



# Pair-Produced LLPs

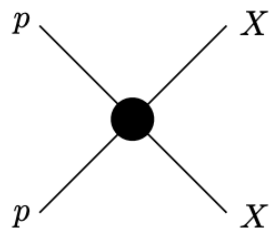
Audrey Kvam

University of Massachusetts, Amherst

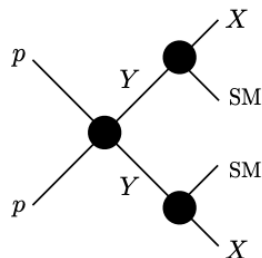


# Pair-production modes for LLPs

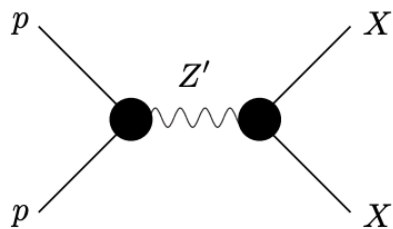
Consider the minimal set of “interesting production modes” for LLPs specified by the [LHC LLP community white paper](#). 4 of 5 feature pair-production:



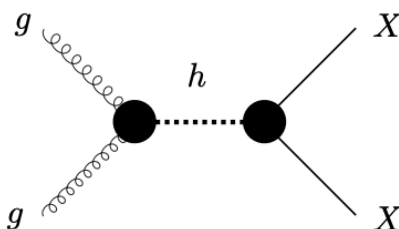
Direct-Pair Production



Heavy Parent



Heavy Resonance



Higgs Portal

We'll see several examples in the next slides!

FYI:

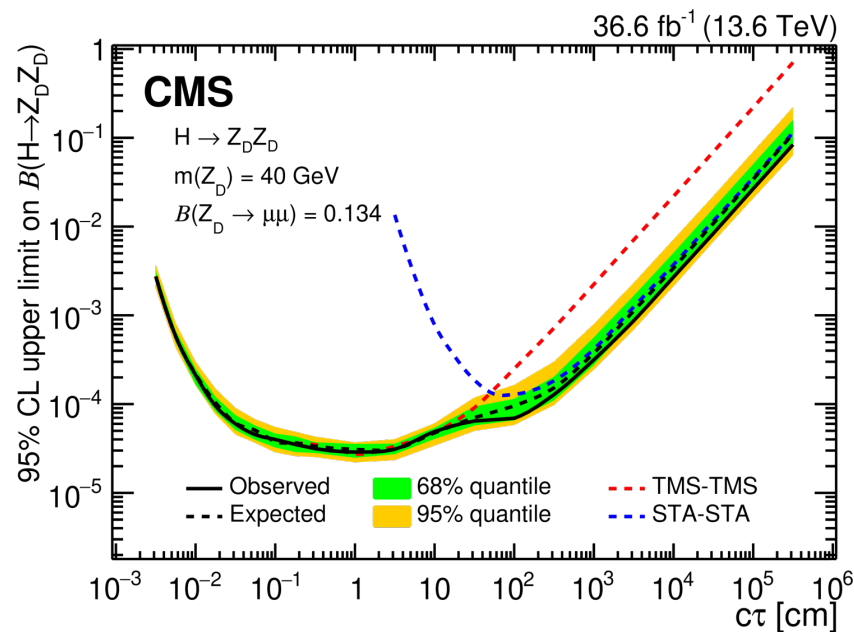
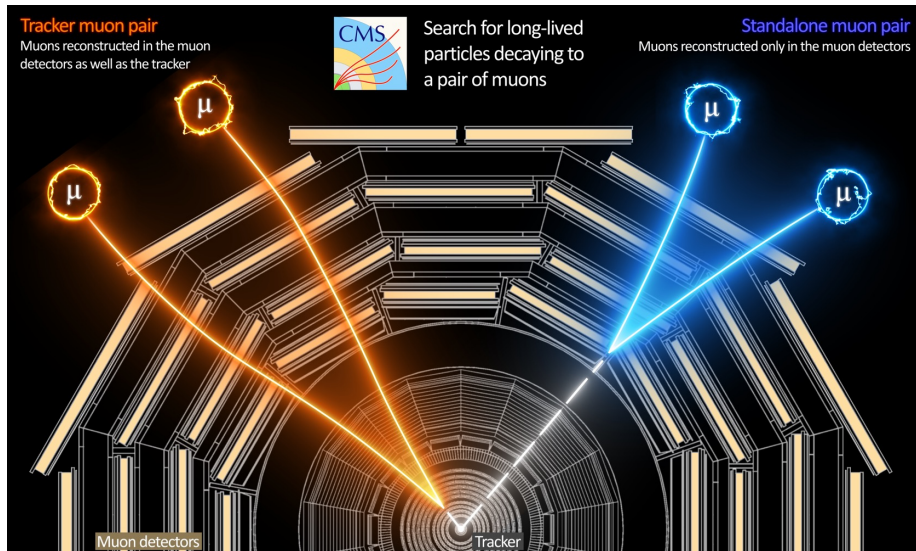
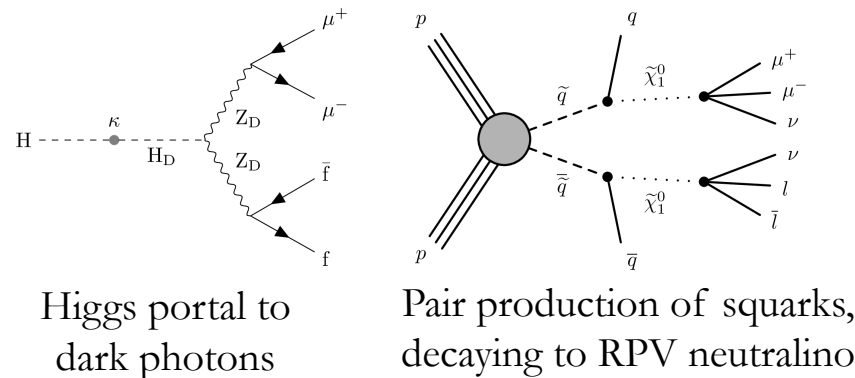
I've organized this talk in a signature-driven way, organizing searches by their final states featuring dileptons, dijets, or diphotons

# Displaced dilepton signatures

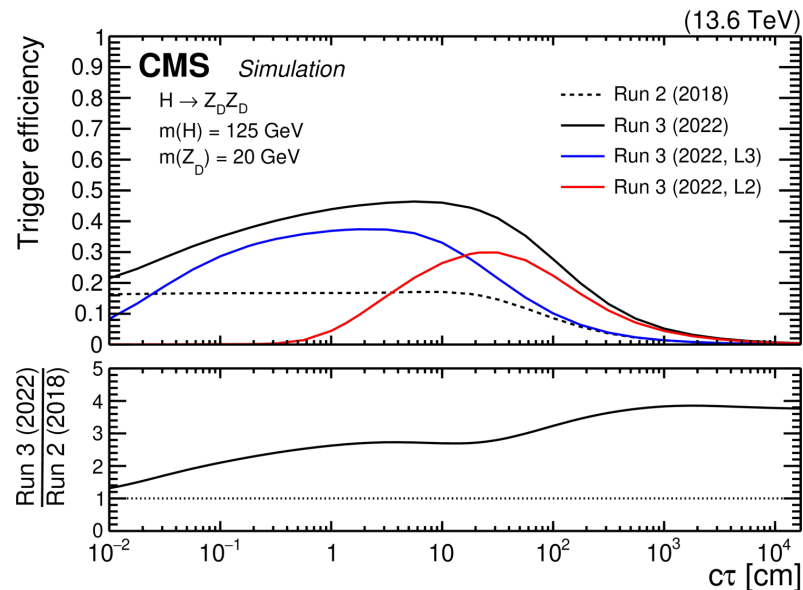
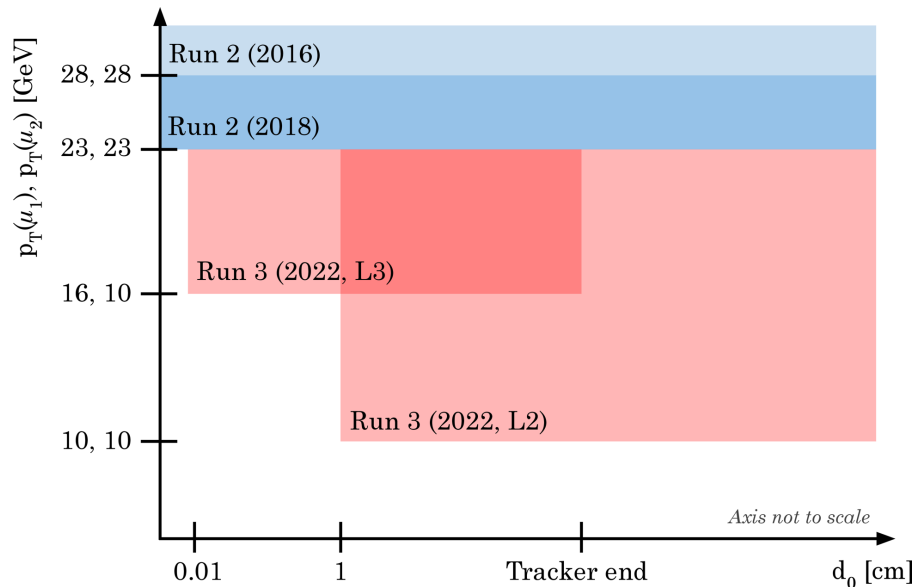
# Displaced dimuon vertices using 2022 data

CERN-EP-2024-025

Search targets the case where at least one of the LLPs decays to 2 muons, giving a displaced dimuon vertex, ranging from  $\sim$ hundreds  $\mu\text{m}$  to several meters



# Note: new displaced dimuon triggers in Run 3!



The search benefits from newly designed Run 3 dimuon triggers that extend to lower  $p_T$ , where the thresholds depend on  $d_0$

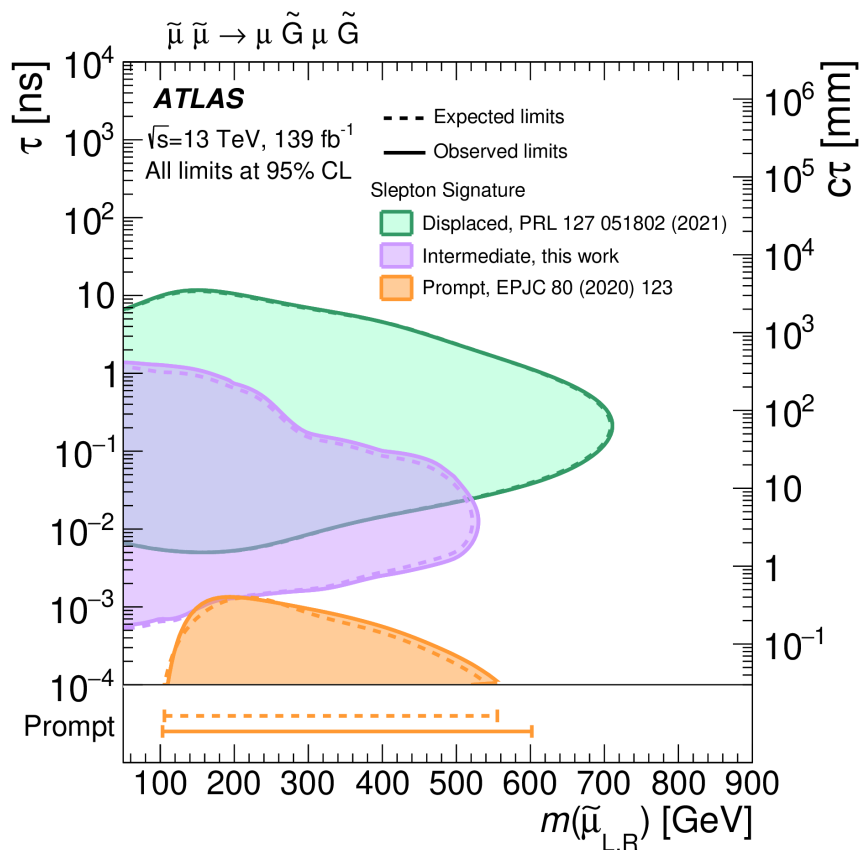
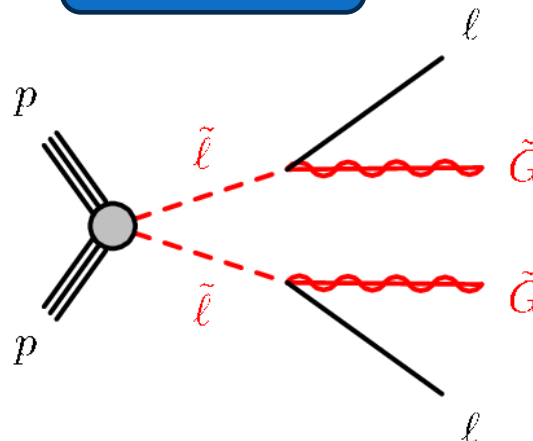
(2022, L2): uses MS-only information to reconstruct muon candidates, then attempts to reconstruct with tracker info as well. If either candidate is reconstructed with  $d_0 < 1$  cm, the event is discarded.

(2022, L3): uses MS+tracker information to reconstruct muon candidates, with  $d_0 > 0.01$  cm threshold

# Displaced dileptons in Run 2

## Simplified SUSY model

- Direct production of slepton pairs
- Slepton decays to lepton+gravitino



### [CERN-EP-2020-205](#)

#### “High- $d_0$ ” analysis:

- Search for displaced electron or muon pairs with  $3 \text{ mm} < d_0 < 300 \text{ mm} + \text{MET}$
- Used photon triggers and MS-only muon triggers

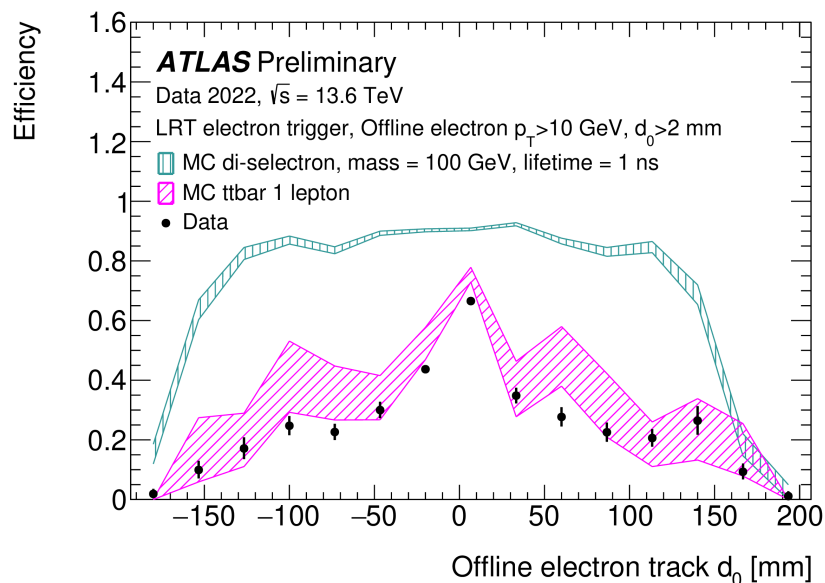
### [CERN-EP-2023-038](#)

#### “Micro-displaced muons” analysis:

- Search for isolated opposite sign muon pairs with  $0.6 < d_0 < 3 \text{ mm}$
- Used standard, prompt triggers and tracking
- Complementary to “high- $d_0$ ” and prompt searches!

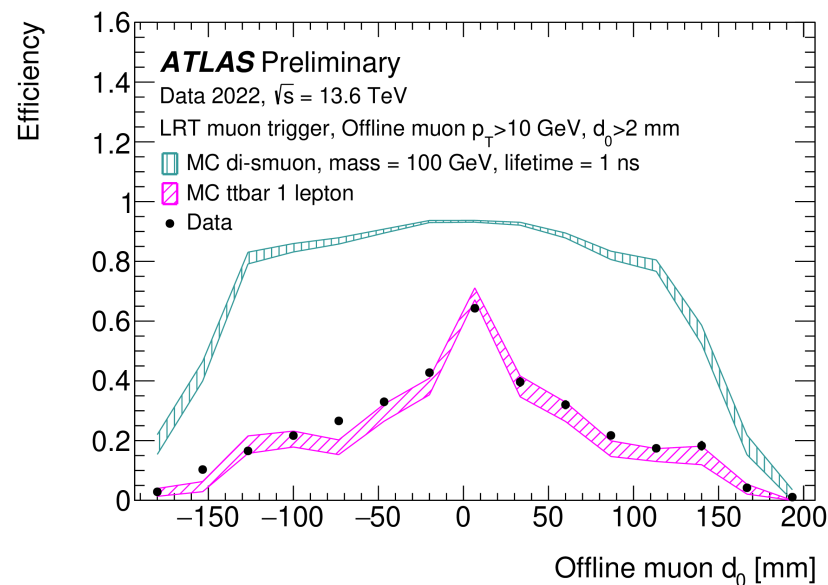
## Note: new displaced lepton triggers in Run 3!

Dedicated triggers for displaced leptons have been introduced, making use of improvements in Large Radius Tracking (LRT)



Displaced single-electron trigger runs  
LRT in RoI around calo candidate

$$p_T > 30 \text{ GeV}, d_0 > 3 \text{ mm}$$



Displaced single-muon trigger runs  
LRT in RoI around MS candidate

$$p_T > 20 \text{ GeV}, d_0 > 2 \text{ mm}$$

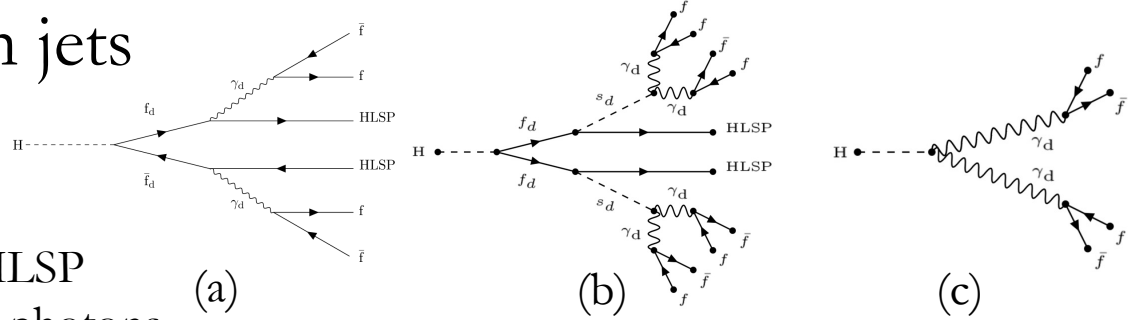
# Displaced dijet signatures





# Displaced dark-photon jets

(a),(b): FRVZ model: Higgs or Higgs-like scalar to two dark fermions, then to dark photon+HLSP  
 (c): HAHM model: Higgs to dark photons

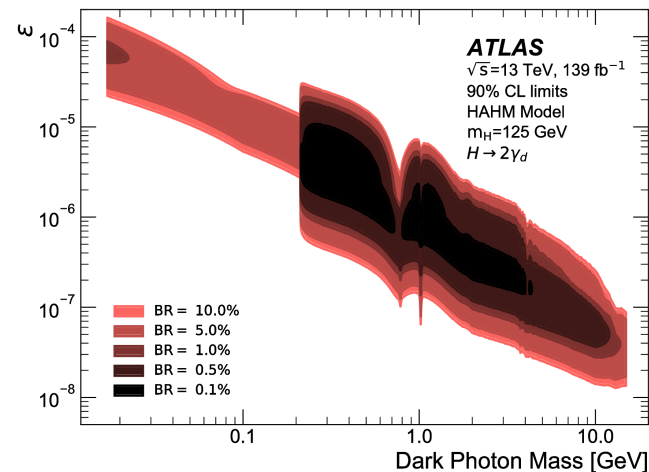
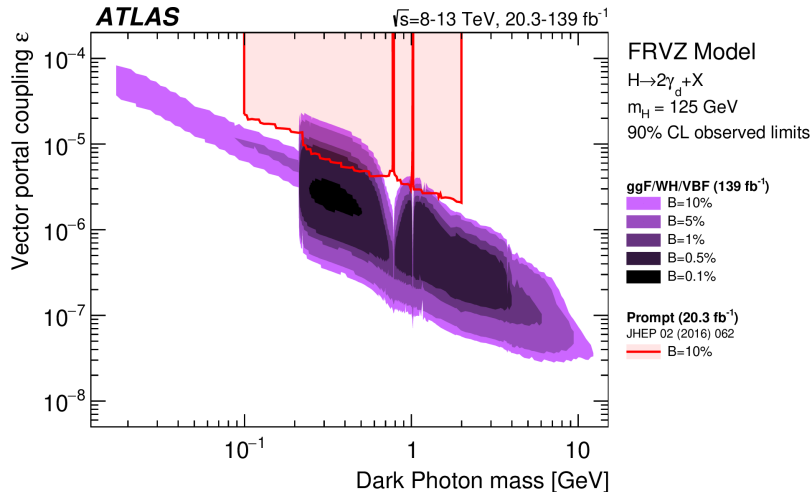


[CERN-EP-2022-054](#)

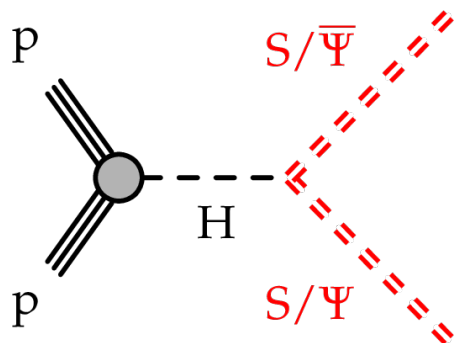
[CERN-EP-2023-226](#)

Targets dark photons decaying outside the ID to collimated

- Muon pairs: Candidates are reconstructed by clustering standalone MS tracks. A cosmic-ray tagger classifies background from cosmic.
- Electron or quark pairs: Candidates are jets with an EMF<0.4. A QCD tagger and a BIB tagger are used to classify backgrounds.

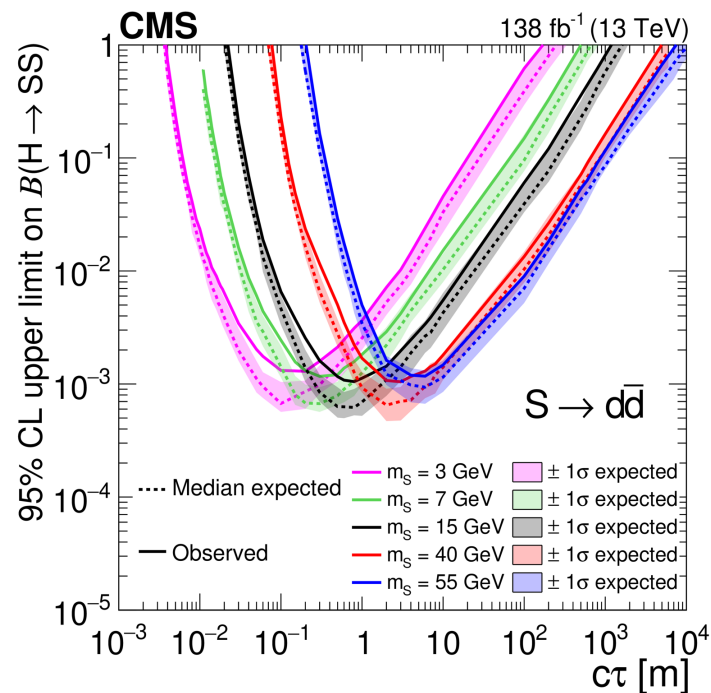
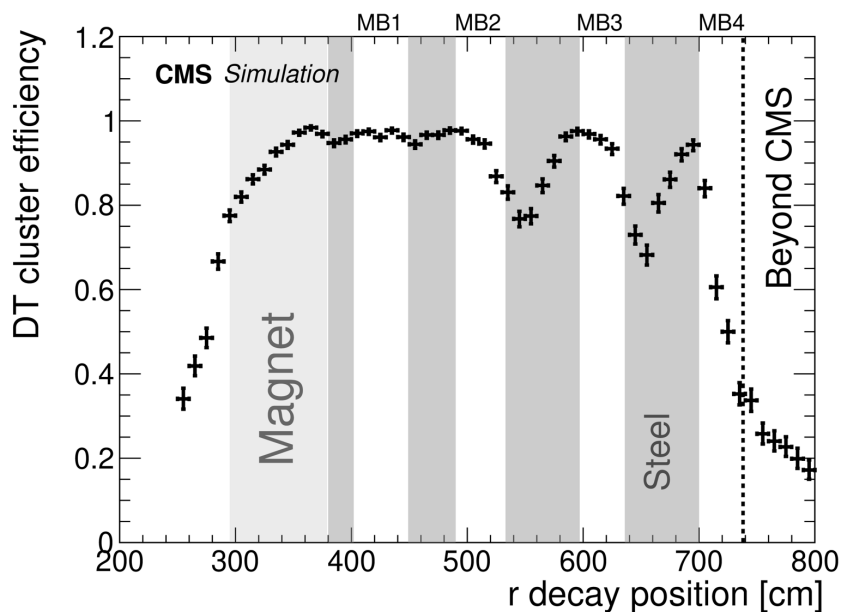


## LLP showers in the muon detectors

[CERN-EP-2024-008](#)

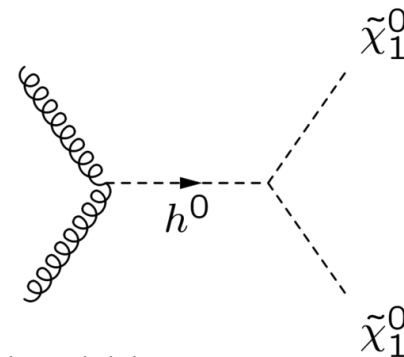
- Higgs portal to a pair of neutral long-lived scalars (S) or to a pair of dark-sector quarks (Ψ)
- LLP decays to hadrons, electrons, photons, taus

This Run 2 search uses the CMS muon detectors as a sampling calorimeter to detect showering from LLP decays



# Displaced semileptonic decays

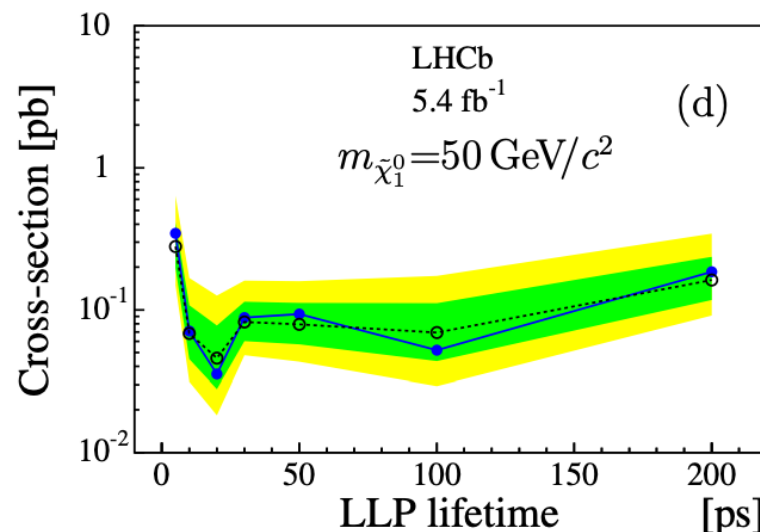
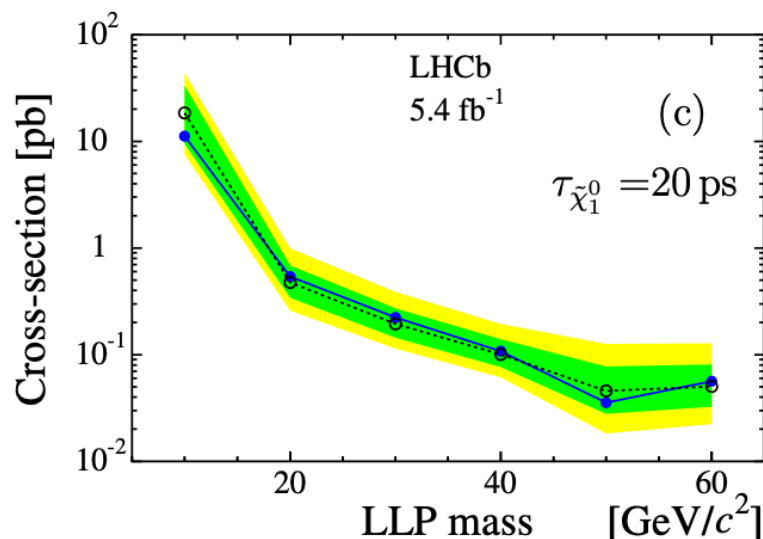
[CERN-EP-2021-186](#)



Higgs portal to two long-lived neutralinos

Neutralino decays semileptonically, to 1 muon and 2 quarks

- Targets  $h^0$  masses 30-200 GeV, LLP masses  $10 - h^0/2$  GeV, and lifetimes 5-200 ps, such that decays occur predominantly within VELO
- MVA classifier trained to separate signal from background (mainly  $b\bar{b}$  and  $c\bar{c}$ )
- Forward acceptance and low muon trigger  $p_T$  threshold makes result complementary to other LHC experiments



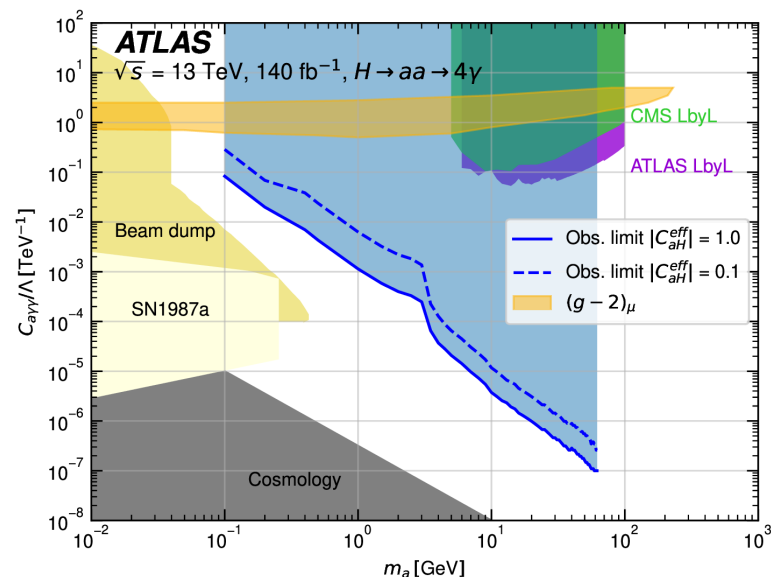
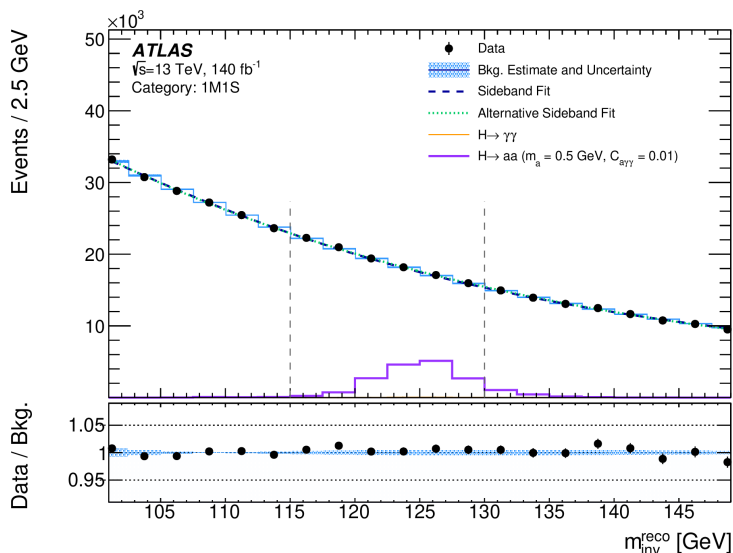
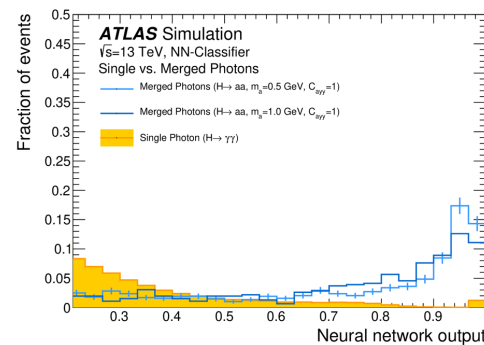
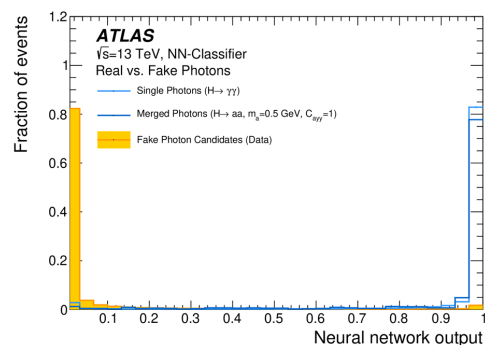
# Displaced diphoton signatures

# Short- and long-lived ALPs in $H \rightarrow aa \rightarrow 4\gamma$ [CERN-EP-2023-202](#)

ALP coupling to photons  $C_{a\gamma\gamma} < 0.1$  leads to displaced vertex

Considering  $0.1 < m_a < 62$  GeV, where  $m_a < 3.5$  GeV dominantly yields collimated, merged photon signatures

- 1<sup>st</sup> NN trained to separate real photon signatures from ‘fake photons’ from multijet background
- 2<sup>nd</sup> NN trained to separate single-photon signatures from collimated signatures





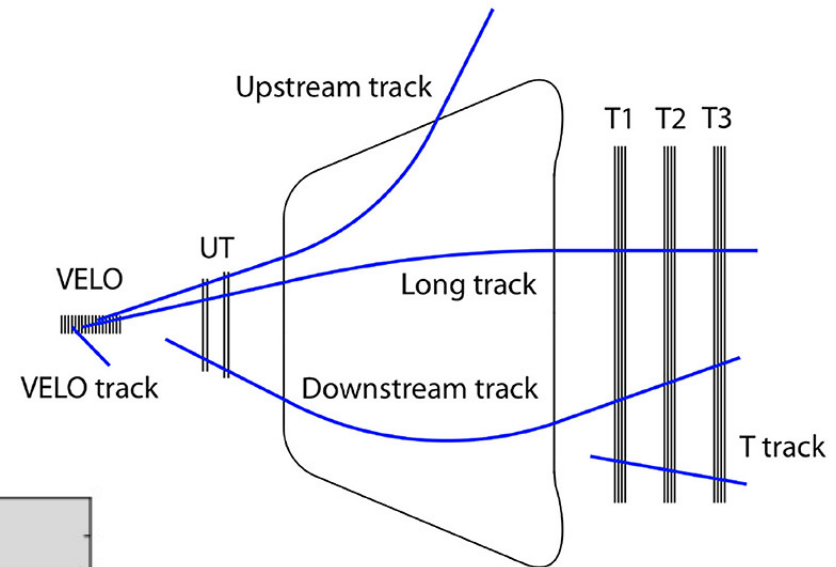
Bonus:  
Expected improvements from Run 3 upgrades!



# Displaced dark photons with LHCb

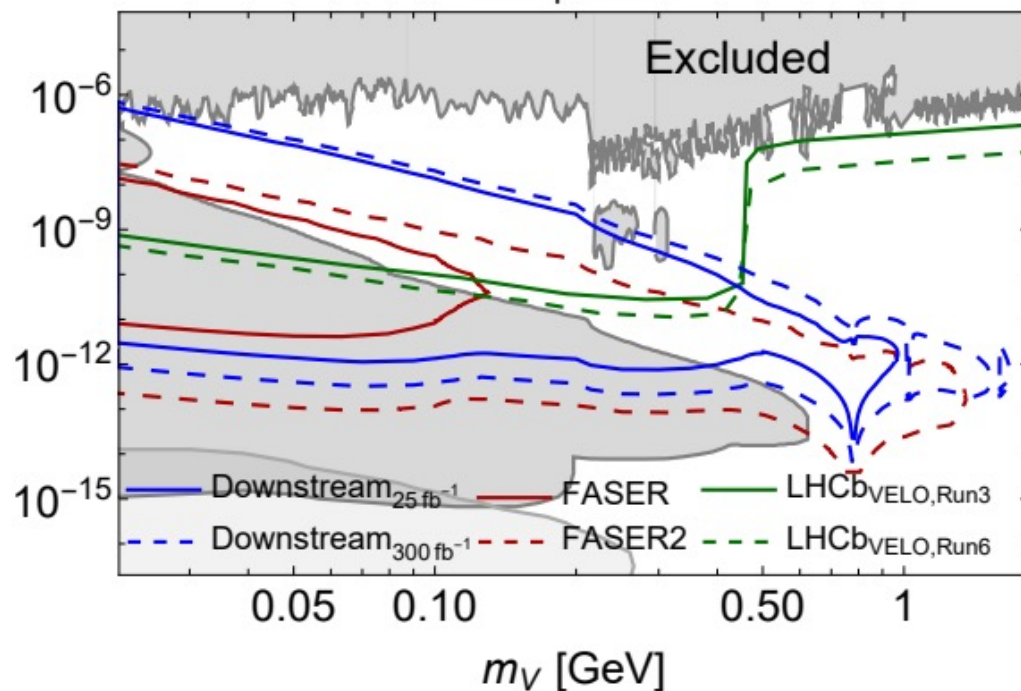
NEW in Run 3, the LHCb trigger system has been dramatically upgraded

- Fully software trigger
- Can trigger on downstream tracks
- Significant gain in sensitivity to LLPs!



Dark photons

Excluded



Expected sensitivity to dark photons:

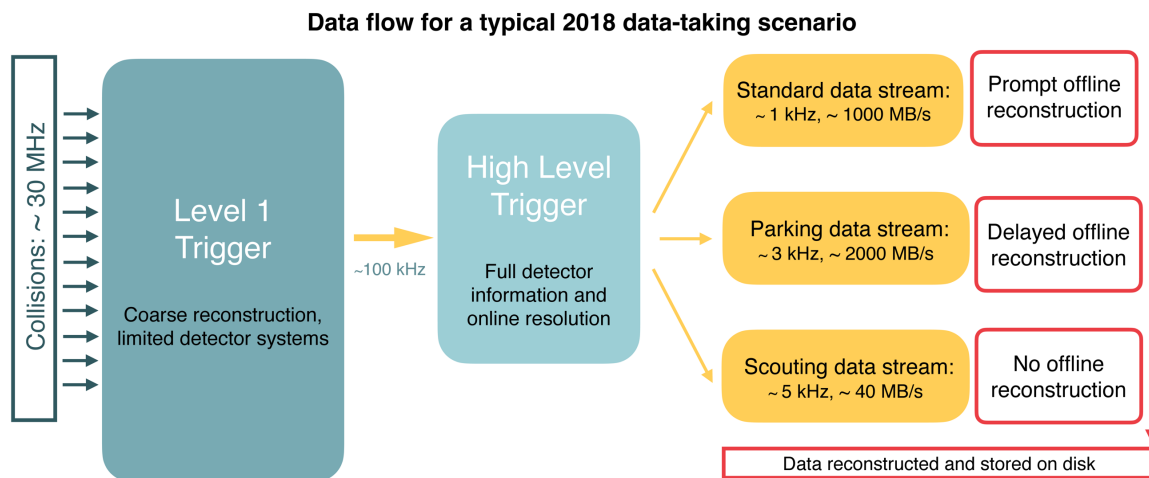
Shows nice complementarity between searches utilizing VELO and searches utilizing downstream tracks

## Improved data scouting: Prospects for LLPs

[CERN-EP-2024-068](#)

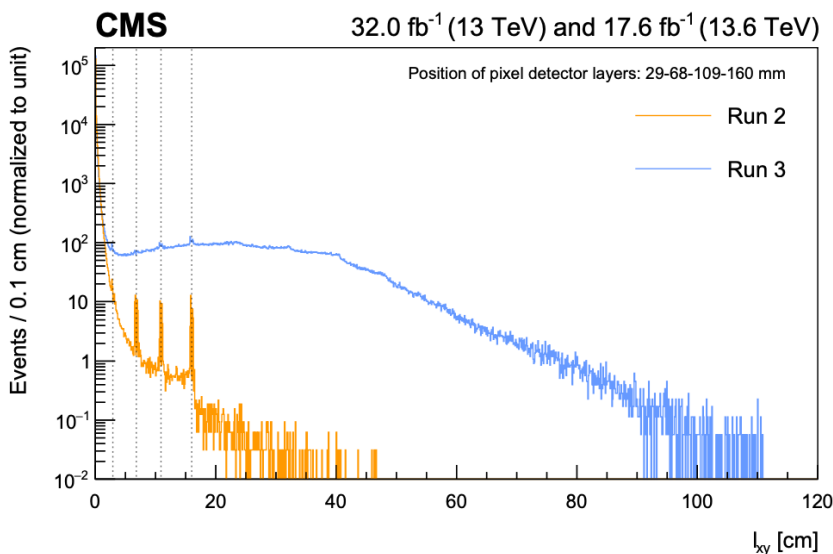
CMS has had “scouting” data streams implemented since Run 1

→ Trades complete event information for higher rates



In Run 3, hardware upgrades and GPU-based HLT reconstruction allows for:

- Lower scouting jet trigger thresholds
- Scouting electron/photon reconstruction, identical to online reconstruction (New!)
- **No minimum number of pixel hits for scouting muons**





# Conclusion

Pair-production of LLPs is a common feature of many models being probed at the LHC, leading to many searches focusing on dilepton, dijet, or diphoton final states.

We've seen a lot of impressive results and creative strategies in Run 2, with many analyses utilizing machine learning techniques.

There are many exciting improvements in Run 3, in particular at trigger level. We're starting to get Run 3 results now, with plenty more to come!

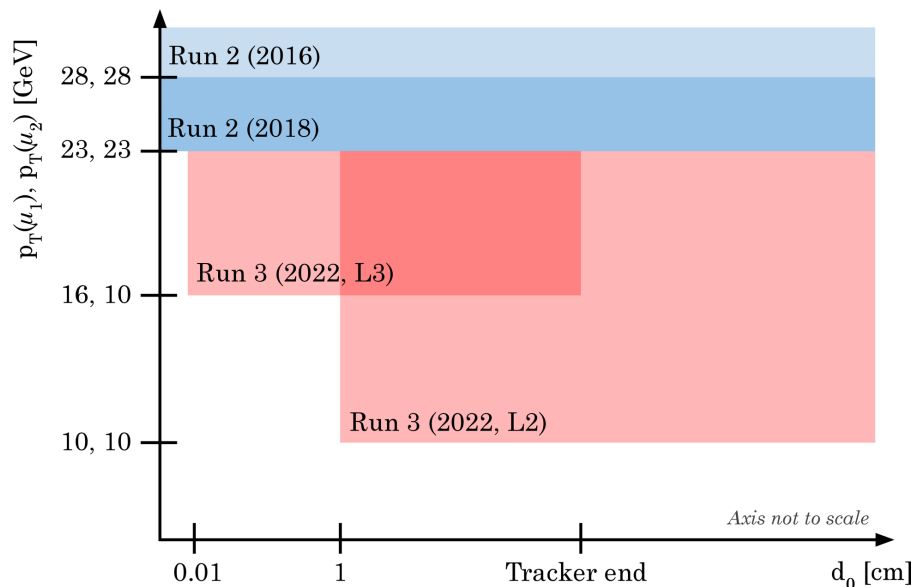
I've only highlighted a few results here, there are many more!! Find more pair-produced LLP results at the following links:

[ATLAS exotics results](#)   [CMS exotics results](#)   [LHCb results](#)

THANK YOU! QUESTIONS?

# BACKUP

## Note: new displaced dimuon triggers in Run 3!



Two new sets of L1 trigger algorithms, which do not use any beam spot constraint:

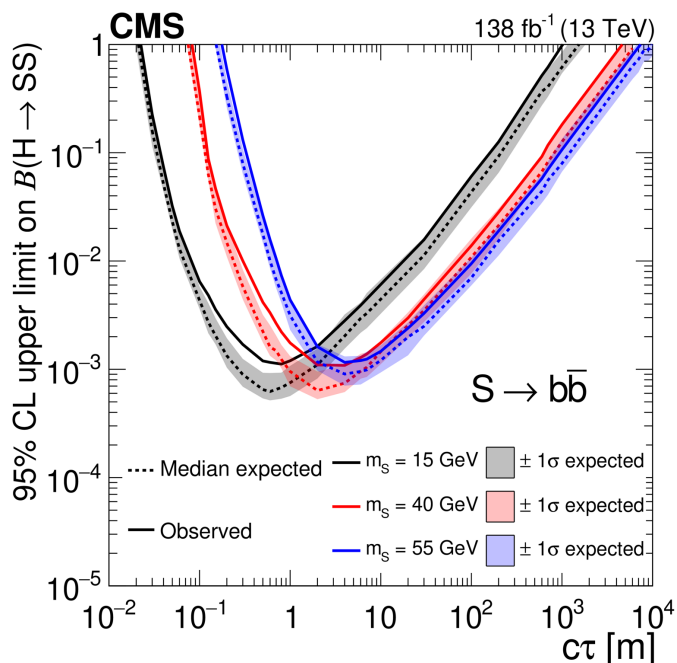
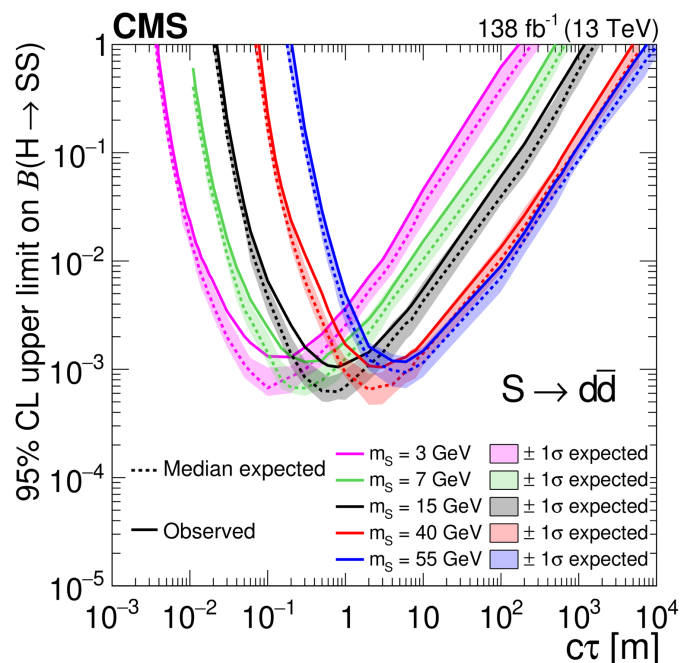
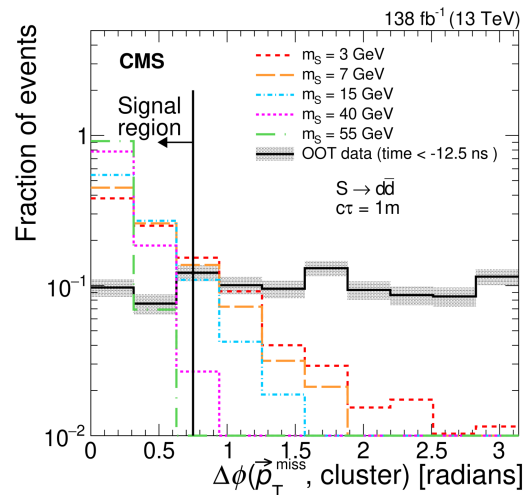
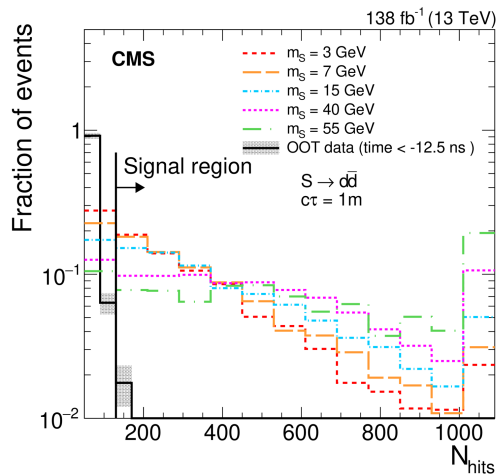
1. Dimuon triggers with very low muon- $p_T$  thresholds, with additional requirements on max number of measurements used in reconstructing L1 candidates and max angle between those candidates
2. Triggers utilizing new track-finding procedure in the barrel

New HLT L2 path: Online reconstruction in muon system alone, then attempts to reconstruct muon candidates at L3 as well. If either is reconstructed at L3 with  $d_0 < 1$  cm, the event is discarded. Improves STA-STA signal efficiency.

New HLT L3 path: Online reconstruction in muon system + tracker with a threshold of  $d_0 > 0.01$  cm. Improves TMS-TMS signal efficiency.

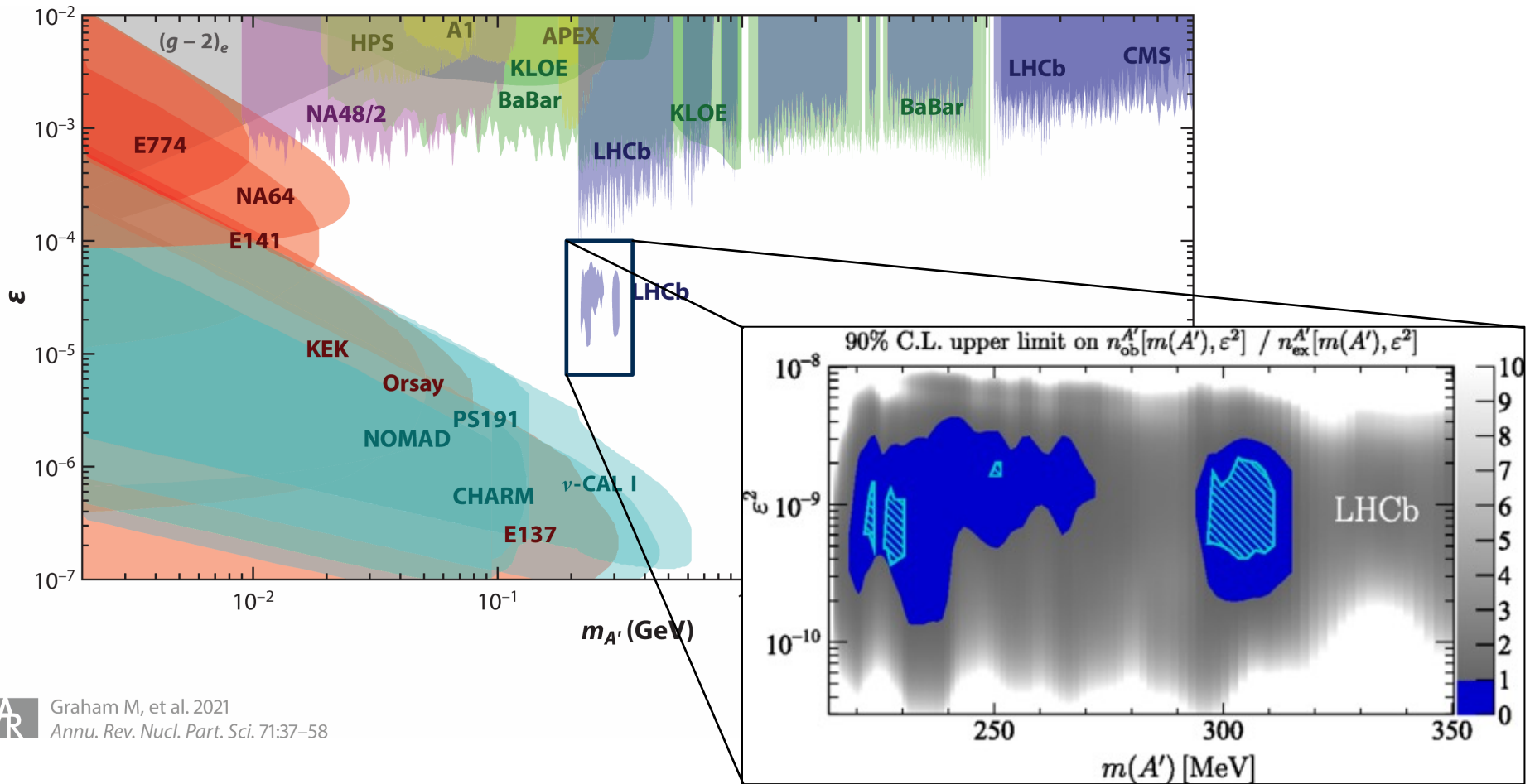
# LLP showers in the muon detectors

Main discriminating variables are number of hits in the muon detectors and  $\Delta\phi(\vec{p}_T^{\text{miss}}, \text{cluster})$ , which form axes of ABCD planes



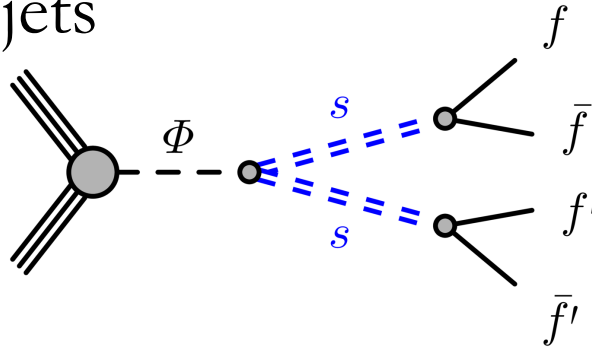
# Displaced dark photons with LHCb

Dark photons to dimuons: LHCb search targeted displaced decays reaches unique area of phase space



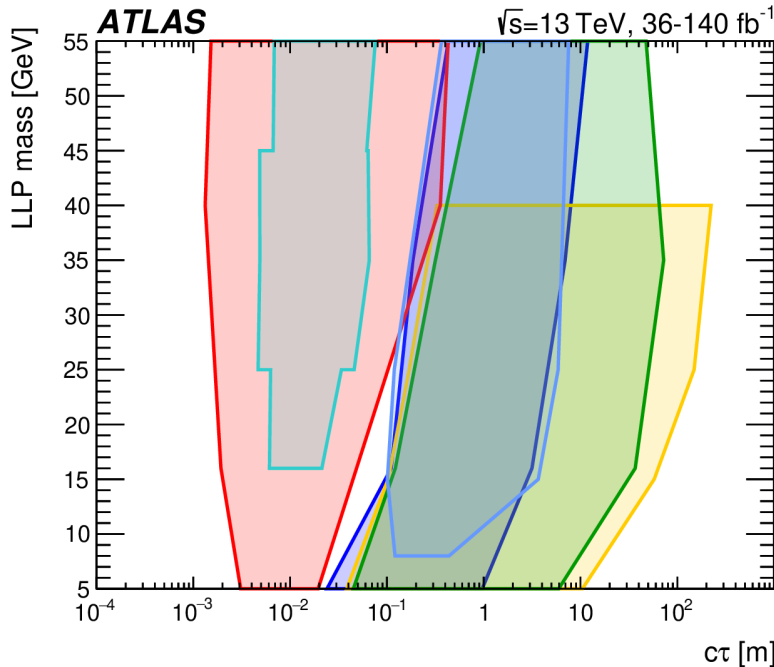
# Displaced hadronic jets

Higgs portal to a pair of neutral long-lived scalars ( $s$ )



Decays to SM fermions

3 analyses to search for decays in the 3 subdetectors:

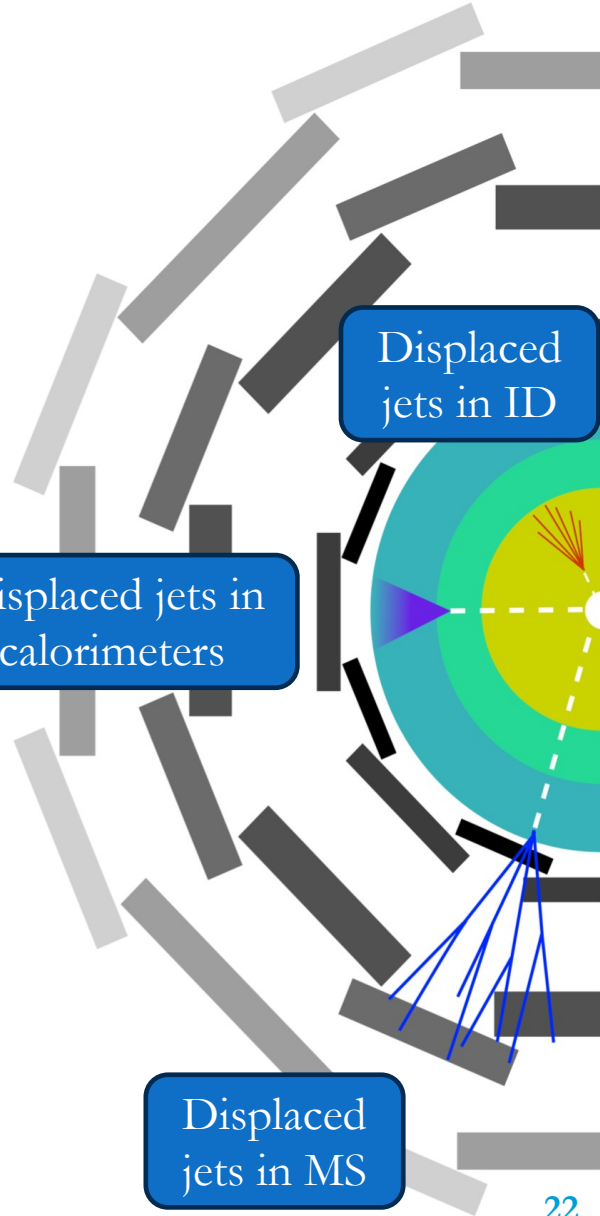


Hidden Sector,  $m_H = 125\text{ GeV}$   
 $B(H \rightarrow ss) = 10\%$   
 95% CL observed limits

Displaced jets in calorimeters

Displaced jets in ID

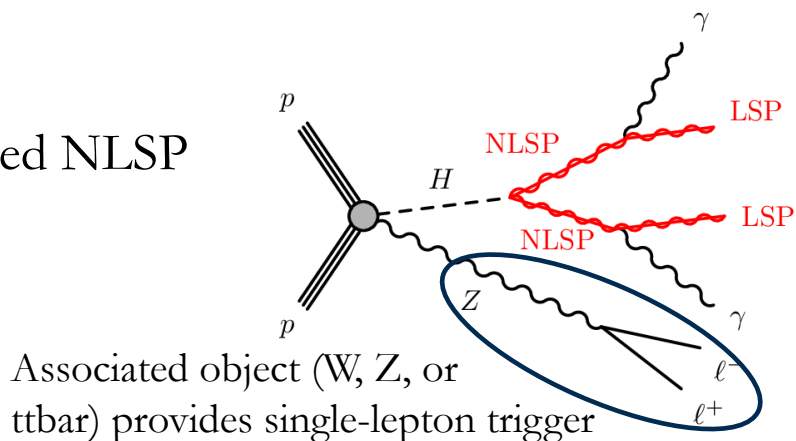
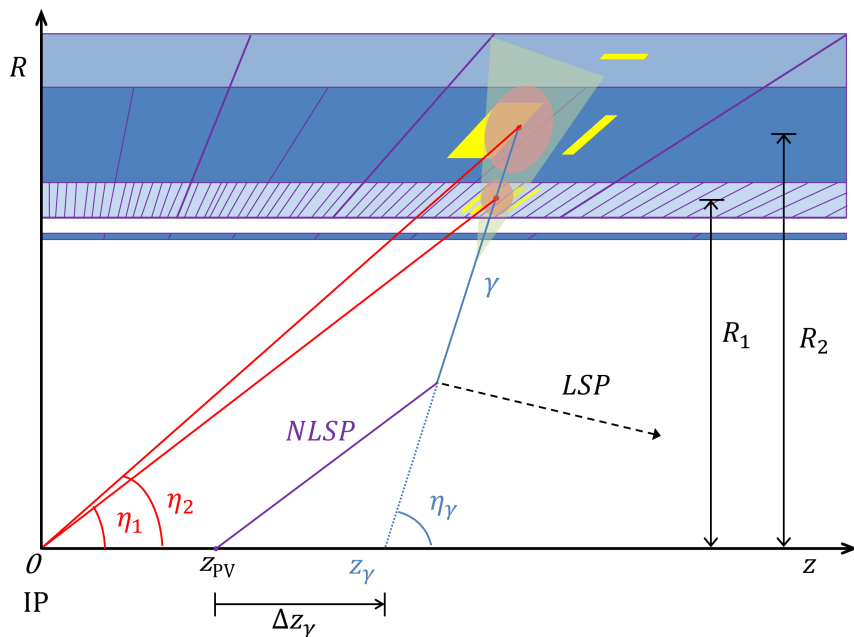
Displaced jets in MS



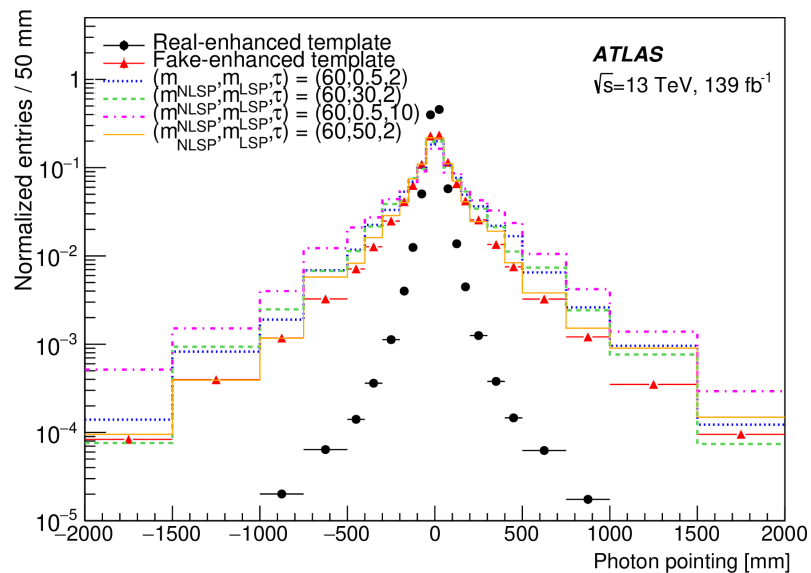
# Displaced diphotons

VH production where H decays to long-lived NLSP  
Decays to photon+LSP

- Photons can be nonpointing, delayed, or both
- Precise pointing and time measurements are key



Associated object (W, Z, or ttbar) provides single-lepton trigger



# Displaced diphotons

