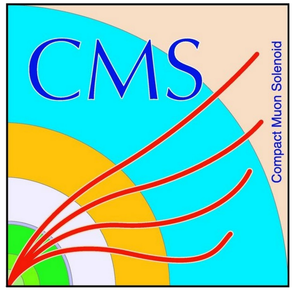


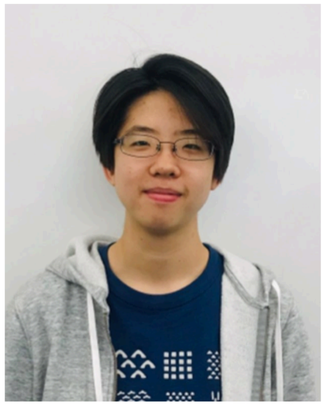

# Search for Long-lived Particles with Muon Detector Showers

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**

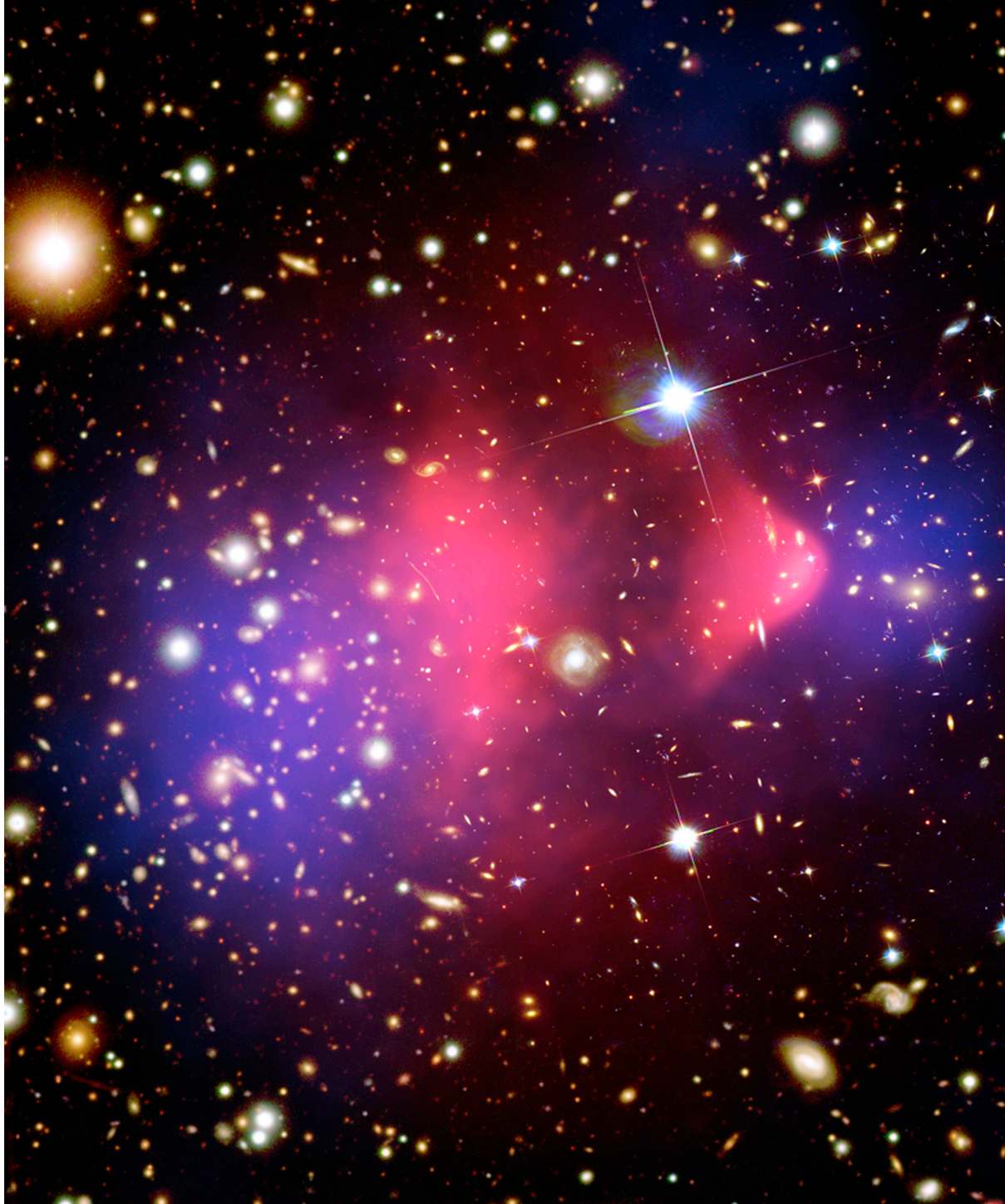
**Martin Kwok**

# Tell us about yourself

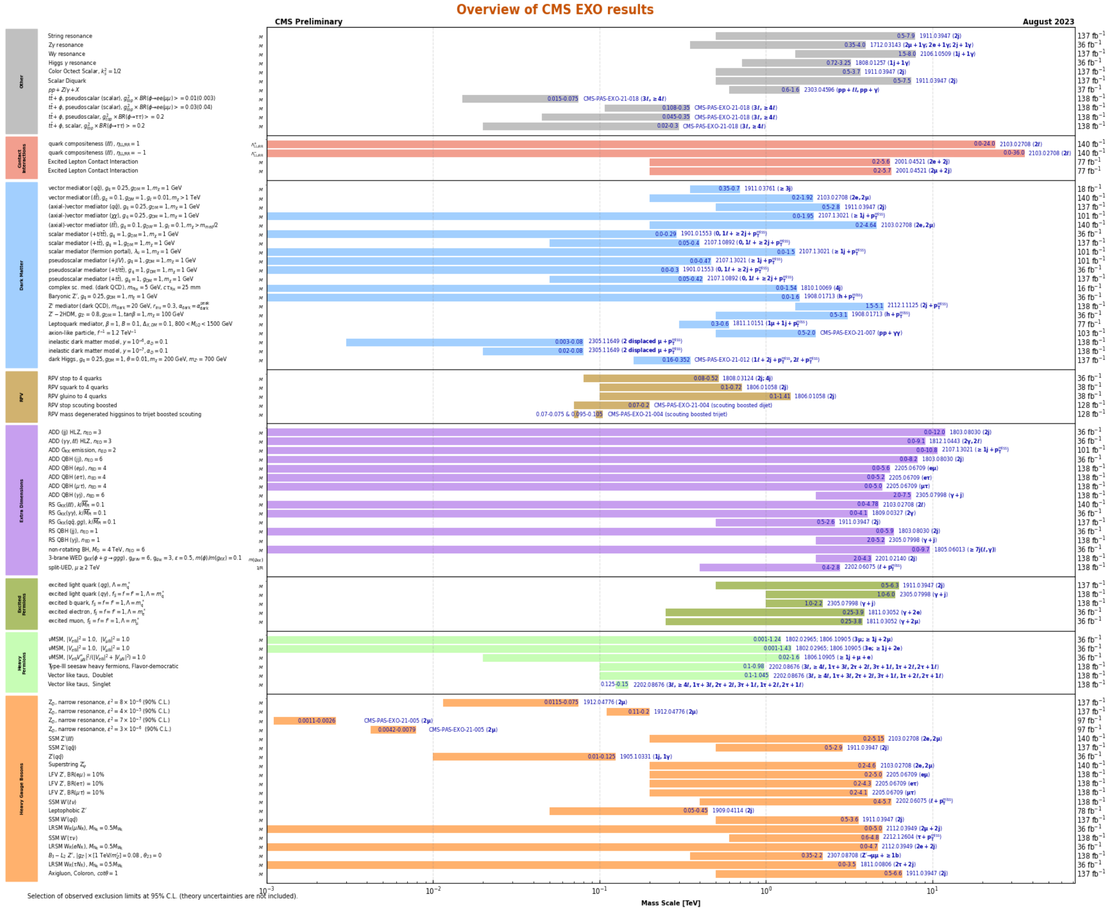
- What year are you in?
- Any experience with data analysis? What will you/are you working on?
- What do you hope to get out of CMSDAS?
- Comments/questions?

# Physics Beyond the Standard Model

- Ample evidence of phenomena that the standard model cannot fully explain:
  - Dark matter
  - Massive neutrinos
  - Light Higgs
- LHC is a unique place to directly search for new physics
  - Highest energy accelerator
  - High intensity collisions



# New Physics Searches at the LHC




**ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits**

*Status: March 2023*

***ATLAS*** Preliminary

$\int \mathcal{L}\, dt$ = (3.6 – 139) fb$^{-1}$

$\sqrt{s}$ = 13 TeV

| | Model | $\ell, \gamma$ | Jets† | $E_T^{miss}$ | $\int \mathcal{L}\, dt$[fb$^{-1}$] | Limit | Reference |
|---|---|---|---|---|---|---|---|
| Extra dimen. | ADD $G_{KK} + g/q$ | 0 $e, \mu, \tau, \gamma$ | 1 – 4 j | Yes | 139 | $M_D$ 11.2 TeV $n = 2$ | 2102.10874 |
| | ADD non-resonant $\gamma\gamma$ | 2 $\gamma$ | – | – | 36.7 | $M_S$ 8.6 TeV $n = 3$ HLZ NLO | 1707.04147 |
| | ADD QBH | – | 2 j | – | 139 | $M_{th}$ 9.4 TeV $n = 6$ | 1910.08447 |
| | ADD BH multijet | – | ≥3 j | – | 3.6 | $M_{th}$ 9.55 TeV $n = 6$, $M_D = 3$ TeV, rot BH | 1512.02586 |
| | RS1 $G_{KK} \to \gamma\gamma$ | 2 $\gamma$ | – | – | 139 | $G_{KK}$ mass 4.5 TeV $k/\overline{M}_{Pl} = 0.1$ | 2102.13405 |
| | Bulk RS $G_{KK} \to WW/ZZ$ | multi-channel | | | 36.1 | $G_{KK}$ mass 2.3 TeV $k/\overline{M}_{Pl} = 1.0$ | 1808.02380 |
| | Bulk RS $g_{KK} \to tt$ | 1 $e, \mu$ | ≥1 b, ≥1J/2j | Yes | 36.1 | $g_{KK}$ mass 3.8 TeV $\Gamma/m = 15\%$ | 1804.10823 |
| | 2UED / RPP | 1 $e, \mu$ | ≥2 b, ≥3 j | Yes | 36.1 | KK mass 1.8 TeV Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$ | 1803.09678 |
| Gauge bosons | SSM $Z' \to \ell\ell$ | 2 $e, \mu$ | – | – | 139 | $Z'$ mass 5.1 TeV | 1903.06248 |
| | SSM $Z' \to \tau\tau$ | 2 $\tau$ | – | – | 36.1 | $Z'$ mass 2.42 TeV | 1709.07242 |
| | Leptophobic $Z' \to bb$ | – | 2 b | – | 36.1 | $Z'$ mass 2.1 TeV | 1805.09299 |
| | Leptophobic $Z' \to tt$ | 0 $e, \mu$ | ≥1 b, ≥2 J | Yes | 139 | $Z'$ mass 4.1 TeV $\Gamma/m = 1.2\%$ | 2005.05138 |
| | SSM $W' \to \ell\nu$ | 1 $e, \mu$ | – | Yes | 139 | $W'$ mass 6.0 TeV | 1906.05609 |
| | SSM $W' \to \tau\nu$ | 1 $\tau$ | – | Yes | 139 | $W'$ mass 5.0 TeV | ATLAS-CONF-2021-025 |
| | SSM $W' \to tb$ | – | ≥1 b, ≥1 J | – | 139 | $W'$ mass 4.4 TeV | ATLAS-CONF-2021-043 |
| | HVT $W' \to WZ$ model B | 0-2 $e, \mu$ | 2 j / 1 J | Yes | 139 | $W'$ mass 4.3 TeV $g_V = 3$ | 2004.14636 |
| | HVT $W' \to WZ \to \ell\nu\ell'\ell'$ model C | 3 $e, \mu$ | 2 j (VBF) | Yes | 139 | $W'$ mass 340 GeV $g_V c_H = 1$, $g_f = 0$ | 2207.03925 |
| | HVT $Z' \to WW$ model B | 1 $e, \mu$ | 2 j / 1 J | Yes | 139 | $Z'$ mass 3.9 TeV $g_V = 3$ | 2004.14636 |
| | LRSM $W_R \to \mu N_R$ | 2 $\mu$ | 1 J | – | 80 | $W_R$ mass 5.0 TeV $m(N_R) = 0.5$ TeV, $g_L = g_R$ | 1904.12679 |
| CI | CI $qqqq$ | – | 2 j | – | 37.0 | $\Lambda$ 21.8 TeV $\eta_{LL}^-$ | 1703.09127 |
| | CI $\ell\ell qq$ | 2 $e, \mu$ | – | – | 139 | $\Lambda$ 35.8 TeV $\eta_{LL}^-$ | 2006.12946 |
| | CI $eebs$ | 2 $e$ | 1 b | – | 139 | $\Lambda$ 1.8 TeV $g_* = 1$ | 2105.13847 |
| | CI $\mu\mu bs$ | 2 $\mu$ | 1 b | – | 139 | $\Lambda$ 2.0 TeV $g_* = 1$ | 2105.13847 |
| | CI $tttt$ | ≥1 $e, \mu$ | ≥1 b, ≥1 j | Yes | 36.1 | $\Lambda$ 2.57 TeV $\lvert C_{4t} \rvert = 4\pi$ | 1811.02305 |
| DM | Axial-vector med. (Dirac DM) | – | 2 j | – | 139 | $m_{med}$ 3.8 TeV $g_q$=0.25, $g_\chi$=1, $m(\chi)$=10 TeV | ATL-PHYS-PUB-2022-036 |
| | Pseudo-scalar med. (Dirac DM) | 0 $e, \mu, \tau, \gamma$ | 1 – 4 j | Yes | 139 | $m_{med}$ 376 GeV $g_q$=1, $g_\chi$=1, $m(\chi)$=1 GeV | 2102.10874 |
| | Vector med. $Z'$-2HDM (Dirac DM) | 0 $e, \mu$ | 2 b | Yes | 139 | $m_{Z'}$ 3.0 TeV tan$\beta$=1, $g_Z$=0.8, $m(\chi)$=100 GeV | 2108.13391 |
| | Pseudo-scalar med. 2HDM+a | multi-channel | | | 139 | $m_a$ 800 GeV tan$\beta$=1, $g_\chi$=1, $m(\chi)$=10 GeV | ATLAS-CONF-2021-036 |
| LQ | Scalar LQ 1st gen | 2 $e$ | ≥2 j | Yes | 139 | LQ mass 1.8 TeV $\beta = 1$ | 2006.05872 |
| | Scalar LQ 2nd gen | 2 $\mu$ | ≥2 j | Yes | 139 | LQ mass 1.7 TeV $\beta = 1$ | 2006.05872 |
| | Scalar LQ 3rd gen | 1 $\tau$ | 2 b | Yes | 139 | LQ mass 1.49 TeV $\mathcal{B}(LQ_3^u \to b\tau) = 1$ | 2303.01294 |
| | Scalar LQ 3rd gen | 0 $e, \mu$ | ≥2 j, ≥2 b | Yes | 139 | LQ mass 1.24 TeV $\mathcal{B}(LQ_3^u \to t\nu) = 1$ | 2004.14060 |
| | Scalar LQ 3rd gen | ≥2 $e, \mu$, ≥1 $\tau$ | ≥1 j, ≥1 b | – | 139 | LQ mass 1.43 TeV $\mathcal{B}(LQ_3^d \to t\tau) = 1$ | 2101.11582 |
| | Scalar LQ 3rd gen | 0 $e, \mu$, ≥1 $\tau$ | 0 – 2 j, 2 b | Yes | 139 | LQ mass 1.26 TeV $\mathcal{B}(LQ_3^d \to b\nu) = 1$ | 2101.12527 |
| | Vector LQ mix gen | multi-channel | ≥1 j, ≥1 b | Yes | 139 | LQ mass 2.0 TeV $\mathcal{B}(\bar{U}_1 \to t\mu) = 1$, Y-M coupl. | ATLAS-CONF-2022-052 |
| | Vector LQ 3rd gen | 2 $e, \mu, \tau$ | ≥1 b | Yes | 139 | LQ mass 1.96 TeV $\mathcal{B}(LQ_3^Y \to b\tau) = 1$, Y-M coupl. | 2303.01294 |
| Vector-like fermions | VLQ $TT \to Zt + X$ | 2$e$/2$\mu$/≥3$e,\mu$ | ≥1 b, ≥1 j | – | 139 | T mass 1.46 TeV SU(2) doublet | 2210.15413 |
| | VLQ $BB \to Wt/Zb + X$ | multi-channel | | | 36.1 | B mass 1.34 TeV SU(2) doublet | 1808.02343 |
| | VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$ | 2(SS)/≥3 $e, \mu$ | ≥1 b, ≥1 j | Yes | 36.1 | $T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \to Wt) = 1$, $c(T_{5/3}Wt) = 1$ | 1807.11883 |
| | VLQ $T \to Ht/Zt$ | 1 $e, \mu$ | ≥1 b, ≥3 j | Yes | 139 | T mass 1.8 TeV SU(2) singlet, $\kappa_T = 0.5$ | ATLAS-CONF-2021-040 |
| | VLQ $Y \to Wb$ | 1 $e, \mu$ | ≥1 b, ≥1 j | Yes | 36.1 | Y mass 1.85 TeV $\mathcal{B}(Y \to Wb) = 1$, $c_R(Wb) = 1$ | 1812.07343 |
| | VLQ $B \to Hb$ | 0 $e, \mu$ | ≥2b, ≥1j, ≥1J | – | 139 | B mass 2.0 TeV SU(2) doublet, $\kappa_B = 0.3$ | ATLAS-CONF-2021-018 |
| | VLL $\tau' \to Z\tau/H\tau$ | multi-channel | ≥1 j | Yes | 139 | $\tau'$ mass 898 GeV SU(2) doublet | 2303.05441 |
| Exctd ferm. | Excited quark $q^* \to qg$ | – | 2 j | – | 139 | $q^*$ mass 6.7 TeV only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1910.08447 |
| | Excited quark $q^* \to q\gamma$ | 1 $\gamma$ | 1 j | – | 36.7 | $q^*$ mass 5.3 TeV only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1709.10440 |
| | Excited quark $b^* \to bg$ | – | 1 b, 1 j | – | 139 | $b^*$ mass 3.2 TeV | 1910.08447 |
| | Excited lepton $\tau^*$ | 2 $\tau$ | ≥2 j | – | 139 | $\tau^*$ mass 4.6 TeV $\Lambda = 4.6$ TeV | 2303.09444 |
| Other | Type III Seesaw | 2,3,4 $e, \mu$ | ≥2 j | Yes | 139 | $N^0$ mass 910 GeV | 2202.02039 |
| | LRSM Majorana $\nu$ | 2 $\mu$ | 2 j | – | 36.1 | $N_R$ mass 3.2 TeV $m(W_R) = 4.1$ TeV, $g_L = g_R$ | 1809.11105 |
| | Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$ | 2,3,4 $e, \mu$ (SS) | various | Yes | 139 | $H^{\pm\pm}$ mass 350 GeV DY production | 2101.11961 |
| | Higgs triplet $H^{\pm\pm} \to \ell\ell$ | 2,3,4 $e, \mu$ (SS) | – | – | 139 | $H^{\pm\pm}$ mass 1.08 TeV DY production | 2211.07505 |
| | Multi-charged particles | – | – | – | 139 | multi-charged particle mass 1.59 TeV DY production, $\lvert q \rvert = 5e$ | ATLAS-CONF-2022-034 |
| | Magnetic monopoles | – | – | – | 34.4 | monopole mass 2.37 TeV DY production, $\lvert g \rvert = 1g_D$, spin 1/2 | 1905.10130 |

$\sqrt{s}$ = 13 TeV partial data

$\sqrt{s}$ = 13 TeV full data

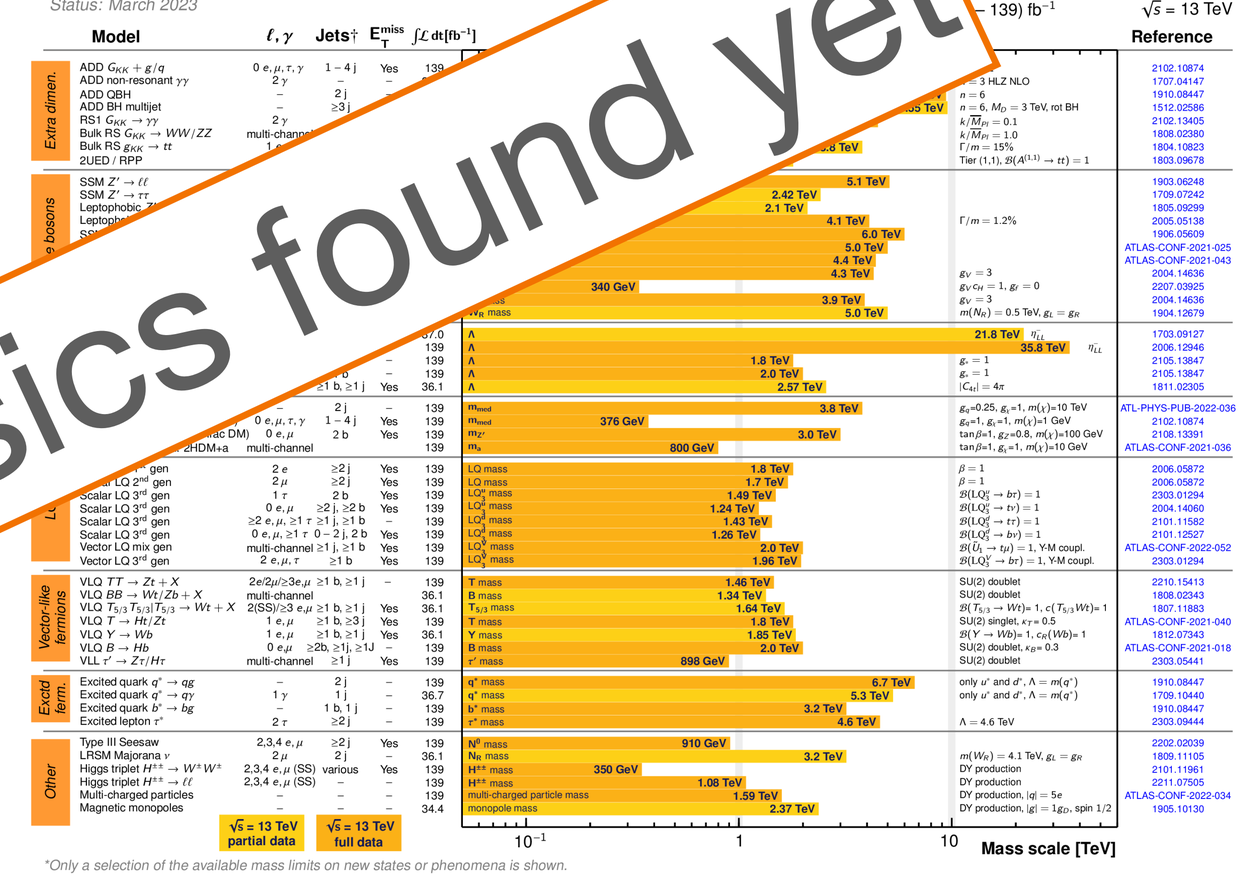
$10^{-1}$ 1 10 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Hundreds of new physics searches at the LHC

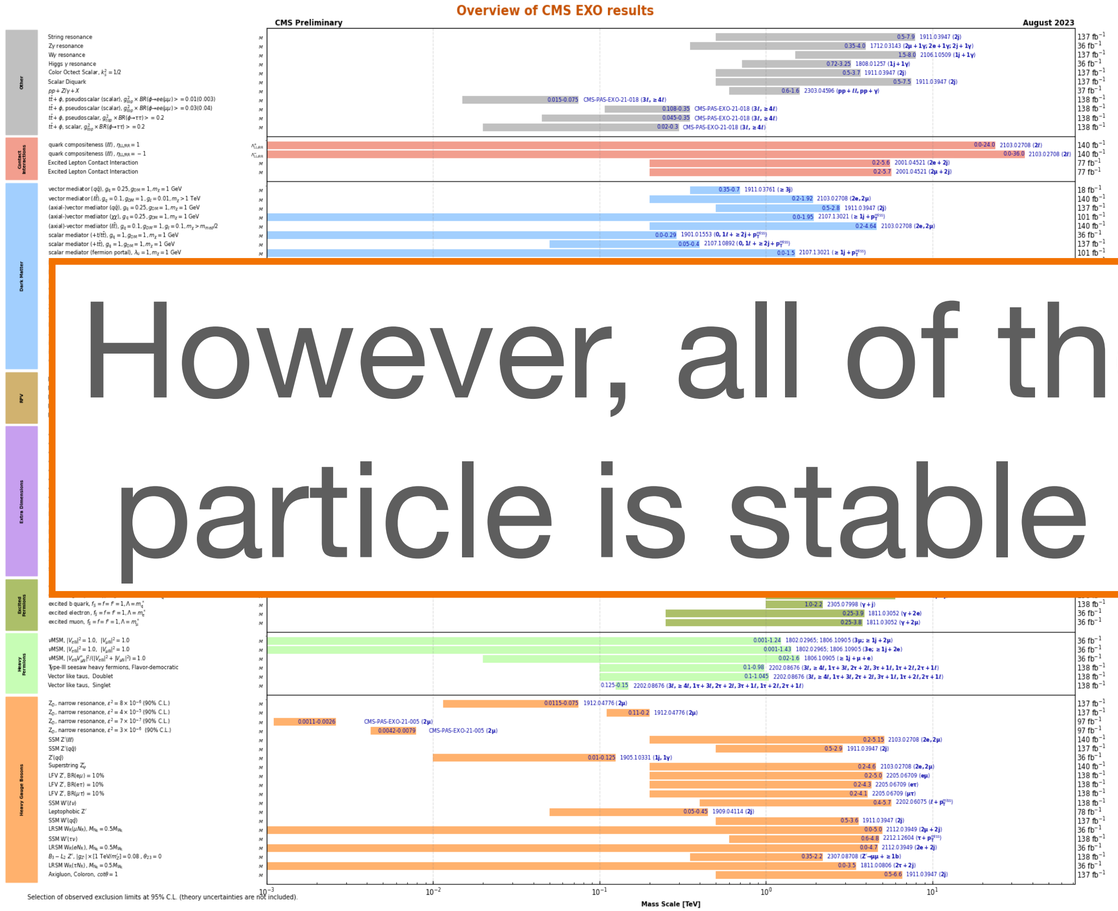
# New Physics Searches at the LHC

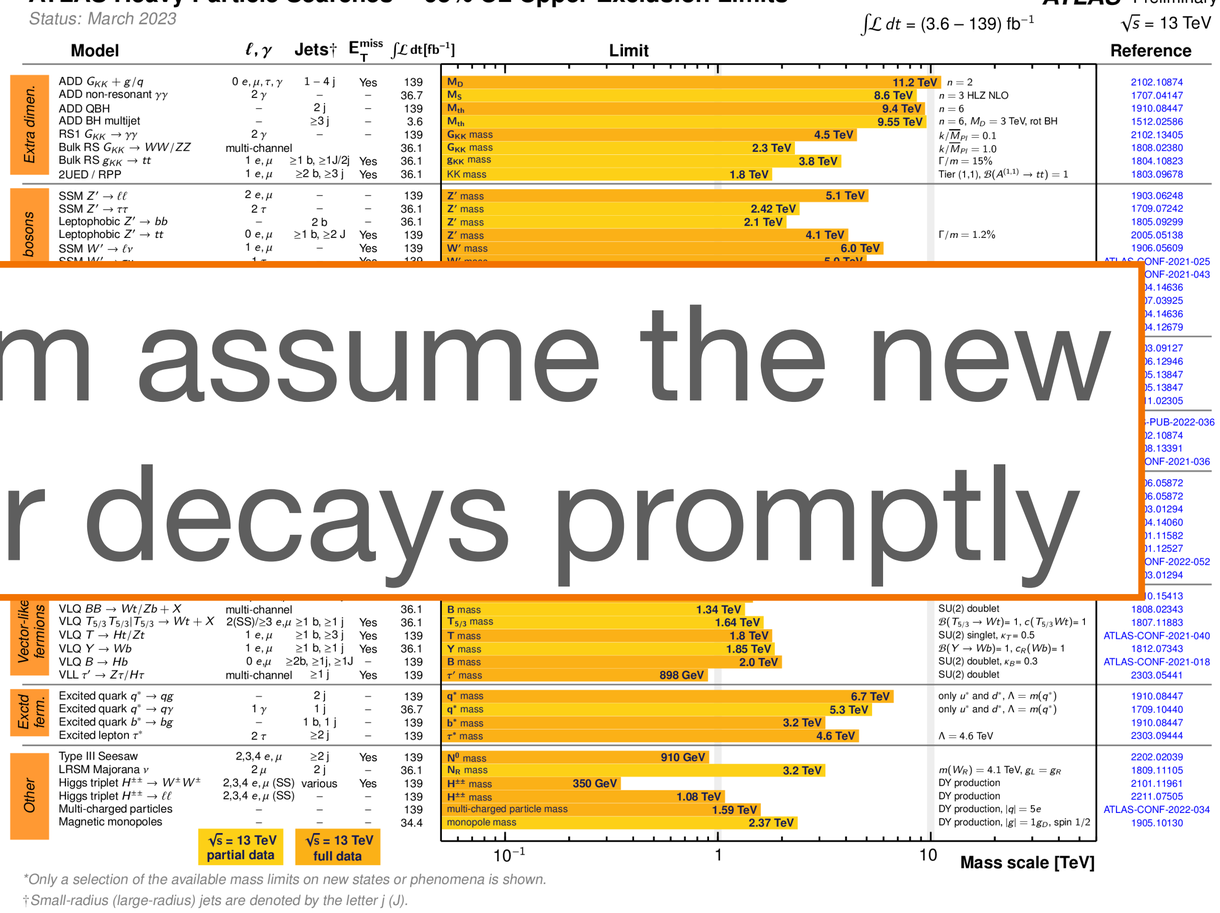




No new physics found yet

Hundreds of new physics searches at the LHC

# New Physics Searches at the LHC

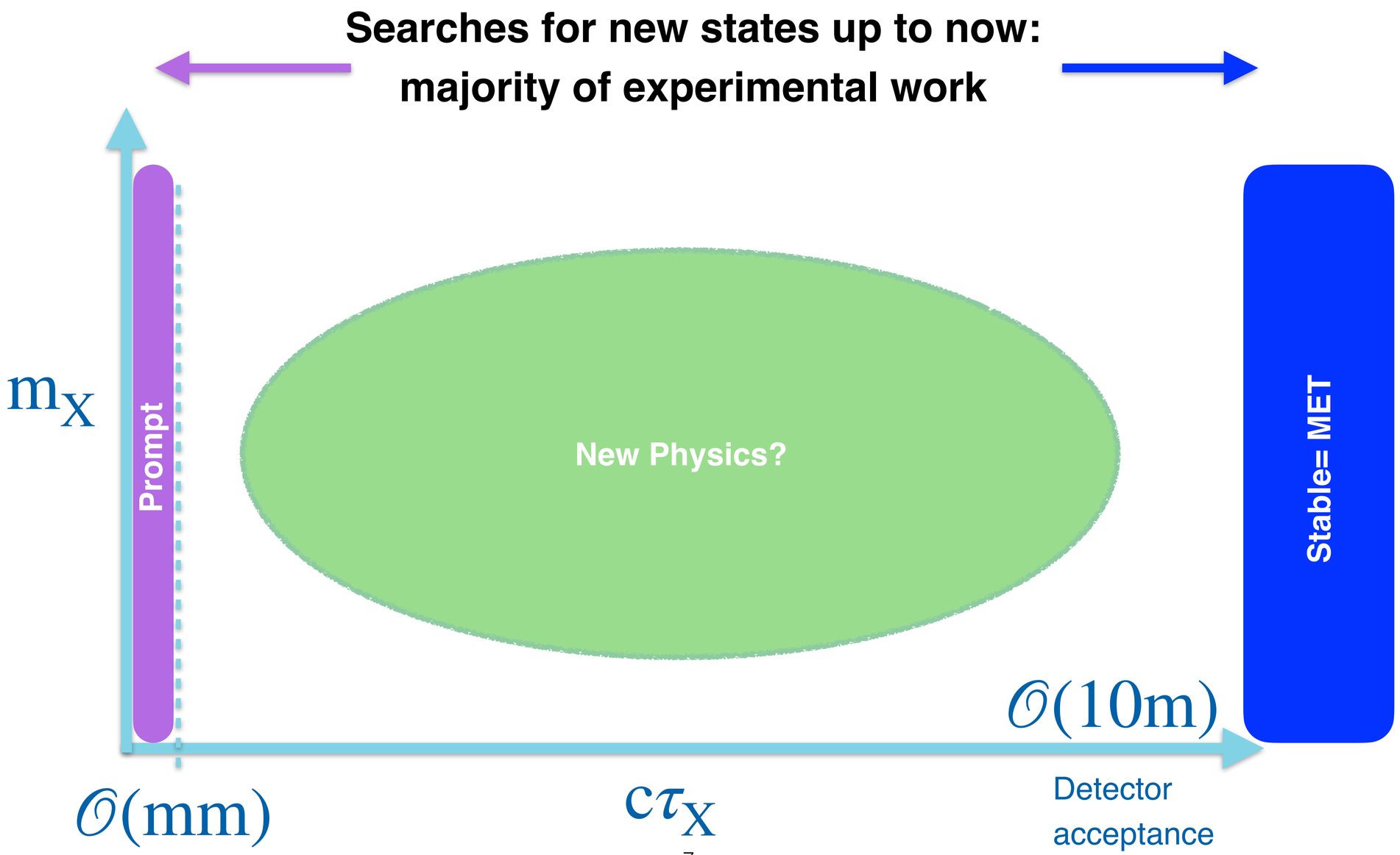


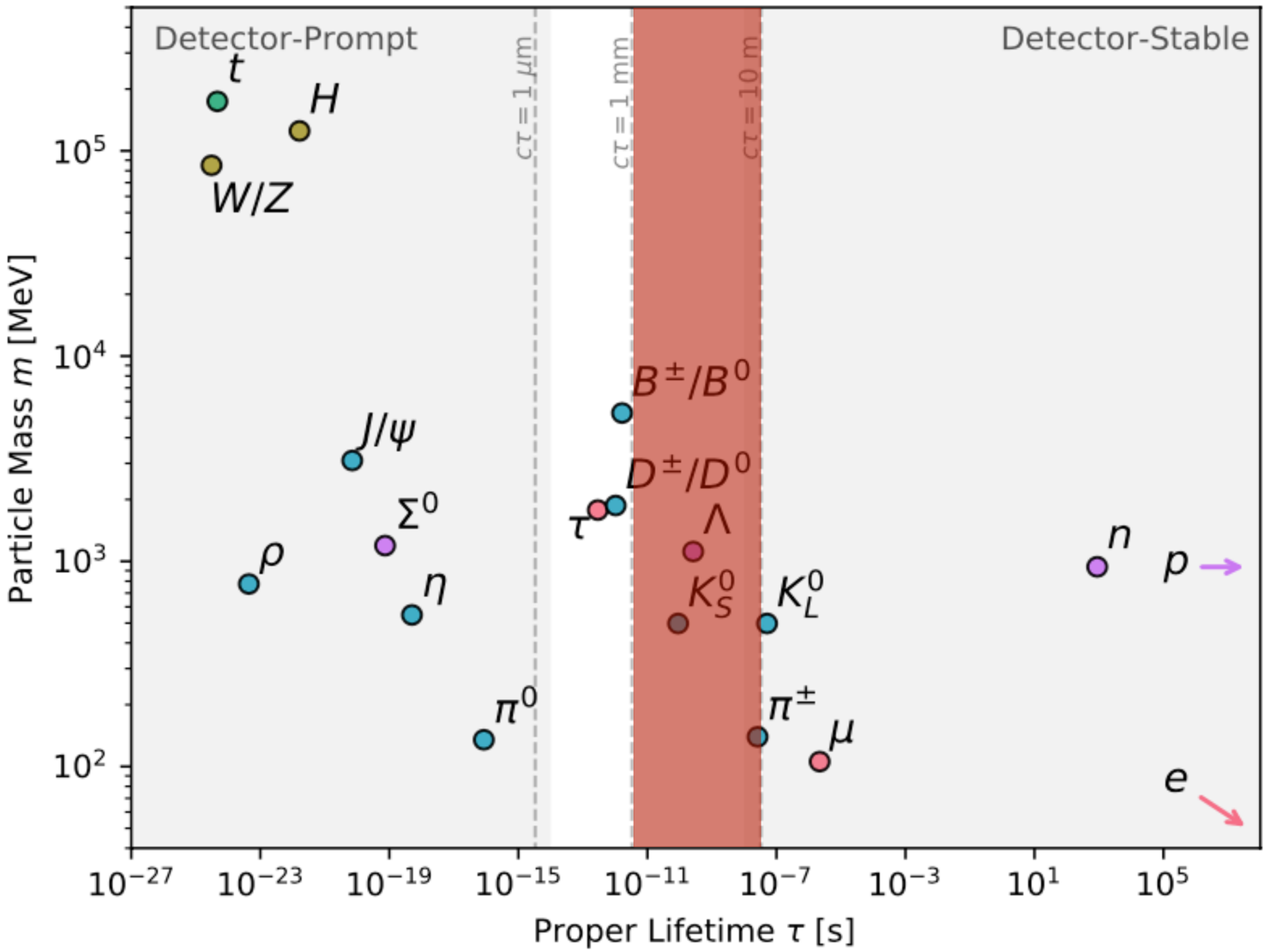

However, all of them assume the new particle is stable or decays promptly

Hundreds of new physics searches at the LHC

# New Physics at LHC: Long-lived particles



# Long-Lived Particles in the SM

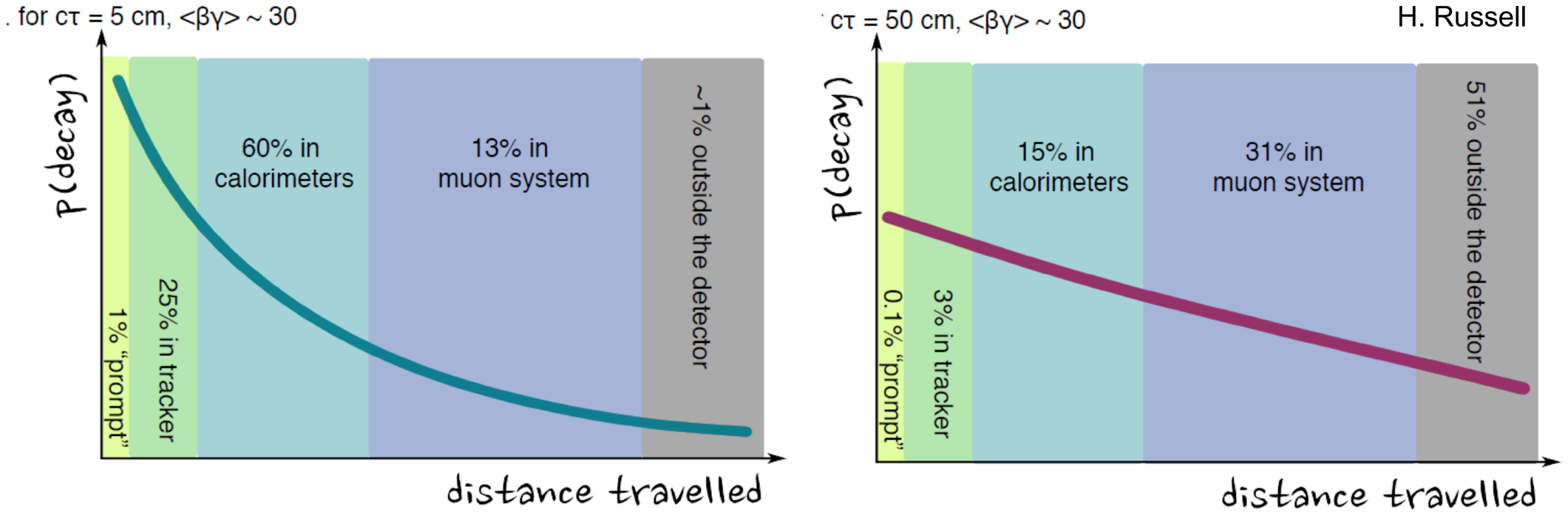



- Small coupling
- Massive mediator
- Small phase space

Same mechanisms apply to LLPs in BSM theories

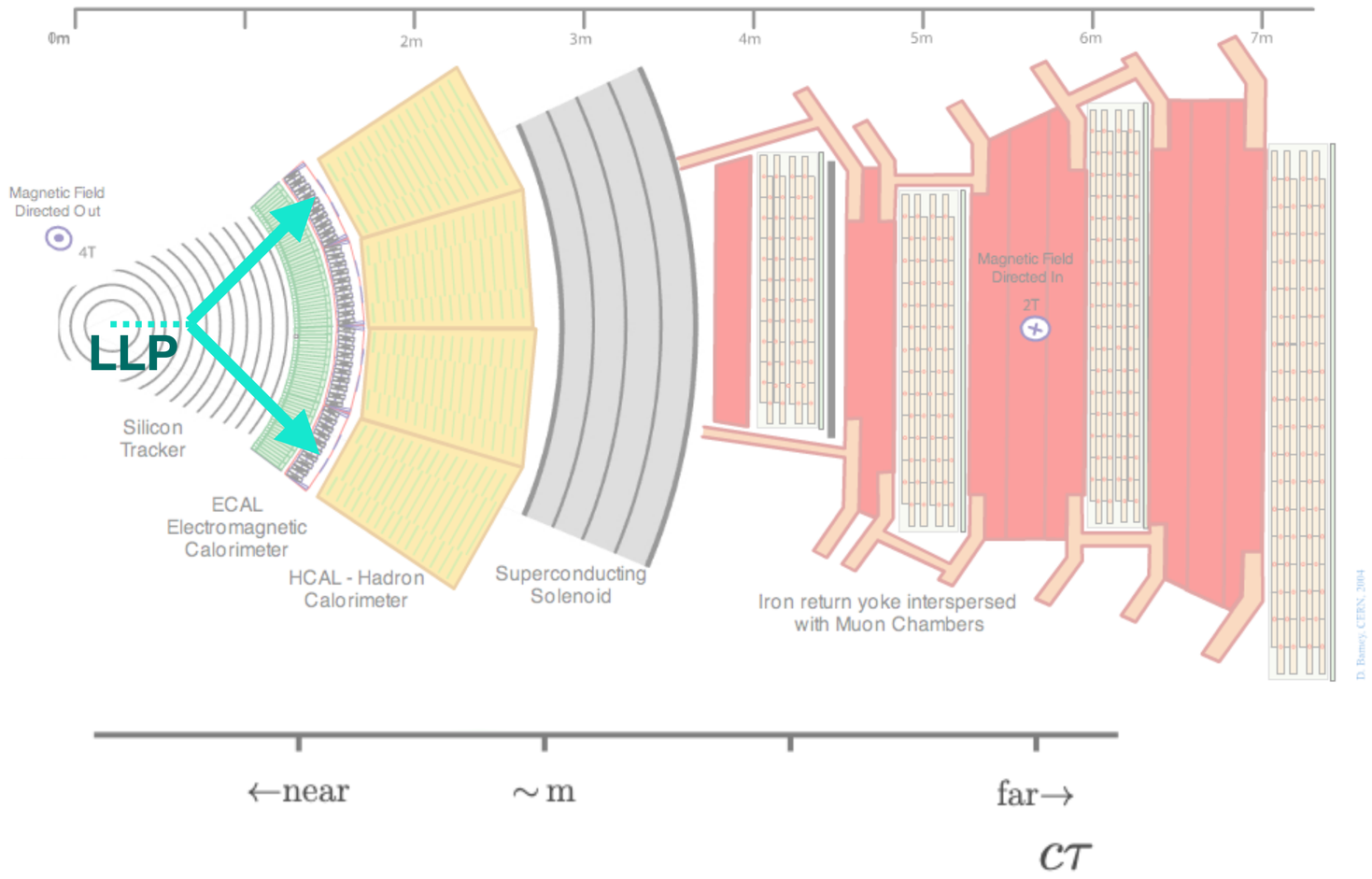
# LLP Decay Region

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



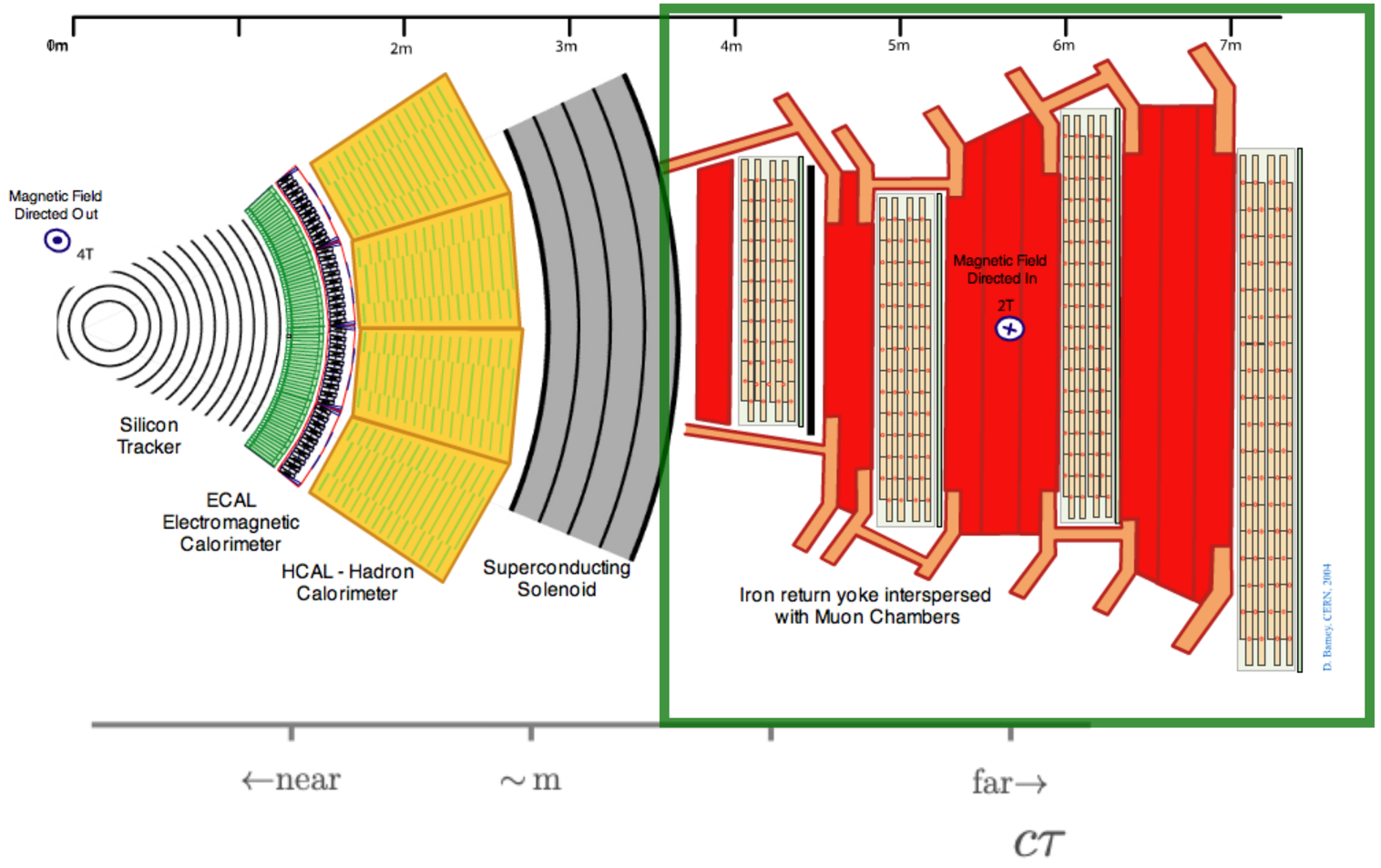

- Search strategy strongly depends on proper lifetime and boost of LLP
- Every sub-detector is important

# LLP Landscape in CMS




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

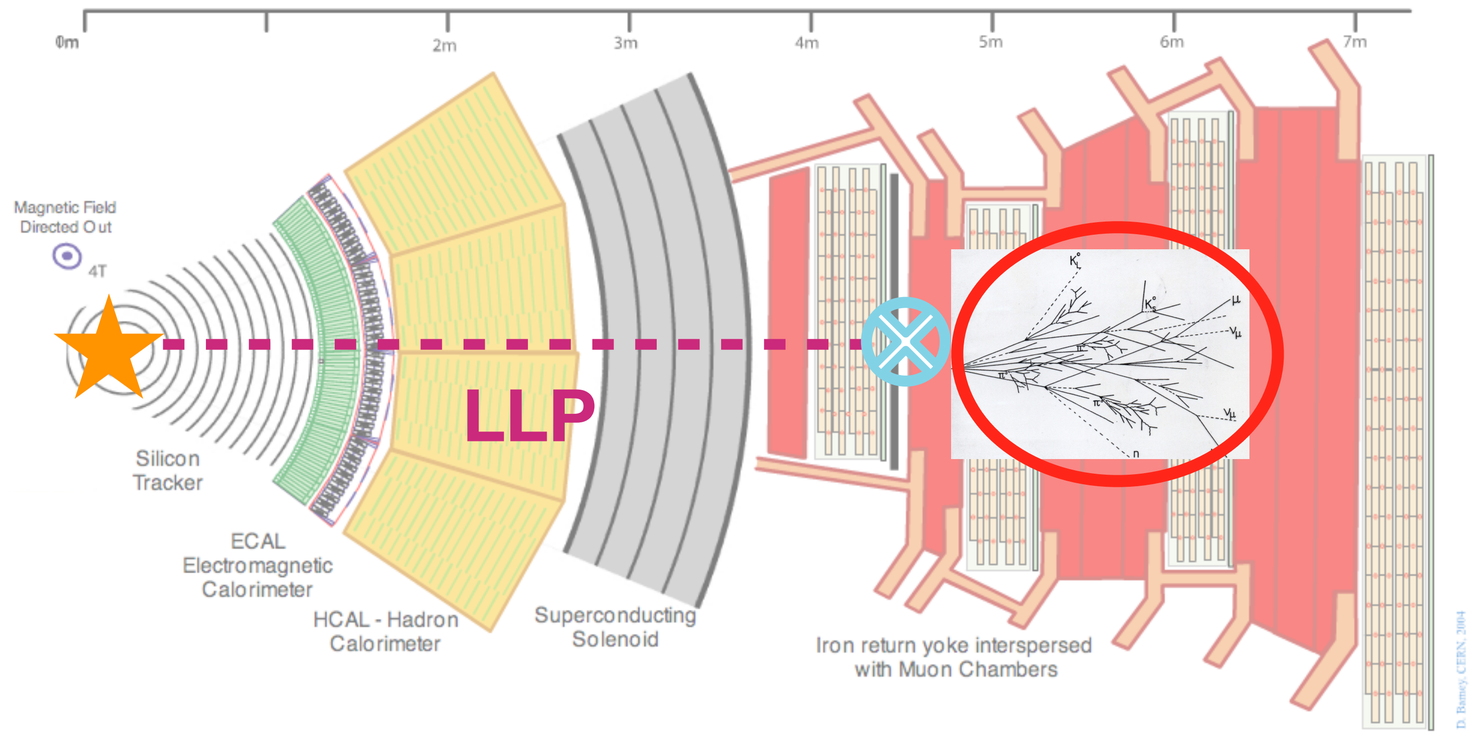
# Close gaps in search coverage




Muon detector

**Searches for light LLP with large c$\tau$ using LLP decays in the muon detector**

# Search for LLPs in Decaying in CMS Muon System

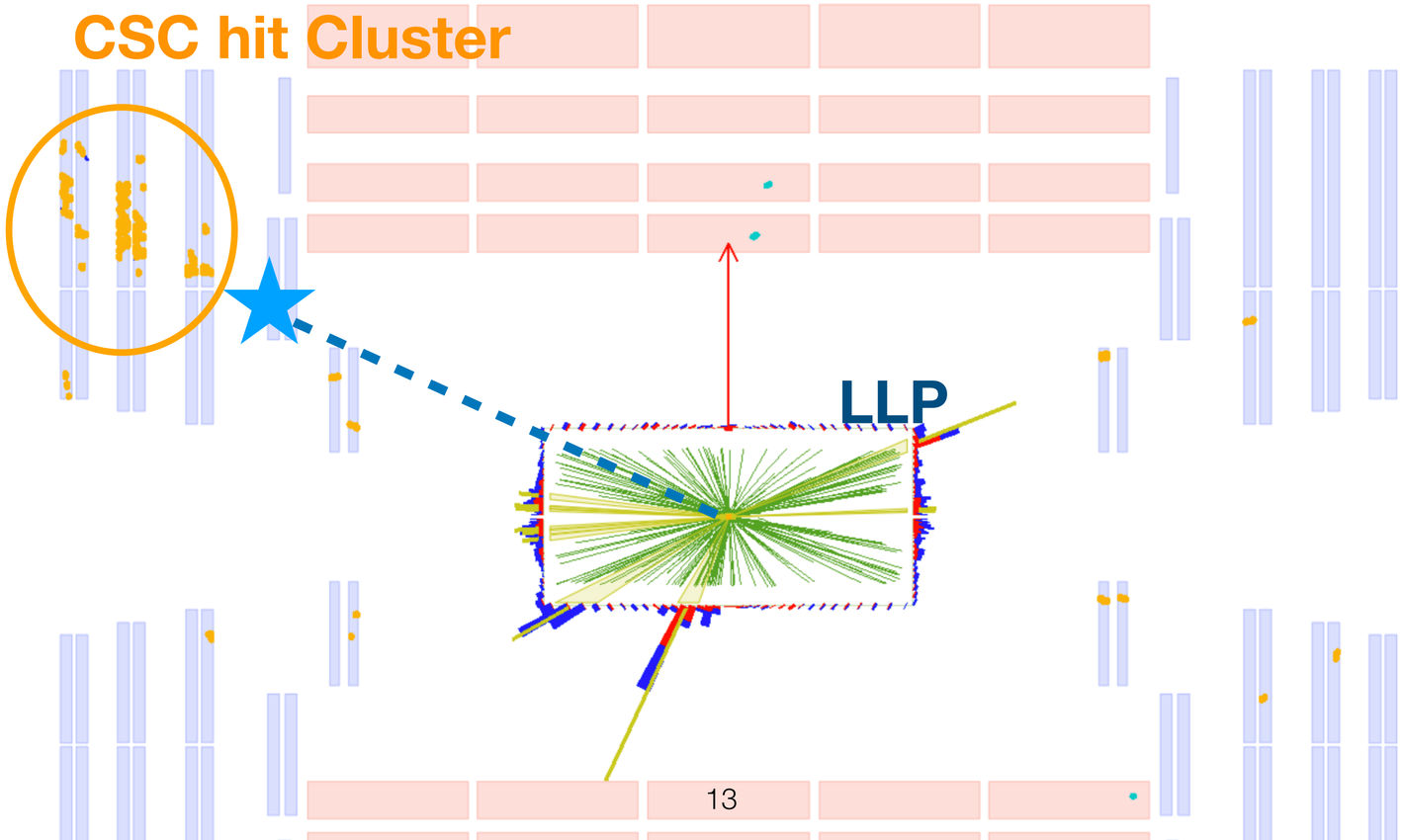



LLP decay results in particle shower with **large hit multiplicity**

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

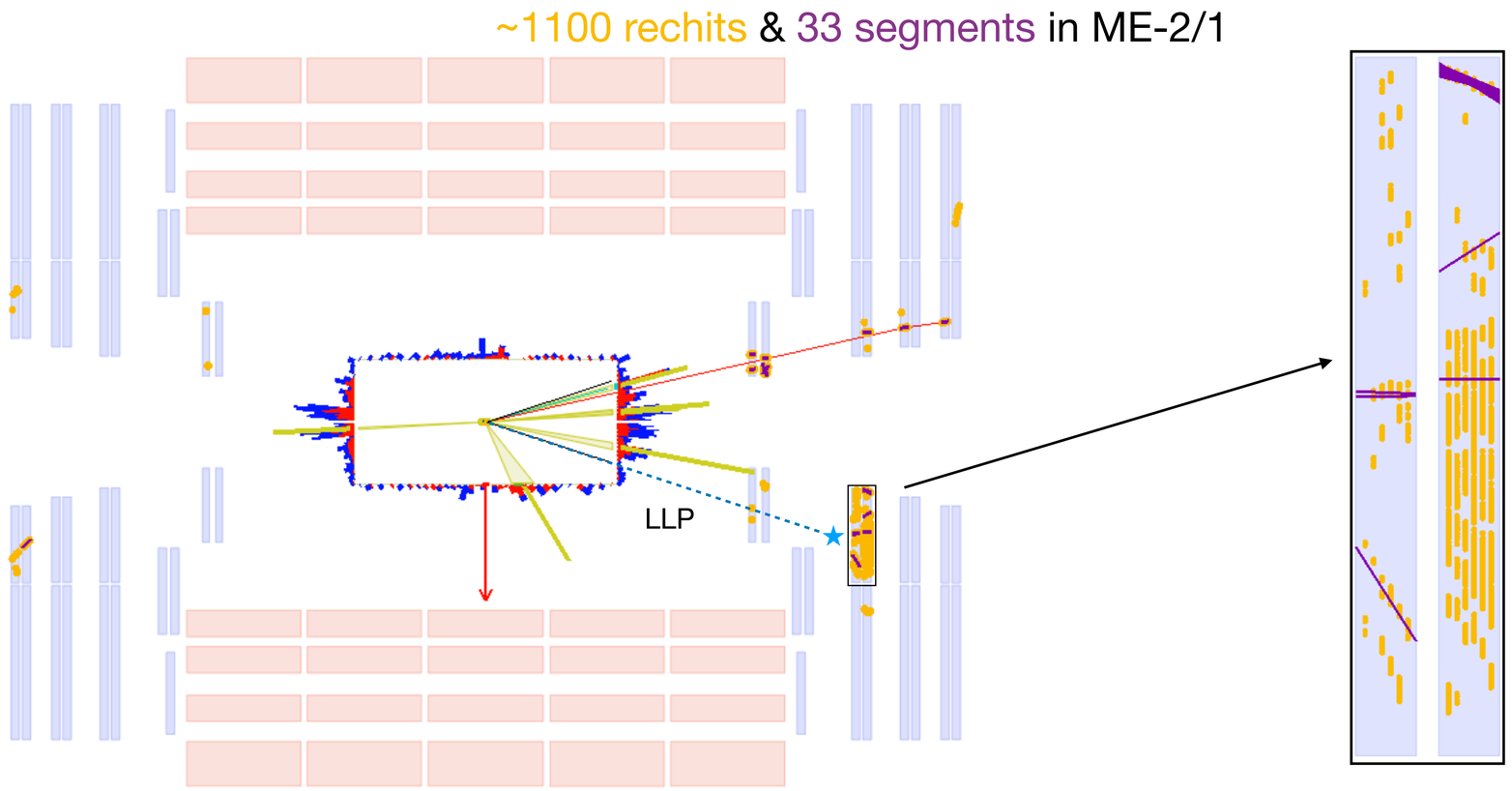
# Search for LLPs with Muon Detector Showers

- Large **cluster of hits (>100 hits)** in the muon system with no jets or tracks
- **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



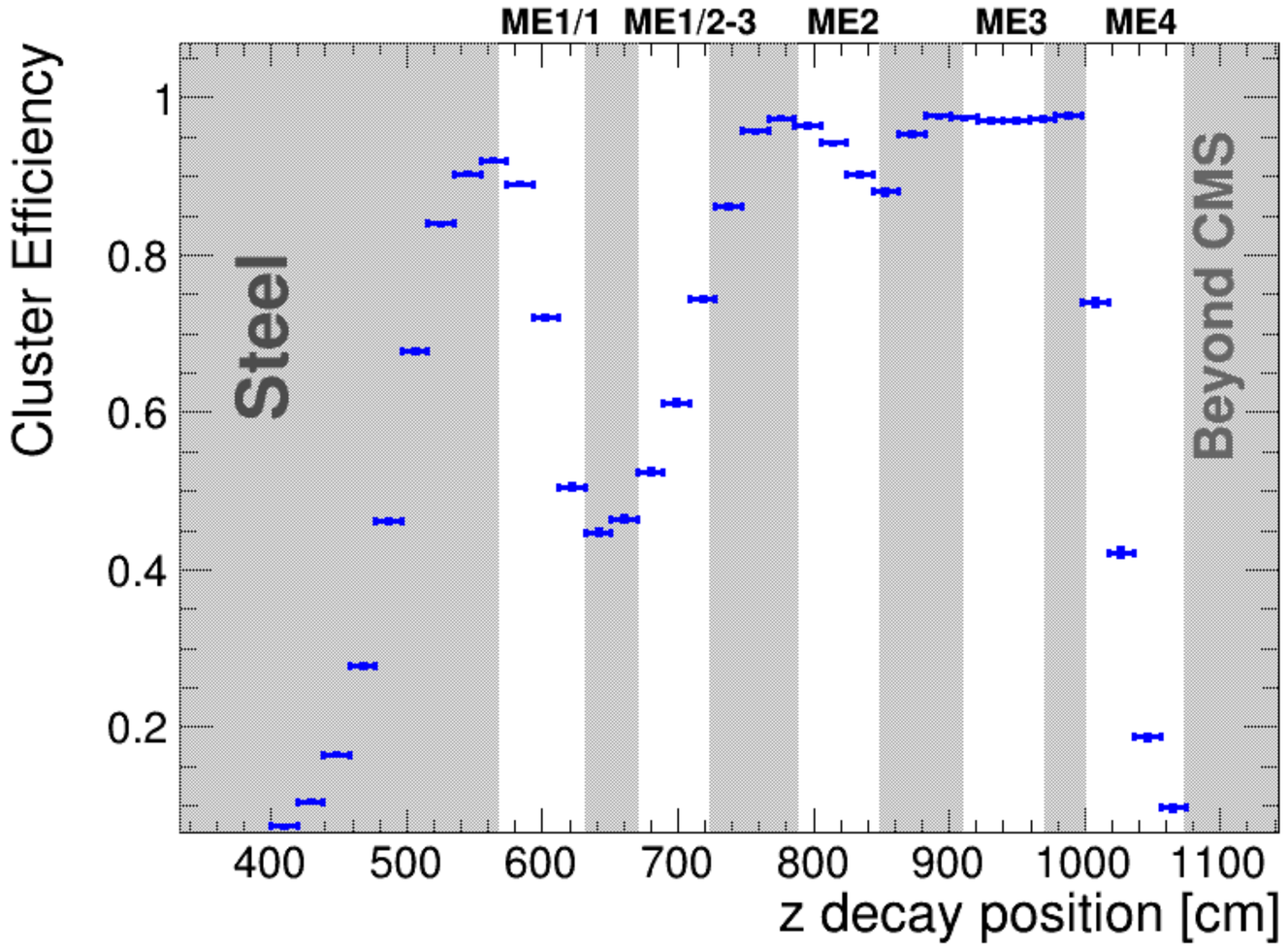
# Reconstruction for MDS

- 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)**



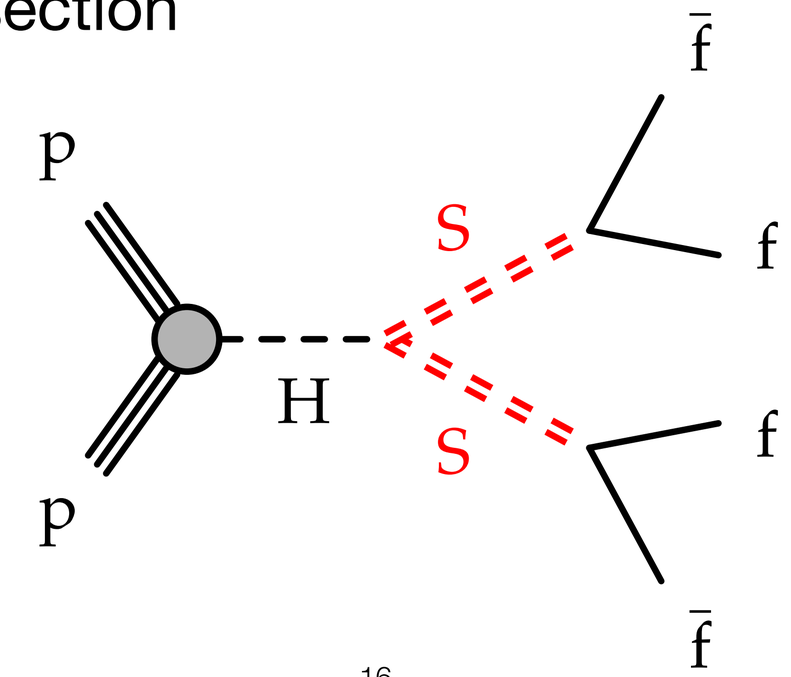
# Reconstruction for MDS in Endcap

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



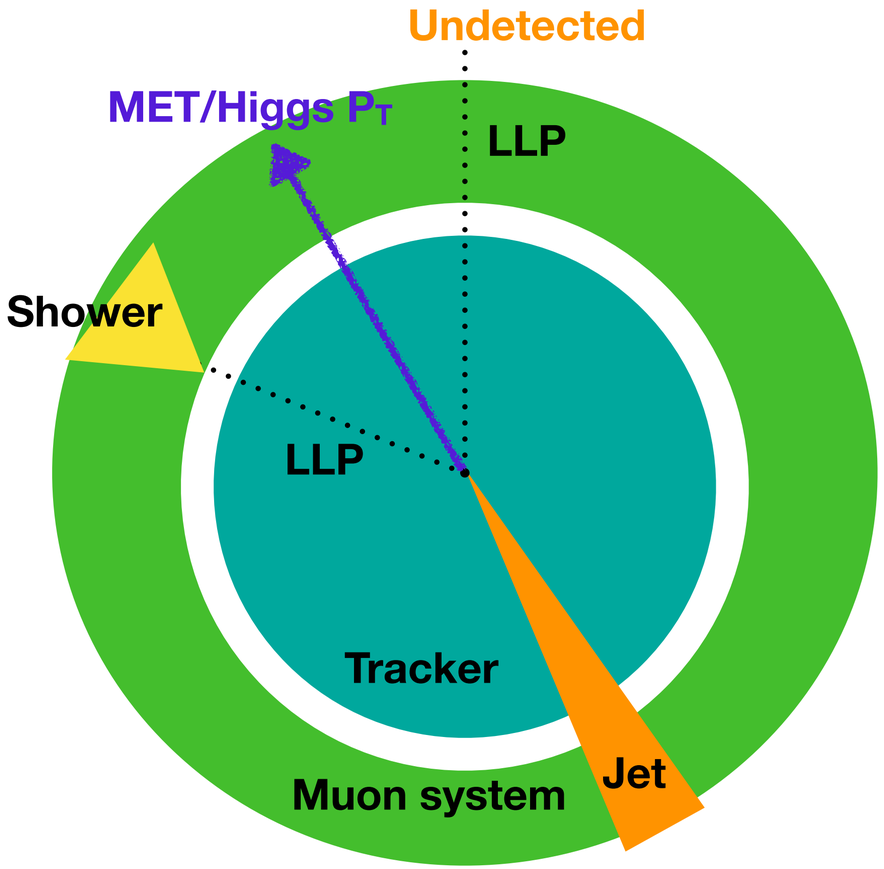
# Benchmark Signal Model

- 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



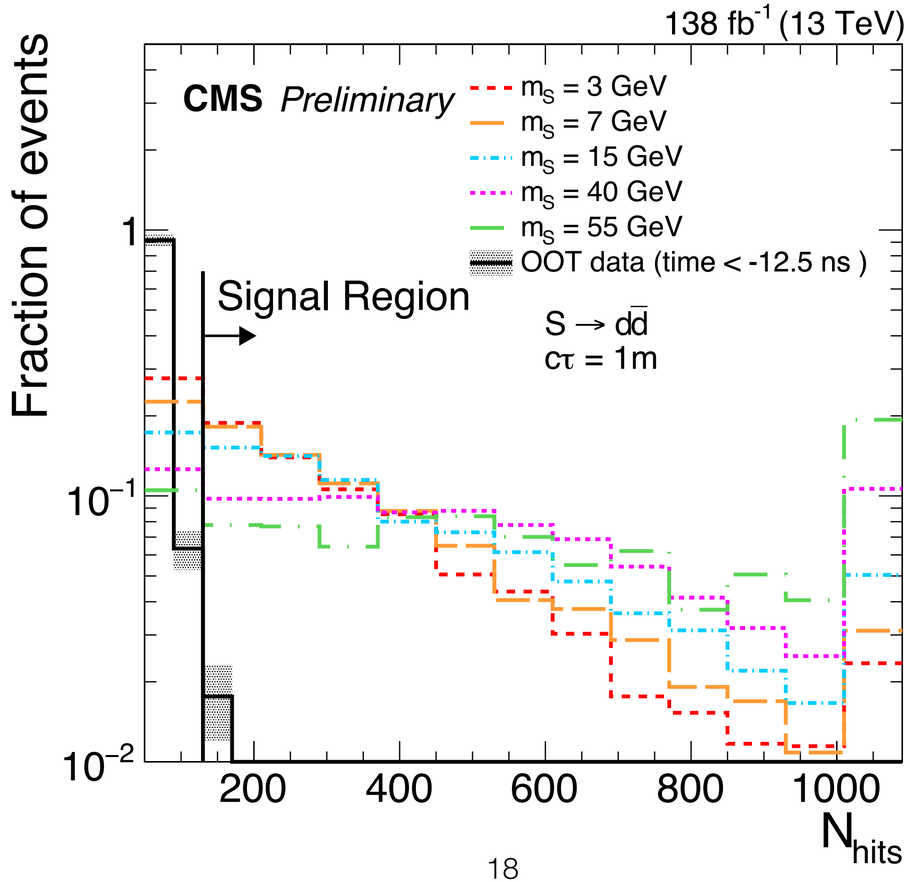
# Trigger Strategy

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



# Analysis Strategy

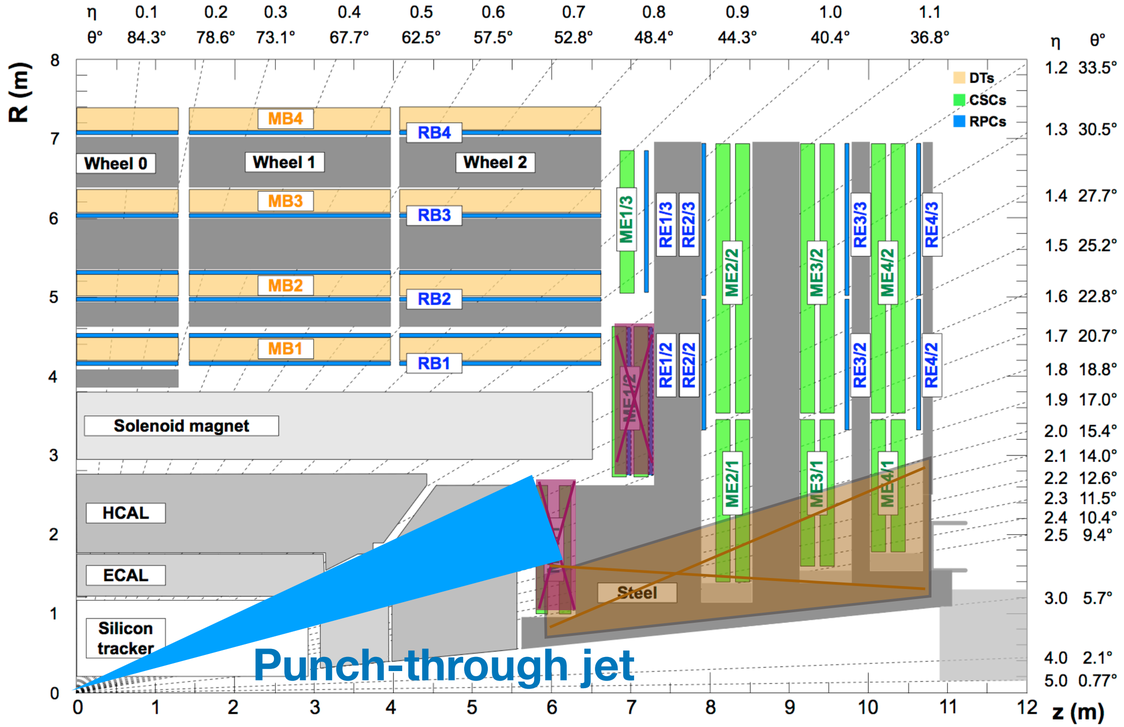
- **Event selection:** select high MET (MET > 200 GeV) and boosted Higgs phase space
- Focus on **endcap muon detector** in this exercise and apply cluster-level selections to achieve $10^6$ background rejection
- $N_{hits}$ serves as the main discriminator



# 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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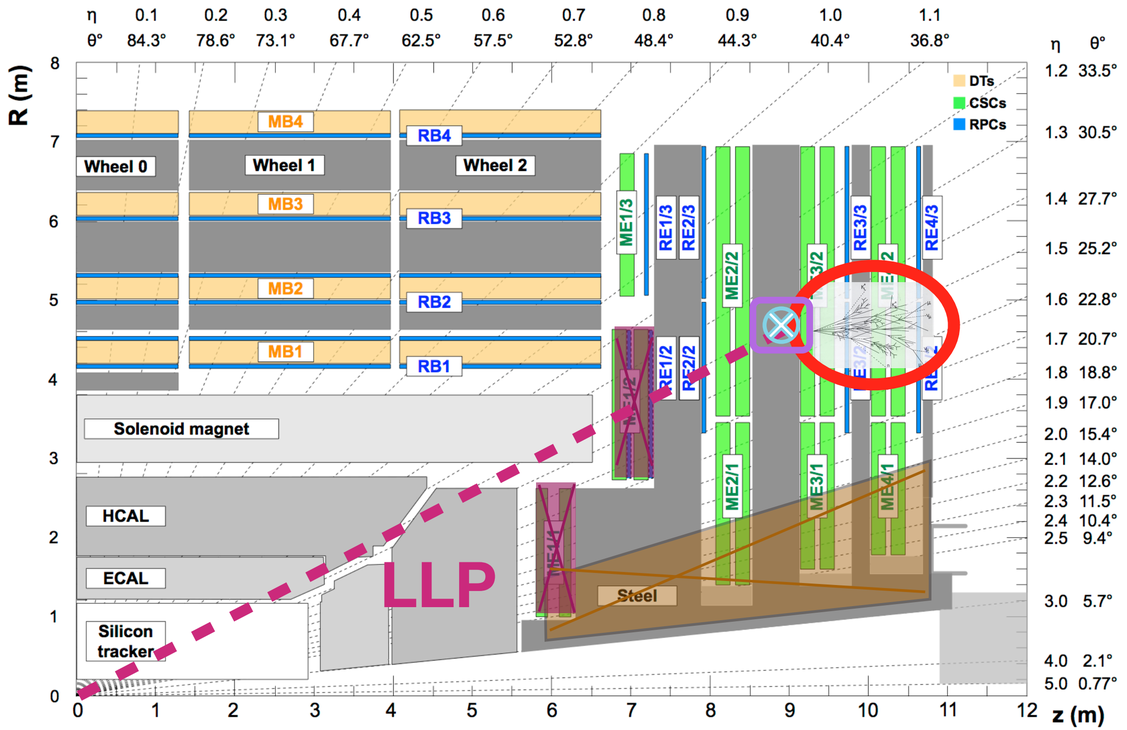
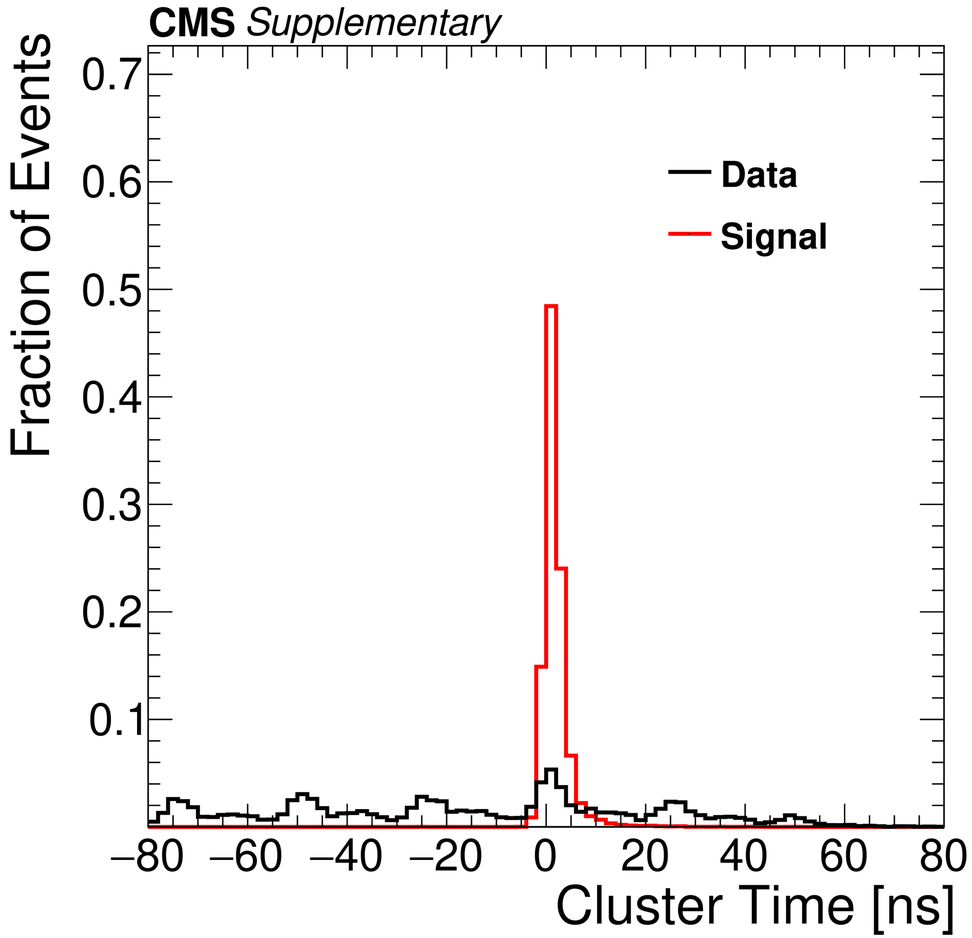


# Cluster Time

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

- 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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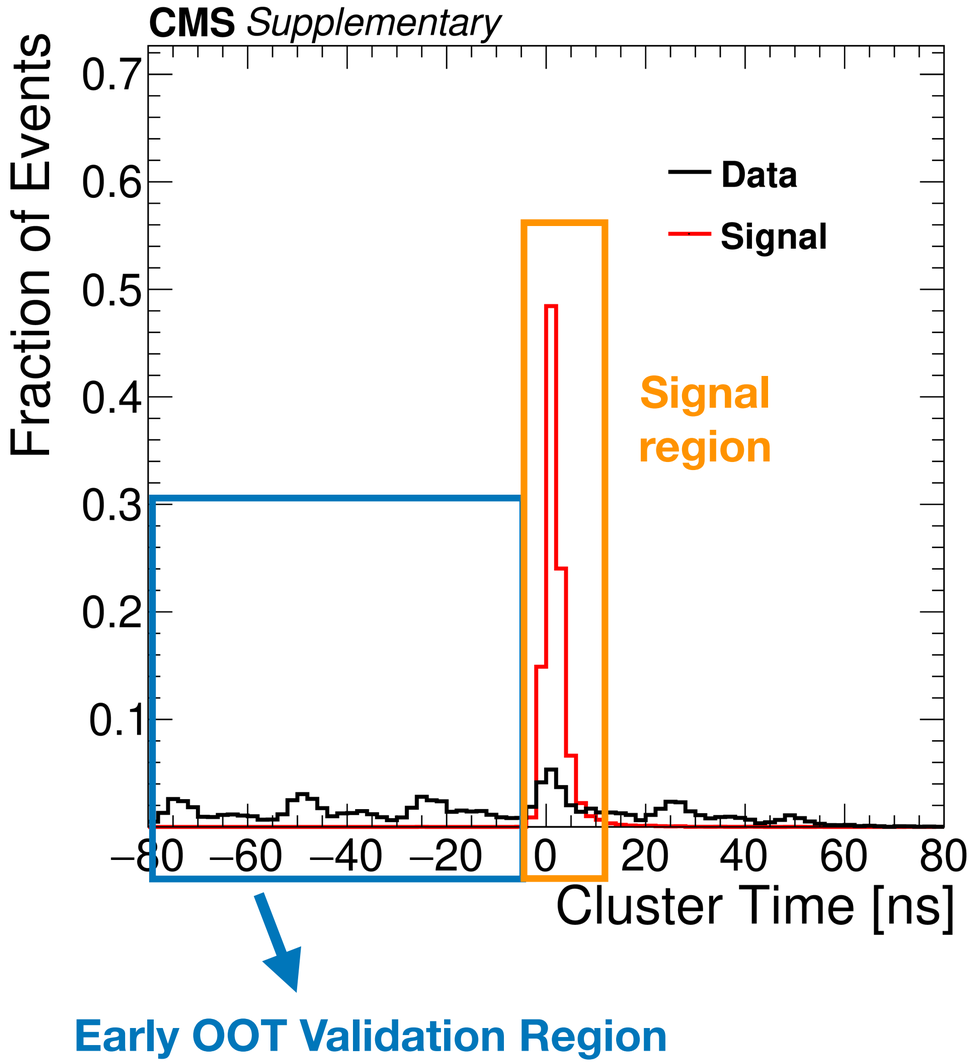
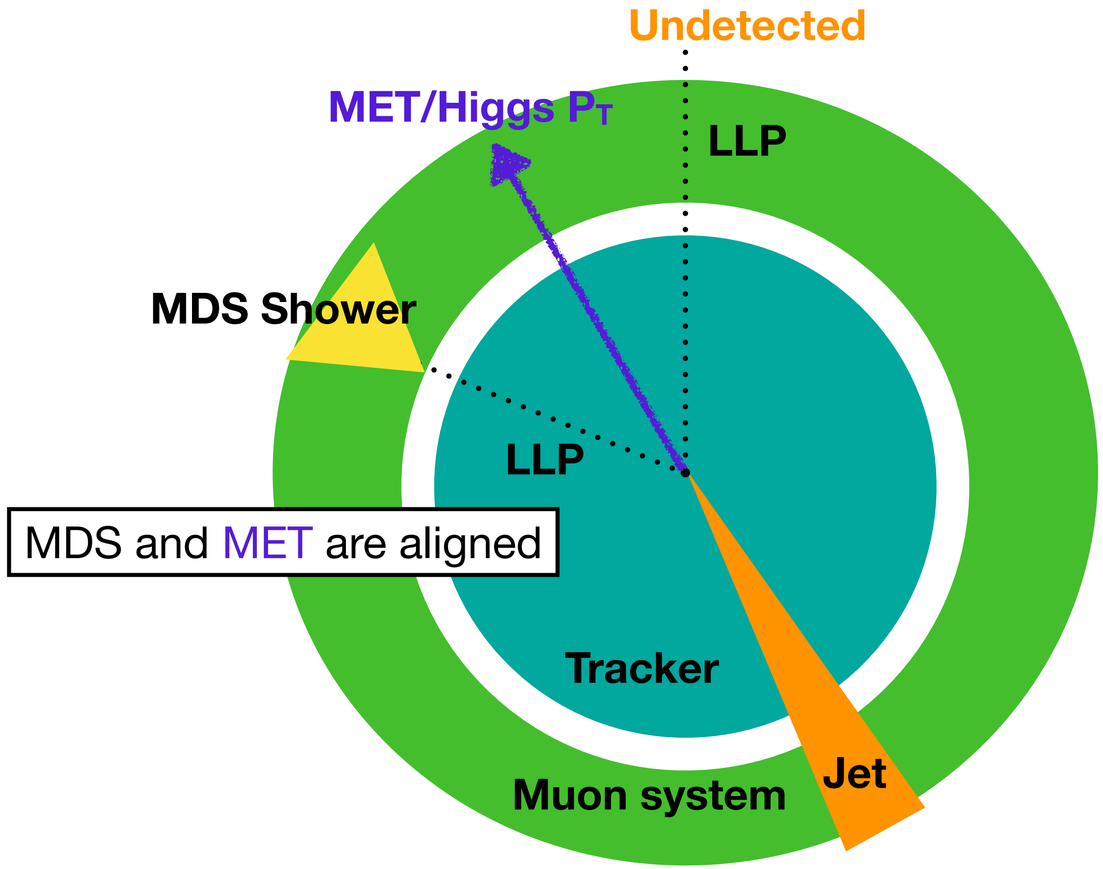
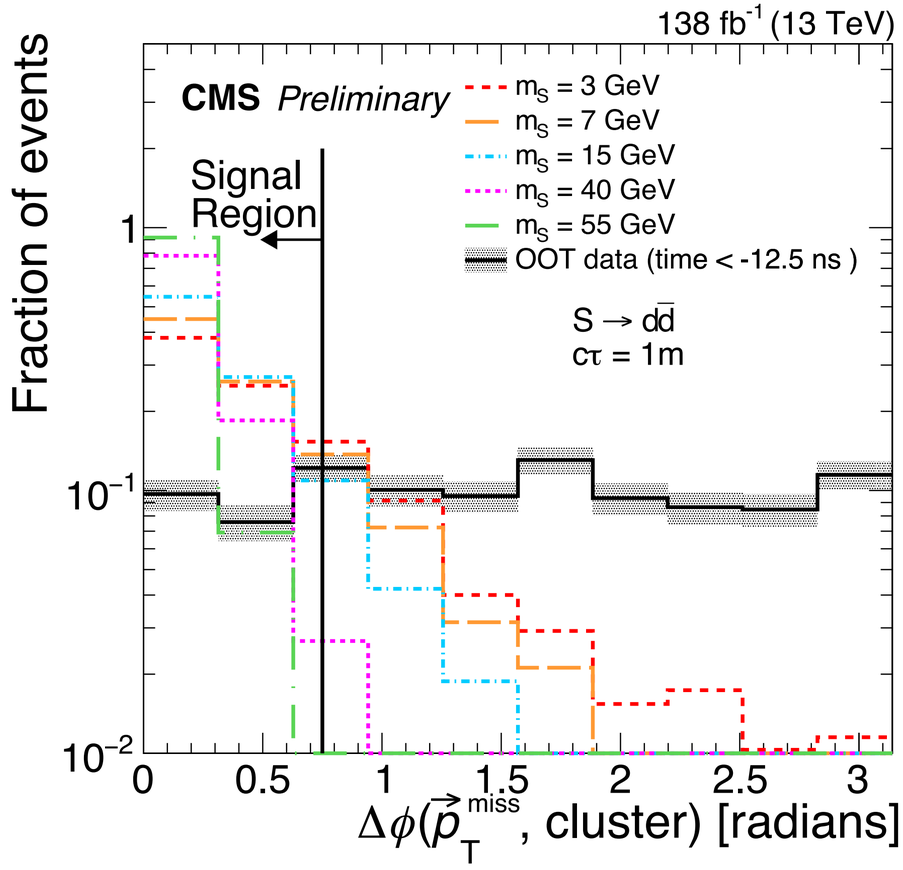


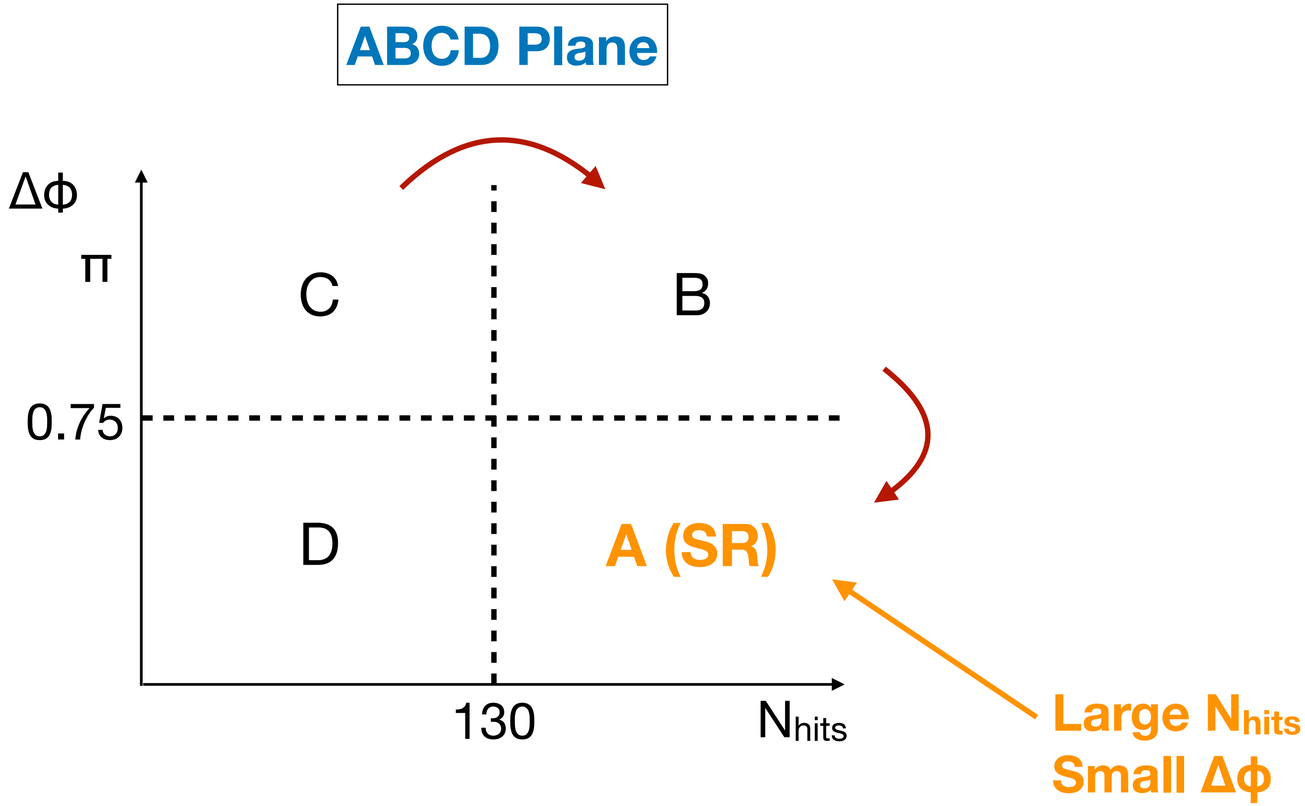
# $\Delta\phi(\text{cluster}, \vec{p}_T^{miss})$




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

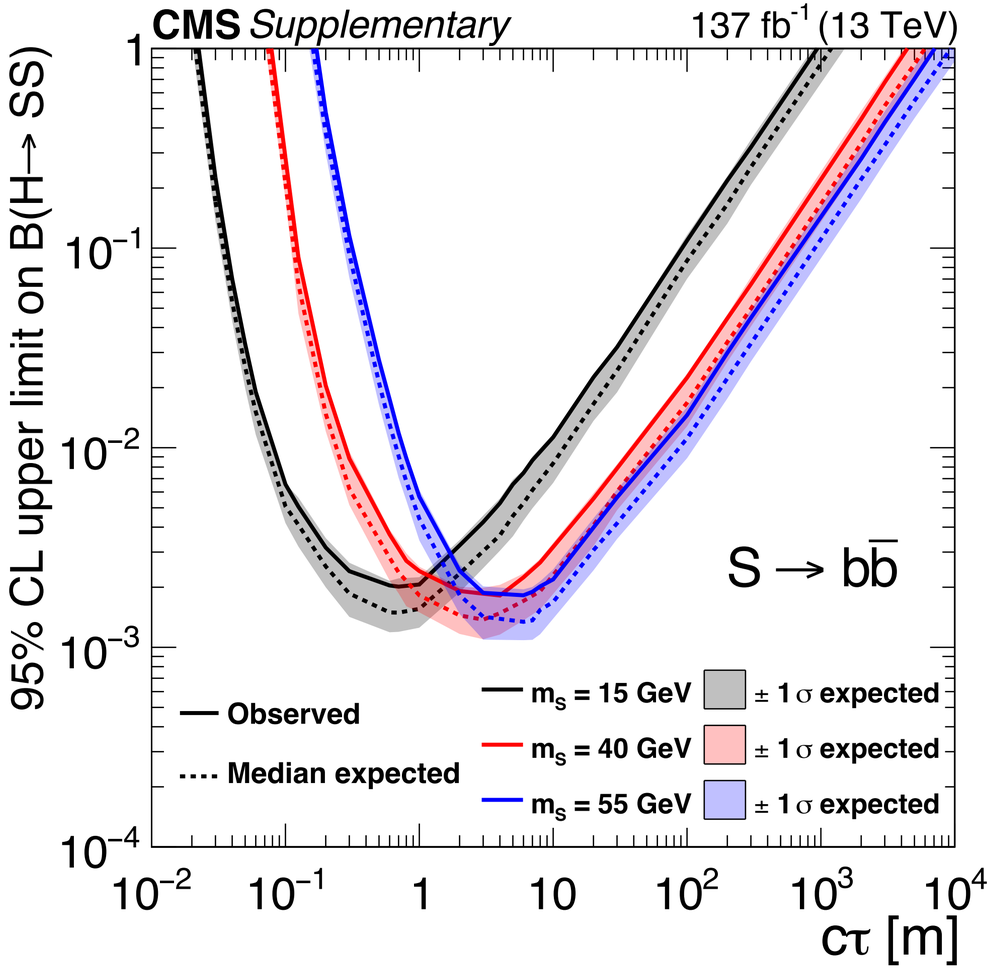



$$A = B \times \frac{D}{C}$$

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

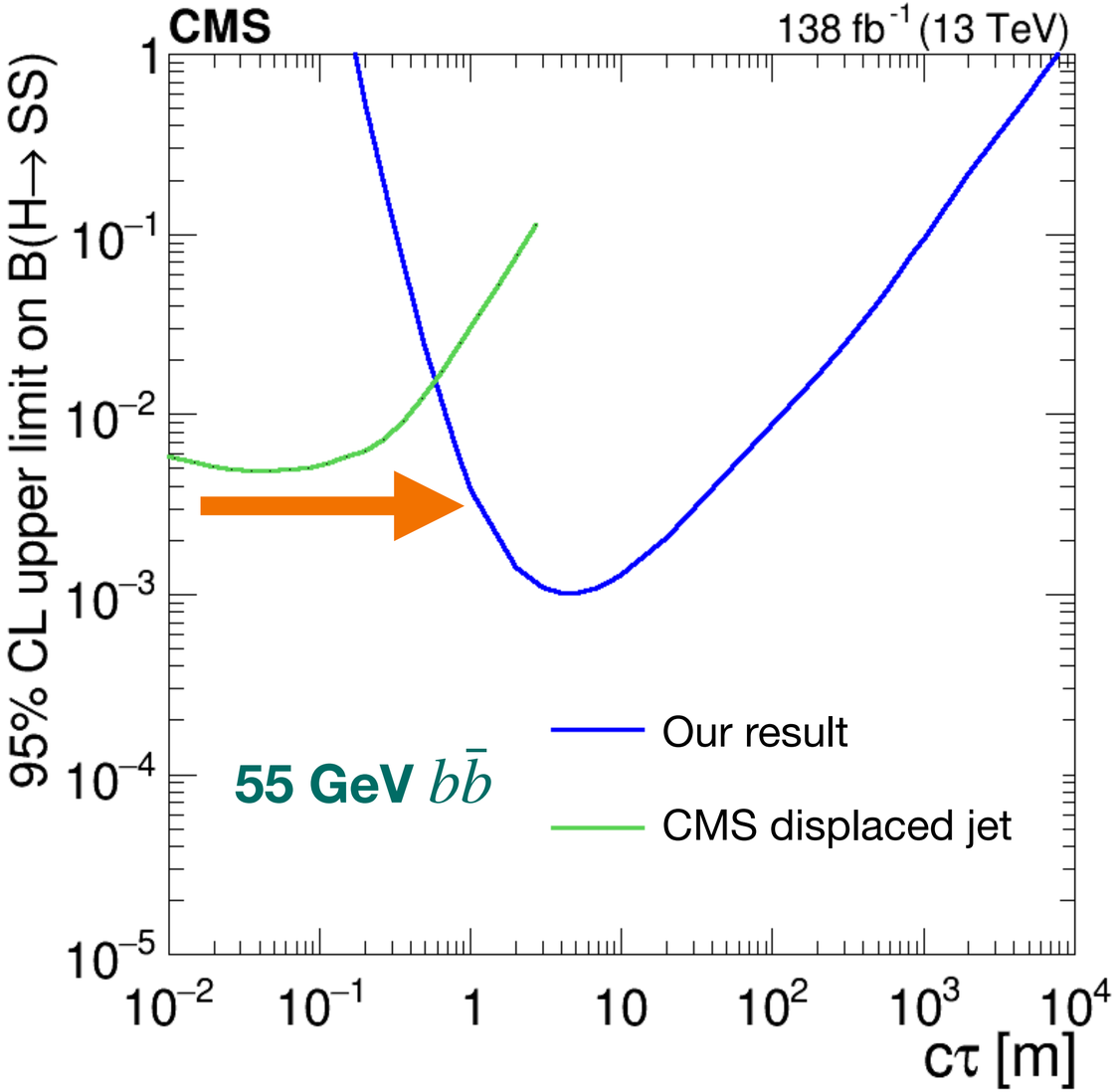
# Observed and Expected Limits

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




- No excess above SM background observed: 3 events observed (2 ± 1 bkg predicted)
- Achieve sensitivity to BR(H →ss) = $10^{-3}$ level
- Analysis sensitivity is **independent of LLP masses**

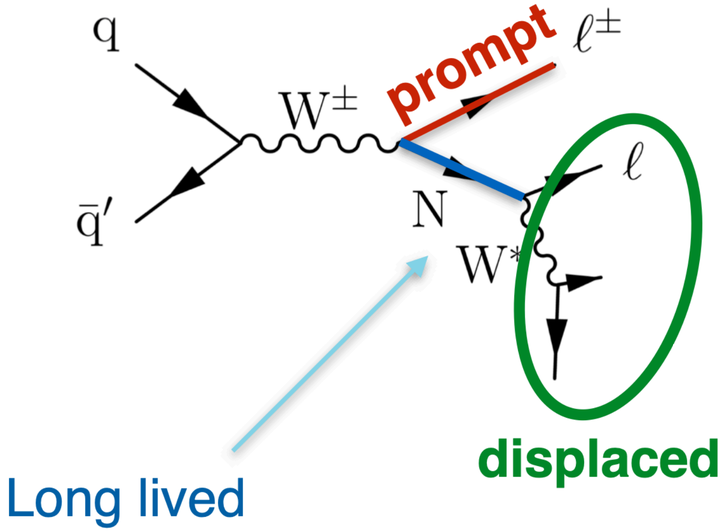
# Comparison to Other Searches

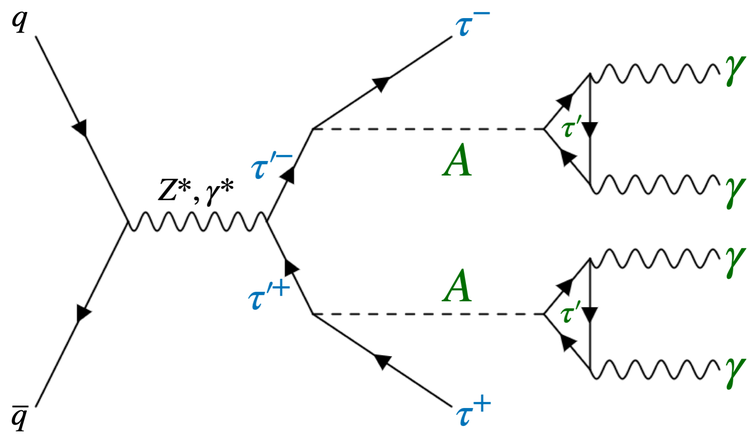


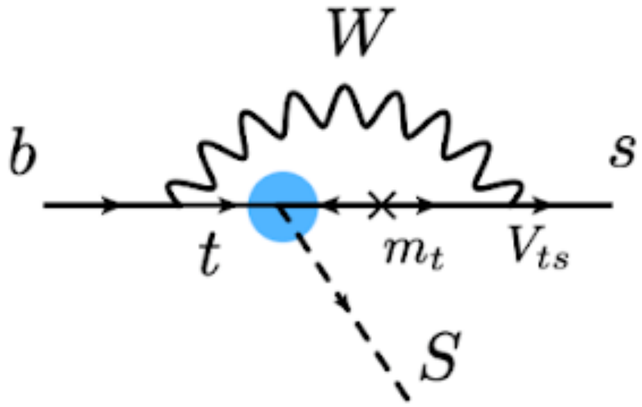

Significantly extended the reach to larger LLP lifetime compared to tracker-based searches

# 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

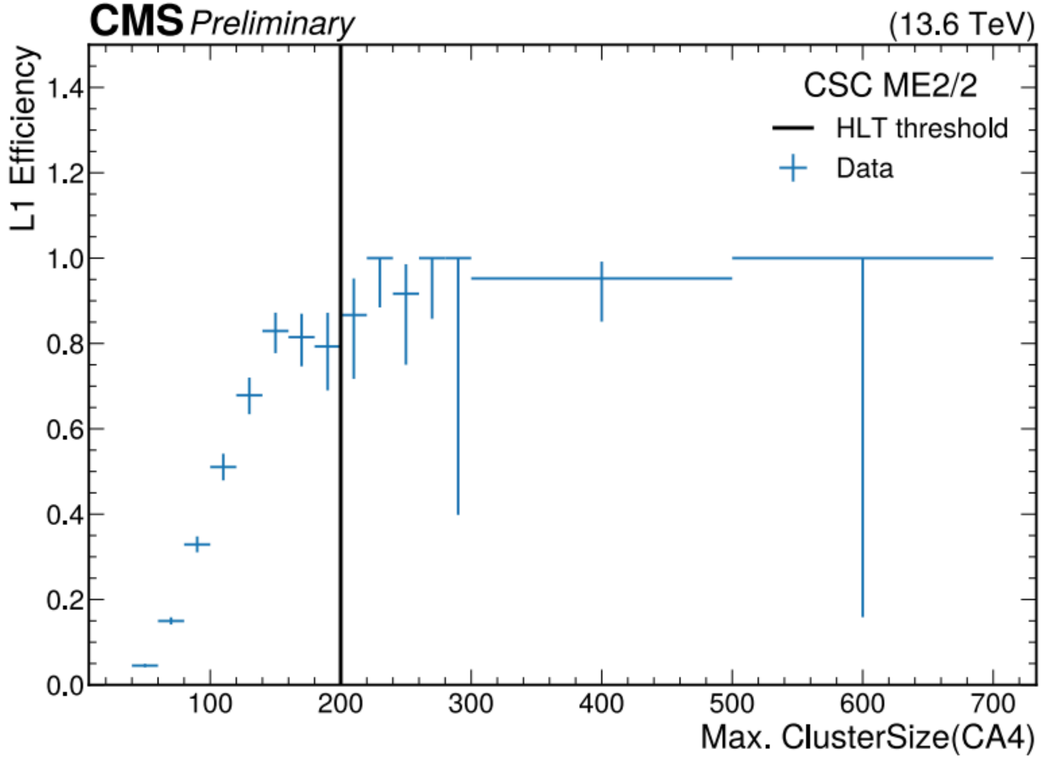


# CMS LLP Physics Program with MDS (Run 3)

- **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 + $e, \mu, \tau, \gamma$)
- 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
- 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!

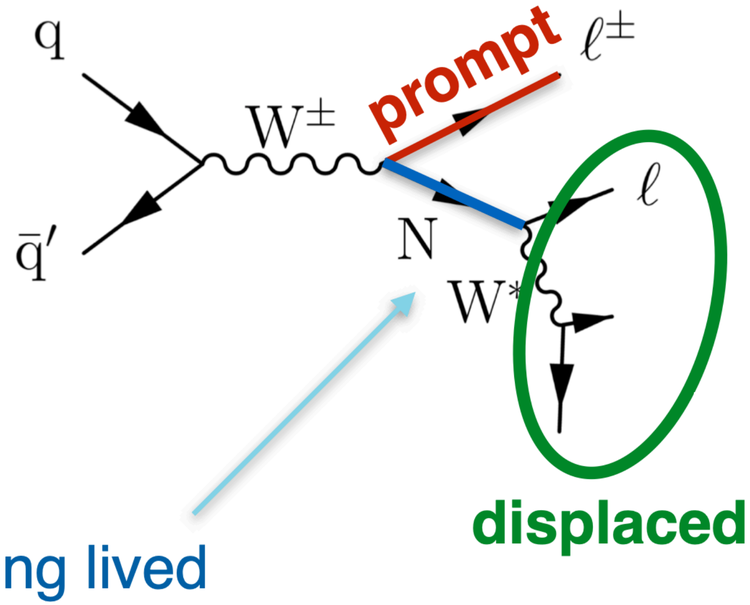
# Schedule

| | | |
|---|---|---|
| | Setup | Download files required for the lesson |
| 00:00 | 1. Introduction | Why do we search for long-lived particles?<br>Why do we use muon detectors?<br>What signatures are we looking for? |
| 00:30 | 2. Long-lived Particles (LLPs) | What is a long-lived particle?<br>What is a particle proper decay lengths and lab frame decay lengths?<br>How often does an LLP decay in the muon detectors? |
| 02:40 | 3. MDS Reconstruction | What is Muon Detector Shower (MDS)?<br>How are MDS reconstructed? |
| 06:10 | 4. Analysis Strategy | What trigger do we use?<br>What selections do we make to select for signal clusters and reject background clusters?<br>What are the remaining background compositions for MDS? |
| 08:25 | 5. Background Estimation | What are the source of background for MDS?<br>How do we estimate the background contribution? |
| 09:25 | 6. Results and Statistical Analysis | What is the unblinded result?<br>How to constrain the ABCD relationship for background in datacards? |
| 12:25 | 7. Event Display (optional) | How to make event displays of interesting signal simulation? |
| 13:25 | Finish | |

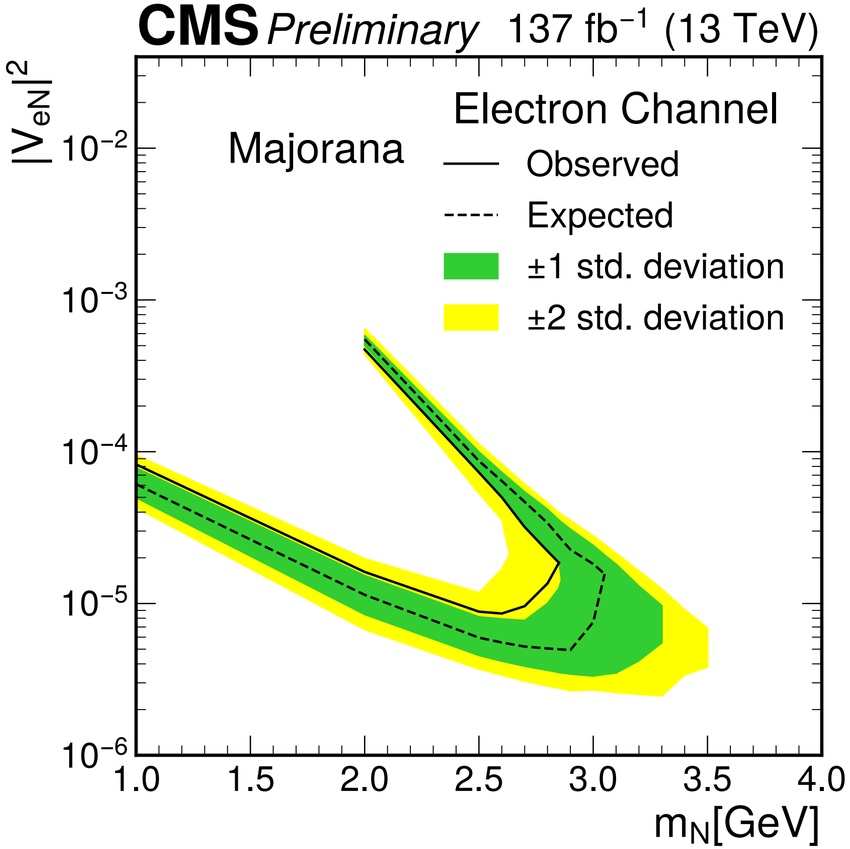
# Backup Slides

# 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

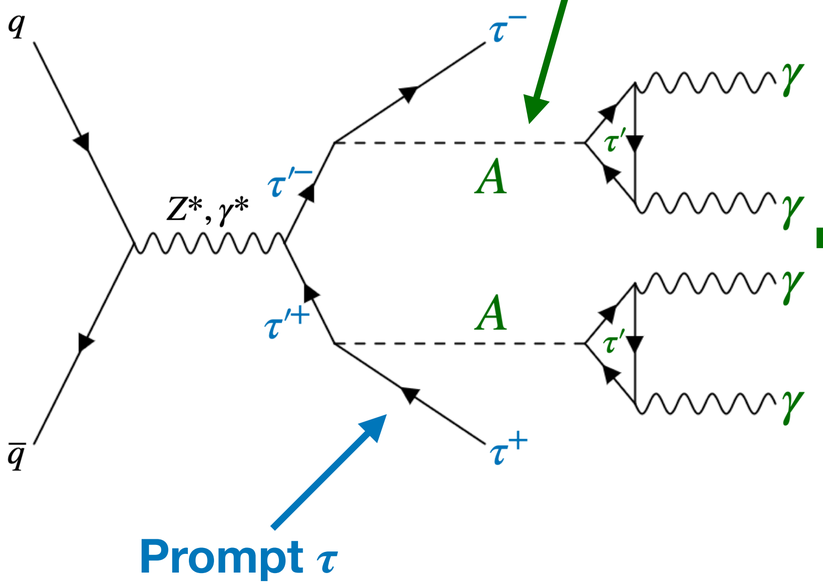
# Search for Vector-like Leptons with MDS

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

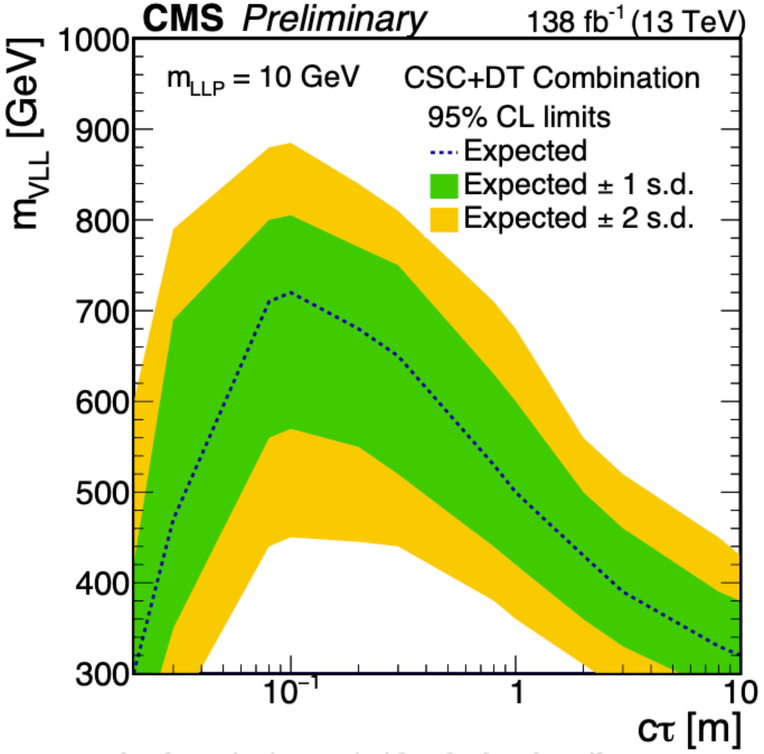
  **Two prompt $\tau$'s and two electromagnetic LLP decays in muon system**

- MDS + $\tau_h$ 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: $c\tau_A \propto \frac{m_{\tau'}^2}{g_A^2 m_A^3}$



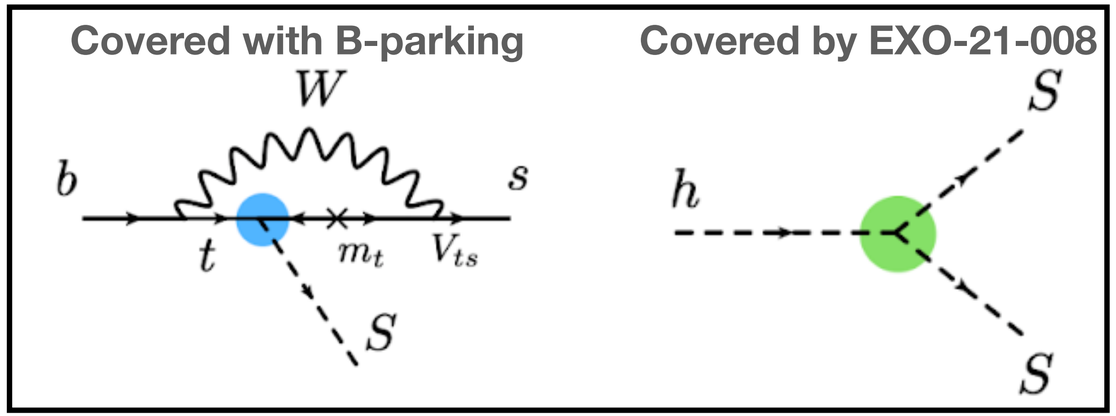

Photon-initiated showers in muon detectors

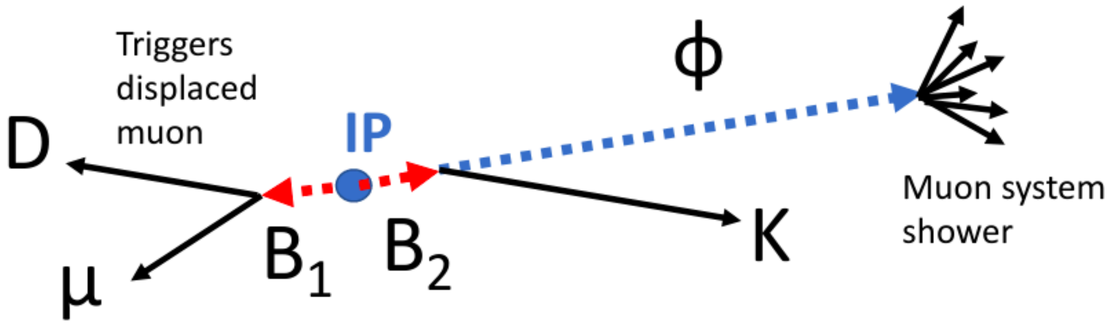


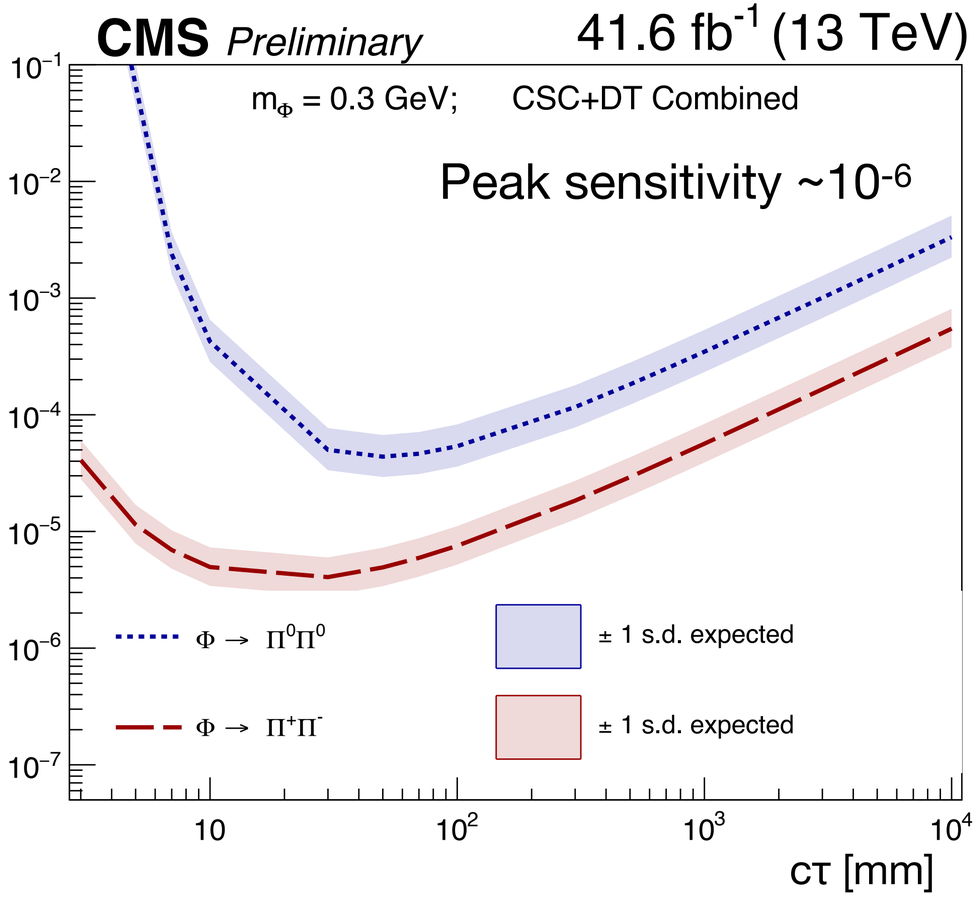
# Search LLPs from B Decays with MDS

- 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**



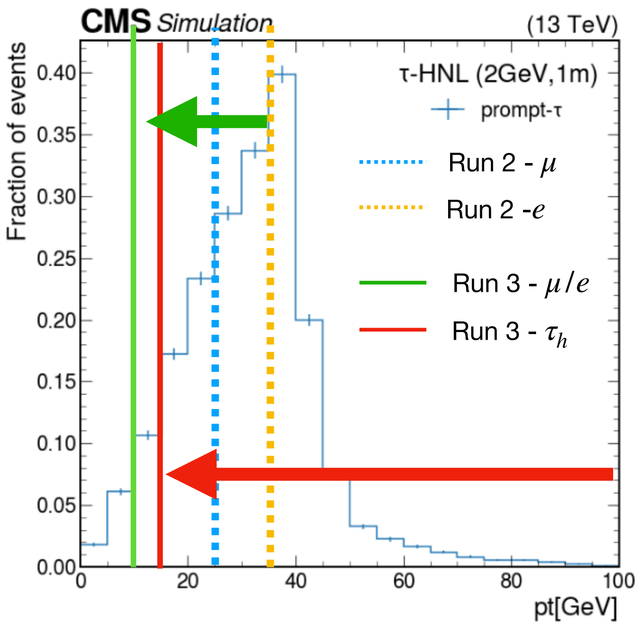



# Physics Impact

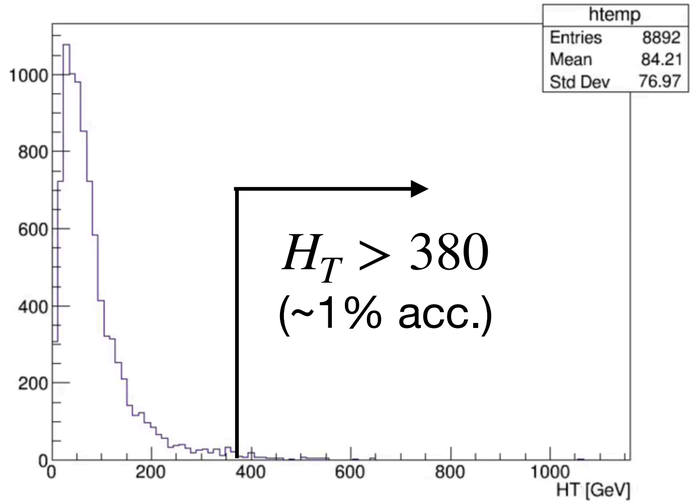
- Run 2 HNL acceptance limited by high lepton pT threshold - especially for tau-HNL
  - New triggers accepts 17%(Muon) / 114% (Electron) / ~400% (tau) more signal events w.r.t Run 2
    - Lower lepton pT + cluster selections included in new trigger
  - **New** hadronic channel alone gives 3-4x more signal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






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

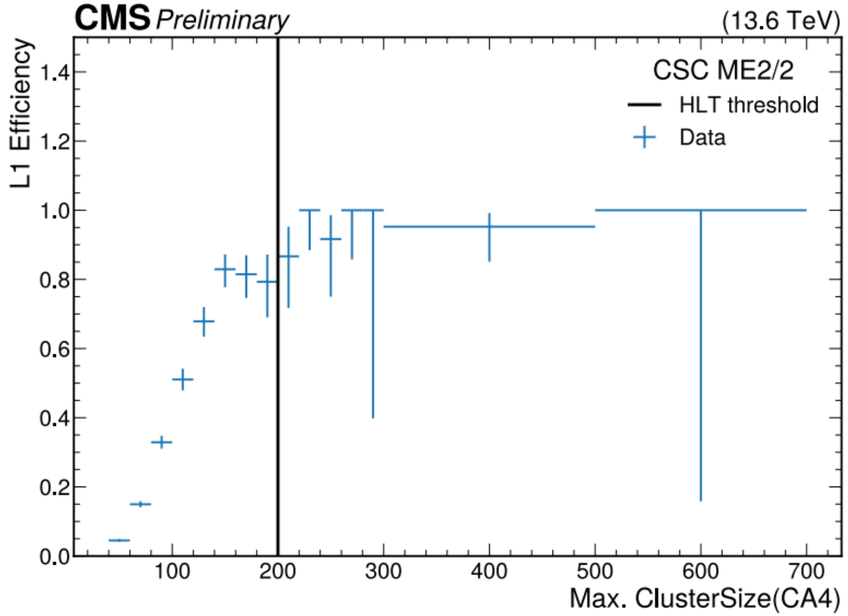
- Total rate of all 4 paths **~10 Hz**
- Minimal overlap with single MDS path (nHit>200+)
- Exploring further improvements:
  - Mu5/Ele5/Tau10 with tighter cluster size cut
  - Use PNet ID for tau instead of DeepTau

**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

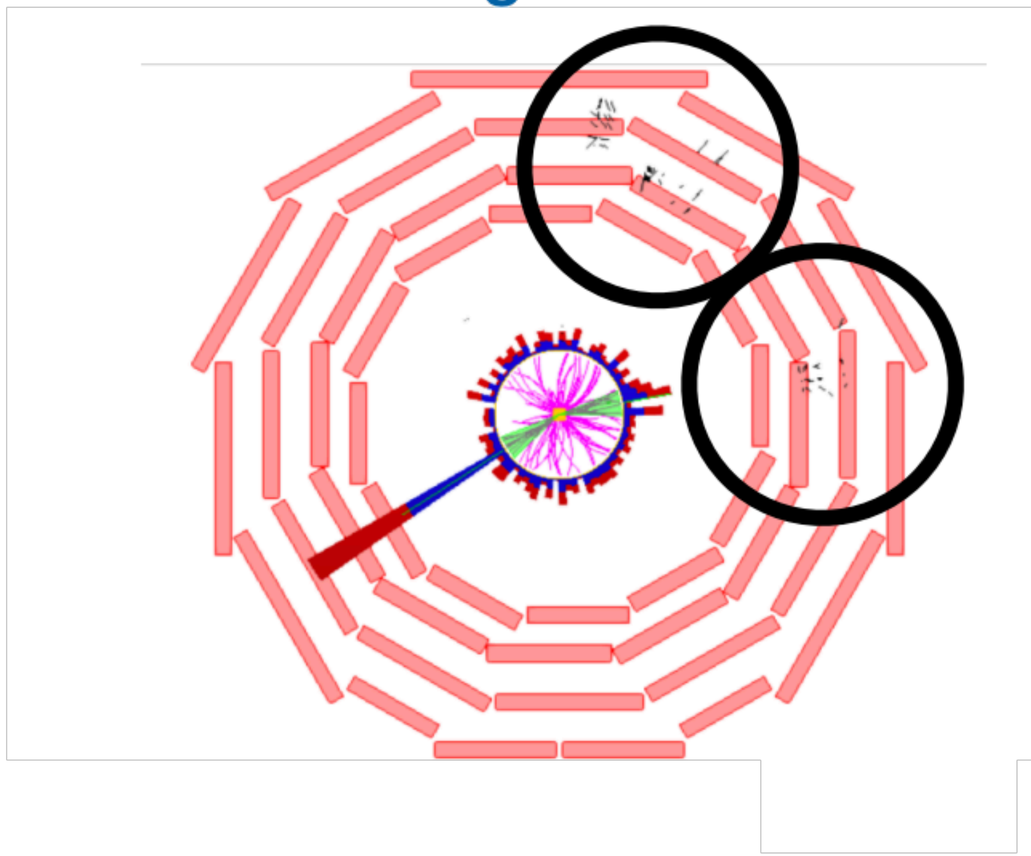


# Muon Shower Triggers in 2023

- 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 | - |

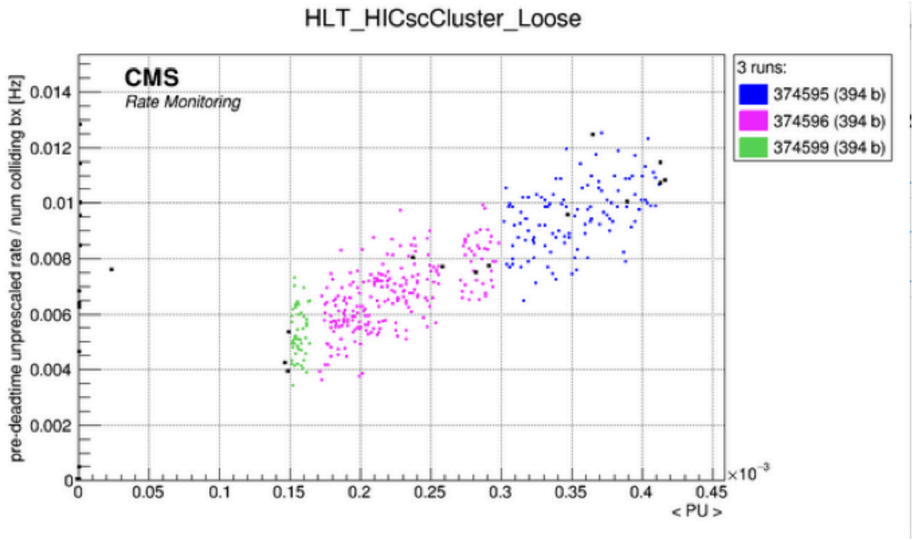
Double shower events from signal MC



# 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?

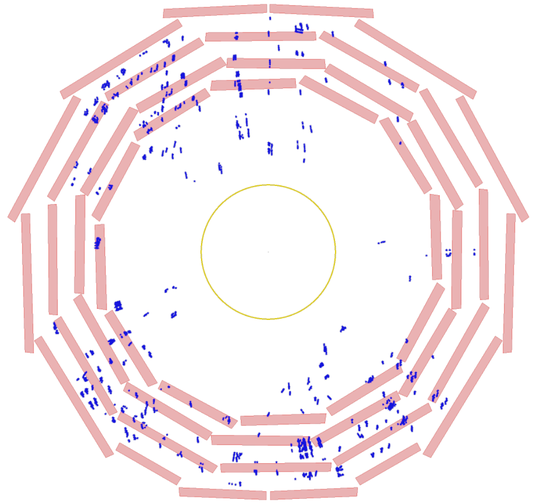
**HMT in Heavy-Ion collision**




**HMT in Heavy-Ion collision**

Run: 371290 Lumi Section : 382. Event 6001408

**An event with 13 Clusters!**



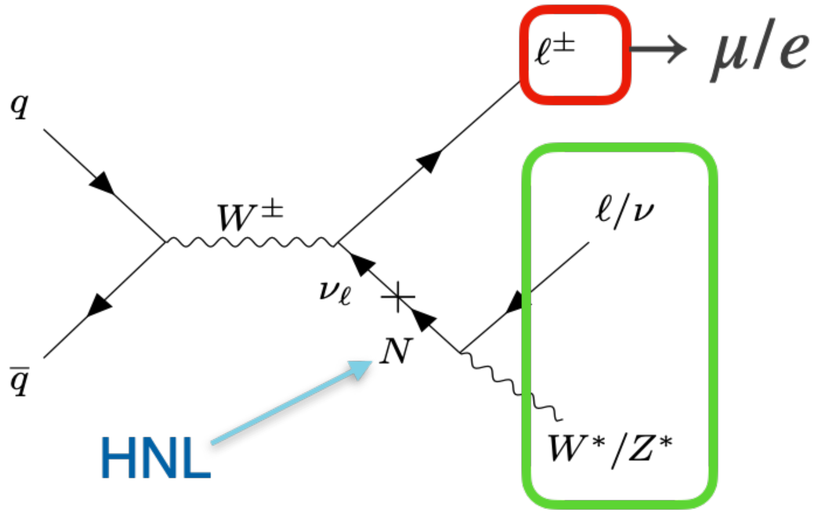
slides

# MDS + X ( X = $e, \mu, \tau, \gamma$) HLT Paths for 2024

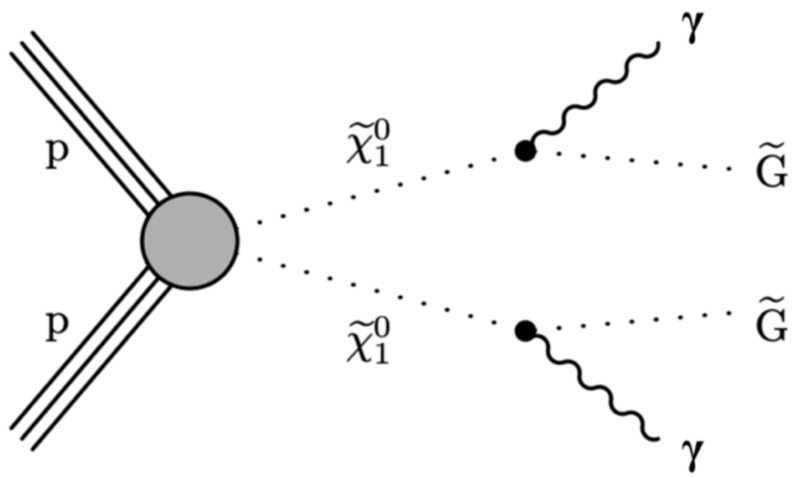
- MDS L1 seed is very effective in background suppression
- Exploit MDS with cross-triggers
  - Sensitive to LLP produced with associated objects
    - Long-lived HNL: e/mu/tau + LLP (Lower prompt lep pT)
  - EWK-SUSY: photon + LLP (No large HT requirement)
- Signal gain of 17% to ~400% w.r.t Run 2 analysis

More details at
Trigger deep dive

$\tau$-HNL



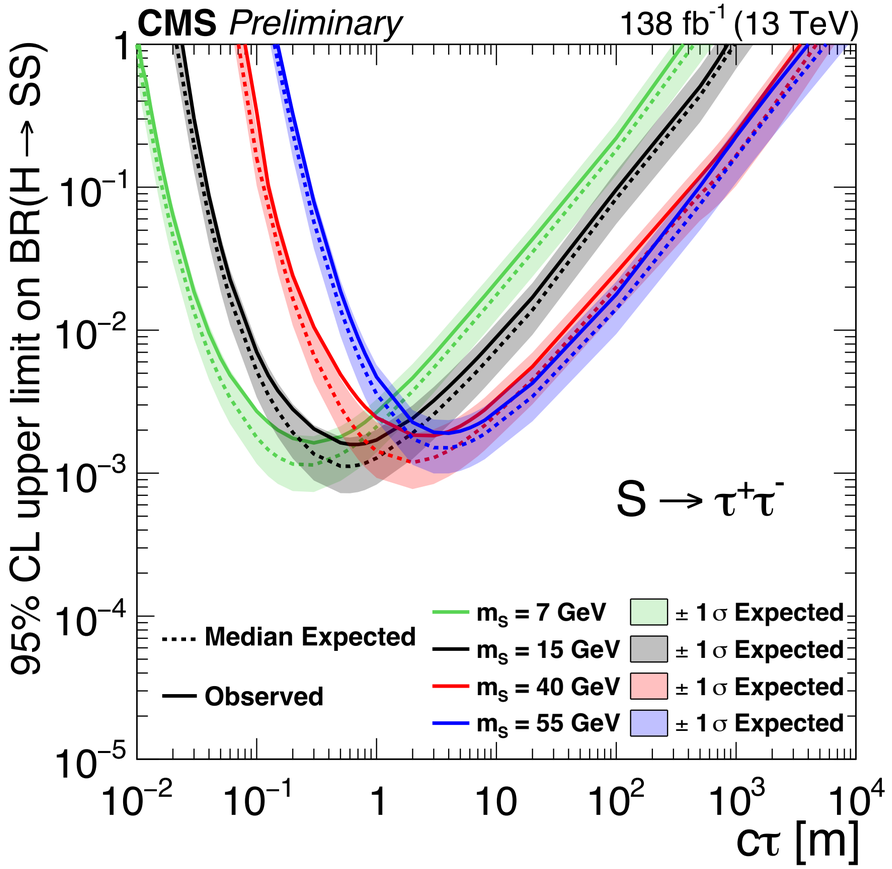

EWK-SUSY : MDS + $\gamma$



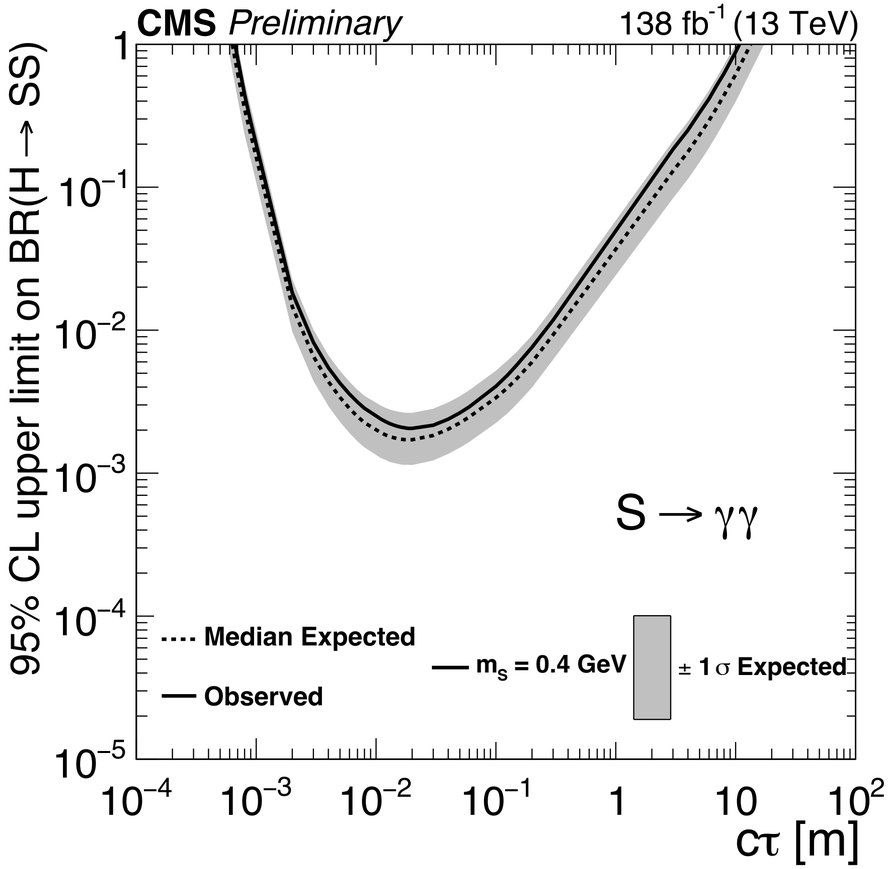
# Observed and Expected Limits

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

**Hadronic & EM shower**



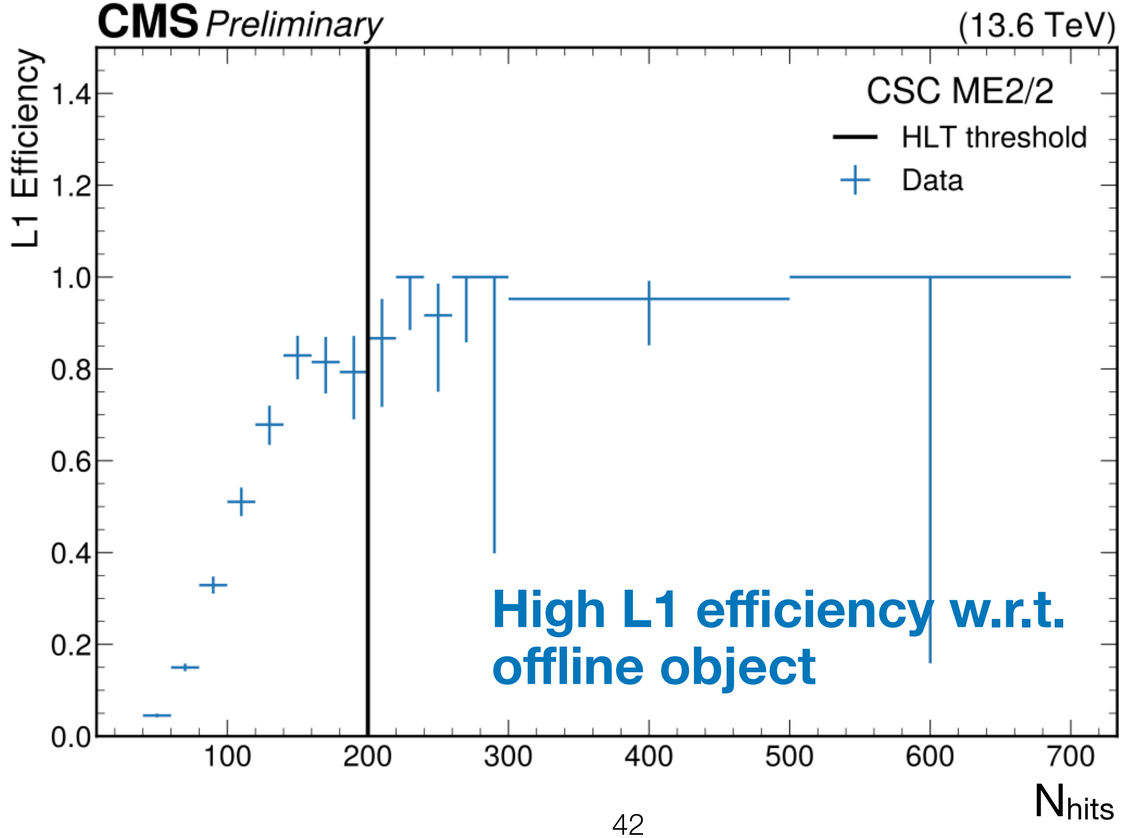

**Fully EM shower**




- 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