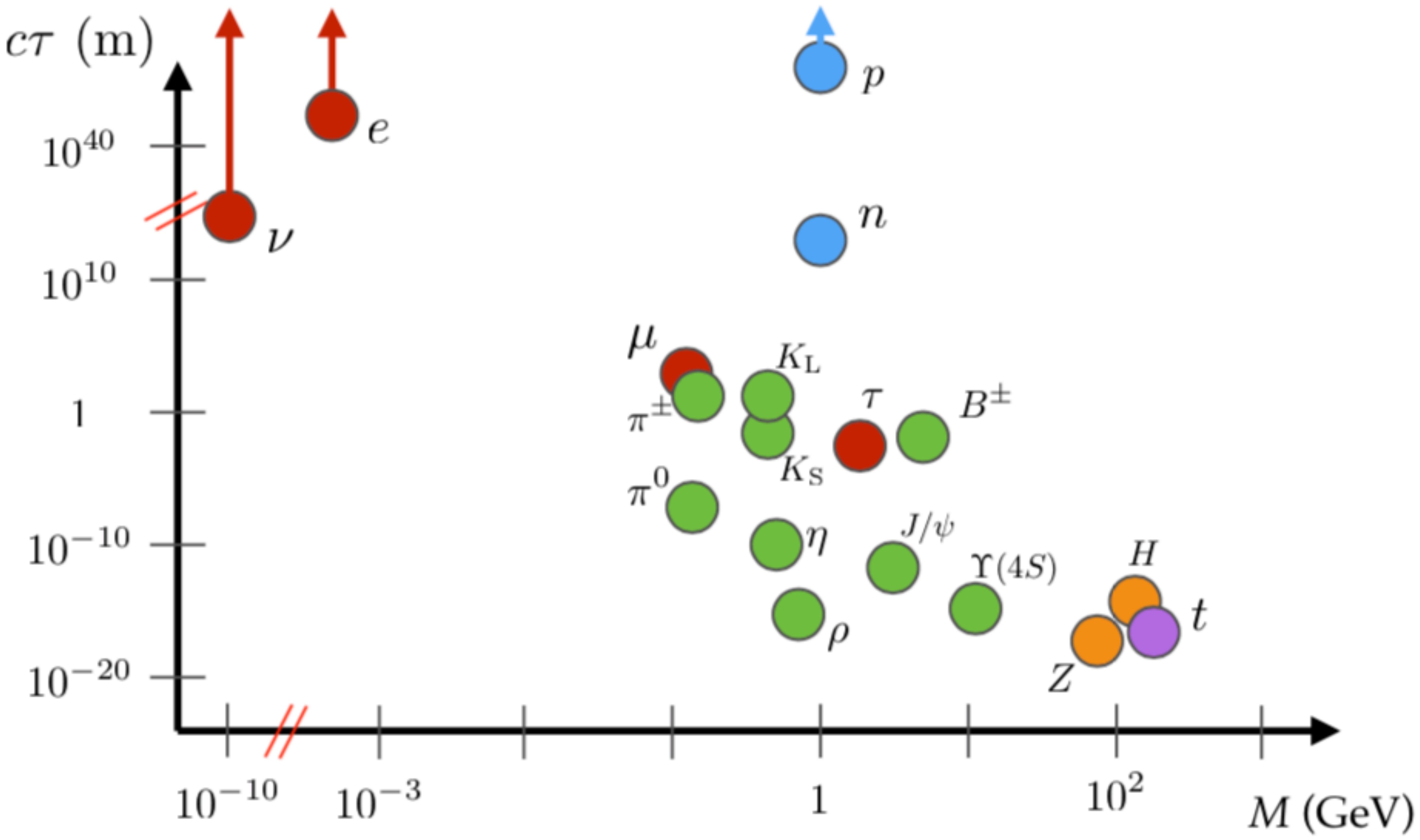
Search for new physics with long-lived and unconventional signatures in CMS

Christina Wang on behalf of the CMS Collaboration

SUSY2023

07/19/2023

Long-Lived Particles



$m \ll \Lambda$: Scale suppression

$$\tau^{-1} = \Gamma \sim y^2 \left(\frac{m}{\Lambda}\right)^n \Phi$$

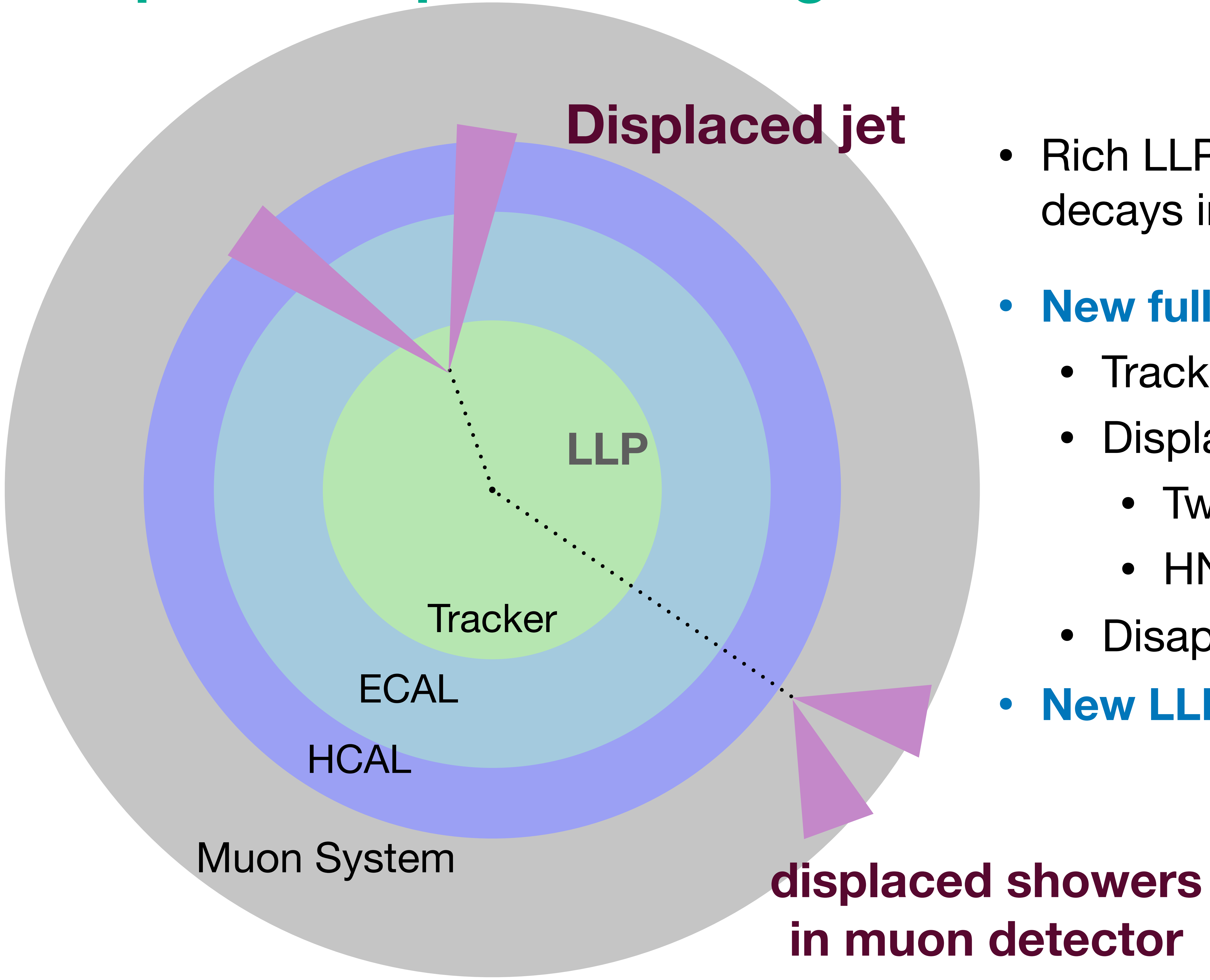
Small coupling

Small phase space

- Long-lived particles are common in SM as well as BSM
- Well motivated and predicted in many BSM models: SUSY, Heavy neutral leptons, Higgs portals …

Long-lived Particle Search @ LHC

Displaced experimental signature

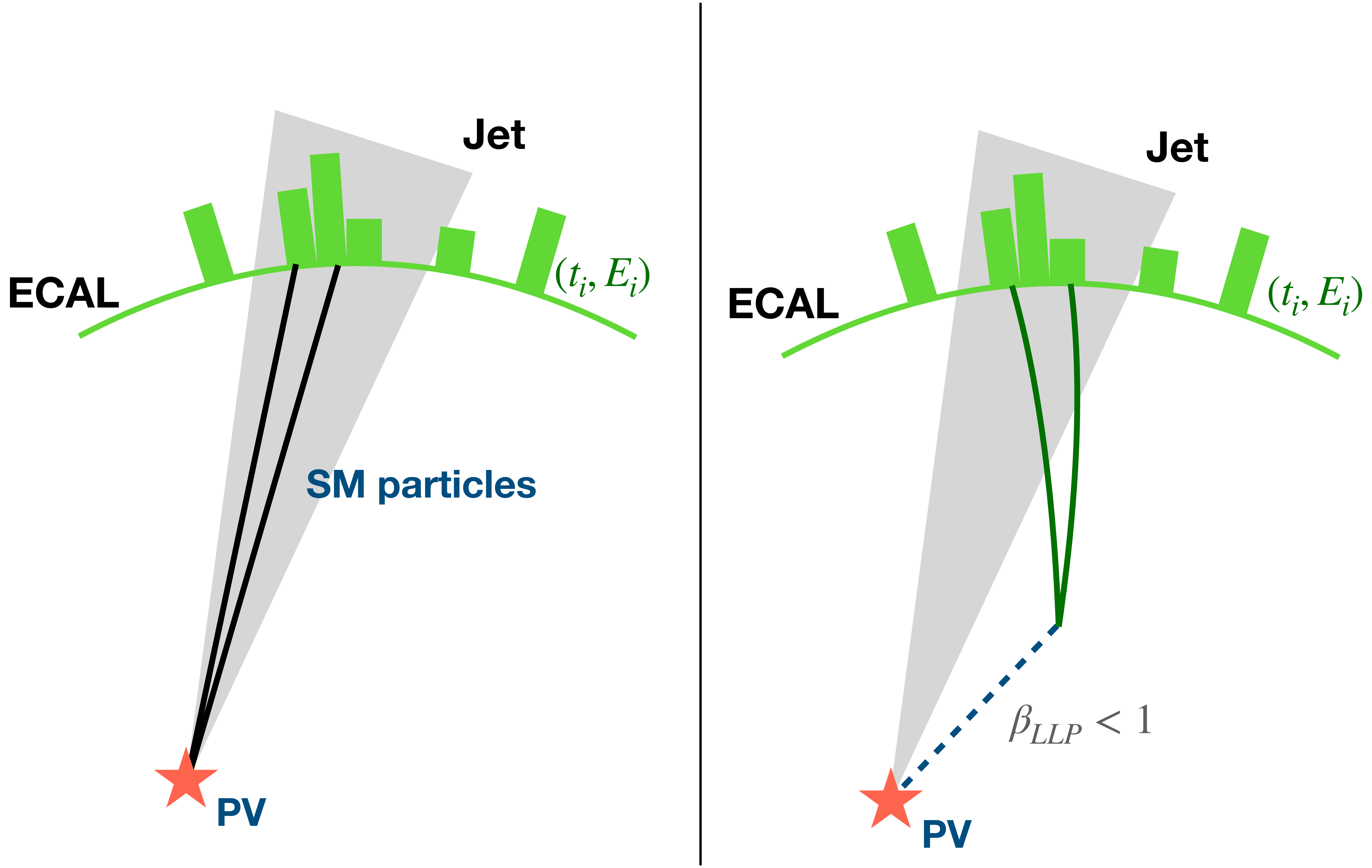


- Rich LLP physics program at CMS using Run 2 data covering LLP decays in different **detector volumes**
- **New full Run 2 results from CMS:**
  - Trackless + delayed jets with ECAL timing
  - Displaced showers in muon detectors **New!**
    - Twin Higgs with MET (EXO-21-008)
    - HNL with single lepton (EXO-22-017)
  - Disappearing tracks → covered in Samuel Bein's talk on Friday
- **New LLP triggers in Run 3 extending the discovery reach of CMS**

New!

arXiv: 2212.06695

Delayed + Trackless Jet with ECAL



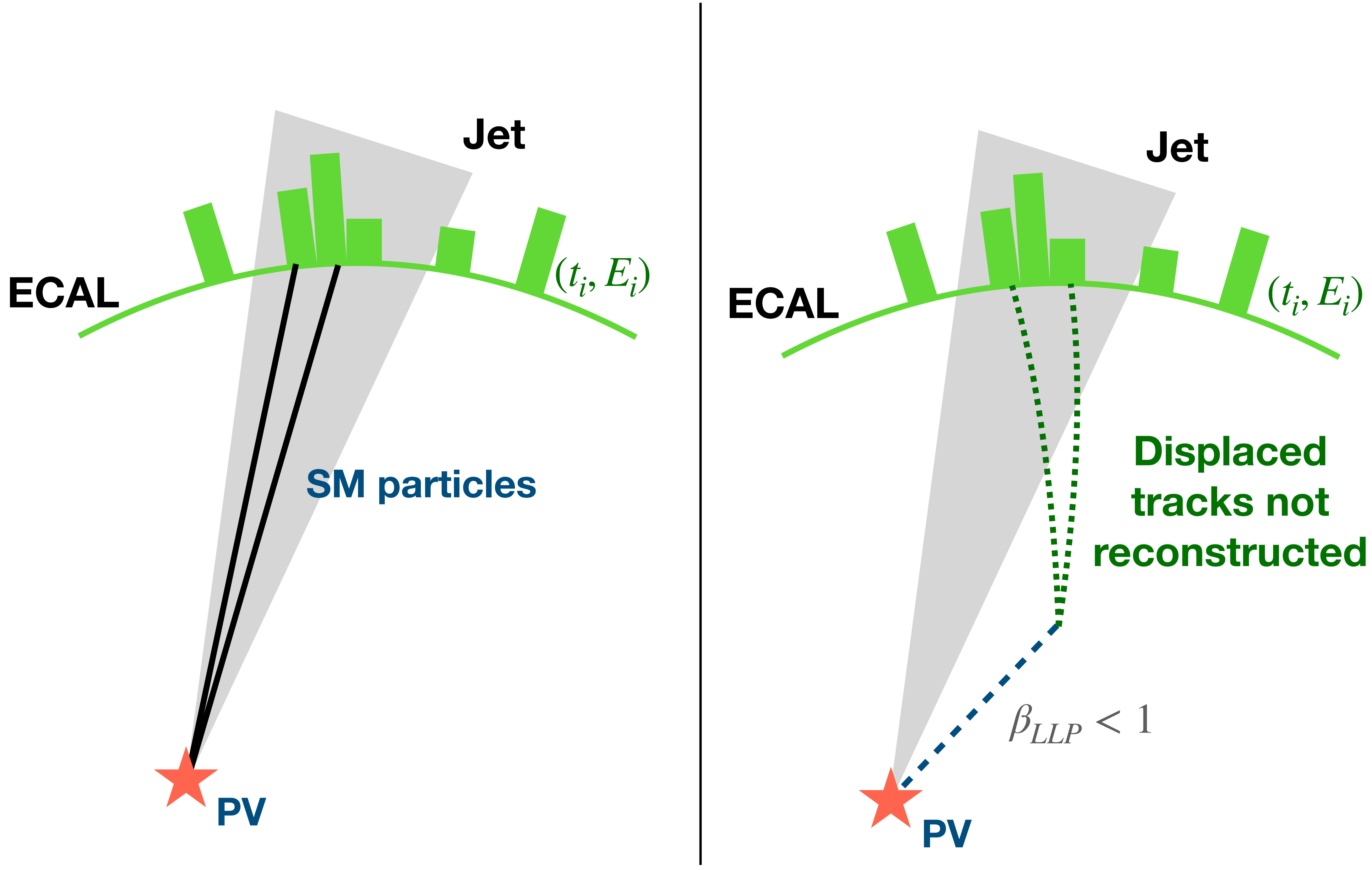
Background-like prompt jet

Signal-like delayed+trackless jet

- Jets are delayed (ECAL timing):
  - Longer path length
  - Heavy long-lived particles
- Jets are trackless:
  - No tracks pointing in the same direction as jet

arXiv: 2212.06695

Delayed + Trackless Jet with ECAL



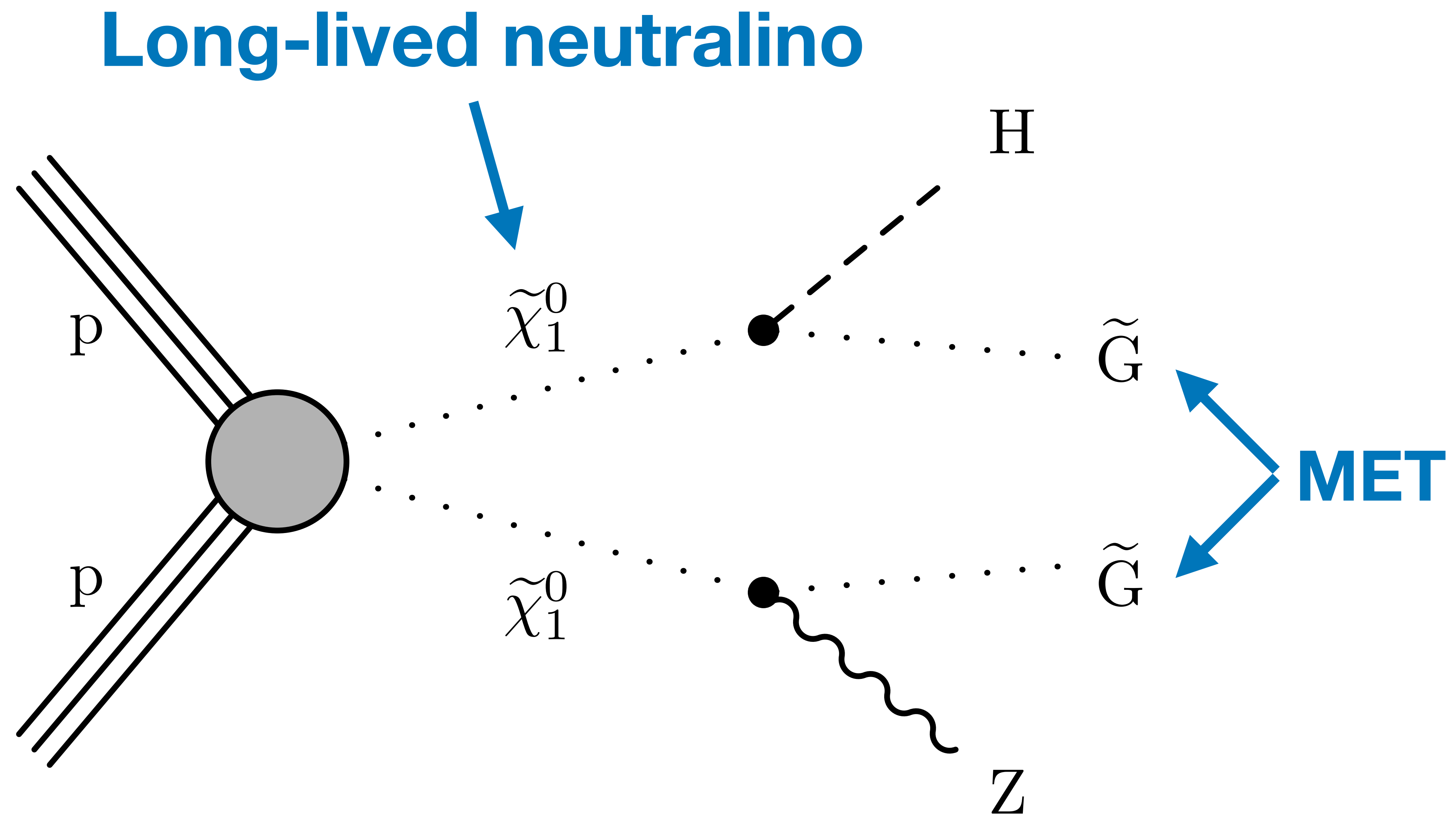
Background-like prompt jet **Signal-like delayed+trackless jet**

- Jets are delayed (ECAL timing):
  - Longer path length
  - Heavy long-lived particles
- Jets are trackless:
  - No tracks pointing in the same direction as jet

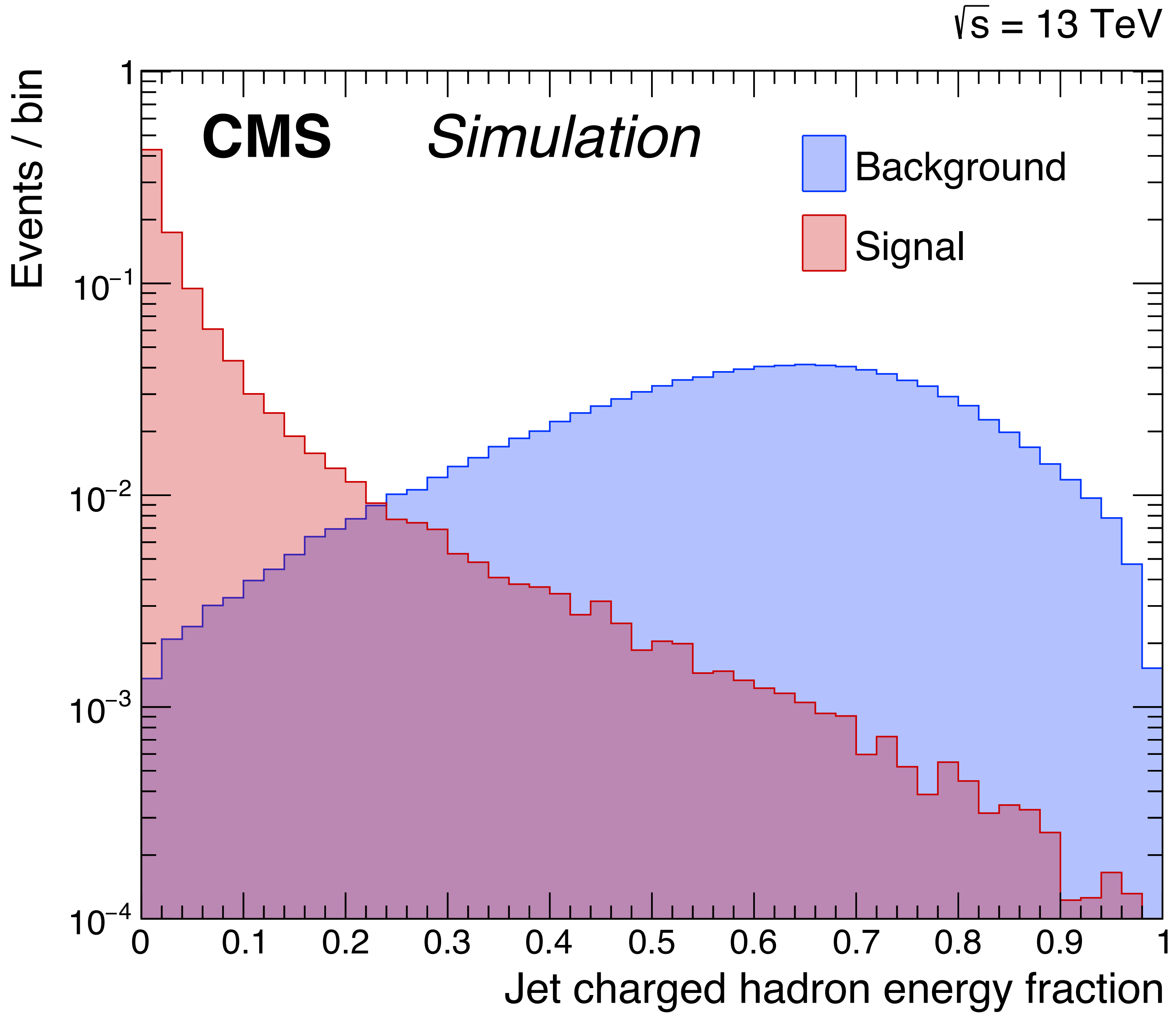
Delayed + Trackless Jet with ECAL

arXiv: 2212.06695

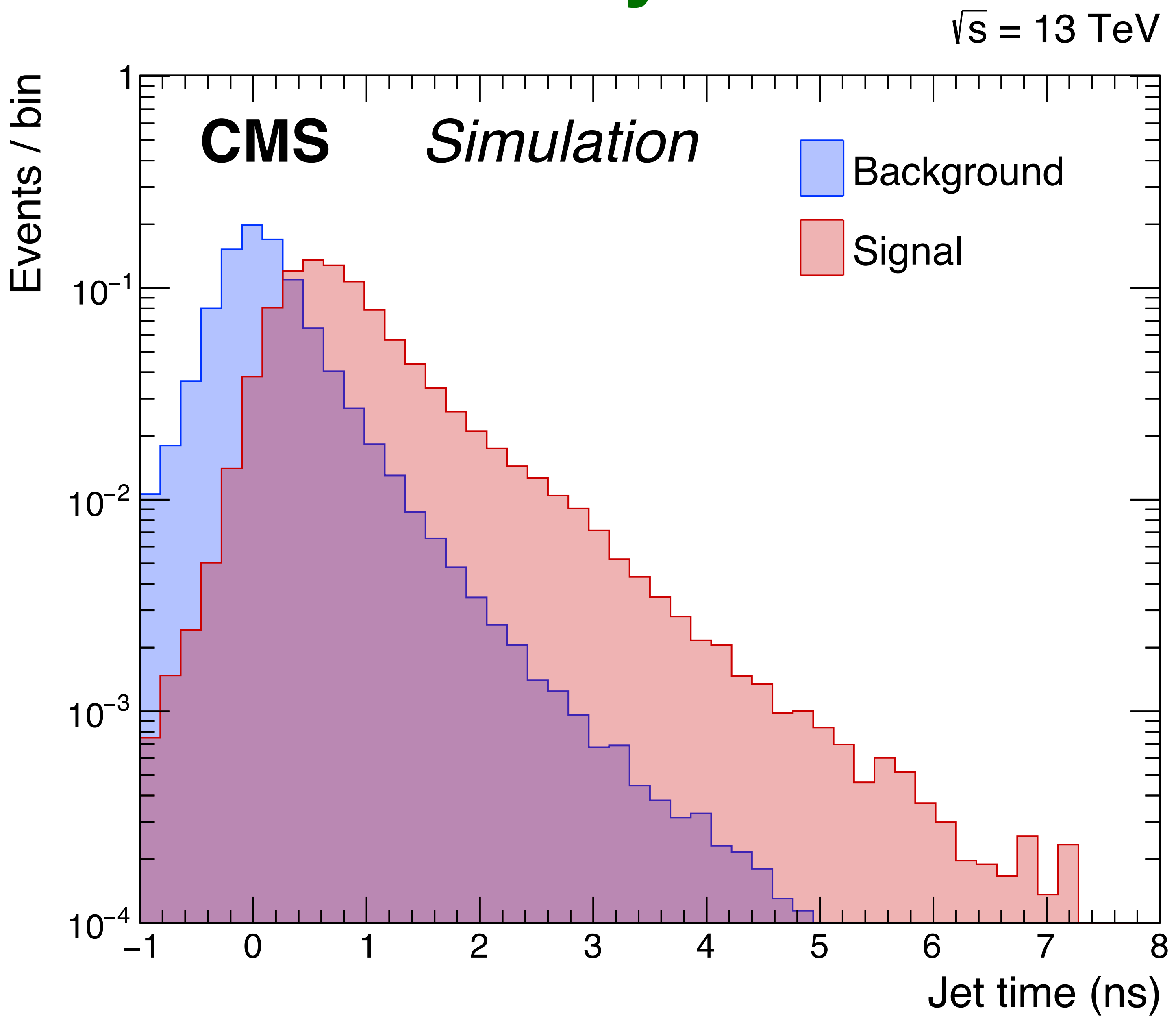
- Search for hadronic decays of LLPs using MET + delayed and trackless jets
- **Dedicated DNN jet tagger using ECAL time and trackless variables**
  - 82% signal efficiency with 1e4 background rejection
  - Significantly improves reach to lighter LLPs compared to previous analysis



Trackless



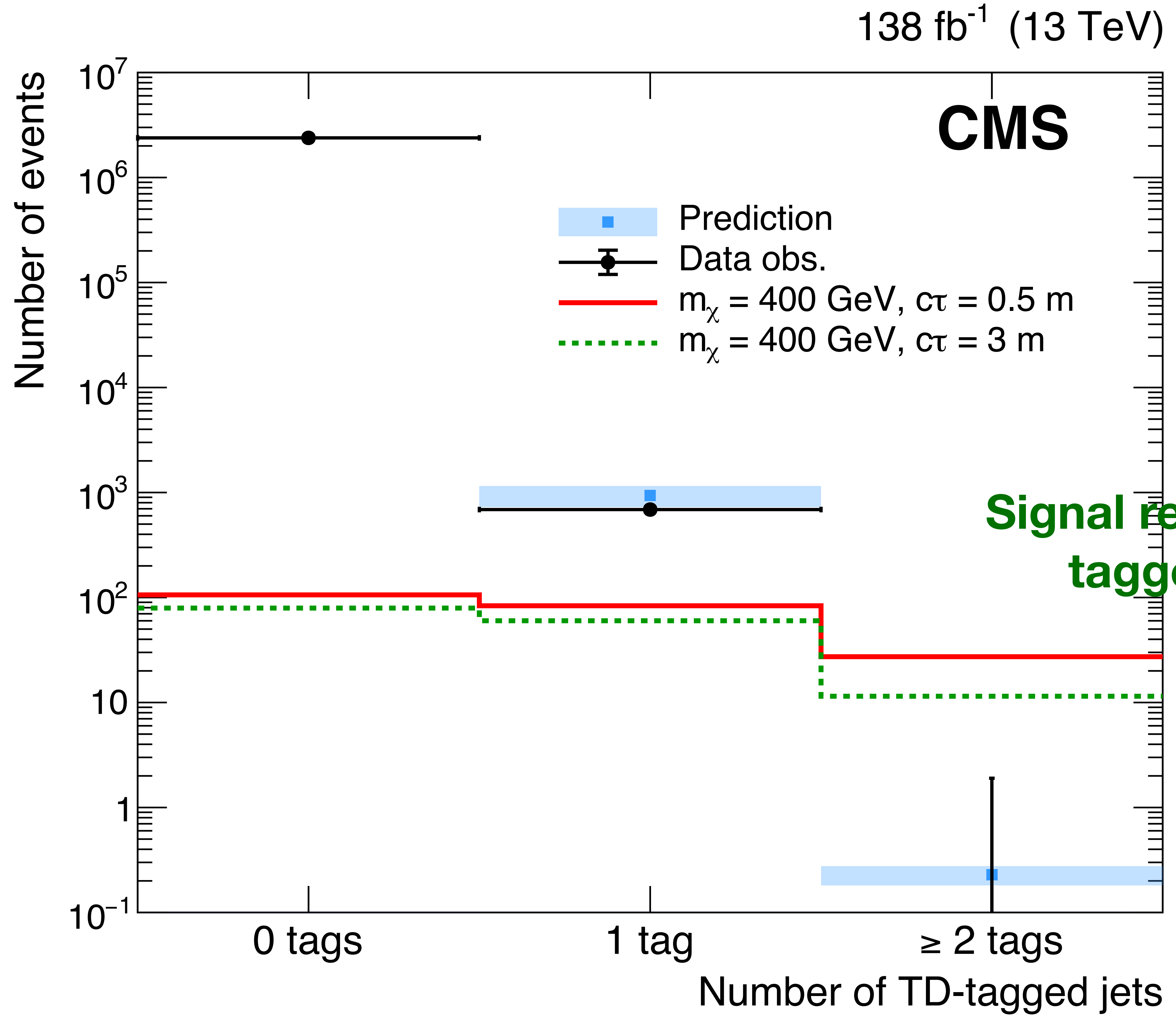
Delayed



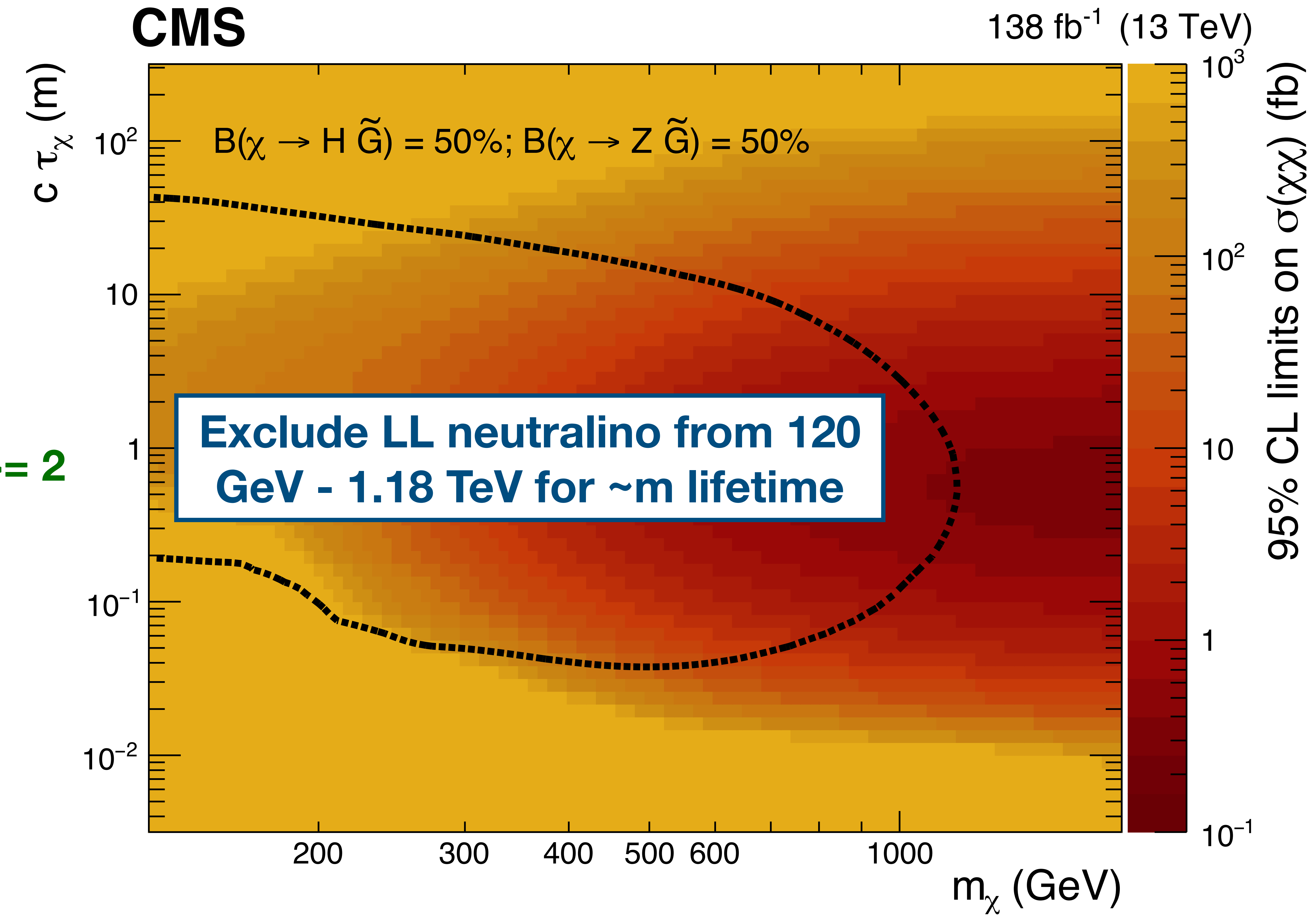
Delayed + Trackless Jet with ECAL

arXiv: 2212.06695

- Estimate background using mistag rate measured in lepton + jet control region
- Exclude LL neutralino from 120 GeV - 1.18 TeV for ~m lifetime

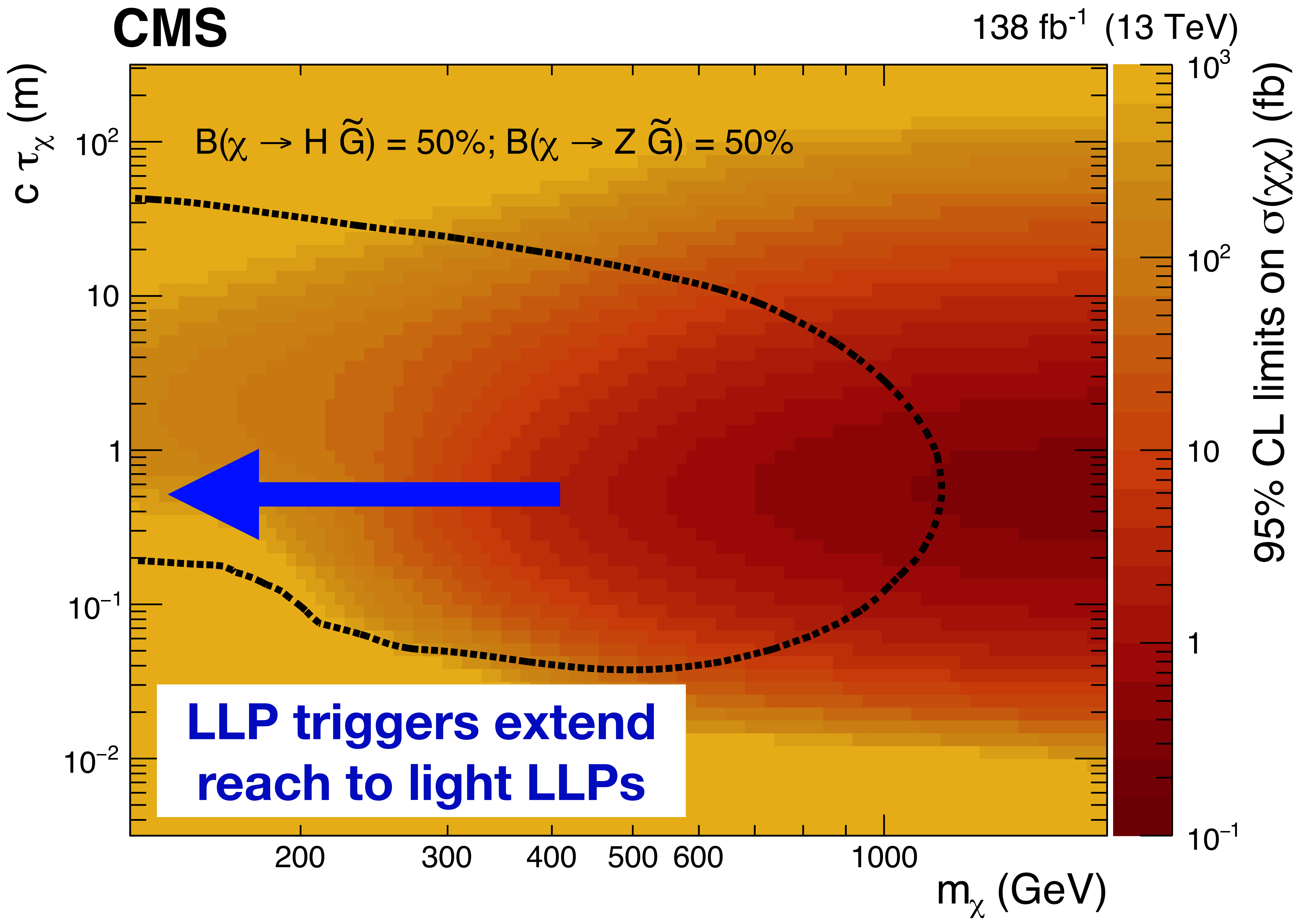


Signal region: >= 2 tagged jets

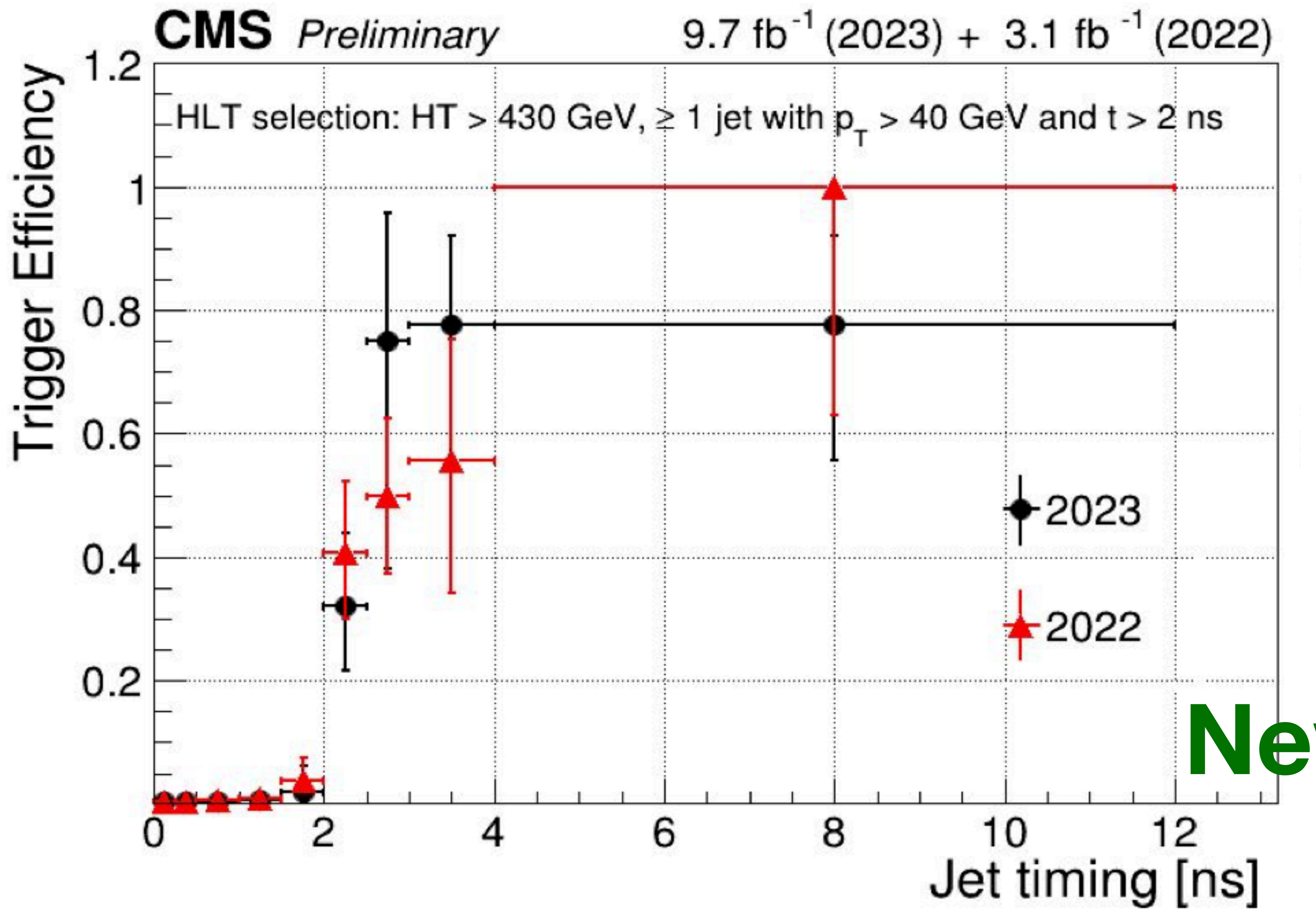


Run3: Delayed + Trackless Jet with ECAL Timing

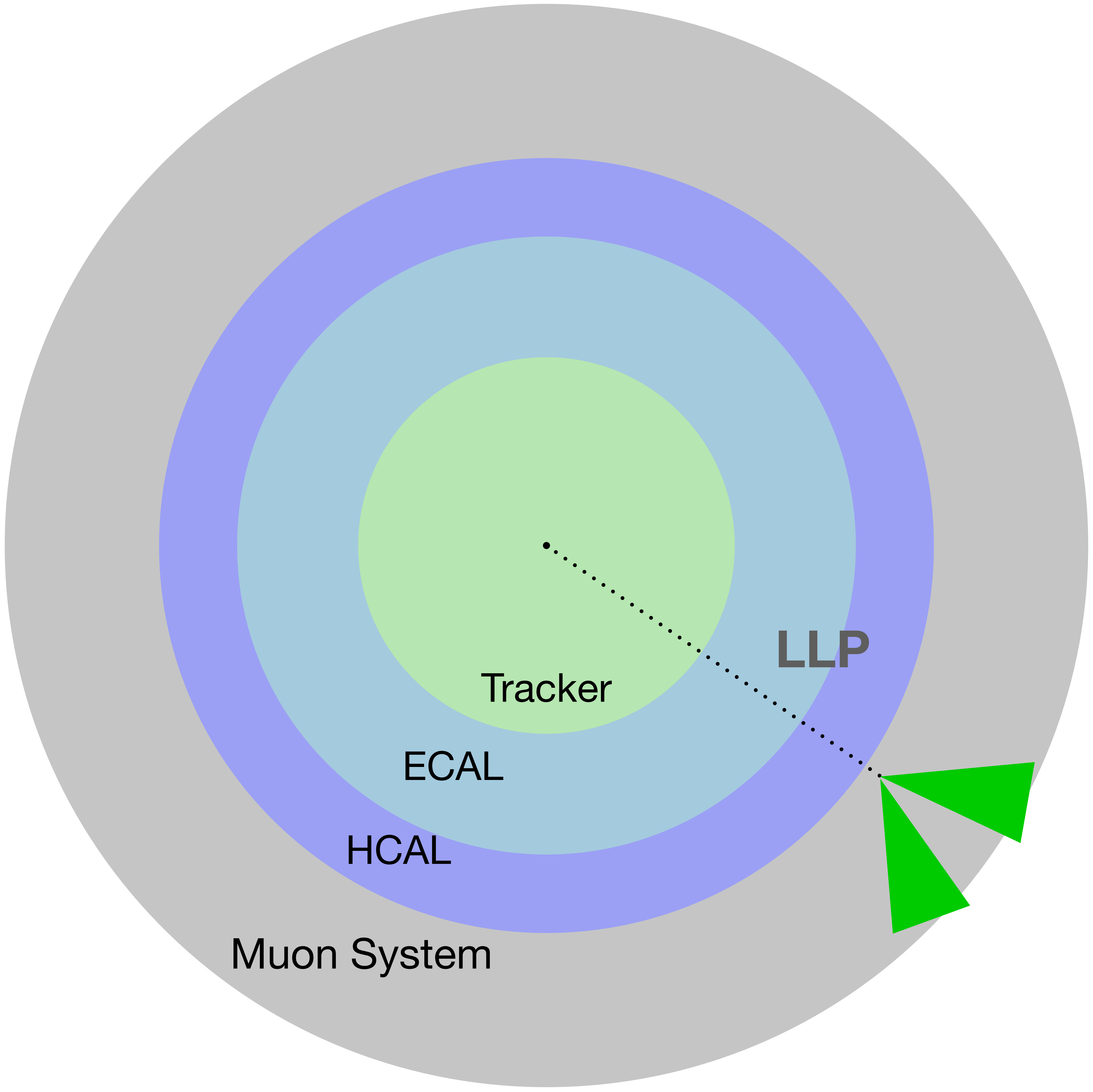
- Run 2 analysis limited by the MET trigger: limited sensitivity to low mass mediators
- New suite of HLT paths in Run 3 using ECAL timing would enable sensitivity to new models and allow access to delayed jets from <100 GeV LLPs



High trigger efficiency for delayed jets



New!

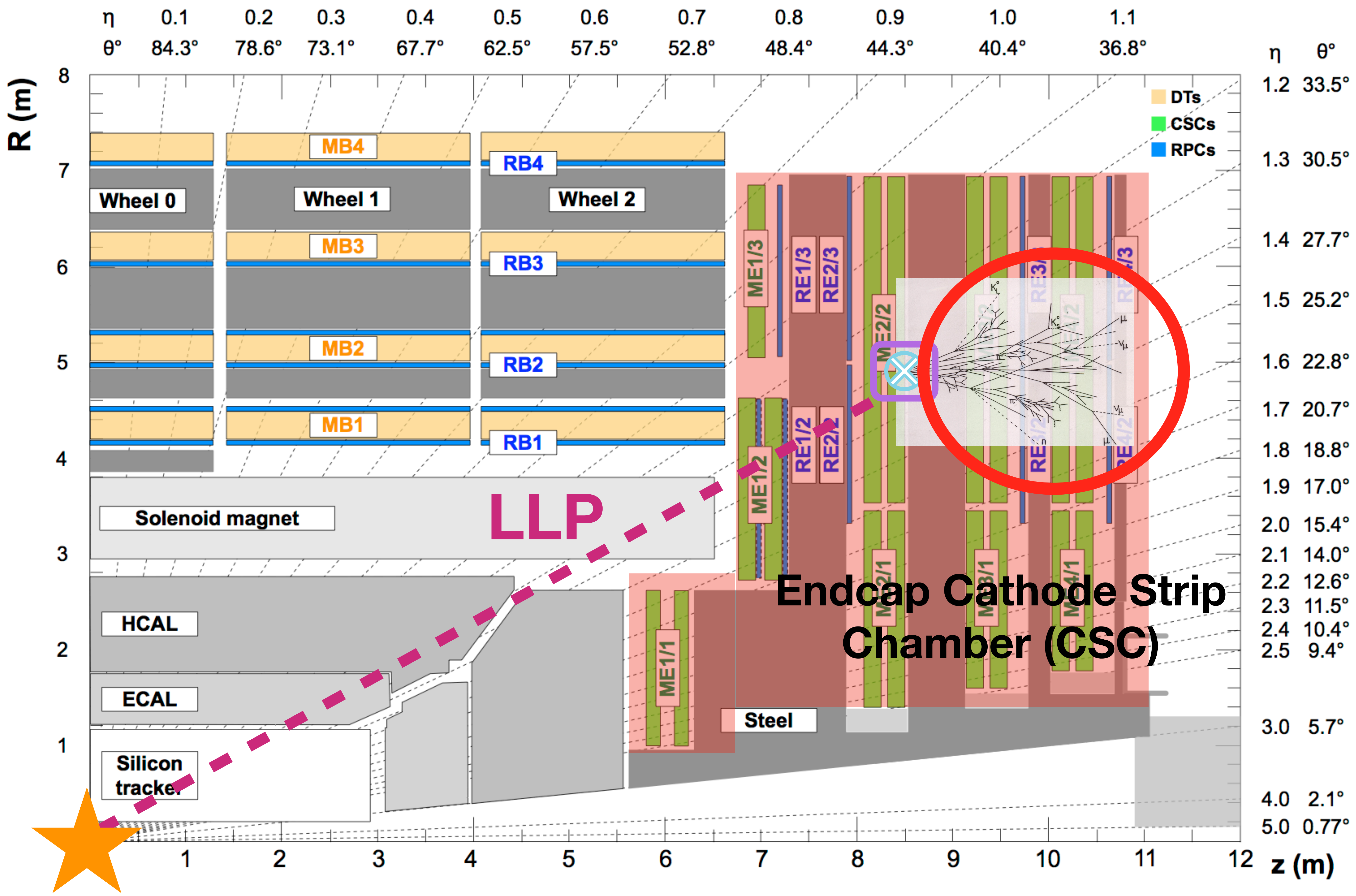


Muon Detector Showers

- Twin Higgs with high MET (EXO-21-008)
- HNL with single lepton (EXO-22-017)

Displaced Showers in the CMS Muon System

PAS-EXO-21-008
PAS-EXO-22-017



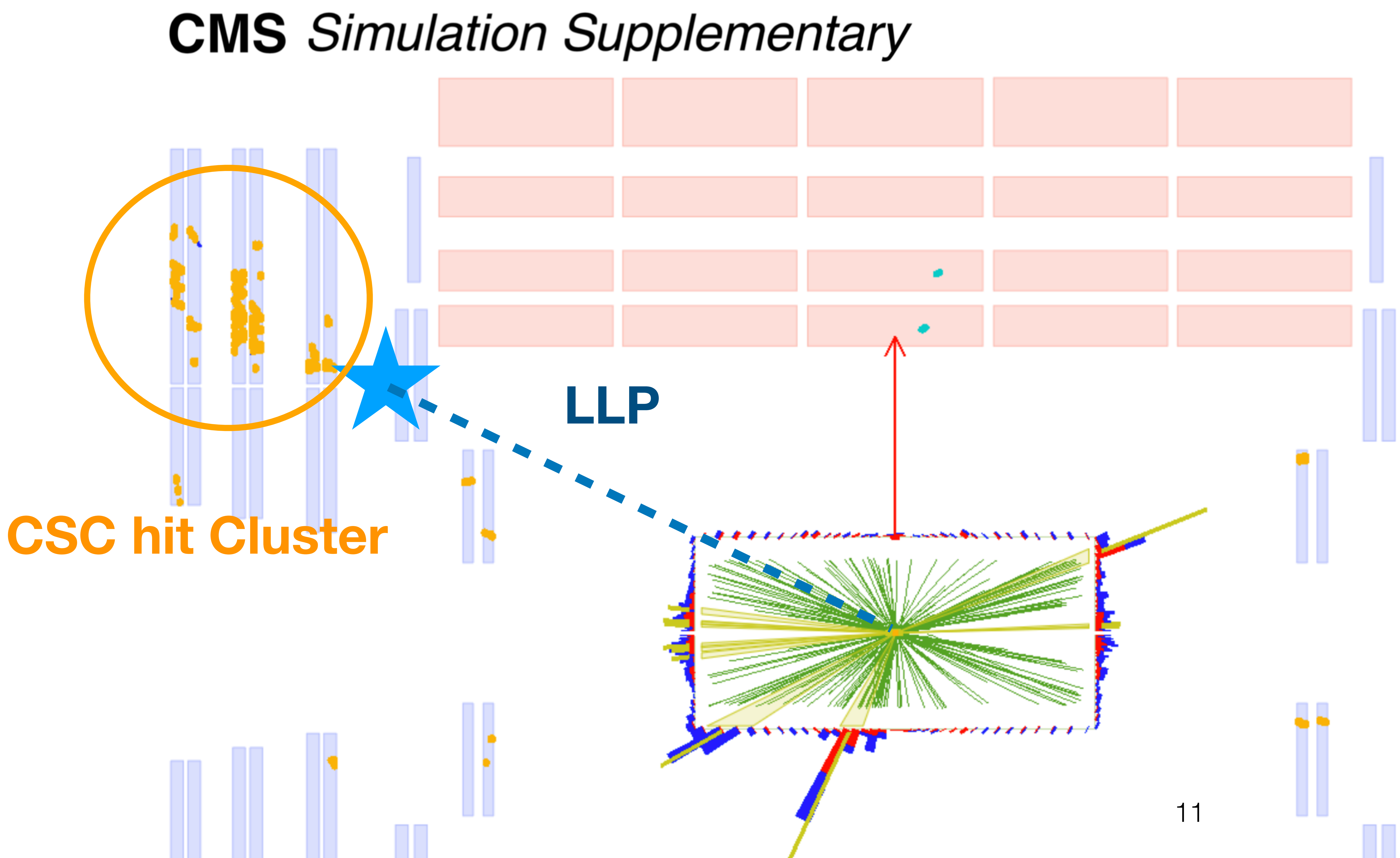
LLP decay and resulting particle shower is detected with a **large hit multiplicity**

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

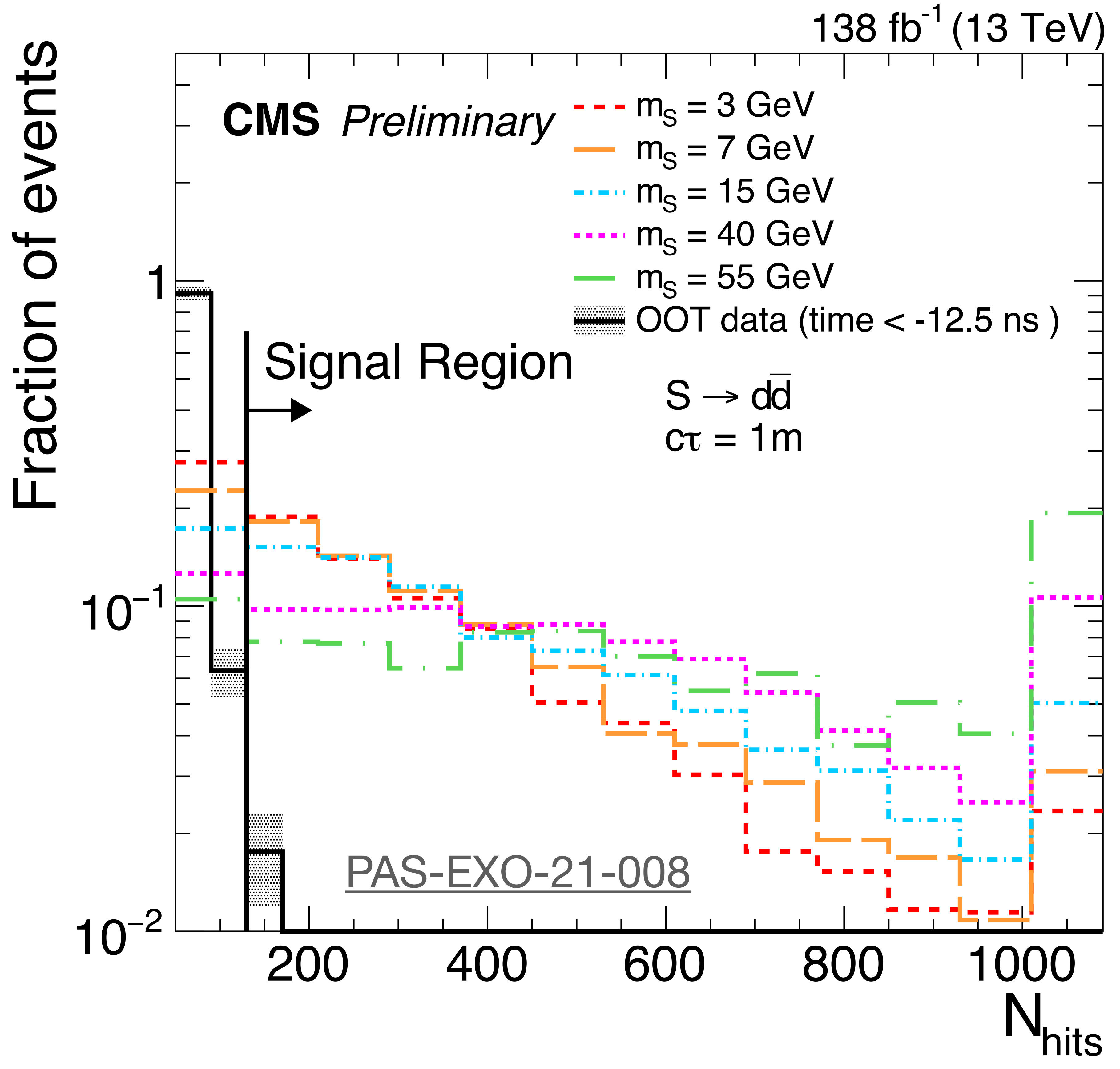
Displaced Showers in the CMS Muon System

PAS-EXO-21-008
PAS-EXO-22-017

- Muon system acts as a **sampling calorimeter:** sensitive to a broad range of decays: quarks, taus, pions, kaons, electrons, photons…
- Search for **displaced shower with high multiplicity** isolated from jets and muons
- Due to the shielding and the exotic signature, this analysis can be sensitive to **very light LLPs** (m_{LLP} < 1 GeV)



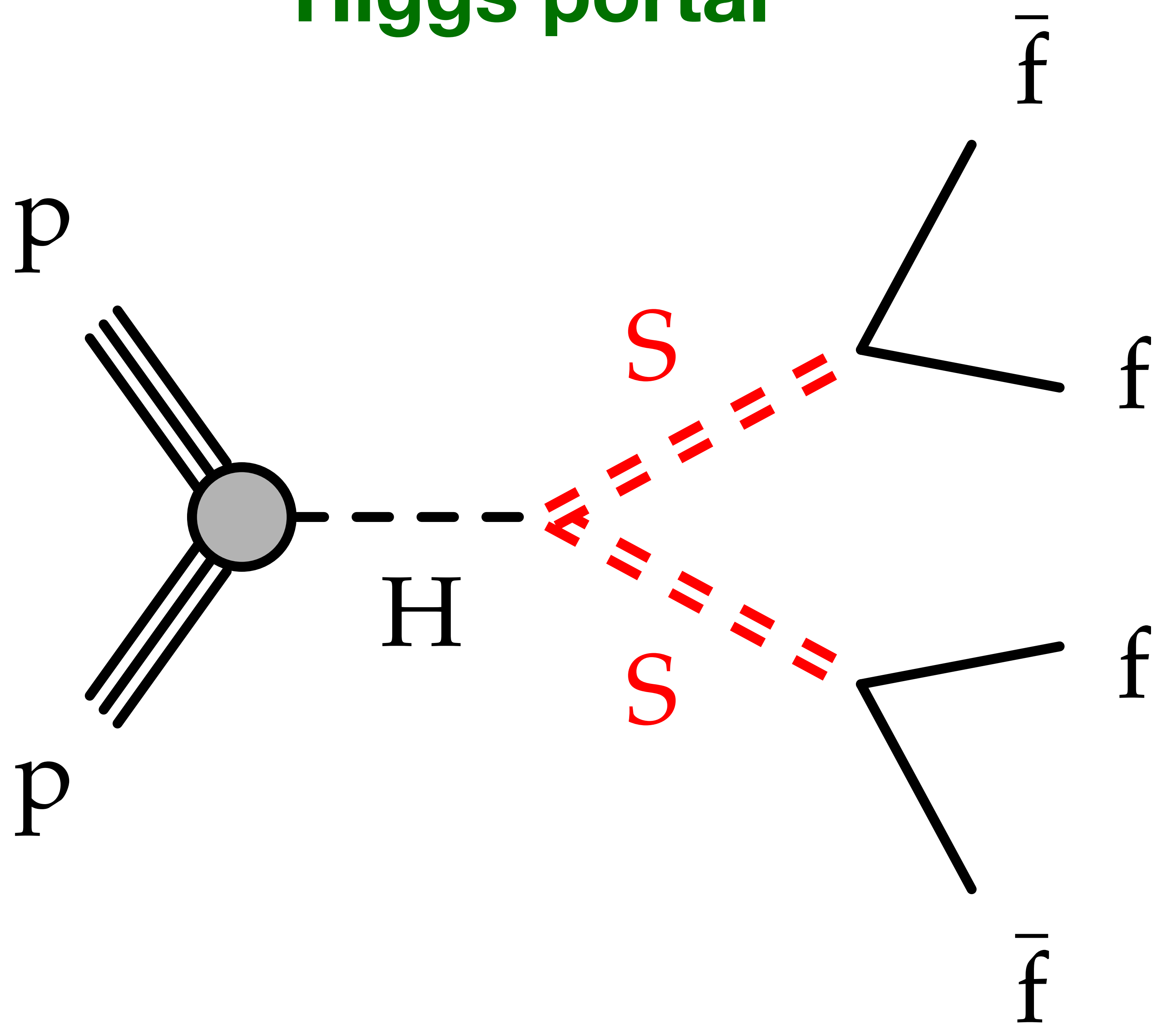
N_{hits} as main discriminator for both analyses



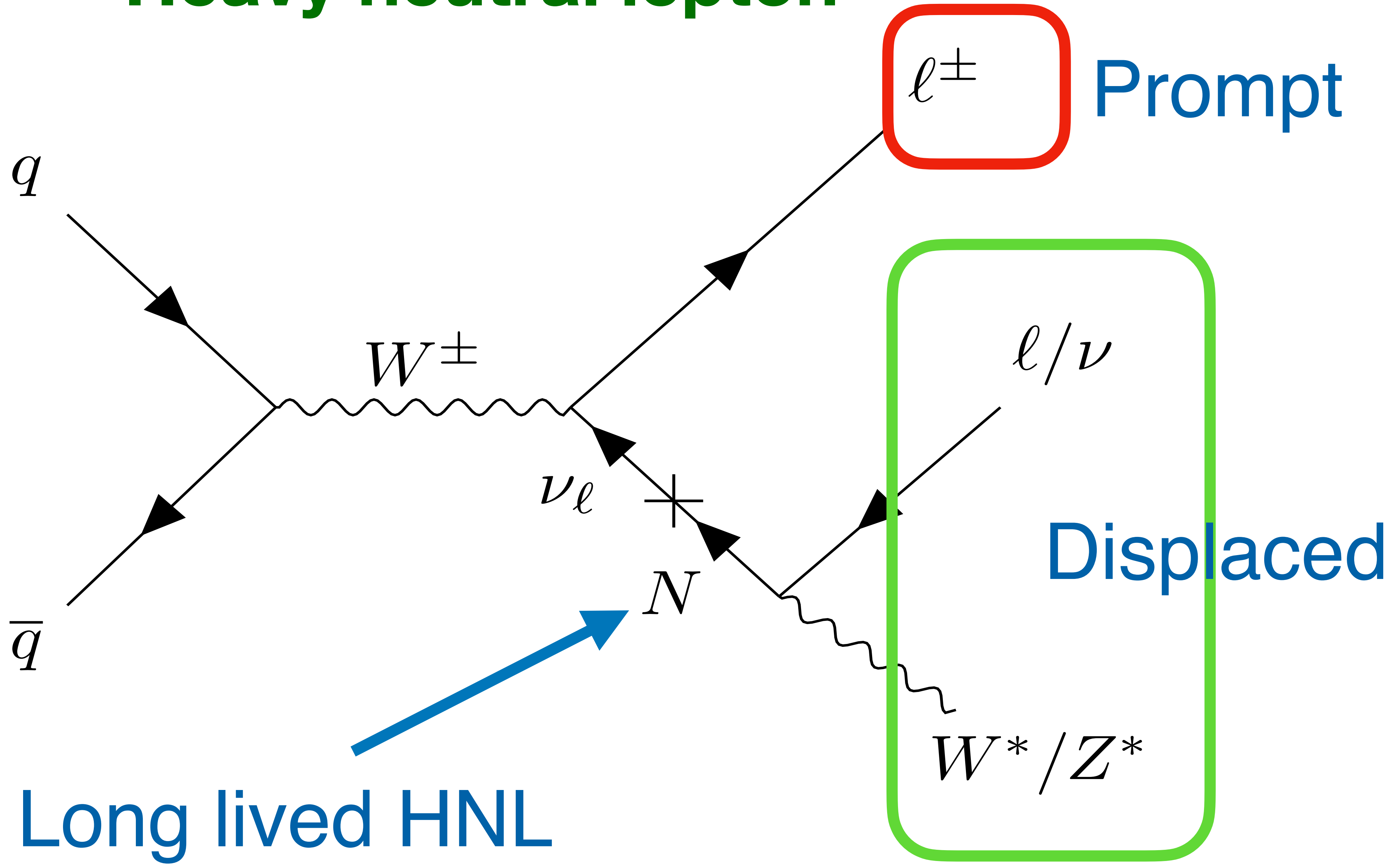
Muon System Analysis Trigger Strategy

- **Due to the lack of dedicated trigger, use separate triggers to target different models**
  - Target Higgs portal models with MET trigger (PAS-EXO-21-008)
    - MET comes from recoiling with an energetic jet, selecting for boosted Higgs phase space
  - Target Heavy neutral leptons with single lepton triggers (PAS-EXO-22-017)
    - Trigger on the prompt muon or electron produced with HNL

Higgs portal



Heavy neutral lepton

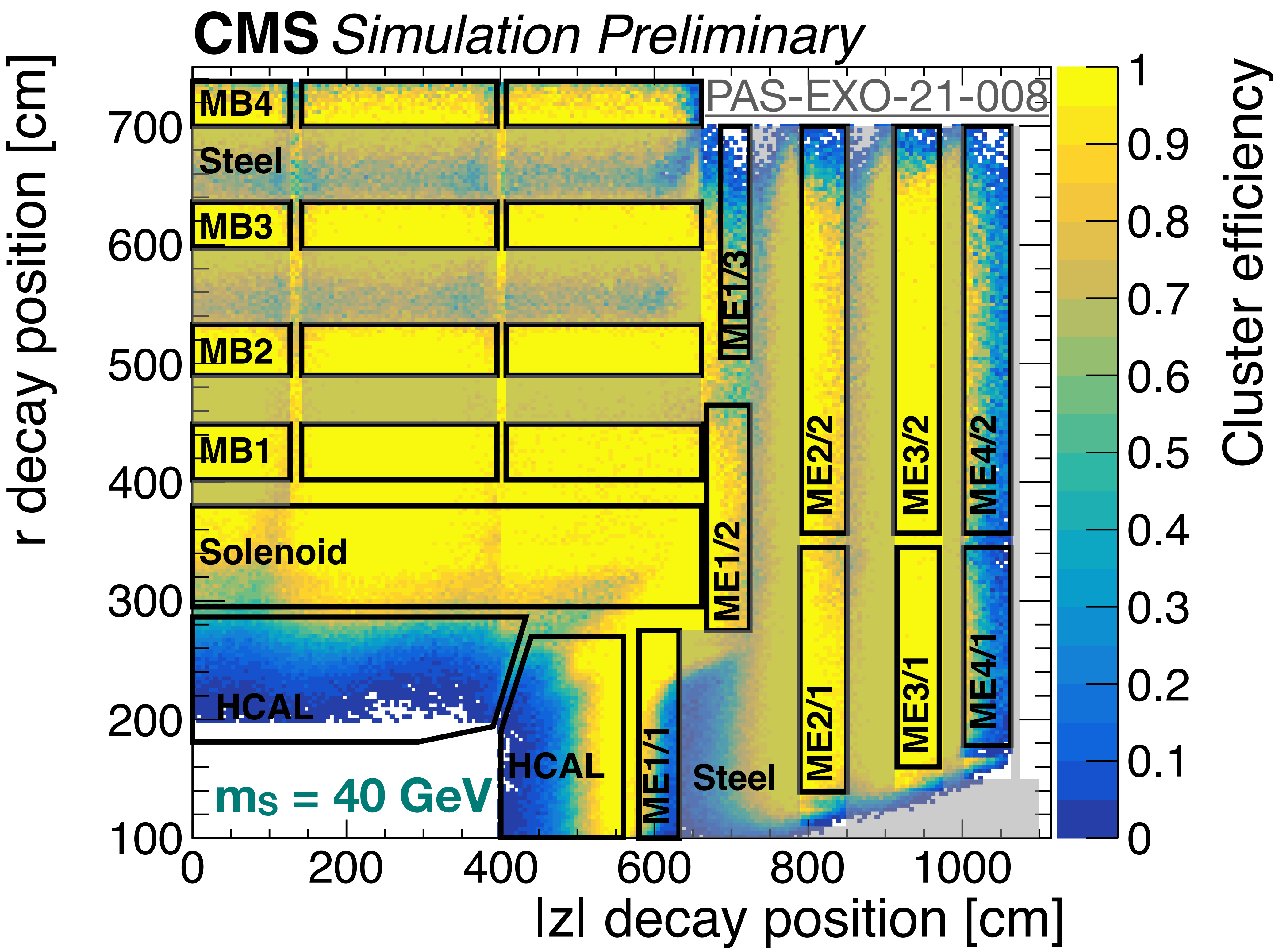


[PAS-EXO-21-008](#)
[PAS-EXO-22-017](#)

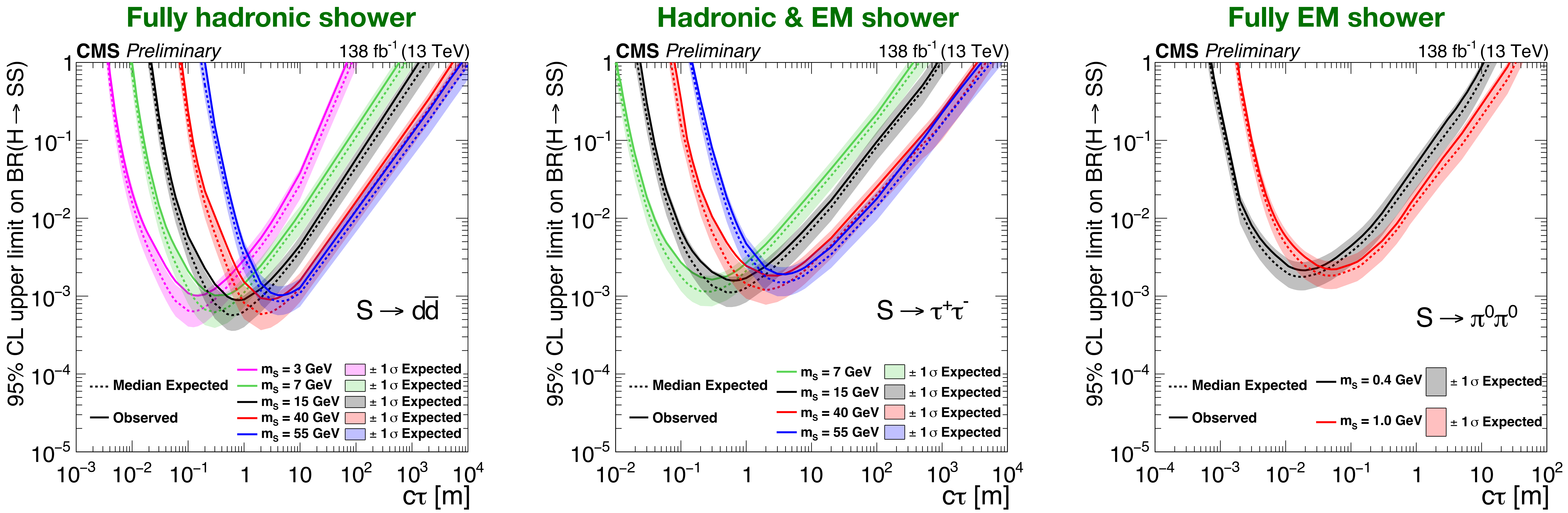
Muon System Analysis Strategy

- Reconstruct muon detector clusters with CSC/DT hits
- Use **cluster ID** selections to enhance signal purity and reject background from main collision (overall background rejection ~10^6)
  - 3 categories twin Higgs: single cluster in barrel, single cluster in endcap, double clusters
  - 2 categories for HNL analysis, due to singly-produced HNL
- **N_{hits} is the main discriminator for both analyses**

High cluster reconstruction efficiency



Limits on twin Higgs model



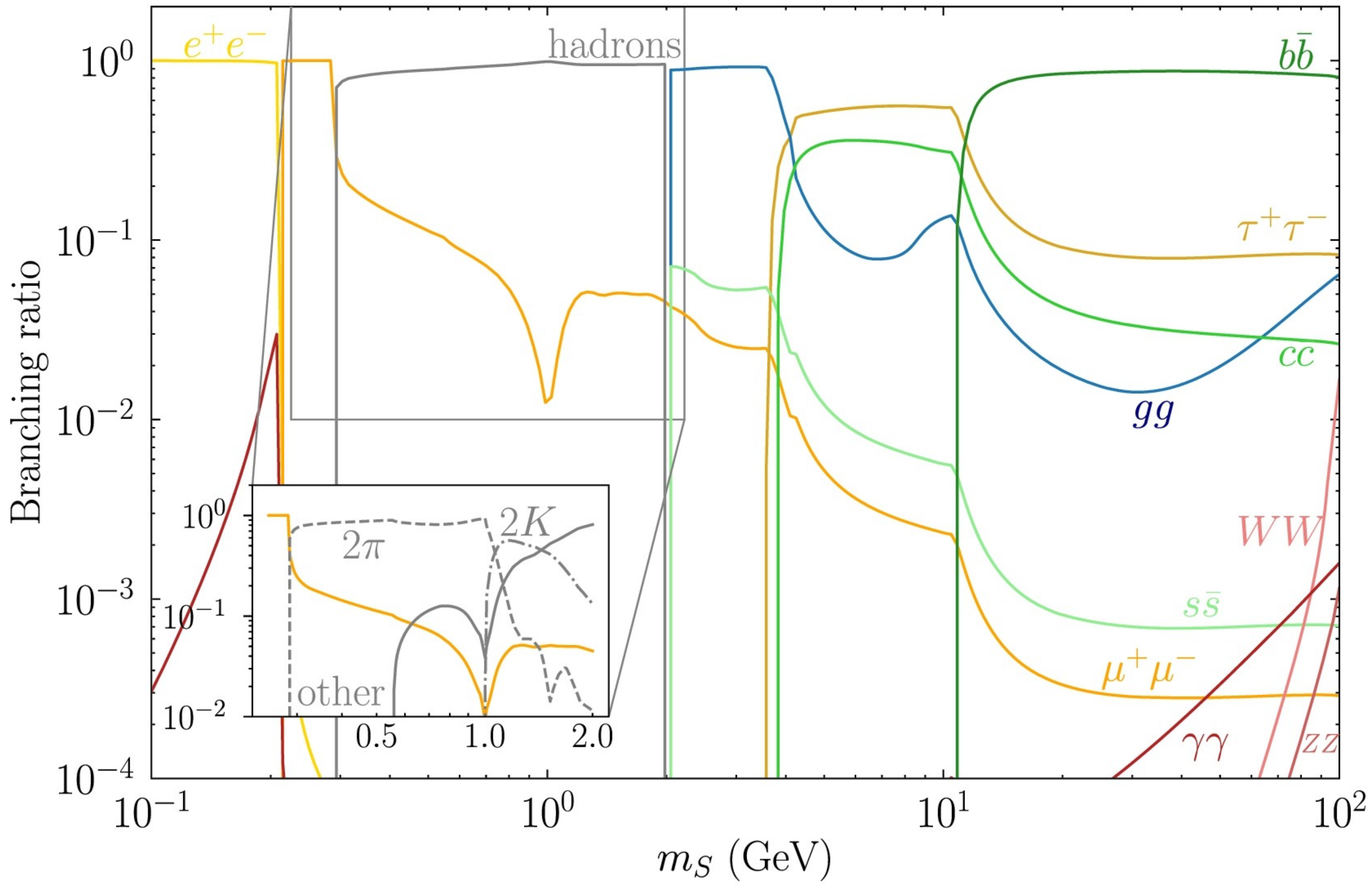
- No excess above SM background observed
- Interpret the search result in different decay modes with hadronic shower ($d\bar{d}$), EM shower ($\pi^0\pi^0$), or both ($\tau^+\tau^-$)
  - Better sensitivity for hadronic showers due to higher cluster reconstruction efficiency
- Analysis sensitivity is **independent of masses**
- Achieve first LHC sensitivity to **sub-GeV mass LLPs** at BR(H →ss) = 10^{-3} level

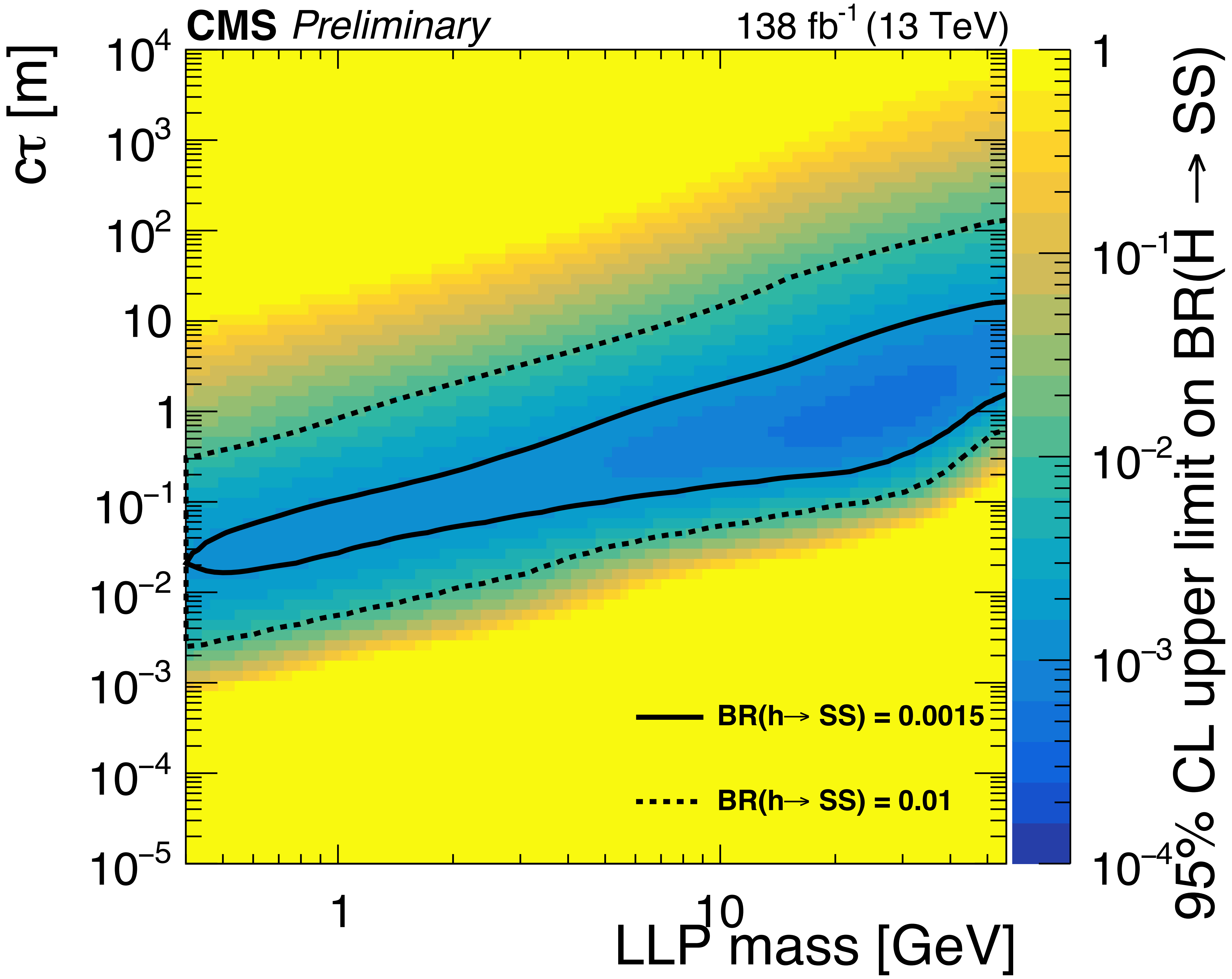
Limits on twin Higgs Model

- Show limits as a function of both LLP mass and lifetime incorporating the BR inherited from the Higgs
- The limit improves at higher masses, due to larger branching fractions for decays to hadronic showers
- Significant extension and improvement to the previous endcap-only analysis (EXO-20-015)
- Working on providing reinterpretation materials for the barrel muon detector clusters

Due to mixing between S and the Higgs boson, S inherits all the coupling of the Higgs evaluated at m_S

https://arxiv.org/pdf/2012.07864.pdf

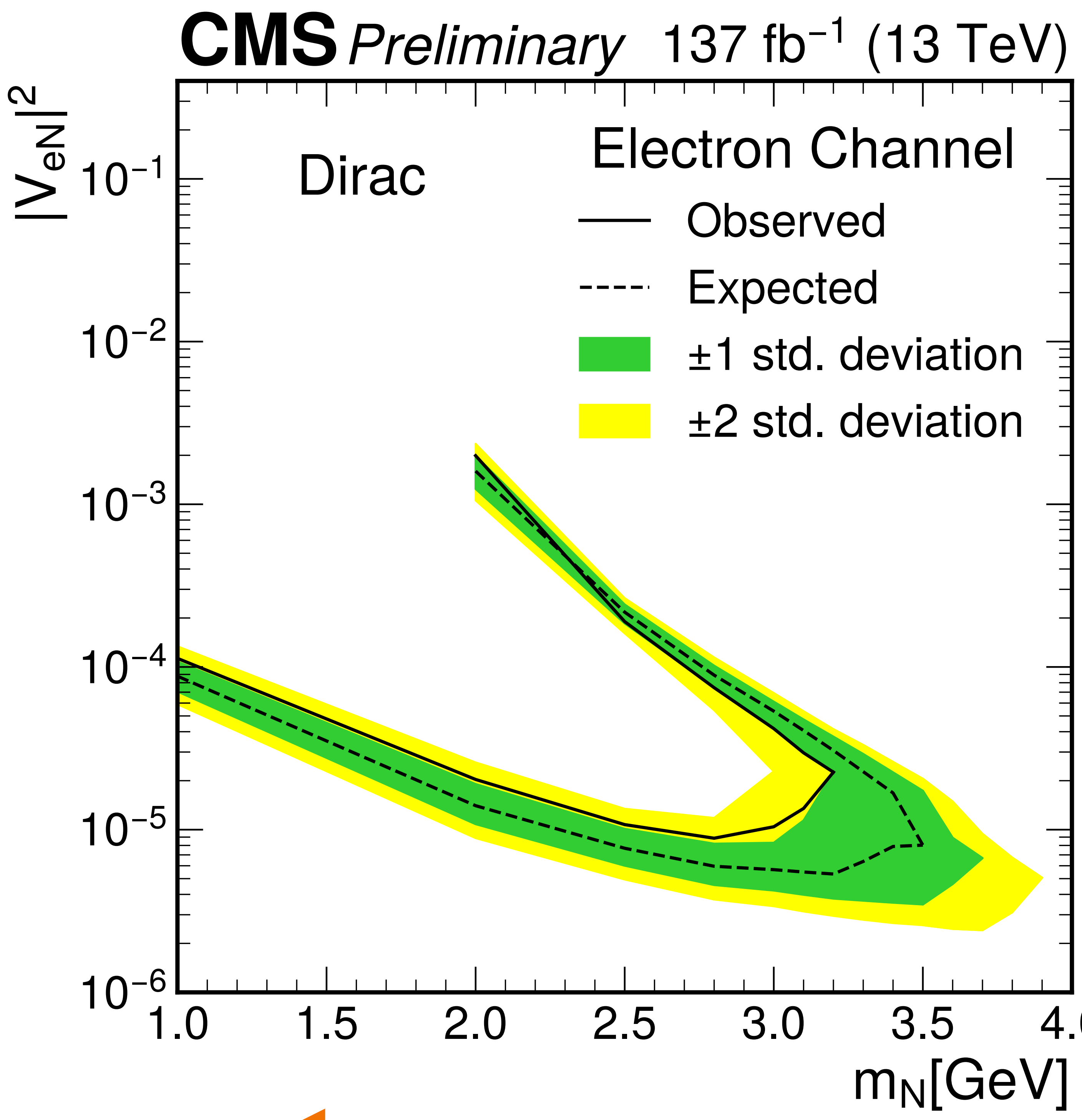




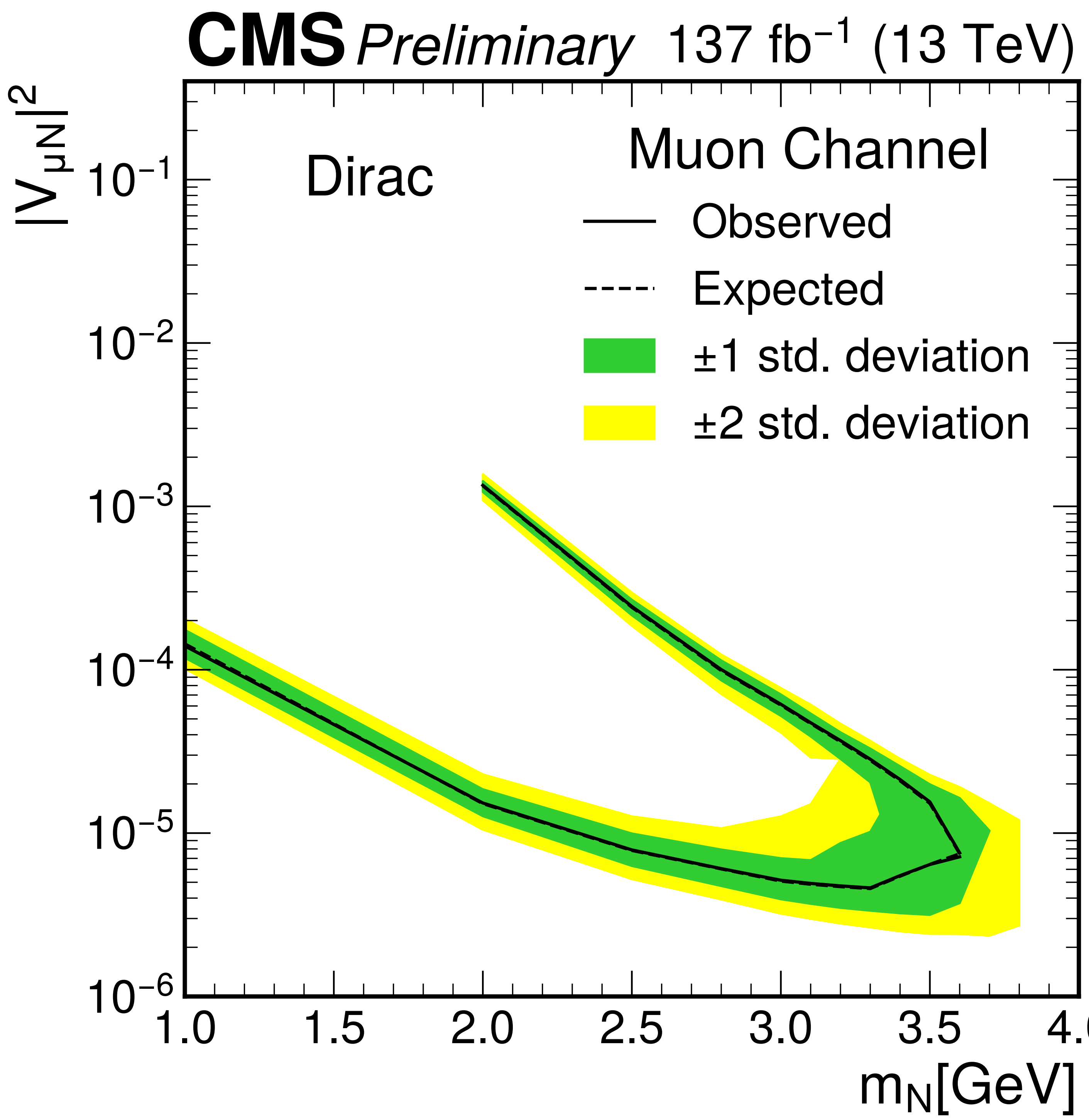
Limits for Heavy Neutral Leptons

- No significant excess observed
- Analysis is sensitive to all HNL types and significantly extends sensitivity to **smaller mass and mixing angle**
- First CMS result for Tau-HNLs

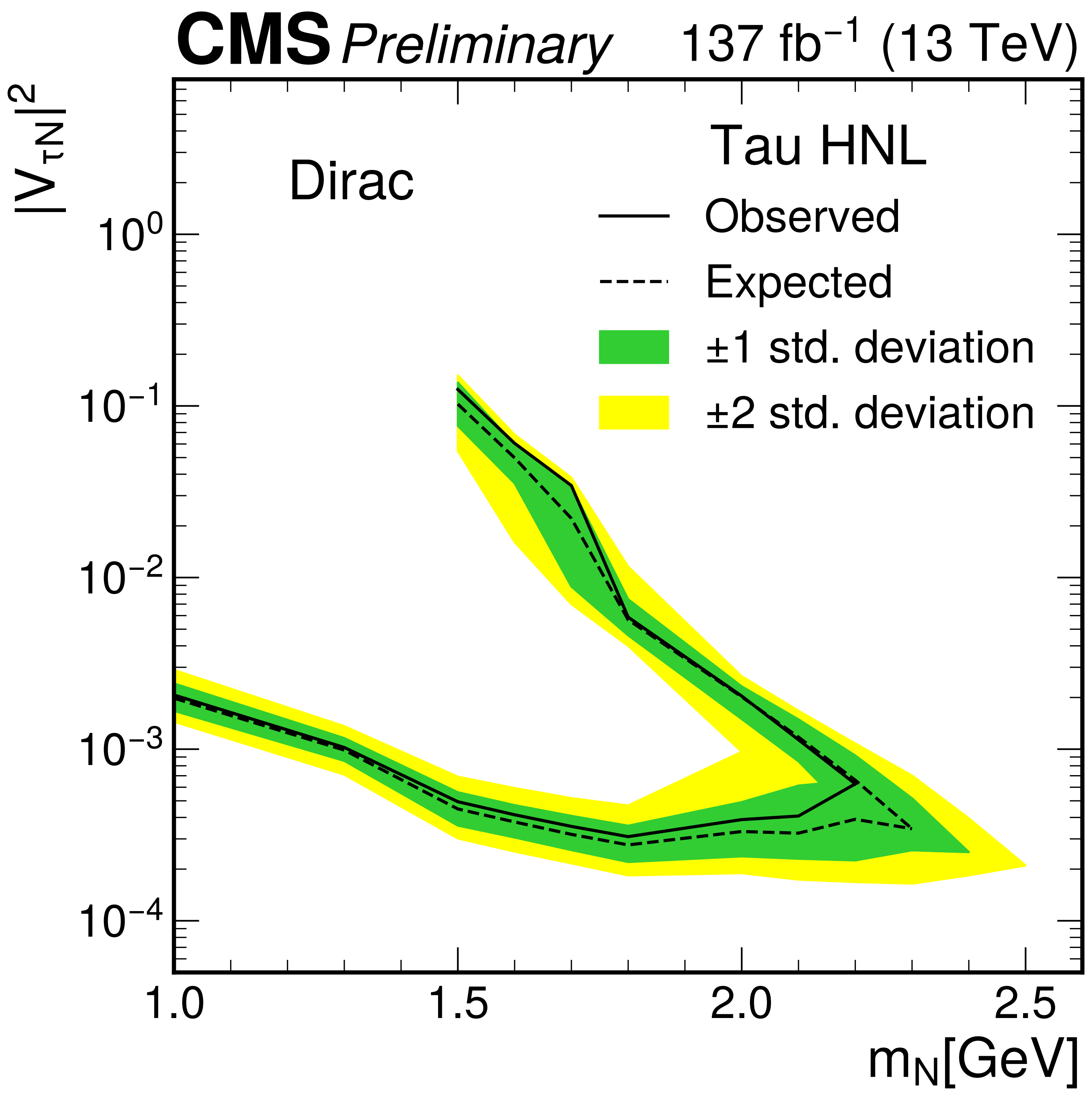
Electron HNL



Muon HNL



Tau HNL



Longer lifetime

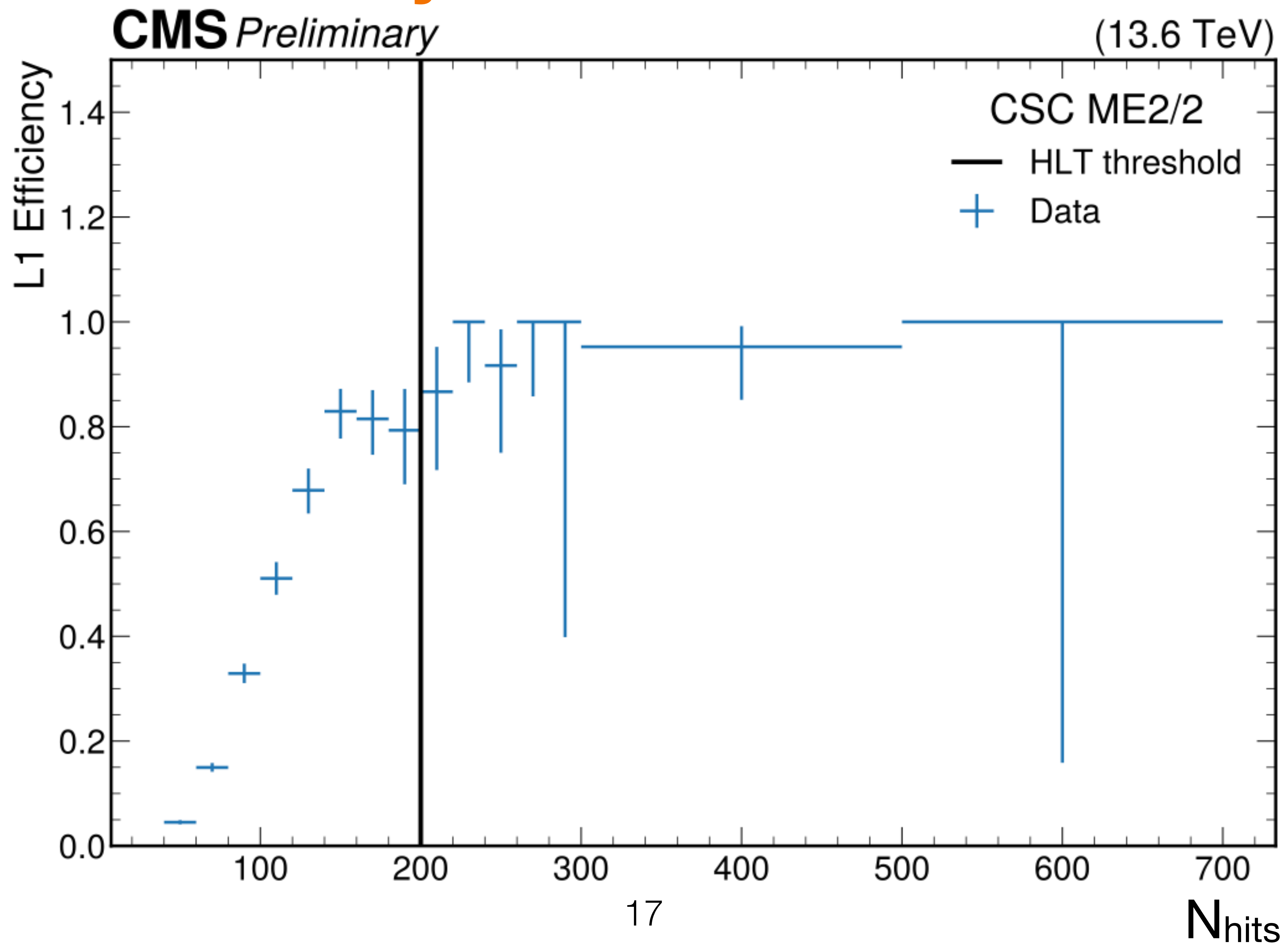
Extend sensitivity to lower mass

Outlook to Run 3: Muon Detector Shower

DP-22-062

- For Run 2, triggering on single lepton or MET (only 1% efficiency for higgs portal)
- **New L1 CSC shower seed** selecting for a large number of cathode and anode-wire hits in CSC chambers
- **New HLT paths** targeting single and double muon detector showers
- **Actively analyzing the 23/fb of data taken in 2022**

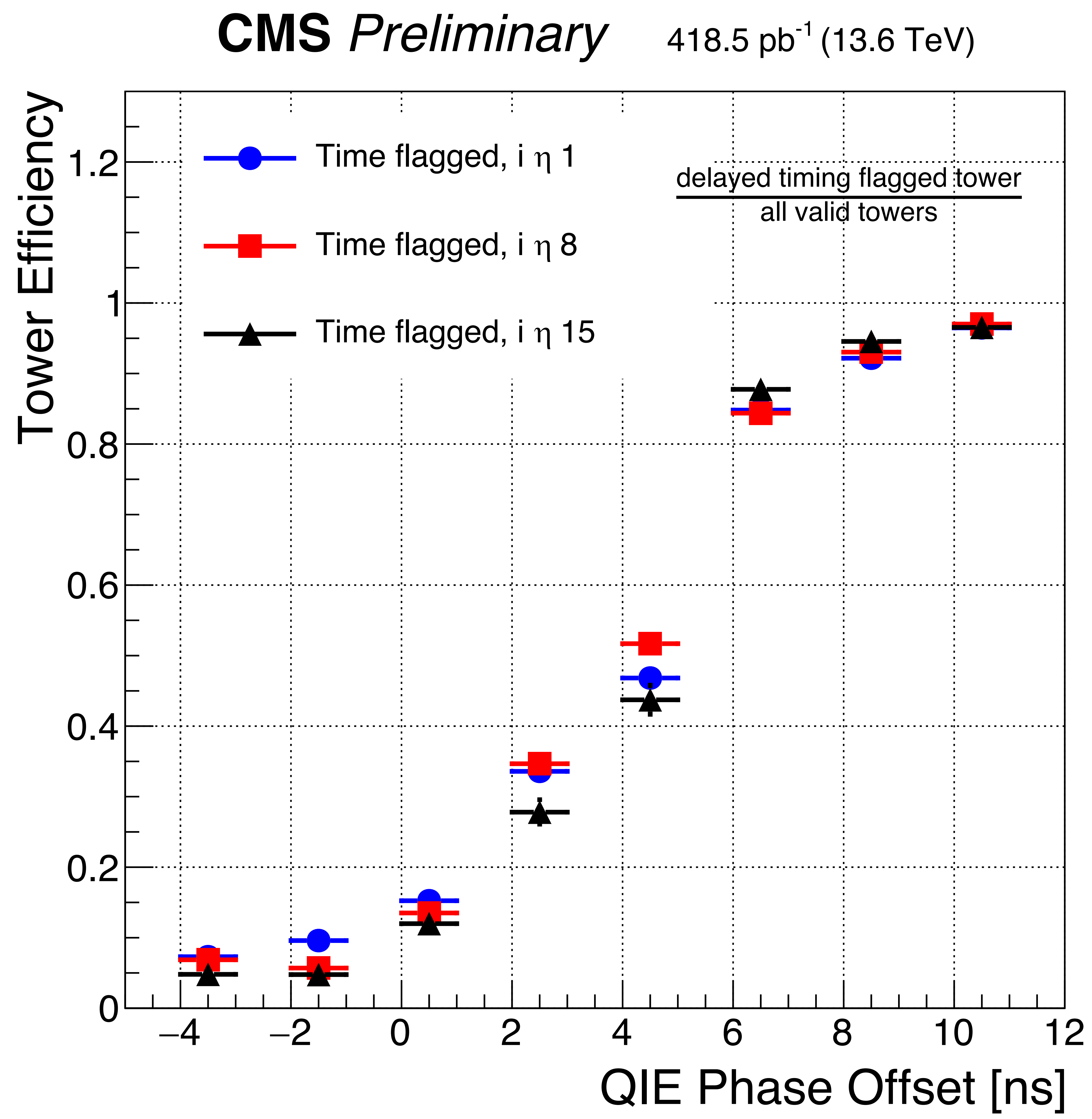
High L1 efficiency measured w.r.t. offline object



New Run 3 Trigger: Delayed + Trackless Jet with HCAL

- **New L1 seed LLP decays using upgraded HCAL (Phase 1)**
  - **Timing** to select LLPs that are delayed wrt collision
  - **Depth information** to select LLPs that deep in HCAL
- Enable new searches with LLPs decay using calorimeter for CMS

High L1 trigger efficiency measured in 2023 phase scan data

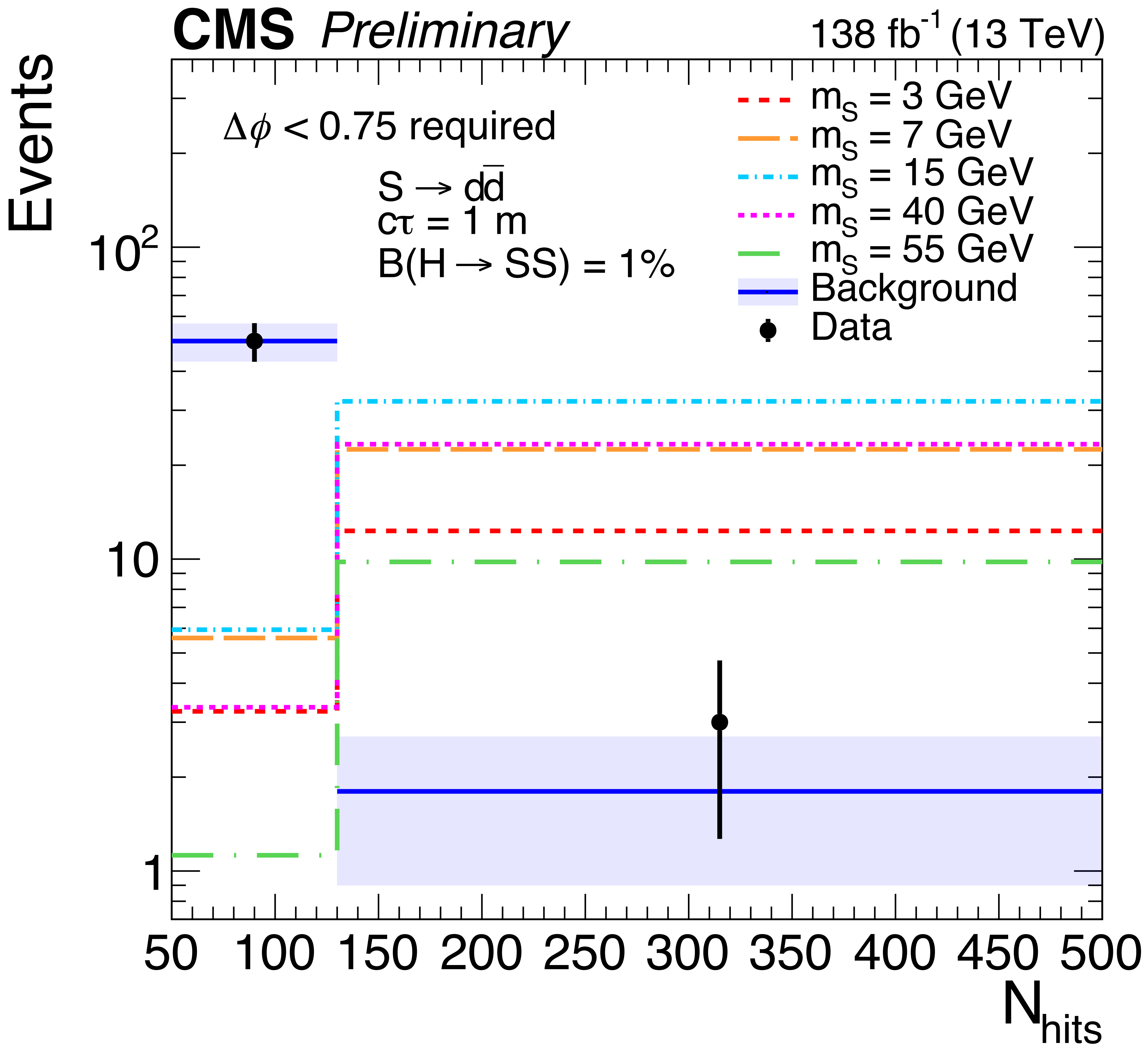


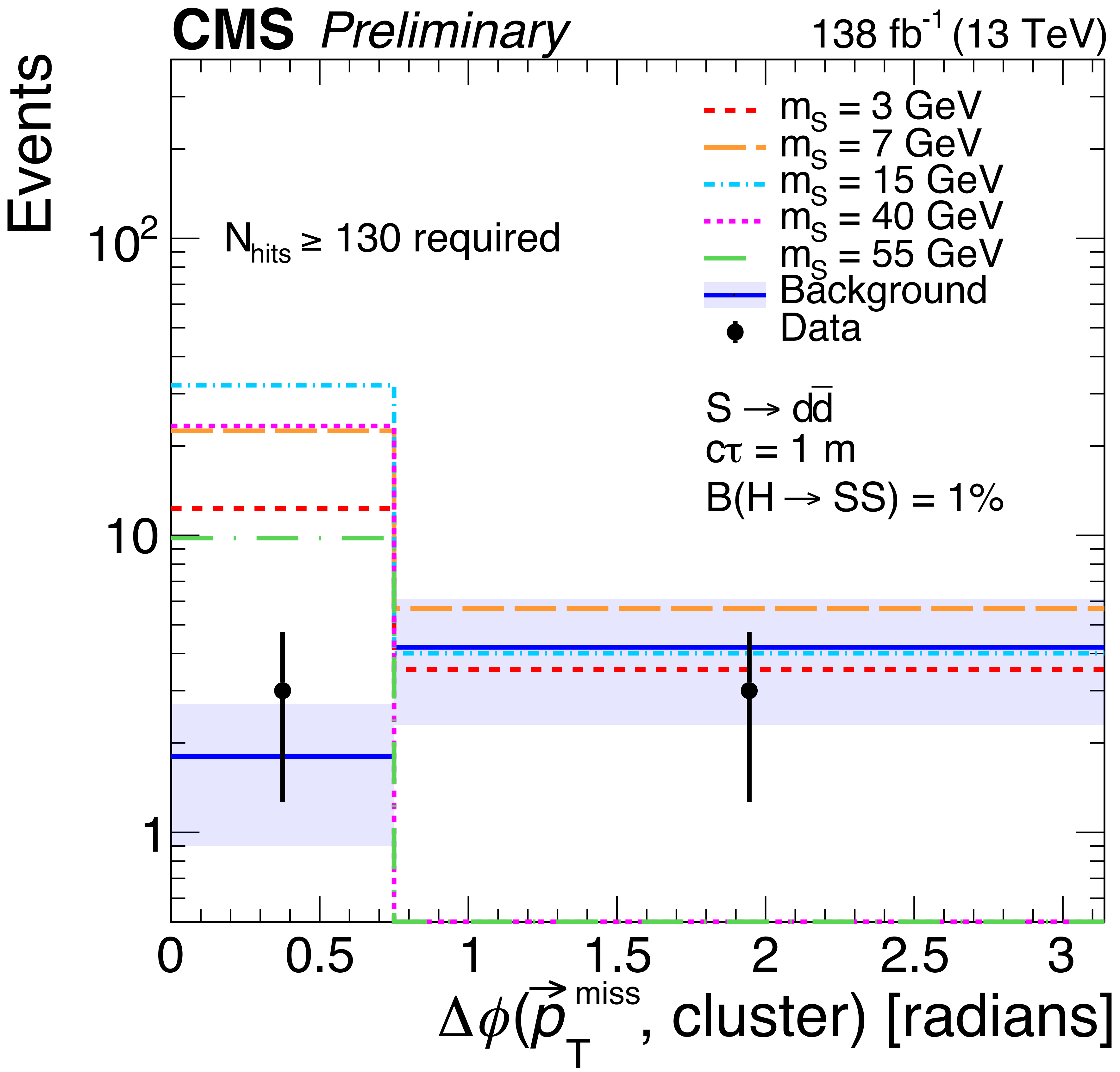
Summary

- Presented brand new LLP search results from CMS targeting different decay modes and using different sub-detectors with full Run 2 dataset
  - Displaced showers in muon detectors
  - Trackless + delayed jets with ECAL timing
- New Run 3 trigger capabilities (L1 + HLT) will enable new discovery potential!

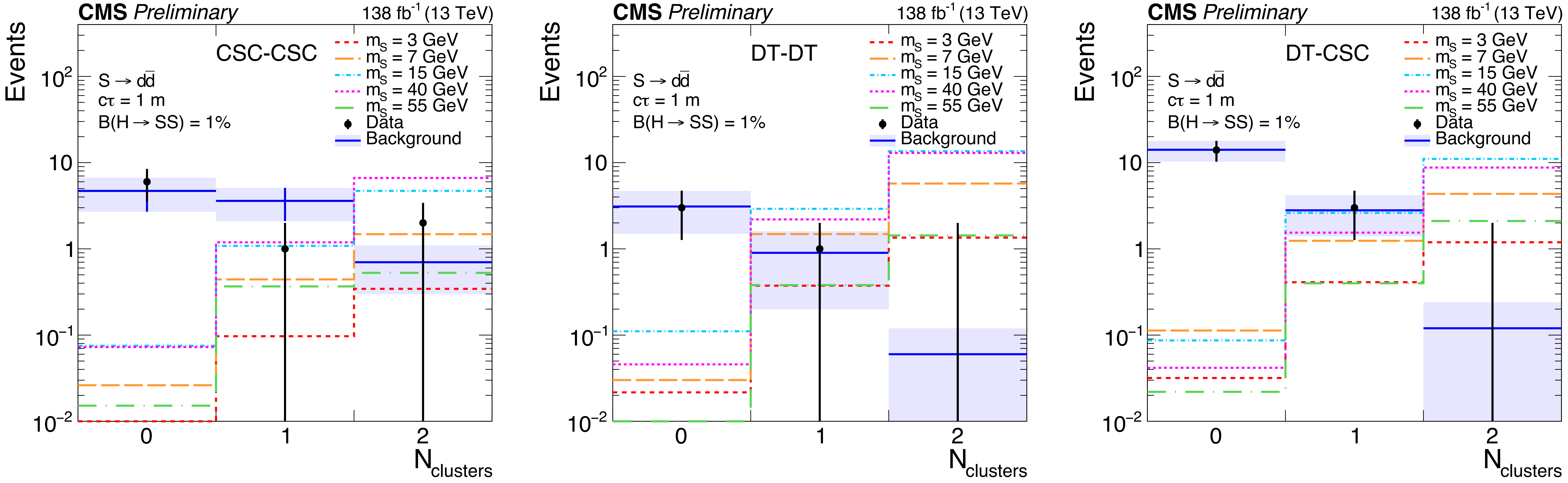
Backup Slides

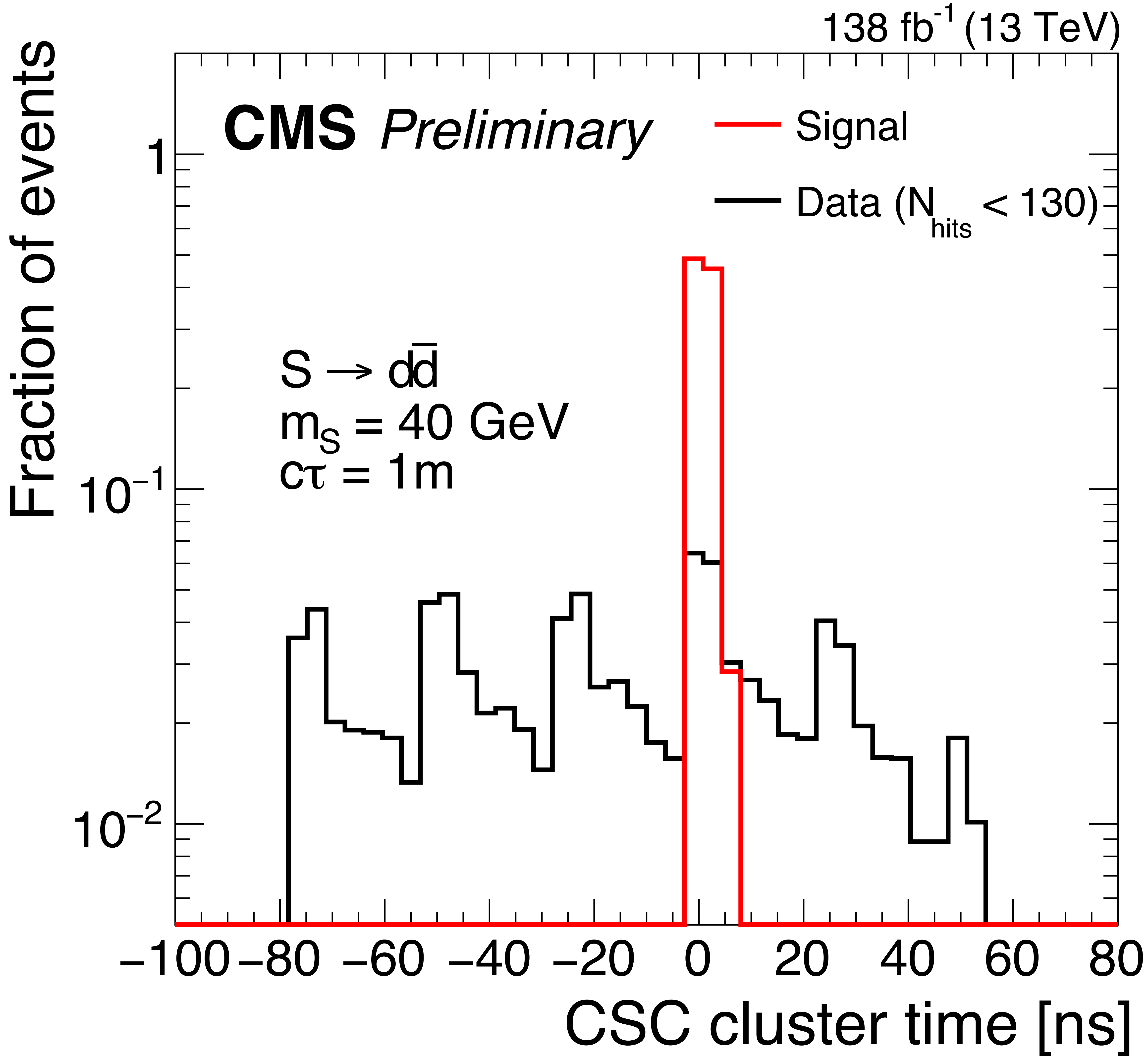
Data-driven Background Estimation





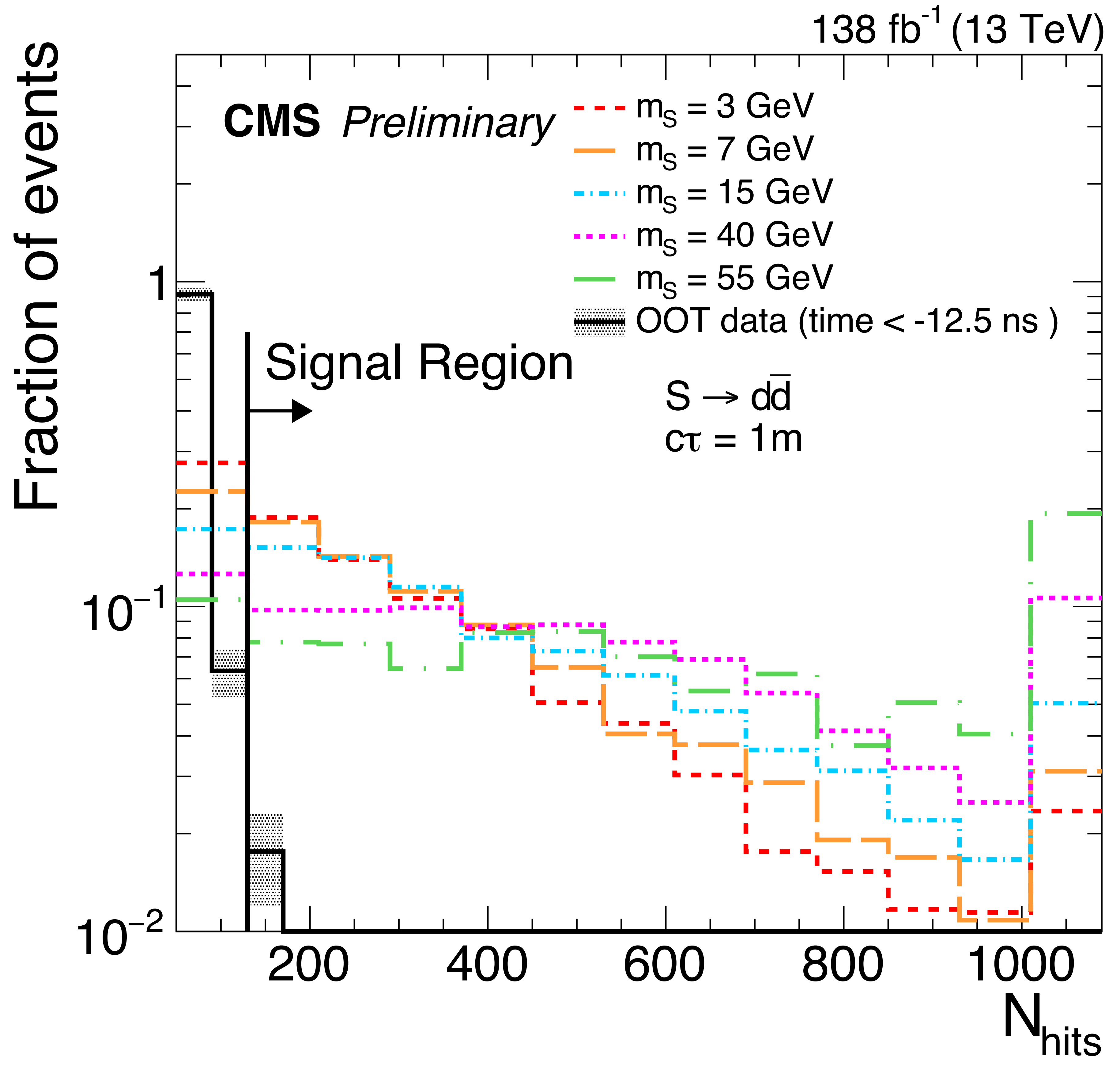
- Use fully data-driven background estimation method (ABCD method) for all 3 categories
- Cluster and MET directions are aligned for signal
- Background estimation method validated in 2 separate validation region


CMS Preliminary
138 fb^{-1} (13 TeV)
CSC-CSC
DT-DT
DT-CSC
S → d$\bar{d}$
cτ = 1 m
B(H → SS) = 1%
m_S = 3 GeV
m_S = 7 GeV
m_S = 15 GeV
m_S = 40 GeV
m_S = 55 GeV
Data
Background
Events
$N_{clusters}$

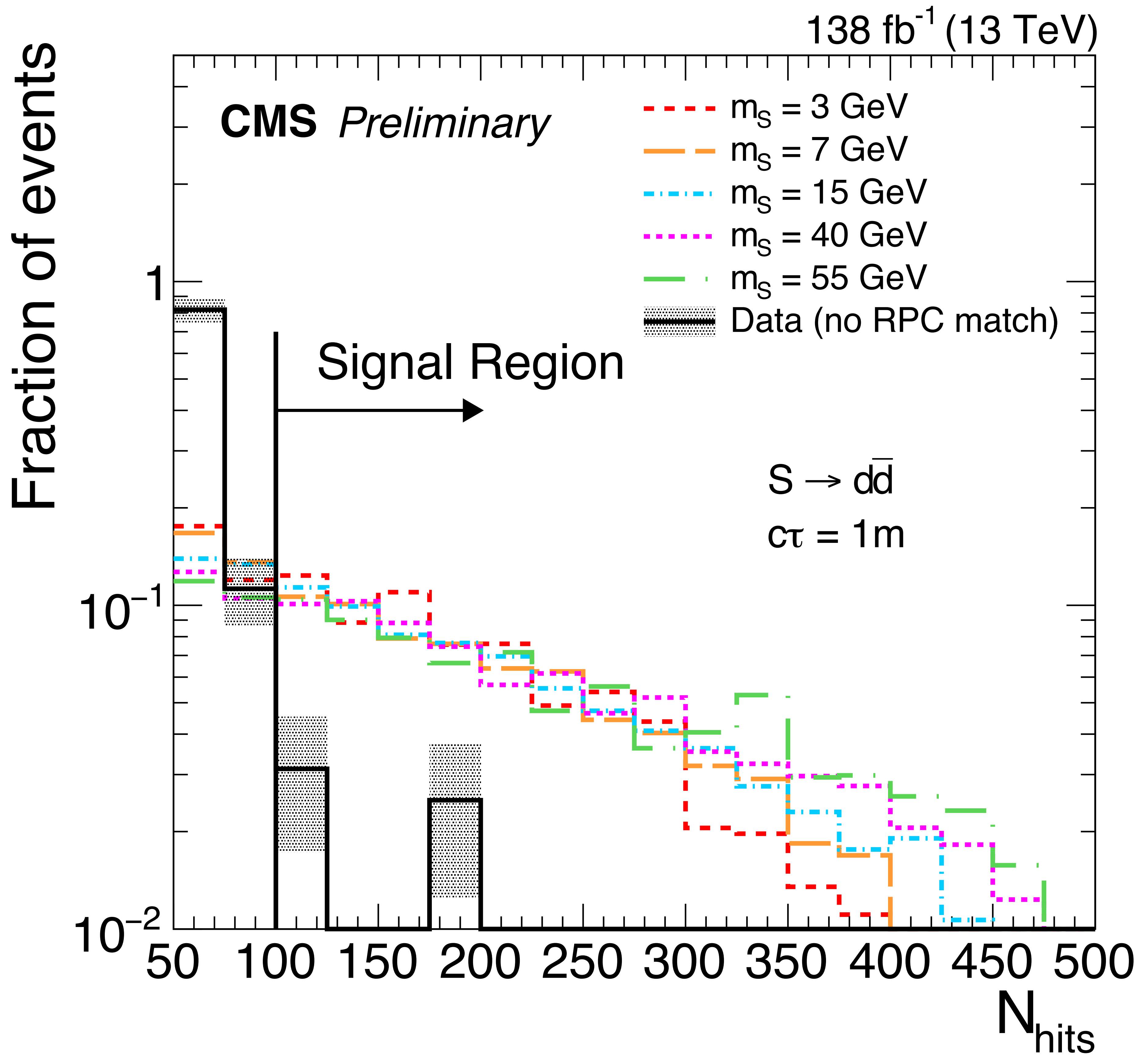

138 fb-1 (13 TeV)
CMS Preliminary
Signal
Data (Nhits < 130)
S → dd̄
mS = 40 GeV
cτ = 1m
Fraction of events
1
10−1
10−2
−100
−80
−60
−40
−20
0
20
40
60
80
CSC cluster time [ns]

Nhits Distribution

Single CSC category



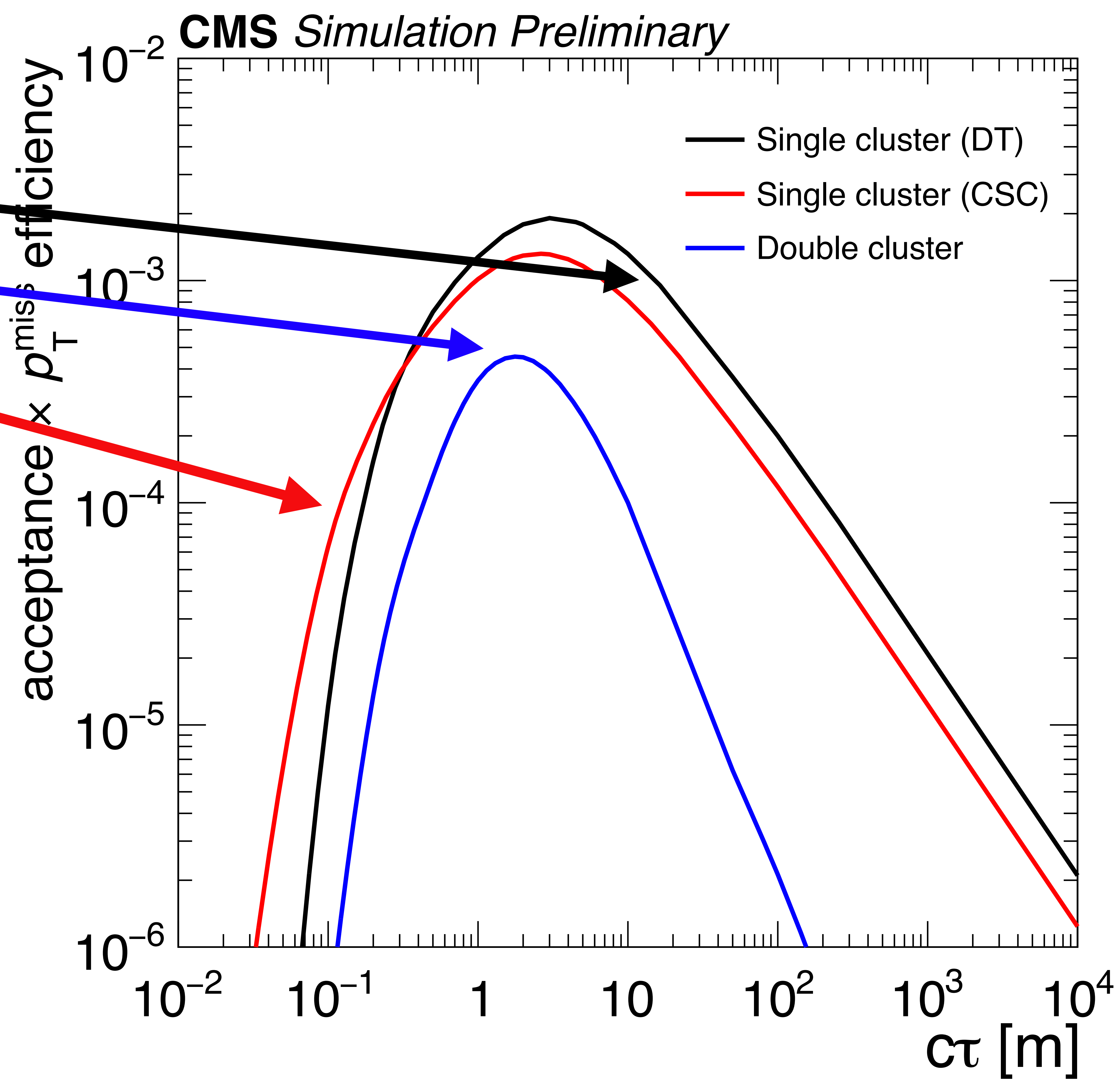
Single DT category



Analysis Strategy

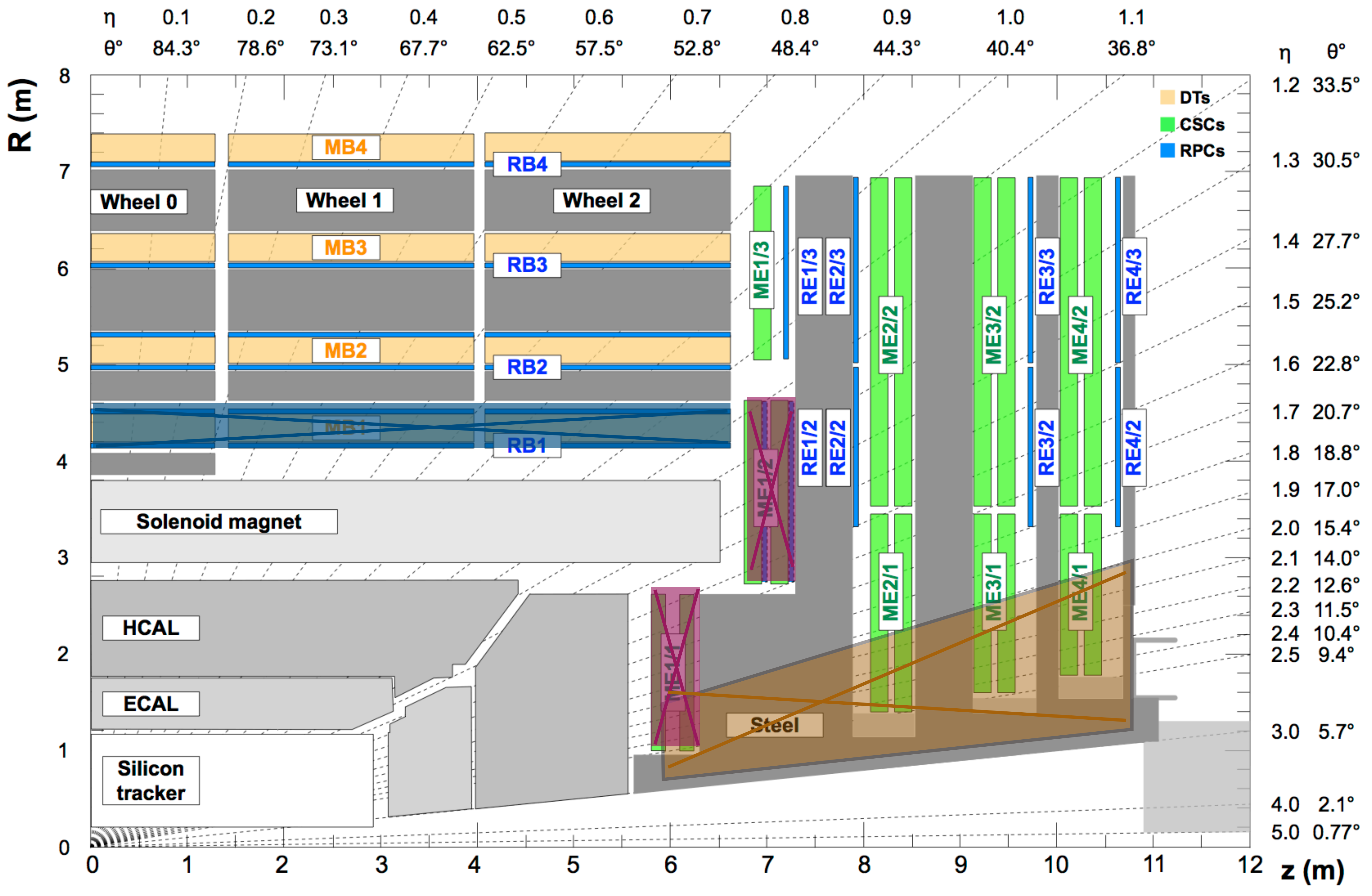
- Single DT cluster dominates at large cτ
- Double cluster dominates at intermediate cτ
- Single CSC cluster dominates at low cτ

LLP mass = 40 GeV

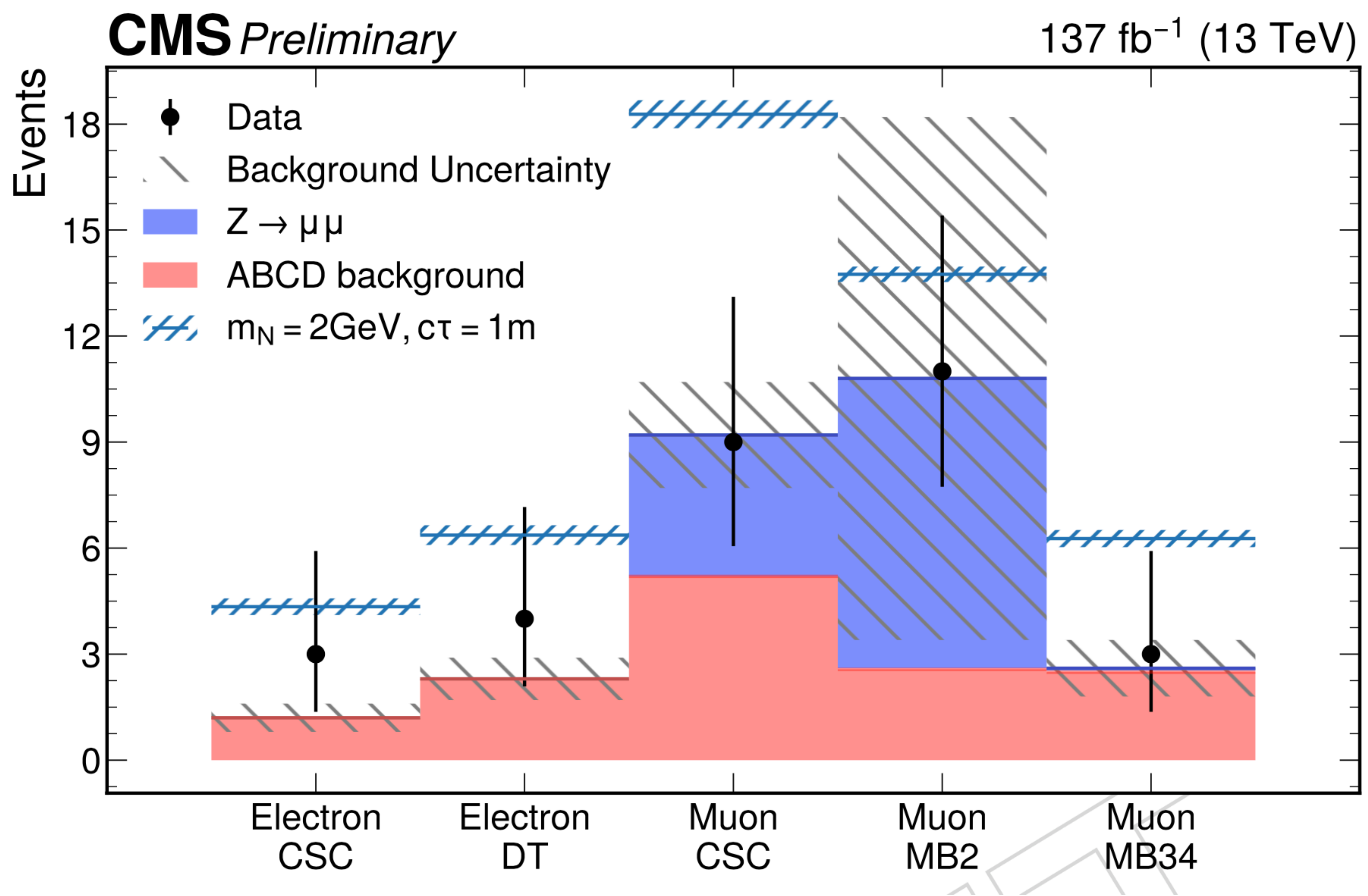


Cluster Selections

- 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 or MB1)
- ~50% signal efficiency when LLP decays between ME1 and ME4
- Background rejection is ~10^6



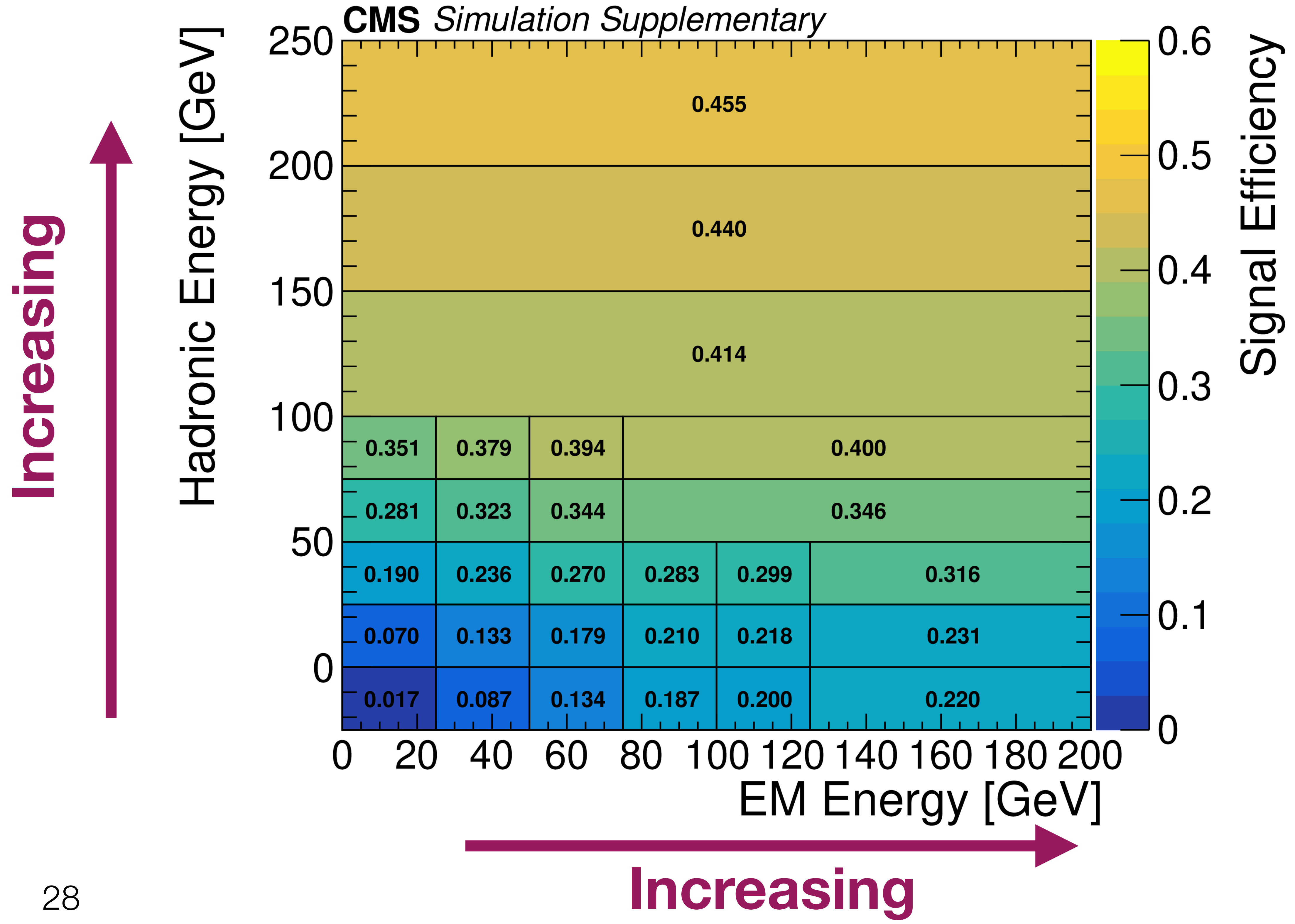
$$c\tau_N \propto \left(\frac{1\mathrm{GeV}}{m_N}\right)^5 \left(\frac{0.1}{|V_{lN}|^2}\right)[\mathrm{mm}]$$



Reinterpretation Materials

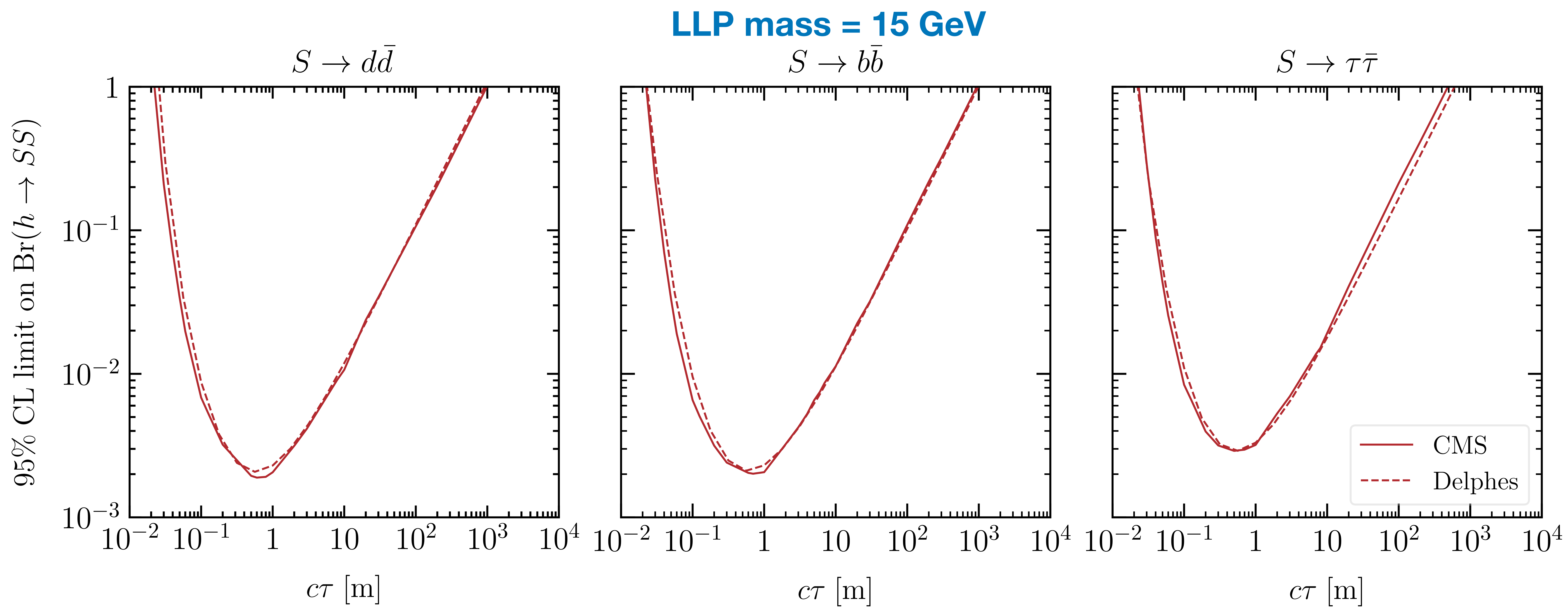
- **LLPs can arise in MANY other models…**
- The search is driven by the displaced signatures and is **model independent**
- Along with the CMS result, we released a set of detector response function parameterized using only gen-level LLP information that would allow for recasting of the analysis with other models
- **Only gen-level LLP hadronic energy, EM energy, and decay positions are needed as inputs to the parameterization**

https://www.hepdata.net/record/104408



Delphes Module for Recasting

- Integrated the CSC cluster objects with the detector response functions as official Delphes classes and modules: https://github.com/delphes/delphes/pull/103
  - Validated that we are able to reproduce the limits from CMS for all 3 decay modes to within 30%
- We recasted the CMS analysis in a number of models: dark scalar, dark photon, ALPs, inelastic DM, hidden valley models, and HNL
  - Will focus on dark scalar and HNL today



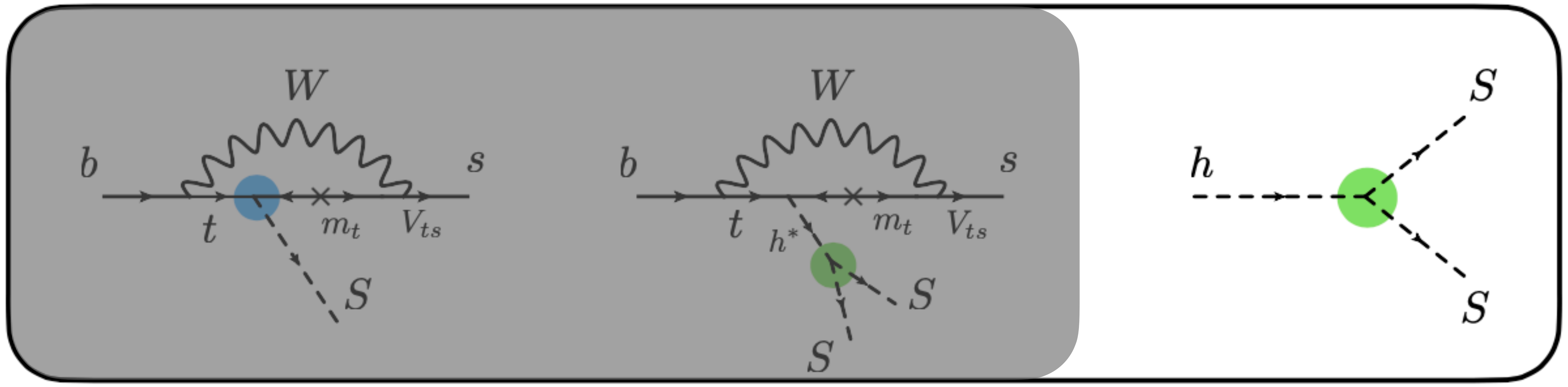
Light Scalar Model

$$\mathcal{L}_{SH} = \mathcal{L}_{\rm SM} + \underbrace{\frac{1}{2}\partial_\mu \hat{S}\,\partial^\mu \hat{S} - \frac{\mu_S^2}{2}\hat{S}^2}_{\mathcal{L}_{\rm DS}} - \underbrace{\left(A_{HS}\hat{S} + \lambda_{HS}\hat{S}^2\right)\hat{H}^\dagger \hat{H}}_{\text{Higgs portal}}$$

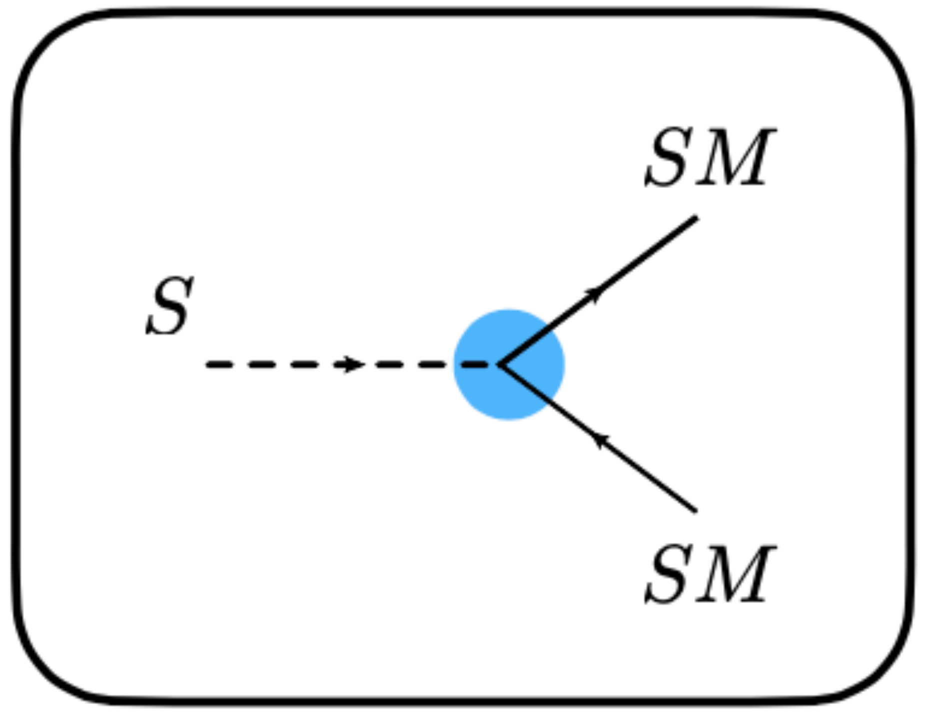
A_{HS}: controls the $\hat{H} - \hat{S}$ mixing

λ_{HS}: controls $Br(H \to SS)$

production



decay



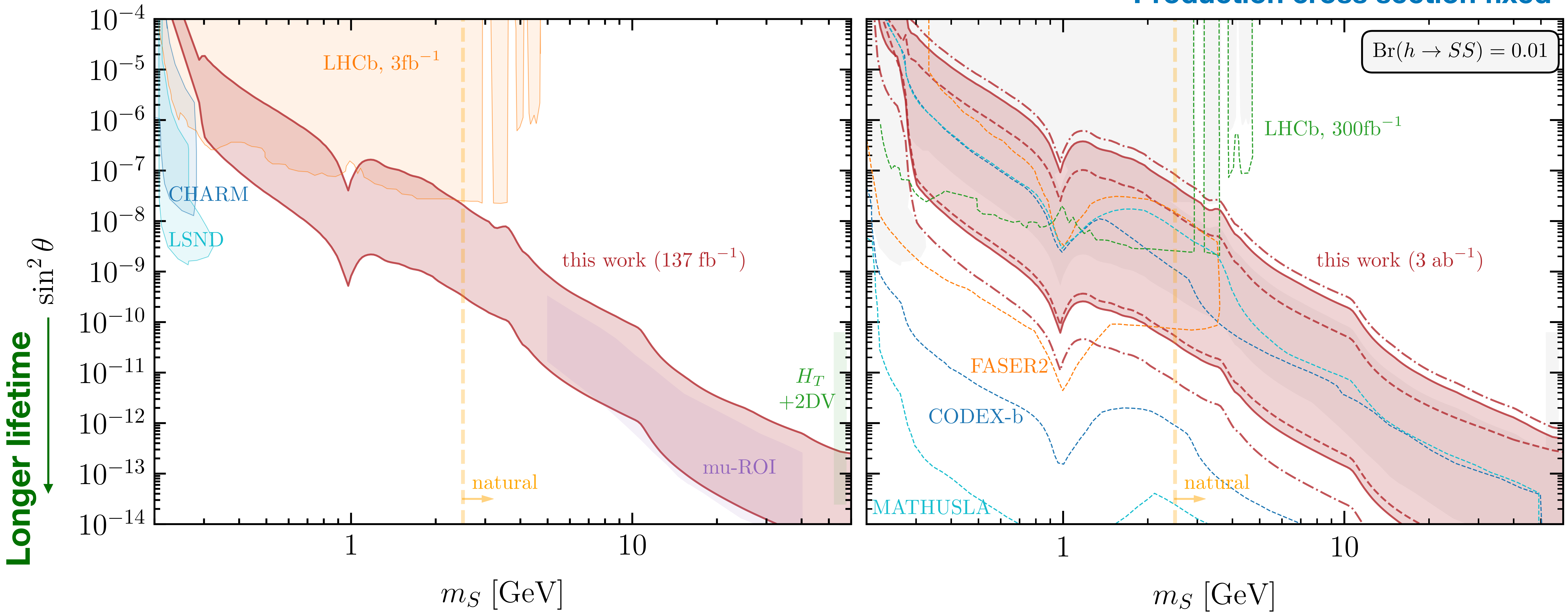
No reach in this analysis
(due to MET > 200 GeV cut)

Production and decay channels are decoupled

Light Scalar Reinterpretation

arXiv:2304.06109
Submitted to PRD

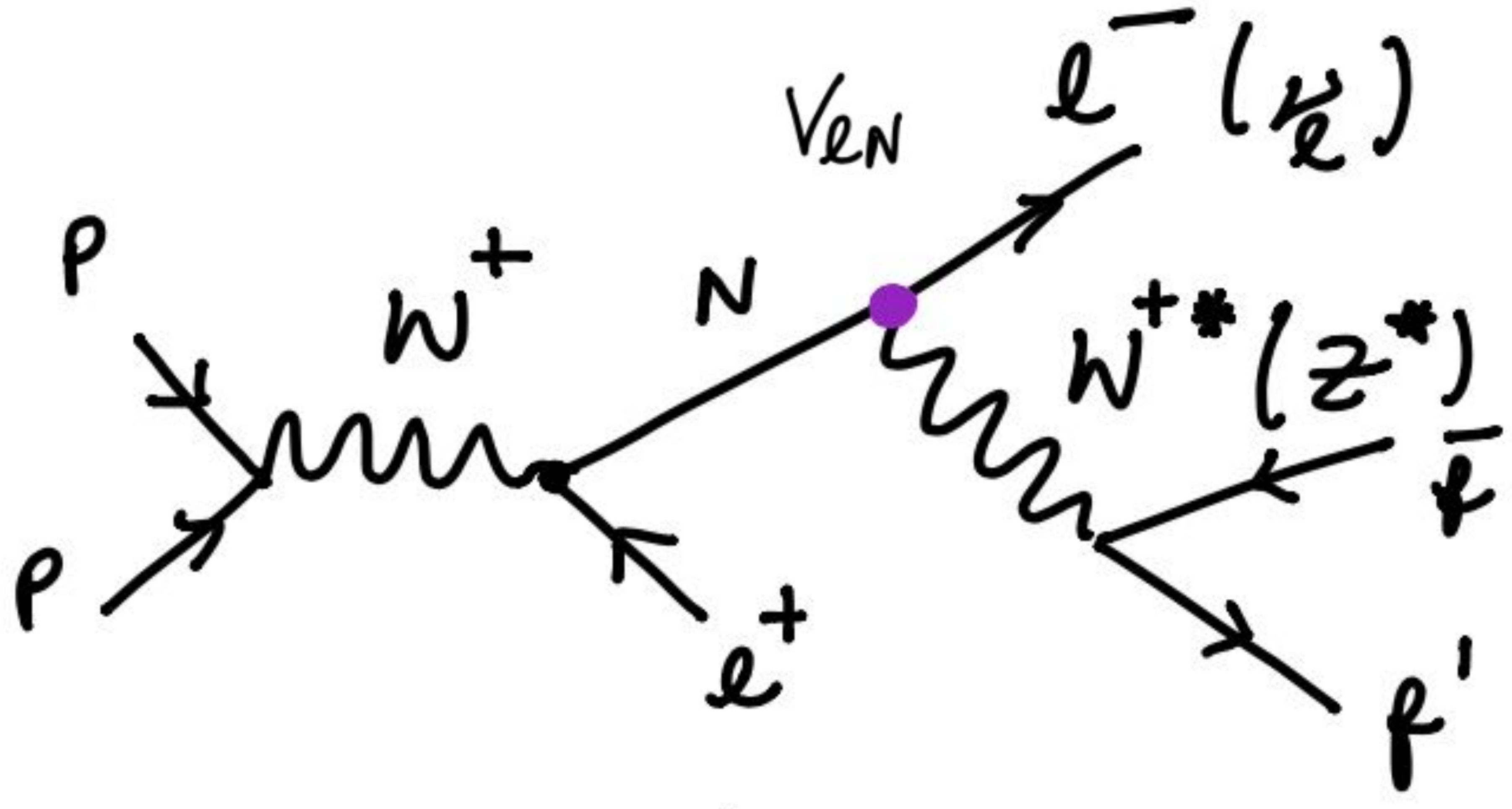
Production cross section fixed

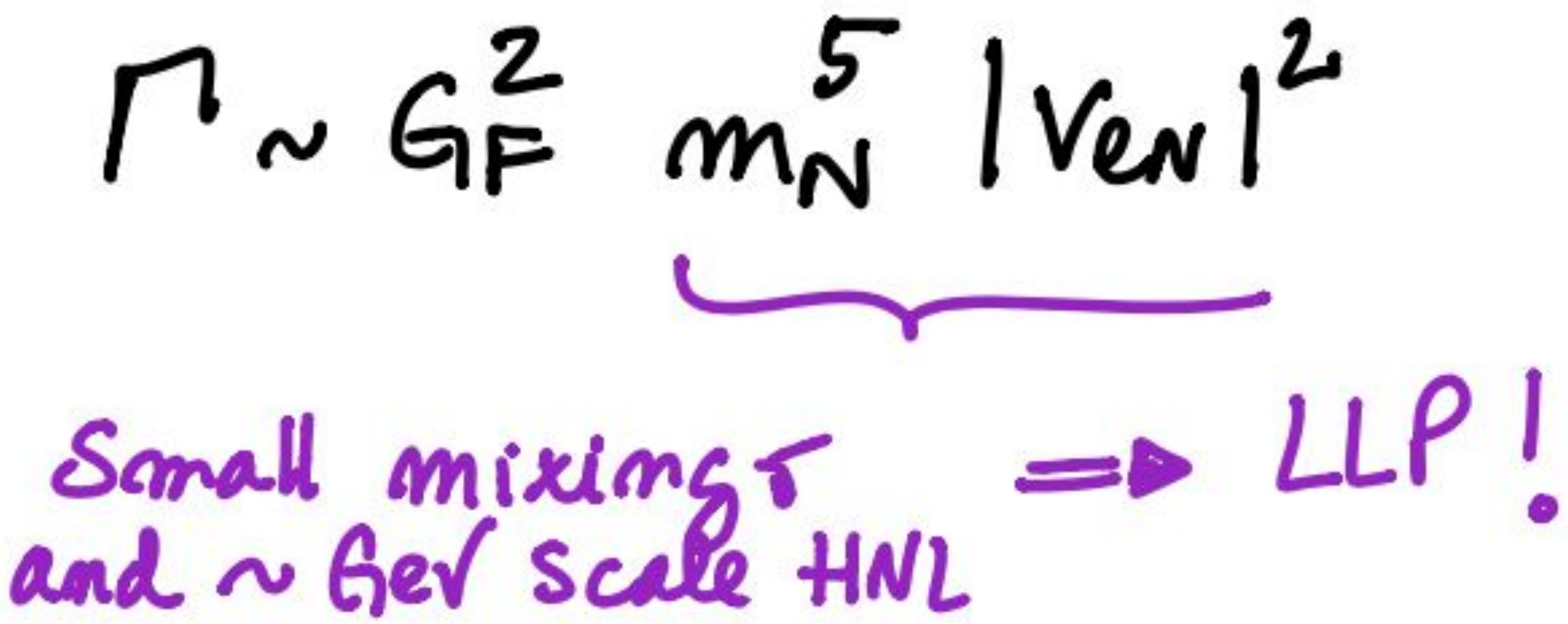


- m_S controls the decay mode and affects the acceptance
- 3 search strategies considered for phase 2:
  - Solid line : same analysis strategy and simply scale the result by luminosity
  - Dot-dashed line: increase N_{hit} cut until 0 bkg is achieved
  - Dotted line: remove MET cut and require 2 CSC clusters

Heavy Neutral Leptons

G. Cottin



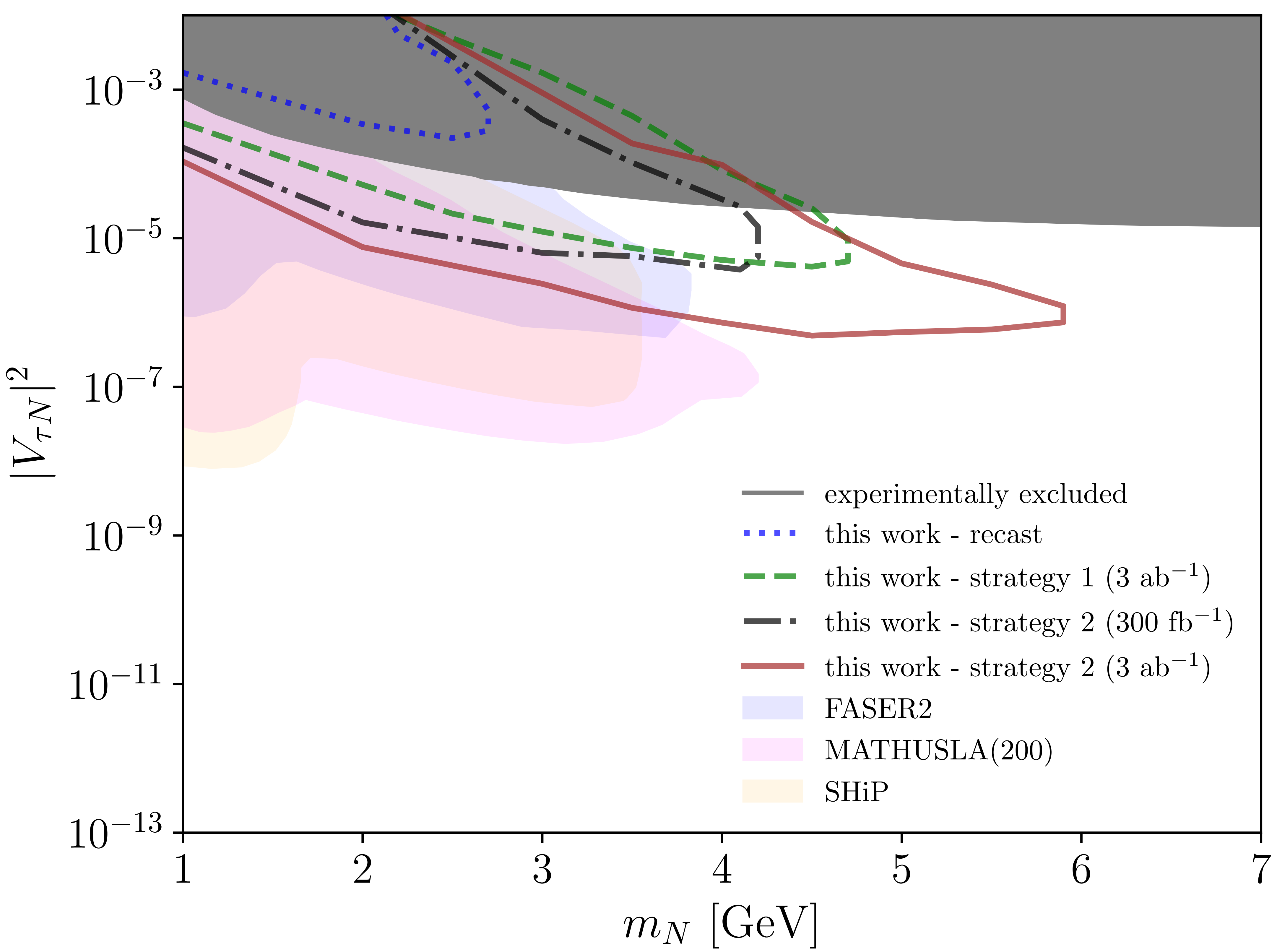


- Latest HNL searches at the LHC use prompt lepton triggers (e/μ) and displaced vertex signature targeting leptonic decays of W*/Z*
- Tau mixing is not covered yet at the LHC
- **Muon detector shower: target HNLs decaying in the muon system, sensitive to particle showers from the displaced lepton and inclusive W*/Z* decays**

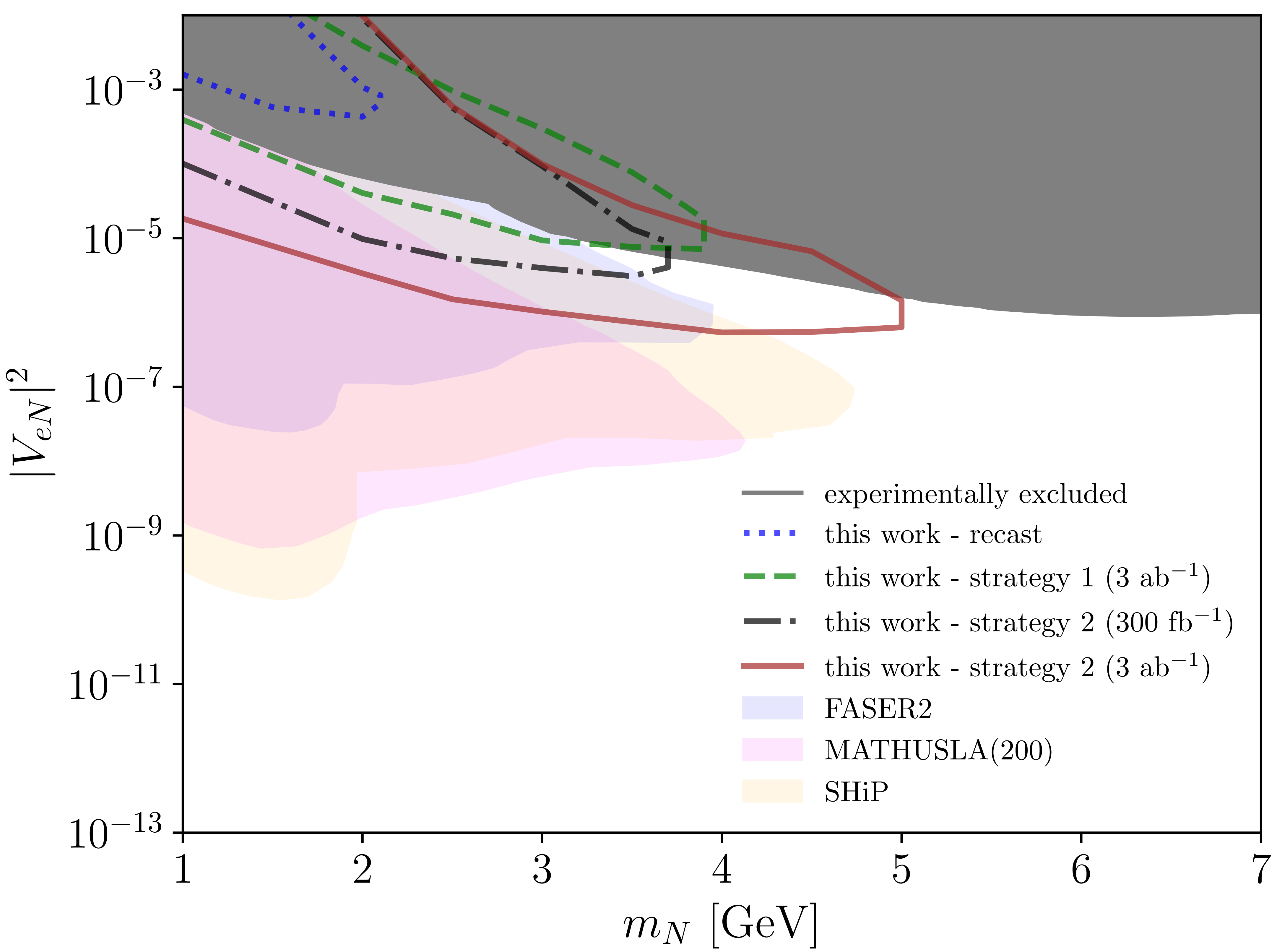
HNL Reinterpretation

JHEP 02 (2023) 011

τ-type



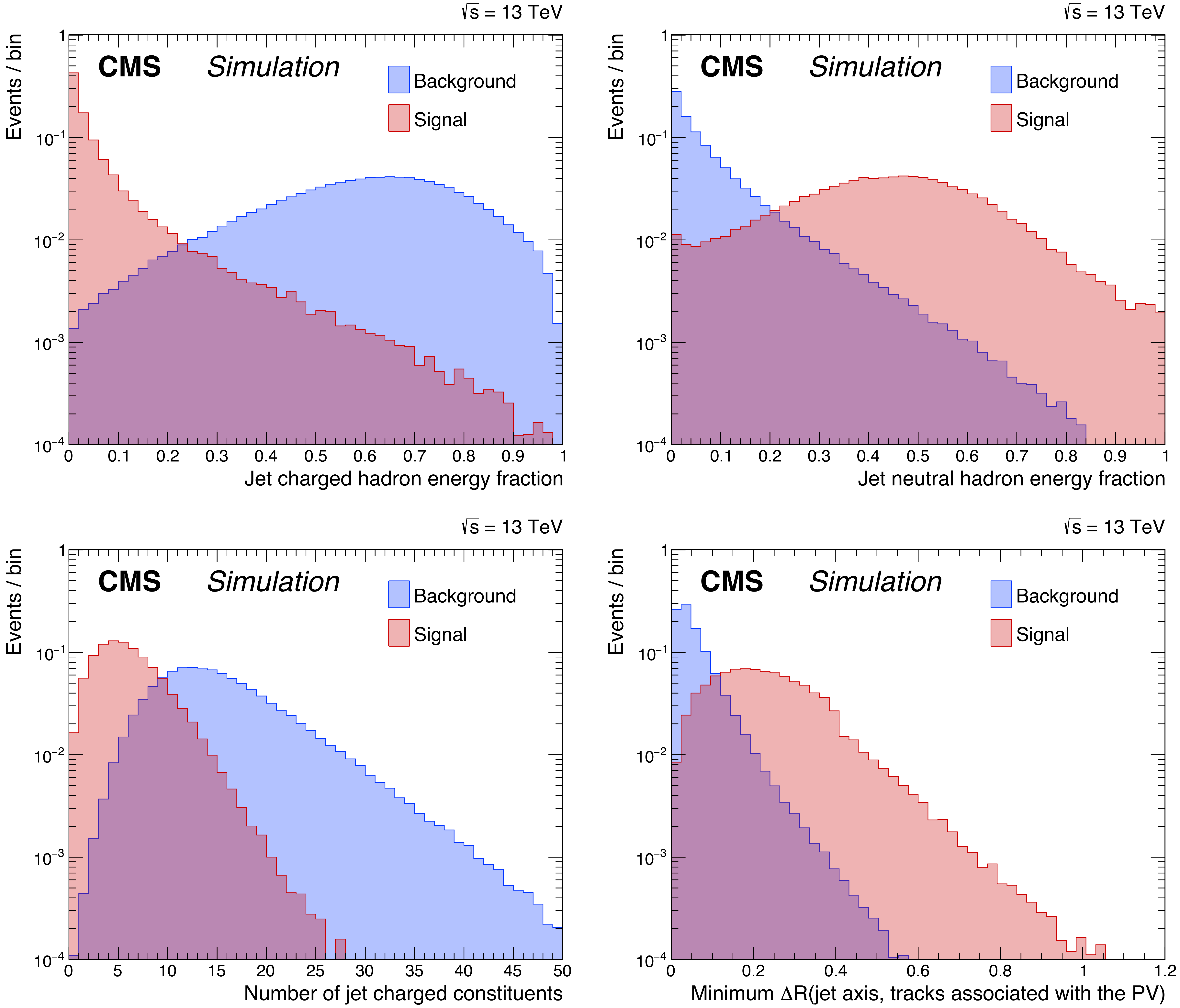
Electron-type

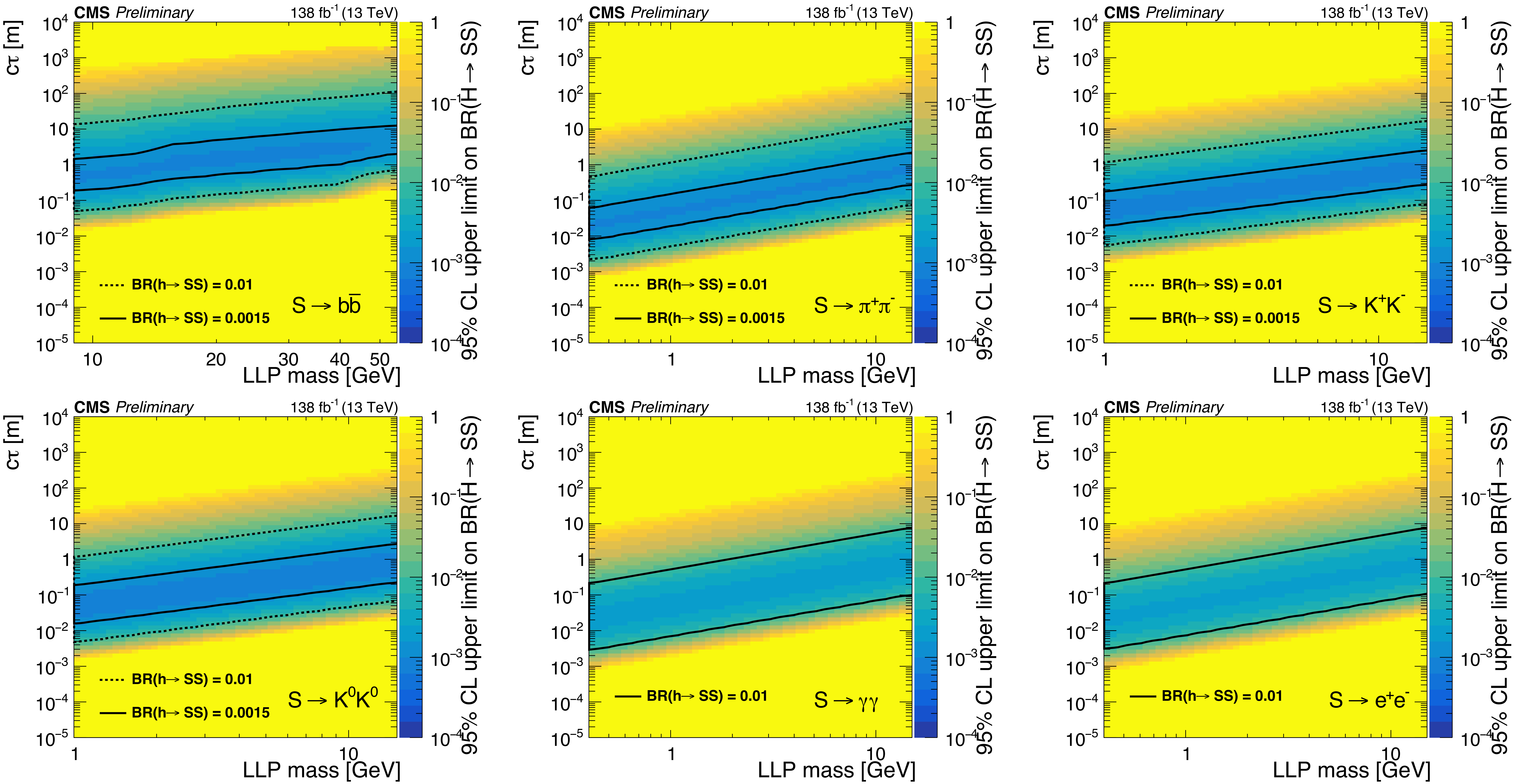


- **Can reach mixings as low as ~5 x 10^{-7} and HNL masses between 1 and 6 GeV for both electron and τ-type**
  - Strategy 1 : Maintains high MET trigger but with a tighter N_{hit} cut.
  - Strategy 2: Lower MET cut > 50 GeV and increased N_{hit}. Enabled by the new dedicated trigger for Run 3

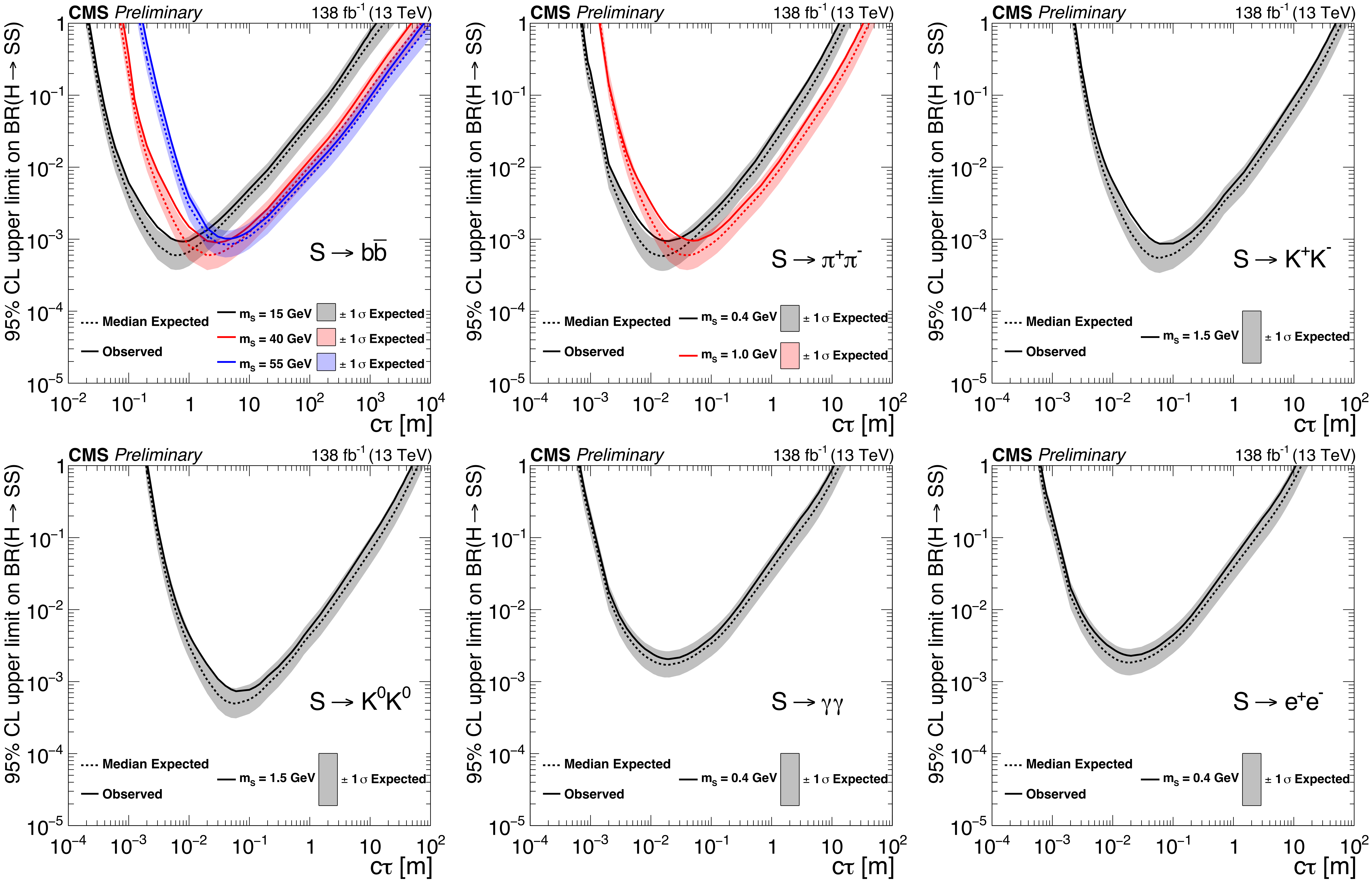
Architecture

- 5 fully connected layers (64,32, 16, 8 and 1 node)
- Relu + softmax activation, categorical cross entropy
- 10% dropout + early stopping
- Training 1000 epochs, 2018 MC, 2.5 M events (S/B = 1/8)
- Gen matched signal jets


CMS Simulation
√s = 13 TeV
Background
Signal
Events / bin
Jet charged hadron energy fraction
Jet neutral hadron energy fraction
Number of jet charged constituents
Minimum ΔR(jet axis, tracks associated with the PV)



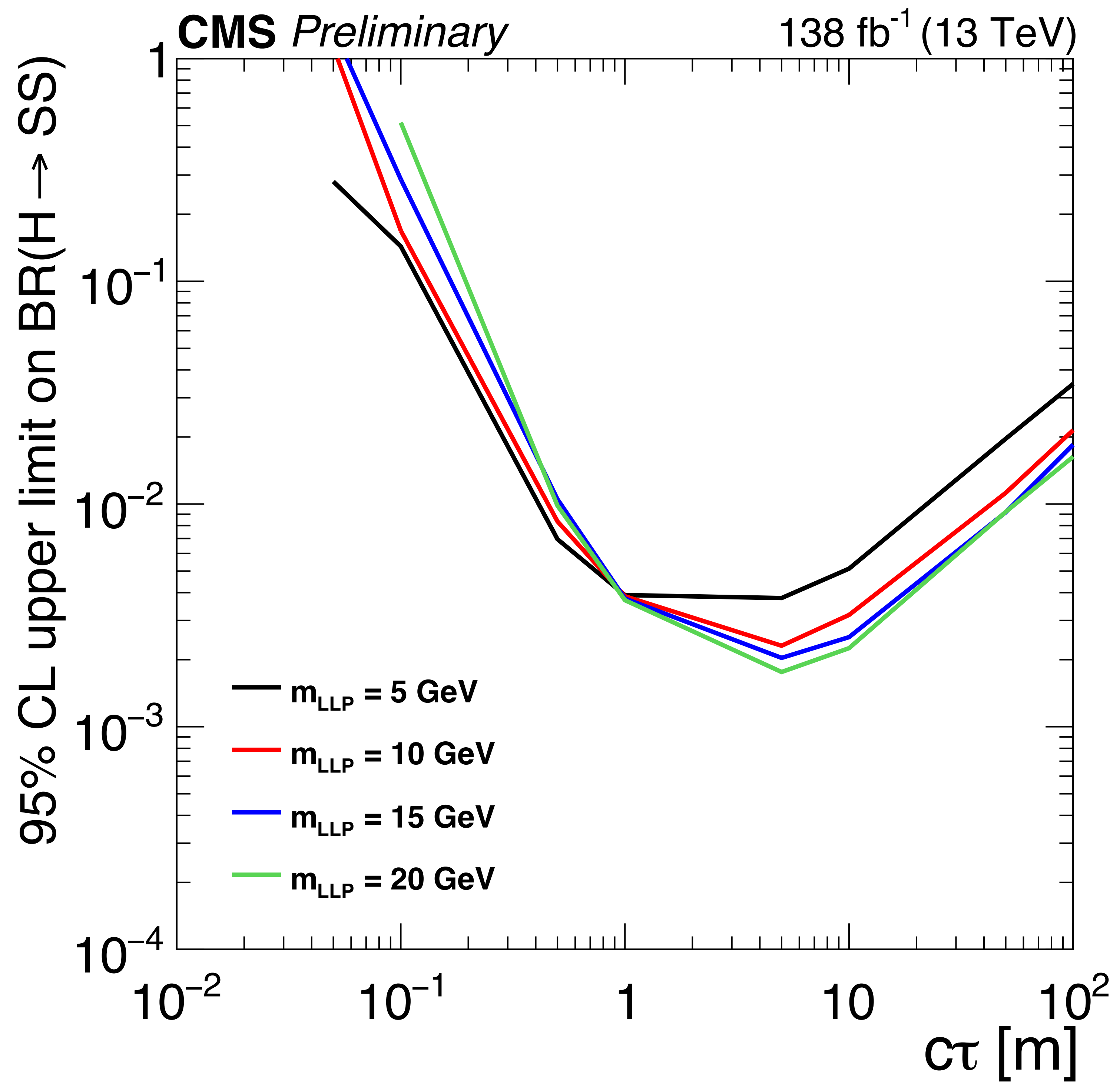
CMS Preliminary
138 fb-1 (13 TeV)
cτ [m]
LLP mass [GeV]
95% CL upper limit on BR(H → SS)
BR(h→ SS) = 0.01
BR(h→ SS) = 0.0015
S → bb̄
S → π+π-
S → K+K-
S → K0K0
S → γγ
S → e+e-



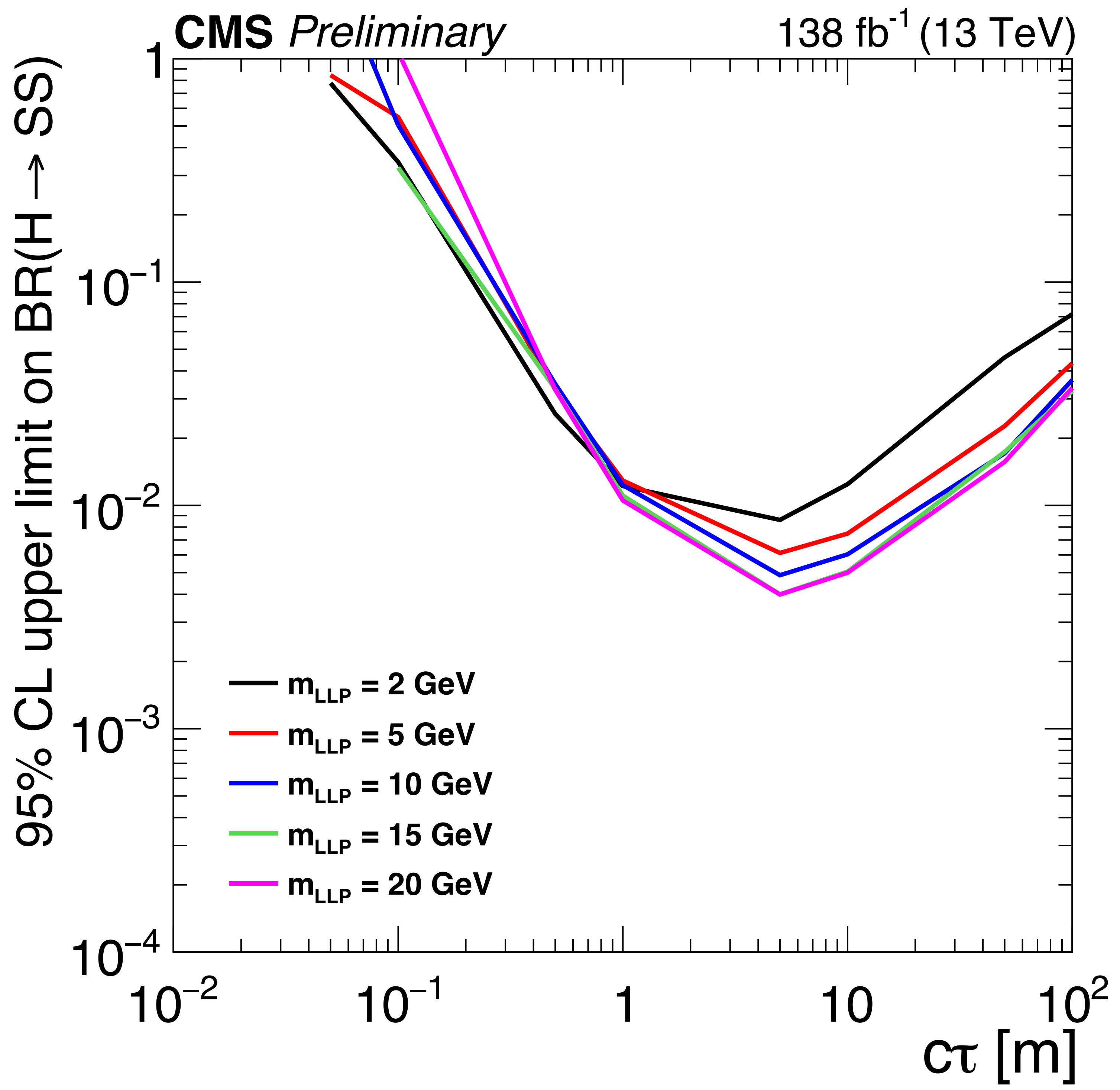
CMS Preliminary
138 fb-1 (13 TeV)
95% CL upper limit on BR(H → SS)
cτ [m]
S → bb̄
Median Expected
Observed
ms = 15 GeV
ms = 40 GeV
ms = 55 GeV
± 1 σ Expected
S → π+π-
ms = 0.4 GeV
ms = 1.0 GeV
S → K+K-
ms = 1.5 GeV
S → K0K0
S → γγ
S → e+e-

Limits on Dark Shower Model

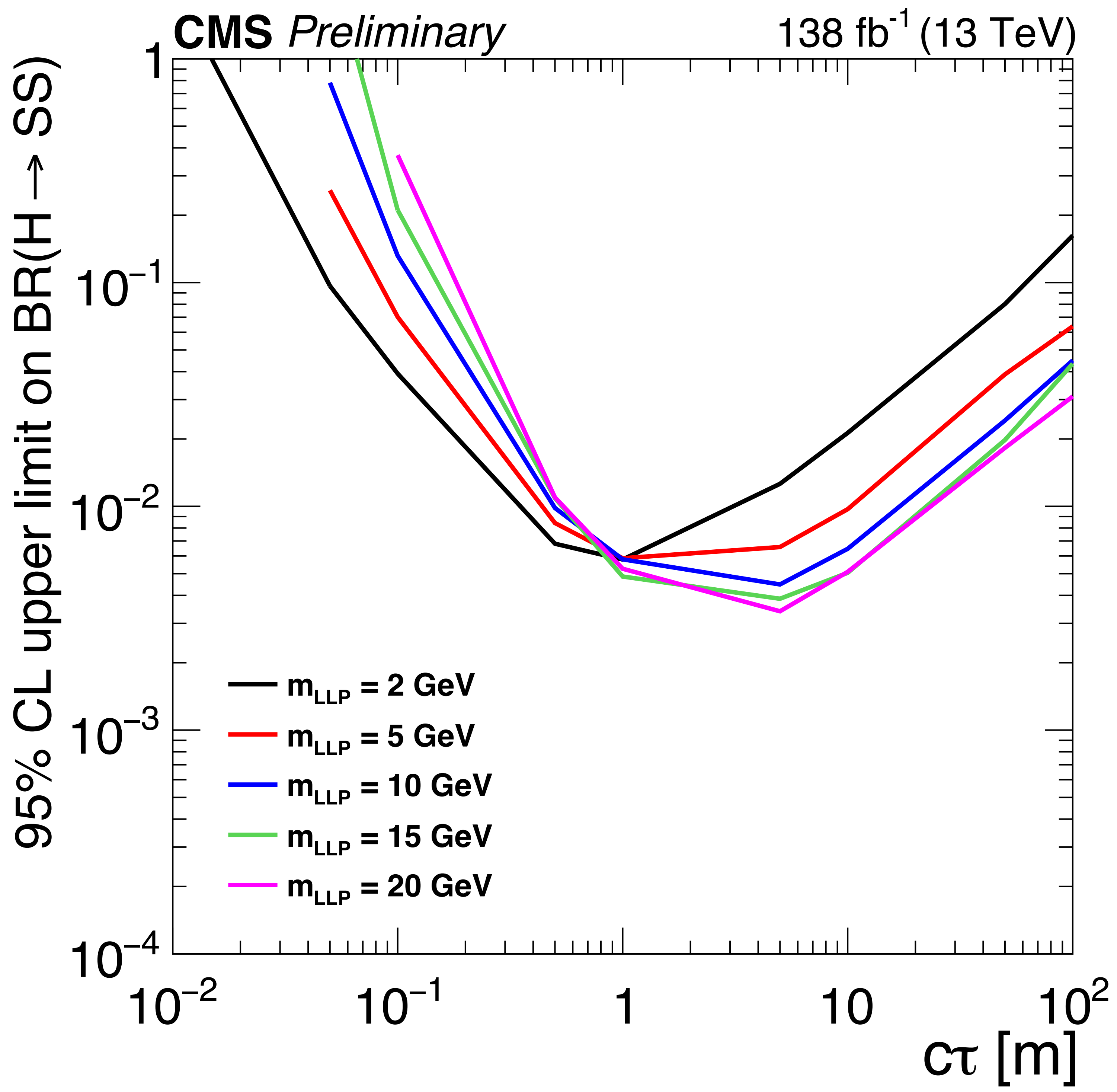
Gluon portal (hadronic shower)



Photon portal (photon shower)



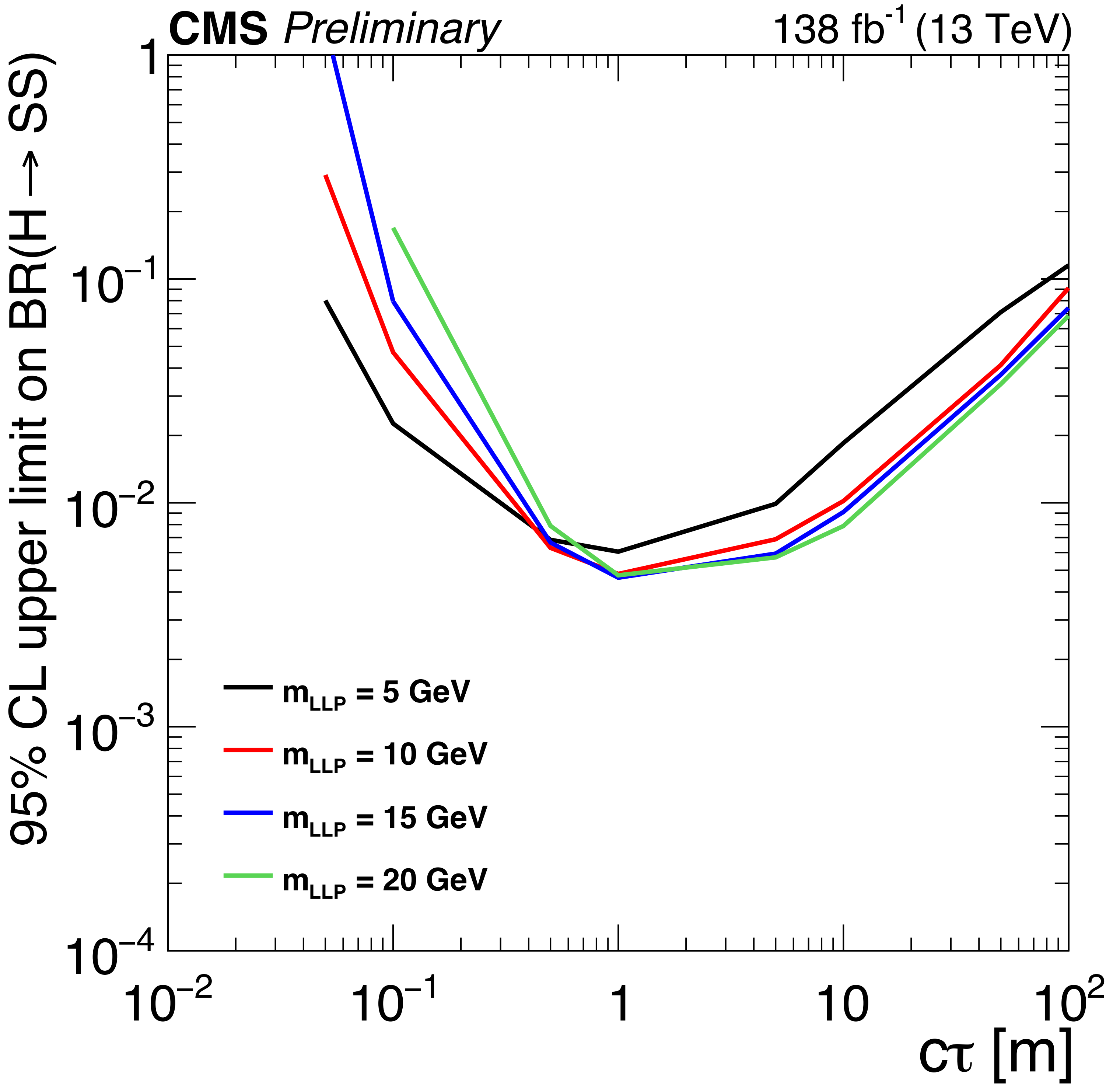
Vector portal (semi-visible shower)



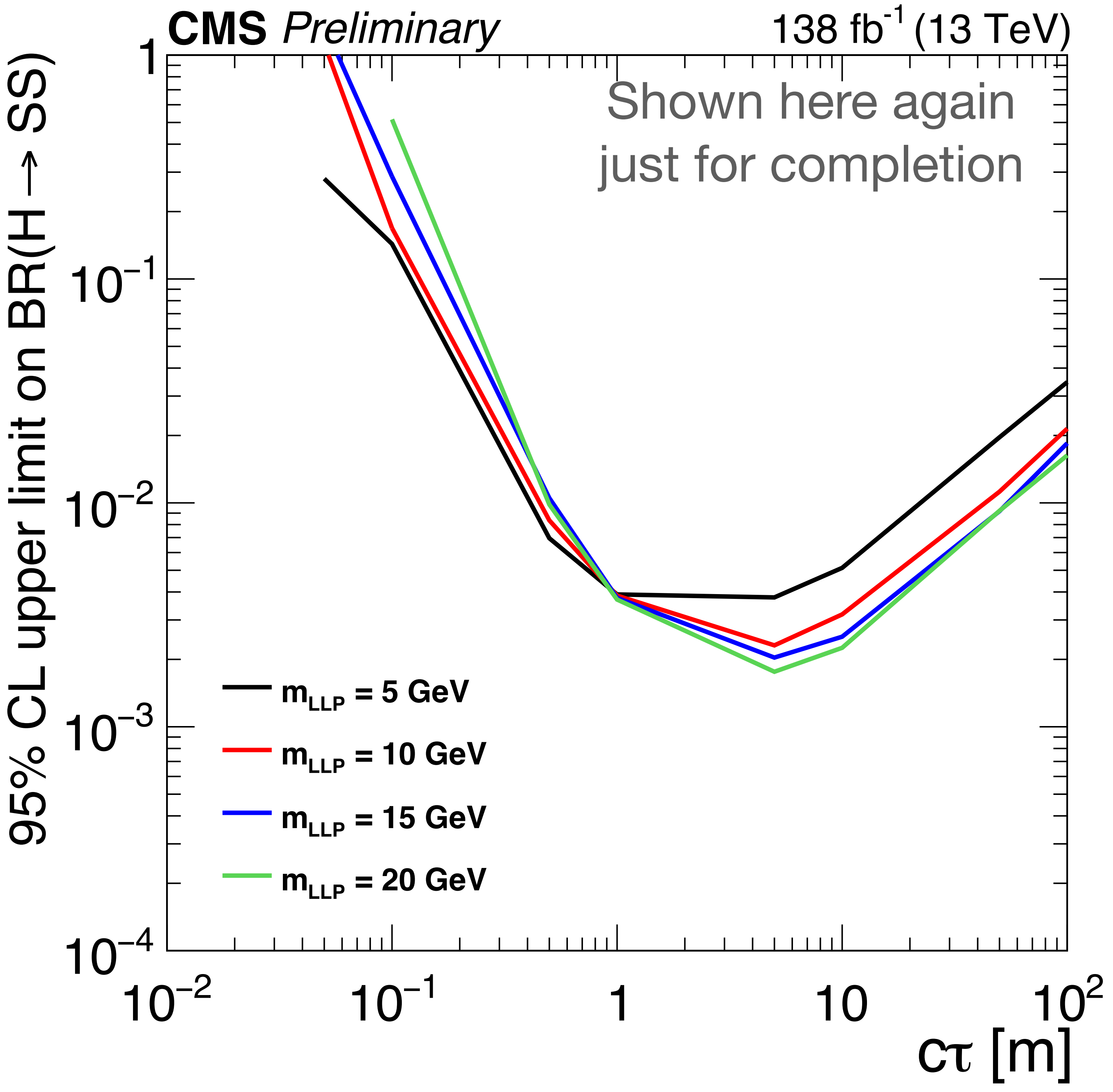
- **Achieve first sensitivity to dark shower model produced from Higgs decay at BR(H →ss) = 10^{-3} level**

Limits on Dark Shower Model (Gluon Portal)

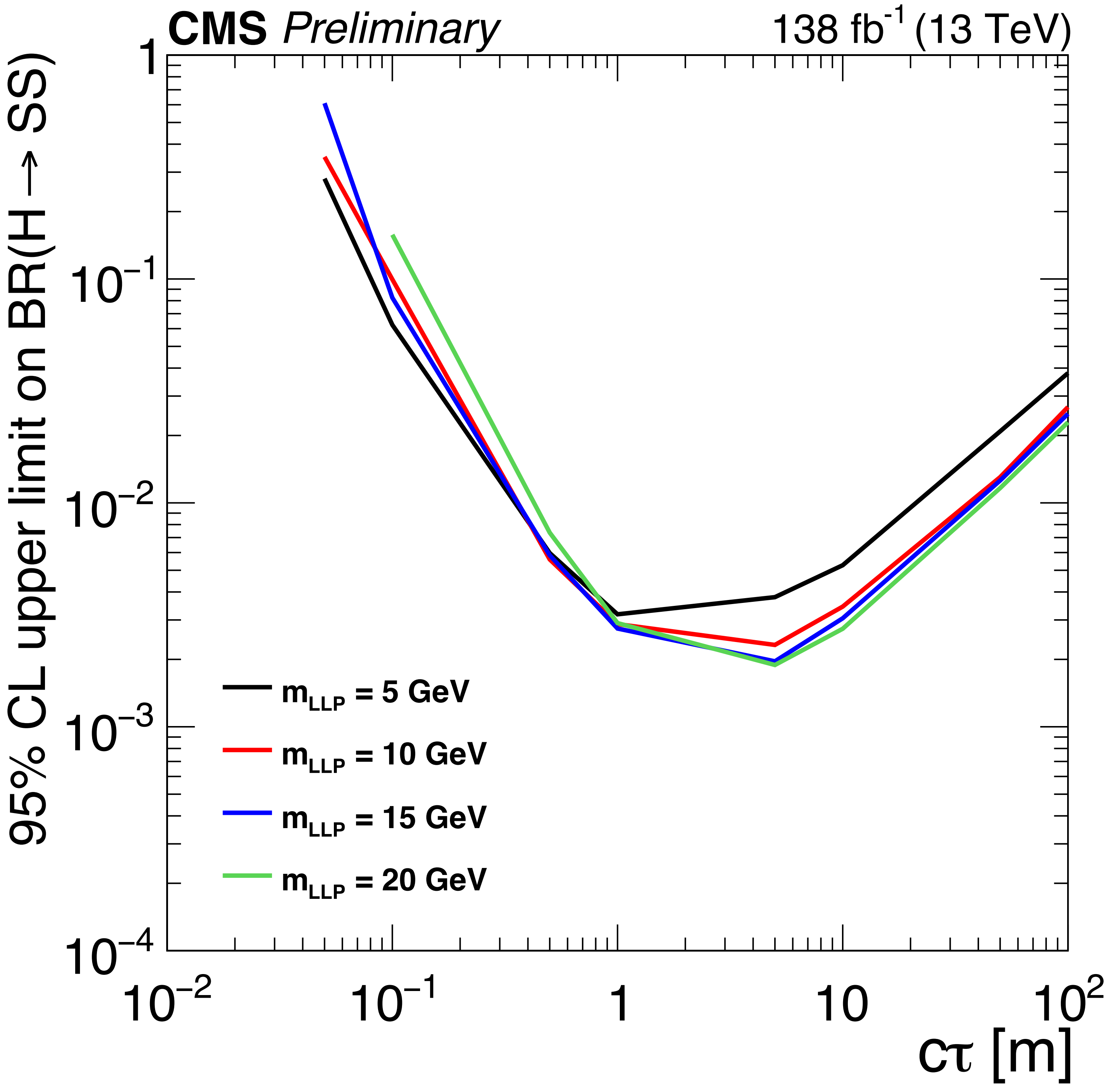
$(x_{i\omega}, x_{i\Lambda}) = (1,1)$



$(x_{i\omega}, x_{i\Lambda}) = (2.5,1)$

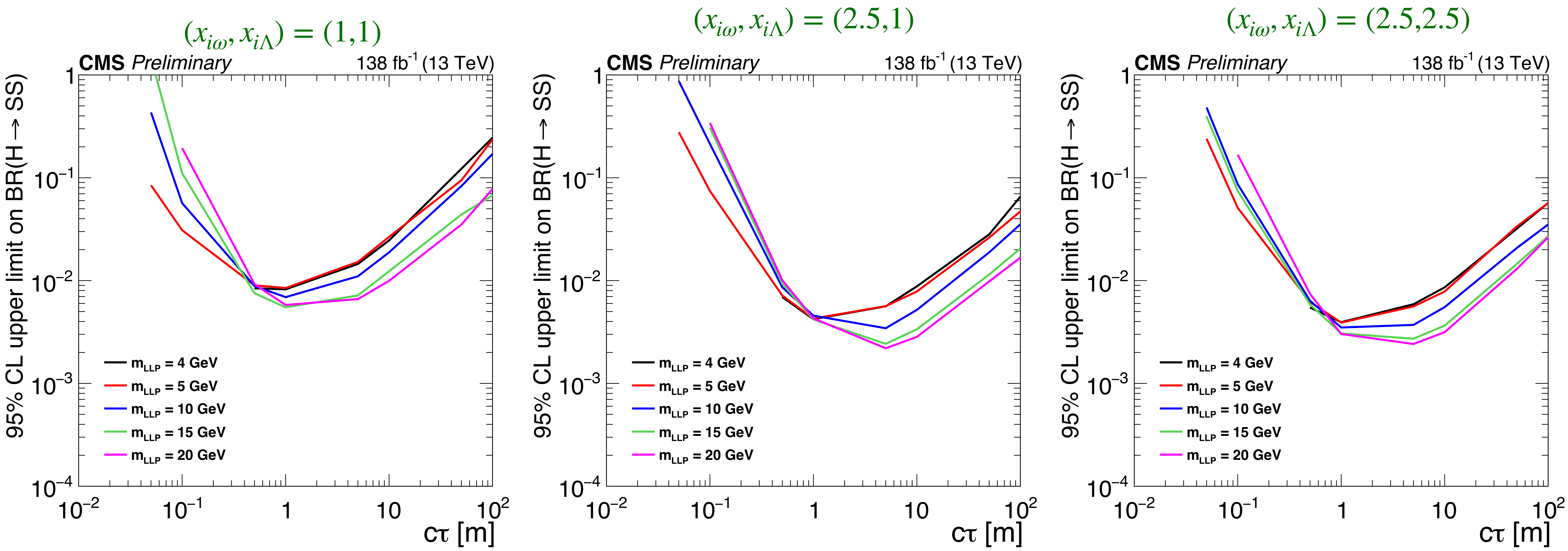


$(x_{i\omega}, x_{i\Lambda}) = (2.5,2.5)$



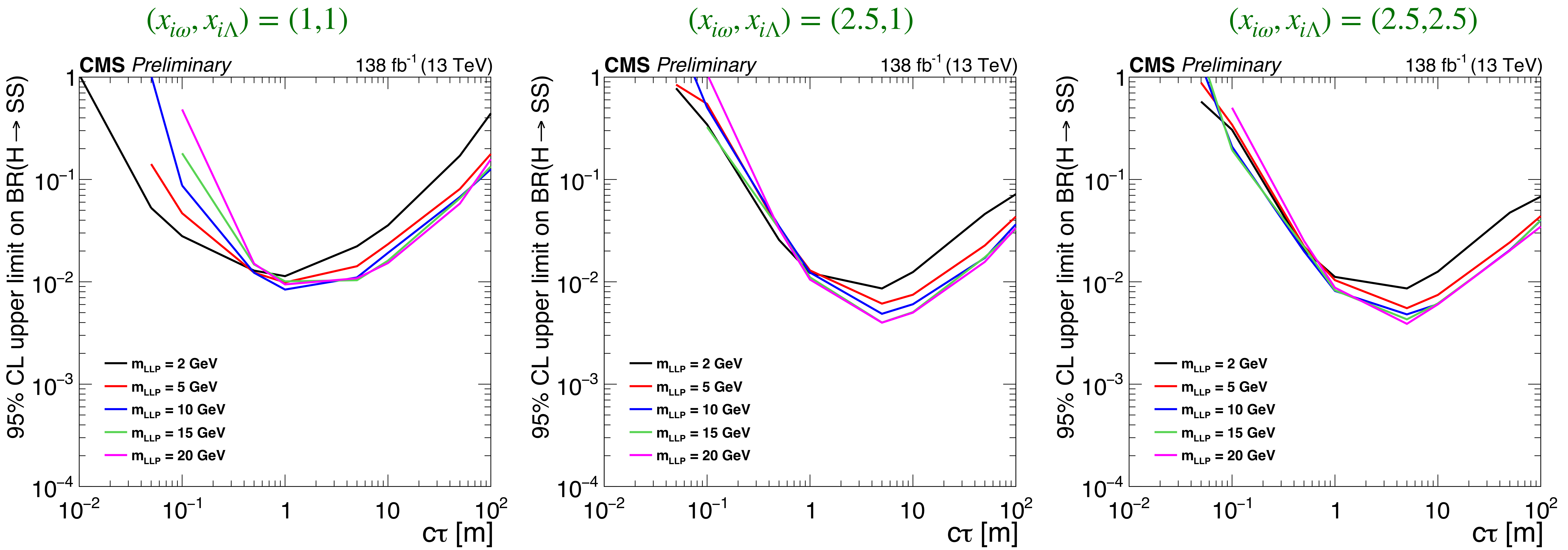
- Achieve first sensitivity to dark shower model produced from Higgs decay at BR(H →ss) = 10^{-3} level
  - Better sensitivity for fully visible showers as expected

Limits on Dark Shower Model (Higgs Portal)



- Achieve first sensitivity to dark shower model produced from Higgs decay at BR(H →ss) = 10^{-3} level
  - Better sensitivity for fully visible showers as expected

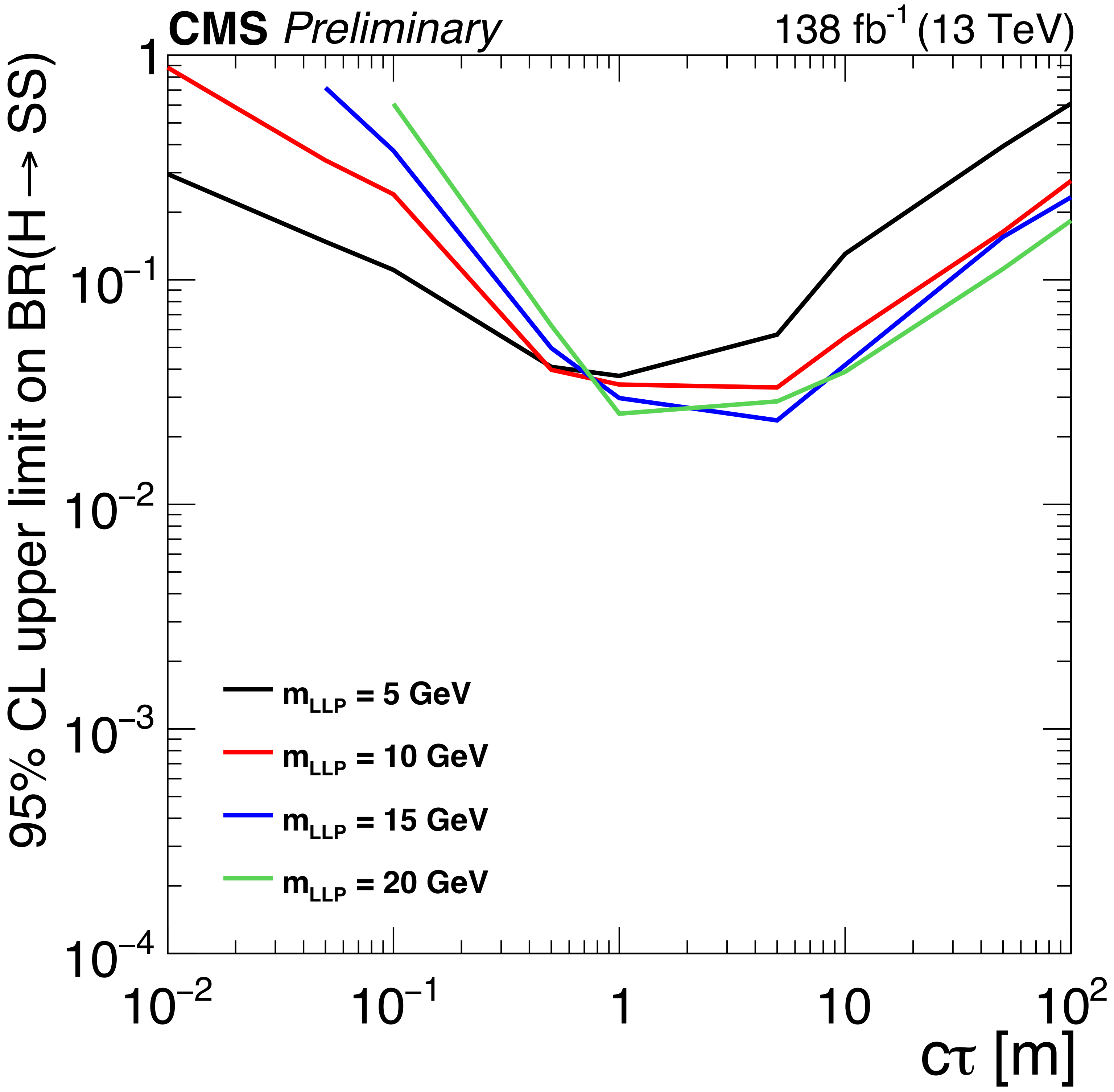
Limits on Dark Shower Model (Photon Portal)



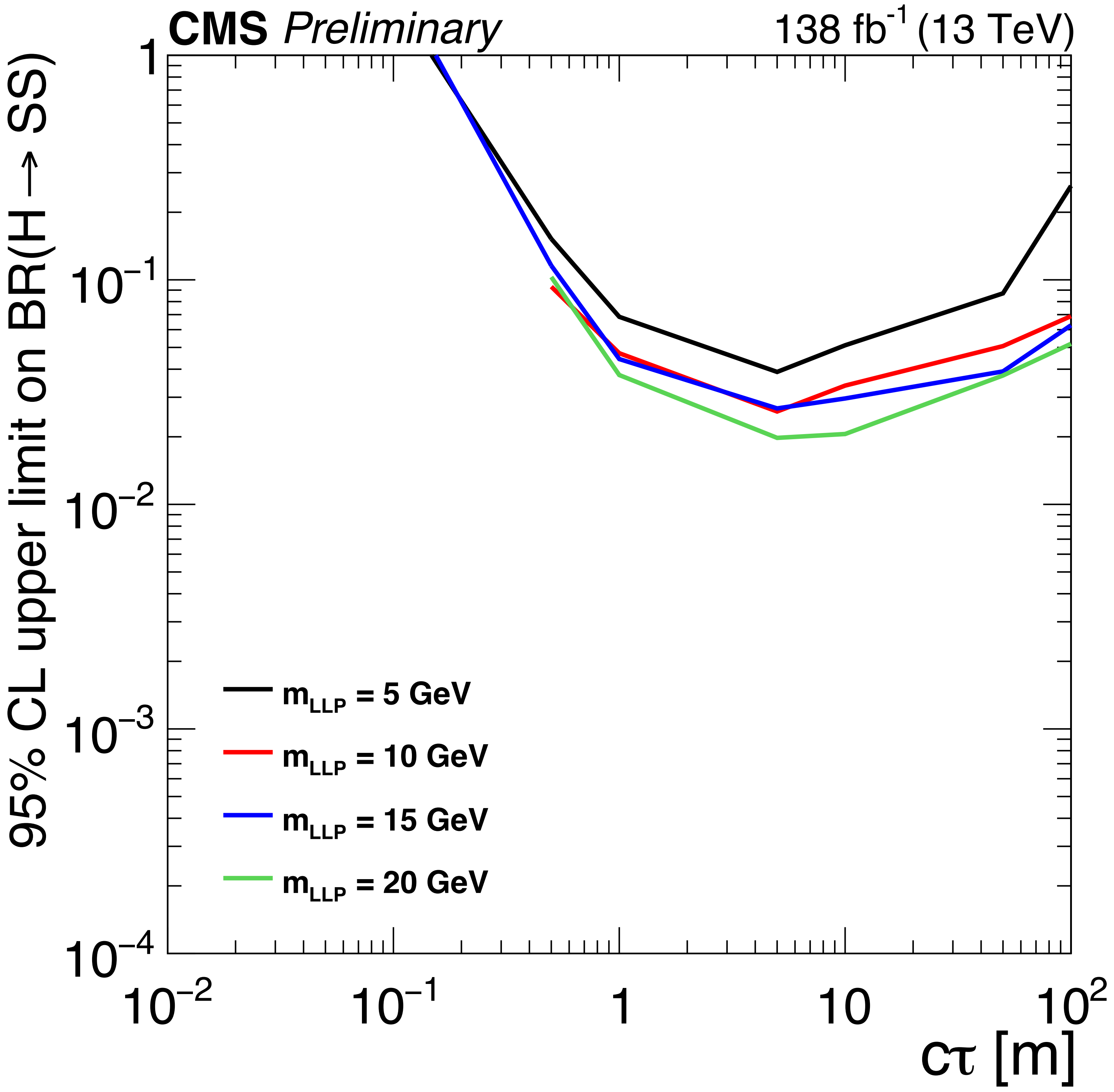
- Achieve first sensitivity to dark shower model produced from Higgs decay at BR(H →ss) ~ 4e-3
  - Sensitivity is slightly worse compared to fully hadronic showers, due to lower cluster reconstruction efficiency for EM showers
  - Better sensitivity for fully visible showers as expected

Limits on Dark Shower Model (Dark Photon Portal)

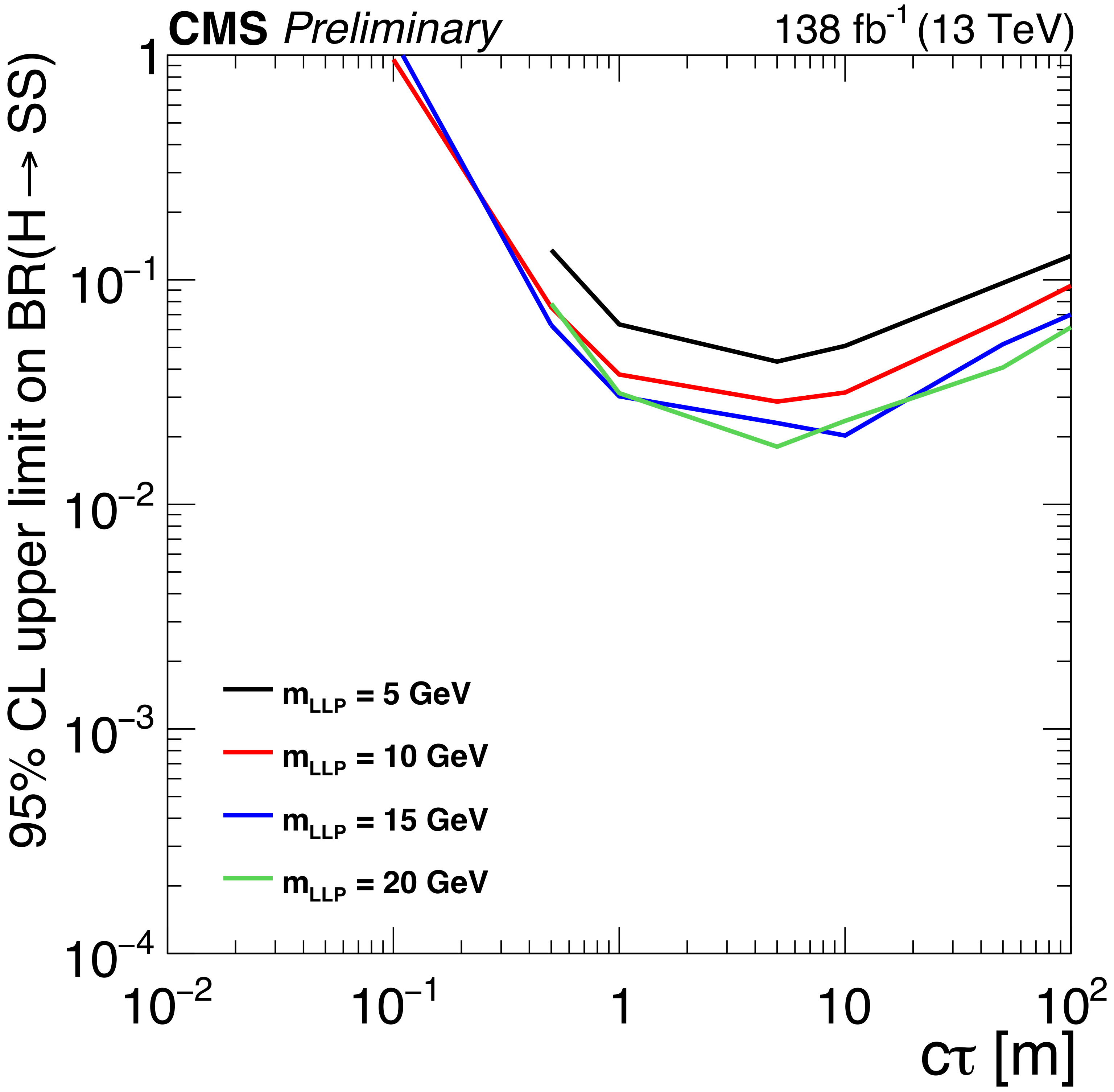
$(x_{i\omega}, x_{i\Lambda}) = (1,1)$



$(x_{i\omega}, x_{i\Lambda}) = (2.5,1)$



$(x_{i\omega}, x_{i\Lambda}) = (2.5,2.5)$



- Achieve first sensitivity to dark shower model produced from Higgs decay at BR(H →ss) ~ 1e-2
- In the dark photon portal, dark scalar meson promptly decays to two dark photons (LLPs) that decay back to SM → LLP multiplicity doubles compared to other portals
- Jet veto efficiency is much lower in dark photon portal, since LLPs that decay in tracker and create jets can veto the muon detector shower