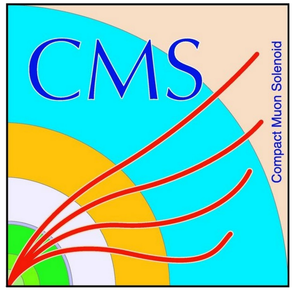


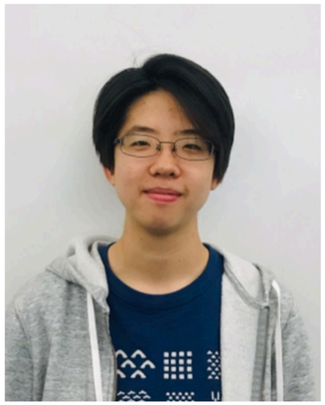
Search for Long-lived Particles with Muon Detector Showers

Michael Carrigan, Pallabi Das, Daniel Diaz, Daniel Guerrero,
Martin Kwok, Christina Wang

2024 CMS Data Analysis School

Introduction

- Join our mattermost channel: https://mattermost.web.cern.ch/cmsdaslpc2024/channels/longexllp
- Website: https://christinaw97.github.io/MDS_CMSDAS
- Facilitators:



Christina Wang

Michael Carrigan

Daniel Diaz

Pallabi Das

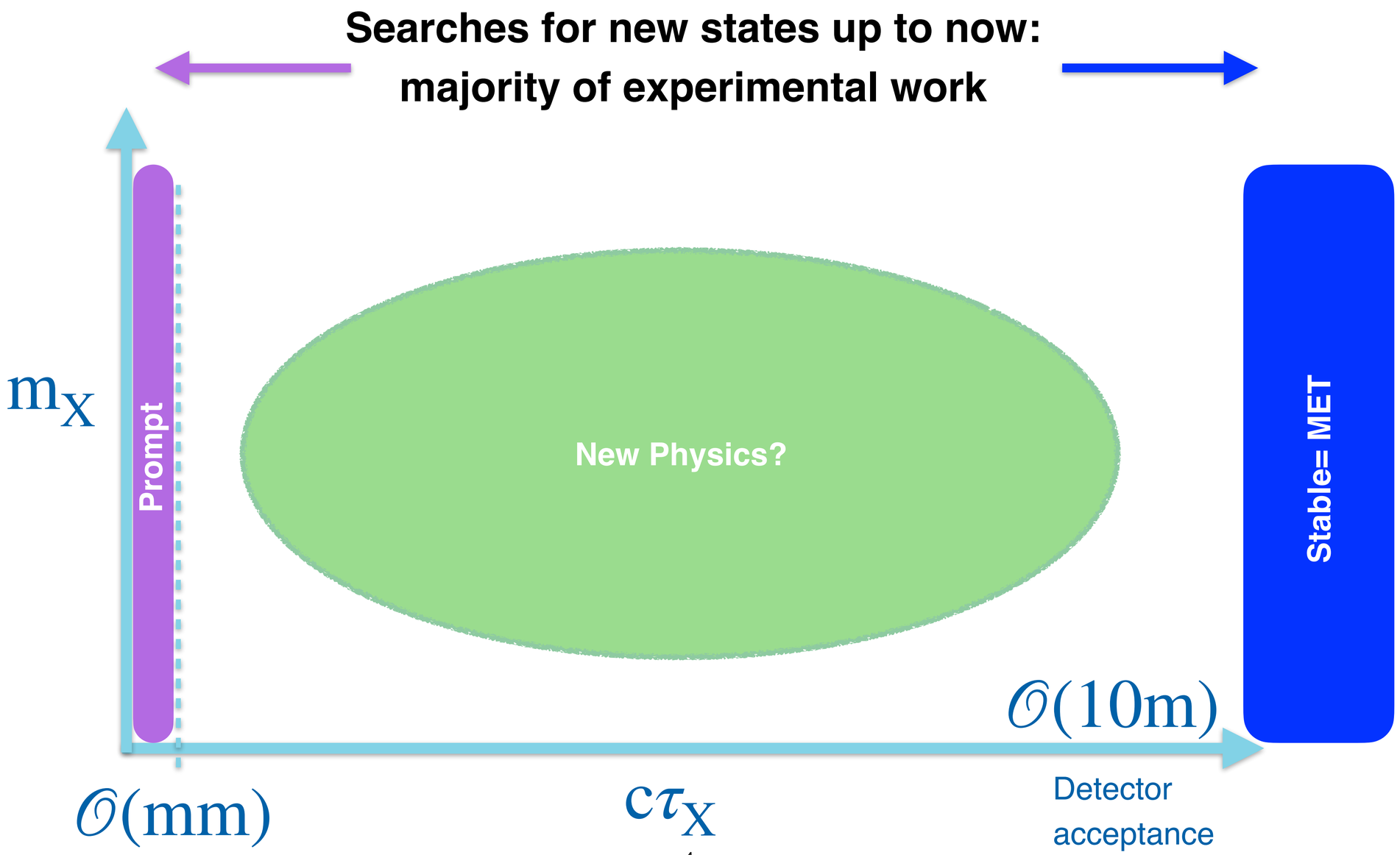
Daniel Guerrero

Martin Kwok

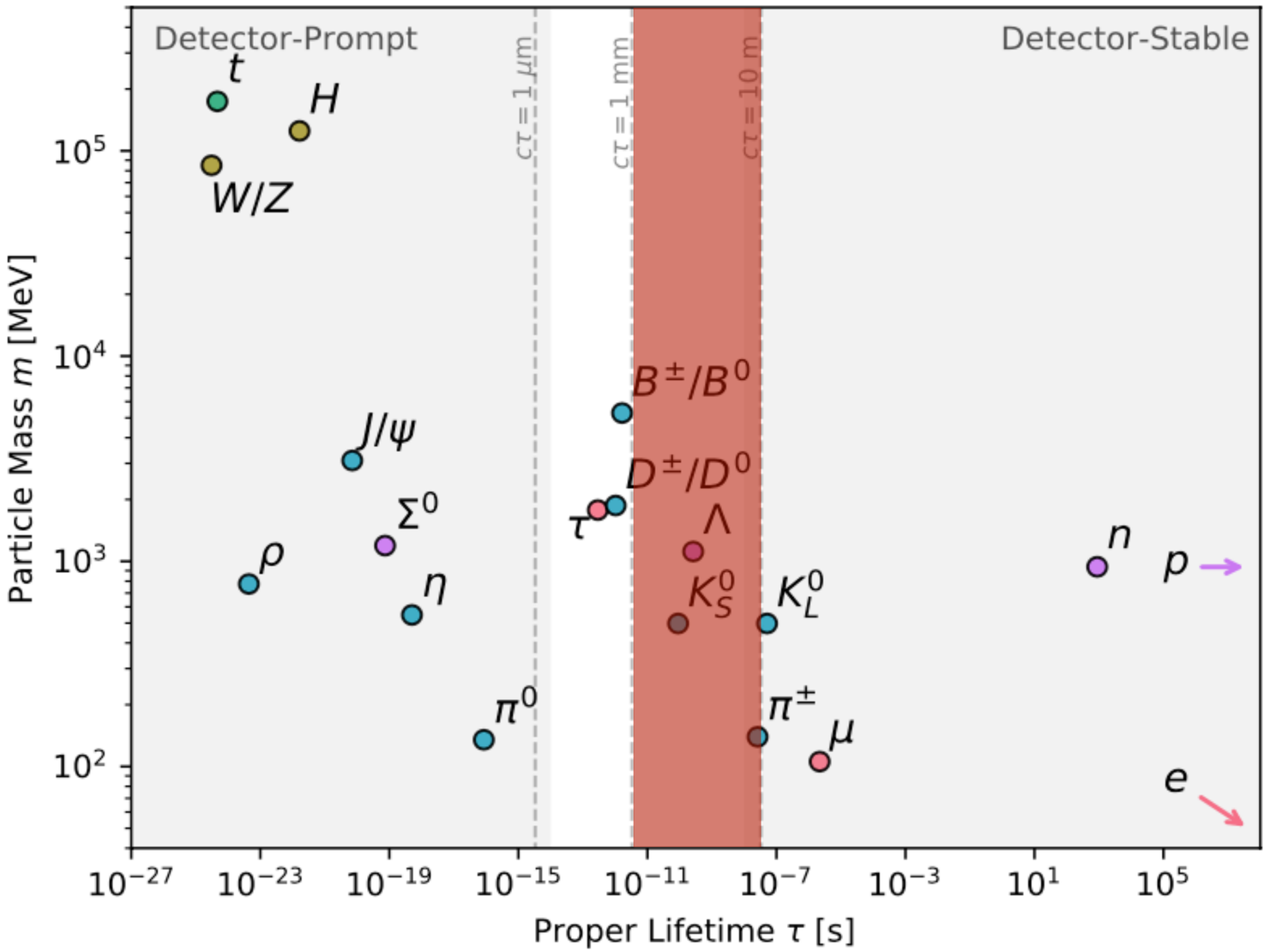
Tell us about yourself

- What year are you in?
- Any experience with data analysis? What will you/are you working on?
- What do you hope to get out of CMSDAS?
- Comments/questions?

New Physics at LHC: Long-lived particles

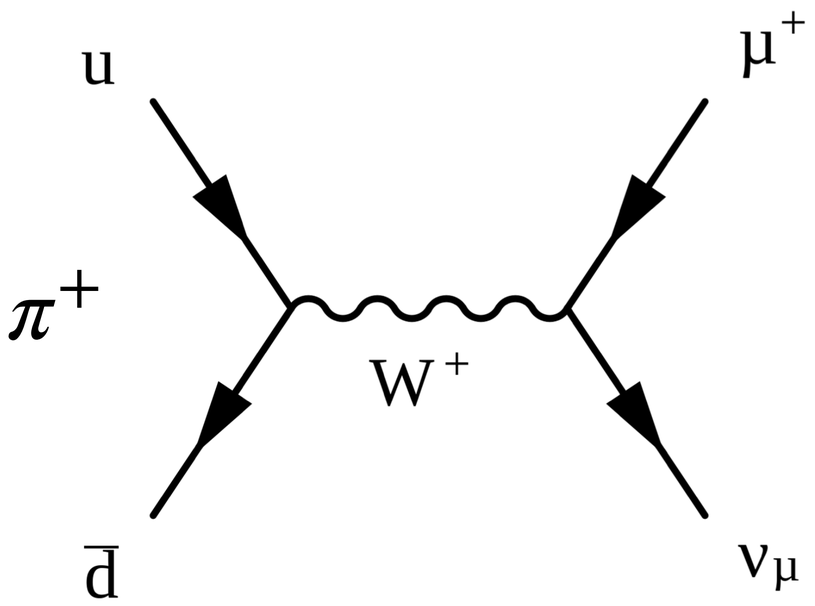


Long-Lived Particles in the SM



- Small coupling
- Massive mediator
- Small phase space

Long-Lived Particles in the SM: π^+



Small coupling

$$\tau^{-1} = \Gamma \sim \left[\frac{g^2}{M_W^2} \frac{m_\mu}{m_\pi} (m_\pi^2 - m_\mu^2) \right]^2$$

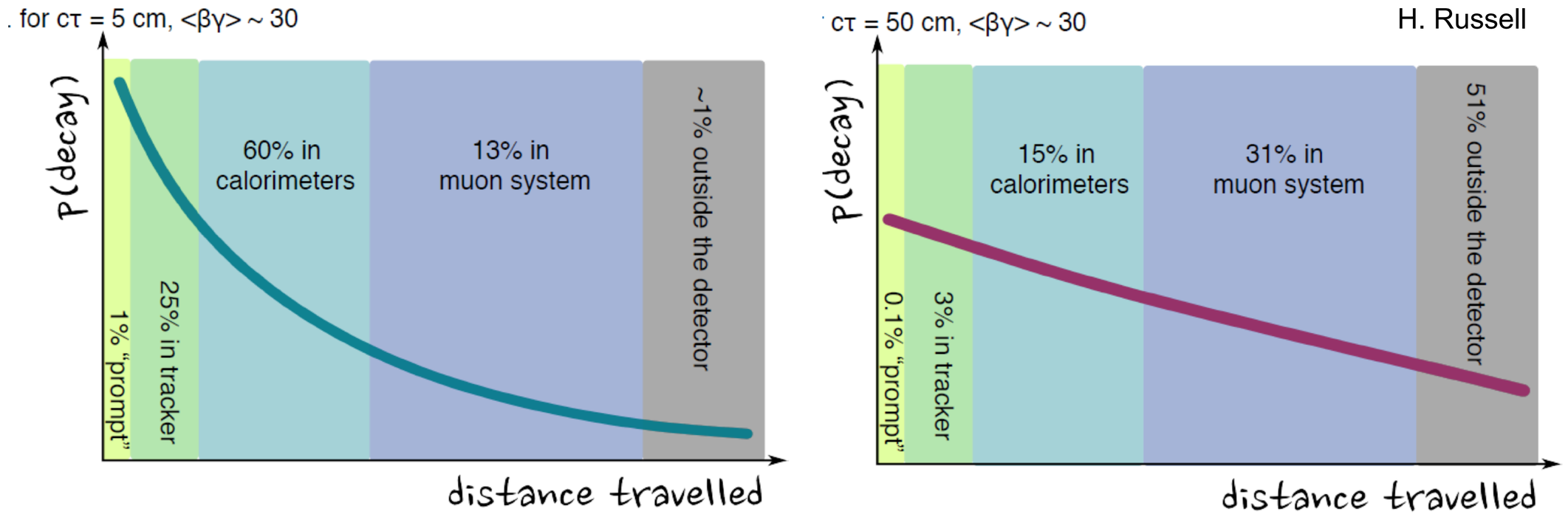
Heavy mediator

Small phase space

Same mechanisms apply to LLPs in BSM theories

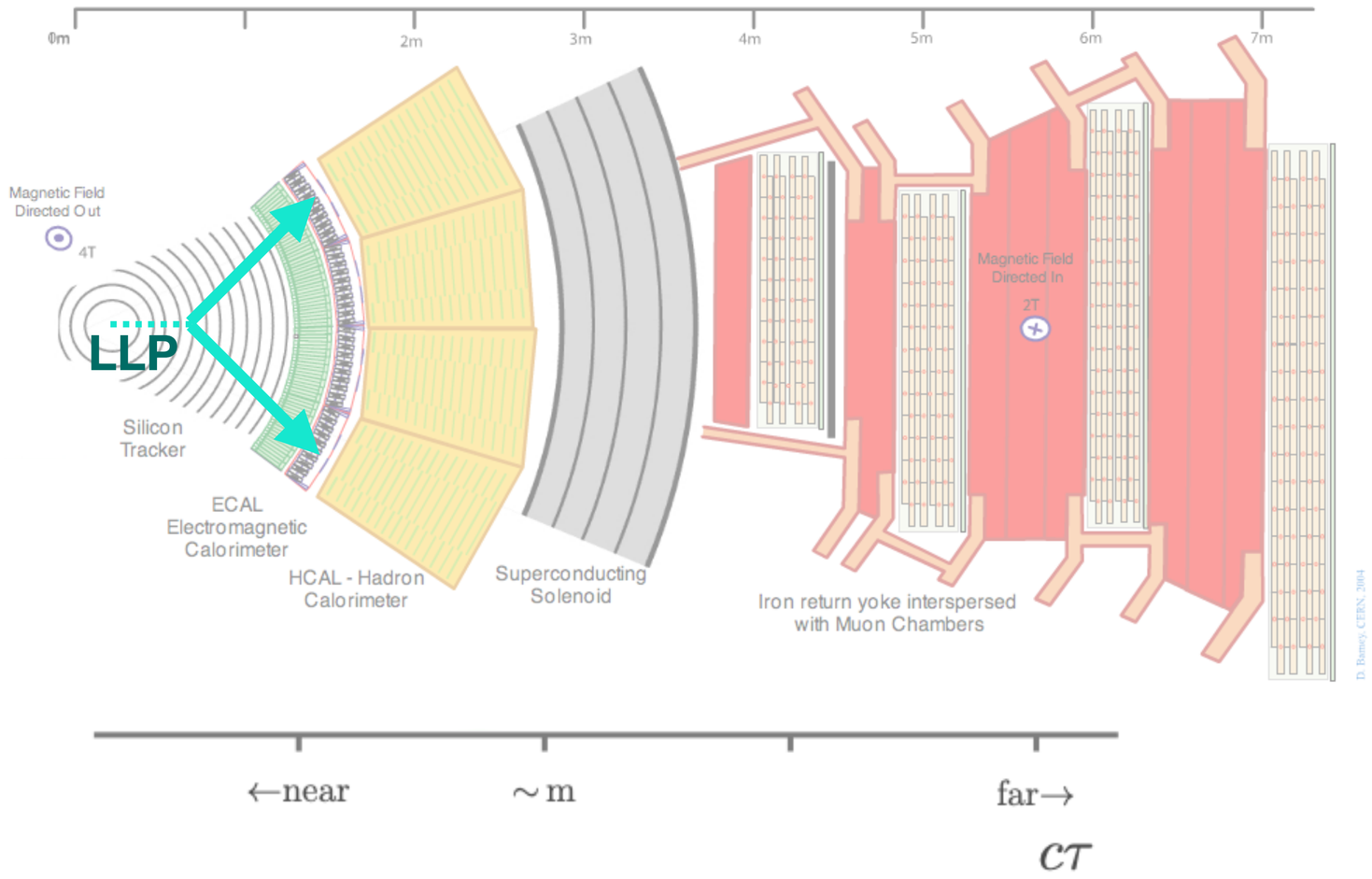
LLP Decay Region

distance travelled $= \beta\gamma \times c\tau$



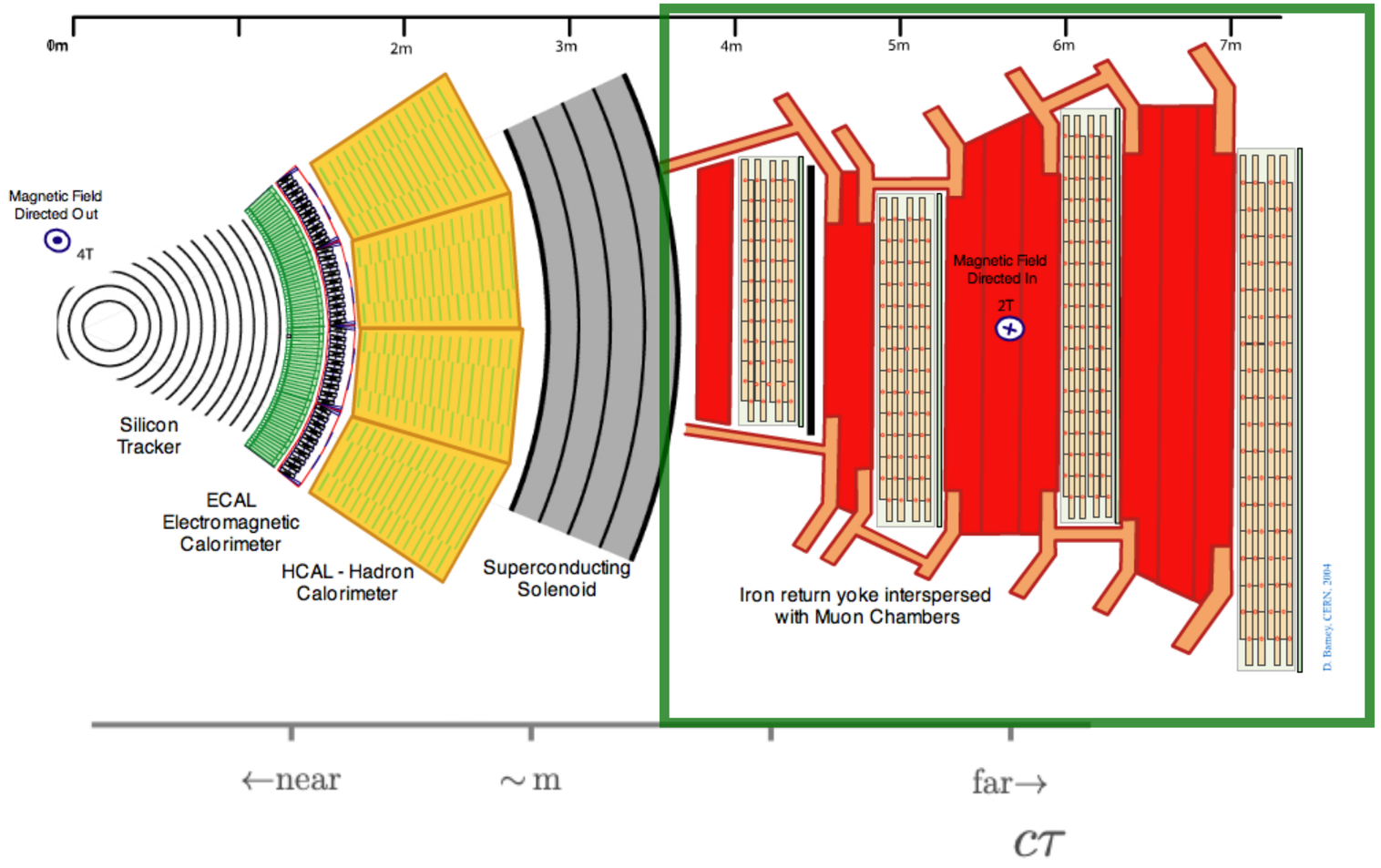
- Search strategy strongly depends on proper lifetime and boost of LLP
- Every sub-detector is important

LLP Landscape in CMS



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

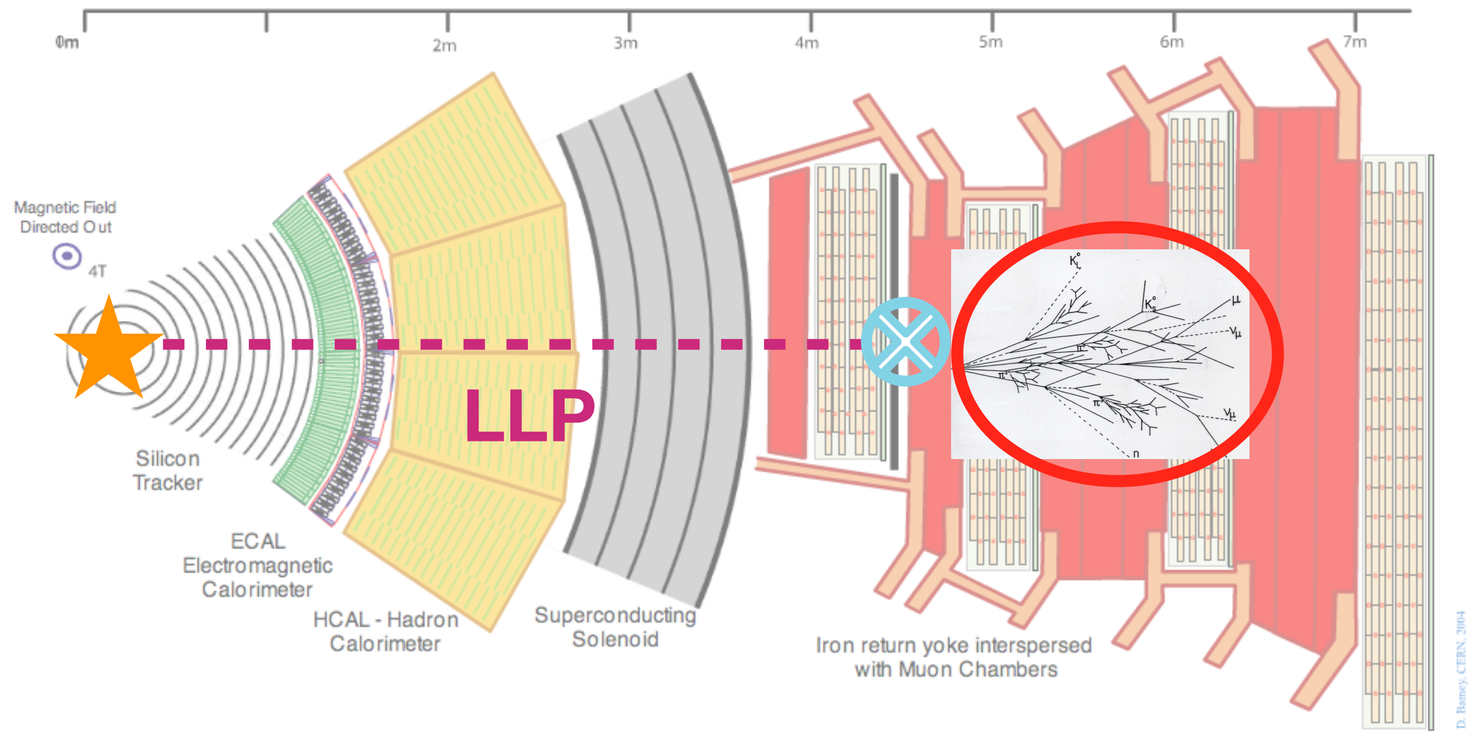
Close gaps in search coverage



Muon detector

Searches for light LLP with large cτ using LLP decays in the muon detector

Search for LLPs in Decaying in CMS Muon System

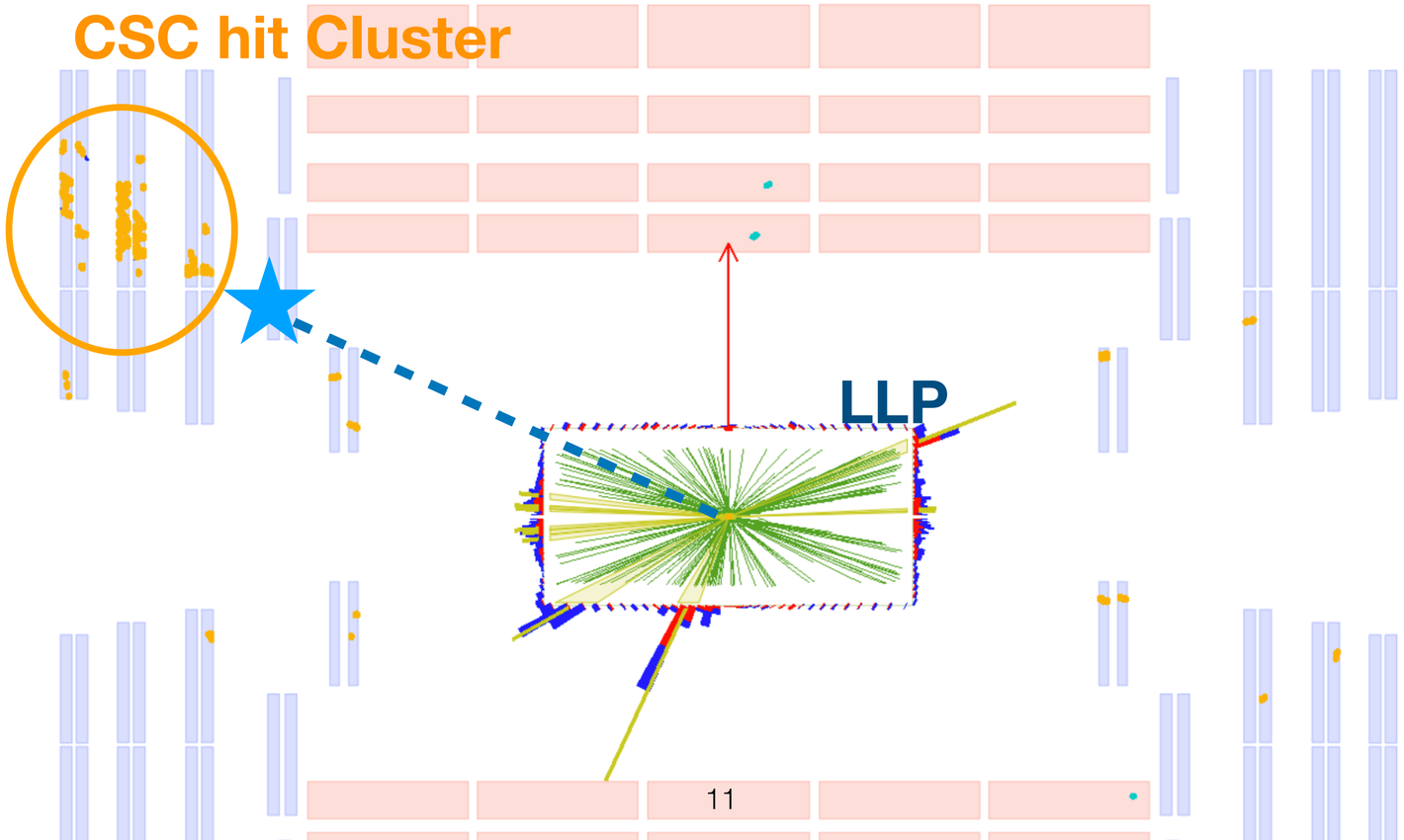


LLP decay results in particle shower with **large hit multiplicity**

- Covers decays far away from IP (sensitive to large cτ)
- Excellent **background suppression** from shielding material
- Steel interleaved with active chambers → **sampling calorimeter**

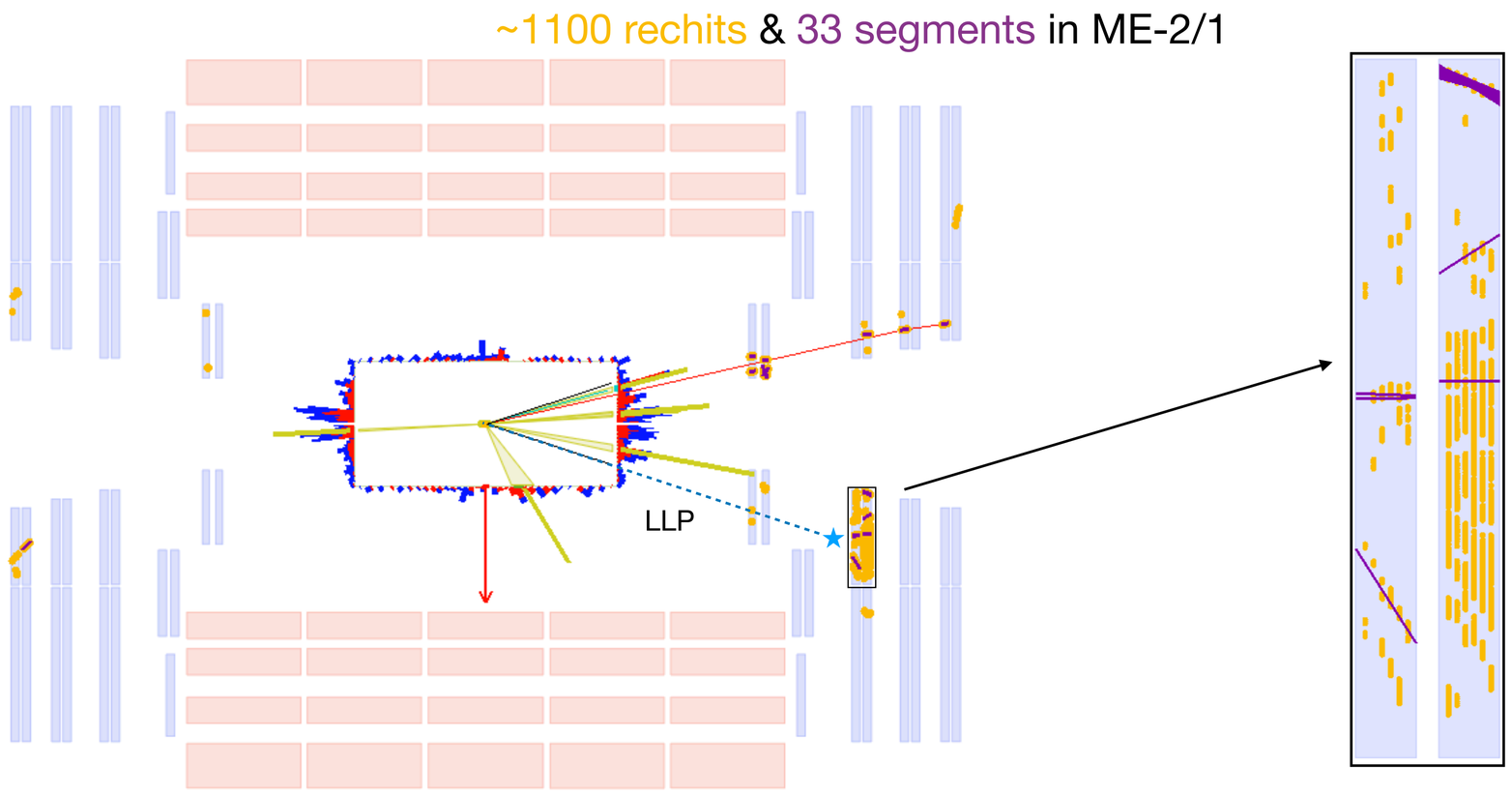
Search for LLPs with Muon Detector Showers

- Large **cluster of hits (>100 hits)** in the muon system with no jets or tracks
- Excellent **background suppression** from shielding material: background rejection of 1e6
- **Unique signature** due to the presence of steel in the CMS muon system
- First search in CMS that uses this novel signature: EXO-20-015



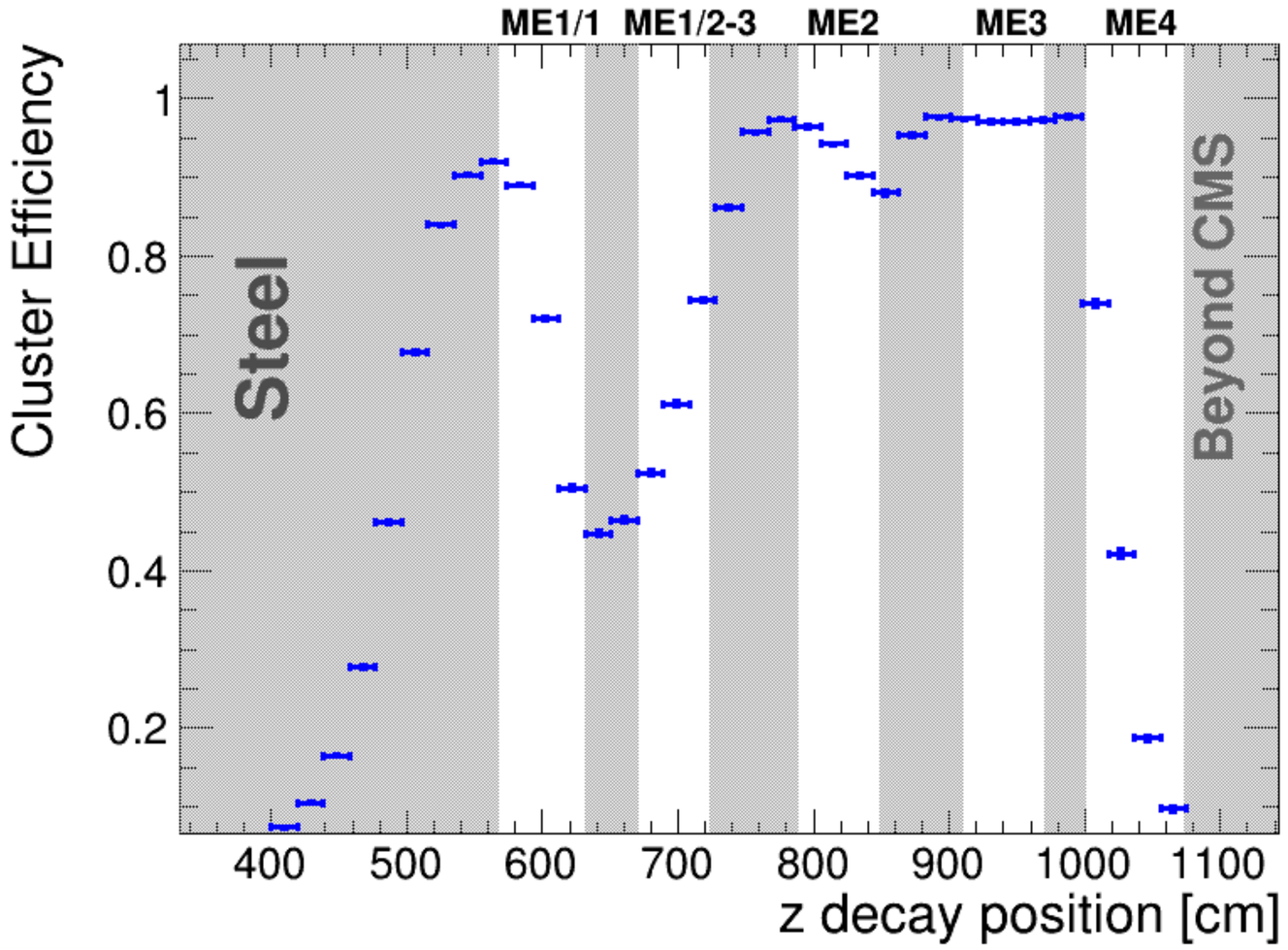
Reconstruction for MDS

- The standard reconstruction sequence in the muon system is optimized for muons rather than high-multiplicity showers
- More optimal to use **Rechits that only exist in RAW-RECO data format**
- **Cluster rechits to efficiently reconstruct muon detector shower (MDS)**



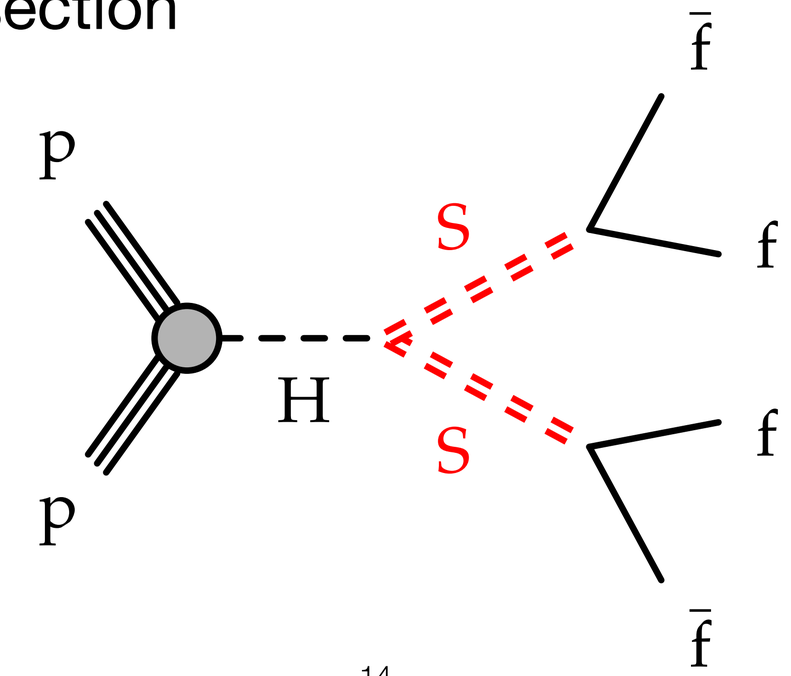
Reconstruction for MDS in Endcap

- **Reconstruction efficiency depends on the LLP decay position**



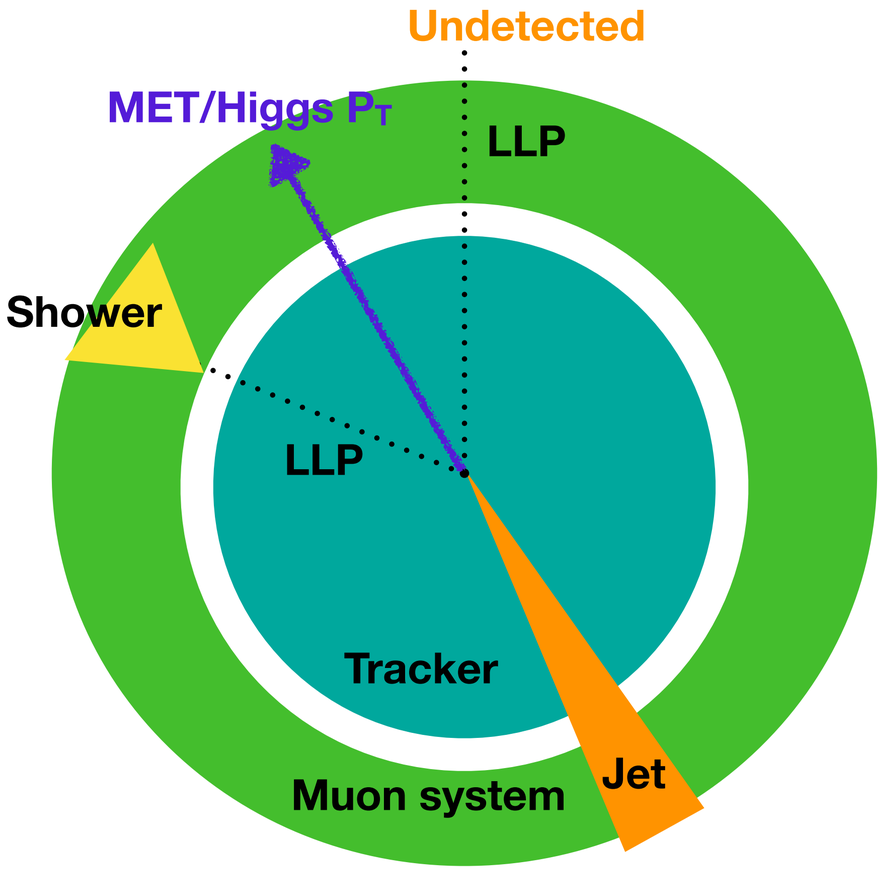
Benchmark Signal Model

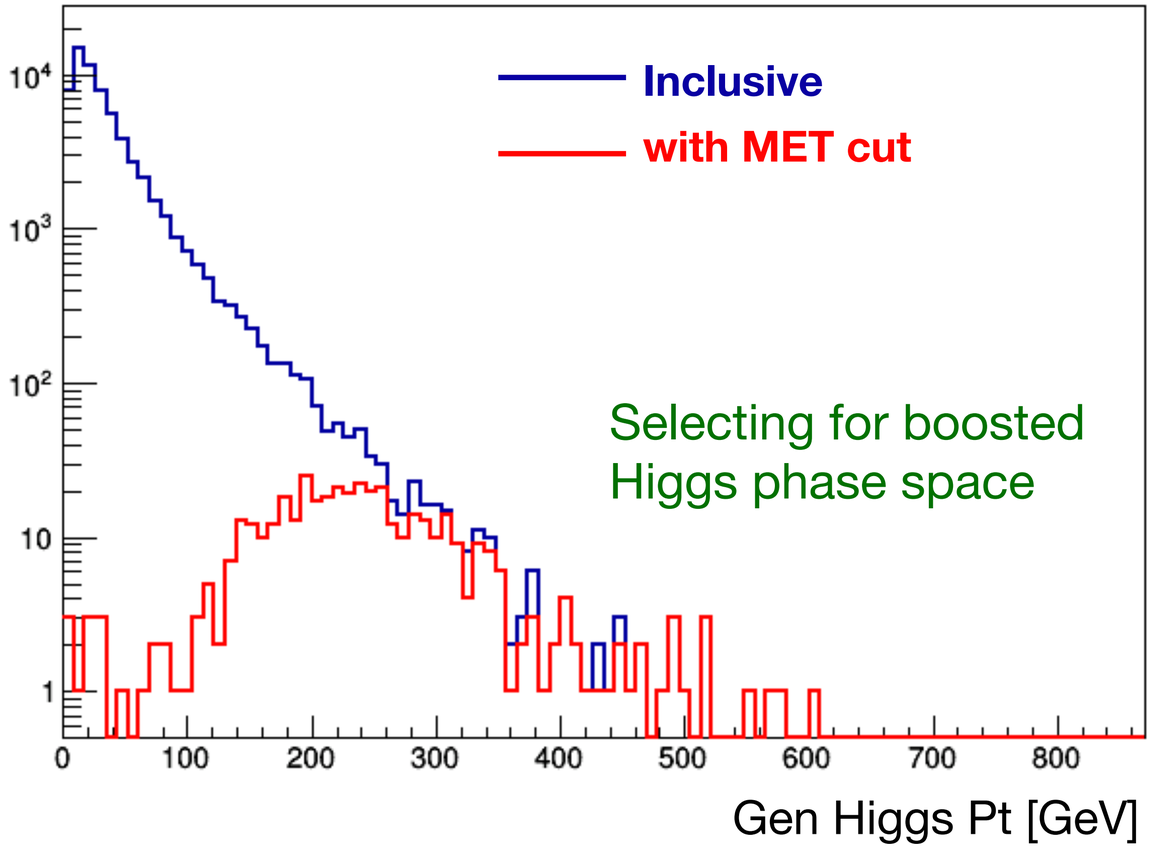
- While this signature is model-independent, to develop an analysis strategy we use Higgs-portal to scalar LLP production as the benchmark model
- This LLP benchmark is difficult to detect because:
  - No stable WIMPs to produce large MET
  - No high-mass resonances decaying to high p_T final state objects
  - Low production cross section



Trigger Strategy

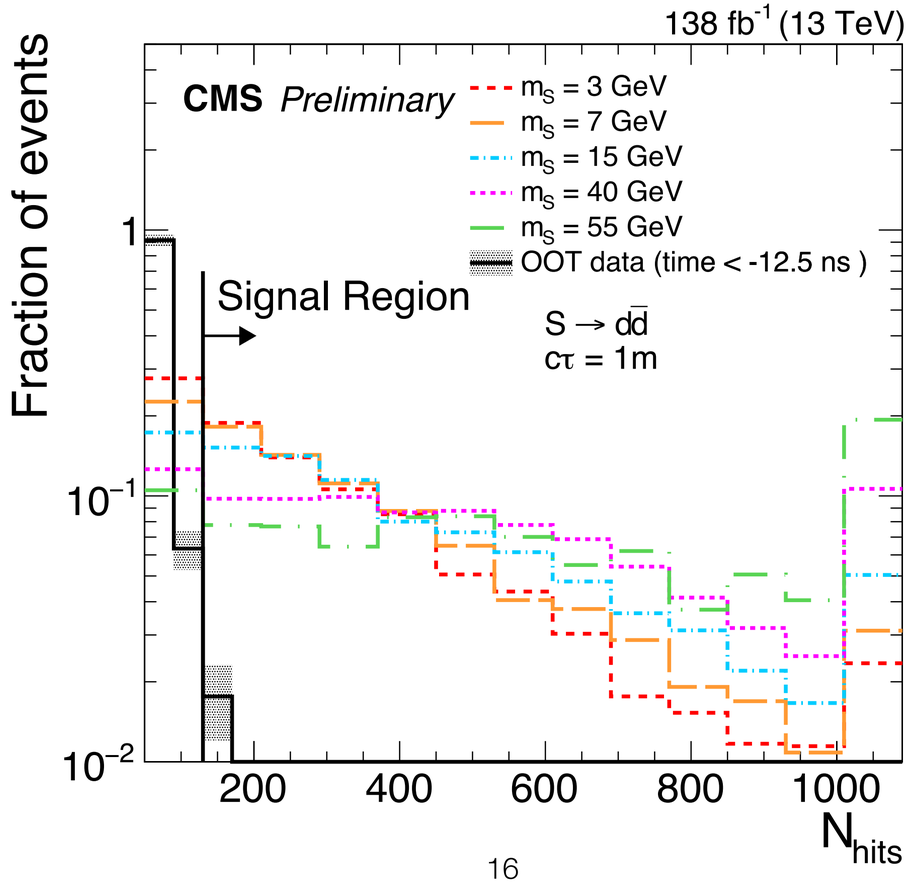
- Trigger on **MET due to lack of dedicated trigger in Run2 (signal efficiency is ~1%)**
- New dedicated trigger implemented for Run3





Analysis Strategy

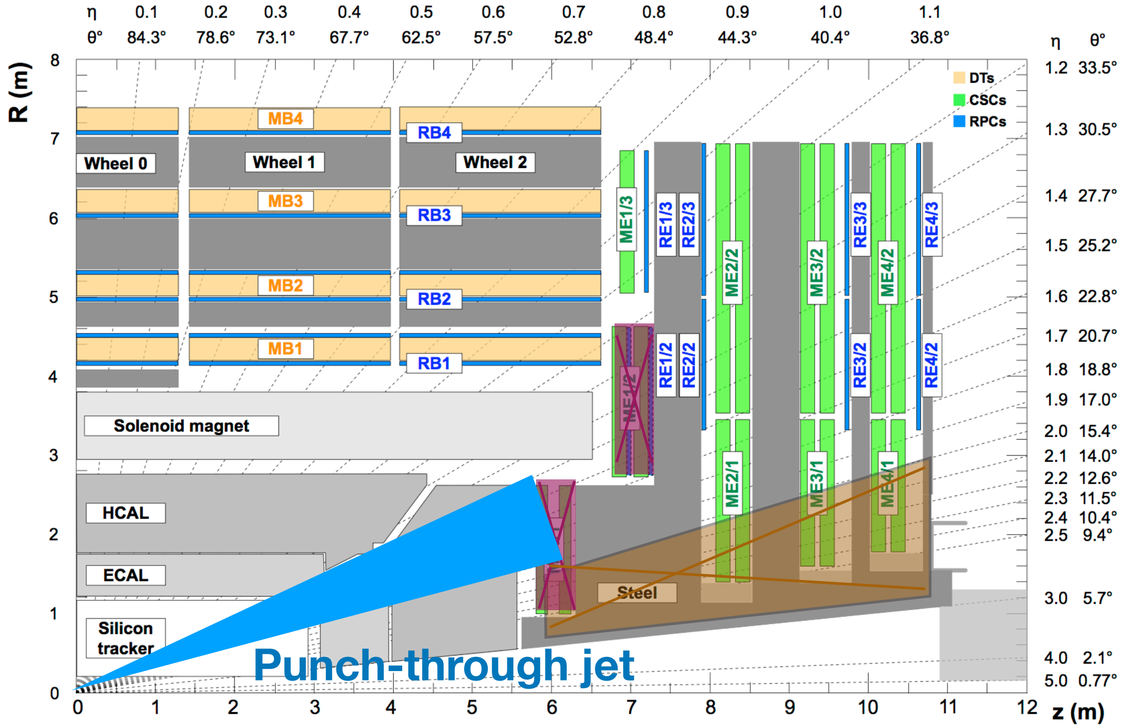
- **Event selection:** select high MET (MET > 200 GeV) and boosted Higgs phase space
- Focus on **endcap muon detector** in this exercise and apply cluster-level selections to achieve 10^6 background rejection
- N_{hits} serves as the main discriminator



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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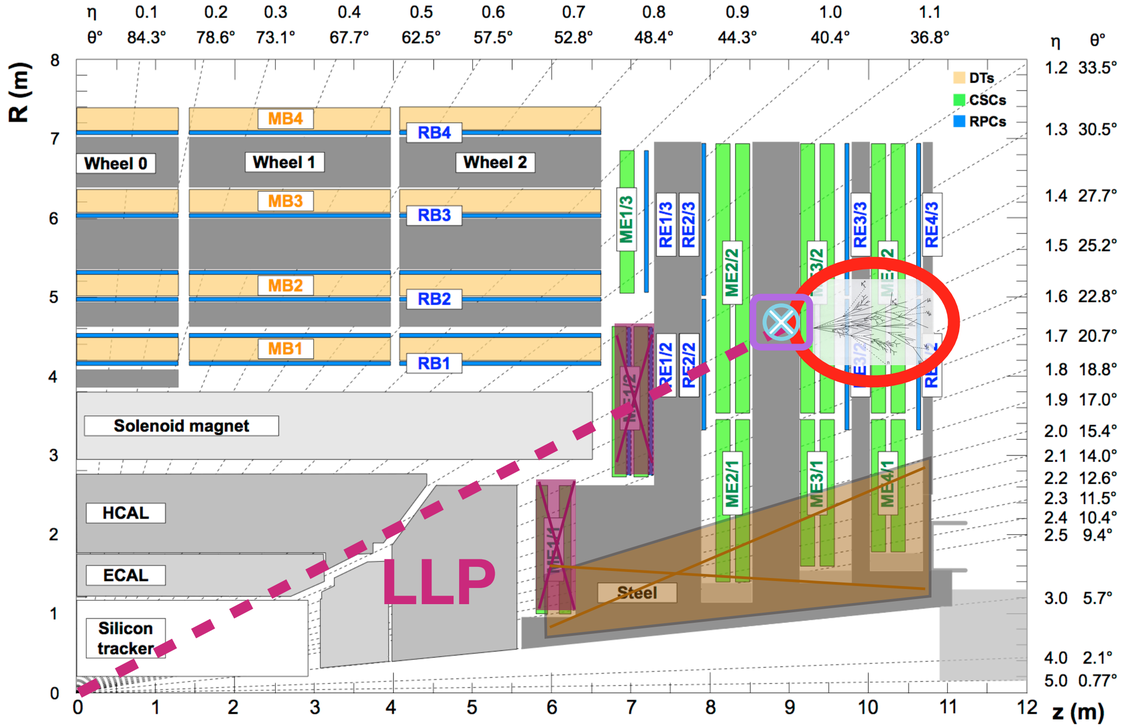
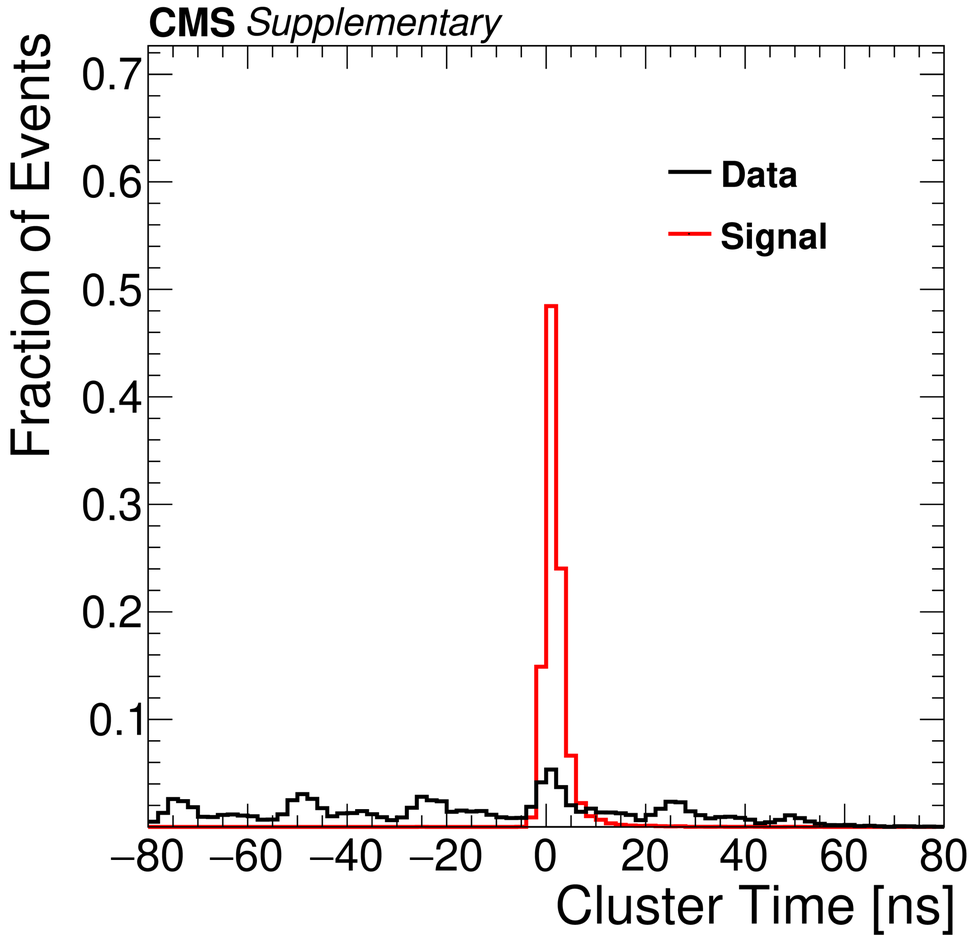


Cluster Time

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

- 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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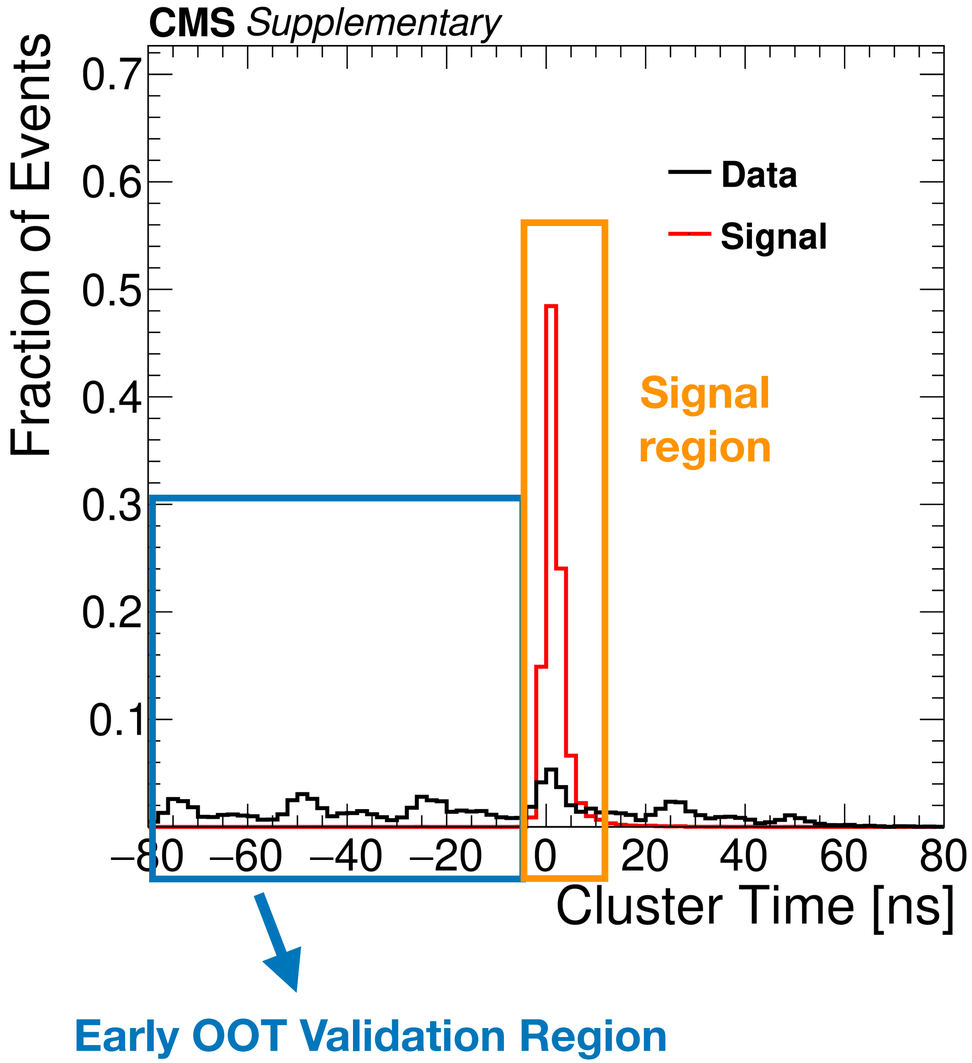
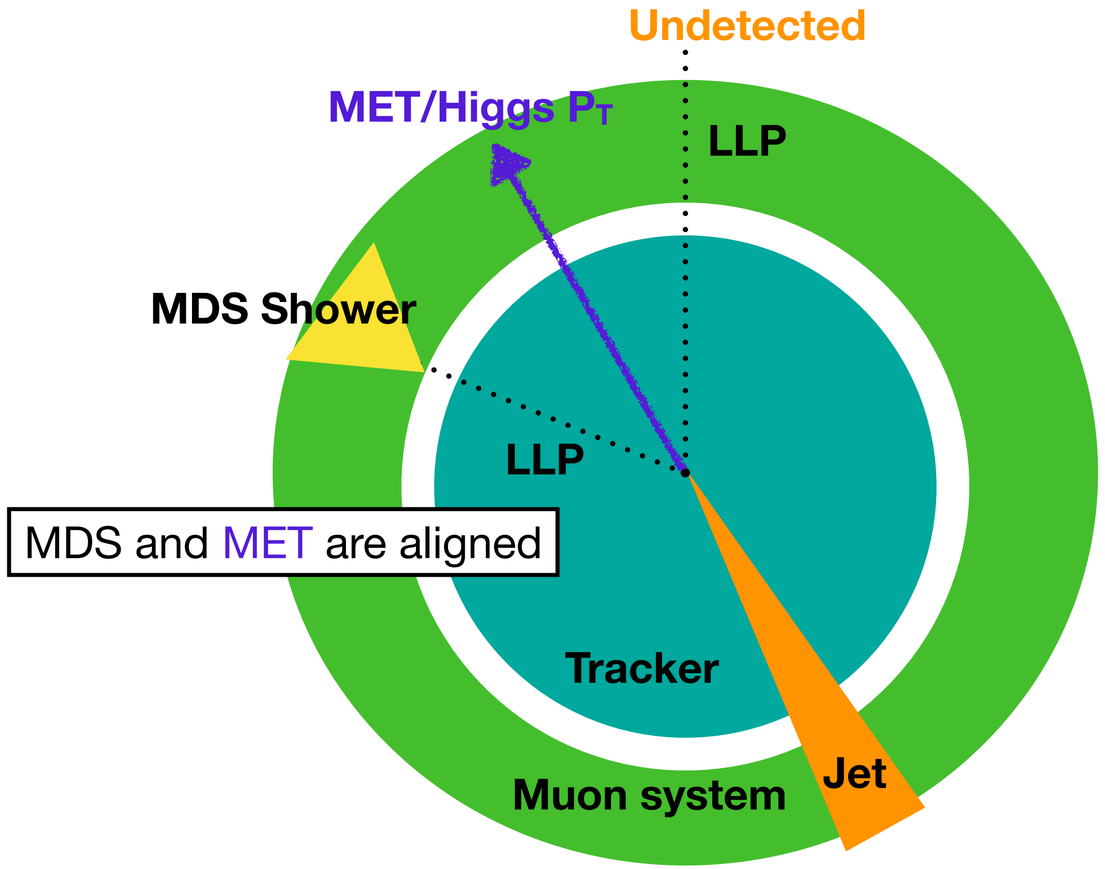
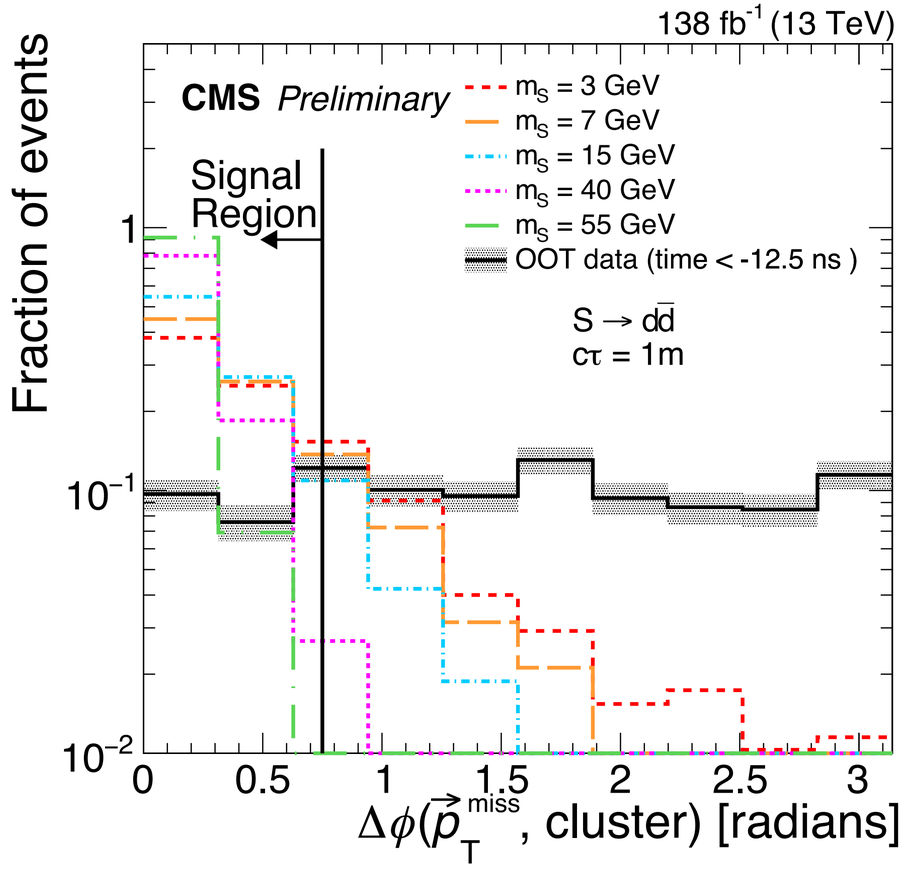


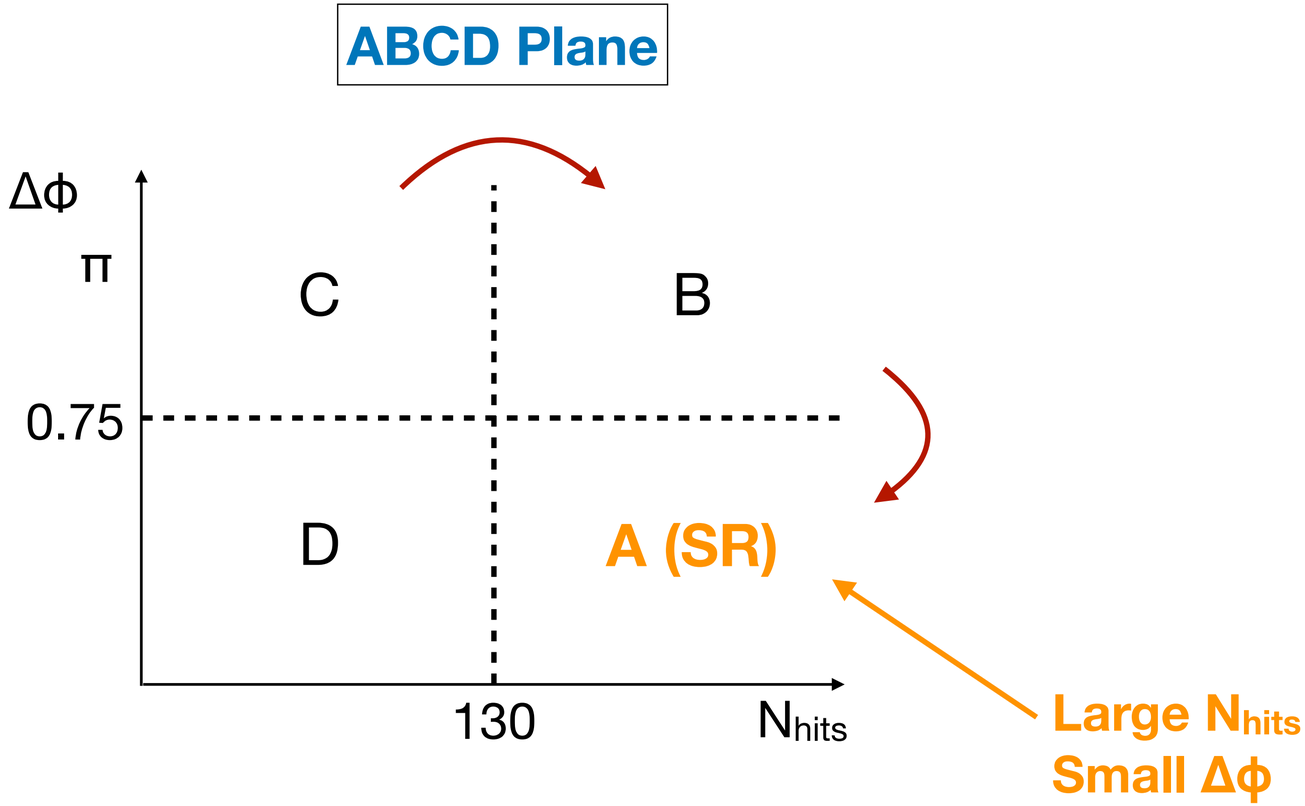
$\Delta\phi(\text{cluster}, \vec{p}_T^{miss})$





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

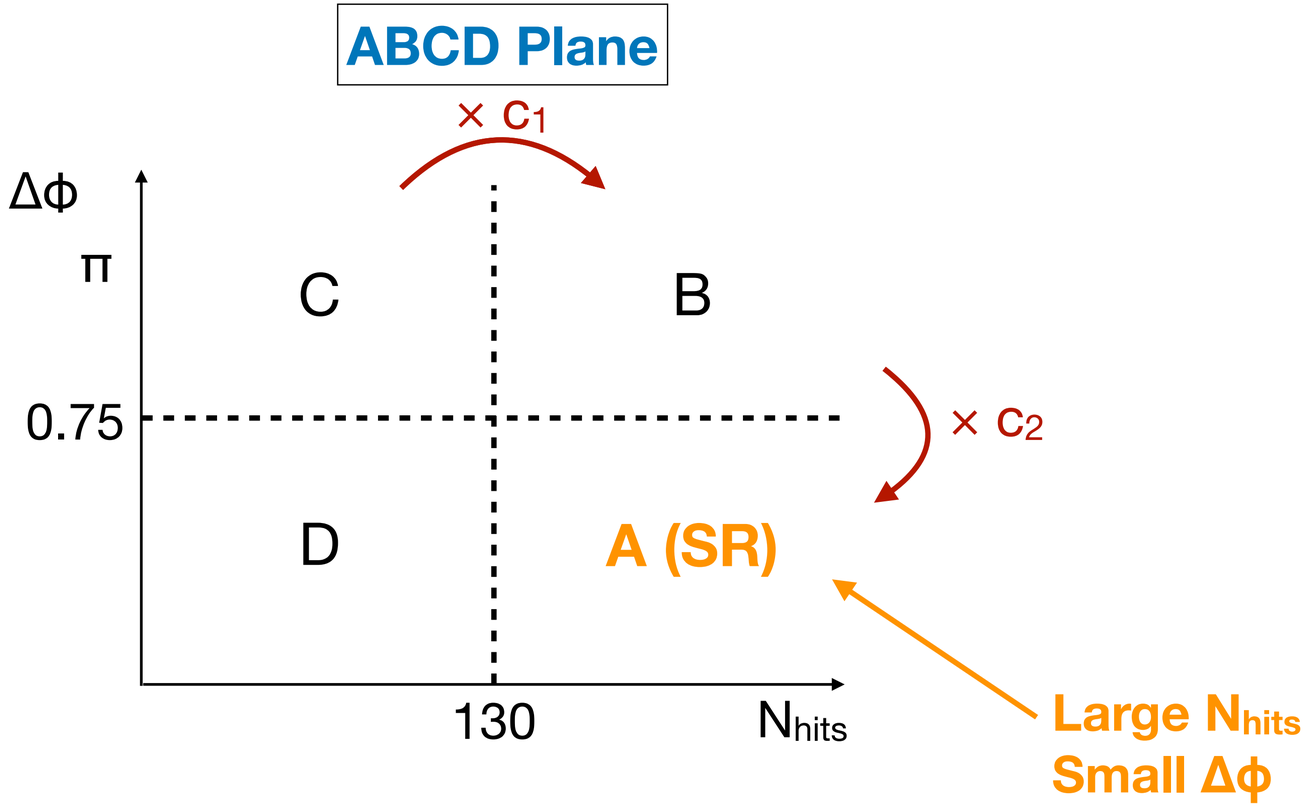
Fully Data-Driven Background Estimation using ABCD



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

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

Fully Data-Driven Background Estimation using ABCD



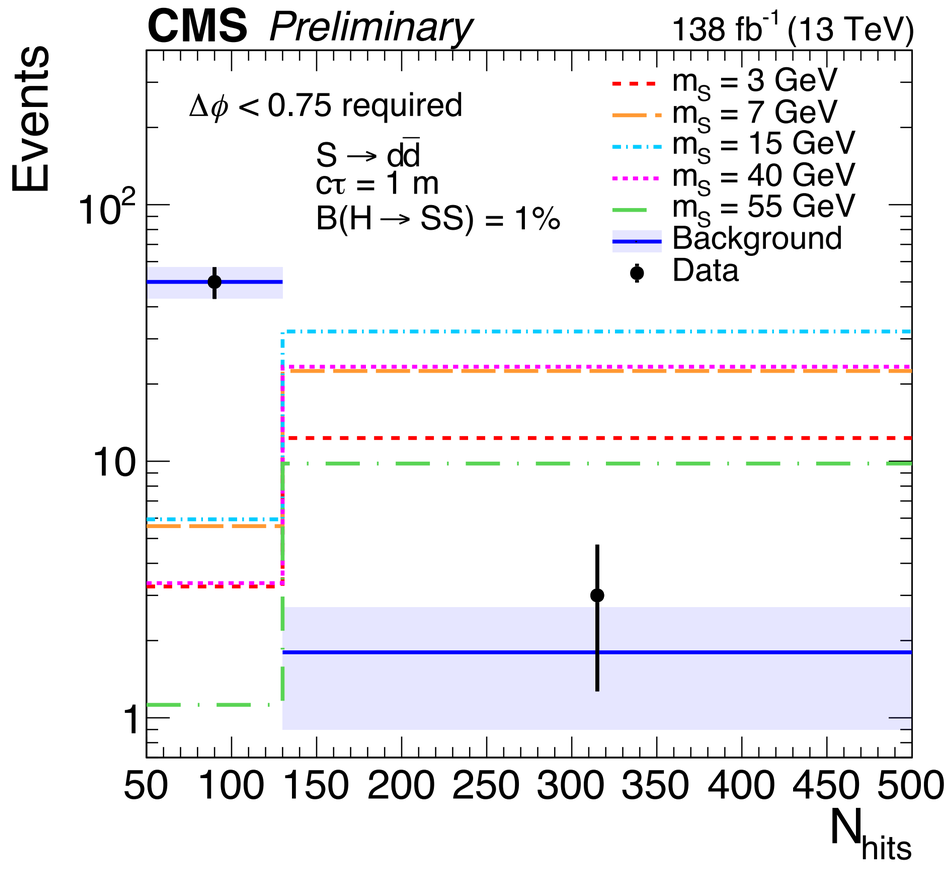
$$A = B \times \frac{D}{C}$$

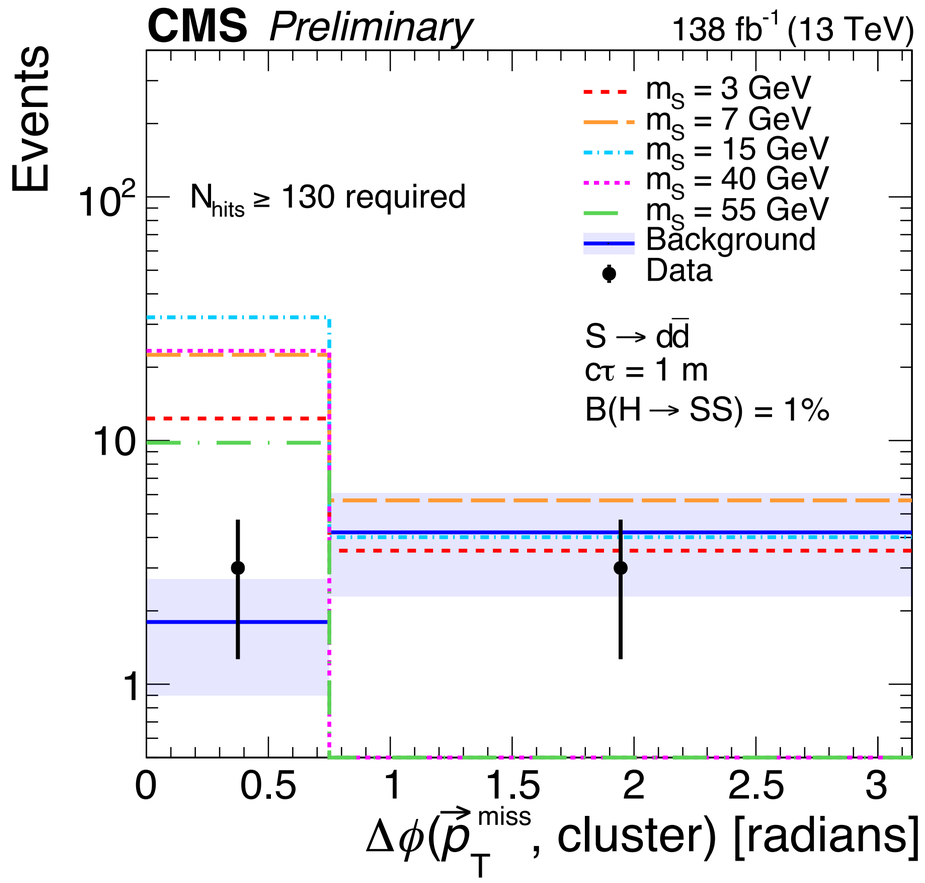
$$N_A = c_1 \times c_2 \times Bkg_C + \mu \times SigA$$
$$N_B = c_1 \times Bkg_C + \mu \times SigB$$
$$N_C = Bkg_C + \mu \times SigC$$
$$N_D = c_2 \times Bkg_C + \mu \times SigD$$

$c_1 = Bkg_B / Bkg_C$
$c_2 = Bkg_D / Bkg_C$
4 unknowns: c_1, c_2, μ, Bkg_C

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

Result

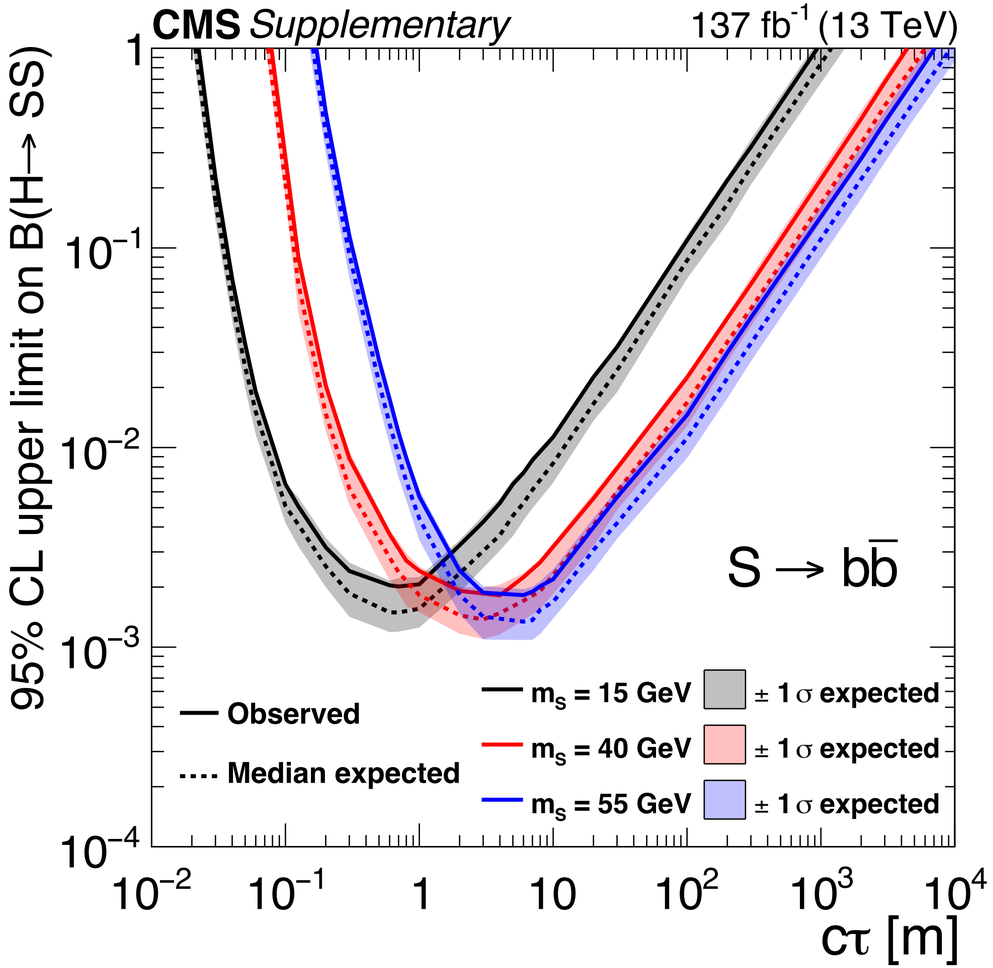




No excess above SM background observed

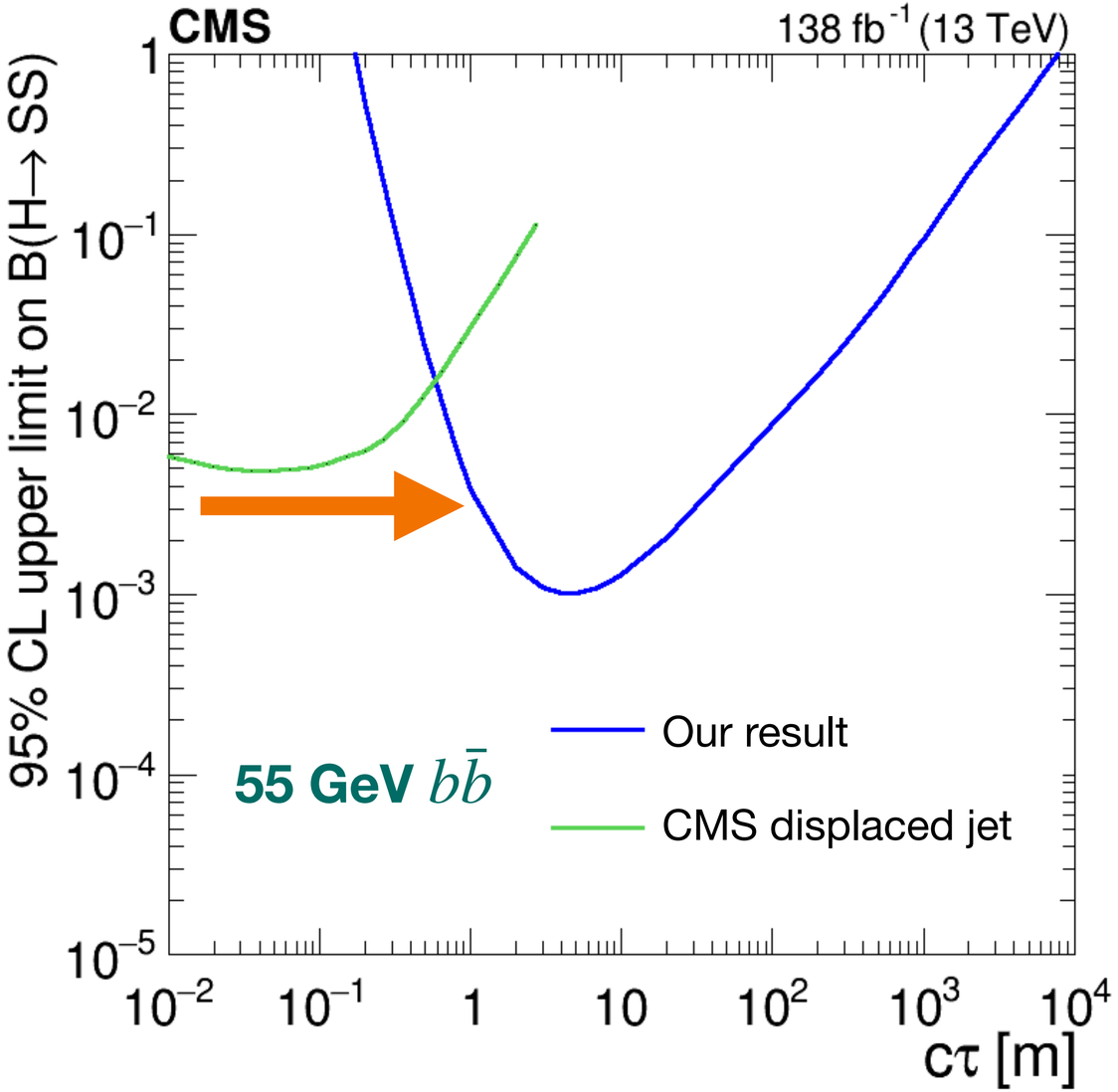
Observed and Expected Limits

Phys. Rev. Lett. 127, 261804
EXO-20-015



- Achieve sensitivity to BR(H →ss) = 10^{-3} level
- Analysis sensitivity is **independent of LLP masses**

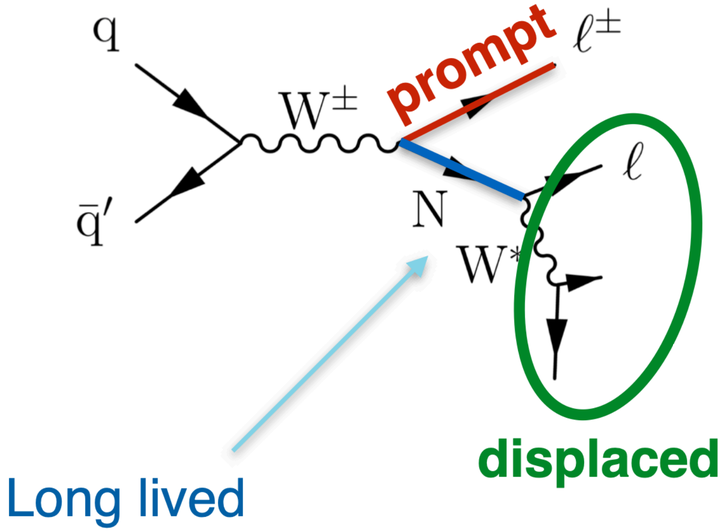
Comparison to Other Searches

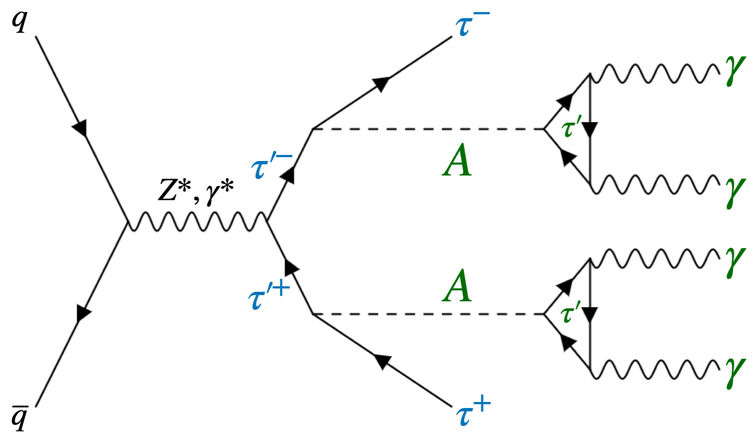


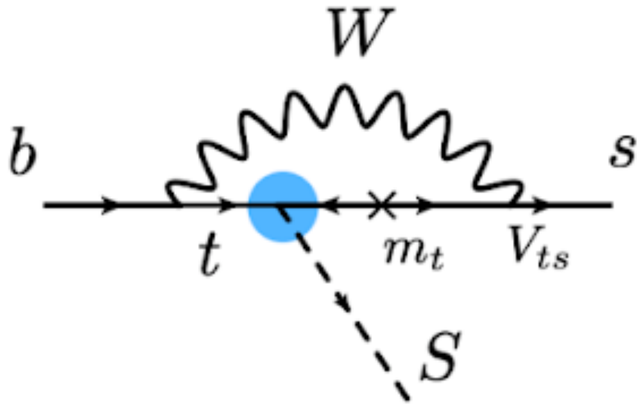
Significantly extended the reach to larger LLP lifetime compared to tracker-based searches

CMS LLP Physics Program with MDS (Run 2)

- **Four Run 2 analyses covering a wide range of models:**
  - Higgs portal and dark shower with MET dataset (EXO-21-008)
  - HNL with single lepton dataset (EXO-22-017)
  - Vector-like lepton with tau and MET dataset (EXO-23-015)
  - LLP from B decays with B-parking dataset

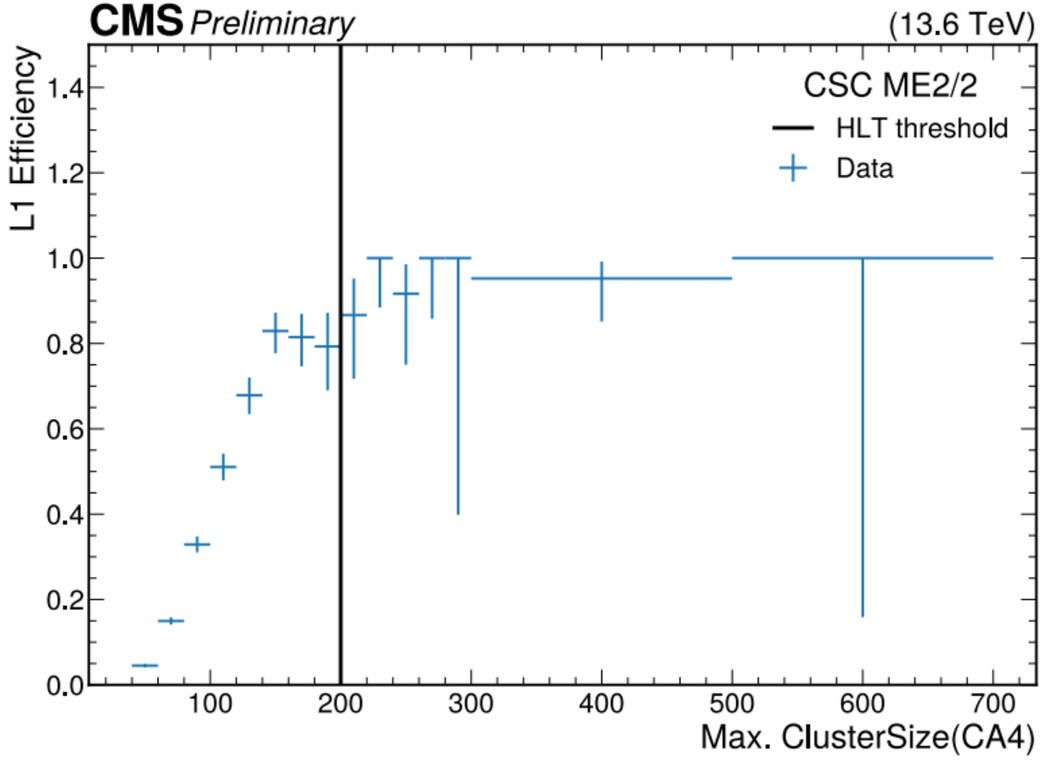






CMS LLP Physics Program with MDS (Run 3)

- **However, Run 2 analyses were trigger limited → new triggers in Run 3 will open up new phase space:**
  - New dedicated L1 + HLT trigger implemented in since 2022
  - New trigger with Cosmic and Heavy Ion collisions in 2023
  - Will add more triggers in 2024 (MDS + e, μ, τ, γ)
- Ongoing efforts to analyze new data in Run 3
- **Let us know if you are interested in joining the effort!**



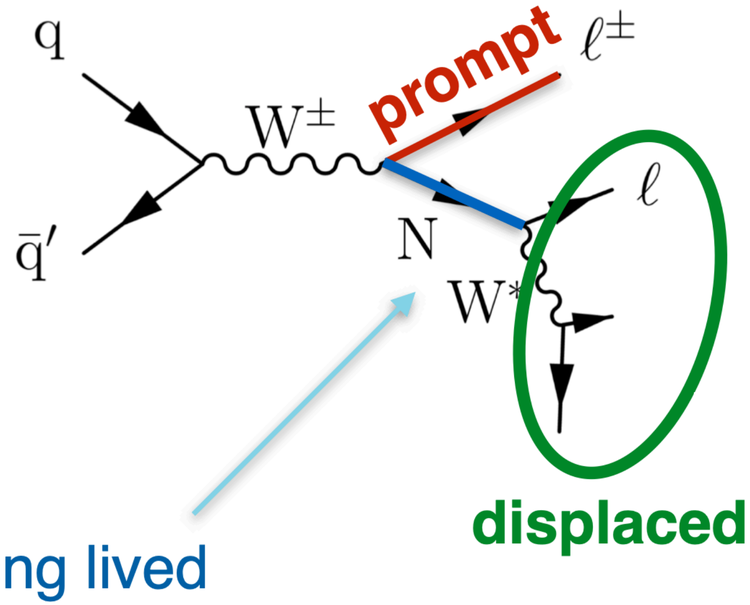
Now Your Turn!

- Learn about general properties of particle lifetimes
- Reconstruct MDS from rechits and calculate reconstruction efficiency
- Study and apply cluster-level selections to reject background
- Estimate background with fully data-driven ABCD method
- Statistical analysis to produce limit on BR(h→SS) for different LLP lifetimes
  - By creating datacards, running higgs Combine and plotting the limits
- Present your result at the Mini-Symposium on Friday!

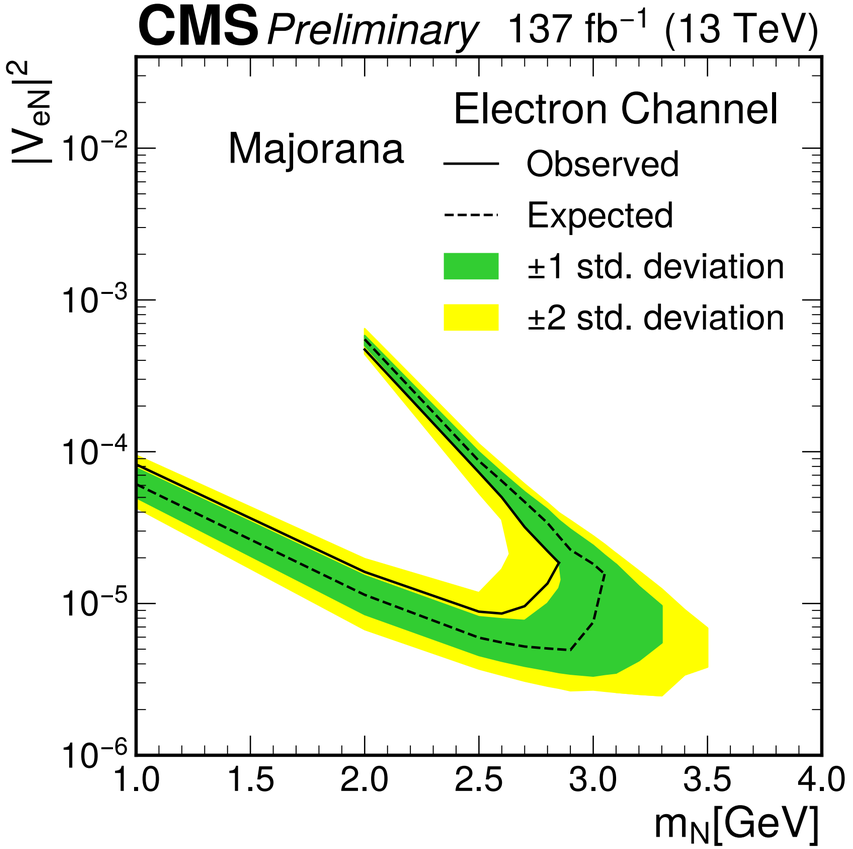
Backup Slides

Search for Heavy Neutral Leptons with MDS

- Search for HNL decay in muon system in association with a **prompt and triggering electron or muon**
  - Sensitive to all visible HNL energy: particle showers from the **displaced lepton and inclusive W* decays**
  - Extend sensitivity to **smaller mass and mixing angle**
- New dedicated trigger in Run 3 would enable sensitivity for tau-type HNLs



$$c\tau_N \propto \left(\frac{1\text{GeV}}{m_N}\right)^5 \left(\frac{0.1}{|V_{lN}|^2}\right) [\text{mm}]$$



EXO-22-017

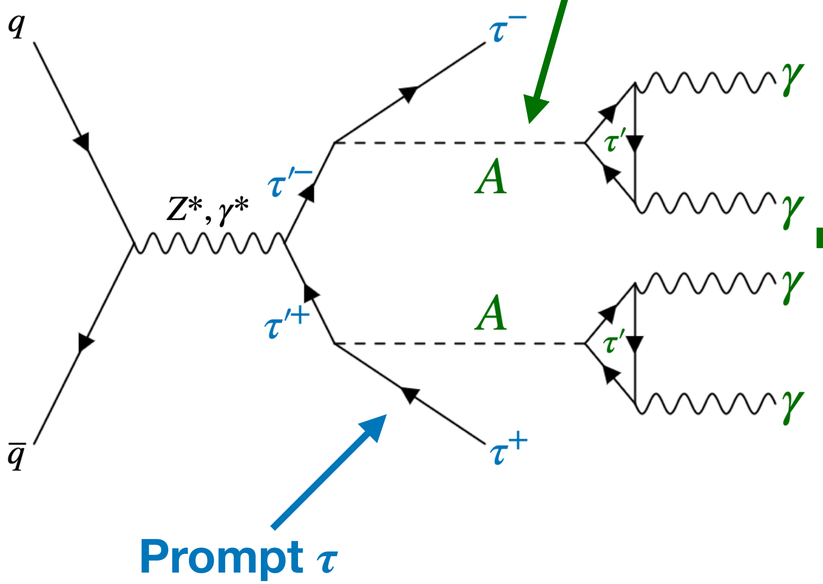
Search for Vector-like Leptons with MDS

- EXO-23-015: Novel VLL signature at the LHC, targeting difficult photon decay mode:

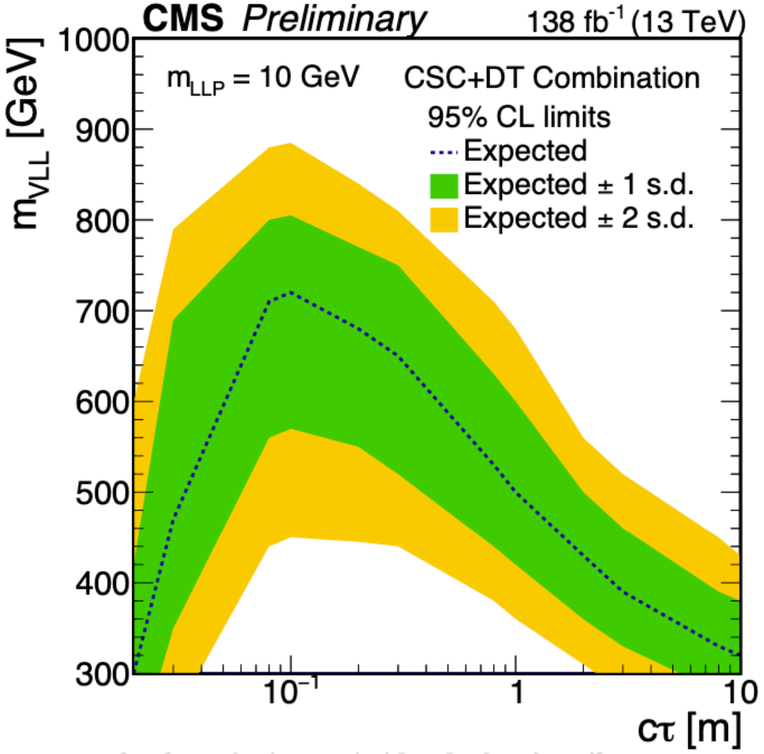
  Two prompt τ's and two electromagnetic LLP decays in muon system

- MDS + τ_h analysis strategy is complete and documented in AN
- Promising sensitivity to VLLs masses up to 700 GeV
- Analysis currently going through object review, targeting Moriond 2024

A is long lived: $c\tau_A \propto \frac{m_{\tau'}^2}{g_A^2 m_A^3}$



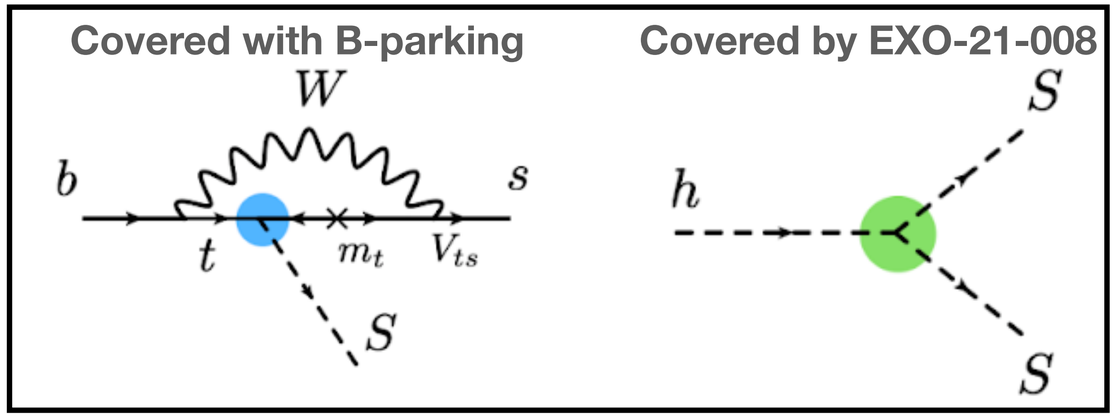
Photon-initiated showers in muon detectors

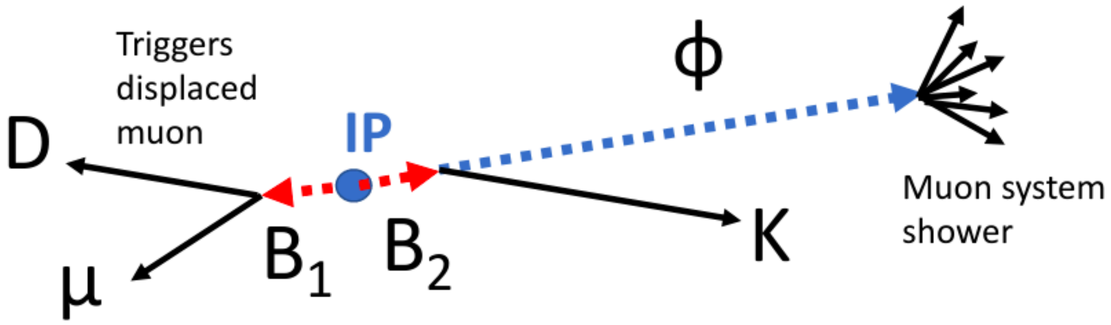


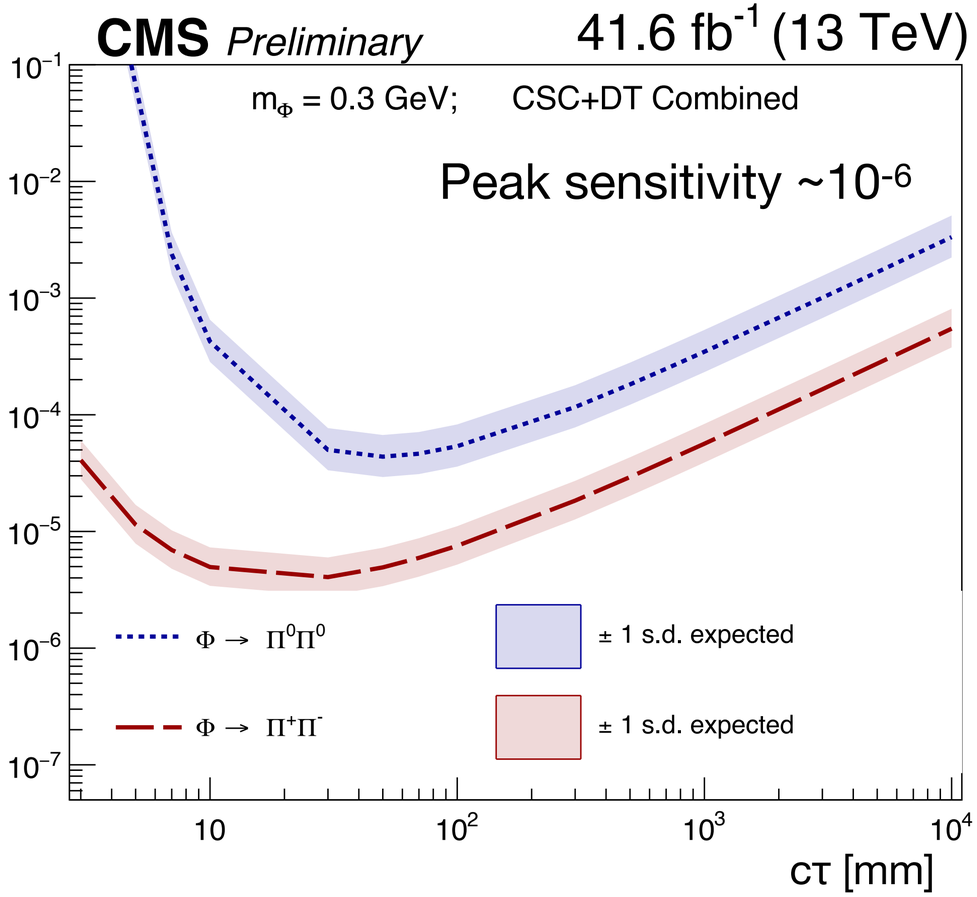
Search LLPs from B Decays with MDS

- B-parking dataset: ~10 billion $B\bar{B}$ events recorded end of 2018 triggering on a single, displaced muon
- The triggering muon originates from the "tag-side" B that undergoes a b→μX decay. **The "signal-side" B decay is inclusive → enable searches for LLPs produced from B decays**
- Wrapping up background estimation and documentation in the AN, aim to send first draft of AN to conveners by end of the year (More details in Aram's talk)

Scalar portal production modes





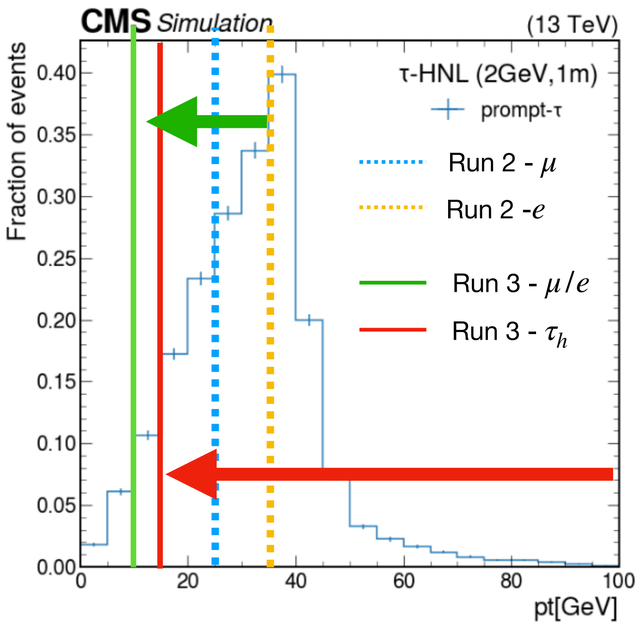


Physics Impact

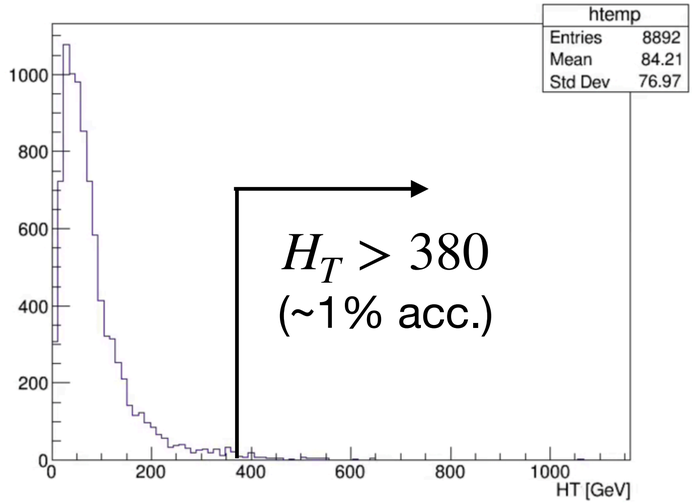
- Run 2 HNL acceptance limited by high lepton pT threshold - especially for tau-HNL
  - New triggers accepts 17%(Muon) / 114% (Electron) / ~400% (tau) more signal events w.r.t Run 2
    - Lower lepton pT + cluster selections included in new trigger
  - **New** hadronic channel alone gives 3-4x more signal than $\tau \rightarrow (e/\mu)$ combined

- GMSB EWK-SUSY model gains ~3x signal acceptance
  - Run 2 acceptance is limited by high HT threshold

HNL : MDS + $e/\mu/\tau$



EWK-SUSY : MDS + γ



Fermilab

Cross trigger proposal summary

- Minimal cluster selection then varied pT threshold on X
- Common “Cluster50” selection:
  - ME11/12 veto
  - “in-time” cluster: -5ns< t <12.5ns
  - >= 50 hits

→ Common Run 2 analysis cuts

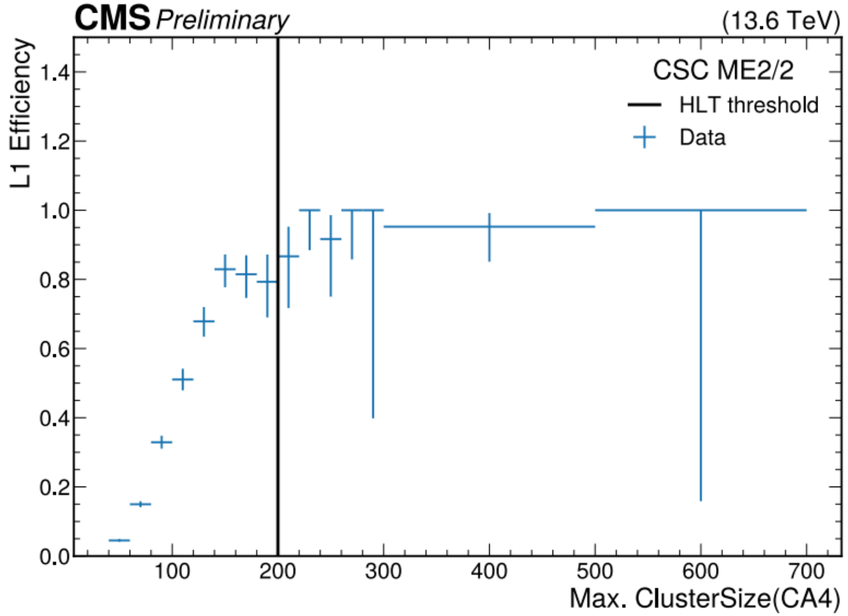
- Total rate of all 4 paths **~10 Hz**
- Minimal overlap with single MDS path (nHit>200+)
- Exploring further improvements:
  - Mu5/Ele5/Tau10 with tighter cluster size cut
  - Use PNet ID for tau instead of DeepTau

Total ~10 Hz

	L1 seed	Cluster selection	Additional	Rate @PU70
MDS + e	L1_SingleMuShower _nominal	Cluster50	pT >10 GeV, Loose CaloId	2.4 Hz
MDS + mu	L1_SingleMuShower _nominal	Cluster50	pT>10 GeV	6.1 Hz
MDS + tau	L1_SingleMuShower _nominal	Cluster50	pT>15 GeV, Medium DeepTauID	2.9 Hz
MDS + gamma	L1_SingleMuShower _nominal	Cluster50	pT >30 GeV, Loose CaloId	0.03 Hz

New L1 Seed for MDS in CSC

- For Run 2, triggering on prompt associated objects or MET (only 1% efficiency for higgs portal)
- New L1 CSC shower seed (L1 rate ~ 2 kHz) commissioned as of 2022E
  - Select for a large number of cathode and anode-wire hits in CSC chambers
- **High L1 efficiency measured w.r.t. offline object**
- New HLT paths targeting single + pair-produced LLPs

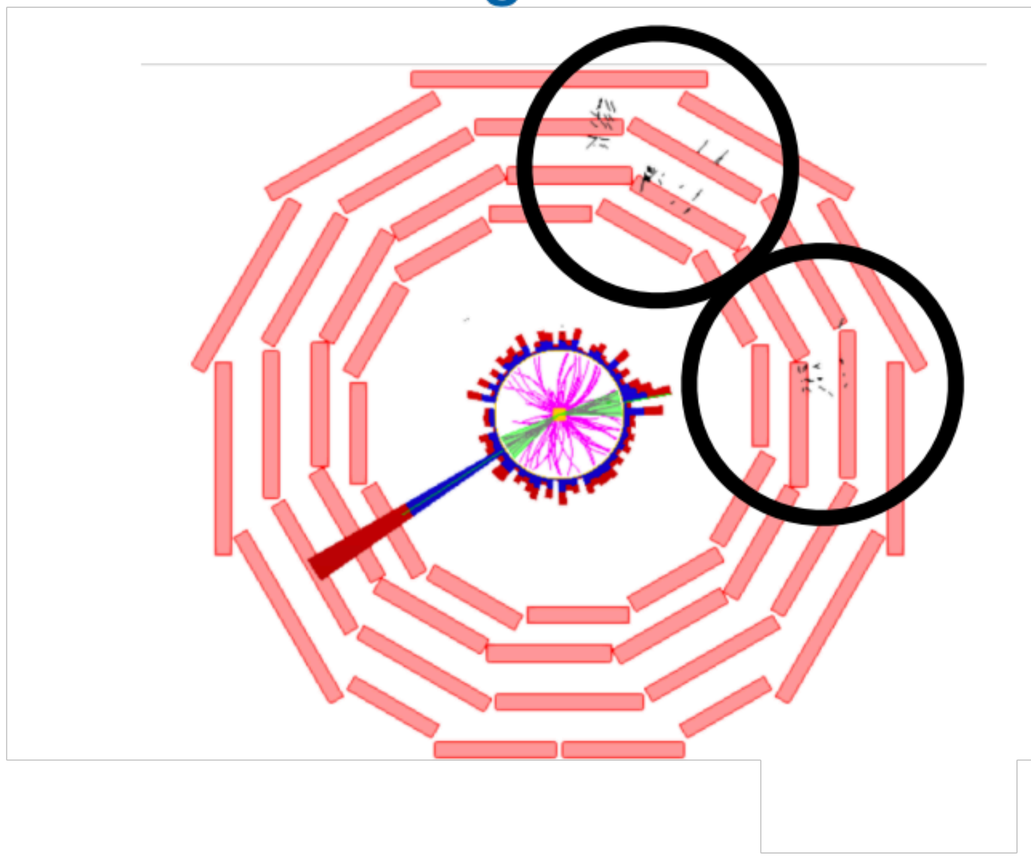


Muon Shower Triggers in 2023

- New double shower L1 trigger in 2023
  - L1 seed + HLT path with lower thresholds (L1_TwoMuShower_Loose)
- Targets models with pair-produced LLPs and enable searches with very low background
- Expect adding **10-25%** extra signal efficiency on top of single MDS trigger
- Active for ~ 1/3 of 2023 pp-data

	ME13	ME21	ME22	ME31	ME32	ME41	ME42
Anode Loose	14->7	56->23	28->12	55->21	26->12	62->25	27->12
Cathode Loose	-	33->14	-	31->12	-	34->14	-

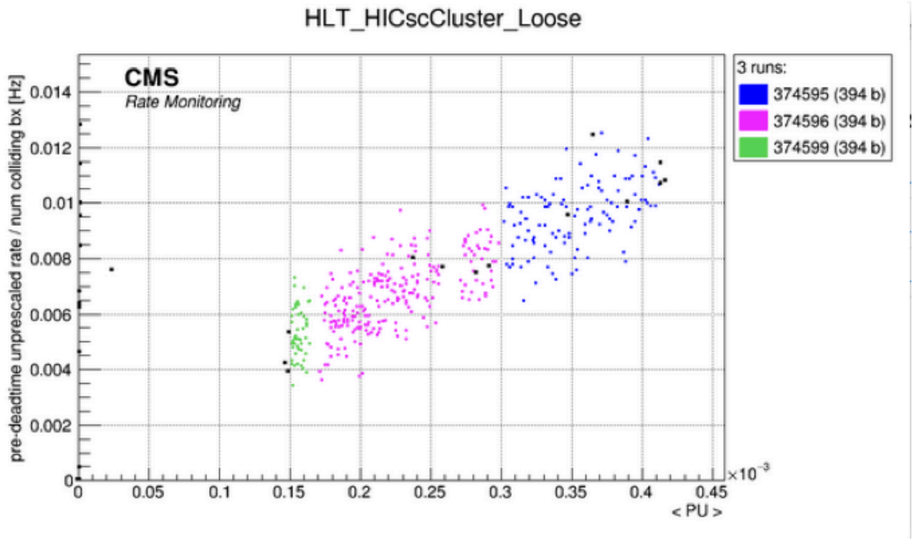
Double shower events from signal MC



Exploring new dataset with MDS

- HMT in Heavy-Ion collision:
  - Extremely low background (L1 thres. set to very close to muon hits)
  - Active for full Pb-Pb run (1.8/nb ~same as 2018 Pb-Pb run)
  - Exploring HNL decays from b-meson in HI-dataset
- HMT in cosmic:
  stopped/trapped LLP searches / background studies / better IceCube?

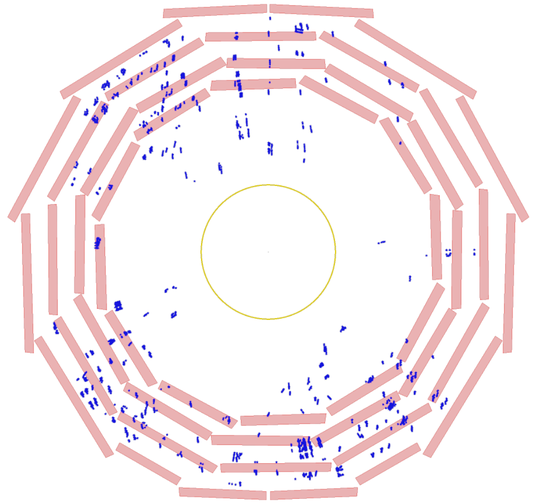
HMT in Heavy-Ion collision



HMT in Heavy-Ion collision

Run: 371290 Lumi Section : 382. Event 6001408

An event with 13 Clusters!



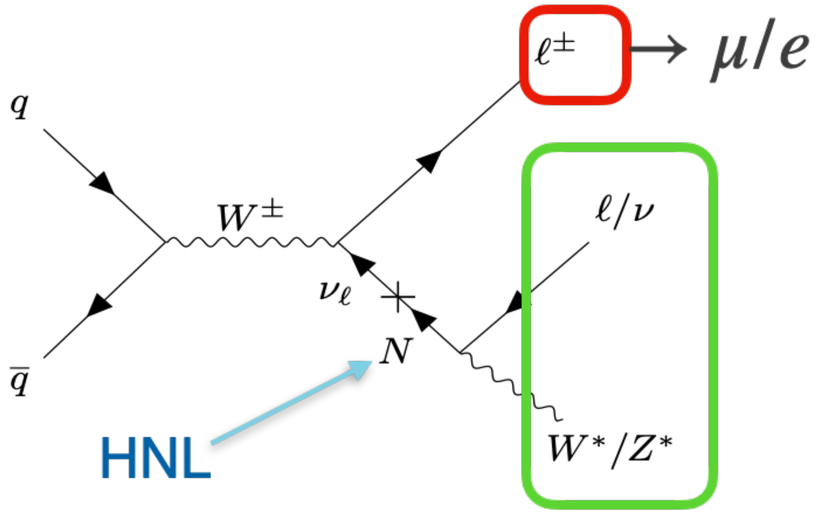
slides

MDS + X (X = e, μ, τ, γ) HLT Paths for 2024

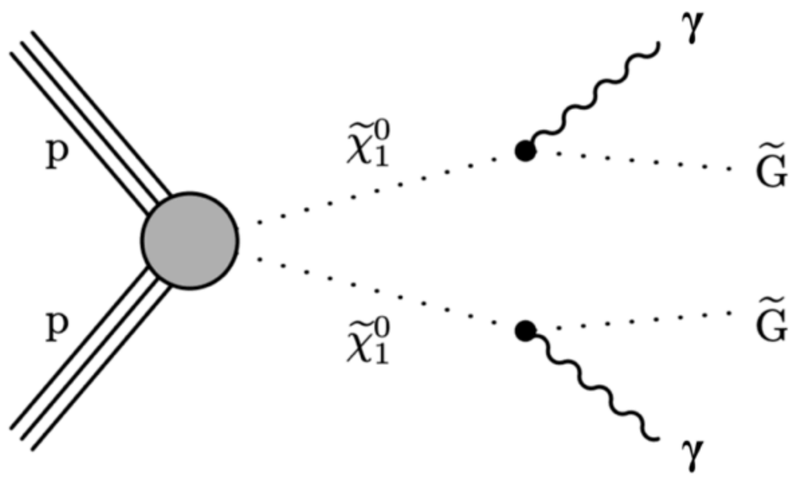
- MDS L1 seed is very effective in background suppression
- Exploit MDS with cross-triggers
  - Sensitive to LLP produced with associated objects
    - Long-lived HNL: e/mu/tau + LLP (Lower prompt lep pT)
  - EWK-SUSY: photon + LLP (No large HT requirement)
- Signal gain of 17% to ~400% w.r.t Run 2 analysis

More details at
Trigger deep dive

τ-HNL



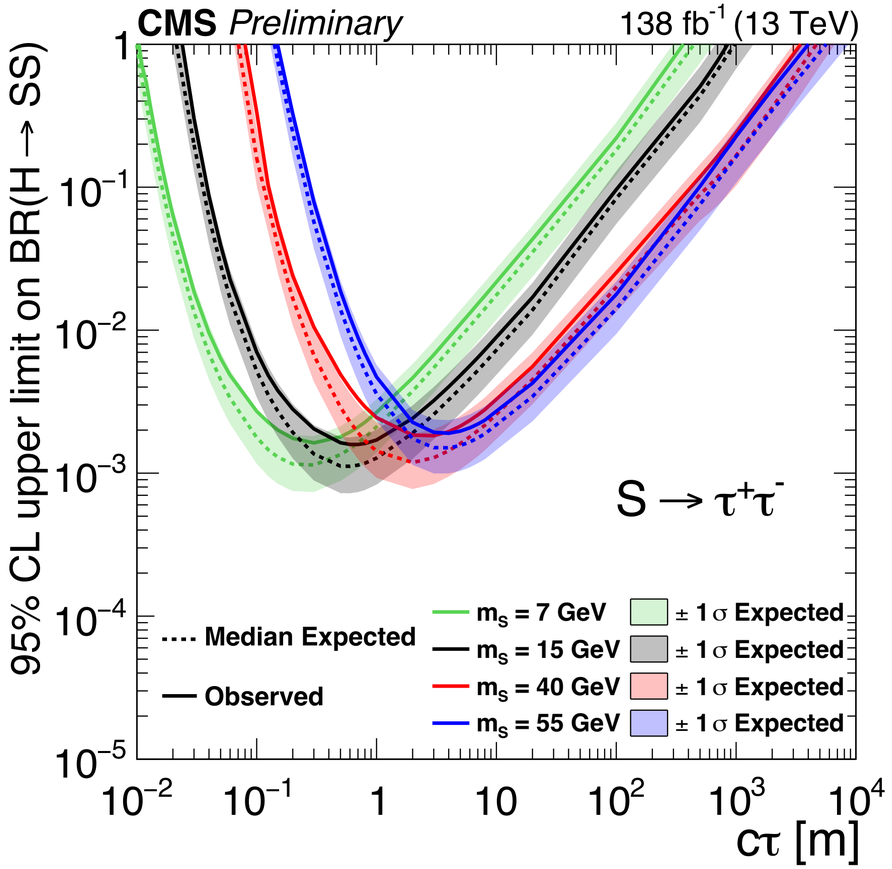
EWK-SUSY : MDS + γ



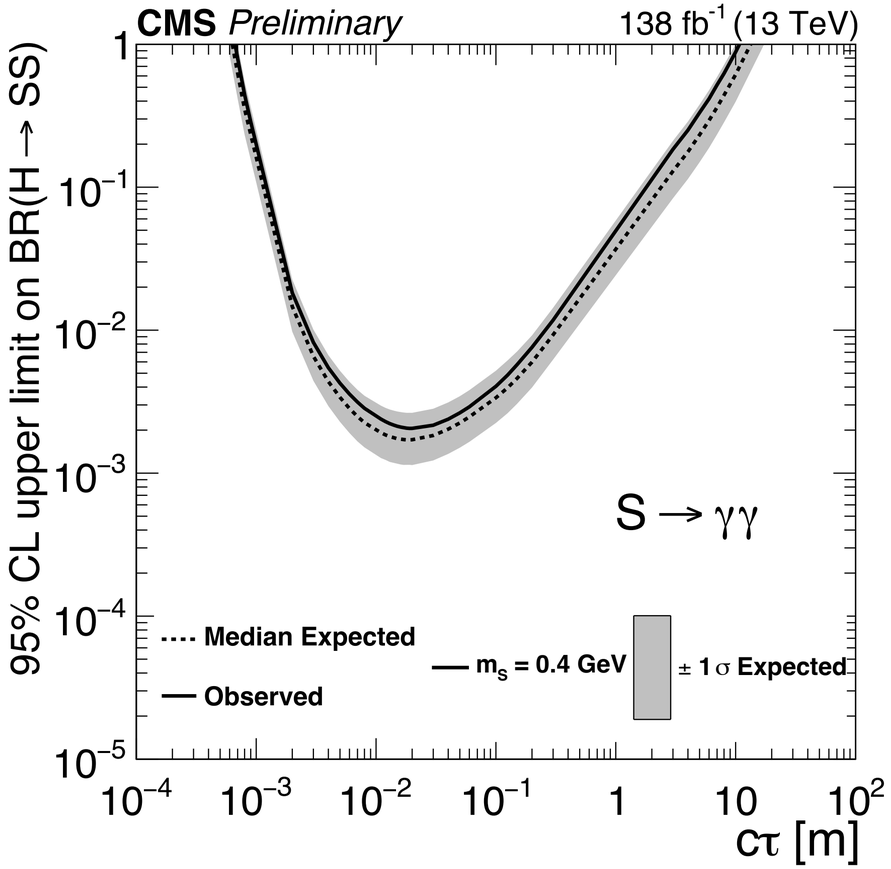
Observed and Expected Limits

Phys. Rev. Lett. 127, 261804
PAS-EXO-21-008

Hadronic & EM shower



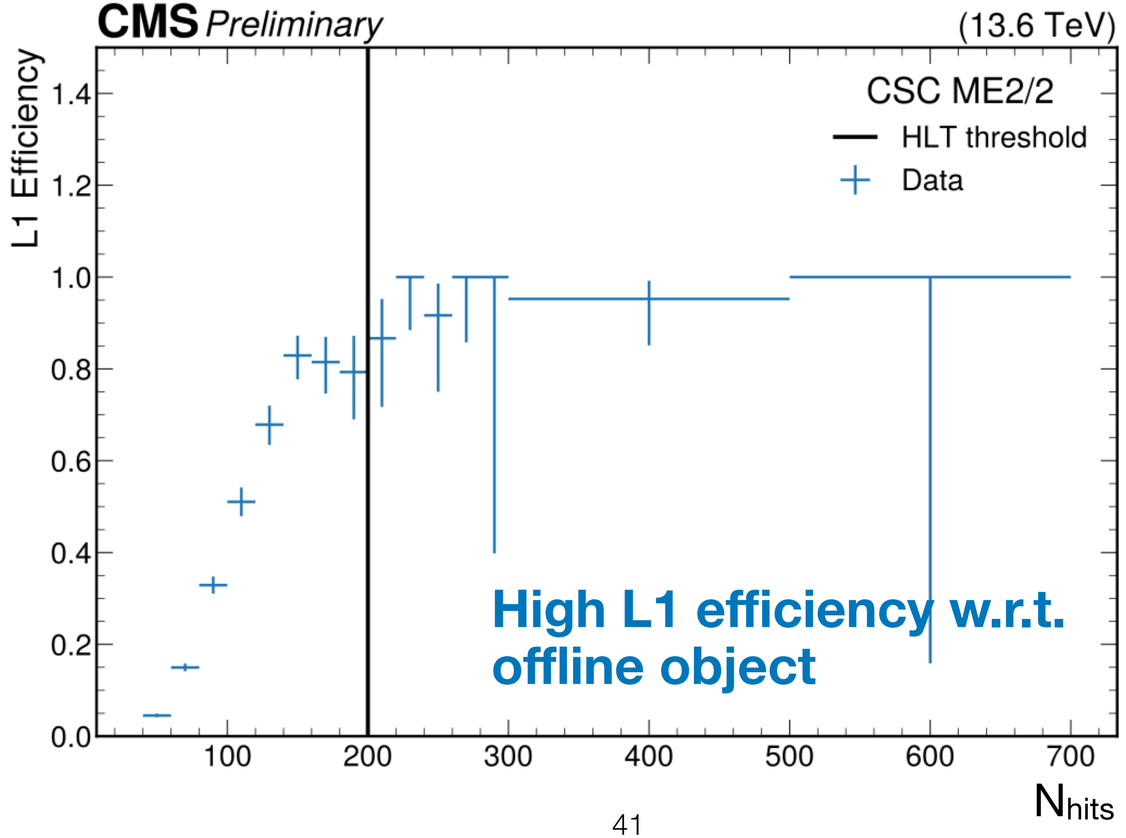
Fully EM shower



- 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 LLPs** at BR(H →ss) = 10^{-3} level

Looking Forward: New Trigger in Run 3

- For Run 2, triggering on MET (only 1% efficiency for higgs portal)
- New L1 seed and HLT paths successfully commissioned in 2022
  - Simple logic at L1 due to limited information and bandwidth
- **Improve LLP efficiency by 10x with respect to Run 2 → potential to reach BR ~ 1e-4 !**



CMS-DP-2023-043

CMS-DP-2022-062