EXO-20-015 Approval

04/29/2021

Physics Plenary Meeting

Jiajing Mao, María Spiropúlu, Nathan Suri, Christina Wang, Si Xie (Caltech)

Artur Apresyan, Zoltan Gecse, Cristián Peña (Fermilab)

Lisa Benato, Gregor Kasieczka, Joerg Schindler (Hamburg)

Matthew Citron, James Sheplock (UCSB)

Daniel Diaz, Javier Duarte (UCSD)

LPC LLP Group

Analysis Details

- Documentation
    - CADI: EXO-20–015
    - Twiki
    - AN-19-154 (v13)
    - Paper draft (v10)
- ARC: Juliette Alimena, Christopher Scott Hill, Harvey Newman (CCLE), Daniele Trocino, Viatcheslav Valuev (Chair)
    - We thank for ARC for a very thorough and thoughtful review
- Changes from ARC review:
    - background uncertainty
    - Improved signal corrections and uncertainties

Motivation for Long-lived Particle Searches

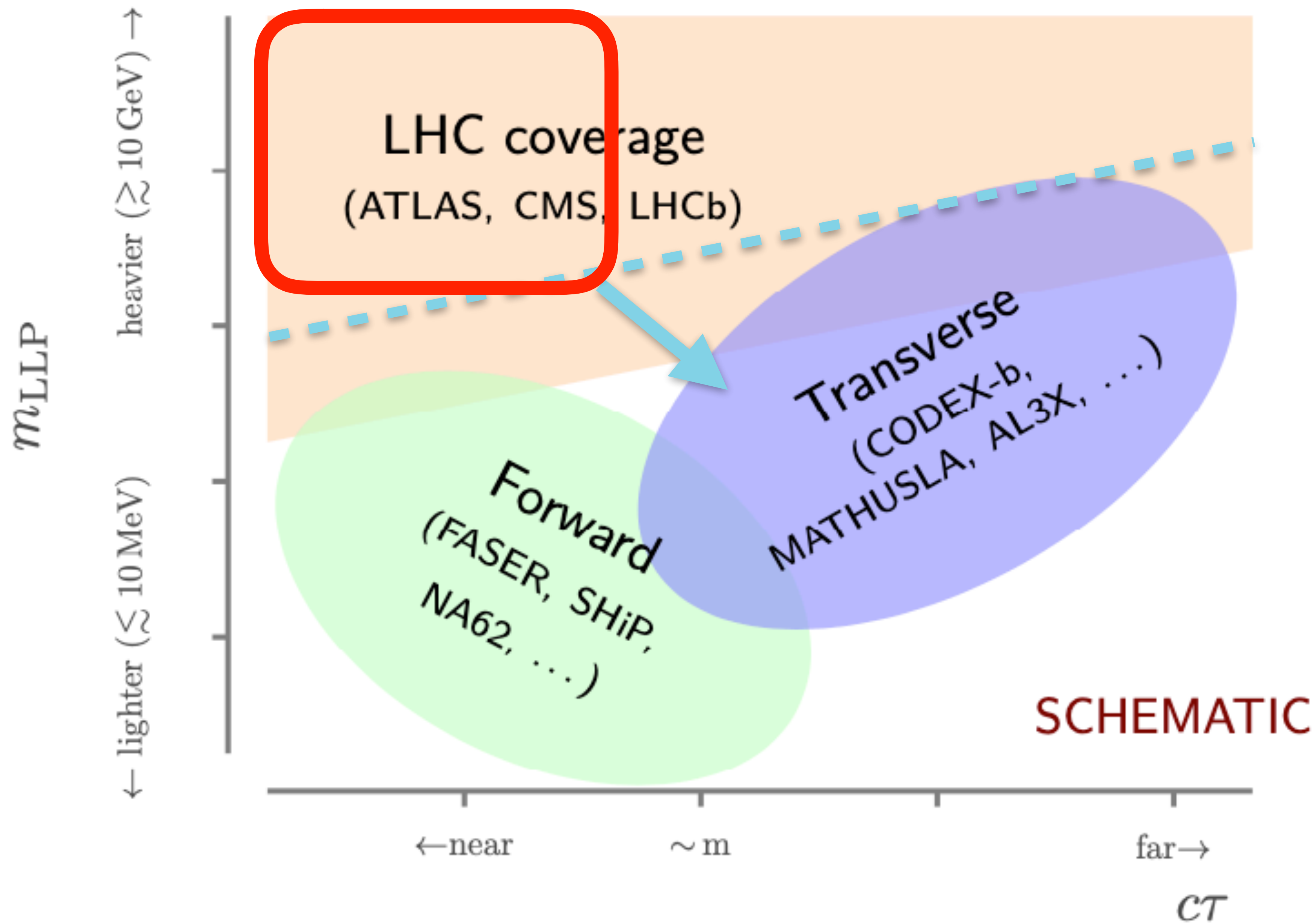
LLPs are ubiquitous in SM and BSM physics

$$\Gamma \sim \frac{g^2}{8\pi}\left(\frac{m}{M}\right)^{2n} m$$

Three general mechanisms to give small decay width and macroscopic lifetimes:

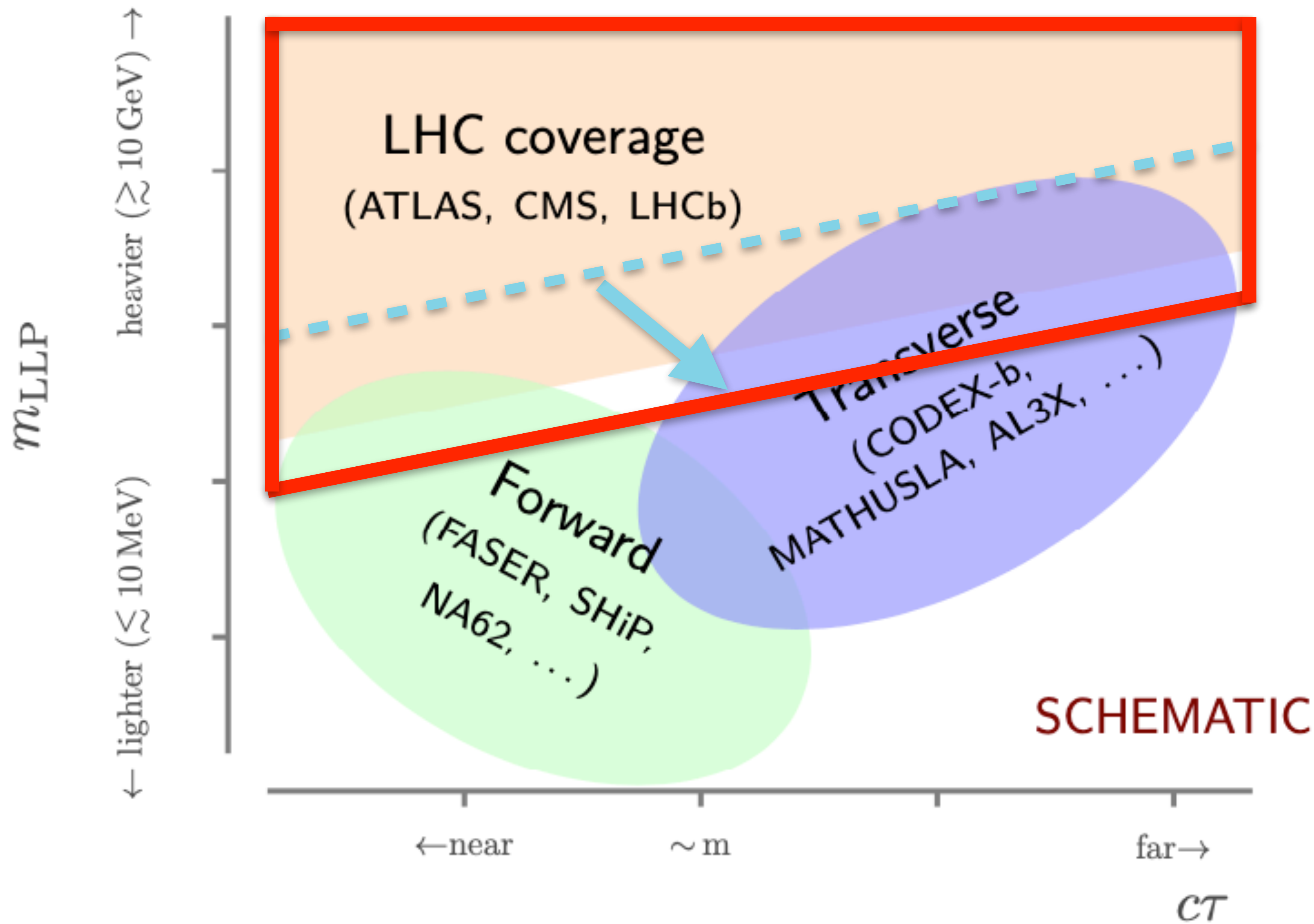
	BSM Examples
1. Feeble coupling to SM	Hidden-Valley / DM Portals
2. Scale suppression	GMSB SUSY
3. Phase space suppression	Small Mass-Splitting

LLP Landscape in CMS



- CMS has excellent discovery reach for $c\tau$ < 1m and M_{LLP} > 50 GeV
- Enabled by precision tracker: displaced jets

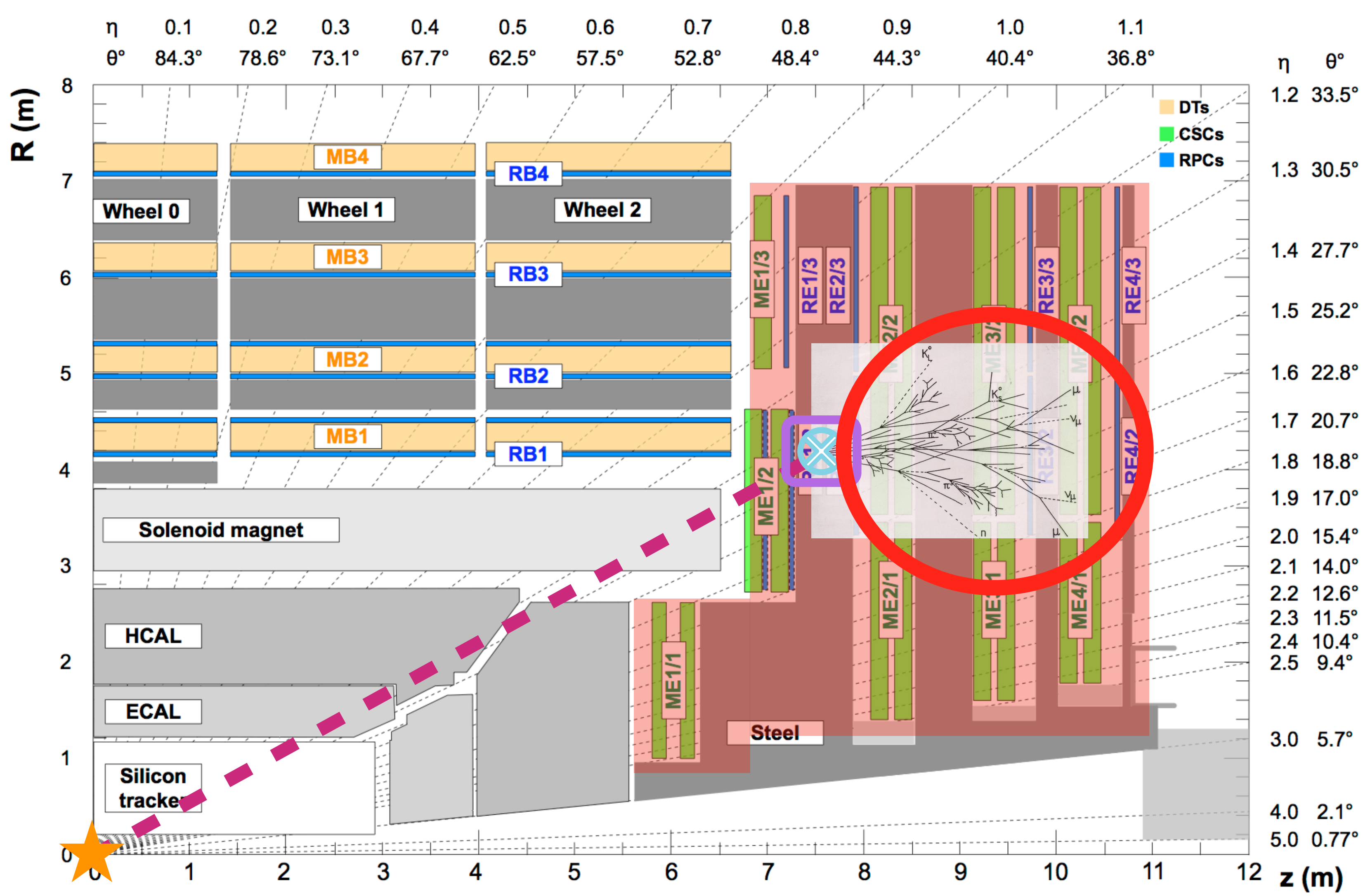
Key Goal : Close gaps in search coverage



- Strategy: Enable searches for light LLP with large $c\tau$ using LLP decays beyond the tracker region

Search for LLPs in Muon System

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

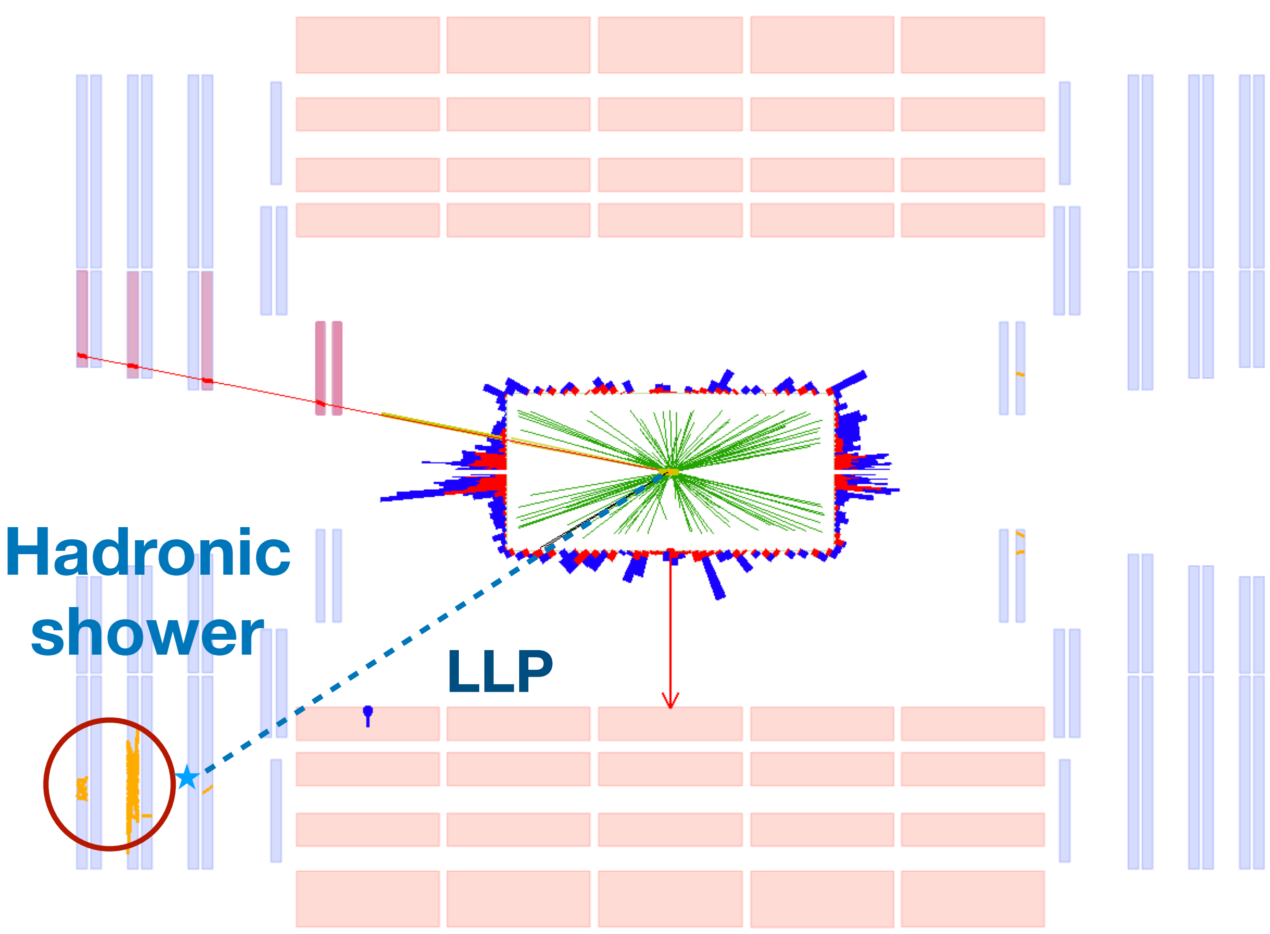


EXO-20-015: Endcap Muon System Analysis

LLP decay and resulting particle shower is detected as multi-hit signals in the gas ionization chambers

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 RecHits** in the muon system
- Muon system acts as a sampling calorimeter: sensitivity to a broad range of decays

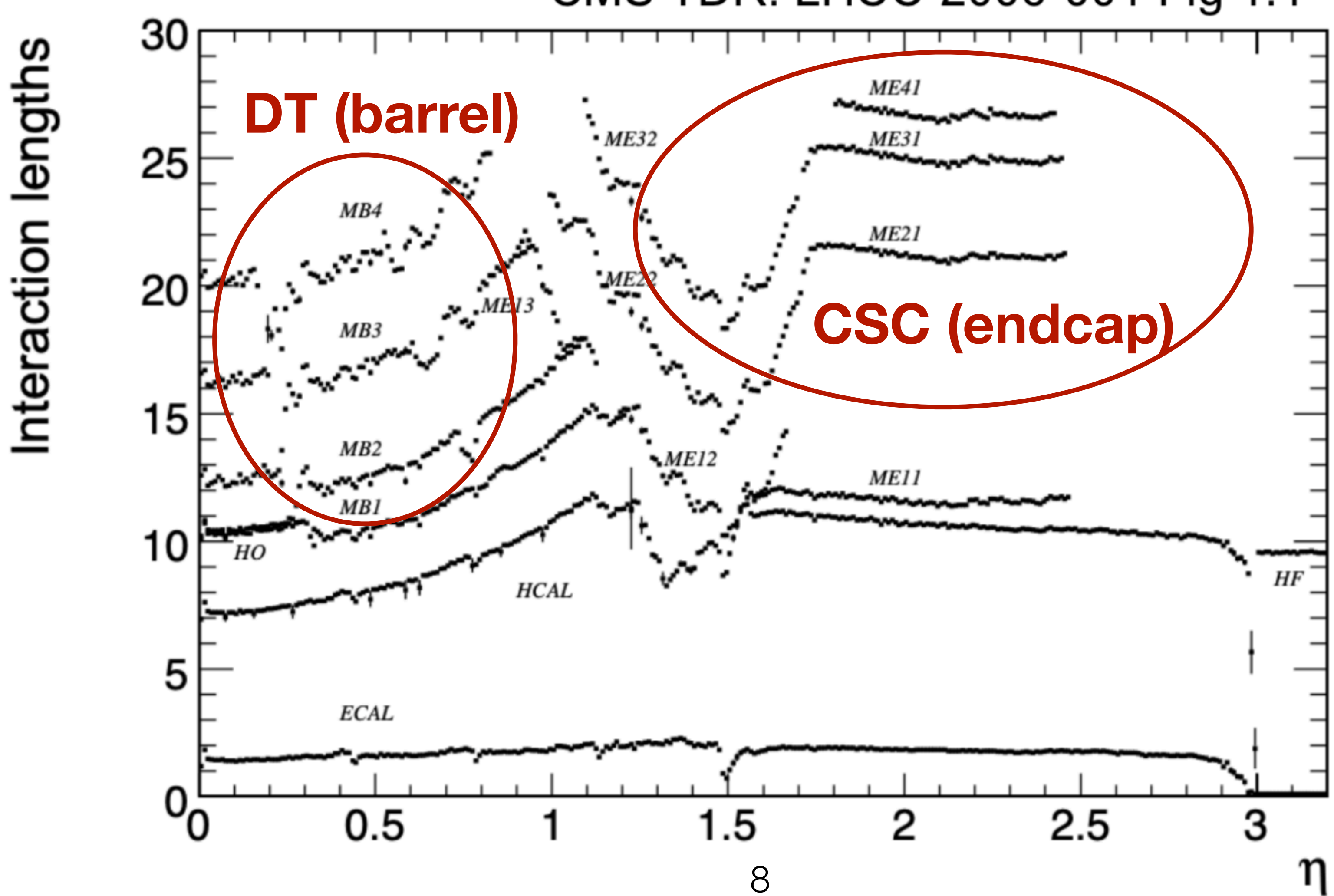


- **Unique signature** due to the presence of steel in the CMS muon system
- **First search in CMS that uses this novel signature**

Unique Opportunity for CMS

- The steel between stations of the muon system allow us to
  - Use the muon system as a **sampling calorimeter** to detect displaced hadronic showers
  - **Reject more punch-through jets** (12-27 interaction lengths depending on the location)
- Due to the shielding of the muon system and the exotic signature, this analysis can be sensitive to **light LLPs** ($m_{LLP} < 10$ GeV)

CMS TDR: LHCC-2006-001 Fig 1.4

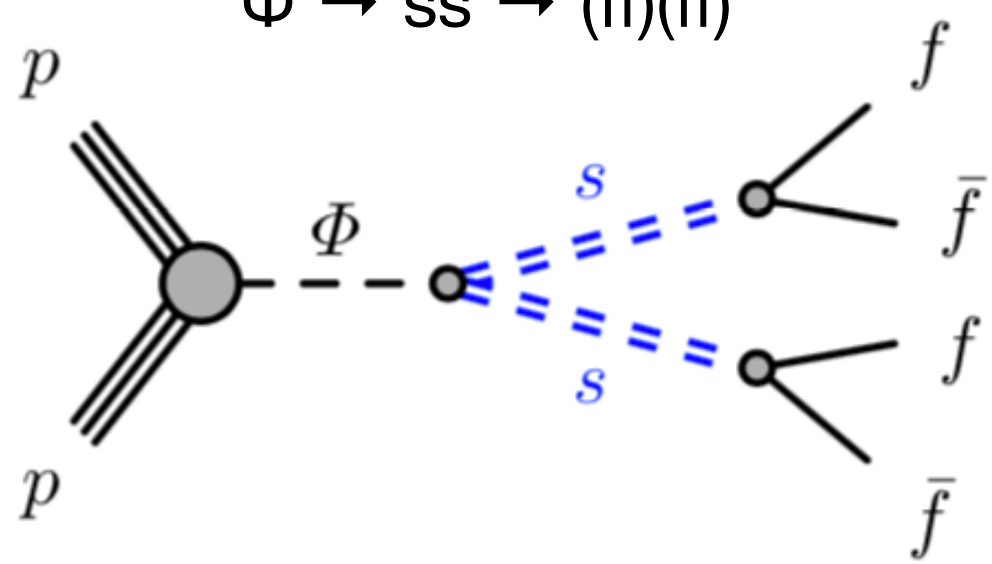


Benchmark Signal Model

- While this search is generically sensitive to LLPs in a model-independent way, we use Higgs-portal to scalar LLP production as the benchmark model
- This LLP benchmark is difficult to detect because:
  - No stable WIMPs to produce large MET
  - No high-mass resonances decaying to high p_T final state objects
  - Low production cross section

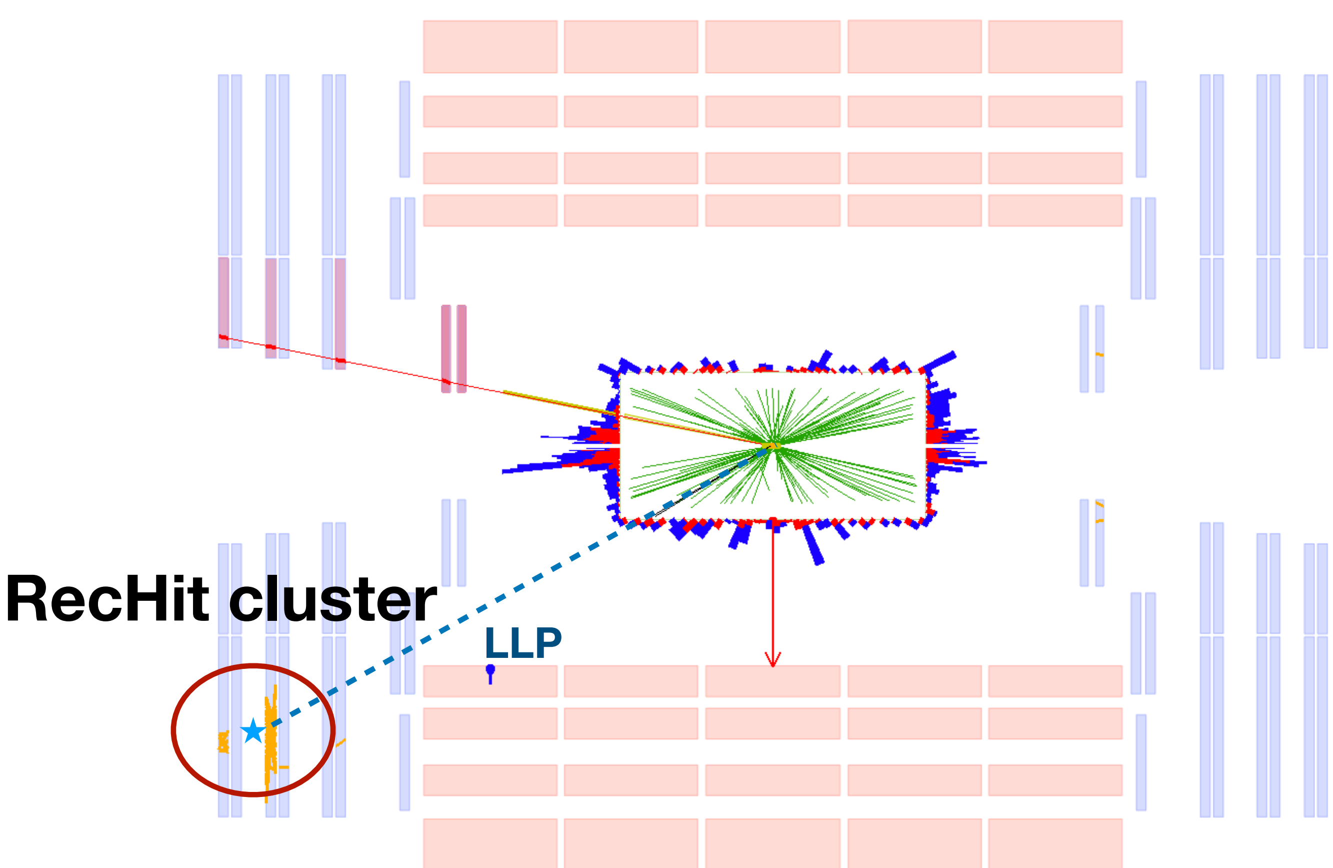
Higgs-portal as benchmark model:

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

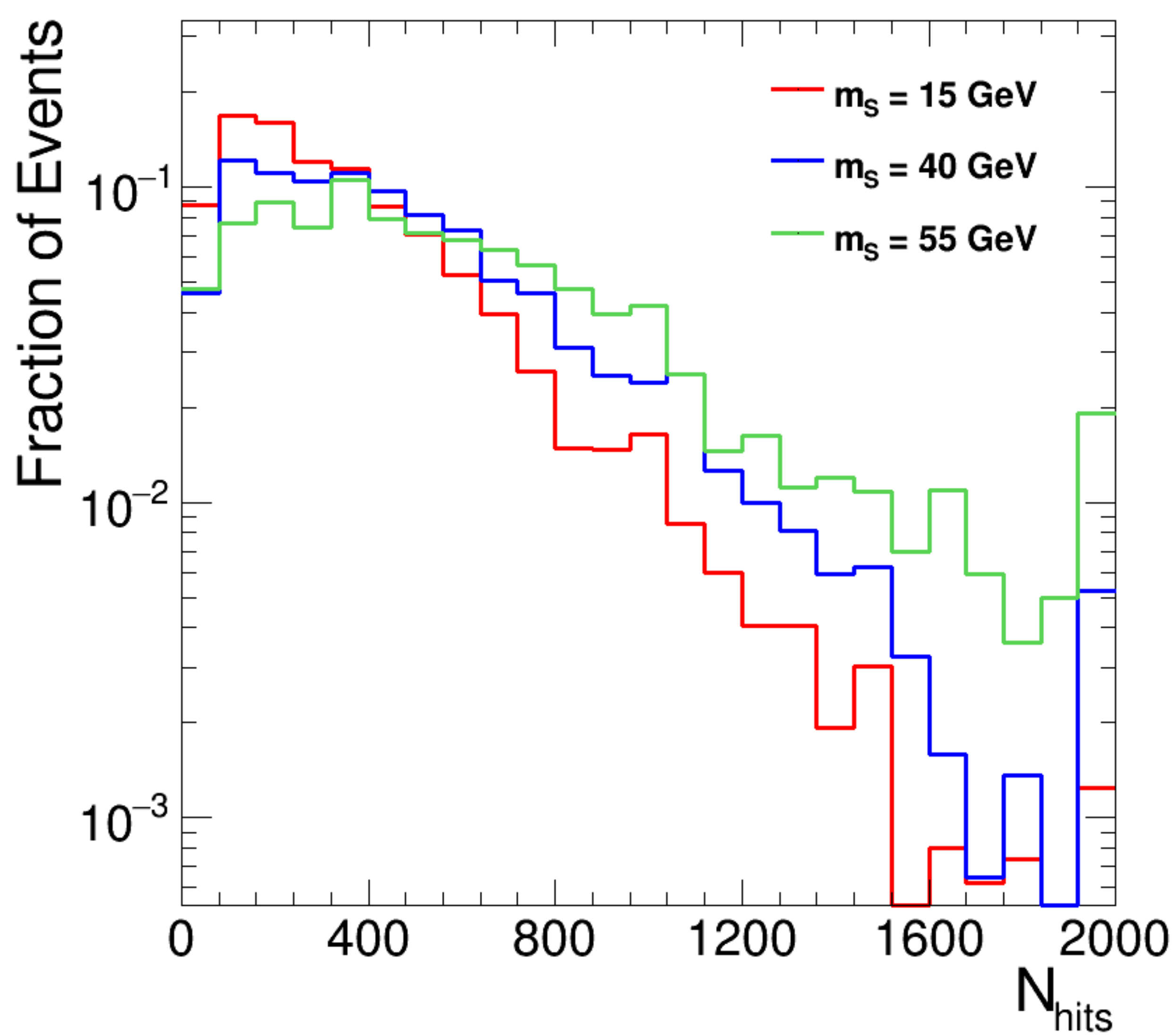


Reconstruction for High Multiplicity Signals

- Signature is based on counting the number of CSC RecHits
- Signals typically have > 200 CSC RecHits

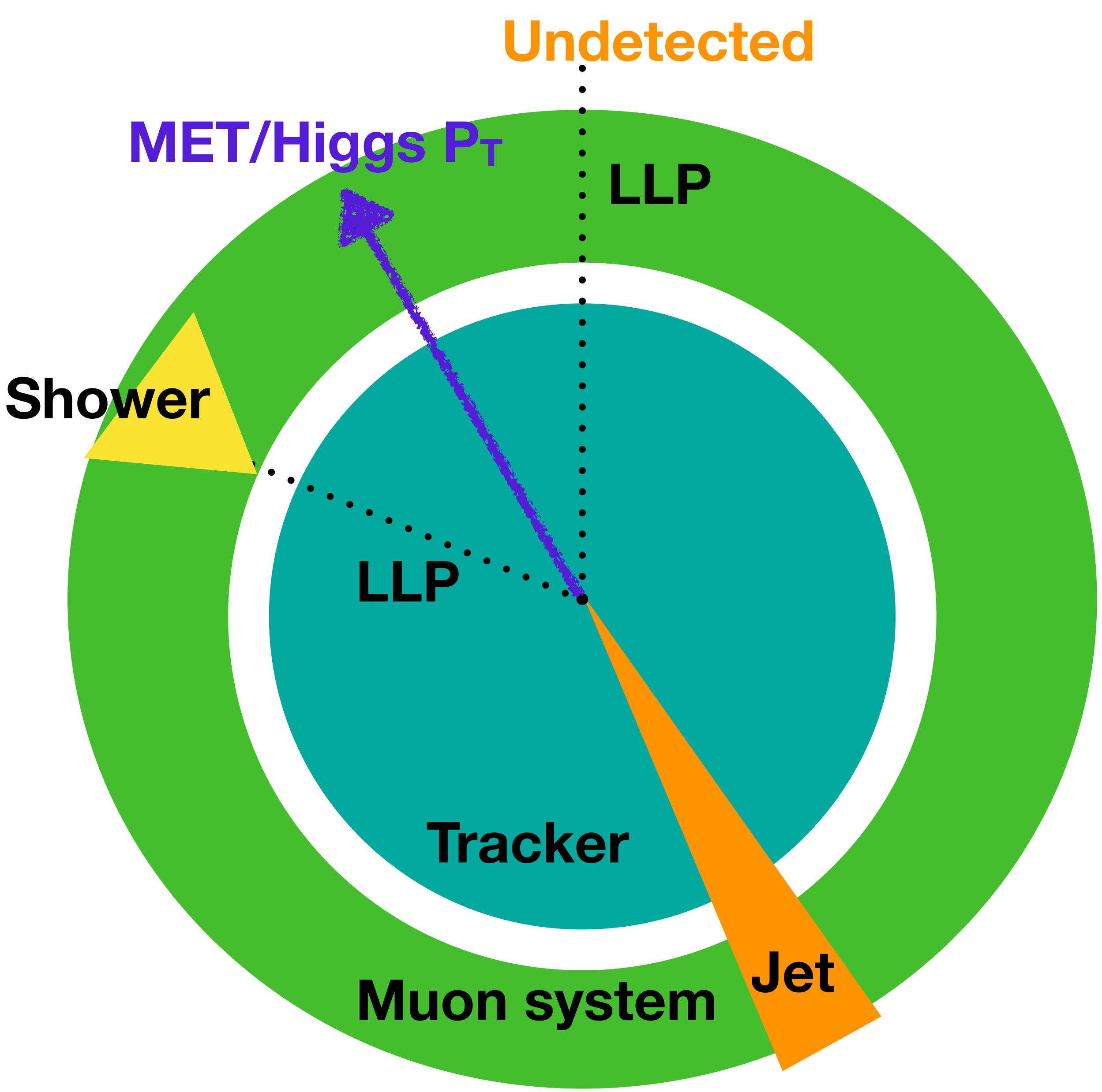


Main discriminator for analysis



Trigger Strategy

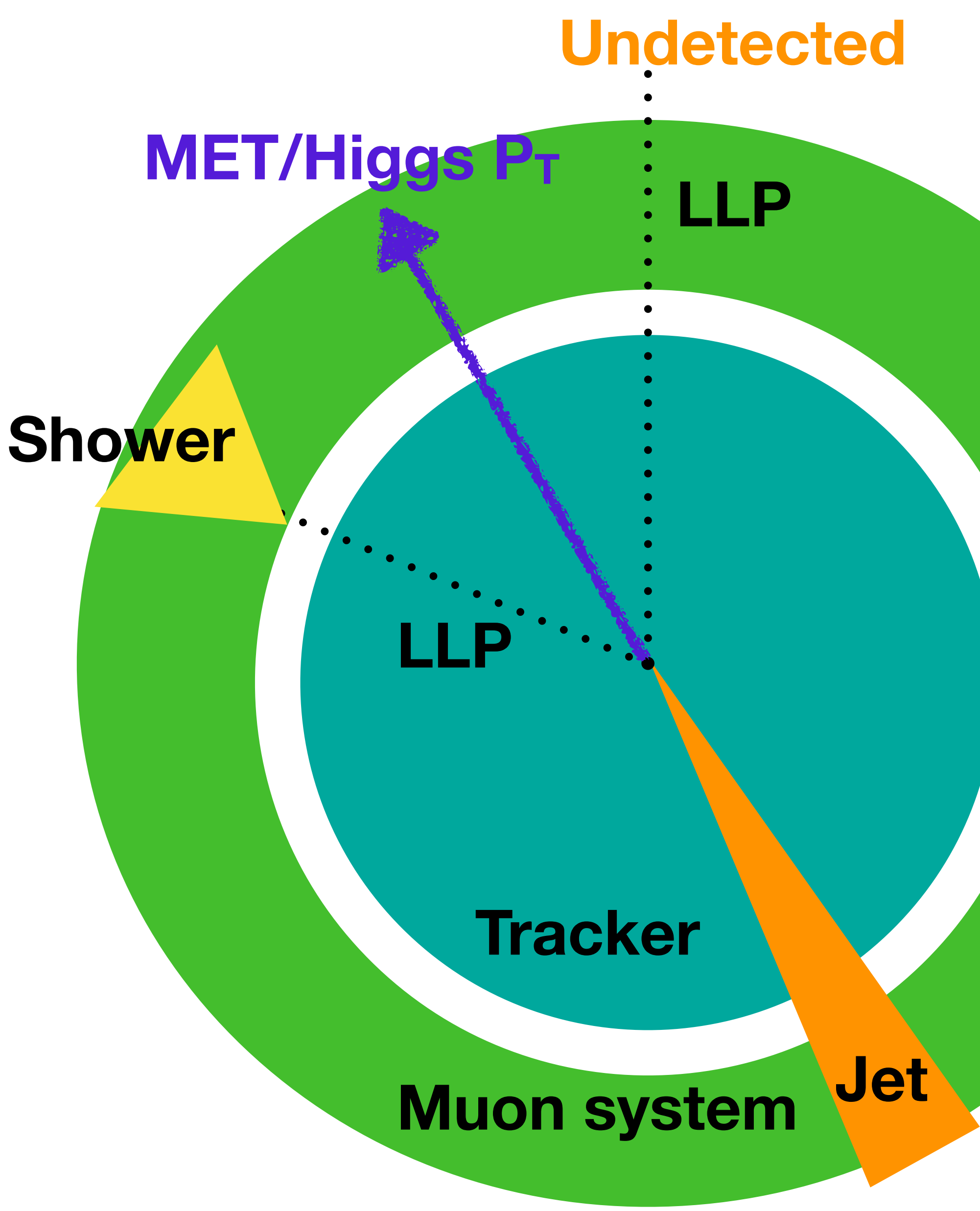
- Trigger on **MET (lack of dedicated trigger)**
  - **2016:** HLT_PFMETNoMu120_PFMHTNoMu120_IDTight
  - **2017 & 2018:**
    HLT_PFMETNoMu120_PFMHTNoMu120_IDTight **OR**
    HLT_PFMETNoMu140_PFMHTNoMu140_IDTight **OR**
    HLT_PFMETNoMu120_PFMHTNoMu120_IDTight_PFHT60

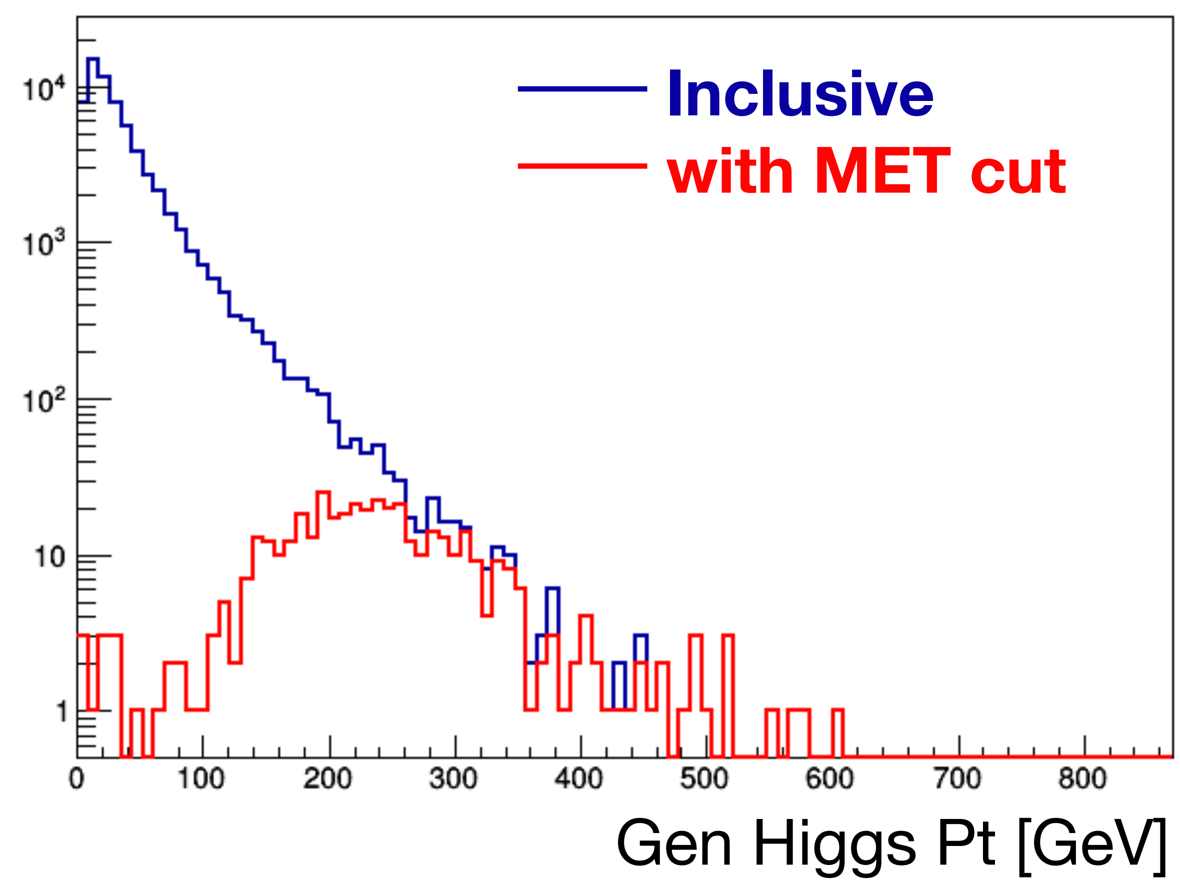


- MET comes from recoil of Higgs against ISR
  - For large cτ one of the LLPs will decay outside the calorimeter

Trigger Strategy

- Signal events that pass trigger are produced with large Higgs boost
  - Signal efficiency is ~1%
  - Signal yield after MET cut assuming BR(H → ss) = 100%: ~9000





Data/MC Samples

- Analysis performed using **RAW-RECO** data-tier
- **DataSet:** RAW-RECO MET-skim dataset (MET≥200 GeV)
- **MC Signal Samples:**
  - Higgs production modes: ggH, VBF, WH, ZH, ttH
  - LLP decay modes: bb, dd, ττ
  - LLP cτ: 0.1, 1, 10, 100m
  - LLP masses: 7, 15, 40, 55 GeV

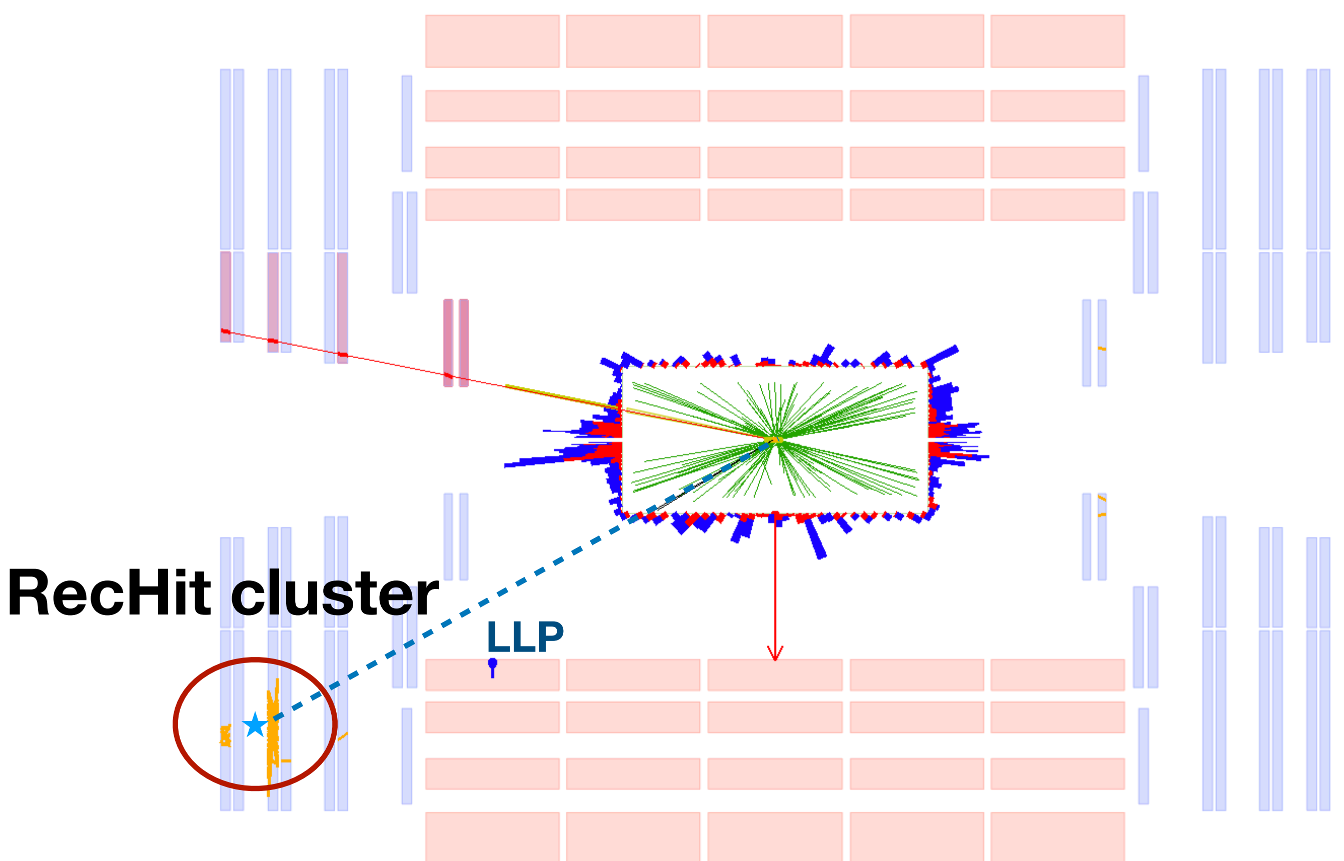
Dataset
/MET/Run2016B-HighMET-07Aug17_ver1-v1/RAW-RECO
/MET/Run2016B-HighMET-07Aug17_ver2-v1/RAW-RECO
/MET/Run2016C-HighMET-07Aug17-v1/RAW-RECO
/MET/Run2016D-HighMET-07Aug17-v1/RAW-RECO
/MET/Run2016E-HighMET-07Aug17-v1/RAW-RECO
/MET/Run2016F-HighMET-07Aug17-v1/RAW-RECO
/MET/Run2016G-HighMET-07Aug17-v1/RAW-RECO
/MET/Run2016H-HighMET-07Aug17-v1/RAW-RECO
/MET/Run2017B-HighMET-17Nov2017-v1/RAW-RECO
/MET/Run2017C-HighMET-17Nov2017-v1/RAW-RECO
/MET/Run2017D-HighMET-17Nov2017-v1/RAW-RECO
/MET/Run2017E-HighMET-17Nov2017-v1/RAW-RECO
/MET/Run2017F-HighMET-17Nov2017-v1/RAW-RECO
/MET/Run2018A-HighMET-17Sep2018-v1/RAW-RECO
/MET/Run2018B-HighMET-17Sep2018-v1/RAW-RECO
/MET/Run2018C-HighMET-17Sep2018-v1/RAW-RECO
/MET/Run2018D-HighMET-PromptRECO-v1/RAW-RECO
/MET/Run2018D-HighMET-PromptRECO-v2/RAW-RECO

	MC Signal Samples	xsec (pb)
Central	/ggH HToSSTo* MH-125 Tune* 13TeV-powheg-pythia8/*/GEN-SIM-RECO	48.58
	/VBFH HToSSTo* MH-125 Tune* 13TeV-powheg-pythia8/*/GEN-SIM-RECO	3.78
Private	/VBFHToSS STodd ms* pl*/*/USER	3.78
	/WminusHToSS STo* ms* pl*/*/USER	0.5328
	/WplusHToSS STo* ms* pl*/*/USER	0.8400
	/ZHToSS STo* ms* pl*/*/USER	0.7612
	/ttH HToSS STo* ms* pl*/*/USER	0.5071

Analysis Strategy

- **Event selection:** select MET skim (≥ 200 GeV) phase space
  - METNoMu tiggers
  - MET ≥ 200 GeV
  - Require ≥ 1 jet, with jetPt > 50 GeV, $|\eta| < 2.4$
  - Require 0 leptons
- Use **signal-like RecHit cluster ID** selections to enhance signal purity and reject background from main collision— exact definition on next slides
- **Background Estimation**
  - Use **ABCD** method with two independent variables: $\Delta\phi$(cluster, MET) and $N_{rechits}$
  - $N_{rechits}$ serves as the main discriminator
  - Validate the background estimation method with two separate **validation regions**

RecHit Clusters

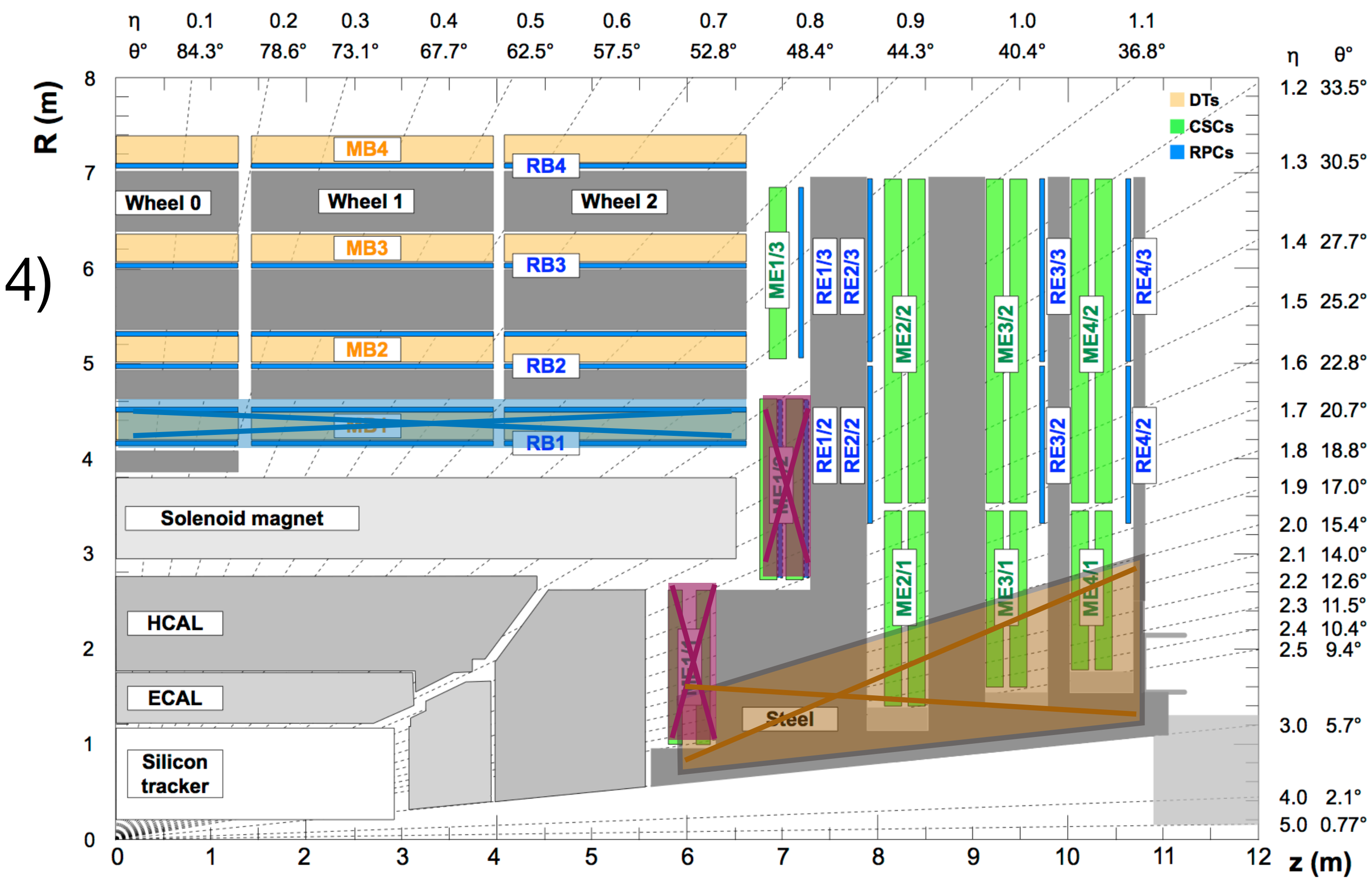


- Each CSC RecHit is defined by their position, specified by η, ϕ
- Cluster RecHits with η-ϕ, distance parameter ΔR = 0.2
- Require > 50 RecHits per cluster
- Merge clusters if two clusters are within ΔR < 0.6

CSC Cluster Selections

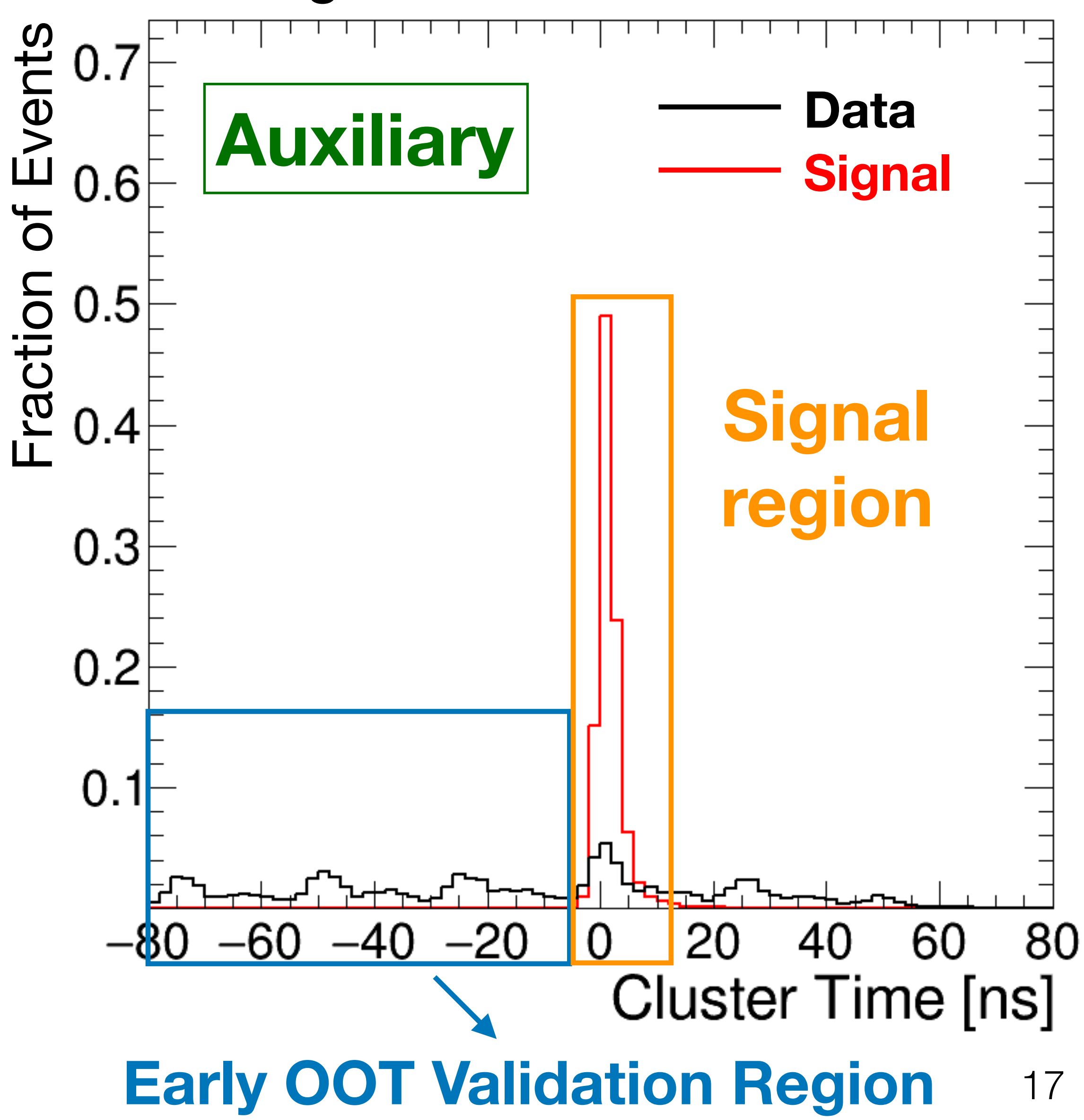
Reject background from the main collision

- Reject **punch-through jets**:
  - Veto clusters matched to jets ($\Delta R < 0.4$)
- Reject **muon bremstralung shower**:
  - Veto clusters matched to muons ($\Delta R < 0.4$)
  - Veto clusters with RecHits in **ME-1/1 or ME-1/2**
  - Veto clusters that are matched to **RE1/2 hits**
  - Veto clusters that are matched to **MB1 segments or RB1 hits**
  - Veto clusters with **$|\eta| > 2.0$**



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
- Require cluster time spread < 20 ns, to avoid clusters with RecHits from different bunch crossings

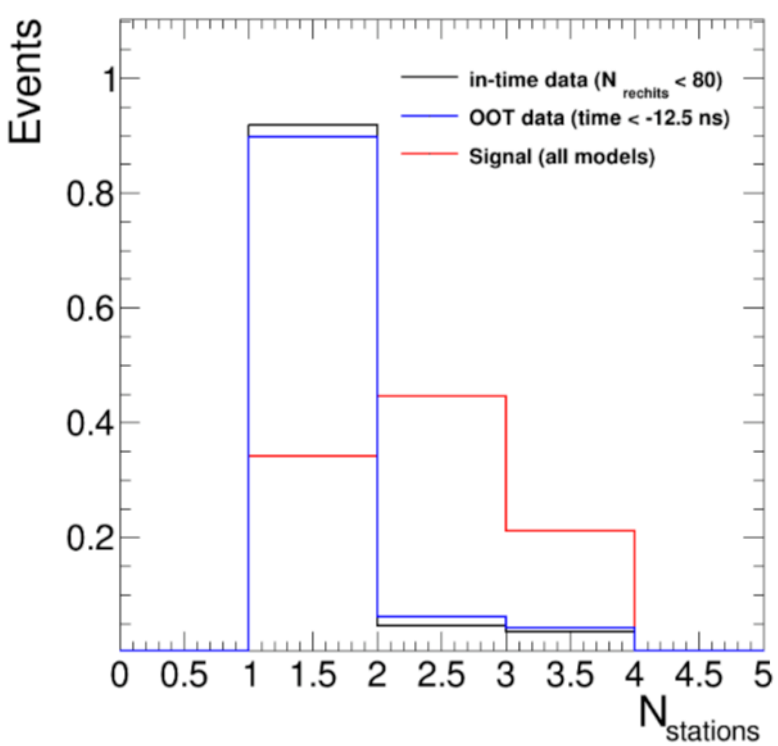


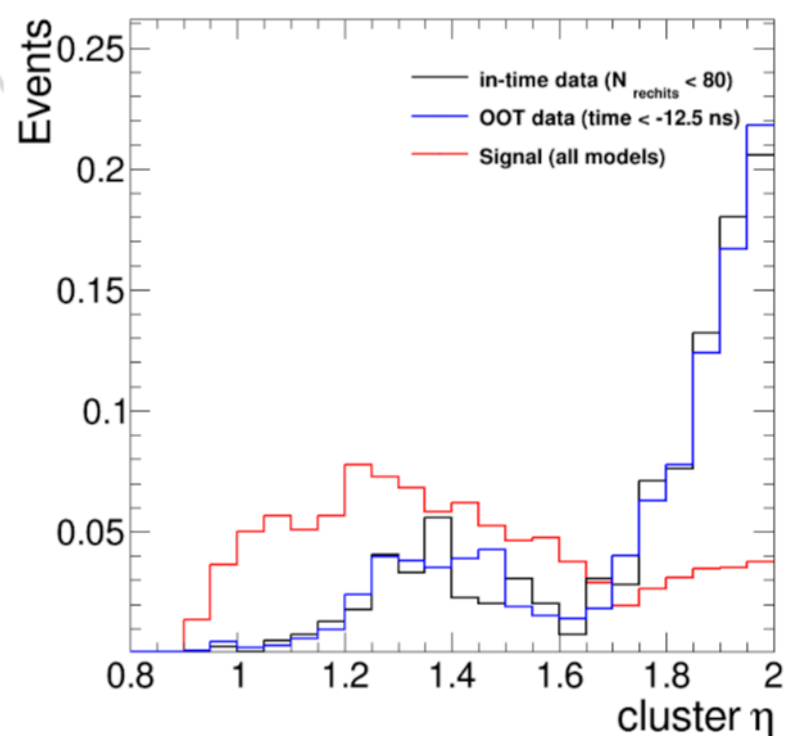
$$\textbf{cluster time} = \frac{\sum_{i=1}^{N_{rechits}} t_i}{N_{rechits}}$$

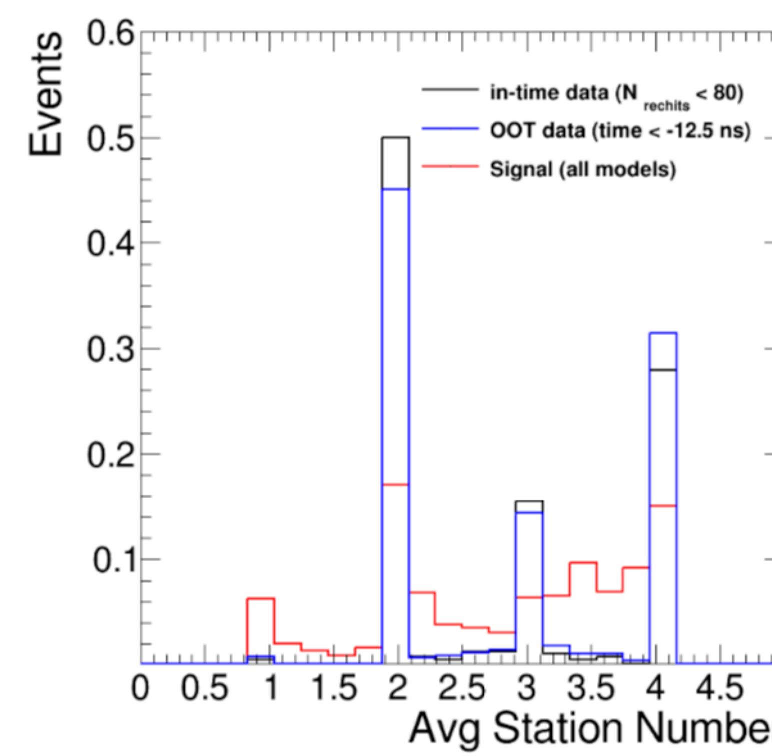
$$\textbf{time spread} = \sqrt{\frac{\sum_{i=1}^{N_{rechits}} (t_i - \bar{t})^2}{N_{rechits}}}$$

Cluster-Level ID

- Signal and background clusters have different **shapes** and **preferred positions**
- Developed a **cut-based ID** using: $N_{stations}$, abs(η), average station number
- Samples used for optimization:
  - Background: negative half of OOT data (time < -12.5 ns)
  - Signal: ggH signal sample with clusters matched to gen-level LLPs

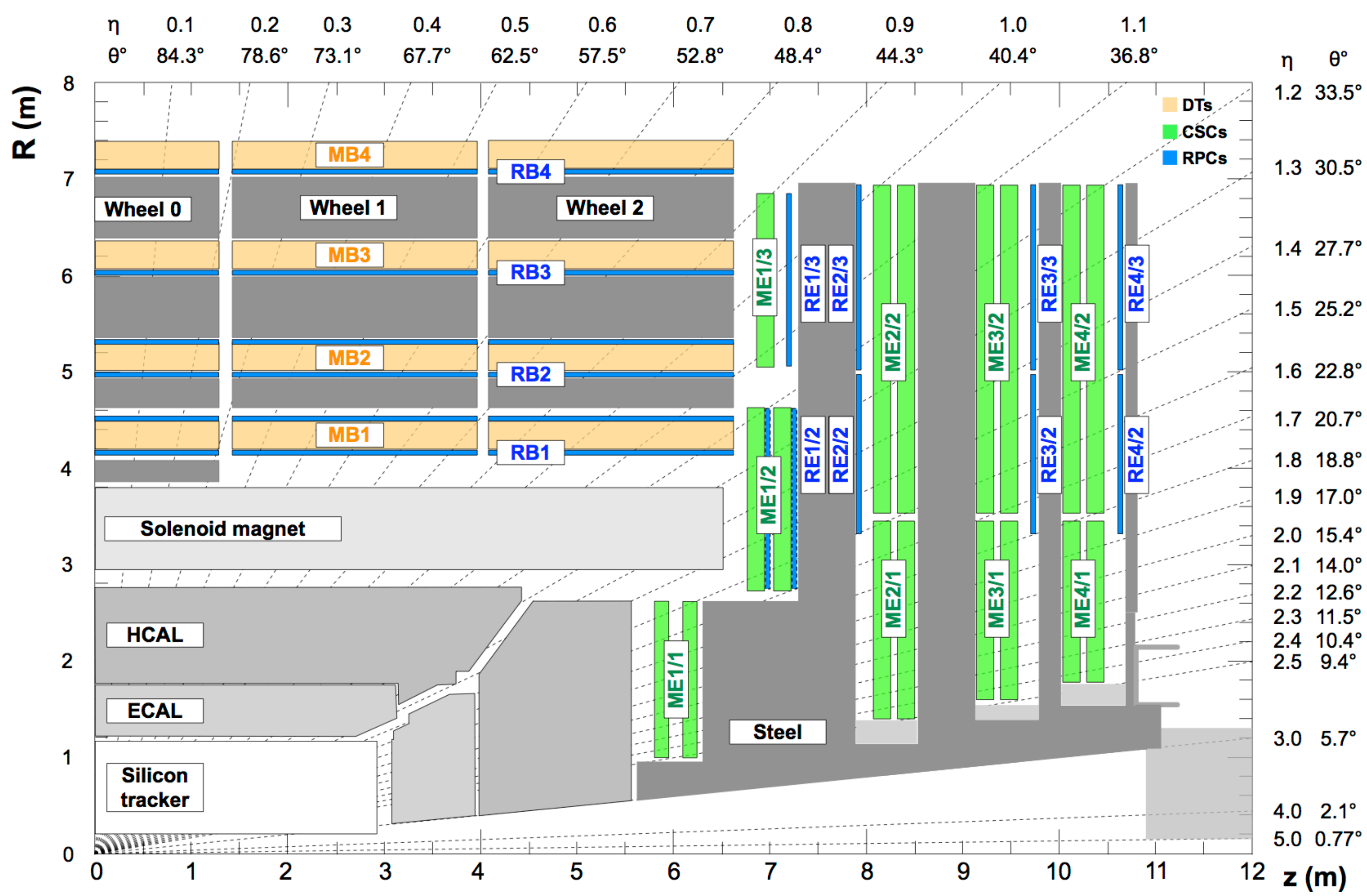






Cut-based ID

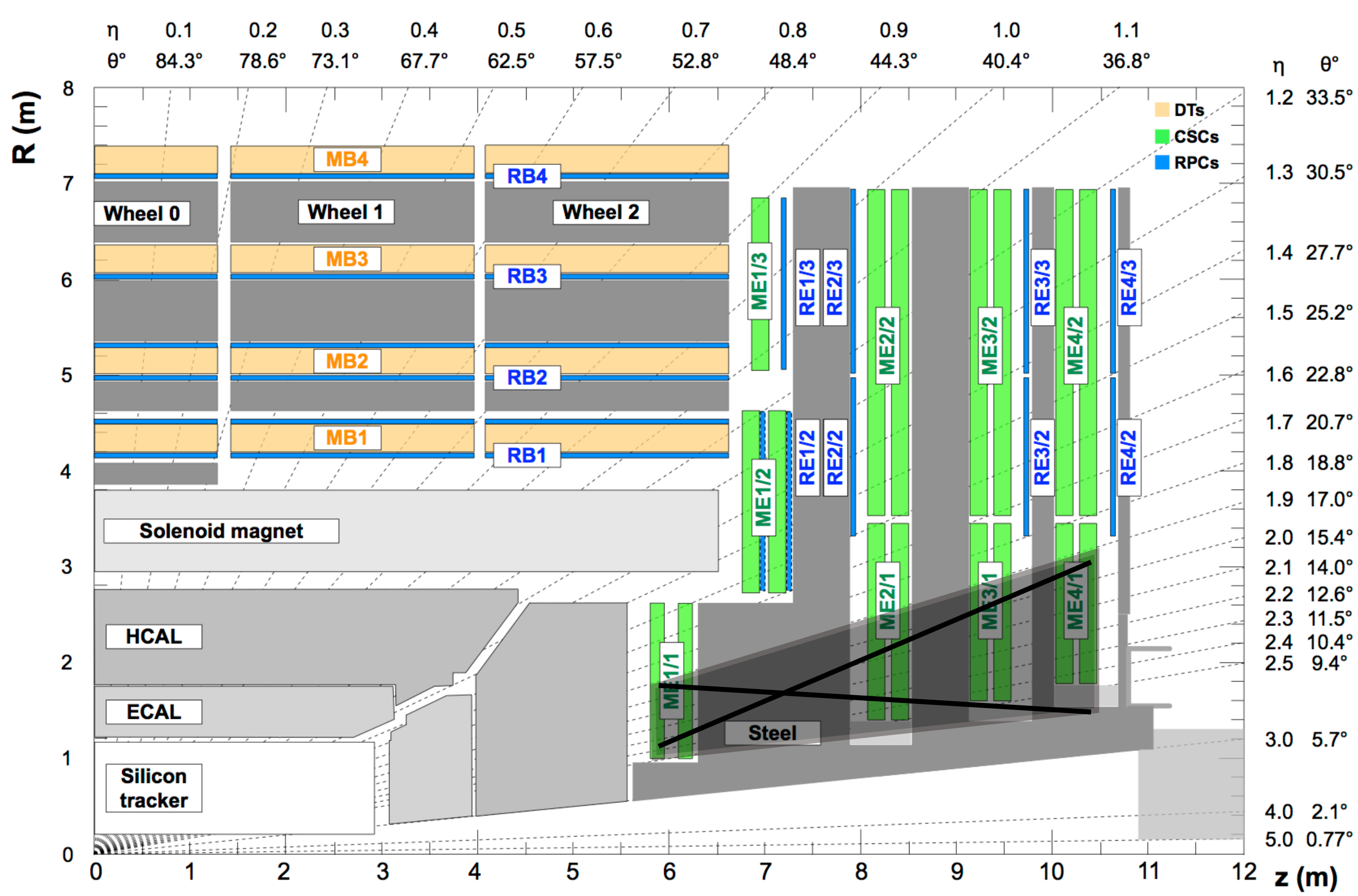
- Cut based selection makes progressively looser η cuts as AvgStation increases



Cut-based ID

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

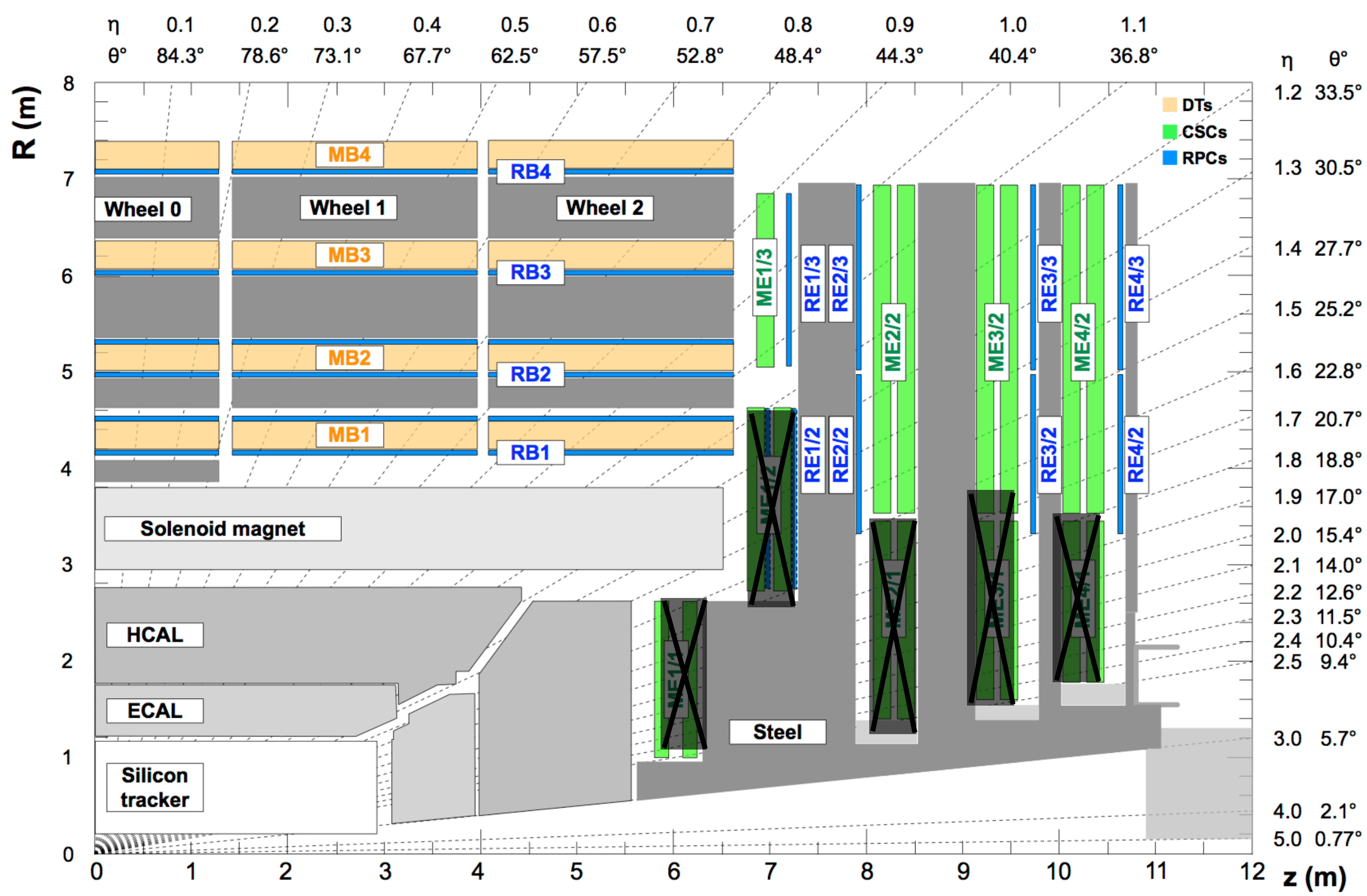
$N_{station}$ > 1



Cut-based ID

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

$N_{station} = 1$



Cut-based ID

- Cut based selection makes progressively tighter η cuts as AvgStation(distance to IP) decrease
  - $N_{station} > 1$: $|\eta| < 1.9$
  - $N_{station} = 1$ & avgStation = 4: $|\eta| < 1.8$
  - $N_{station} = 1$ & avgStation = 3: $|\eta| < 1.6$
  - $N_{station} = 1$ & avgStation = 2: $|\eta| < 1.6$
  - $N_{station} = 1$ & avgStation = 1: implicit cut (ME11/12 veto implies only ME13 is allowed, so $|\eta| <$ ~1.1)
- **Resulting performance: signal efficiency 82% , bkg rejection ~3**
- **Cut-based ID also allow us to define an in-time validation region with clusters that fail the cut-based ID.**

Signal Efficiency vs. Decay Position

Efficiency of all the cluster selections wrt events passing MET cut

m_S = 15 GeV

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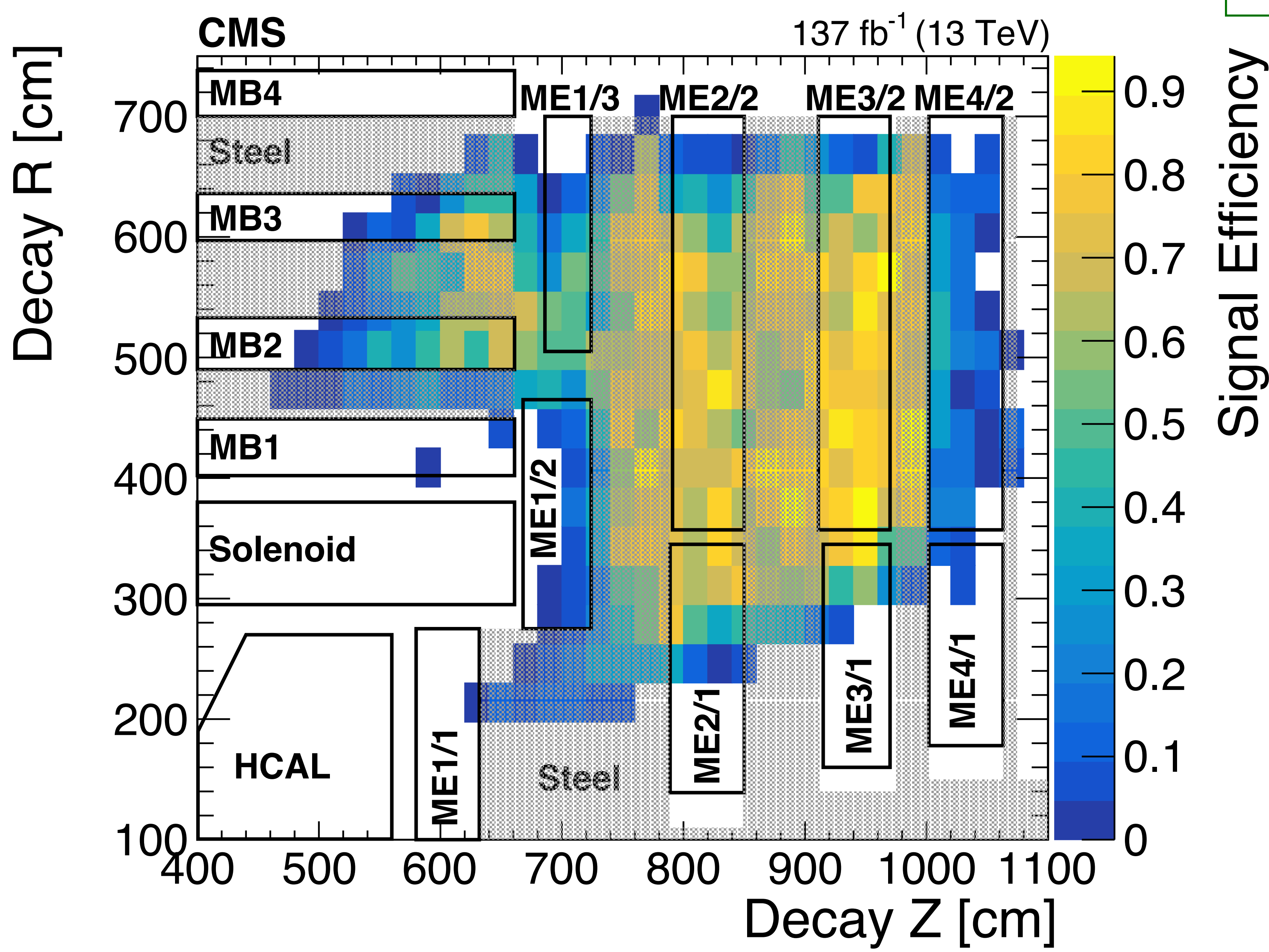
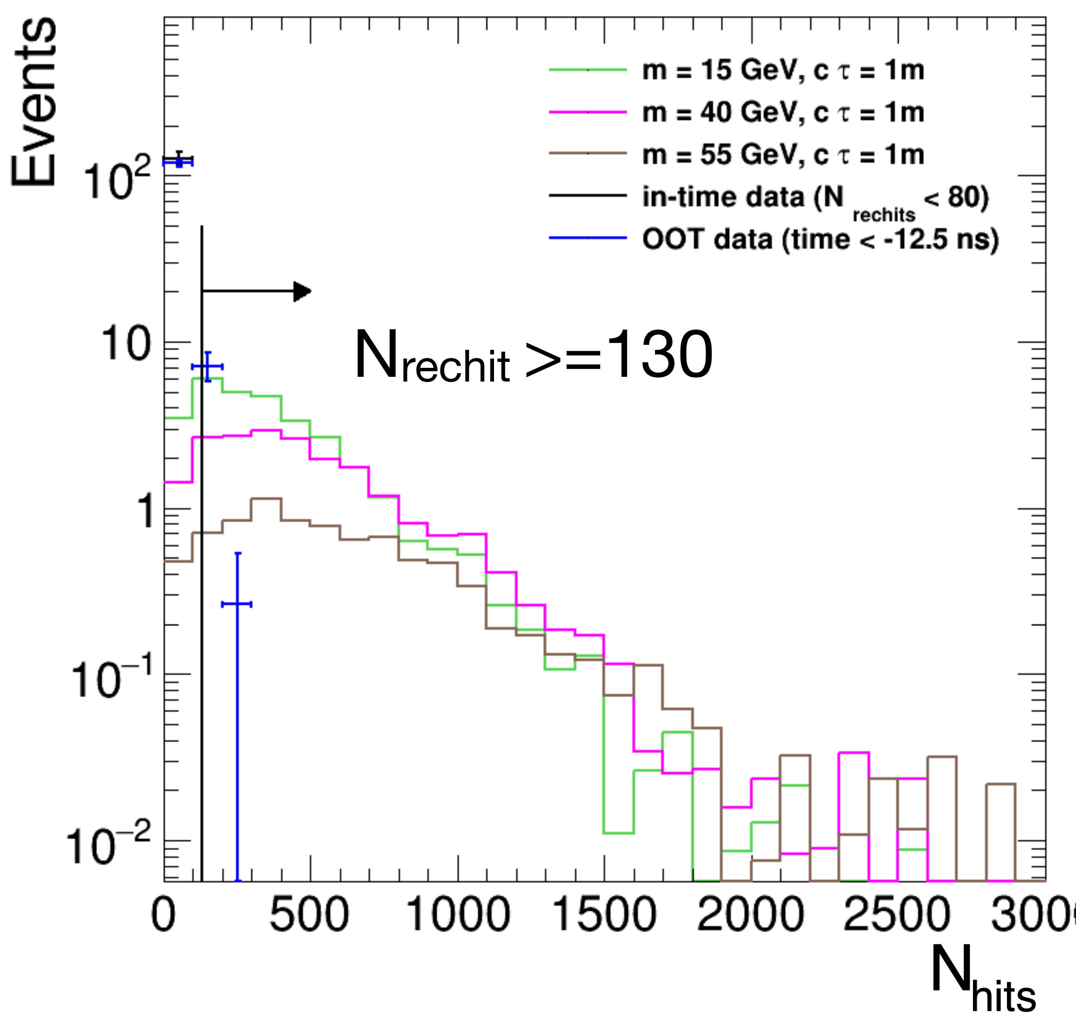


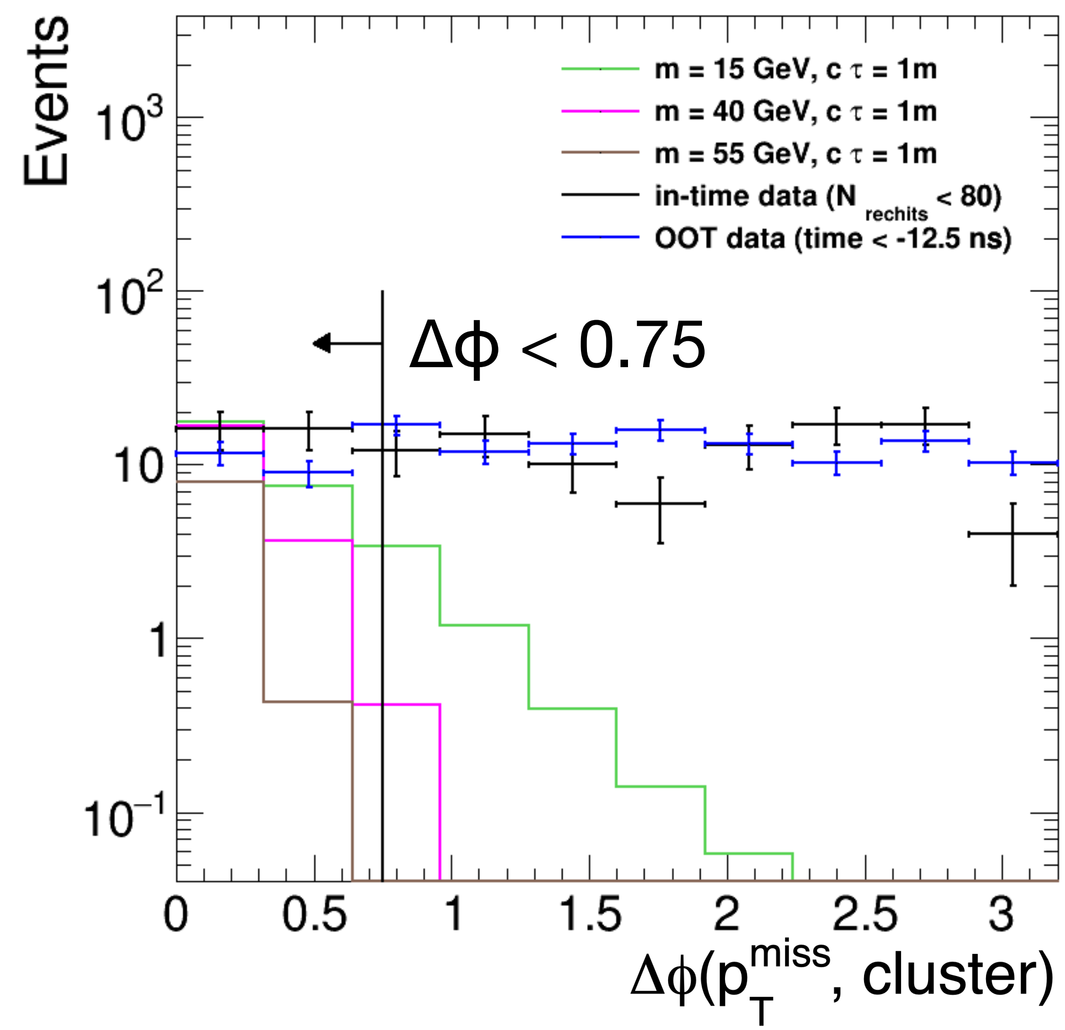
~50% signal efficiency when LLP decays between ME1 and ME4

$N_{rechits}$ & Δϕ(MET, cluster)

Signal BR(H → ss) = 1%

l = 137 fb^{-1}





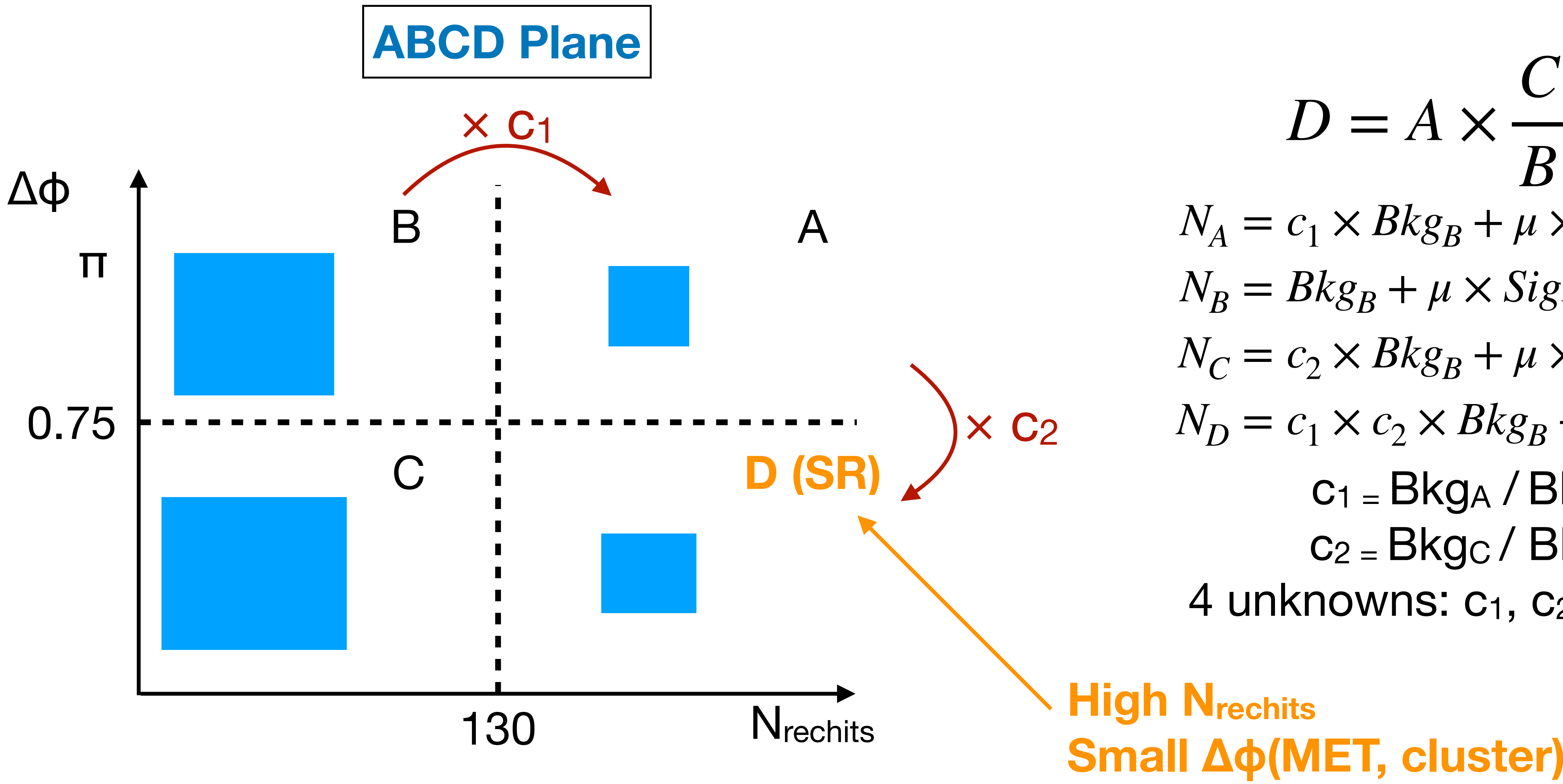
N_{rechi}

- Main discriminator against background
- N_{rechit} boundary optimized for the best expected limit (N_{rechit} >=130)

$\Delta\phi(p_T^{miss}$, cluster)

- Provides additional discrimination
- For signal, MET and cluster are aligned because the LLP p_T is responsible for the MET
- More importantly, provides a variable that's uncorrelated with $N_{rechits}$ for the ABCD method

Background Estimation using ABCD Method



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

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

$c_1 = Bkg_A / Bkg_B$

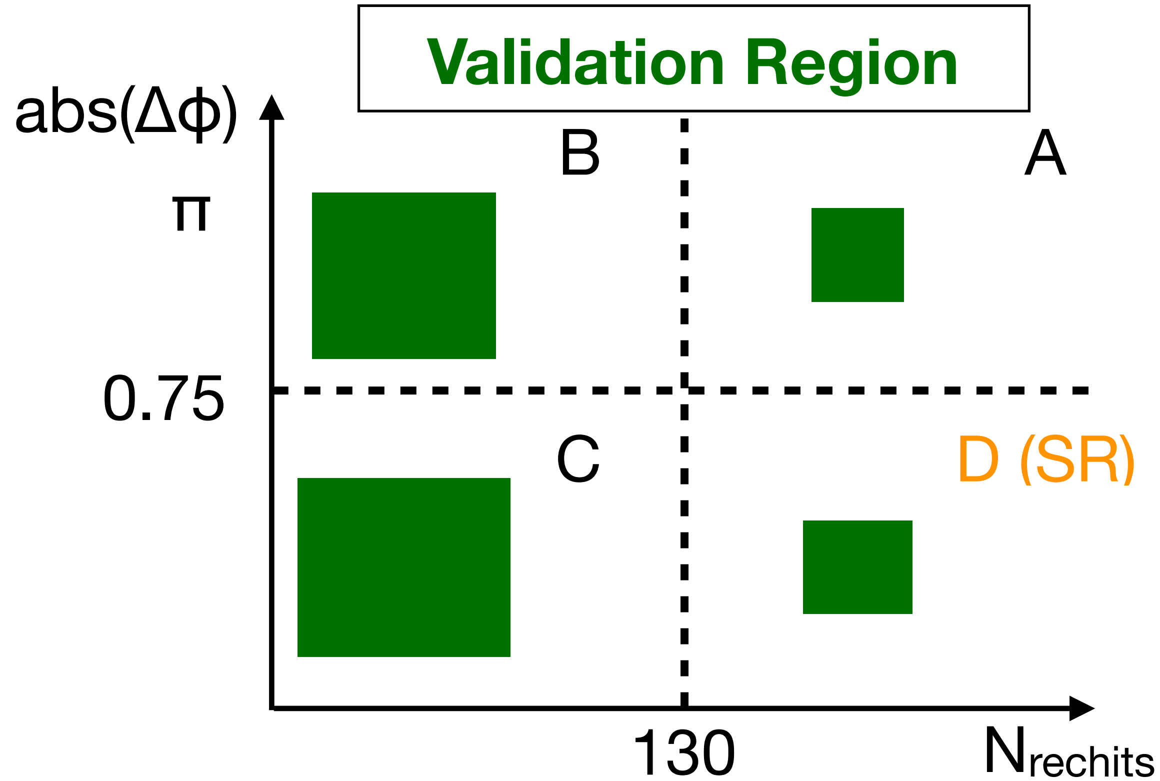
$c_2 = Bkg_C / Bkg_B$

4 unknowns: c_1, c_2, μ, Bkg_B

- Δϕ(MET, cluster) and $N_{rechits}$ are independent for background
- Validate the method in two separate **validation regions**:
    - Require cluster time < -12.5ns (**Early OOT validation region**)
    - In-time cluster that fails cut-based ID (**In-time validation region**)

Closure Test in Early OOT Validation Region

- Invert time cut (time < -12.5 ns) to have **early OOT validation region**



$N_{rechits} \geq 130$
$abs(\Delta\phi) \leq 0.75$

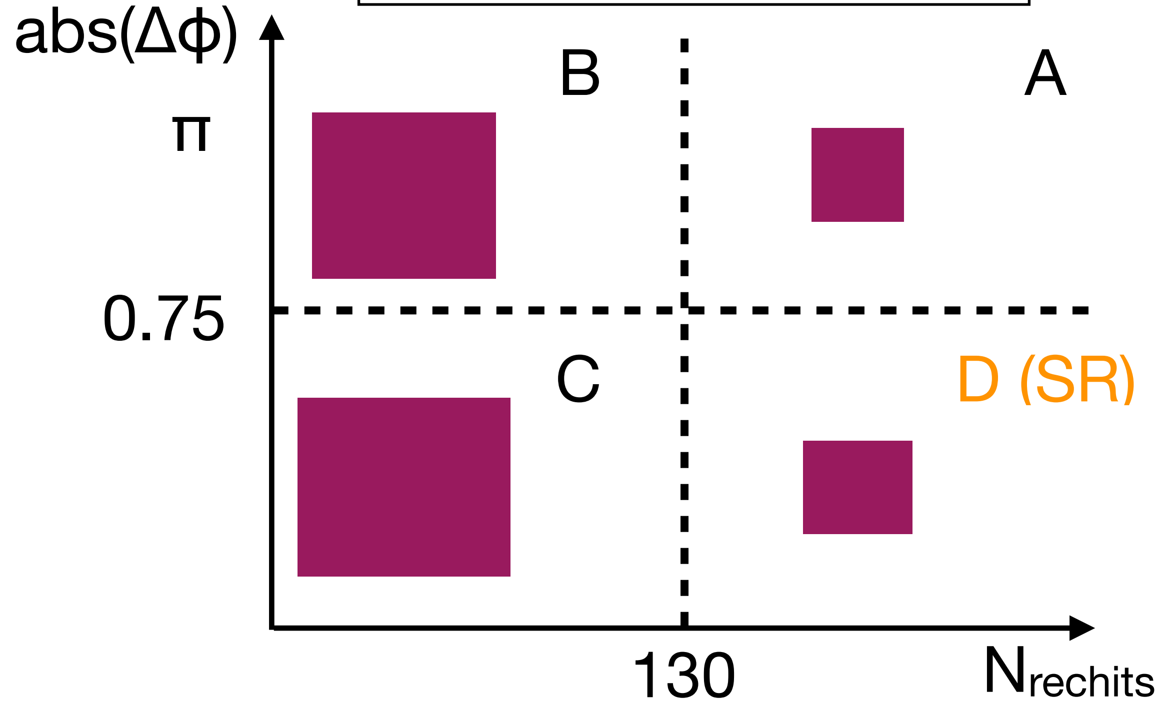
	A	B	C	D (SR)	Prediction (A * C / B)
Pass Cluster ID	5	373	97	2	1.3 ± 0.6
Fail Cluster ID	26	732	222	6	7.9 ± 1.7

- Pileup component is enhanced in this region
- Test is closed in both passing and failing clusterID region
- Test is closed as the boundary for $N_{rechits}$ & $abs(\Delta\phi)$ are scanned.

Closure Test in In-Time Validation Region

- Invert cut-based cluster ID cut to have **in-time validation region**

Validation Region



$N_{rechits} \geq 130$
$abs(\Delta\phi) \leq 0.75$

	A	B	C	D (SR)	Prediction (A * C / B)
Fail Cluster ID	5	269	74	2	1.4 ± 0.6

- Test for any non-negligible background contribution from main collision
- Test is closed in this region
- Test is closed as the boundary for $N_{rechits}$ & abs(Δϕ) are scanned.
- Combine the statistics in the two VR (1/sqrt(1.4 + 1.3)) and propagate the statistical uncertainty (61%) as a background systematic uncertainty on the ABCD method.

Signal Systematics and Corrections (Simulation Modelling)

- **Muon bremsstrahlung-induced showers** are used to understand the simulation modeling of the CSC clusters
- Use tag and probe method to select $Z \rightarrow \mu\mu$ events and then select CSC clusters that are geometrically matched to the probe muon in MC and data
- The efficiency of all cluster-level selections applied are measured in MC and data
- The disagreement in the vetos are applied as correction (**10% correction in total**) and statistical uncertainties on the measurements are applied as signal systematics
- The disagreements in other selections are assigned as uncertainties (**8% uncertainty in total**)

	Uncertainty	Correction
Cluster efficiency (N_{hits} >130)	4%	/
Cluster ID	5%	/
Muon, Jet, Rechit vetos	5%	10%
Cluster time spread	3%	/
Cluster time	1%	/

Signal Systematics (Theory Uncertainties)

- **Higgs pT shape uncertainty from missing higher order corrections**:
  - Vary the renormalization and factorization scale by a factor of 0.5 and 2 and reweight signal Higgs pT shape to resulting distributions
  - Evaluate the relative change in signal yield prediction in signal region.
  - Combine the 6 scale variations in quadrature **(dominant uncertainty for ggH)**
- **Cross section**: taken from the LHC Higgs Cross Section working group yellow report 4.
- **PDF**: taken from the LHC Higgs Cross Section working group yellow report 4.

	ggH	VBF	WH	qqZH	ggZH	ttH
Higgs pT	**20.5%(-) 13.3%(+)**	0.6%(-) 1.0%(+)	5.4%(-) 0.6%(+)	1.7%(-) 0.6%(+)	**20.8%(-) 13.3%(+)**	2.8%(-) 1.0%(+)
Cross section	6.7%(-) 4.6%(+)	0.3%(-) 0.4%(+)	0.7%(-) 0.5%(+)	0.6%(-) 0.5%(+)	25.1%(-) 18.9%(+)	9.2%(-) 5.8%(+)
PDF+α_s	3.2%	2.1%	1.9%	1.9%	2.4%	3.6%

Summary of Systematics

- **Signal systematics** are dominated by the **simulation modeling** uncertainty and the **Higgs pT** uncertainty
  - Additional uncertainties are included, but the impacts are negligible:
    - Jet energy scale: 4.1%
    - Luminosity: 1.8%
    - Pileup: 1.1%
    - MC statistics: ~3-5%
- **Background systematics:**
  - 61% uncertainty is propagated from the combination of the statistical power of the two validation regions

$N_{rechits}$ & Δϕ(MET, cluster)

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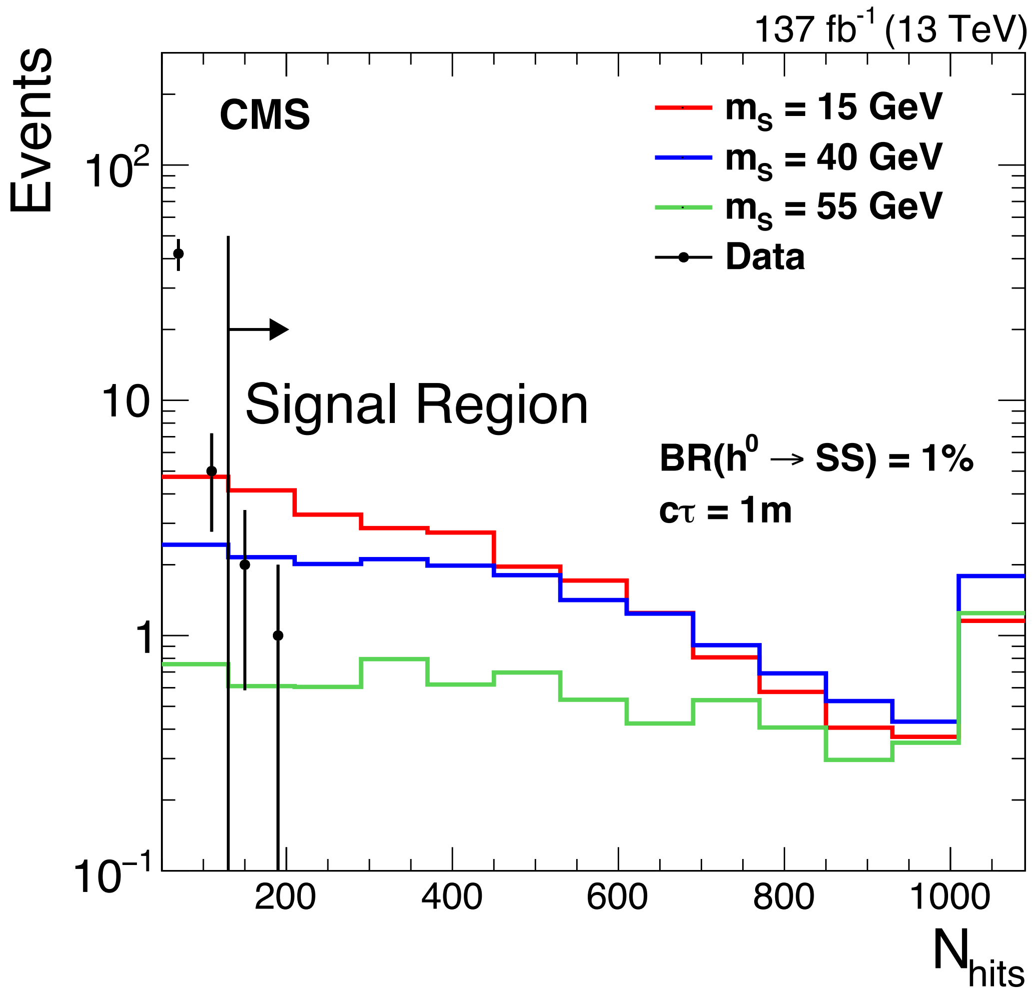

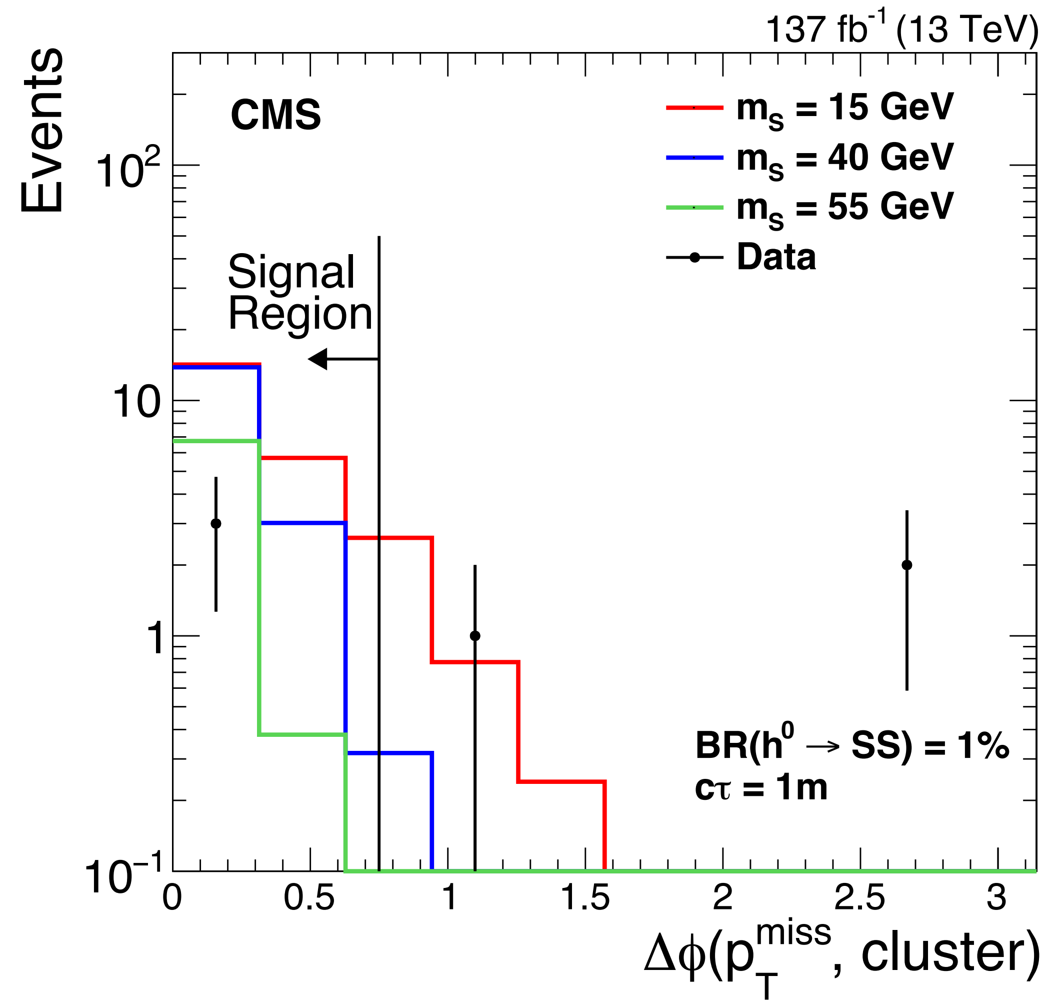

$N_{rechits}$

- Main discriminator against background
- N_{rechit} boundary optimized for the best expected limit (N_{rechit} >=130)

$\Delta\phi(p_T^{miss}$, cluster)

- Provides additional discrimination
- For signal, MET and cluster are aligned because the LLP p_T is responsible for the MET
- More importantly, provides a variable that's uncorrelated with $N_{rechits}$ for the ABCD method

Results

Background Estimation in Signal Region

	A	B	C	D (SR)	Bkg prediction
N_{rechit} = 130	3	96	47	3	2.2 ± 0.9 (stat) ± 0.9 (syst)

ABCD yield and background prediction → PAPER

Signal yield in bin D @ BR(H →ss) = 1%

LLP mass \ cτ	0.1 m	1 m	10 m	100 m
15 GeV	9.7	33	7.7	0.8
40 GeV	0.2	27	22.6	3
55 GeV	0	11.2	28.9	4.3

- No excess above SM prediction observed
- Signal yield prediction includes ggH(65%), VBF(19%), WH(7%), ZH(5%), and ttH(4%)

Observed & Expected Limits (HybridNew)

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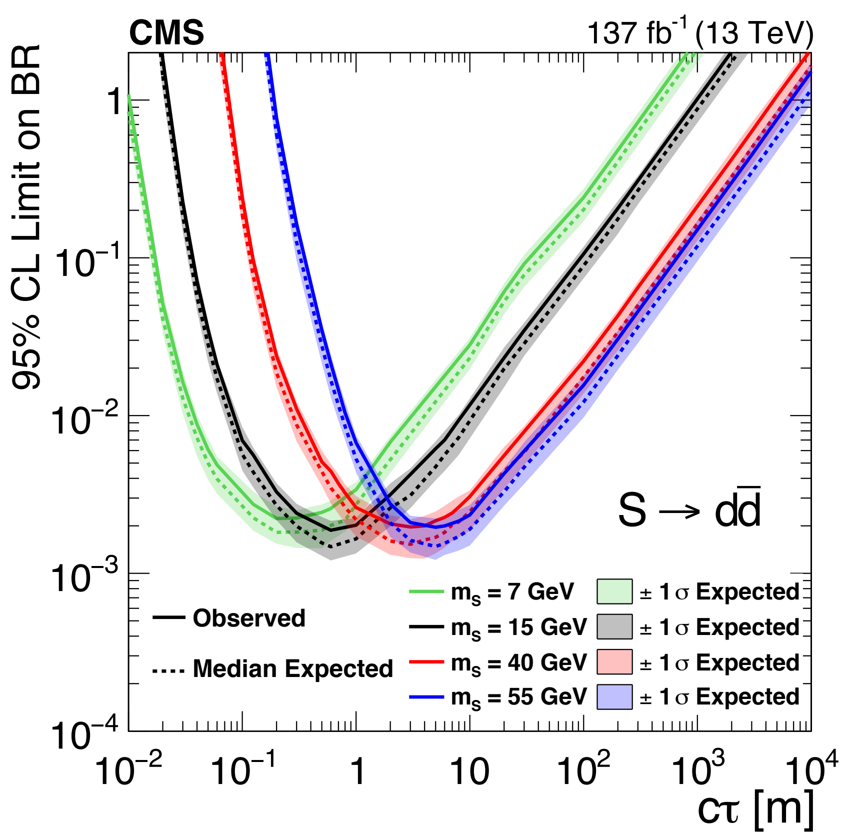
H →ss→(dd)(dd)



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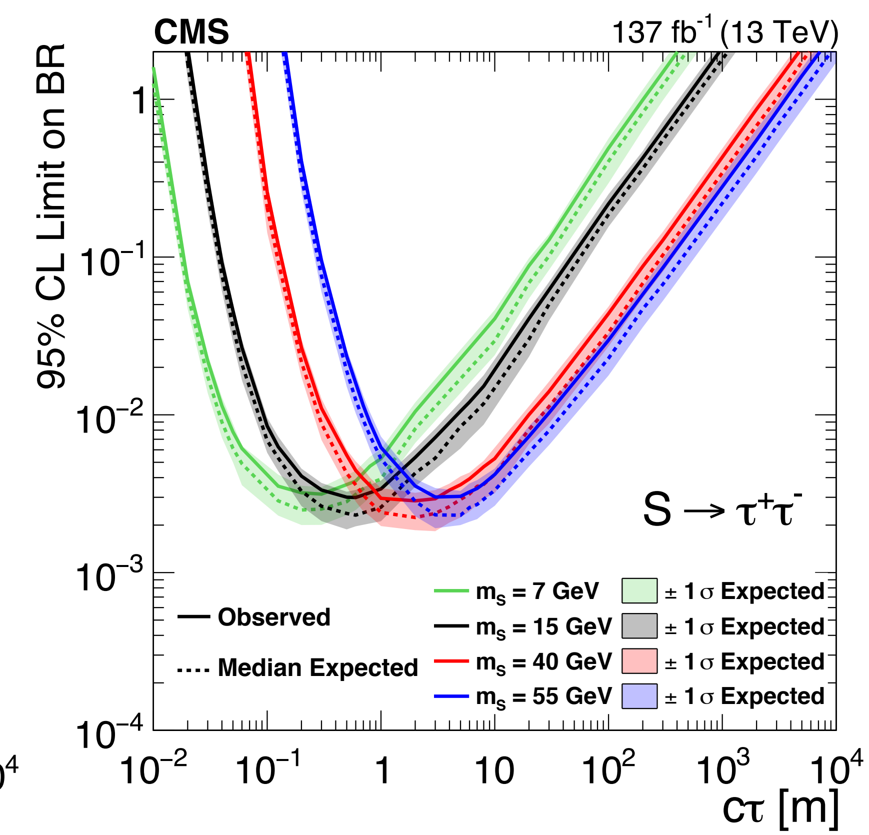
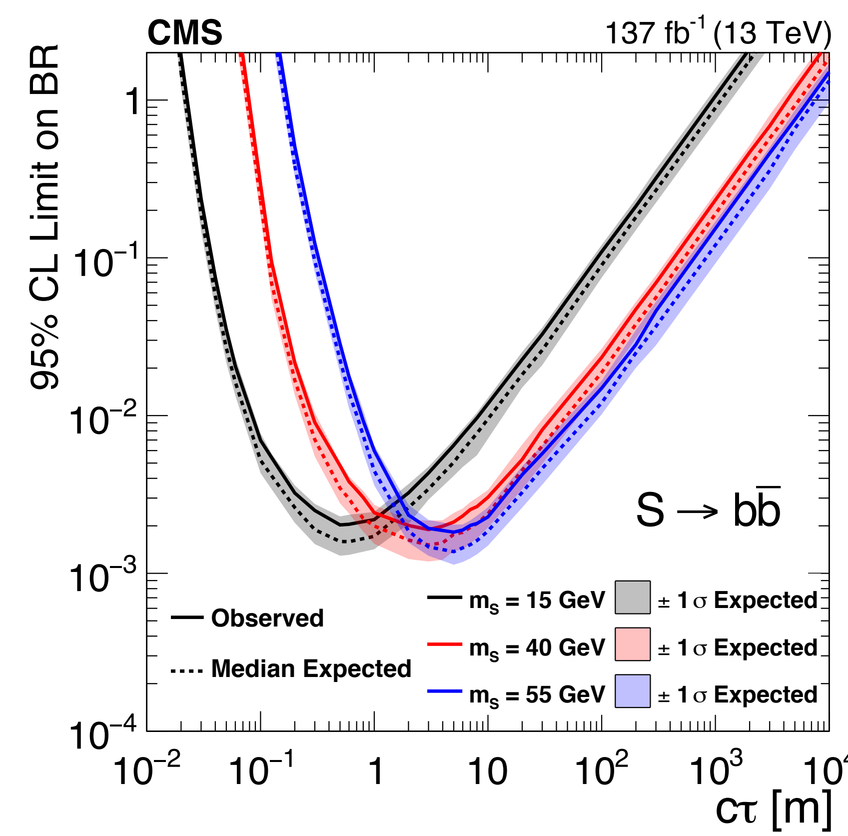
H →ss→(ττ)(ττ)



Auxiliary

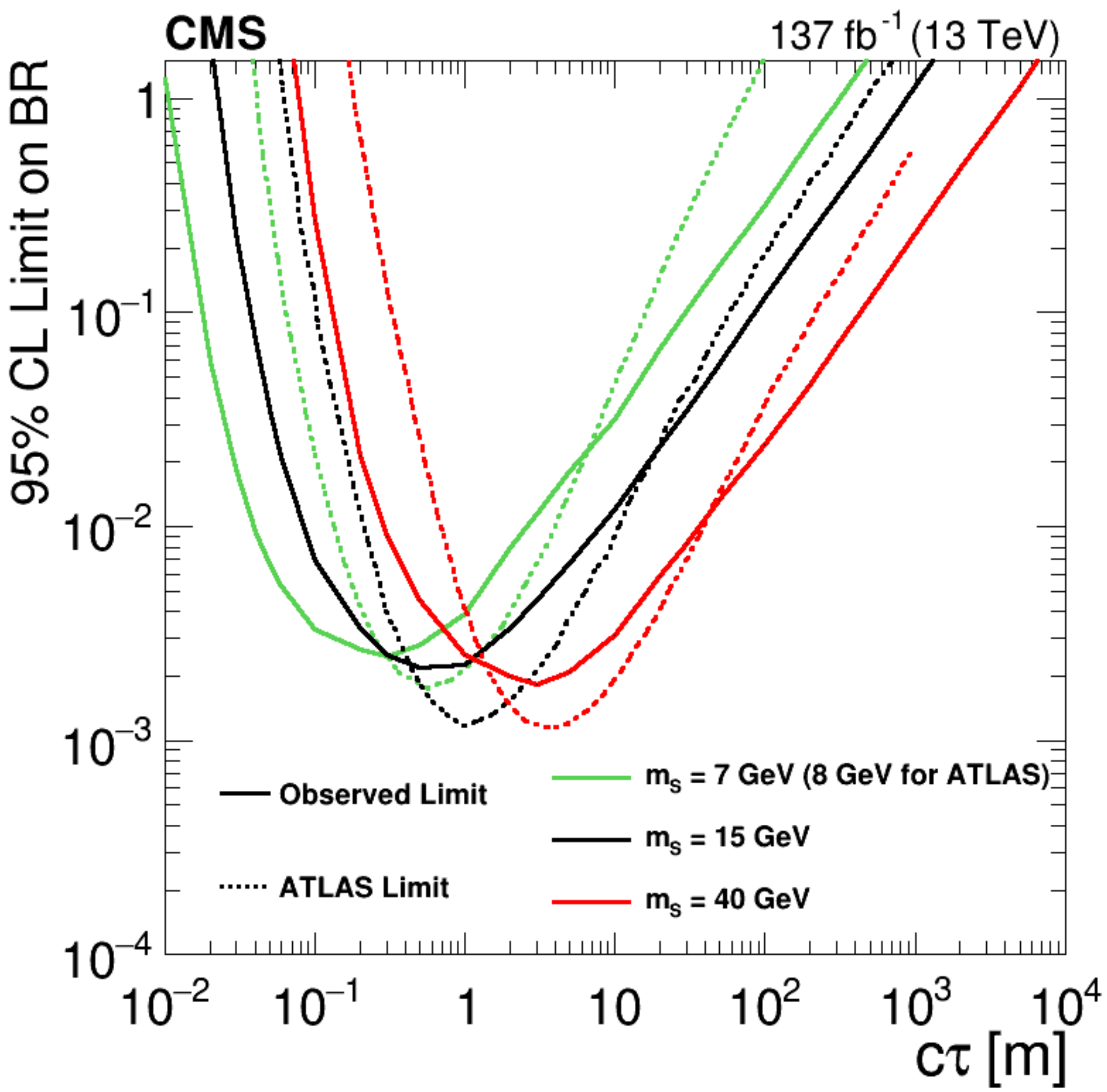
H →ss→(bb)(bb)



- Ran the limits with HybridNew method, a few % difference compared to Asymptotic limits
- Analysis sensitivity is **independent of the decay modes and masses**
- Achieve first sensitivity to **τ decay modes** at BR(H →ss) = 10^{-3} level

Comparison with ATLAS

- **Comparison with current best limit from ATLAS**
- **Reweighted according to the BR(S → ff) used by ATLAS**



Provide best limit for proper lifetime above 6, 20, and 45 m for m_S 7, 15, and 40 GeV, respectively

Summary & Outlook

- Presented first search for LLPs using the CSC muon system as a sampling calorimeter
- Among the best sensitivity for LLPs with $c\tau$ 1-1000m
- This result is the start of an **exciting new probe for BSM LLP Physics** with many improvements and directions to come in the next few years:
    - New L1+HLT triggers for Run3
    - Alternative production modes
    - Low LLP mass reach
- We ask for approval of the result EXO-20-015

Supplementary Materials

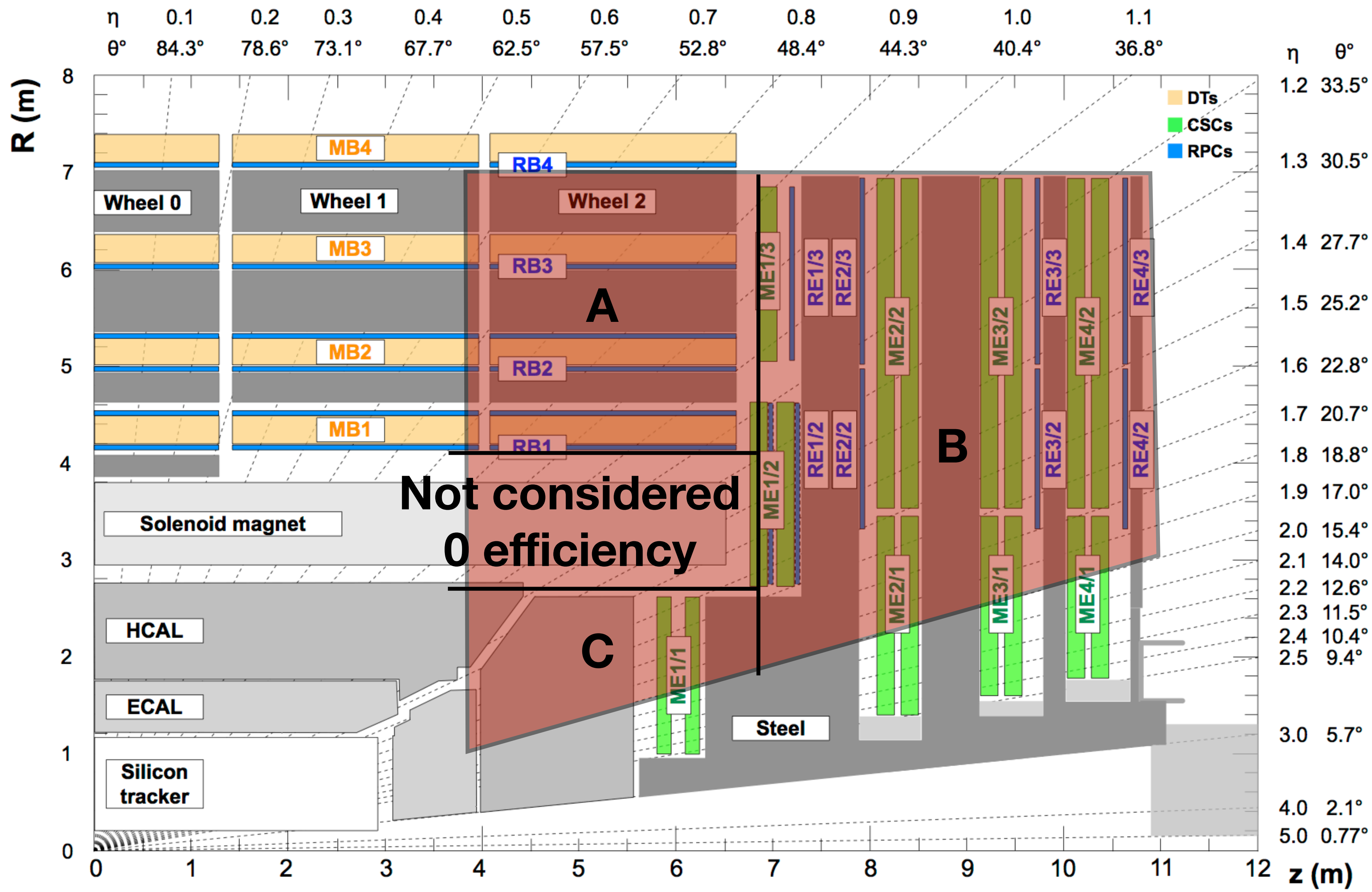
- Digitized versions of the limits
  - Separately for $h \to SS \to 4b$, $h \to SS \to 4d$, and $h \to SS \to 4\tau$
- Signal efficiency parameterization for reinterpretations
  - Cluster efficiency (>50 hits and >130 hits) including all cluster-level selections, excluding the jet veto and time cut
  - Cut-based efficiency
- With those parameterizations, it's possible to reproduce full-sim signal yield predictions for ANY model to within ~20% systematic uncertainty
- Uploaded preliminary version of supplementary material on HEPData

Cluster Efficiency Parametrization

- We demonstrate that a simple parameterization in **gen-level Hadronic Energy, EM Energy, and LLP decay position** is sufficient to reproduce full-sim signal efficiencies for ANY model to within systematic error of ~20%
    - EM Energy = sum of energies of any pi0, electron, photon produced from the LLP decay
    - Had Energy = sum of energies of any other particle except neutrinos or muons produced from the LLP decay
    - Match any stable (status 1) gen-level particle to LLP if the particle production vertex is within 0.1m from the LLP decay vertex
- We perform the parametrization using 4 τ samples, because τ decays produce both EM and hadronic energy

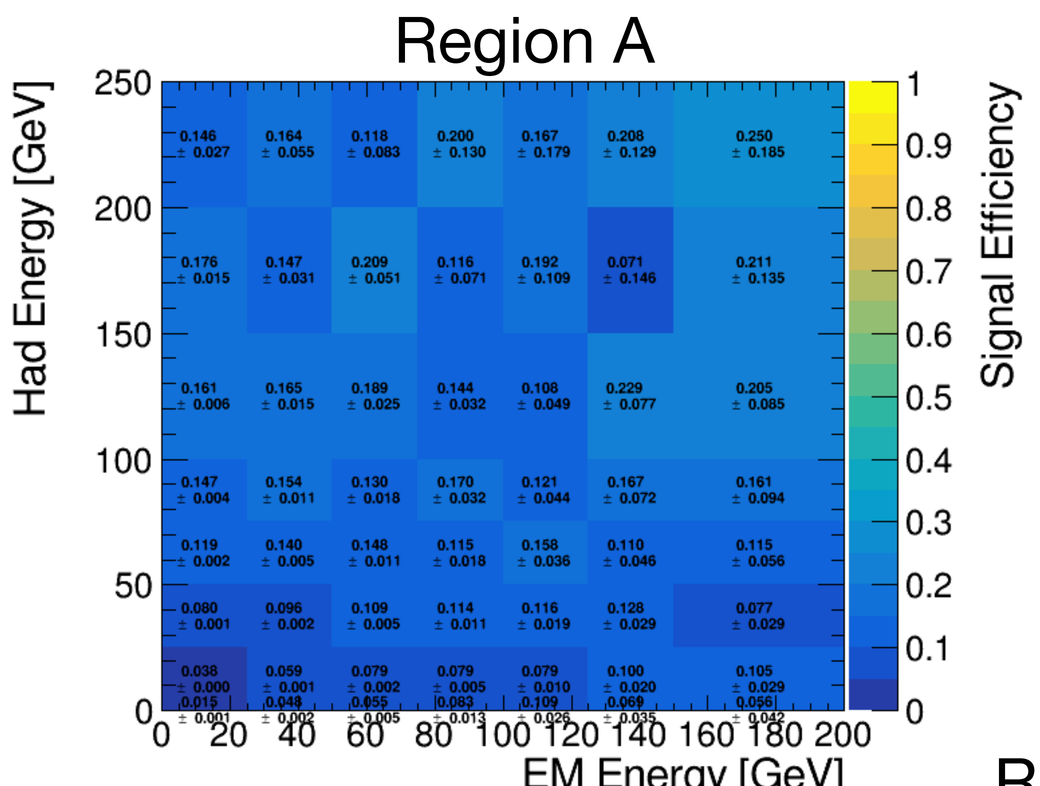
Cluster Efficiency Parameterization

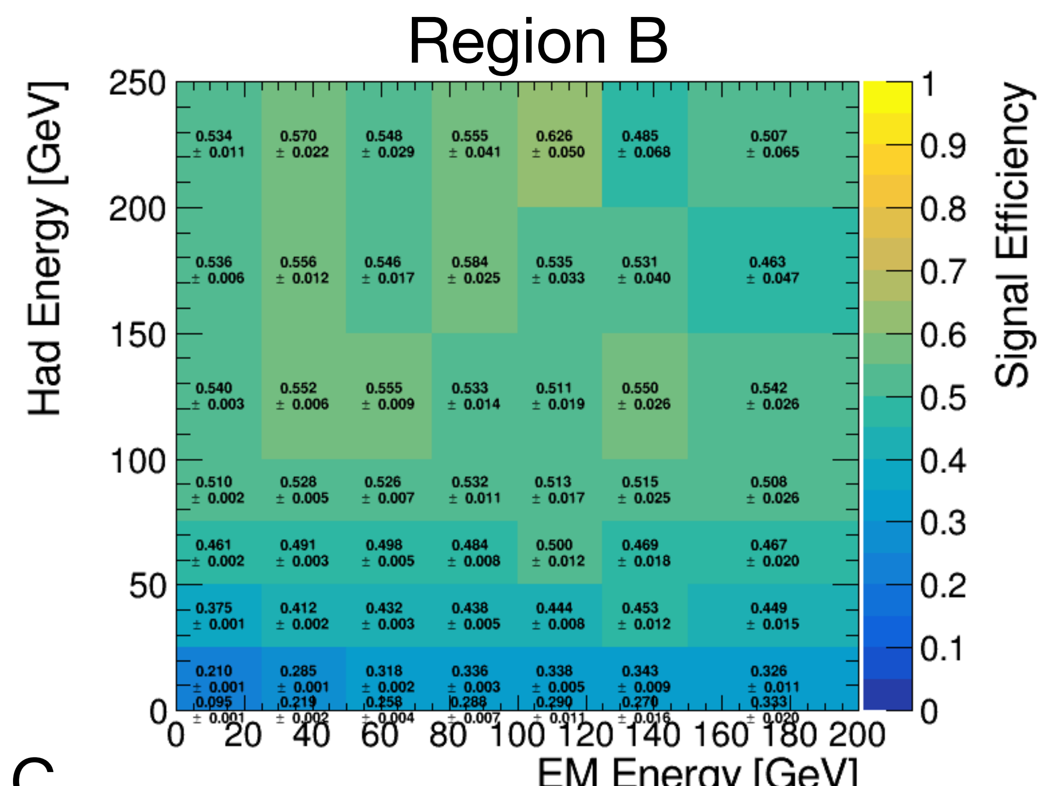
- **LLP decay location is categorized into 3 regions shown below**
    - These 3 regions have qualitatively different behavior
    - Within each region, they have quantitatively similar behavior
- For most samples, about 25% of LLPs decay in A and C, and the rest of the 50% of LLPs decay in B
- For LLPs with ctau = 0.1 m, 3% decay in A, 17% decay in B, and 80% decay in C
- However, the signal efficiency in both A and C are low, such that **more than 90% of clusters passing all selections are from LLPs that decay in region B**

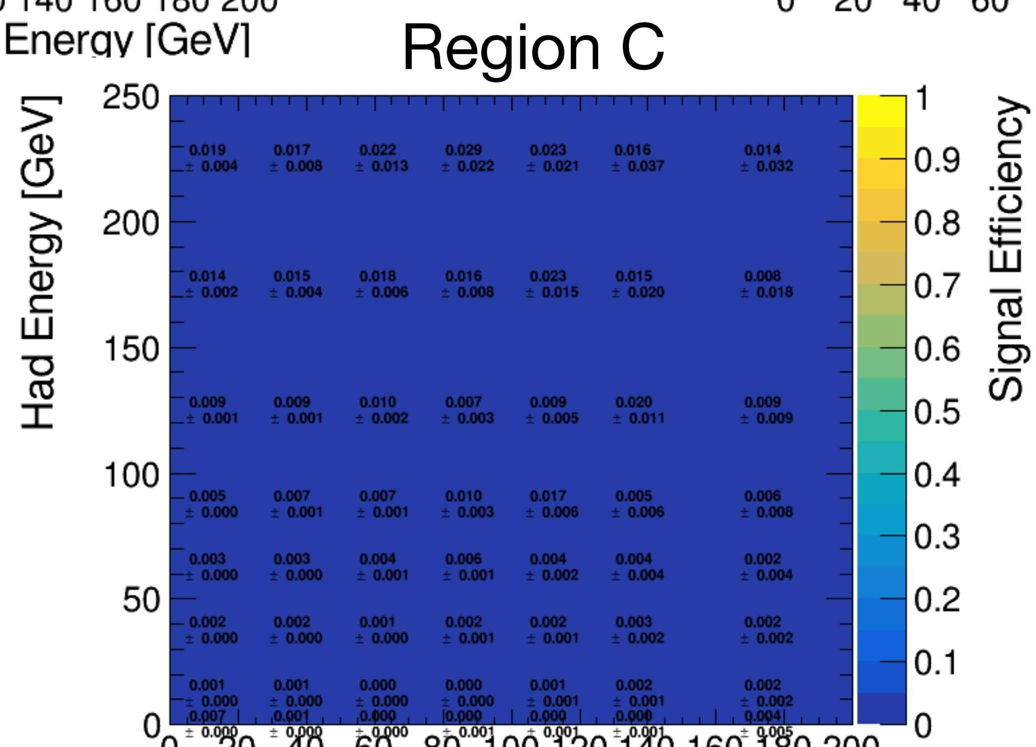


Cluster Efficiency Parameterization (>50 hits)

- Cluster Efficiency is binned in Had Energy and EM Energy as shown below
- Will also have another set of parameterization with > 130 hits





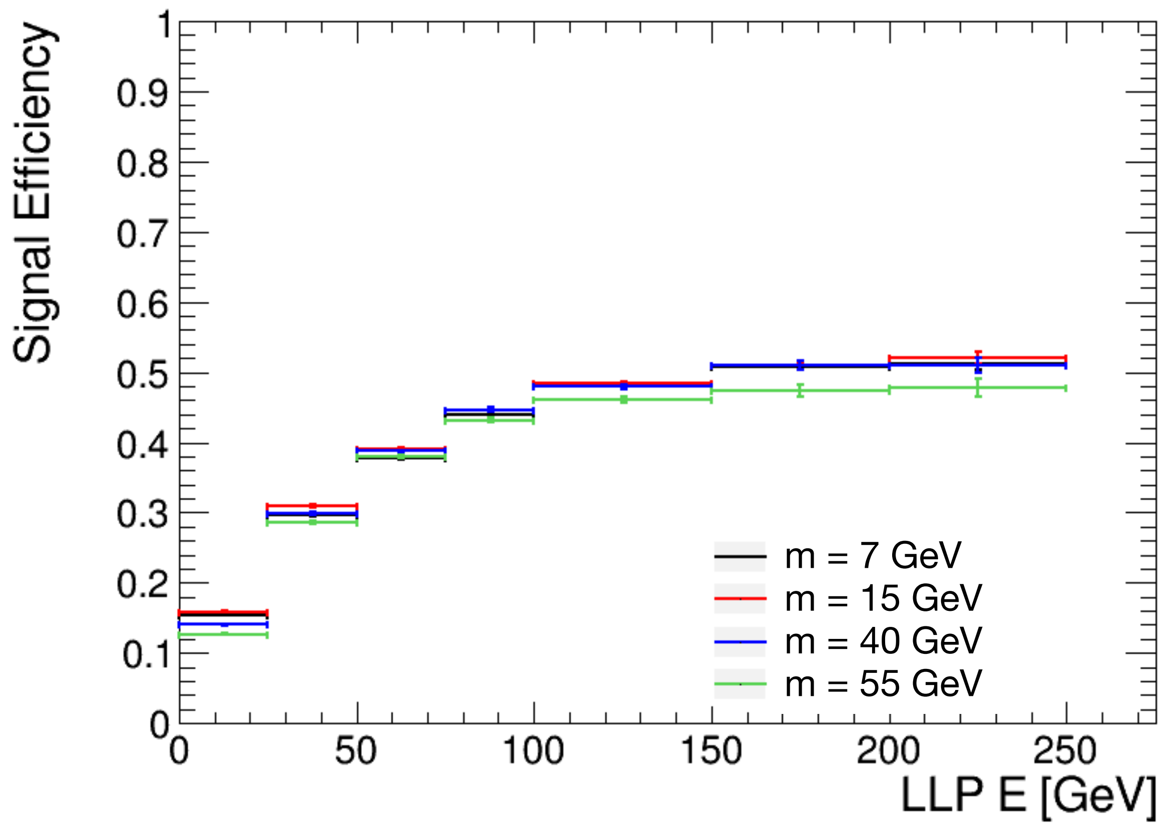


Auxiliary

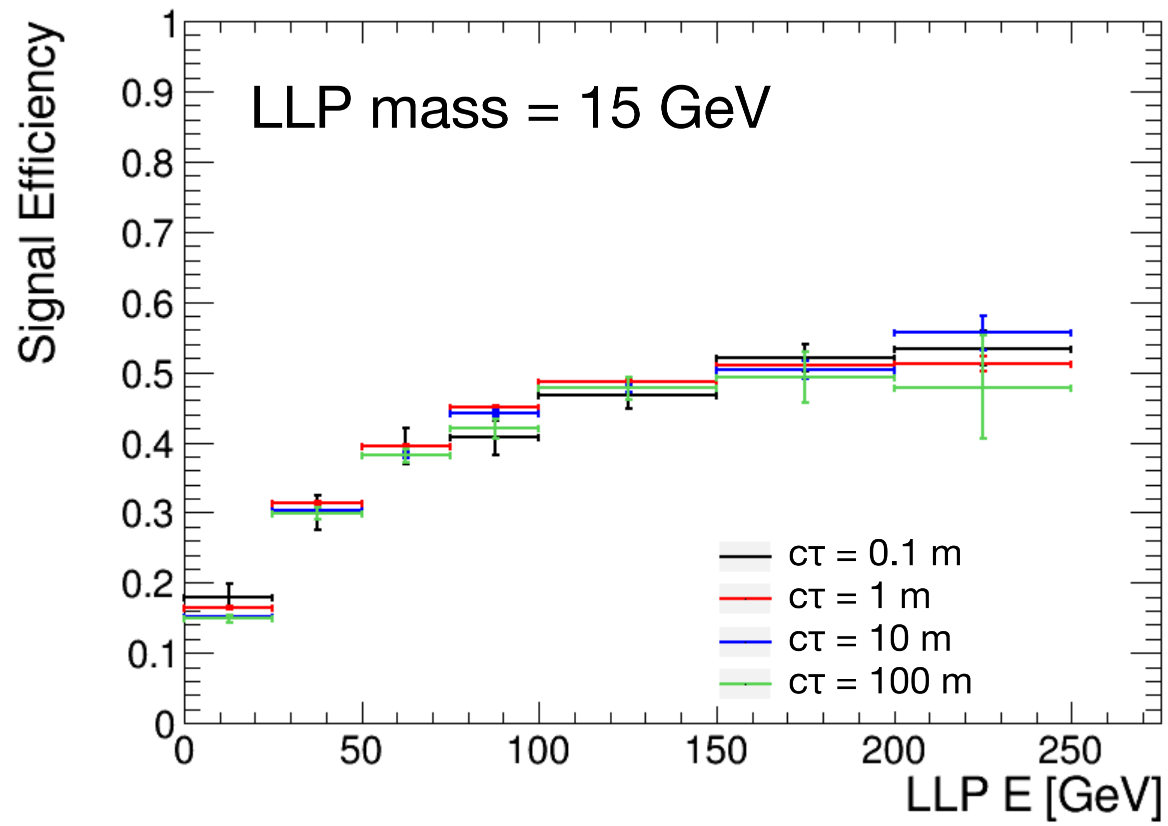
Model Independence of Cluster Efficiency (region B)

- We show this parametrization of cluster efficiency is independent of LLP mass and ctau within each LLP decay region (region A and C are in backup)
- Here we show the parametrization wrt LLP energy, since EM fraction of the same decay mode remains the same. It's easier to visualize the trend with the 1D parametrization

Mass independence



ctau independence



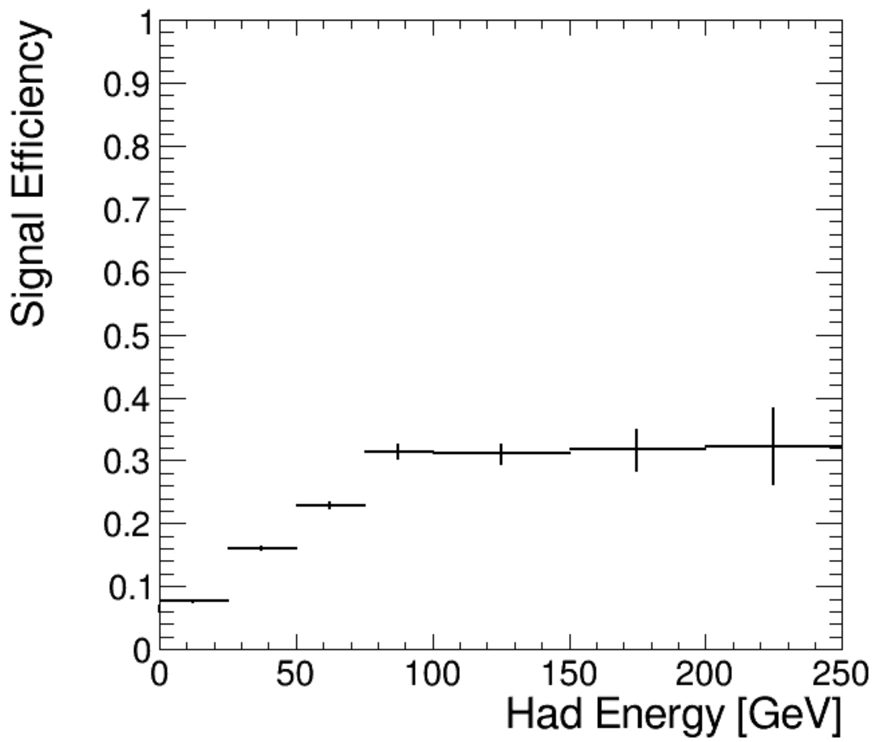
Cluster ID

- Recall that Cluster ID requirement:
  - If $N_{station} > 1$: $|eta| < 1.9$
  - If $N_{station} = 1$: apply $|eta| < X$, where X depends on the Average Station Number
- To parameterize this efficiency we need only two pieces:
  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 $N_{station} = 1$)

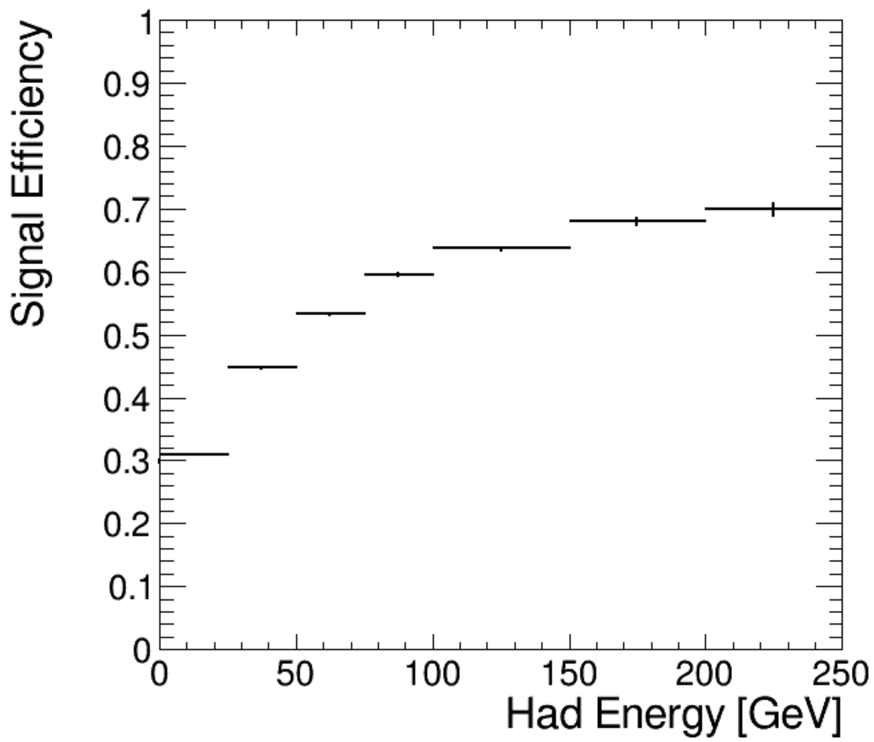
$N_{Station}$>1 Efficiency

- This efficiency can be well parameterized using just the gen-level Hadronic Energy and the 3 LLP decay regions

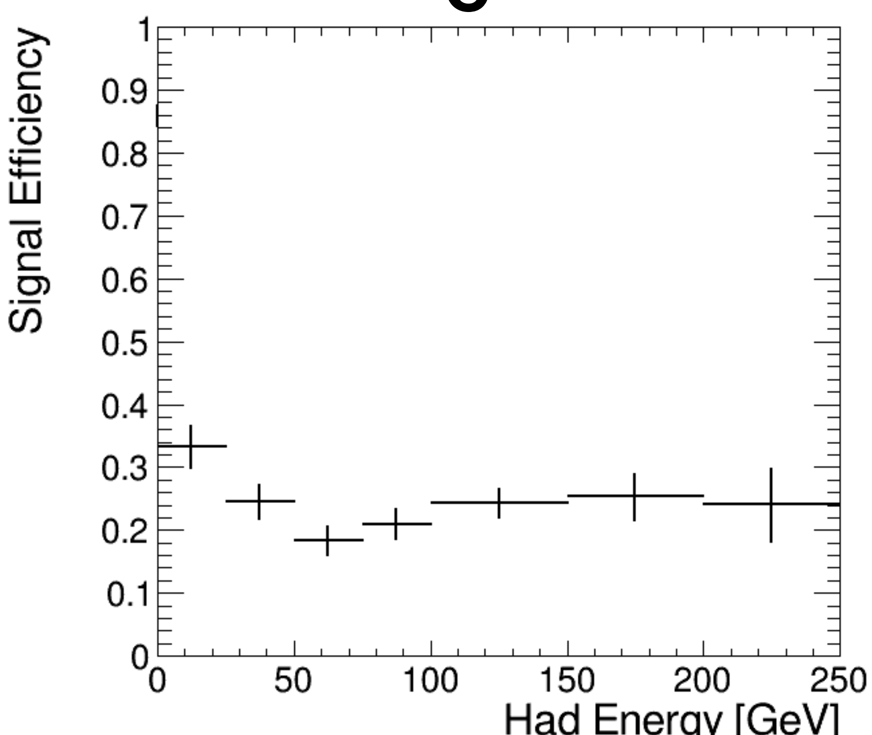
A



B



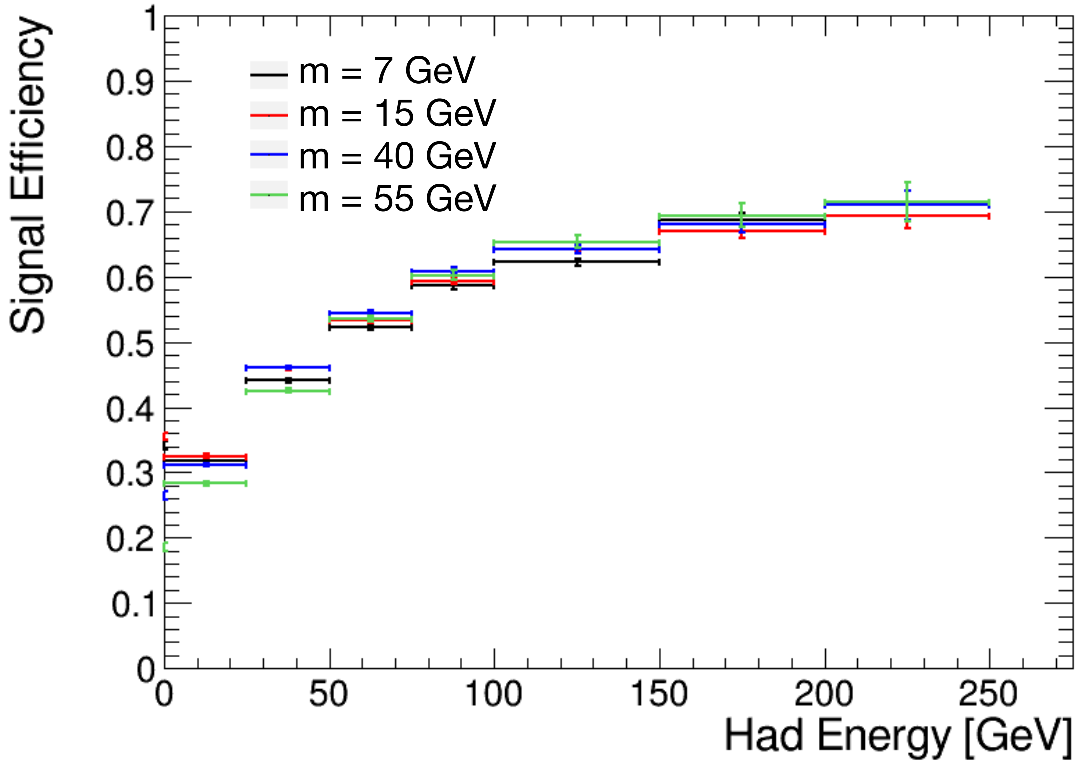
C

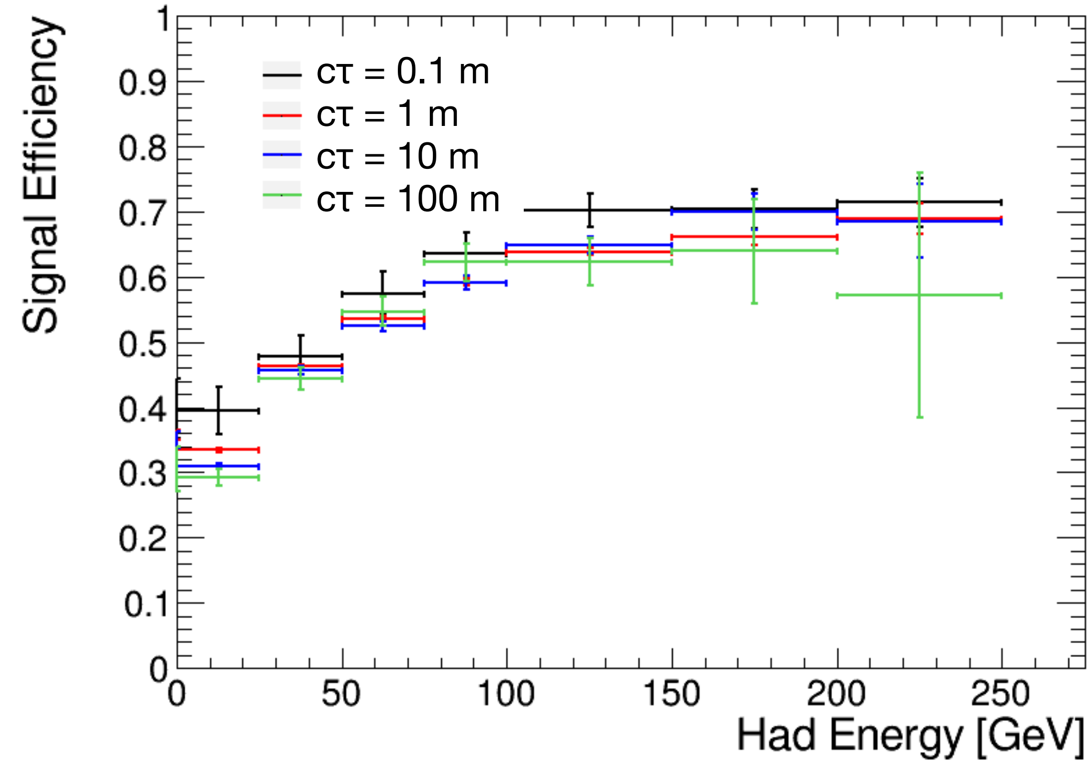


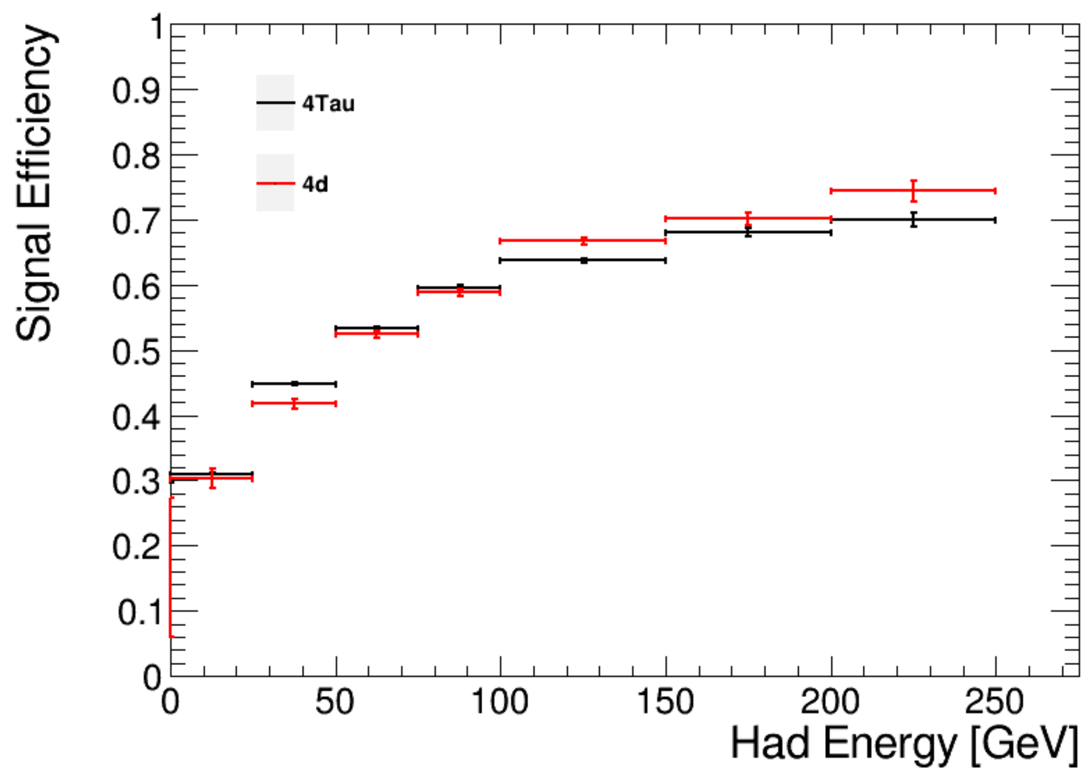
Auxiliary

NStation>1 Efficiency (Region B)

No dependence on mass, lifetime, and decay mode observed within each region (only B is shown here)







Average Station Transfer Function

- A relatively simple transfer function works well:
  - Cluster Average Station = the station subsequent to the LLP decay location
    - Eg. If LLP decays between ME2 and ME3, then average station will be ME3. If LLP decays within ME3, then average station will be ME4
- This code is uploaded as an *Additional Resources* to HEPData

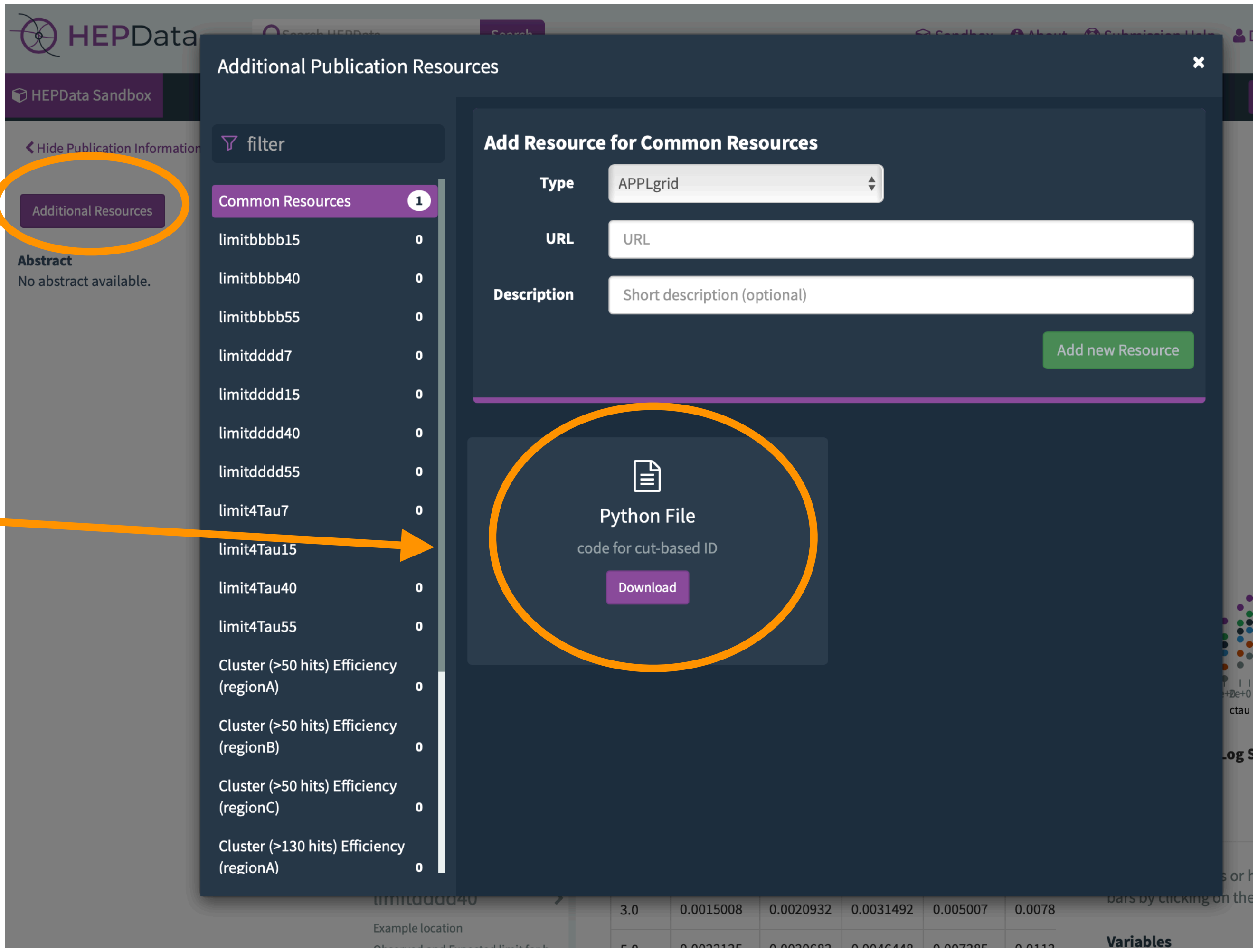
Auxiliary

```
import numpy as np

# given array of LLP decay position Z, R in cm, output the avgStation p
# prediction is 92% accurate
def ZToStation(Z, R):
    station = np.copy(Z)
    station[np.abs(Z)<632] = 1
    station[np.logical_and(np.abs(Z)<724, np.abs(R)>275)] = 1
    station[np.logical_and(station>1, np.abs(Z)<850)] = 2
    station[np.logical_and(np.abs(Z)>=850,np.abs(Z)<970)] = 3
    station[np.abs(Z)>=970] = 4
    return station

#input: list of LLP decay position in Z, R, LLP hadronic energy, LLP et
#input type: z, r, hadE, eta are numpy arrays and eff_hist is TH1F
#output: list of probability that the event passes cut-based ID
def cut_based_id(z, r, hadE, eta, eff_hist):
    avgStation = ZToStation(z, r)
    eta_cut = np.copy(avgStation)
    eta_cut[eta_cut==1]  = 1.8 #implicitly 1.1
    eta_cut[eta_cut==2]  = 1.6
    eta_cut[eta_cut==3]  = 1.6
    eta_cut[eta_cut==4]  = 1.8
    weight=[]
    for j in range(len(hadE)):
        x = eff_hist.GetXaxis().FindFixBin(np.abs(hadE)[j])
        weight.append(eff_hist.GetBinContent(x))
    weight = np.array(weight)

    #apply eta<1.9 if NStation>1, else apply different eta cut as defi
    weight = weight*(np.abs(eta)<1.9)+(1-weight)*(np.abs(eta)<eta_cut)
    return weight
```



BACKUP SLIDES

Signal Yield by Production Mode

- Additional contribution from **VBF**(30%), **WH**(10%), **ZH**(8%), and **ttH**(6%), increases the signal yield by a total of **54%** from ggH-only signal yield
- As expected, increase in signal yield is **independent of LLP mass and lifetime**

ggH

LLP mass $c\tau$	0.1 m	1 m	10 m	100 m
15 GeV	6.3	21.4	5.1	0.6
40 GeV	0.2	17.4	14.9	1.8
55 GeV	0.0	7.1	18.6	2.8

VBF

LLP mass $c\tau$	0.1 m	1 m	10 m	100 m
15 GeV	1.9	6.3	1.5	0.1
40 GeV	0.0	5.3	4.4	0.7
55 GeV	0.0	2.2	5.9	0.9

WH

LLP mass $c\tau$	0.1 m	1 m	10 m	100 m
15 GeV	0.6	2.2	0.5	0.1
40 GeV	0.0	1.7	1.2	0.2
55 GeV	0.0	0.8	1.8	0.2

qqZH

LLP mass $c\tau$	0.1 m	1 m	10 m	100 m
15 GeV	0.3	1.1	0.2	0.0
40 GeV	0.0	1.1	0.8	0.1
55 GeV	0.0	0.5	1.0	0.2

ggZH

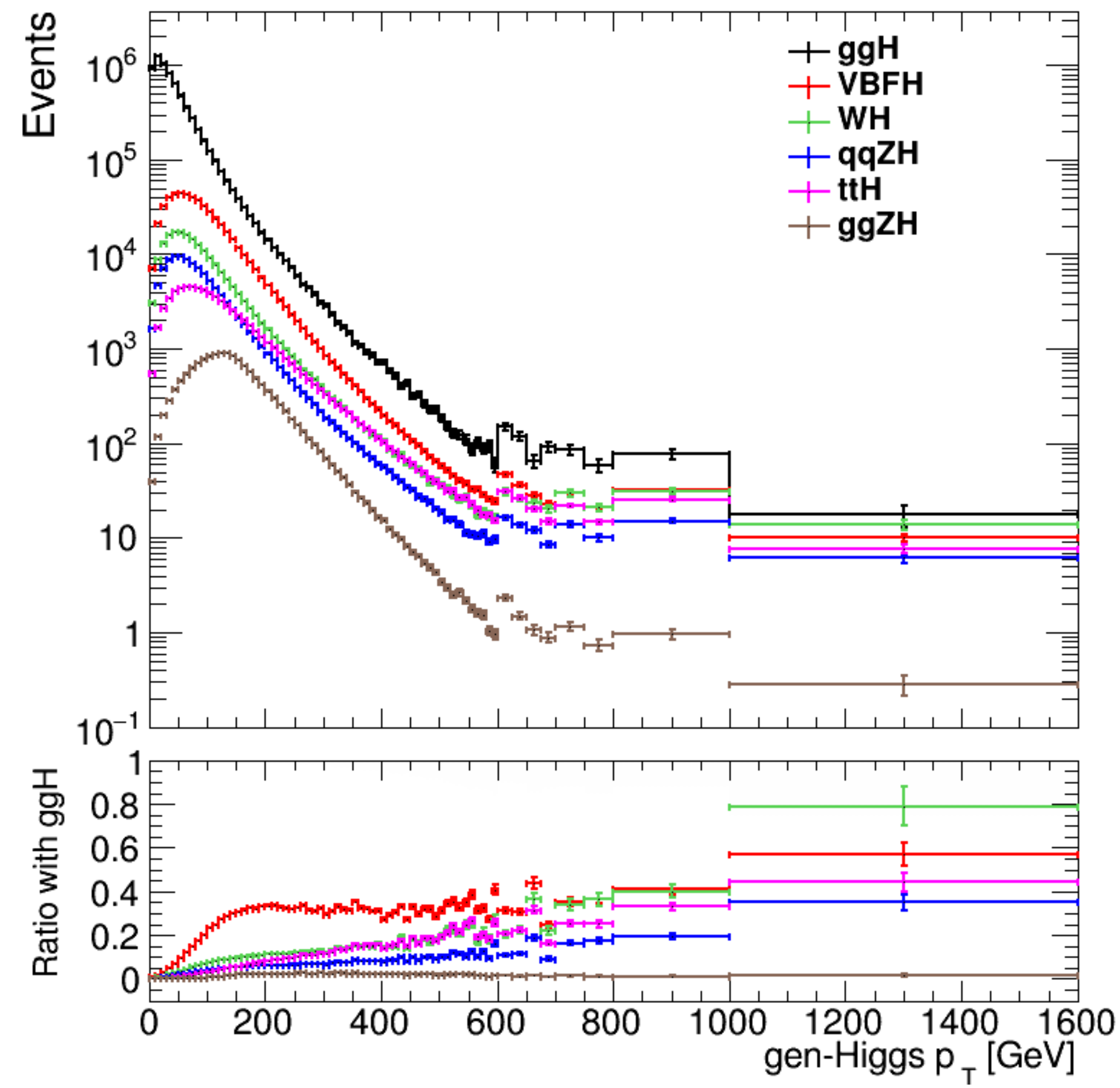
LLP mass $c\tau$	0.1 m	1 m	10 m	100 m
15 GeV	0.1	0.4	0.1	0.0
40 GeV	0.0	0.4	0.3	0.1
55 GeV	0.0	0.1	0.4	0.1

ttH

LLP mass $c\tau$	0.1 m	1 m	10 m	100 m
15 GeV	0.4	1.5	0.3	0.0
40 GeV	0.0	1.1	0.9	0.1
55 GeV	0.0	0.5	1.2	0.2

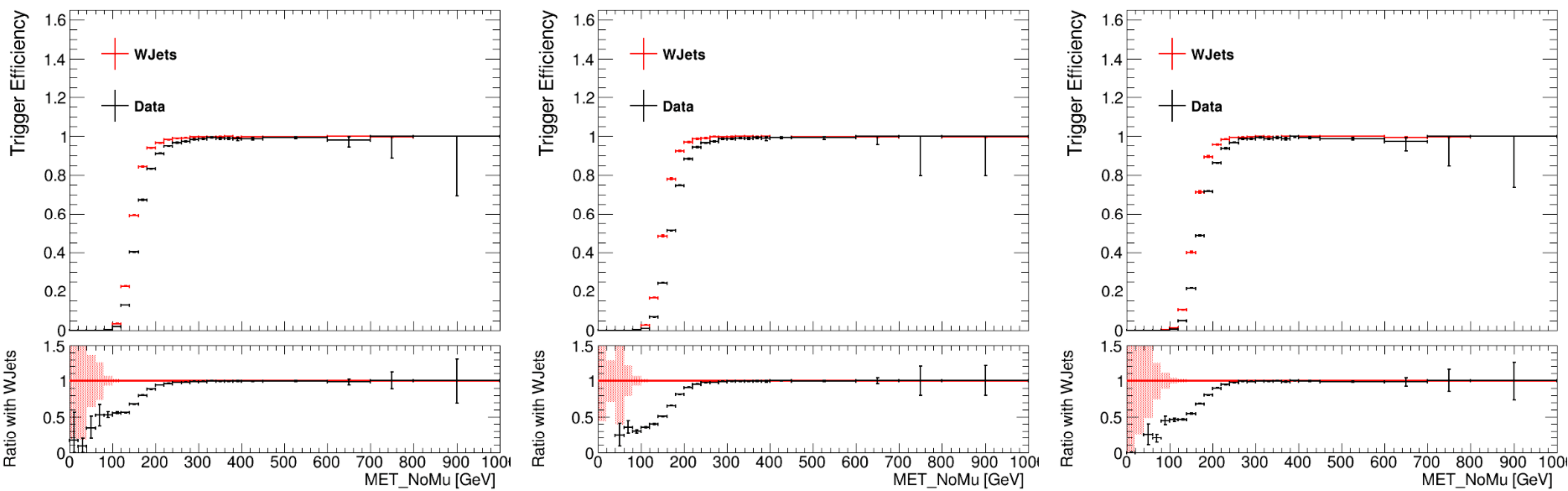
Gen-level Higgs pT

- Large contribution from addition production modes at high Higgs pT
- Additional contribution from VBF(30%), WH(10%), qqZH(6%), ttH(6%), ggZH(2%) increases the signal yield by a total of 54% from ggH-only signal yield



Trigger Scale Factor

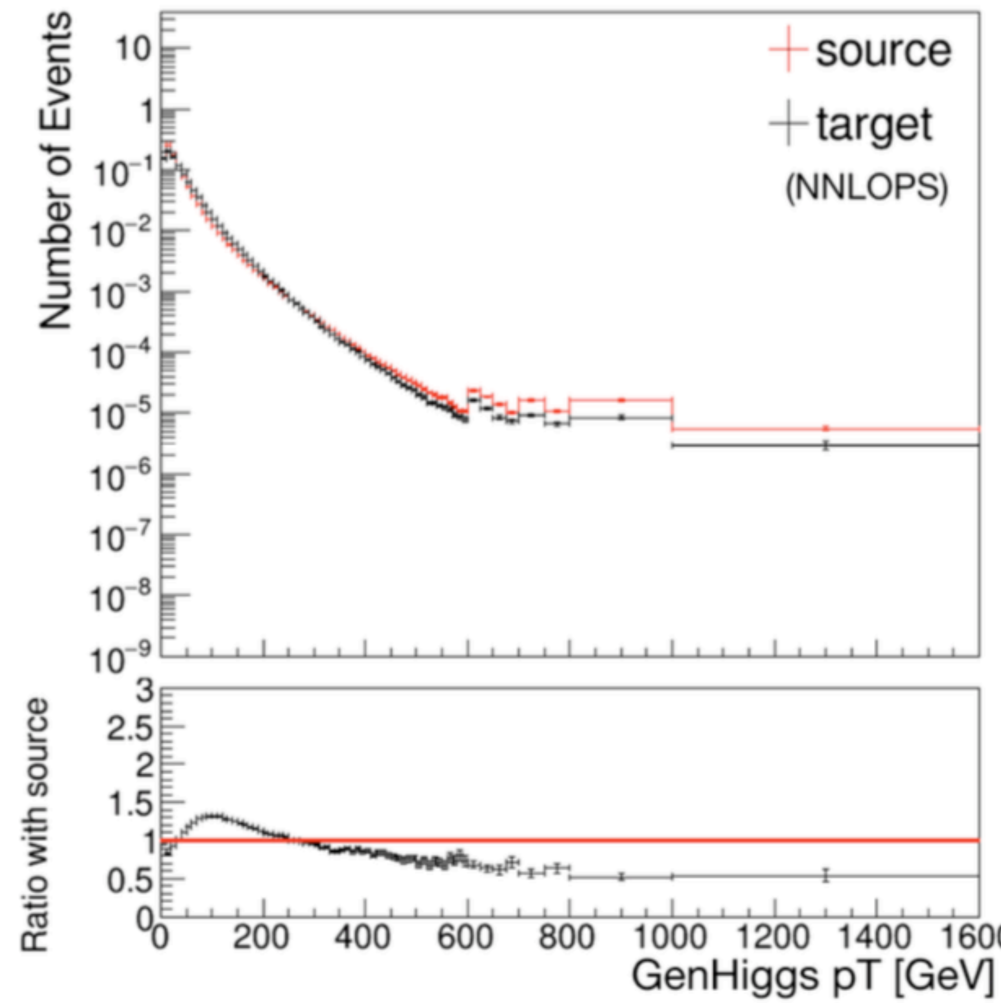
2016 **2017** **2018**



- Trigger efficiency measured in an orthogonal control region using SingleMuon dataset and WJetsToLNu MC samples.
- Scale factor is applied to MC signal sample to correct for the mismodelling of the trigger efficiency.
- The correction decreases the signal yield by ~5% in all signal models

Higgs pT Correction (ggH)

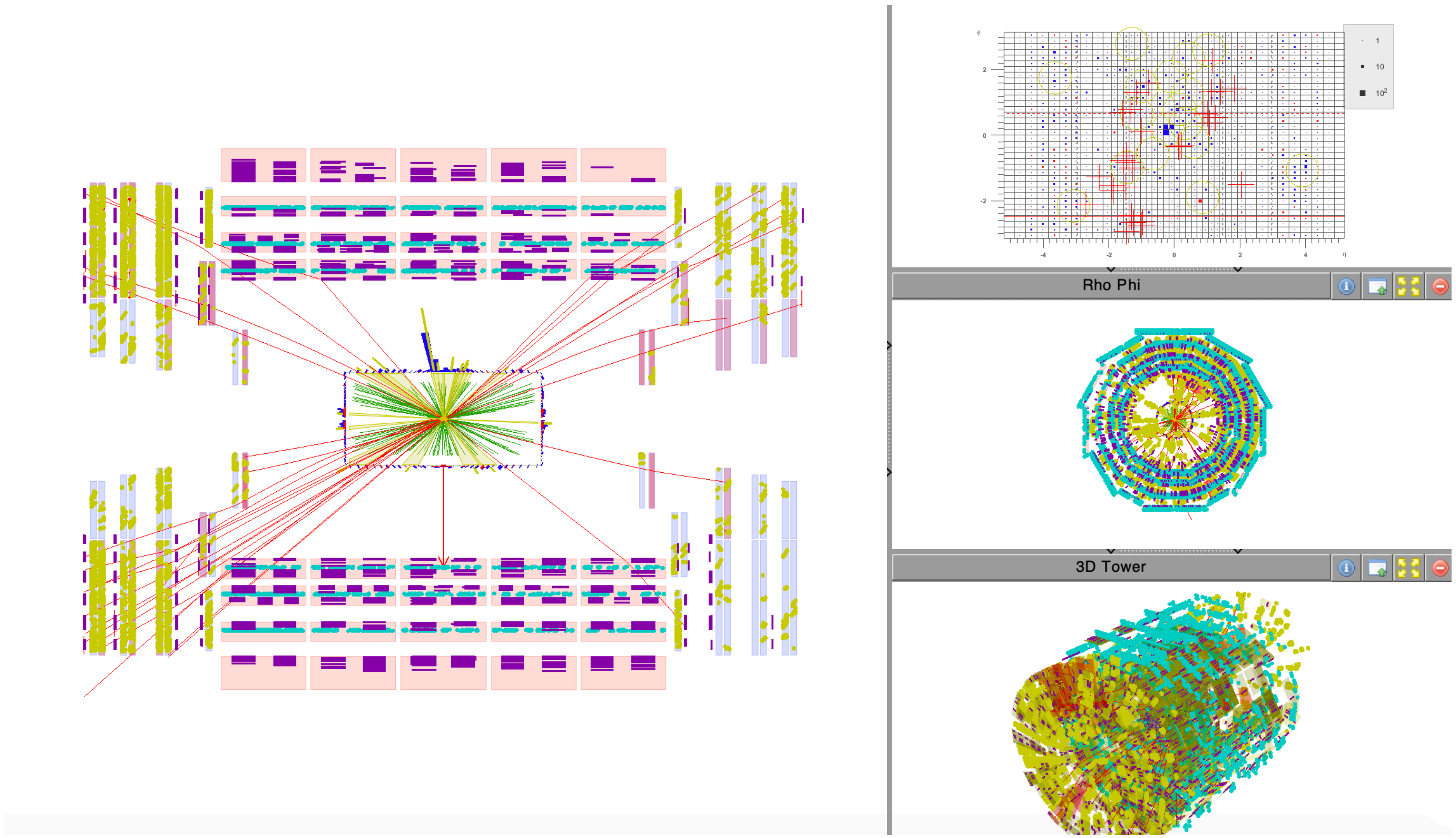
- The gen-level pT of the higgs for ggH production mode is reweighted to the best known theoretical prediction (NNLOPS)
- The correction increases the signal yield by a few %



Increase in signal yield

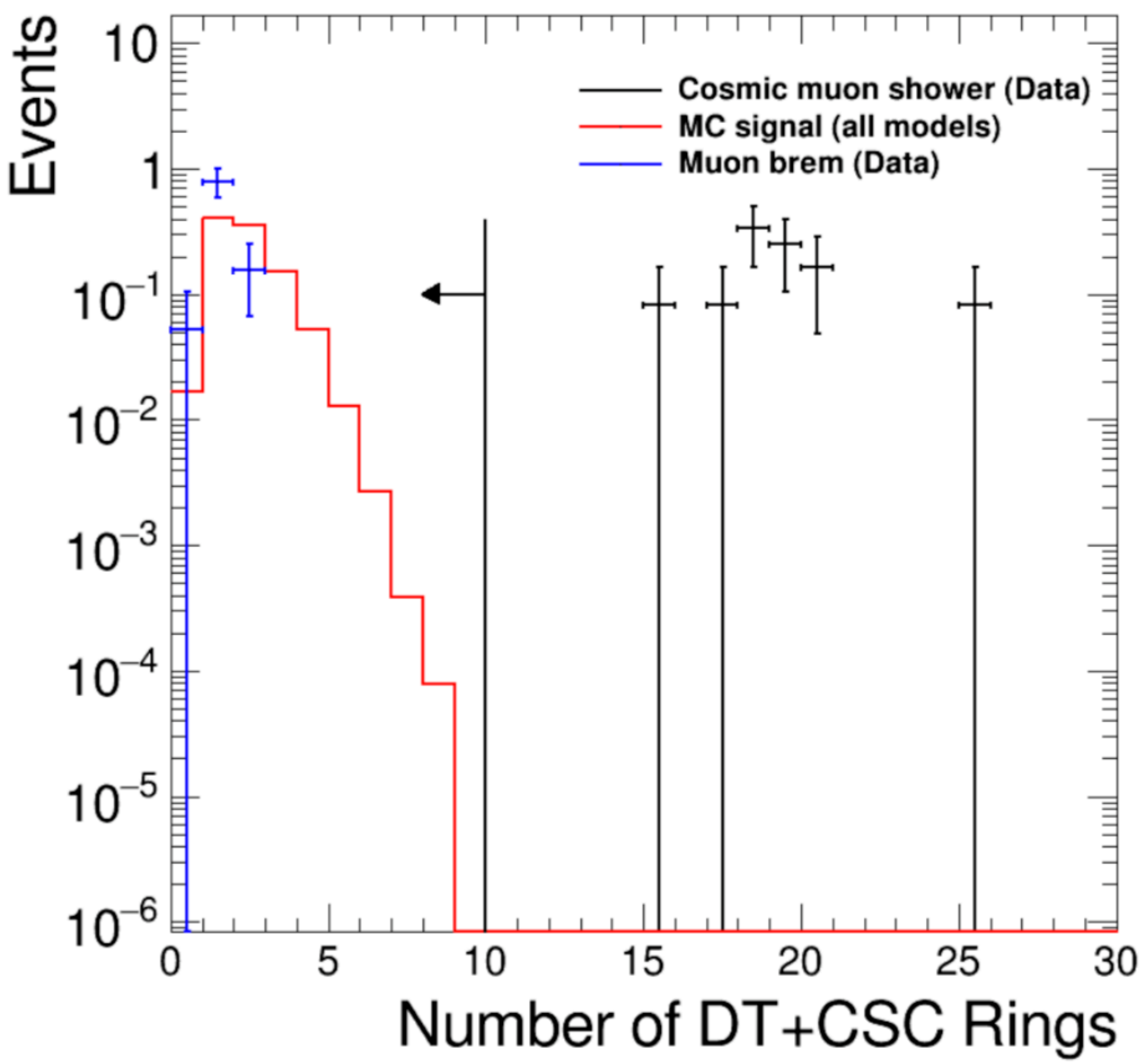
	$c\tau = 0.1\mathrm{m}$	$c\tau = 1\mathrm{m}$	$c\tau = 10\mathrm{m}$	$c\tau = 100\mathrm{m}$
15 GeV	5.11%	1.48%	2.47%	0.65 %
40 GeV	7.28%	0.84%	2.18%	4.28 %
55 GeV	\	4.22%	2.9%	3.13 %

Cosmic Shower Events



- More than 10k CSC rechits, distributed across all bunch crossings
- Occupy a large number of stations/chambers in CSC and DT

Cosmic Shower Events



Data selection

- nEarlyCscRechits (time < -25ns) > 2000

Signal MC selection:

- Event contains 1 cluster that passes all the signal selection

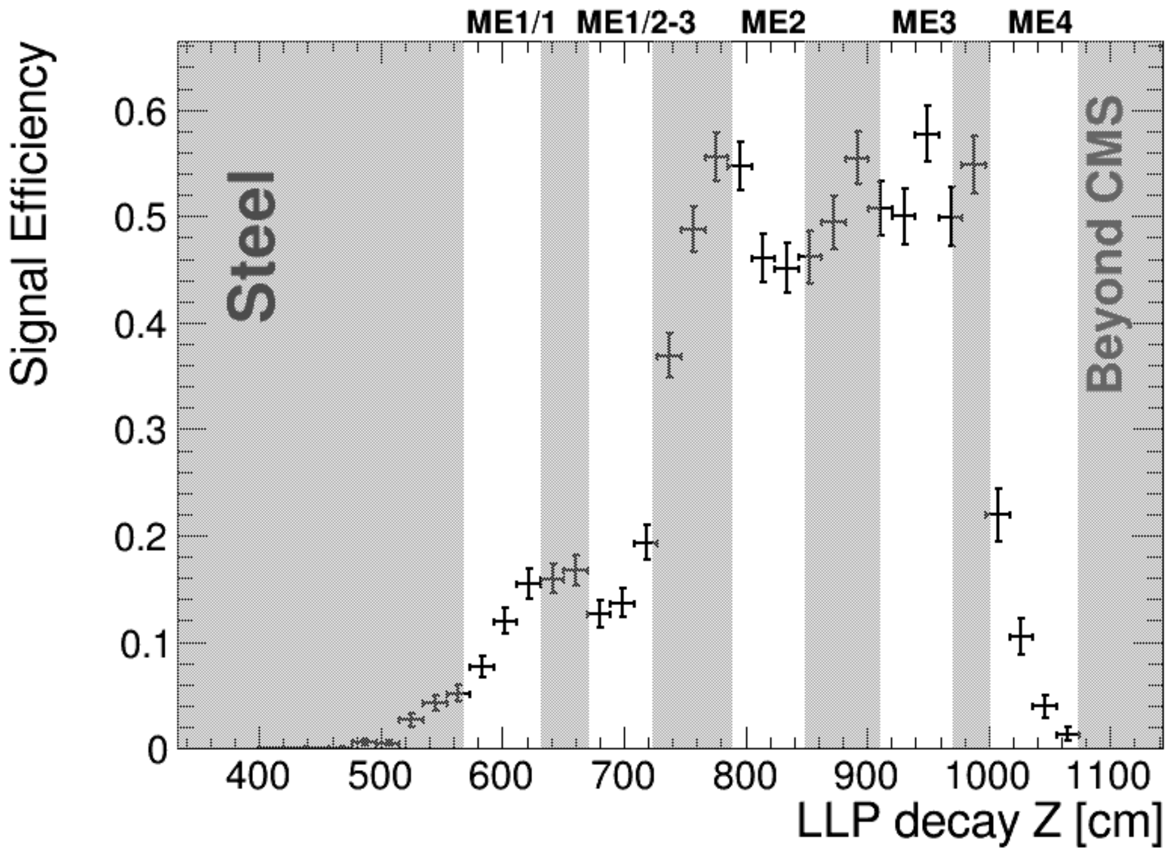
Count number of DT and CSC rings that have at least 50 hits

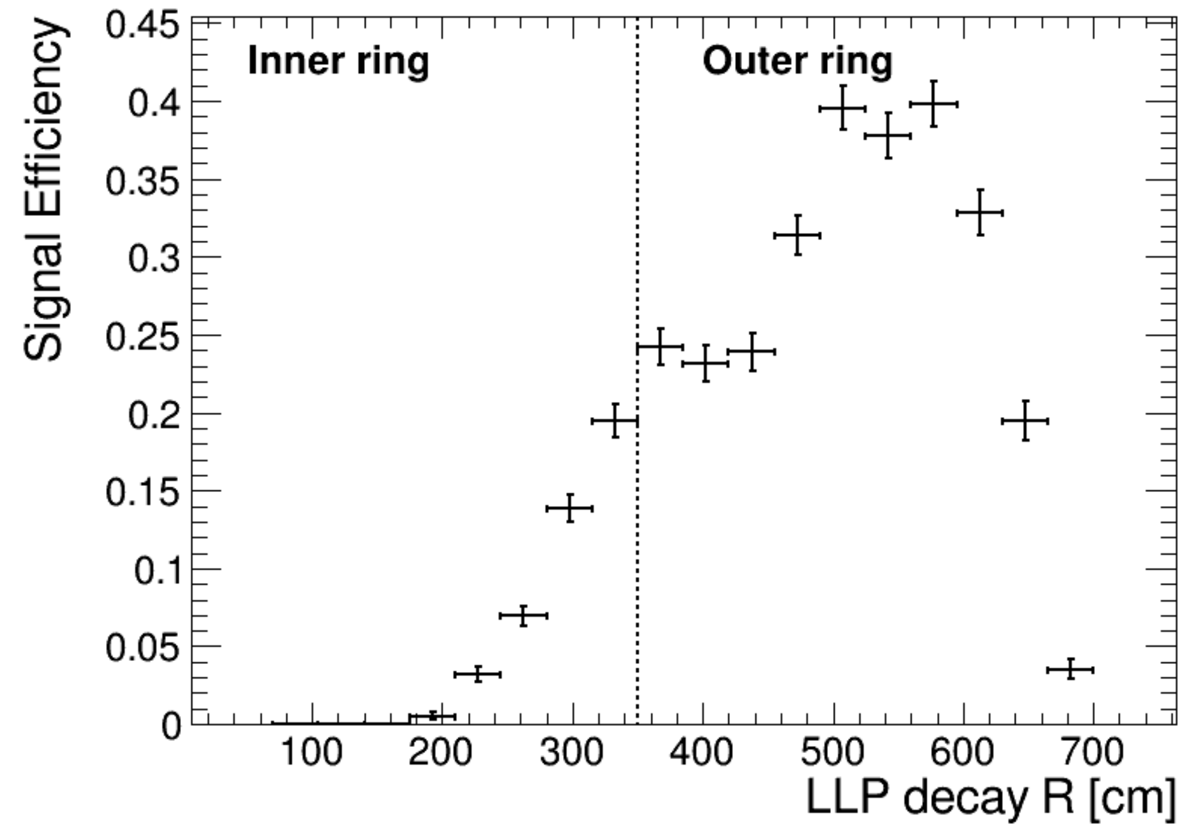
No impact on signal efficiency -- signal does NOT produce such signature

Signal Efficiency vs. Decay Position

Efficiency of all the cluster selections wrt events passing MET cut

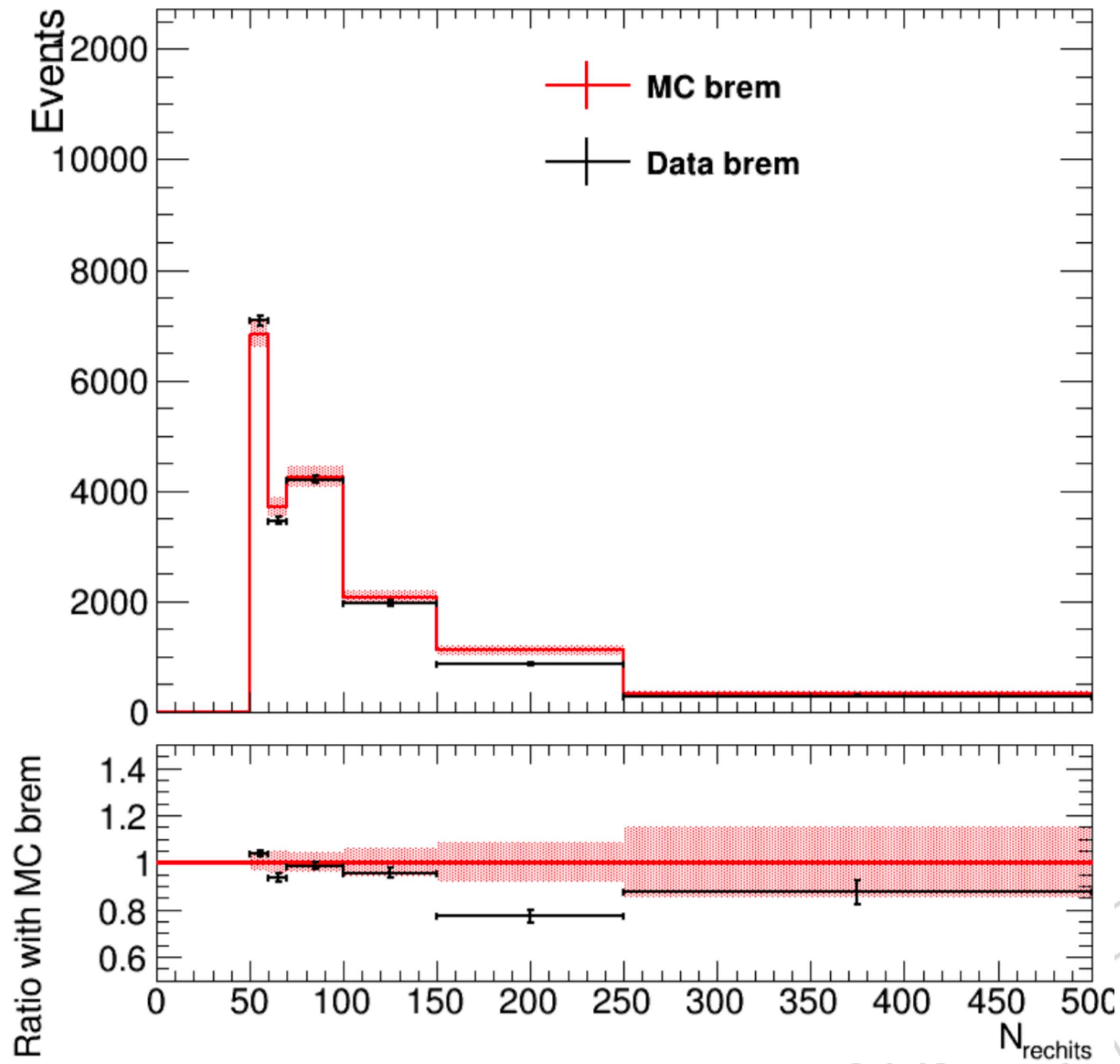
m_S = 15 GeV





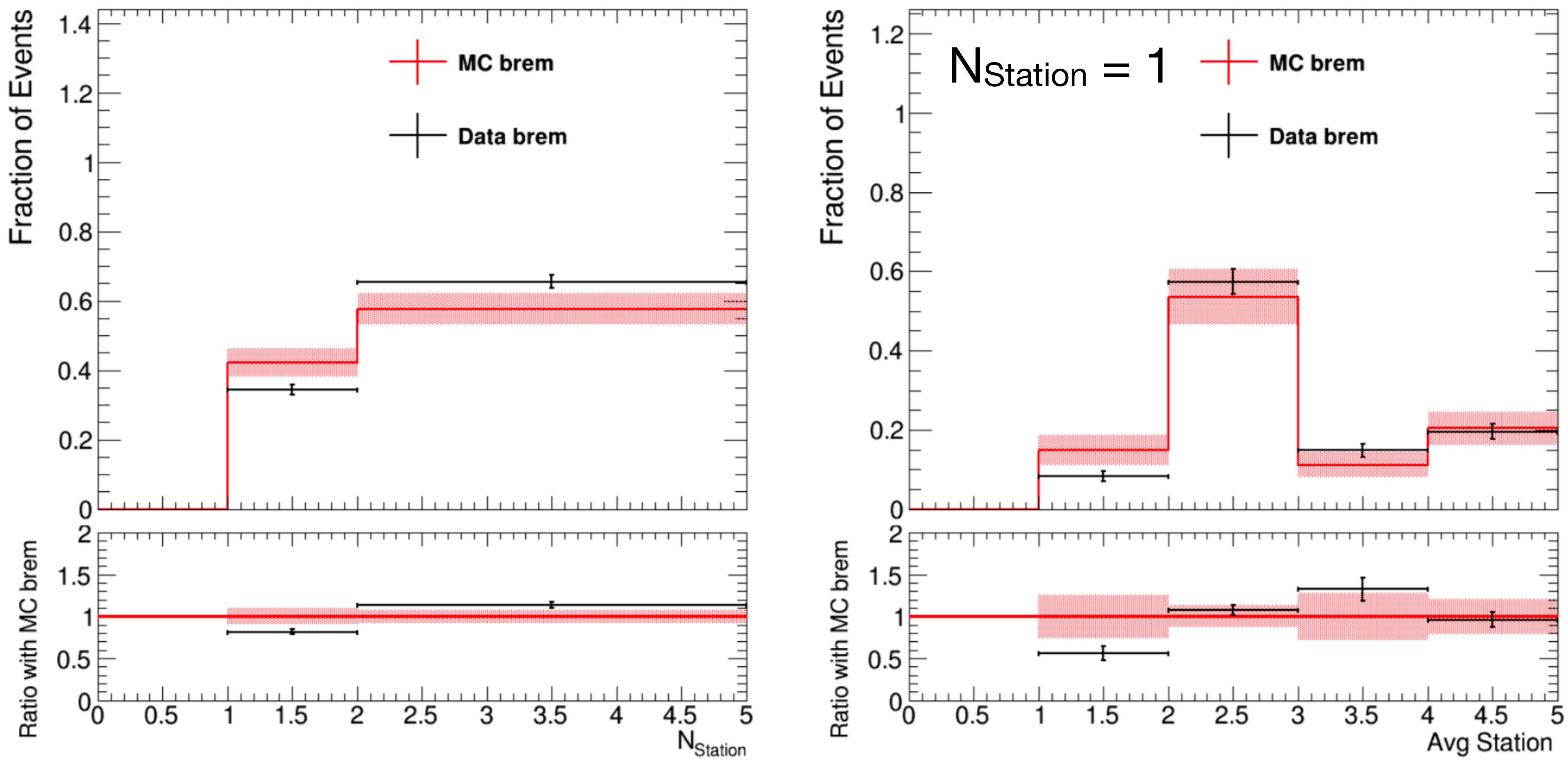
~50% signal efficiency when LLP decays between ME1 and ME4

Cluster Efficiency Uncertainty



- We find that the cluster efficiency measured at N_{rechit}>=137 in MC equals the cluster efficiency of data measured at N_{rechit}>=130.
- Shifting the Nrechit cut from 130 to 137 has a maximum of 3.5% effect on signal yield, so we apply a **3.5% cluster efficiency uncertainty** on signal MC.

Cut-Based ID Efficiency

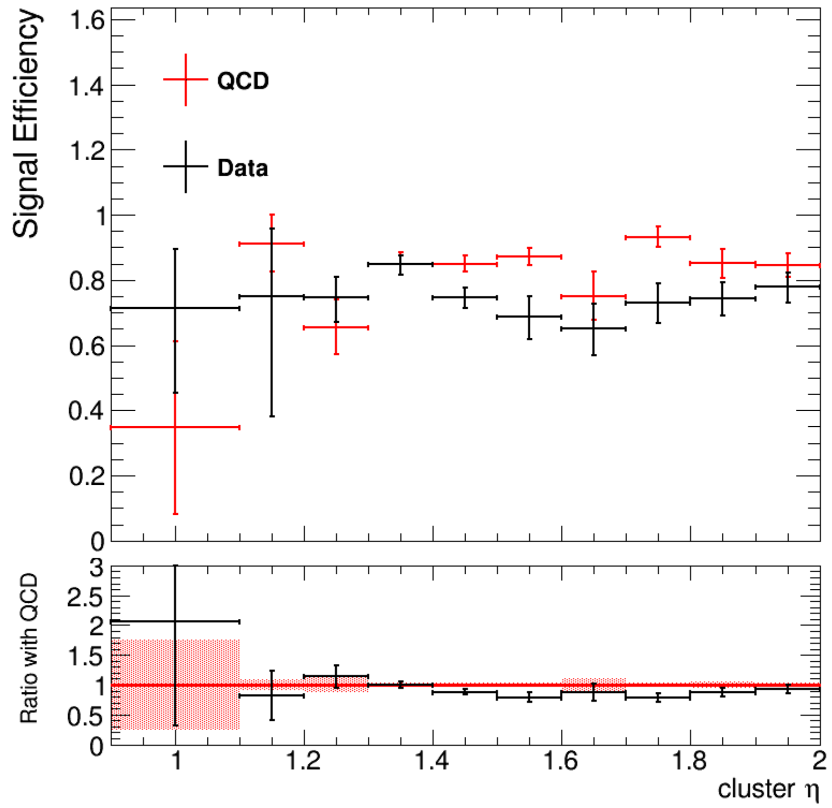


- We measure the mismodelling of the shape of the $N_{Station}$ and Avg Station (only relevant for NStation==1) distributions.
- We observed a 5% difference in signal yield after correcting for the shape difference for the $N_{Station}$ and Avg Station distributions in signal simulation → **apply a 5% signal systematic**

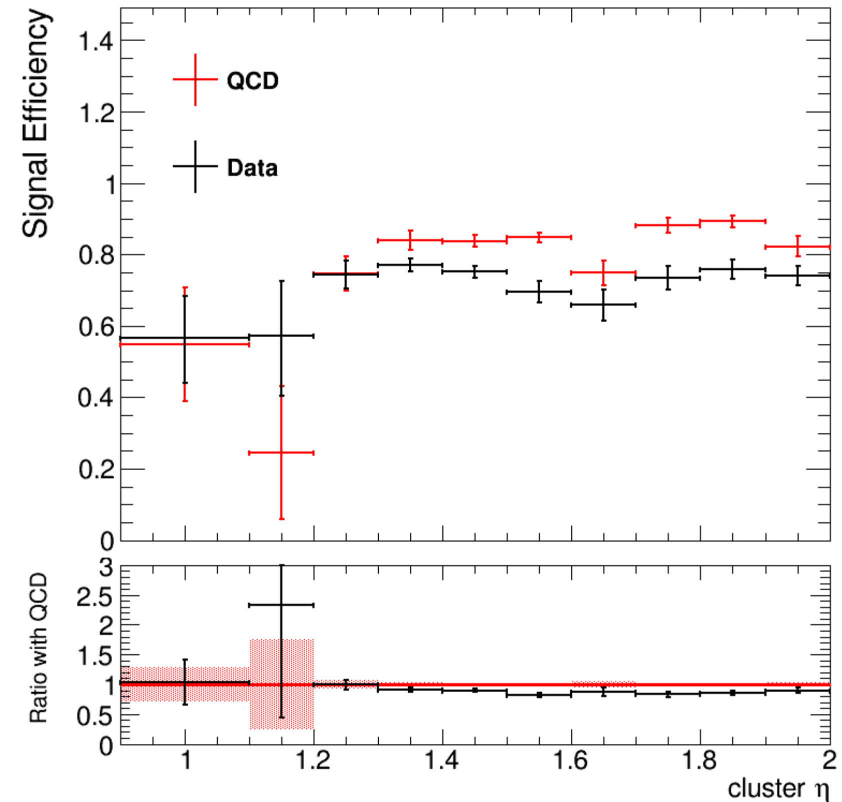
Muon Veto Efficiency

- **Muon veto efficiency is measured using trackless jets in QCD and data at various neutral energy fraction cuts**

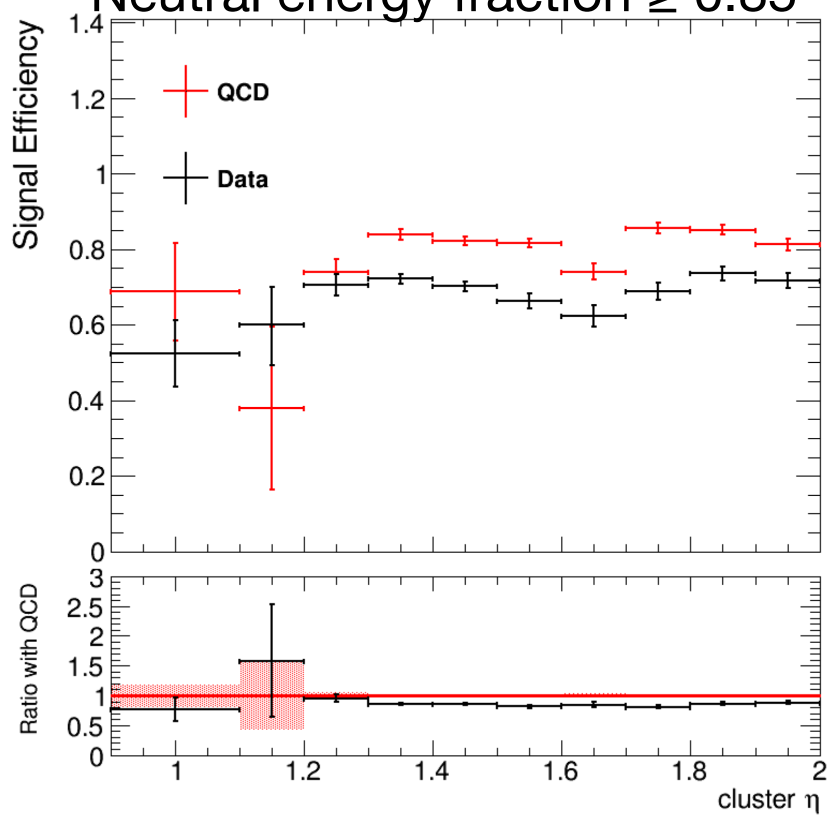
Neutral energy fraction ≥ 0.95



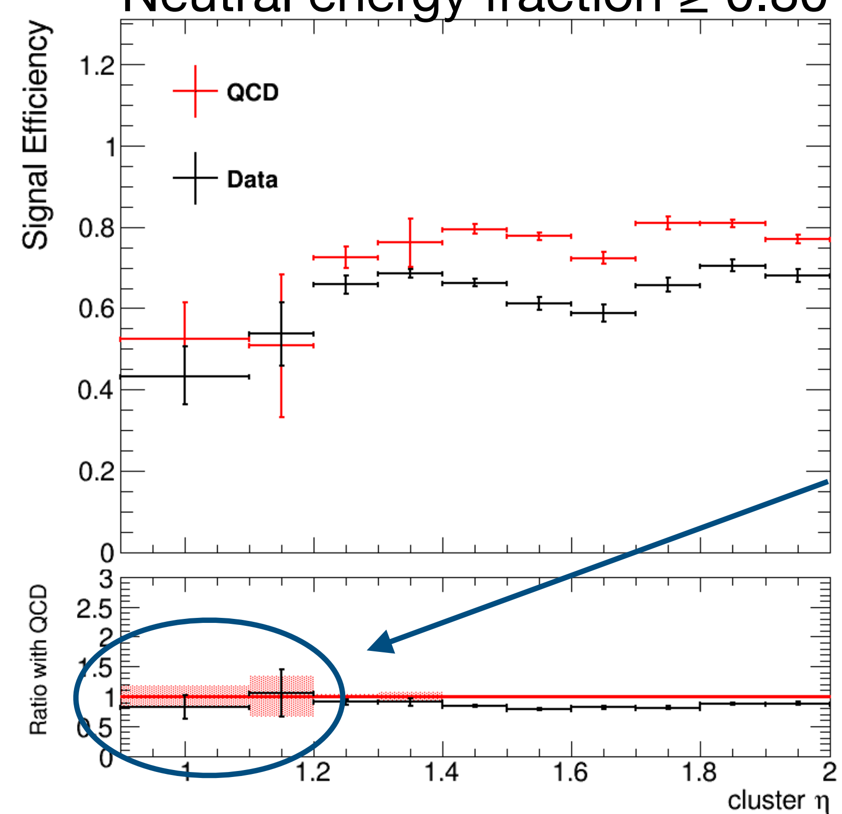
Neutral energy fraction ≥ 0.90



Neutral energy fraction ≥ 0.85



Neutral energy fraction ≥ 0.80



More statistics when we lower the NEF cut

Muon Veto Efficiency

- We use the SF measured at 0.8 NEF for the first two eta bins gain more statistics and using the SF at 0.95 NEF for the other larger eta bins because they are more signal like
- The measured data/MC difference is 8.5% ± 0.5% after reweighing with signal eta distribution.
- The difference is applied as a correction and the statistical uncertainty is applied as a source of signal systematic

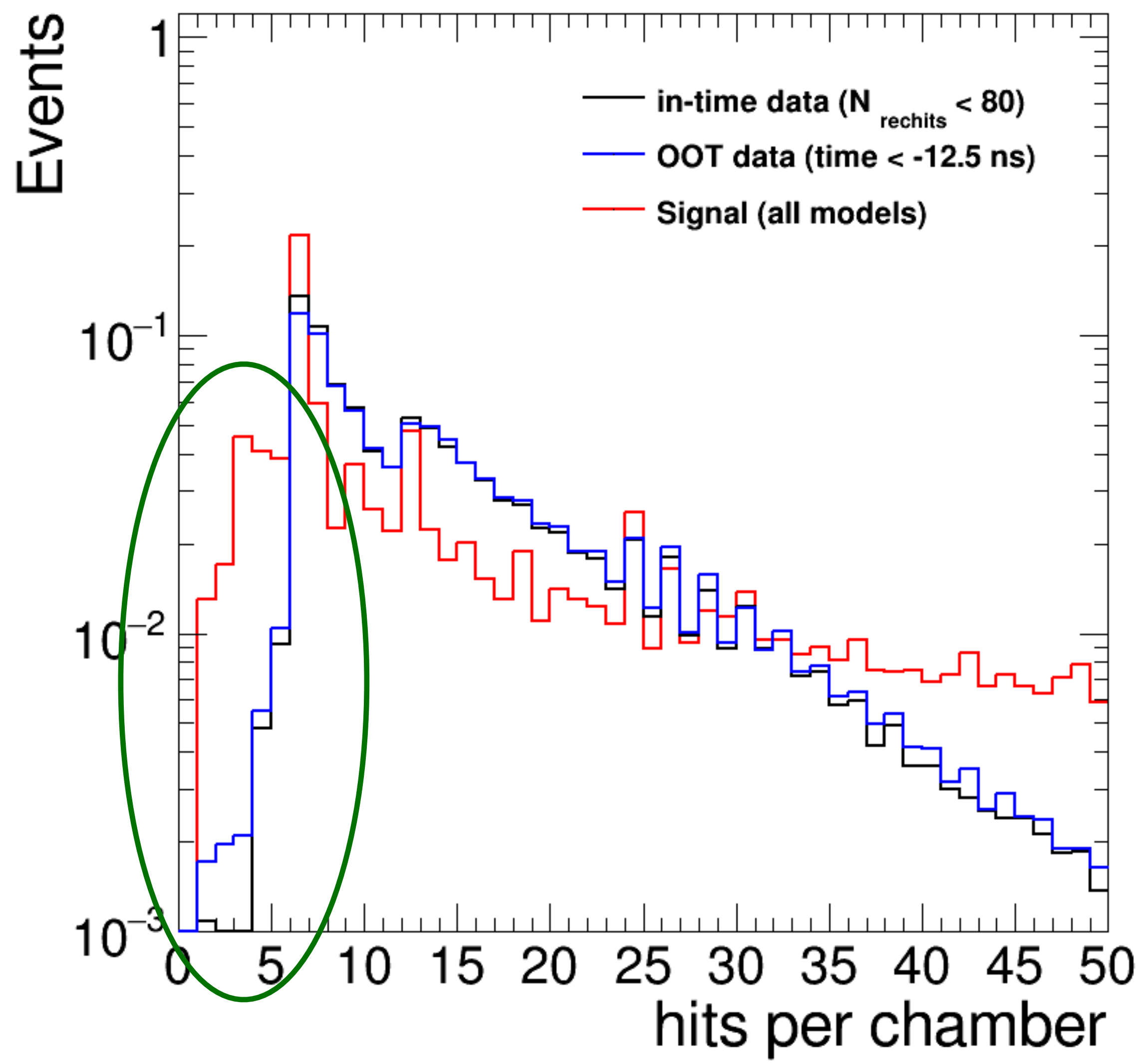
Background Systematic

- Previously, we propagated the statistical power of the two validations region and summed the two statistical uncertainties in quadrature to be conservative (105%)
- It was suggested that we propagate the combination of the statistical power of the two validation regions (61%)
- Other suggestion:
  - Not assign any background uncertainty at all, since the tests are closed

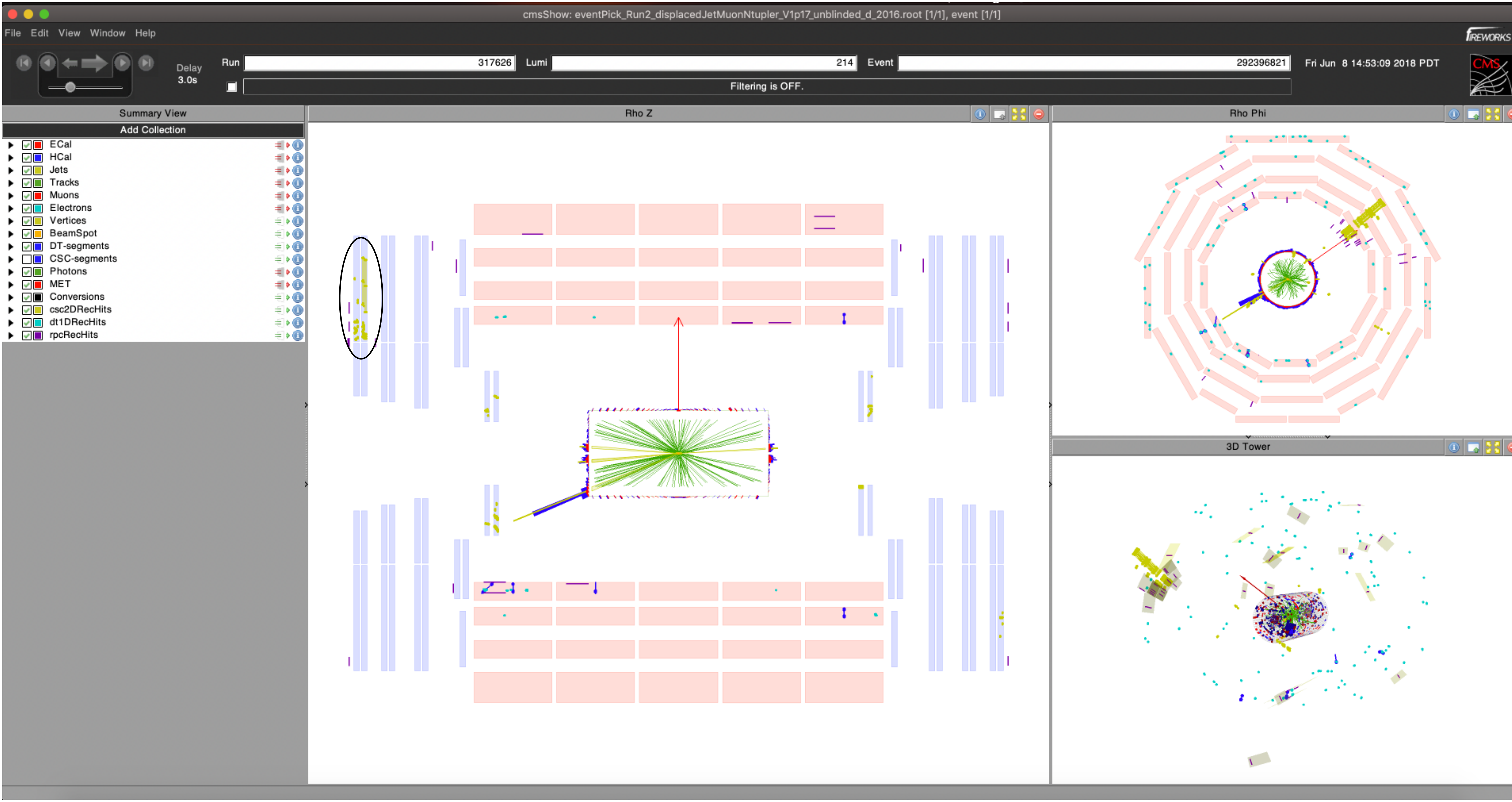
CSC Readout

- In real data, CSC chambers are read out if there are more than two comparator hits in different layers and the hits satisfy some pre-defined trigger patterns. This readout suppression is turned OFF in simulation.
- Two possible effects on signal simulation:
  - Overestimation of $N_{rechits}$ in signal: < 0.1% effect on signal efficiency
  - Underestimation of ME11/12 veto efficiency for signal: **1% systematic assigned**

A few events with 1-5 hits per chamber for signal



Observed Event in bin D

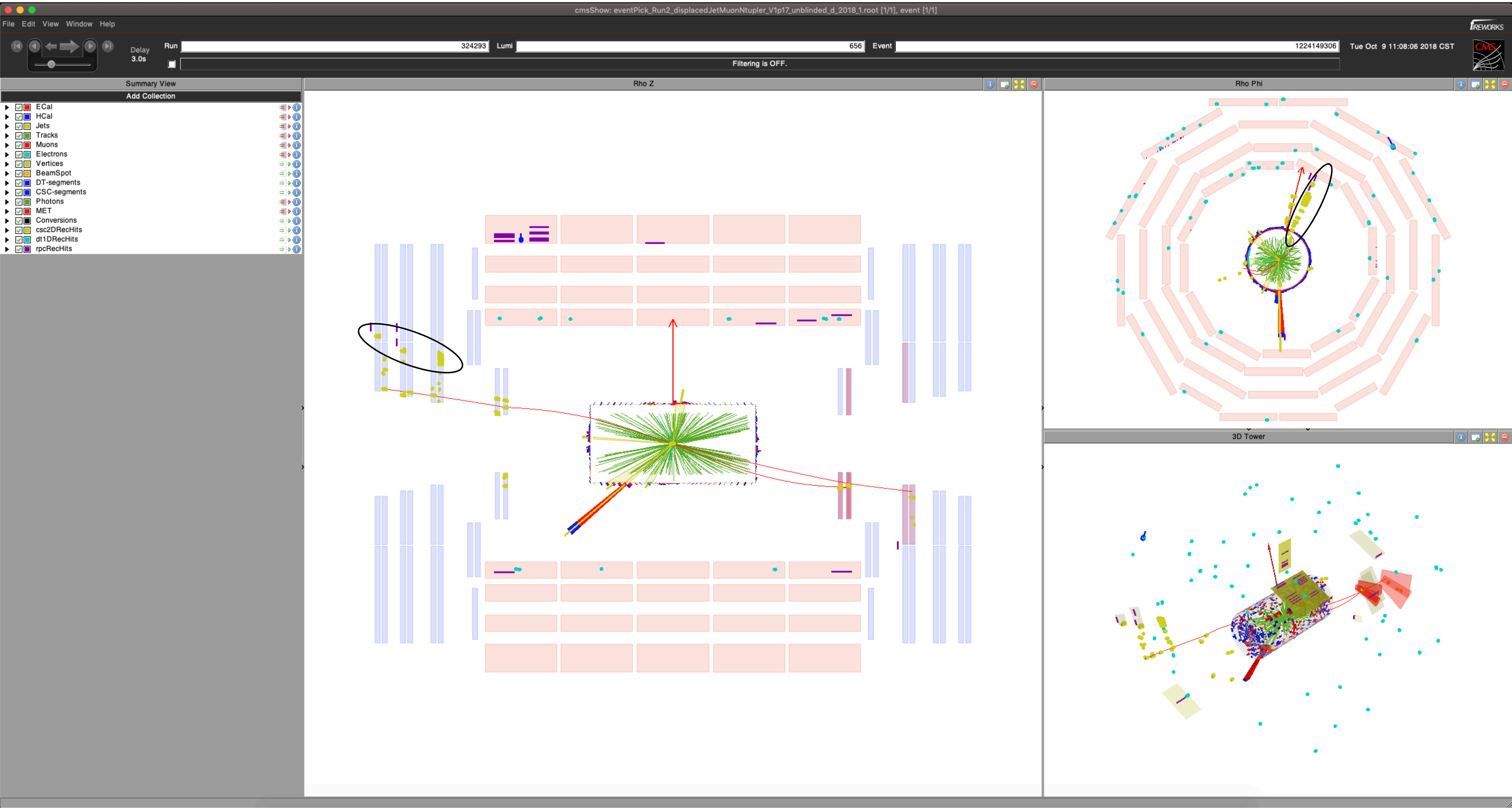


Nrechits: 156
dPhi: 0.01
MET 289.6
metPhi 0.65

Jet
Eta = -1.6
Phi = -2.6
pT = 256.3 GeV

Cluster
Eta = -1.57
Phi = 0.66
Time = -3.2 ns

Observed Event in bin D



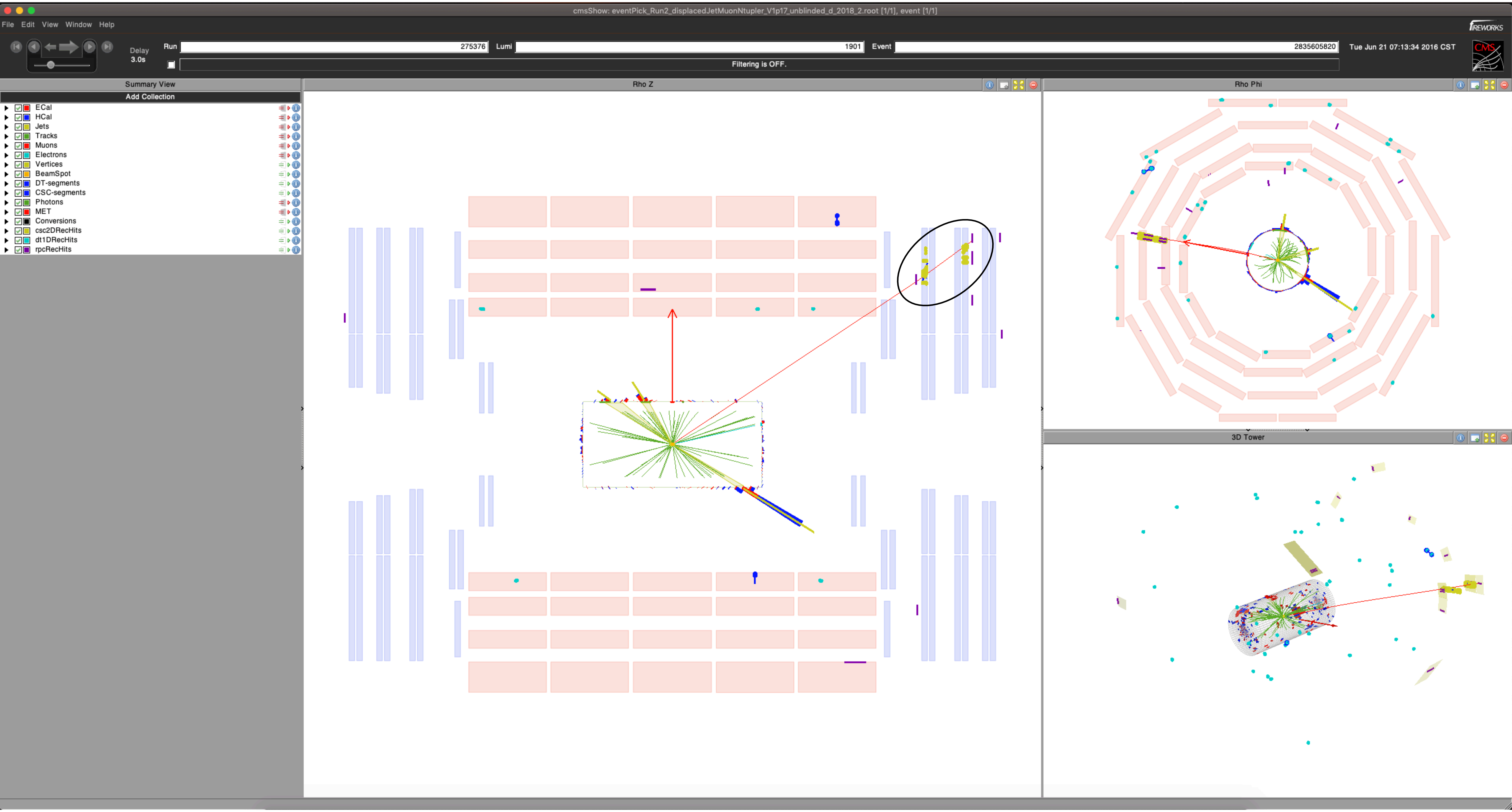
Nrechits: 192
dPhi: 0.21
MET 467.3
metPhi 1.34

Muon pT = 1.09 GeV
Eta = -1.811
Phi = 0.255

Jet
Eta = -1.0
Phi = -1.5
pT = 434.5 GeV

Cluster
Eta = -1.7492
Phi = 1.1332
Time = 1.0 ns

Observed Event in bin D



Nrechits: 169
dPhi: 0.01
MET 323.4
metPhi 2.96

Muon pT = 12.19 GeV
Eta = 1.2
Phi = 2.96

Jet
Eta = 1.3
Phi = -0.6
pT = 287 GeV

Cluster
Eta = 1.20
Phi = 2.97
Time = 0.01

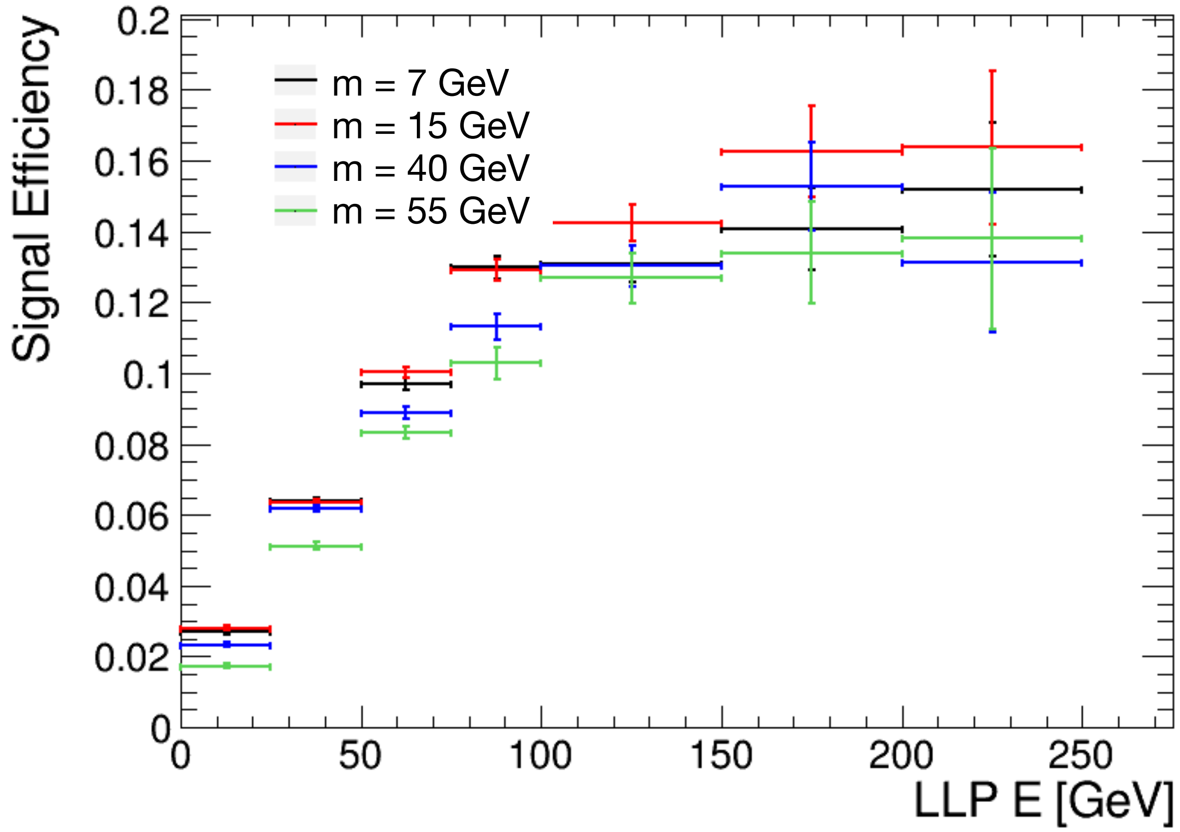
BR(S → ff) used by ATLAS

Model	Mass point [GeV]	Branching fraction to final state particles	
$\Phi \to ss$	$[m_\Phi, m_s] = [100,8]$	$[b\bar{b}\ ,\ c\bar{c}\ ,\ \tau^+\tau^-\ ,\ \mu^+\mu^-] =$	[- , 0.68 , 0.32 , 0.0010]
	$[m_\Phi, m_s] = [100,25]$		[0.86 , 0.09 , 0.05 , 0.0002]
	$[m_\Phi, m_s] = [125,5]$		[- , 0.75 , 0.25 , 0.0030]
	$[m_\Phi, m_s] = [125,8]$		[- , 0.69 , 0.31 , 0.0010]
	$[m_\Phi, m_s] = [125,15]$		[0.79 , 0.14 , 0.07 , 0.0002]
	$[m_\Phi, m_s] = [125,25]$		[0.86 , 0.09 , 0.05 , 0.0002]
	$[m_\Phi, m_s] = [125,40]$		[0.87 , 0.08 , 0.04 , 0.0004]
	$[m_\Phi, m_s] = [200,8]$		[- , 0.69 , 0.32 , 0.0010]
	$[m_\Phi, m_s] = [200,25]$		[0.85 , 0.10 , 0.05 , 0.0001]
	$[m_\Phi, m_s] = [200,50]$		[0.87 , 0.08 , 0.04 , 0.0001]
	$[m_\Phi, m_s] = [400,50]$		[0.88 , 0.08 , 0.04 , 0.0002]
	$[m_\Phi, m_s] = [400,100]$		[0.88 , 0.08 , 0.04 , 0.0001]
	$[m_\Phi, m_s] = [600,50]$		[0.87 , 0.08 , 0.04 , 0.0002]
	$[m_\Phi, m_s] = [600,150]$		[0.88 , 0.08 , 0.04 , 0.0001]
	$[m_\Phi, m_s] = [1000,50]$		[0.87 , 0.09 , 0.05 , 0.0001]
	$[m_\Phi, m_s] = [1000,150]$		[0.88 , 0.08 , 0.04 , 0.0001]
	$[m_\Phi, m_s] = [1000,400]$		[0.88 , 0.08 , 0.04 , 0.0001]

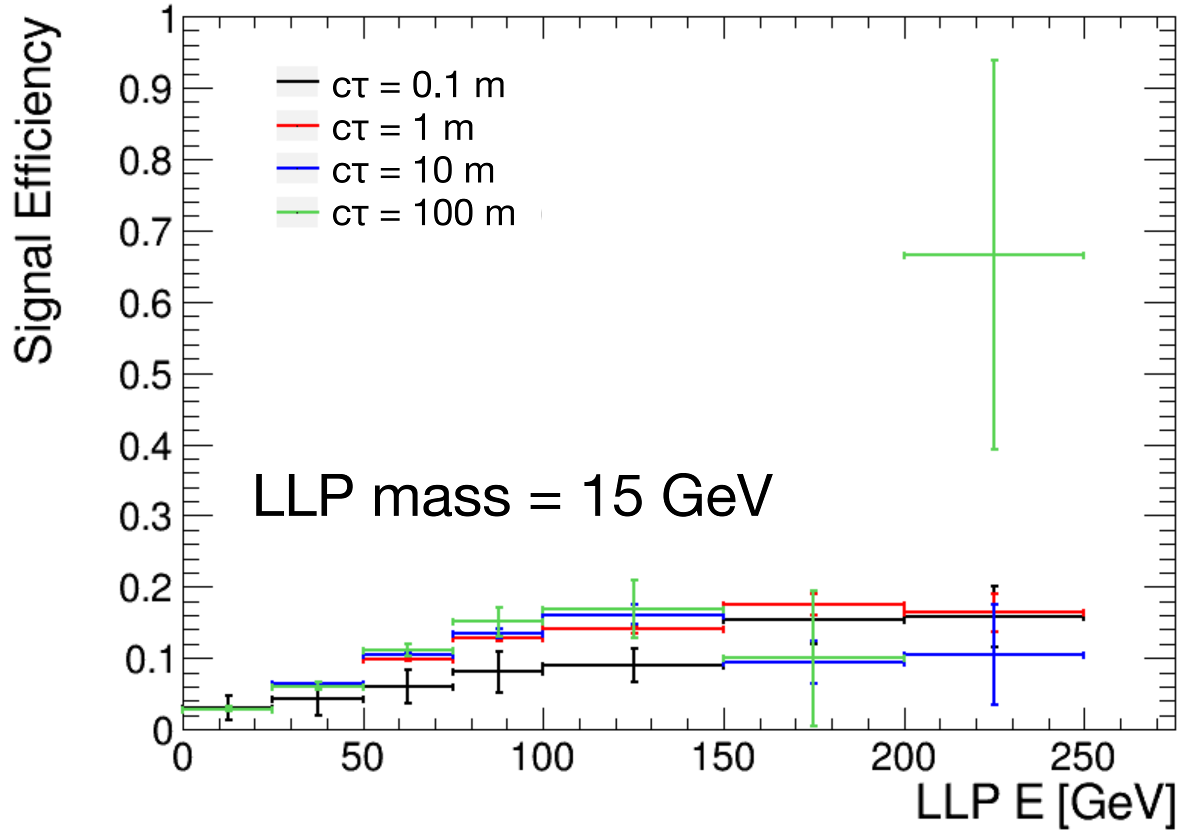
Model Independence of Cluster Efficiency (region A)

- We show this parametrization of cluster efficiency is independent of LLP mass and ctau within each LLP decay region
- Here we show the parametrization wrt LLP energy, since EM fraction of the same decay mode remains the same. It's easier to visualize the trend with the 1D parametrization

Mass independence



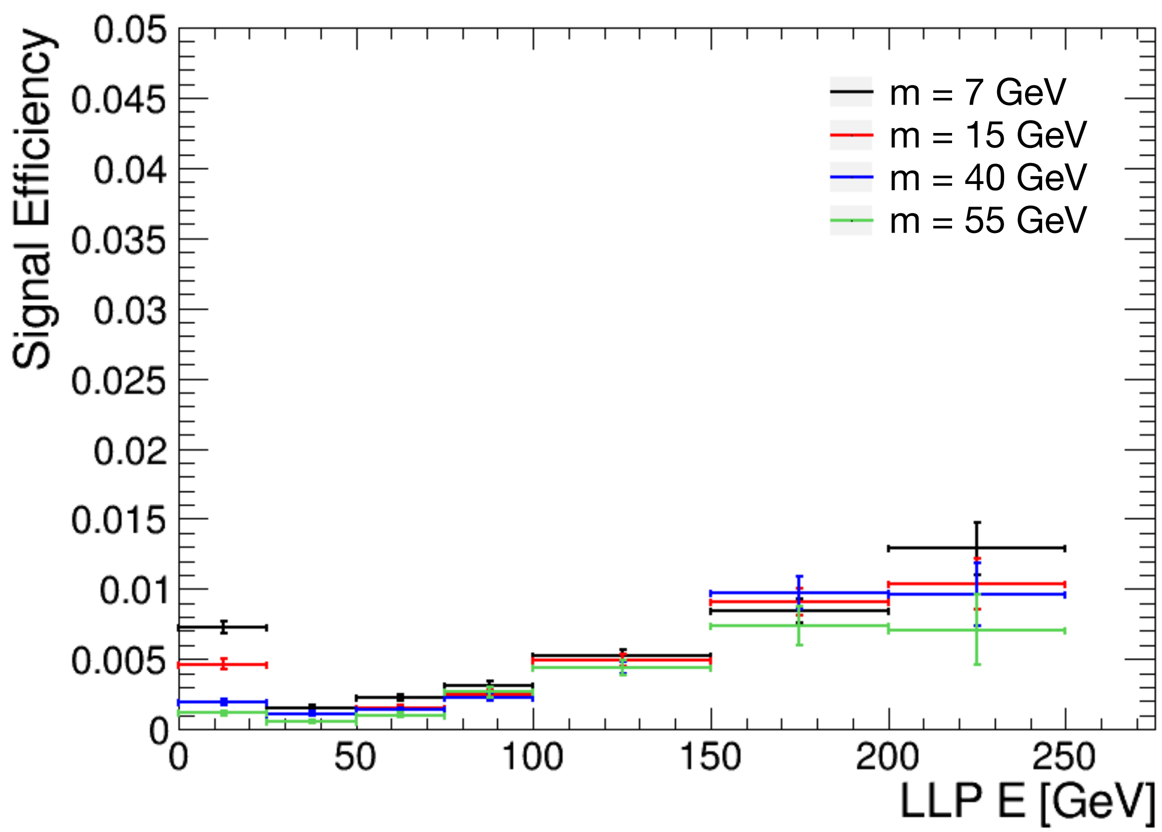
ctau independence



Model Independence of Cluster Efficiency (region C)

- We show this parametrization of cluster efficiency is independent of LLP mass and ctau within each LLP decay region
- Here we show the parametrization wrt LLP energy, since EM fraction of the same decay mode remains the same. It's easier to visualize the trend with the 1D parametrization

Mass independence



ctau independence