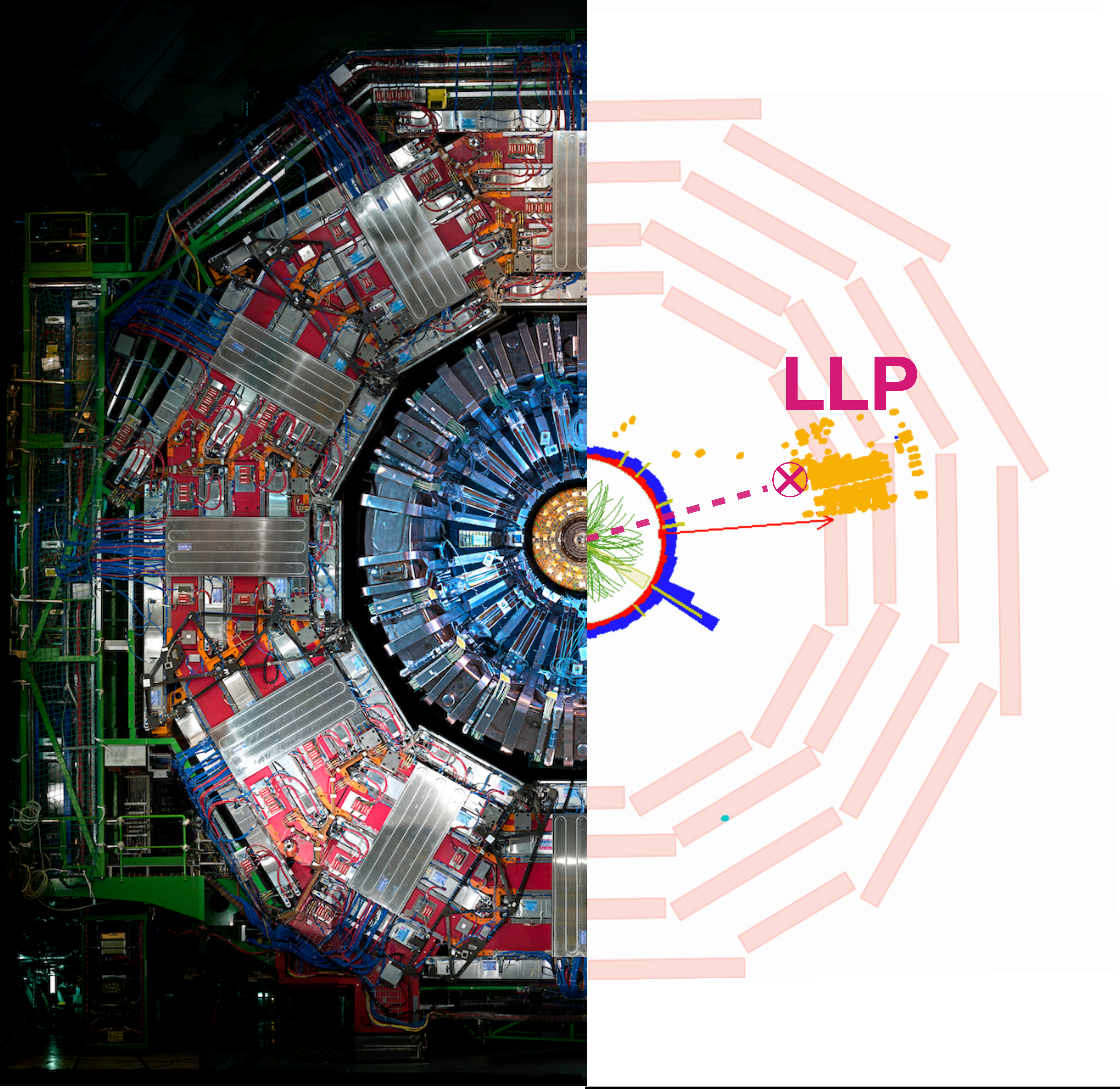
Search for Long-lived Particles in CMS



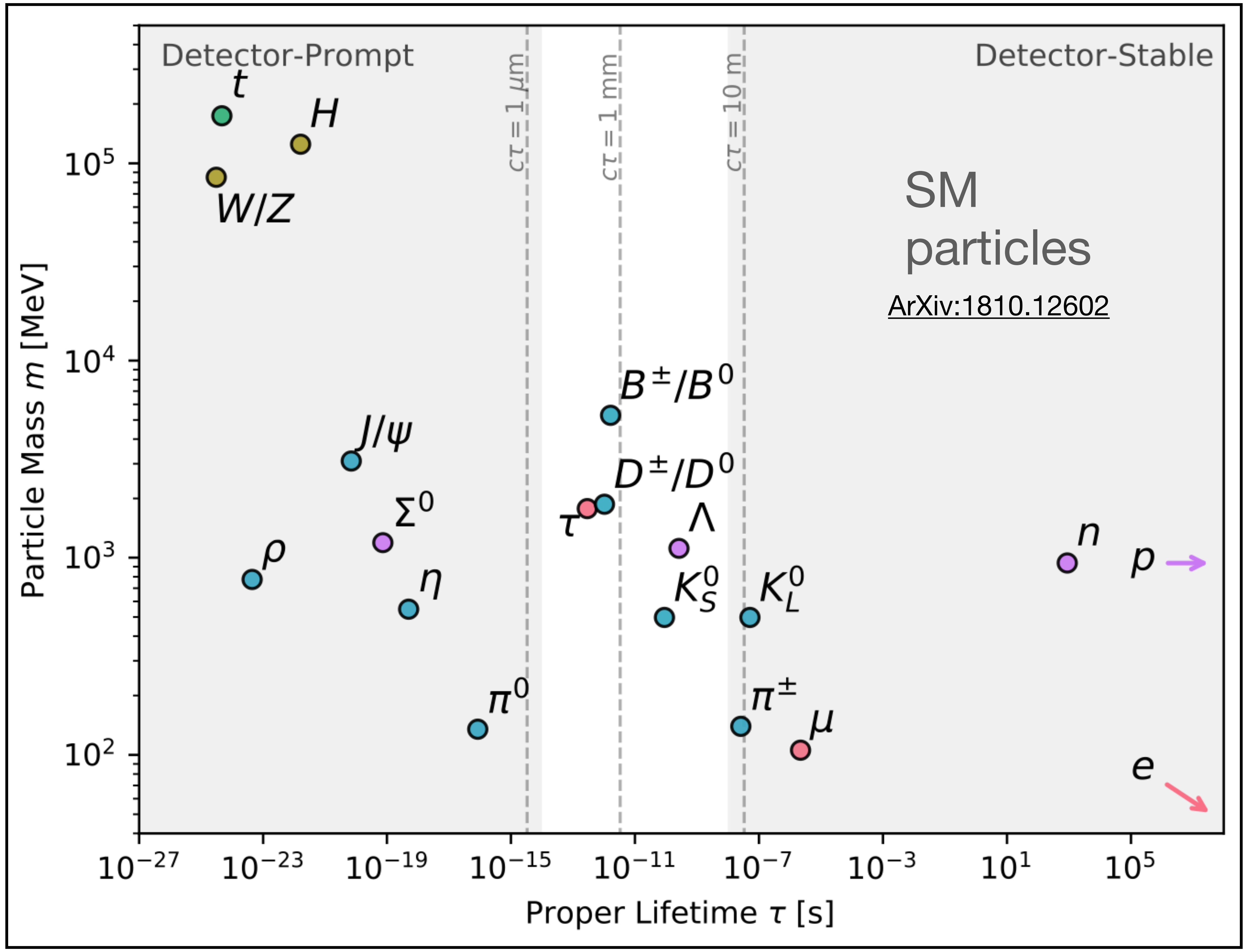
Daniel Guerrero (Fermilab) on behalf of the CMS Collaboration

XIII International Conference on New Frontiers in Physics

August 27, 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)
- **BSM scenarios** predict new particles with sizable lifetimes τ (small decay width Γ)

Suppressed couplings
e.g. Higgs portals to hidden/dark sectors

Phase space suppression (small mass splitting)
e.g. Inelastic dark matter

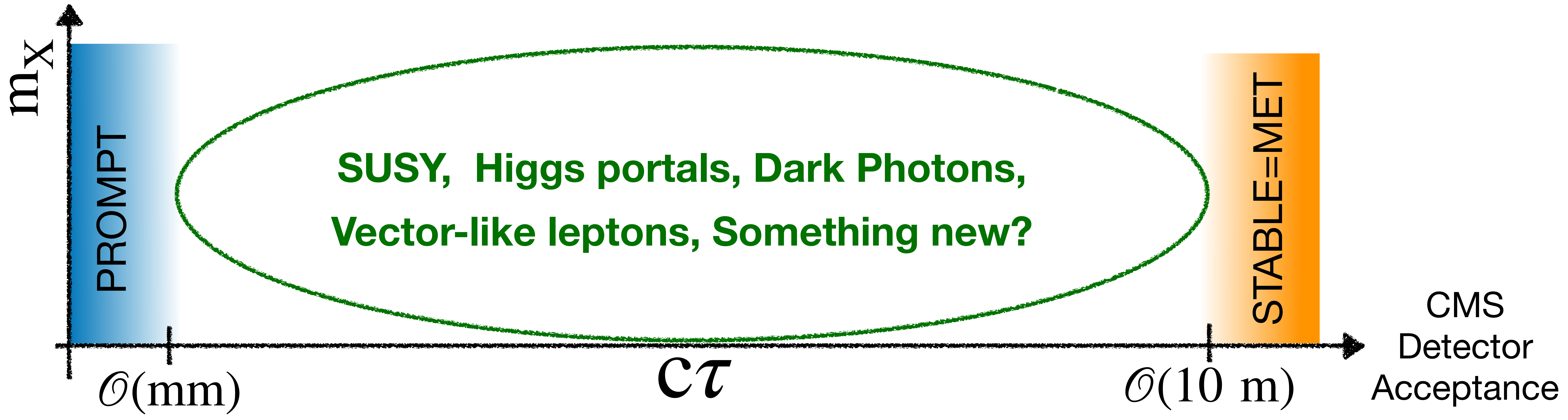
$$\frac{1}{\tau} = \Gamma \sim \frac{g^2}{(8\pi)^{a-1}} \frac{m^n}{M^{n-1}}$$

where:
n (odd, pos int) depends on symmetries of the theory
a (pos int): # of final state particles

Scale suppression (heavy virtual mediator)
e.g. split-SUSY

Long-lived Particles: A gateway to BSM

- **SM** is an example of fundamental laws giving rise to long-lived particles (LLPs)
- **BSM scenarios** predict new particles with sizable lifetimes τ (small decay width Γ)
- Most BSM searches probe **short-lived** or **stable** signatures, **LLP frontier is yet to be fully exploited at the LHC!**



Search for LLPs in CMS

- **Program is enriched with "unconventional" searches**
  - Broad signatures (lifetime, charge, decays, interaction w/ detectors)
  - Designed for signatures and interpreted for various benchmarks
- **Common challenges:**
  - Standard triggers and object reconstruction are not fully efficient
  - Unconventional backgrounds (e.g. cosmic rays and rare SM processes)
- **Tailored strategies:**
  - Novel triggers and object reconstructions
  - Innovative machine learning applications
- **Today's talk** focuses on recent **Run-2** and **Run-3** results

Other LLP searches can be found here: preliminary results and publications

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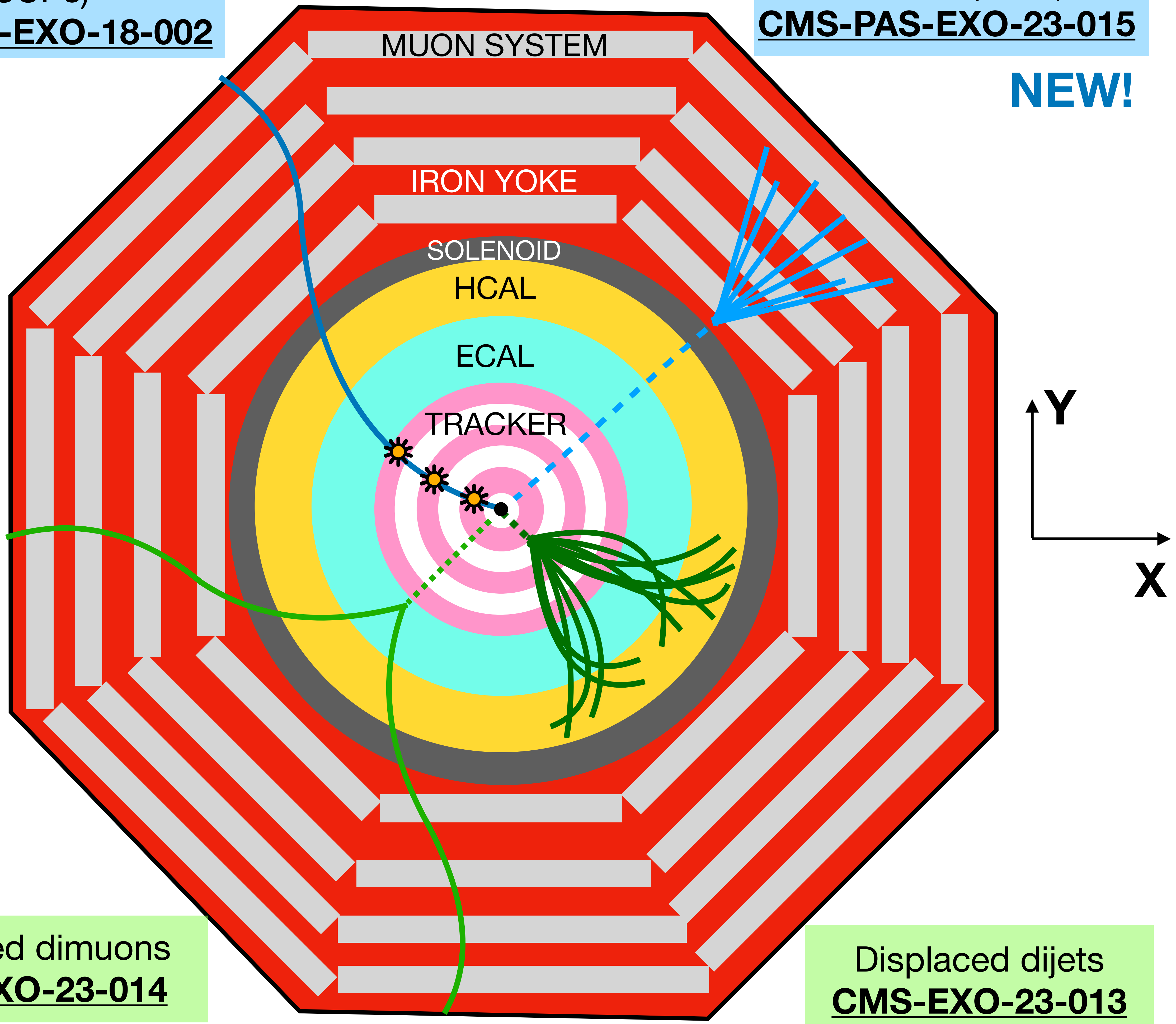
13 TeV 13.6 TeV

Heavy Stable Charged Particles (HSCPs)
CMS-PAS-EXO-18-002

Vector-like leptons using muon detector showers (MDS)
CMS-PAS-EXO-23-015

NEW!



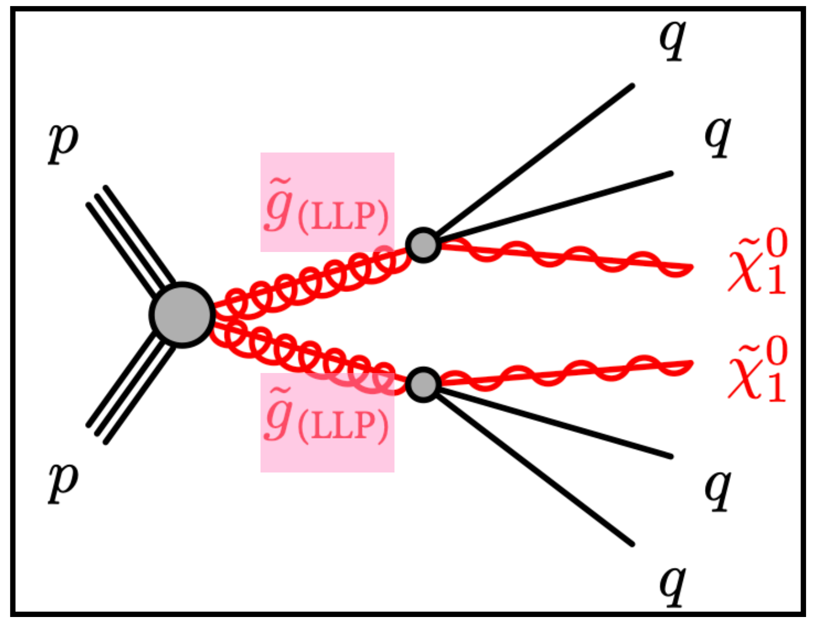
Displaced dimuons
CMS-EXO-23-014

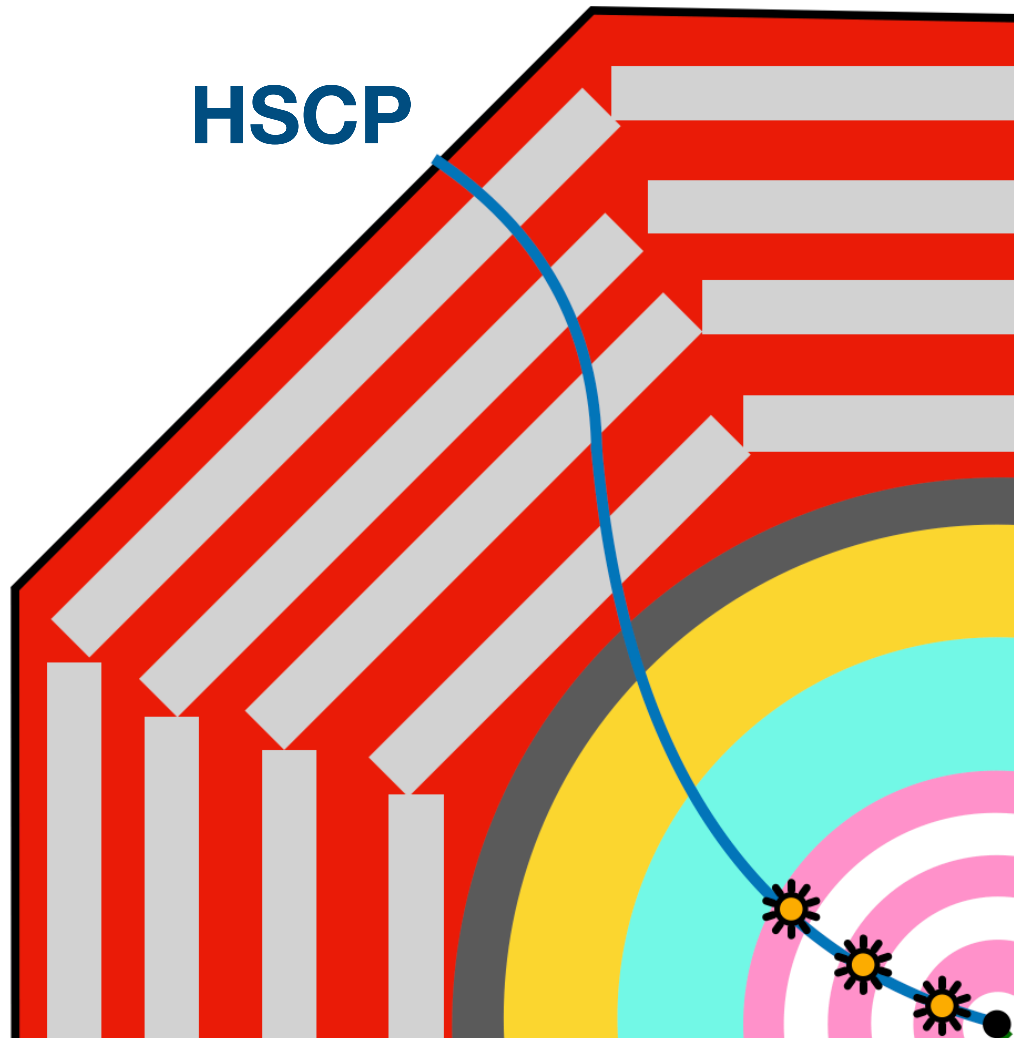
Displaced dijets
CMS-EXO-23-013

Other LLP searches can be found here: preliminary results and publications

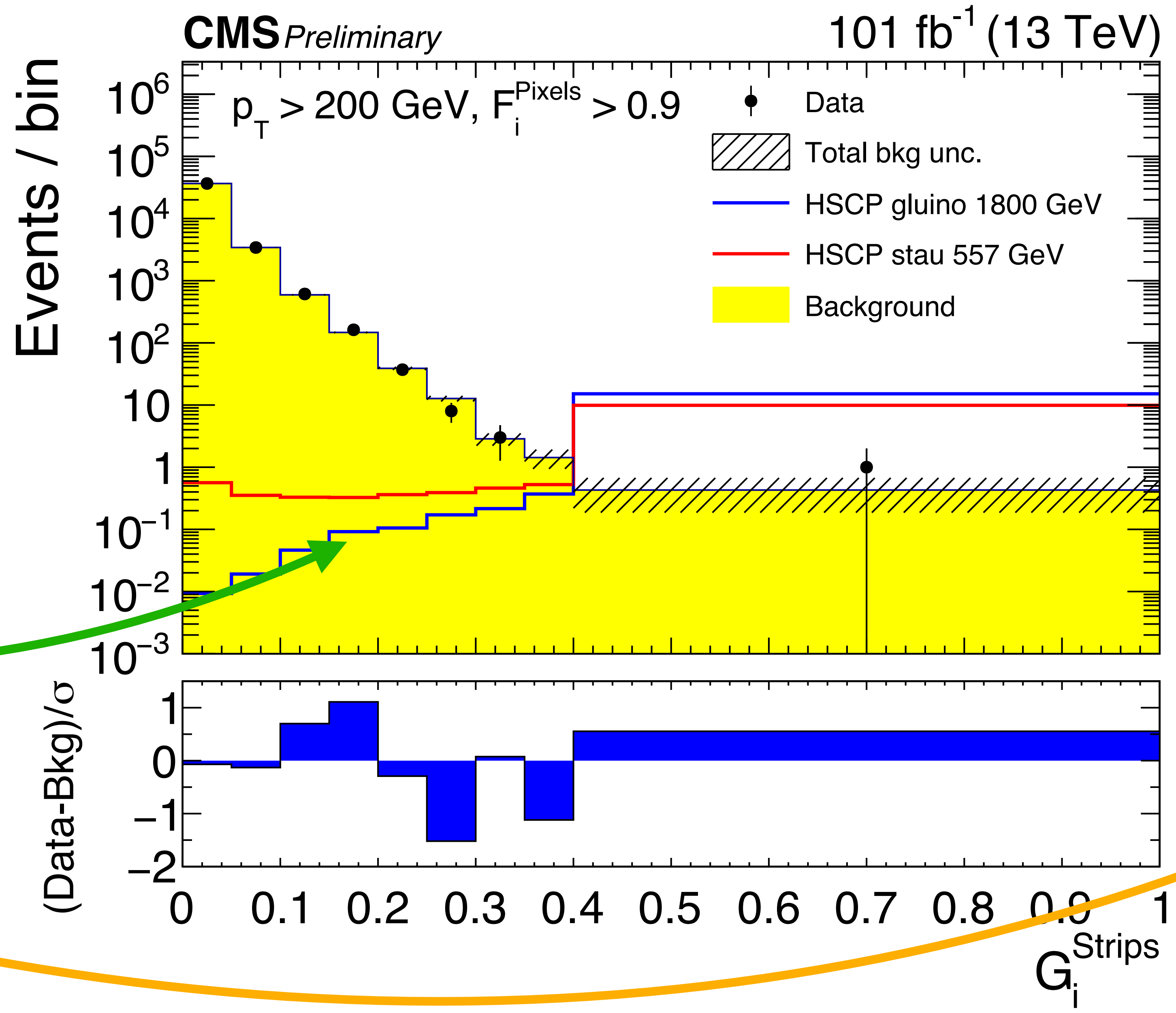
Search for HSCPs: Overview

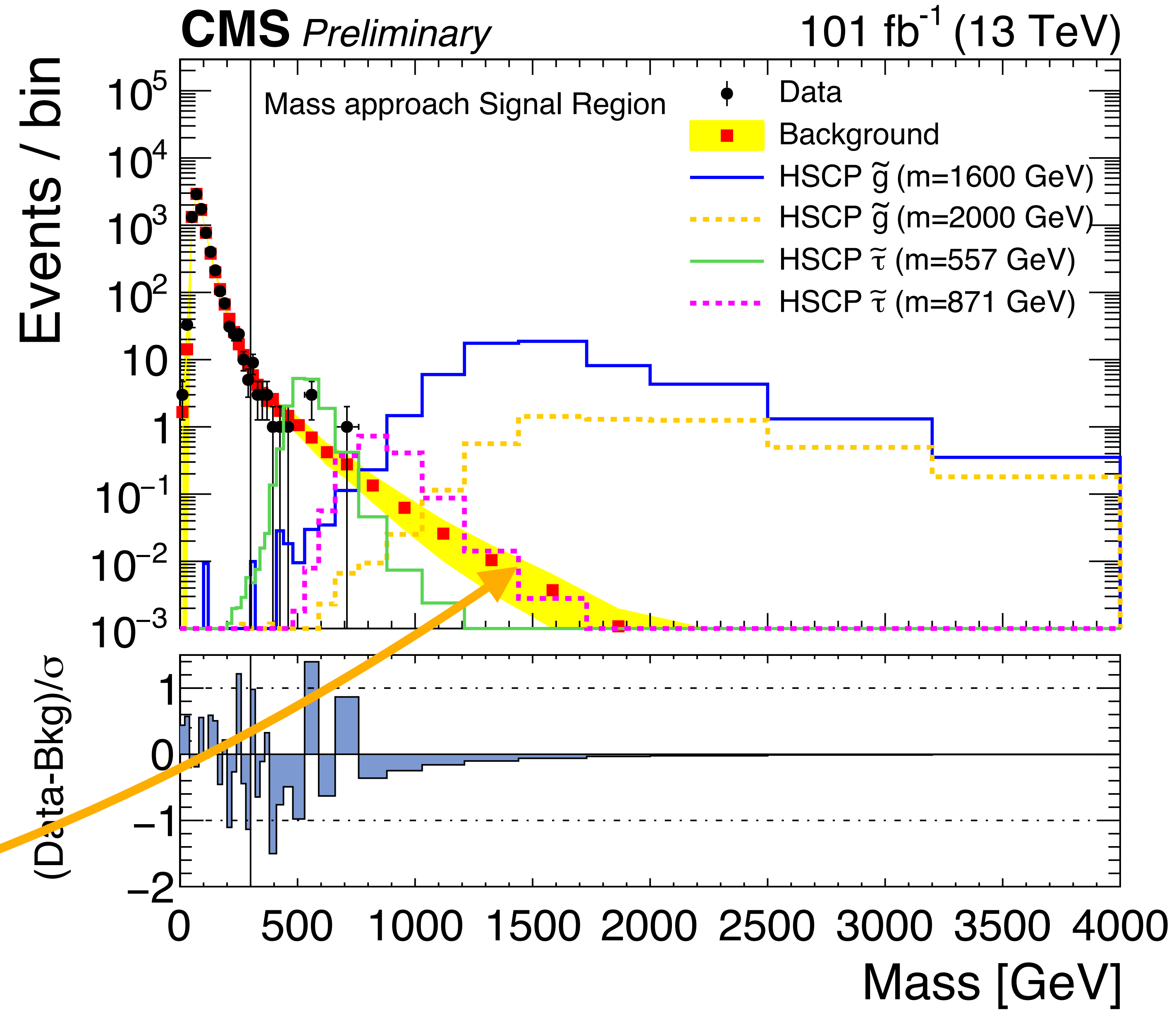
CMS-PAS-EXO-18-002





- **Model independent search** with broad interpretations
  - Strongly interacting (e.g. gluino R-hadrons) and lepton-like (e.g. τ') HSCP
  - ATLAS 3.3 global excess at $m_{\tilde{g}}$=1.4 TeV (JHEP06(2023)158)
- **Signature:** Isolated high-p_T track with large ionization energy losses (dE/dx) in silicon tracker
  - Backgrounds: Fake tracks, bad ionization measurement, overlapping tracks (pileup, boosted mesons)
- **Run-2 strategy**
  - Single muon trigger, track in silicon tracker
  - Data-driven background model:
    - Ionization method
      - Ionization discriminants: G_i^{Strips} and F_i^{Pixels}
      - G_i^{Strips} shape from control region (F_i^{Pixels}< 0.9)
      - Fit it to signal region data (F_i^{Pixels}>0.9)
    - Mass method:
      - Exploits mass relation with dE/dx and momentum
      - Derive shape and normalization from control regions

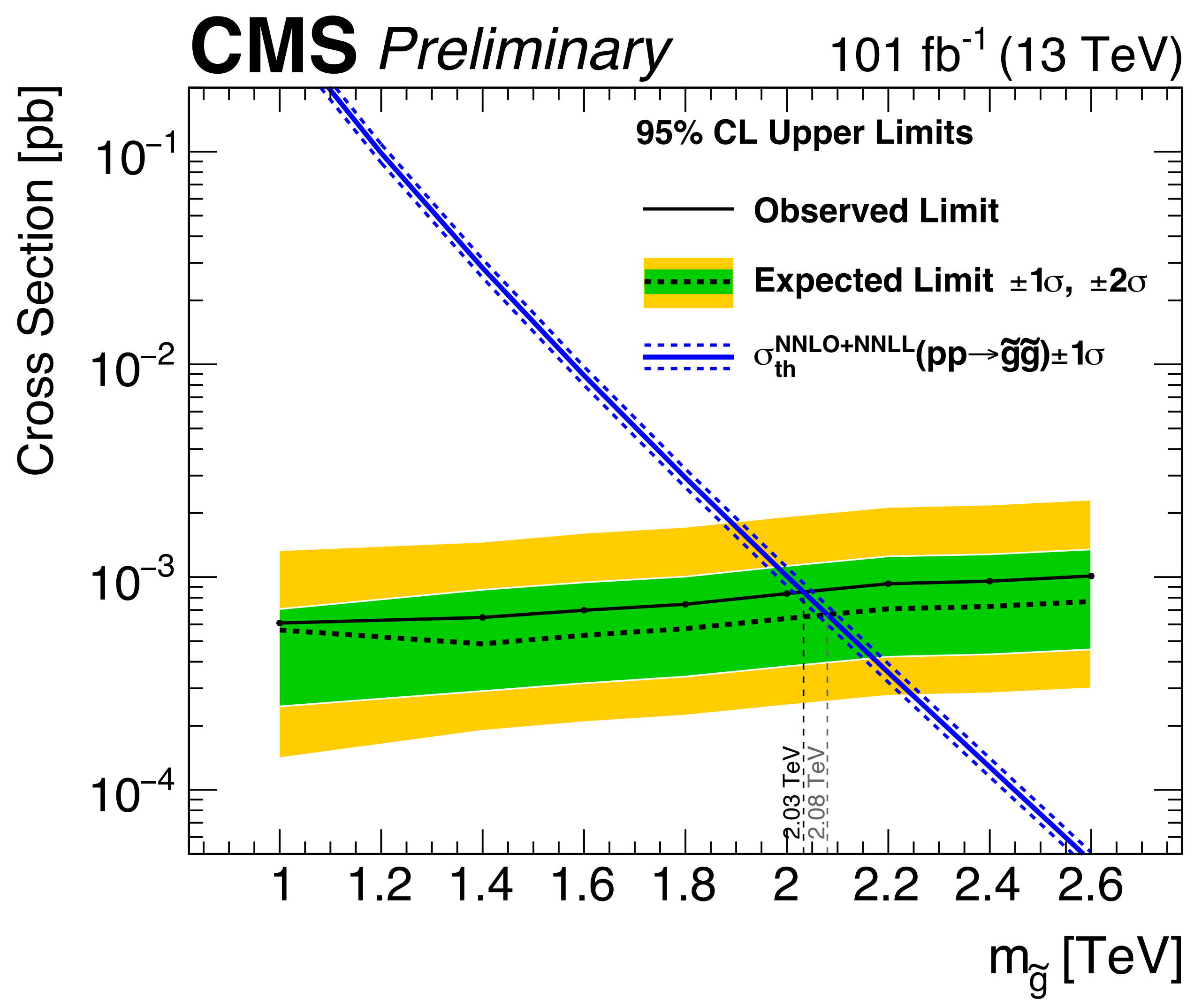


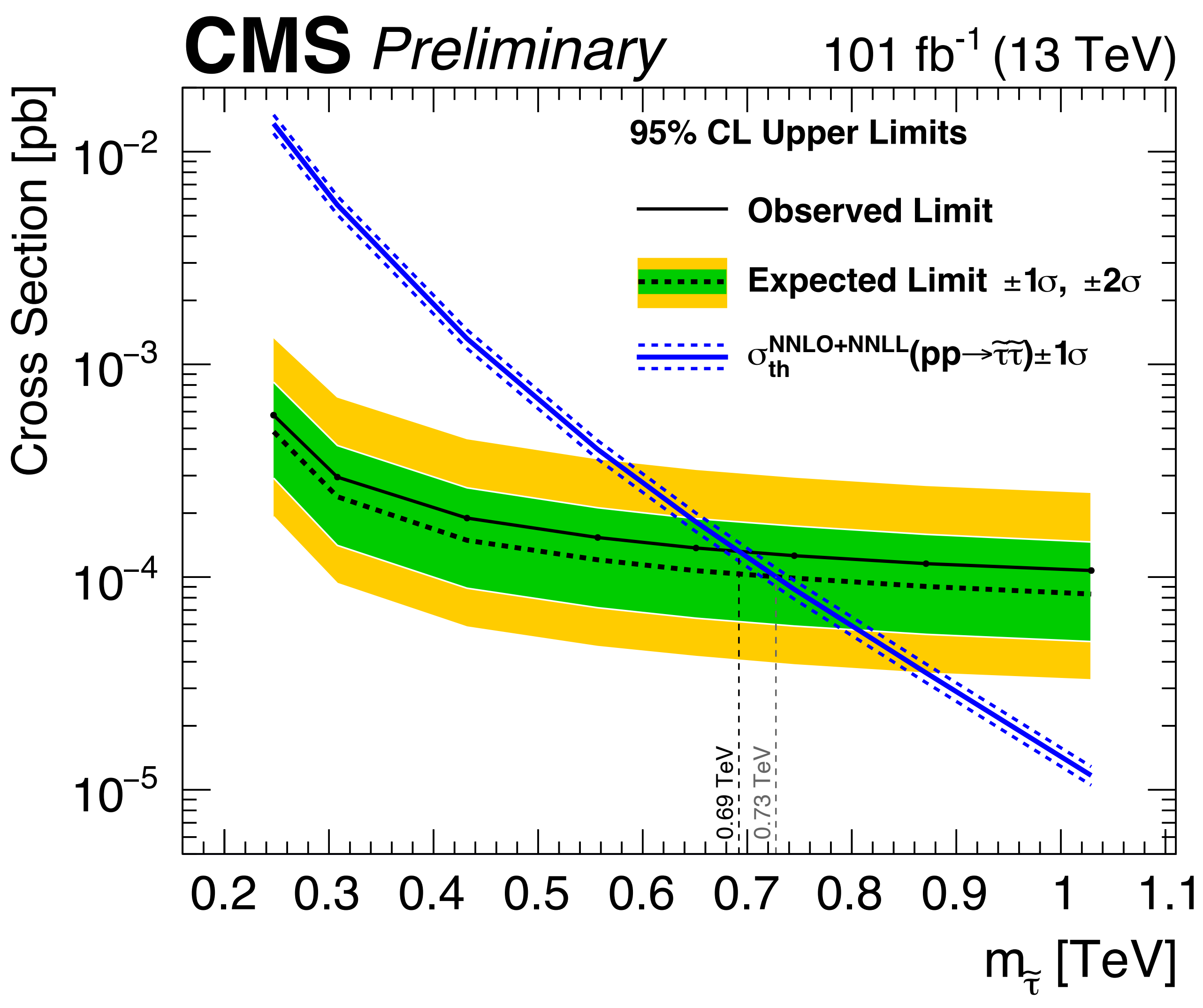


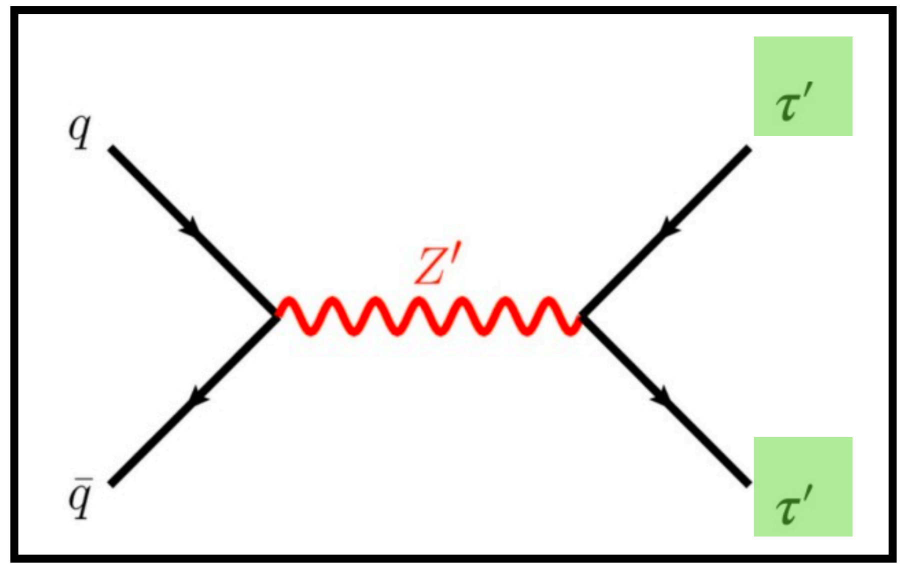
Search for HSCPs: Results

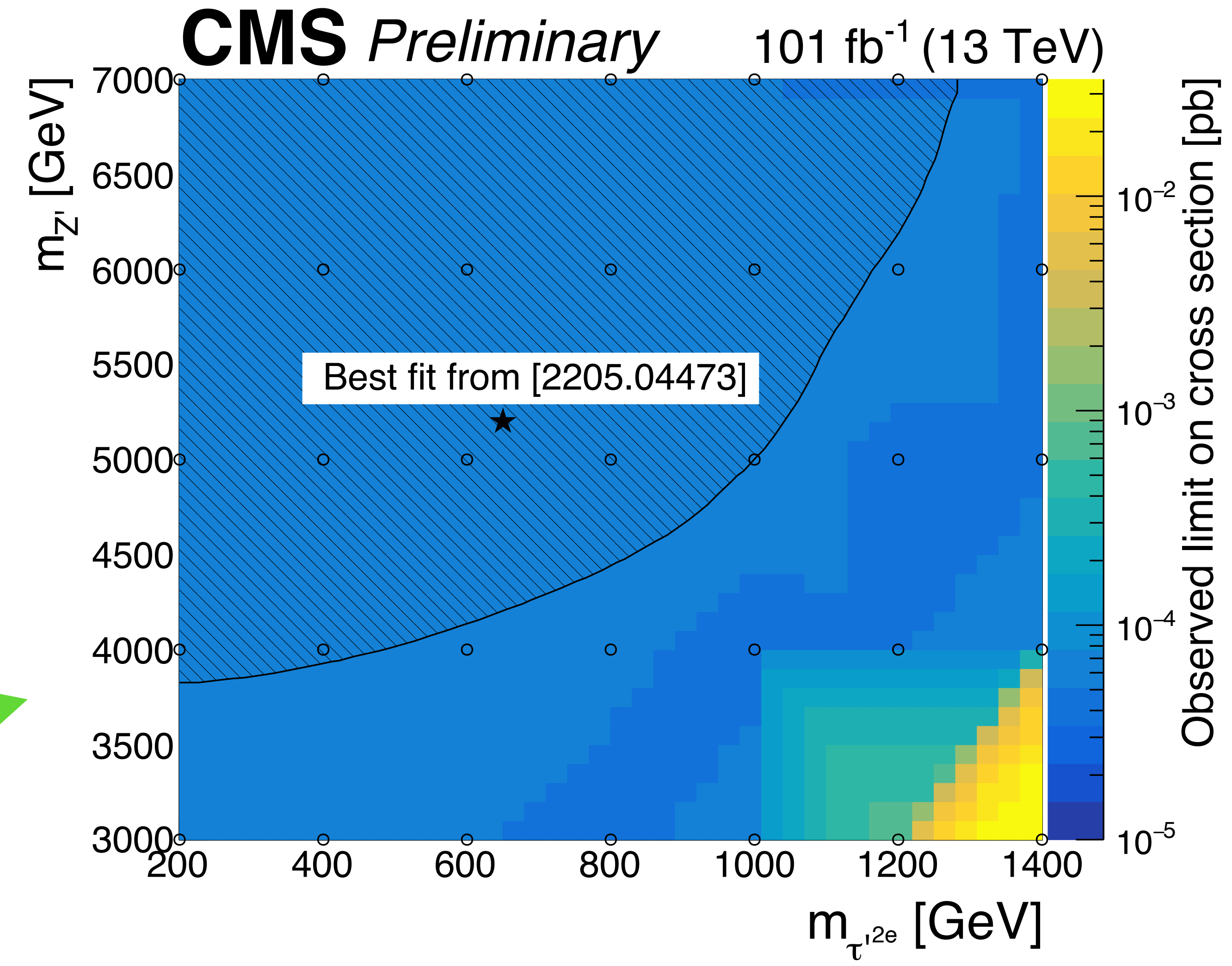
CMS-PAS-EXO-18-002

- **No significant excess** over background expectation
  - Two methods lead to similar sensitivities
- **Interpretations:**
  - 95% CL limits on production cross sections (σ)
  - Total of 10 different benchmarks:
    - split SUSY: $\tilde{g}$ and $\tilde{t}$ R-hadrons
      - ATLAS excess corresponds to $\sigma_{\tilde{g}\tilde{g}} = 0.59$ fb
      - CMS limit: $\sigma_{\tilde{g}\tilde{g}} < 0.32$ fb
    - GMSB $\tilde{\tau}$, pair-produced $\tilde{\tau}$ ($\tilde{\tau}_R\tilde{\tau}_R$, $\tilde{\tau}_L\tilde{\tau}_L$ and $\tilde{\tau}_L\tilde{\tau}_R$)
    - $Z/\gamma \rightarrow \tau^{'(1e)}\tau^{'(1e)}$ and $Z/\gamma \rightarrow \tau^{'(2e)}\tau^{'(2e)}$
    - $Z'_\psi \rightarrow \tau^{'(2e)}\tau^{'(2e)}$ and $Z'_{SSM} \rightarrow \tau^{'(2e)}\tau^{'(2e)}$
      - Excess motivated model (2205.04473)
      - CMS limit ($m_{\tau'(2e)}$ = 5 TeV, $m_{\tau'(2e)}$ = 600 GeV): $\sigma_{Z'} < 0.03$ fb







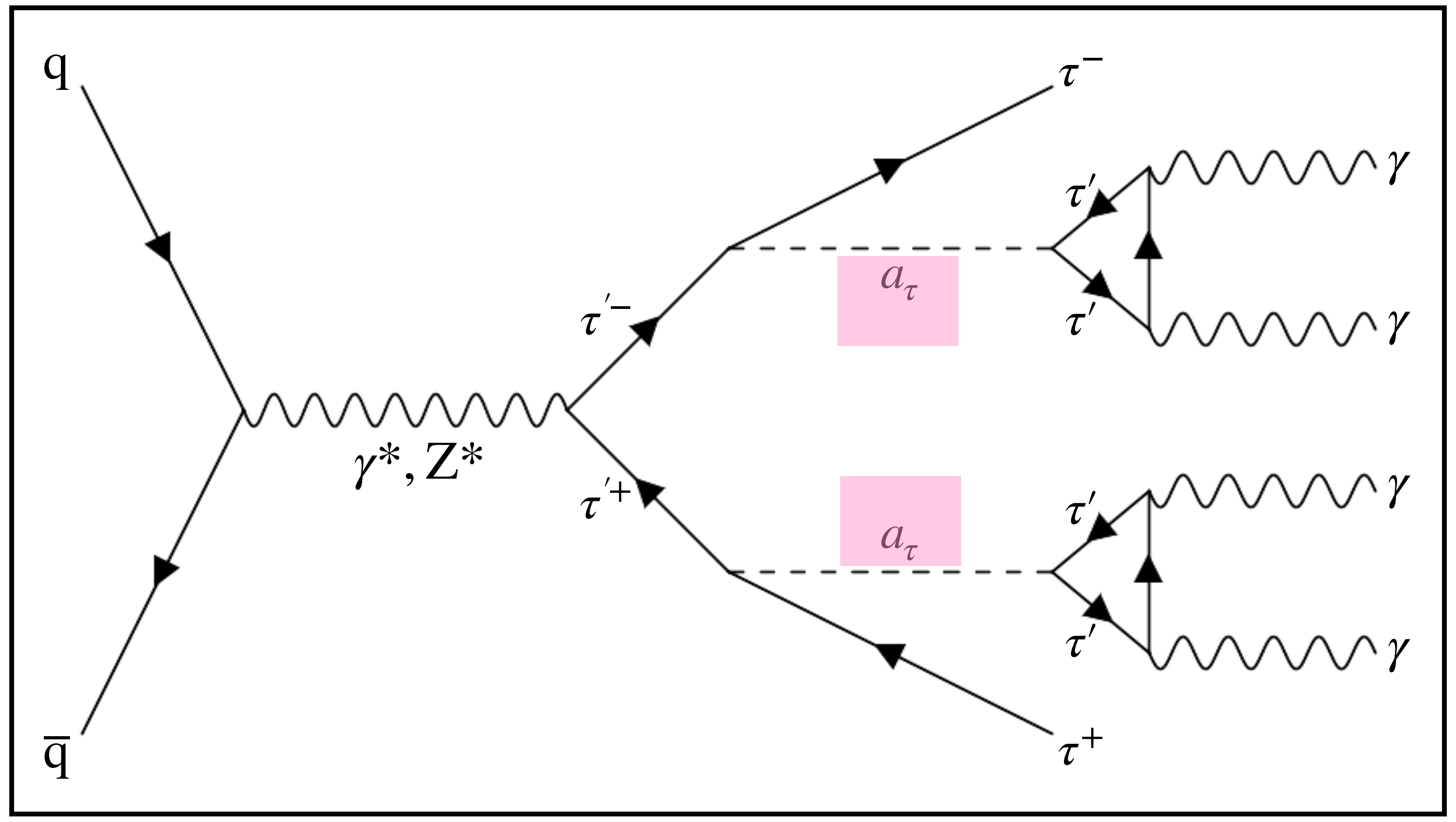


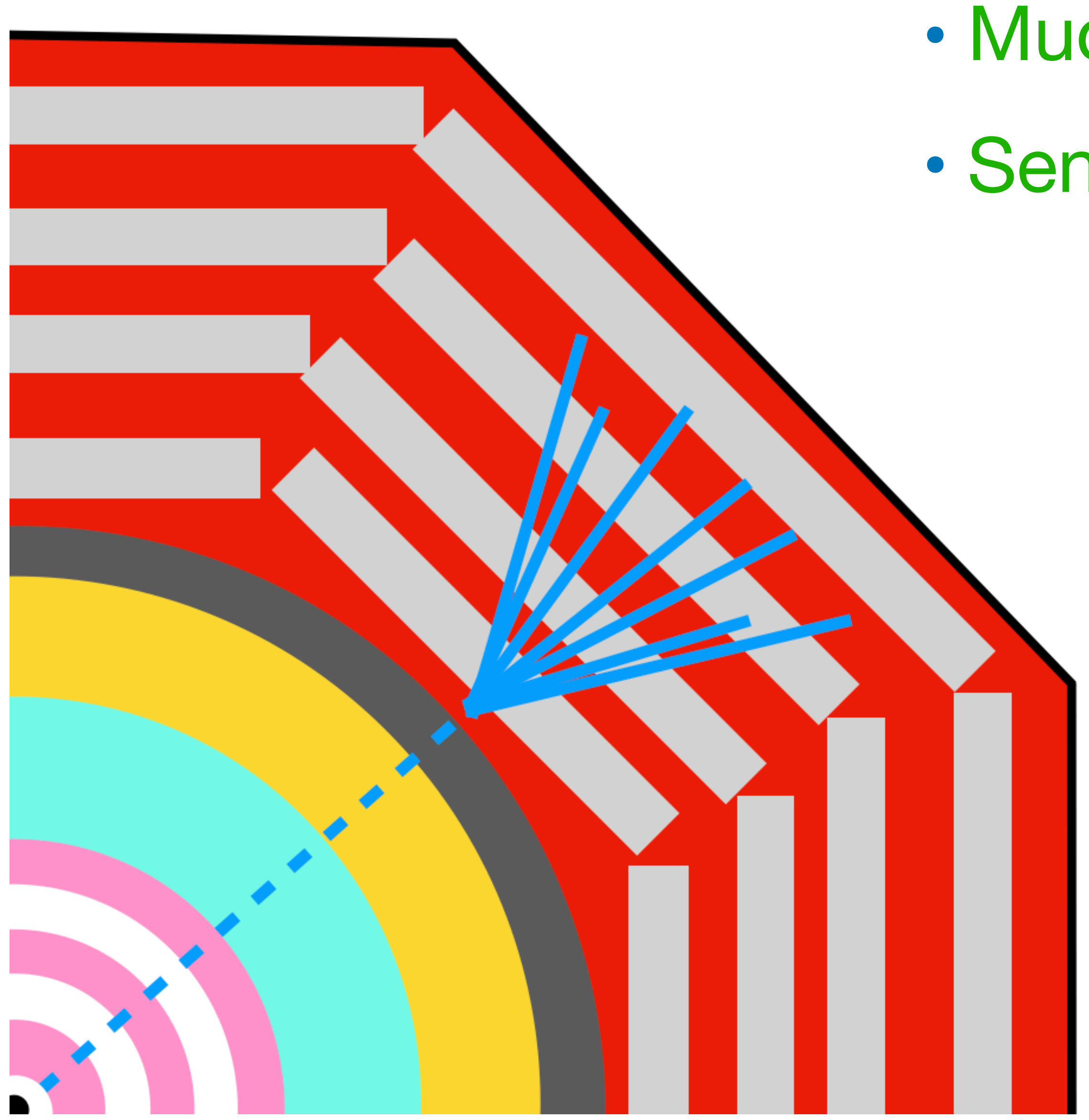
Ionization method results

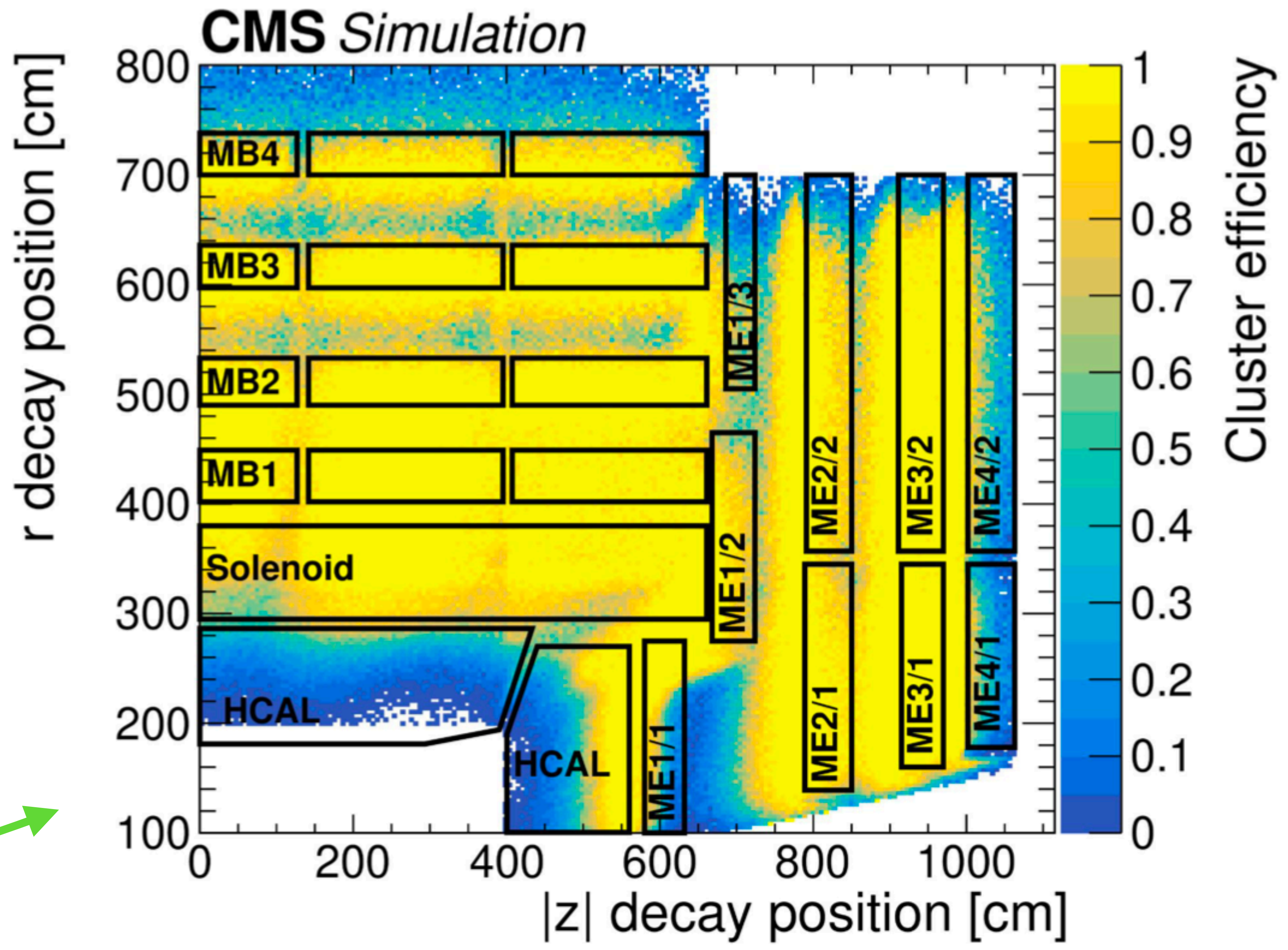
Search for VLLs w/ MDS showers: Overview

CMS-PAS-EXO-23-015

- **Search for vector-like leptons (VLLs) with LLP decays**
  - VLL singlet decays into a long-lived pseudoscalar (a_τ) and prompt τ (JHEP06(2023)158)
  - a_τ is very light and decays to photons
- **Signature:** Displaced diphoton decays + prompt τ decays
- **LLP decays in the muon system:**
  - a_τ decays → EM shower (like a sampling calorimeter)
  - Muon detector shower (MDS) → large cluster of muon hits
  - Sensitive signature:
    - High cluster reconstruction efficiency (DBSCAN clustering)
    - Small background due to large shielding material
      - jet punch-through, muon brems, cosmic muons, pile-up, SM (K_L^0)
    - Used previously in CMS analyses:
      - (CMS-EXO-21-008, CMS-EXO-22-017)



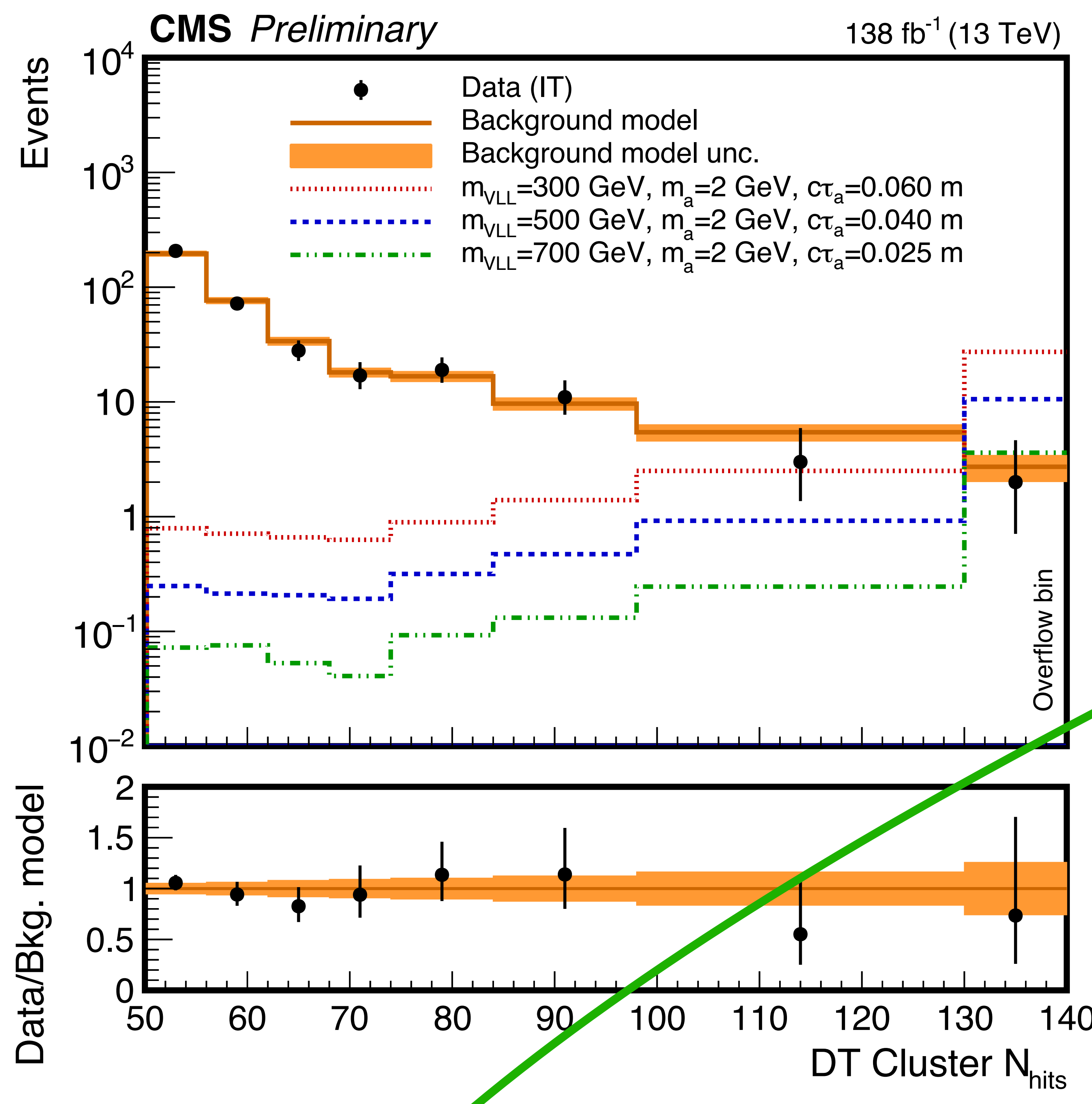


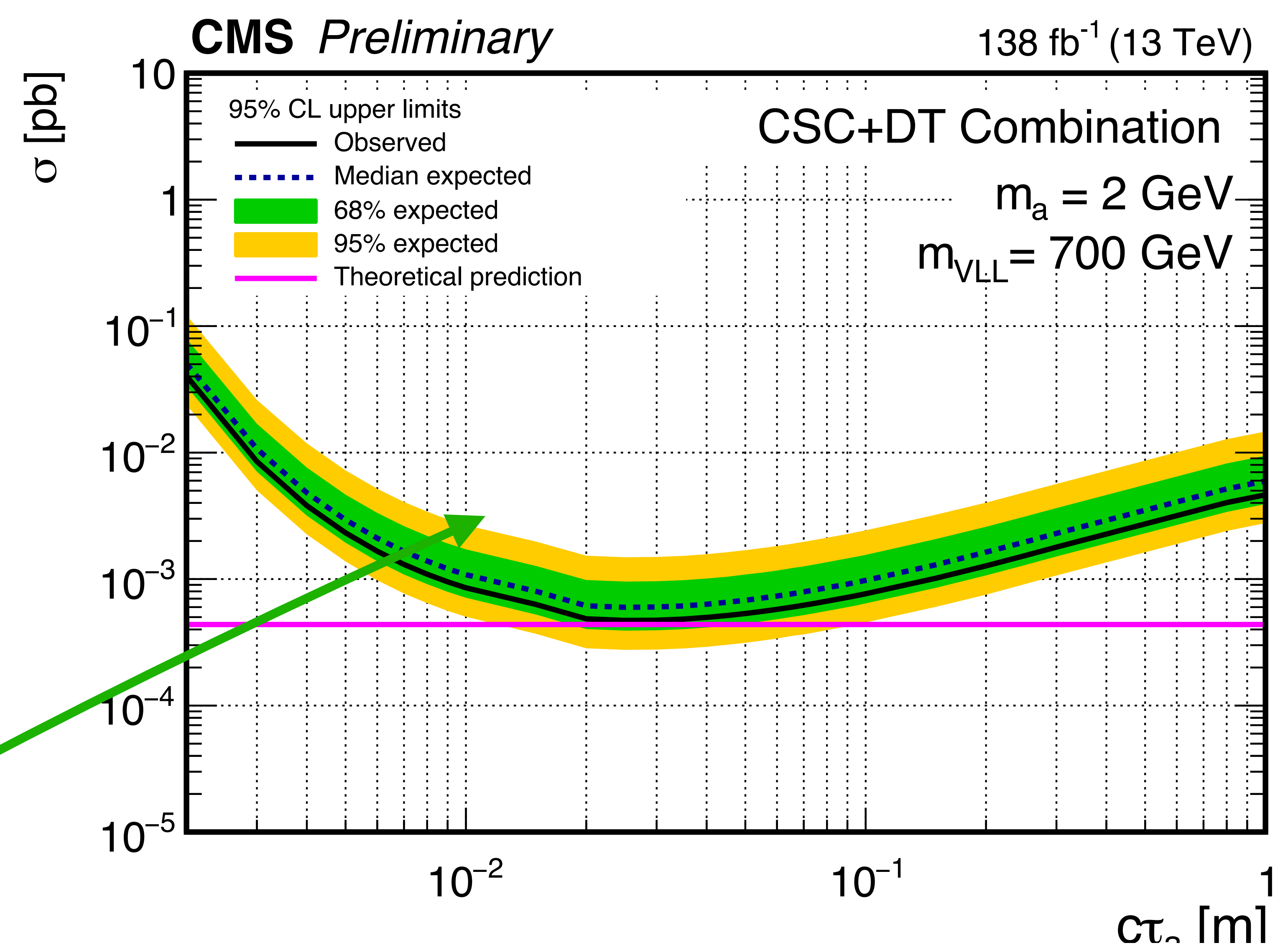


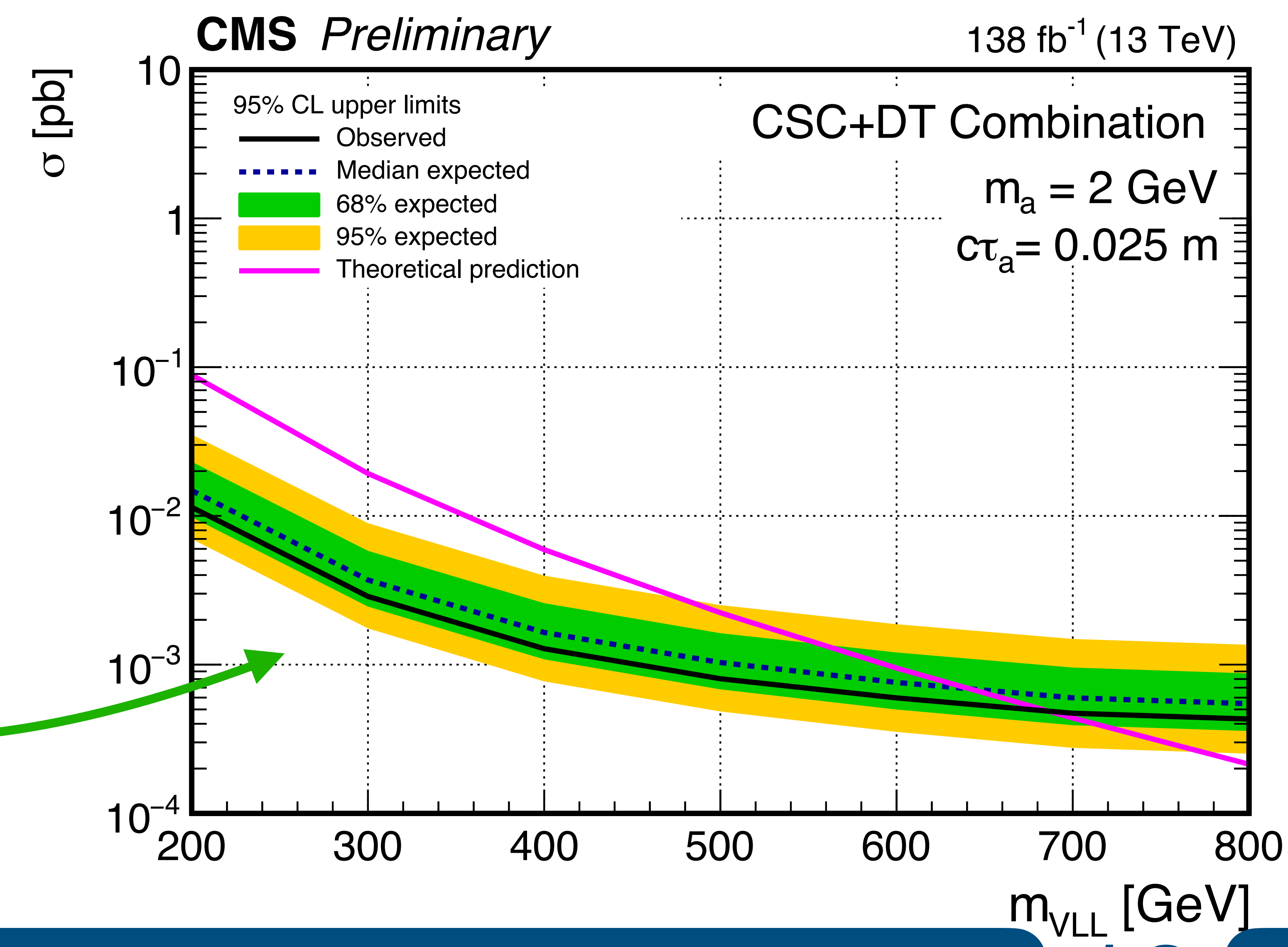
Search for VLLs w/ MDS showers: Results

CMS-PAS-EXO-23-015

- **Run-2 Strategy:**
  - MET triggers
  - At least 1 hadronic tau (τ_h) and 1 MDS cluster
  - **Categories:** Barrel (DT) or Endcap (CSC) cluster
  - Discriminant variable: # of hits in the cluster ($\mathrm{N_{hits}}$)
  - **Background estimate from data**
    - $\mathrm{N_{hits}}$ shape from control region (reverting τ_h ID cuts)
    - Normalization from fit to signal region data
- **No significant excess** is observed
- **Interpretations:**
  - Very light pseudoscalar, $\mathrm{m_a}$= 2 GeV
  - 95% CL production cross section vs pseudoscalar lifetime ($c\tau_a$) and VLL mass
  - VLL masses are excluded up to ~690 GeV, depending on pseudoscalar $c\tau_a$



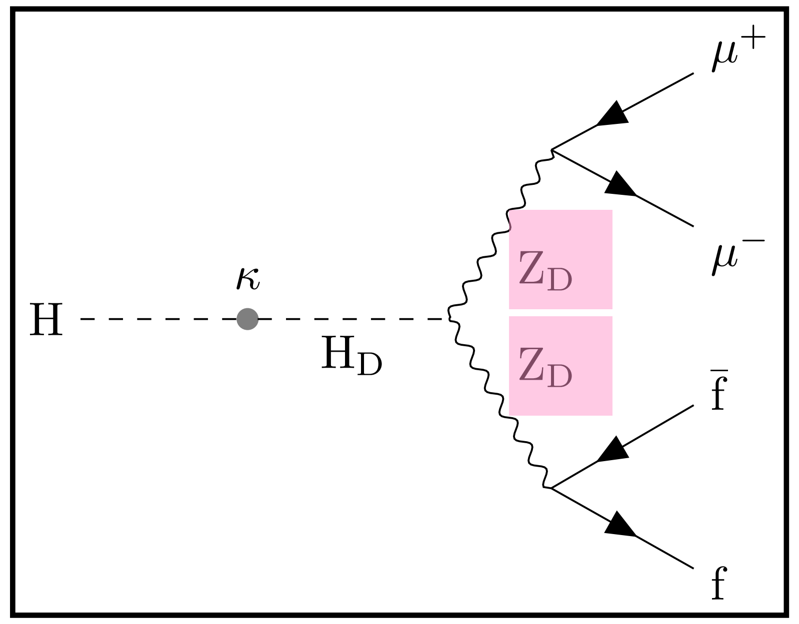


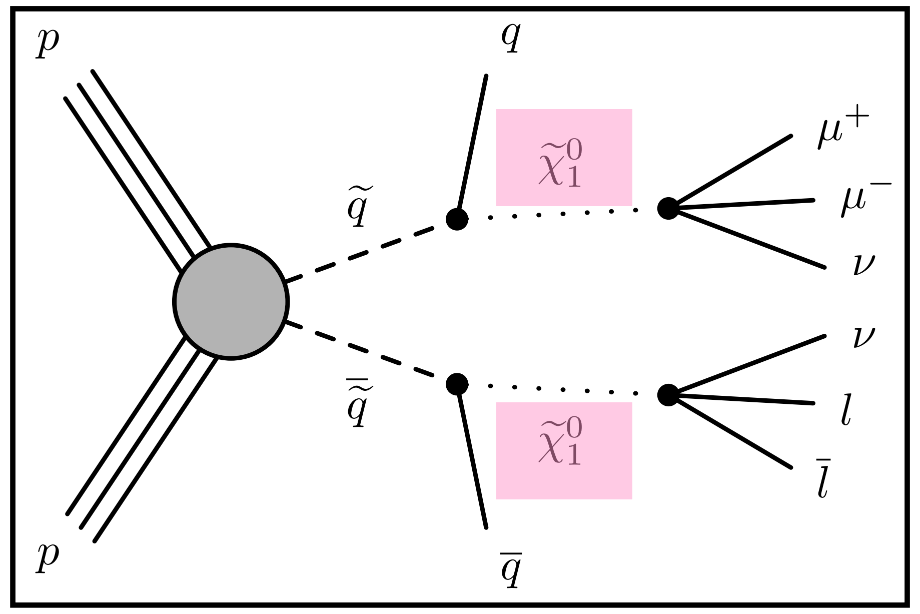


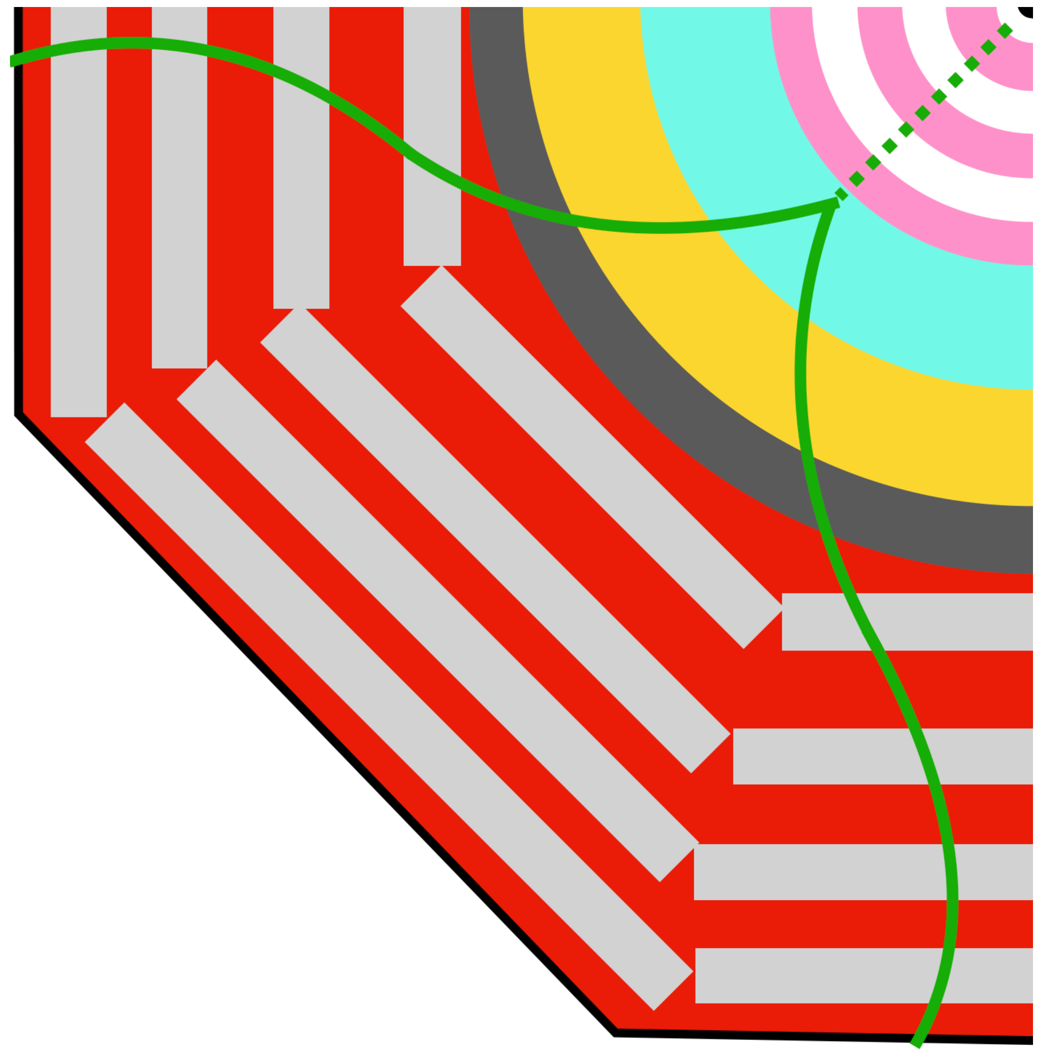
Search for displaced di-muons: Overview

CMS-EXO-23-014/JHEP05(2024)047

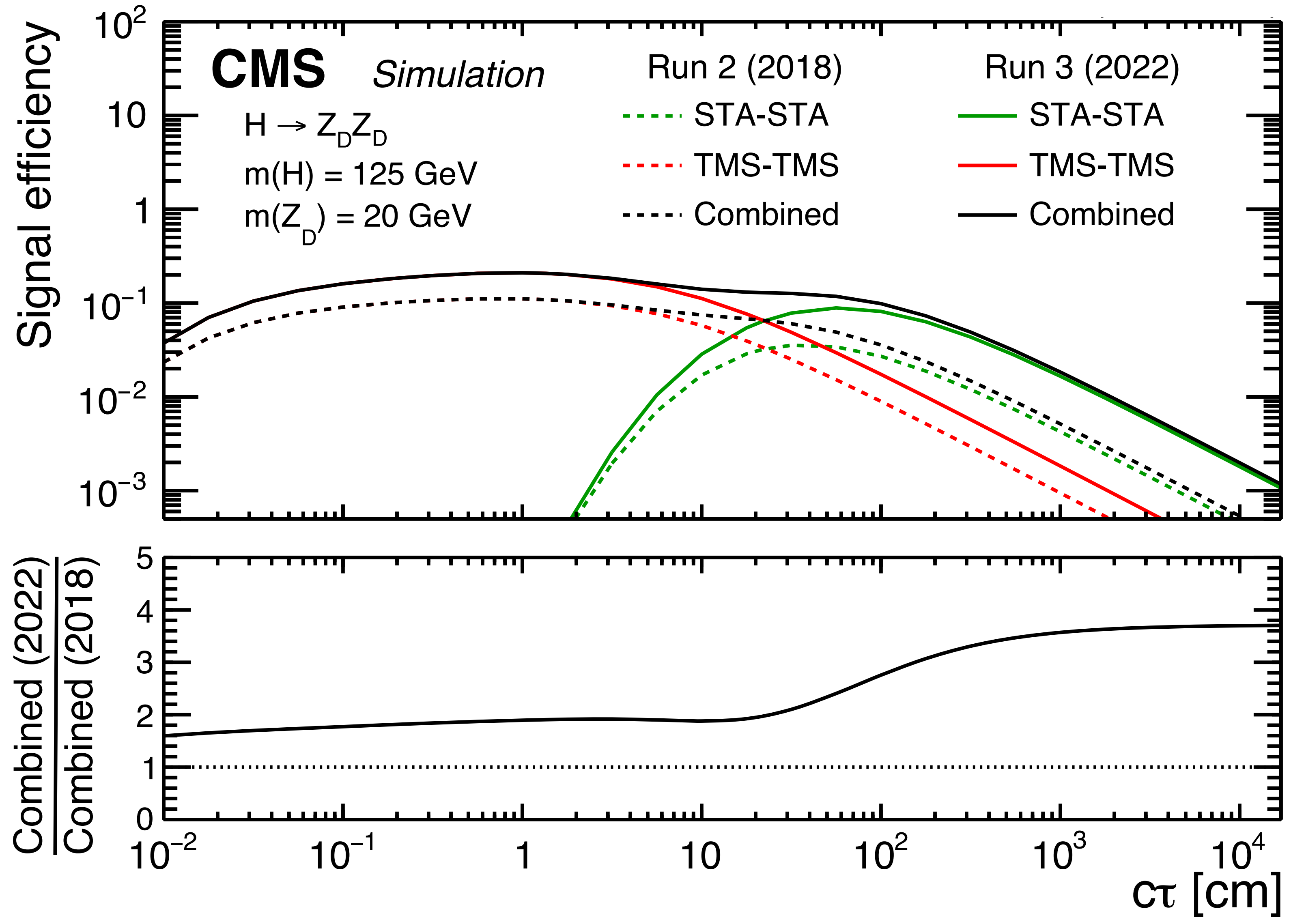
- **Inclusive search for neutral LLPs decaying to muons**
  - Hidden Abelian Higgs model ($H \rightarrow Z_D Z_D$, $Z_D \rightarrow \mu\mu$)
  - RPV SUSY model ($\tilde{q} \rightarrow q\tilde{\chi}^0_1$, $\tilde{\chi}^0_1 \rightarrow \mu\mu\nu$)







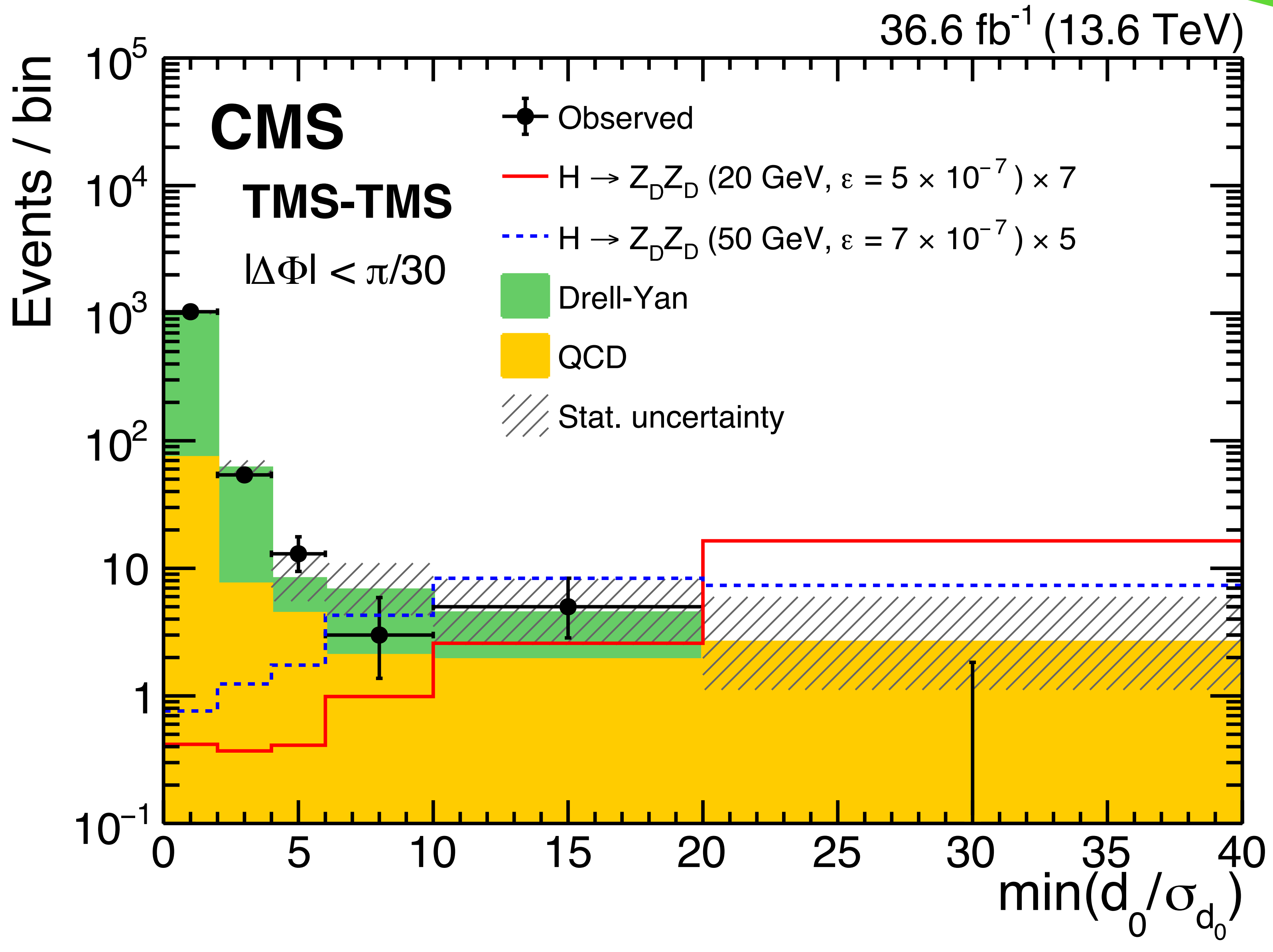
- **Signature:**
  - Displaced opposite-charged dimuons
  - Backgrounds due to instrumentation and reconstruction mistakes
- **Run-3 strategy (2022 data)**
  - New dimuon trigger:
    - Lower trigger p_T and d_0 thresholds → 2-4 x signal w.r.t. 2018 (Run-2)
  - Muon types: STA (muon system only) and TMS (Tracker+ Muon system)
  - Categories: STA-STA and TMS-TMS

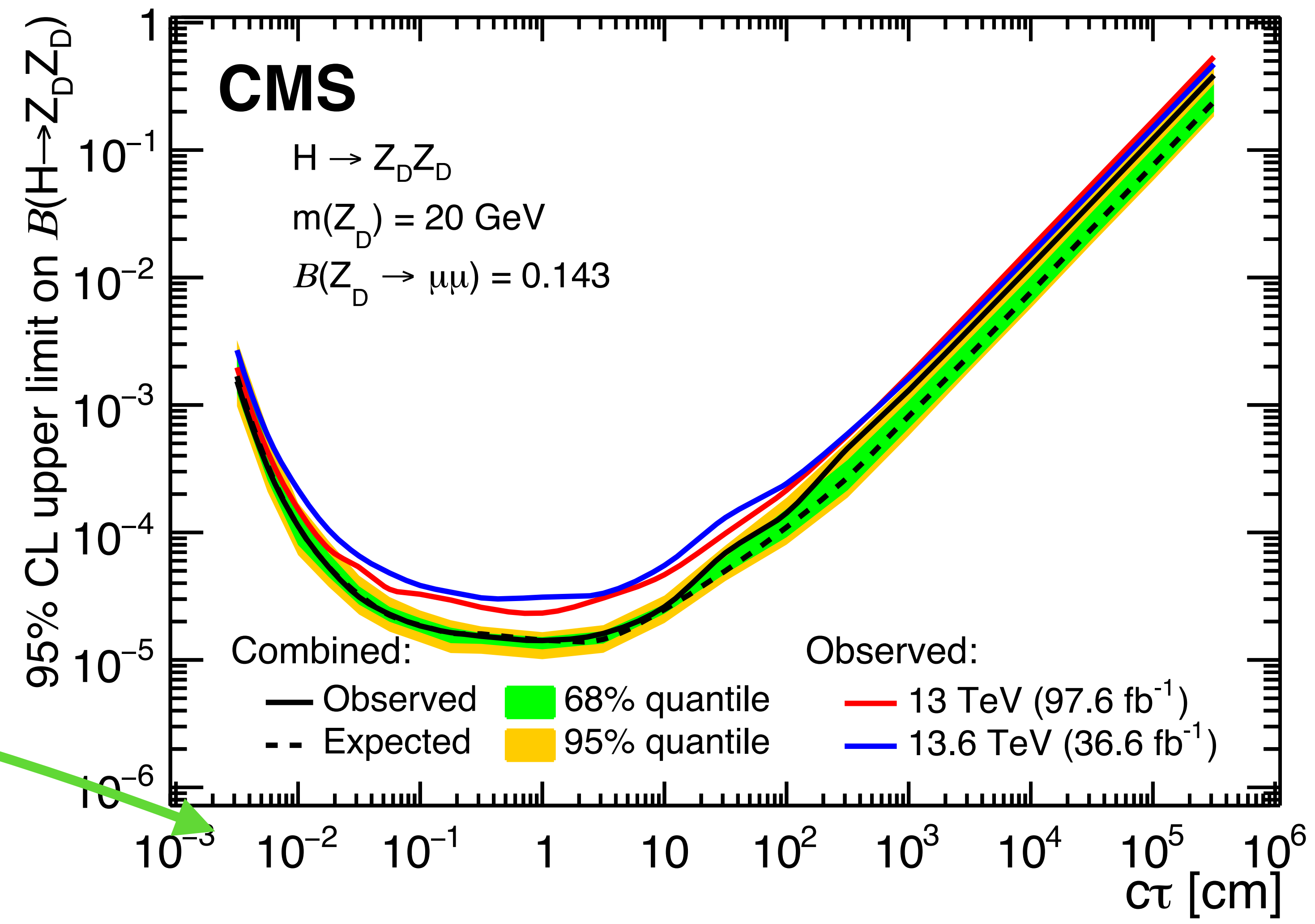


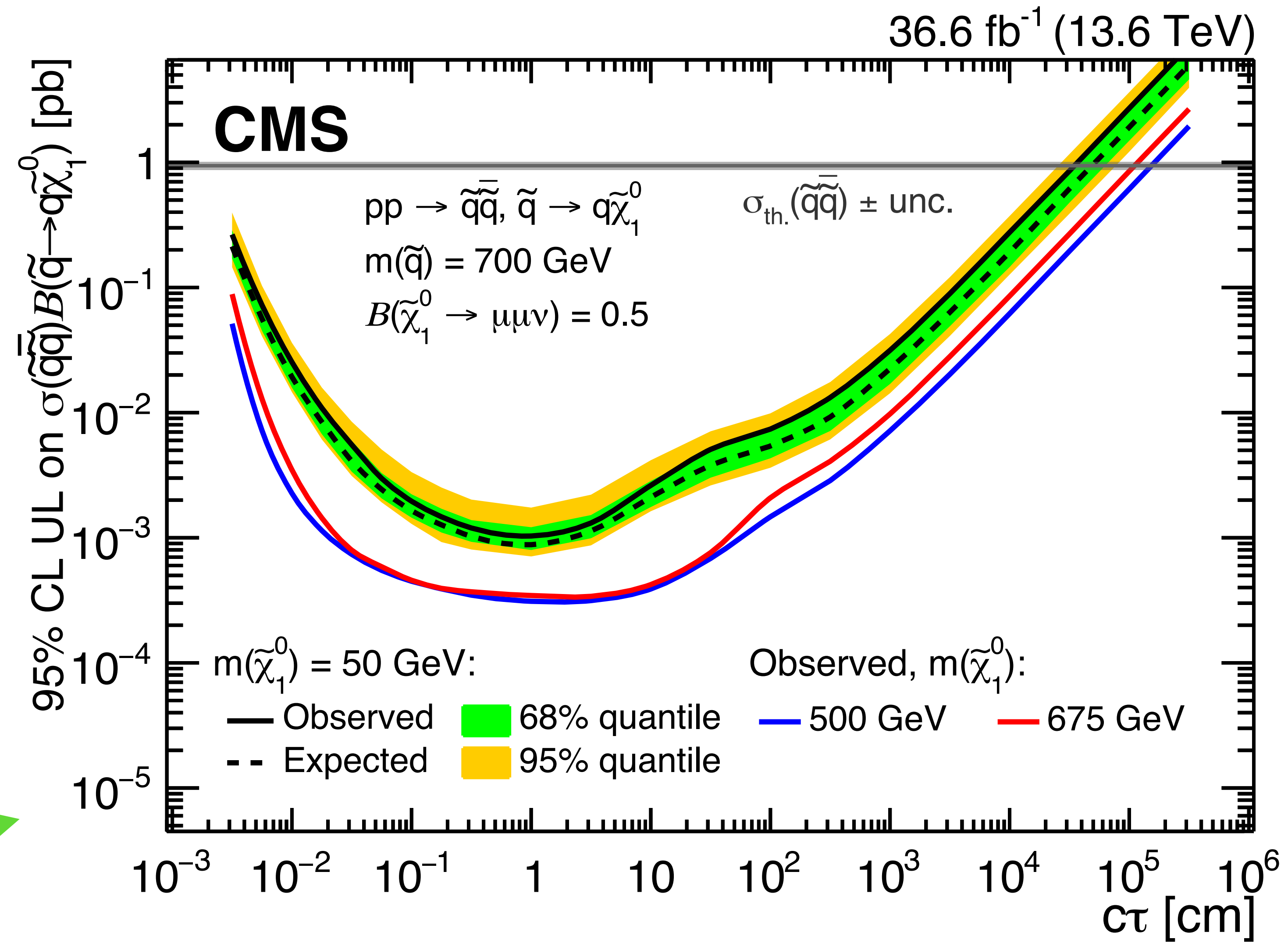
Search for displaced di-muons: Results

CMS-EXO-23-014/JHEP05(2024)047

- **Background estimate from control region data:**
  - Drell-Yan (DY): Mismeasured Z/γ, $t\bar{t}$, dibosons, cosmic ray muons, among others
  - QCD: Mismeasured resonances (e.g. J/Ψ), cascade decays with ≥ 2 muons (e.g. B mesons)
- **Observed data consistent with SM expectations**
- **Interpretations:**
  - HAHM (Dark photon) model:
    - 95% CL limits on B($H \rightarrow Z_D Z_D$)
    - Mass m_{Z_D} in range of 10-60 GeV
    - Combination with Run-2 data
  - RPV SUSY model (NEW!):
    - 95% CL limits on $\sigma(\tilde{q} \rightarrow q\tilde{\chi}_1^0)B(\tilde{\chi}_1^0 \mu\mu\nu)$
    - Masses: $m_{\tilde{q}}$ = 125-1600 GeV and $m_{\tilde{\chi}_1^0}$ = 50-1575 GeV

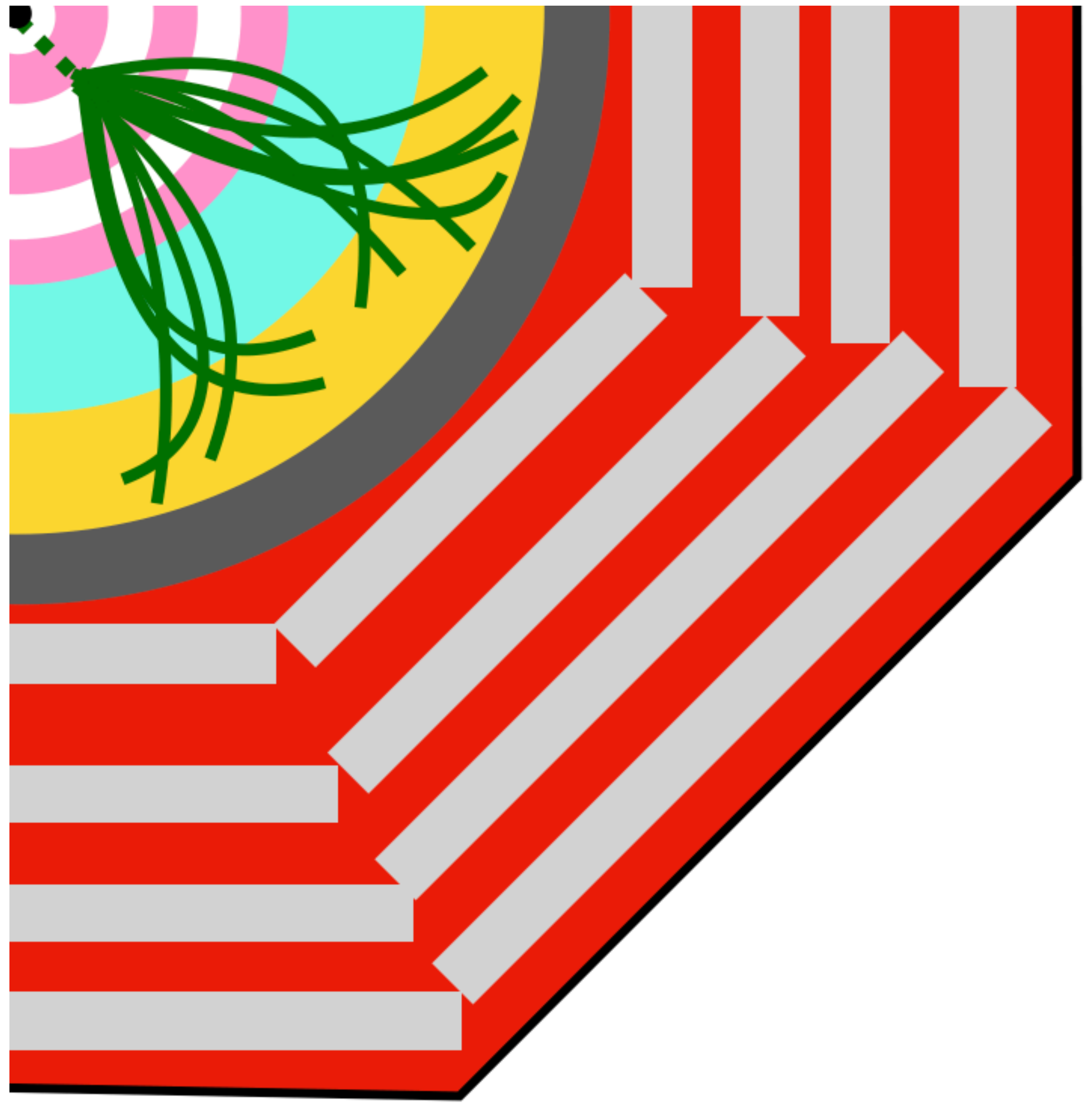




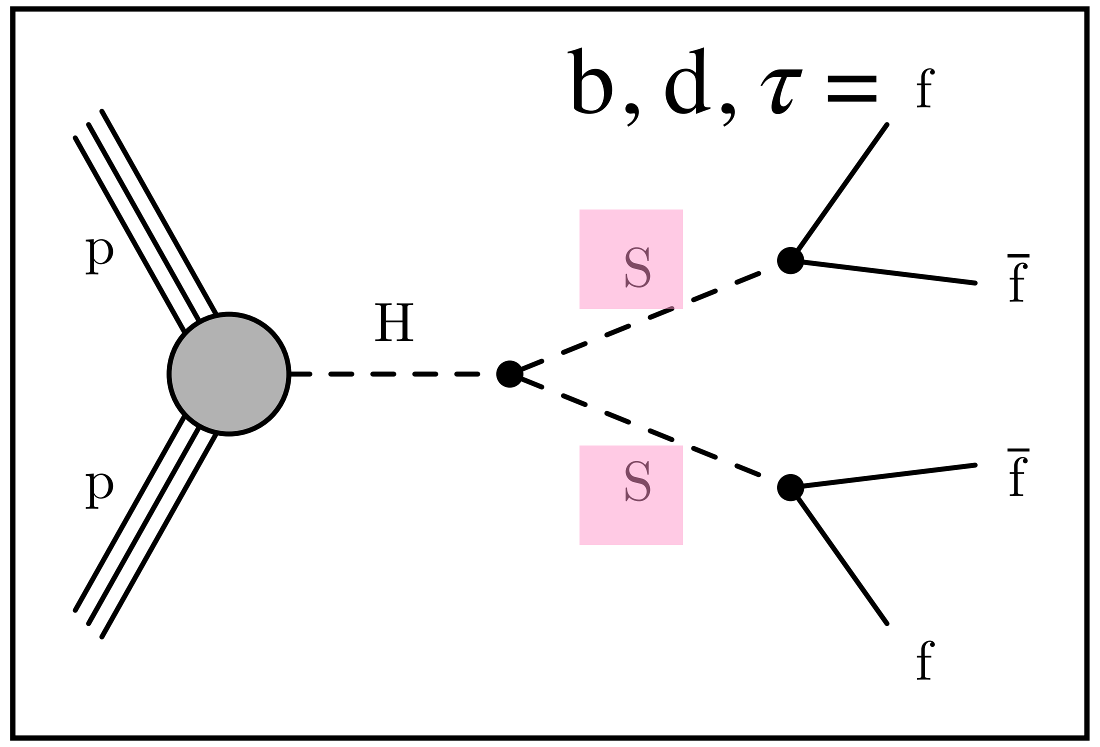


Search for displaced dijets: Overview

CMS-PAS-EXO-23-013

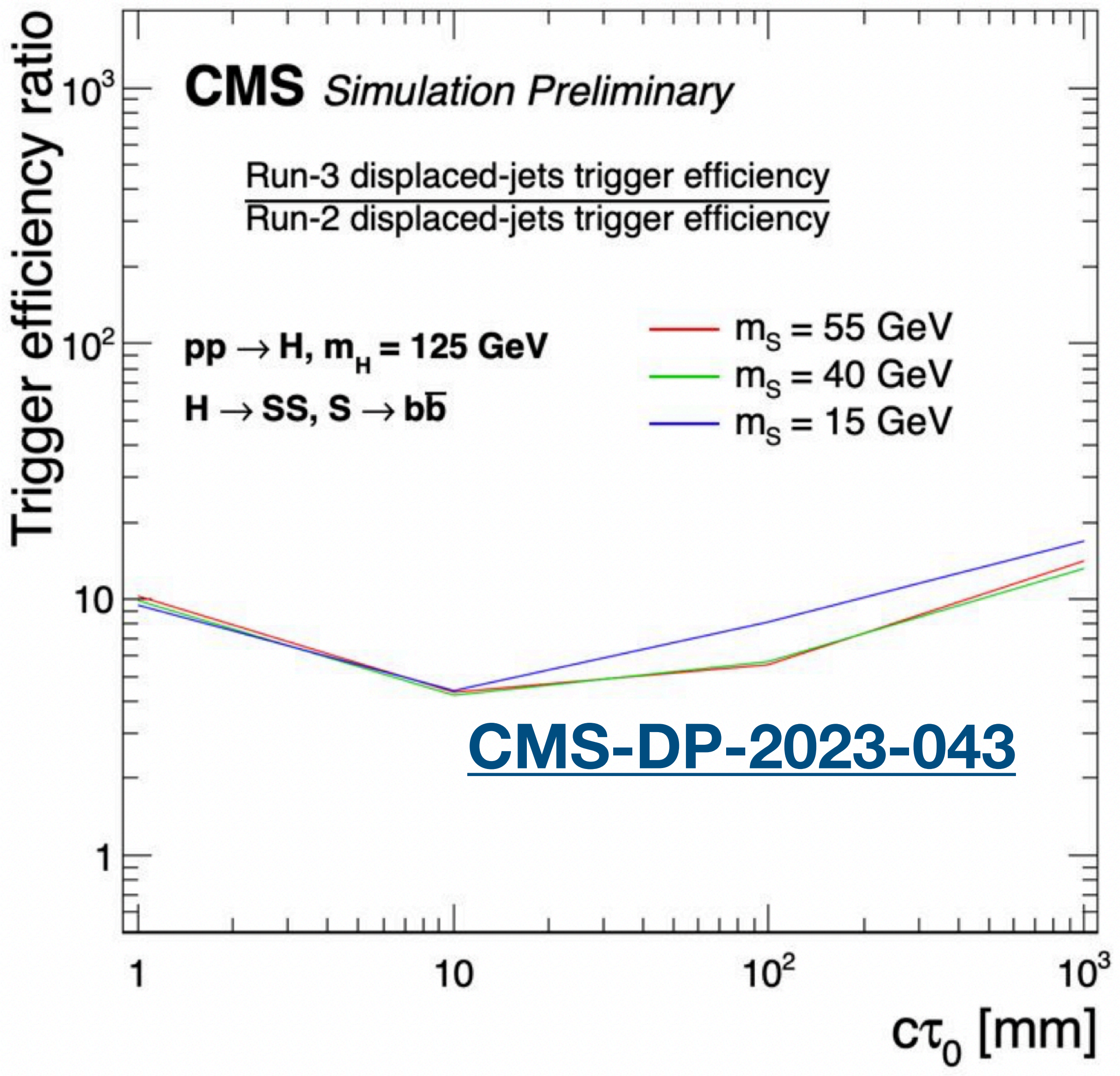


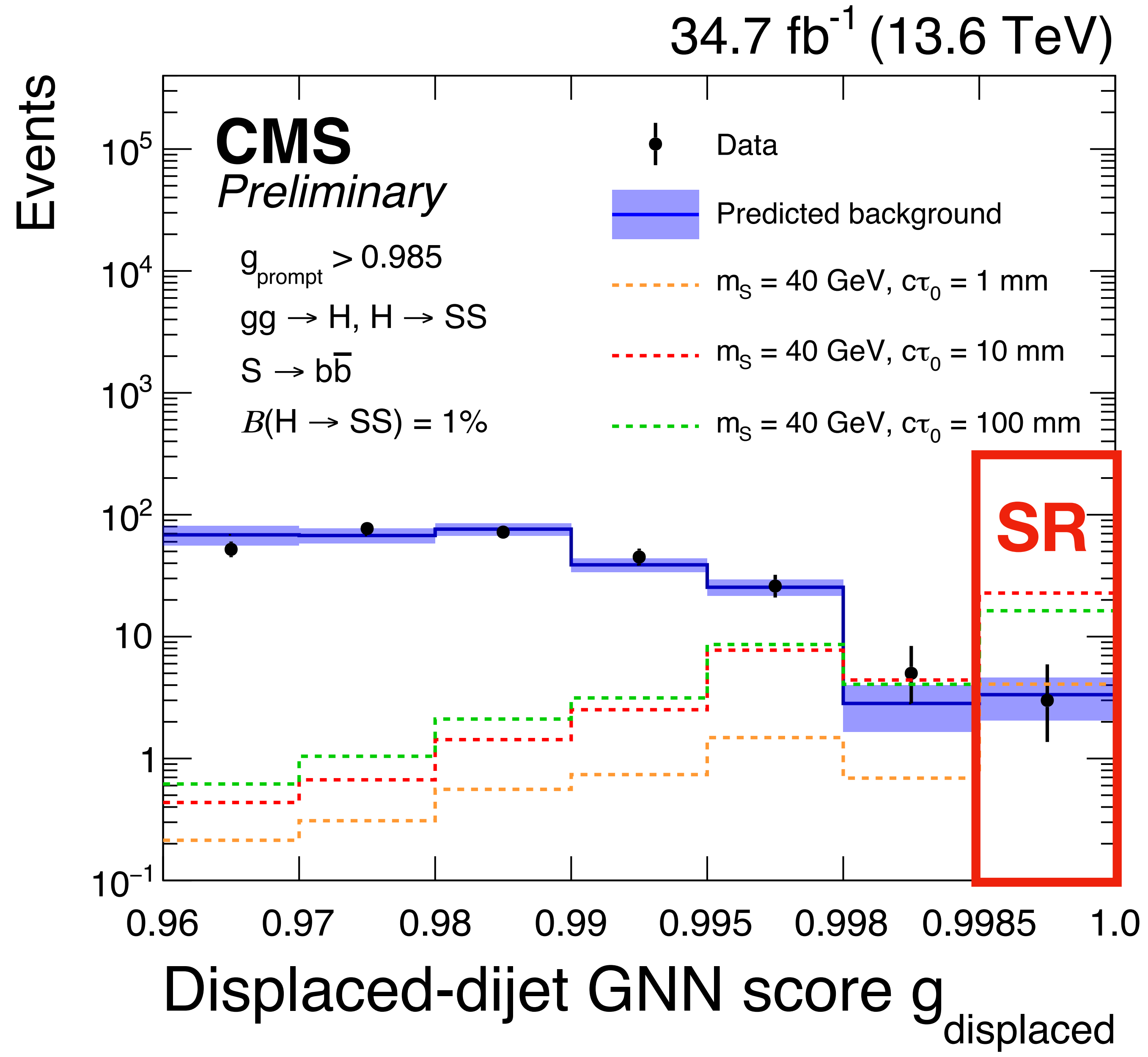
- Search for exotic Higgs decay to long-lived scalars (S) in hadronic final states



- **Signature:** Displaced dijets
- **Run-3 strategy (2022 data)**
  - **Tracker-only based analysis**
  - Challenging due to large QCD background

- **New Run-3 key ingredients**
  - Displaced dijet trigger: 5-10 x signal gain
  - Improved displaced vertex (DV) reconstruction
  - LLP taggers using Graph Neural Networks (GNNs)
    - $g_{displaced}$ combines displaced tracks + DVs info
    - g_{prompt} combines prompt tracks info

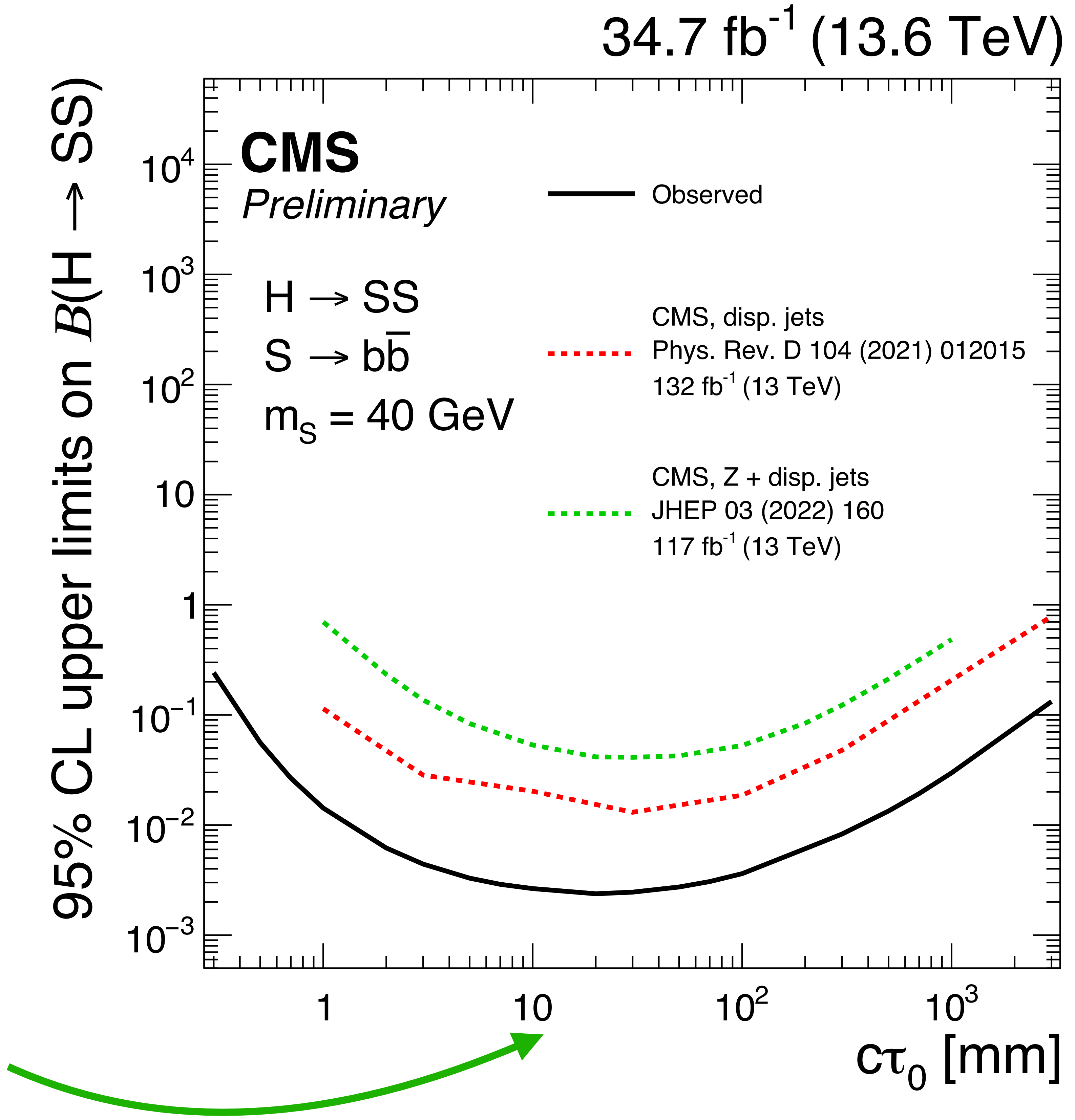


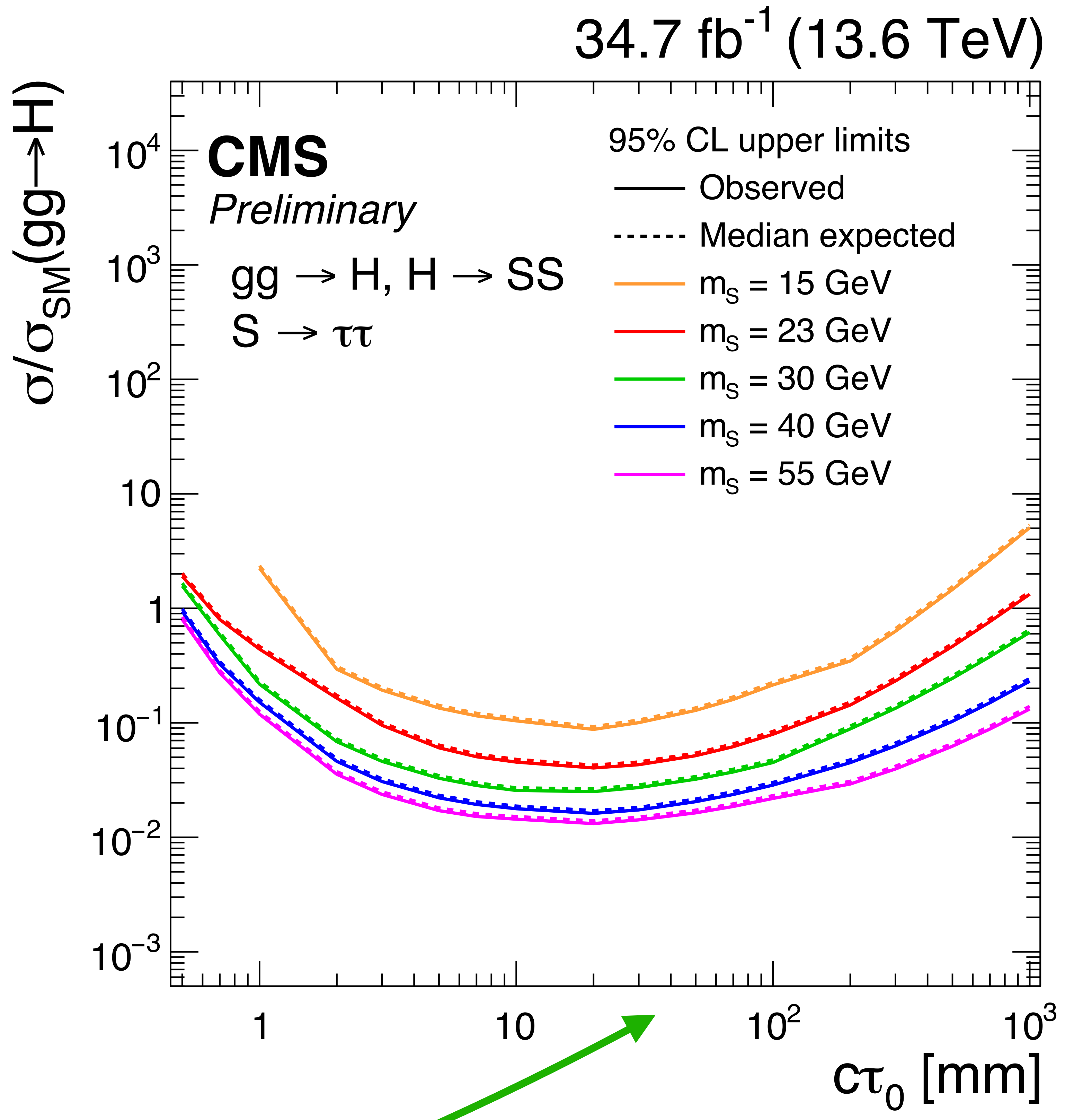


Search for displaced dijets: Results

CMS-PAS-EXO-23-013

- **Background estimate:** ABCD method
  - Cuts on $g_{\mathrm{displaced}}$ and g_{prompt} scores
  - Expected background: 3.34 ± 1.28 events
- **Observation:** 3 data events
- **Interpretations:**
  - 95% CL limits on BR(H→SS), $S \rightarrow b\bar{b}, d\bar{d}, \tau\tau$
  - LLP mass range: 15-55 GeV
  - 10 x sensitivity improvement w.r.t Run-2 results
  - First-ever displaced $S \rightarrow \tau\tau$ sensitivity for $c\tau$ < 1 m



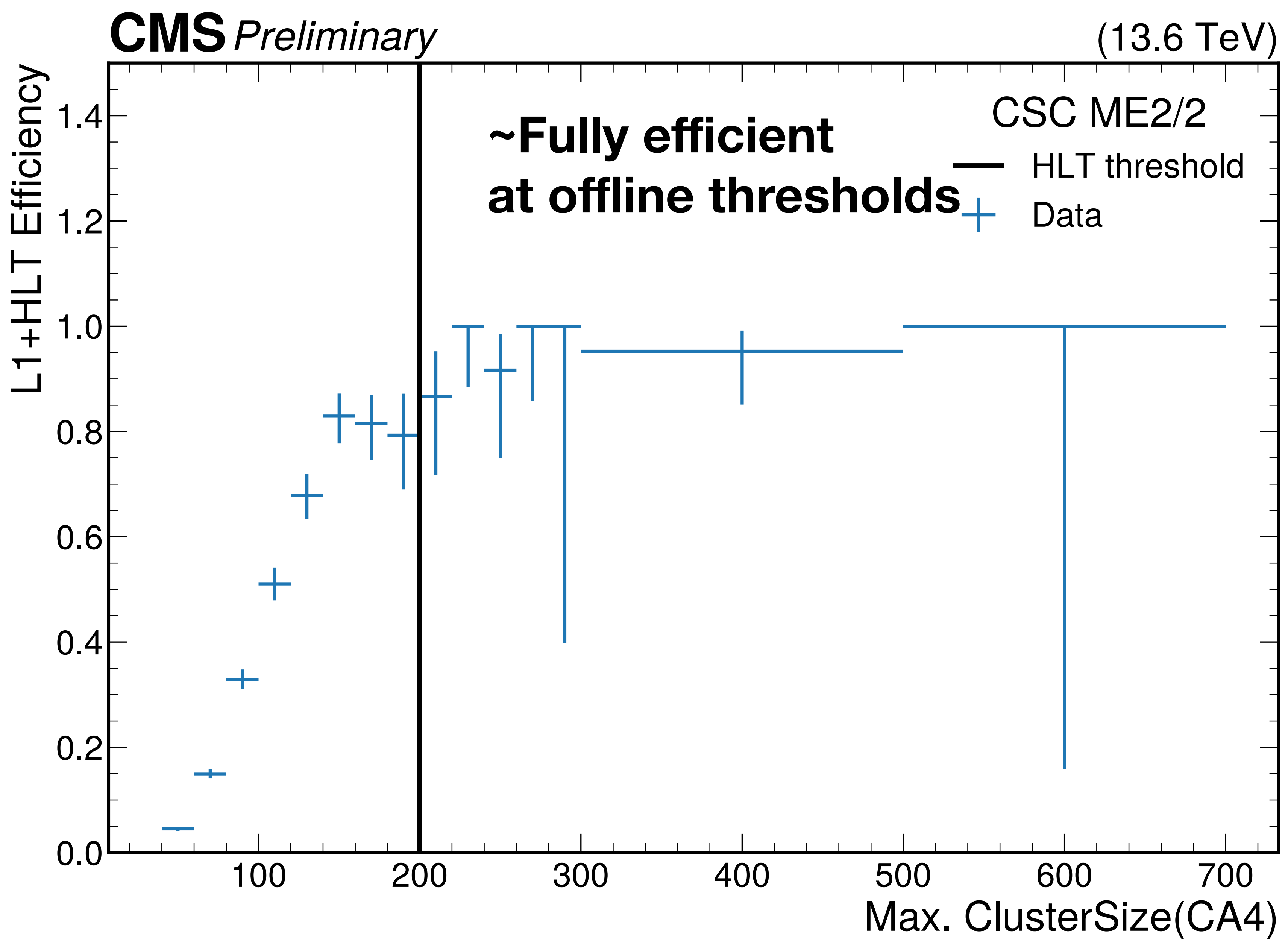


Outlook to Run 3: New MDS trigger

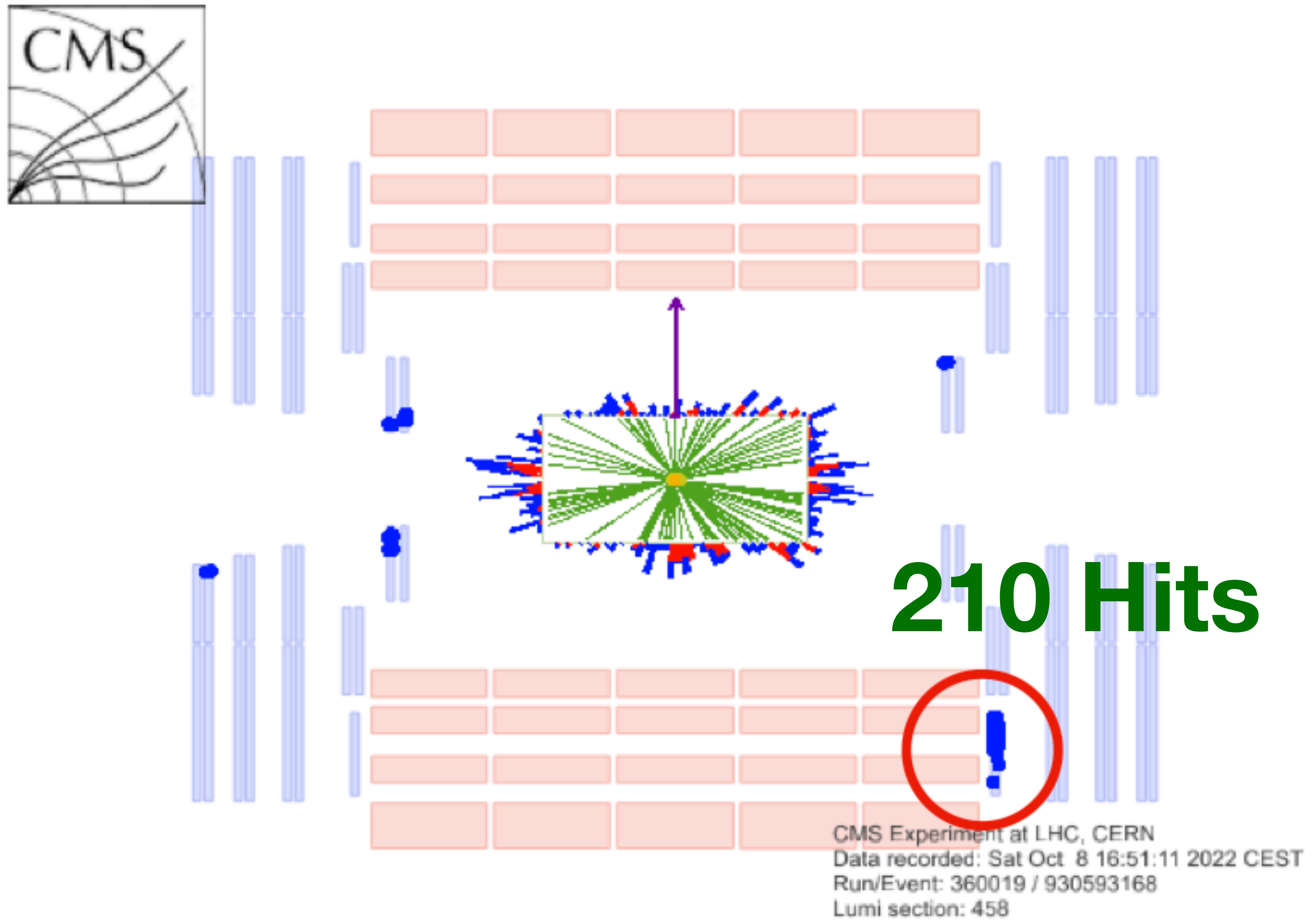
- Run-2 MDS analyses relied on available MET and lepton triggers
- **New Run-3 L1 CSC High-Multiplicity Trigger (HMT) seed** using number of hits
- **New Run-3 HLT paths** targeting single and double MDS clusters
- **Actively collecting and analyzing Run-3 data!**

CMS-DP-2023-043

More on New LLP triggers



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



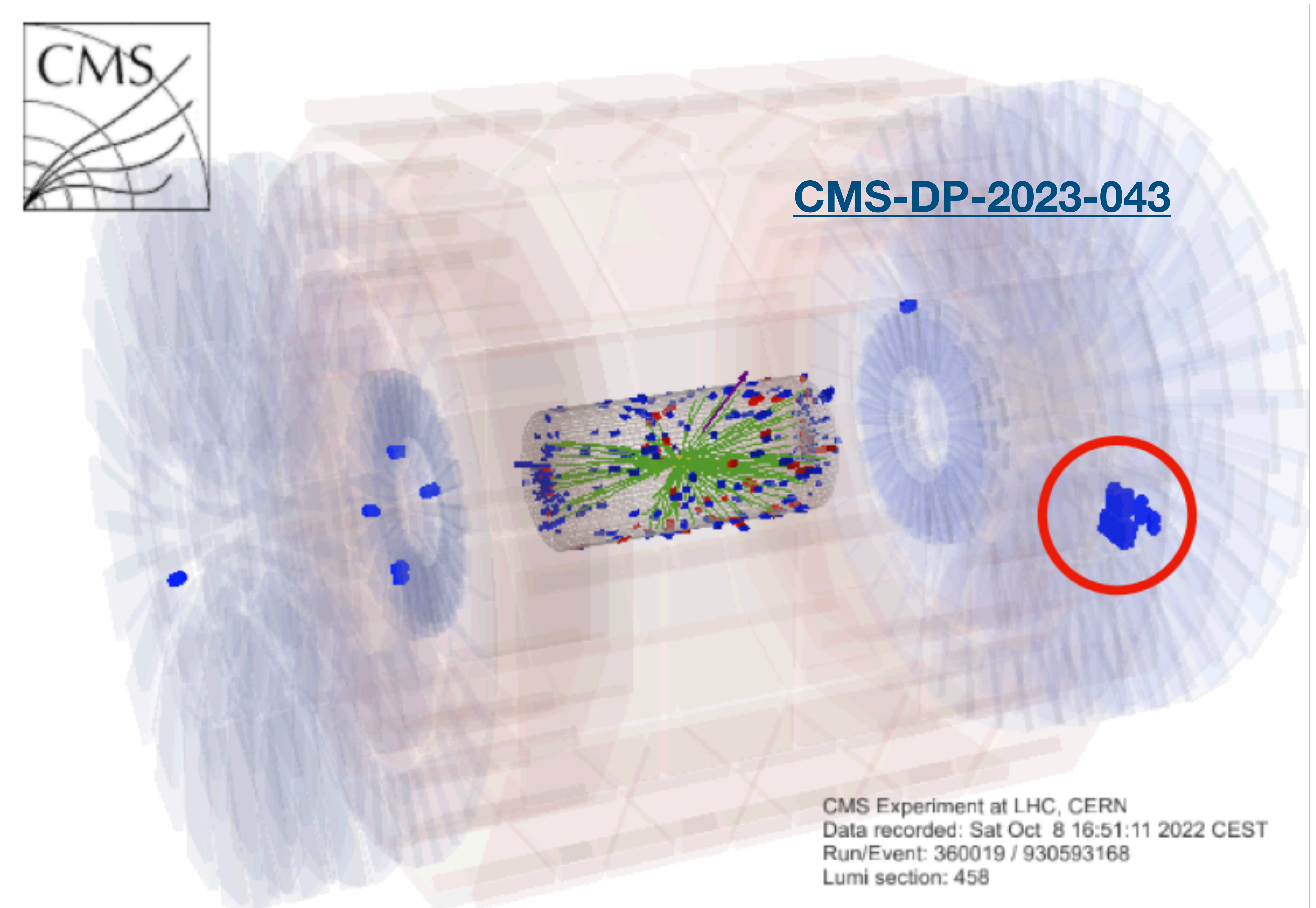
Event triggered by the CSC HMT trigger in 2022

Summary

- **Innovative use of the detectors** is crucial to advancing LLP frontier at the LHC and the HL-LHC

- **LLP Searches: Great example of a fully integrated effort**
  - Theory, triggers, data management, algorithms, and analysis

- **Recent CMS searches were presented today:**
  - Run-2: HSCPs and VLLs with LLP decays in the muon system
  - Run-3: Displaced dimuons and displaced dijets

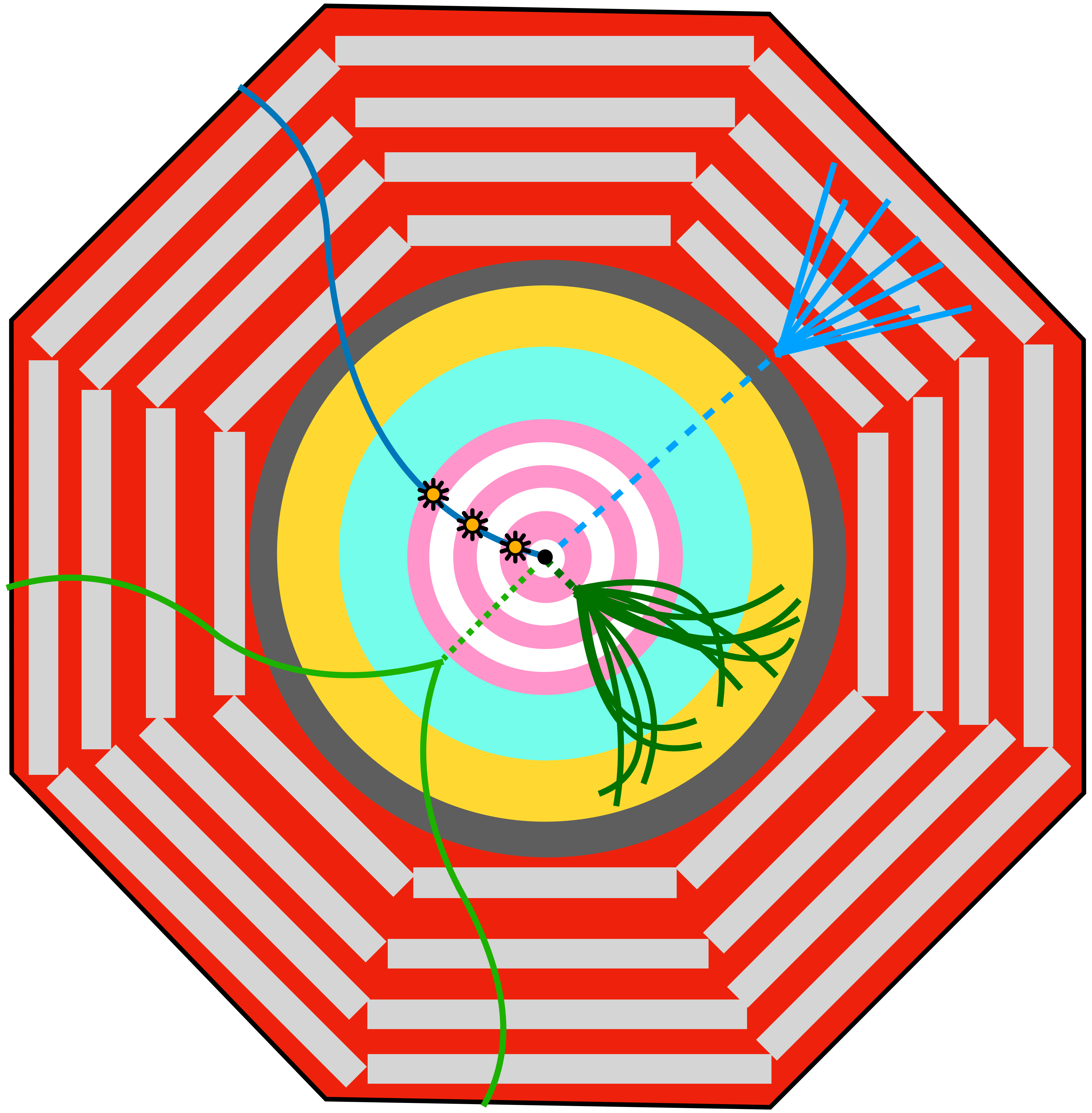


Run-3 HMT triggered event

- Run-3 brings LLP-tailored strategies that could enable future discoveries

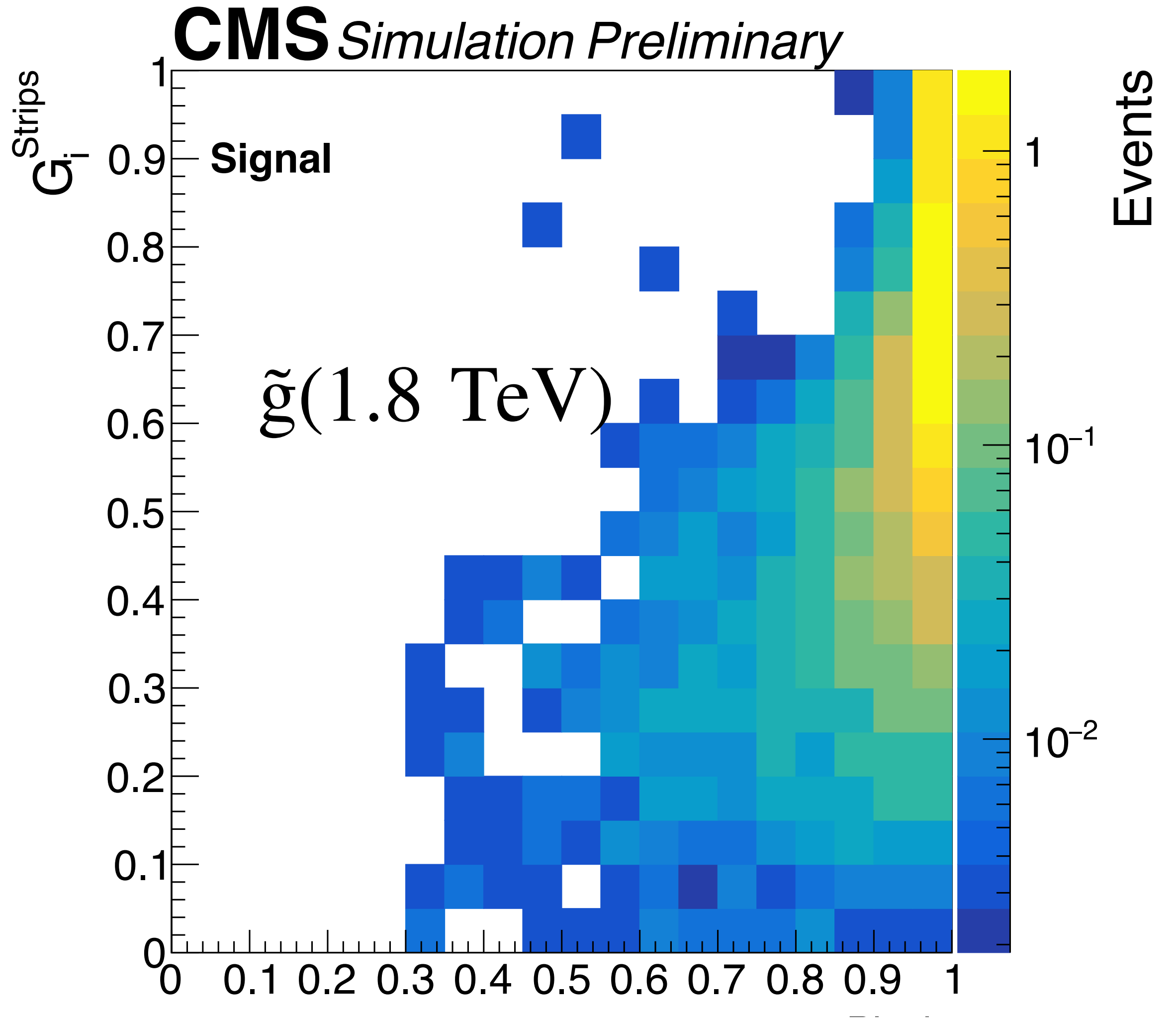
STAY TUNED!

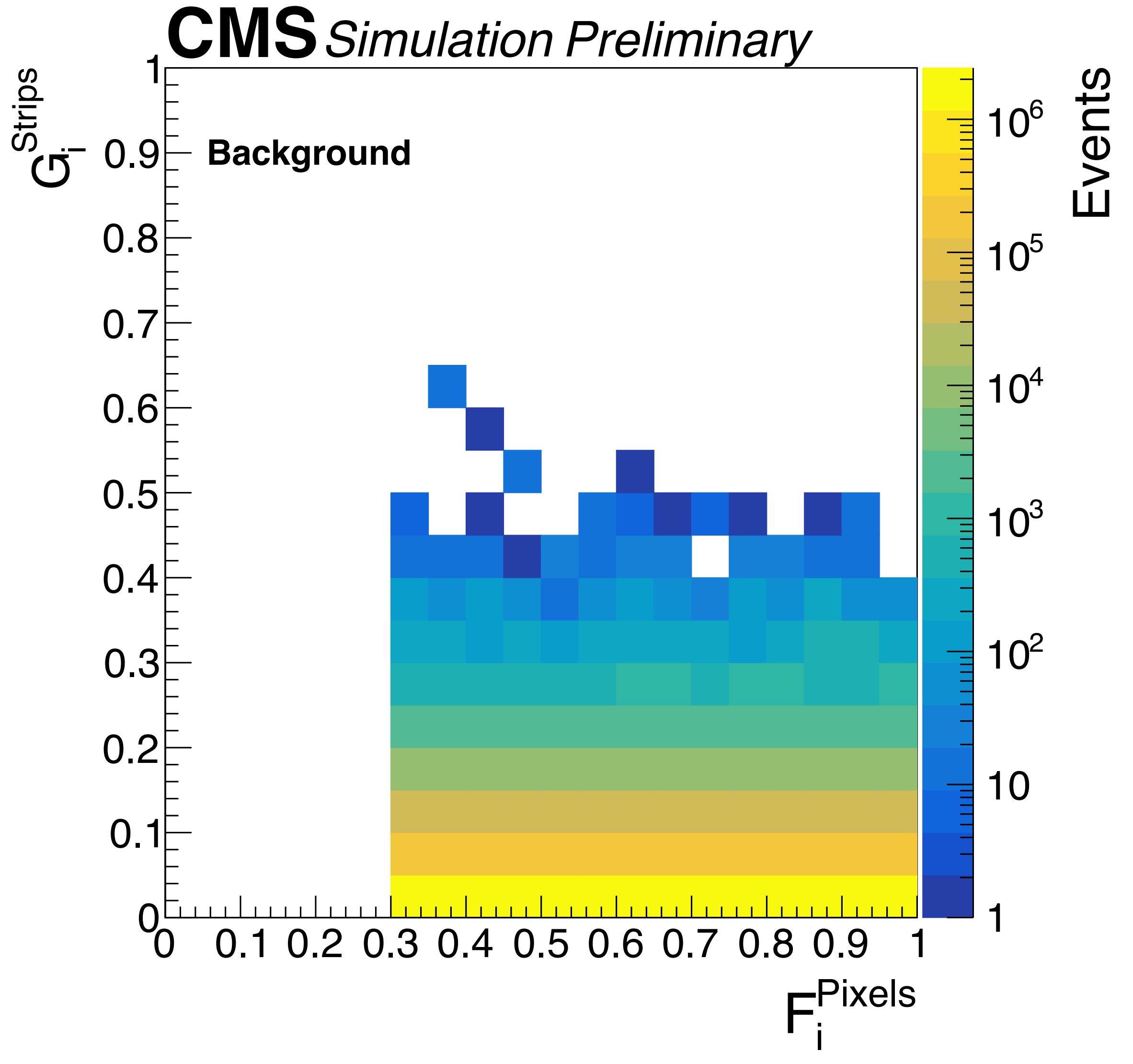
Additional Material



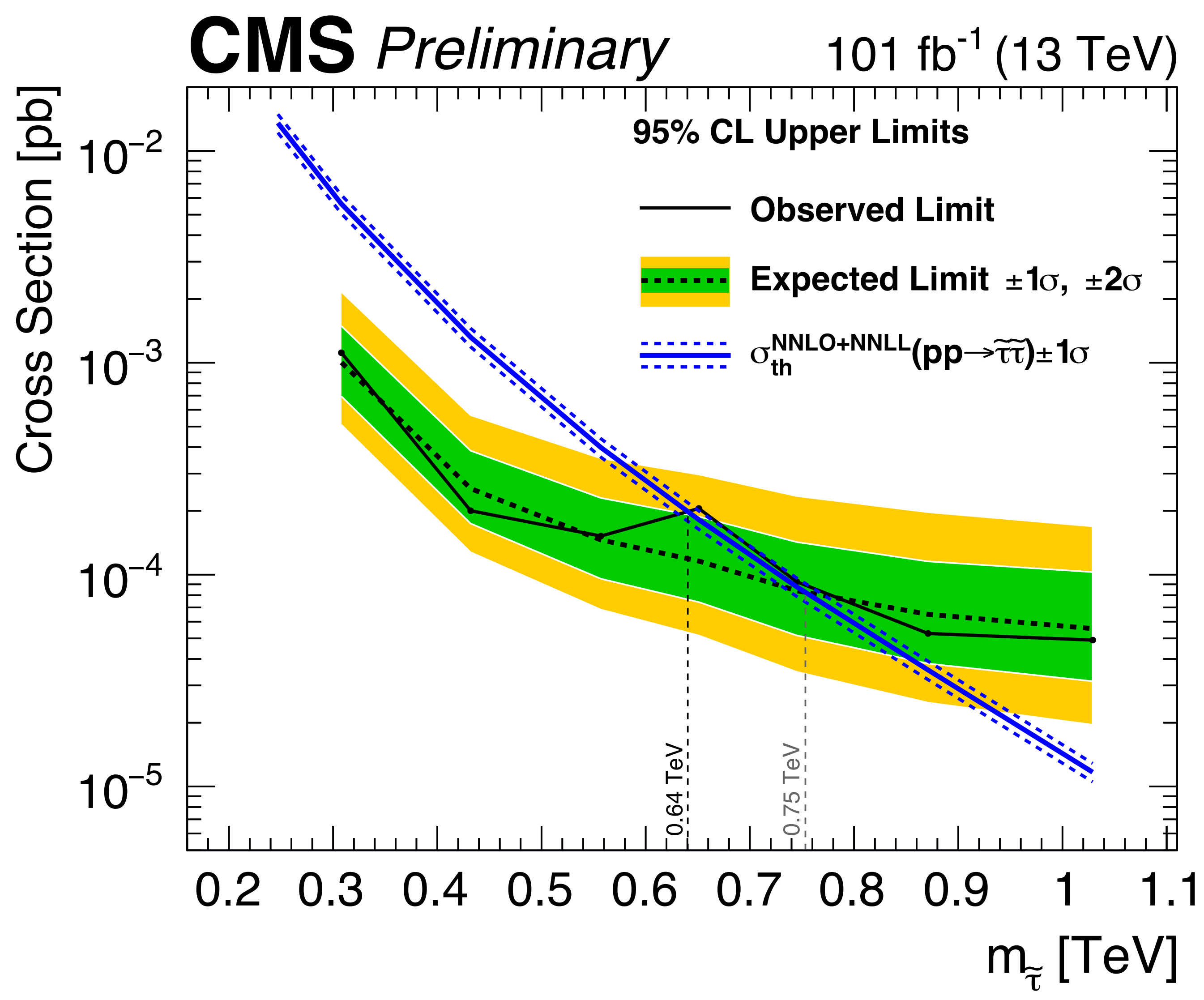
Search for HSCPs: Extended

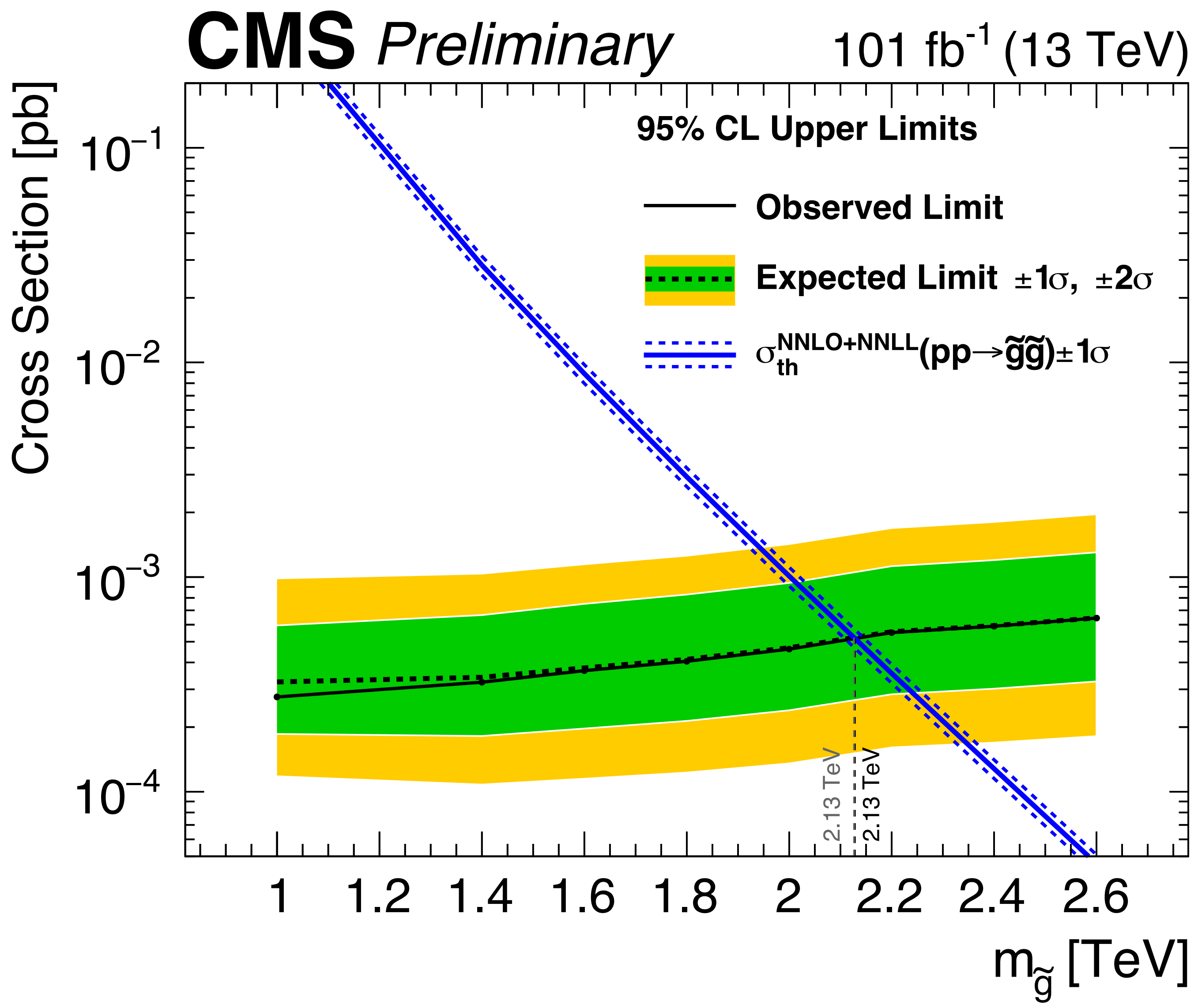
CMS-PAS-EXO-18-002

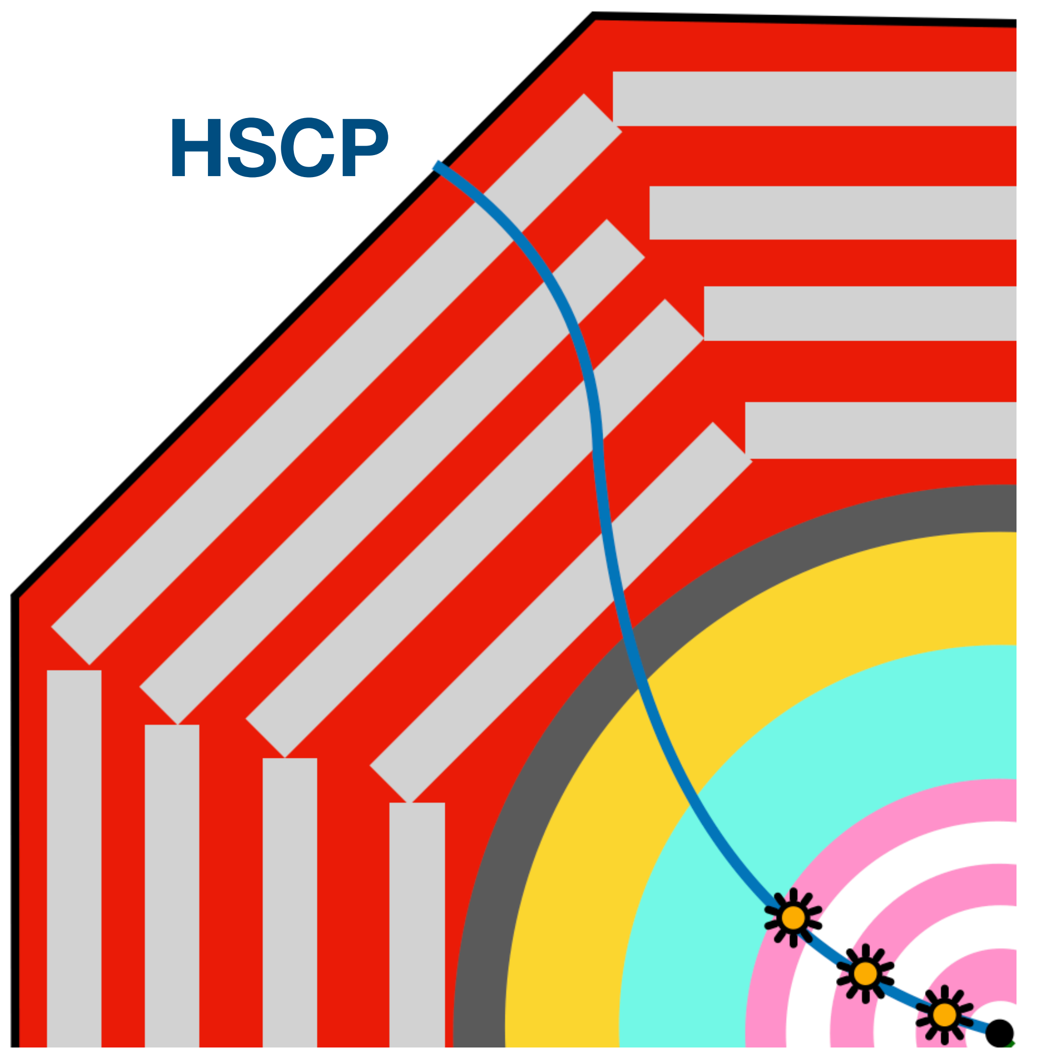


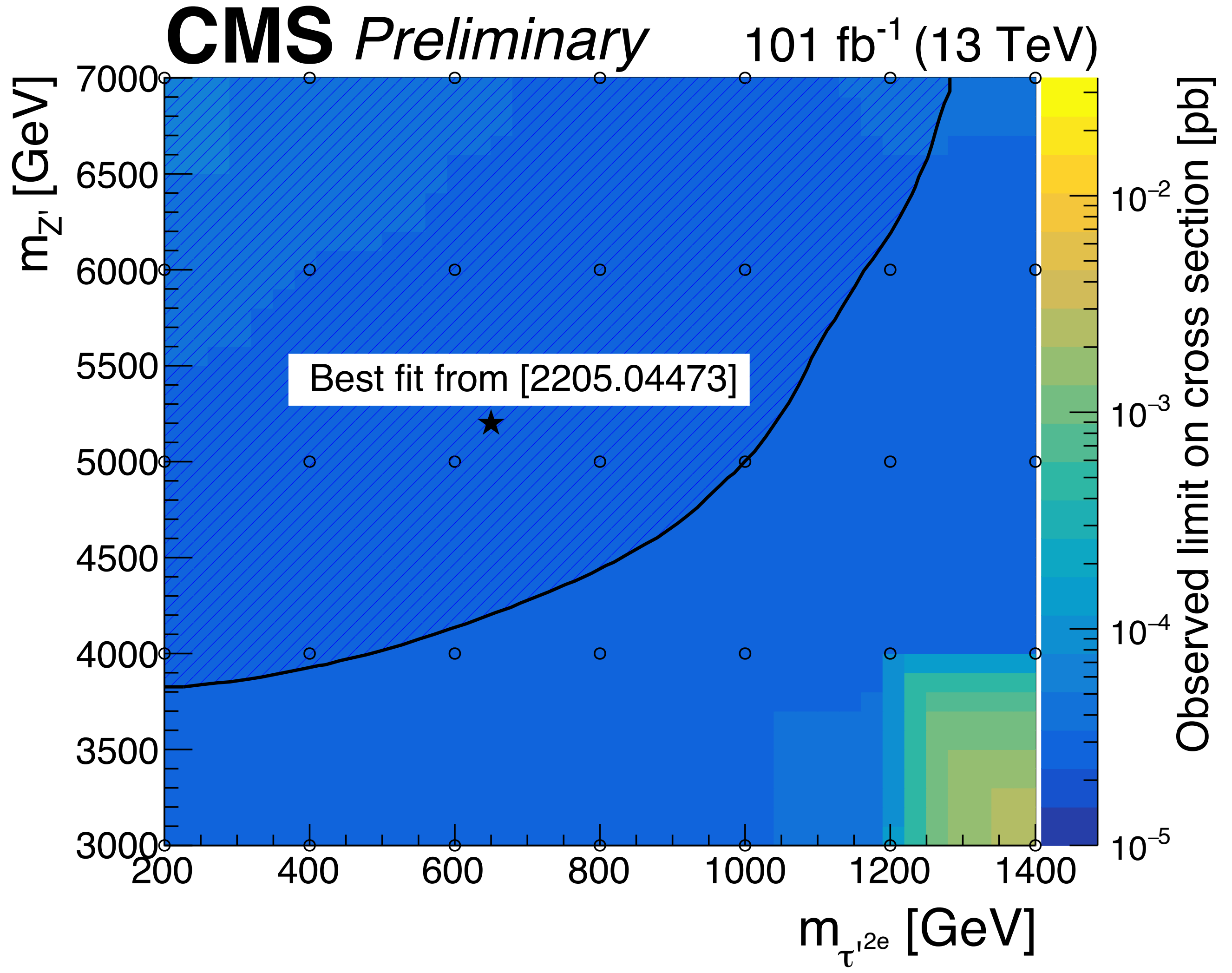


Background method details





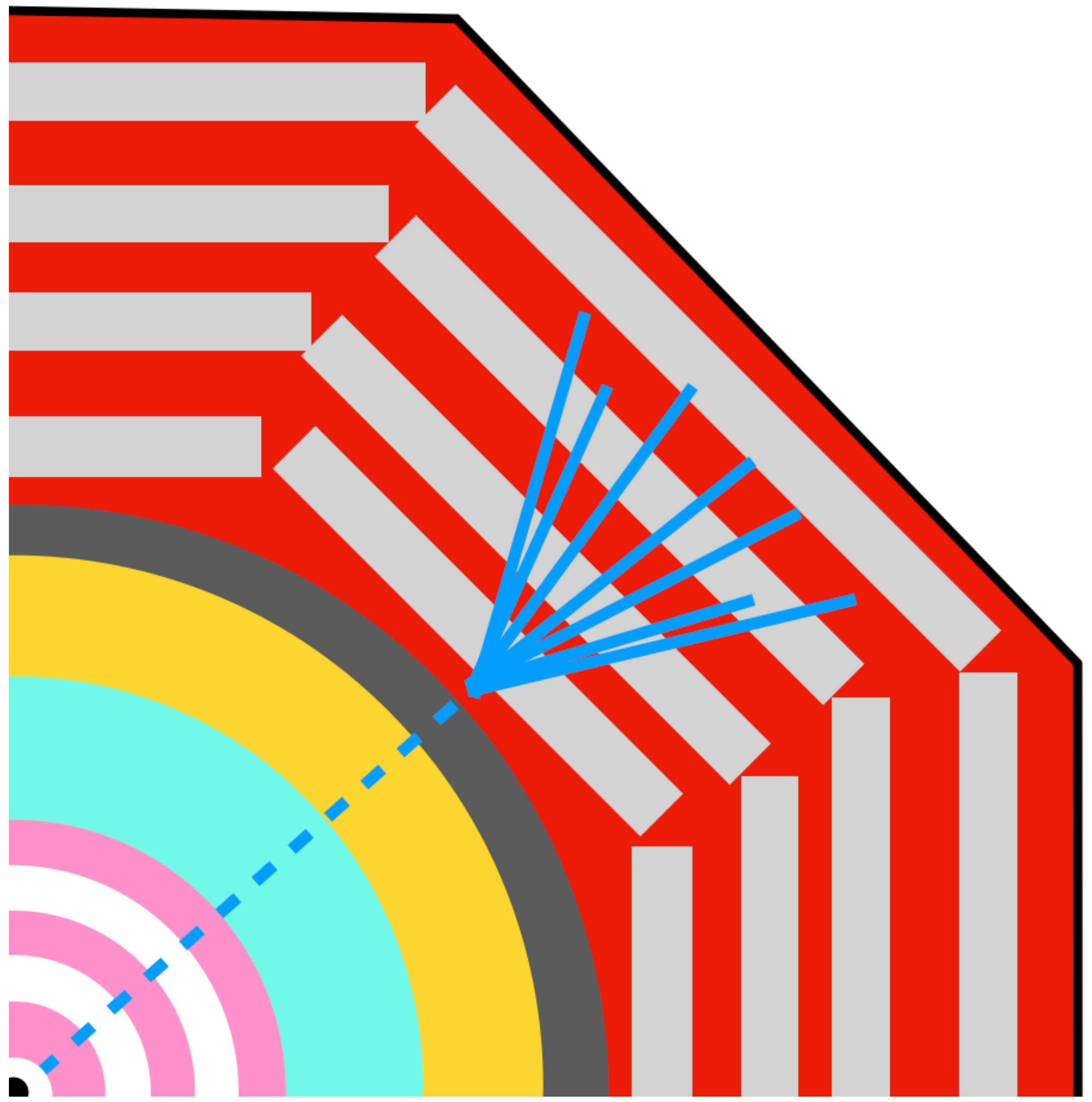


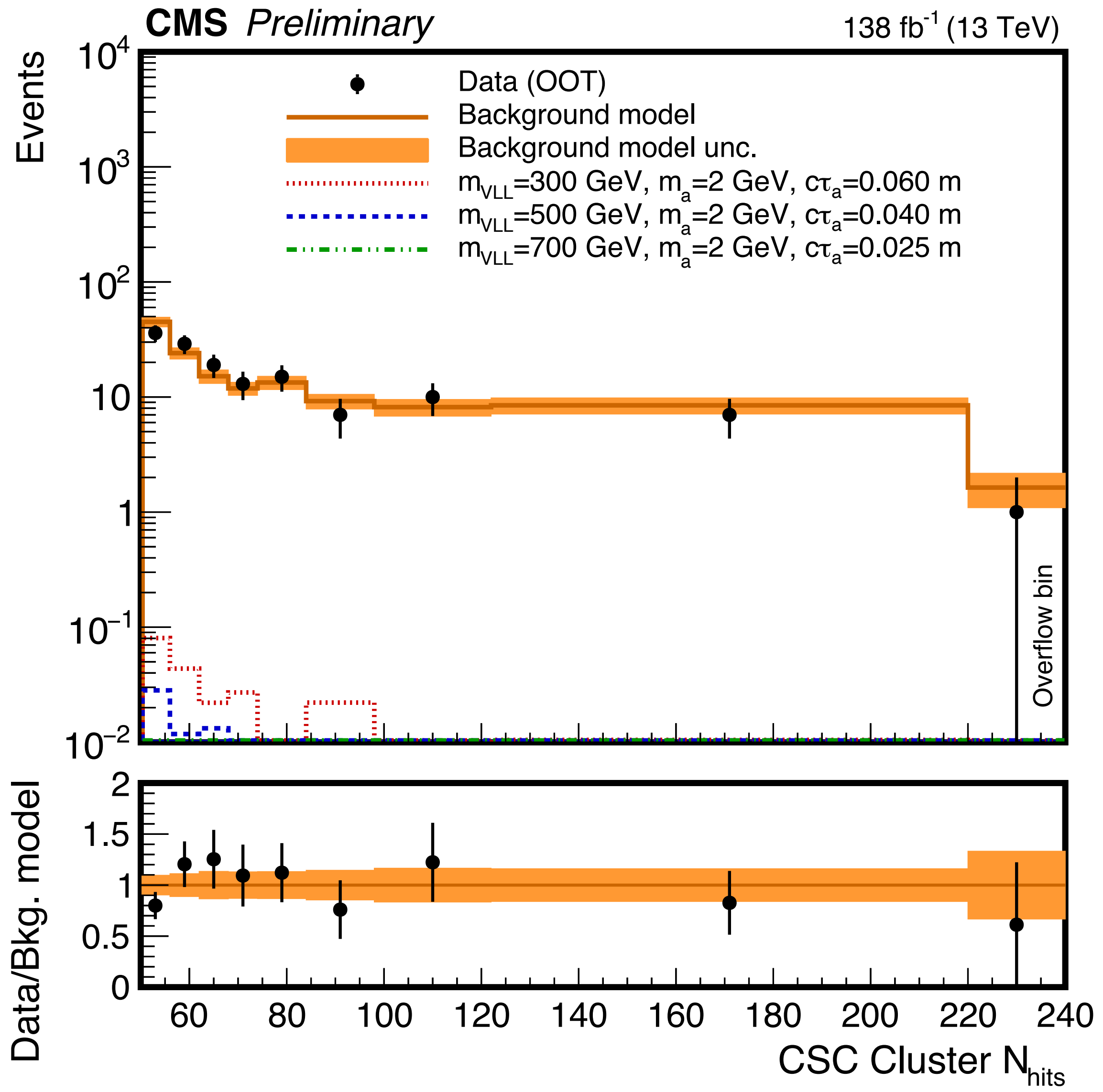


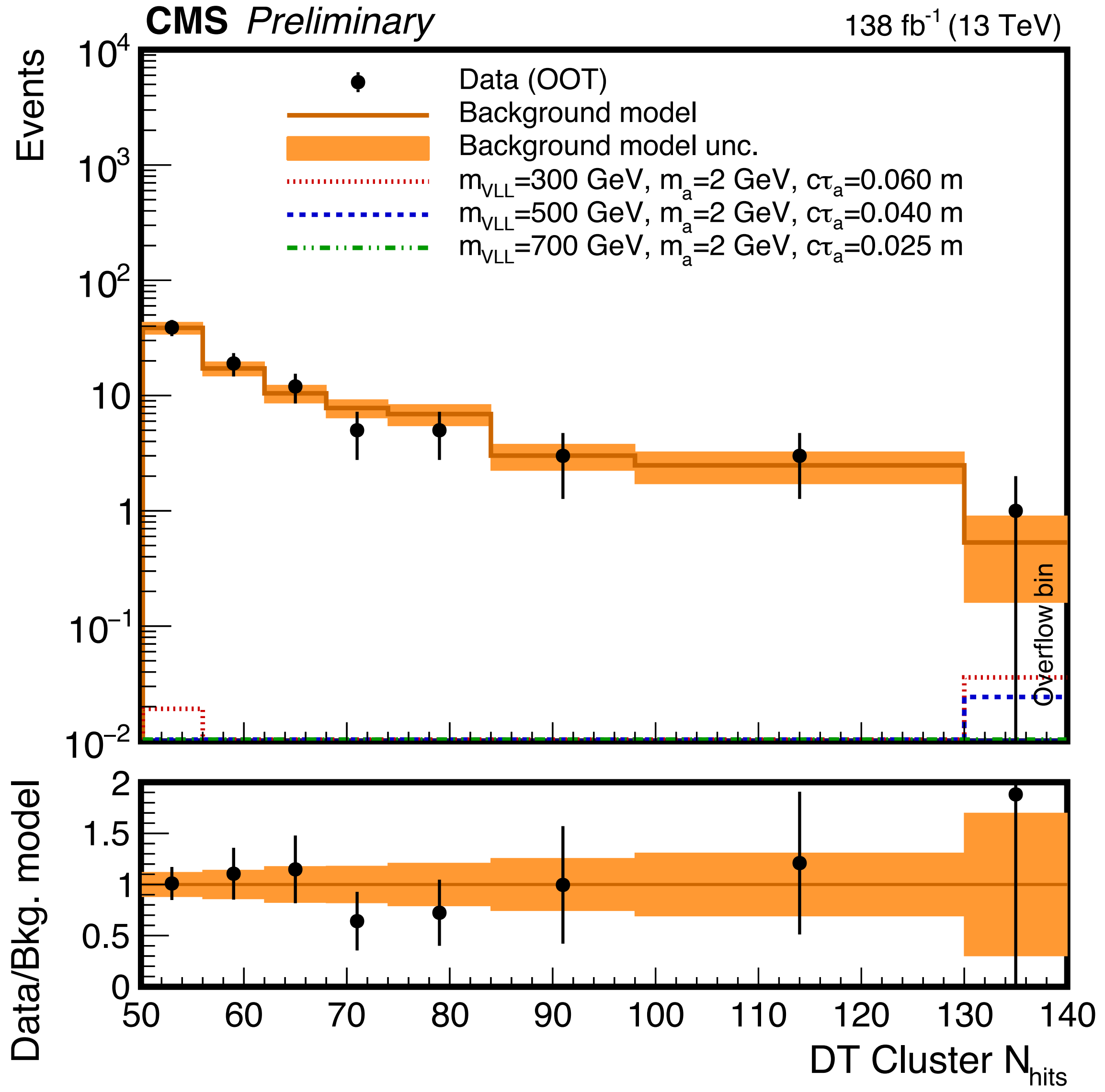
Mass method results

Search for VLLs w/ MDS showers: Extended

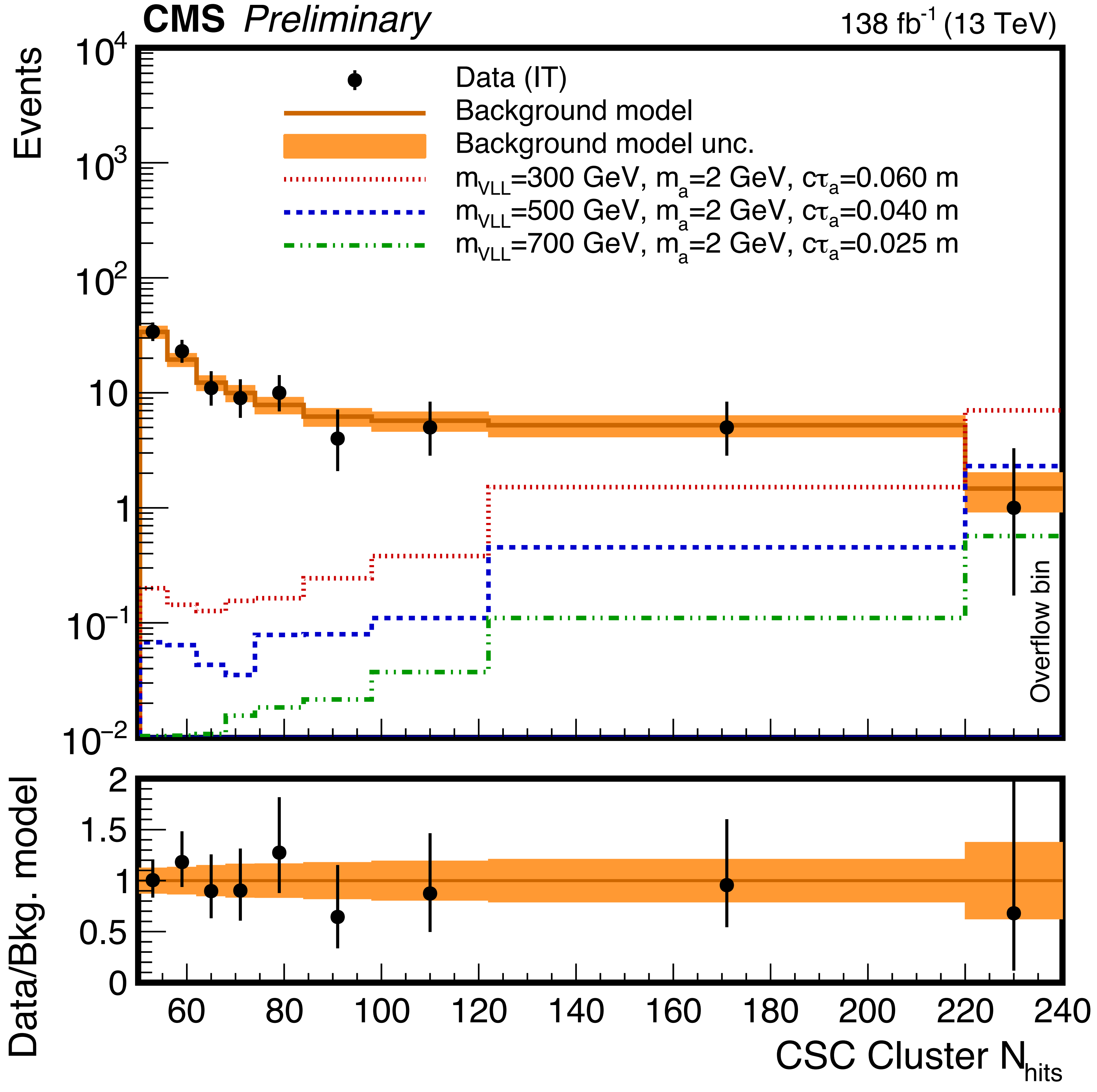
CMS-PAS-EXO-23-015







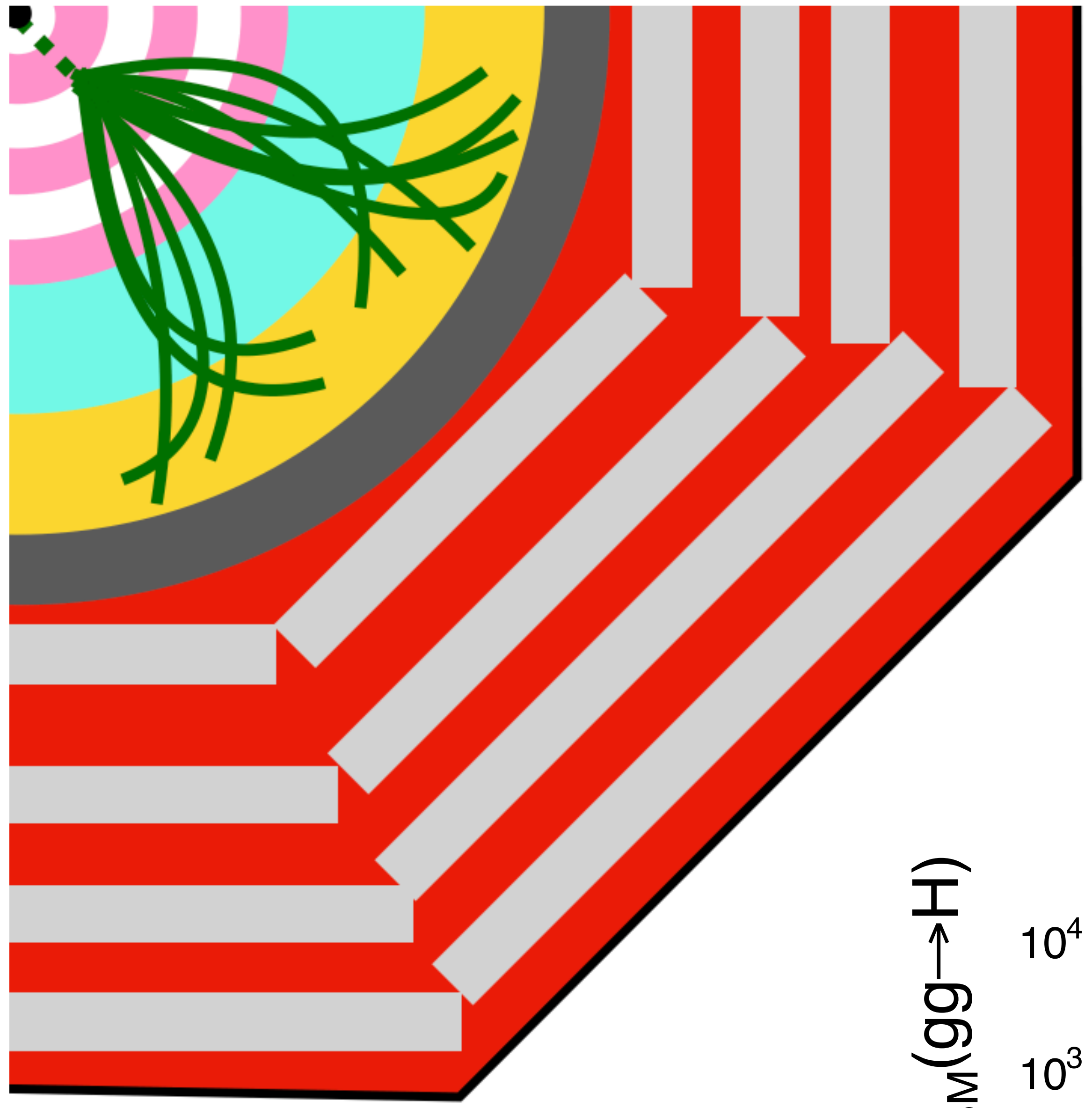
Background estimate validation

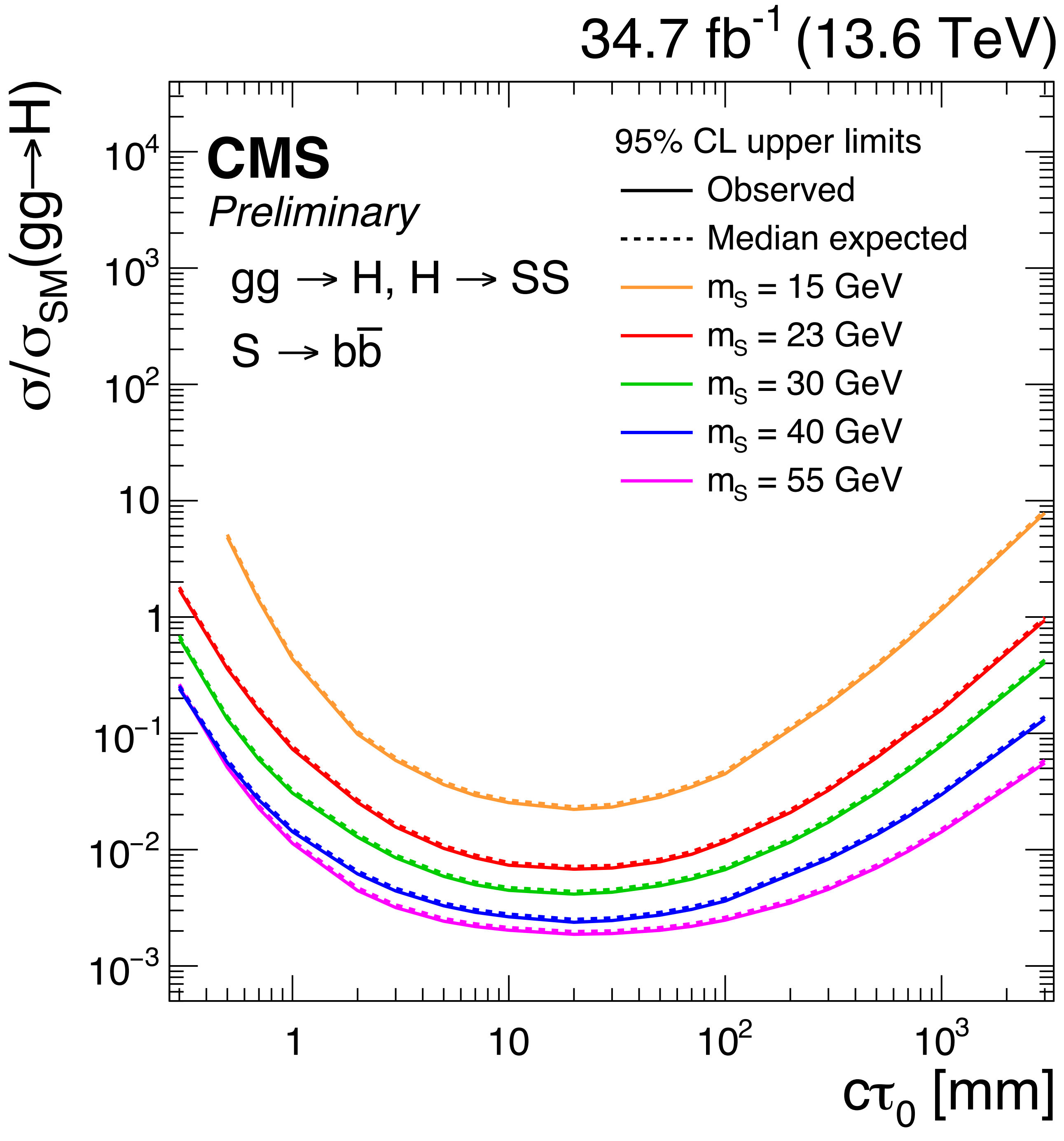


CSC category observable

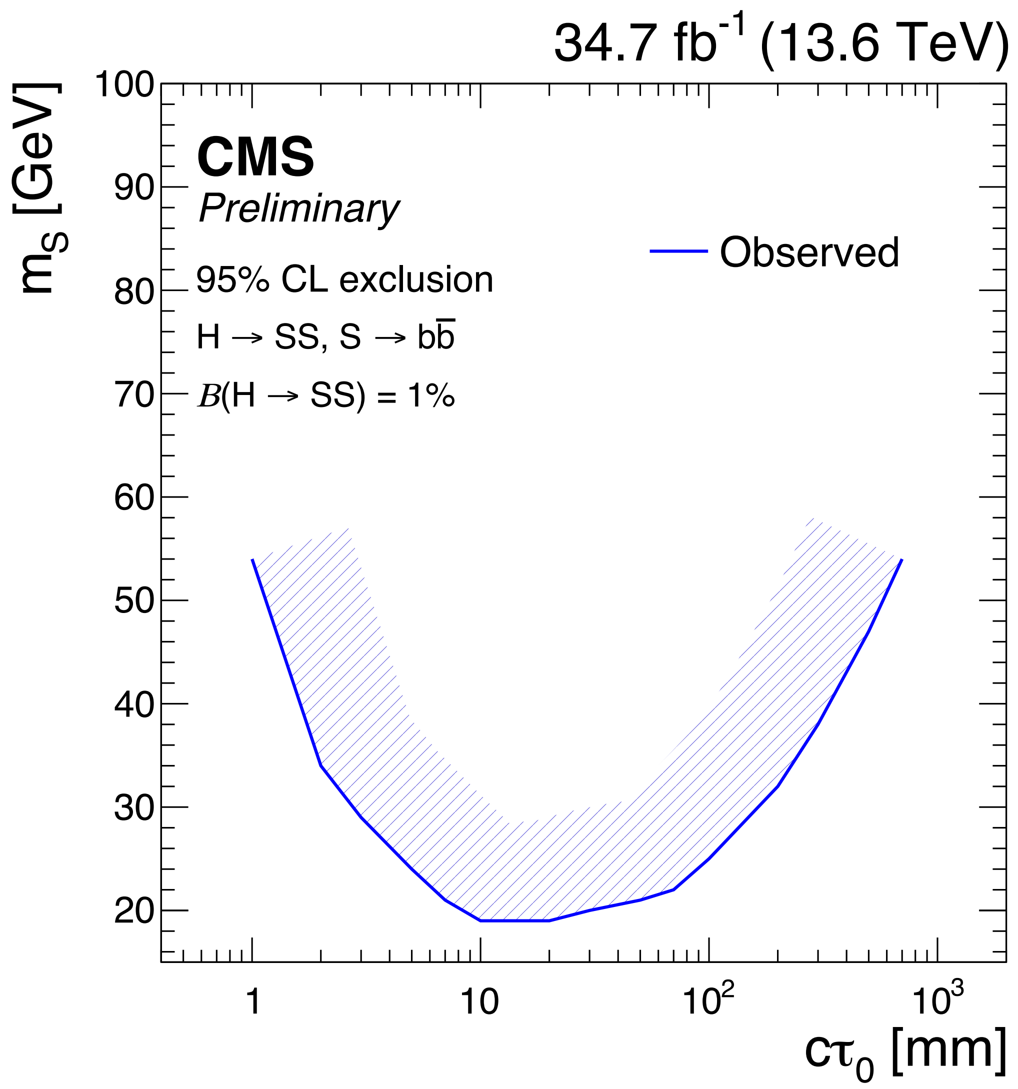
Search for displaced dijets: Extended

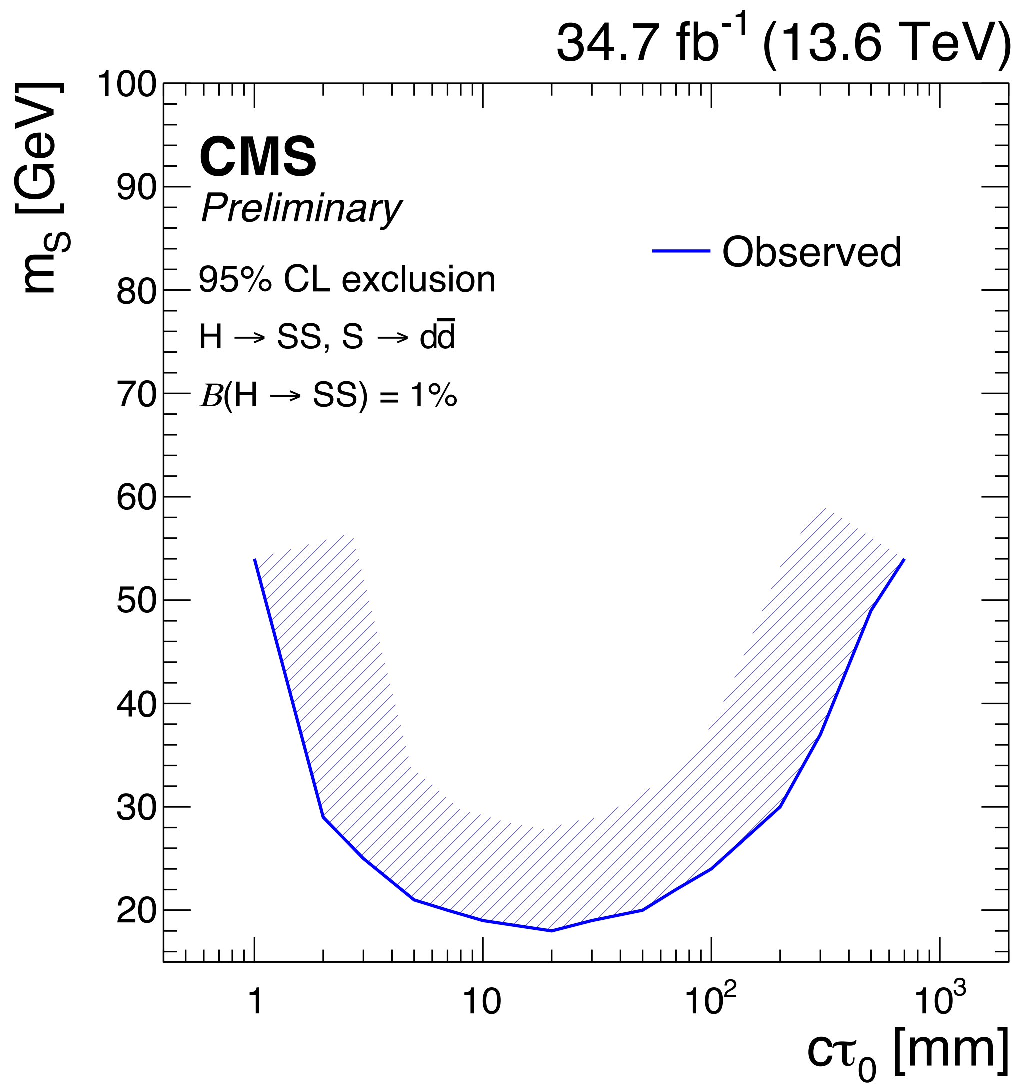
[CMS-PAS-EXO-23-013]

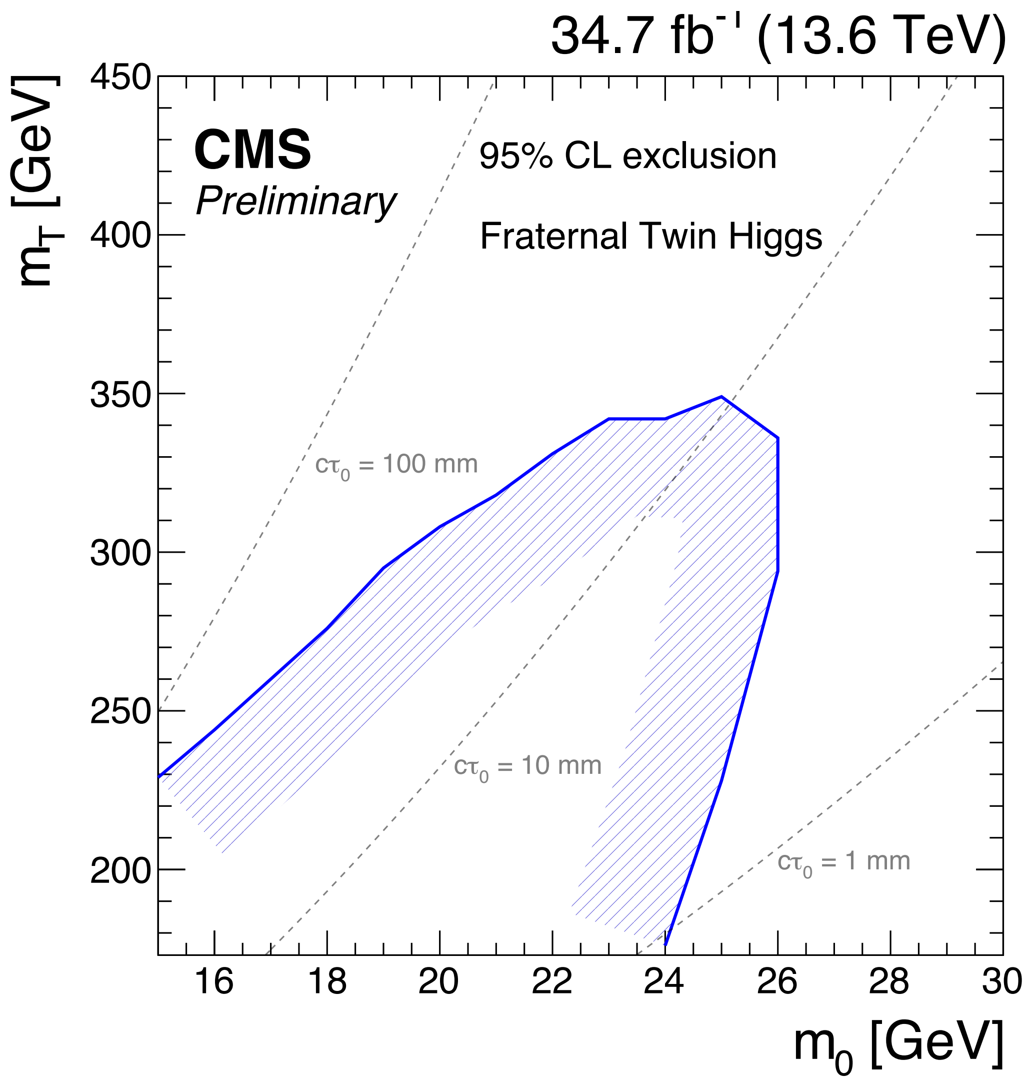


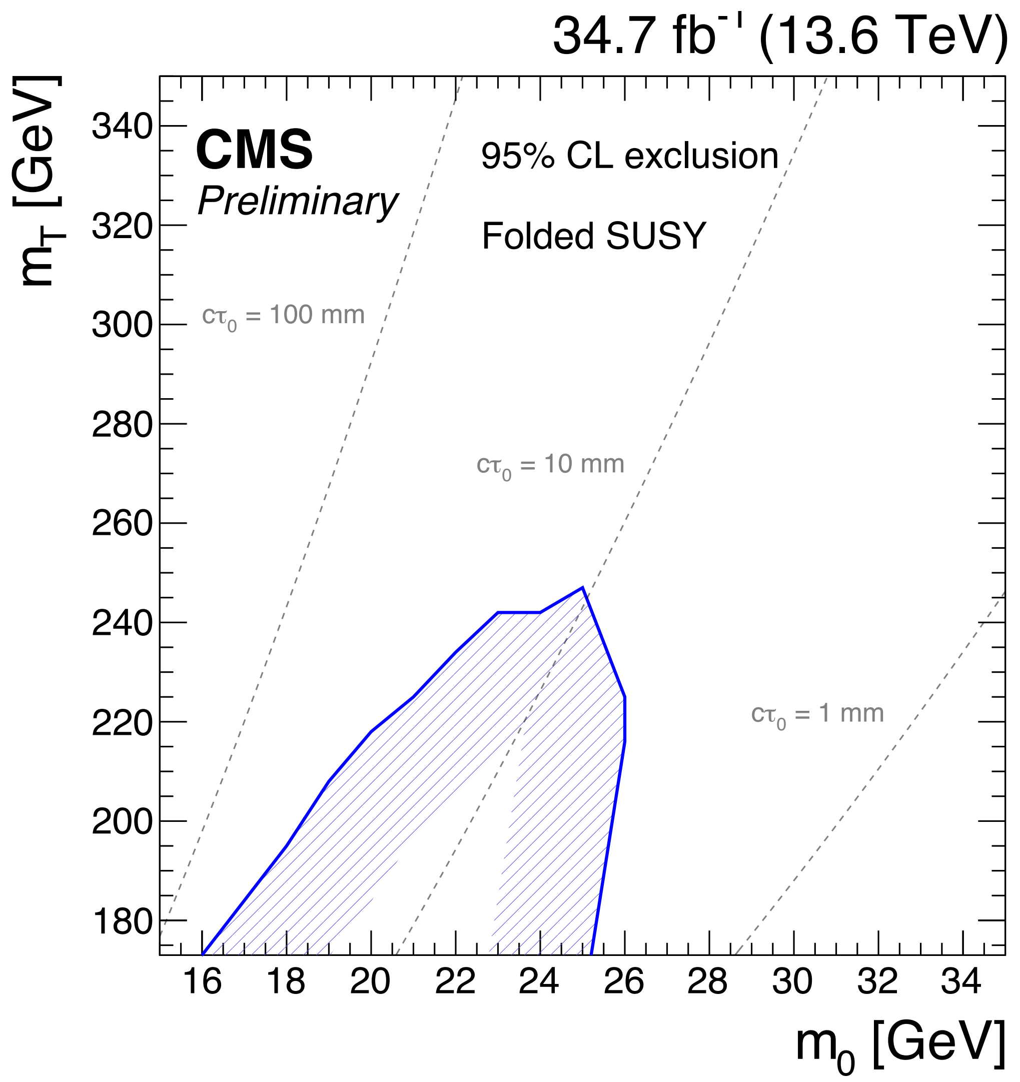


Other results









Additional Interpretations

Search for displaced di-muons: Extended

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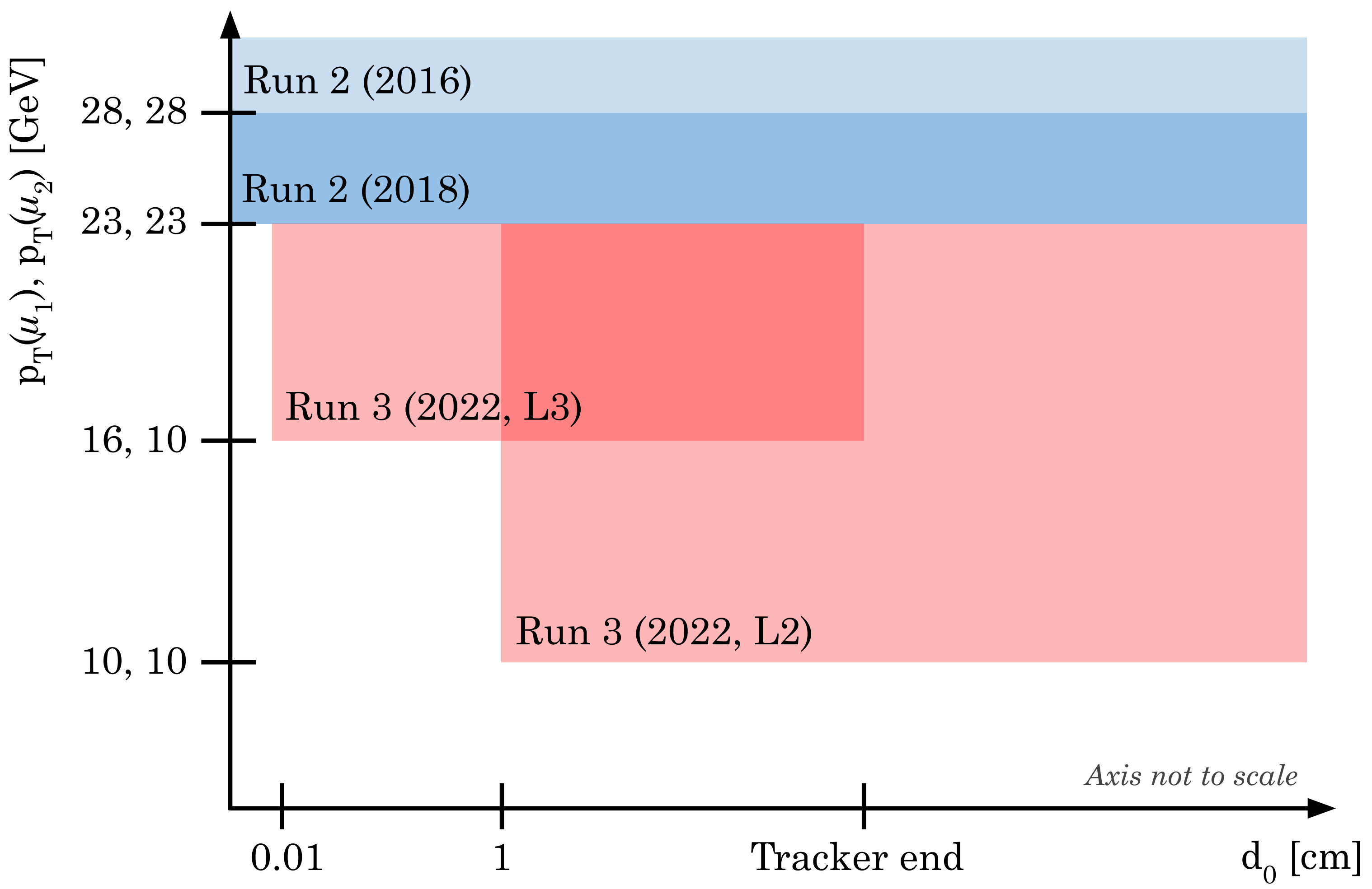
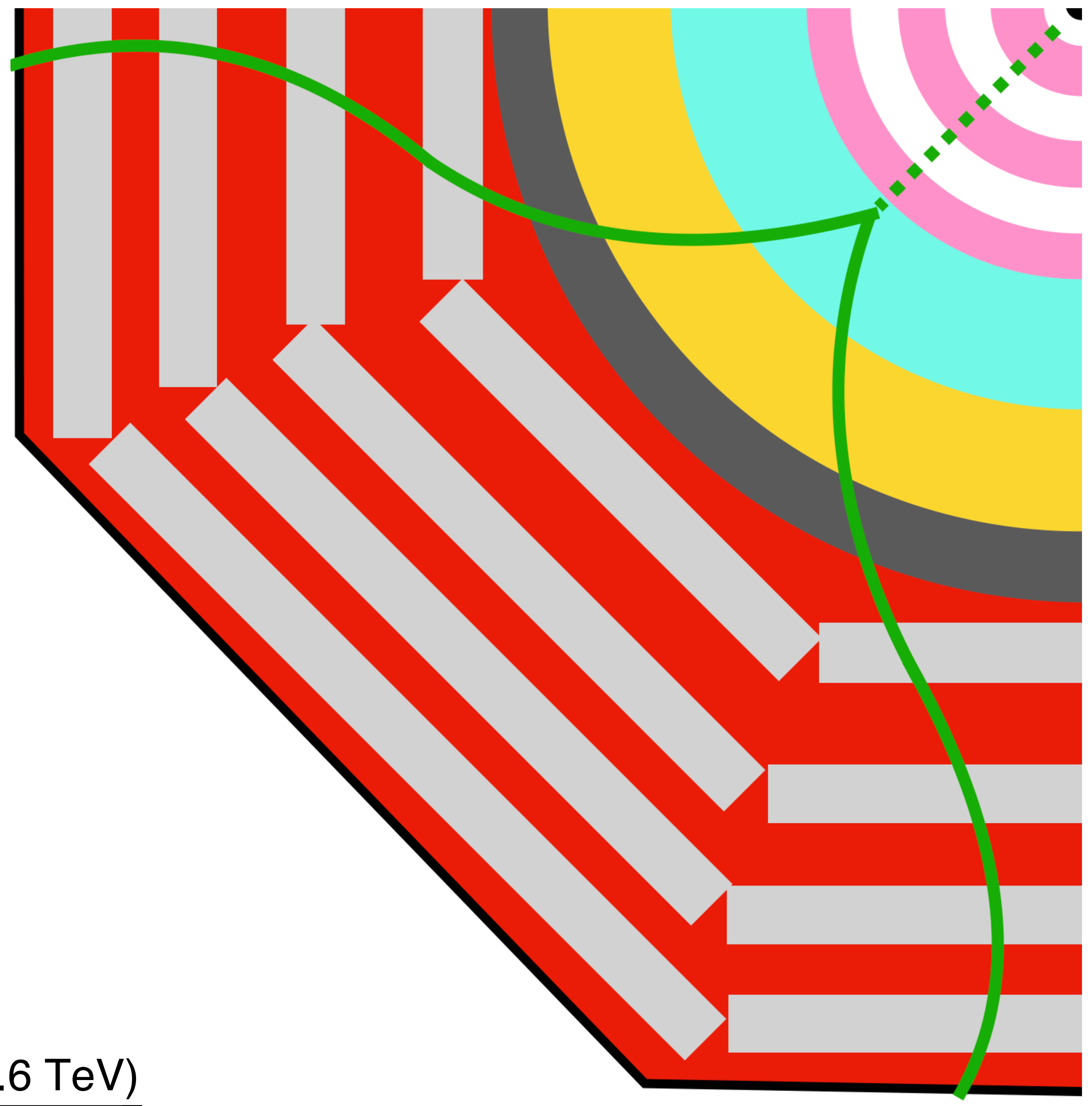
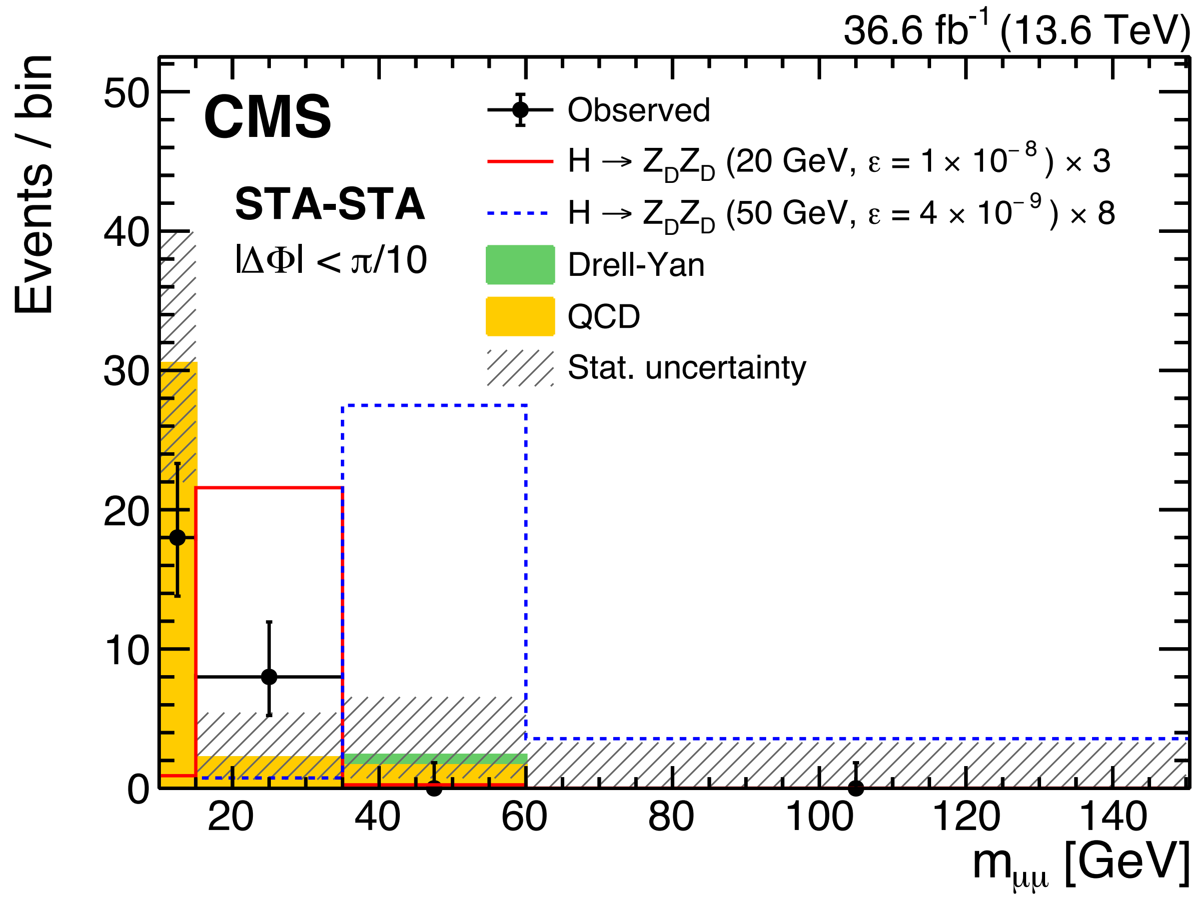
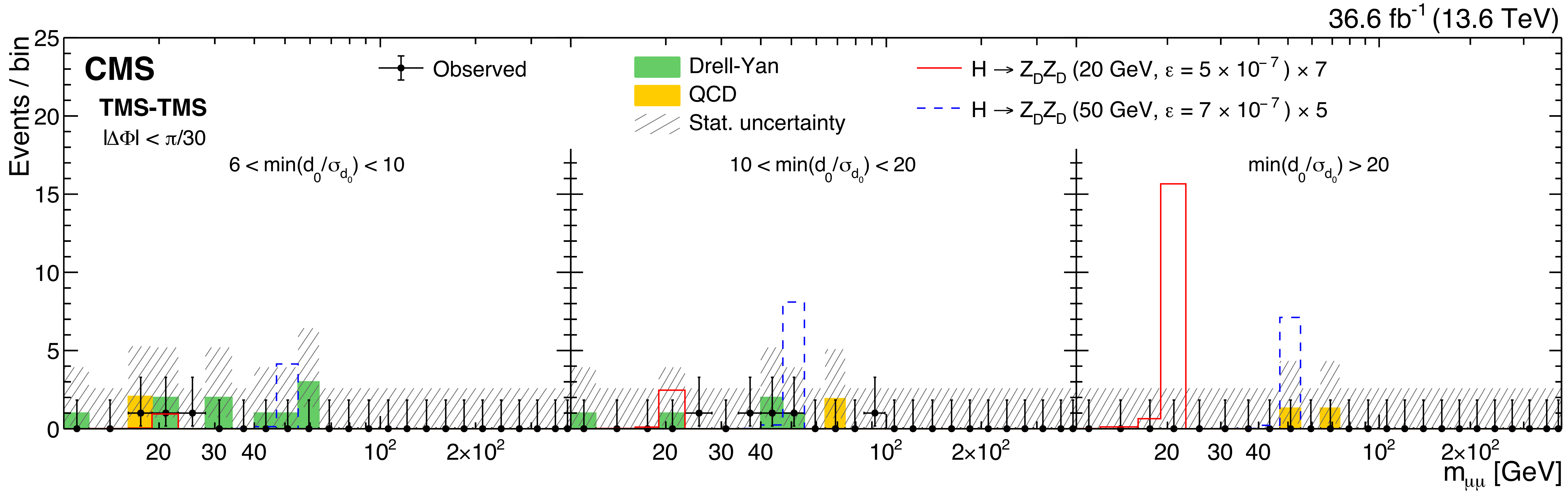
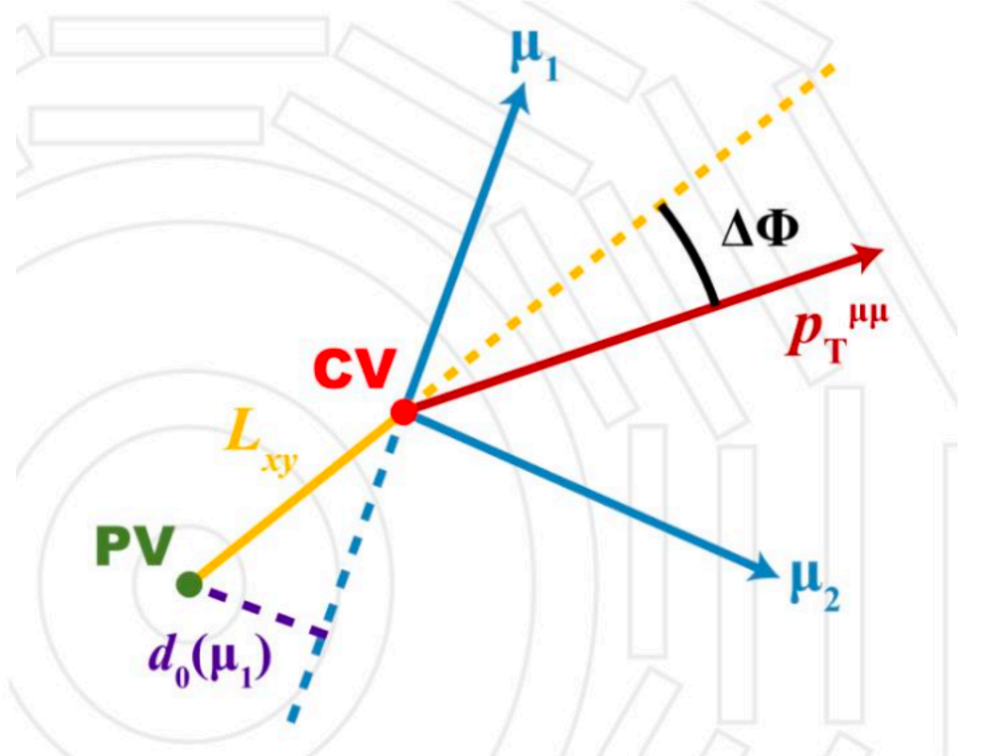


Run-2/3 Trigger thresholds



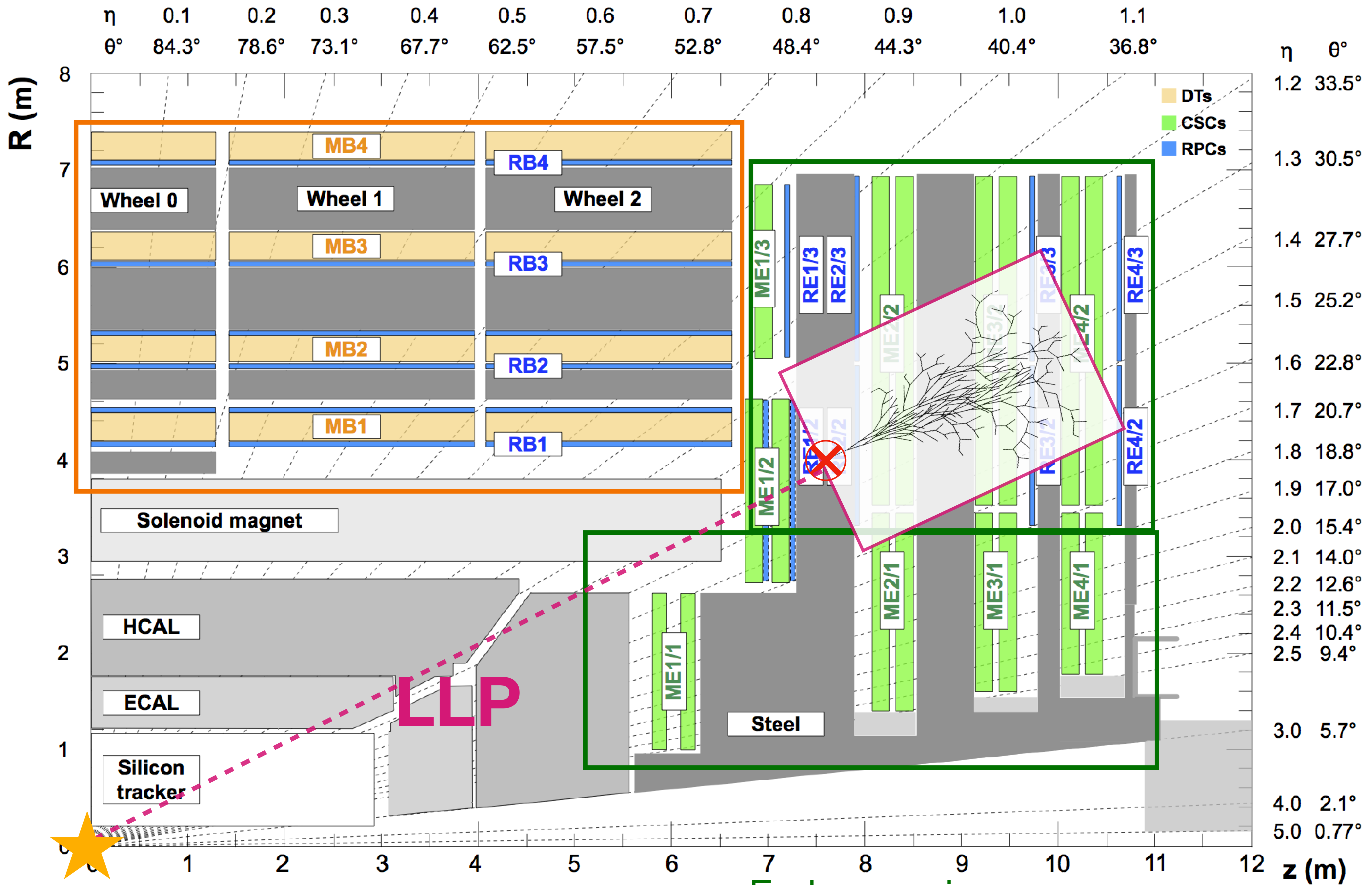






STA-STA and TMS-TMS mass distributions (Dark photon model)

Unlocking the CMS Muon System to catch LLPs



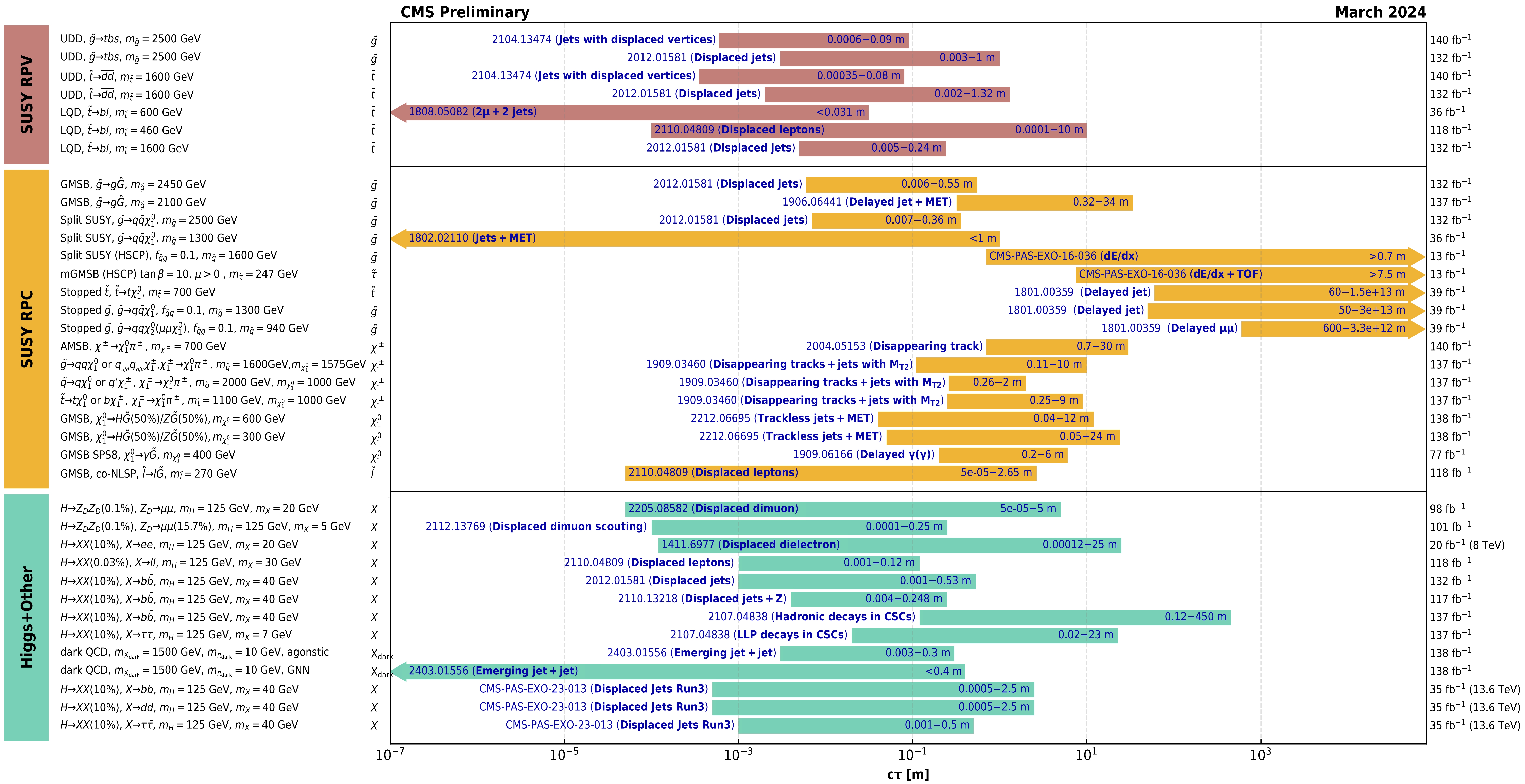
- Muon system acts as a **sampling calorimeter:**
  - 4 detector layers (active material) and steel (absorber)
  - LLP decays induce a particle shower
- **Large background suppression** from steel shielding
- **Extra LLP coverage:**
  - Sensitivity to large lifetimes (> a few meters)
  - Sensitive to LLP energy → 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!

CMS LLP Summary

CMS LLP Summary Plots

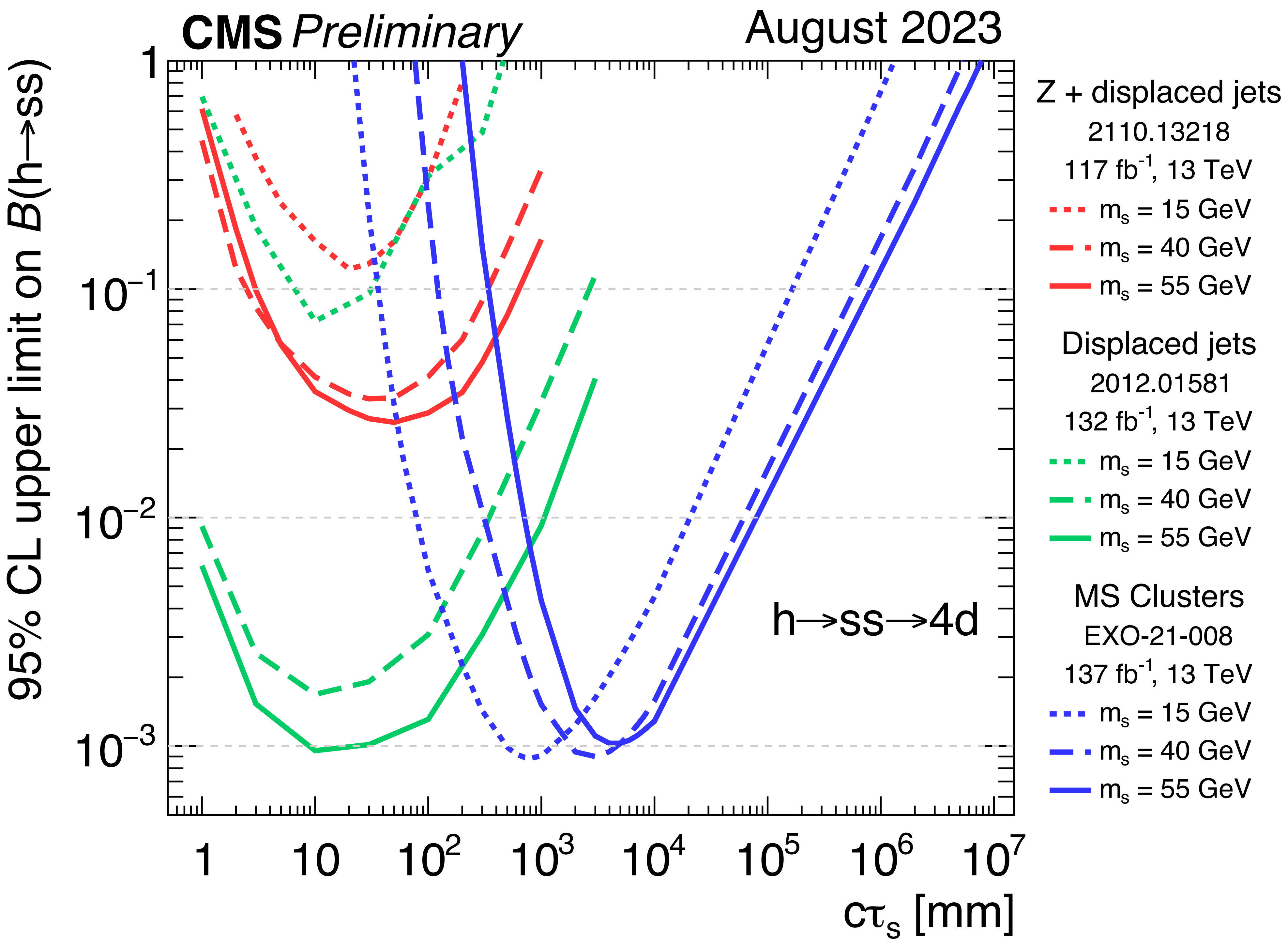
Overview of CMS long-lived particle searches



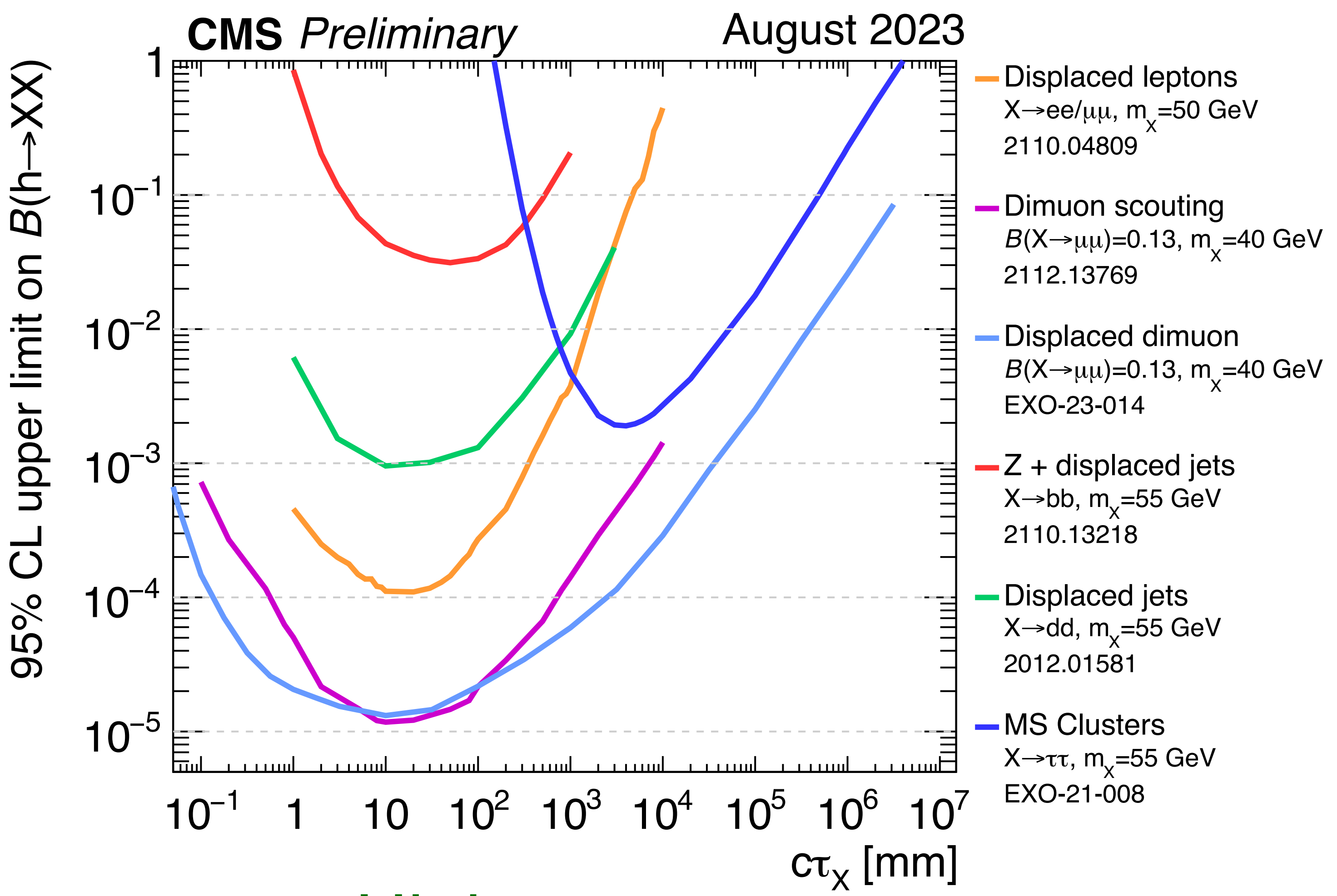
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

CMS Higgs to LLPs Summaries

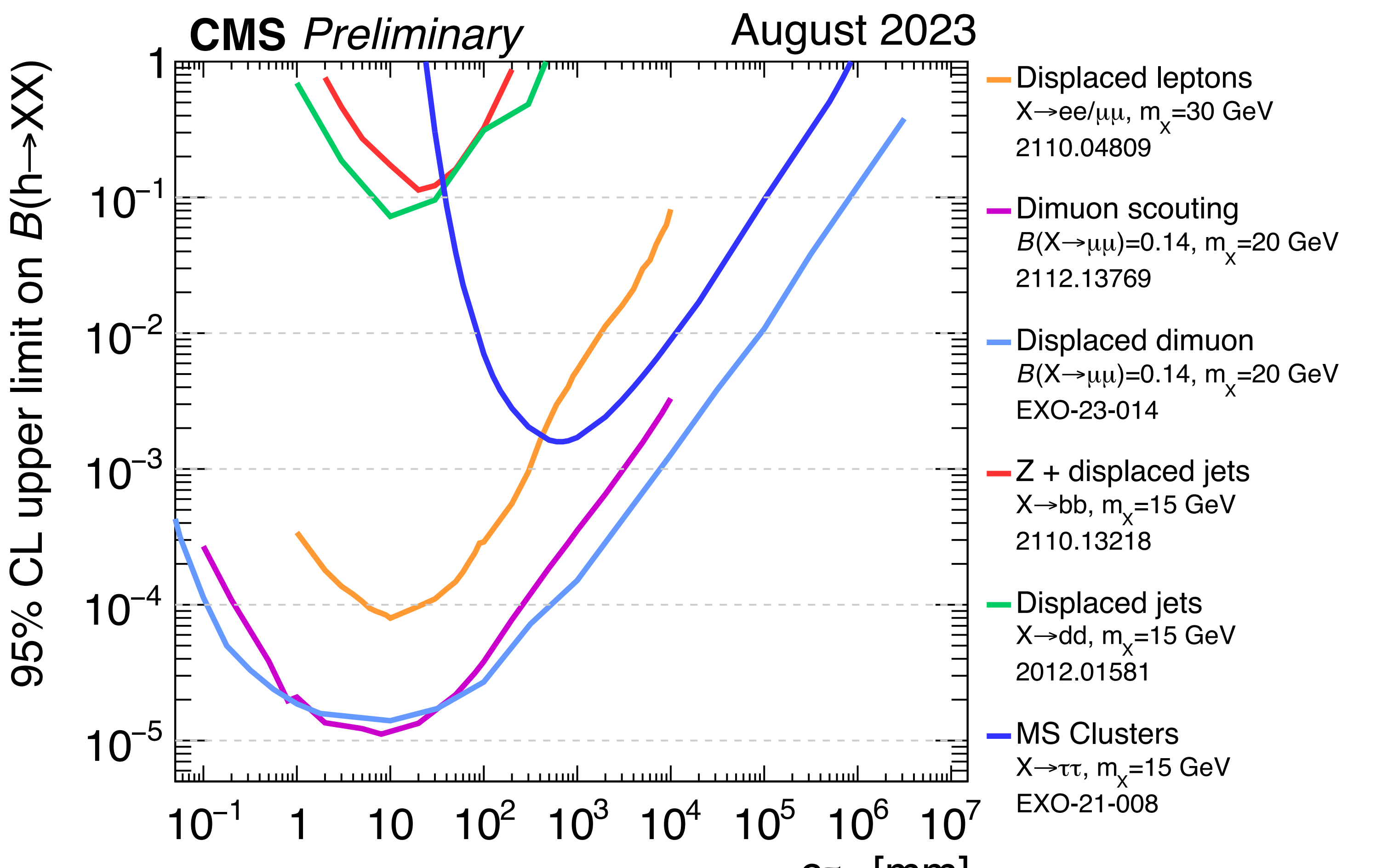
CMS LLP Summary Plots



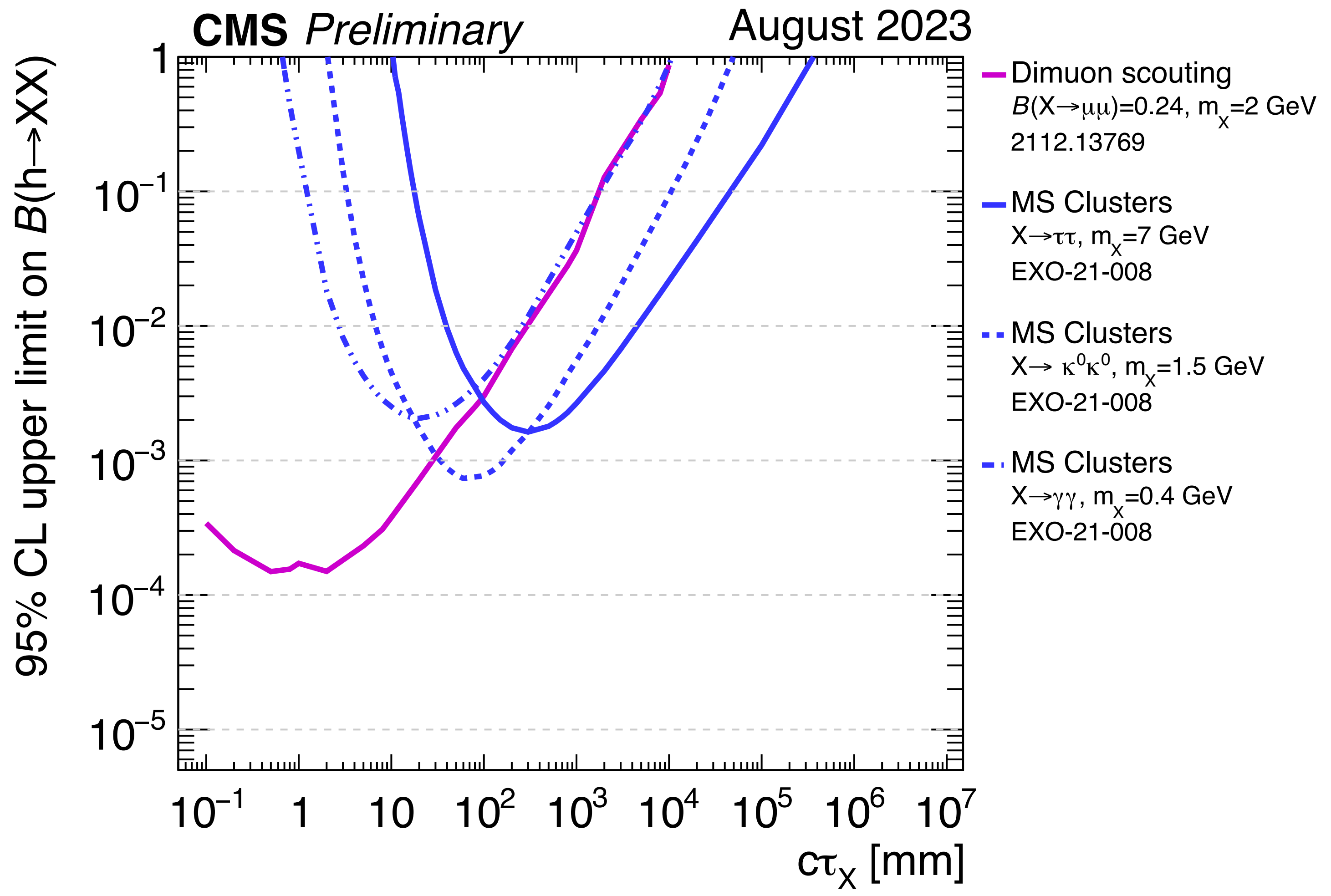
Hadronic-only LLP decays



High mass



Low mass

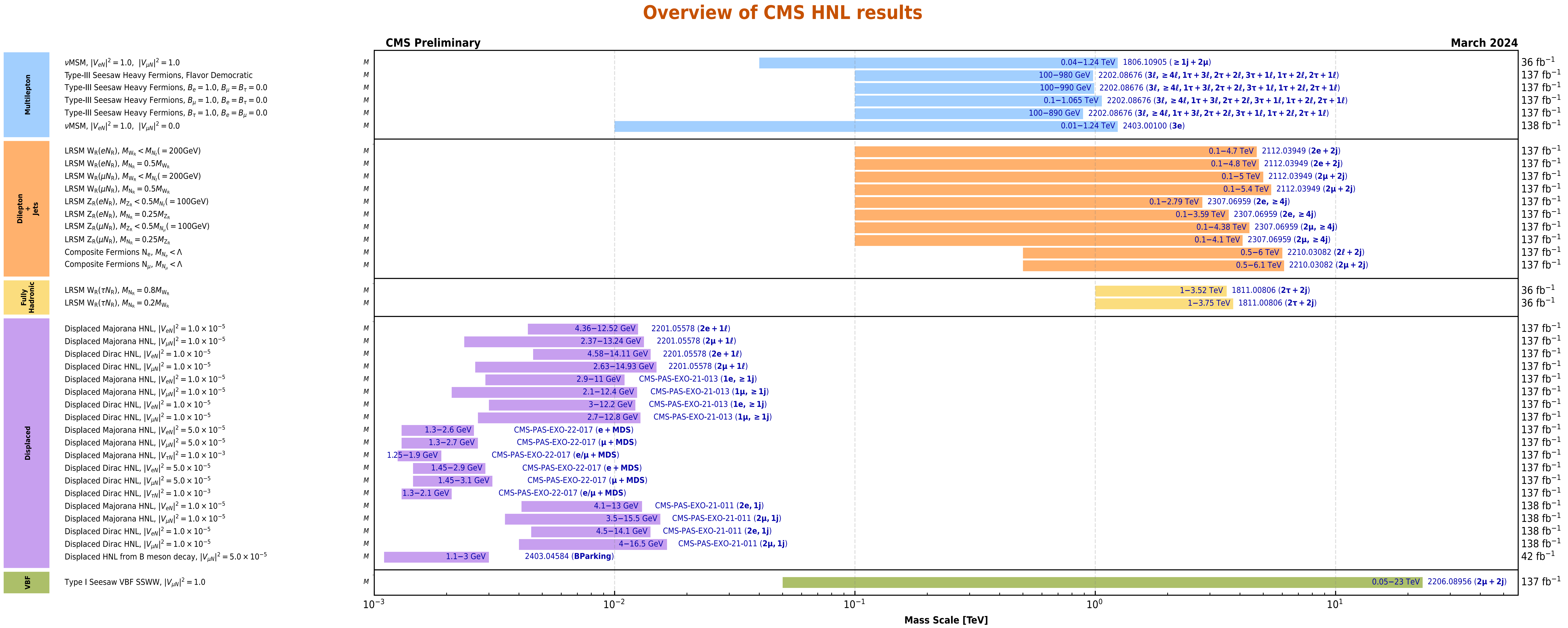


Very-low mass

Note: It does not include Run-3 displaced jets results

CMS HNL Summary

[CMS LLP Summary Plots]



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