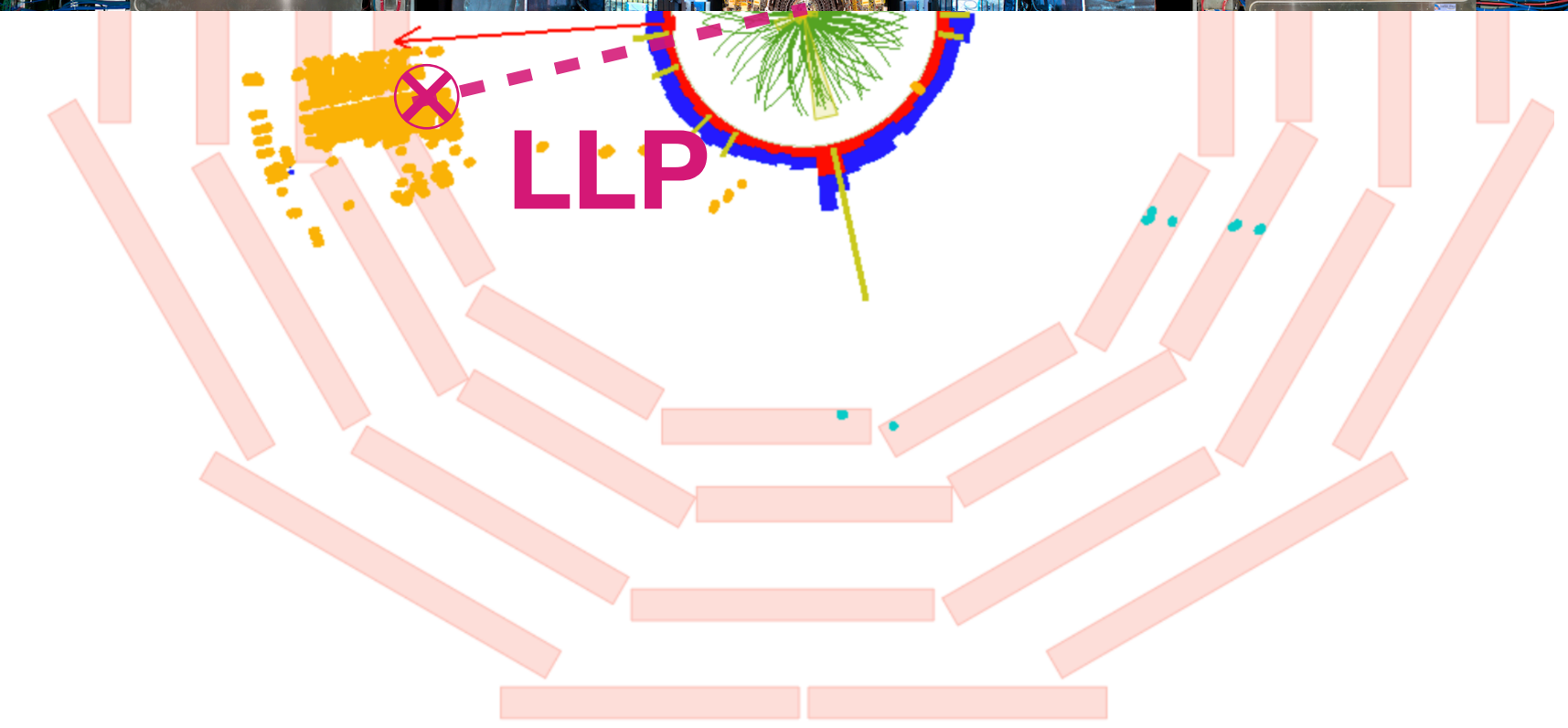


Searches for Long-lived Particles in the CMS Muon System

Daniel Guerrero on behalf of the CMS Collaboration

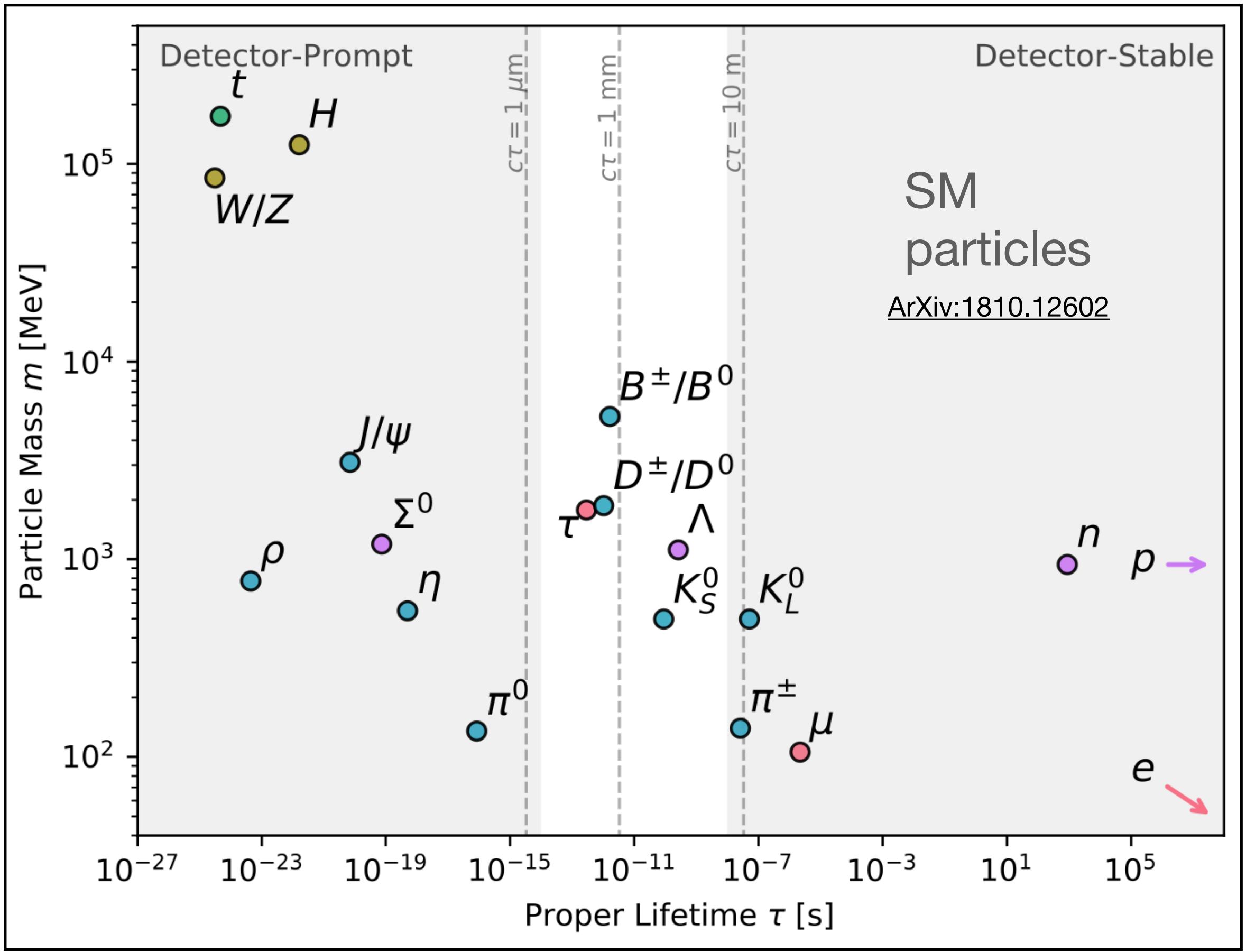
DPF-Pheno Meeting: BSM Session

May 16, 2024



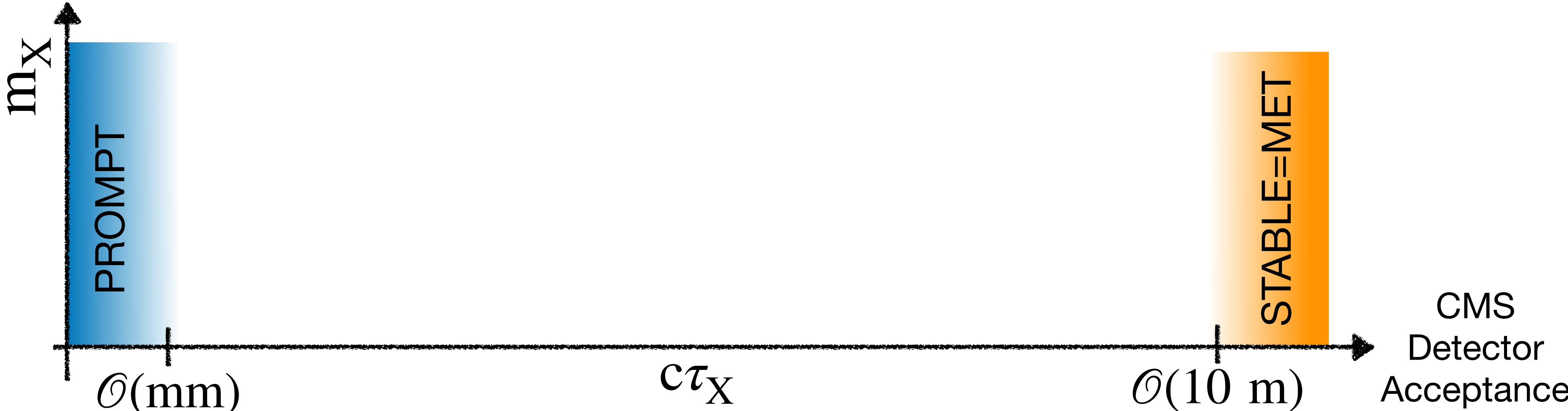
Long-lived Particles, a gateway to BSM

- **SM** is an example of fundamental laws giving rise to long-lived particles (LLPs)



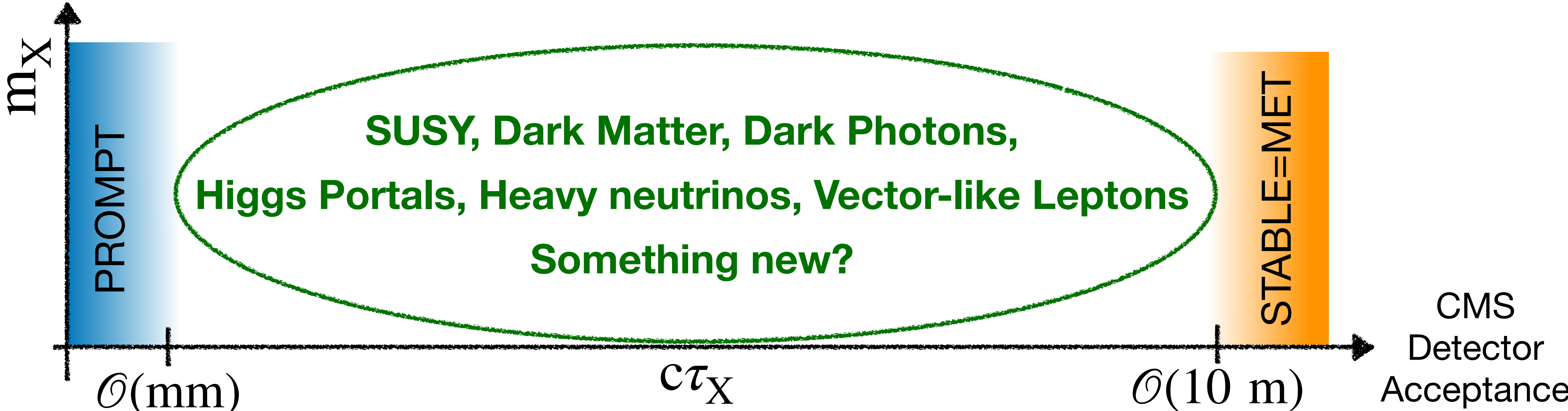
Long-lived Particles, a gateway to BSM

- SM is an example of fundamental laws giving rise to long-lived particles (LLPs)
- Majority of BSM searches probe **short-lived** or **stable** signatures



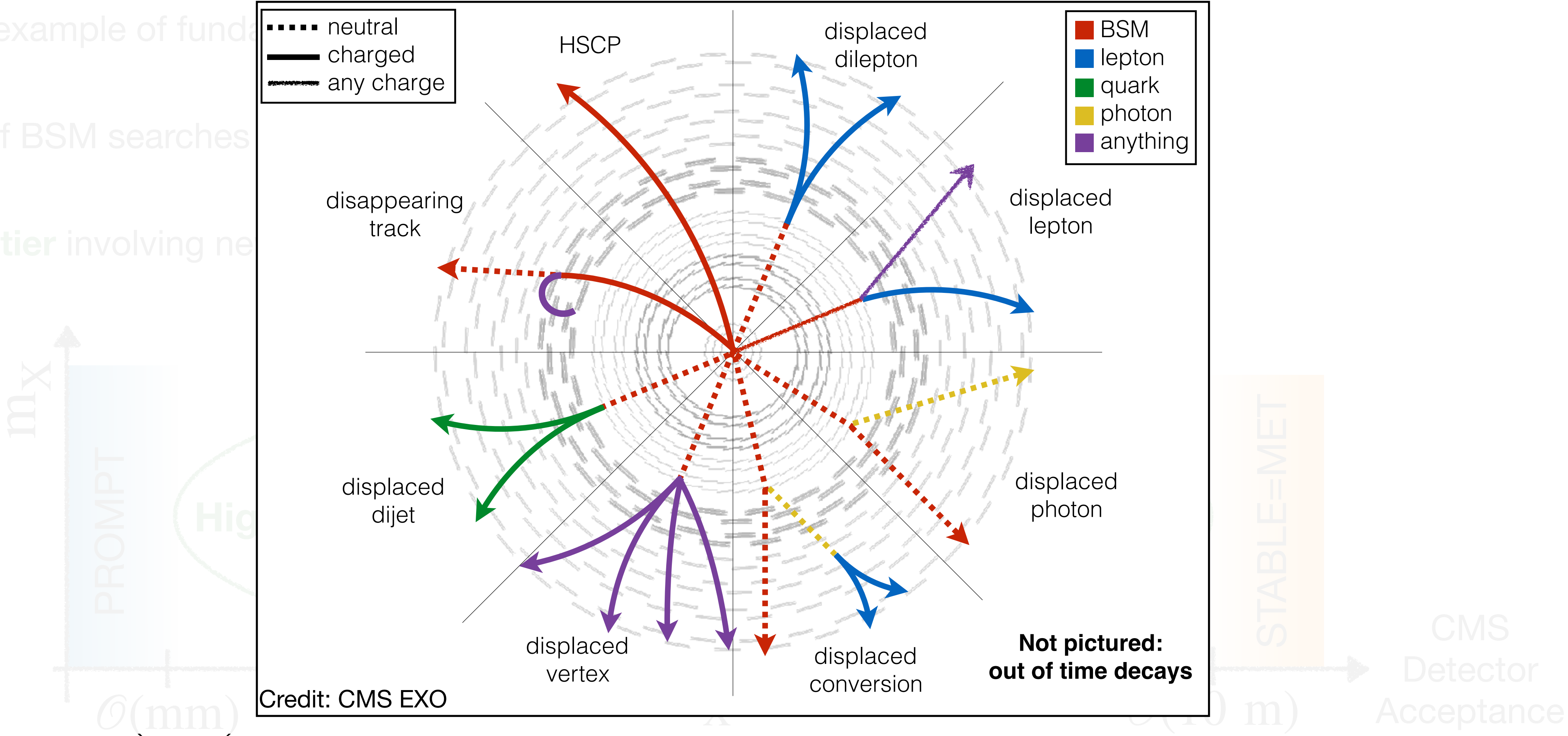
Long-lived Particles, a gateway to BSM

- SM is an example of fundamental laws giving rise to long-lived particles (LLPs)
- Majority of BSM searches probe short-lived or stable signatures
- **BSM frontier** involving new particles (X) with long lifetimes ($c\tau_X$) to be fully exploited!



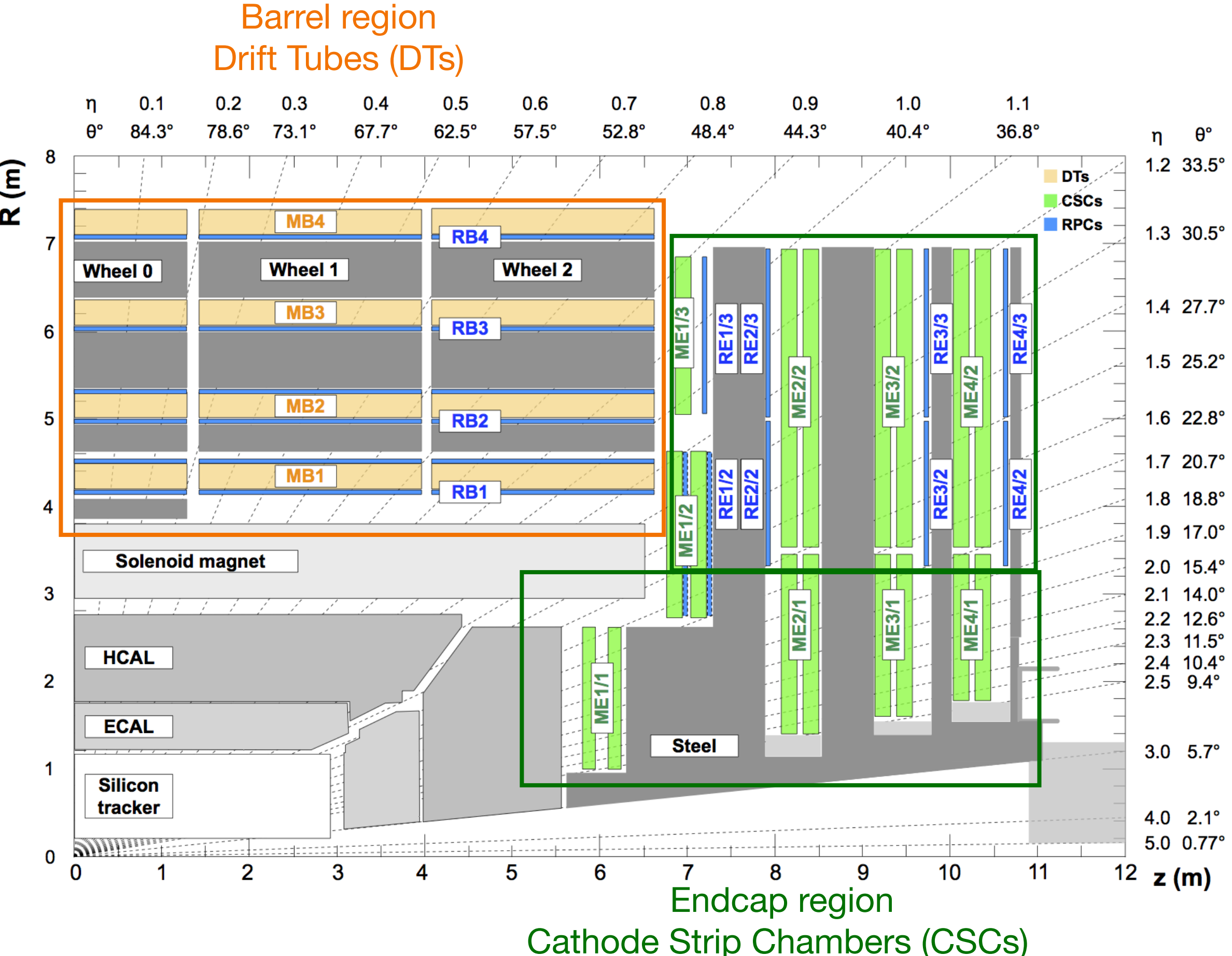
Long-lived Particles, a gateway to BSM

- SM is an example of fundamental particles
- Majority of BSM searches
- BSM frontier involving new

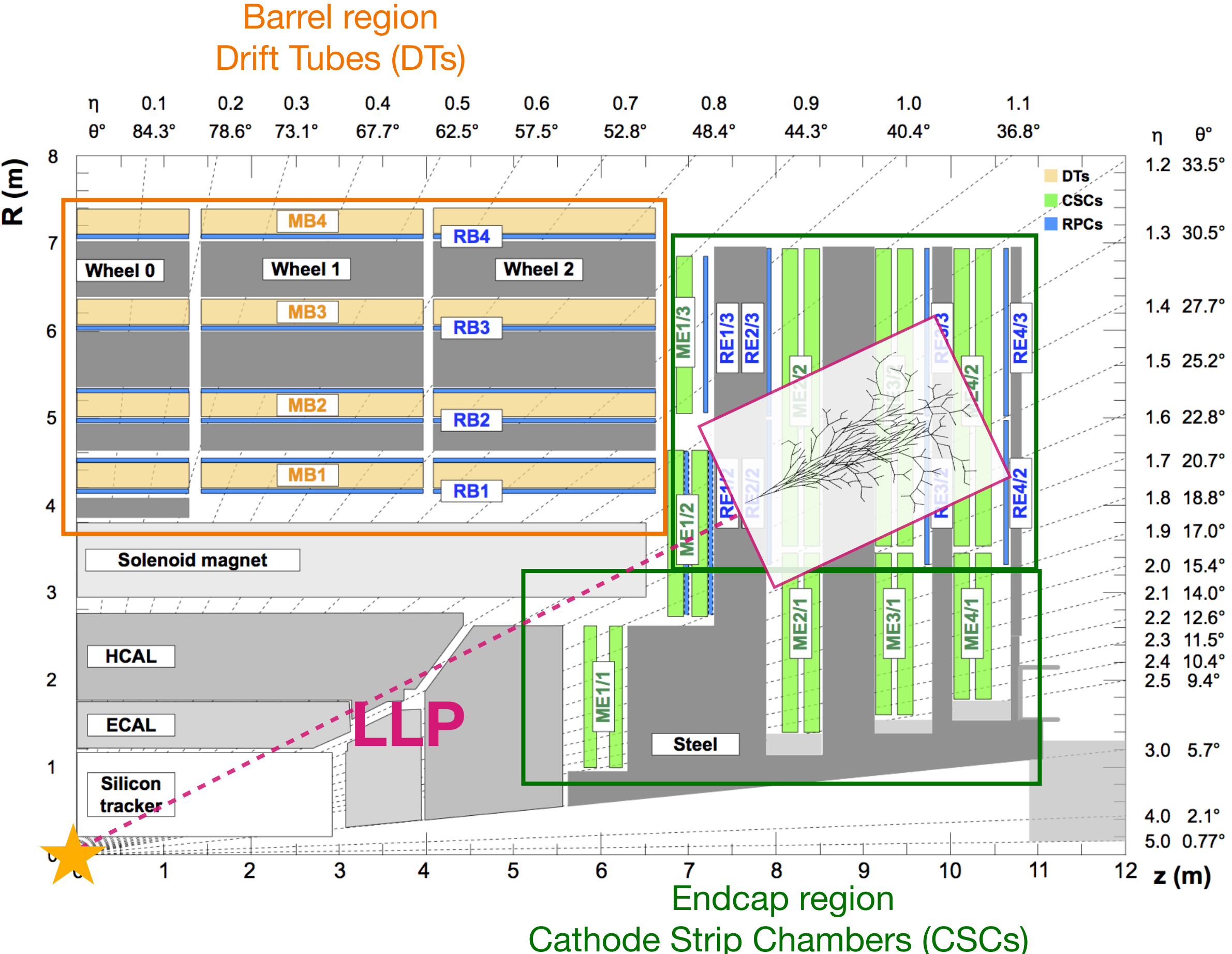


Rich experimental signatures: displaced vertex, displaced dijets, HSCPs, among others!
Common challenges: lack of triggers, low-level detector information, rare backgrounds, etc

Unlocking the CMS Muon System to catch LLPs

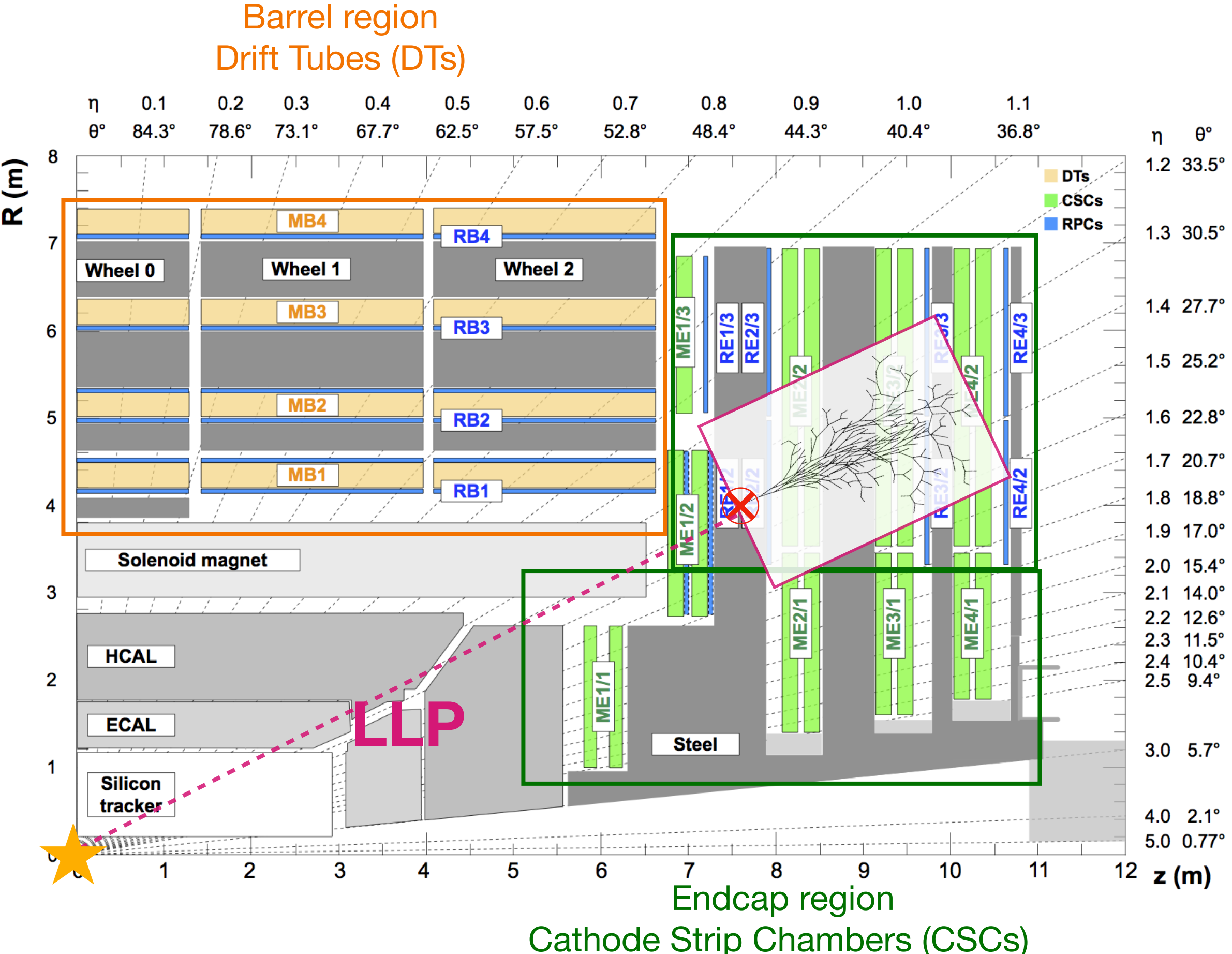


Unlocking the CMS Muon System to catch LLPs



- Muon system acts as a **sampling calorimeter**:
 - 4 detector layers (active material) and steel (absorber)
 - LLP decays induce a **particle shower**

Unlocking the CMS Muon System to catch LLPs



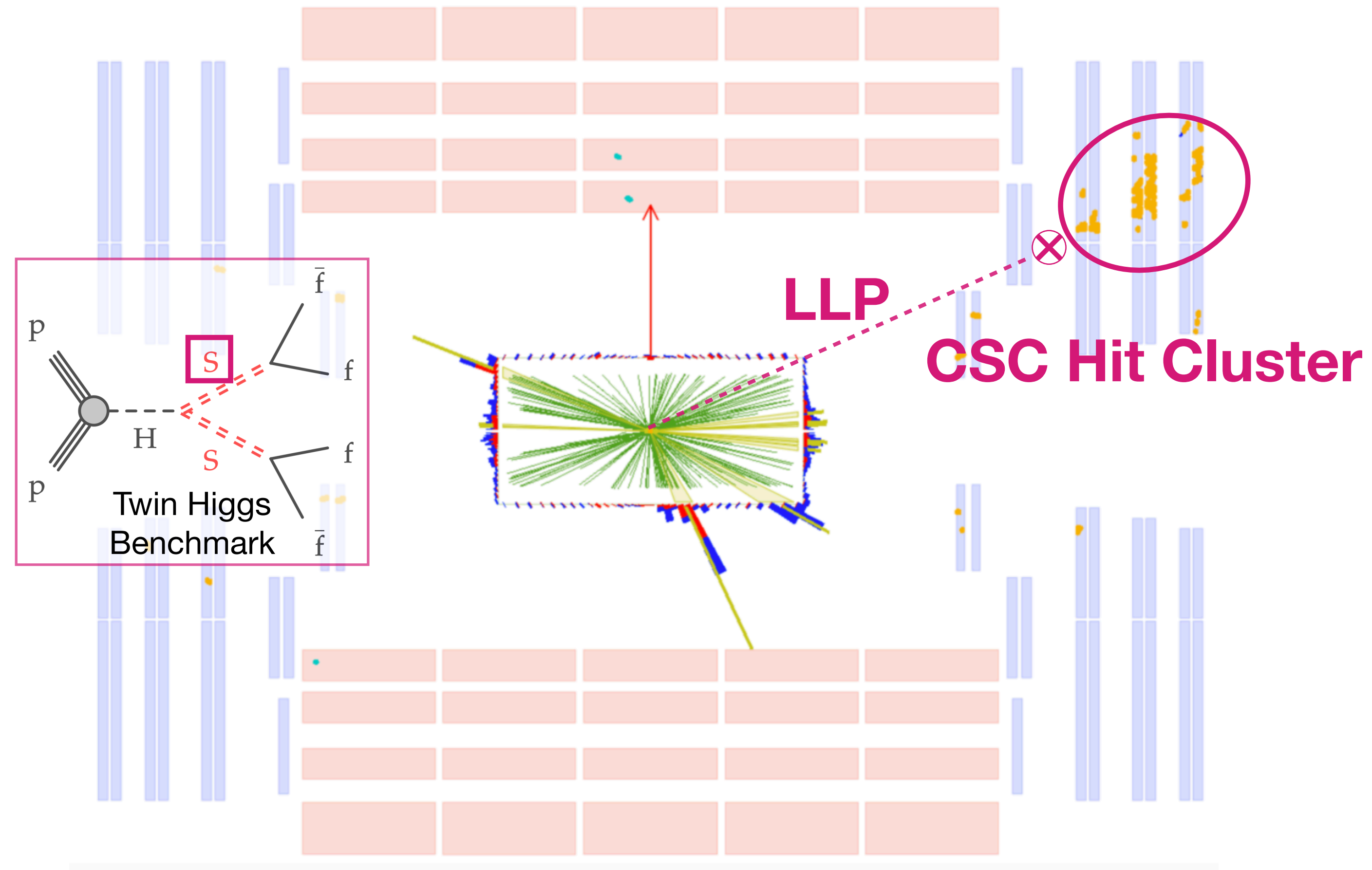
- Muon system acts as a **sampling calorimeter**:
 - 4 detector layers (active material) and steel (absorber)
 - LLP decays induce a **particle shower**
- **Large background suppression** from steel shielding
- **Extra LLP coverage**:
 - Sensitivity to large lifetimes (> a few meters)
 - Sensitive to LLP energy \rightarrow very light LLPs, $\mathcal{O}(1 \text{ GeV})$
 - Broad range of LLP decays: $qq, \pi^+\pi^-, KK, \tau^-\tau^+, ee, \gamma\gamma$

Muon System provides us with a unique opportunity to extend our LLP discovery reach!

Muon Detector Shower (MDS) Signature

- Particle shower is reconstructed as a localized and **large cluster of hits** in the muon chambers

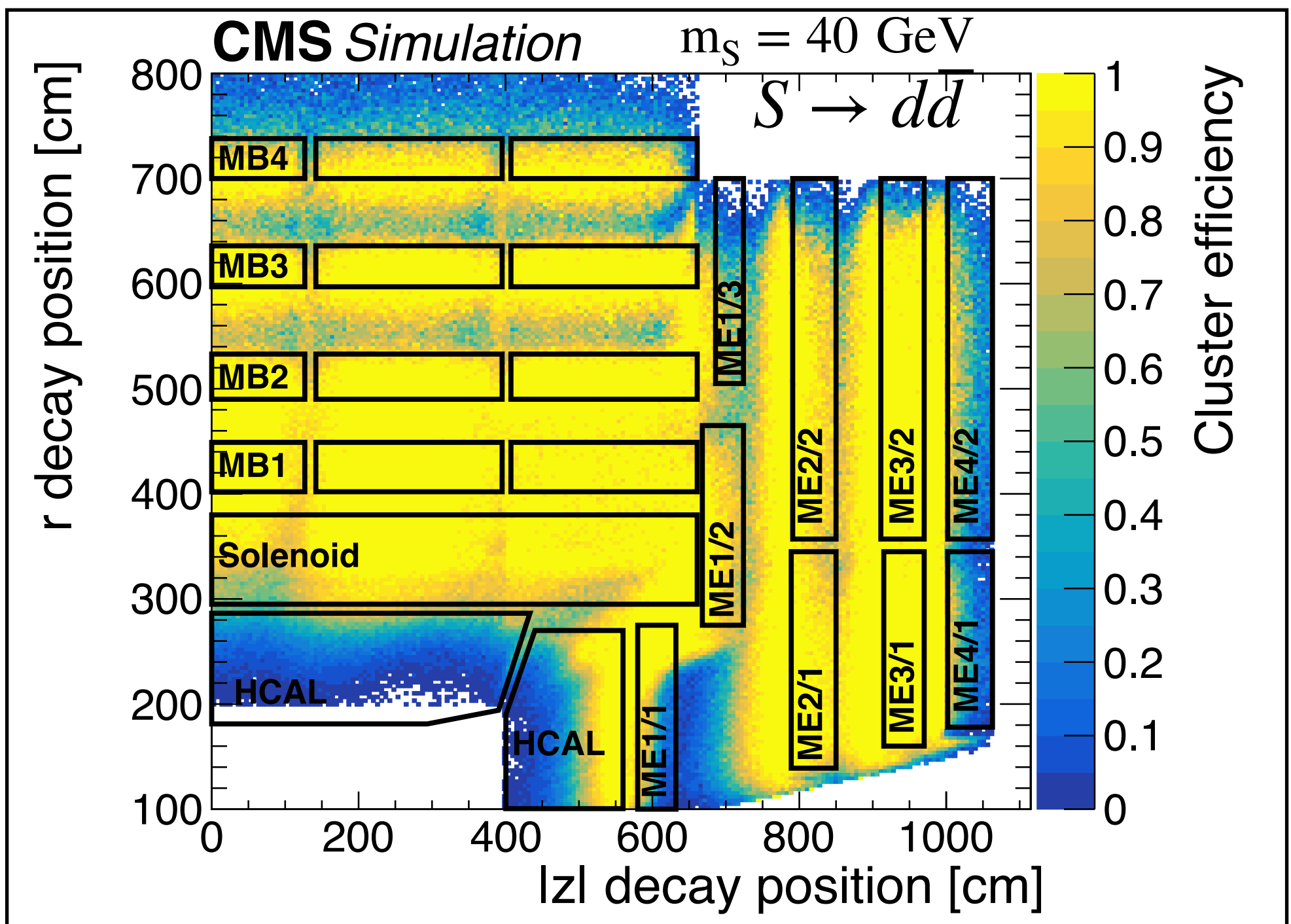
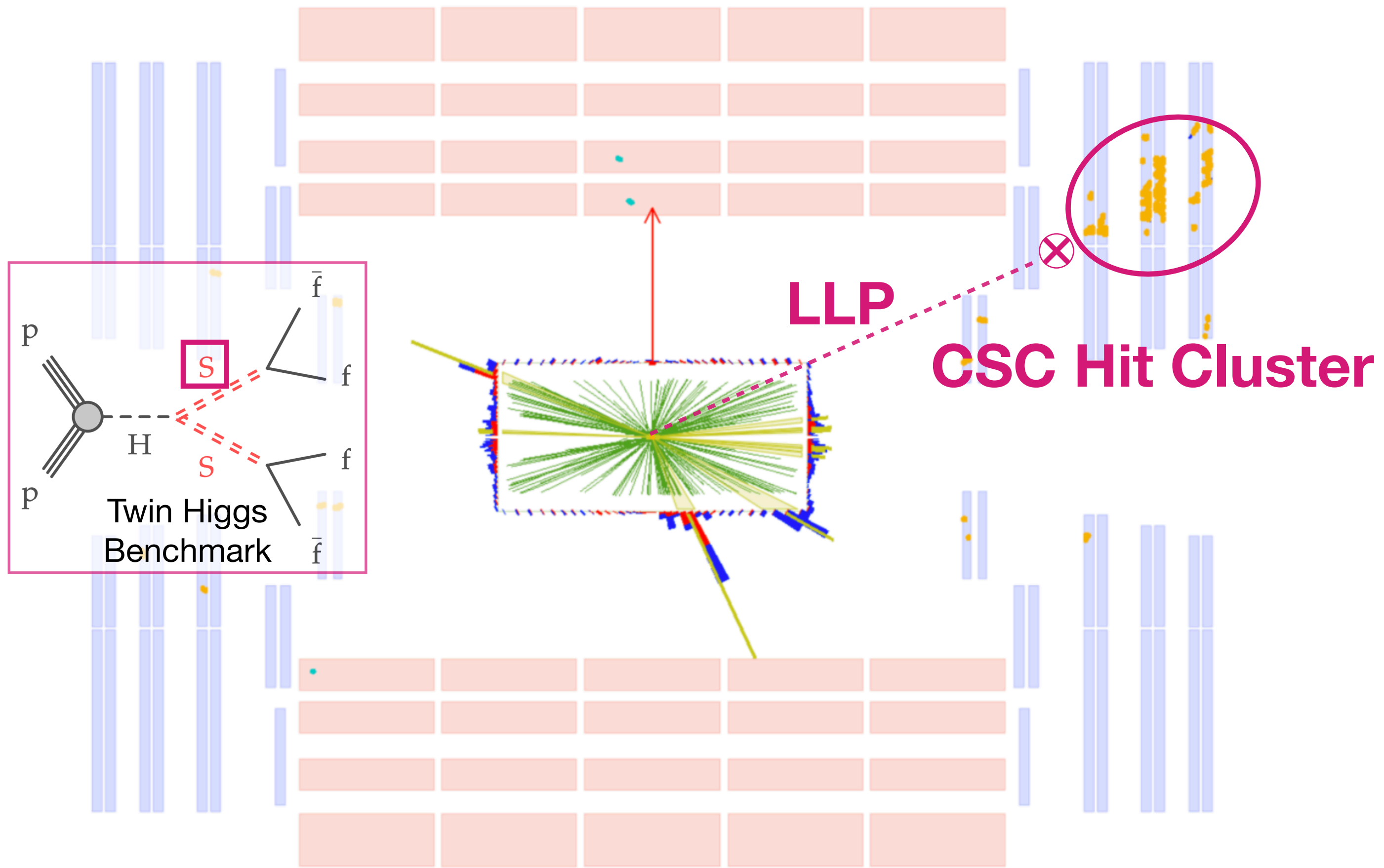
[ArXiv:2402.01898](https://arxiv.org/abs/2402.01898)
Accepted by PRD



Muon Detector Shower (MDS) Signature

- Particle shower is reconstructed as a localized and **large cluster of hits** in the muon chambers
- **High cluster reconstruction efficiency**

ArXiv:2402.01898
Accepted by PRD

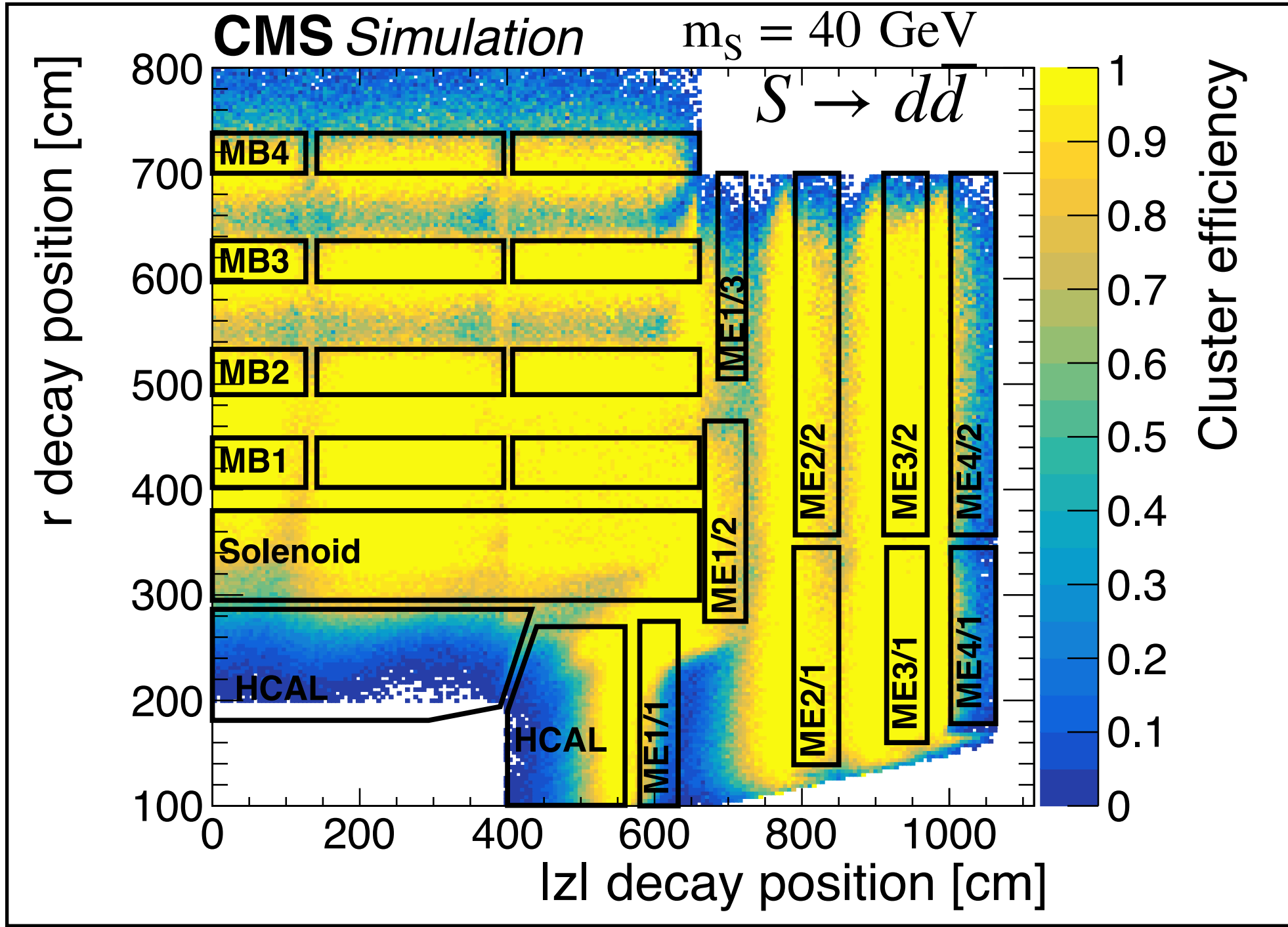
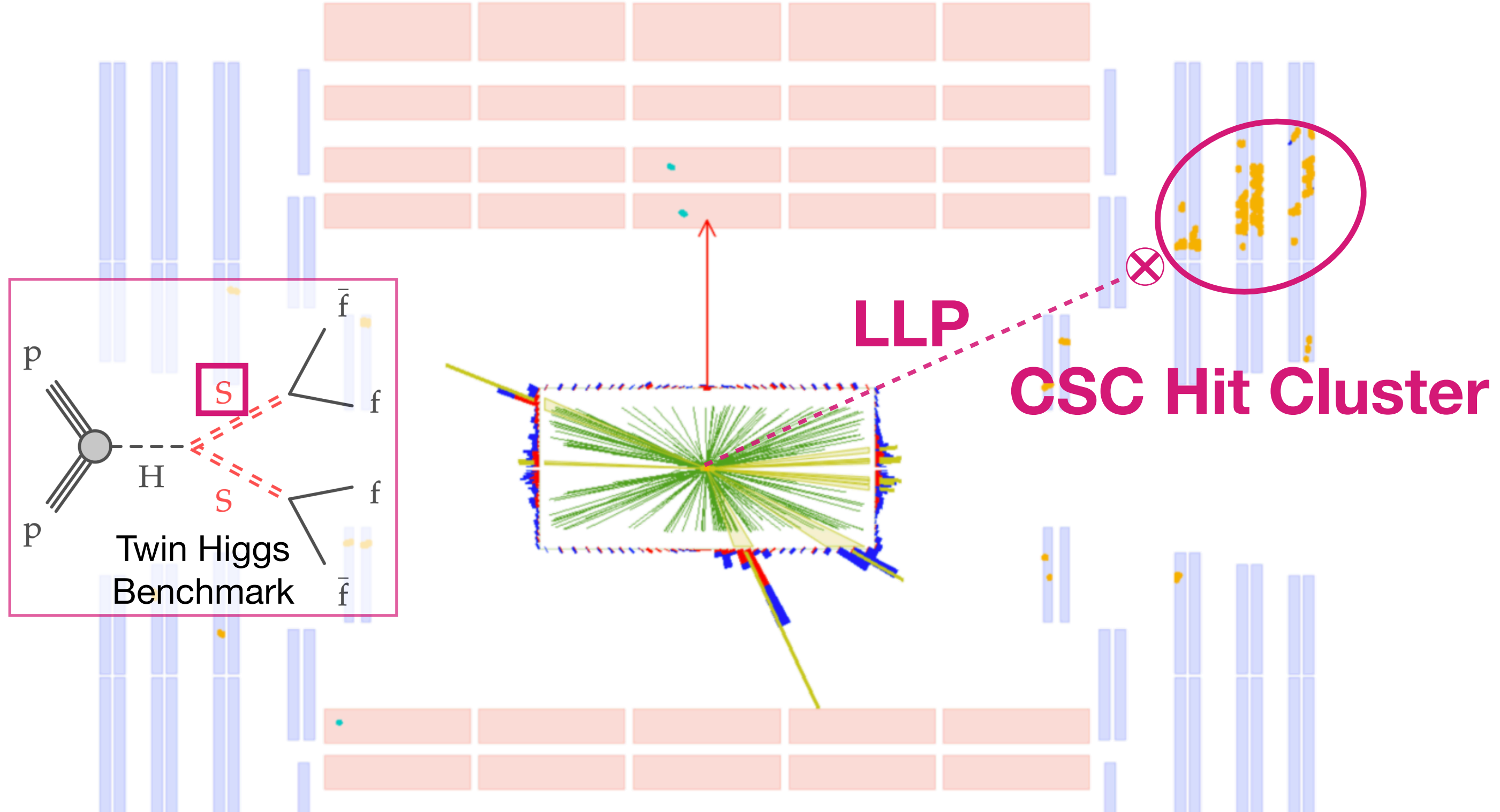


CSC and DT cluster efficiency (>50 hits) (DBSCAN, d=0.2) as function of decay position

Muon Detector Shower (MDS) Signature

- Particle shower is reconstructed as a localized and **large cluster of hits** in the muon chambers
- **High cluster reconstruction efficiency**

[ArXiv:2402.01898](https://arxiv.org/abs/2402.01898)
Accepted by PRD



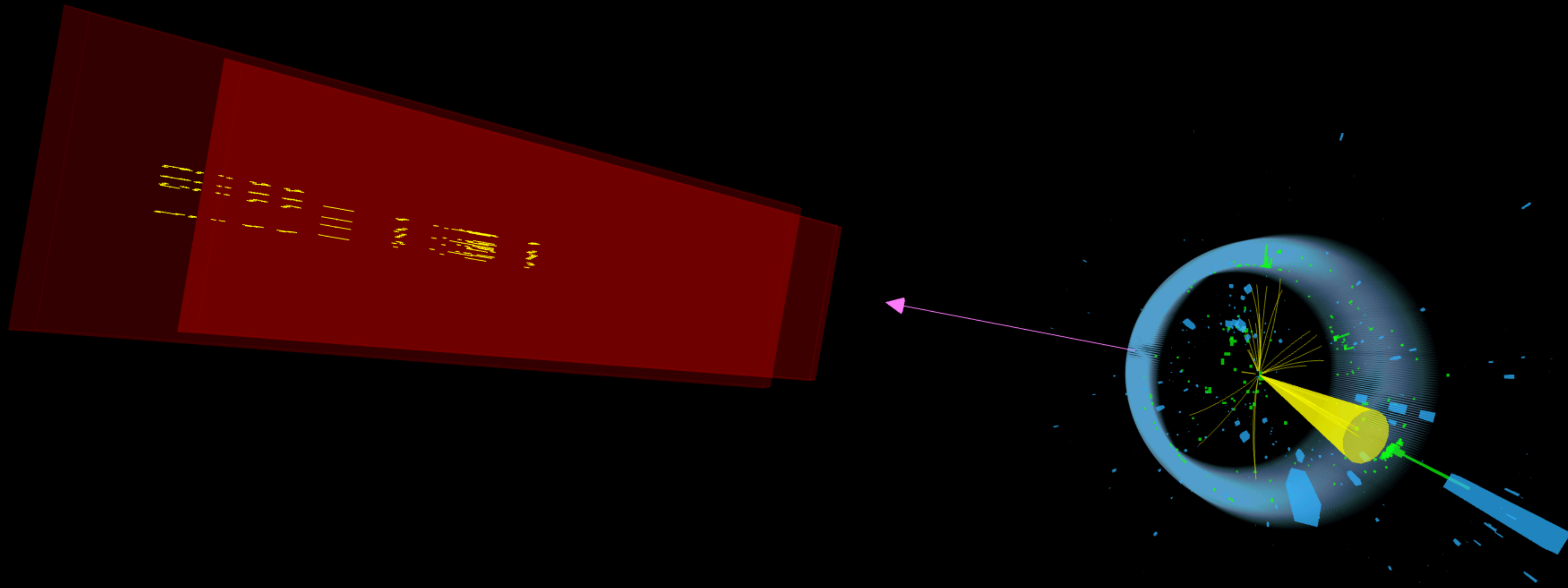
CSC and DT cluster efficiency (>50 hits) (DBSCAN, $d=0.2$) as function of decay position

- **Backgrounds** from punch-through jets, muon bremsstrahlung, cosmic showers/muons, pile-up, SM LLPs (e.g. K_L^0)
- **Run-2 searches:** Neutral LLPs ([PRL 127\(2021\)261804](https://arxiv.org/abs/2106.12004), [ArXiv:2402.01898](https://arxiv.org/abs/2402.01898)) and Long-lived HNLs ([arXiv:2402.18658](https://arxiv.org/abs/2402.18658))



CMS Experiment at the LHC, CERN
Data recorded: 2018-Jun-08 21:53:09.379718 GMT
Run / Event / LS: 317626 / 292396821 / 214

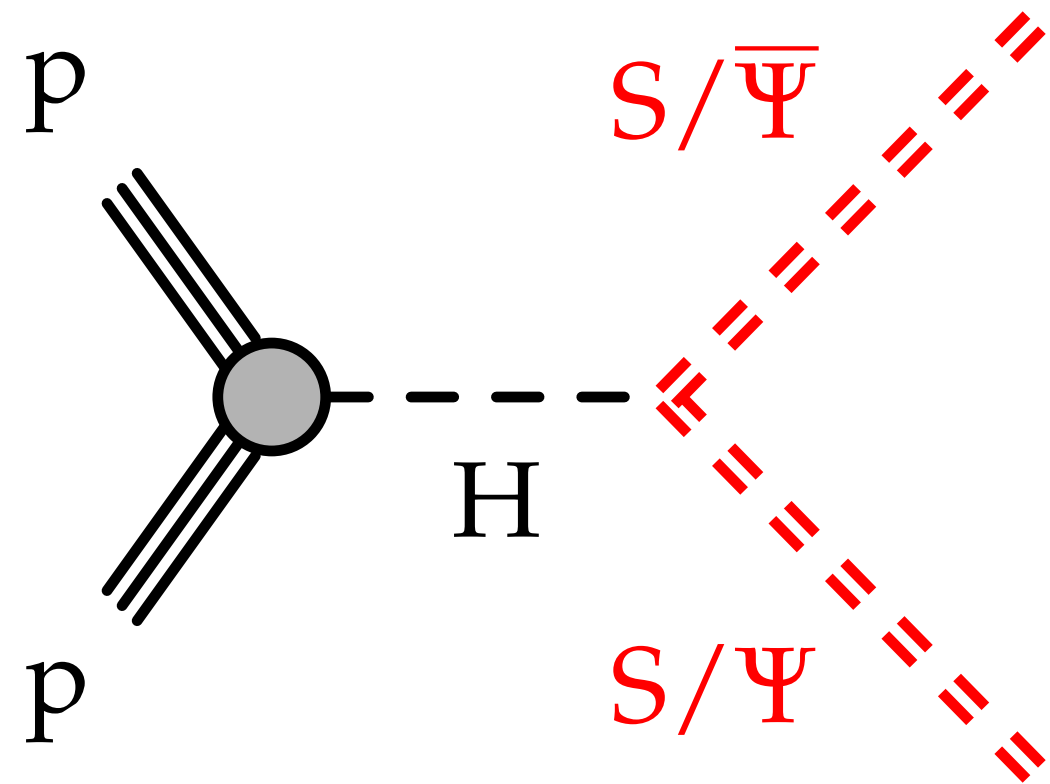
CMS Interactive
Event Display



Search for Higgs to Neutral LLPs

Search for Higgs to Neutral LLPs: Strategy

[ArXiv:2402.01898](https://arxiv.org/abs/2402.01898)
Accepted by PRD

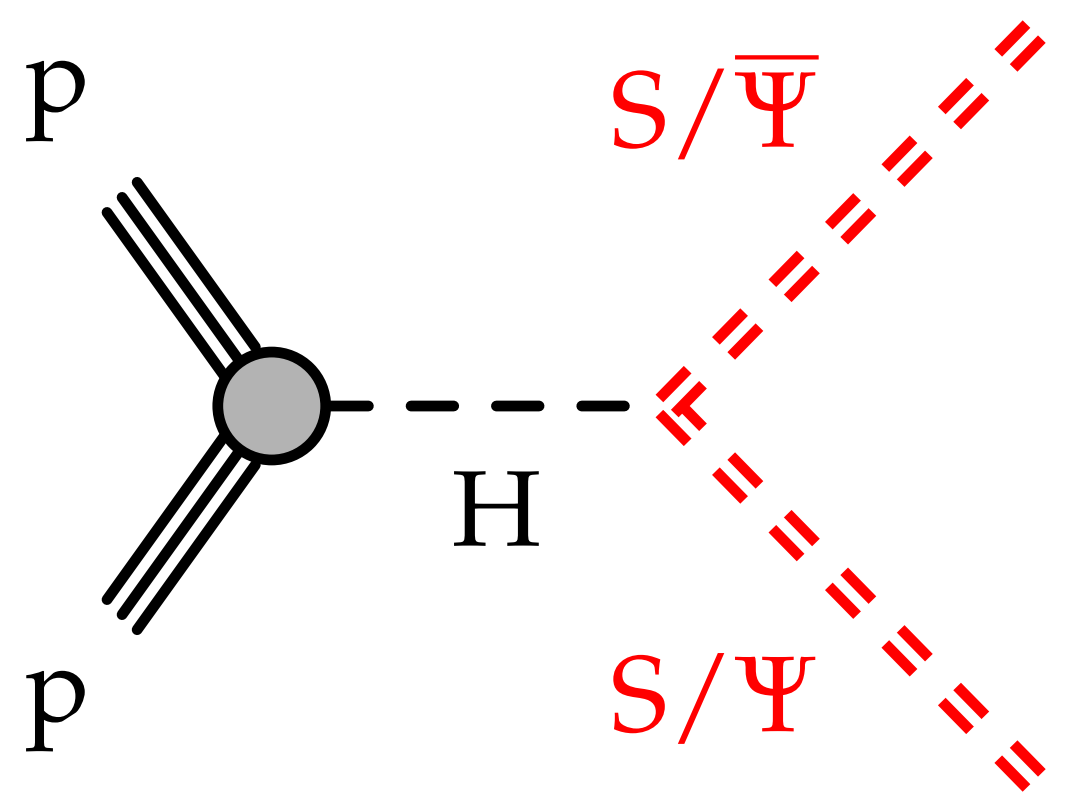


Twin Higgs/Dark Shower benchmarks

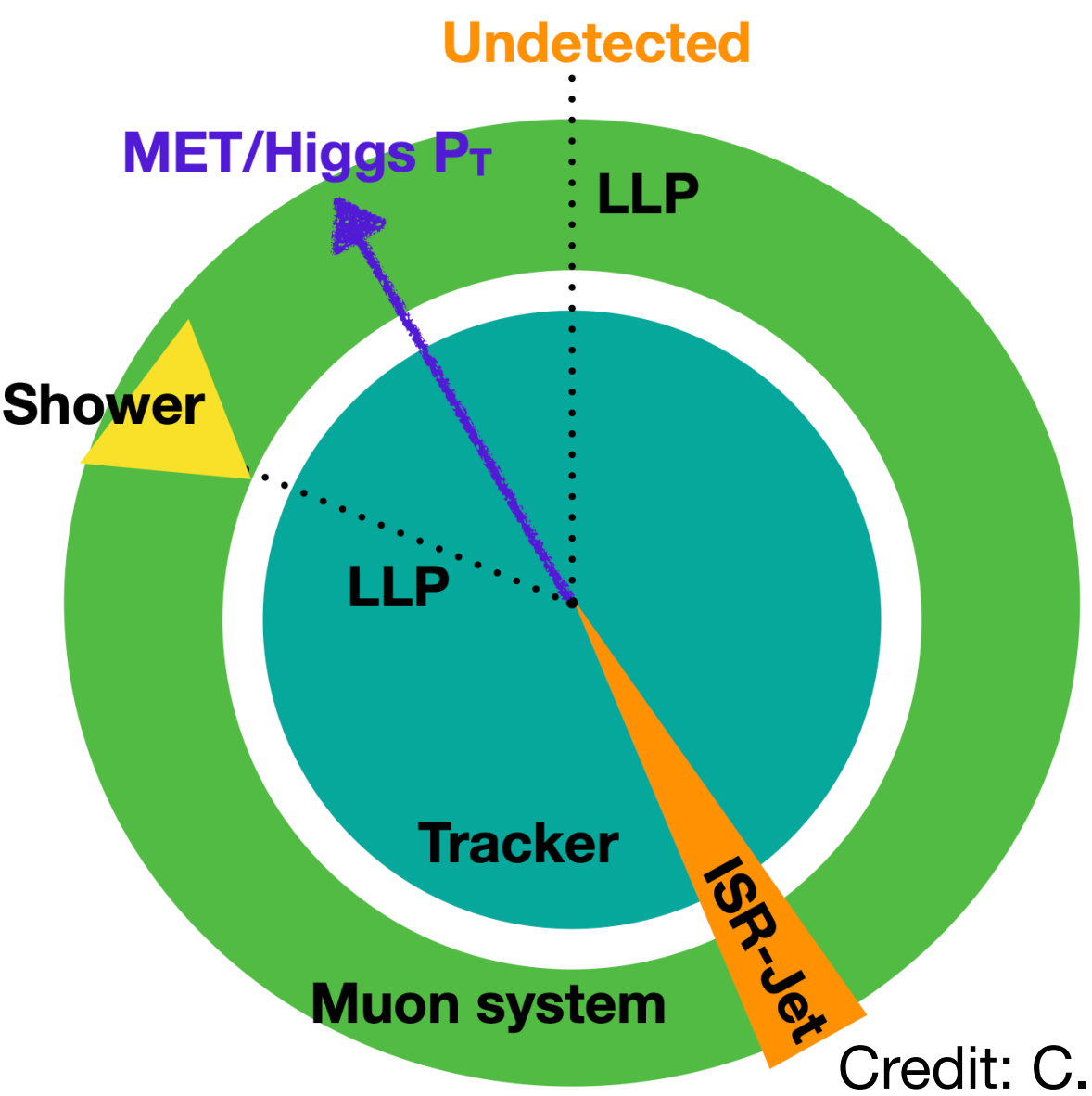
Search for Higgs to Neutral LLPs: Strategy

[ArXiv:2402.01898](https://arxiv.org/abs/2402.01898)
Accepted by PRD

- Run-2 analysis based on **MET triggers and MET > 200 GeV**



Twin Higgs/Dark Shower benchmarks

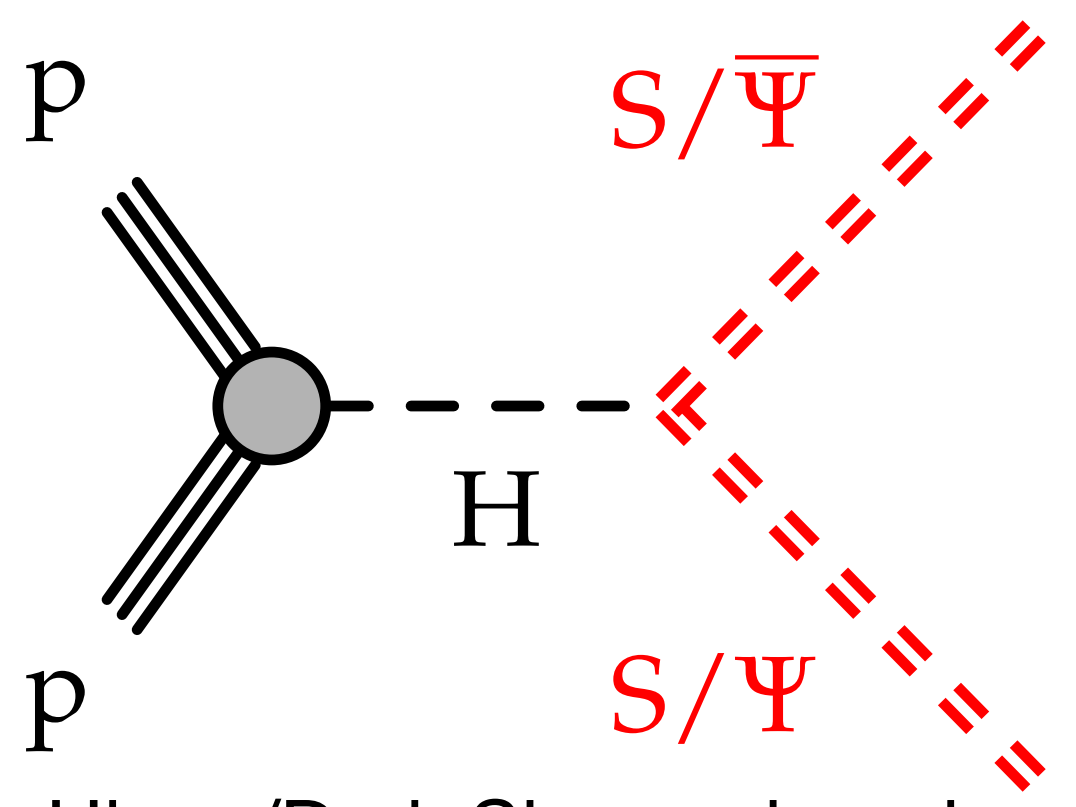


Credit: C. Wang

Experimental Signature

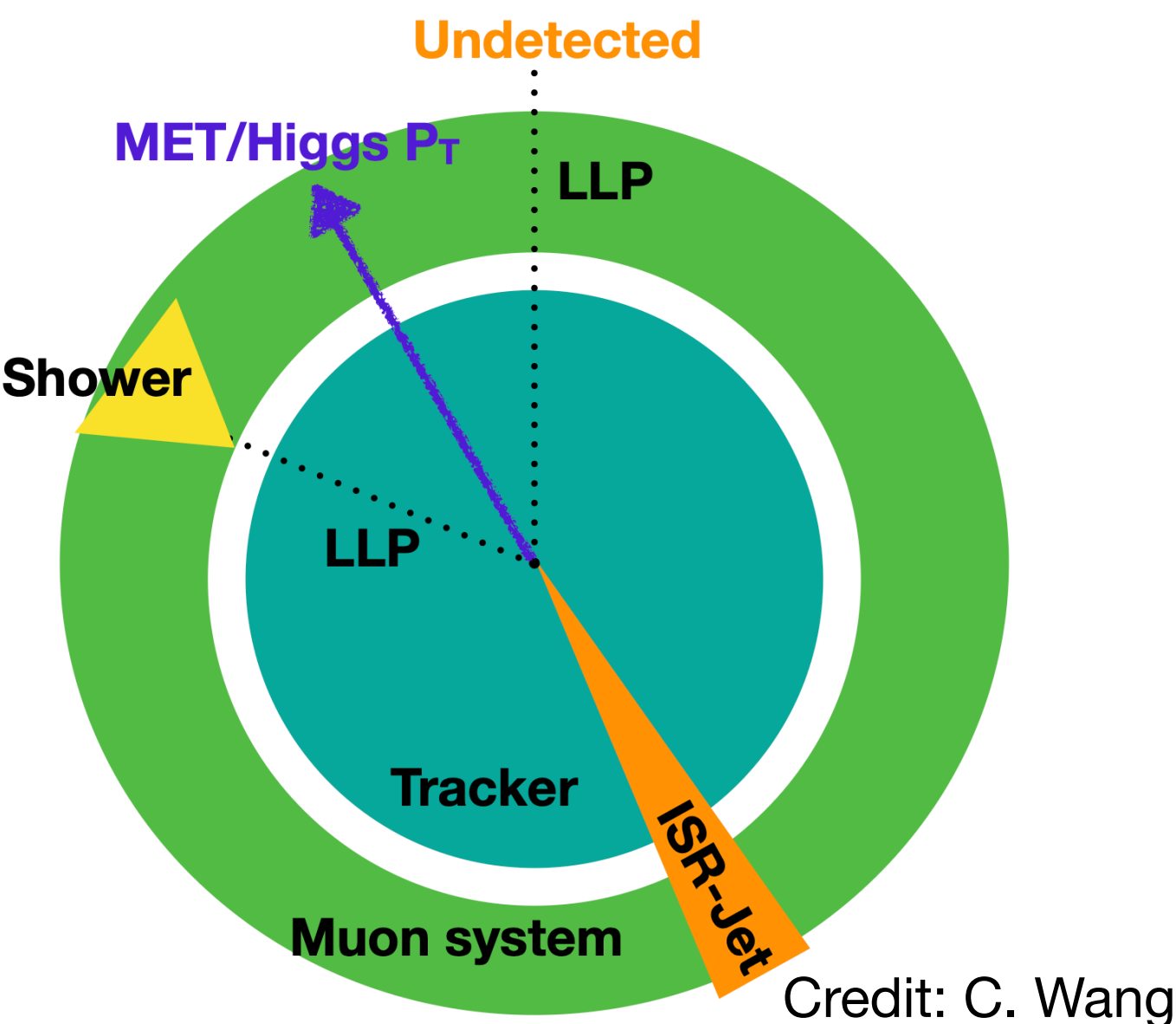
Search for Higgs to Neutral LLPs: Strategy

ArXiv:2402.01898
Accepted by PRD



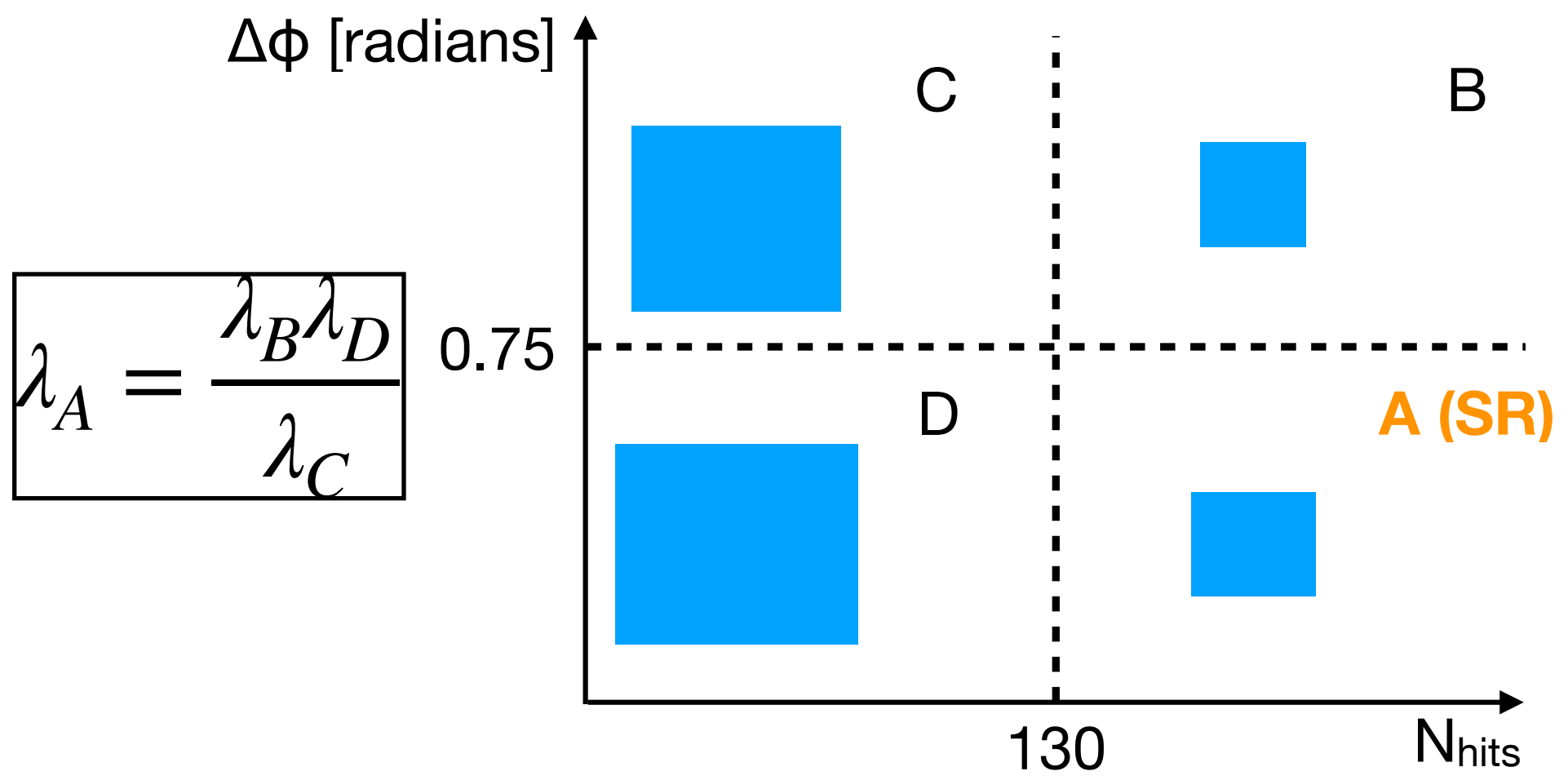
Twin Higgs/Dark Shower benchmarks

- Run-2 analysis based on **MET triggers and MET > 200 GeV**
- Events divided in 3 categories based on MDS cluster:
 - Single CSC, Single DT cluster, and Double clusters
- **Data-driven background model:**
 - ABCD method using N_{hits} and $\Delta\phi(MET, cls)$ as main signal discriminants

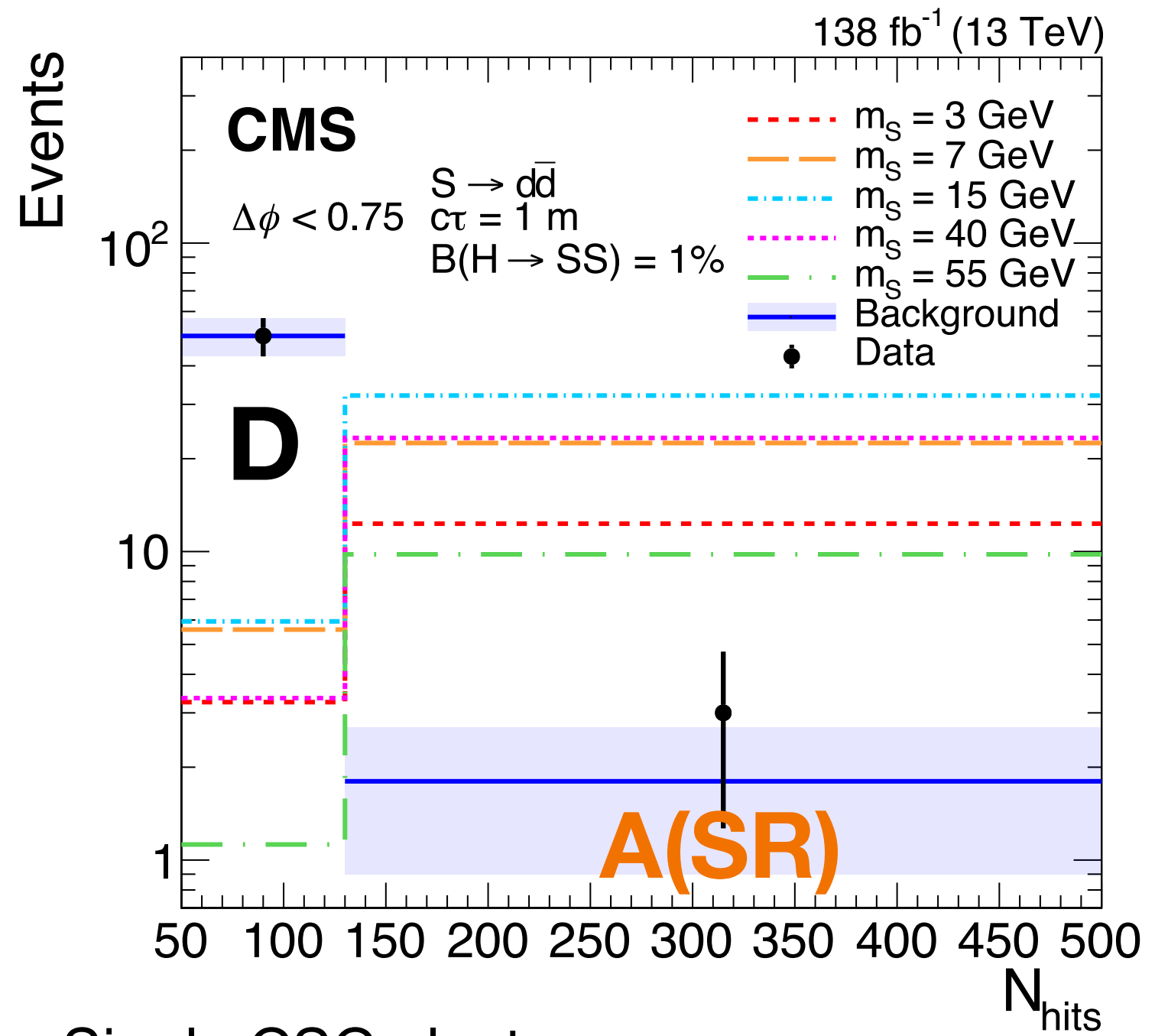


Credit: C. Wang

Experimental Signature



ABCD background estimate example: Single CSC cluster



Search for Neutral LLPs: Results

ArXiv:2402.01898
Accepted by PRD

- **No excess is observed** above the background expectation

- Results are interpreted in **9 decay modes**:

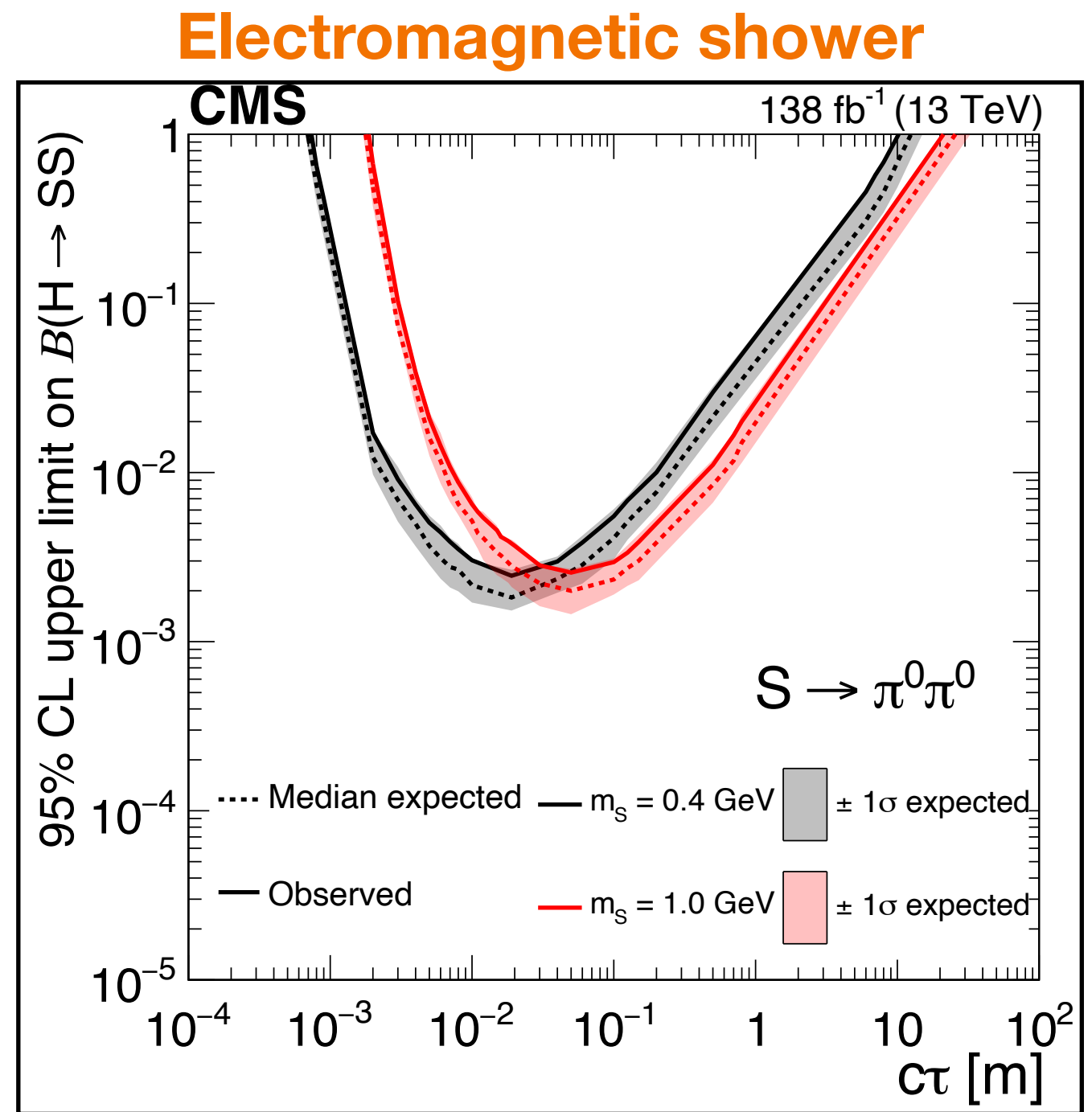
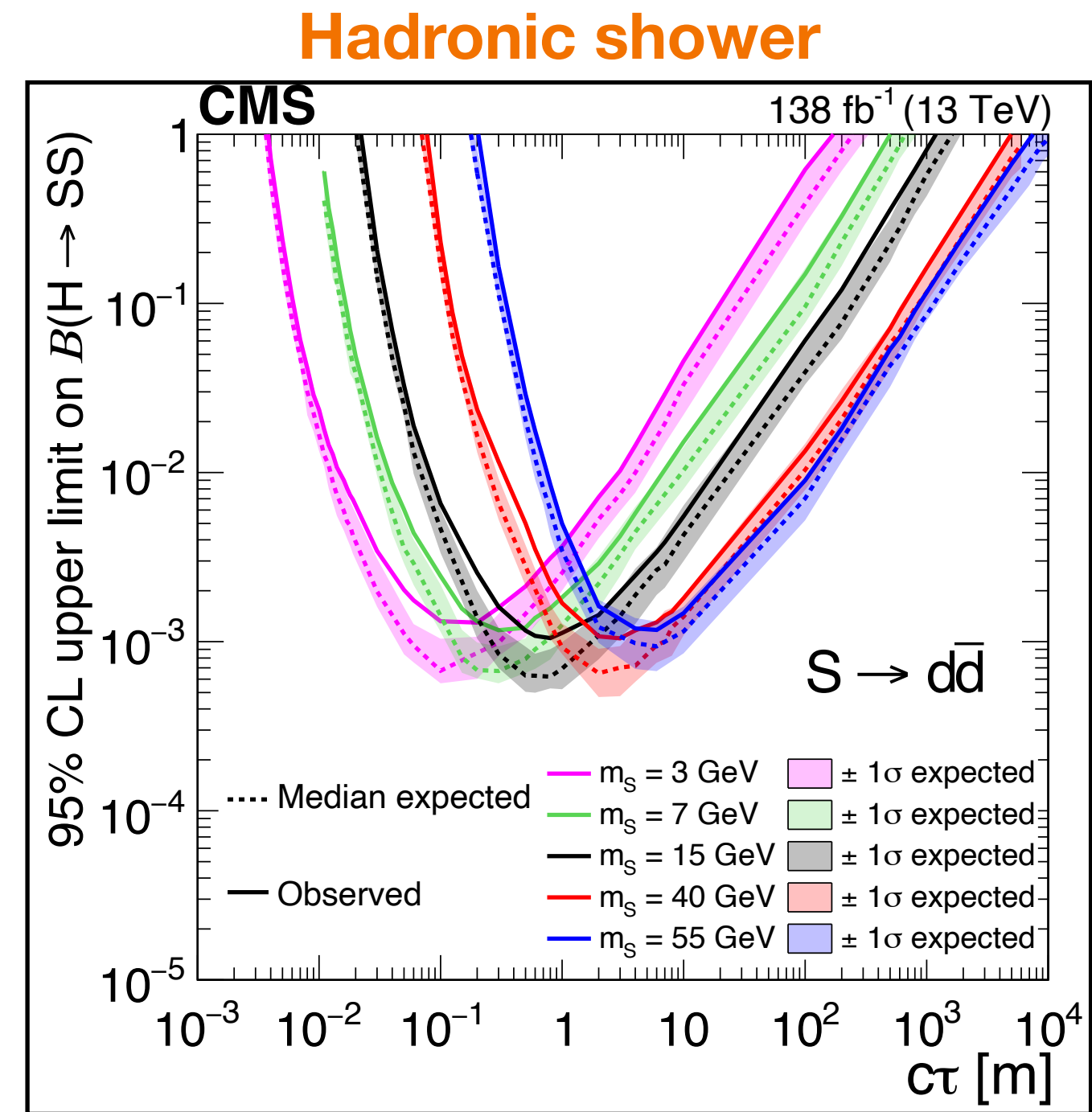
- Hadronic shower: $b\bar{b}, d\bar{d}, K^+K^-, K^0K^0, \pi^+\pi^-$
- EM shower: $\pi^0\pi^0, \gamma\gamma, e^+e^-$
- Both: $\tau^+\tau^-$

- **Excellent sensitivity:** $B(H \rightarrow SS) \approx 10^{-3}$ level

- **LLP-mass independent**

- First **sub-GeV LLP** sensitivity

- Most sensitive for $m_{LLP} < 10$ GeV (excluding $S \rightarrow \mu^+\mu^-$)



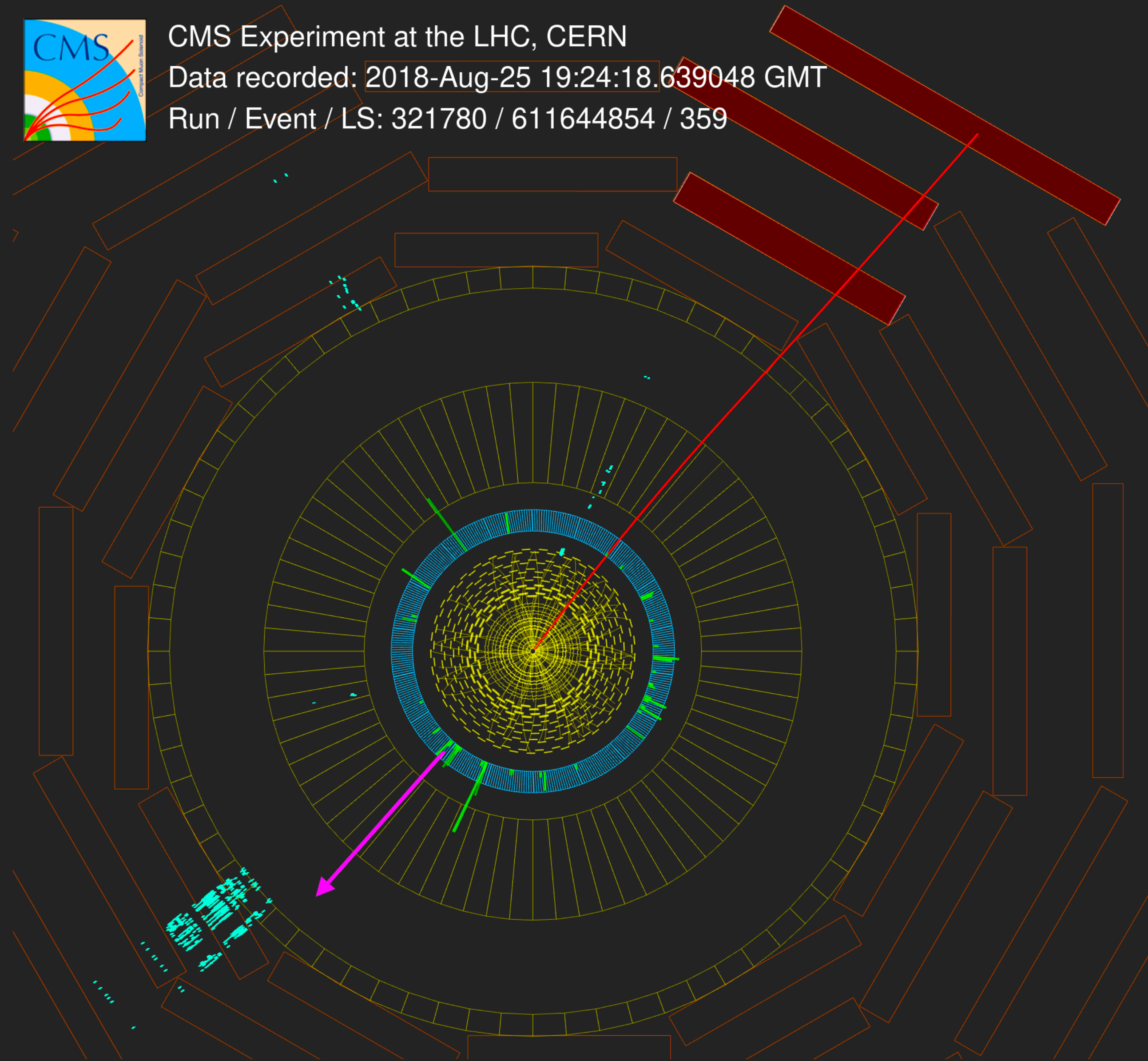
Twin Higgs model interpretations
(More interpretations in additional material)



CMS Experiment at the LHC, CERN

Data recorded: 2018-Aug-25 19:24:18.639048 GMT

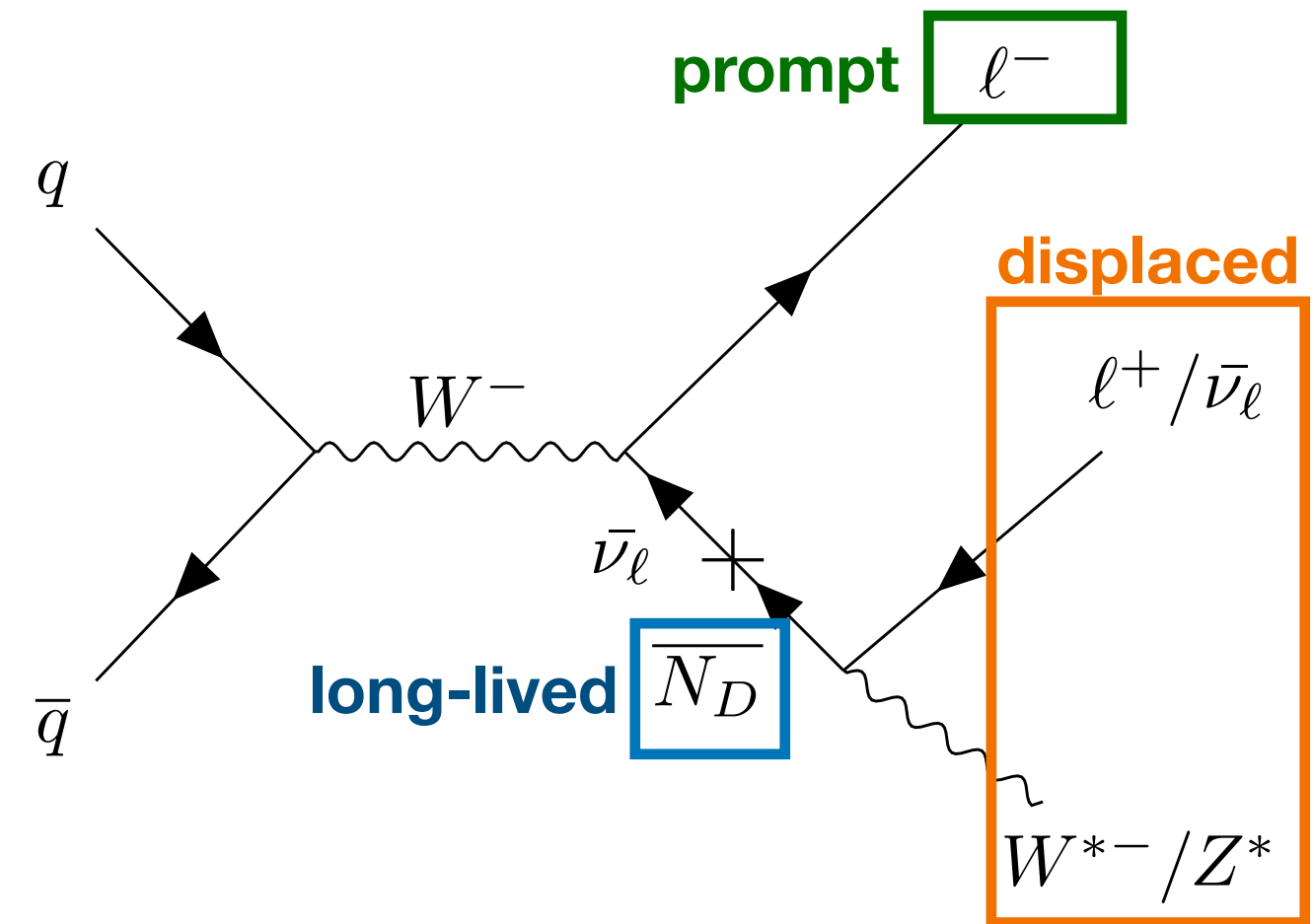
Run / Event / LS: 321780 / 611644854 / 359



Search for long-lived HNLs

Search for long-lived HNLs: Strategy

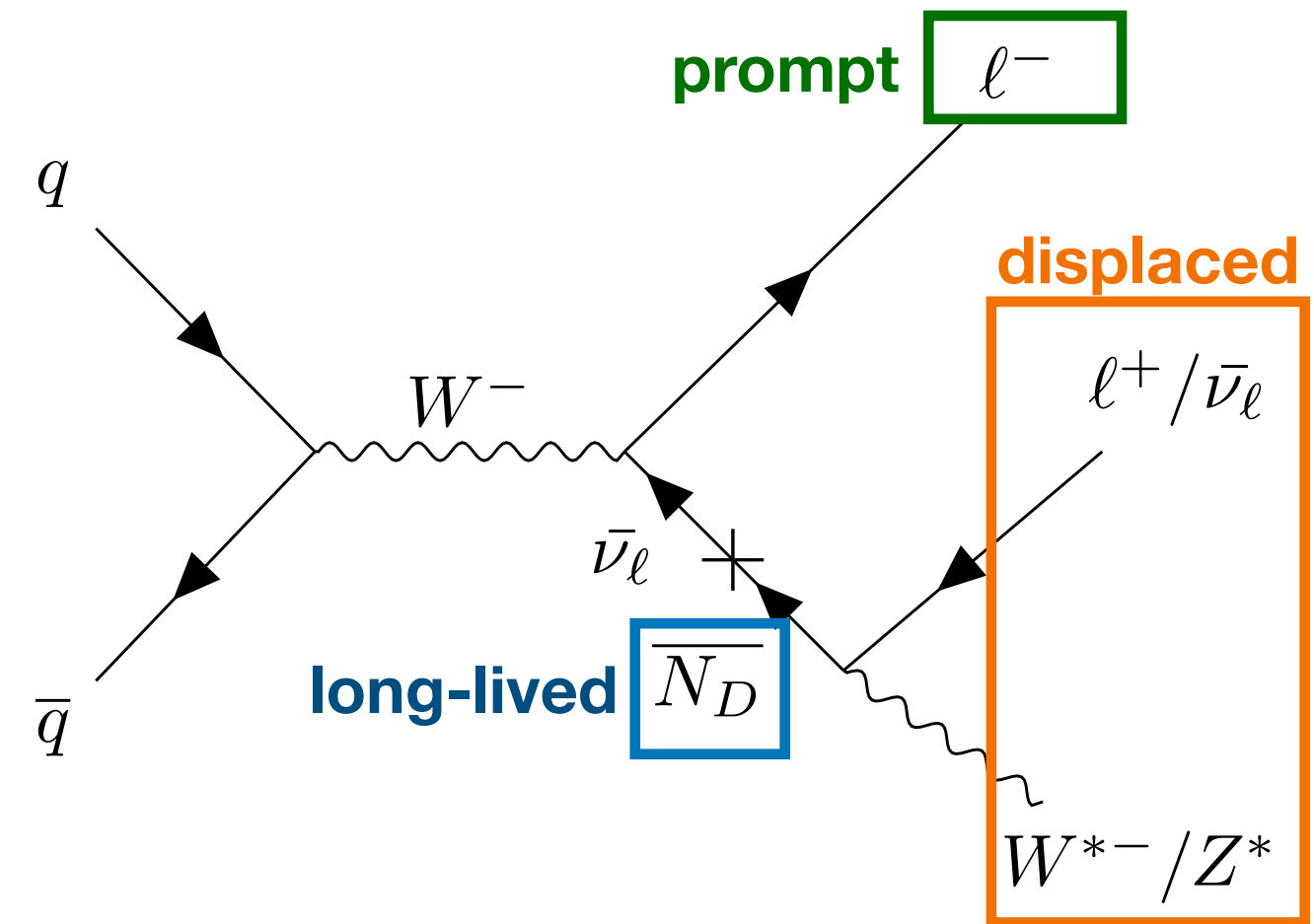
[ArXiv:2402.18658](https://arxiv.org/abs/2402.18658)
Submitted to PRD



Dirac HNLs in W-decays

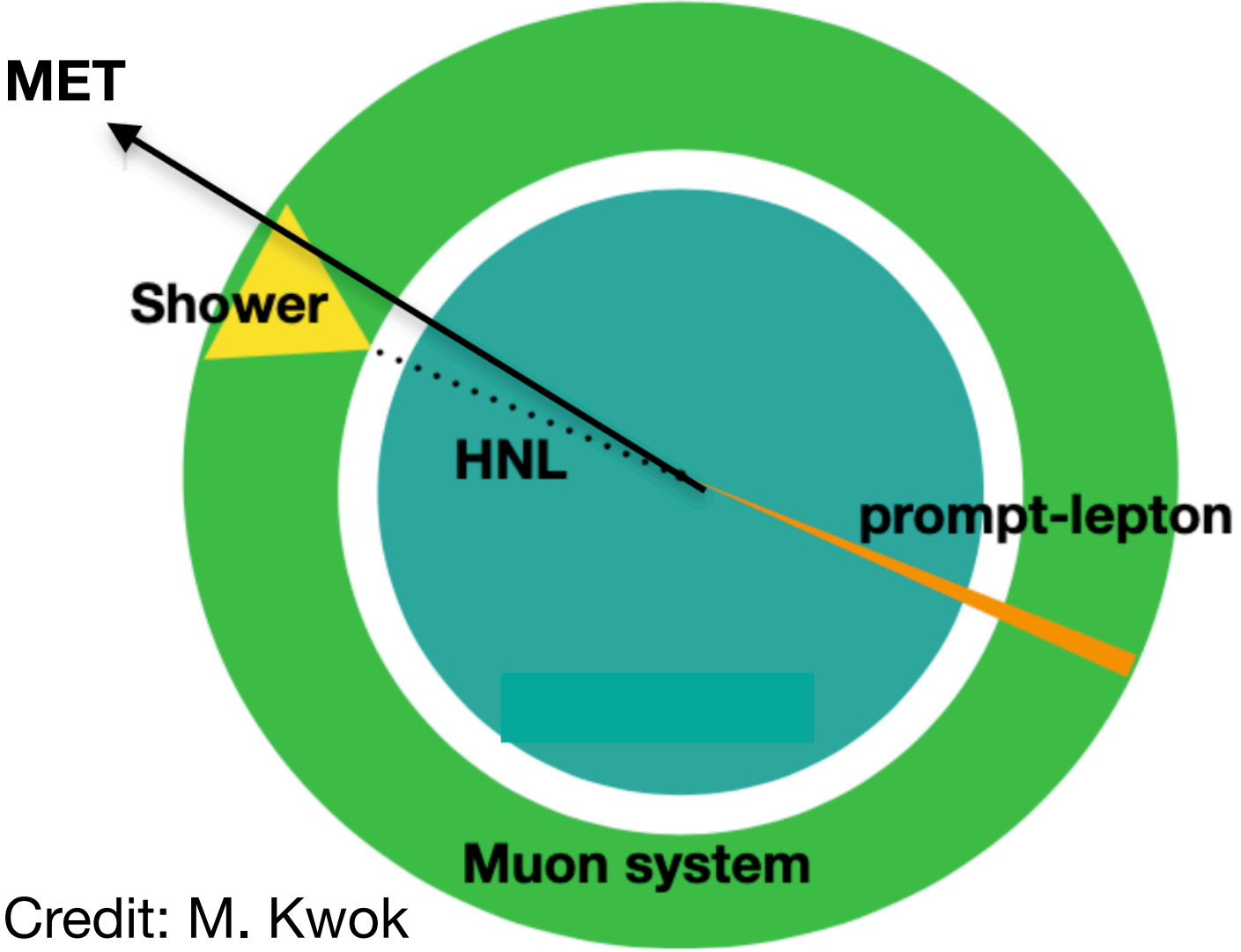
Search for long-lived HNLs: Strategy

[ArXiv:2402.18658](https://arxiv.org/abs/2402.18658)
Submitted to PRD



- Run-2 analysis based on **single electron and muon triggers**

Dirac HNLs in W-decays

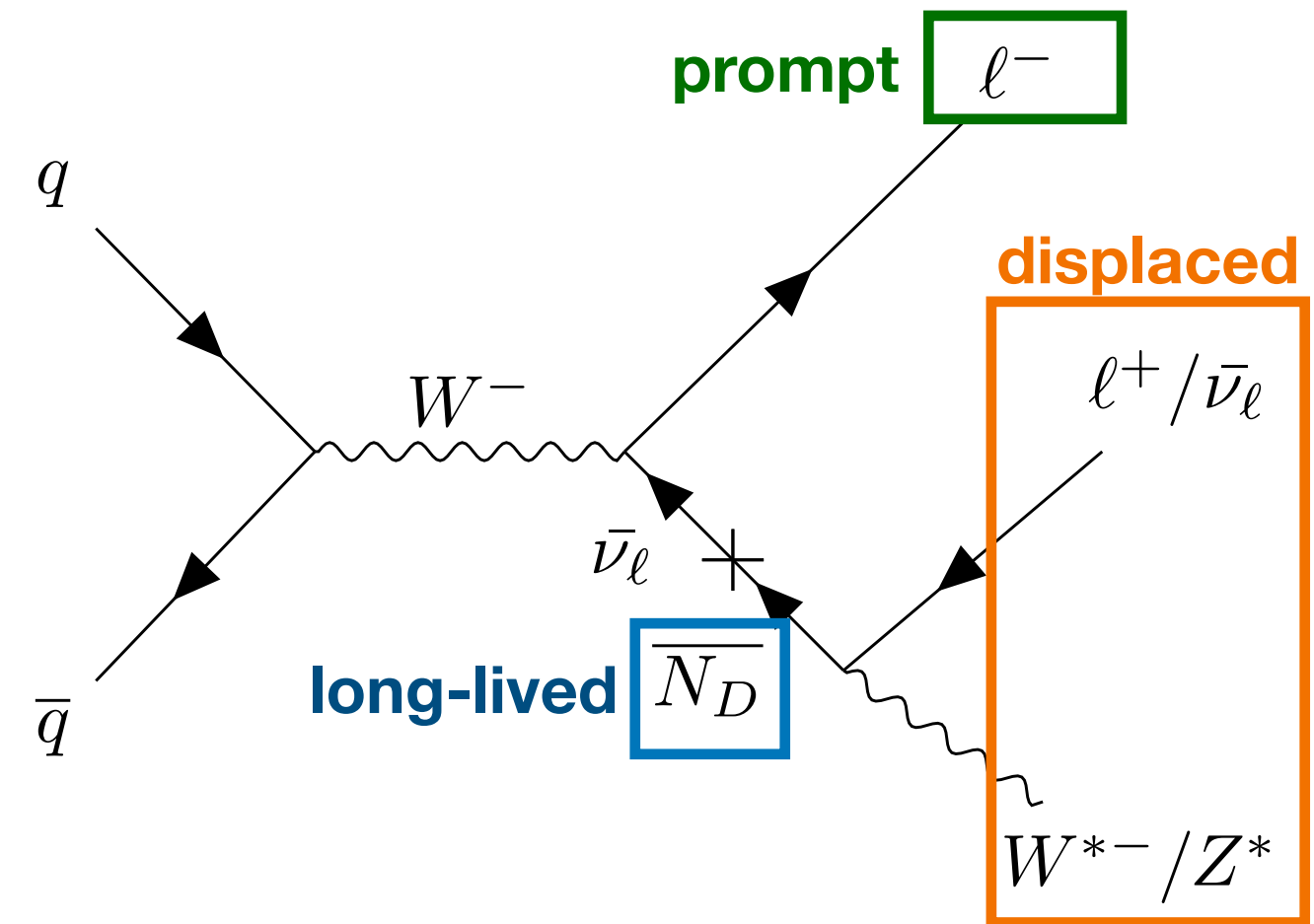


Credit: M. Kwok

Experimental Signature

Search for long-lived HNLs: Strategy

ArXiv:2402.18658
Submitted to PRD

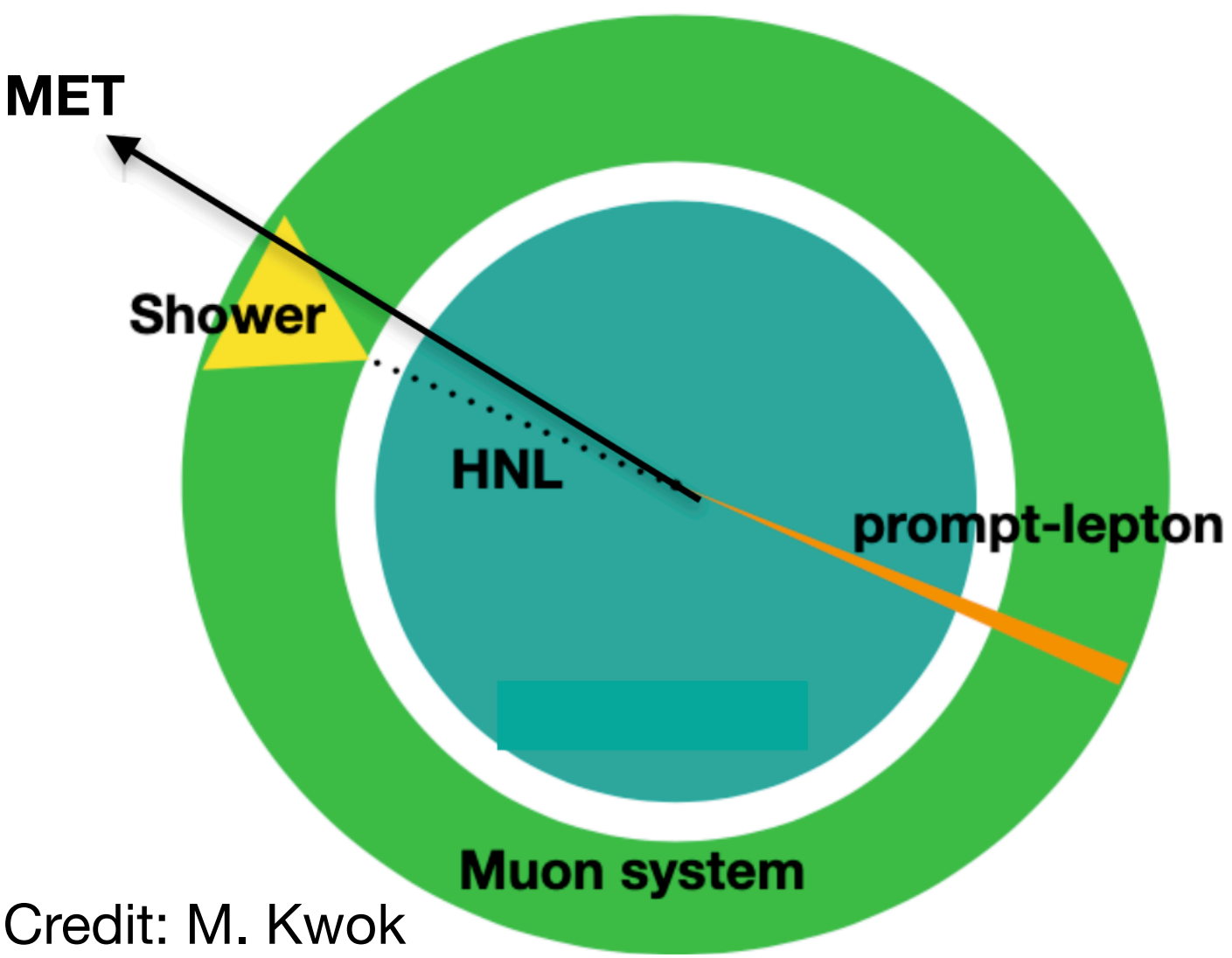


Dirac HNLs in W-decays

- Run-2 analysis based on **single electron and muon triggers**
- Events divided in 5 categories based on prompt-lepton and MDS clusters:
 - Electron + CSC, Electron-DT, Muon-CSC, Muon-DT(MB2) and Muon-DT(MB34)
- **Data-driven background model:**
 - ABCD method: N_{hits} and $\Delta\phi(\text{lep}, \text{cls})$ as main discriminants
 - Muon channel only: $Z \rightarrow \mu\mu$ bkg from control regions

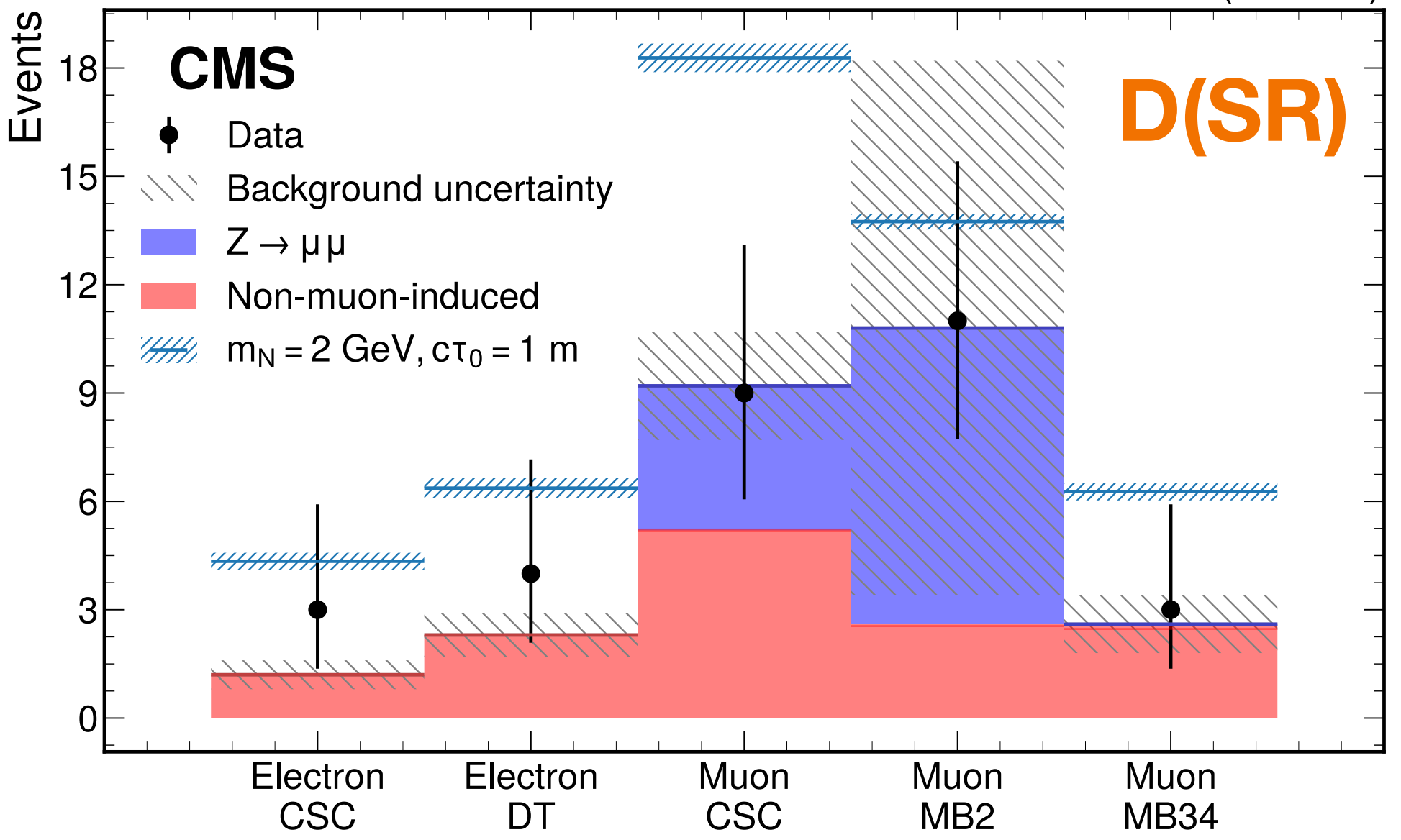
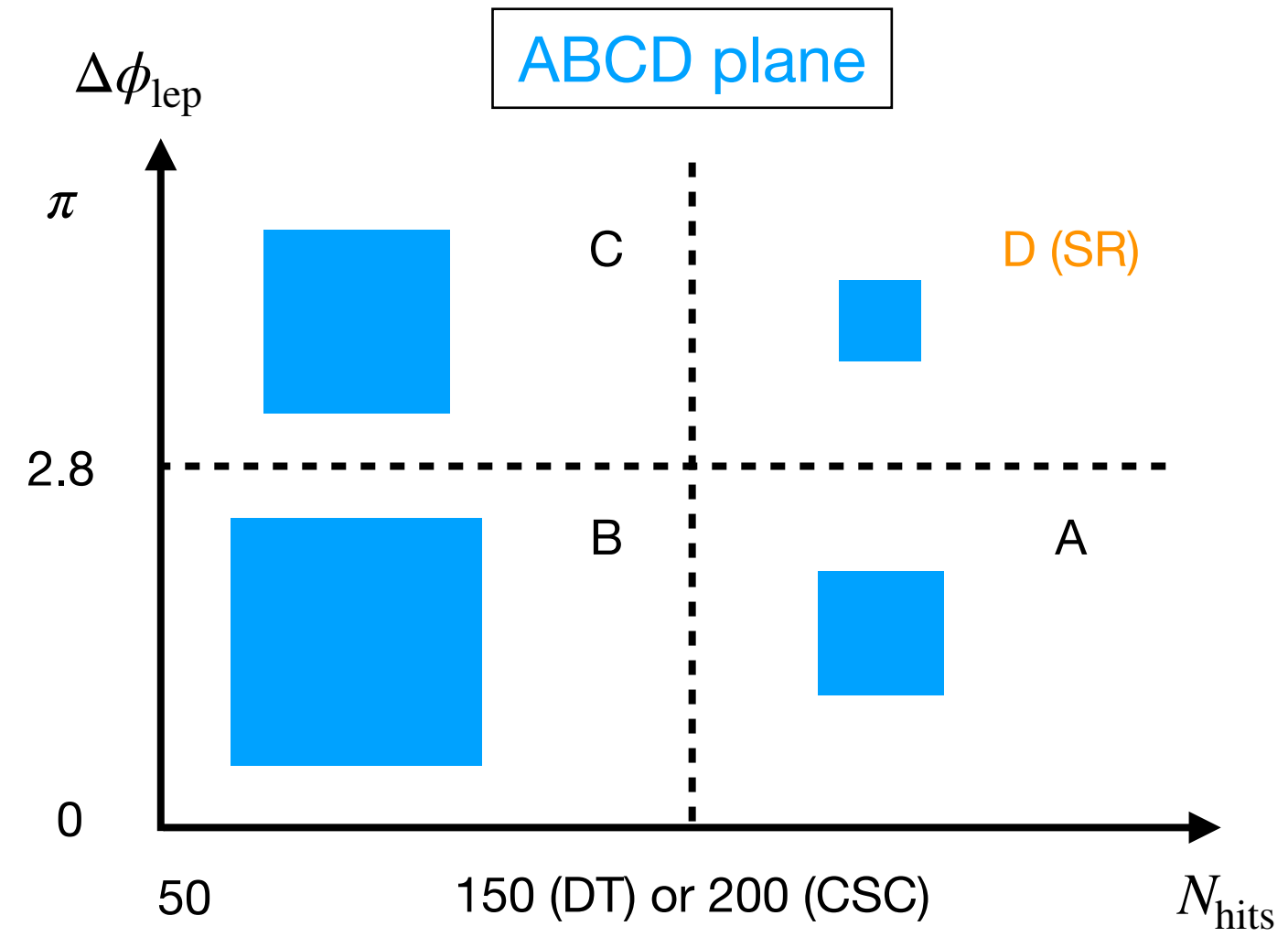
$$\lambda_D = \frac{\lambda_A \lambda_C}{\lambda_B}$$

138 fb⁻¹ (13 TeV)



Credit: M. Kwok

Experimental Signature



Signal region background estimate

Search for long-lived HNLs: Results

ArXiv:2402.18658
Submitted to PRD

- **No excess is observed** above the background expectation

- Results interpretations:

- **Dirac and Majorana HNLs**

- **All three lepton generations**

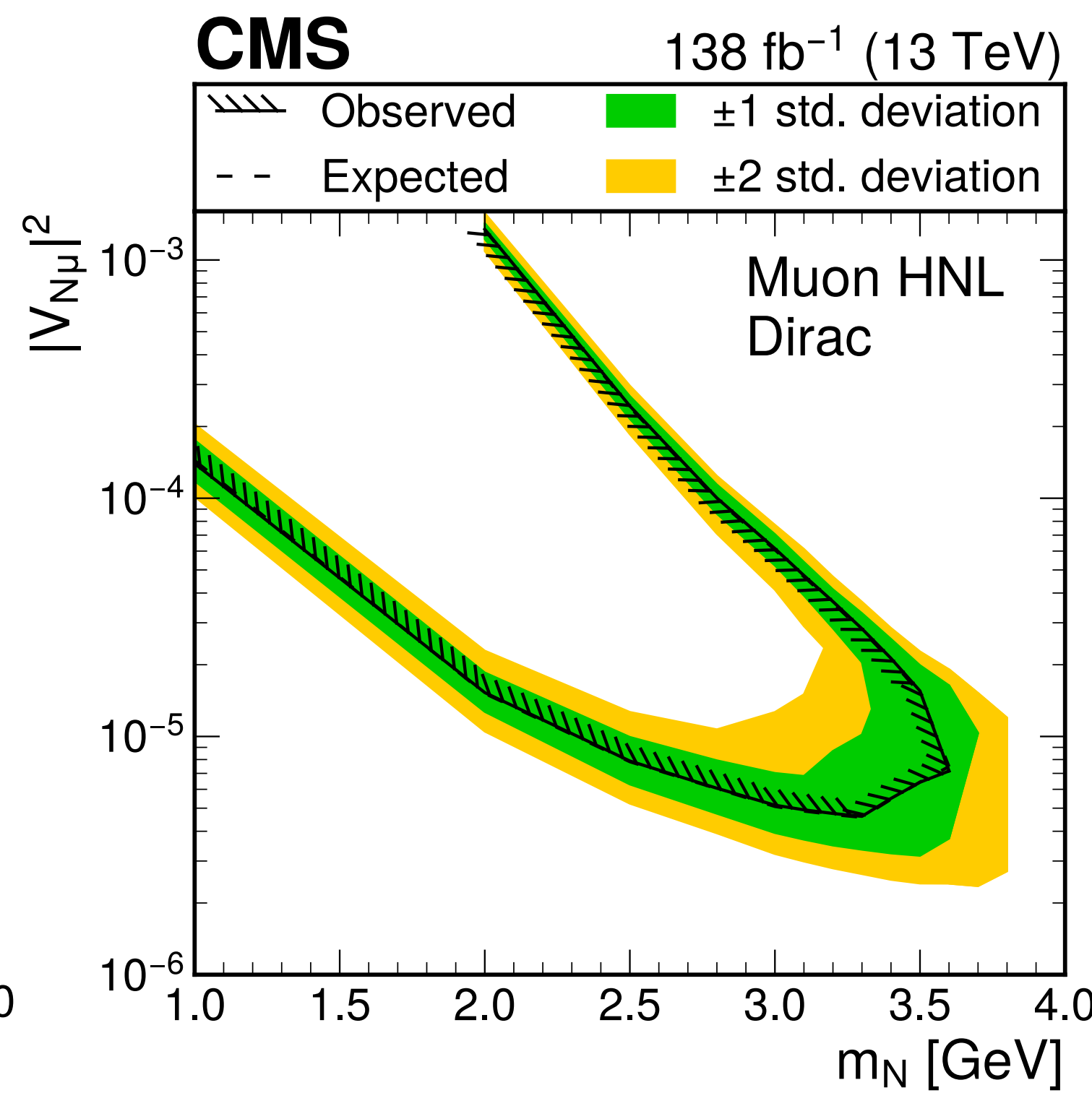
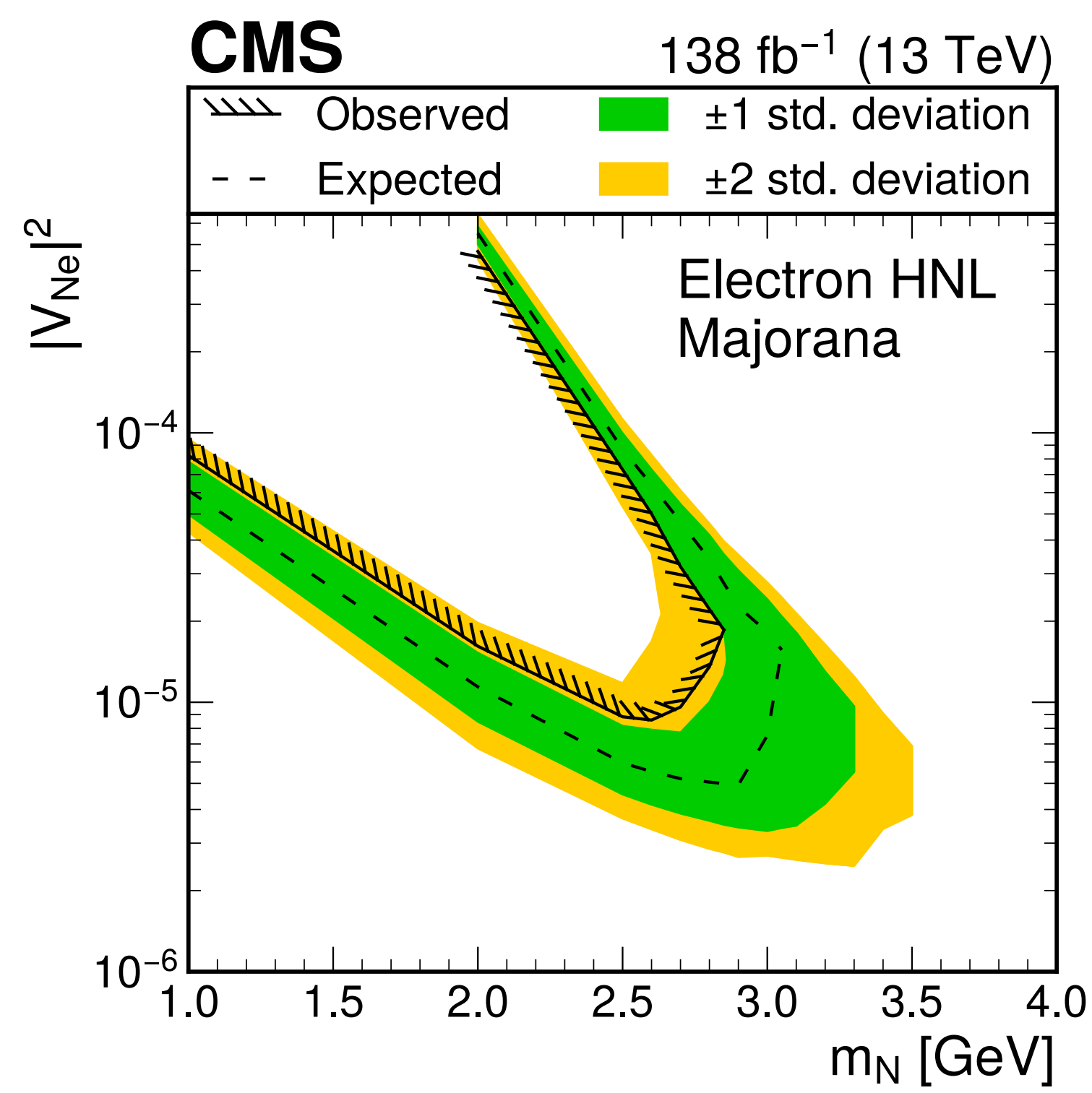
- Complementary sensitivity to existing searches

- $|V_{Ne}|^2$ ($|V_{N\mu}|^2$) as low as 8.6 (4.6) $\times 10^{-6}$

- **Most stringent constraints on $|V_{Ne}|^2$:**

- Electron channel with $m_N = 2.1 - 3.0$ GeV

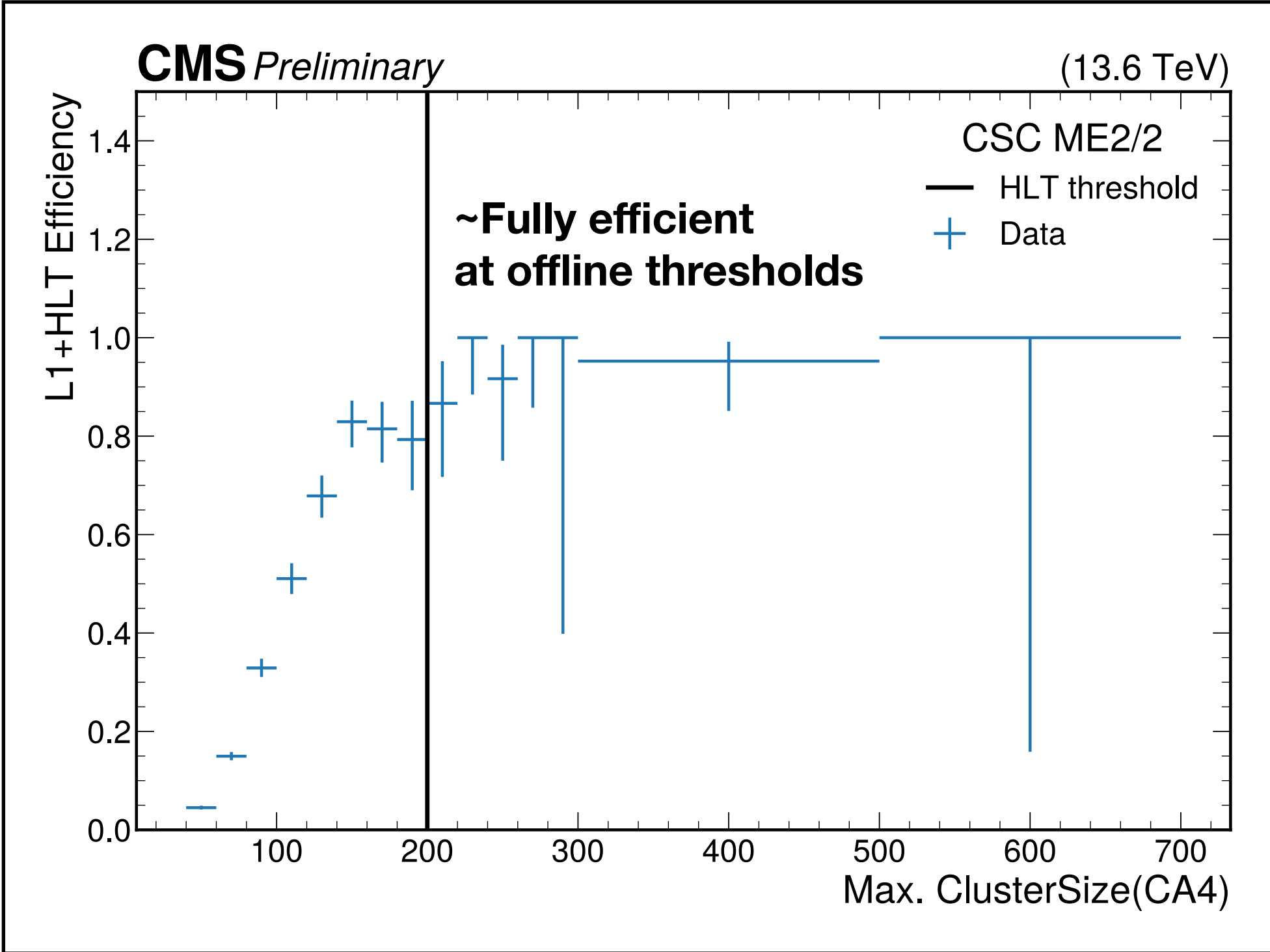
- Muon channel with $m_N = 1.9 - 3.3$ GeV



Selected HNL interpretations
(More interpretations in additional material)

Outlook to Run 3

- Run-2 MDS analyses relied on available MET and lepton triggers
- **New Run-3 L1 CSC High-Multiplicity Trigger (HMT)** using number of CSC hits
- **New Run-3 HLT paths** targeting single and double MDS clusters

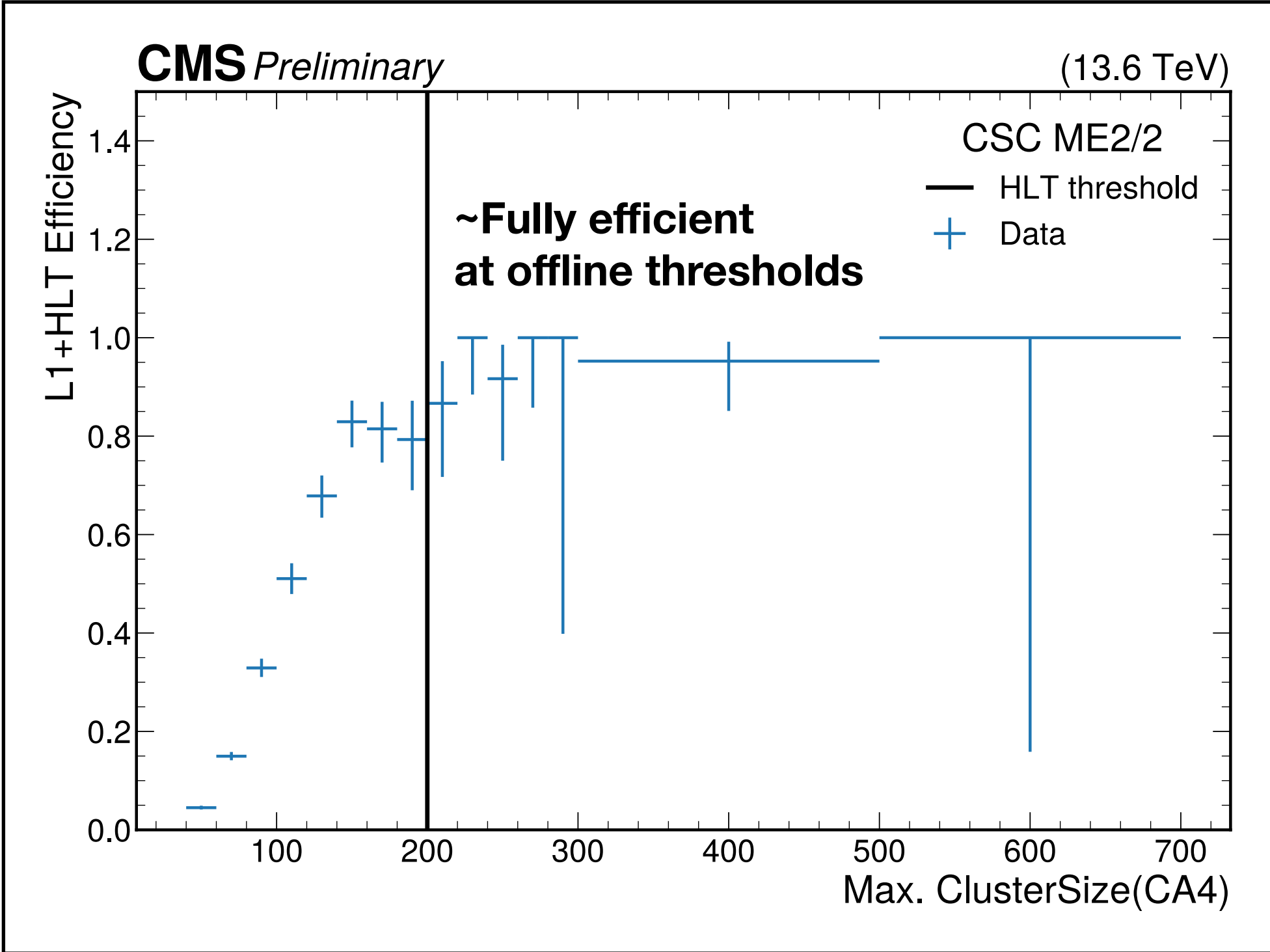


Trigger efficiency as function of the largest CSC cluster size (N_{hits})

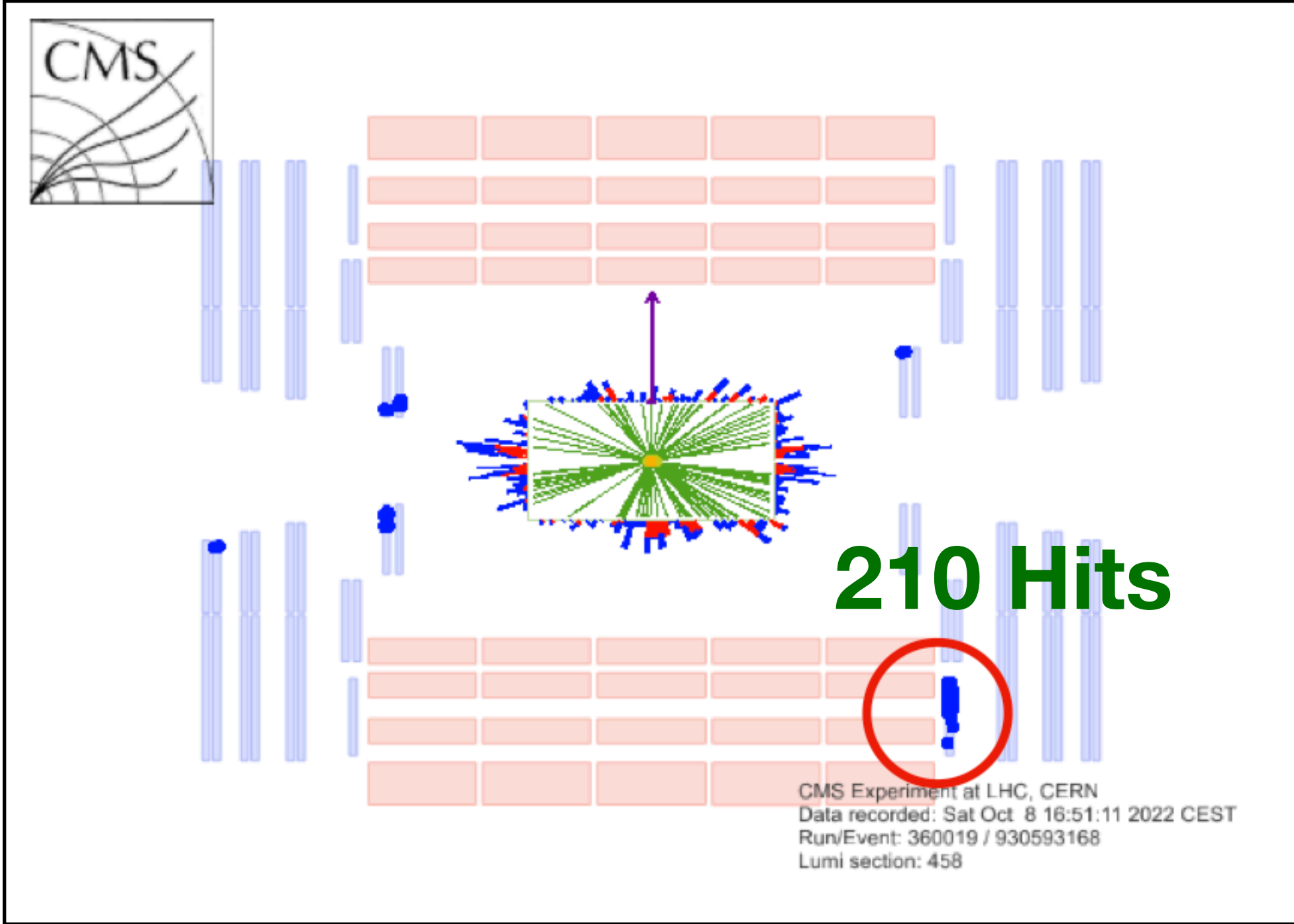
Outlook to Run 3

- Run-2 MDS analyses relied on available MET and lepton triggers
- **New Run-3 L1 CSC High-Multiplicity Trigger (HMT)** using number of CSC hits
- **New Run-3 HLT paths** targeting single and double MDS clusters

• **Actively collecting and analyzing Run-3 data!**



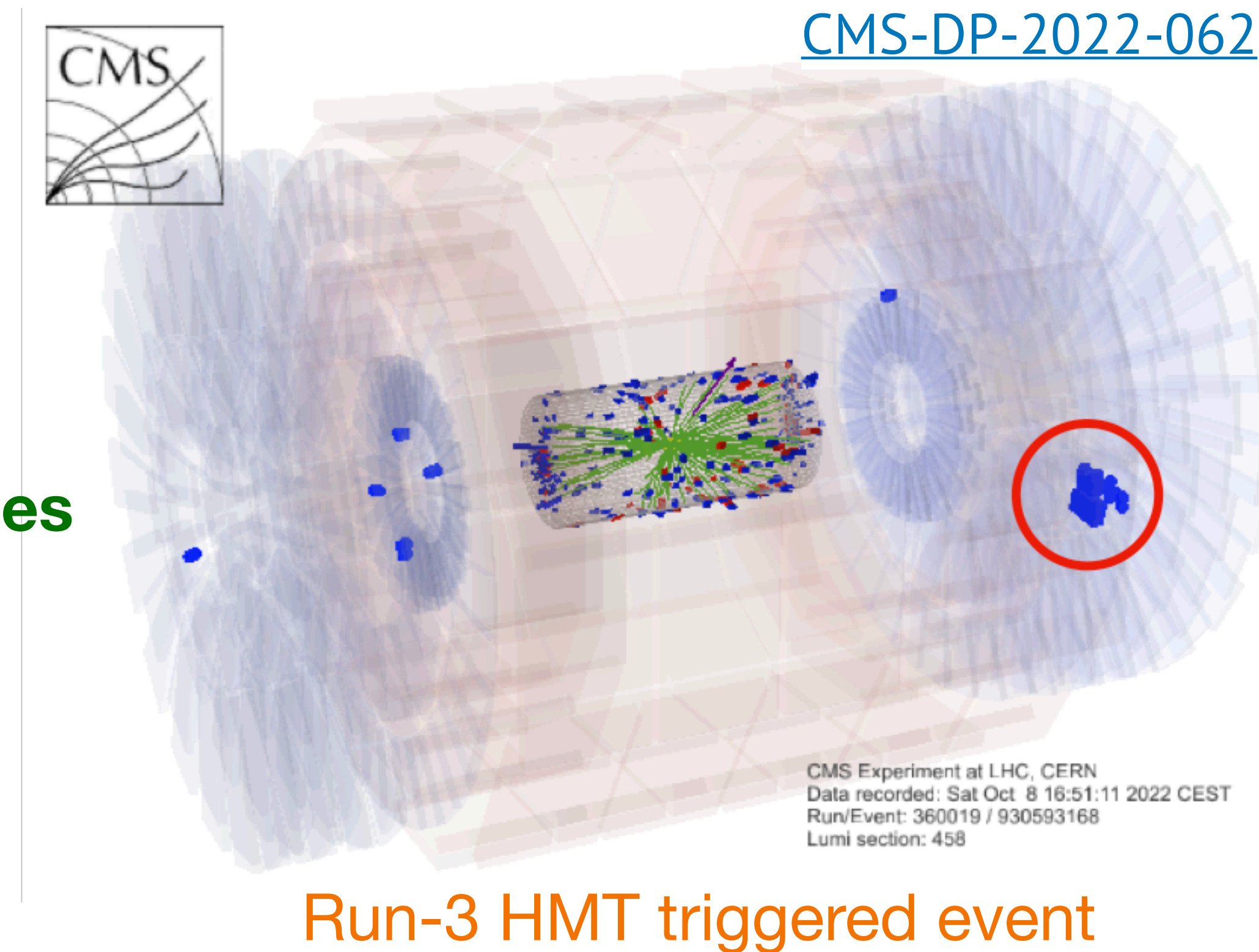
Trigger efficiency as function of the largest CSC cluster size (N_{hits})

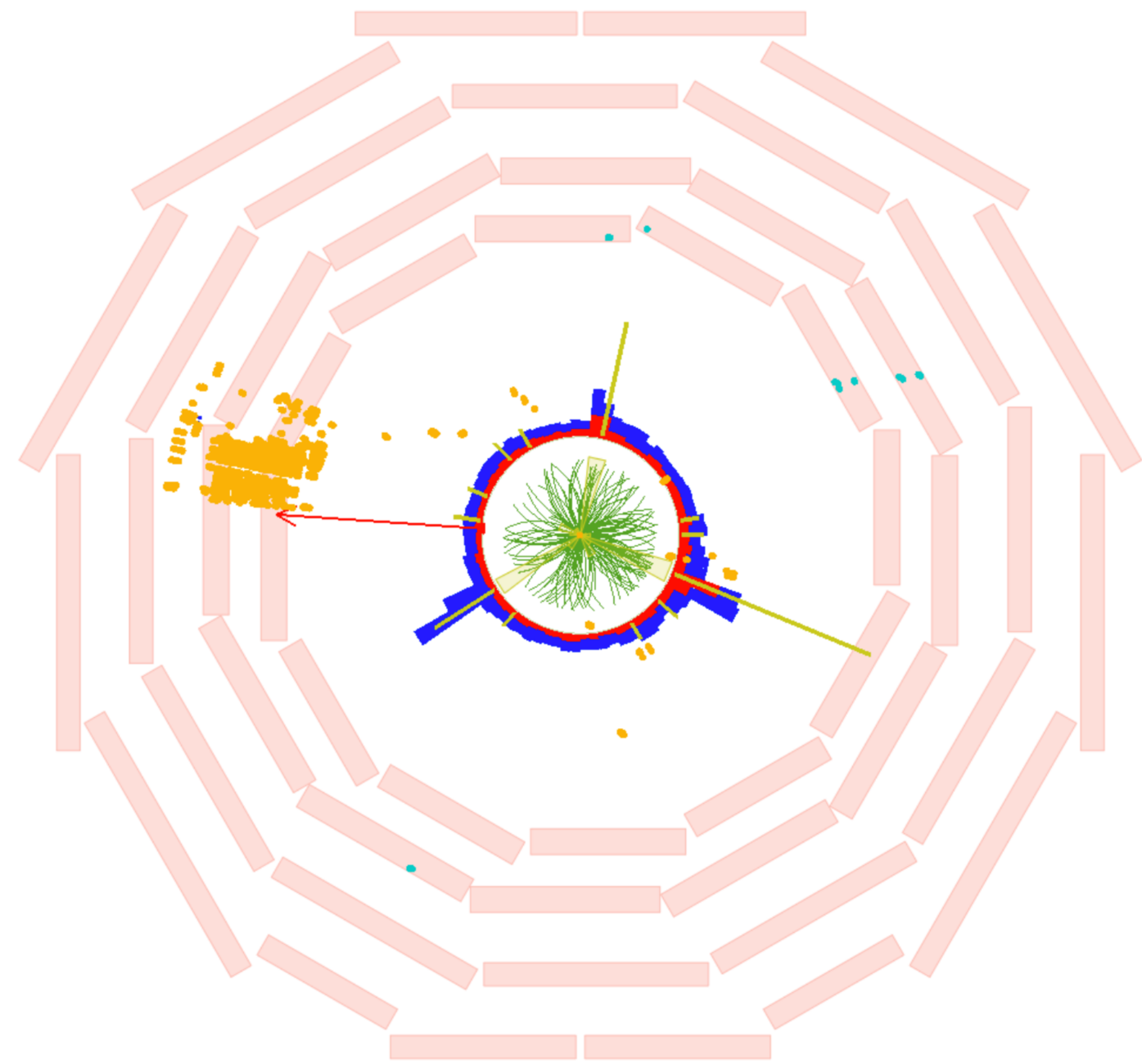


Event triggered by the CSC HMT trigger in 2022

Summary

- **Innovative use of the detector** is crucial to advancing LLP frontier now, Run-3 and the HL-LHC
- **MDS: Great example of a fully integrated effort**
 - Theory, triggers, data management, algorithms, and analysis
- **MDS: powerful and complementary tool for LLPs searches**
 - Run-2 search for Higgs decays to neutral LLPs ([ArXiv:2402.01898](#))
 - Run-2 search for Long-lived HNLs ([arXiv:2402.18658](#))
- Run-3 brings new LLP strategies (e.g. **MDS triggers**) that could enable future discoveries!

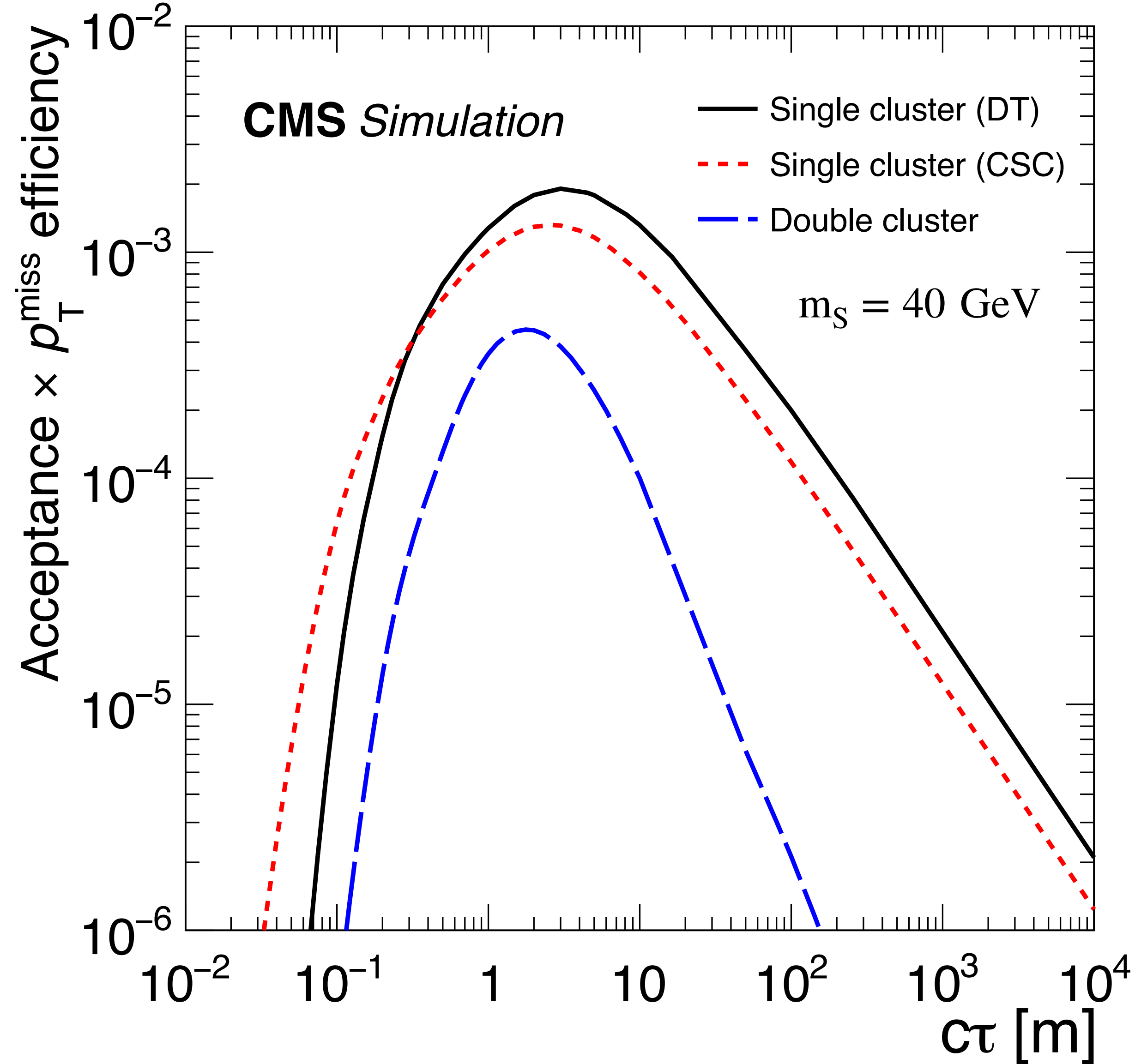




Additional Material

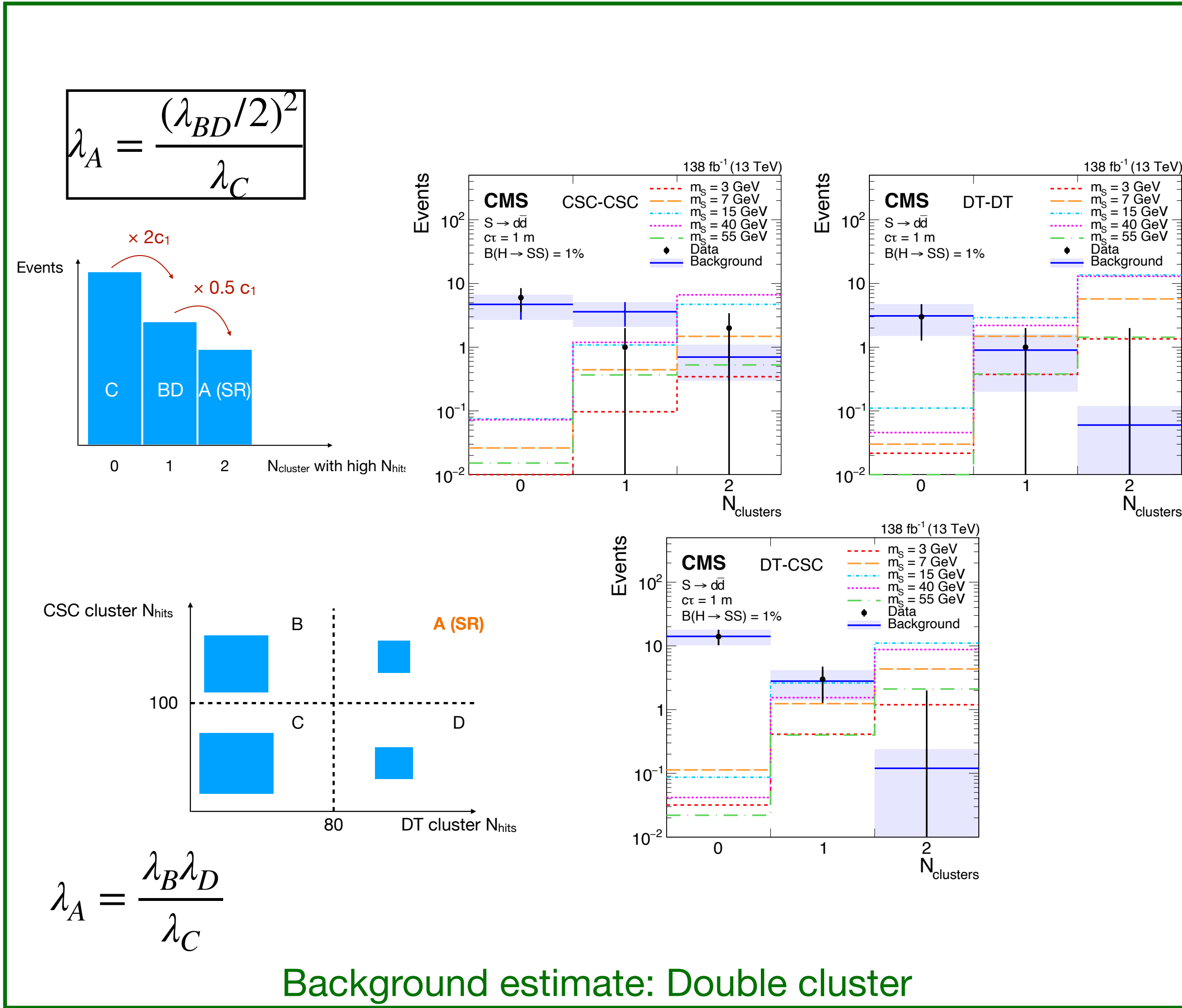
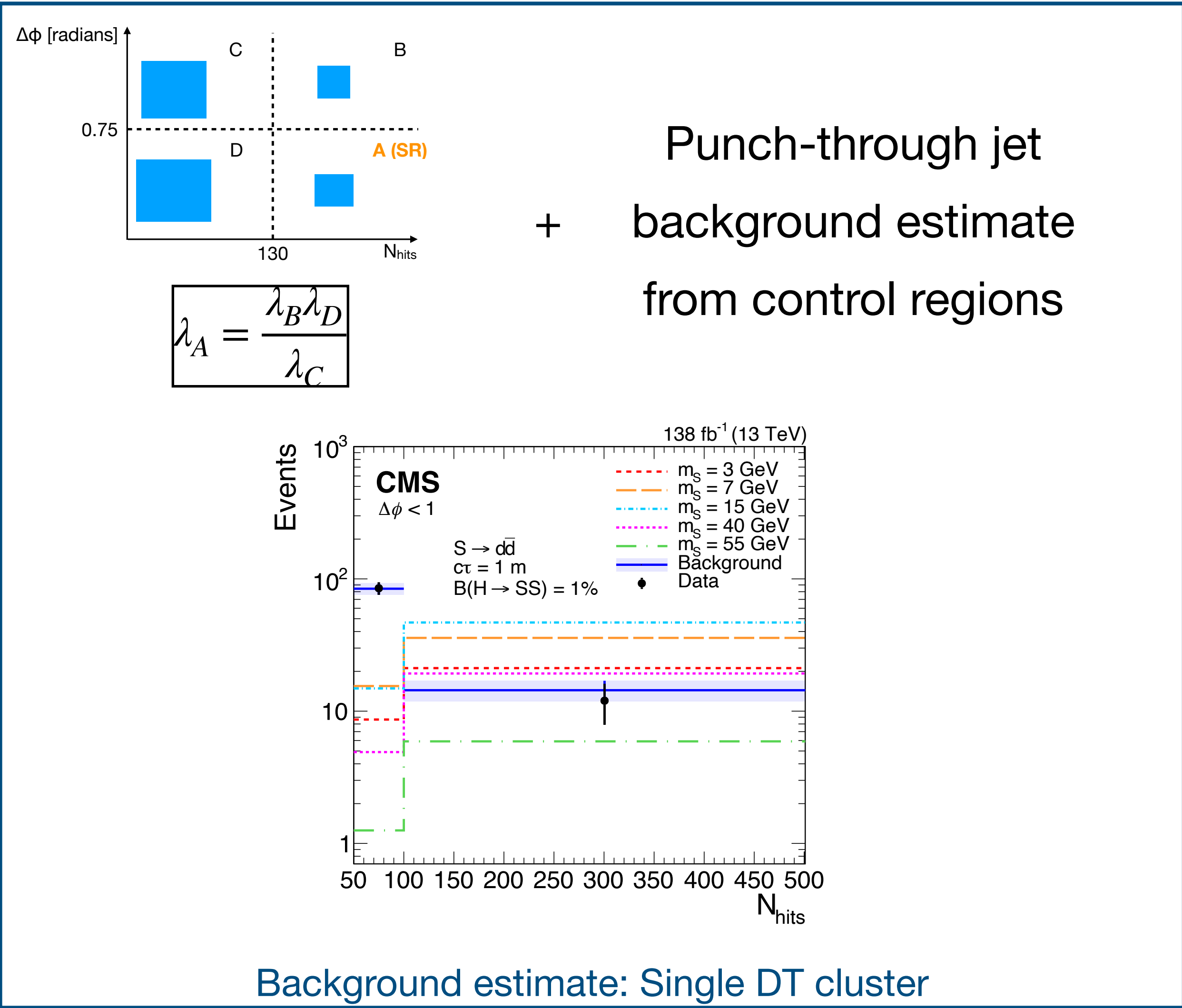
Search for Neutral LLPs: $A \times \text{MET Eff.}$

[ArXiv:2402.01898](https://arxiv.org/abs/2402.01898)
Accepted by PRD



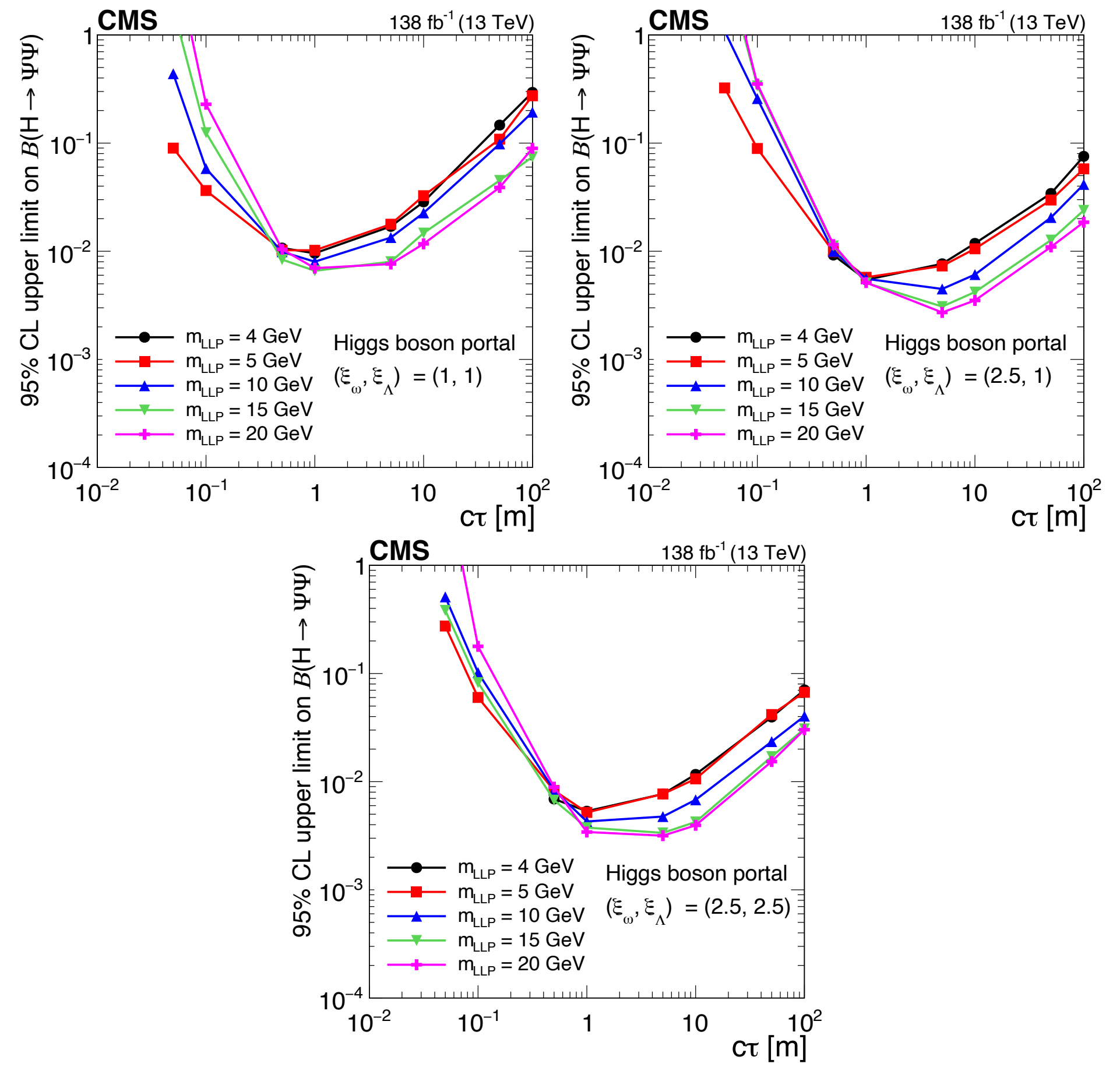
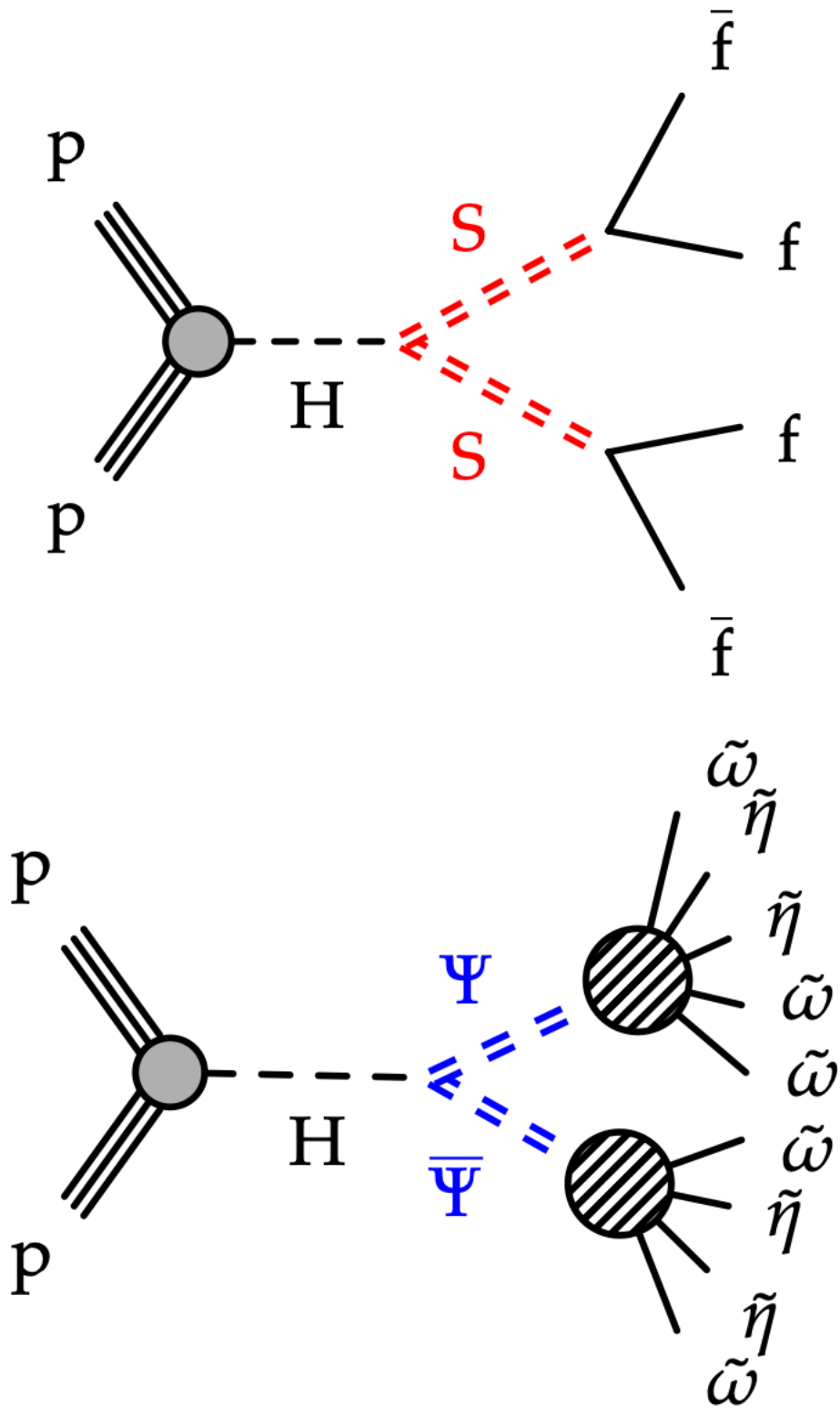
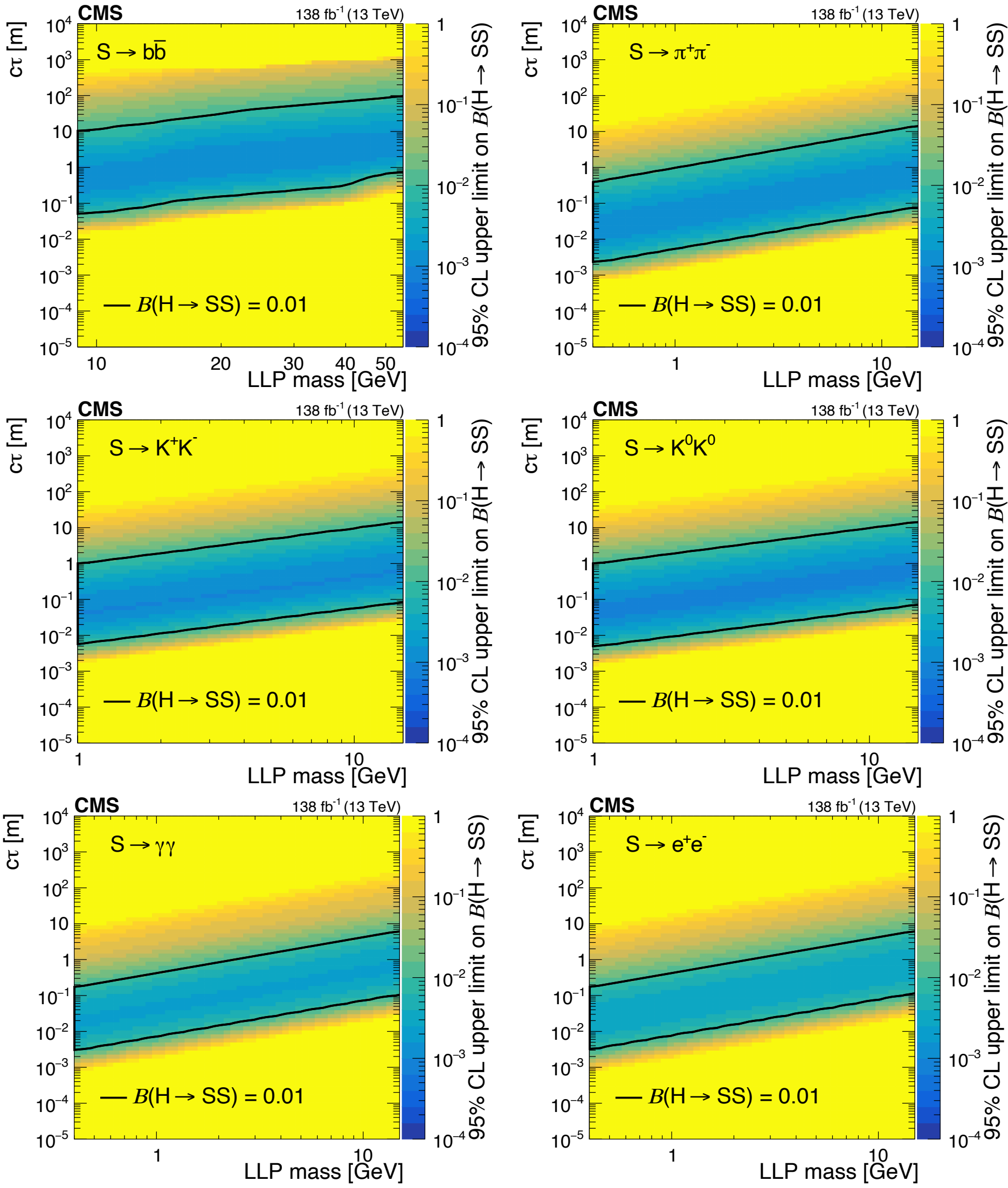
Search for Neutral LLPs: Background model

ArXiv:2402.01898
Accepted by PRD



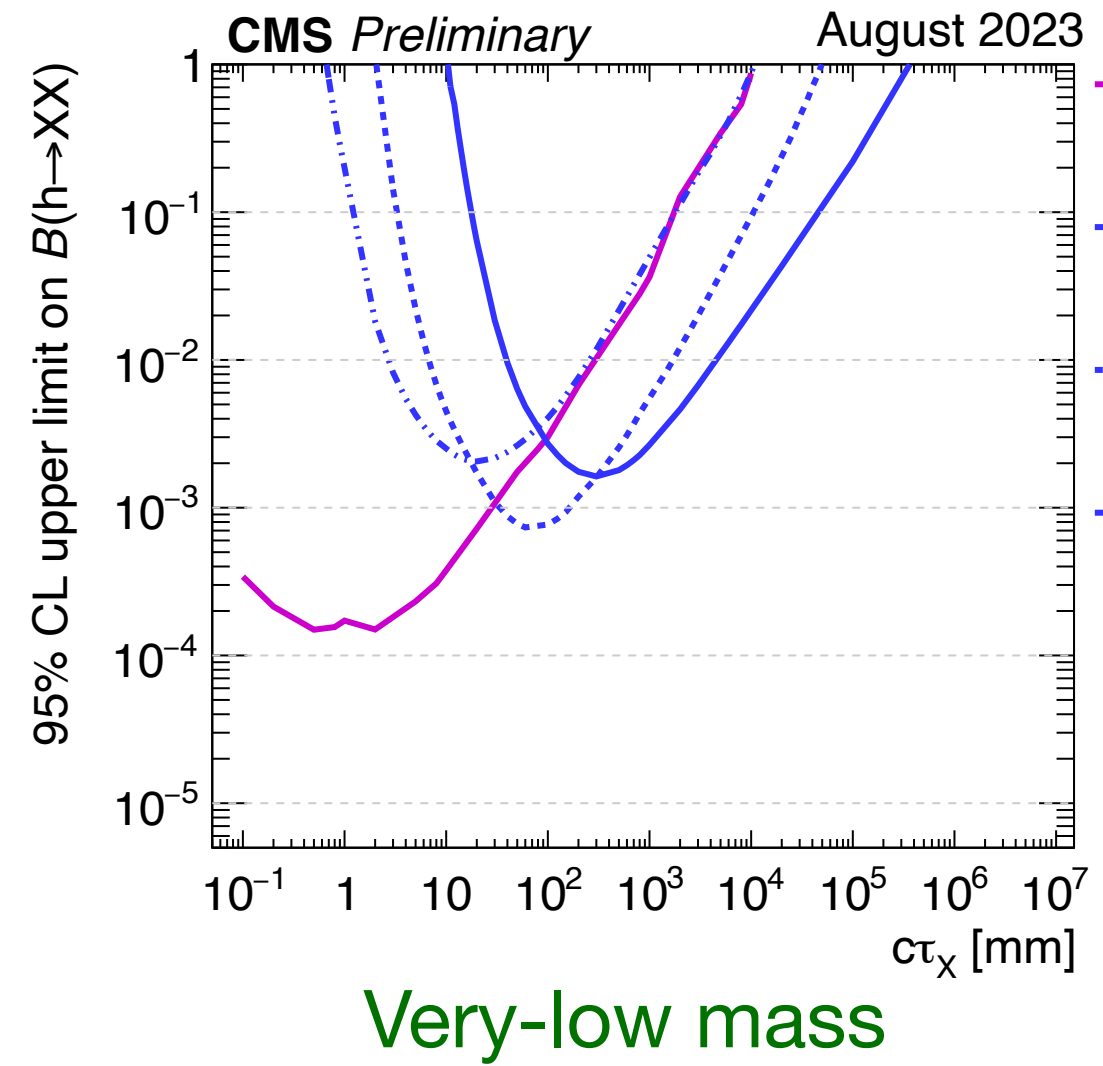
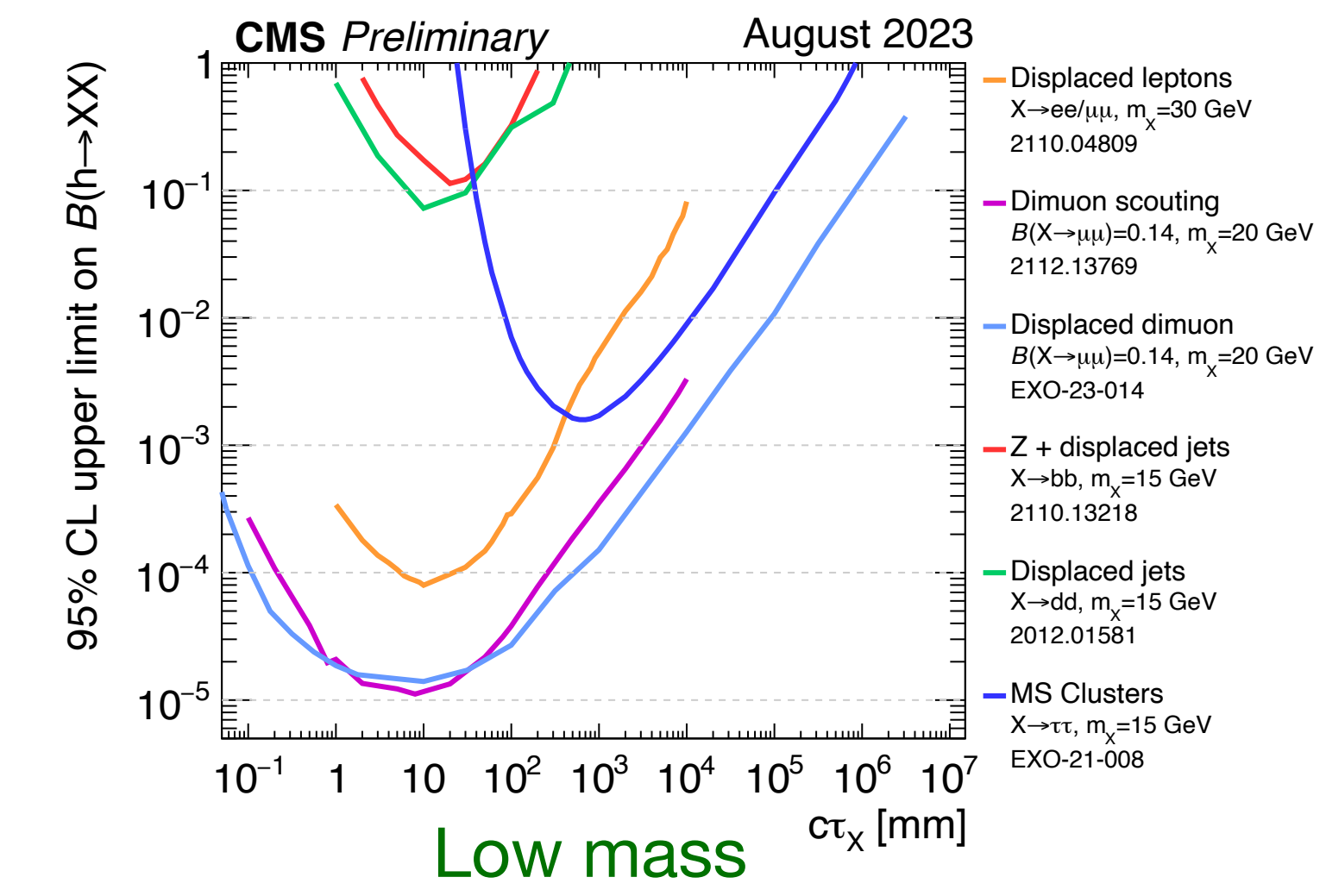
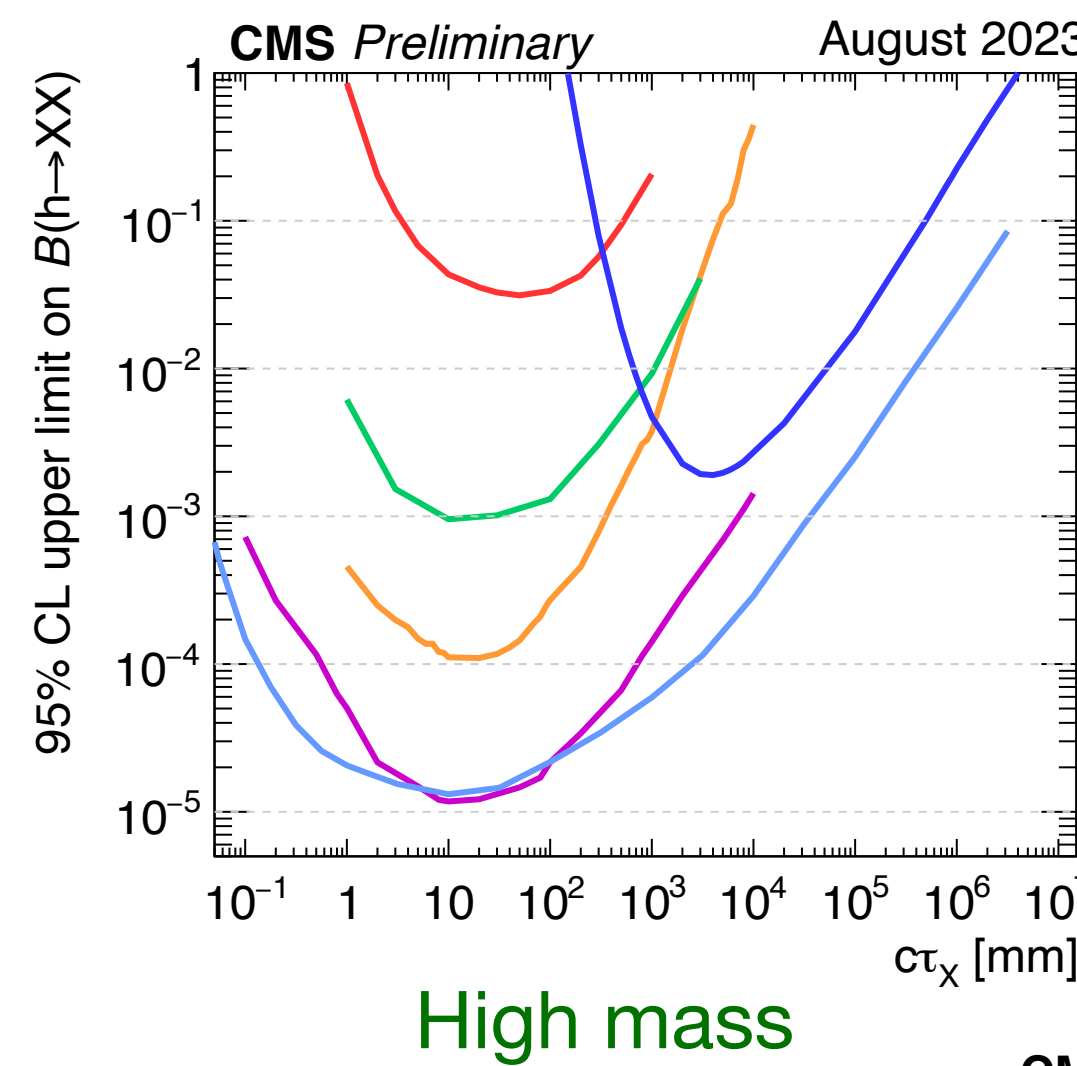
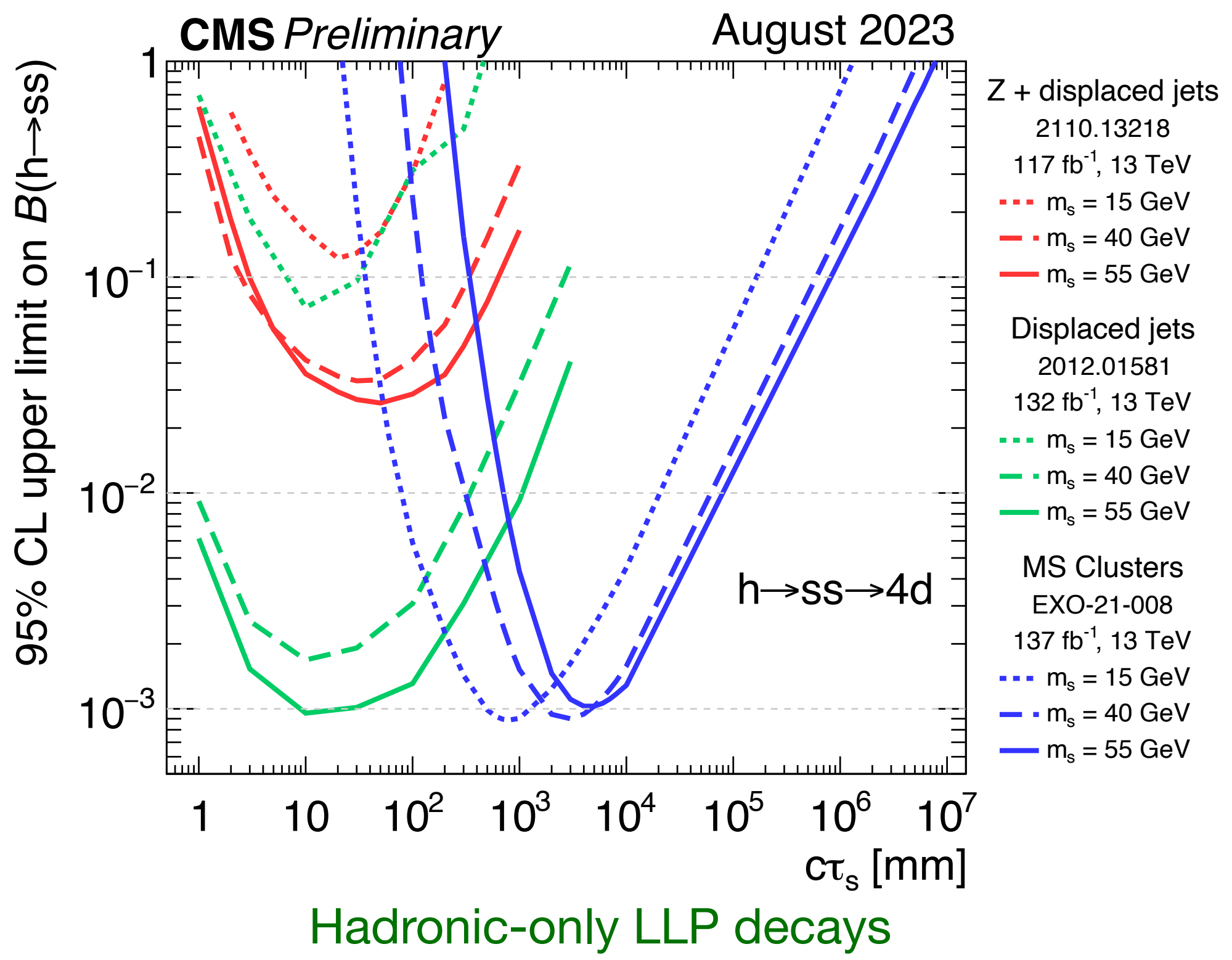
Search for Neutral LLPs: Interpretations

ArXiv:2402.01898
Accepted by PRD



CMS Higgs to LLPs Summaries

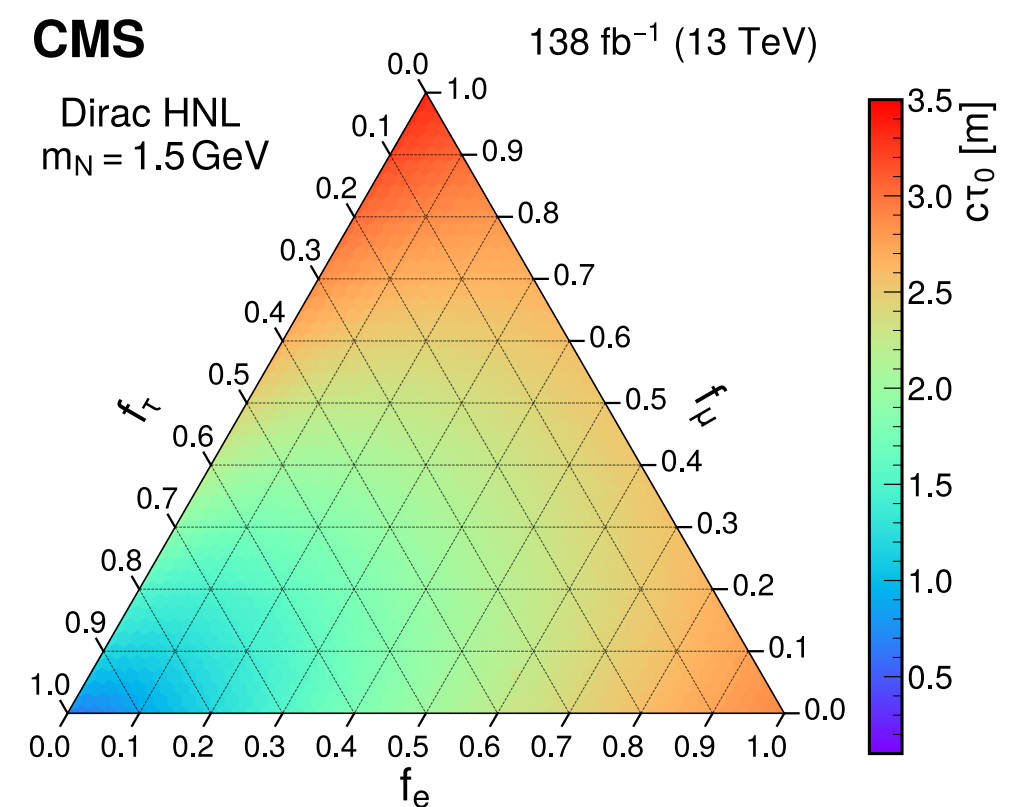
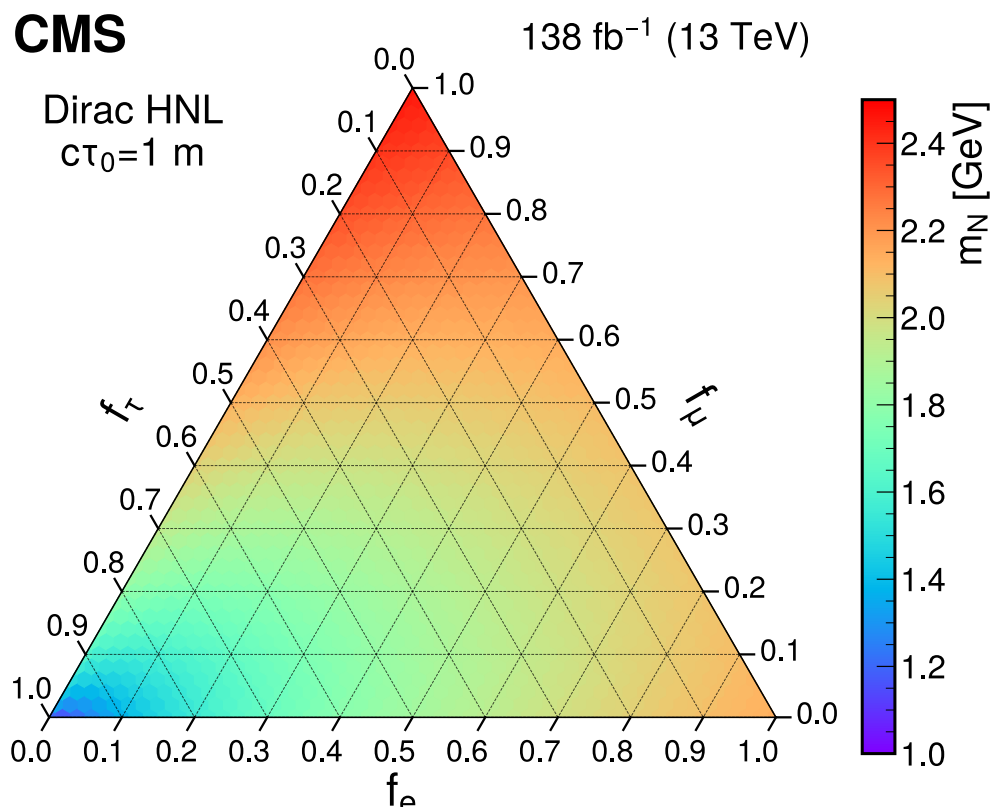
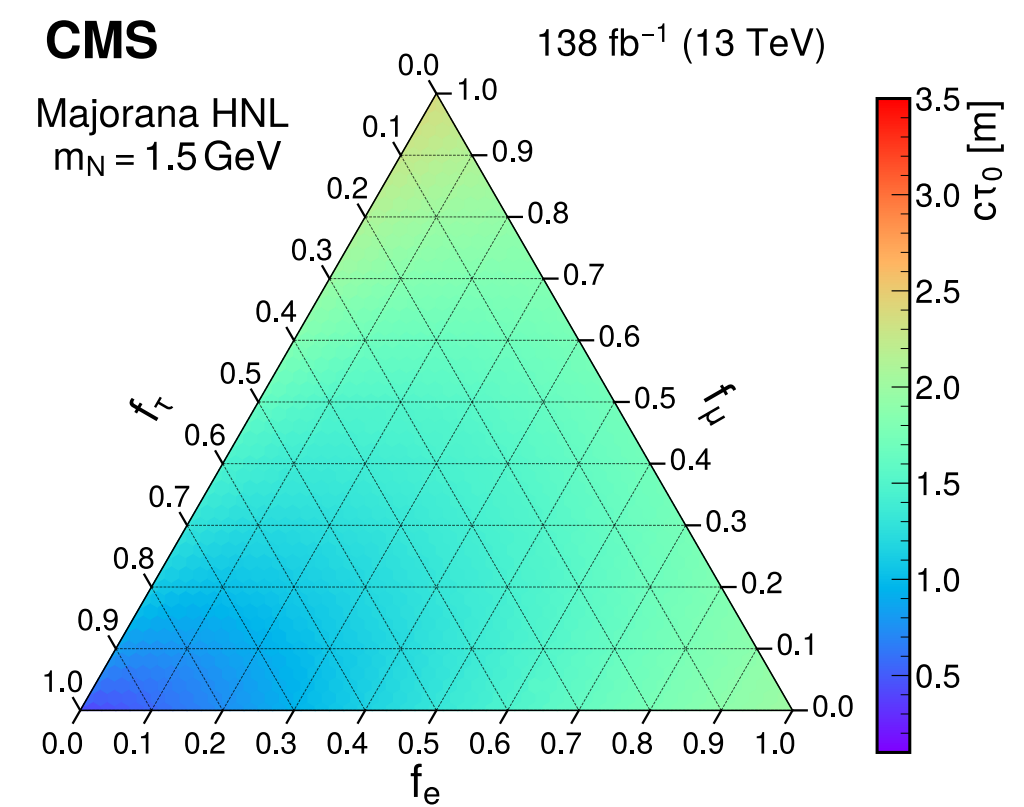
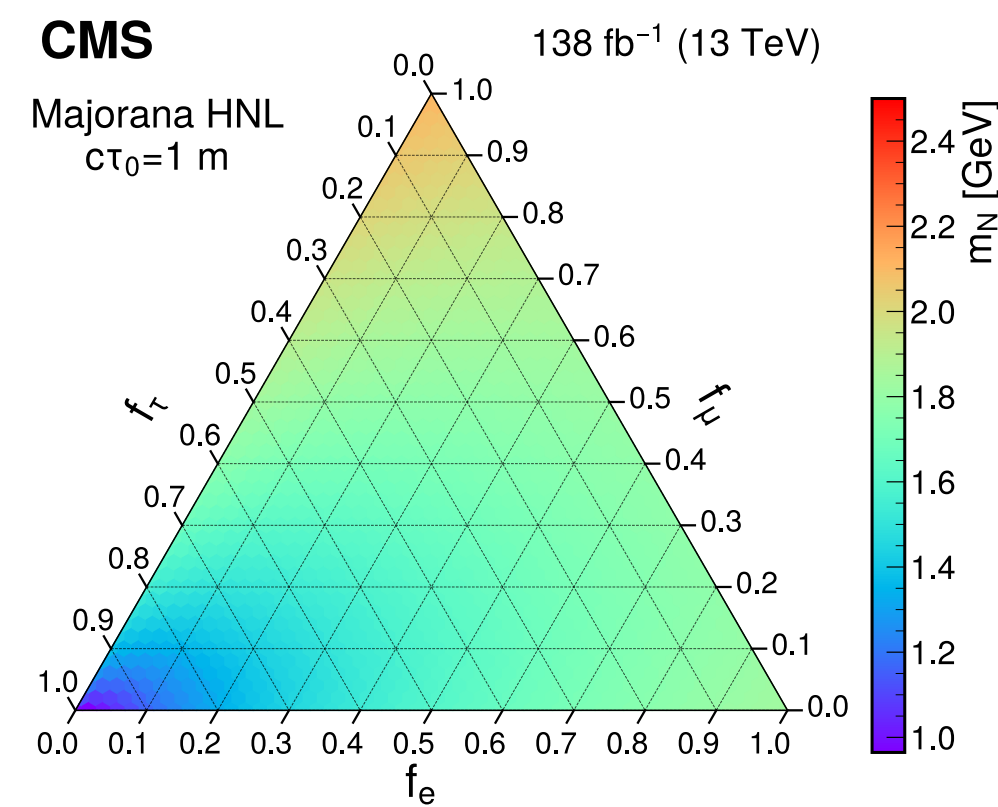
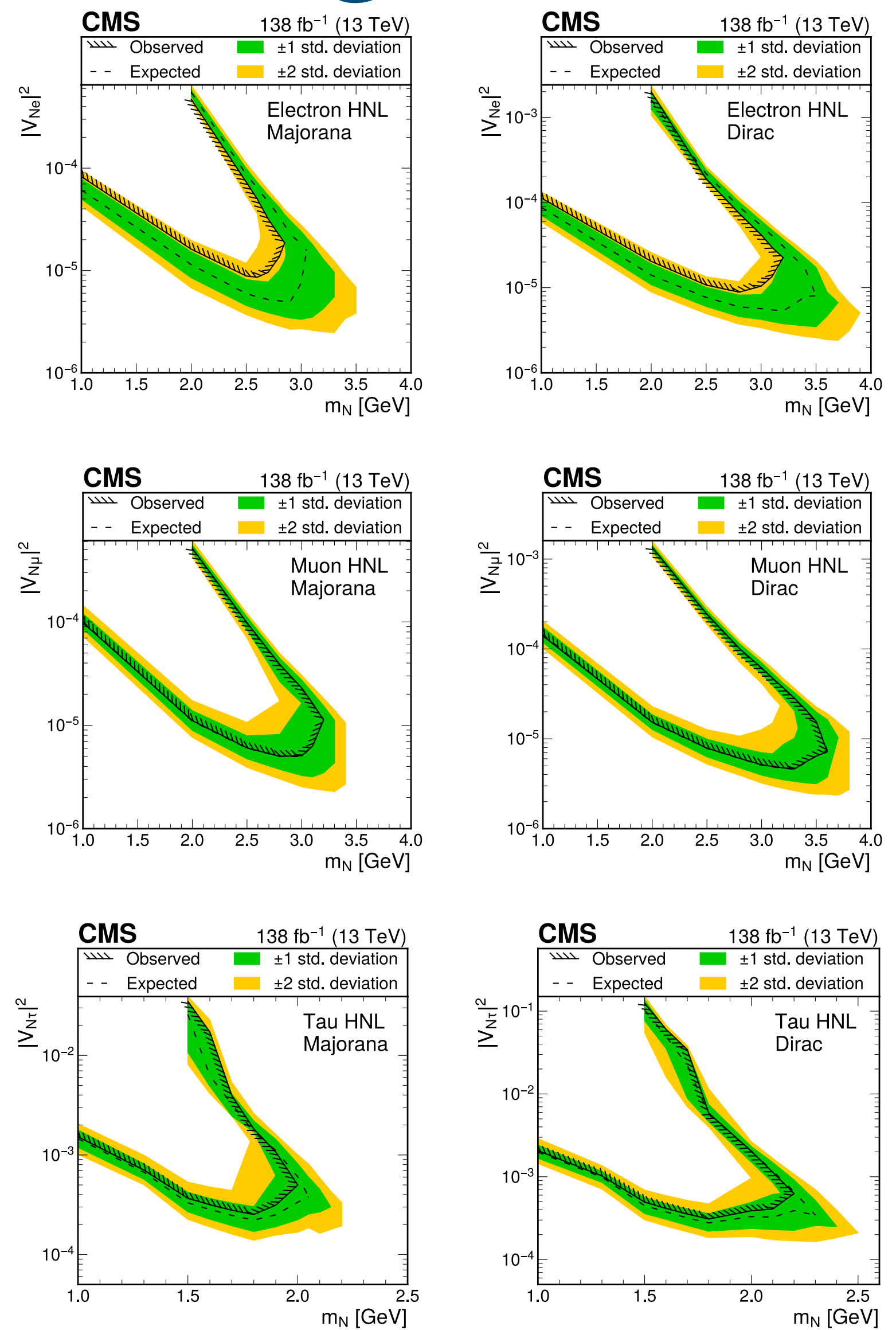
CMS LLP Summary Plots



Note: It does not include [Run-3 displaced jets results](#)

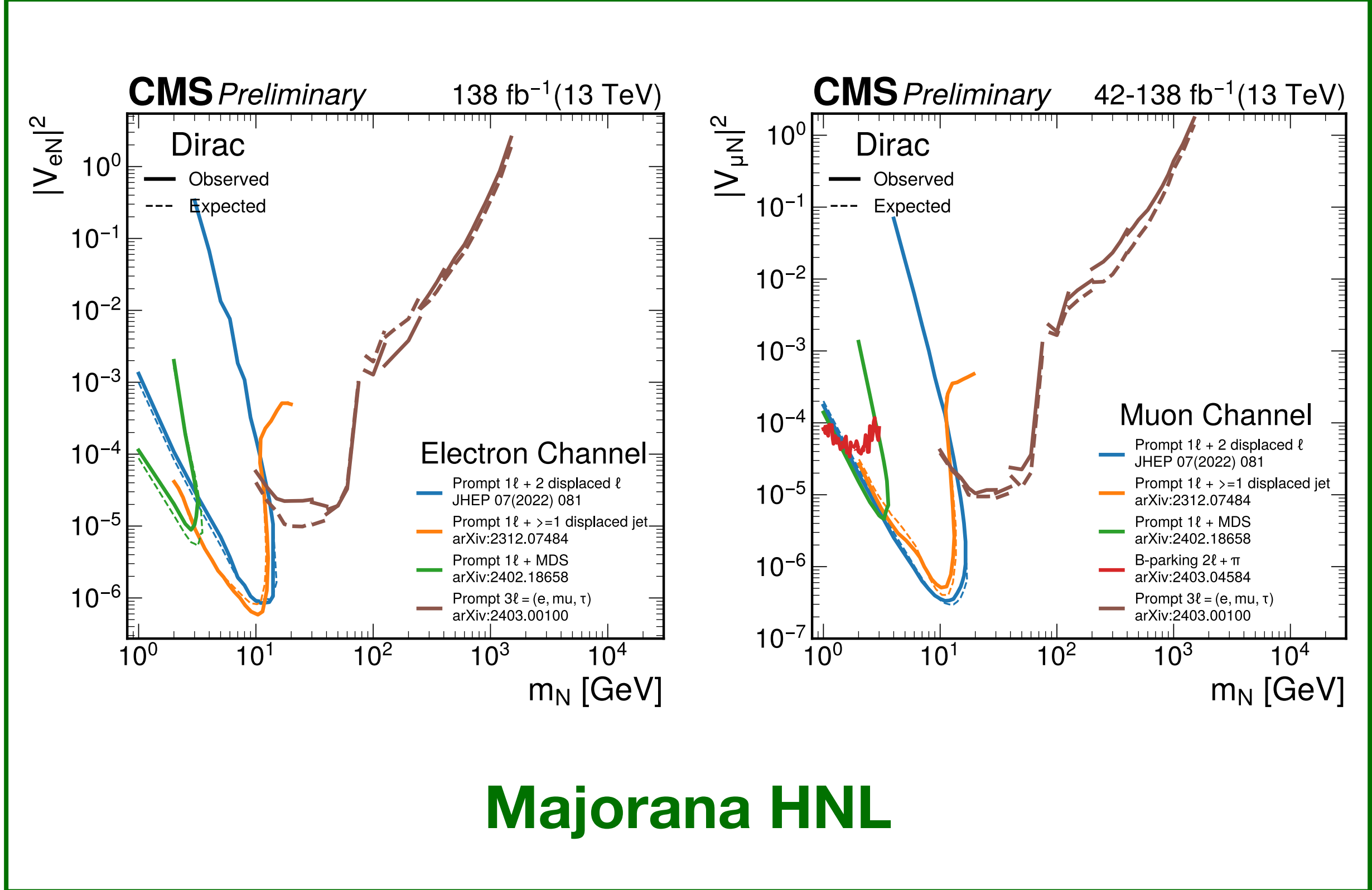
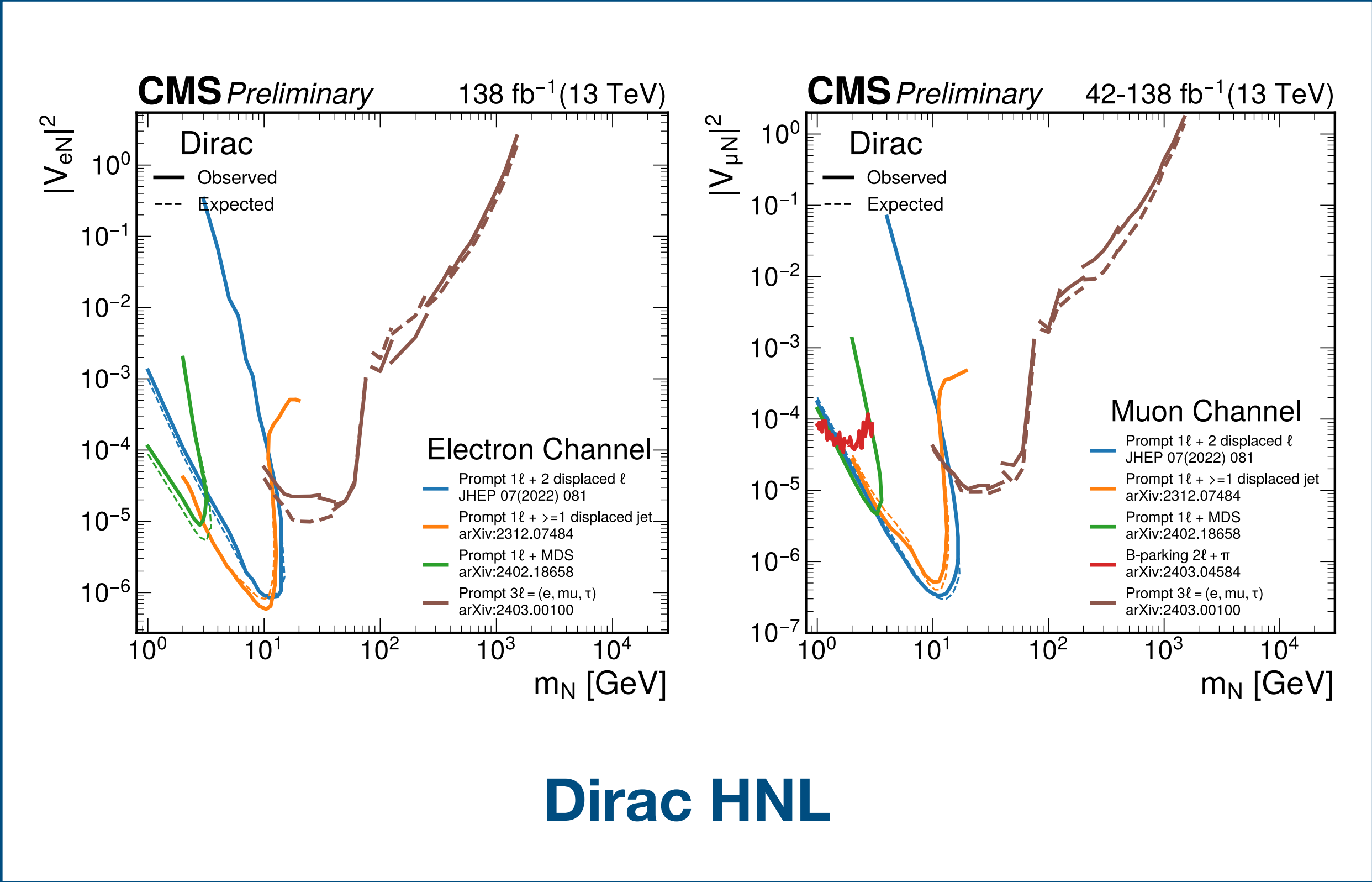
Search long-live HNL Interpretations

[ArXiv:2402.18658](https://arxiv.org/abs/2402.18658)
Submitted to PRD

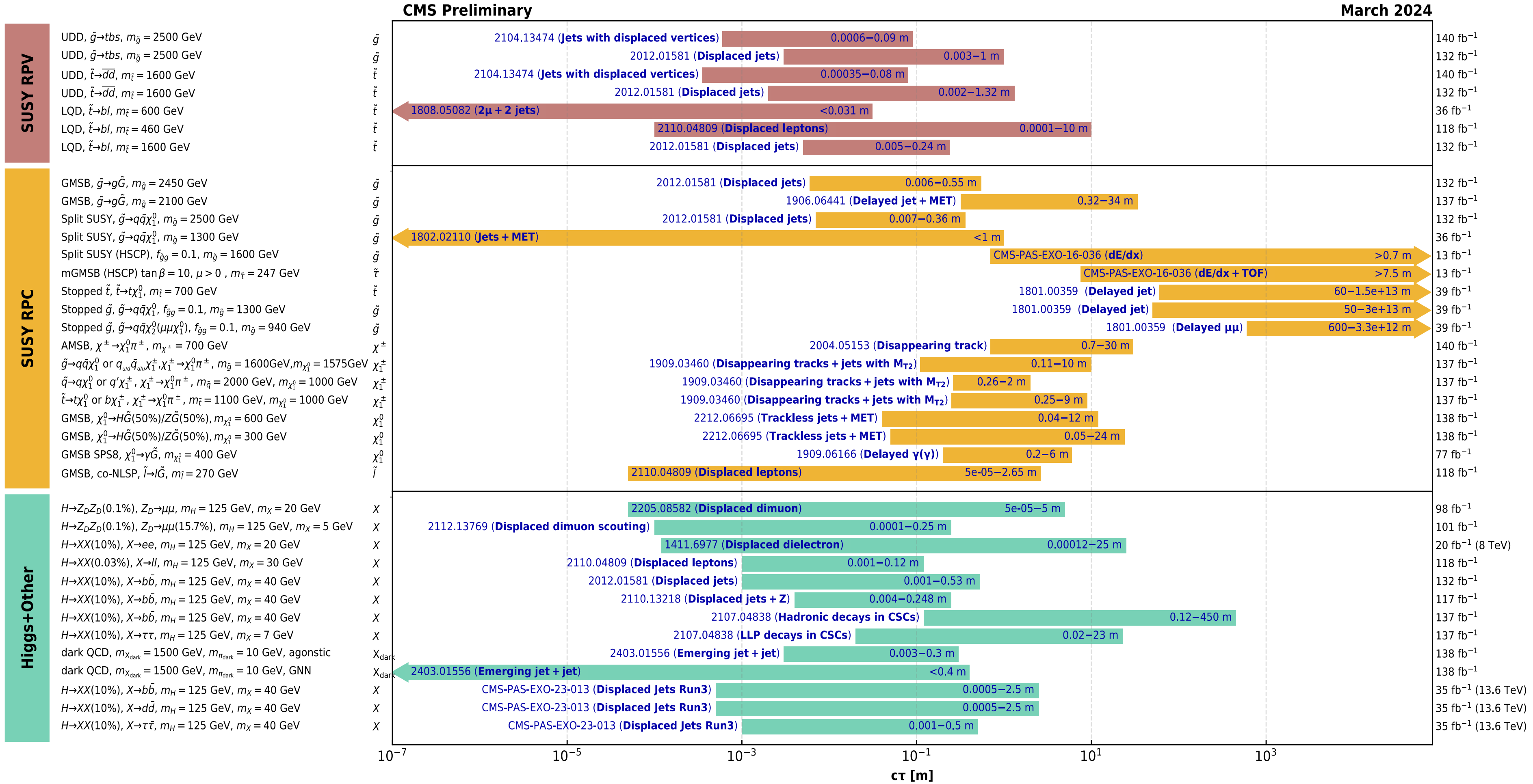


CMS HNL Summary

CMS LLP Summary Plots



Overview of CMS long-lived particle searches

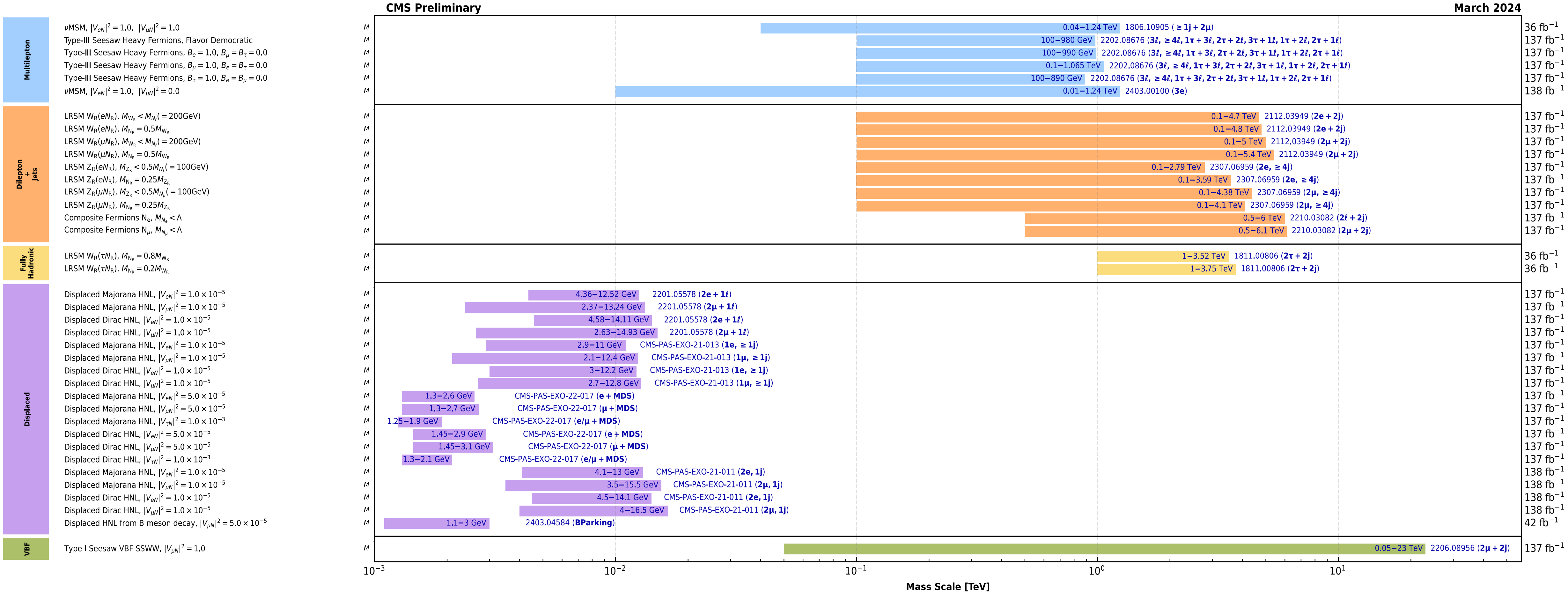


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

CMS HNL Summary

CMS LLP Summary Plots

Overview of CMS HNL results



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).