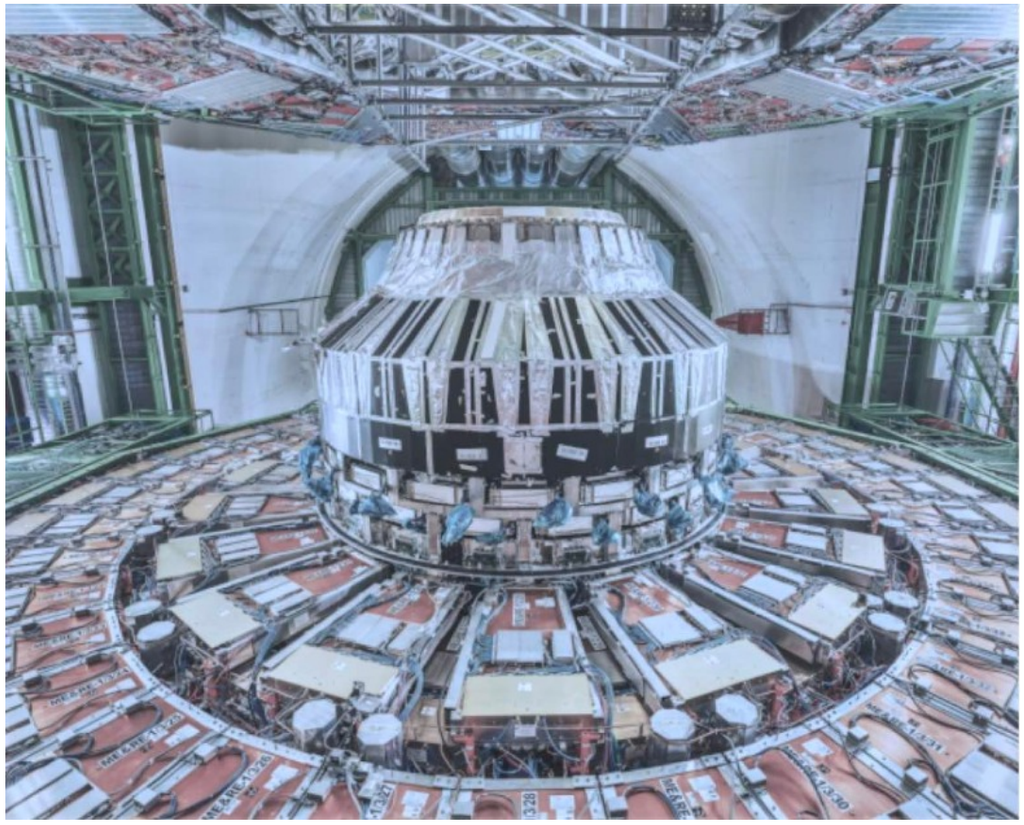
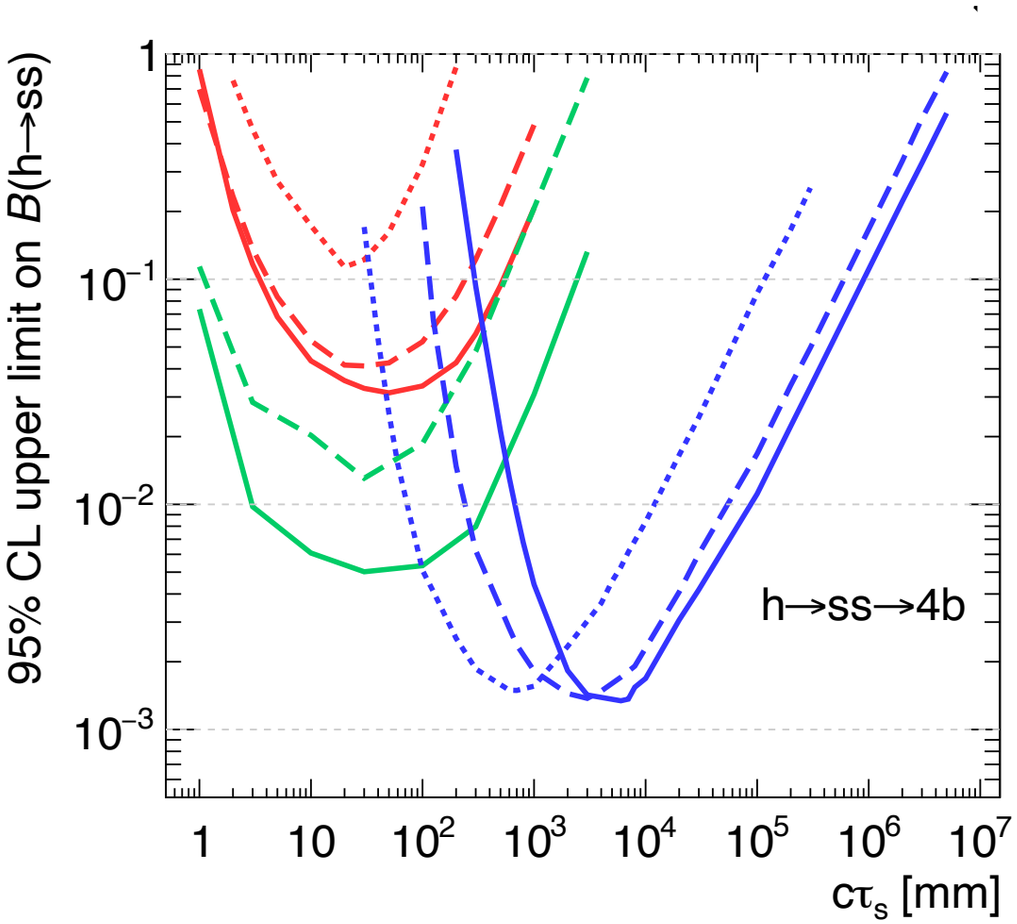
Long-lived Particles at CMS





Cristián H. Peña

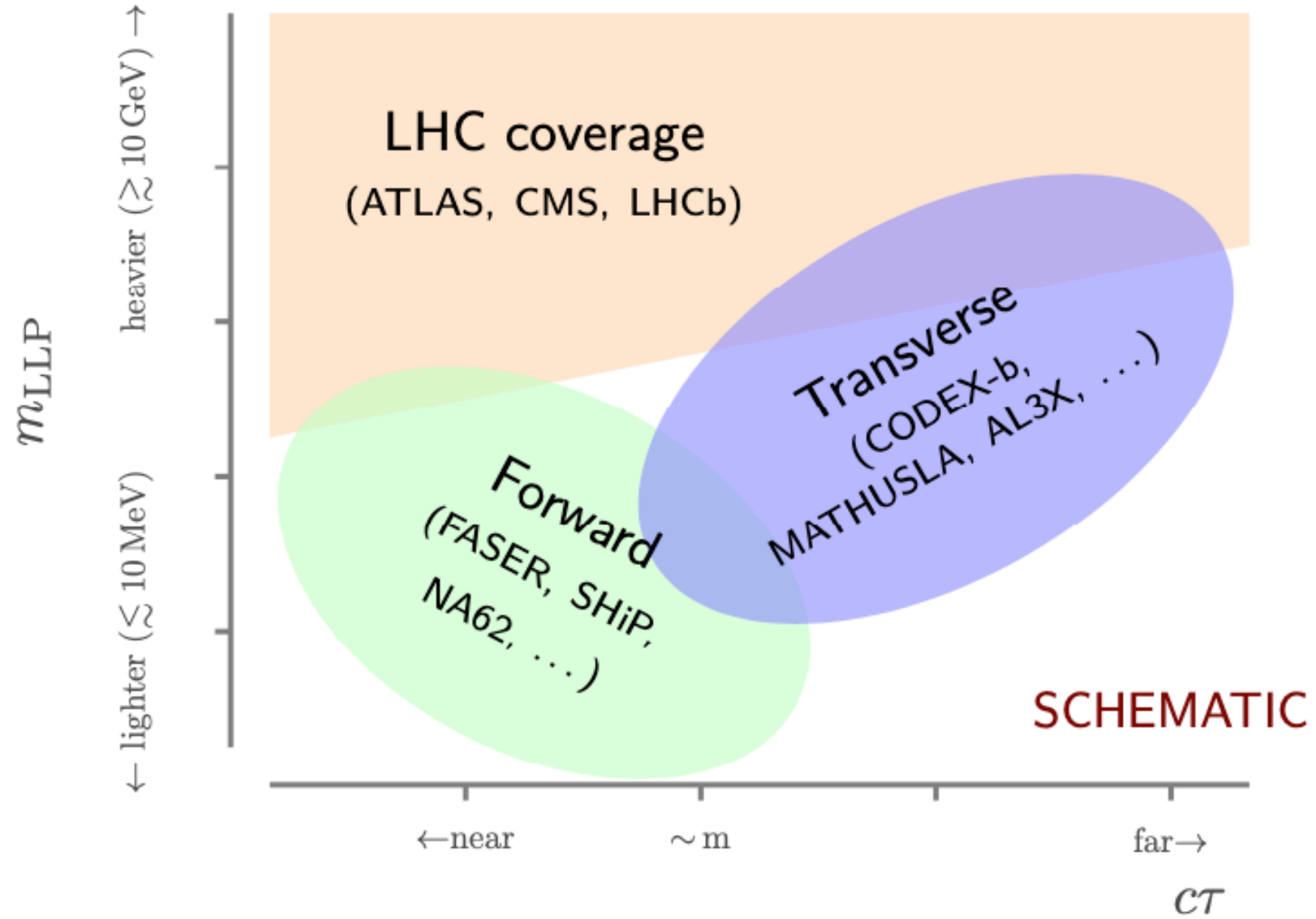
Fermilab

May 25 2021

9th workshop of the LLP Community

CMS and LLPs

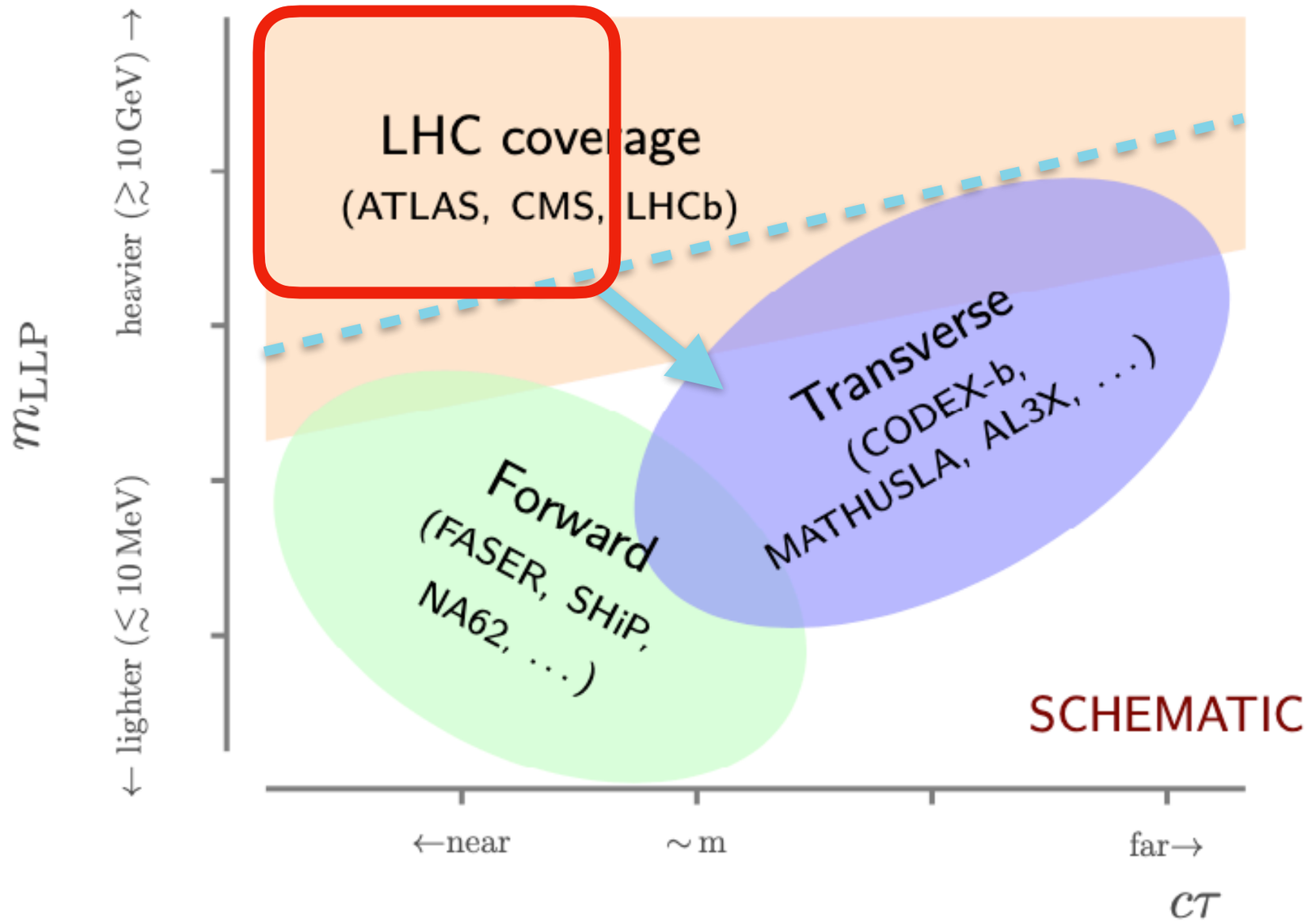
arxiv:1911.00481 — CODEX-b



- How to unlock CMS' full LLP discovery reach?
- How far can we extend the mass and lifetime?

CMS Plays a Crucial Role on LLPs

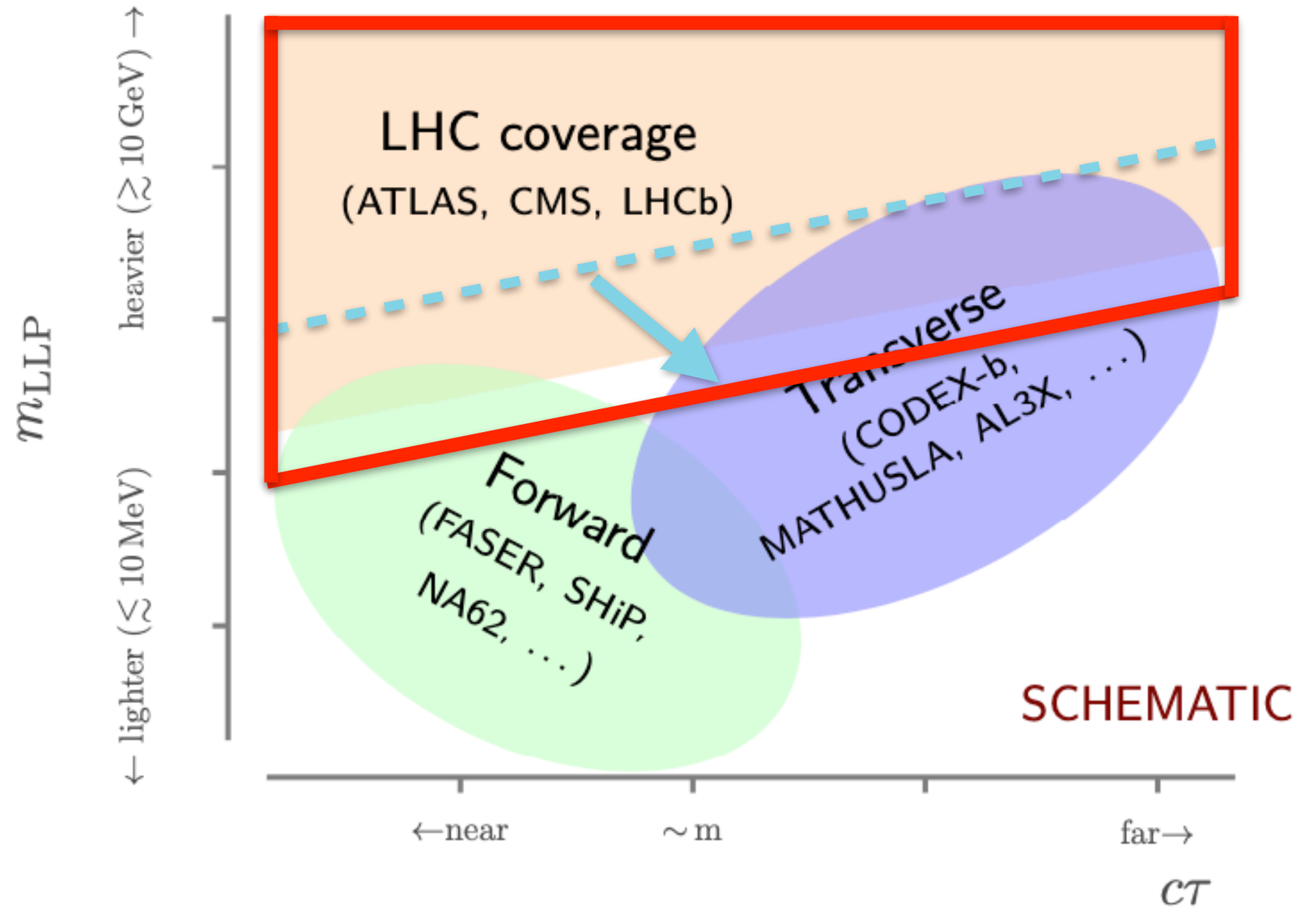
arxiv:1911.00481 — CODEX-b



- CMS is doing well for **cτ < 1m** and **m_{LLP} > 50 GeV**
- Enabled by precision tracker: displaced jets

CMS Plays a Crucial Role on LLPs

arxiv:1911.00481 — CODEX-b

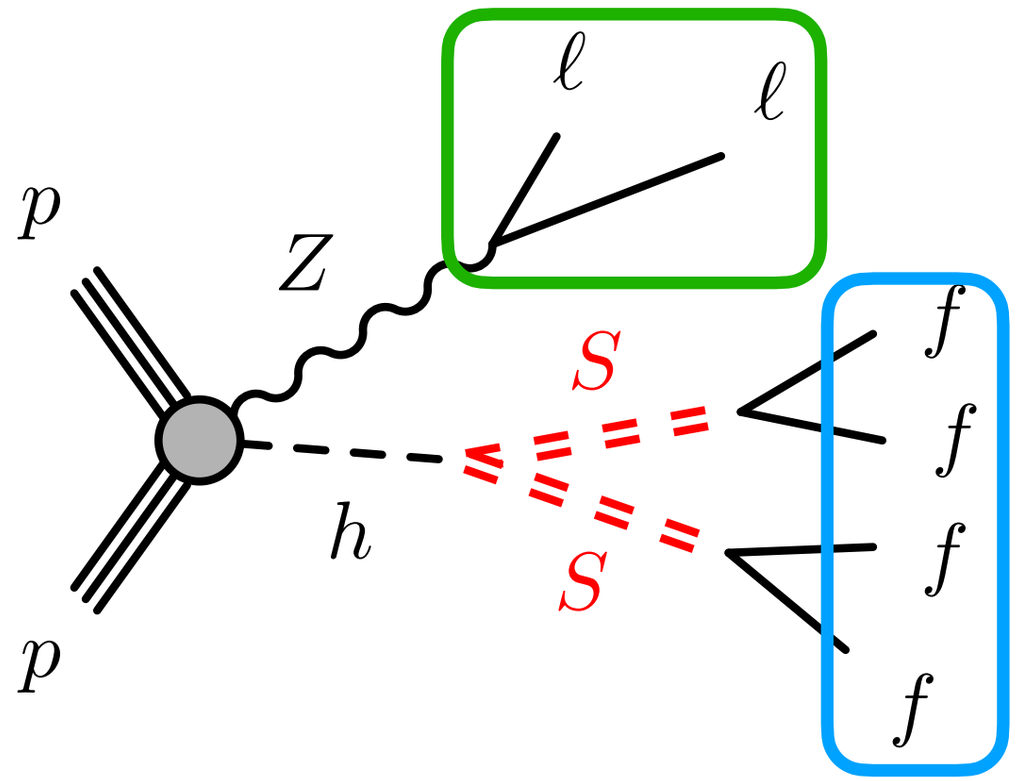


- Goal: close coverage gaps and extend CMS reach
- Strategy: Enable a **large cτ** and **light LLP** searches

EXO-20-003

Search for LLP in associating with a Z

- **Tracker-based quantities**
  - **LLPs make displaced-jet**
- **Access light LLPs**
  - **trigger on Z→$\ell\ell$**
- **New CMS sensitivity to light LLPs**



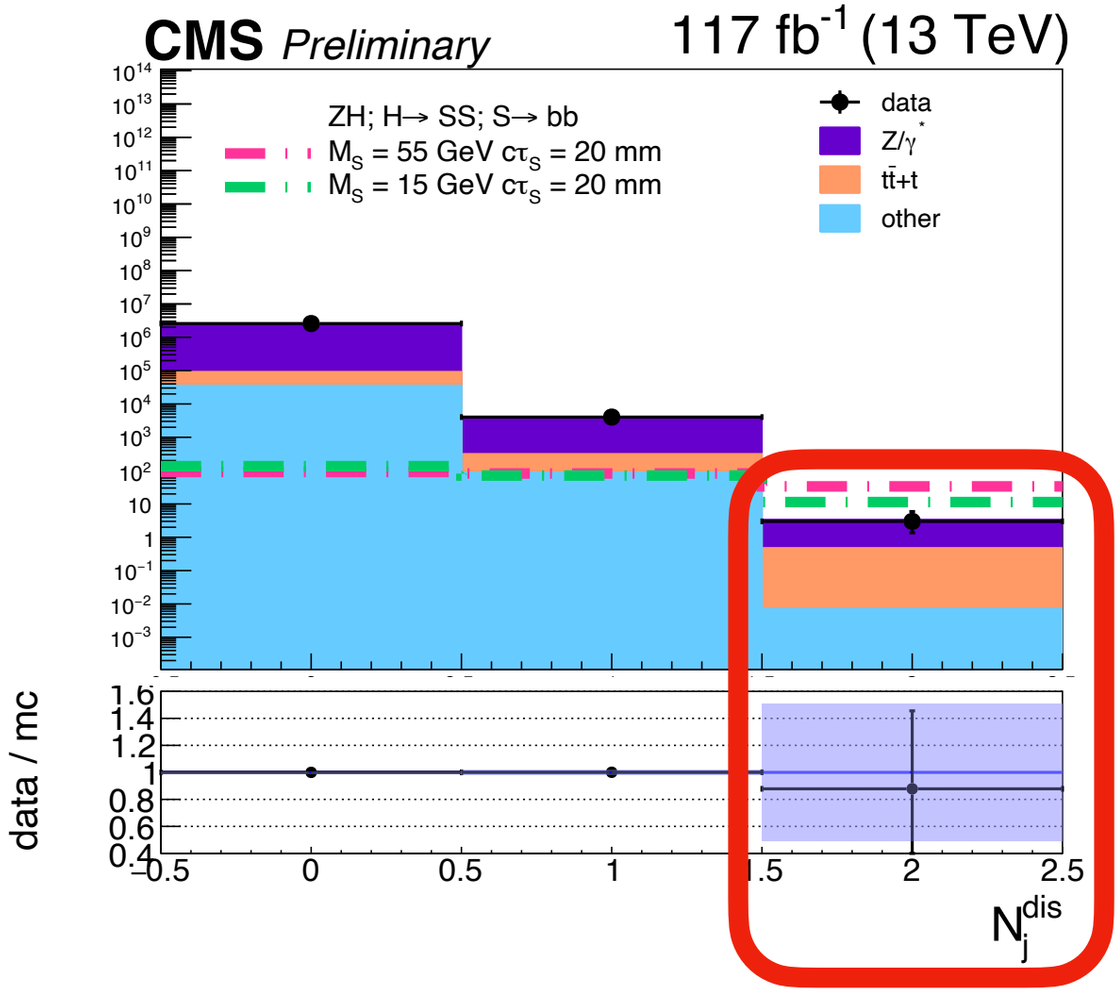
Signal: up to 4 displaced jets

See D. Diaz talk

EXO-20-003

Search for LLP in associating with a Z

Bkg falls rapidly when counting the number of displaced jets (N_j^{dis})

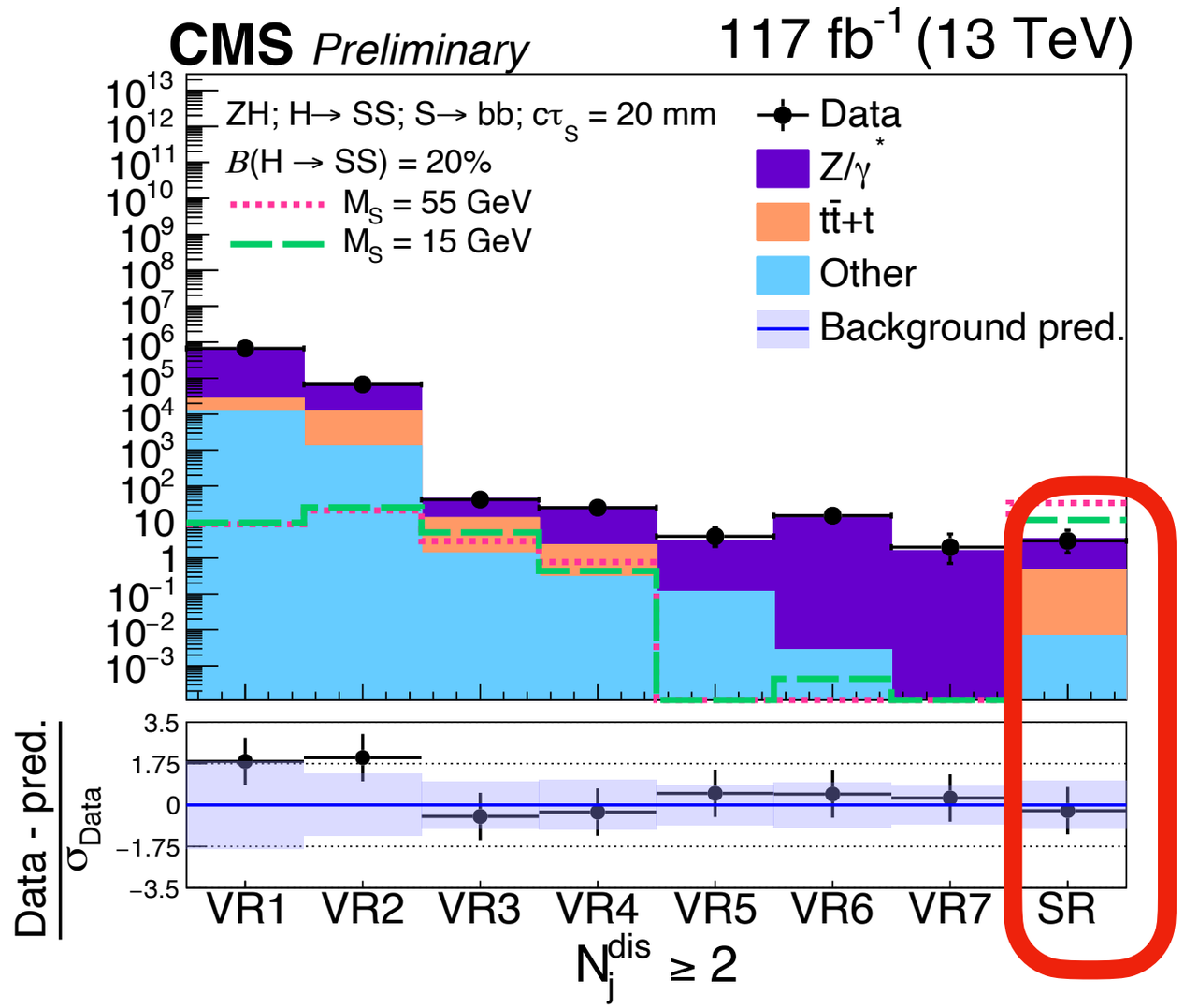


LLP signals tend to have events with 2 or more displaced jets (N_j^{dis})

EXO-20-003

Search for LLP in associating with a Z

- N_j^{dis} >=2 defines the signal region
- We define 7 validation samples to check the bkg estimation

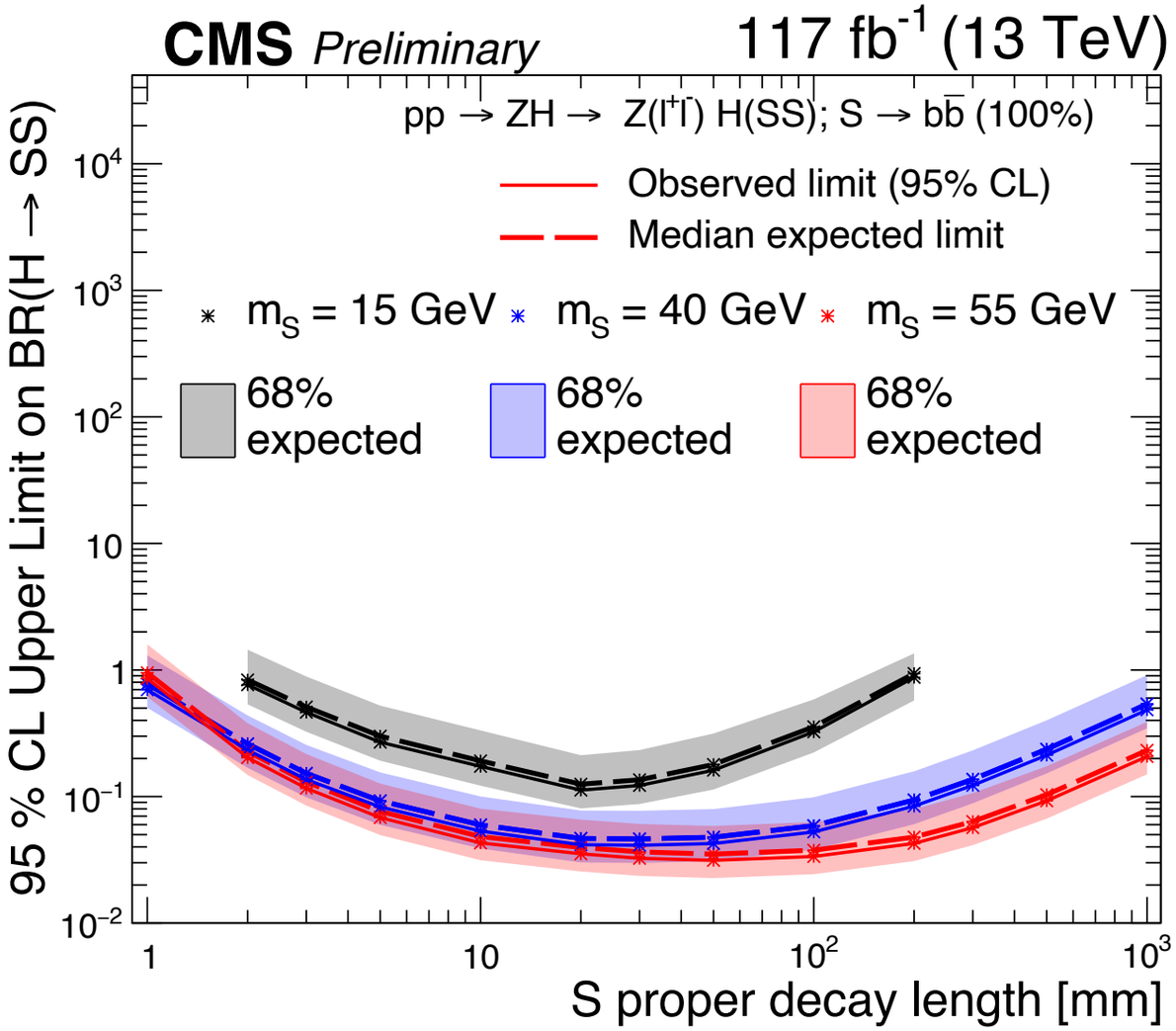


Expected bkg = 3.5 +/- 1.8 **Observed = 3**

EXO-20-003

Search for LLP in associating with a Z

Best sensitivity at BR(H→SS) ~ 5×10^{-2} !!



CMS new result

- **ENABLED new CMS LLP sensitivity to light LLP**
- **Access LLPs as light as 15 GeV with tracker-based (~1-100 mm) search**

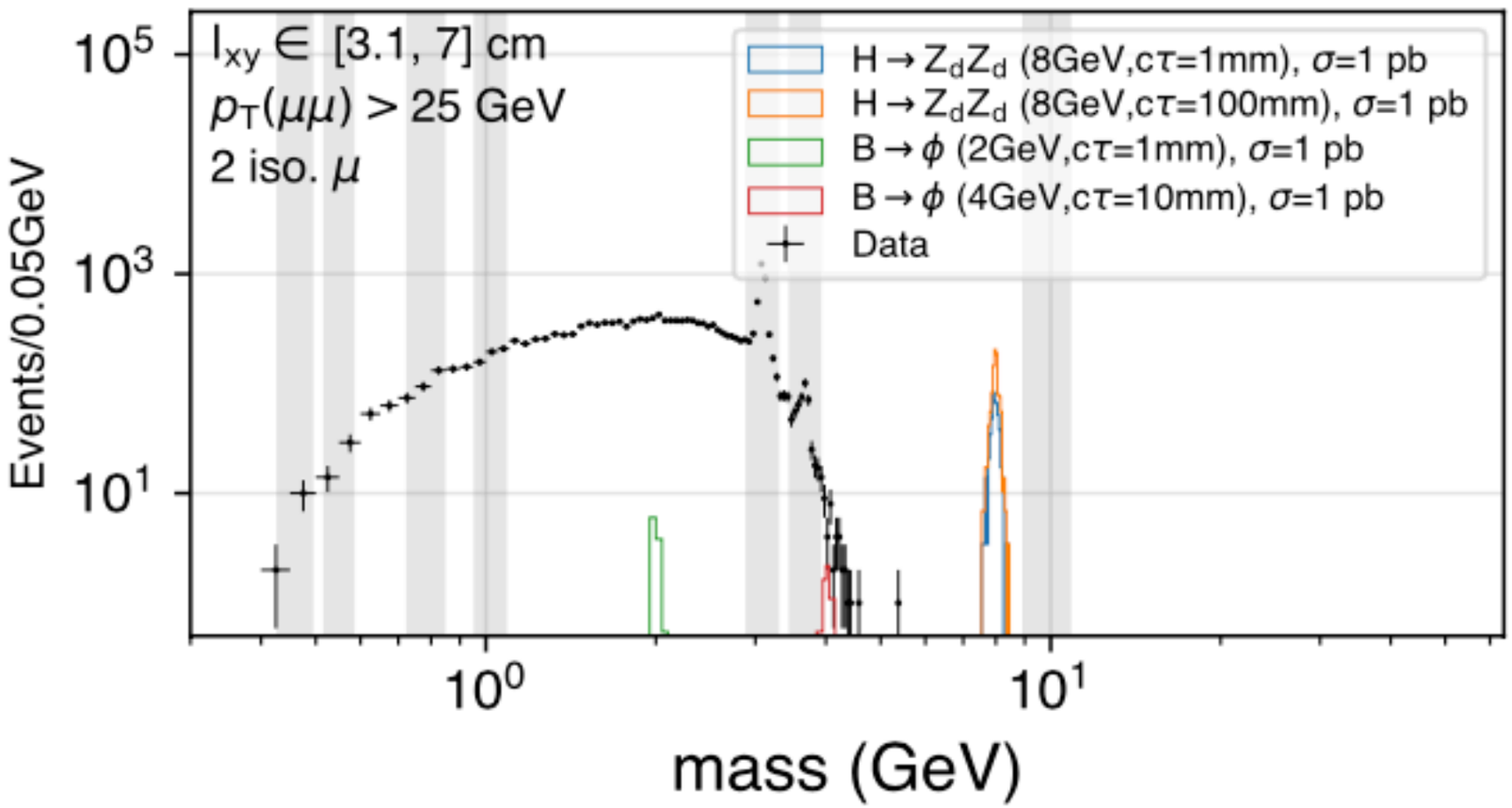
EXO-20-014

Displaced low-mass dimuons

Dimuon scouting allows unprecedented mass reach

$$m_{\mu\mu} \gtrsim 200\,\mathrm{MeV}$$

Strategy: Find low-mass μμ resonances and associated DV

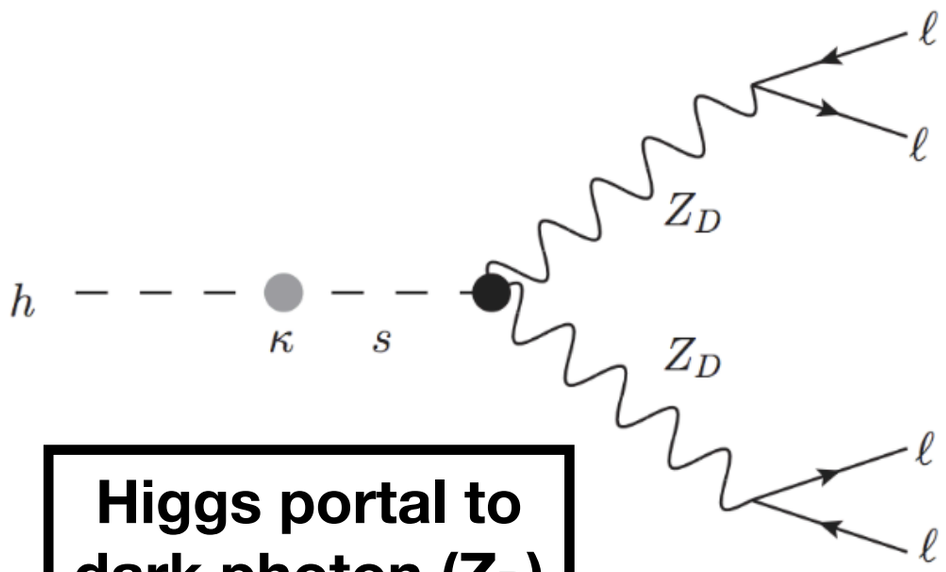


l_{xy}: **Transverse displacement of the μμ-DV**

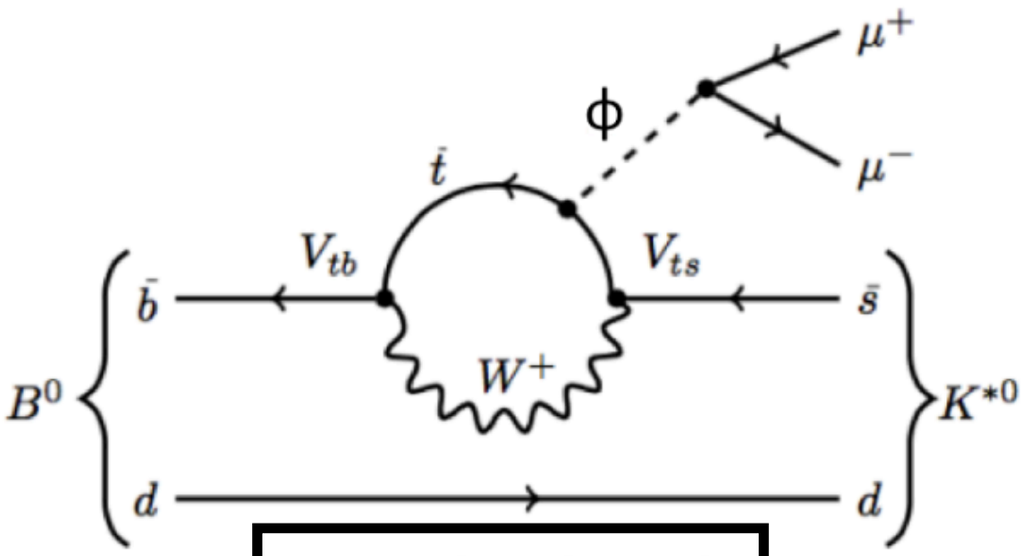
See H. Routray talk

EXO-20-014

Displaced low-mass dimuons



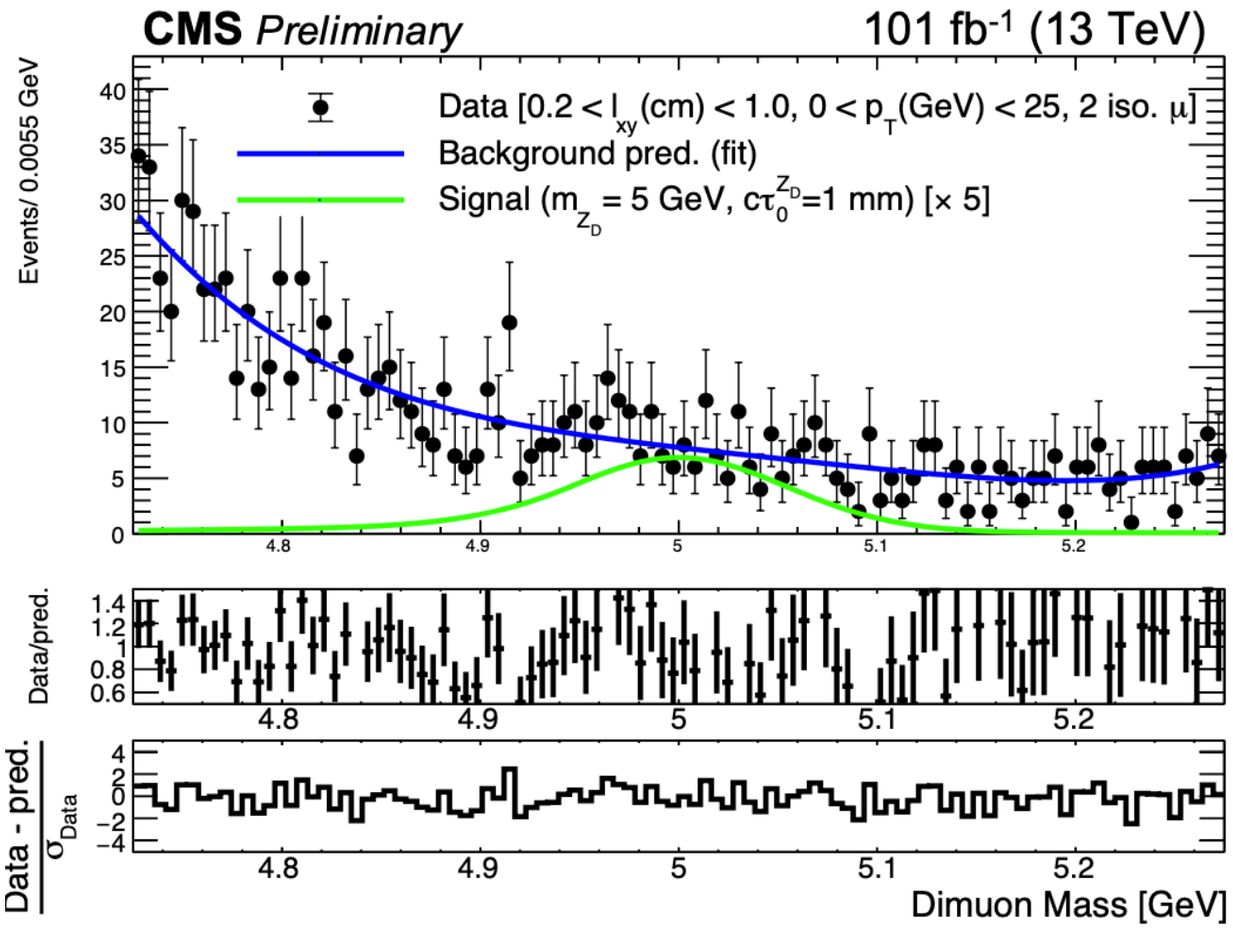
Higgs portal to dark photon (Z_D)



ϕ production via B-hadron decay

Fit $m_{\mu\mu}$ with S+B model

36 total search bins (l_{xy}, pT$^{\mu}$, isolation)

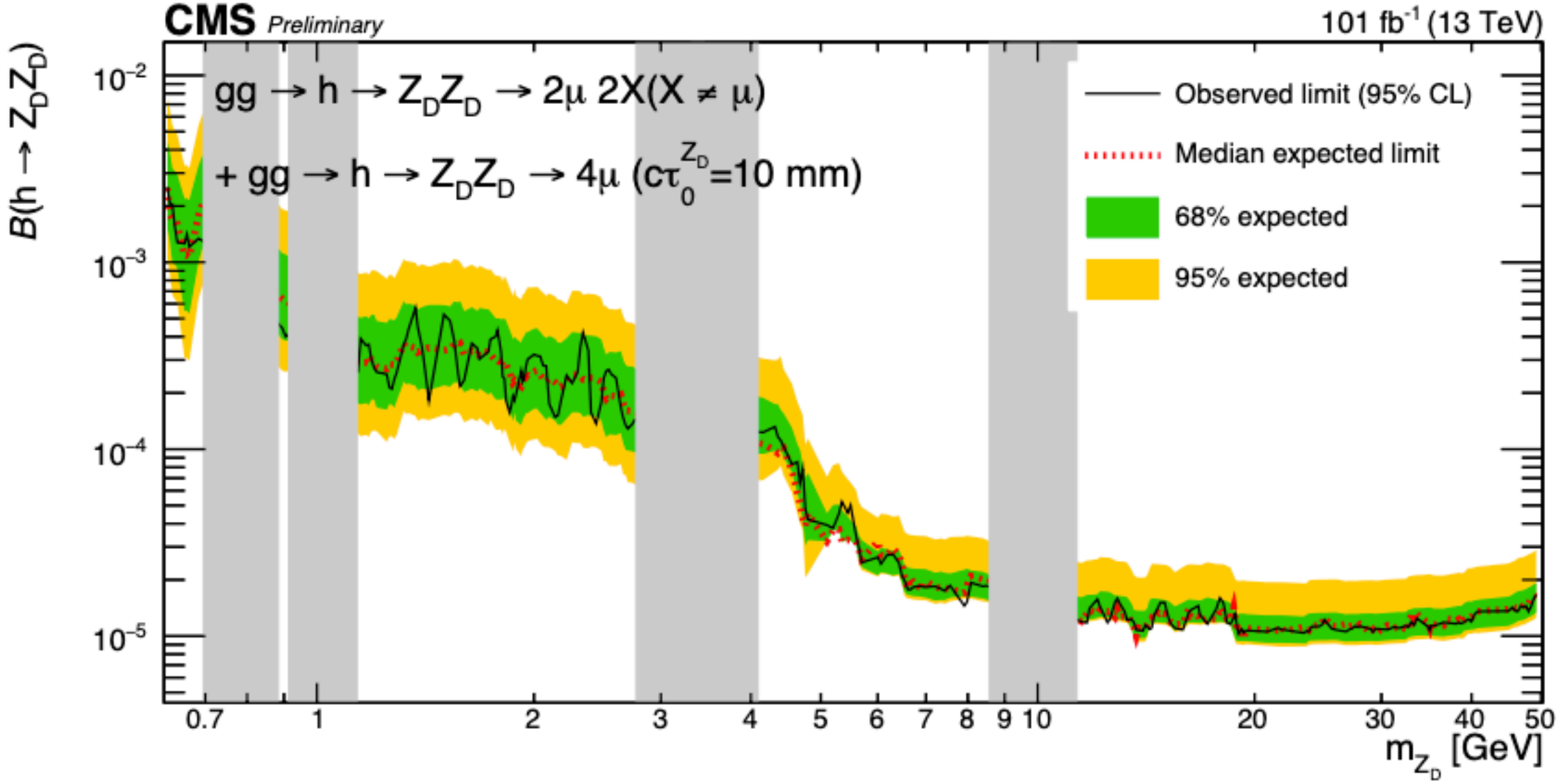


No excess found

EXO-20-014

Displaced low-mass dimuons

$\mathcal{B}(Z_D \to \mu\mu)$ from *JHEP* 02 (2015) 157 **Including 4μ category**



- **$\mathcal{B}(h \to Z_D Z_D)$ exclusion ~3e-3 for m_{Zd} ~1-3 GeV**
- **$\mathcal{B}(h \to Z_D Z_D)$ exclusion ~2e-4 for m_{Zd} ~11-50 GeV**

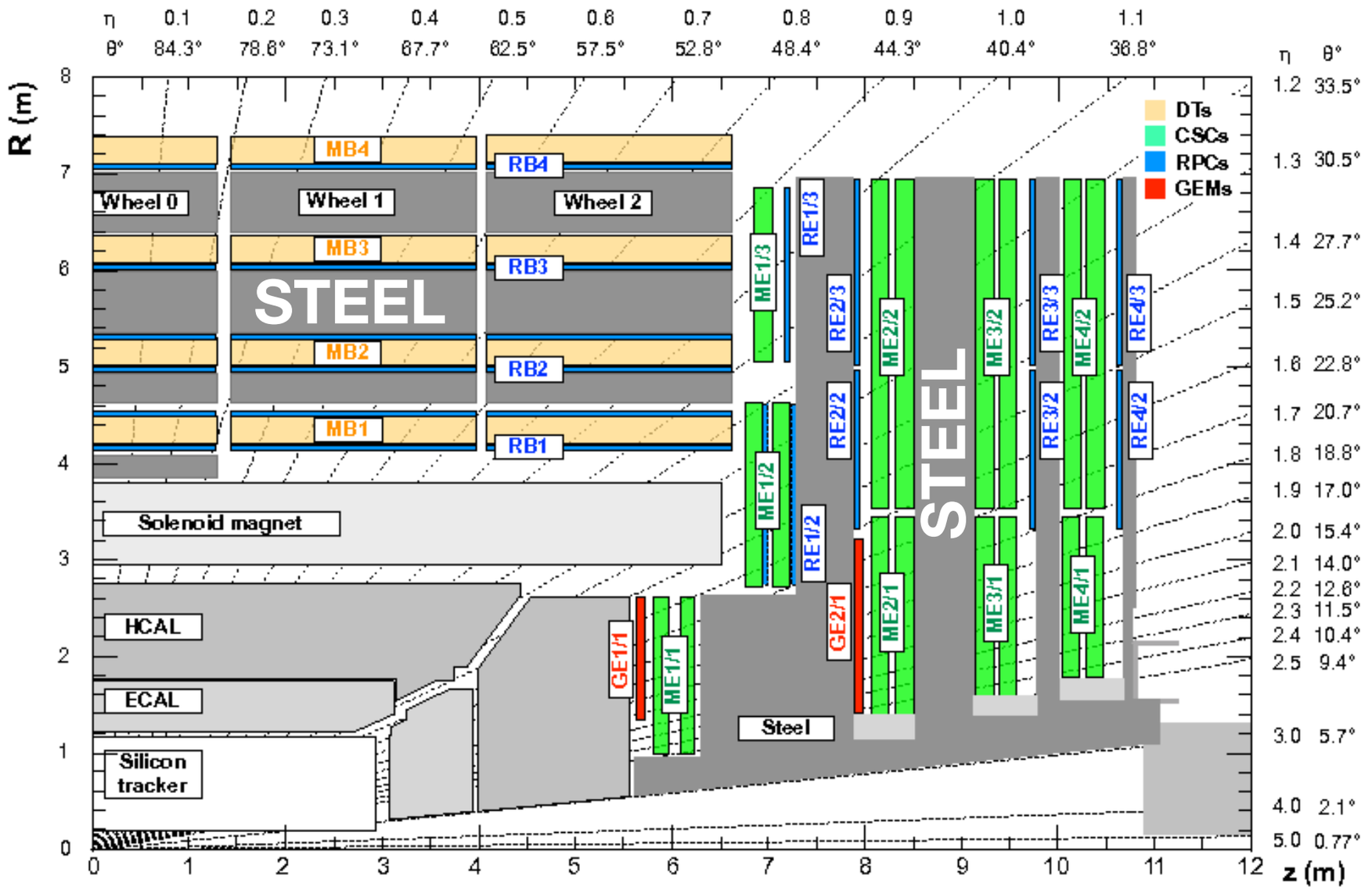
Extending reach to large $c\tau$

EXO-20-015

See C. Wang talk

Compact Muon Solenoid

COMPACT Design + Small $\pi \rightarrow \mu$ **mis-ID** (10^{-3})

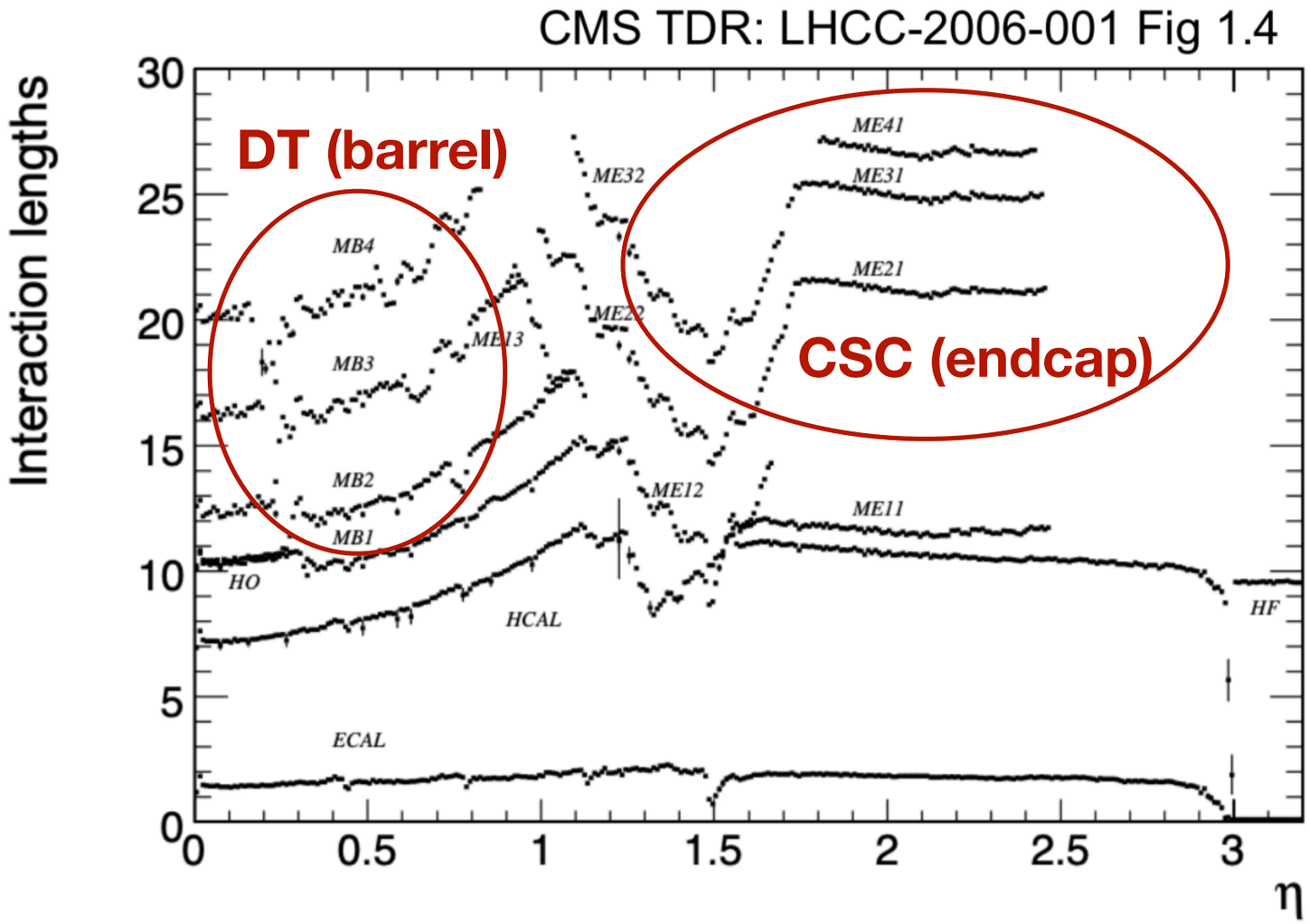


- Lots of STEEL →bkg suppression → Ideal for LLP searches
- 4-layers of highly segmented active element → LLP signal

EXO-20-015

LLP Muon System Analysis

- Despite the lack of a dedicated trigger, CMS has opportunity to provide better sensitivity for 1 displaced vertex search. **CMS has more steel to reject background**

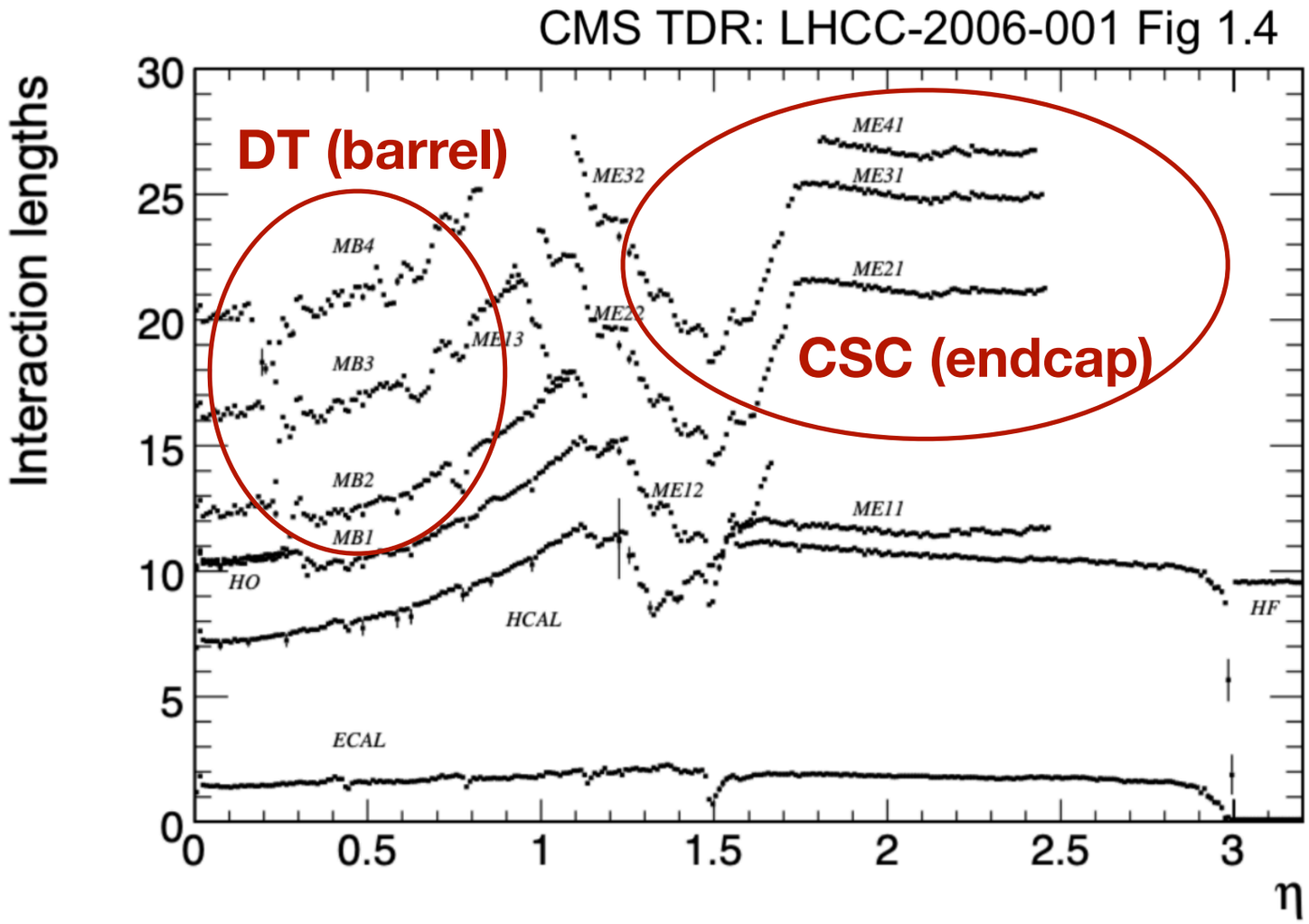


- **Large shielding against bkgs: 12-27 nuclear interaction lengths**

EXO-20-015

LLP Muon System Analysis

- Despite the lack of a dedicated trigger, CMS has opportunity to provide better sensitivity for 1 displaced vertex search. **CMS has more steel to reject background**

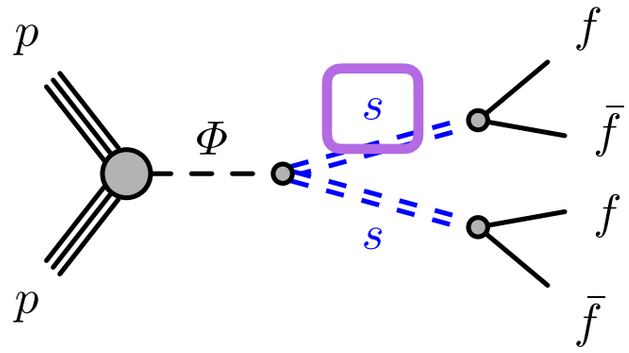


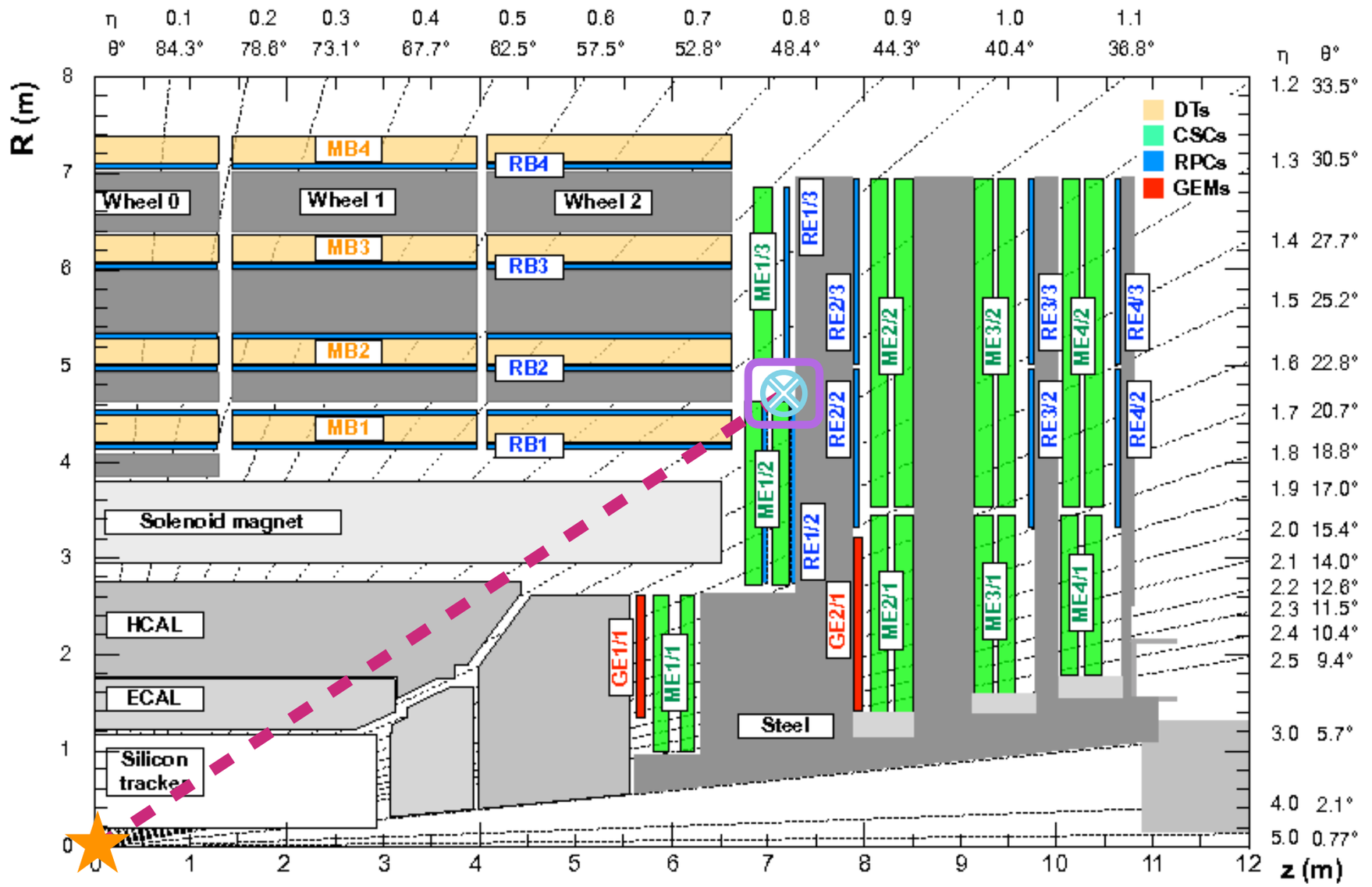
- Opportunity to **extend discovery reach at large lifetimes (> ~few 10 meters)**

EXO-20-015

Search for LLPs in Muon System

LLP decays in MS → shower

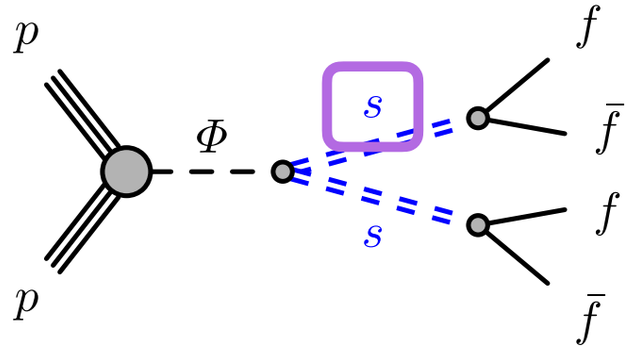




→ LLP (s) decay

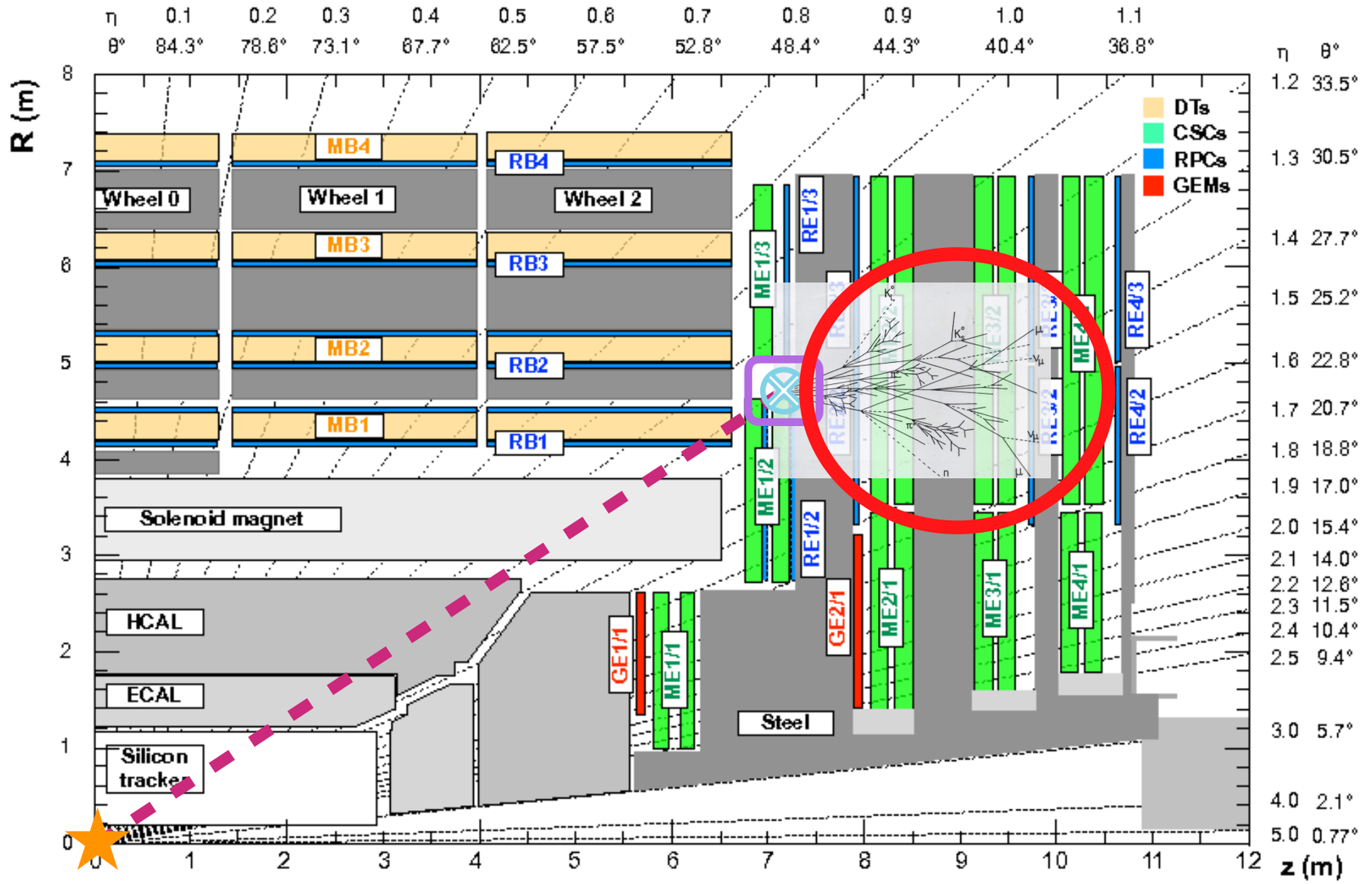
EXO-20-015

Search for LLPs in Muon System



LLP decays in MS → shower

Muon System acts as sampling calorimeter



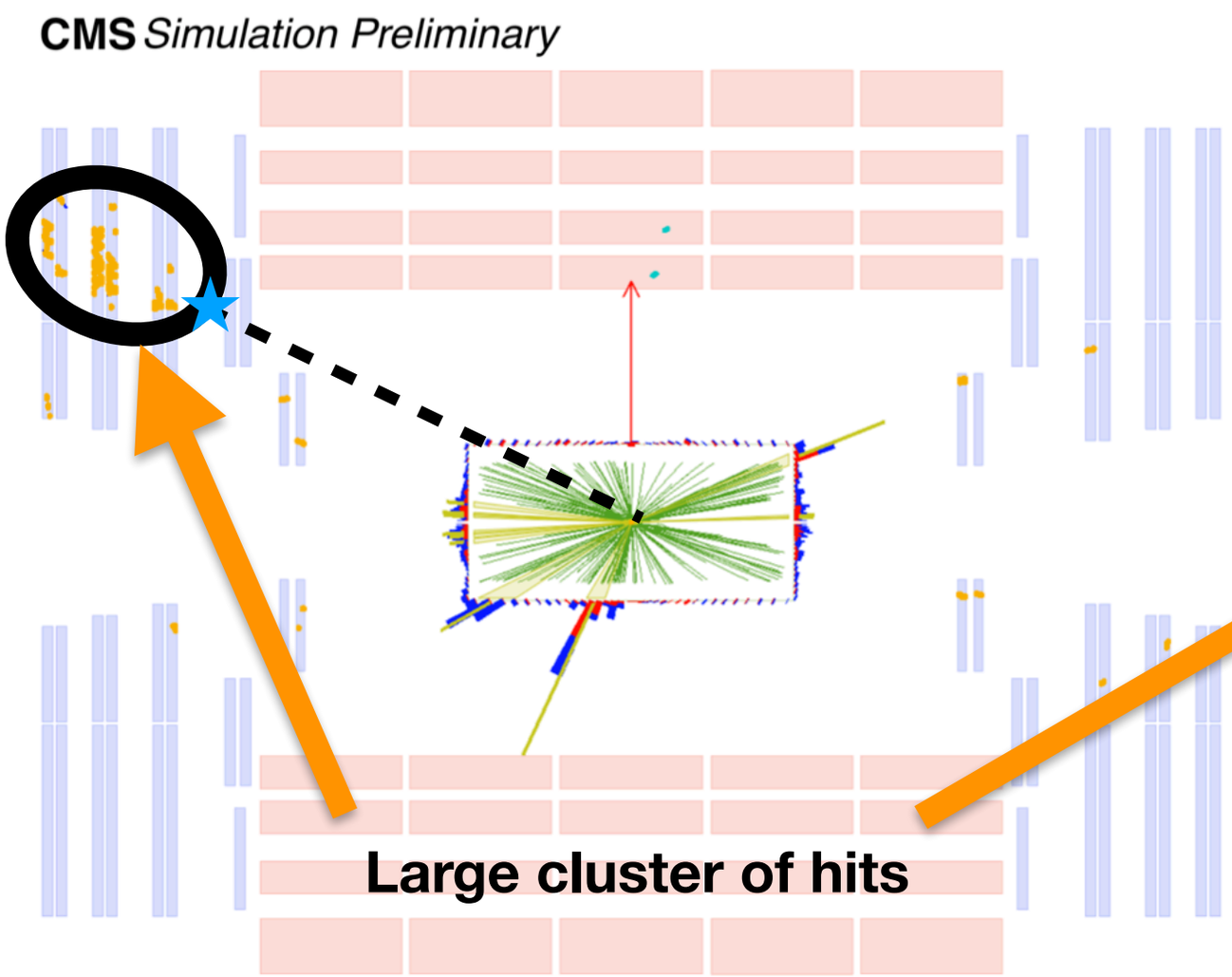
Sensitive to a broad range of LLP decays

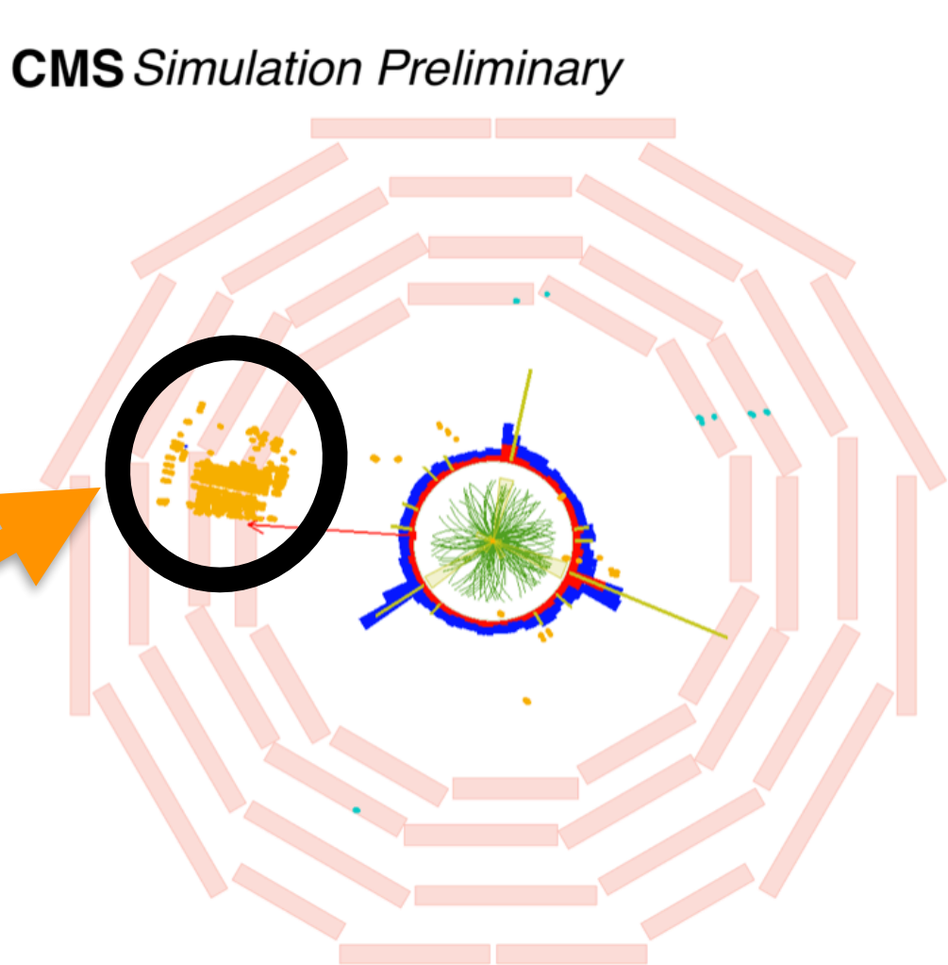
EXO-20-015

LLP Signature in Muon System

First time this signature is explored in CMS

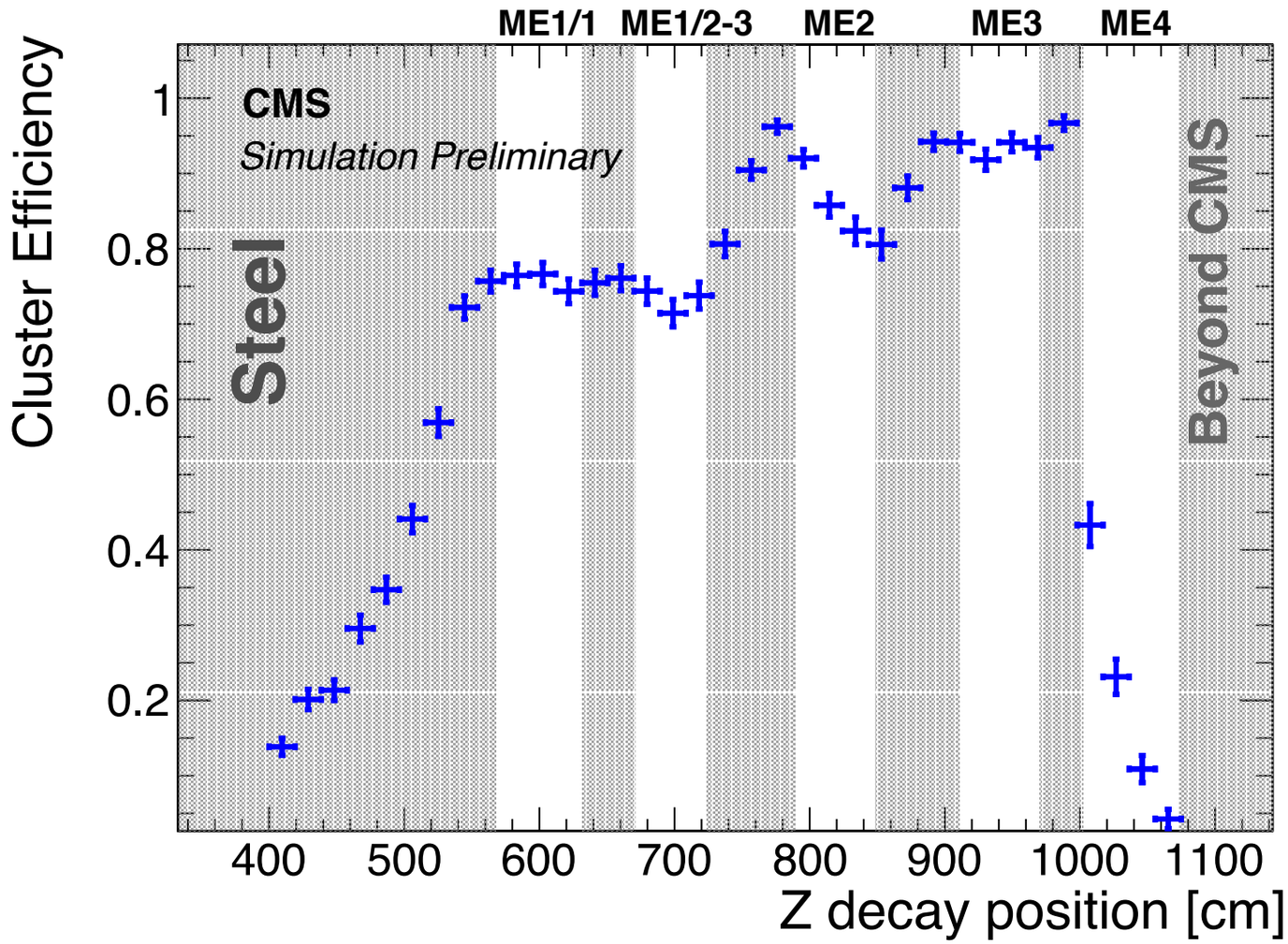
- LLPs that decay in the muons system leave a signature of:
  - **Large cluster of hits** in the muon chambers
- Muon system acts as a **sampling calorimeter (new)**





LLP Efficiency in CMS Muon System

Muon system acts as a **sampling calorimeter**



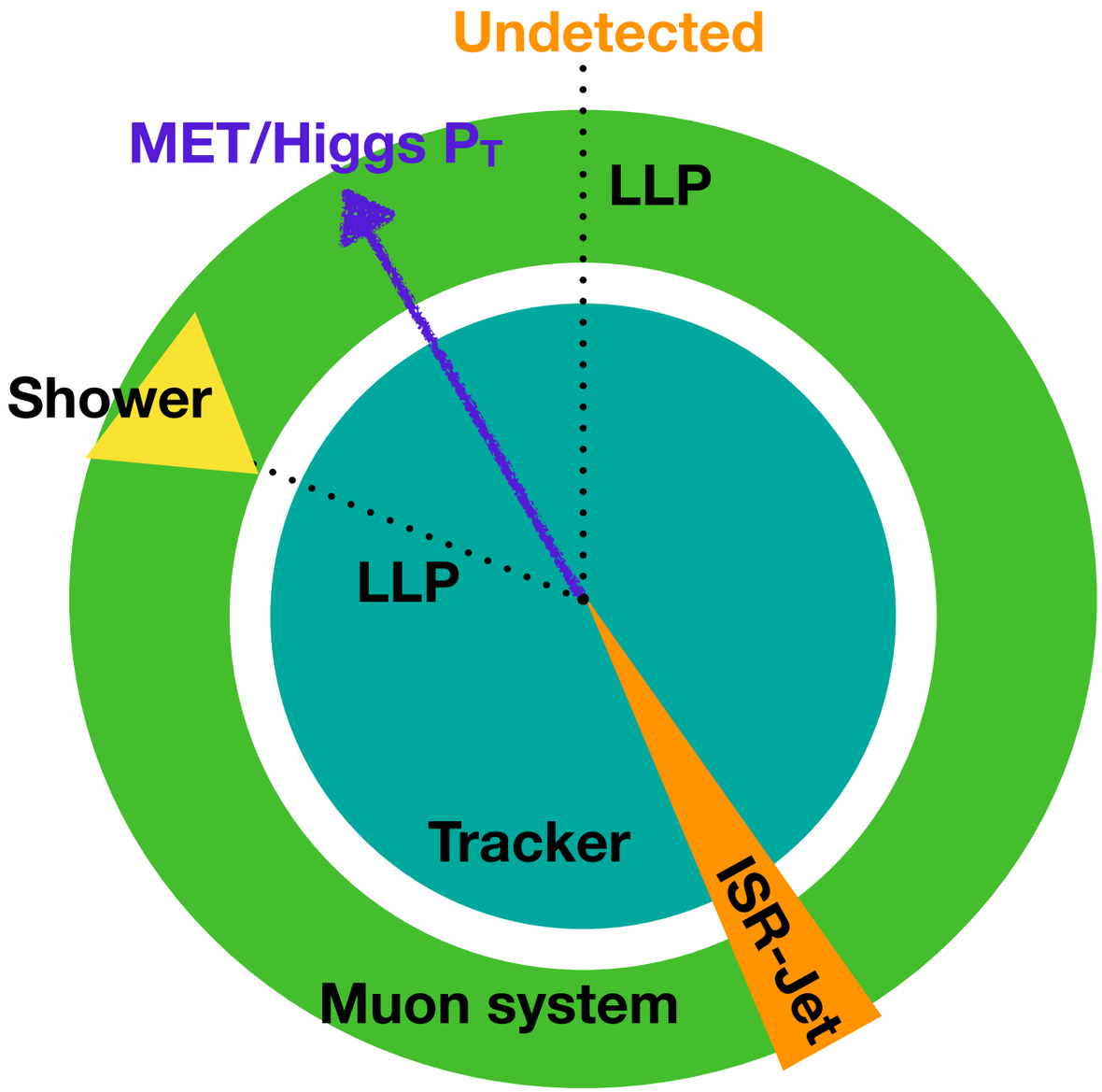
- High cluster reconstruction efficiency ~60%
- Strong dependence on decay position (Z)

EXO-20-015

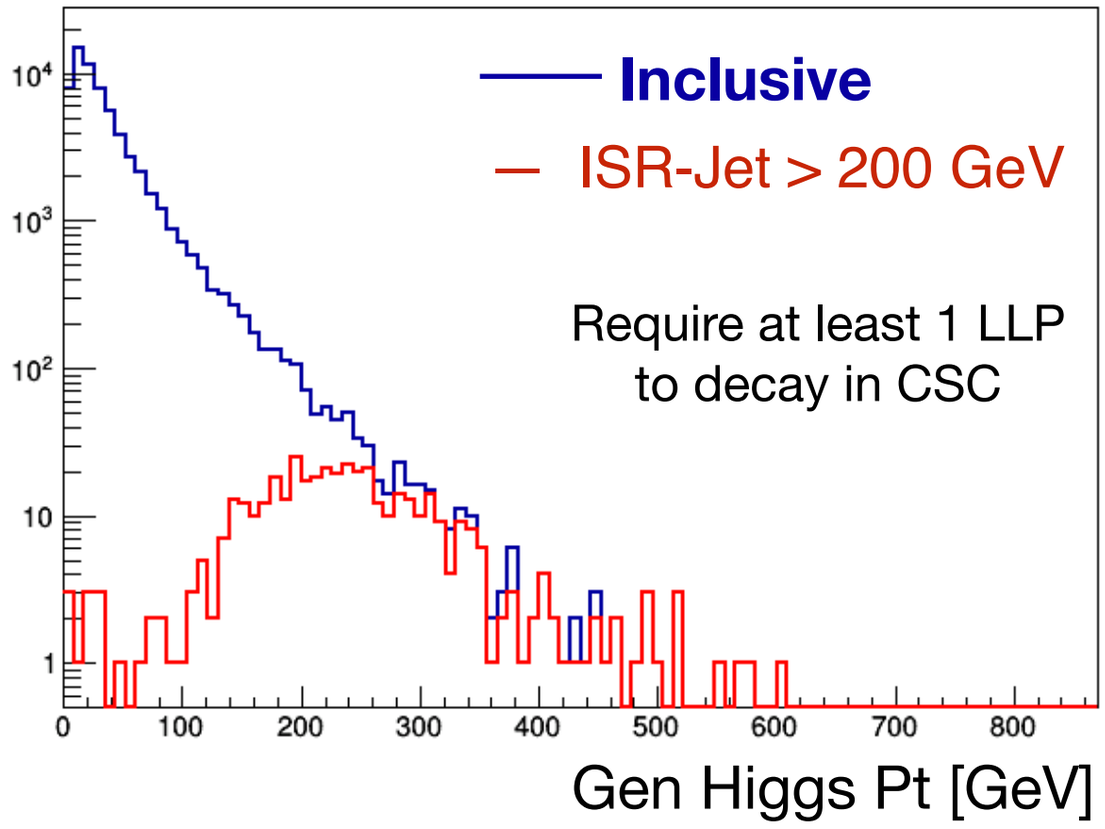
EXO-20-015

LLP Muon System Analysis

- Start with ggH production mode — largest cross section
- Trigger on **MET (lack of dedicated trigger)** — recoil of Higgs against ISR
  - For large cτ one of the LLPs will decay outside the calorimeter

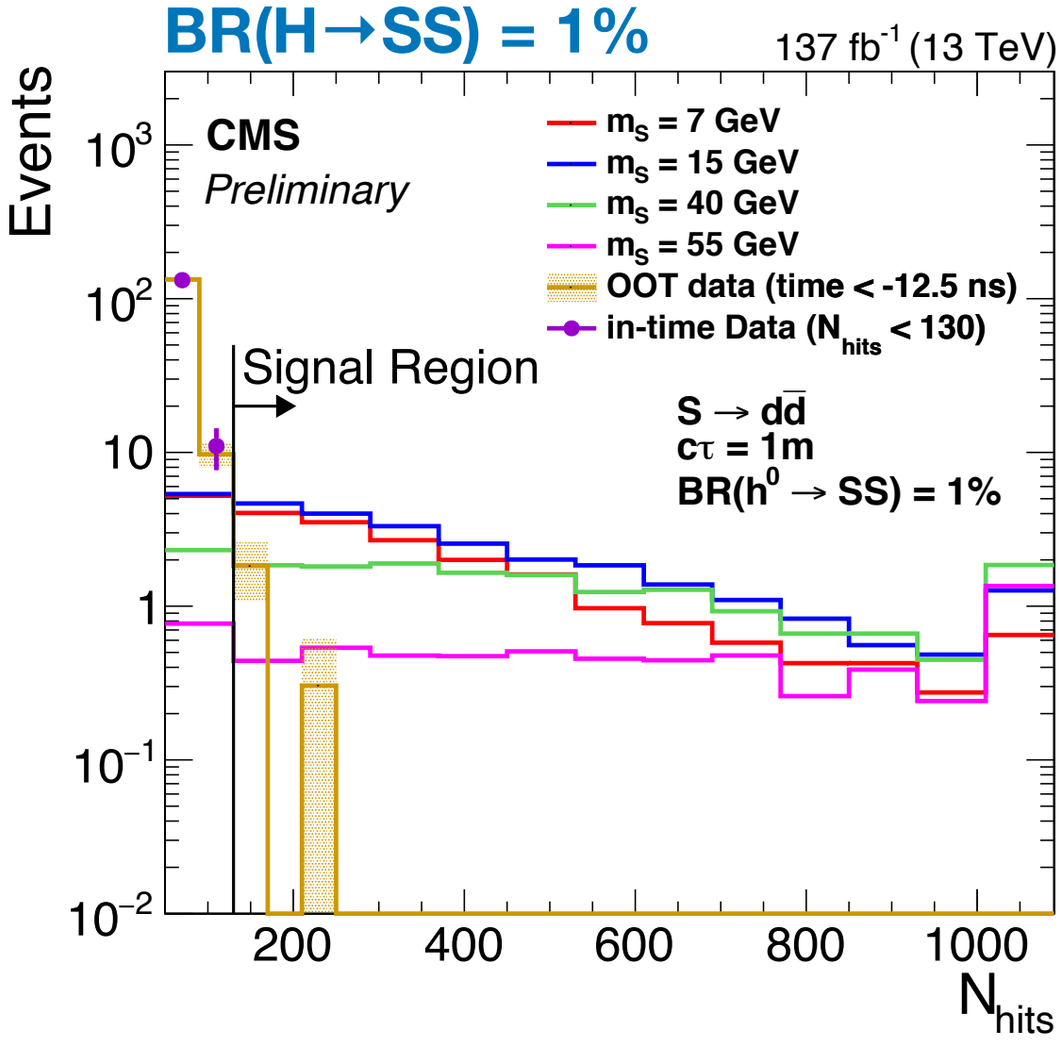


- ~1% signal events kept after MET cut
- **~4500 events in acceptance**



EXO-20-015

LLP with Muon Systems



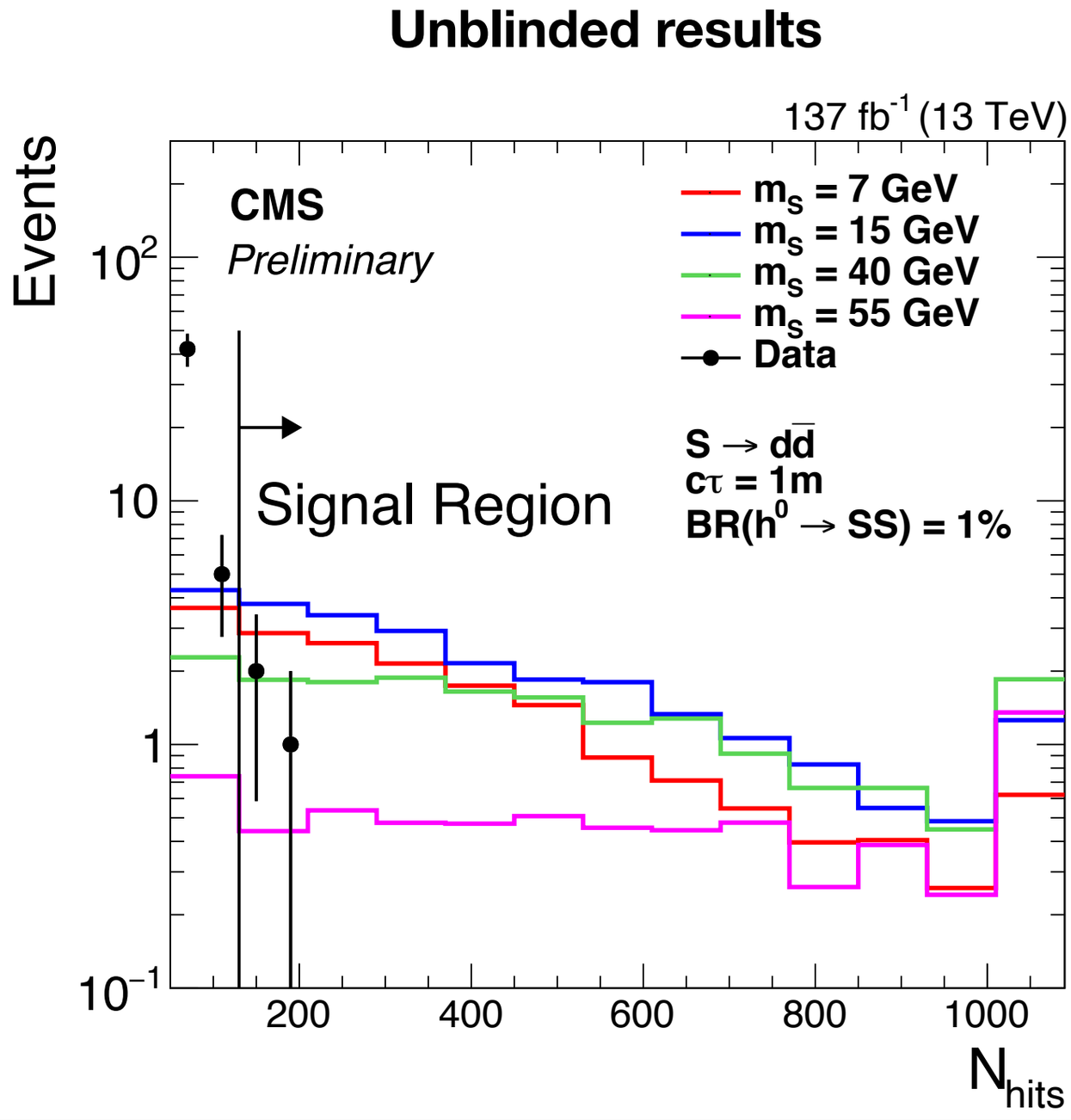
Large signal to bkg separation

- Signal: clusters with high hit-multiplicity
  - signal-clusters with up to 1k hits
- Bkg: quickly falling distribution
  - Nearly no bkg in signal region (SR)

Expect sensitivity below BR(H→SS) ~ 1%

EXO-20-015

LLPs with CMS Muon System

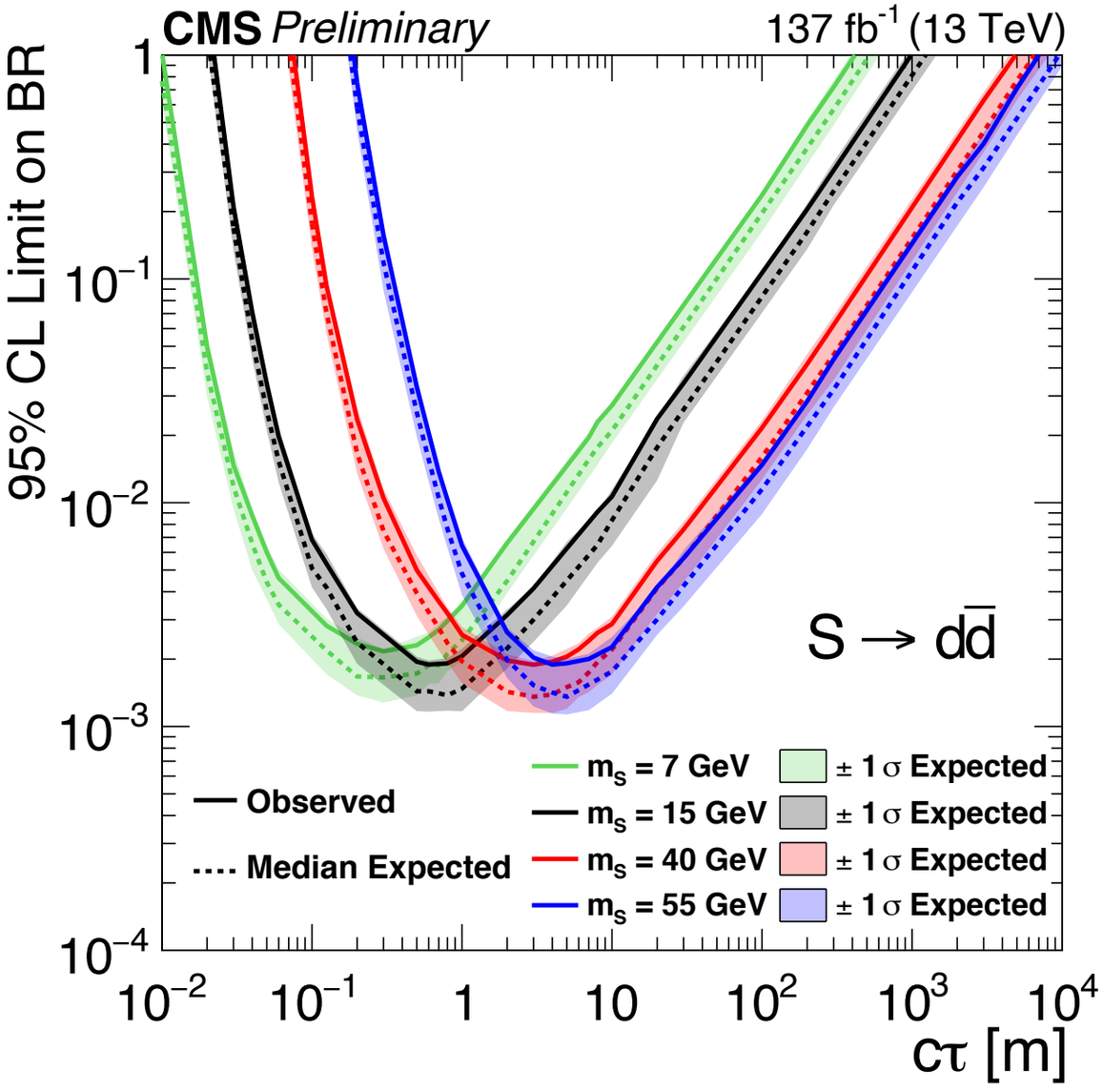


SR Expected Bkg (post-fit): 2.0 ± 1.0 **SR Observed: 3**

EXO-20-015

LLP with Muon Systems

Best sensitivity at BR(H→SS) ~ 10^{-3} !!

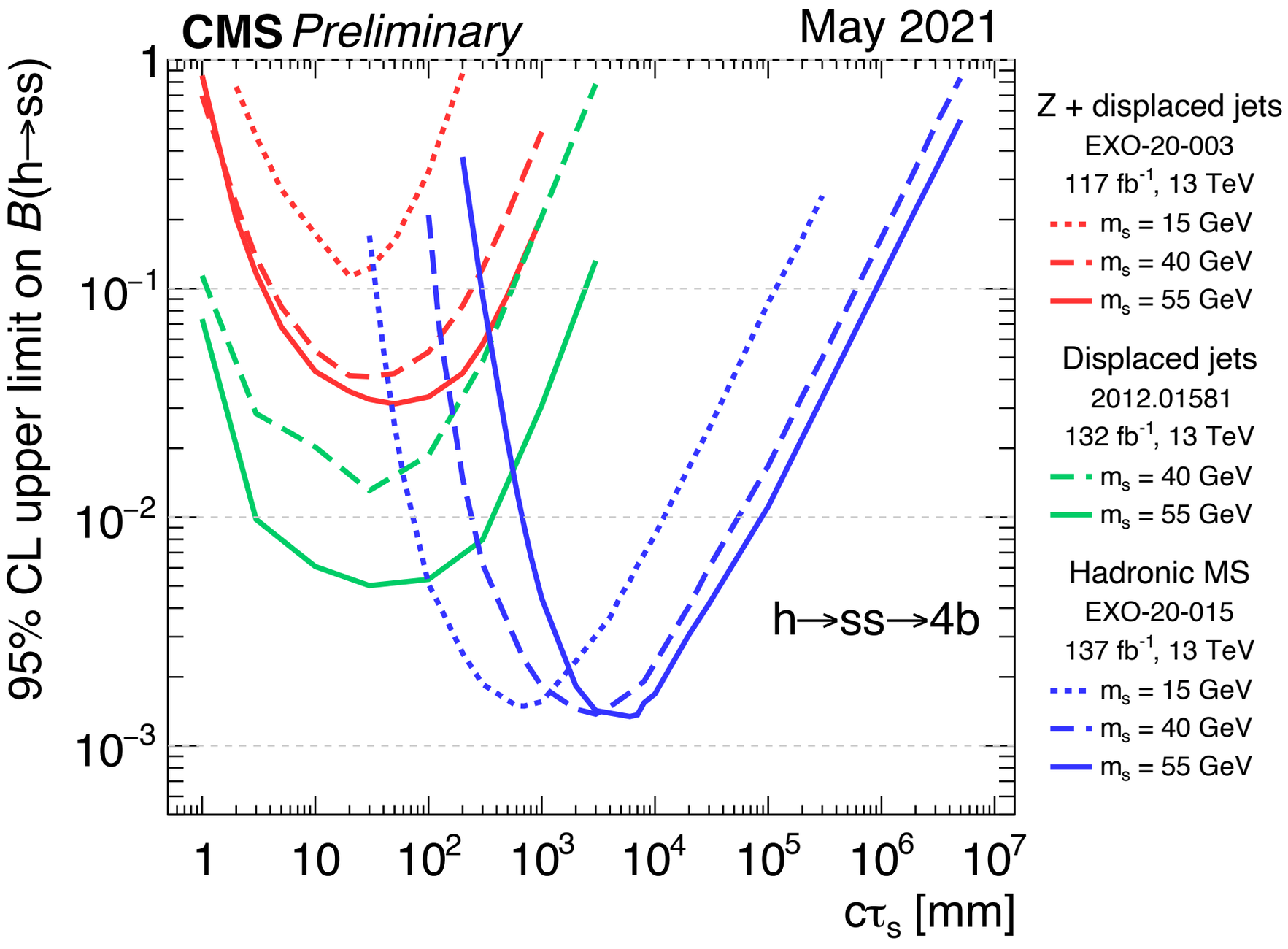


CMS new result

- **ENABLED CMS LLP sensitivity to larger cτ**
- **Access to light LLPs (< 7 GeV)**
  - **Sensitivity to all masses**
  - **Calorimeter: sensitive to LLP energy**

Best results for cτ > 40 m

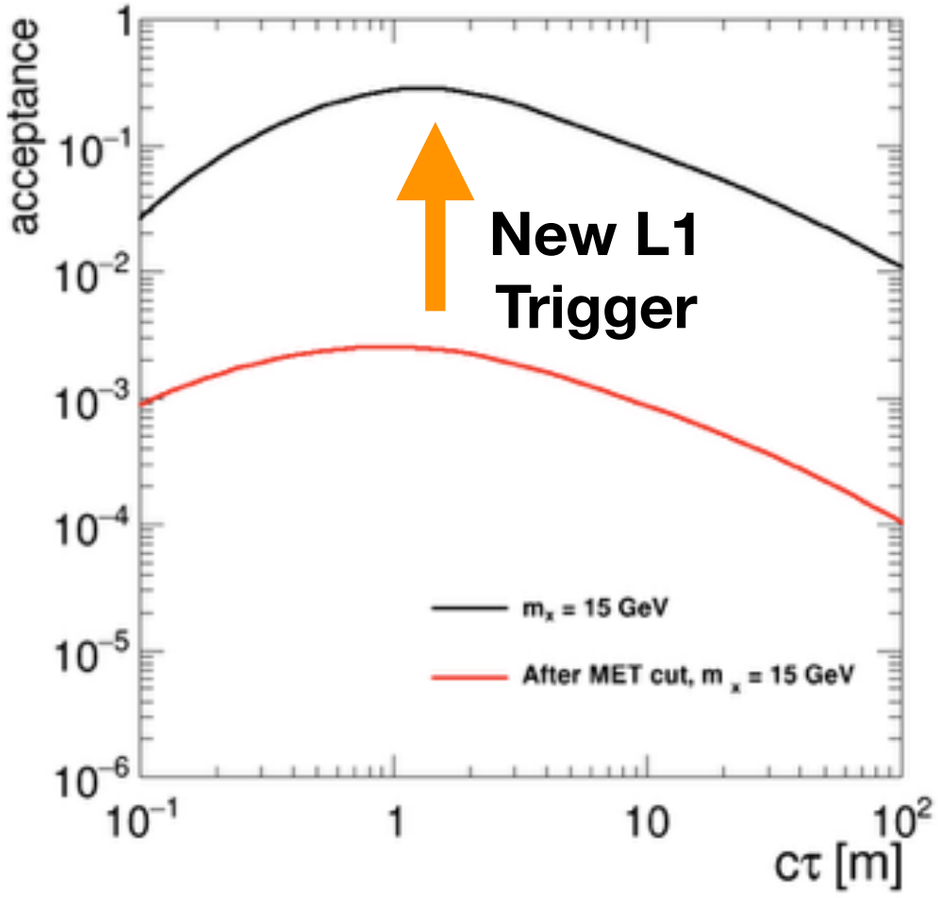
CMS h→SS Summary

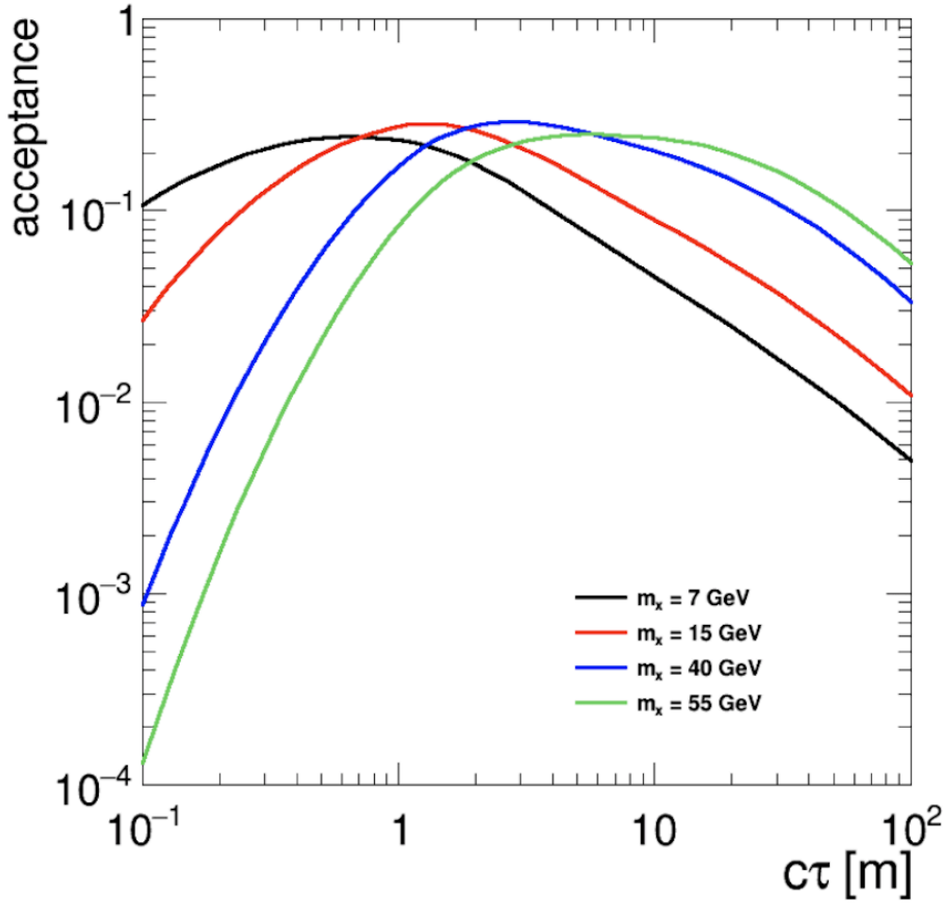


New results extend cτ and mass reach

Muon System Enables Broad LLP Reach

- **NEW L1 (Hardware) trigger with MS signature (@Run3)**:
  - NEW L1 seed expected provide 20x increase in signal
  - Will enable completely new search signatures **MS-MS, MS-ECAL, MS-Tracker**





Outlook

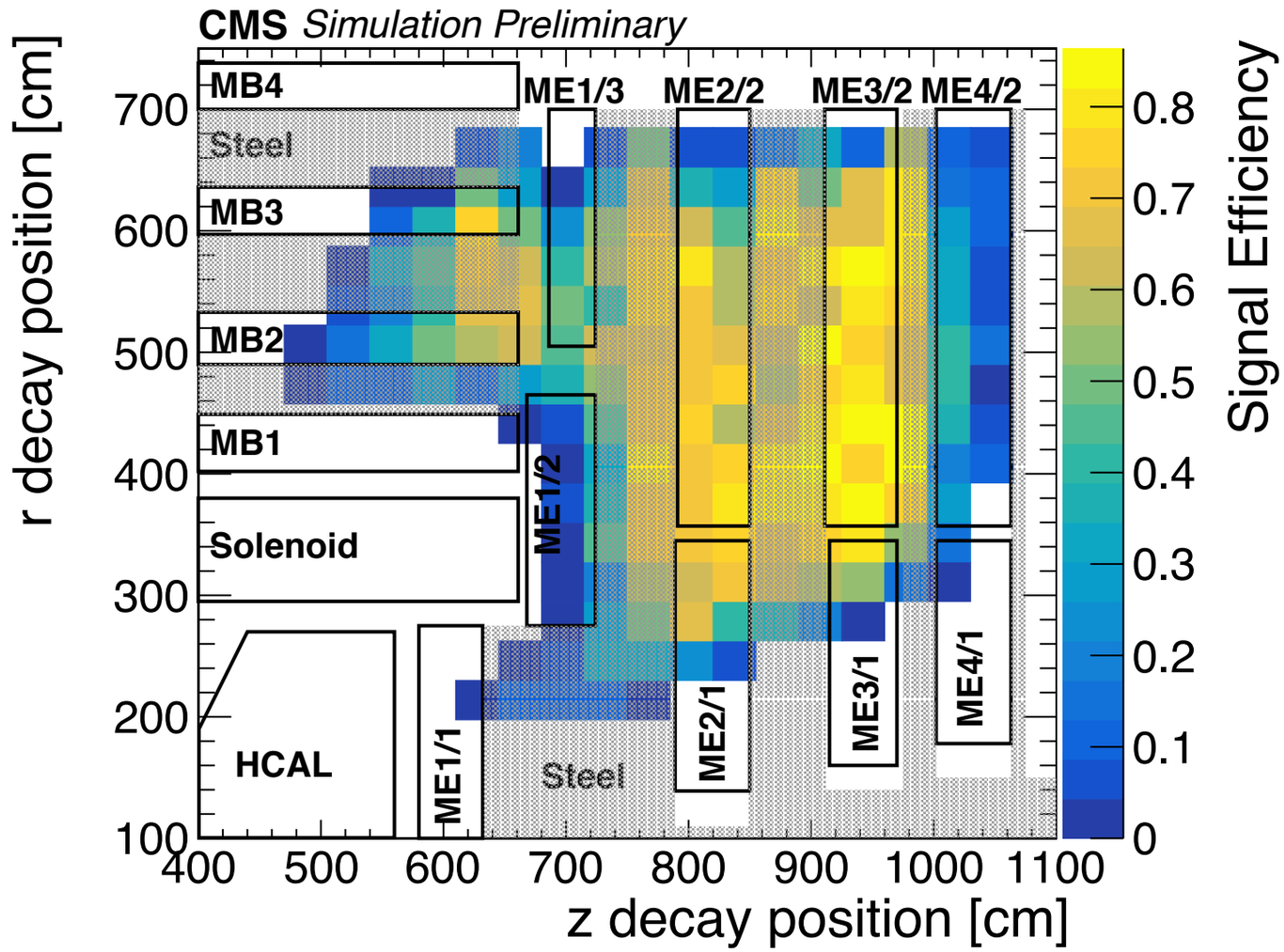
- CMS released three new LLP results
- Significantly extended CMS reach for light LLPs
- Large boost in sensitivity for large cτ — current best result beyond 40 m
  - **@1km $\mathcal{B}$(h→ss) < 20% for masses > 40 GeV**
- Working on a Muon System Shower based L1 trigger for Run3: expect 20x more signal efficiency.

Thank you!

- Backups

LLP Efficiency in CMS Muon System

Muon system acts as a **sampling calorimeter**



- High cluster reconstruction efficiency ~60%
- Strong dependence on decay position (Z)

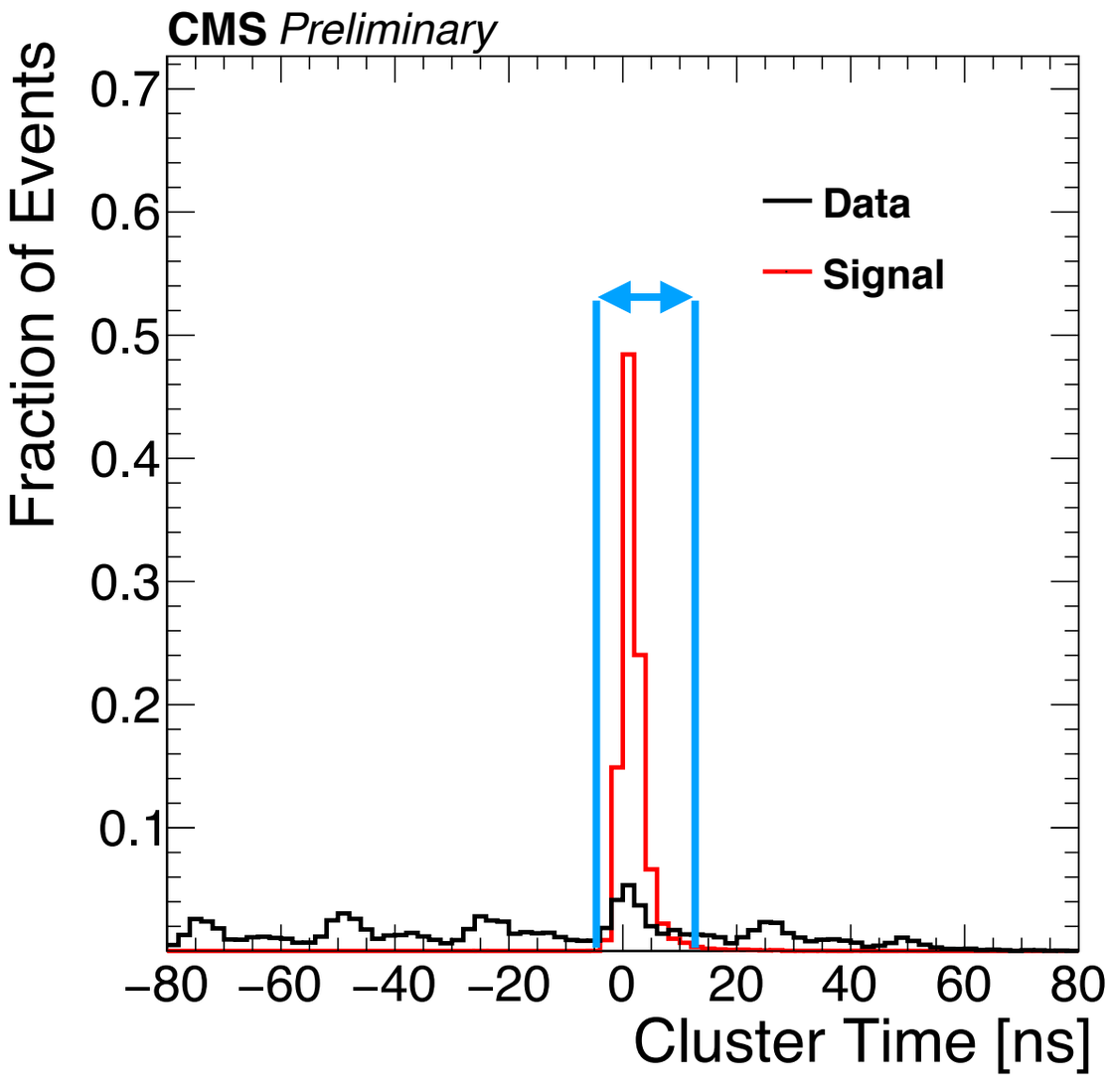
EXO-20-015

EXO-20-015

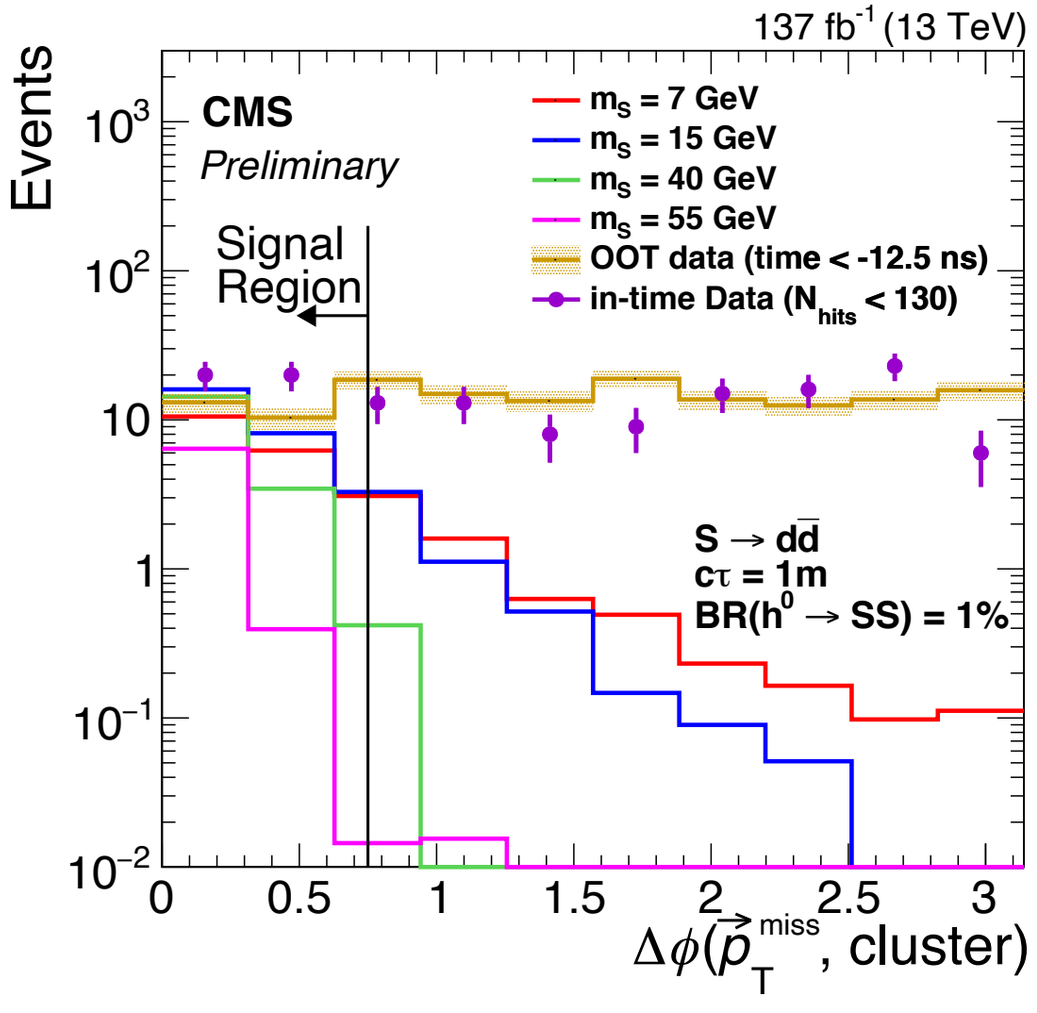
LLP with MS: other key selection

Many bkg cluster from OOT interactions

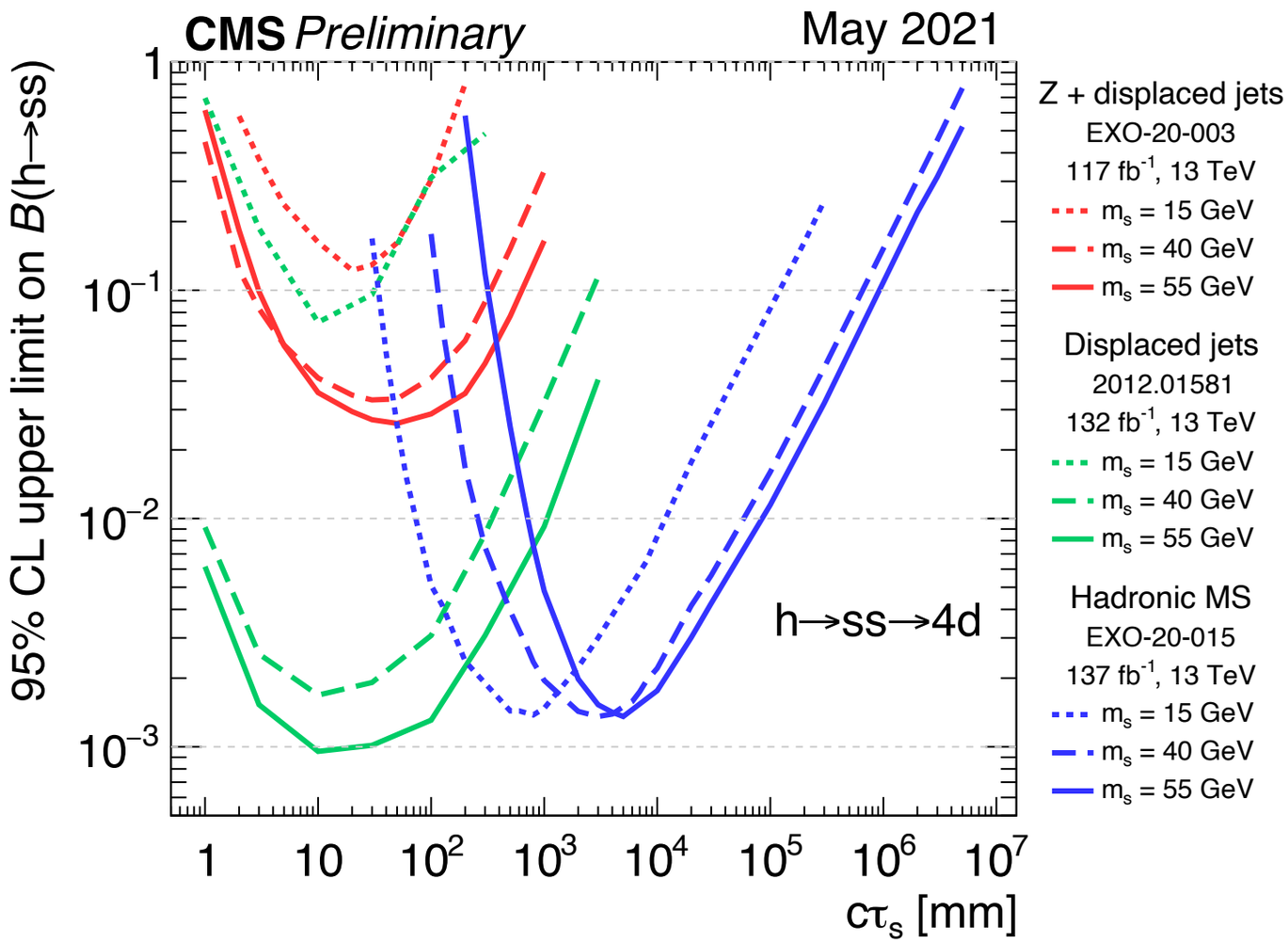
Signal cluster are in-time



Signal: angle between pT_{miss} and cluster position is aligned



Combined 20x bkg rejection power


CMS Preliminary
May 2021
95% CL upper limit on B(h→ss)
1
10⁻¹
10⁻²
10⁻³
1
10
10²
10³
10⁴
10⁵
10⁶
10⁷
cτs [mm]
h→ss→4d
Z + displaced jets
EXO-20-003
117 fb-1, 13 TeV
ms = 15 GeV
ms = 40 GeV
ms = 55 GeV
Displaced jets
2012.01581
132 fb-1, 13 TeV
ms = 15 GeV
ms = 40 GeV
ms = 55 GeV
Hadronic MS
EXO-20-015
137 fb-1, 13 TeV
ms = 15 GeV
ms = 40 GeV
ms = 55 GeV

EXO-20-014

Displaced low-mass dimuons