Search for Neutral Long-lived Particles Decaying in the CMS Endcap Muon Detectors

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Reinterpretation: Auxiliary Material Presentation
RAMP #5
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Introduction

- Paper submitted to PRL: arXiv:2107.04838
- HEPData entry: link
- Analysis twiki: link
- This talk:
  - Overview of the search and the result
  - Summary of the content in HepData entry

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

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2021/07/13

Search for long-lived particles decaying in the CMS endcap muon detectors in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

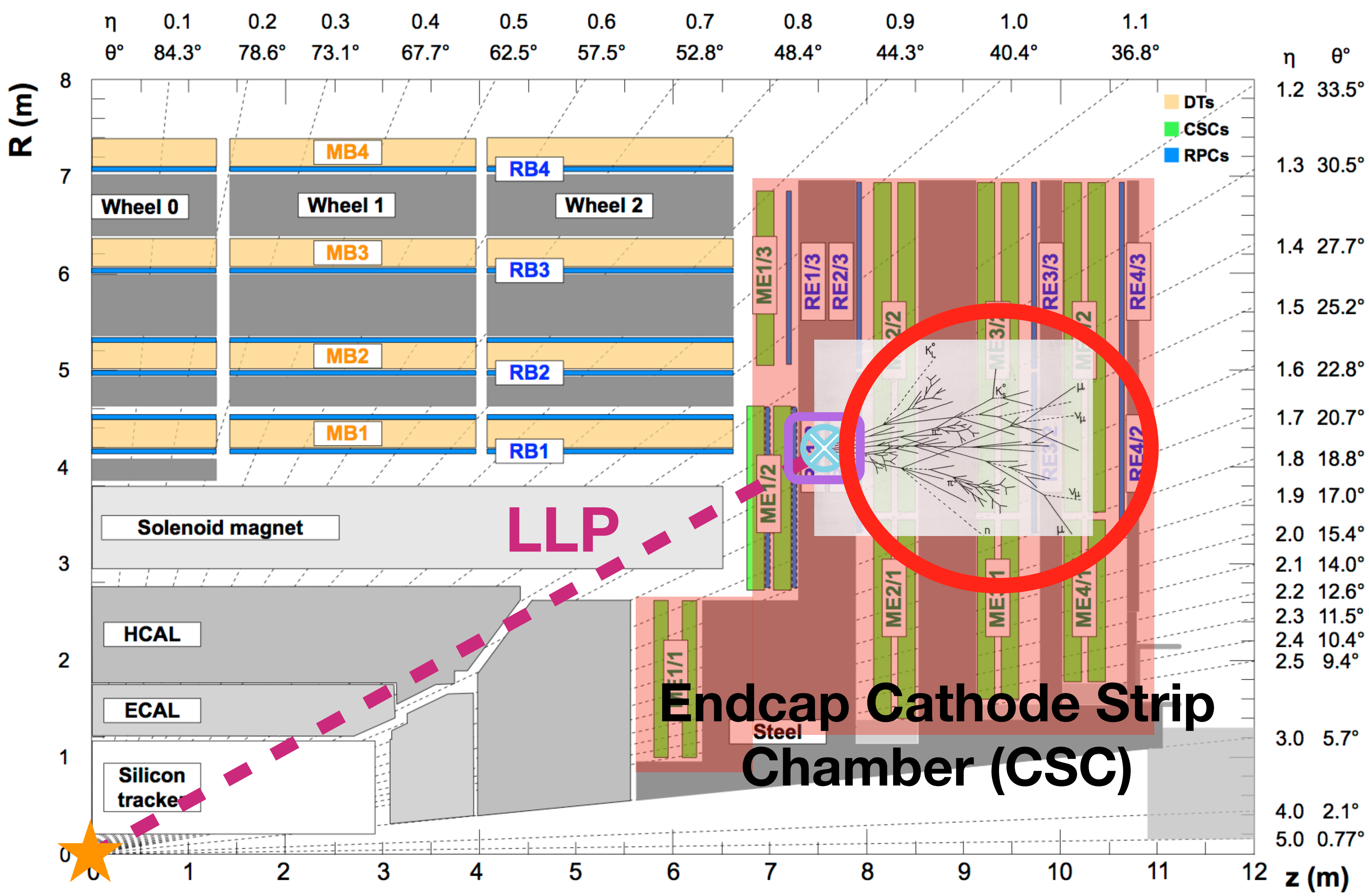
The CMS Collaboration*

Abstract

A search for long-lived particles (LLPs) produced in decays of standard model (SM) Higgs bosons is presented. The data sample consists of $137\,\mathrm{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, recorded at the LHC in 2016–2018. A novel technique is employed to reconstruct decays of LLPs in the endcap muon detectors. The search is sensitive to a broad range of LLP decay modes and to masses as low as a few GeV. No excess of events above the SM background is observed. The most stringent limits to date on the branching fraction of the Higgs boson to LLPs subsequently decaying to quarks and $\tau^+\tau^-$ are found for proper decay lengths greater than 6, 20, and 40 m, for LLP masses of 7, 15, and 40 GeV, respectively.

Submitted to Physical Review Letters

Motivation: Search for LLPs in Muon System

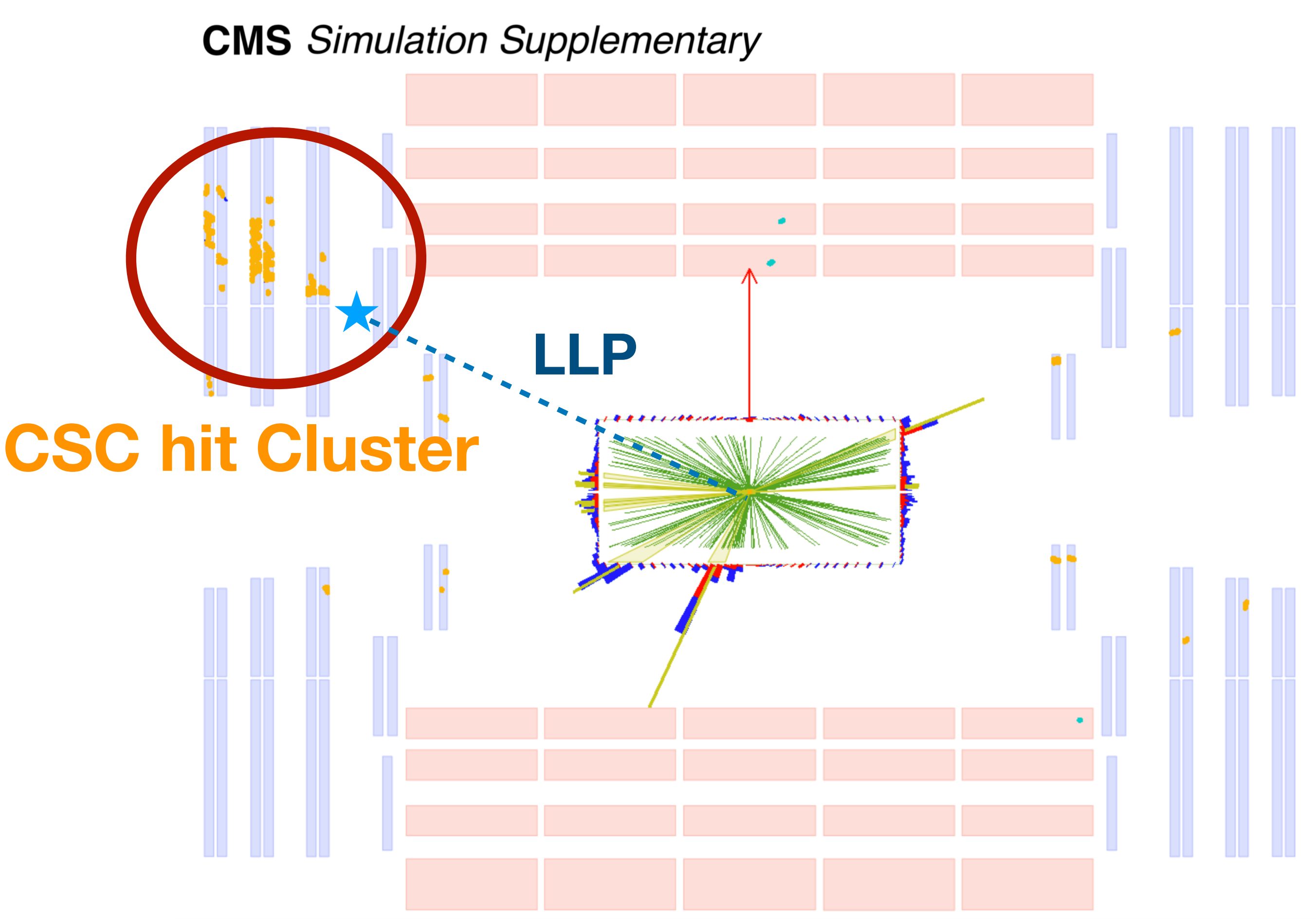


LLP decay and resulting particle shower is detected with a **large hit multiplicity** in a localized region of the gas ionization chambers

- Covers a large geometric acceptance
- Covers decays far away from IP (sensitive to large cτ)
- Excellent background suppression from shielding material

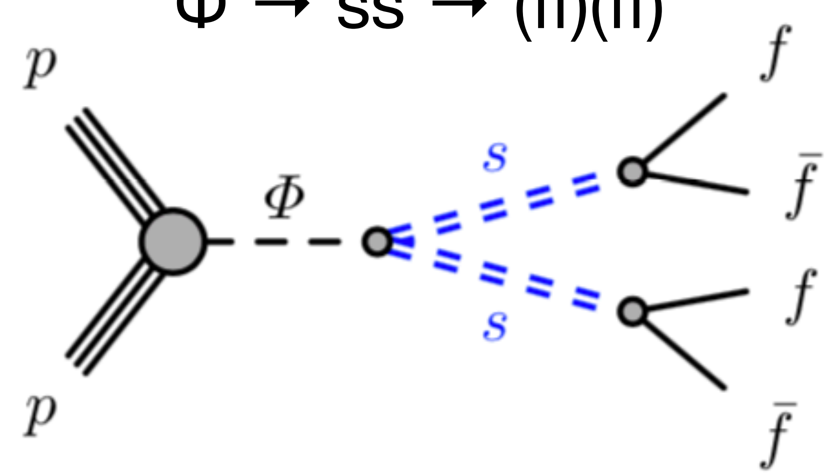
Experimental Signature: Showers in the Muon System

- Neutral long-lived particles decaying in the muon system leave a signature with:
  - No tracks
  - No jets
  - Large **cluster of CSC hits (>100 hits)** in the muon system
- Muon system acts as a **sampling calorimeter:** sensitive to a broad range of decays
- **Unique signature** due to the presence of steel in the CMS muon system
- First search in CMS that uses this novel signature



Twin Higgs as benchmark model:

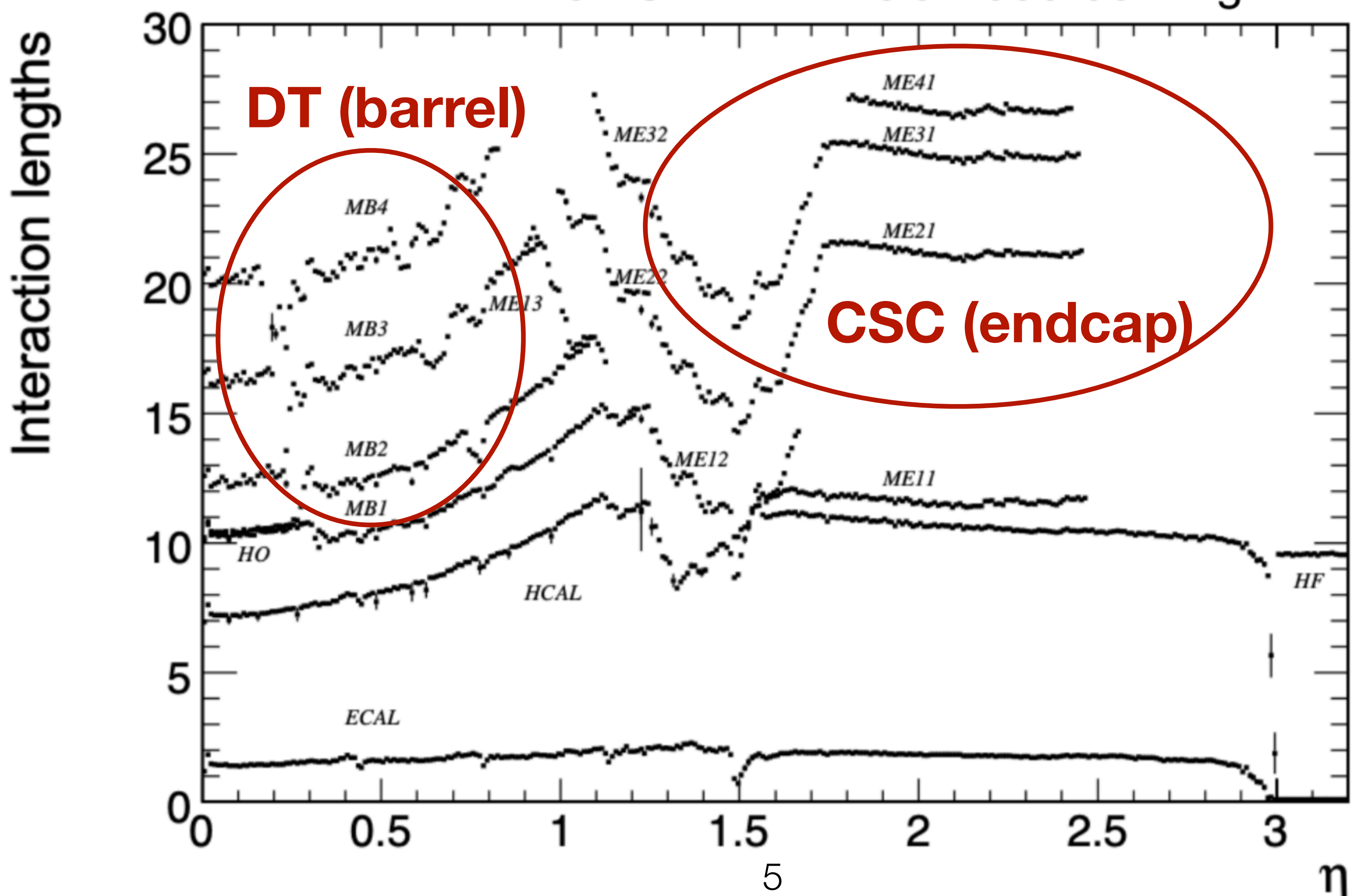
$\Phi \rightarrow ss \rightarrow (ff)(ff)$



Uniqueness of CMS

- The steel between stations of the muon system allow us to
  - **Reject more punch-through jets** (12-27 interaction lengths depending on the location)
  - Use the muon system as a **sampling calorimeter** to detect displaced showers
- By using the muon system as a sampling calorimeter, we are sensitive to LLP energy rather than mass: unique window to look for **light LLPs** ($m_{LLP} < 10$ GeV)

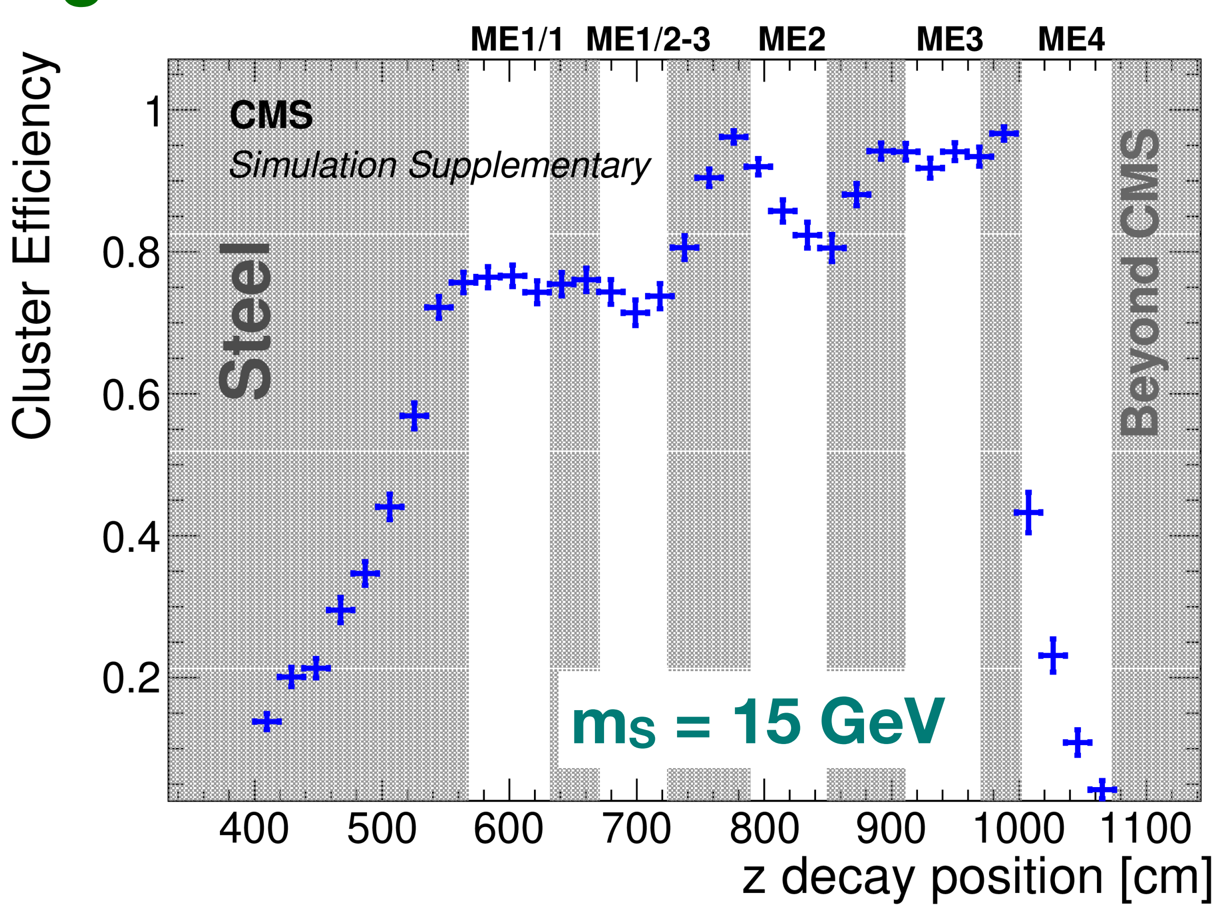
CMS TDR: LHCC-2006-001 Fig 1.4

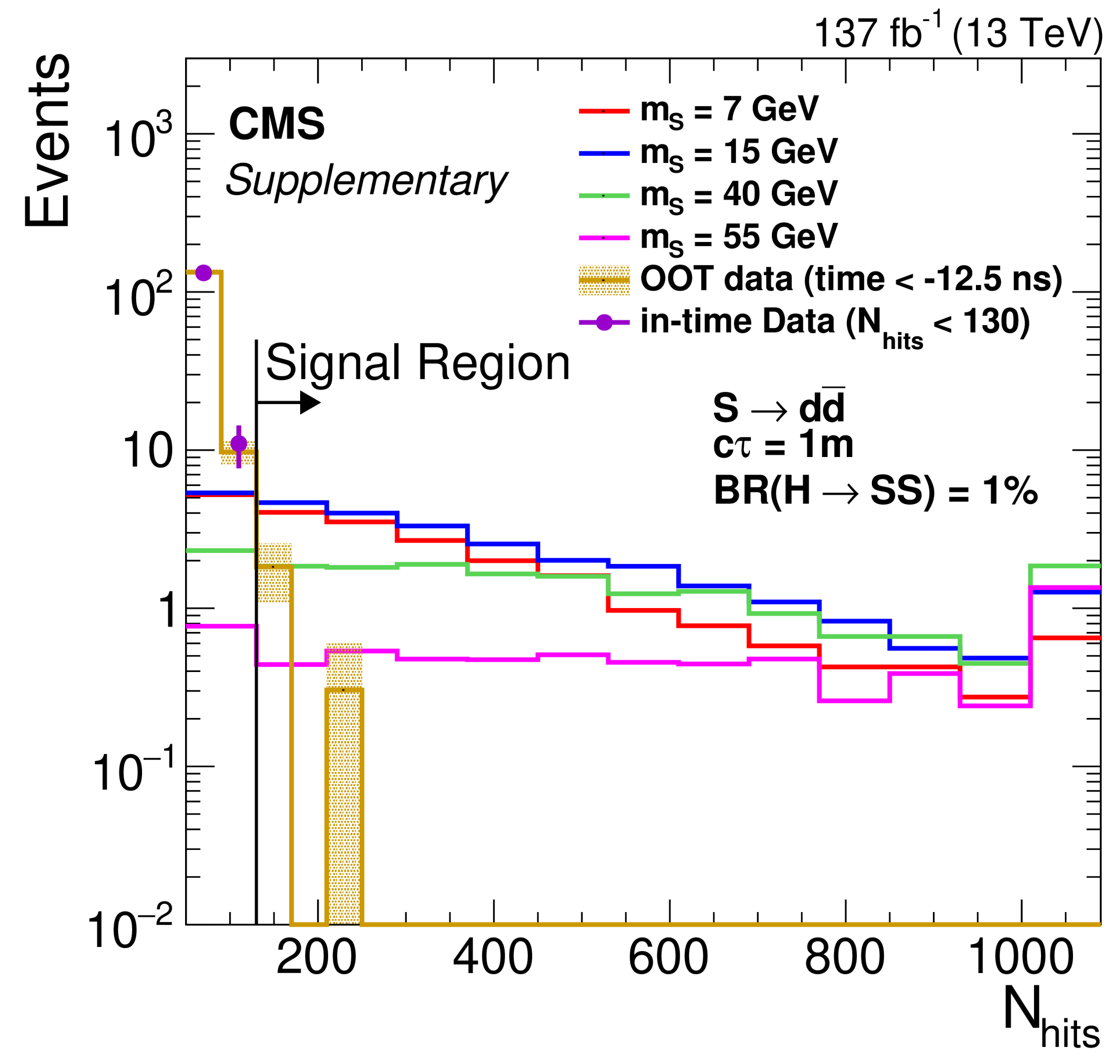


Analysis Strategy

- **Event selection:** select high MET and boosted Higgs phase space
  - Trigger on [MET](#) (lack of dedicated trigger, trigger efficiency is ~1%)
- Use **CSC cluster vetos and cut-based ID** to enhance signal purity and reject background from main collision— exact definition on next slide
- **N_{hits}** serves as the main discriminator

High cluster reconstruction efficiency



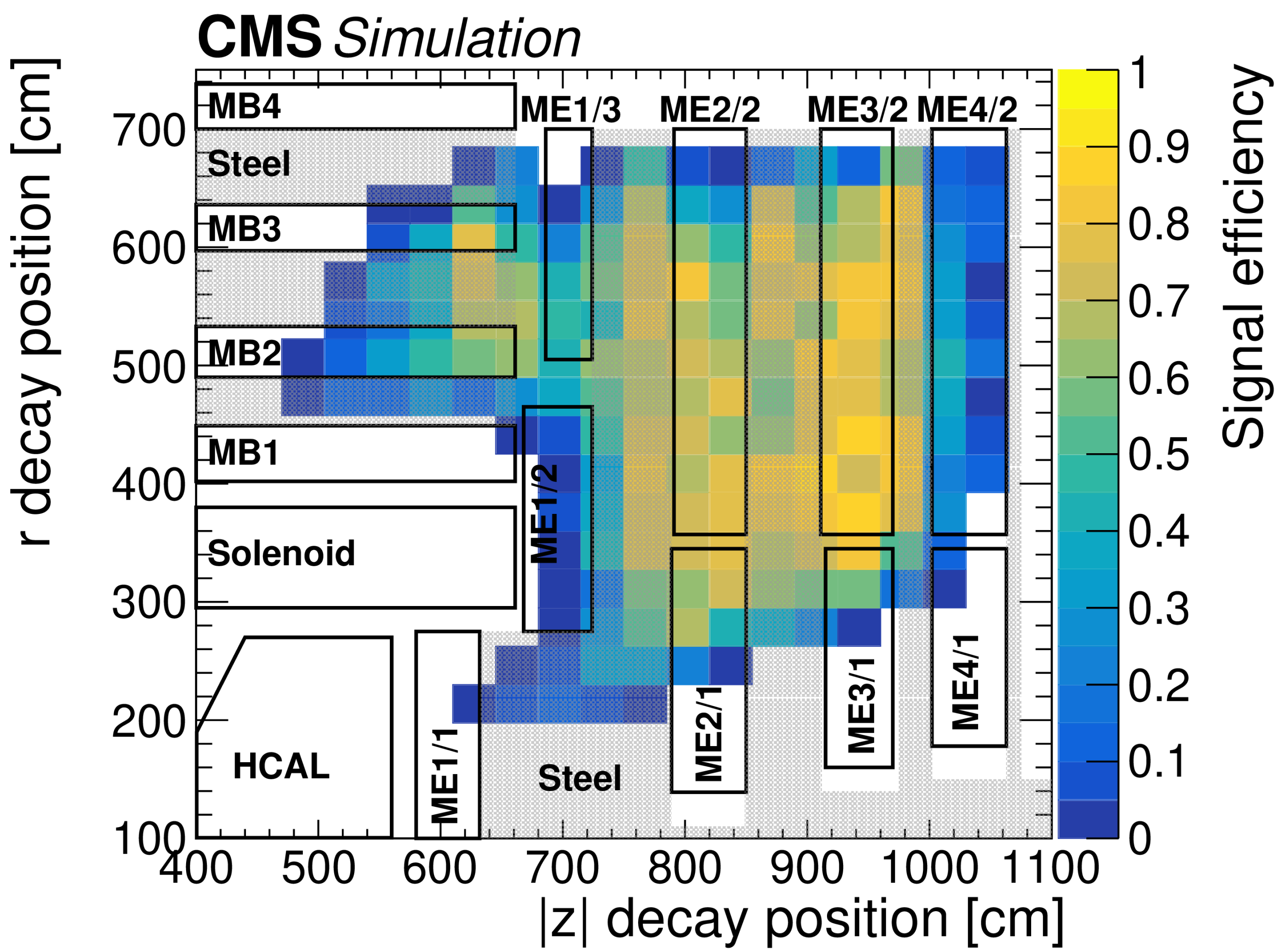


CSC Hit Cluster Selections

Reject background from the main collision

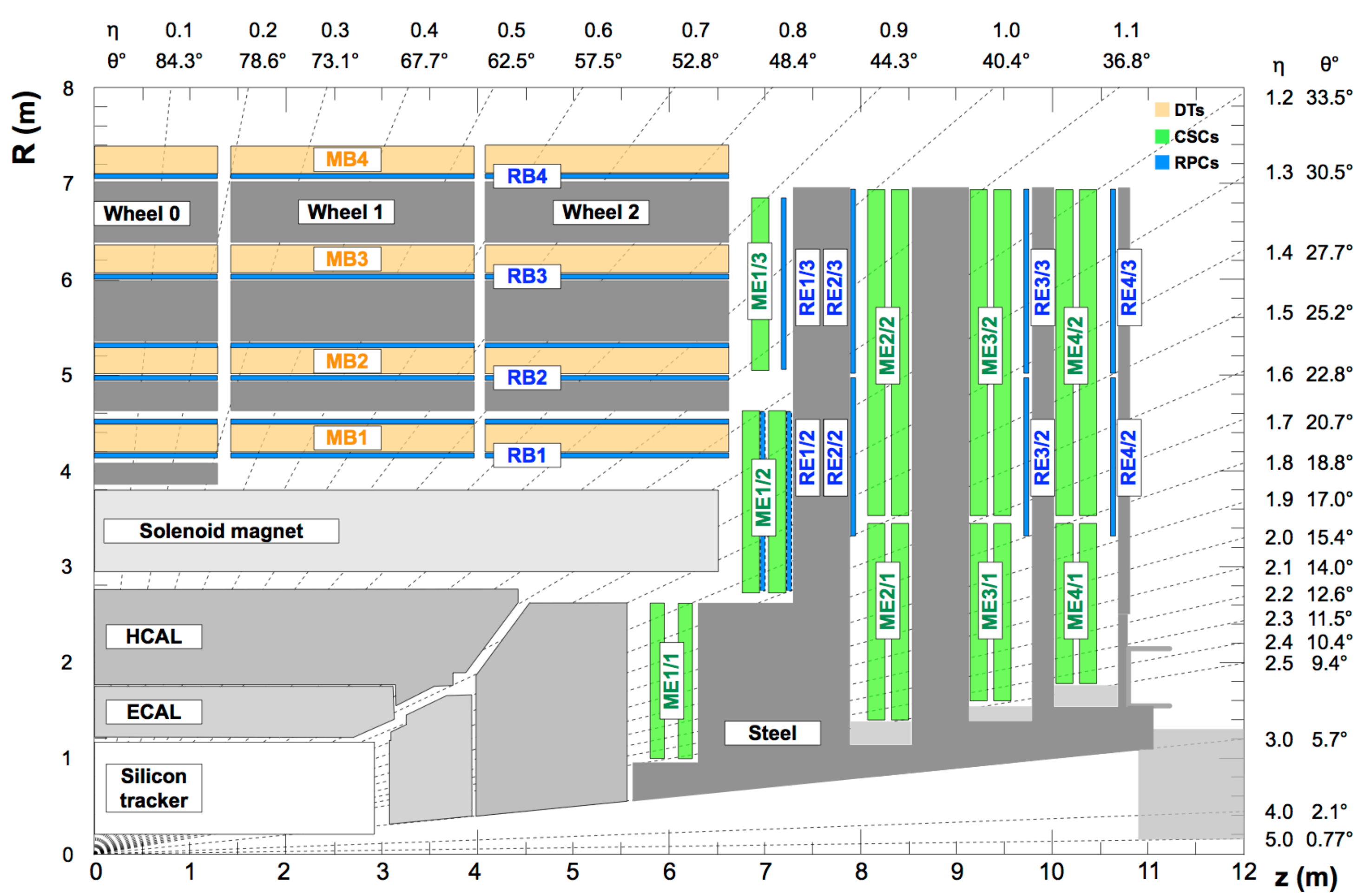
- Reject clusters from **punch-through jets** and **muon bremstralung shower**:
  - Veto clusters matched to jets and muons ($\Delta R < 0.4$)
  - Active vetos in first station (ME11/12)
  - Require -5 ns < cluster time < 12.5 ns
  - Cluster time spread < 20 ns
  - Veto clusters with **$|\eta| > 2.0$**
- ~50% signal efficiency when LLP decays between ME1 and ME4
- Background rejection is ~10^6

m_S = 15 GeV



Cut-based ID

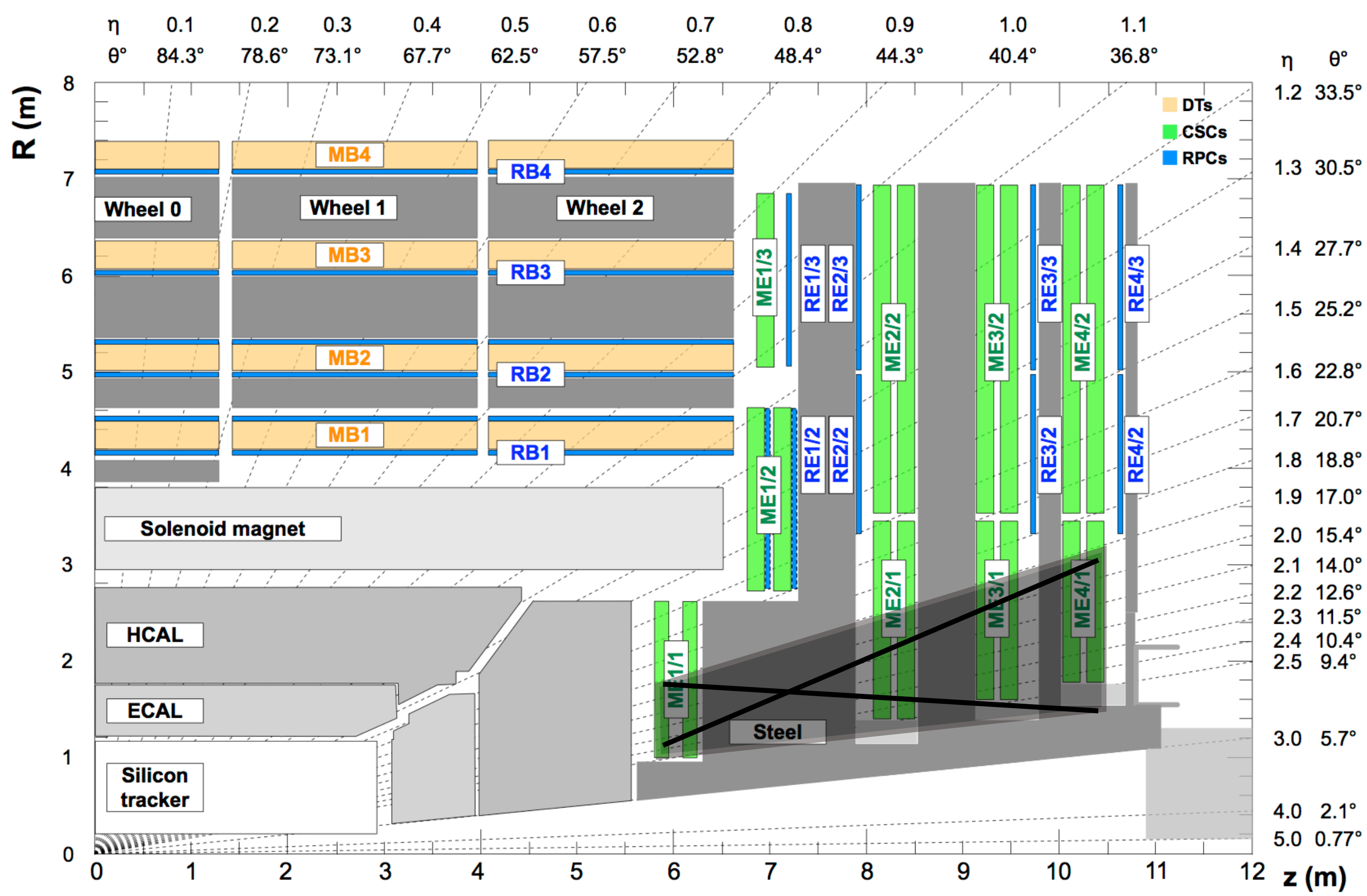
- Cut based selection makes progressively looser η cuts as AvgStation increases



Cut-based ID

- Cut based selection makes progressively looser η cuts as AvgStation increases
  - **$N_{station}$ > 1: |η| < 1.9**

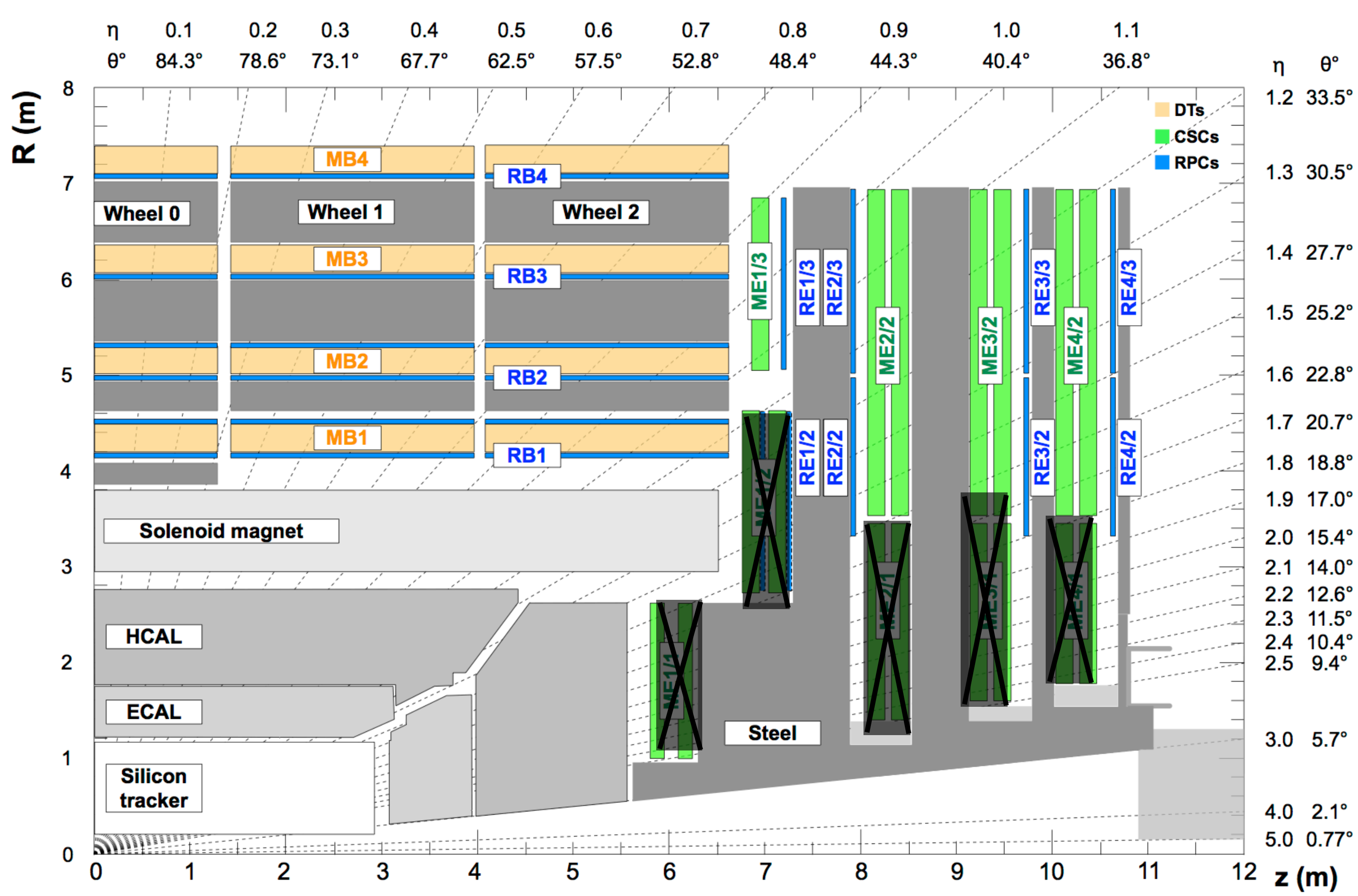
$N_{station} > 1$



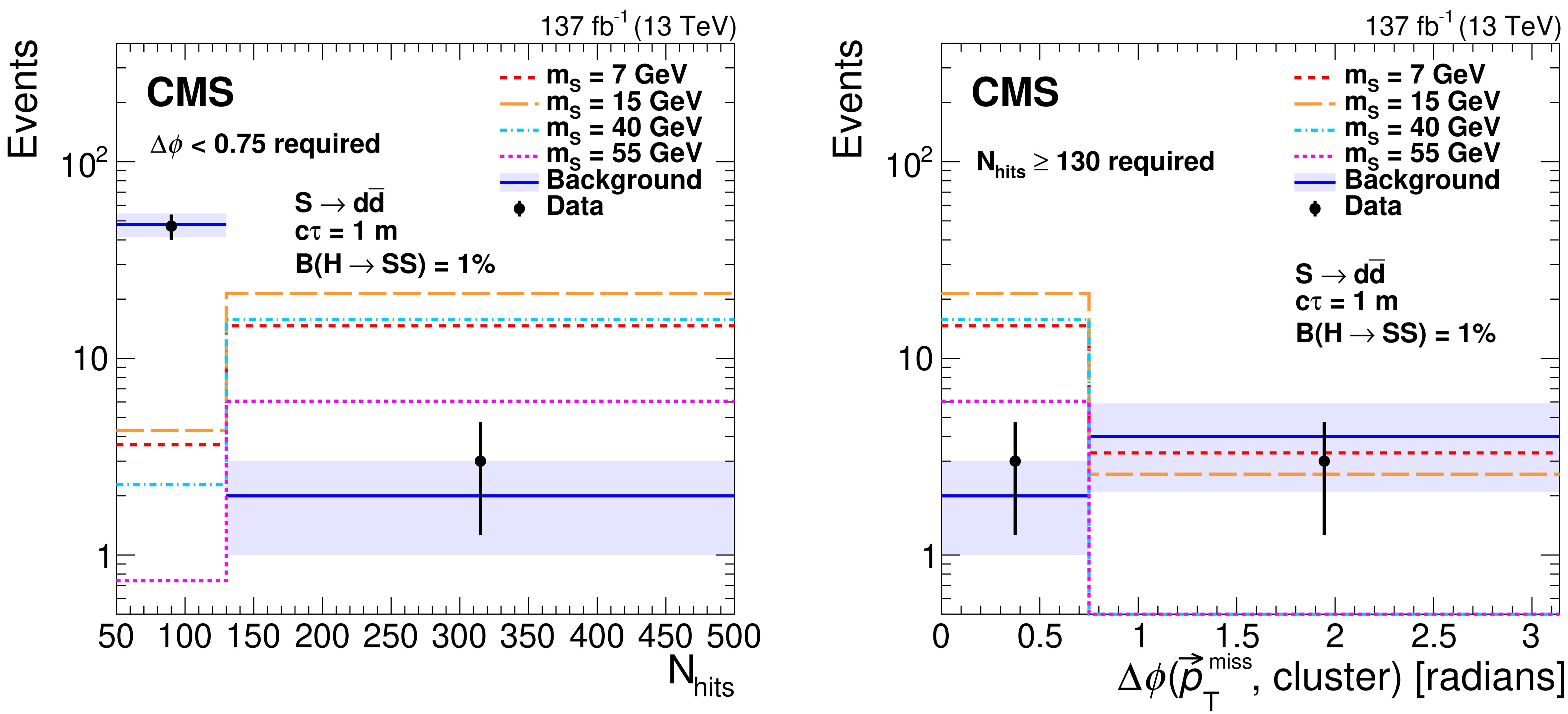
Cut-based ID

- Cut based selection makes progressively looser η cuts as AvgStation increases
  - $N_{station}$ > 1: |η| < 1.9
  - **$N_{station}$ = 1 & avgStation = 4: |η| < 1.8**
  - **$N_{station}$ = 1 & avgStation = 3: |η| < 1.6**
  - **$N_{station}$ = 1 & avgStation = 2: |η| < 1.6**
  - **$N_{station}$ = 1 & avgStation = 1: implicit cut (ME11/12 veto implies only ME13 is allowed, so |η| < ~1.1)**
- Cut-based ID provides: signal efficiency 82% , bkg rejection ~3

$N_{station}$ = 1



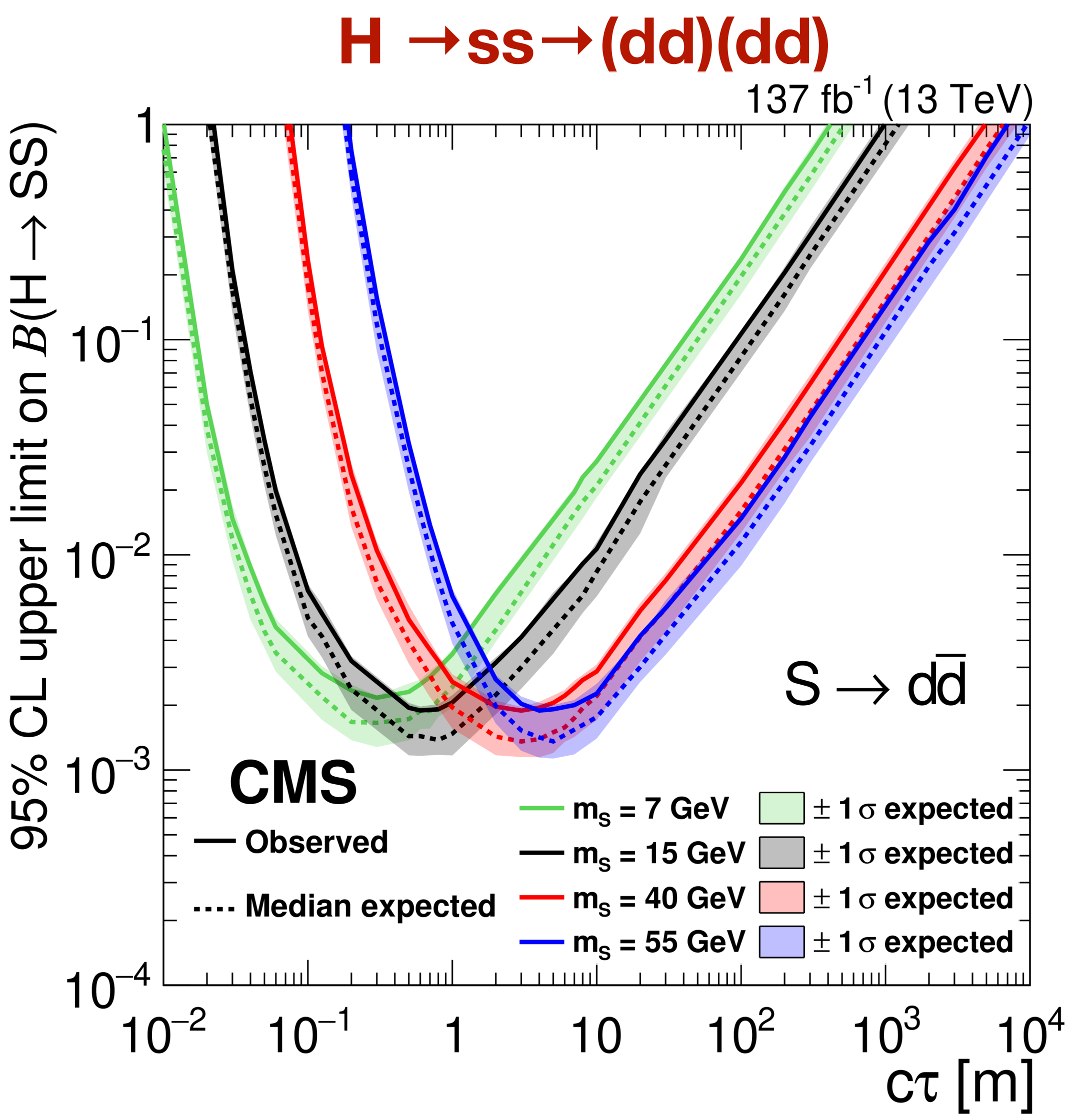
Data-driven Background Estimation

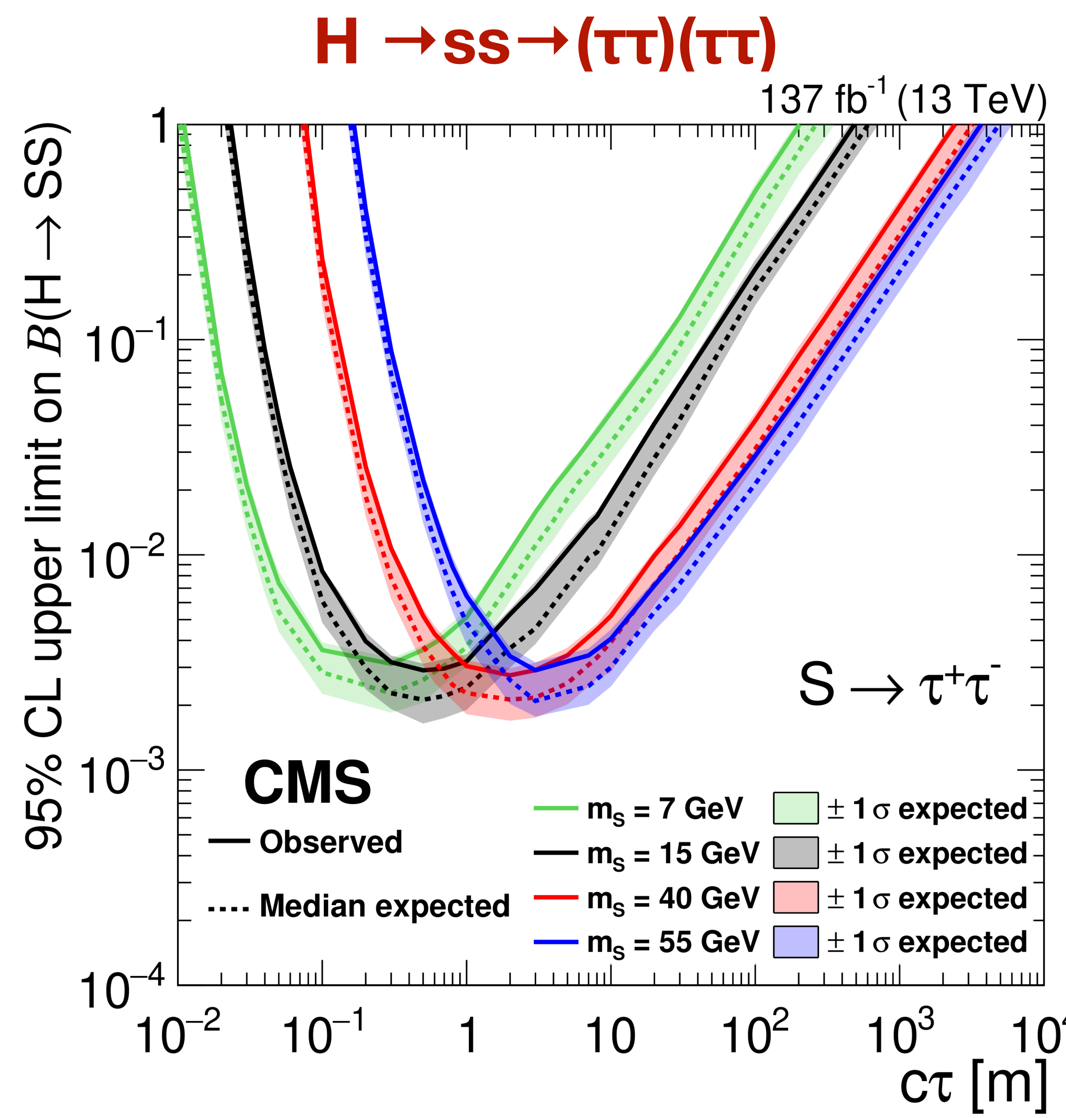


Predict 2 ± 1 background events and observed 3 events

- N_{hits} is the main discriminator for the analysis with large signal to bkg separation
- Cluster and MET directions are aligned for signal
- Data-driven background estimation performed to extract signal using two independent variables for background
- Background estimation method validated in 2 separate validation region

Observed and Expected Limits





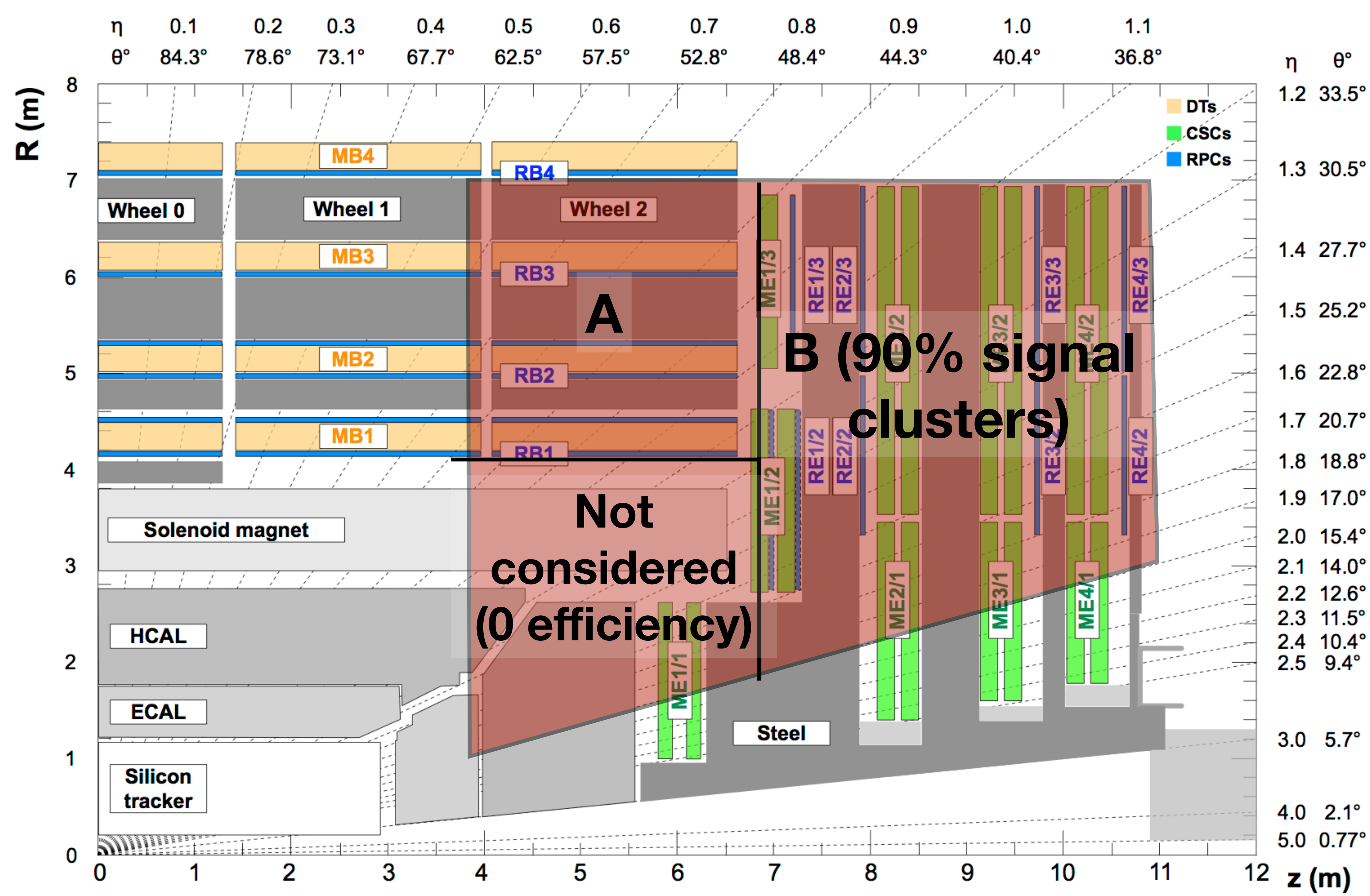
- Limits for S → bb are within 3% to that for S → dd.
- Analysis sensitivity is independent of the **LLP decay modes** and **masses**
- Provides current best LHC limit for LLPs with cτ above 6, 20, and 40 m for mass of 7, 15, and 40 GeV respectively.
- Achieve first sensitivity to **τ decay modes** at BR(H →ss) = 10^{-3} level

HEPData Content Overview

- HEPData entry: link
- We provide instructions, signal generator cards, and signal efficiency parameterization for cluster-level selections that allow reproduction of the signal yield in signal region for various LLP masses, lifetimes and decay modes.
  - The signal efficiency parameterization has been validated to reproduce the full-sim signal yield for LLP masses 7- 55 GeV, lifetimes 0.1 - 100 m and decay modes dd and $\tau^+\tau^-$
- Only **gen-level** LLP hadronic energy, EM energy, and decay positions are needed as inputs to the signal efficiency parameterization
- We split all the signal selection efficiencies into 3 parts:
  - **Cluster efficiency**: includes cluster reconstruction efficiency, muon veto, active rechit veto, time spread cut, and N_{hit} >= 130 cut efficiency. Efficiency is provided as a function of LLP EM and hadronic energy
  - **Cut-based ID efficiency**: Efficiency of the cut-based ID. Code is provided.
  - **Others**: including the **jet veto**, **time cut**, and **$\Delta\phi$(cluster, MET)**. These cuts are model dependent, so are left up to the recaster to implement for specific models
- Observed **data** and expected **background** yield in signal region is provided in paper

LLP Decay Regions

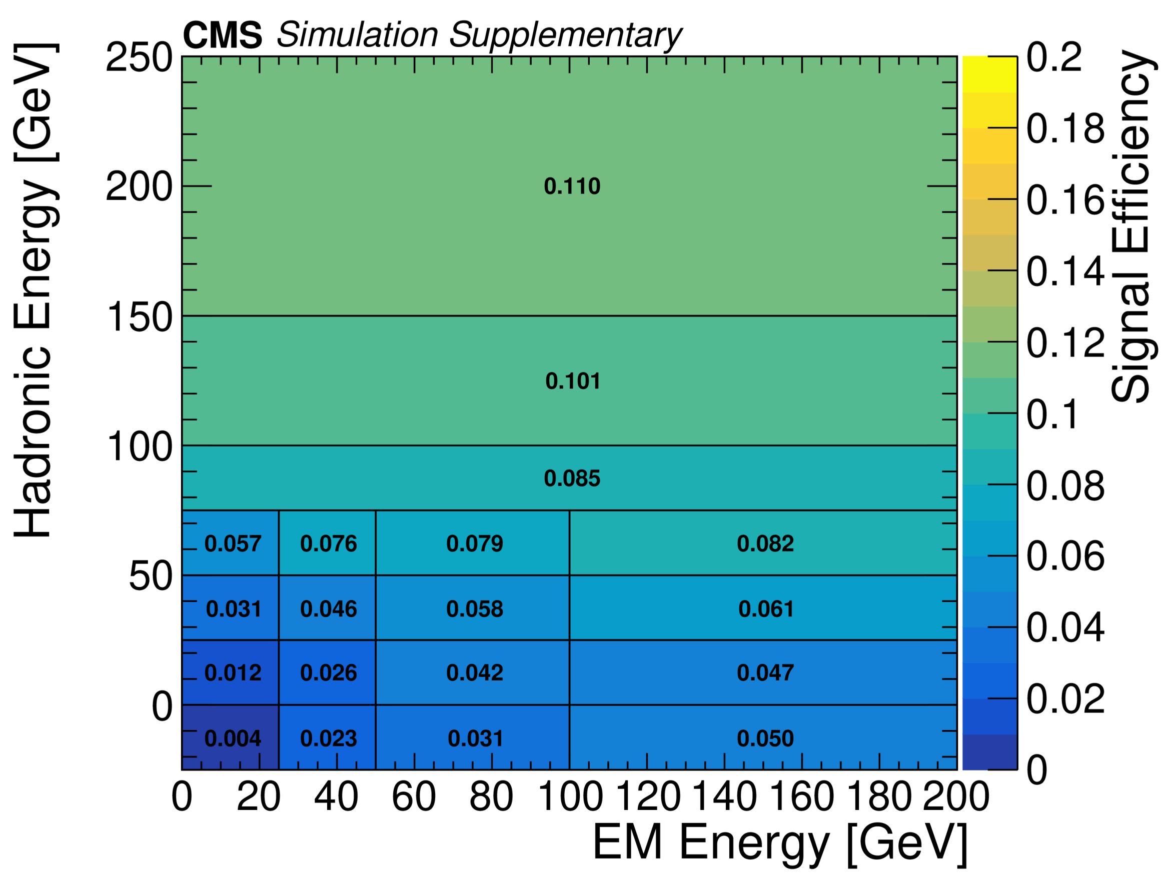
- **LLP decay location is categorized into 2 regions shown below**
- More than 90% of clusters passing all selections are from LLPs that decay in region B
- The region definitions are provided in HEPData entry
- Efficiency parameterization are provided for each region separately



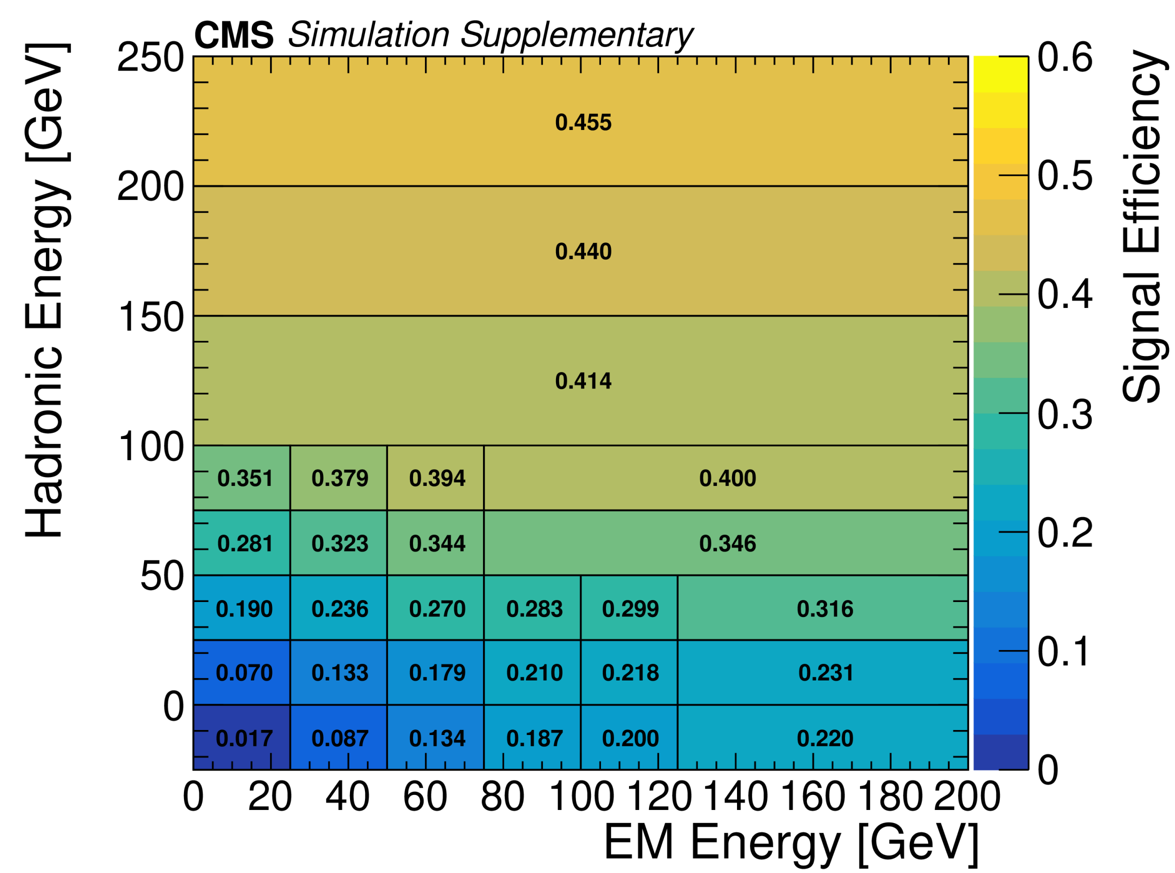
Cluster Efficiency

- Cluster efficiency is binned in hadronic energy and EM energy
  - Independent of LLP mass (7- 55 GeV), cτ (0.1 - 100 m), and decay mode (dd and $\tau^+\tau^-$) within each LLP decay region
  - The full simulation signal yield prediction reproduced using this parameterization to within 35% and 20% for region A and B, respectively.

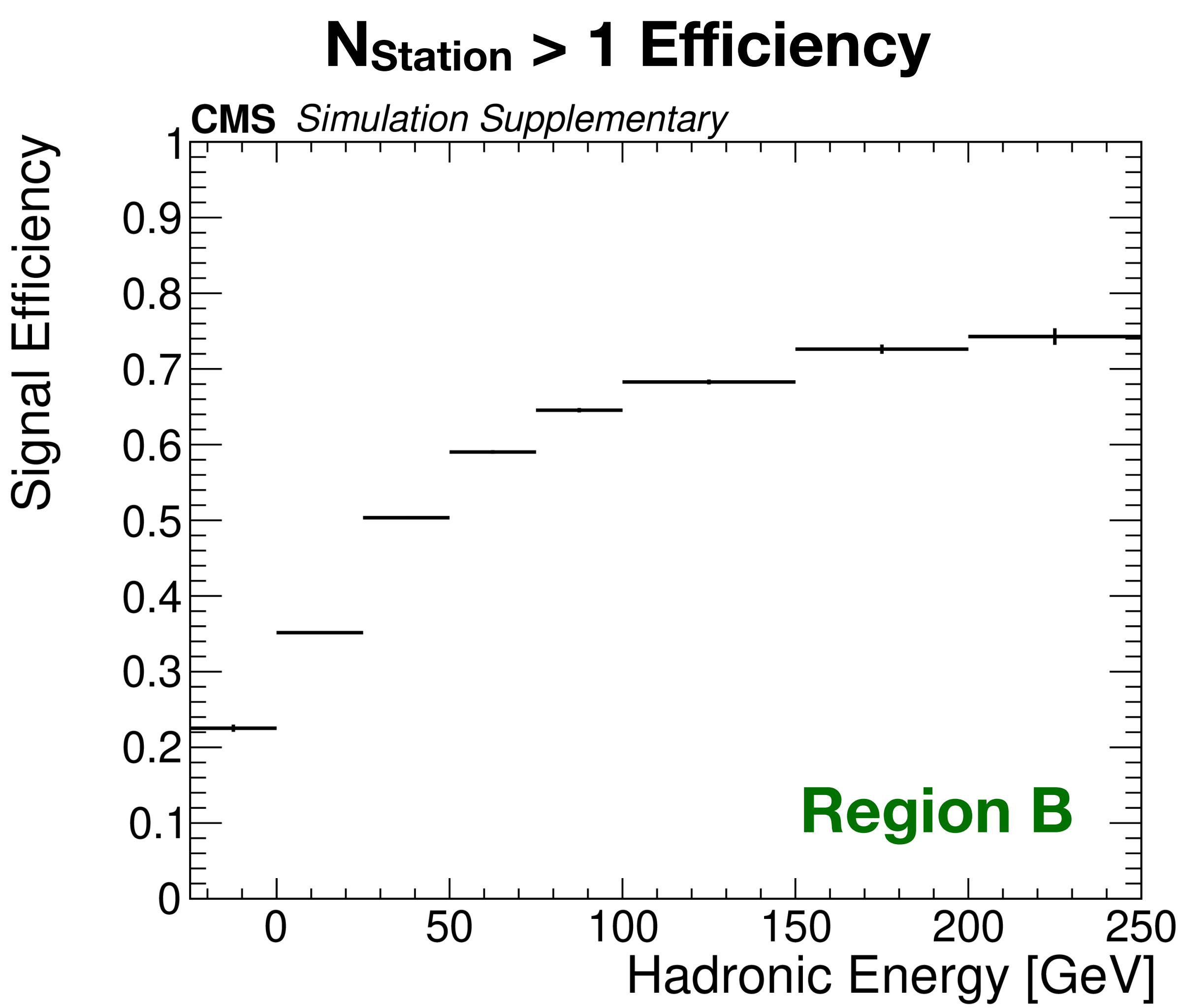
Region A



Region B



Cut-based ID Efficiency



- **Code to calculate cut-based ID efficiency is provided in HEPData Entry**
- **Only gen-level LLP η , decay position, and hadronic energy are needed as input**
- Recall the ID requirement in analysis:
  - If $N_{station} > 1$: $|\eta| < 1.9$
  - If $N_{station} = 1$: apply $|\eta| < X$, where X = 1.6 or 1.8 depending on the Average Station Number
- ID efficiency is 100% for clusters in region A ($|\eta| < 1.3$)
- ID efficiency for region B is calculated using:
  1. Efficiency of $N_{station} > 1$ requirement
  2. Transfer function that takes gen-level LLP decay position to RECO-level cluster Average Station (Only for clusters with $N_{station} = 1$),
  3. LLP η as a proxy for cluster η
- **The full simulation signal yield prediction reproduced using this procedure to within 10%.**

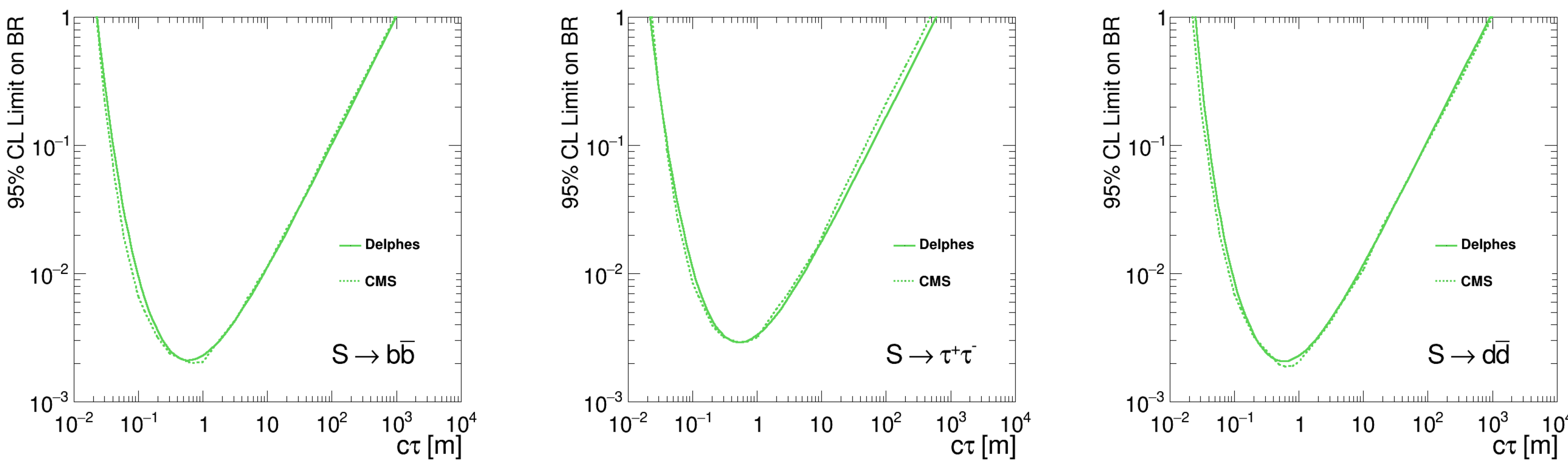
Other Cuts

- **The following cuts are model dependent, so are left for recasters to implement for specific models**
  - **Jet Veto**
    - Clusters matched to jets (>10 GeV) are vetoed
    - Jet veto inefficiency is due to clusters being accidentally matched to pileup or jets from other LLPs
    - Depends on the pileup condition and the number of LLPs in the specific model
  - **Time cut**
    - -5 ns $< t_{cluster} <$ 12.5 ns
    - $t_{cluster}$ can be calculated using gen-level LLP travel time from IP to decay vertex
    - Travel time highly depends on the lifetime and boost of the LLP
  - **$\Delta\phi$ (cluster, MET)**
    - abs($\Delta\phi$ (cluster, MET)) < 0.75
    - Highly dependent on the source of the MET in the model

Limits & Validation

- We have validated the signal efficiency parameterization and implementation of the other cuts using Delphes
- Calculated limits using 1-bin cut and count experiment using RooStat
  - Bin D contains more than 90% of the signal events
- Validated that the standalone workflow is able to reproduce the limits from the CMS analysis for all 3 decay modes to within 30%

LLP mass = 15 GeV

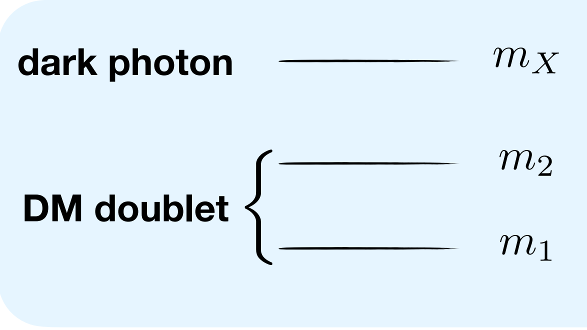


Summary

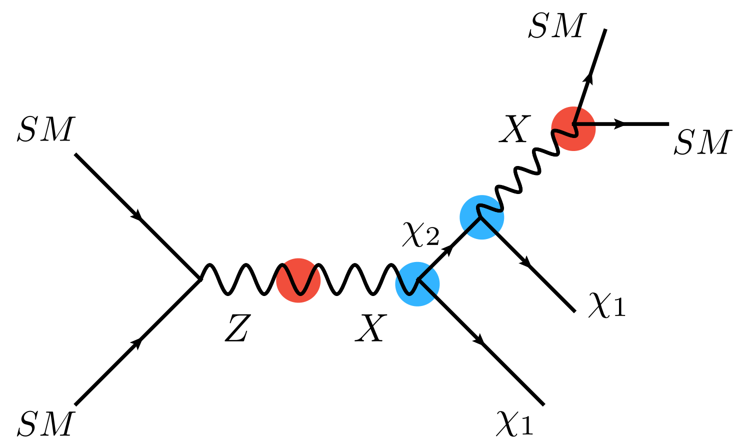
- Presented first search for LLPs using the CMS endcap muon system as a sampling calorimeter to identify displaced showers
- Provides current best LHC limit for LLPs with $c\tau$ above 6, 20, and 40 m for mass of 7, 15, and 40 GeV respectively.
- We provide signal efficiency parameterization that allows for reinterpretation to different models that are independent of the LLP mass, lifetime, and decay mode, while depending only on the LLP energy.
- Any feedback on the additional materials are welcome

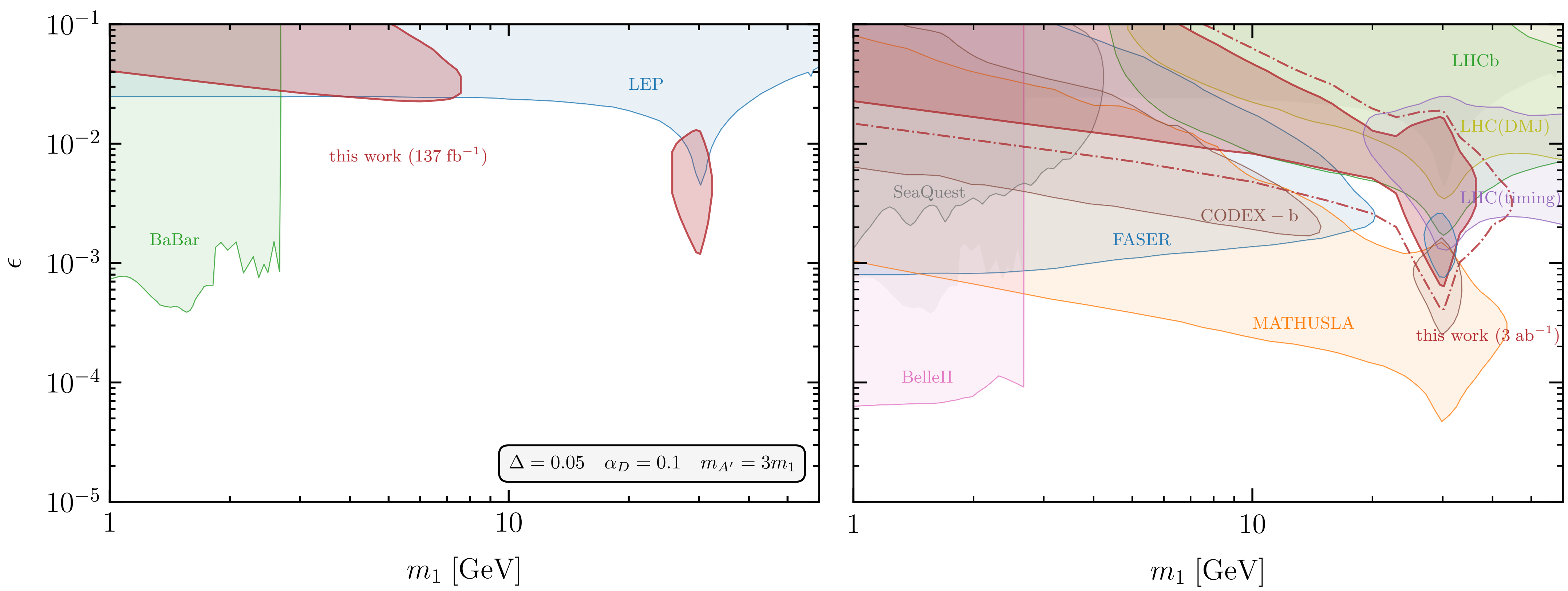
INELASTIC DM

$$\mathcal{L}_{SH} = \mathcal{L}_{\rm SM} + i e_D X^\mu \bar{\chi}_1 \gamma^\mu \chi_2 - \frac{\epsilon}{2\cos\theta_W} \hat{X}_{\mu\nu} \hat{B}^{\mu\nu}$$



$$\Delta \equiv \frac{m_2 - m_1}{m_1}$$



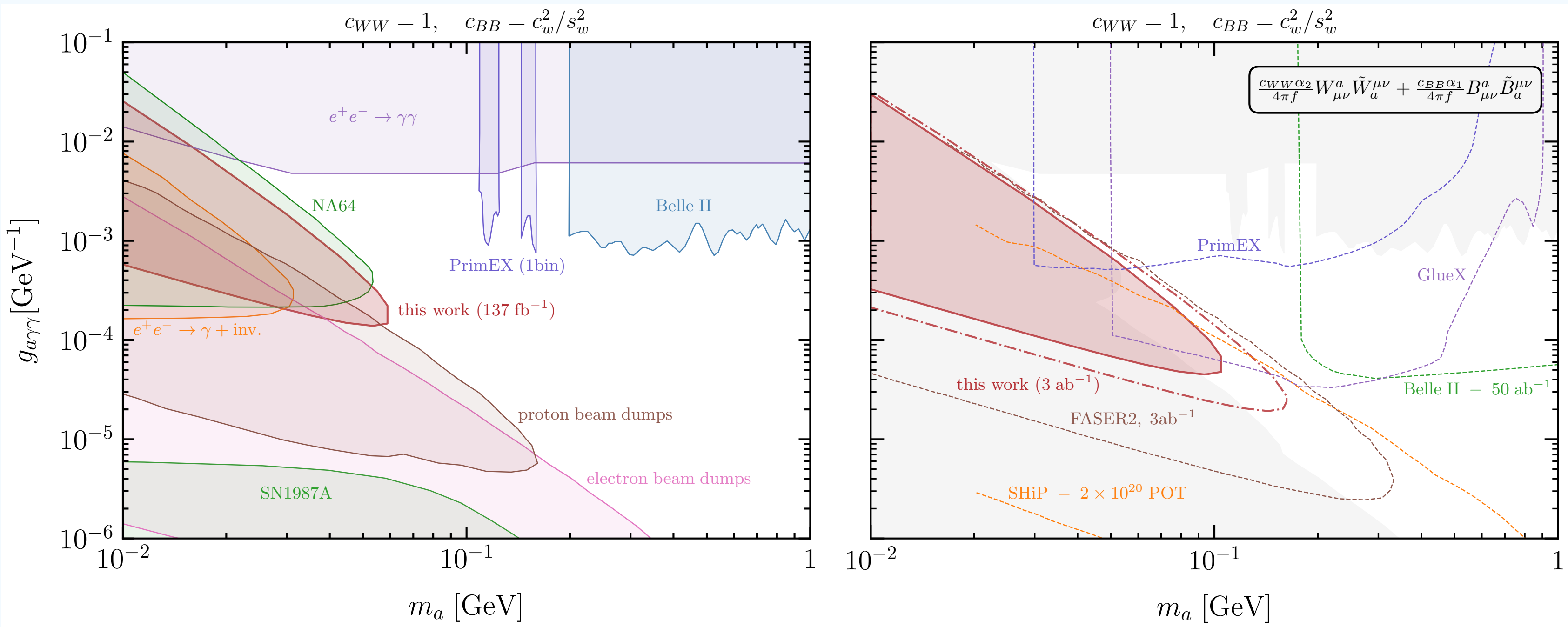


Mitridate, Papucci, Wang, et al. in preparation

ALP

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)^2 - \frac{1}{2} m_a^2 a^2 \frac{a}{4\pi f_a}\left(\alpha_s c_{GG}\, G^a_{\mu\nu}\,\widetilde{G}^{a,\mu\nu} + \alpha_2 c_{WW}\, W^a_{\mu\nu}\widetilde{W}^{a,\mu\nu} + \alpha_1 c_{BB}\, B_{\mu\nu}\widetilde{B}^{\mu\nu}\right) + \ldots$$

photon-coupled ALP

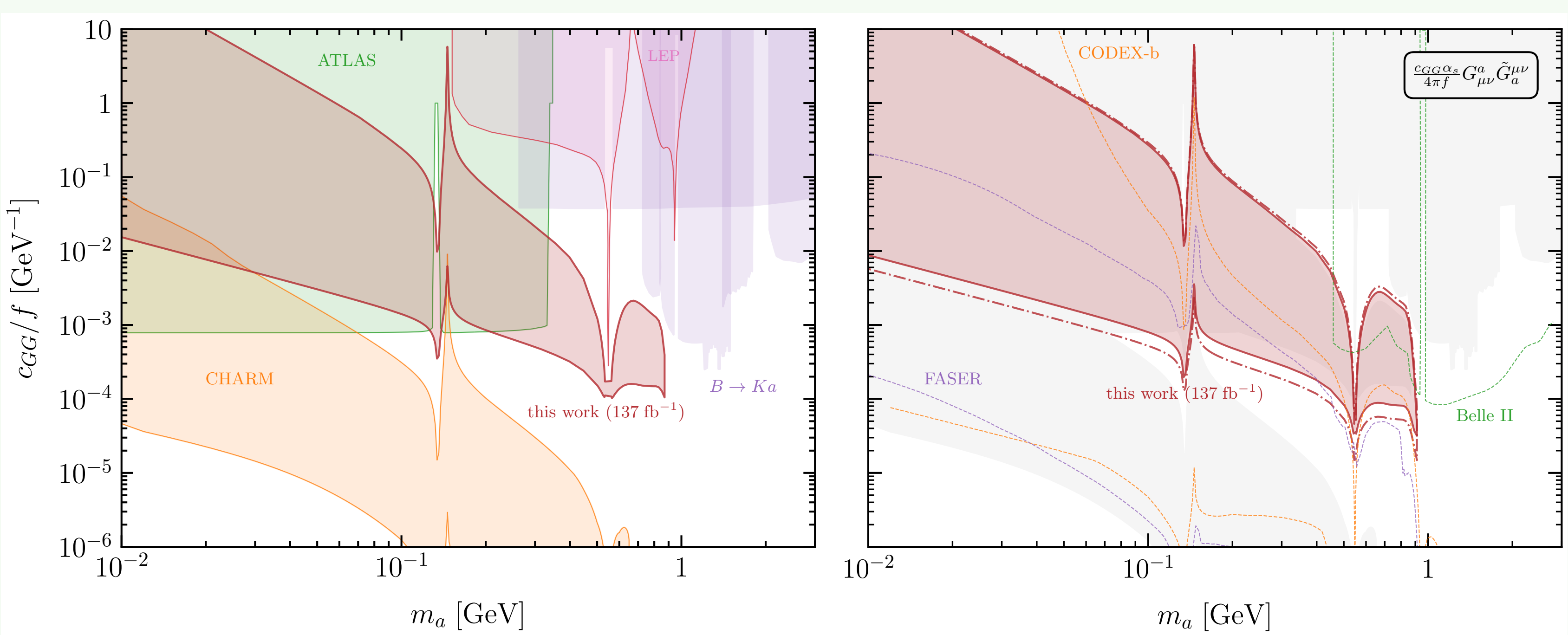


$$c_{WW} = 1 \qquad c_{BB} = c_w^2/s_w^2$$

$$c_{\gamma Z} = c_w^2 c_{WW} - s_w^2 c_{BB} = 0$$

$$c_l = c_q = c_{GG} = 0$$

gluon-coupled ALP



$$c_{GG} \neq 0$$

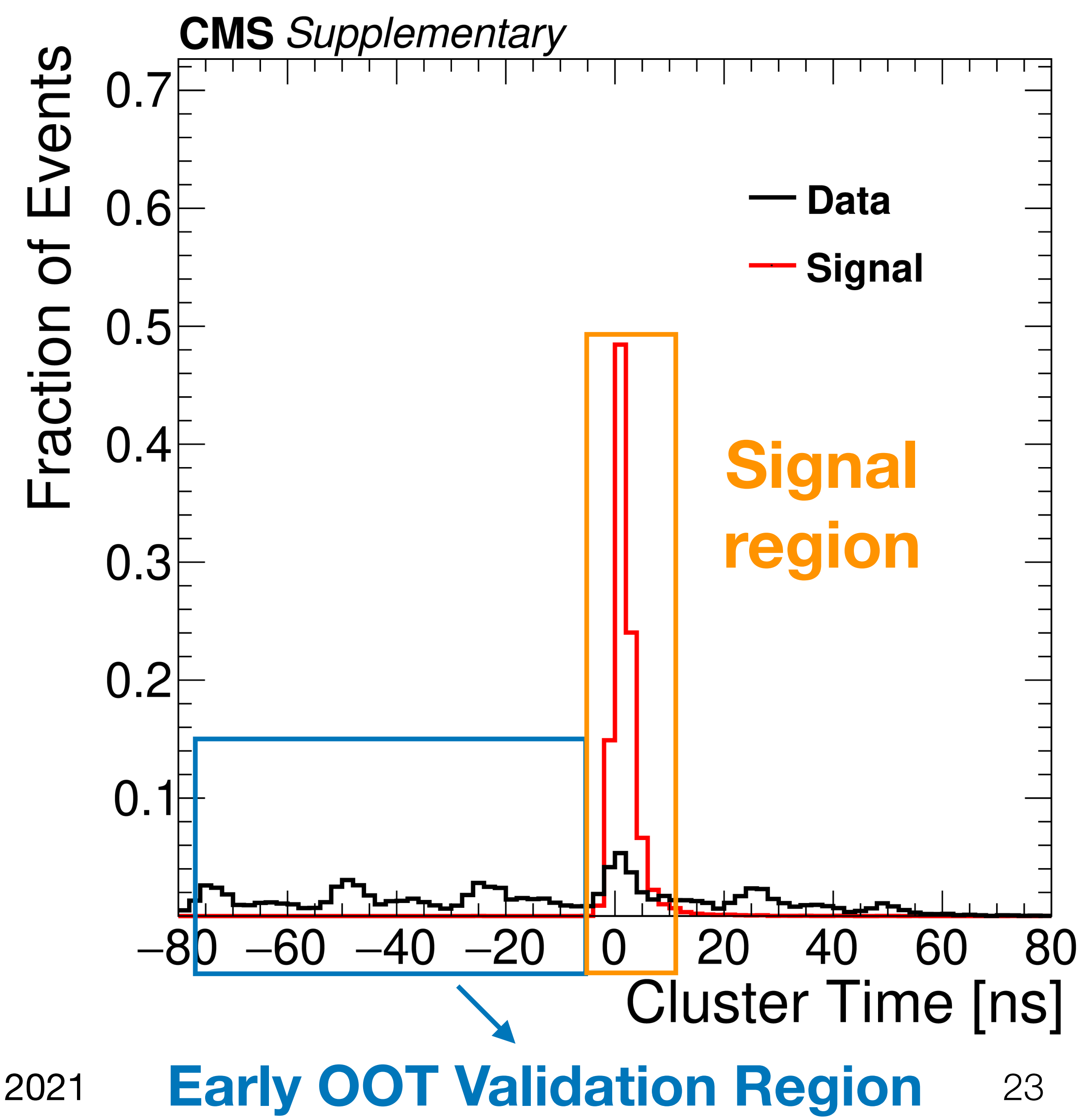
$$c_l = c_q = c_{WW} = c_{BB} = 0$$

Mitridate, Papucci, Wang, et al. in preparation

BACKUP SLIDES

Cluster Time

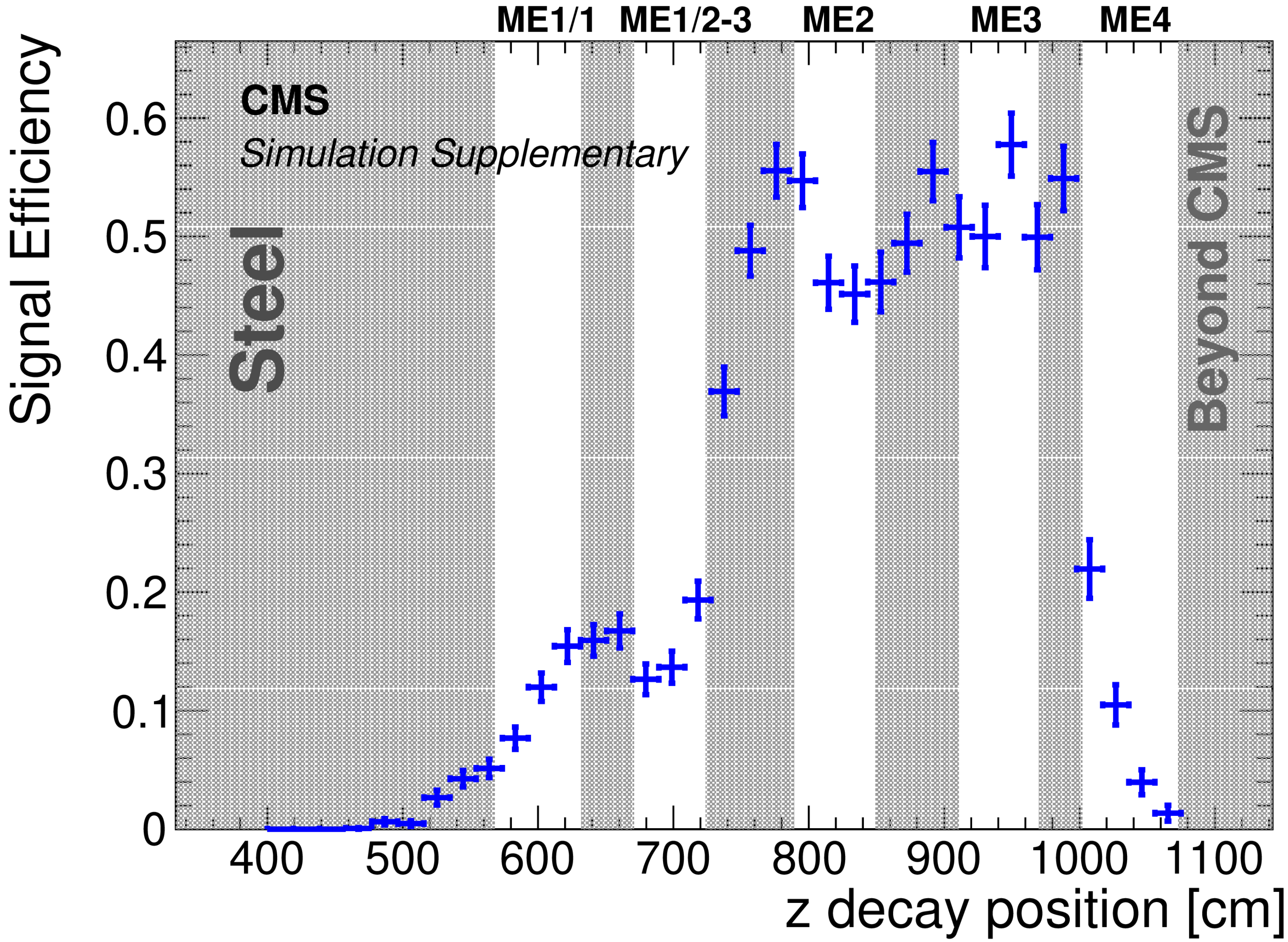
- 5x background rejection by requiring CSC clusters to be **in-time (-5 ns < t < 12.5 ns)**
  - For background, after the vetos the time structure shows contribution from OOT pileup
  - Signals concentrate in the in-time window
- Allow us to define an **early OOT validation region (t < -12.5 ns)** for background estimation



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

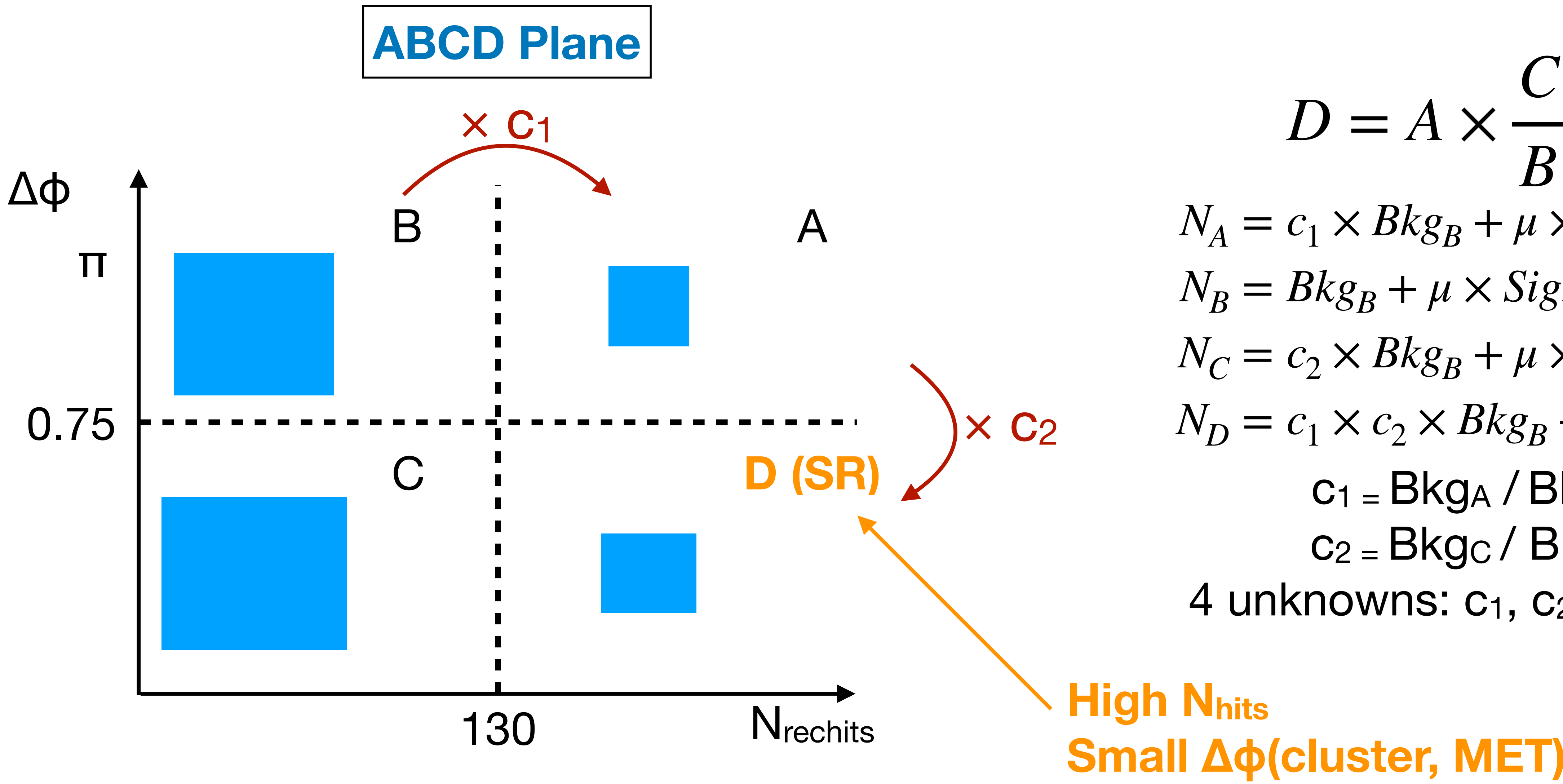
Signal Efficiency vs Z Decay Position

m_S = 15 GeV



~50% signal efficiency when LLP decays between ME1 and ME4

Data Driven Background Estimation



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

$$N_A = c_1 \times Bkg_B + \mu \times SigA$$
$$N_B = Bkg_B + \mu \times SigB$$
$$N_C = c_2 \times Bkg_B + \mu \times SigC$$
$$N_D = c_1 \times c_2 \times Bkg_B + \mu \times SigD$$

$c_1 = Bkg_A / Bkg_B$

$c_2 = Bkg_C / Bkg_B$

4 unknowns: c_1, c_2, μ, Bkg_B

	A	B	C	D (SR)	Bkg prediction
Events	3	96	47	3	2 ± 1

- $\Delta\phi$(cluster, MET) and $N_{rechits}$ are independent for background
- Method has been validated in two separate **validation regions**
- No excess above SM prediction observed