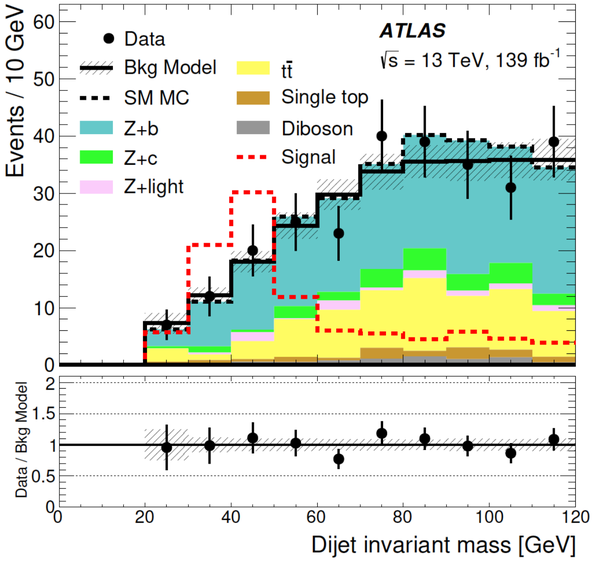
- Next-to-minimal supersymmetric SM (NMSSM) near the Peccei–Quinn symmetry limit [2]: $H \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to a\tilde{\chi}_1^0\tilde{\chi}_1^0, a \to b\bar{b}$
- ZH production: **trigger on $Z \to ee/\mu\mu$** and reduce multijet background
- Strategy:
  - ➡ Select events with opposite sign same flavour (OS SF) lepton pair, large E_T^{miss} and two or more jets (at least one b-tagged)
  - ➡ Search for deviation in m_{jj}

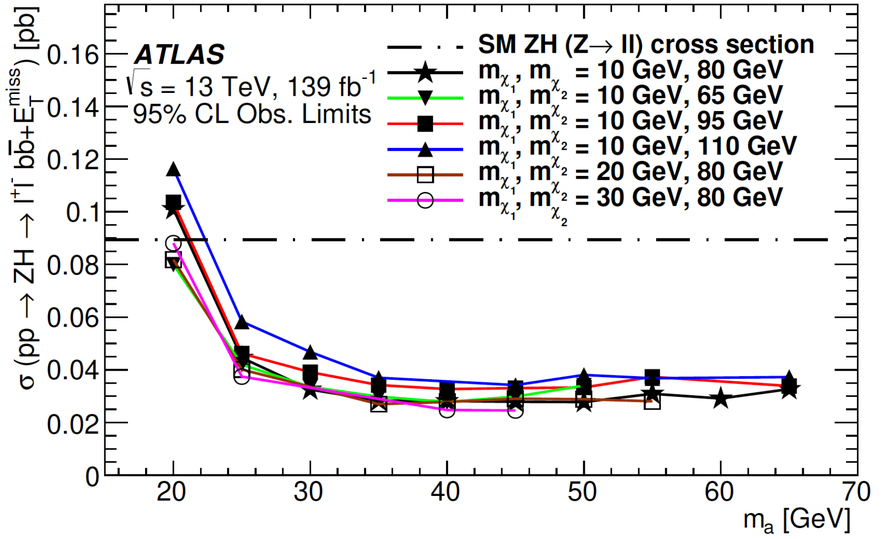


★ Reduce $t\bar{t}$ bakground: $0.8 < \frac{p_{\mathrm{T}}^{jj} + E_{\mathrm{T}}^{\mathrm{miss}}}{p_{\mathrm{T}}^{\ell\ell}} < 1.2$



+ VR-MET





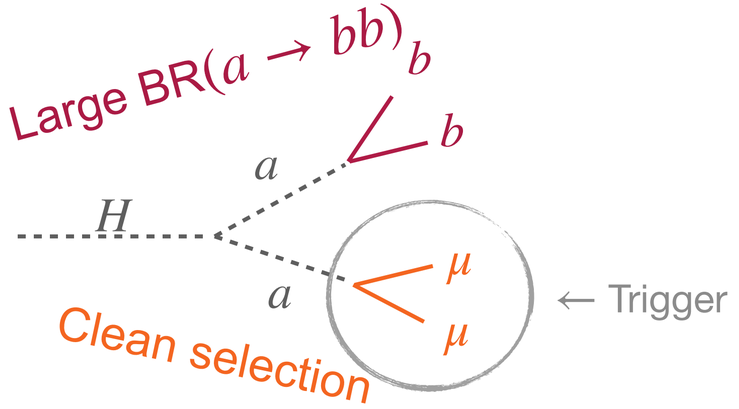
[2] arXiv:0910.1785

Higgs to $bb + \mu\mu$

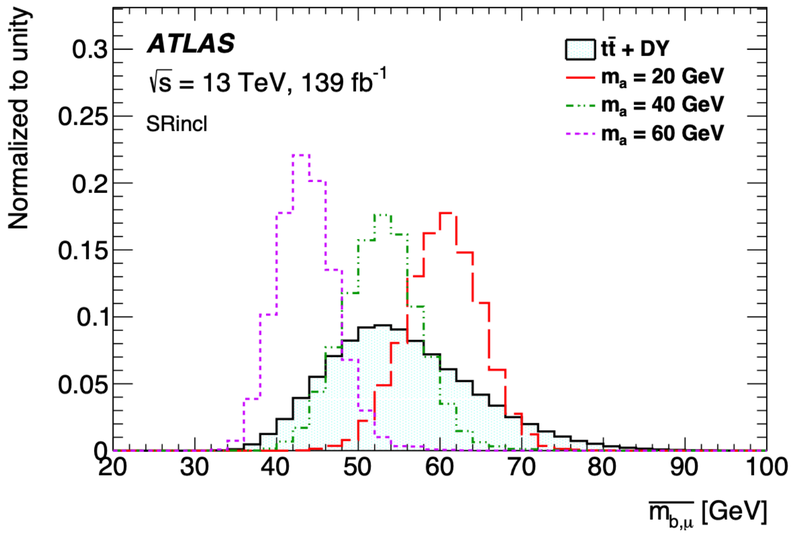
Phys. Rev. D 105 (2022) 012006

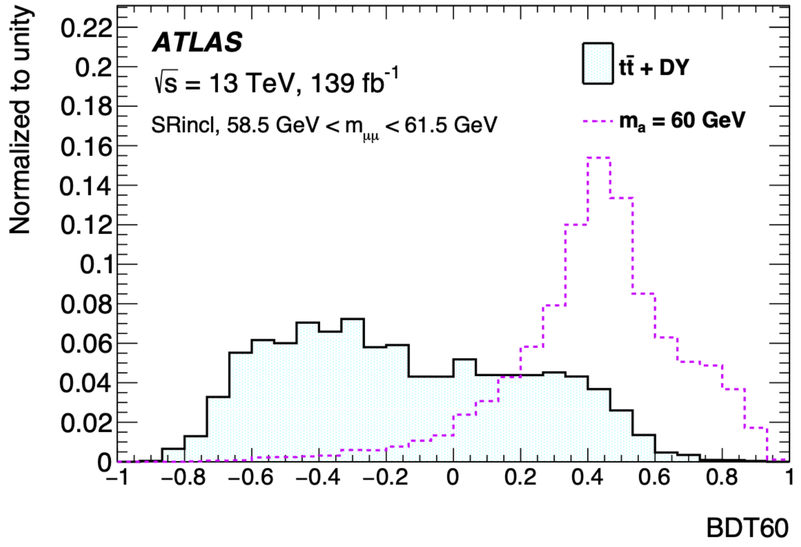
- Higgs decay to a pair of light (pseudo) scalars $H \to aa \to bb\mu\mu$
- Kinematic-likelihood (KL) fit constrains $m_{\mu\mu} \approx m_{bb}$ and improves $m_{\mu\mu bb}$ resolution
- Multiple BDTs trained in **partially overlapping** 8 GeV wide windows in $m_{\mu\mu}$

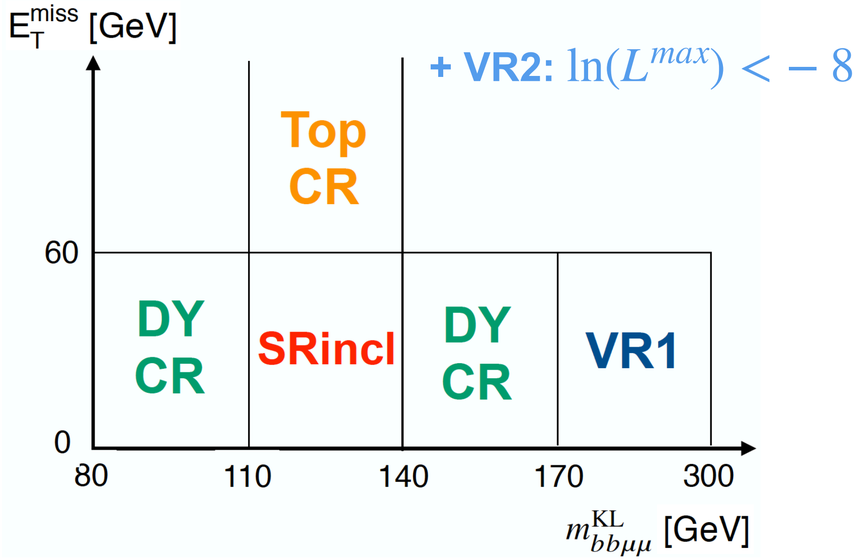
  ➡ Exploit kinematic differences that depend on m_a



Large BR($a \to \mu\mu$) in enhanced lepton coupling scenarios





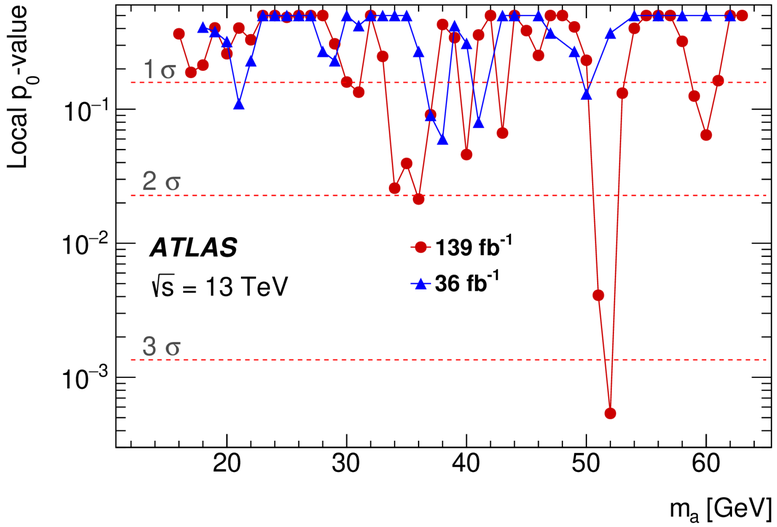


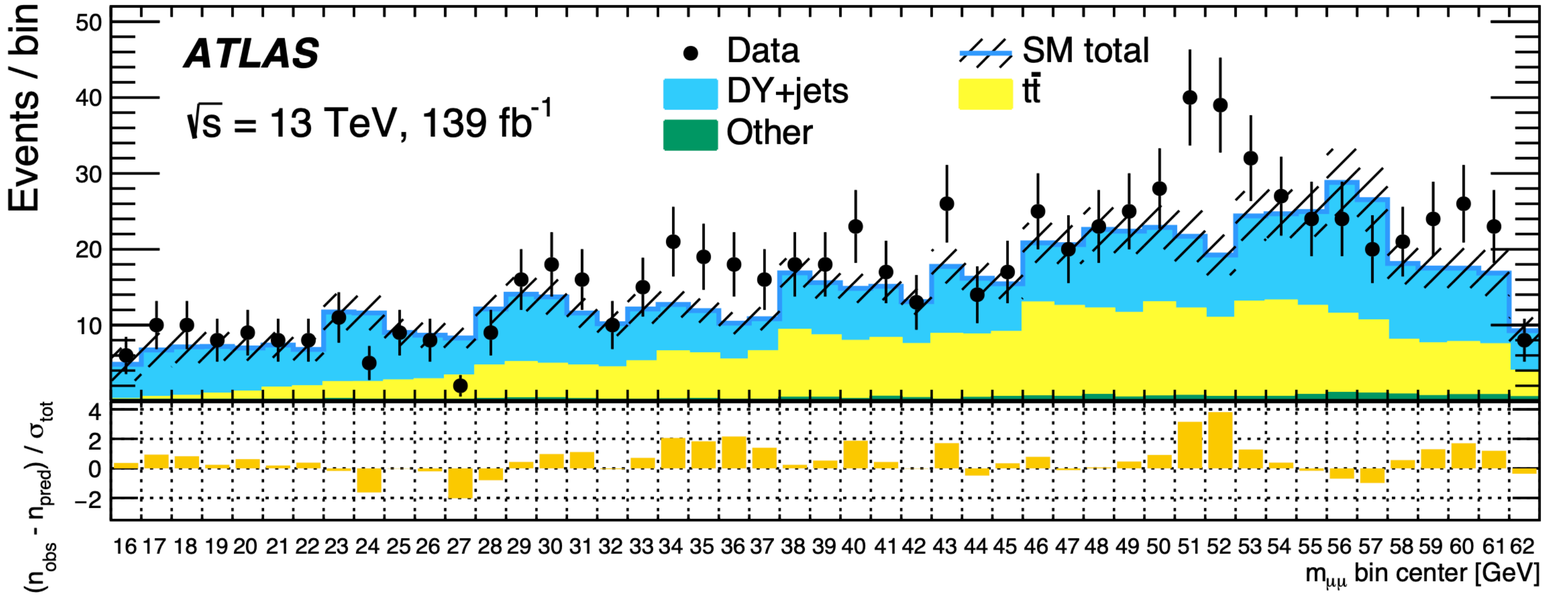
Higgs to $bb + \mu\mu$

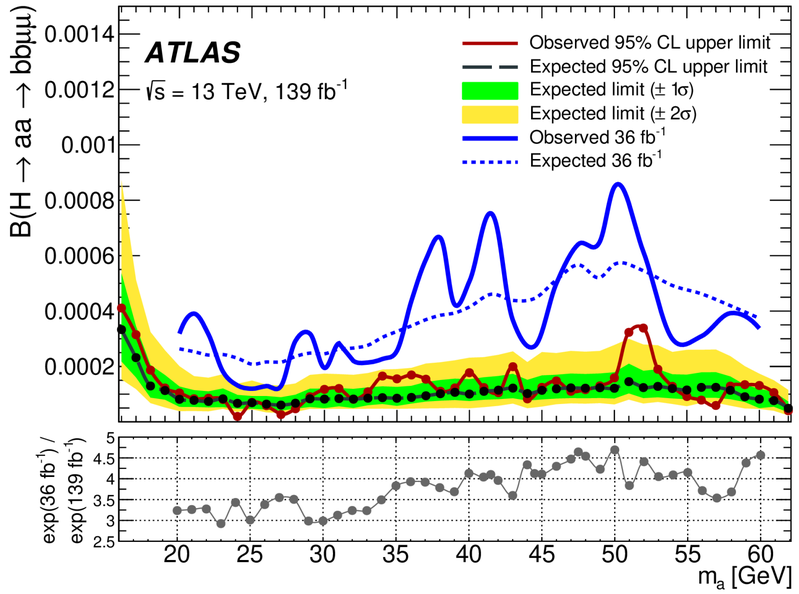
Phys. Rev. D 105 (2022) 012006

- Search performed in dimuon spectrum:16 GeV < $m_{\mu\mu}$ < 62 GeV (2-3 GeV windows)
- Largest excess seen at $m_a = 52$ GeV, 3.3σ local significance (1.7σ global)
- Limits set on $\mathrm{Br}(H \to aa \to bb\mu\mu)$ between $0.2 \times 10^{-4} - 0.4 \times 10^{-4}$

➡ Improve previous ATLAS results by a factor 2 to 5







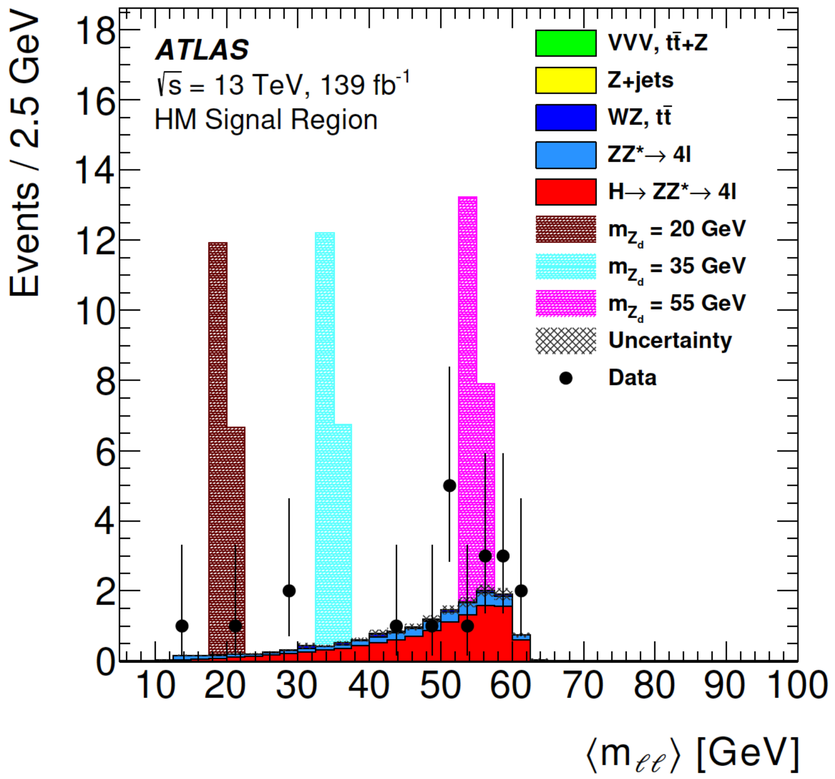
Higgs to 4 leptons: $H \to XX \to 4l$

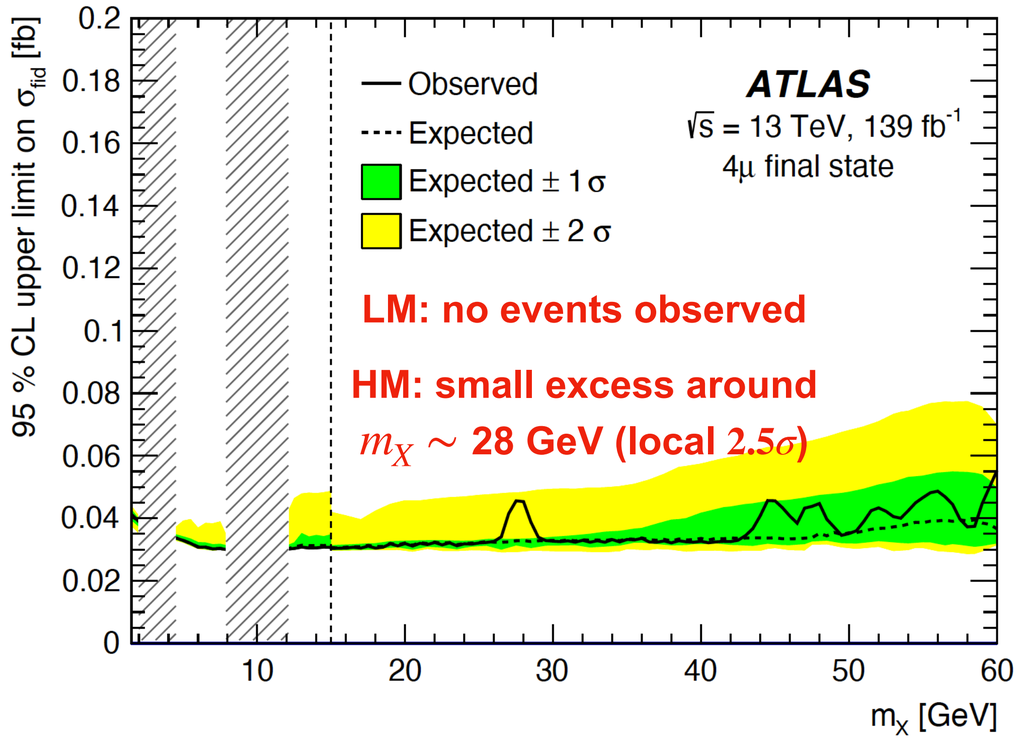
JHEP 03 (2022) 041

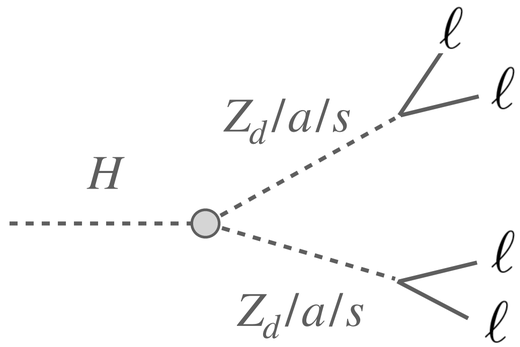
- Search dilepton mass resonances with two OSSF lepton pairs
  - ➡ Impose consistency $m_{12} \approx m_{34}$ and m_{4l} consistent with H
- Limits improve by factor 2-4 with respect to previous 2015+2016 data result:
  - ➡ improved lepton reconstruction and identification, optimized selection and more data

High-mass (HM): $H \to XX \to 4l$, $l = e, \mu$, $m_X \in [15,60]$ GeV

Low-mass (LM): $H \to XX \to \mu\mu$, $m_X \in [1,15]$ GeV







Higgs portal

Interpreted in HAHM and 2HDM+S models

$$\langle m_{ll} \rangle = \frac{m_{12} + m_{34}}{2}$$

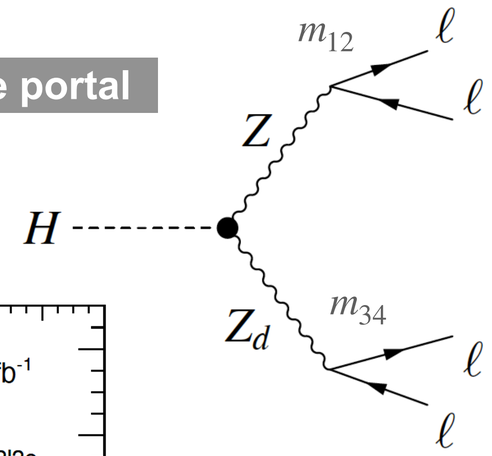
Higgs to 4 leptons: $H \to XZ \to 4l$

JHEP 03 (2022) 041

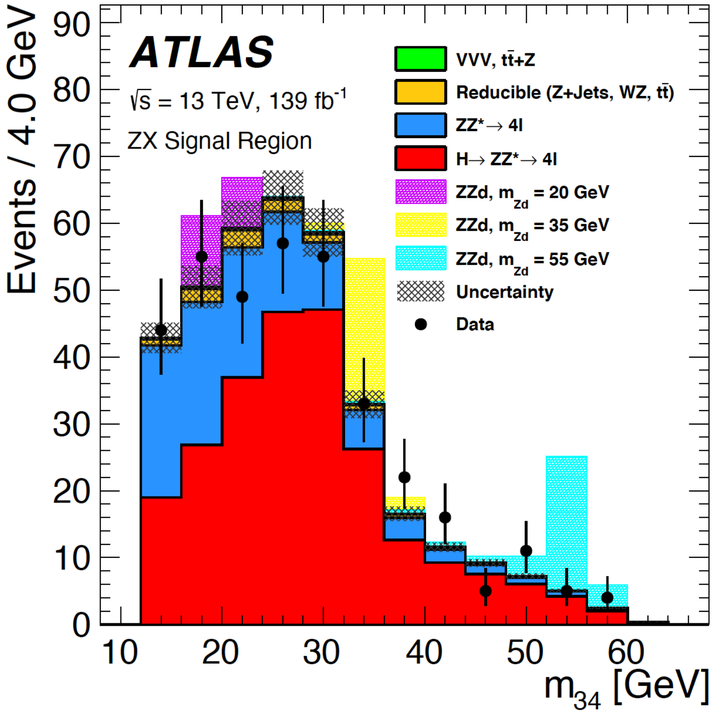
- Search dilepton mass resonances with two OSSF lepton pairs, defined by $|m_{12} - m_Z| < |m_{34} - m_Z|$
  - ➡ Require leading pair m_{12} and m_{4l} consistent with Z and H decays
- Search for excess in lower mass pair: m_{34}
- No significant excess, **limits improve by factor 2** previous 2015+2016 data result

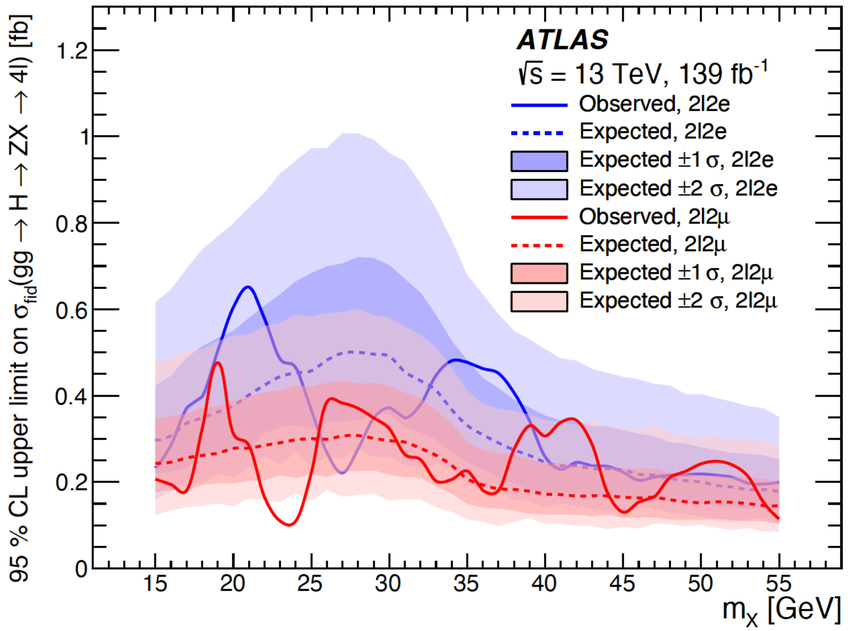
Single Z (ZX): $H \to ZX \to 4l$, $l = e, \mu$
$m_X \in [15,55]$ GeV

Hypercharge portal



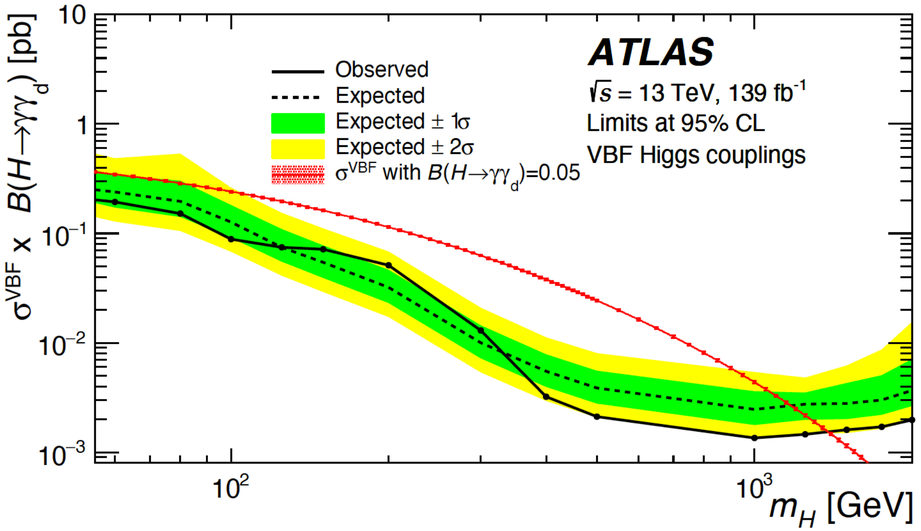
Main backgrounds (ZZ^*, $H \to ZZ^*$) estimated by simulation and validated in m_{4l} sidebands

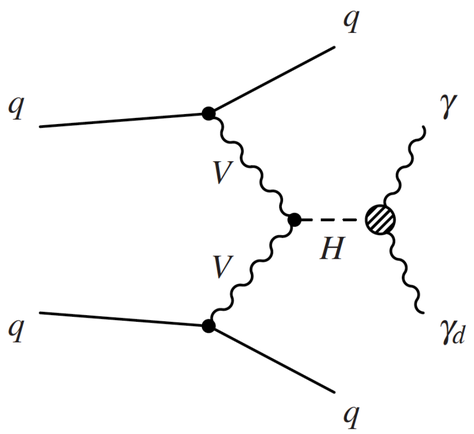




Results interpreted for $H \to ZZ_d \to 4l$ and $H \to Za \to 2l2\mu$

Other recent results





$H \to \gamma\gamma_d$ reinterpretation of electroweak $Z\gamma$ production in association with 2 jets (SM measurement)

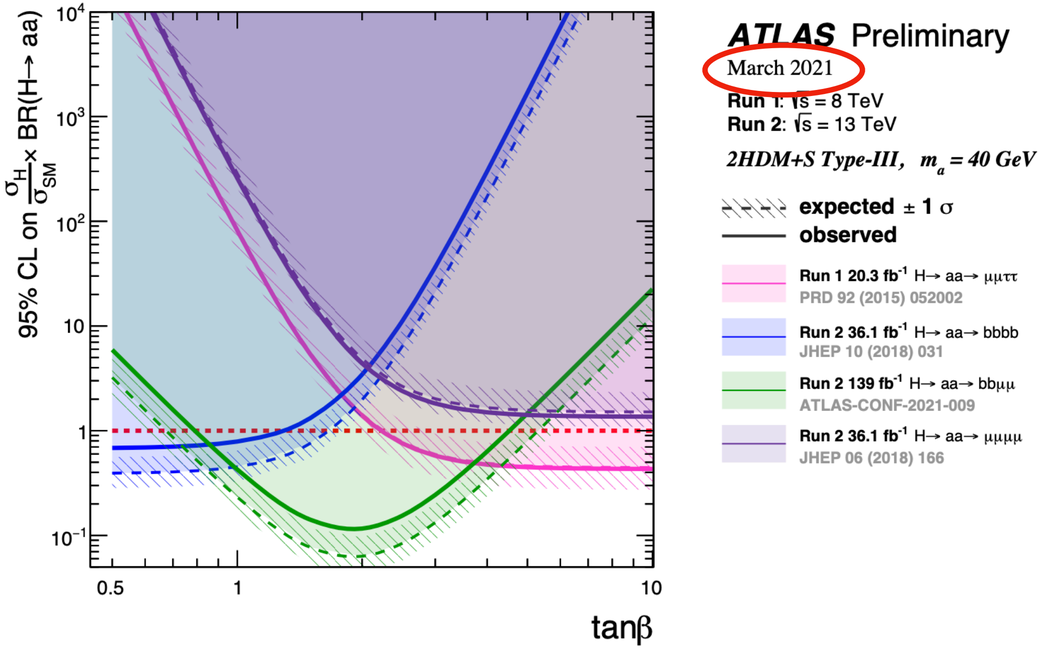
Signature: VBF+E_T^{miss}+Photon

Eur. Phys. J. C 82 (2022) 105

Summary of Exotic Higgs Boson Decays

Model-independent limits on BR($H \to aa \to xx\,yy$) translated on limits of BR($H \to aa$)

ATL-PHYS-PUB-2021-008

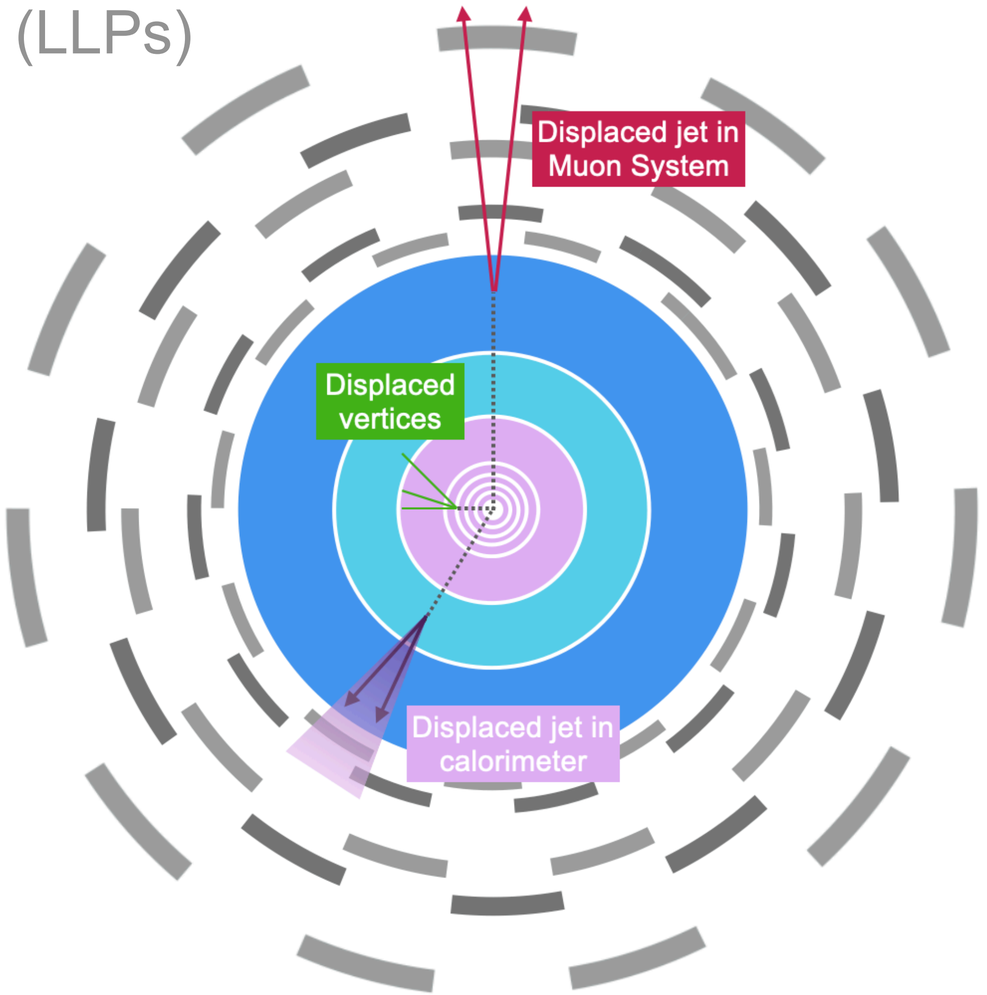


Displaced searches

Weak coupling to the SM leads to long-lived-particles (LLPs)

- Non-prompt photons
- Displaced hadronic jets in the HCAL
- Displaced hadronic jets in the MS

- Summary of ATLAS LLP searches

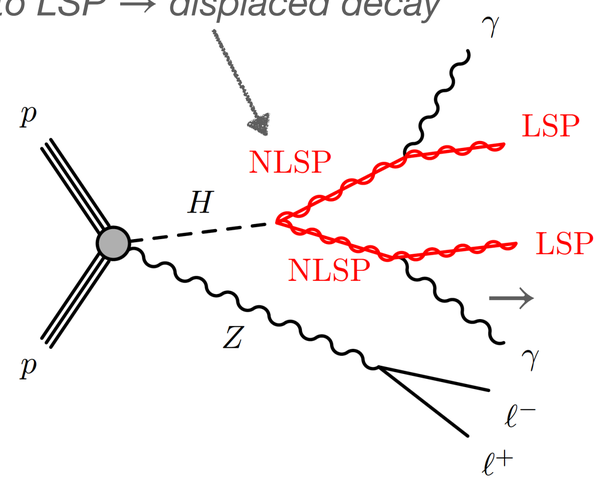


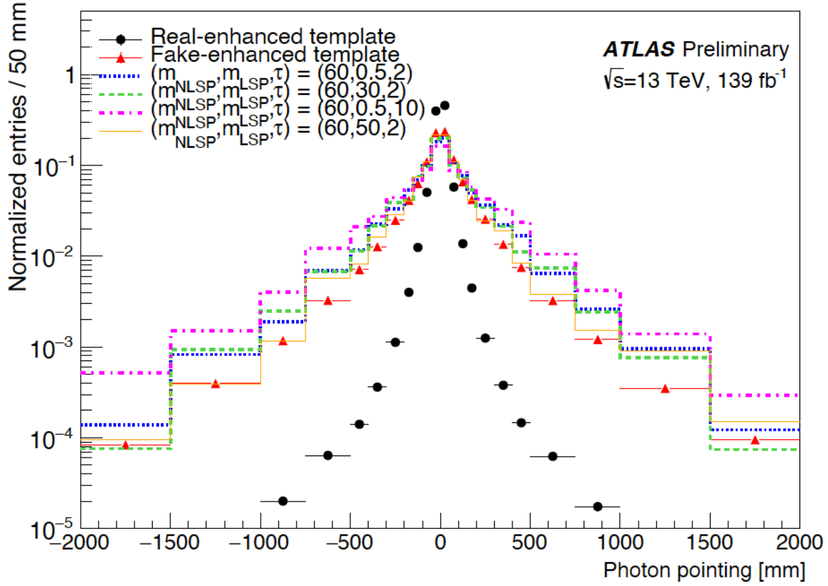
Non-prompt photons

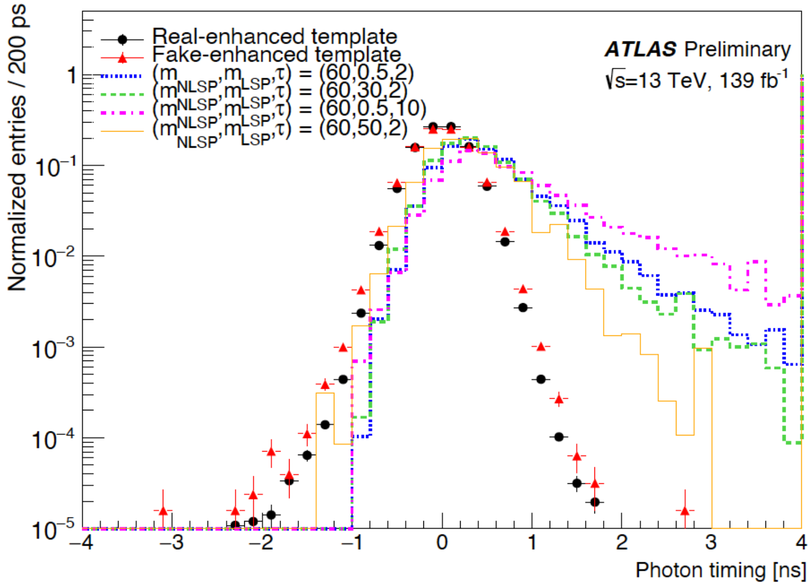
ATLAS-CONF-2022-017

- Gauge-mediated SUSY breaking
- Signature: displaced photons + E_T^{miss} - Consider $Z/W/t\bar{t}$ + H production and require single lepton triggers
- Displacement of photons determined by **timing** and **pointing** measurements unique capabilities of the ATLAS LAr calorimeter
- Calibrated by $Z \rightarrow ee$ events
- Backgrounds: mixture of photon (real) and electrons or jets (fake), mixture factor fitted as a nuisance parameter

Weak coupling to LSP → displaced decay







Non-prompt photons

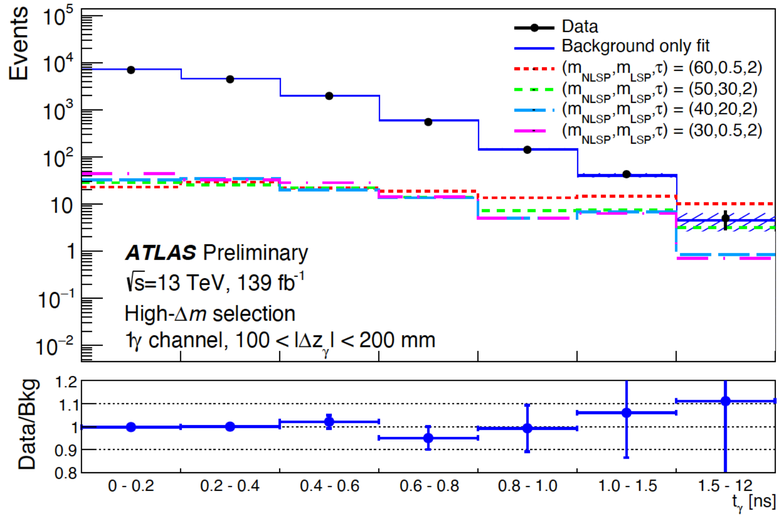
ATLAS-CONF-2022-017

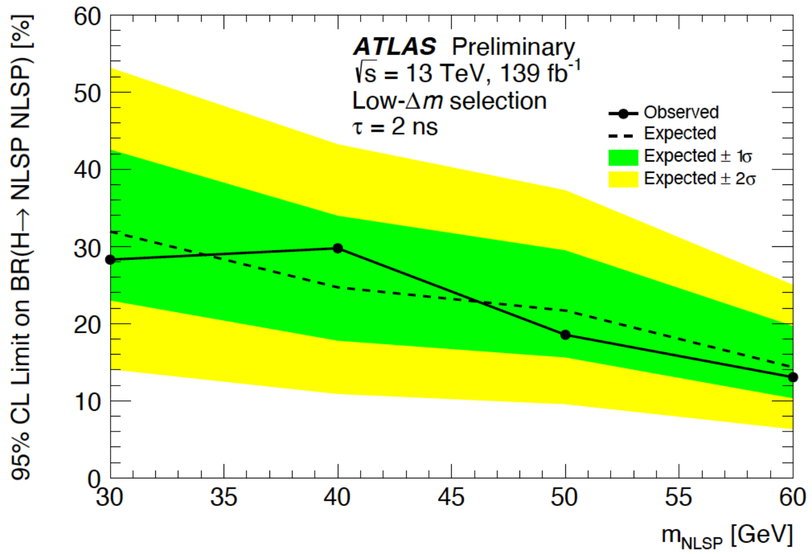
- Signal regions: 1γ and $\geq 2\gamma$, low or high Δm between LSP and NLSP
  - ➡ Better sensitivity and lower background in $\geq 2\gamma$ channel
- Template timing distributions from control regions used in simultaneous fit in signal regions to estimate background

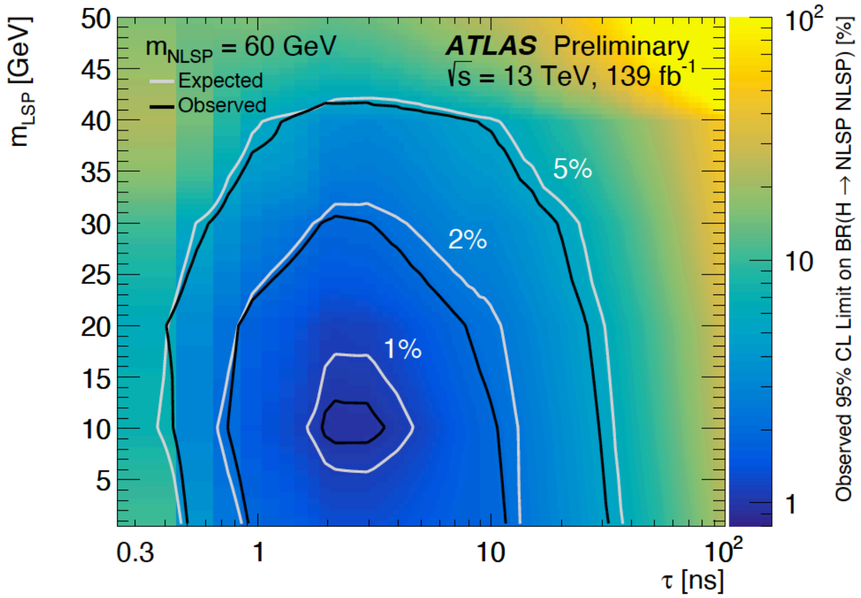
Region	Requirements	Expected	Observed	σ^{95}_{vis} [fb]
1γ	$1.5 < t_\gamma < 12$ ns, $\lvert\Delta z_\gamma\rvert > 300$ mm	3.8 ± 1.6	4	0.042
$\geq 2\gamma$	$1.0 < t_\gamma < 12$ ns, $\lvert\Delta z_\gamma\rvert > 300$ mm	0.28 ± 0.04	0	0.022
$\geq 1\gamma$		4.1 ± 1.7	4	0.041

First limits set for displaced photons from exotic Higgs boson decays

Final discrimination: photon timing





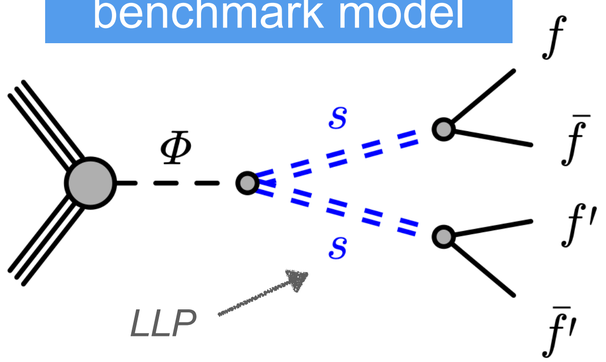


Displaced hadronic jets in HCal

JHEP 06 (2022) 005

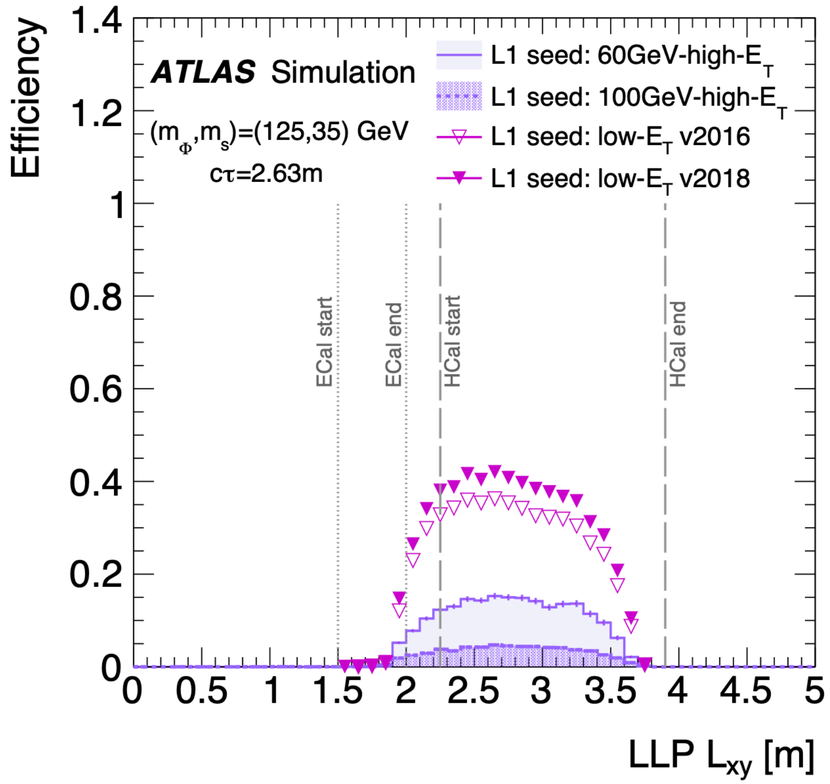
- Identify pair of LLPs decaying hadronically in the HCal
- Dedicated triggers identify narrow, trackless jets with high E_{HCal}/E_{ECal}
- Exotic backgrounds: rare SM multijets (dominant), beam induced background (BIB) and cosmic rays

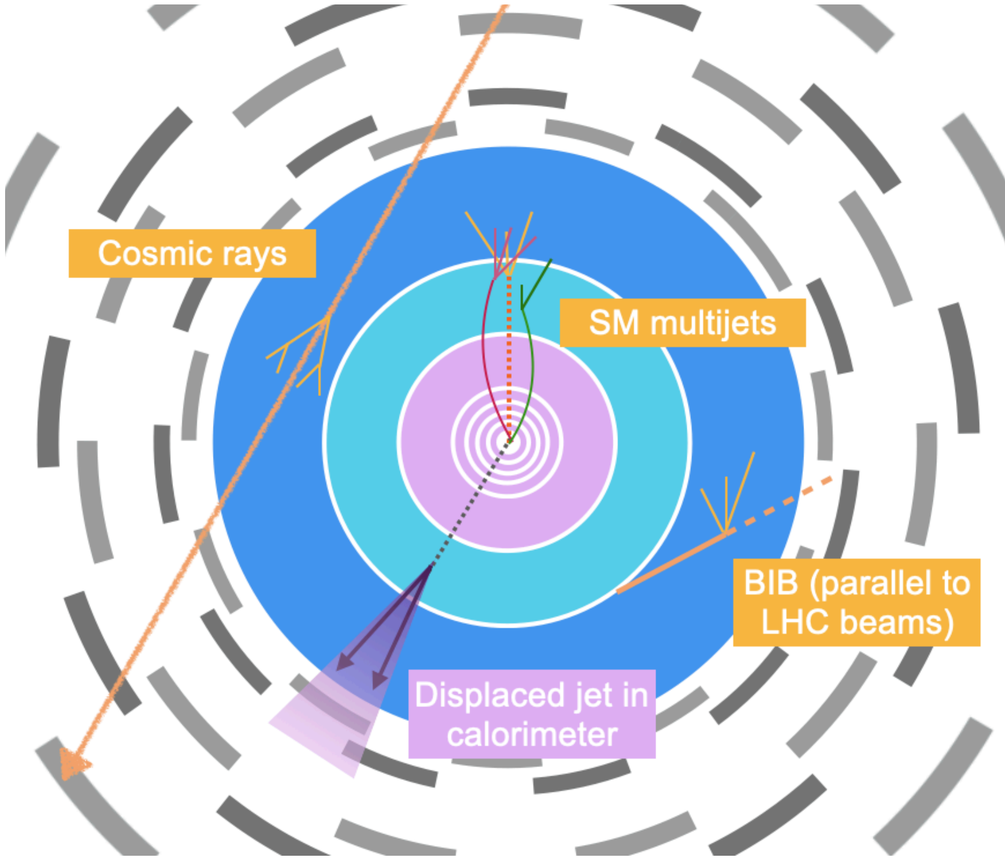
Scalar portal benchmark model



$m_\Phi \in [60,1000]\ GeV$

$m_s \in [5,475]\ GeV$

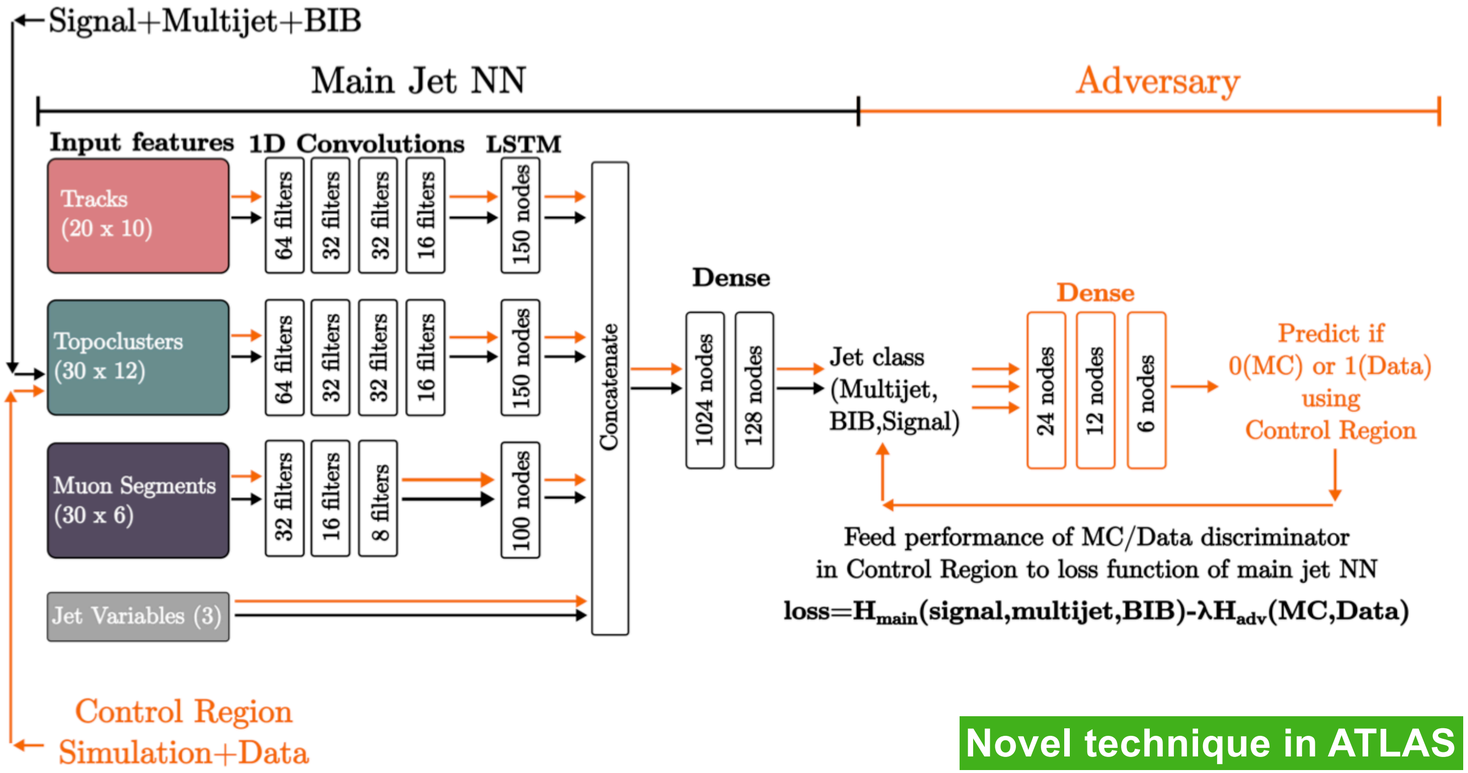




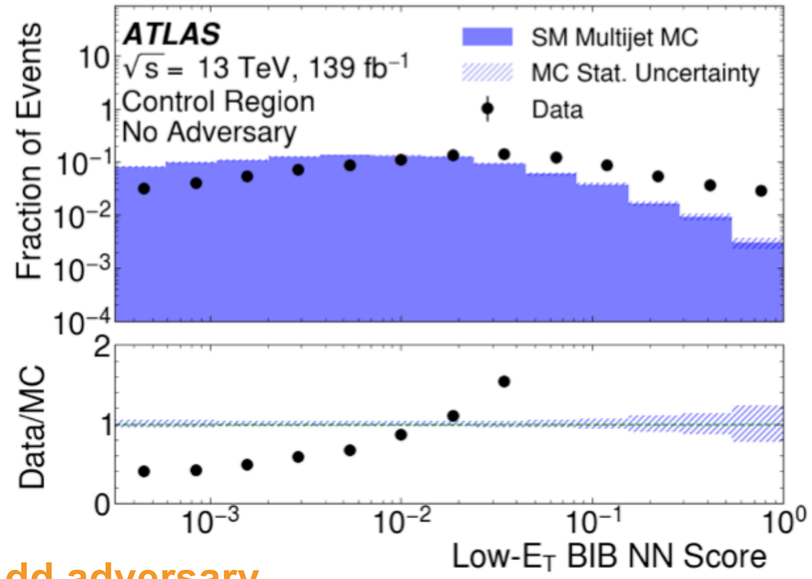
Displaced hadronic jets in HCal

JHEP 06 (2022) 005

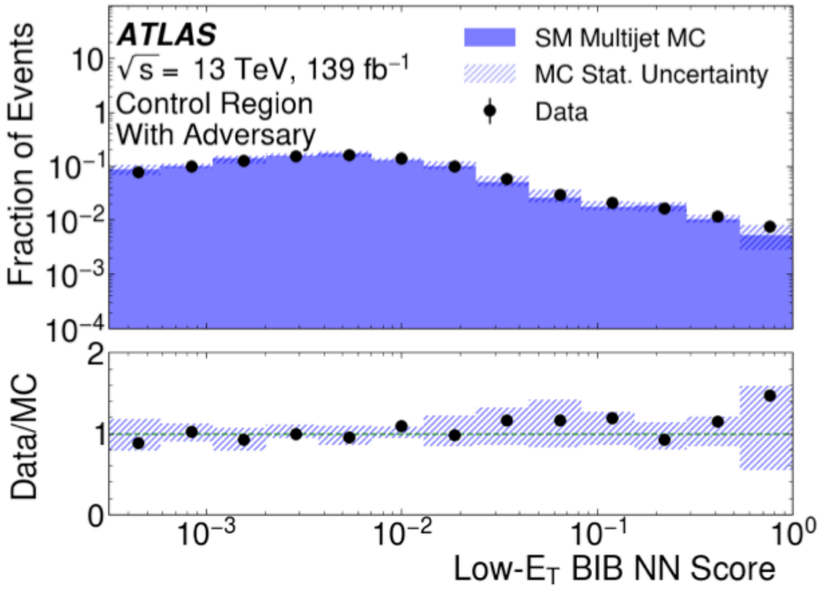
- Per-jet NN: classifies jets as SM multijet, BIB or signal
  - ➡ Trained with signal and multijet **MC simulation** samples and BIB **data**
  - ➡ Adversarial training reduces impact of mismodeling



Novel technique in ATLAS



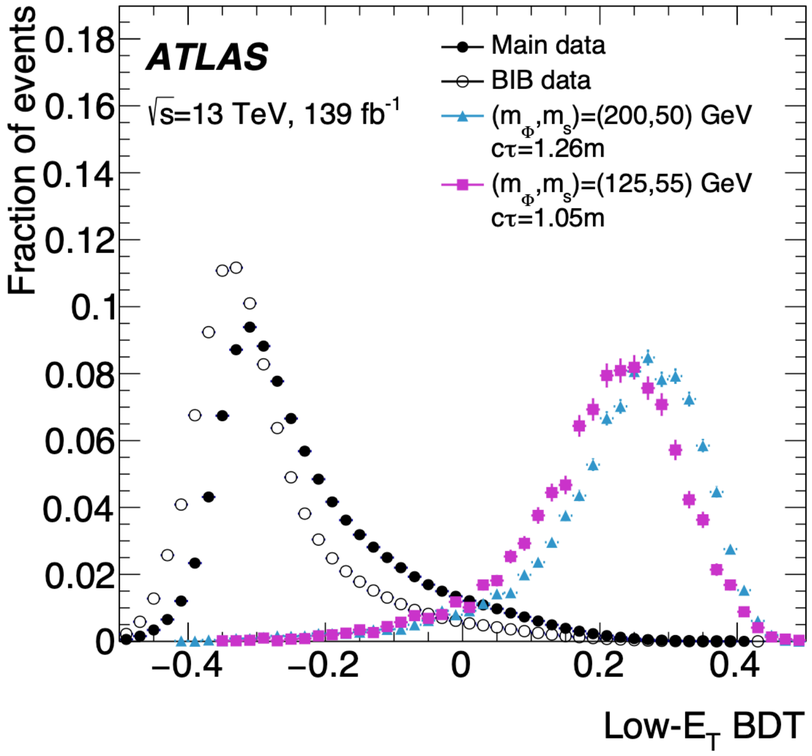
Add adversary

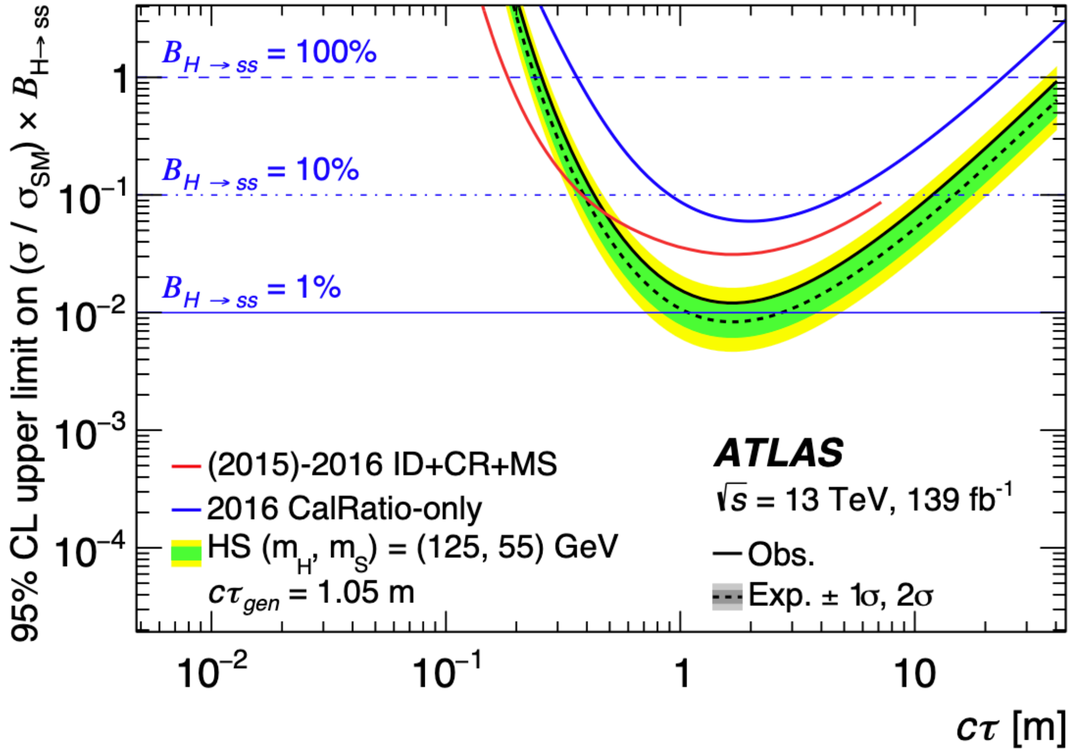


Displaced hadronic jets in HCal

JHEP 06 (2022) 005

- Per-event BDT used to separate signal from BIB, as well as SM multijets
- Data driven ABCD method for background estimation
  - ➡ Discriminators: BDT output and $\sum \Delta R$ between jets and tracks
- No significant excess found and upper limits on $\sigma(\Phi) \times B(\Phi \rightarrow SS)$ set with the CLs method





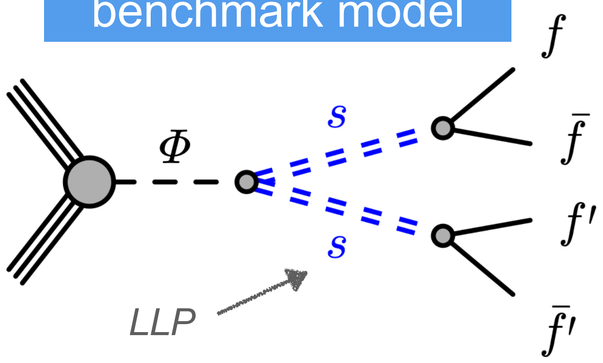
Limits improve by factor ~3 for 125 GeV Higgs mediator

Displaced hadronic jets in MS

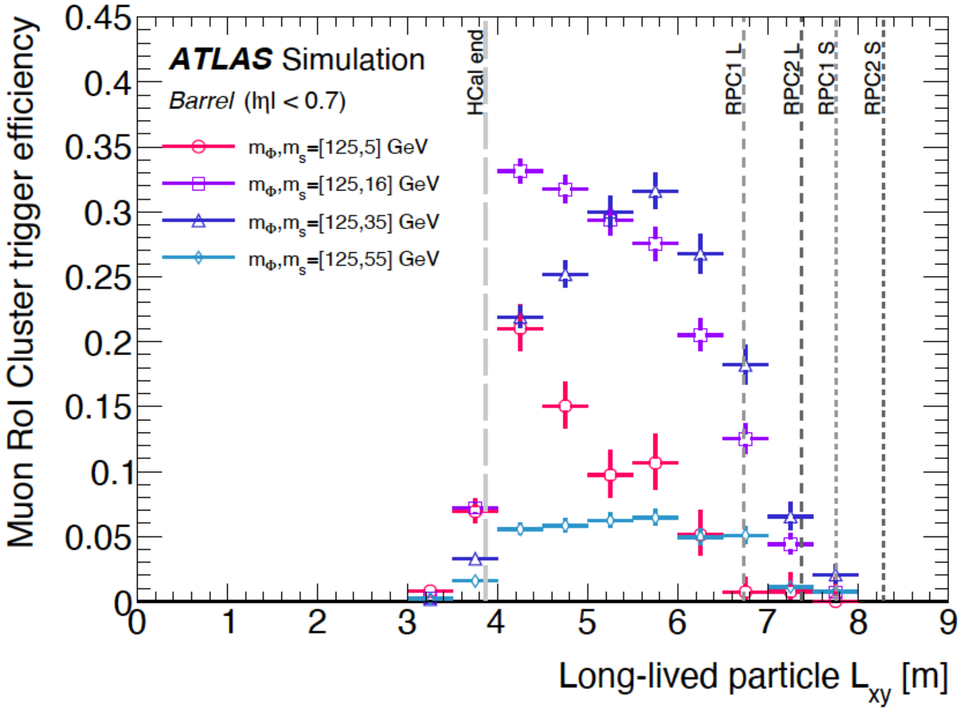
arXiv:2203.00587

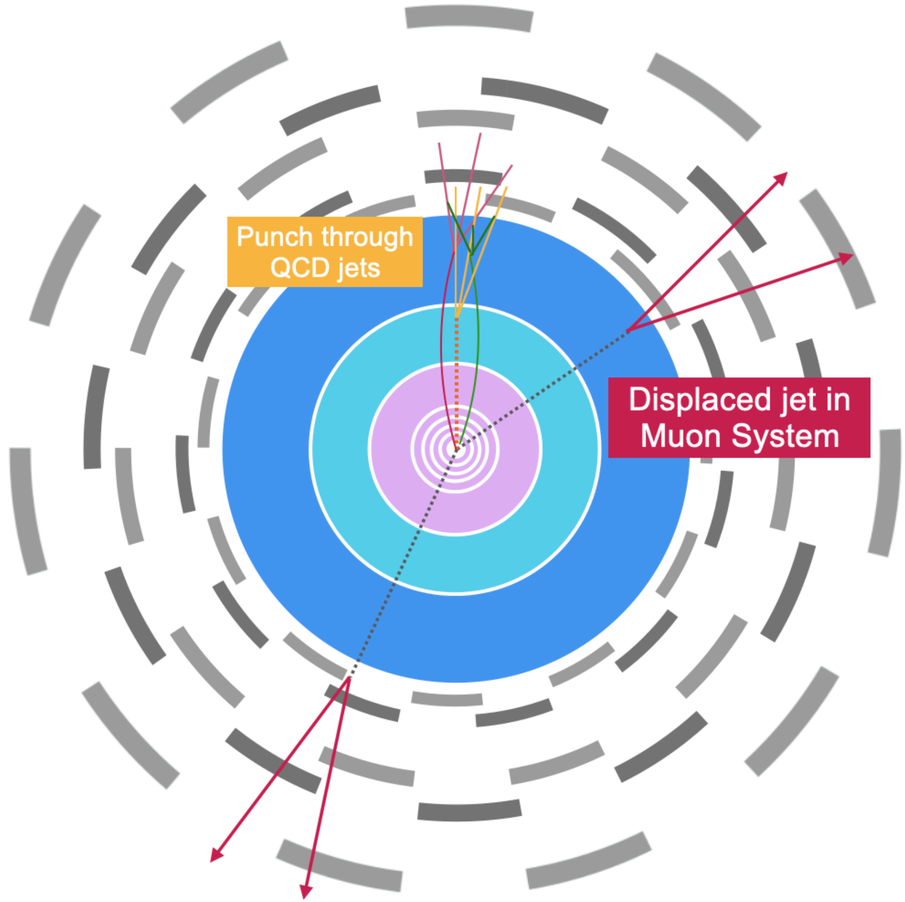
- Identify LLPs decaying hadronically in the MS
- Dedicated trigger makes clusters of muon RoIs from hadronic decay products
- Custom MS vertex reconstruction algorithm
- Main background: punch-through QCD jets

Scalar portal benchmark model



$m_\Phi \in [60,1000]\ GeV$
$m_s \in [5,475]\ GeV$



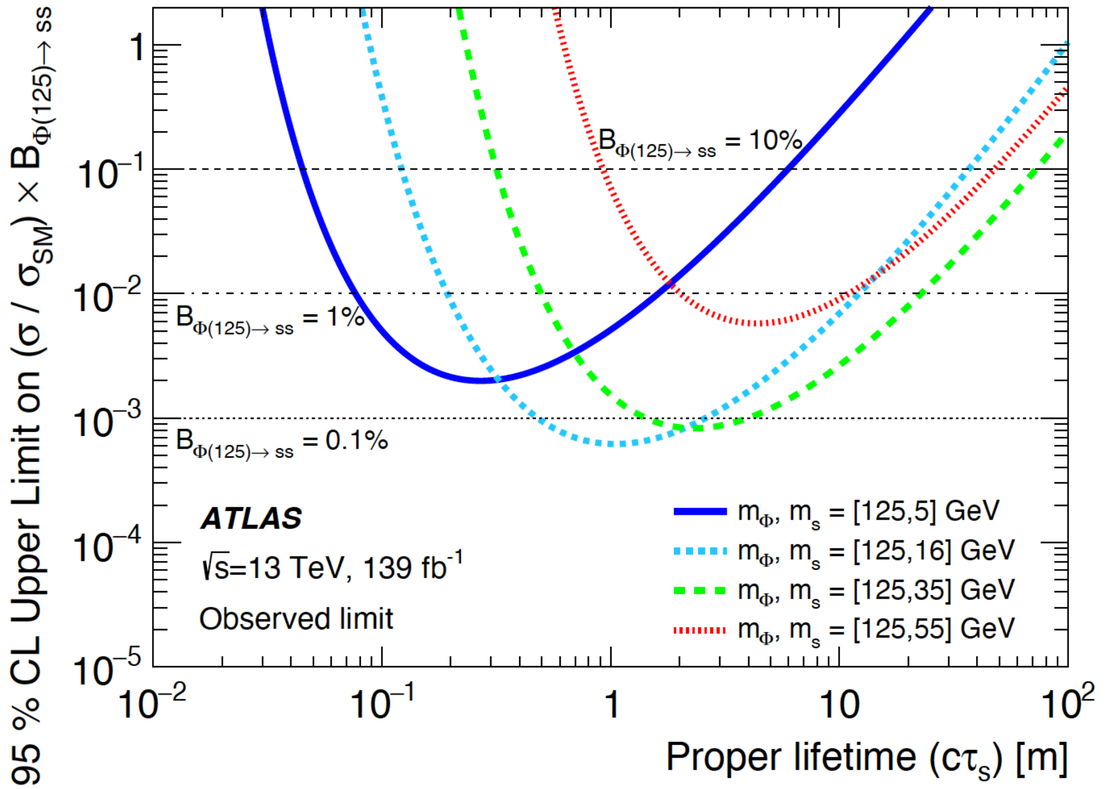


Displaced hadronic jets in MS

arXiv:2203.00587

- Selection:
  - ➡ Require two displaced MS vertices, matched to triggering clusters and isolated from tracks or jets
  - ➡ Require $\Delta R(\text{MS vtx pair}) \geq 1$
- Data-driven background estimate in events passing either the MS DV trigger or a zero-bias trigger

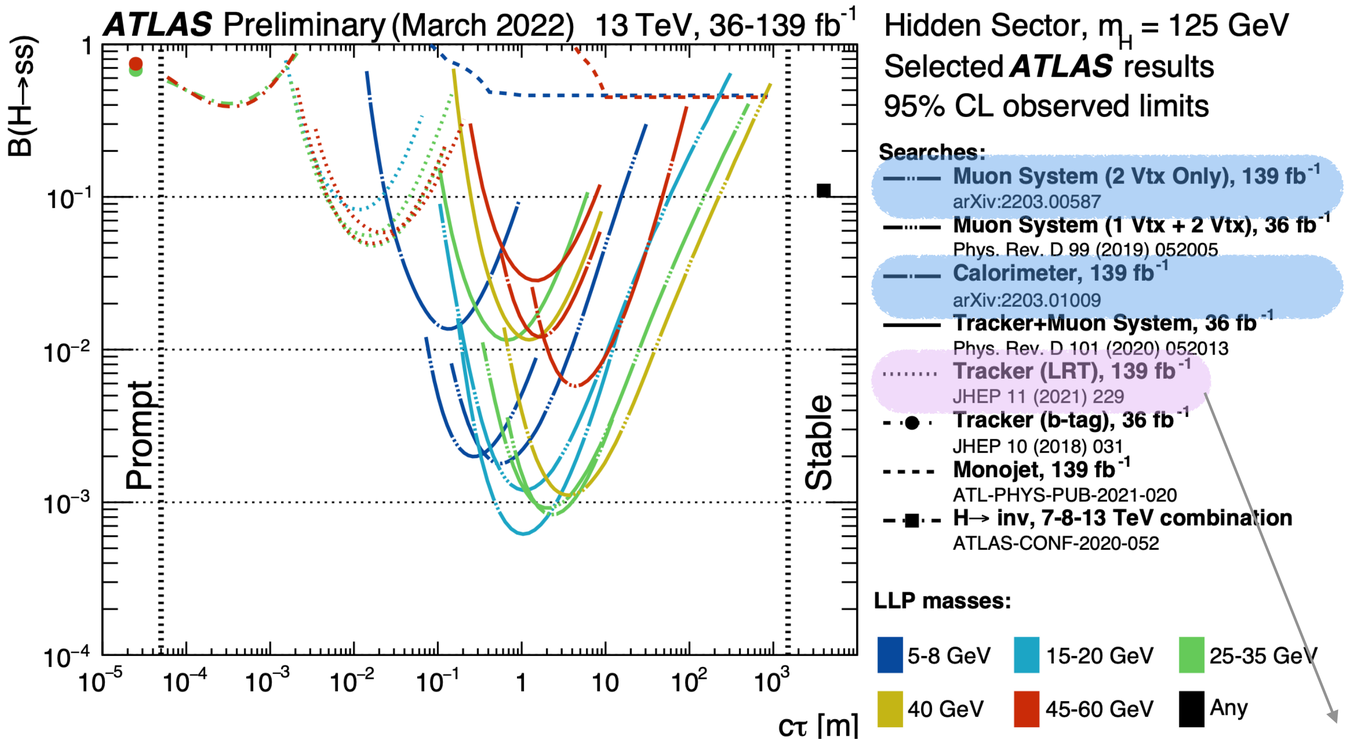
0 events observed in data



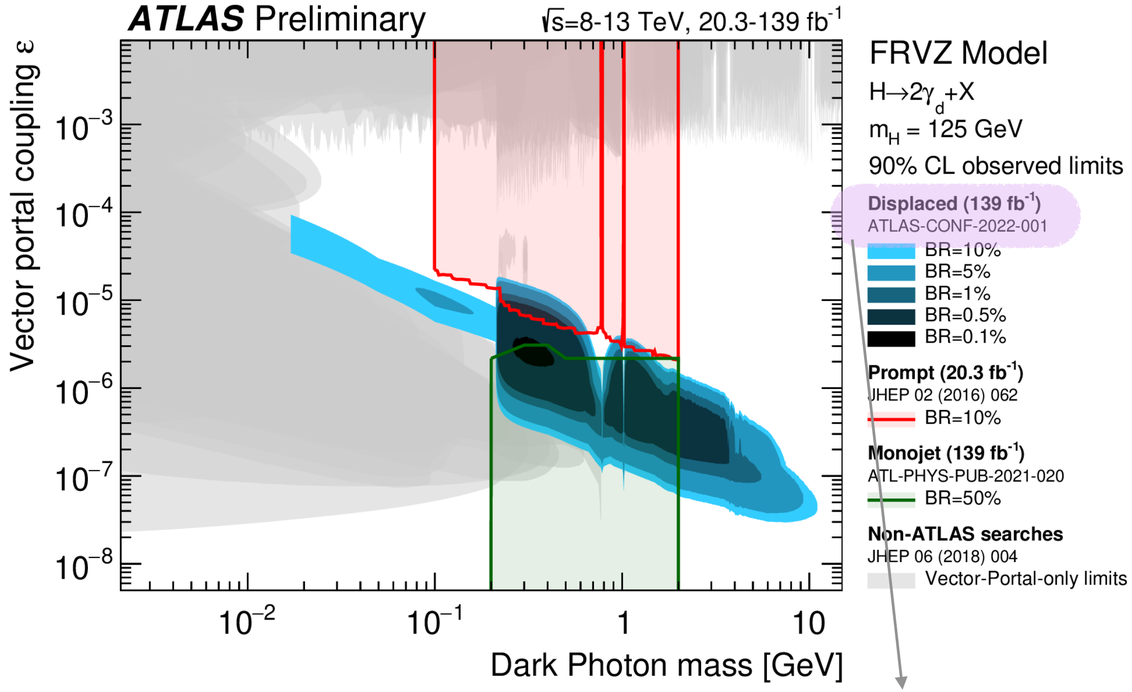
LLP summary plots

ATL-PHYS-PUB-2022-007

- New summary plots for LLP searches from the ATLAS collaboration
- Focuses on two widely-used benchmark models:
  - ➡ Simplified Hidden Sector model → complementarity of LLP searches in different sub detectors
  - ➡ Falkowski–Ruderman–Volansky–Zupan (FRVZ) model



Search for pair of displaced vertices in ID in association with a Z (back-up)



Search for displaced dark photon jets in calorimeter (back-up)

Summary

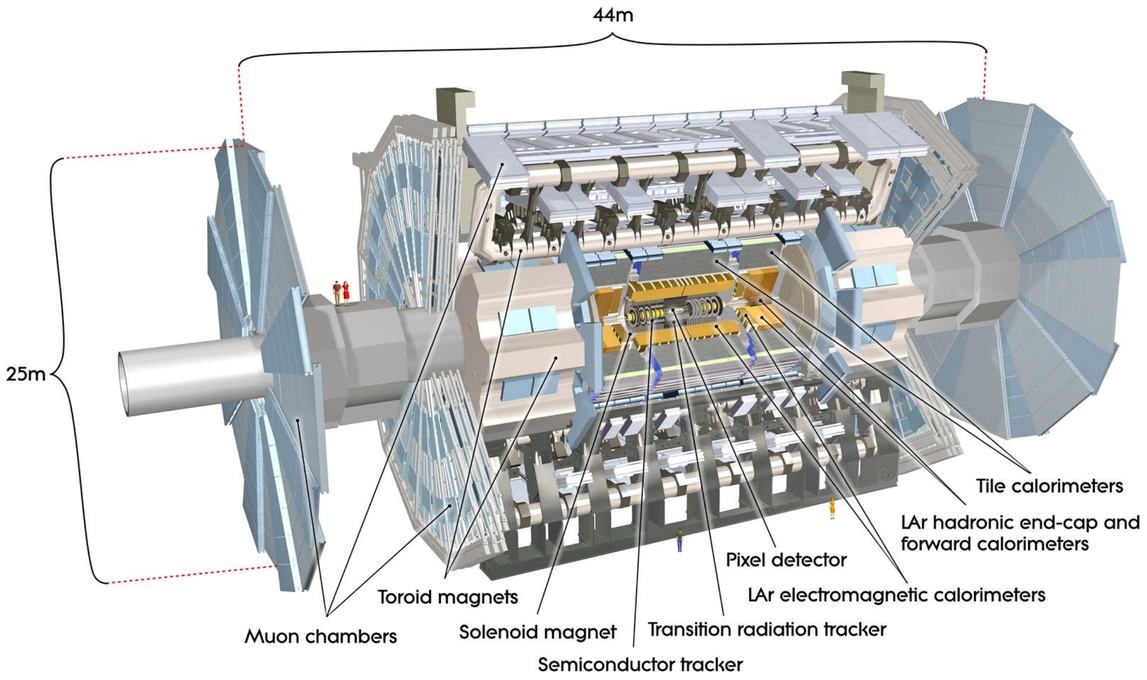
- Presented the latest results from the ATLAS Collaboration in searches for exotic decays of the Higgs boson
- No significant excess has been found **yet**
- Non-standard Higgs decays remain a well-motivated possibility for BSM physics
- More full-Run 2 results coming and Run 3 just started… **stay tuned!**

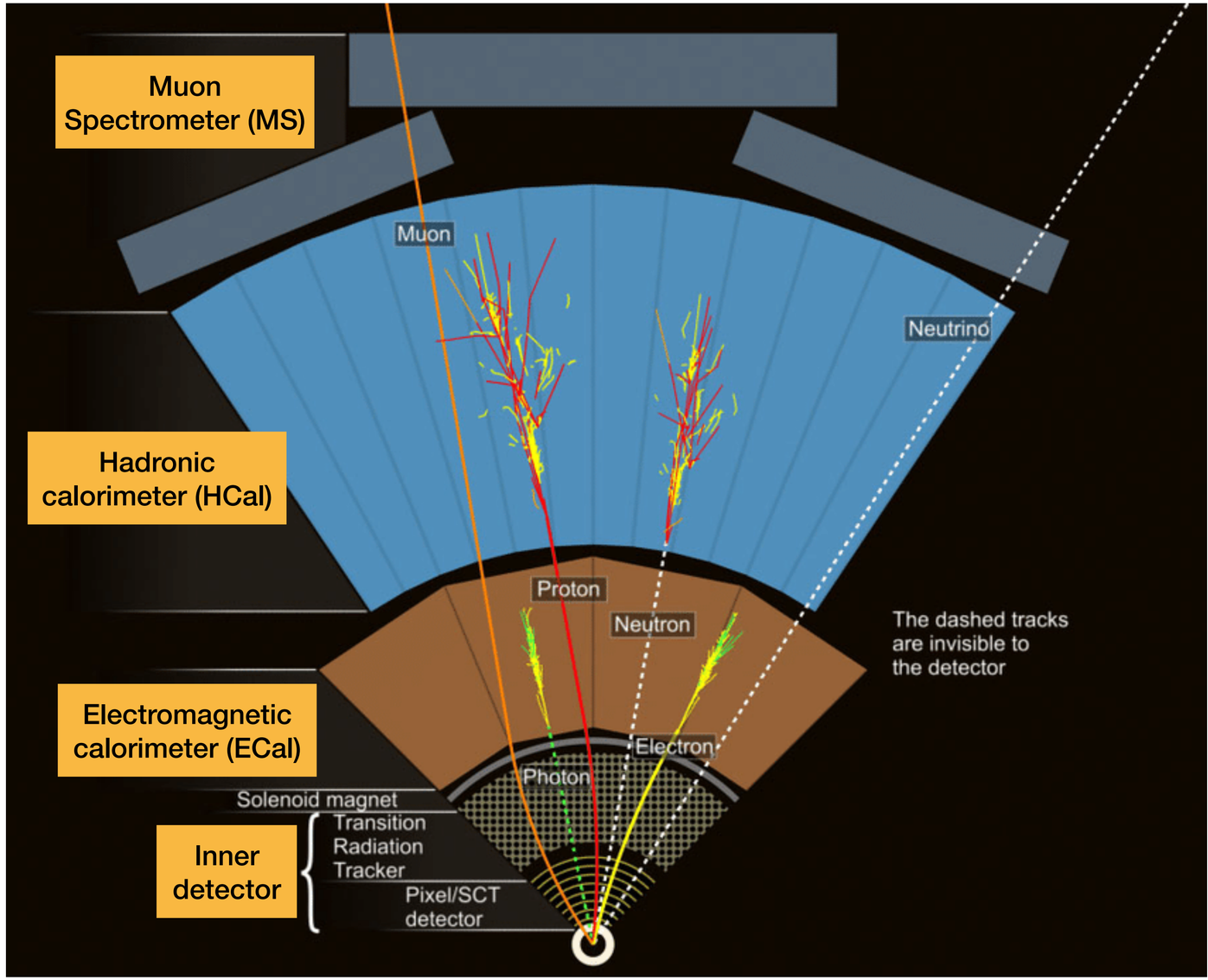
Thanks!

ATLAS public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/

Back up slides

The ATLAS detector

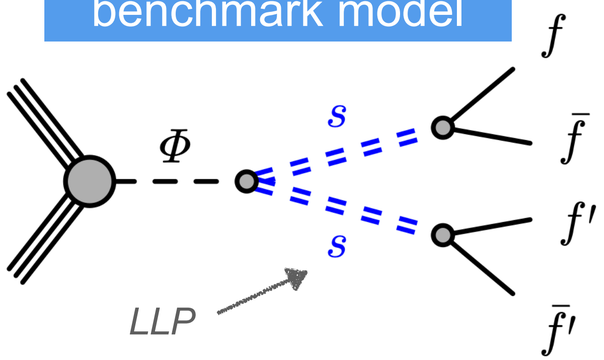




Displaced hadronic jets in MS

arXiv:2203.00587

Scalar portal benchmark model



$m_\Phi \in [60,1000]\ GeV$
$m_s \in [5,475]\ GeV$

- Selection: two MS vtx, matched to triggering clusters, isolated from tracks or jets
- Main background is punch-through QCD jets
- Data-driven background estimate in events passing either the MS DV trigger or a zero-bias trigger:

0 events observed in data

Only one MS Vtx

2 MS Vtx, one cluster unmatched in barrel

2 MS Vtx, one cluster unmatched in endcap

$$N_{2\mathrm{Vx}} = N^{1\mathrm{cl}} \cdot P^{\mathrm{Vx}}_{\mathrm{noMStrig}} + N^{2\mathrm{cl}}_{1\mathrm{UMBcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Bcl}} + N^{2\mathrm{cl}}_{1\mathrm{UMEcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Ecl}} = 0.32 \pm 0.05$$

Probability of vertex in zero-bias trigger events

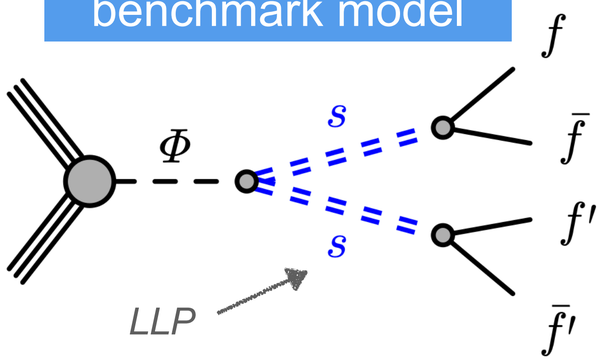
Probability of vertex in the barrel or endcap given a trigger cluster

- Estimate was validated in a dedicated validation region where isolation requirement was inverted

Displaced hadronic jets in MS

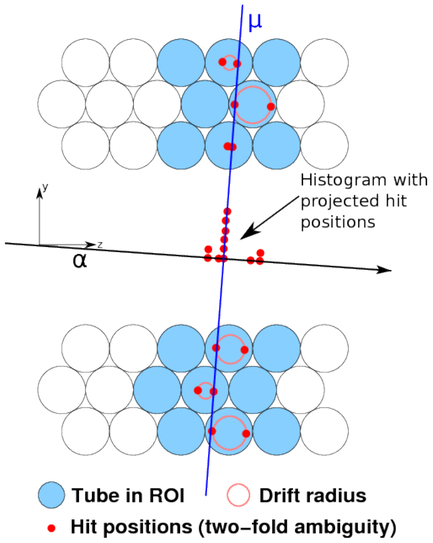
arXiv:2203.00587

Scalar portal benchmark model



$m_{\Phi} \in [60,1000]\ GeV$

$m_{s} \in [5,475]\ GeV$

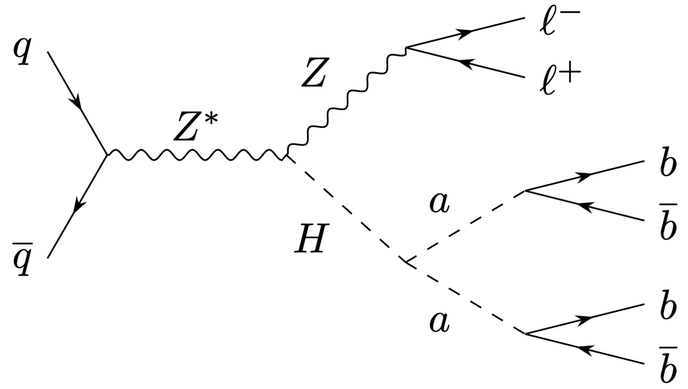


- Vertex reconstruction algorithm uses **spatial separation** between two multilayers of **MDT chamber**:
  - Reconstruct single-multilayer straight-line segments with three or more MDT hits using a χ^2 fit
  - Segments from multilayer 1 are then matched with those from multilayer 2 → *tracklet*
  - MS DV reconstructed from tracklets using a χ^2 fit
  - At least three (four) tracklets are required to be used in the fit in the barrel (endcaps)

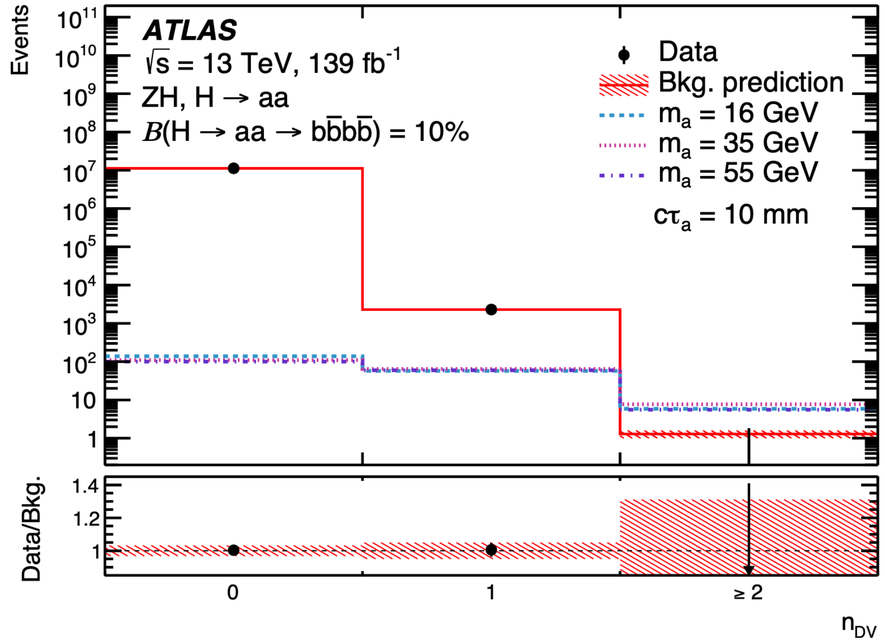
Displaced $VH \rightarrow bbbb$

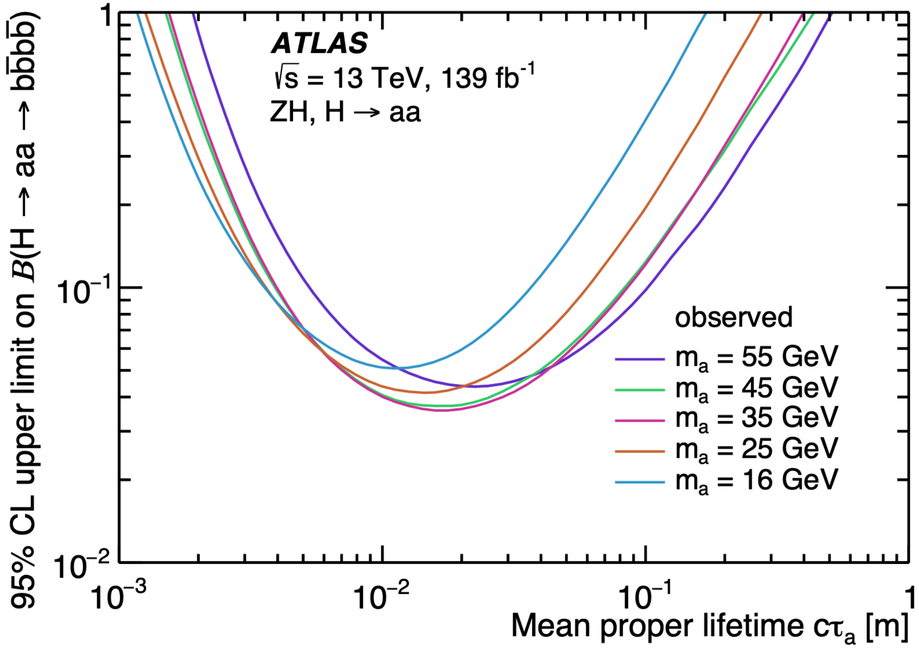
EXOT-2018-57

- Higgs decay to a pair of long-lived pseudoscalars $H \rightarrow aa \rightarrow bbbb$
  - a lifetime 10 mm < $c\tau$ < 1m → displaced vertex (DV) in ID
- Associated ZH production - trigger $Z \rightarrow ll,\ l = e, \mu$
- Signature: 2 leptons + 2 DV
- Dedicated large radius tracking and secondary vertex reconstruction optimized for LLPs
  - ➡ Zero events in SR



Most stringent limits in this lifetime regime for $m_a < 40$ GeV

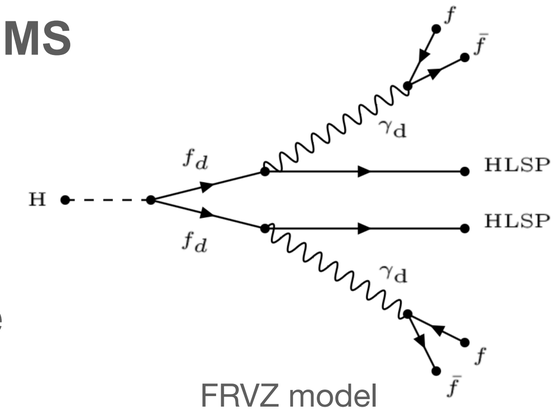




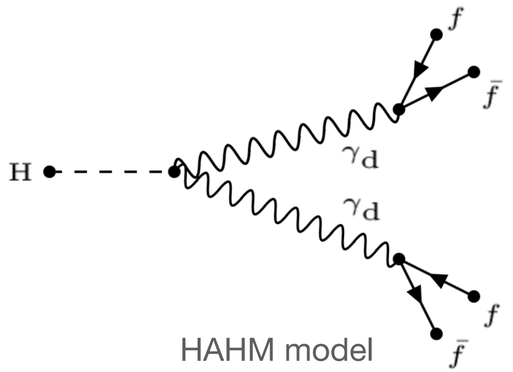
Displaced dark photon jets

EXOT-2019-05

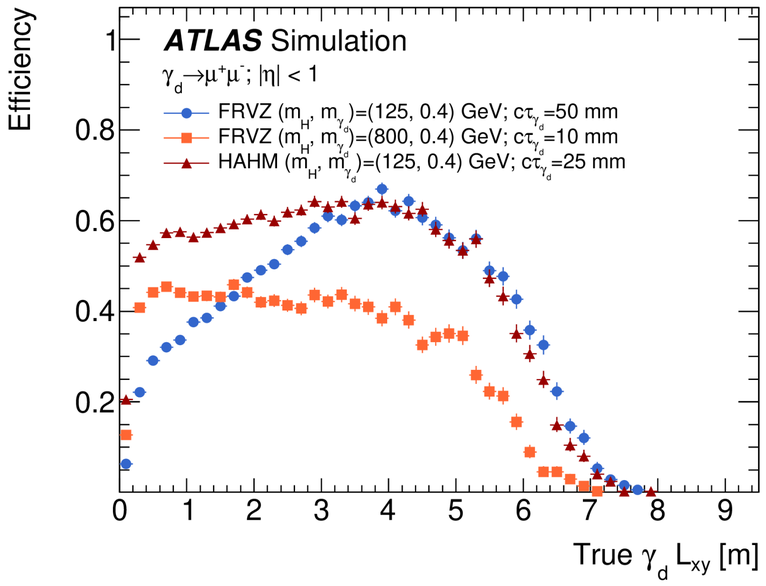
- Search for events with collimated dark photon jets (DPJ) reconstructed in **calorimeter or MS**
- Signal regions: consider different **caloDPJ** and μ**DPJ** multiplicities (2-0, 1-1, 0-2)
  - ➡ Two search categories: gluon fusion and WH associated production
- Main backgrounds: SM multijets, cosmics and BIB → ML taggers developed for each one
  - ➡ DNN for cosmics, convolutional NN for BIB and QCD
- Data driven ABCD method for background estimation

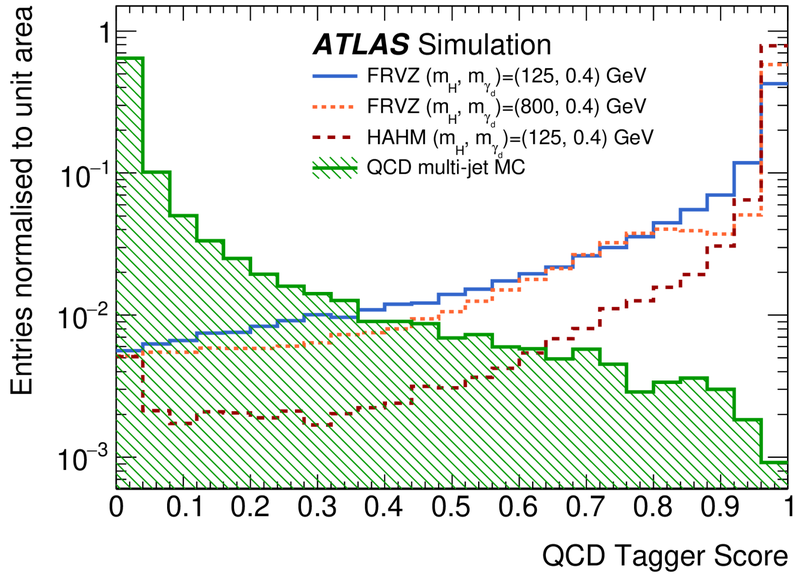


FRVZ model



HAHM model

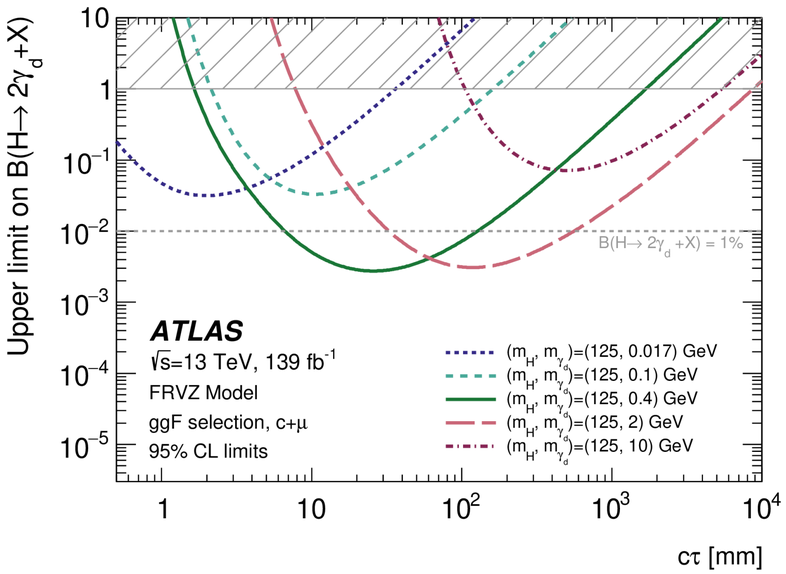


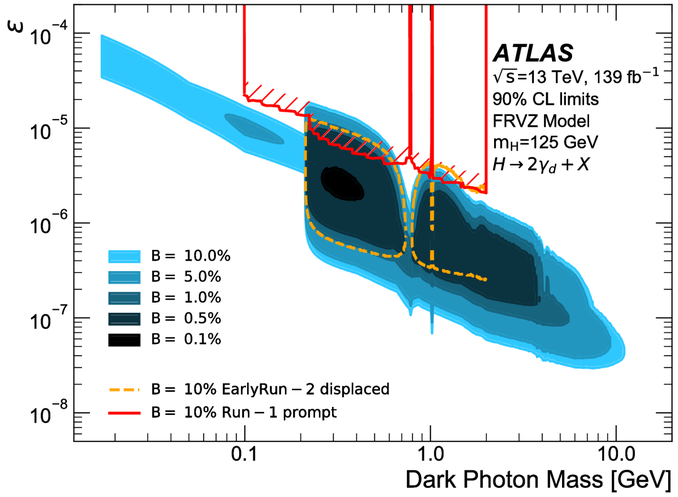


Displaced dark photon jets

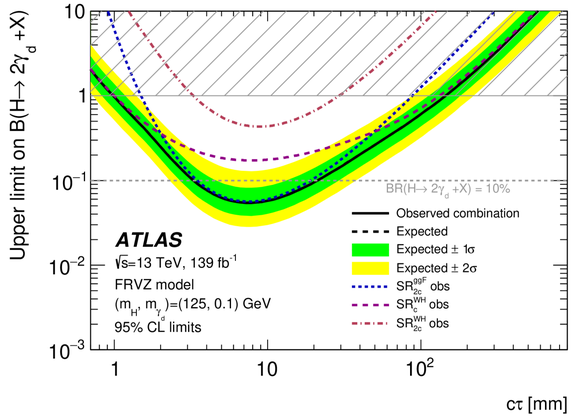
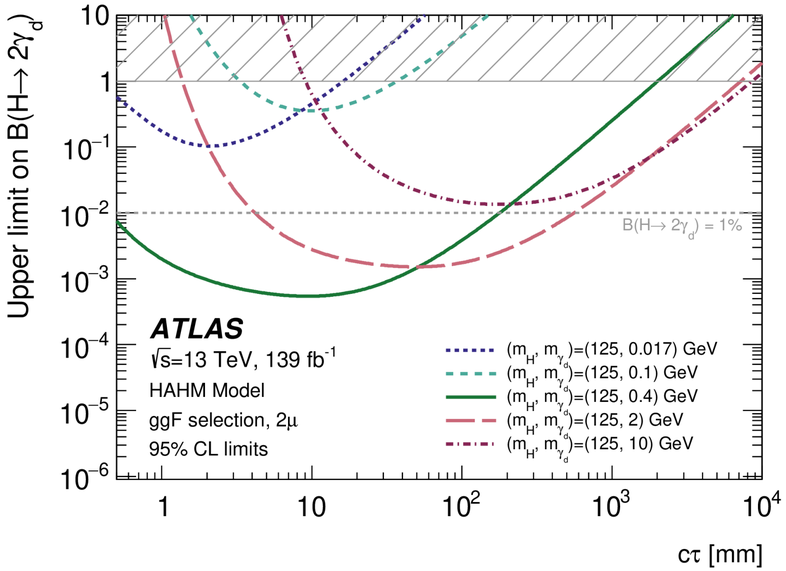
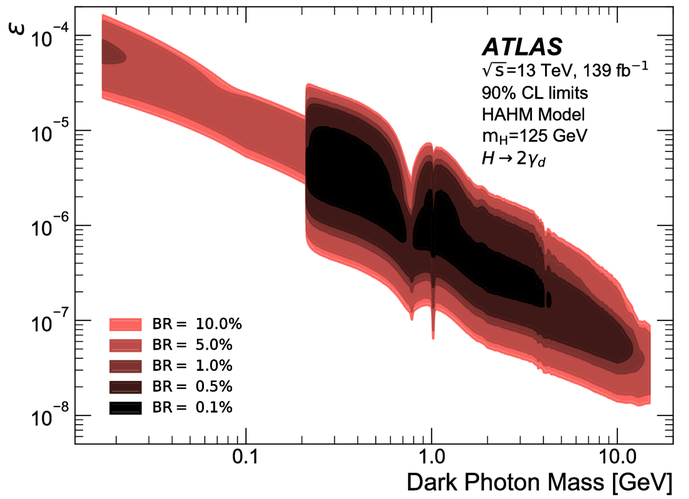
EXOT-2019-05

FRVZ model





Complementarity of WH selection



HAHM model