Searching for LLPs with Muon Detector Showers

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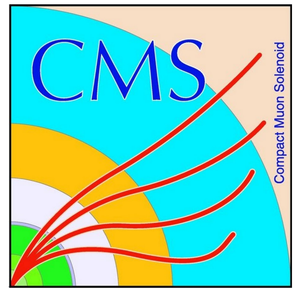
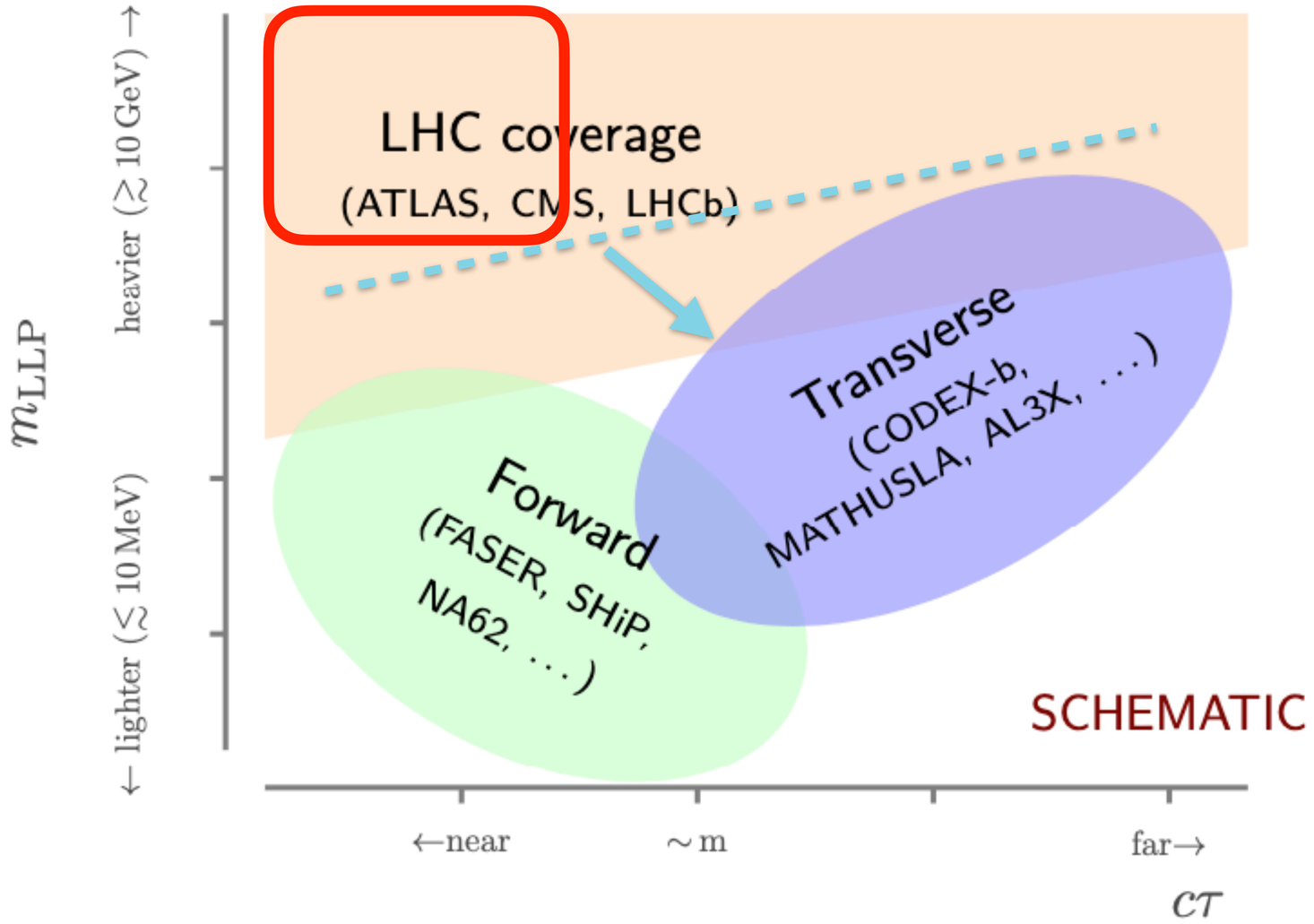
2024 LLP Workshop
07/03/2024

Caltech

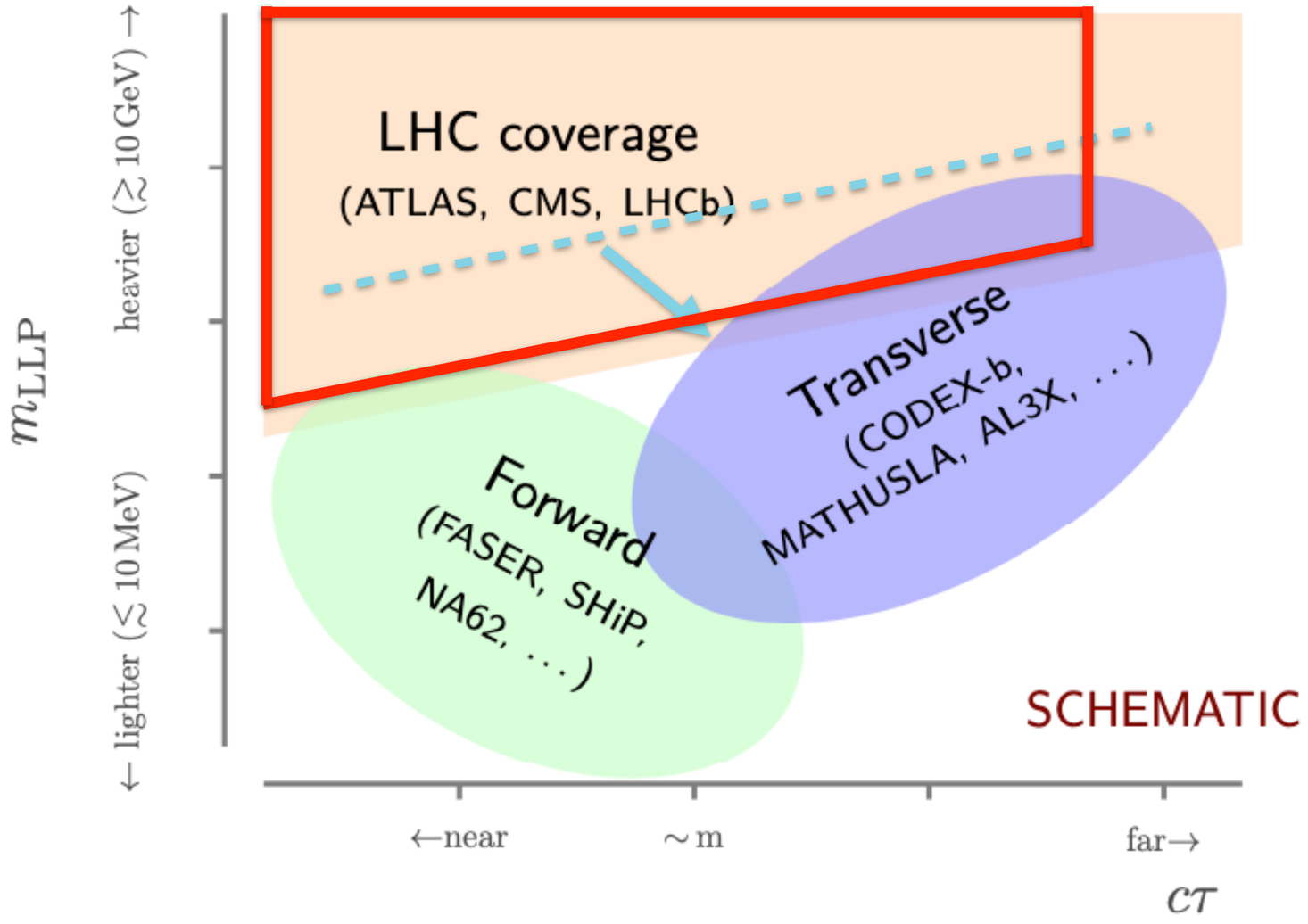


LLP Landscape in CMS



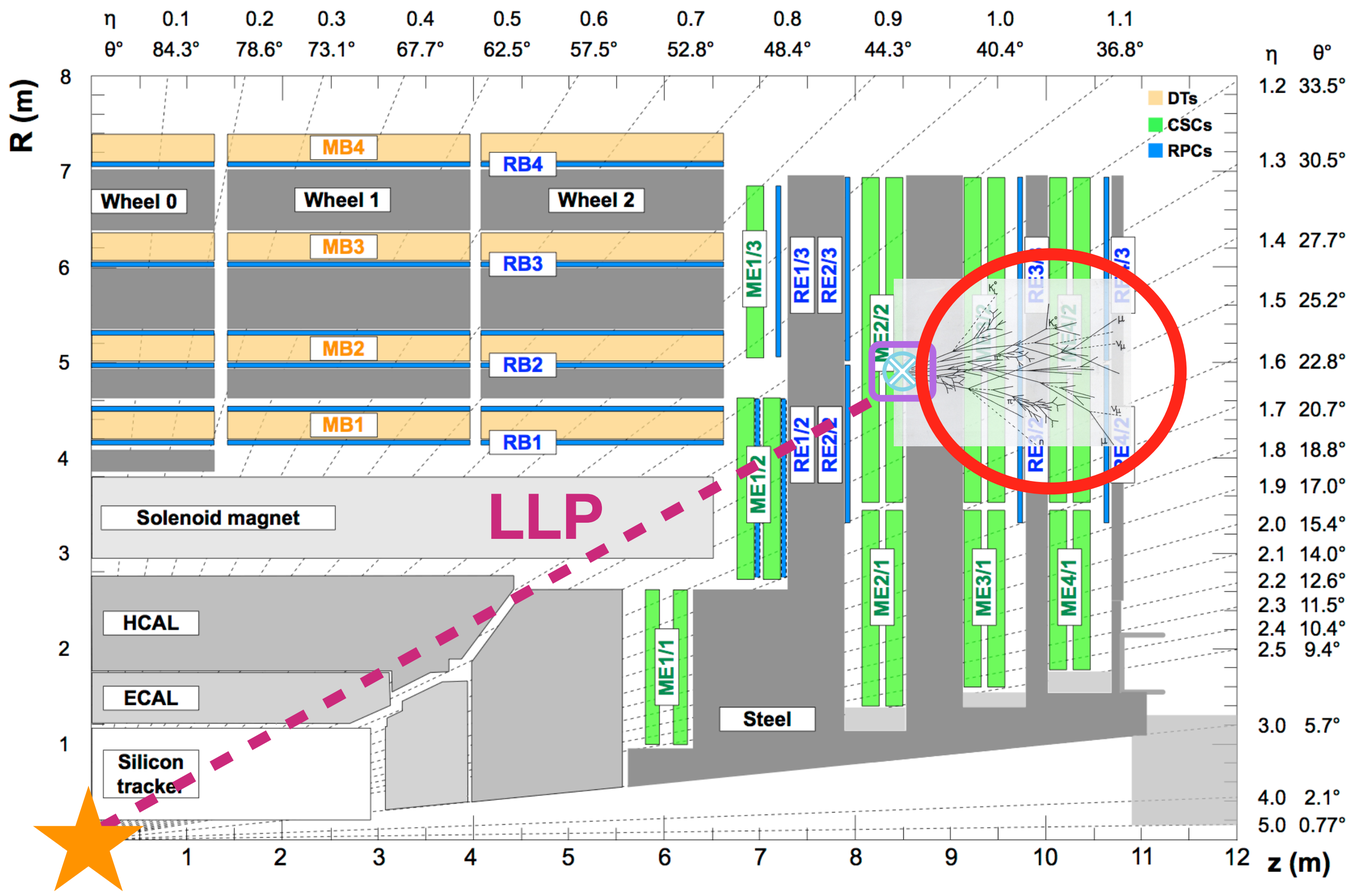
- CMS has excellent discovery reach for $c\tau$ < 1m and M_{LLP} > 50 GeV
- Enabled by precision tracker: displaced jets

Key Goal : Close gaps in search coverage



Strategy: Enable searches for light LLP with large cτ using LLP decays beyond tracker

Motivation: Search for LLPs in CMS Muon System

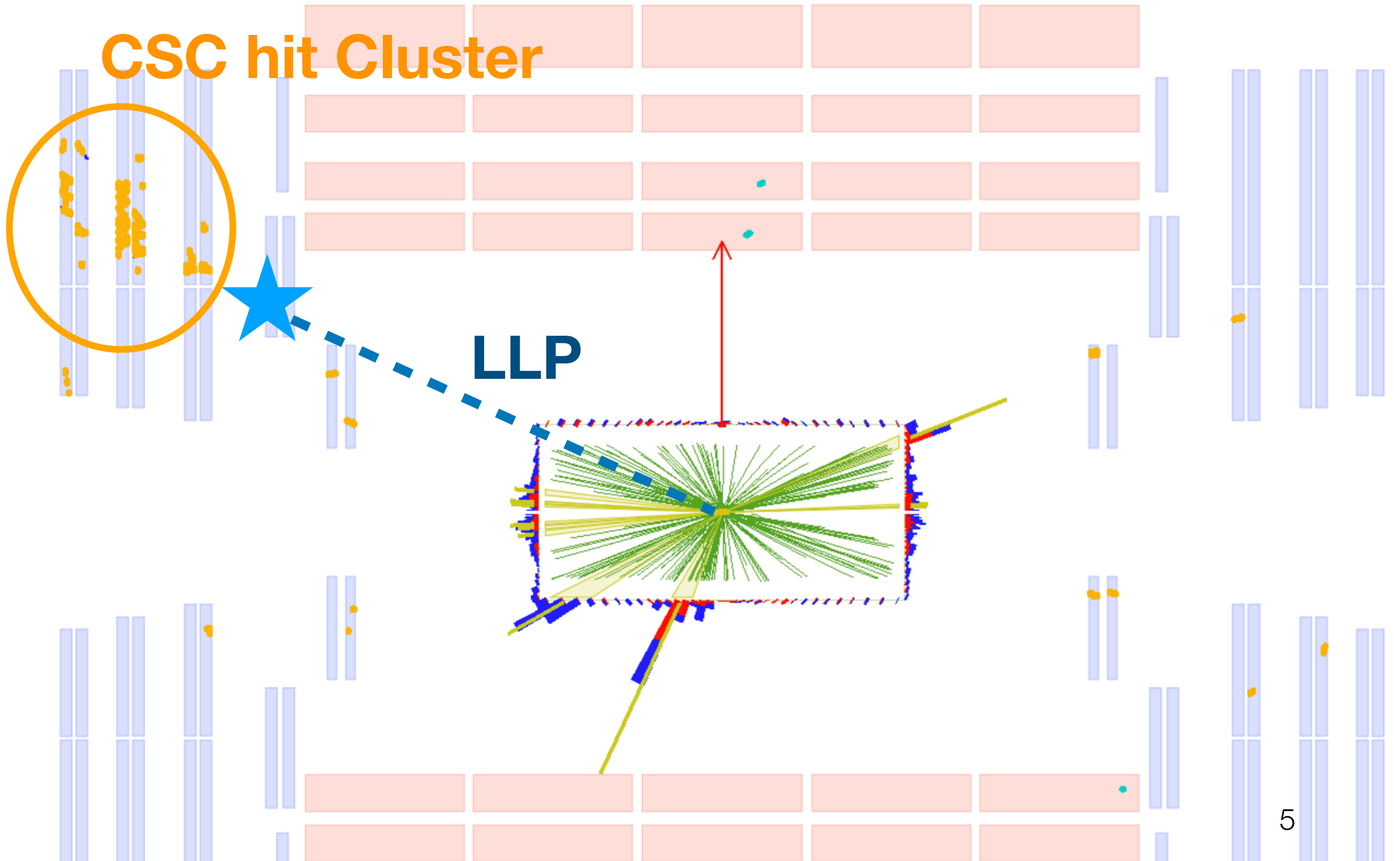


LLP decay and resulting particle shower is detected with a **large hit multiplicity**

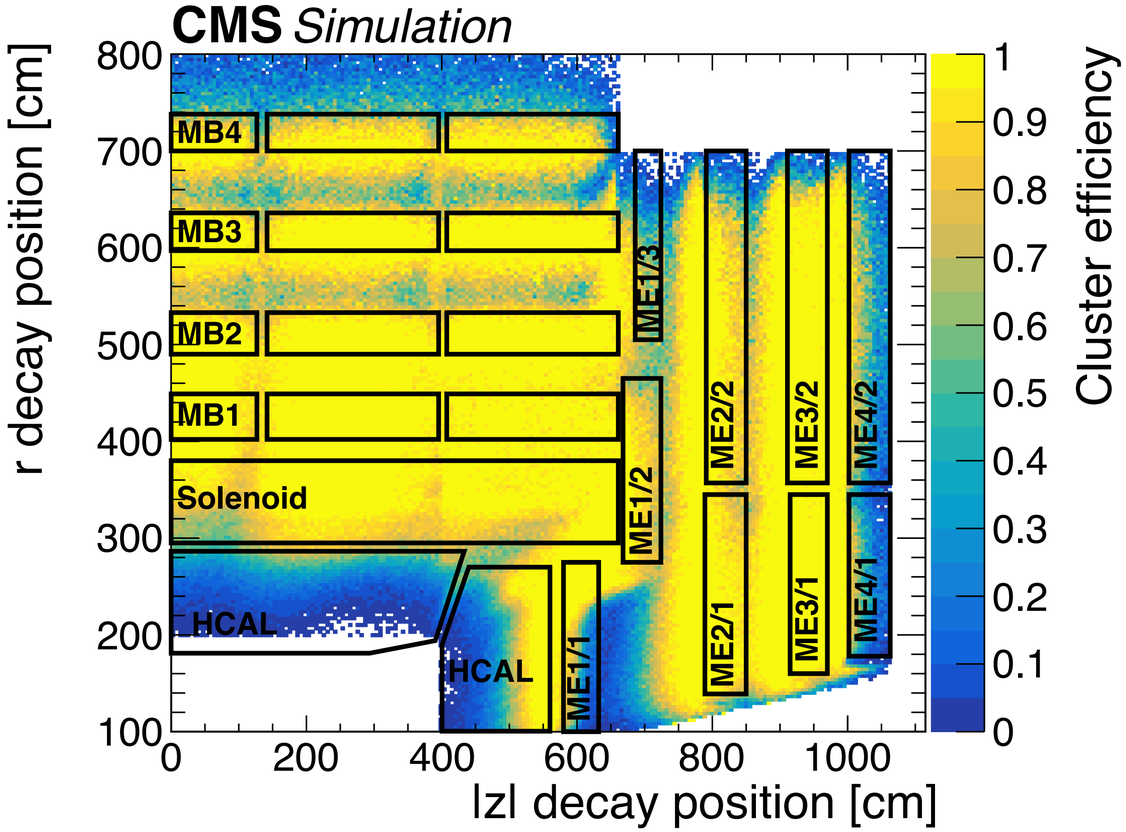
- Covers decays far away from IP (sensitive to large cτ)
- Excellent **background suppression** from shielding material
- Steel interleaved with active chambers → **sampling calorimeter**
- Different designs from ATLAS muon system: gas between stations → tracker for LLP decays

Search for LLPs with Muon Detector Showers

- Large **cluster of hits (>100 hits)** in the muon detectors with no jets or tracks
- Due to the shielding and the exotic signature, this analysis can be sensitive to **very light LLPs** ($m_{LLP} < 1$ GeV)
- Muon system acts as a **sampling calorimeter:** sensitive to a broad range of decays: quarks, taus, pions, kaons, electrons, photons…

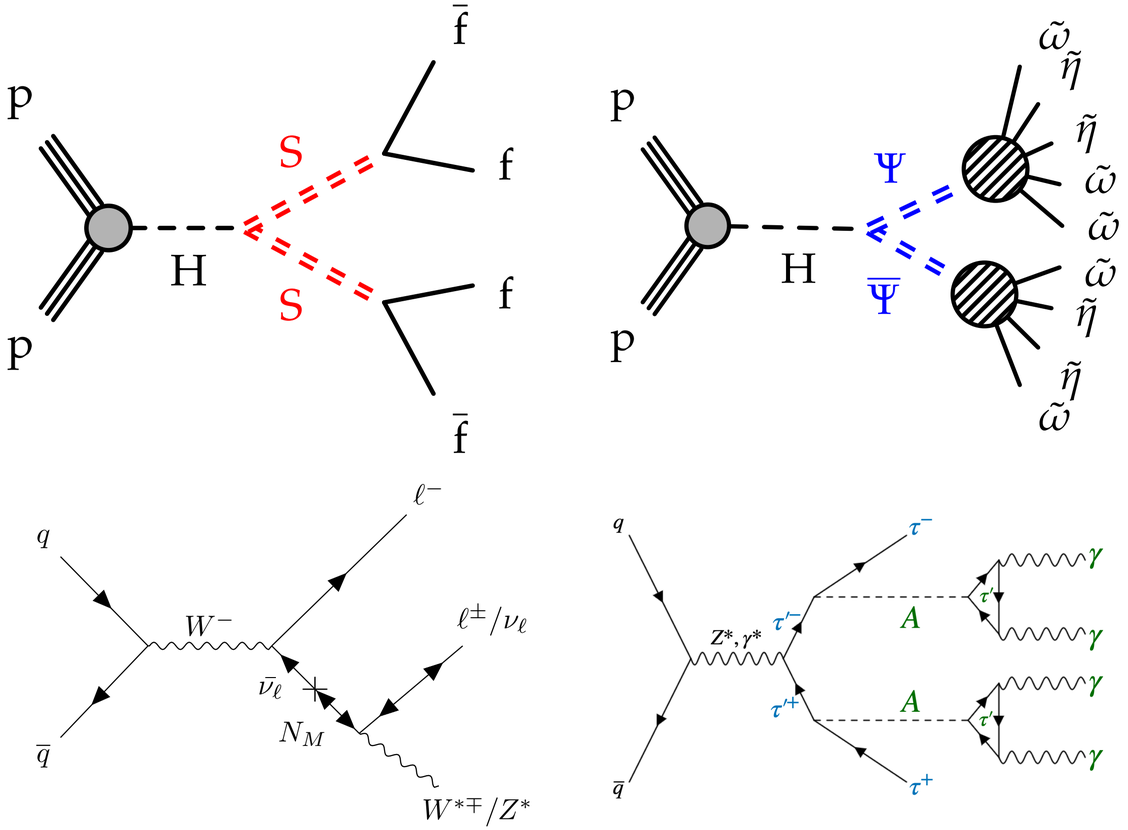


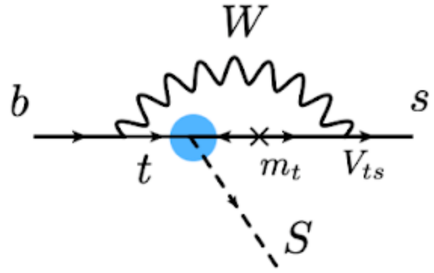
High reconstruction efficiency



Muon Detector Shower Analyses in Run 2

- MDS signature sensitive to a wide range of models and decays
- Due to the lack of dedicated trigger, Run 2 analyses trigger on associated objects:
  - MET-triggered: **Higgs portal models** (CMS-EXO-20-015, CMS-EXO-21-008) → **focus of this talk**
  - Lepton-triggered: **Heavy neutral leptons** (CMS-EXO-22-017) → more details in Martin Kwok's talk
  - MET-triggered: **Vector-like lepton**
  - B-parking dataset: **B-produced LLPs** in scalar portal

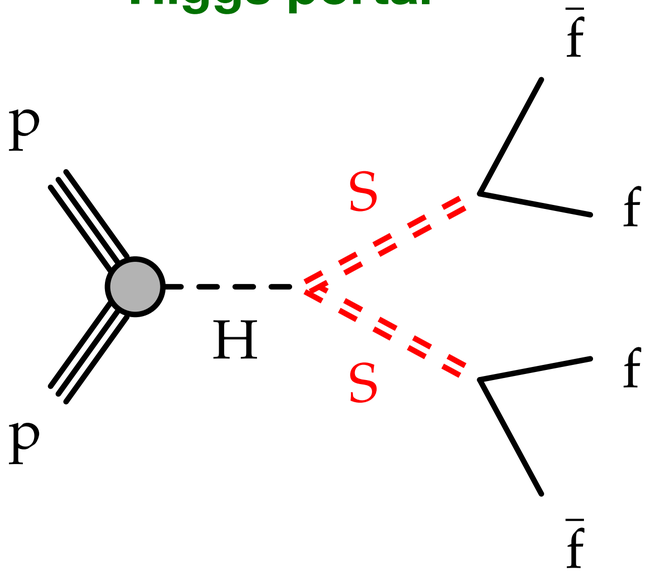




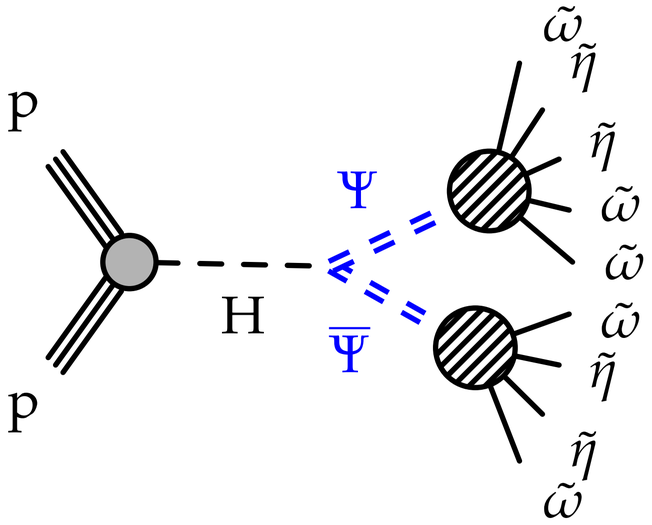
Muon System Analysis Trigger Strategy

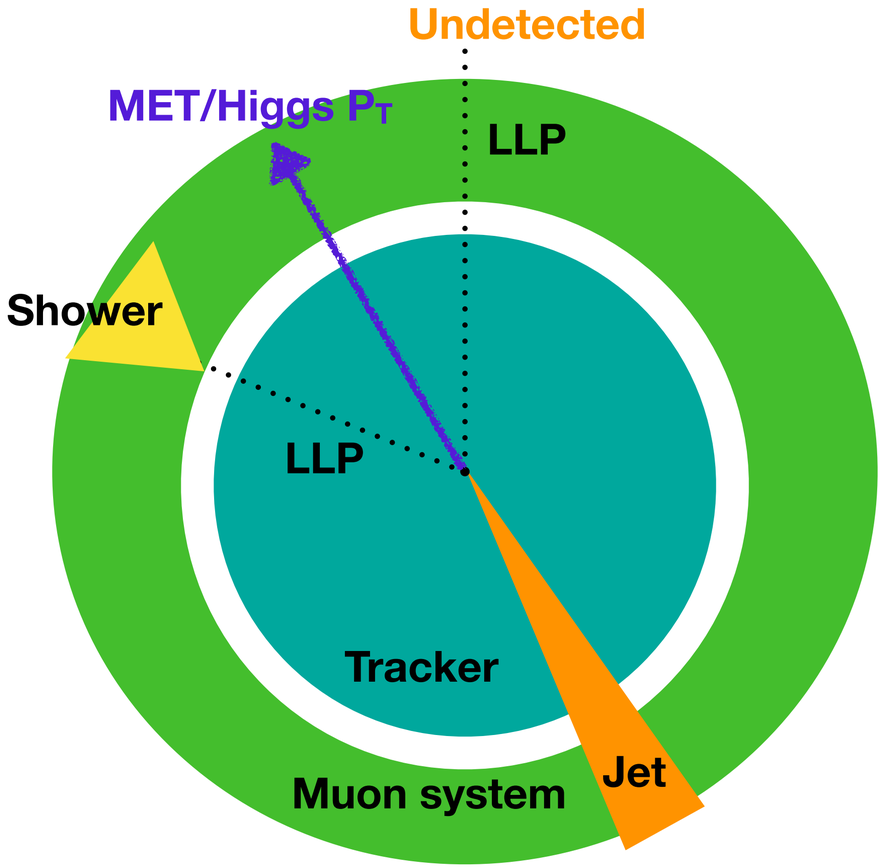
- Trigger on **MET due to lack of dedicated trigger in Run2 (signal efficiency is ~1%)**
- New dedicated trigger implemented for Run3

Higgs portal



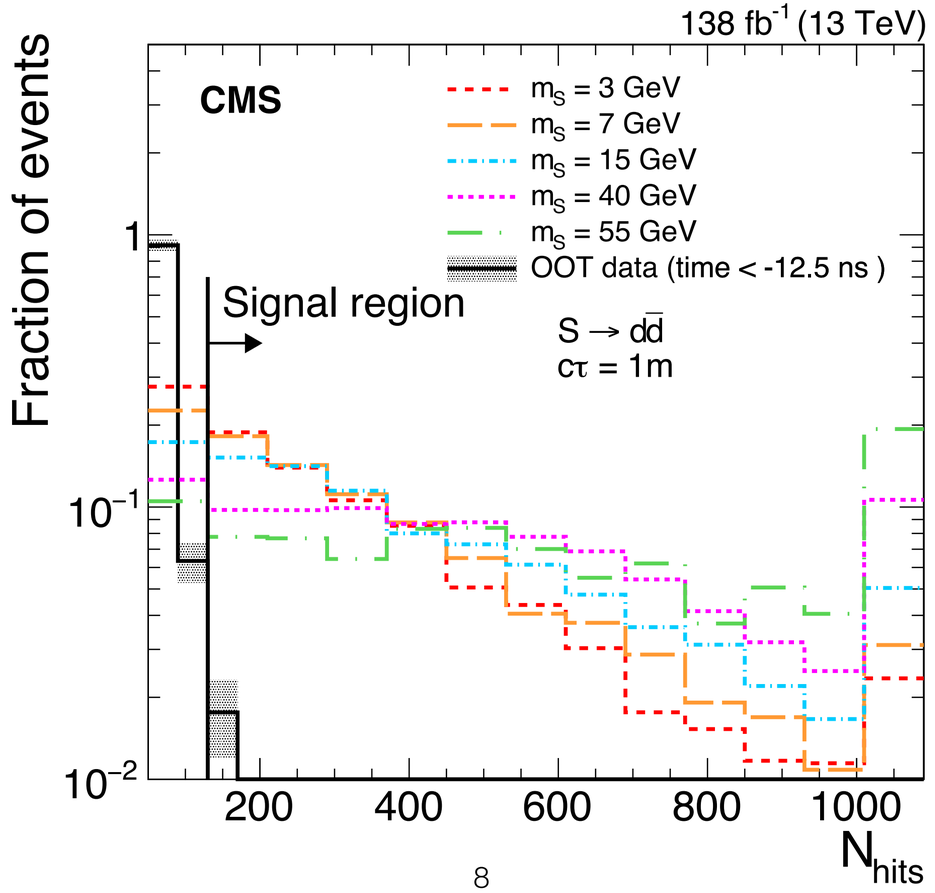
Dark shower model





Analysis Strategy

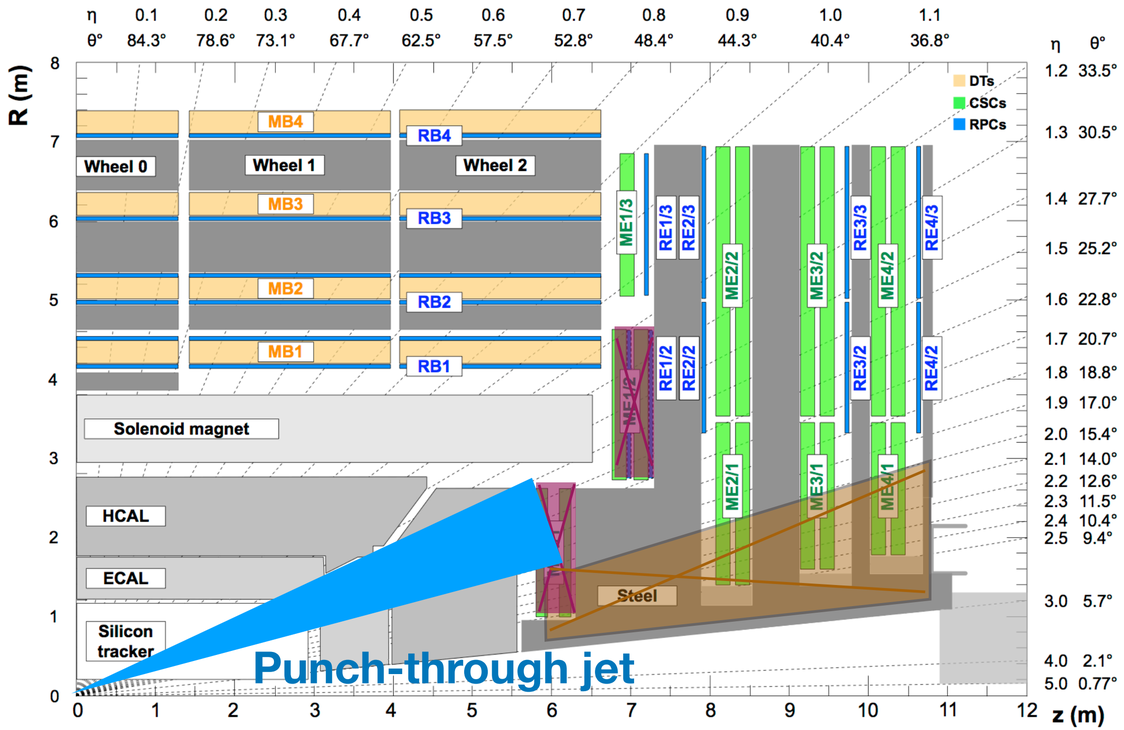
- **Event selection:** select high MET (MET > 200 GeV) and boosted Higgs phase space
- Analysis is split into 3 categories: 1 cluster in CSC; 1 cluster in DT; 2 clusters
- Use **cluster ID** to achieve 10^6 background rejection
- N_{hits} serves as the main discriminator



Cluster ID

Reject background from the main collision

- Reject clusters from **punch-through jets** and **muon bremsstrahlung shower**:
  - Veto clusters matched to jets and muons ($\Delta R < 0.4$)
  - Active vetos in first station (ME11/12)
  - Veto clusters with $|\eta| > 2.0$
- ~50% signal efficiency when LLP decays between 1st and 4th station



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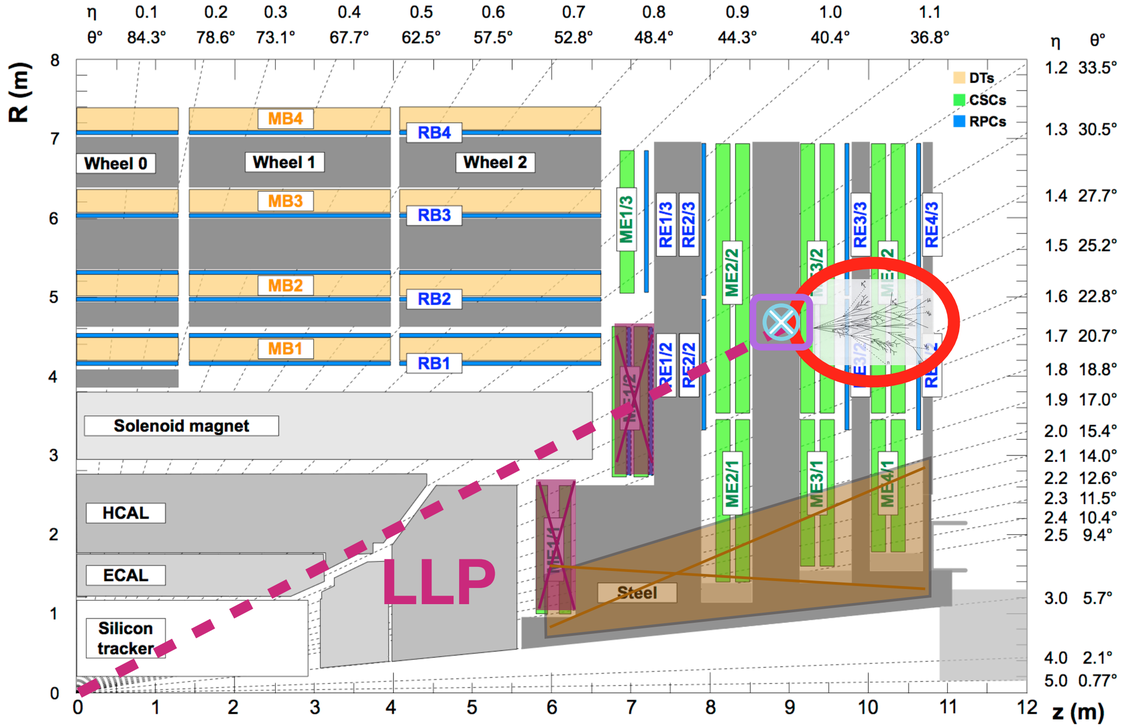
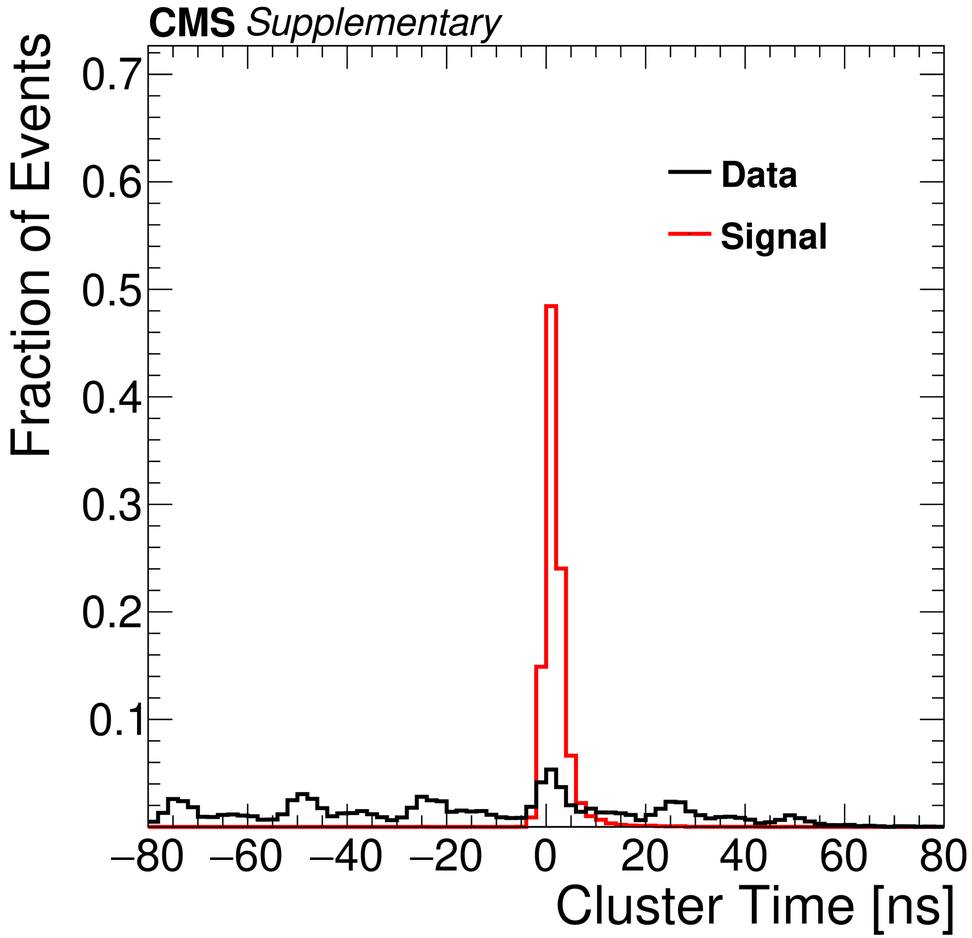


Cluster Time

$$\textbf{cluster time} = \frac{\sum_{i=1}^{N_{rechits}} t_i}{N_{rechits}}$$

- Background distribution shows out-of-time pileup contribution, while signal is in-time
- **5x background rejection** by requiring clusters to be in-time
- Define an **early OOT region for background estimation**



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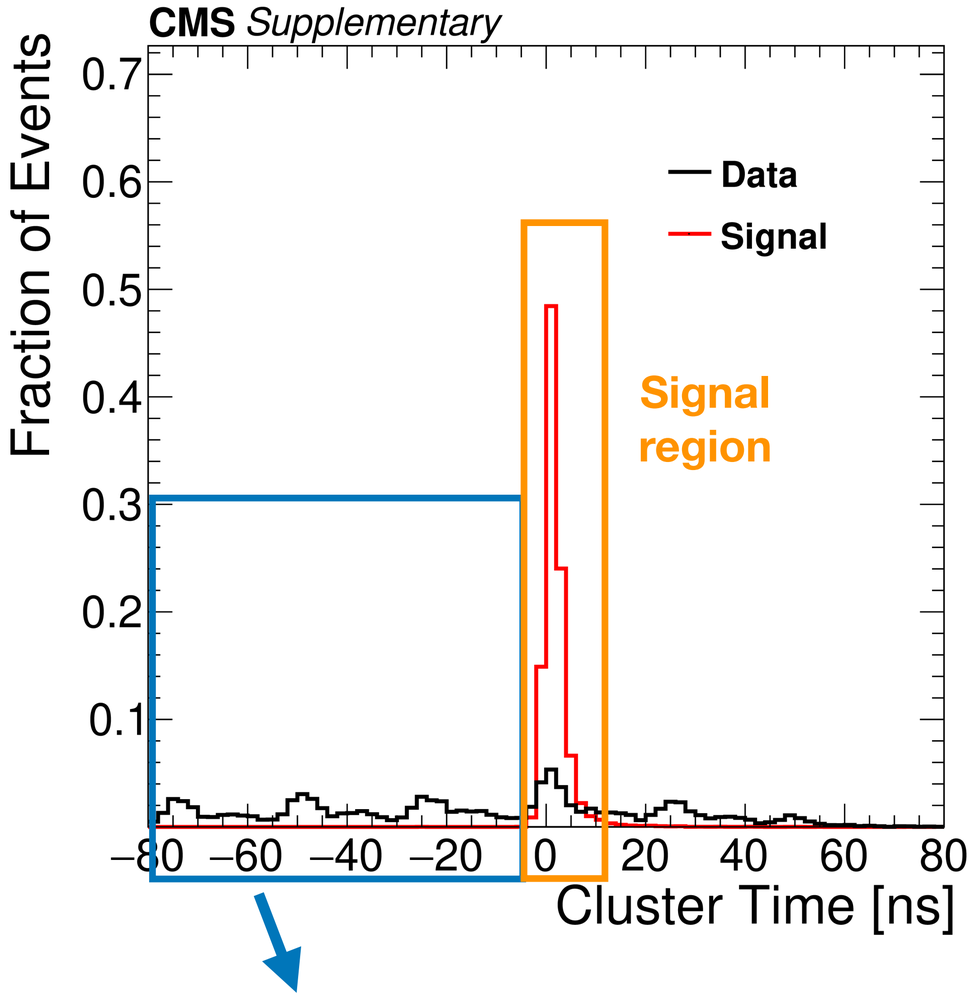
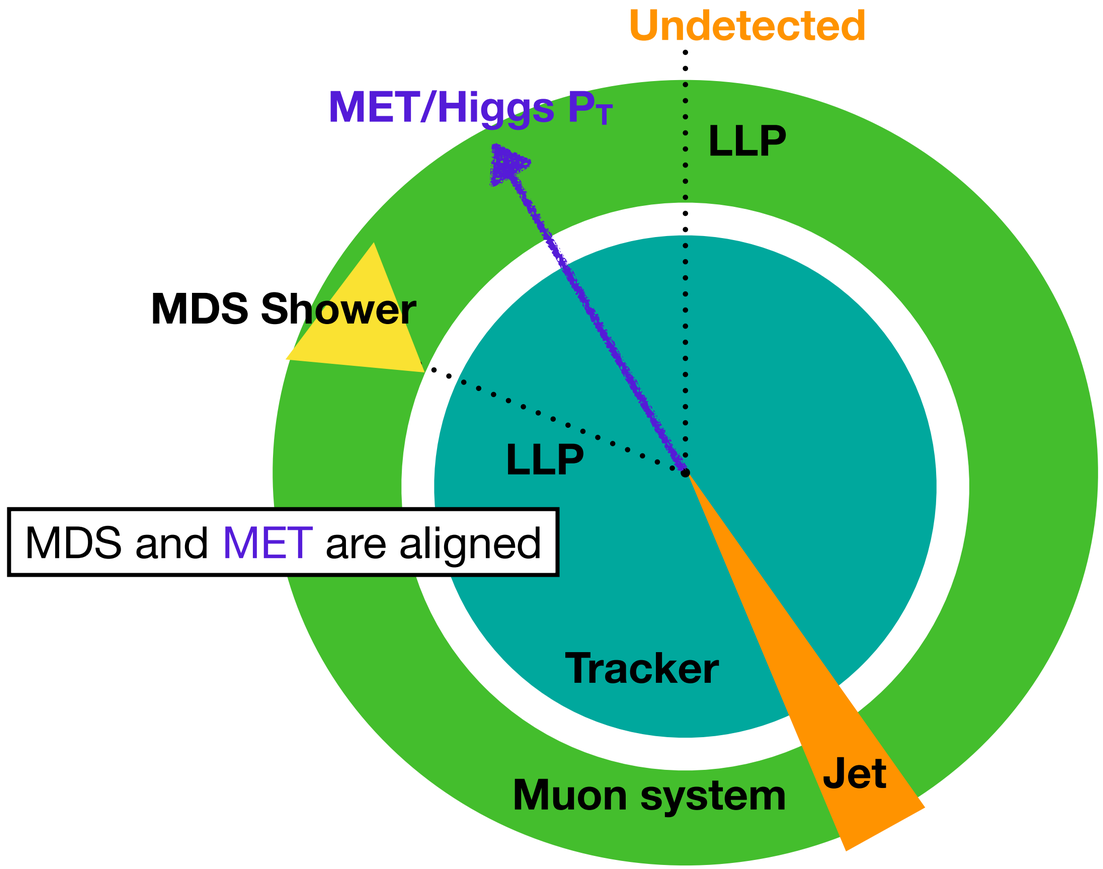
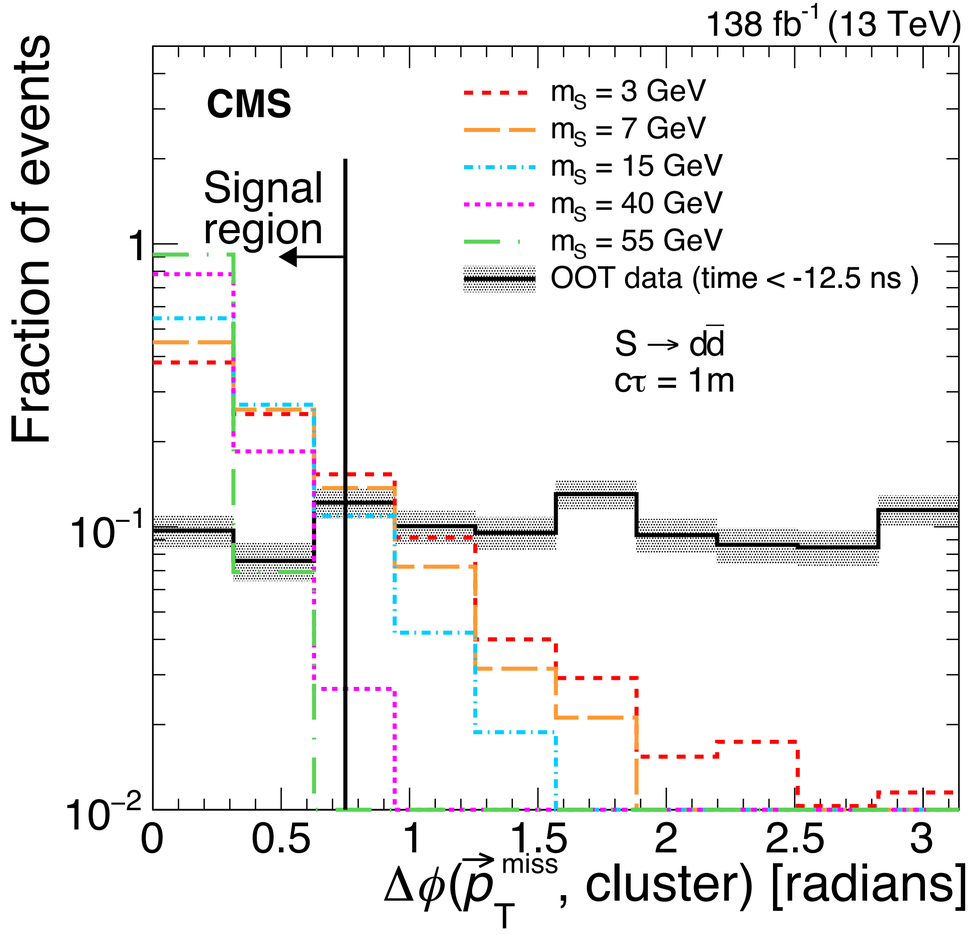


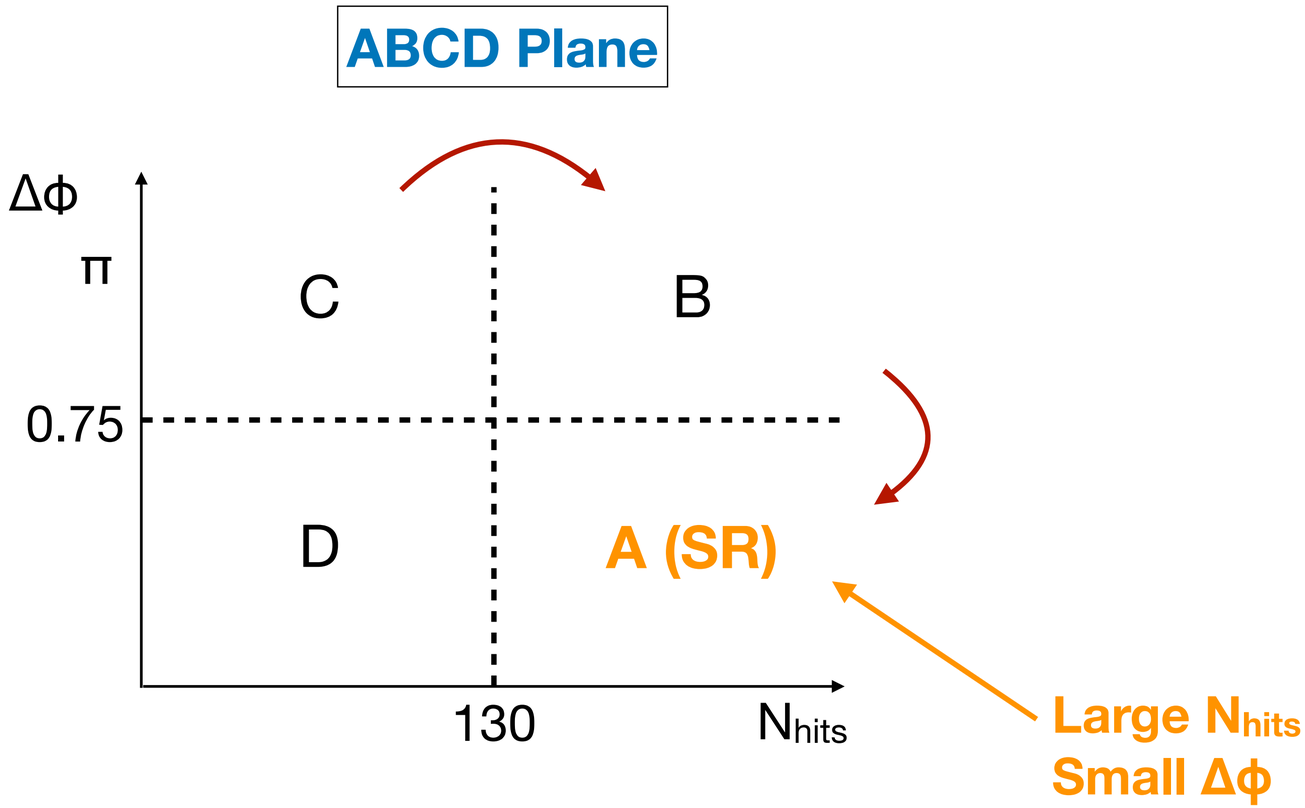
$\Delta\phi(\textbf{cluster}, \vec{p}_T^{miss})$





- $\Delta\phi(\textbf{cluster}, \vec{p}_T^{miss})$ **peak at 0 for signal**
- **Flat** $\Delta\phi(\textbf{cluster}, \vec{p}_T^{miss})$ **distributions for background:**
  - Background clusters are produced from underlying events, while MET is calculated from primary event

Background Estimation using ABCD Method

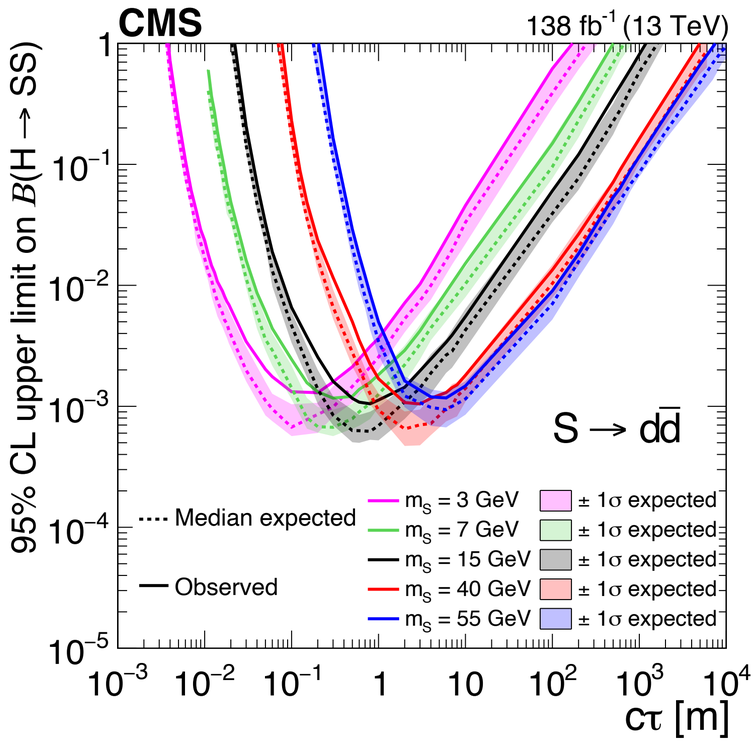


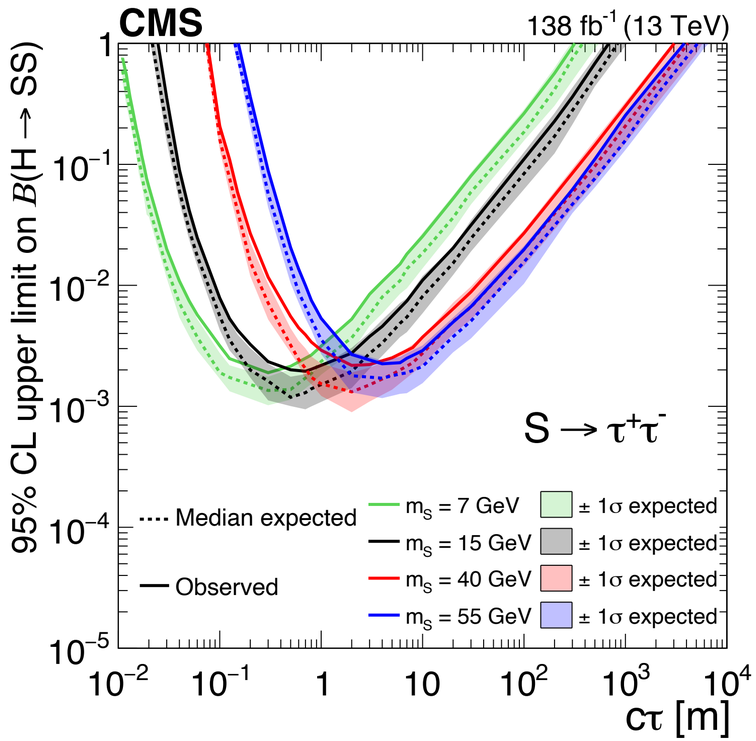
$$A = B \times \frac{D}{C}$$

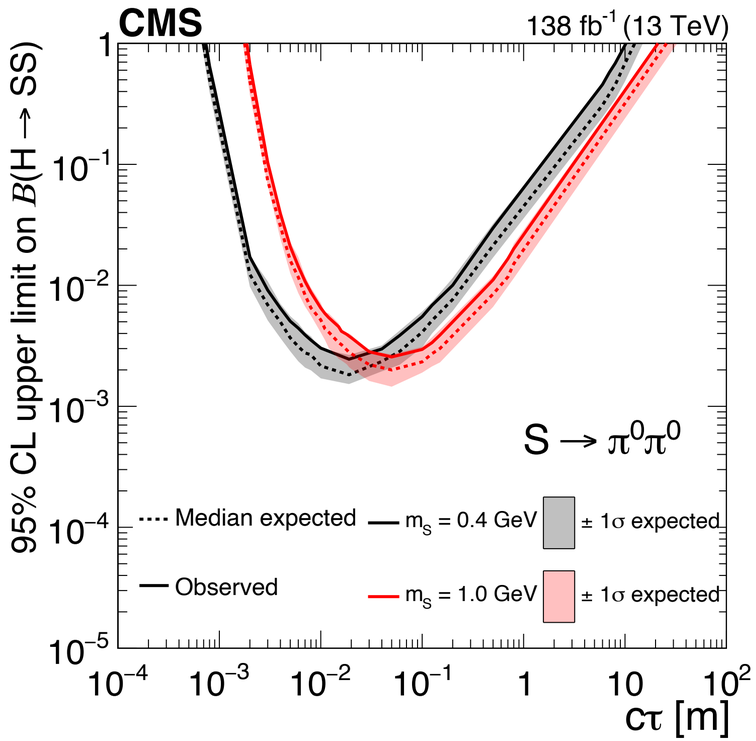
- $\Delta\phi(\text{cluster}, \vec{p}_T^{miss})$ and N_{hits} are independent for background
- Background estimation method validated in 2 separate validation regions

Results & Interpretation in Twin Higgs Model

- No excess above SM background observed
- Signature is largely model-independent, interpreted result in Higgs portal with LLP mass down to 0.4 GeV and 9 decay mode: $d\bar{d}, b\bar{b}, \tau^+\tau^-, \pi^+\pi^-, \pi^0\pi^0, K^+K^-, K^0K^0, e^+e^-, \gamma\gamma$
- First LHC sensitivity to $\tau^+\tau^-$ **and** $\gamma\gamma$ **decay modes** at BR(H →ss) = 10^{-3} level
- First LHC sensitivity to **sub-GeV mass hadronically decaying LLPs** at BR(H →ss) = 10^{-3} level



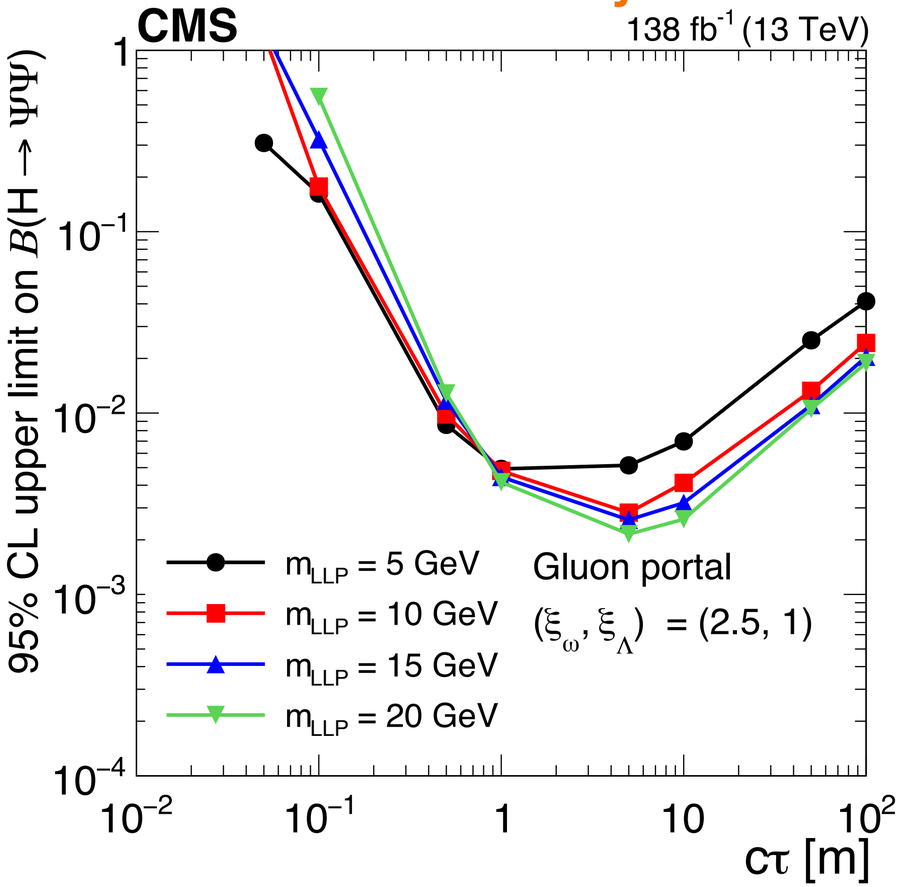




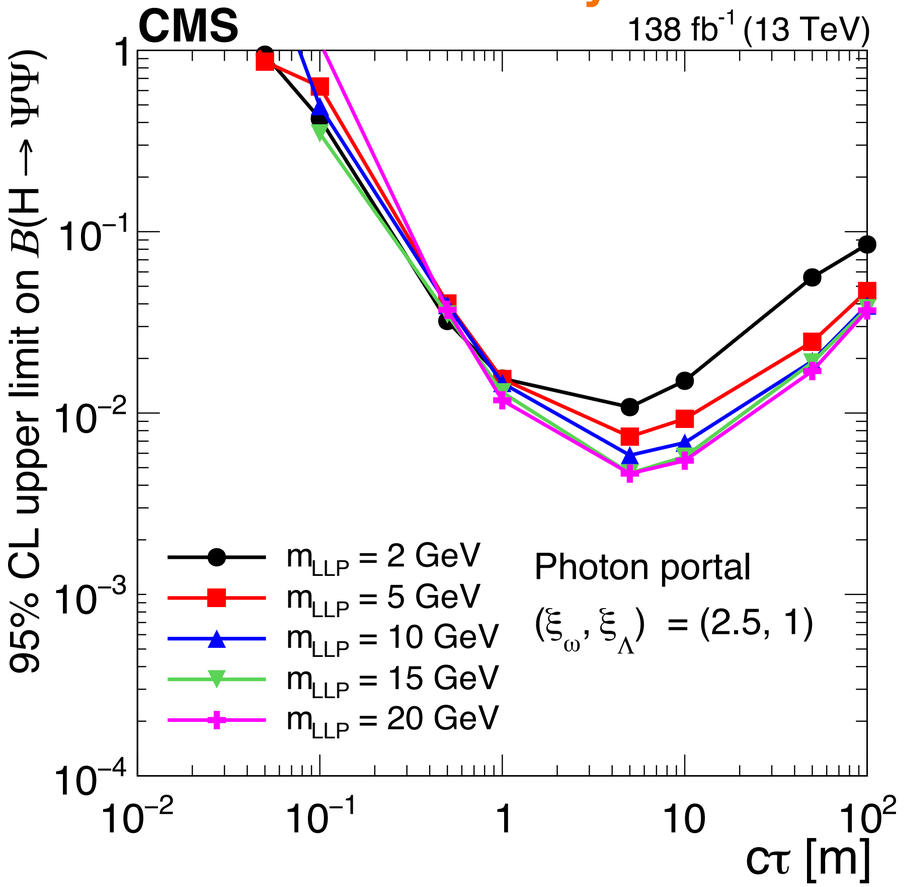
Results & Interpretation in Dark Shower Model

- Signature is largely model-independent, interpreted result in dark shower model in multiple portals for mass between 2 - 20 GeV
- First LHC sensitivity to Higgs portal **dark shower models** at BR(H →ss) = 10^{-3} level

Hadronic decays

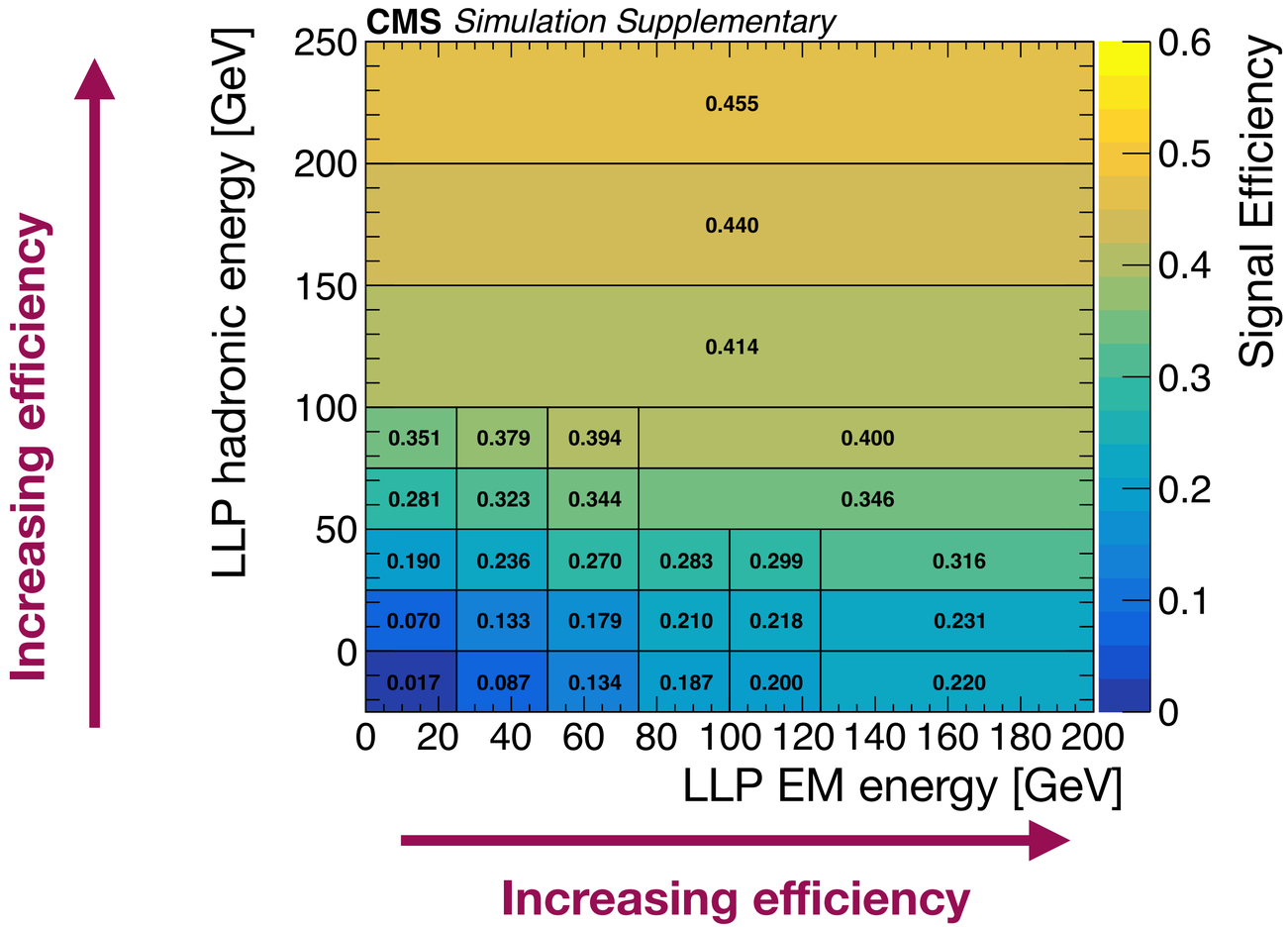


Photon decays



Muon Detector as a Sampling Calorimeter

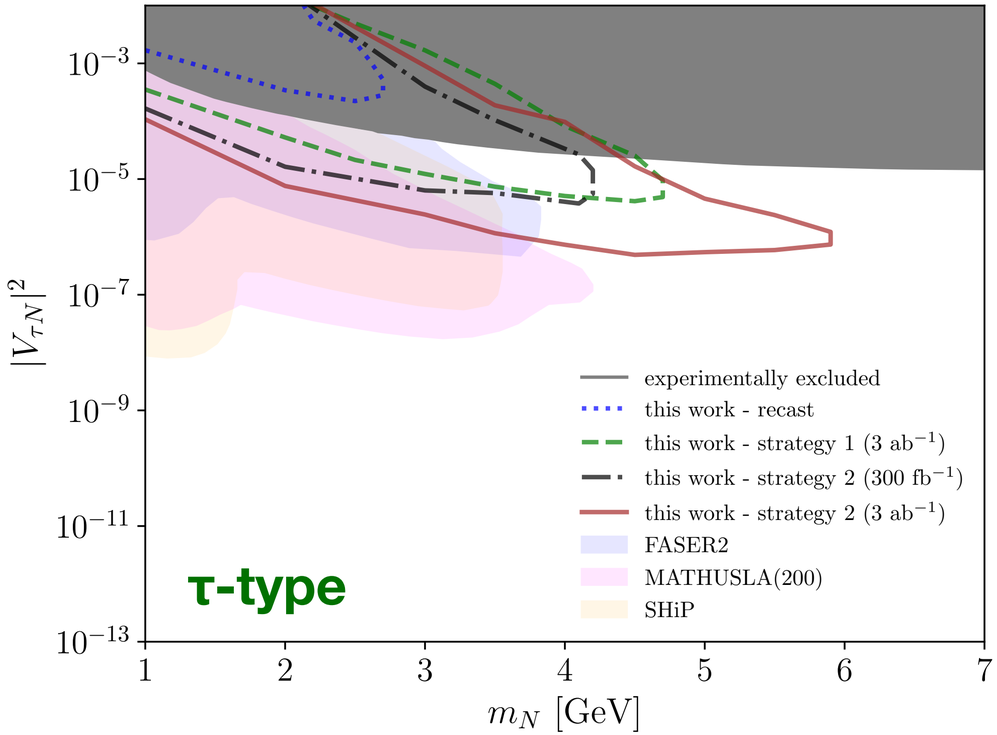
- **Muon detector shower captures both hadronic and EM decays**
  - Efficiency is slightly different due to different behavior in steel

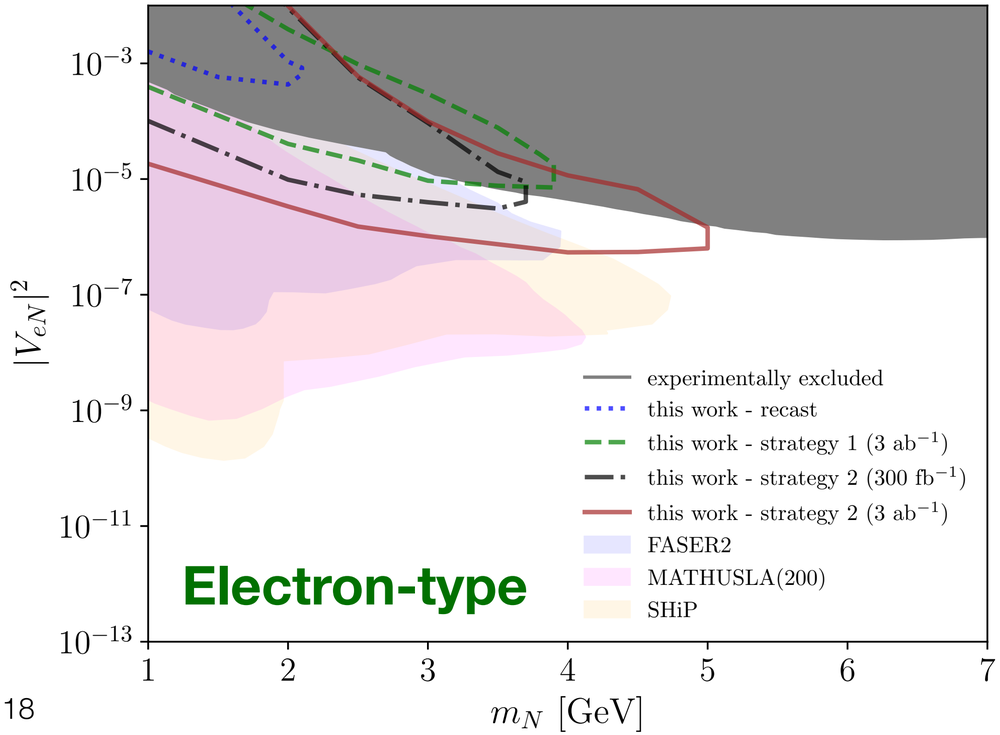


Reinterpretation with Delphes

JHEP 02 (2023) 011
Phys. Rev. D 108, 055040
JHEP 07 (2023) 079

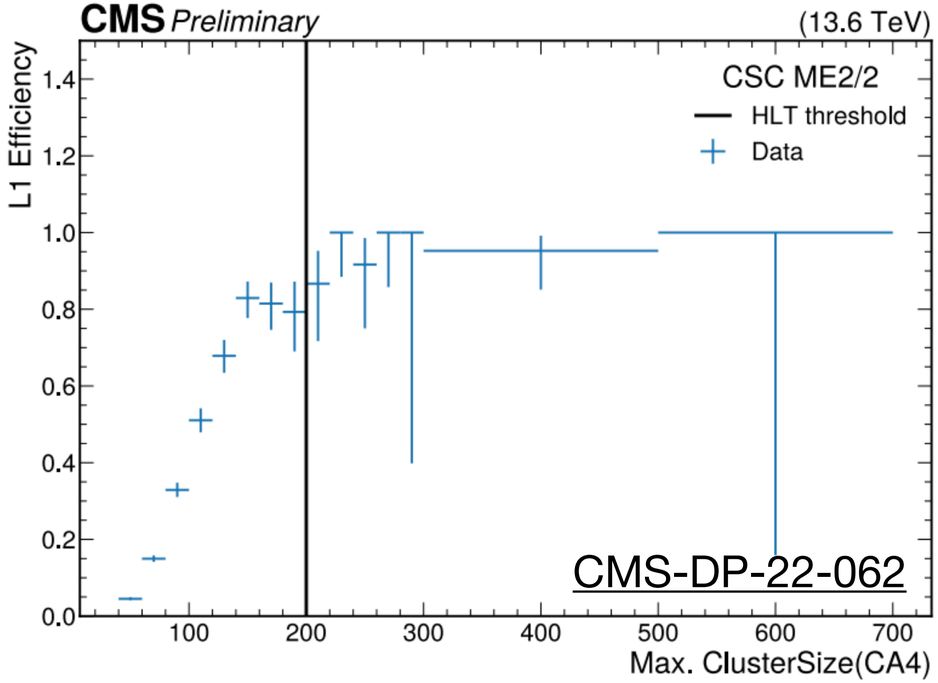
- MDS detector response only depends on generator-level LLP hadronic energy, EM energy, and decay positions → release parameterized functions as supplementary materials on HEPData
- Integrated the CSC cluster detector response functions to Delphes: https://github.com/delphes/delphes/pull/103
- Recasted the analysis and projected sensitivity in a number of models: dark scalar, dark photon, ALPs, inelastic DM, hidden valley models, HNL, and VLL
  - These recasting efforts inspired the ongoing CMS analyses mentioned earlier





New Trigger for MDS in CSC for Run 3

- For Run 2, triggering on MET (only 1% efficiency for higgs portal)
- New L1 CSC shower seed commissioned in 2022
  - Select for a large number of cathode and anode-wire hits in CSC chambers
- New HLT paths targeting **single + pair-produced LLPs** since 2022
- New cross-trigger HLT paths targeting **MDS +** $e/\mu/\tau/\gamma$ commissioned for 2024
- New triggers give us ~10x more signal compared to Run 2



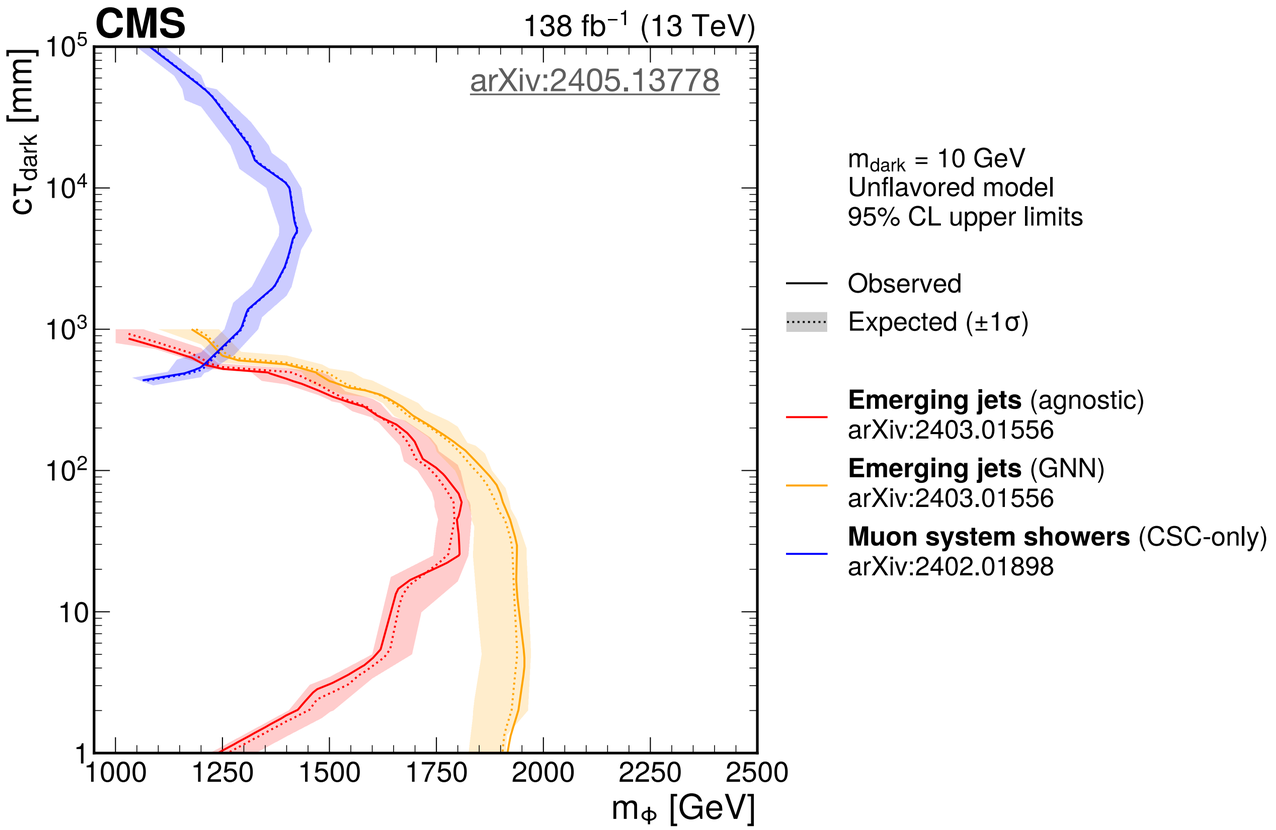
High L1 efficiency measured w.r.t. offline object

Summary

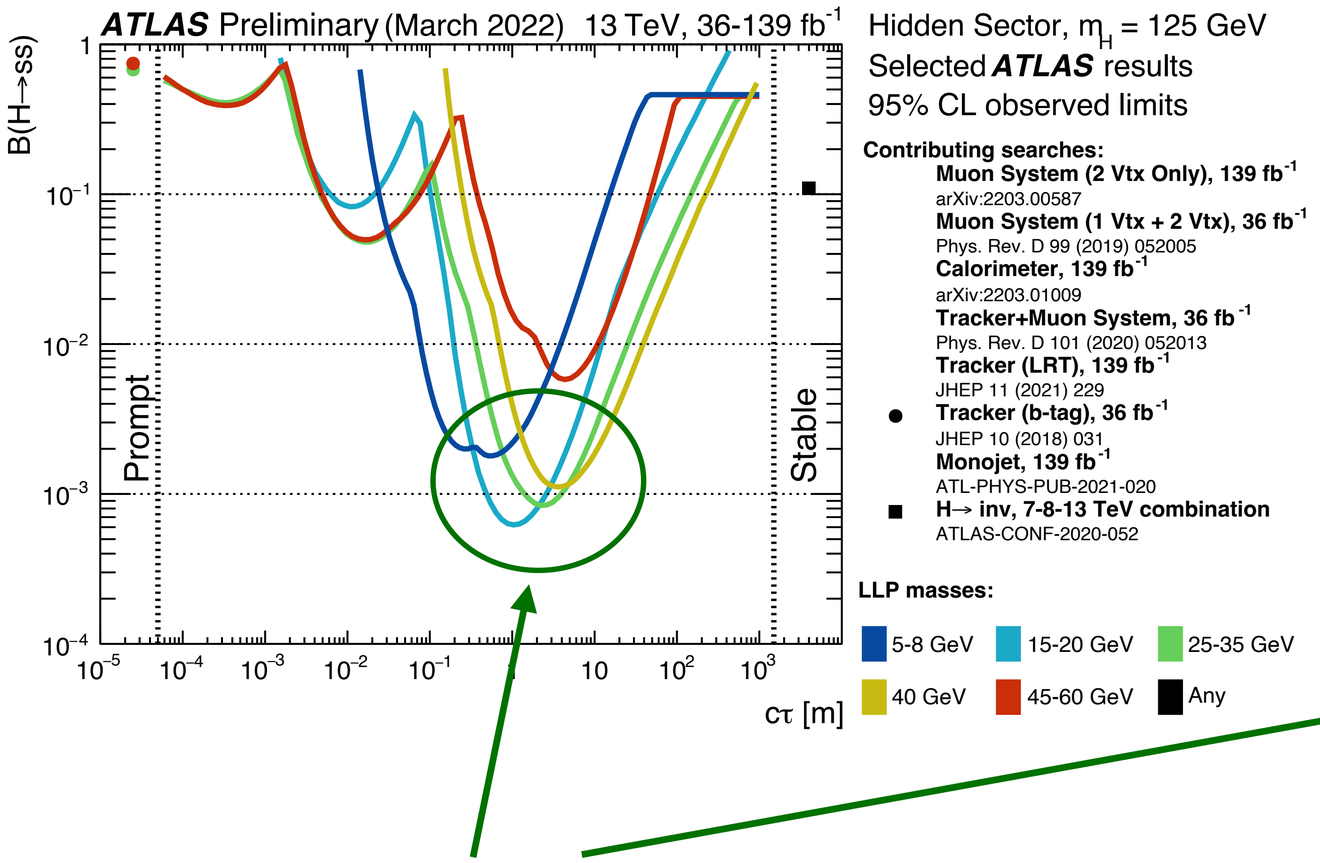
- Presented the first mass-independent search for LLPs using muon detector shower signature
- First LHC sensitivity to low mass Higgs portal model at BR(H →ss) = 10^{-3} level
- The mass-independence and calorimetric nature of the signature allows for parameterization and reinterpretation with Delphes
- **New Run 3 triggers will significantly improve the discovery reach to new models/phase space!**

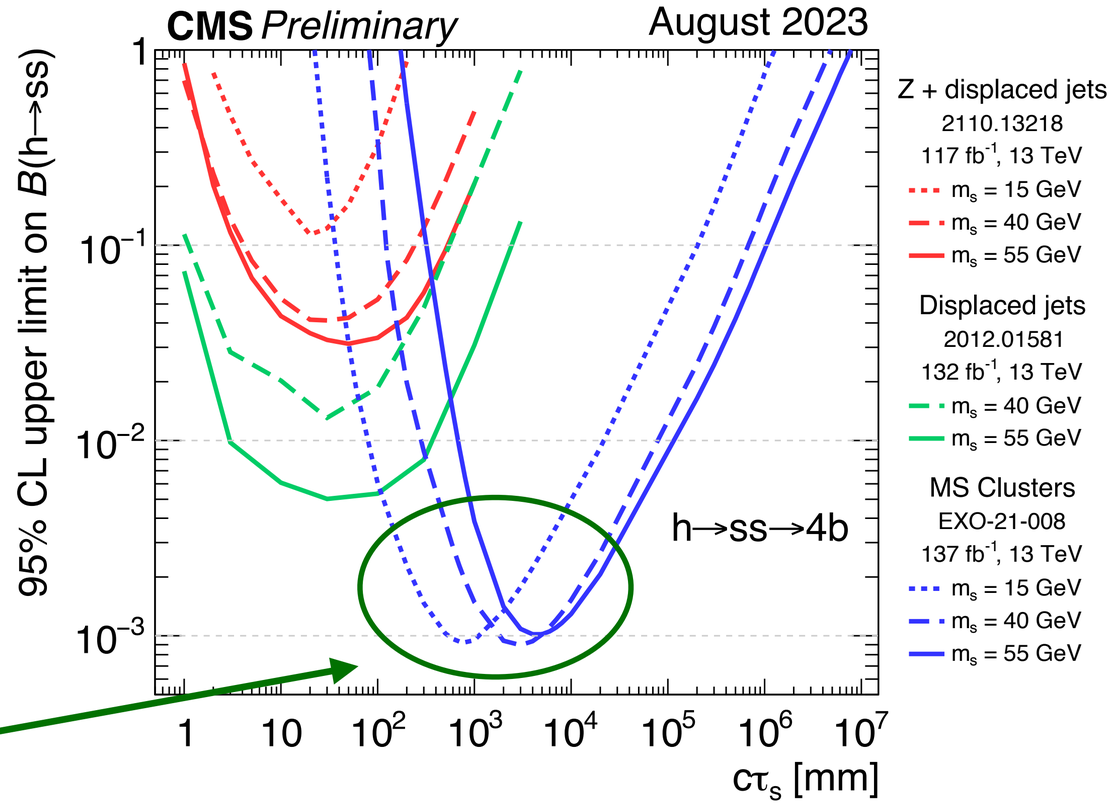
Backup Slides

Complementary to emerging jet analysis



ATLAS & CMS Summary plot





- Muon system analyses are among the most sensitive searches for both ATLAS and CMS

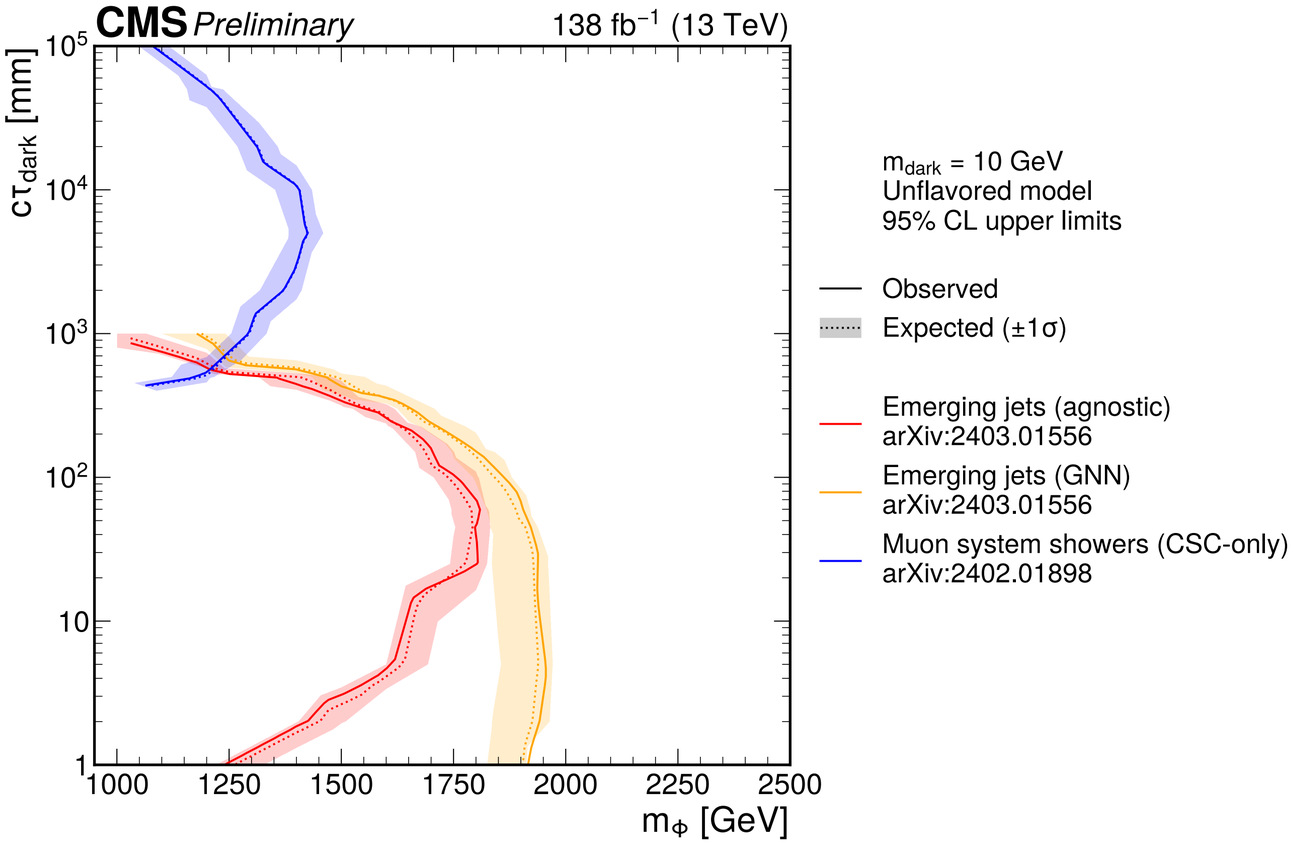
Signal MC Samples (Dark Shower)

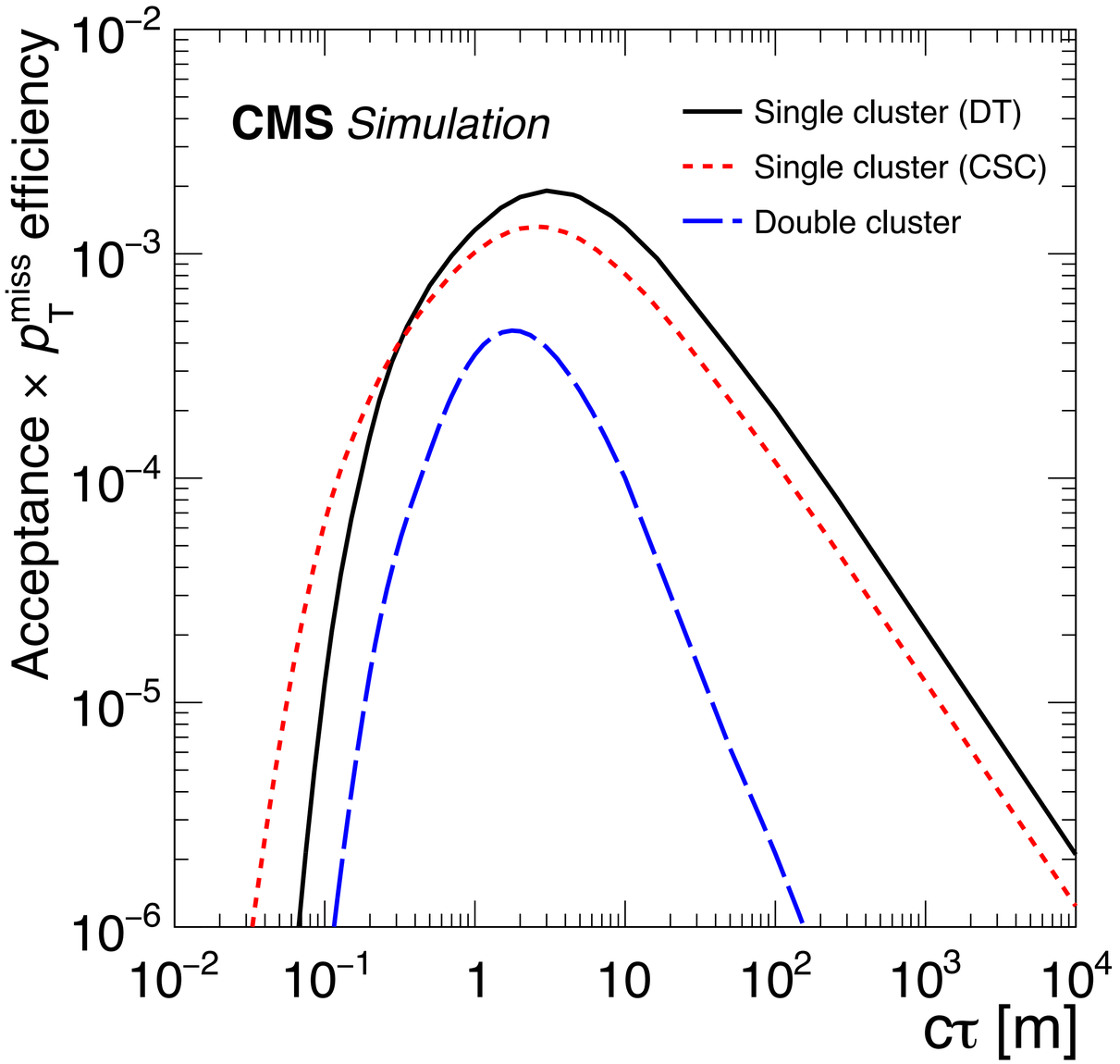
- Dark sector is reduced to a single **dark quark, vector meson, and scalar meson**
- 5 different **decay portals** are generated: gluon, photon, vector, Higgs, dark photon
- 3 pairs of $x_{i\omega}$and $x_{i\Lambda}$ are generated:
  - $(x_{i\omega}, x_{i\Lambda}) = (2.5,2.5)$: both vector and scalar mesons are produced, all vector meson decays to scalar mesons, **shower is fully visible and high multiplicity of visible decay**
  - $(x_{i\omega}, x_{i\Lambda}) = (2.5,1)$: Only scalar mesons are produced, **shower is fully visible**
  - $(x_{i\omega}, x_{i\Lambda}) = (1,1)$: both vector and scalar mesons are produced, but **shower is semi-visible**, scalars couple to SM, while vectors create MET

Decay portal	LLP masses [GeV]	LLP lifetimes [m]	$(x_{i\omega}, x_{i\Lambda})$	Features
Gluon	3, 5, 10, 15, 20	0.5, 1, 5, 10	(1.0,1.0), (2.5,1.0), (2.5,2.5)	hadron-rich shower
Photon	2, 5, 10, 15, 20	0.5, 1, 5, 10	(1.0,1.0), (2.5,1.0), (2.5,2.5)	photon shower
Vector	2, 5, 10, 15, 20	0.5, 1, 5, 10	(1.0,1.0)	semi-visible jet
Higgs	4, 5, 10, 15, 20	0.5, 1, 5, 10	(1.0,1.0), (2.5,1.0), (2.5,2.5)	heavy flavor-rich shower
Dark photon	2, 5, 10, 15, 20	0.5, 1, 5, 10	(1.0,1.0), (2.5,1.0), (2.5,2.5)	lepton-rich shower

$x_{i\omega}$: mass ratio between dark vector and scalar meson

$x_{i\Lambda}$: ratio of dark sector QCD scale to dark scalar meson mass


CMS Preliminary
138 fb^{-1} (13 TeV)
$c\tau_{dark}$ [mm]
10^5
10^4
10^3
10^2
10
1
1000
1250
1500
1750
2000
2250
2500
m_Φ [GeV]
m_{dark} = 10 GeV
Unflavored model
95% CL upper limits
Observed
Expected (±1σ)
Emerging jets (agnostic)
arXiv:2403.01556
Emerging jets (GNN)
arXiv:2403.01556
Muon system showers (CSC-only)
arXiv:2402.01898


CMS Simulation
Single cluster (DT)
Single cluster (CSC)
Double cluster
Acceptance × p_T^{miss} efficiency
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
cτ [m]