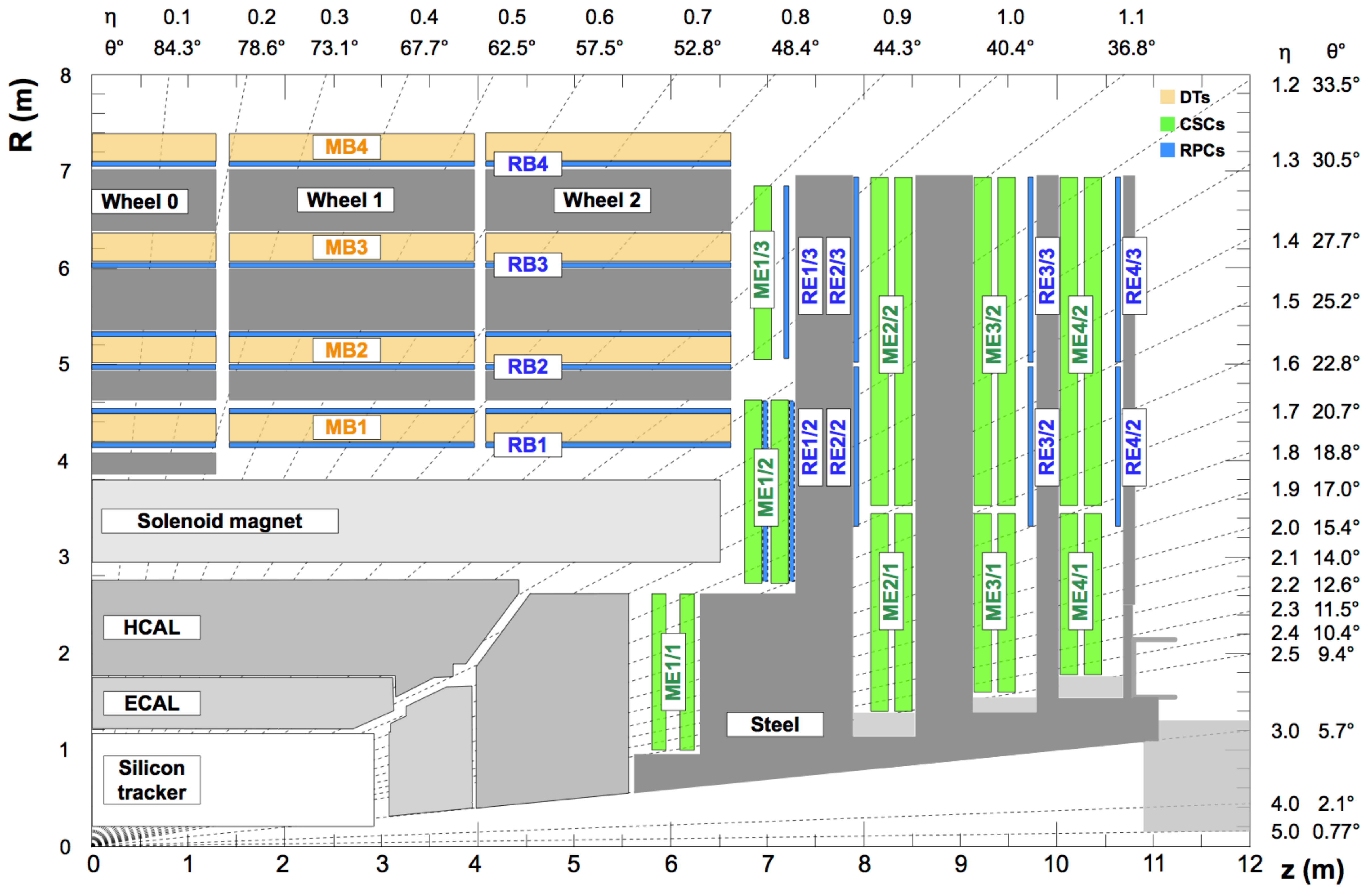
Search for neutral long-lived particles decaying in the CMS Muon System

James Sheplock, University of California, Santa Barbara
on behalf of the CMS collaboration

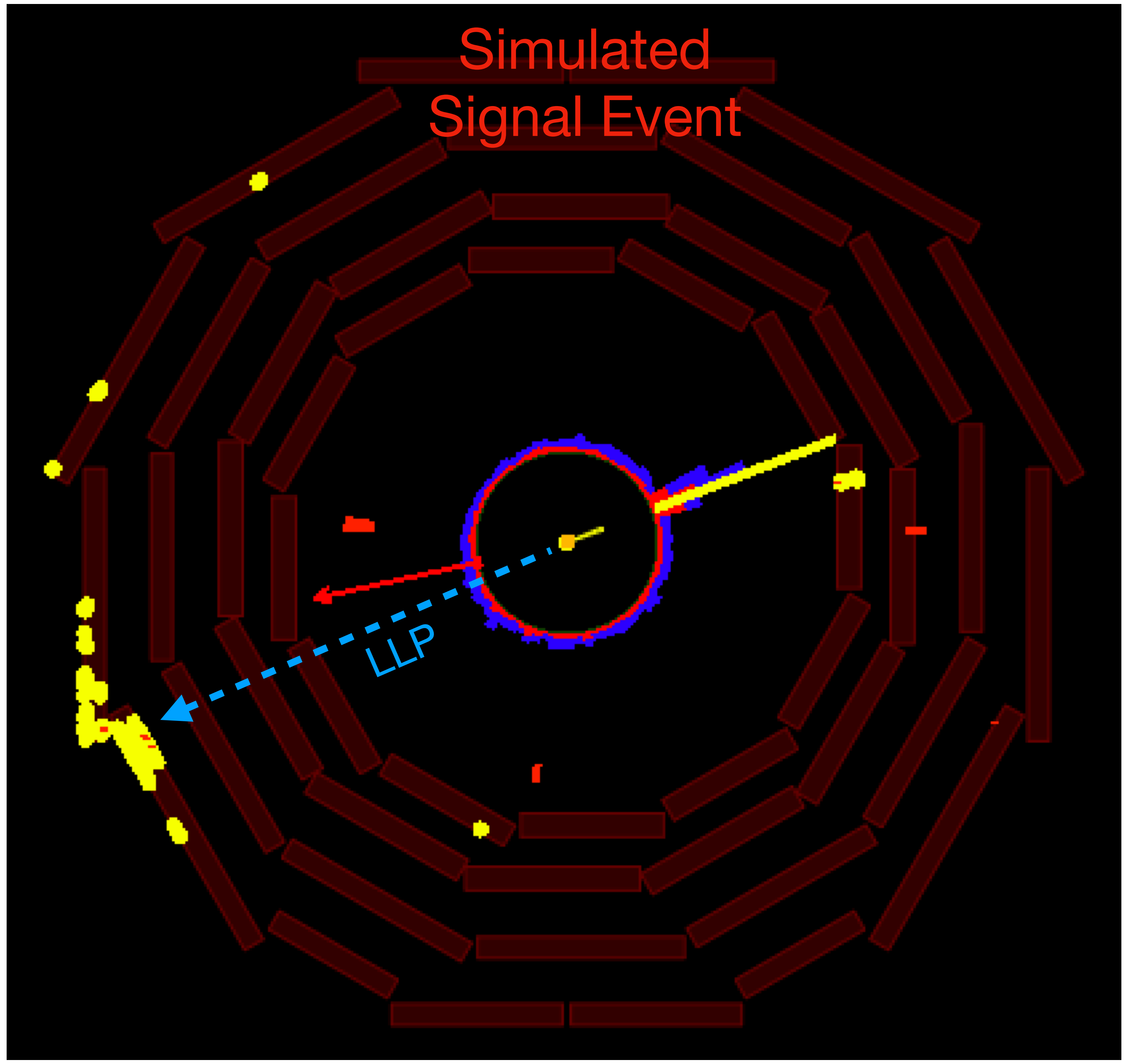
New Perspectives 2023
27 June 2023

Introduction



Decays of LLPs in the muon system give rise to hadronic and electromagnetic showers with **high multiplicity**

There are **no reconstructed objects** associated with the LLP prior to the showering decay



Strategy: Search for LLPs using **clusters of hits in the muon system** that are not matched to any jet signatures in inner detector

Low background for single and double LLP decays

Analysis Overview

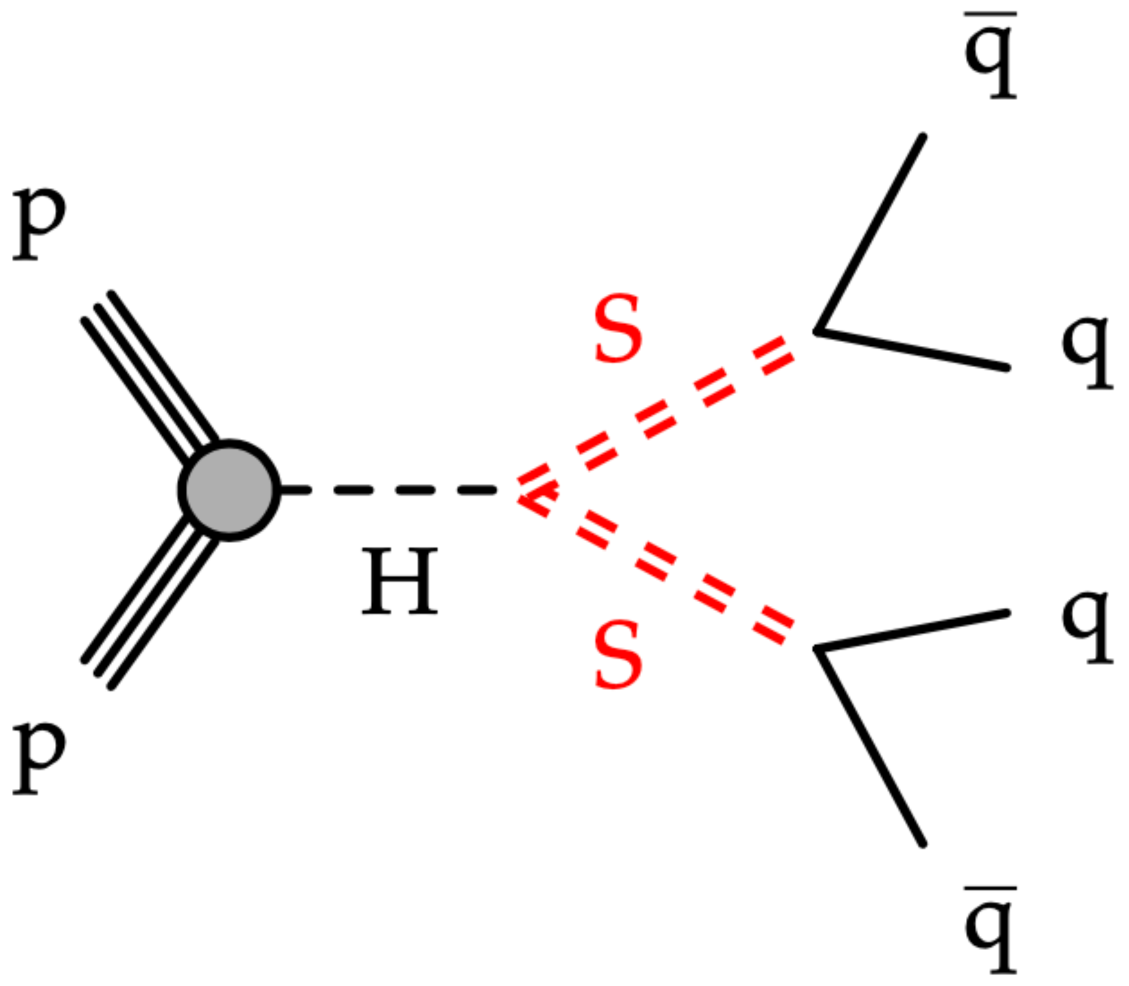
- **3 mutually exclusive categories**
  - 2 clusters
    - 2 endcap, 2 barrel, 1 endcap+1 barrel
  - 1 endcap cluster
  - 1 barrel cluster

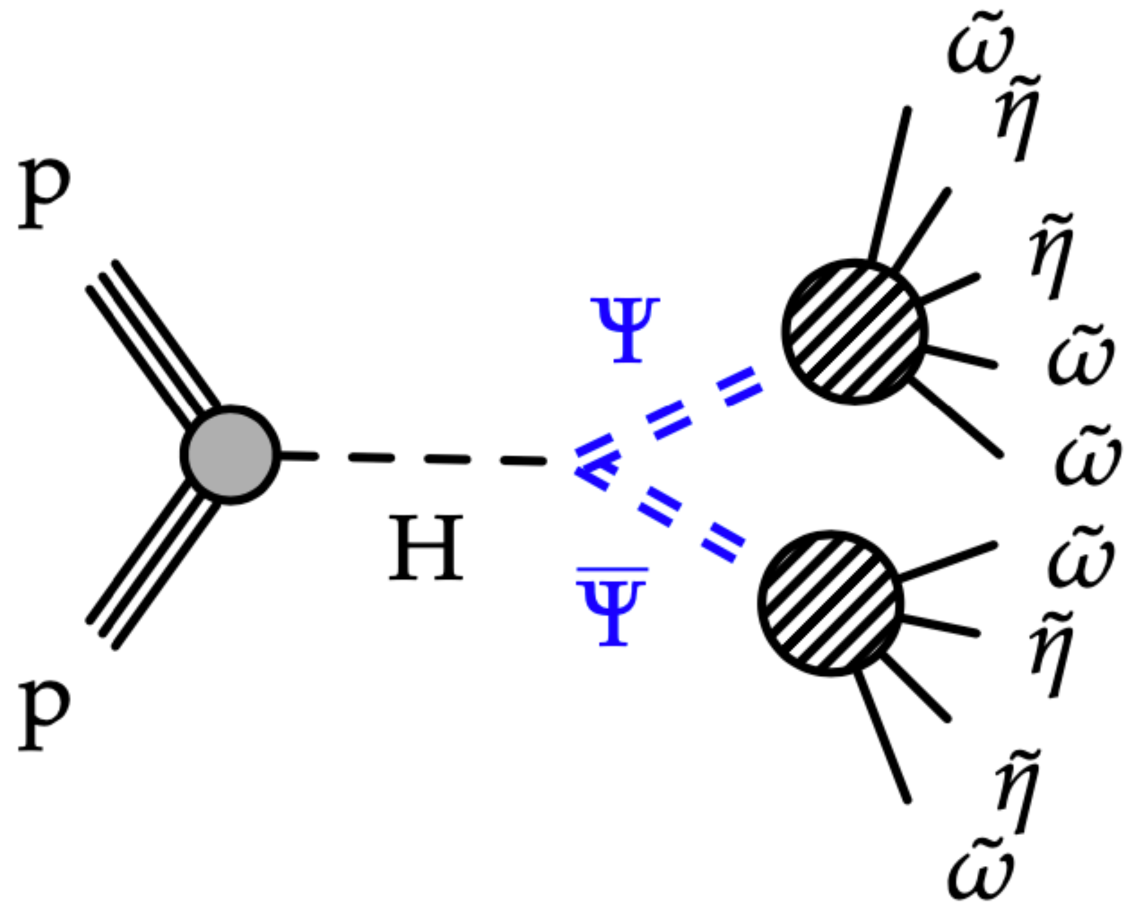
Lowest background, best peak sensitivity from requiring 2 clusters

Result previously published, first with muon system clusters

Higher background, sensitive to larger lifetimes than other categories

- **Trigger using MET** (HLT PF MET > 120 GeV) with offline MET > 200 GeV requirement
- **Vetoes reject background clusters** (muons, punch-through jets, noise)
- **Data-driven ABCD prediction** of background in the signal region using cluster size and |Δφ(cluster, MET)|
- **BSM Interpretation**
  - Twin Higgs: H→SS→ffff
  - Dark Shower: Higgs decays to dark sector quarks which hadronize into a shower with mesons that can eventually decay to SM (5 decay portals considered)
  - LLPs with masses from 0.1 to 55 GeV, lifetimes from 1cm to 100m, several shower properties are considered

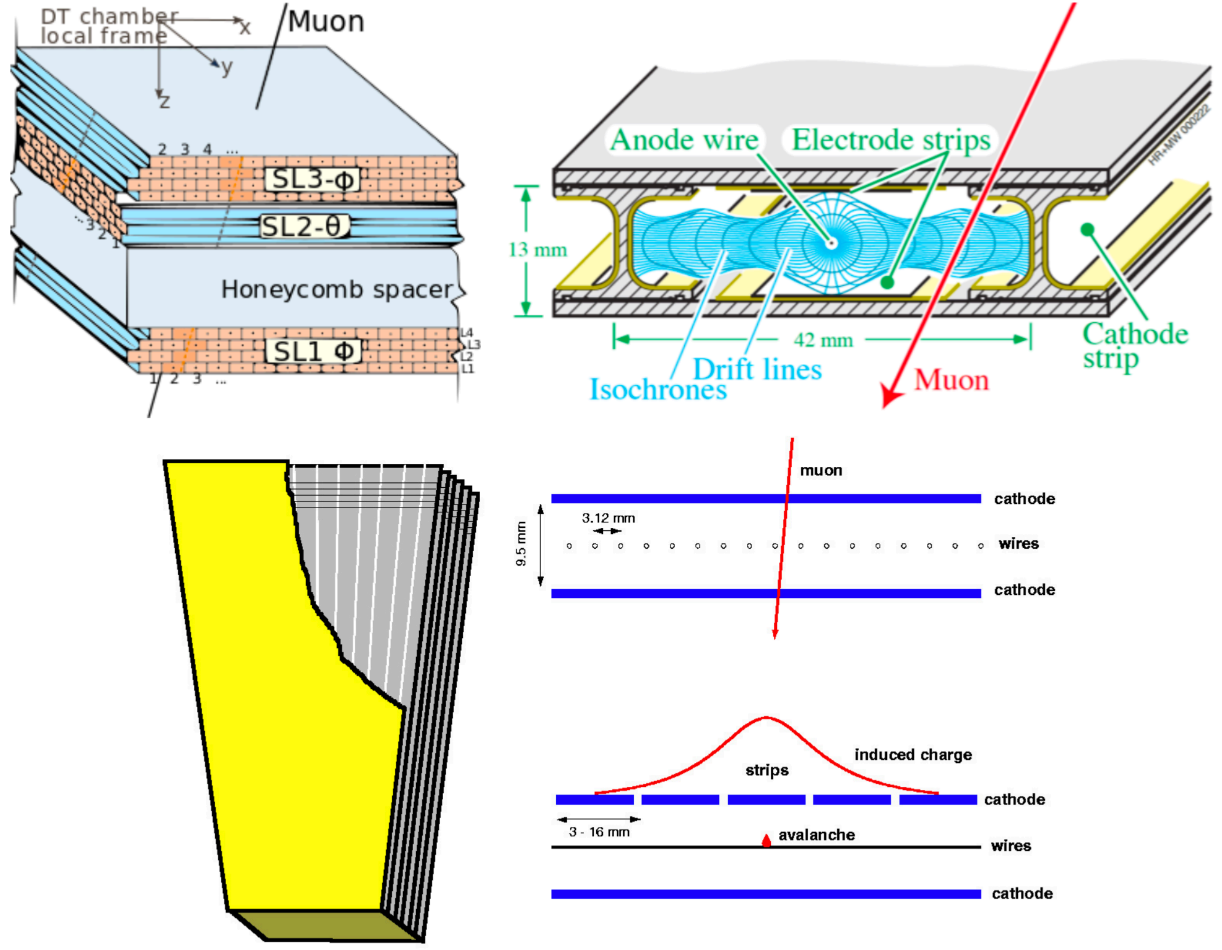




Muon System Clusters

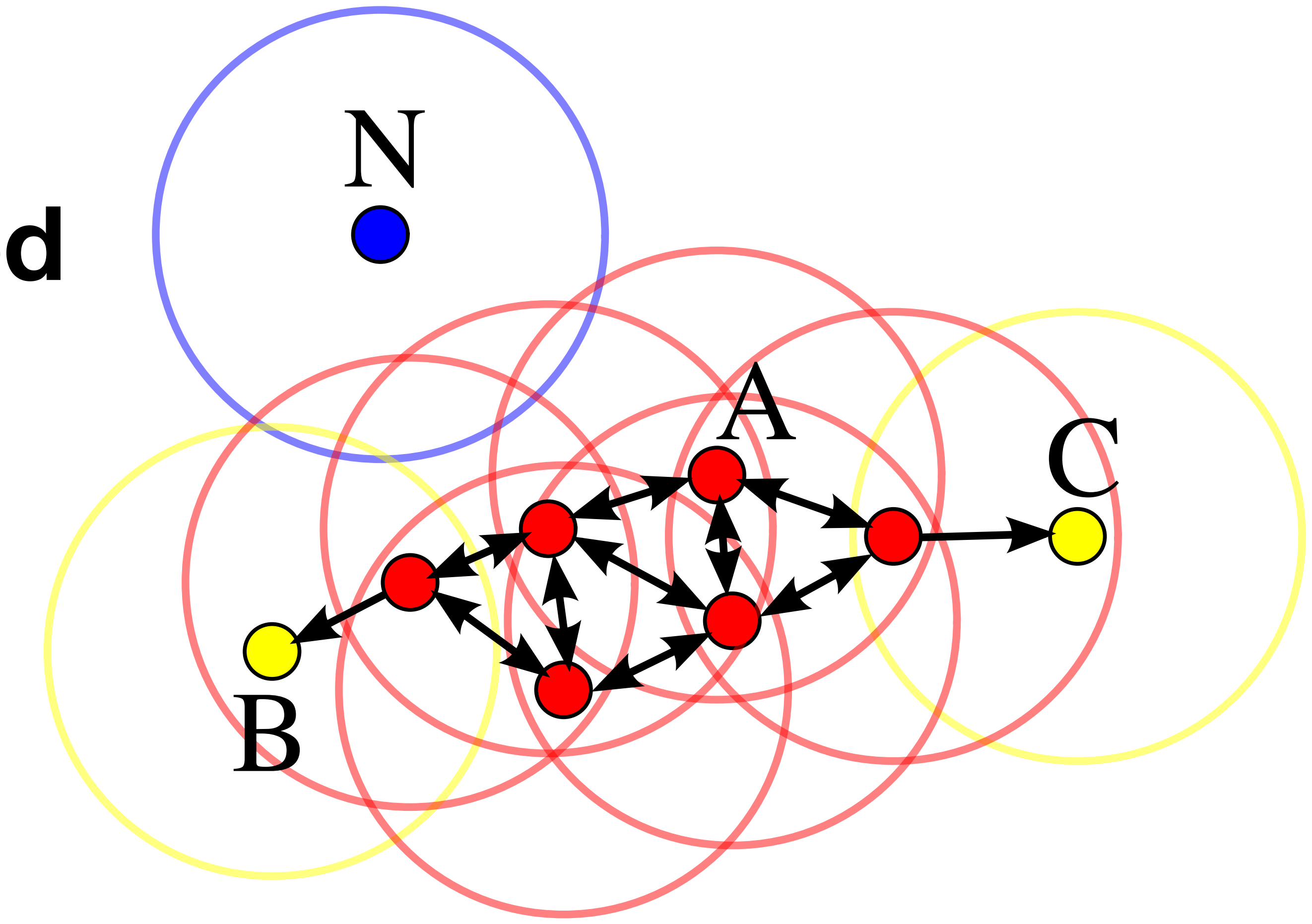
DT
(barrel)
hits

CSC
(endcap)
hits

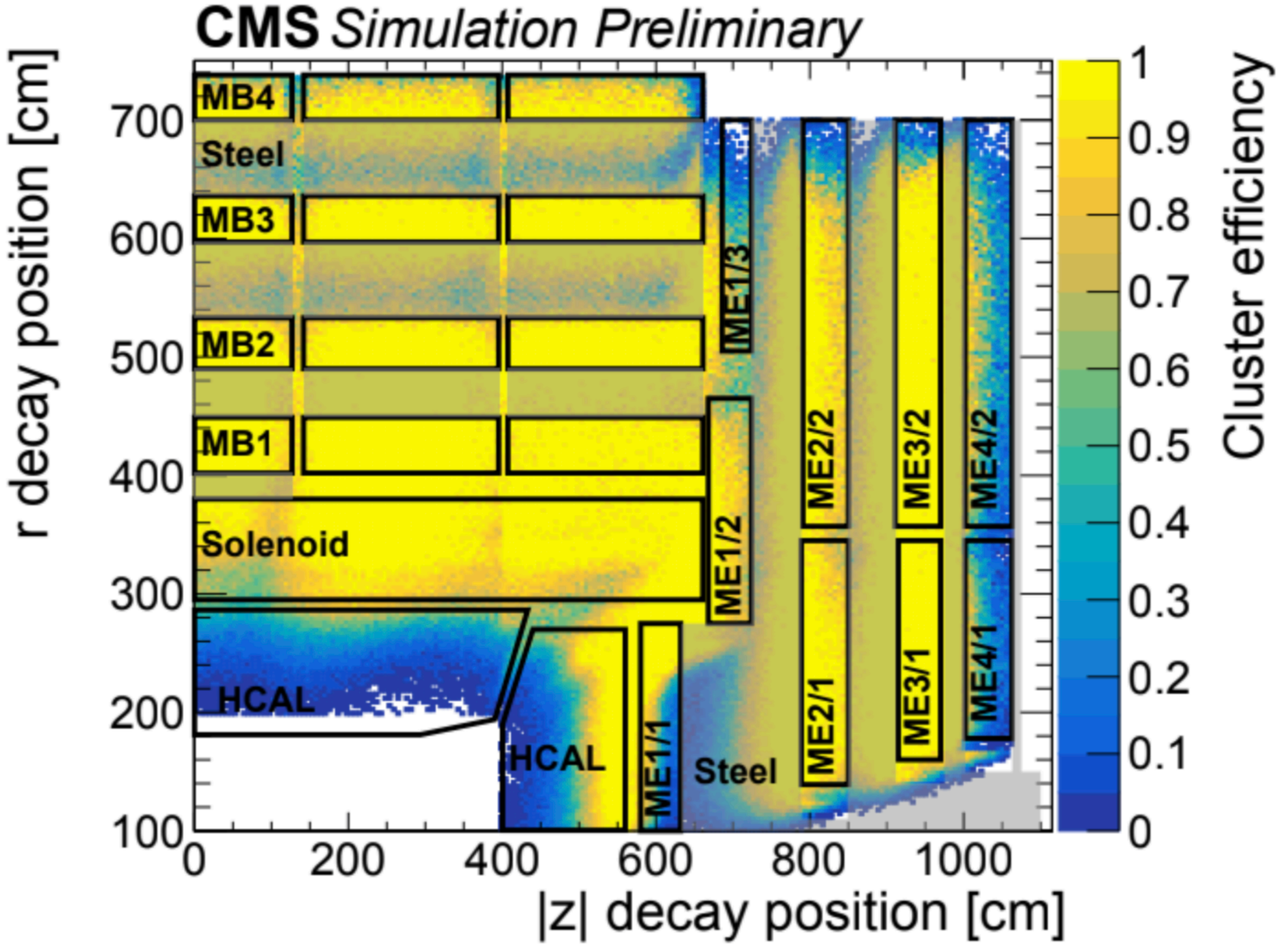


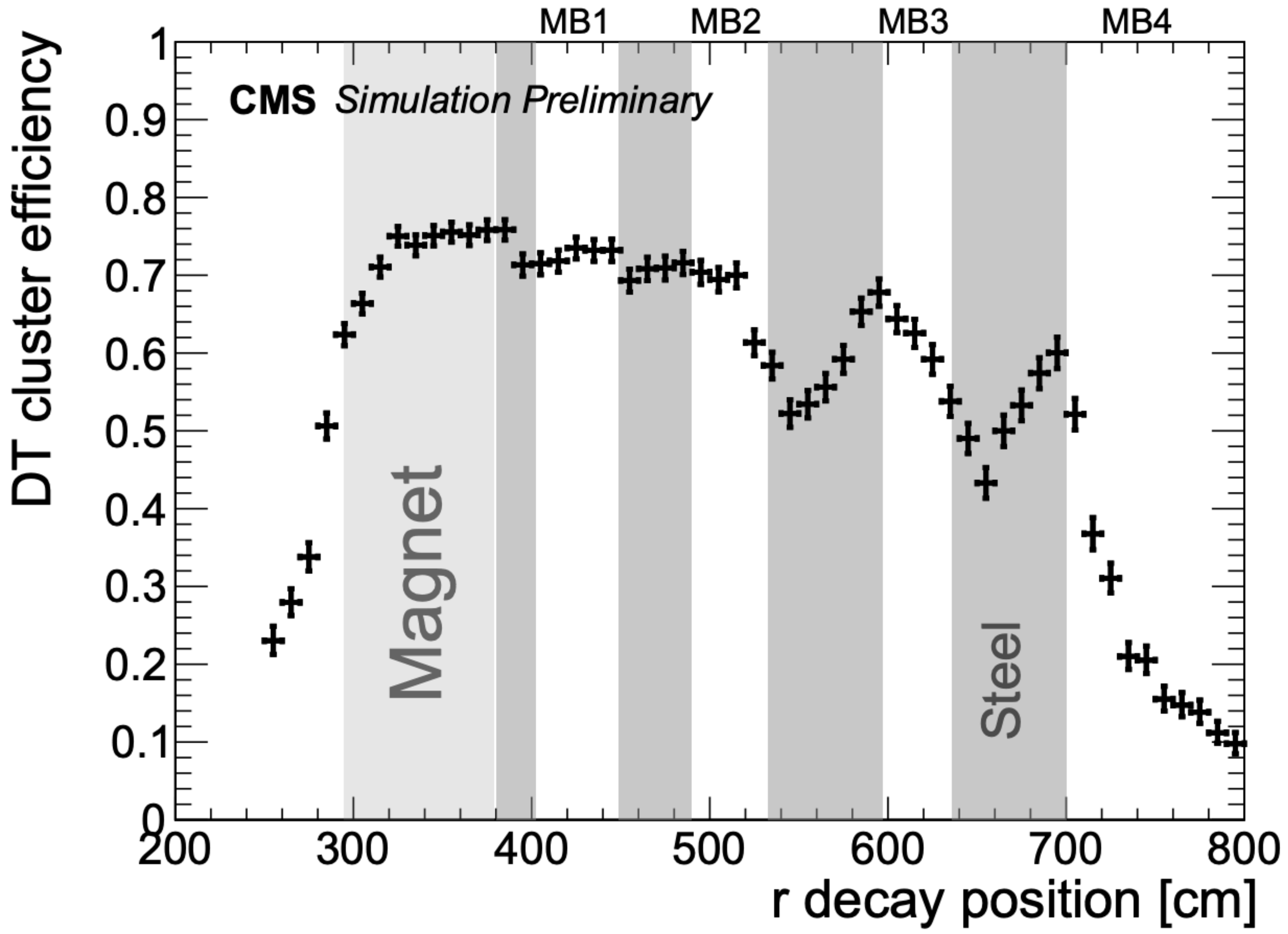
Cathode Strip Chamber (CSC) and Drift Tube (DT) rechits are **separately clustered** using **DBSCAN algorithm** on their η, ϕ positions (ΔR < 0.2, minimum 50 hits)

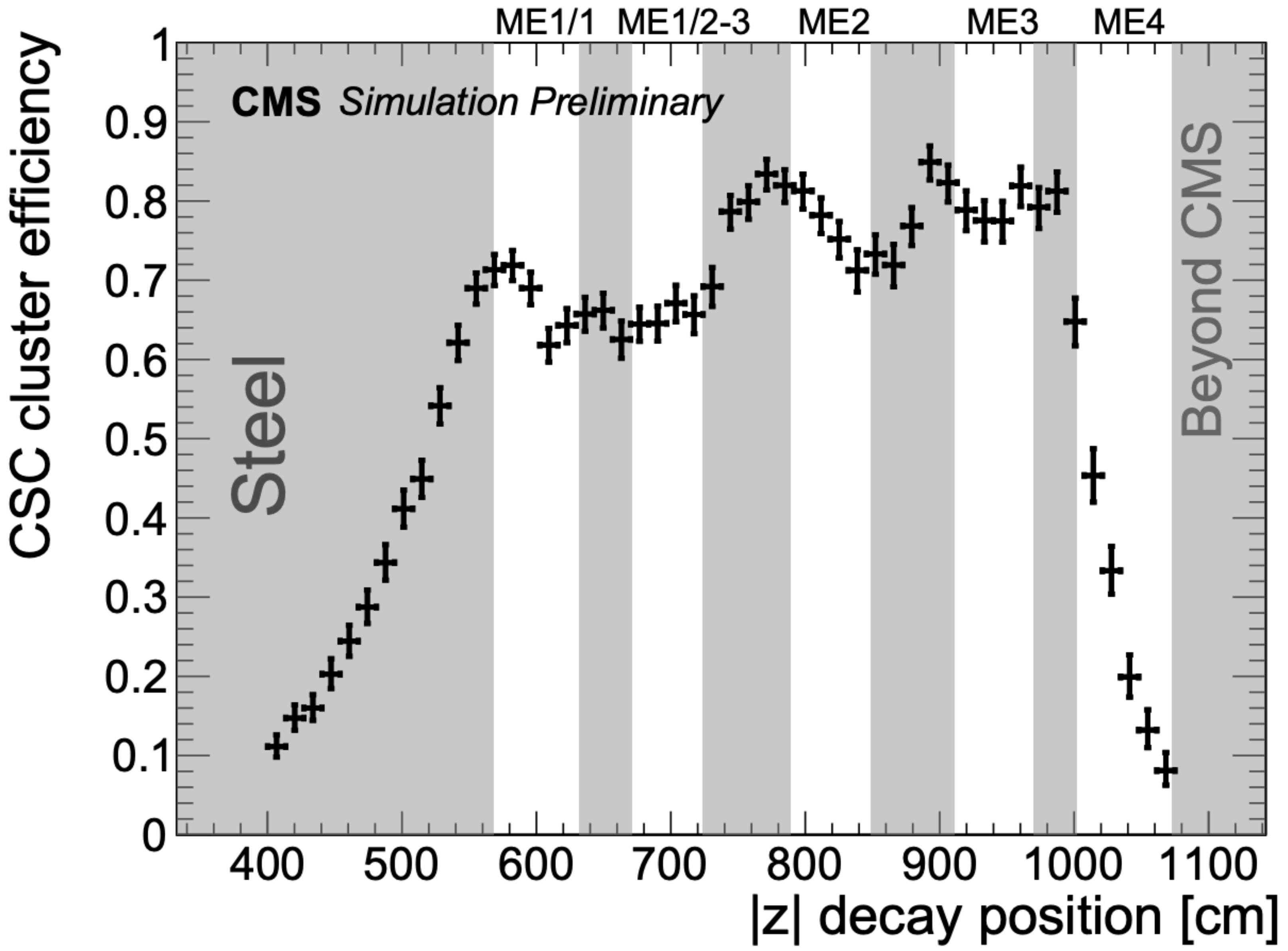
Algorithm clusters high-density regions and handles noise well



40 GeV $d\bar{d}$







Background Sources

- Muons
  - Bremsstrahlung can produce showers in muon system
  - Cosmic showers give high multiplicity, clusters in muon system

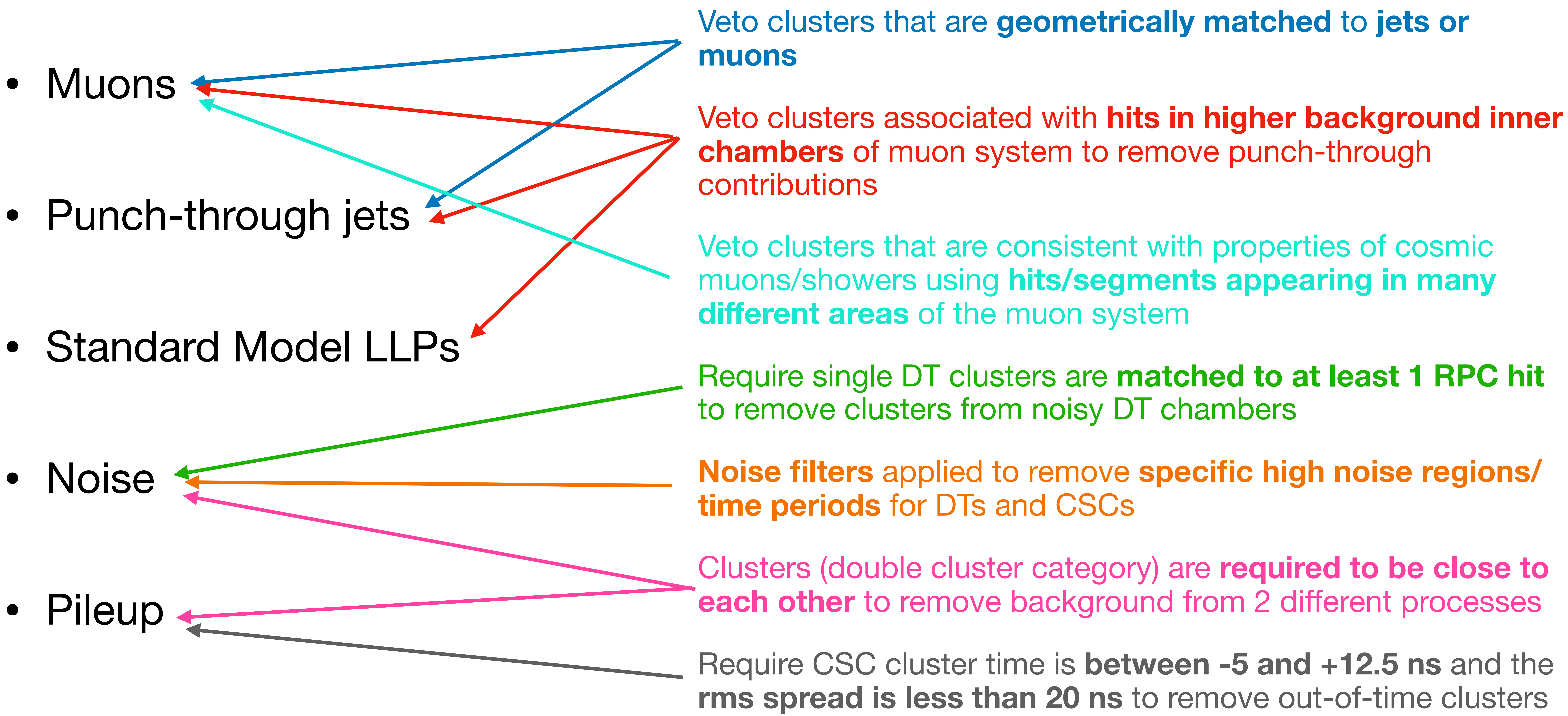
- Punch-through jets
  - Clusters can form in muon system if jet energy is not entirely contained in calorimeters

- Standard Model LLPs
  - Neutral kaon K_L^0 decays look like the signal model signature

- Noise
  - Noisy chambers can give enough hits to form clusters

- Pileup
  - Cluster and event properties can look signal-like due to pileup/out-of-time effects

Background Rejection



- Muons
- Punch-through jets
- Standard Model LLPs
- Noise
- Pileup

Veto clusters that are **geometrically matched** to **jets or muons**

Veto clusters associated with **hits in higher background inner chambers** of muon system to remove punch-through contributions

Veto clusters that are consistent with properties of cosmic muons/showers using **hits/segments appearing in many different areas** of the muon system

Require single DT clusters are **matched to at least 1 RPC hit** to remove clusters from noisy DT chambers

Noise filters applied to remove **specific high noise regions/ time periods** for DTs and CSCs

Clusters (double cluster category) are **required to be close to each other** to remove background from 2 different processes

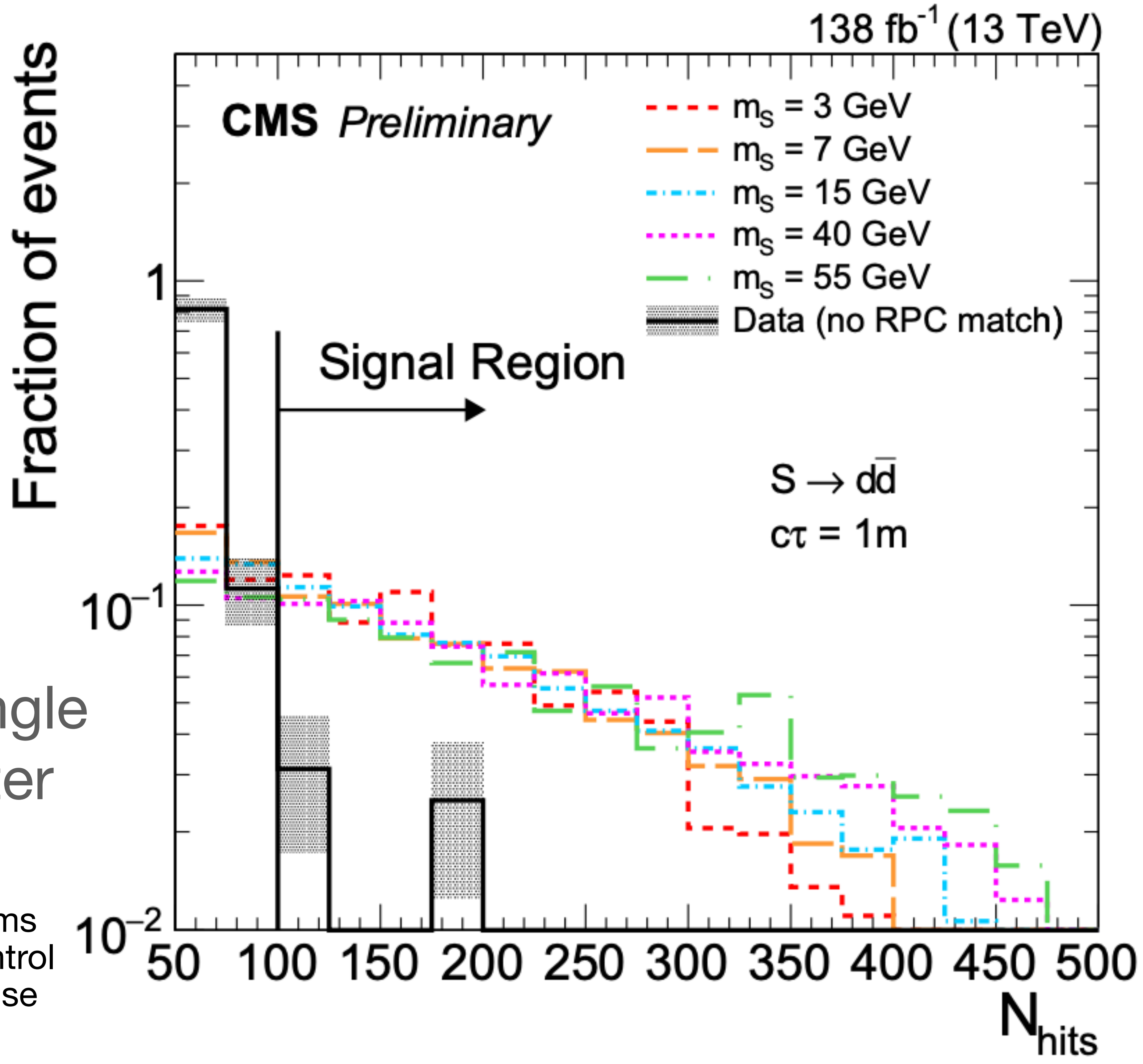
Require CSC cluster time is **between -5 and +12.5 ns** and the **rms spread is less than 20 ns** to remove out-of-time clusters

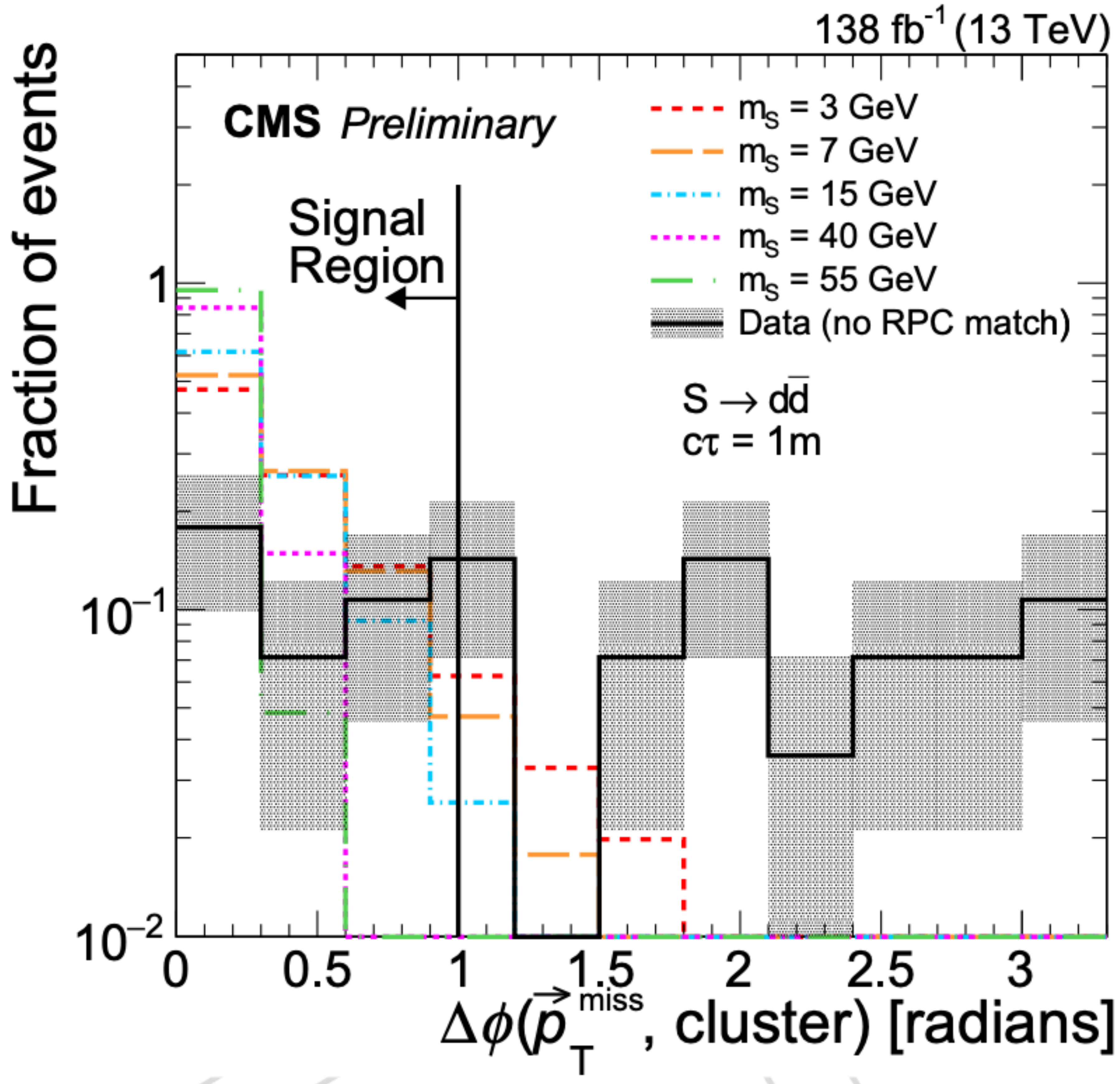
Background Rejection

Clusters required to have **large number of hits** since background cluster size falls off more rapidly

Clusters required to be aligned with the MET since they both come from the LLP

DT single cluster



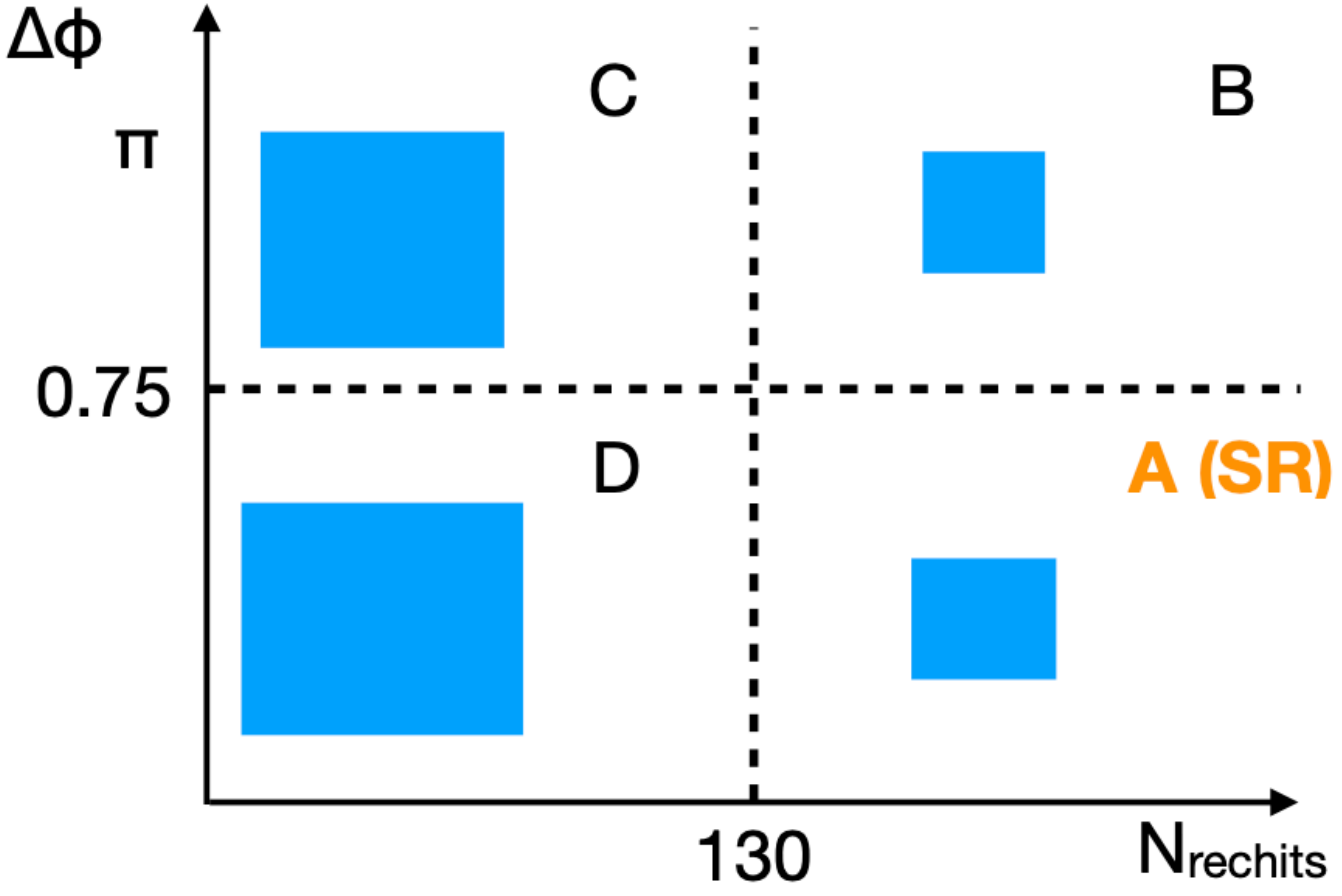


* Background histograms obtained through a control sample enriching in noise background in data

Uncorrelated Background Prediction

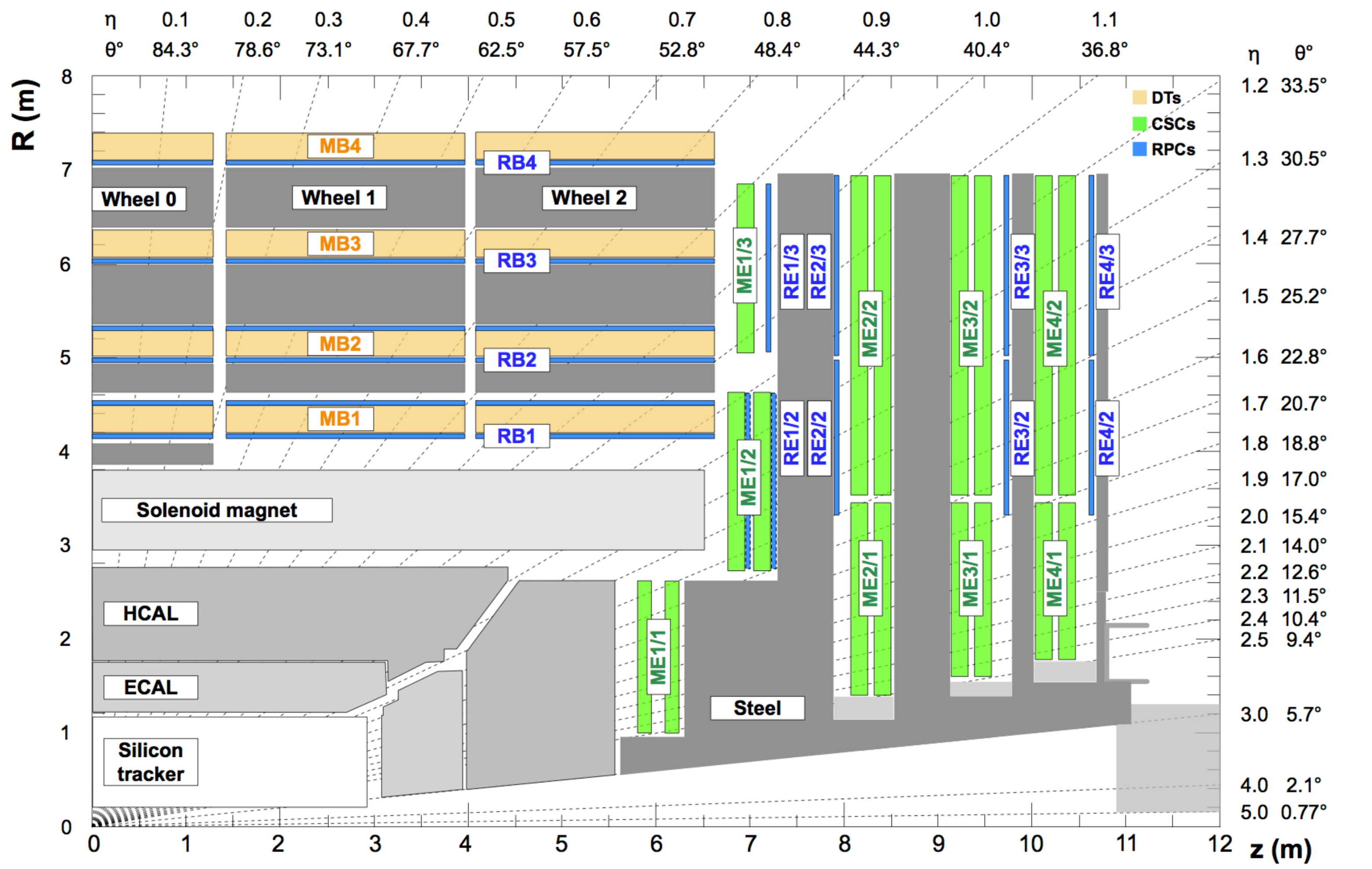
- Non punch-through background is predicted using **data-driven ABCD matrix method**: $\lambda_A = \lambda_B \times \lambda_D / \lambda_C$
- Single cluster signal regions use the **|Δϕ(cluster, MET)|, cluster size** plane to predict background since these are **uncorrelated for background** (noise, pileup)
- **Double cluster** signal regions use **only the cluster sizes**
- A modified matrix method prediction is used for the DT-DT and CSC-CSC categories

CSC single cluster



Correlated Background Prediction: Single DT Cluster

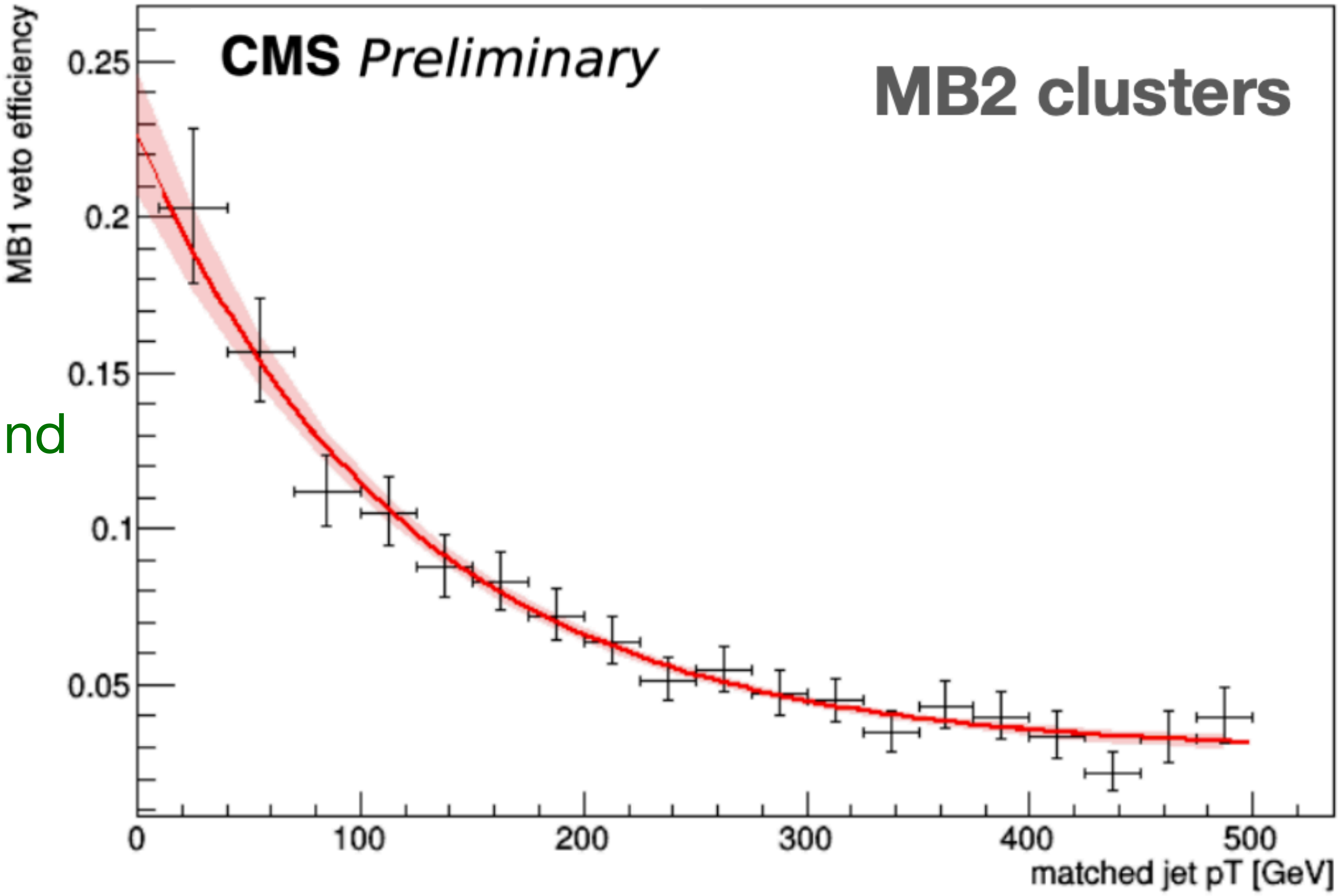
- There is a remaining **punch-through background that is unpredicted by the ABCD method** for the **single cluster DT category** and is a significant contribution to the signal region
- Correlated background is measured in a control region where clusters are matched to hits in inner muon barrel stations (MB1/MB2) in order to enrich in punch-through jet background
- Contribution to the signal region is estimated by measuring the **MB1/MB2 veto efficiency** in a control region where the **DT cluster is matched to a jet**



MB1/MB2 veto efficiency as a function of matched jet pT gives a way to **extrapolate from the inverted MB1/MB2 control region to the signal region** by predicting the veto efficiency for **clusters with matched jet pT < 10 GeV**

CR correlated background ⟶ SR correlated background

Cluster station	CR1	CR2	D2	D1 (pred.)
MB2	3878	222	22.4 ± 6.8	6.5 ± 2.1
MB3	293	21	7.4 ± 2.9	4.4 ± 2.2
MB4	36	1	2.0 ± 1.7	0.8 ± 0.9



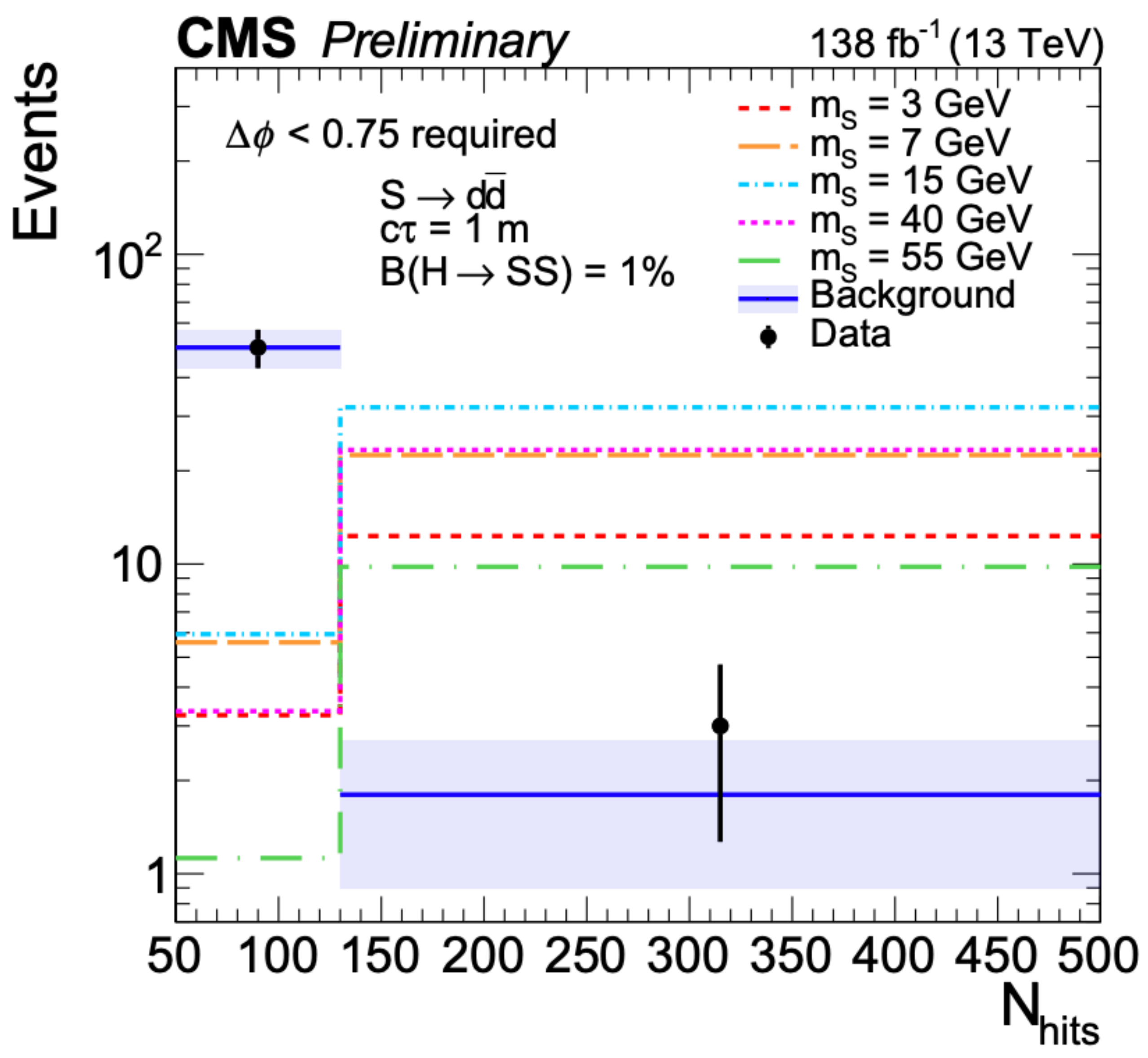
Background Summary

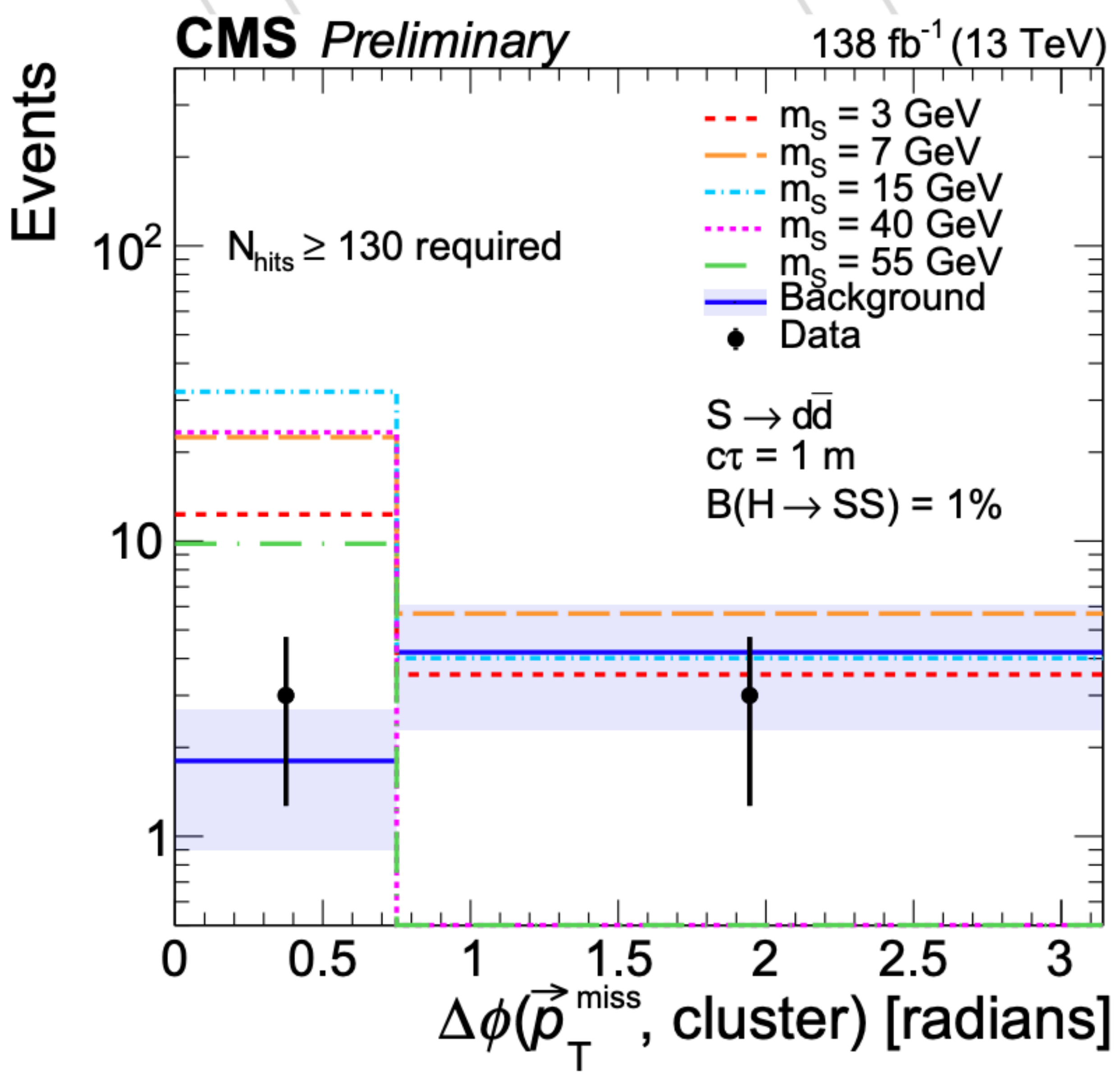
- ABCD (modified) matrix method used to predict uncorrelated background in the signal region
- DT single cluster has an additional correlated background prediction made by extrapolating from inverted MB1/MB2 veto CR to the signal regions
- All background prediction methods are validated in regions where the relevant backgrounds are enriched
- ABCD predictions have only statistical uncertainty on the number of observed events in each bin
- Correlated DT prediction uncertainty comes from statistical uncertainties on the observed number of events and predicted correlated background in the control region and uncertainties from the fit functions

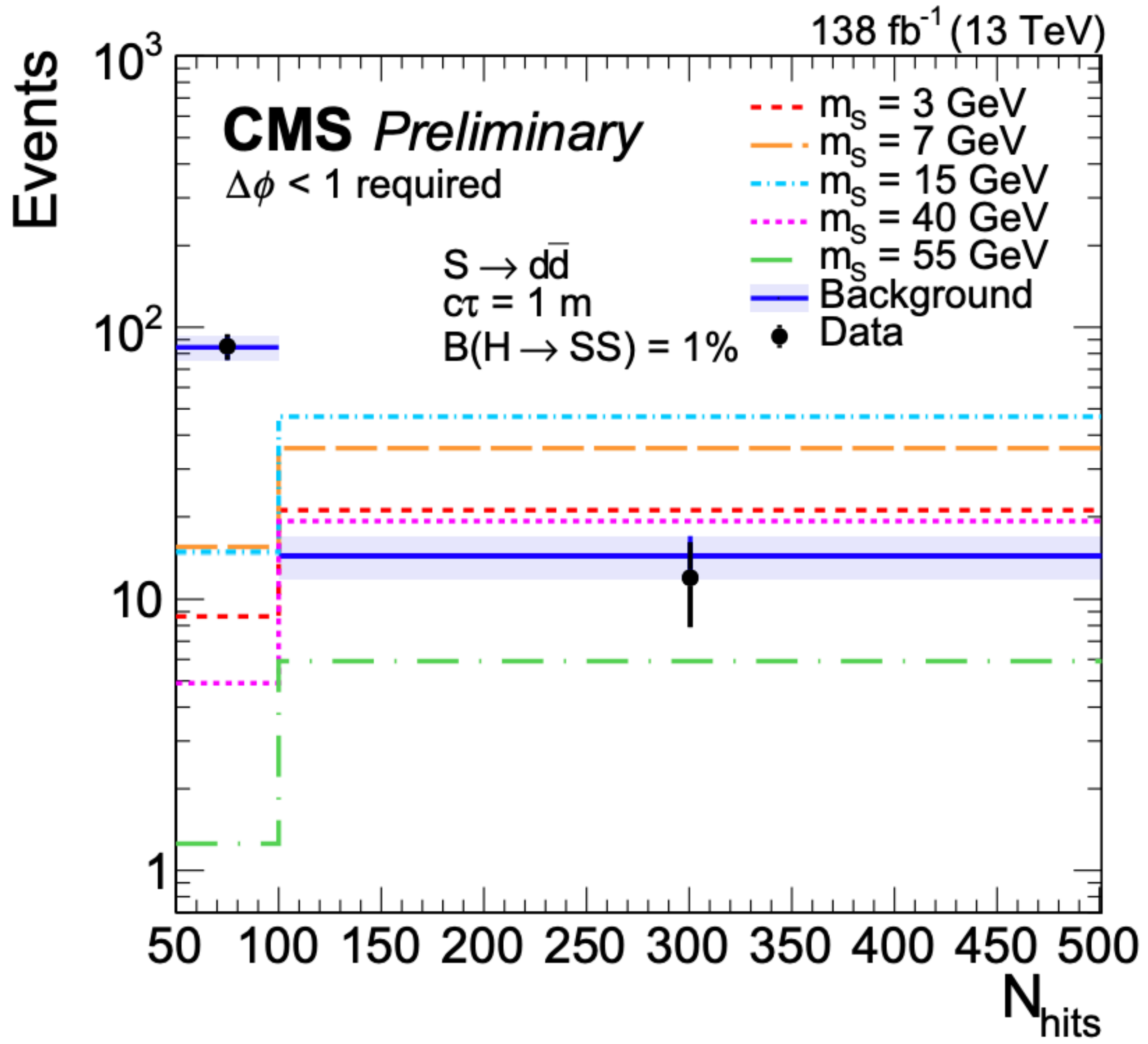
Signal Yield

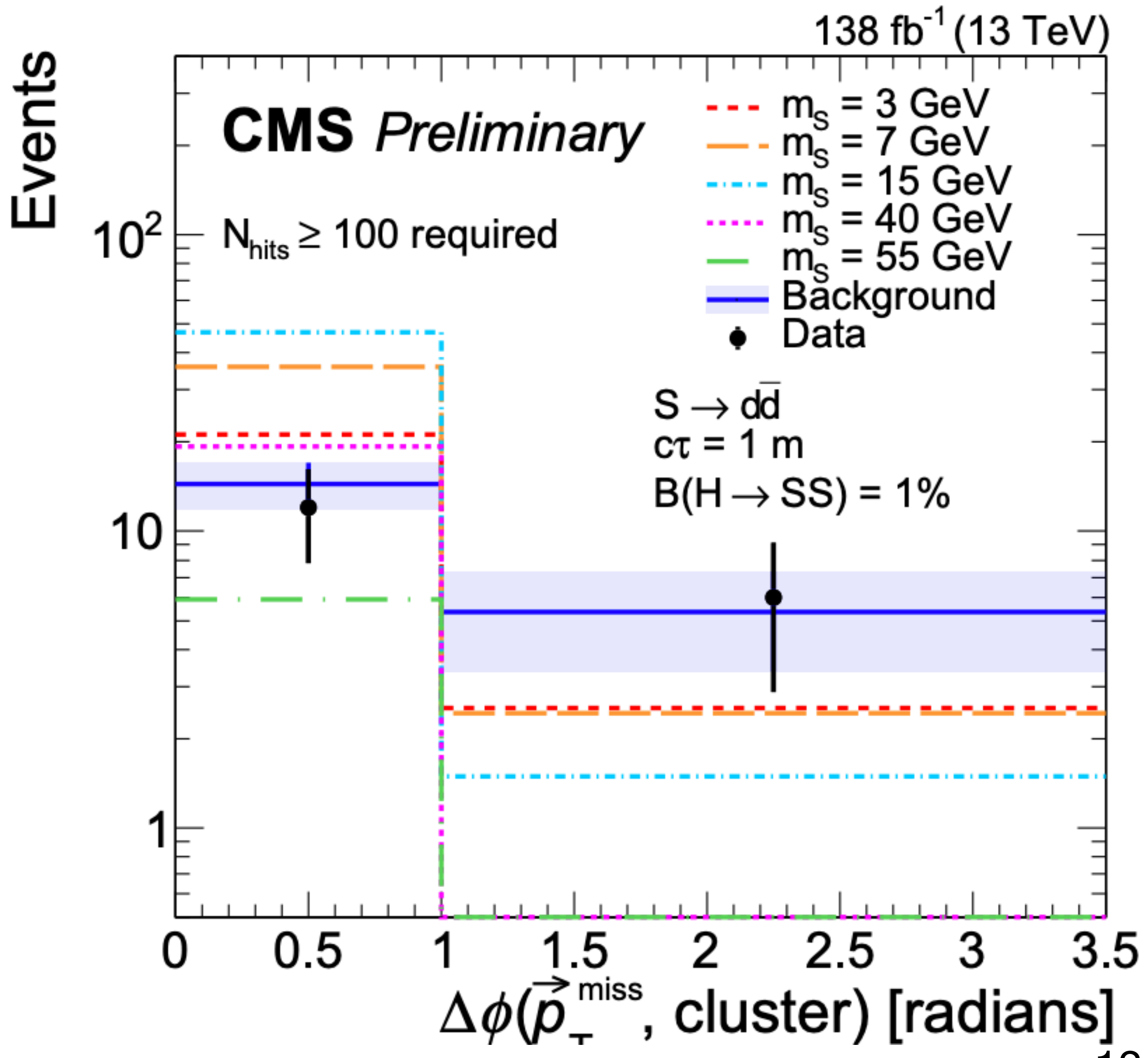
- **Total signal yield is ~20-100 events** (assuming BR(H→SS) = 1%) across 3 categories for various LLP masses, lifetimes, final states
  - At constant mass, single CSCs best at low, double clusters best at intermediate, DTs best at high lifetimes
  - At constant lifetime, DTs do better at low mass, CSCs do better at high mass
- **Largest signal inefficiency comes from MET requirements** (~1% efficiency), geometric acceptance/clustering efficiency (10-50%), single DT MB1/MB2 vetoes (10-50%)
- **Clusters from muon bremsstrahlung** in dimuon events are used as a proxy for signal and random sampling of detector positions is used to study veto efficiencies to **compare simulation and data**
- **Apply O(10%) corrections** to account for muon veto modeling (single CSC), MB1 and RPC rechit modeling (single DT)
- **Derive O(1-10%) uncertainties** due to DT cluster size modeling (single/double DT), clustering/ID efficiencies (single CSC), CSC cluster time spread (double CSC/CSC-DT)
- Other simulation-related uncertainties are all O(1%)
- Higher order corrections to Higgs pT shape, uncertainties on the cross section for each Higgs production method, and uncertainty on the parton distribution functions lead to **~10-20% theory uncertainty** on the signal yields

Results

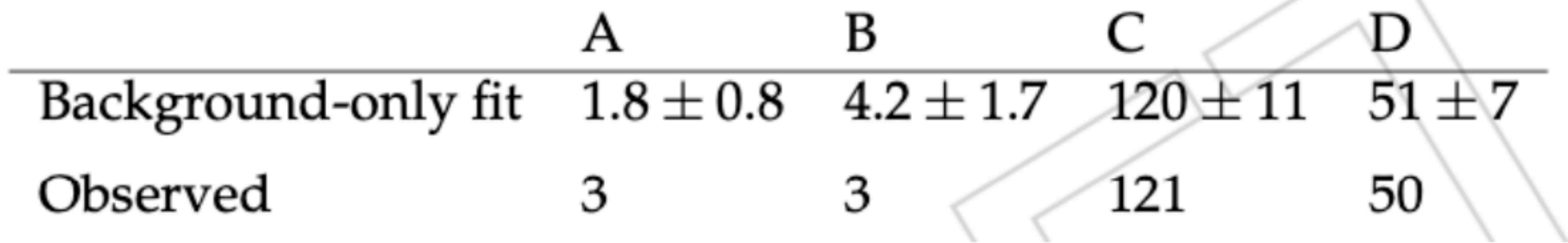








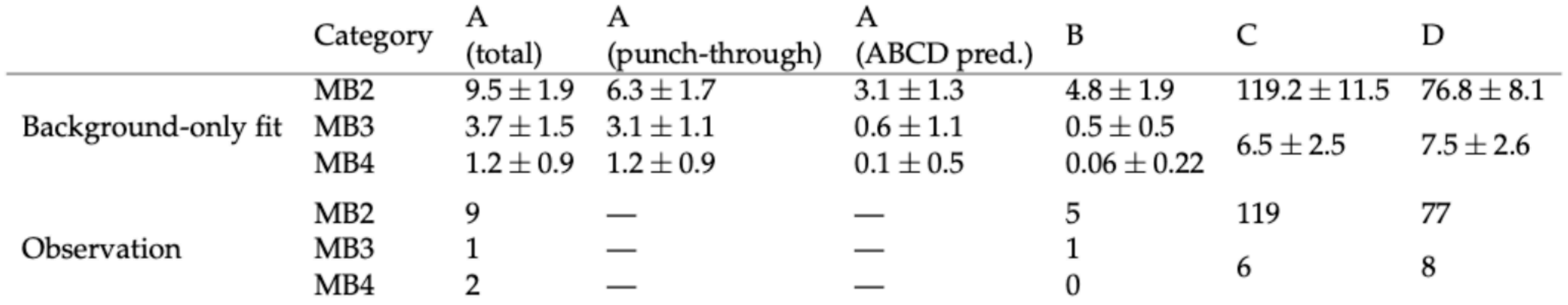
Single CSC cluster



	A	B	C	D
Background-only fit	1.8 ± 0.8	4.2 ± 1.7	120 ± 11	51 ± 7
Observed	3	3	121	50

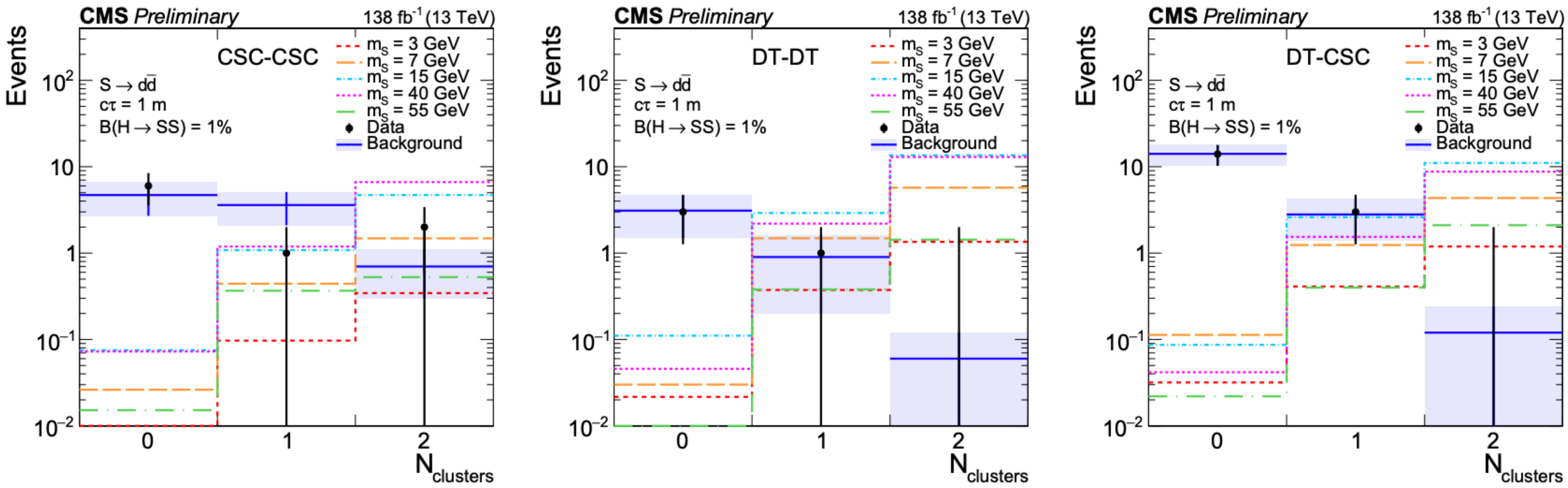
No excess above SM background observed in single CSC or single DT categories

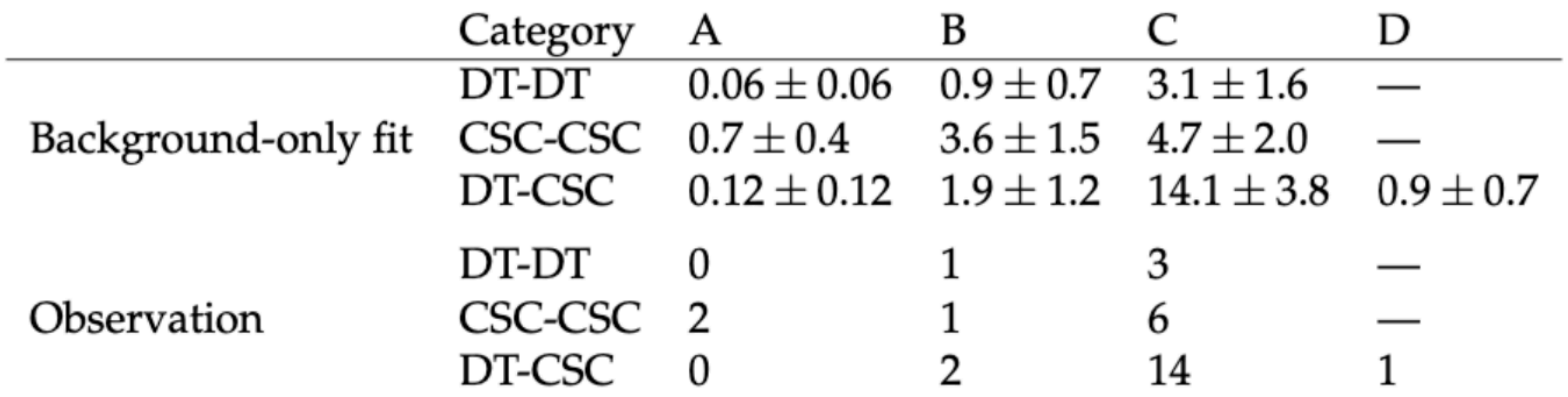
Single DT cluster



	Category	A (total)	A (punch-through)	A (ABCD pred.)	B	C	D
Background-only fit	MB2	9.5 ± 1.9	6.3 ± 1.7	3.1 ± 1.3	4.8 ± 1.9	119.2 ± 11.5	76.8 ± 8.1
	MB3	3.7 ± 1.5	3.1 ± 1.1	0.6 ± 1.1	0.5 ± 0.5	6.5 ± 2.5	7.5 ± 2.6
	MB4	1.2 ± 0.9	1.2 ± 0.9	0.1 ± 0.5	0.06 ± 0.22		
Observation	MB2	9	—	—	5	119	77
	MB3	1	—	—	1	6	8
	MB4	2	—	—	0		

Signal Region

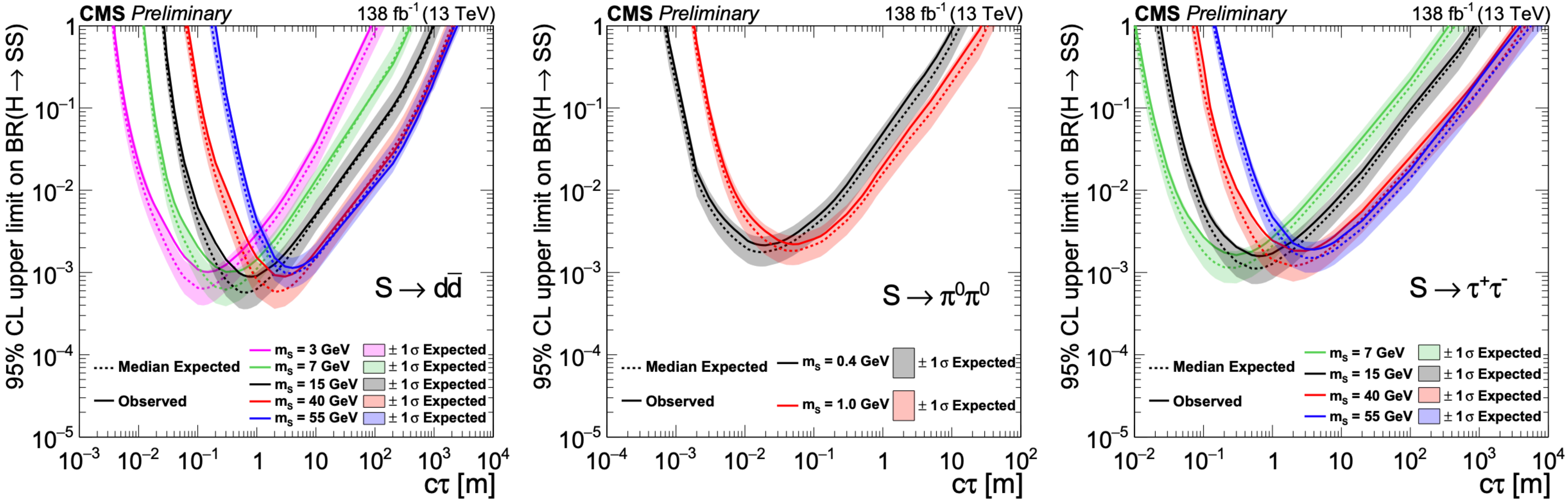




	Category	A	B	C	D
Background-only fit	DT-DT	0.06 ± 0.06	0.9 ± 0.7	3.1 ± 1.6	—
	CSC-CSC	0.7 ± 0.4	3.6 ± 1.5	4.7 ± 2.0	—
	DT-CSC	0.12 ± 0.12	1.9 ± 1.2	14.1 ± 3.8	0.9 ± 0.7
Observation	DT-DT	0	1	3	—
	CSC-CSC	2	1	6	—
	DT-CSC	0	2	14	1

No excess above SM background observed in any of the double cluster categories

Observed Limits

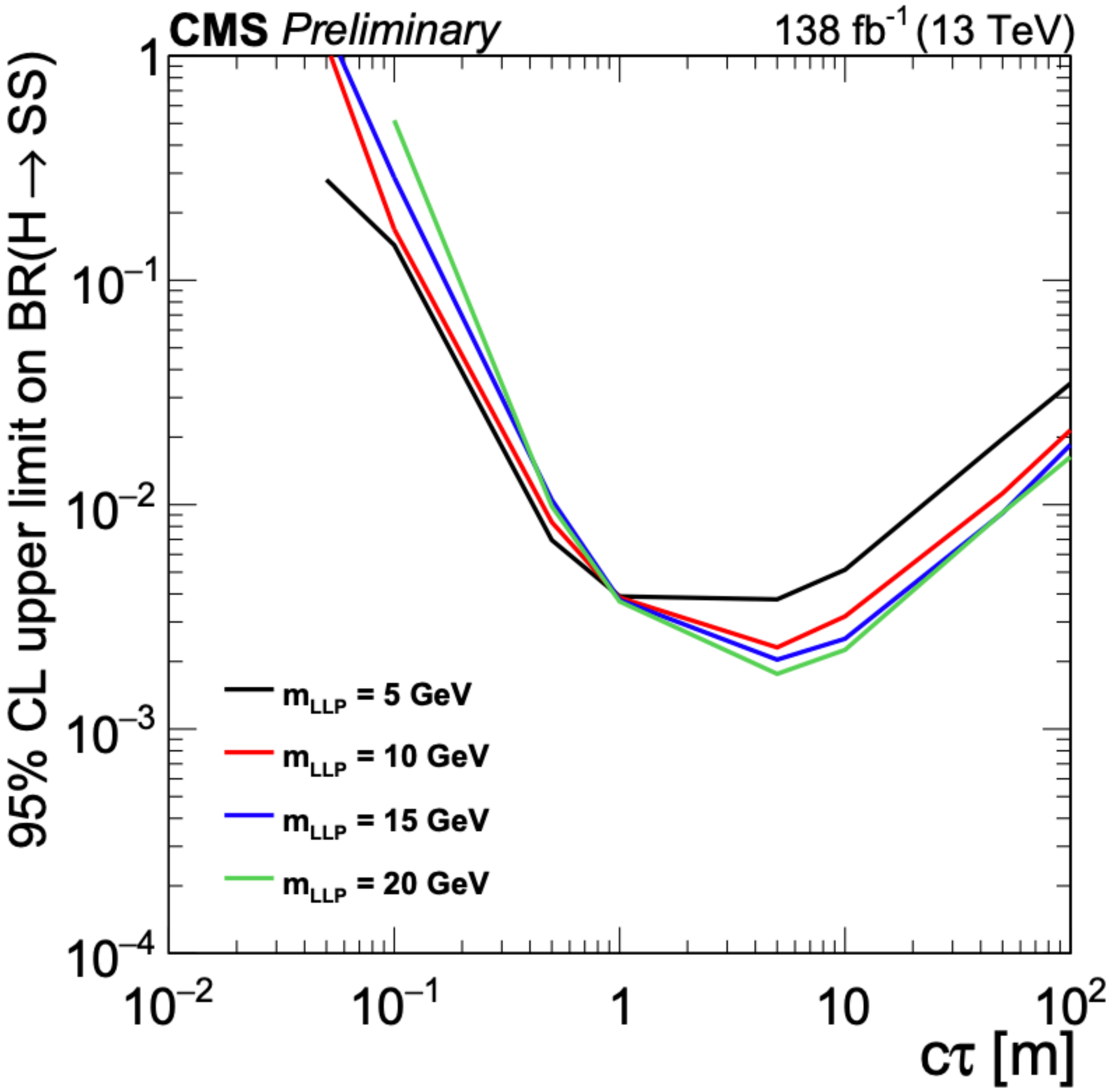


- Given no excess observed, we can set **upper limits on the Higgs BR to LLPs** for a variety of final states with different shower properties (hadronic, EM, both)
- Sensitive to LLP masses **below 1 GeV up to 55 GeV** across a wide range of lifetimes at **10^{-3} level**

Observed Limits

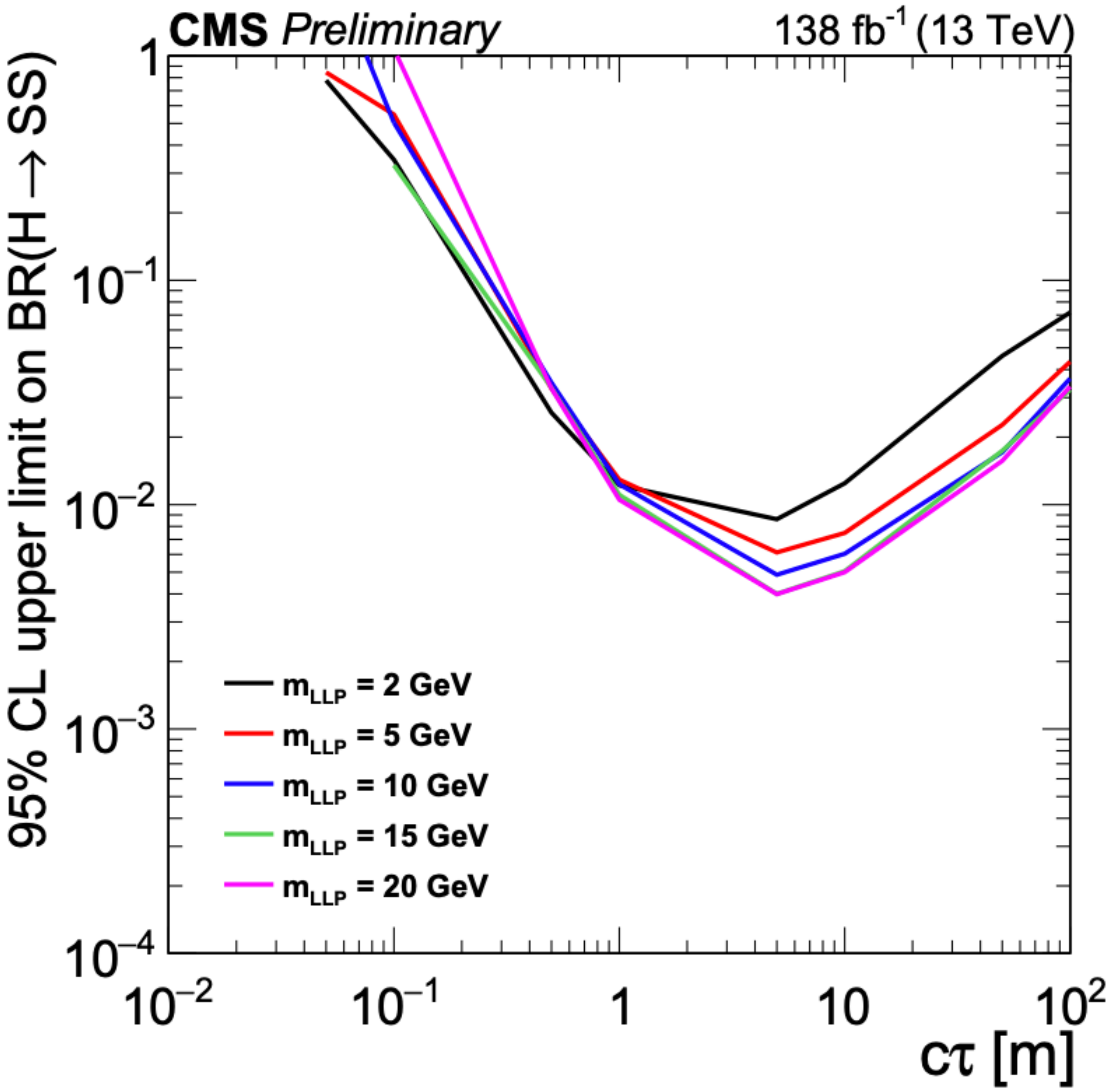
Gluon portal (hadronic shower)

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



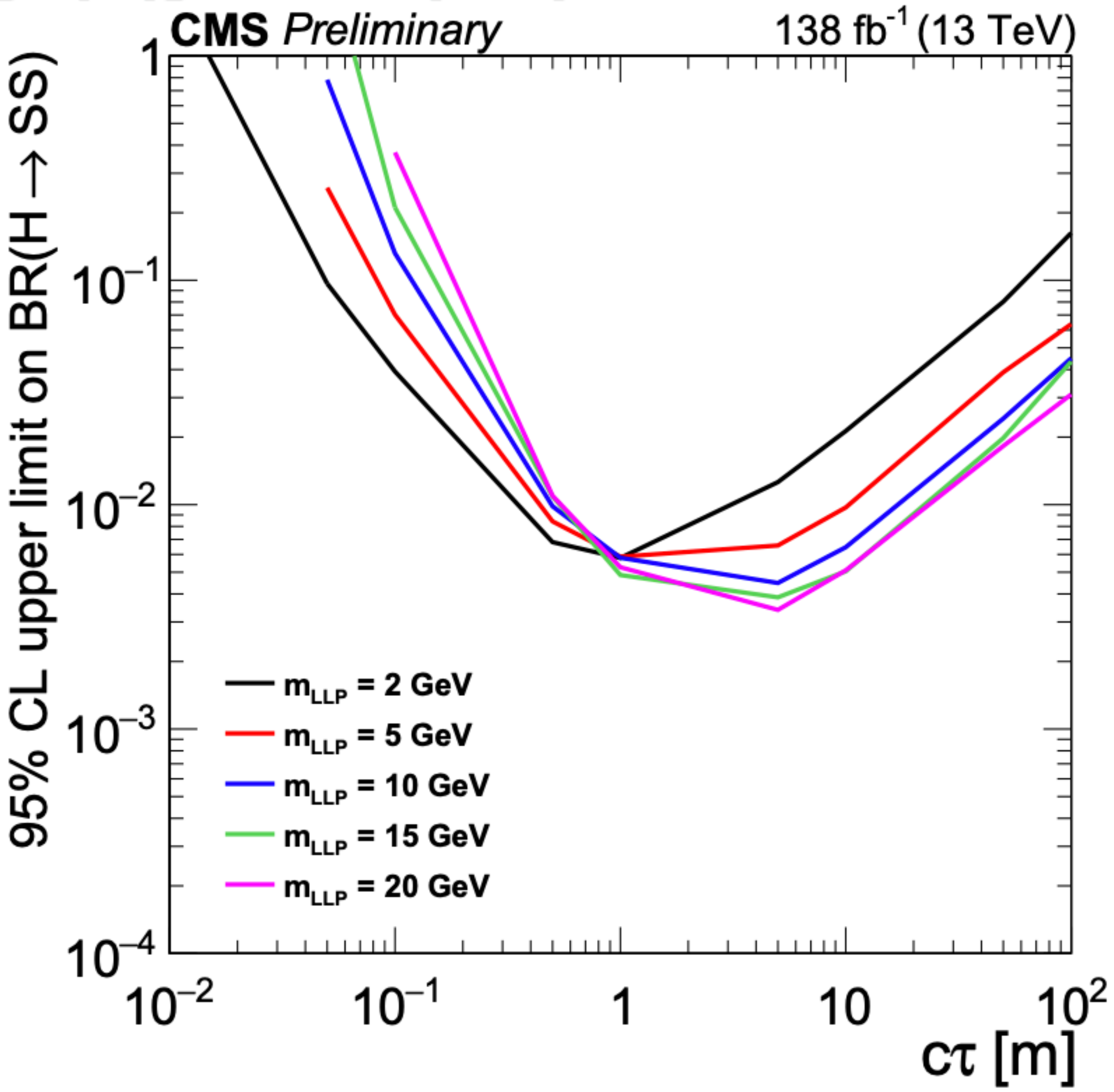
Photon portal (photon shower)

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



Vector portal (semi-visible shower)

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



- First interpretation of **dark shower model coupled to Higgs**
- Sensitive to **various LLP masses and lifetimes** with **different phenomenologies**

Summary

- Presented search for long-lived particles using clusters of hits in muon system using full CMS Run 2 dataset

- Single cluster DT and double cluster categories allow significant extension of search using single CSC clusters only
  - Up to 2x improvement in limits in peak sensitivity region and large lifetimes
  - New interpretations of Twin Higgs final states and LLP masses
  - First interpretation of dark shower model coupled to Higgs

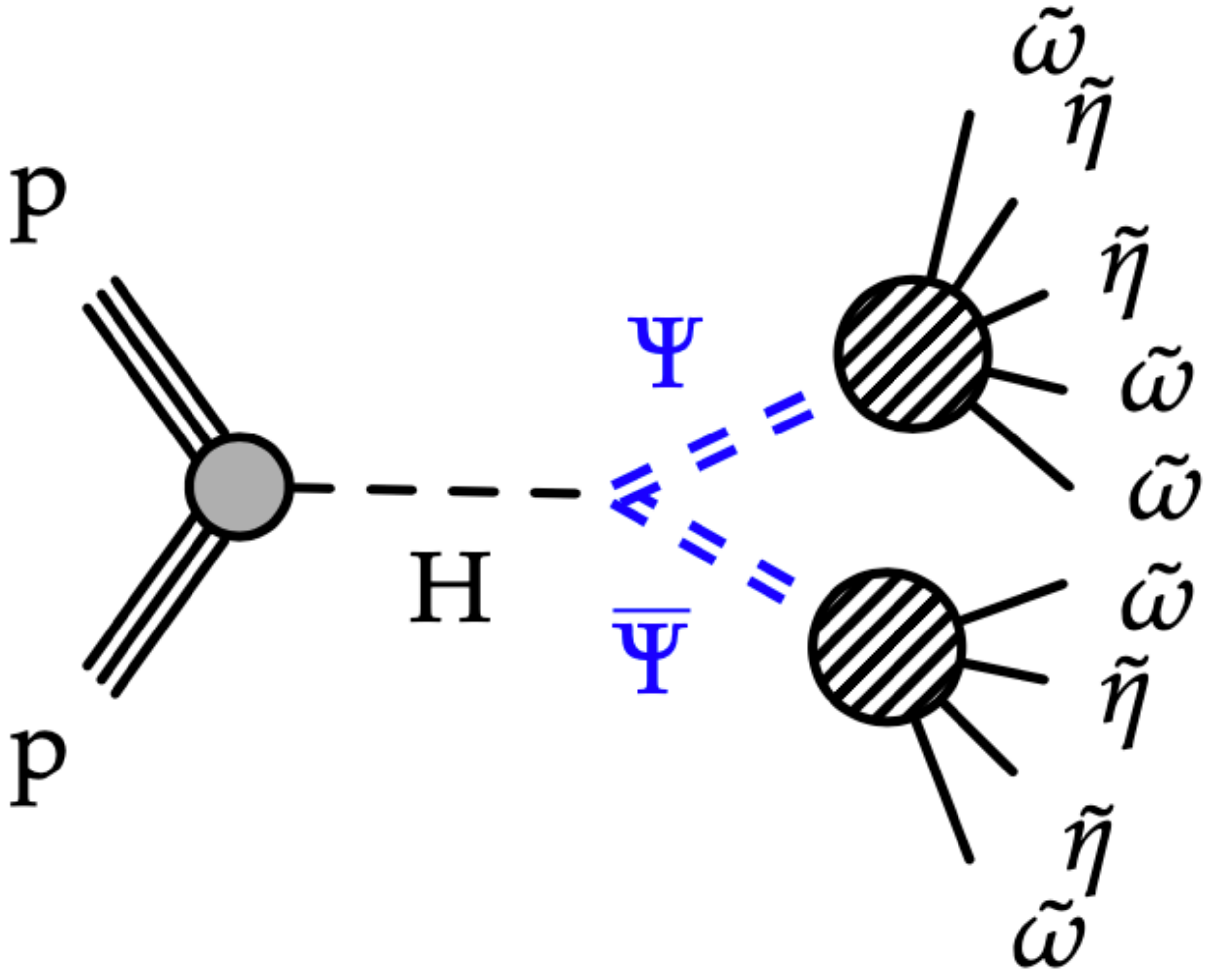
- Limits show sensitivity to LLPs with wide mass/lifetime range with variety of shower signatures

- Method provides exciting opportunities for Run 3 where dedicated triggers will allow searches for this and other LLP signatures

Backup

Dark Shower Signal Model

- Dark sector added to SM consisting of single dark quark, scalar meson η, vector meson ω
- 5 different portals from dark sector to SM considered which lead to different shower features
- For all portals except vector, η couples to SM and ω is invisible (MET) while for vector portal ω couples to SM and η is invisible (MET)
- Previous searches with emerging jets signatures targeted heavy (TeV) mediators, while we can be sensitive to this model with much lighter mediators
- Three hierarchies (x_Ω,x_Λ) setting the ratio of masses and dark QCD scale:
  - (1,1) - semi-visible
  - (2.5, 1) - fully visible (except vector portal)
  - (2.5, 2.5) - fully visible (except vector portal), high multiplicity



Parameters: m_ω, m_η, lifetime of meson coupling to SM, decay portal

Decay portal	decay operator	VDP	other dark hadron	features
A. gluon portal	$\tilde{\eta} G^{\mu\nu} \tilde{G}_{\mu\nu}$	$\tilde{\eta}$	$\tilde{\omega}$ stable or $\tilde{\omega} \to \tilde{\eta}\tilde{\eta}$	hadron-rich shower
B. photon portal	$\tilde{\eta} F^{\mu\nu} \tilde{F}_{\mu\nu}$	$\tilde{\eta}$	$\tilde{\omega}$ stable or $\tilde{\omega} \to \tilde{\eta}\tilde{\eta}$	photon shower
C. vector portal	$\tilde{\omega}^{\mu\nu} F_{\mu\nu}$	$\tilde{\omega}$	$\tilde{\eta}$ stable	semi-visible jet
D. Higgs portal	$\tilde{\eta} H^\dagger H$	$\tilde{\eta}$	$\tilde{\omega}$ stable or $\tilde{\omega} \to \tilde{\eta}\tilde{\eta}$	heavy flavor-rich shower
E. dark photon portal	$\tilde{\eta} F'^{\mu\nu} \tilde{F}'_{\mu\nu} + \epsilon F'^{\mu\nu} F_{\mu\nu}$	A'	$\tilde{\omega}$ stable or $\tilde{\omega} \to \tilde{\eta}\tilde{\eta}$	lepton-rich shower

From paper by Simon Knapen, Jessie Shelton, Dong Xu

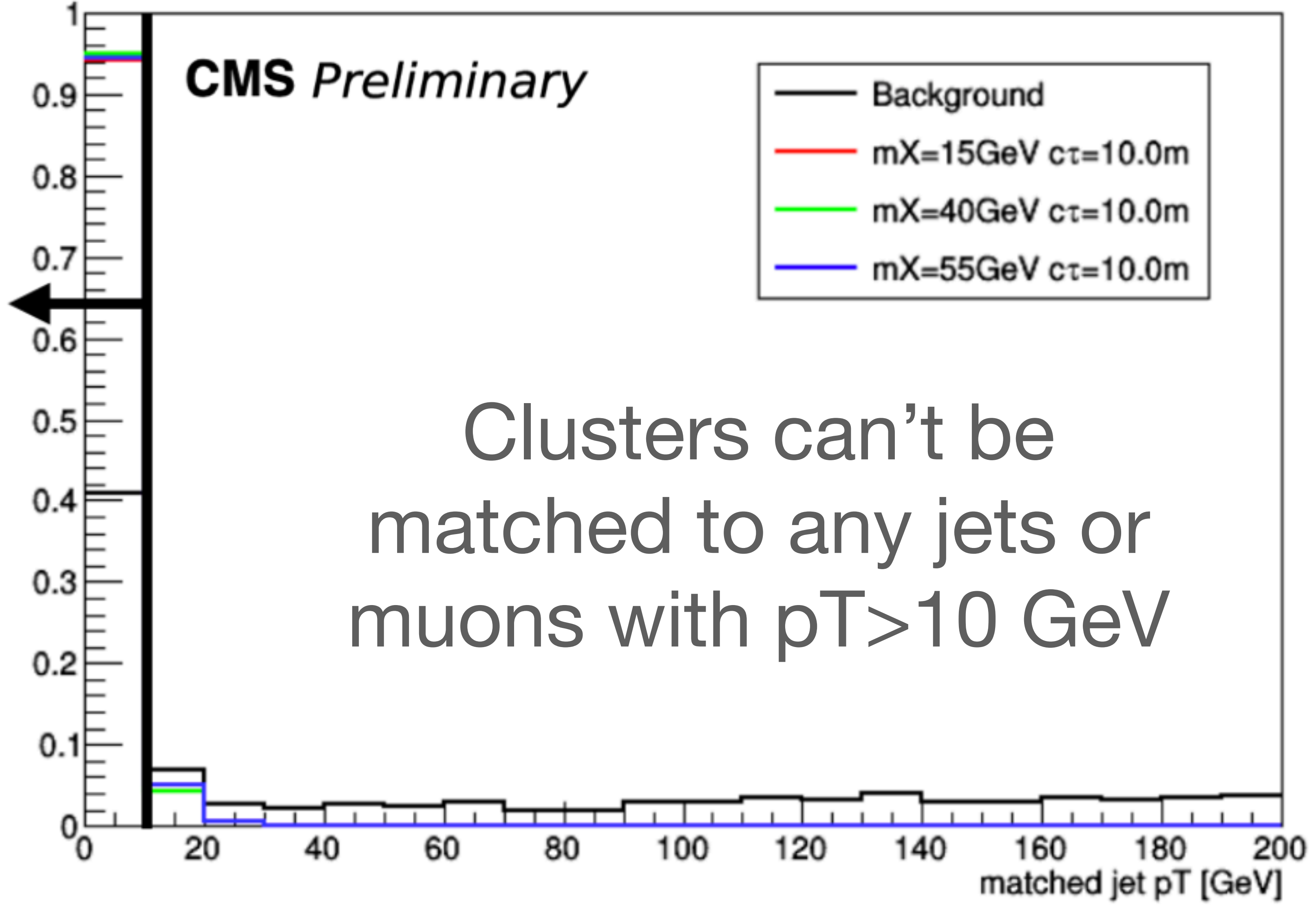
https://arxiv.org/pdf/2103.01238.pdf

Background Rejection

Veto clusters that are **geometrically matched** (ΔR < 0.4) to **any jets or muons**

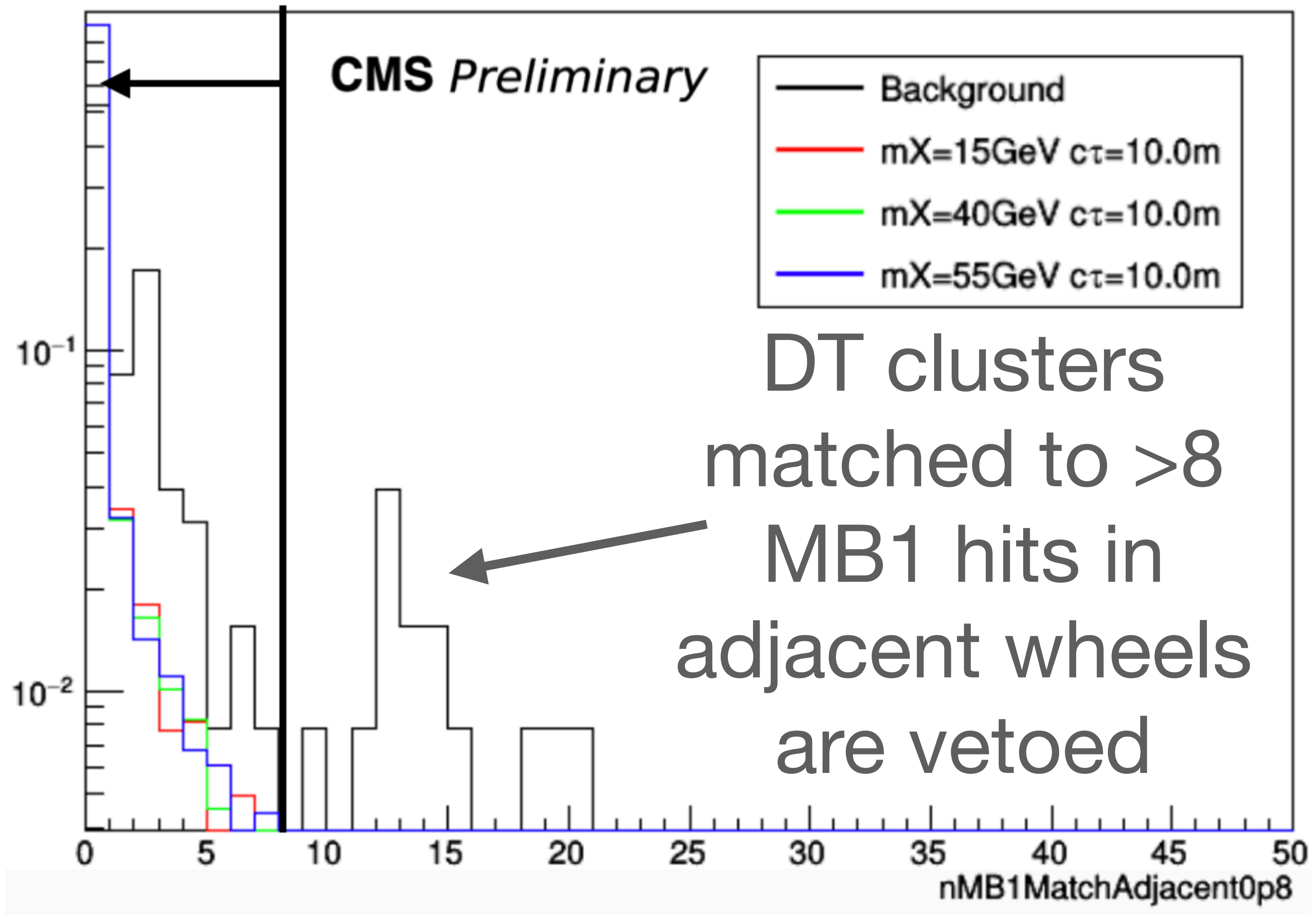
DT single cluster: veto cluster within ΔR < 1.2 of **leading pT jet**

DT single cluster



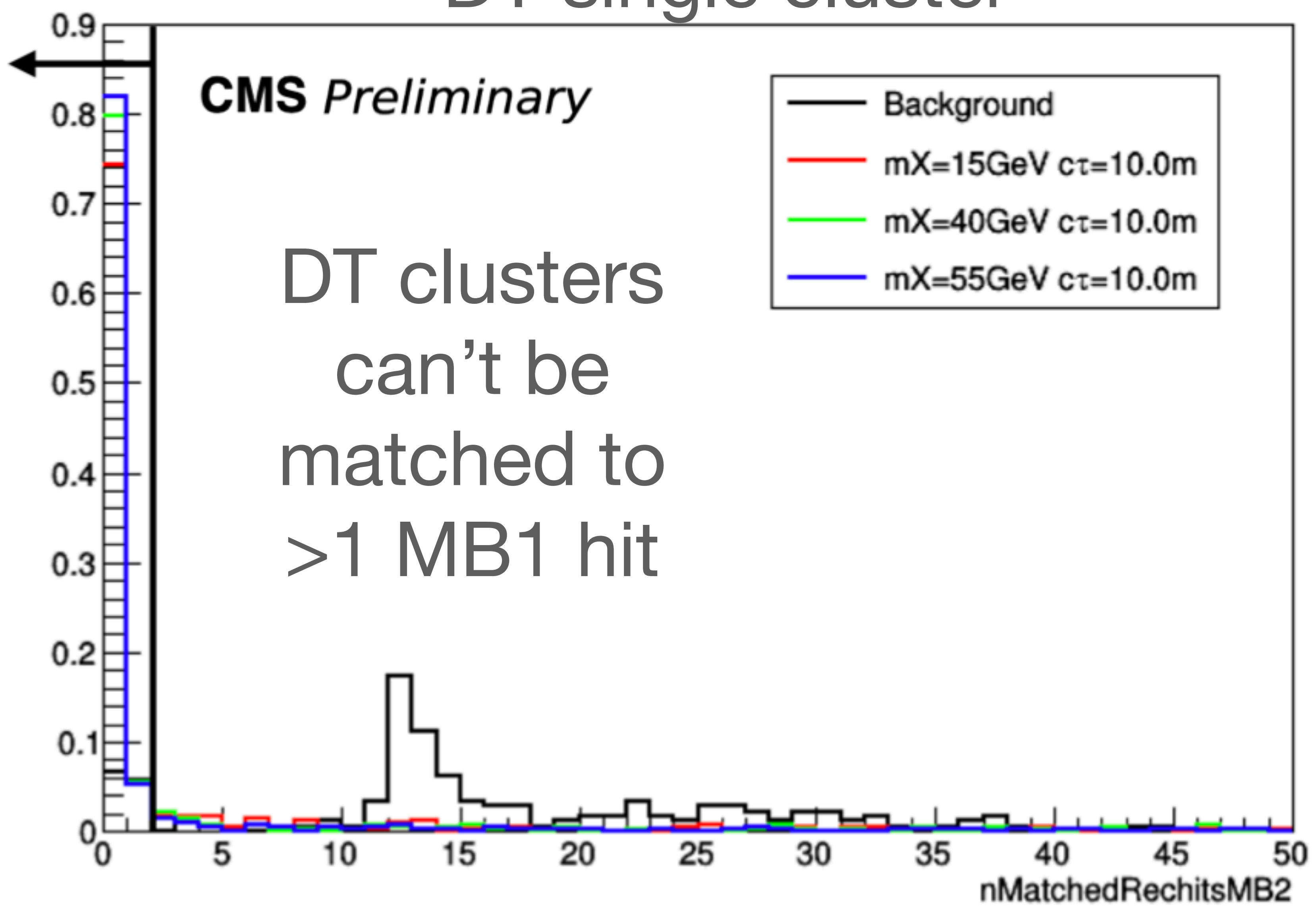
Clusters can't be matched to any jets or muons with pT>10 GeV

DT single cluster



DT clusters matched to >8 MB1 hits in adjacent wheels are vetoed

DT single cluster



DT clusters can't be matched to >1 MB1 hit

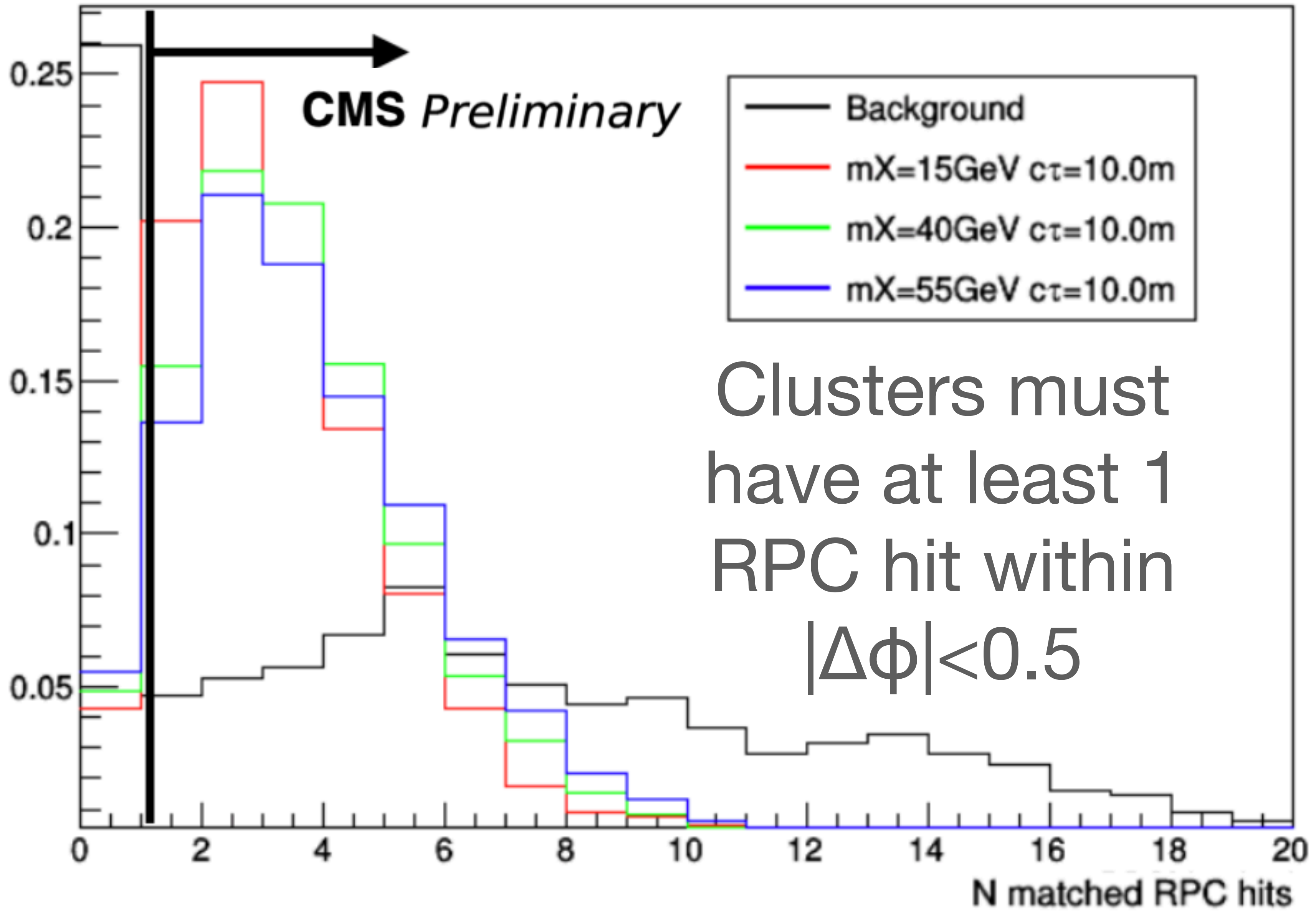
Veto clusters associated with **hits in higher background inner chambers** of muon system to remove punch-through contributions

* Background histograms obtained through a control sample enriching in pileup background in data

Background Rejection

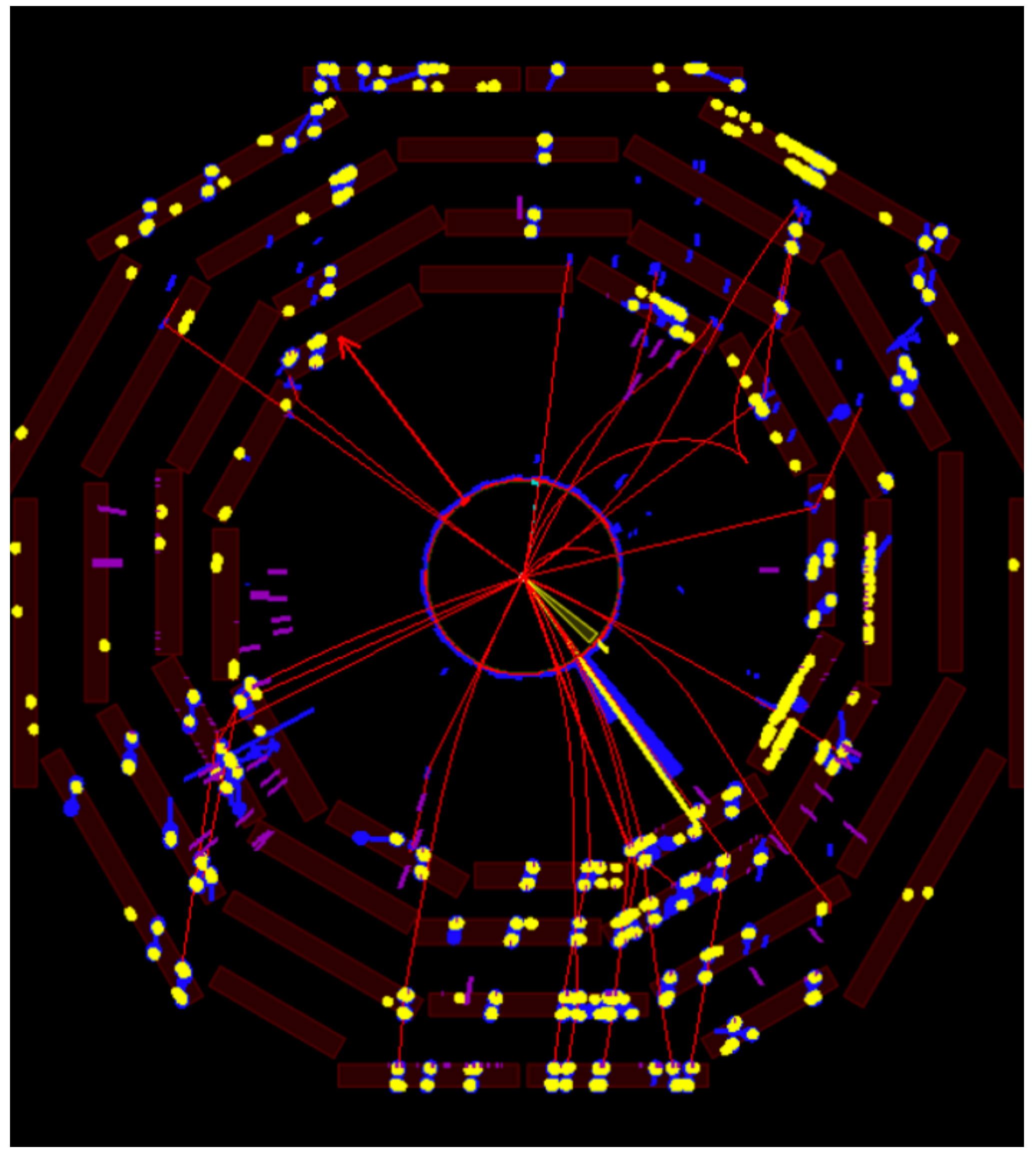
Veto clusters that are consistent with properties of cosmic muons/showers using **hits/segments appearing in many different areas** of the muon system

DT single cluster

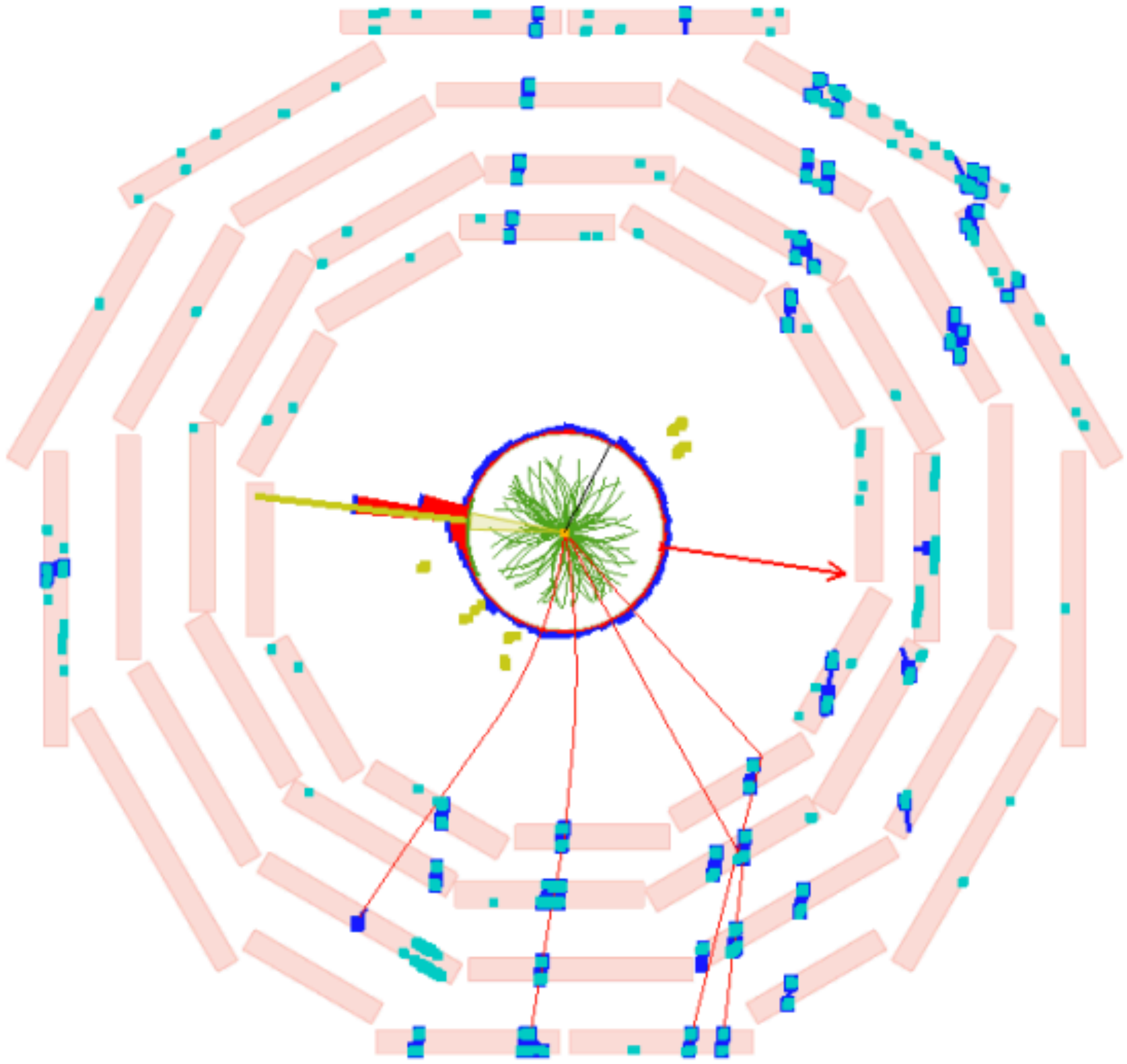


Clusters must have at least 1 RPC hit within $|\Delta\phi|<0.5$

Example DT single cluster cosmic shower event



Example DT double cluster cosmic muon event

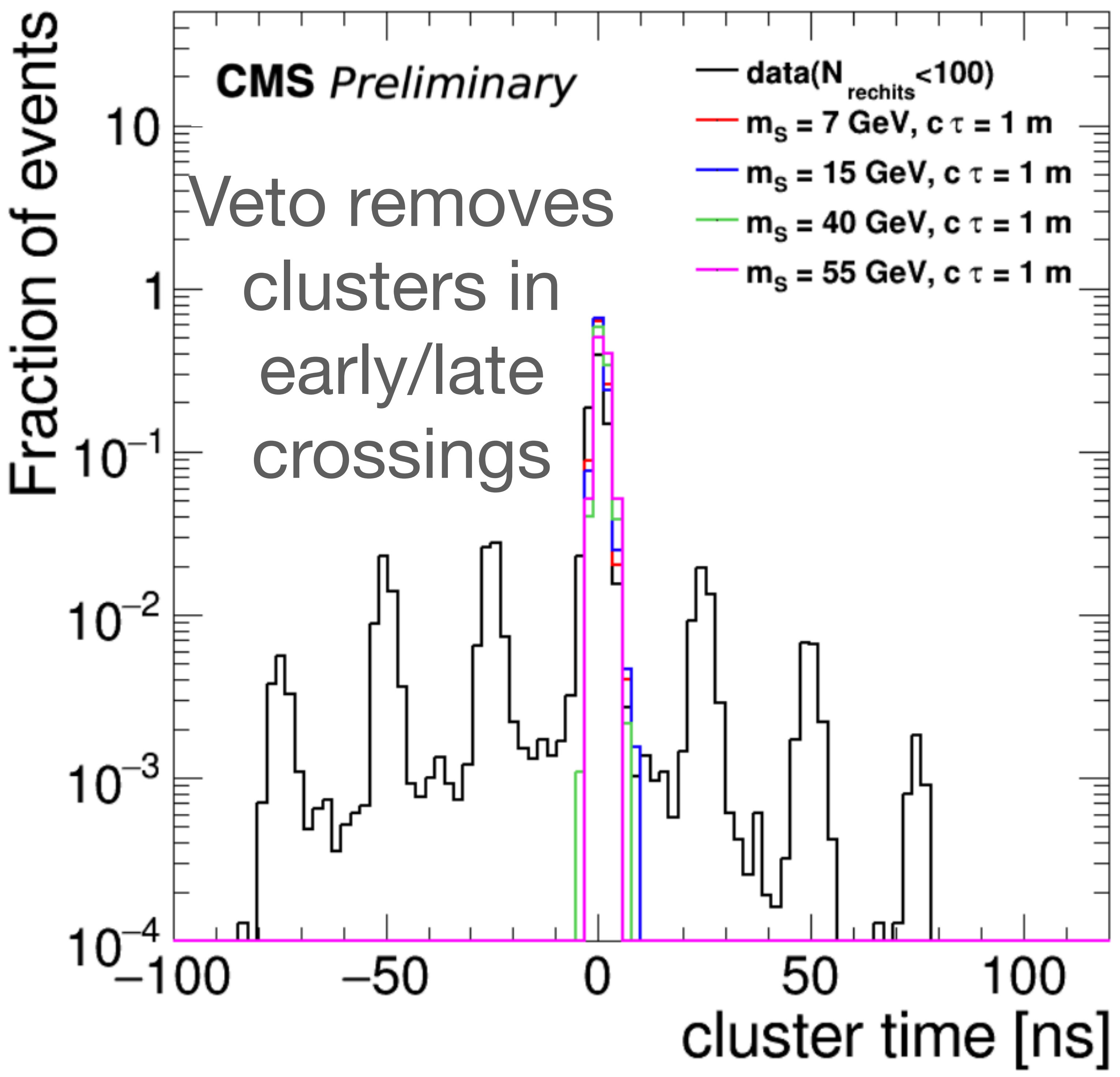


Require single DT clusters are **matched to at least 1 RPC hit** to remove clusters from noisy DT chambers

Noise filters applied to remove **specific high noise regions/time periods** for DTs and CSCs

Background Rejection

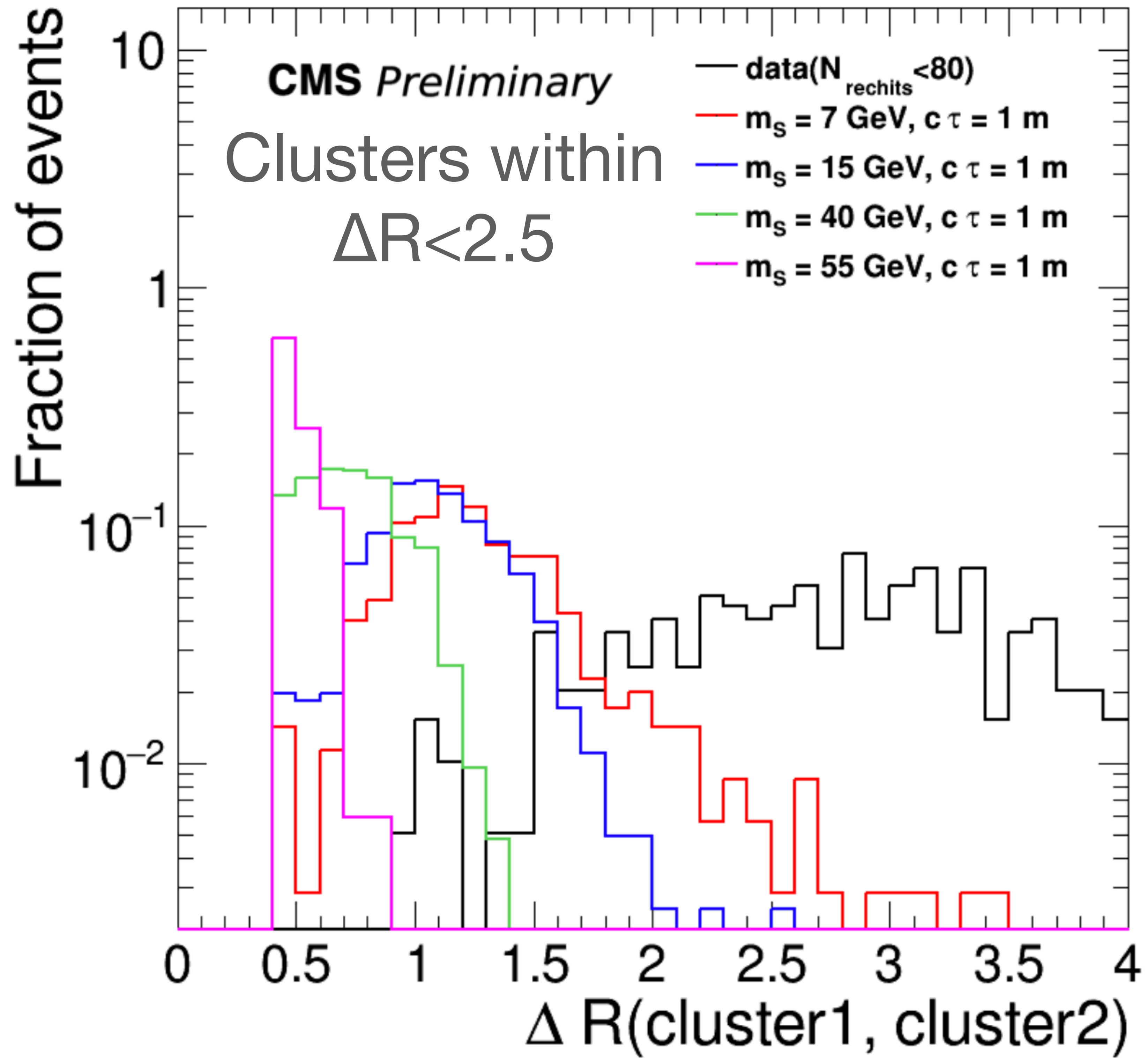
CSC double cluster



Veto removes clusters in early/late crossings

Require CSC cluster time is **between -5 and +12.5 ns** and the **rms spread is less than 20 ns** to remove out-of-time clusters

DT-CSC double cluster



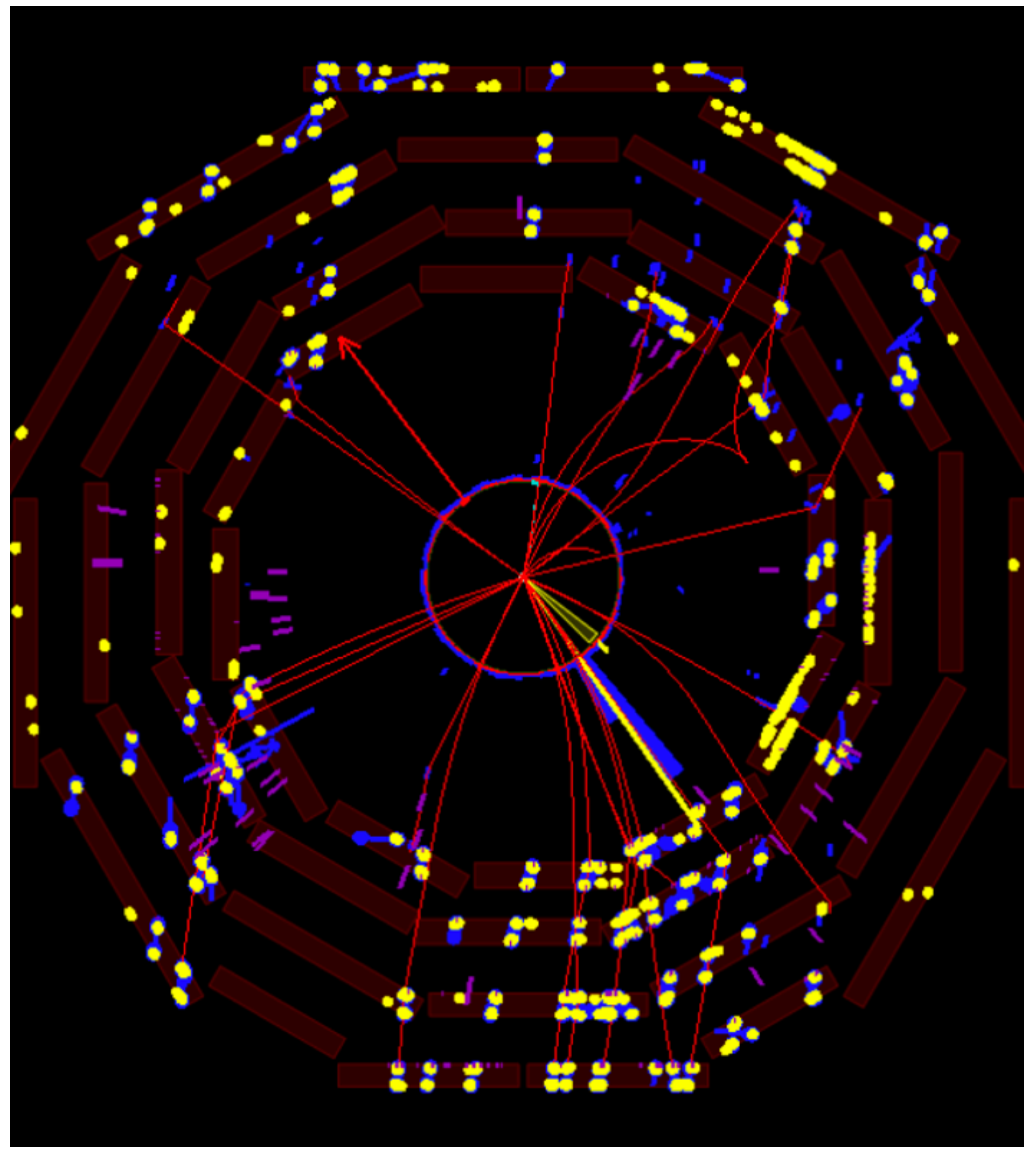
Clusters within ΔR<2.5

Clusters (double cluster category) are **required to be close to each other** to remove background from 2 different processes

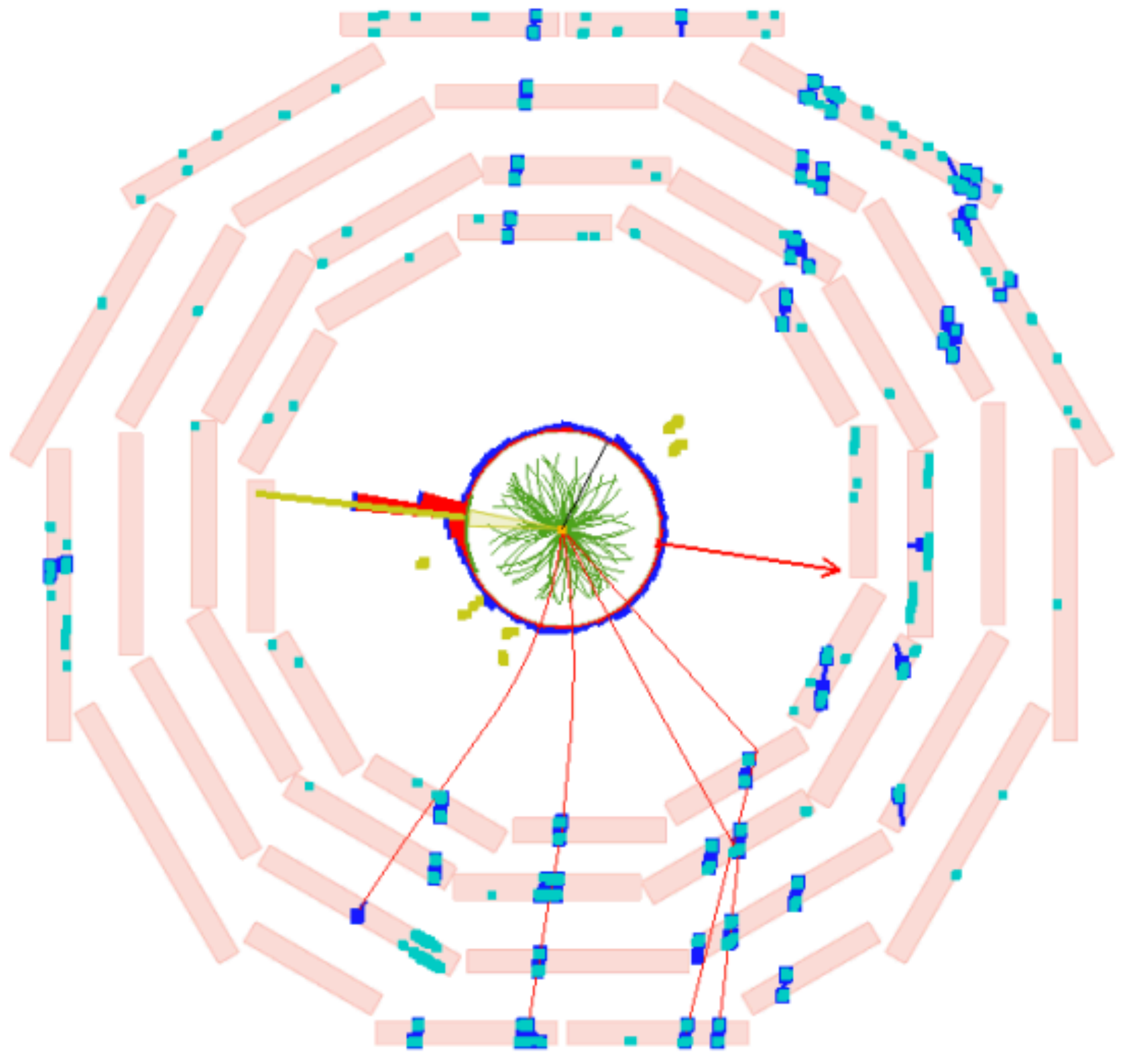
Background Rejection

Veto clusters that are consistent with properties of cosmic muons/showers using **hits/segments appearing in many different areas** of the muon system

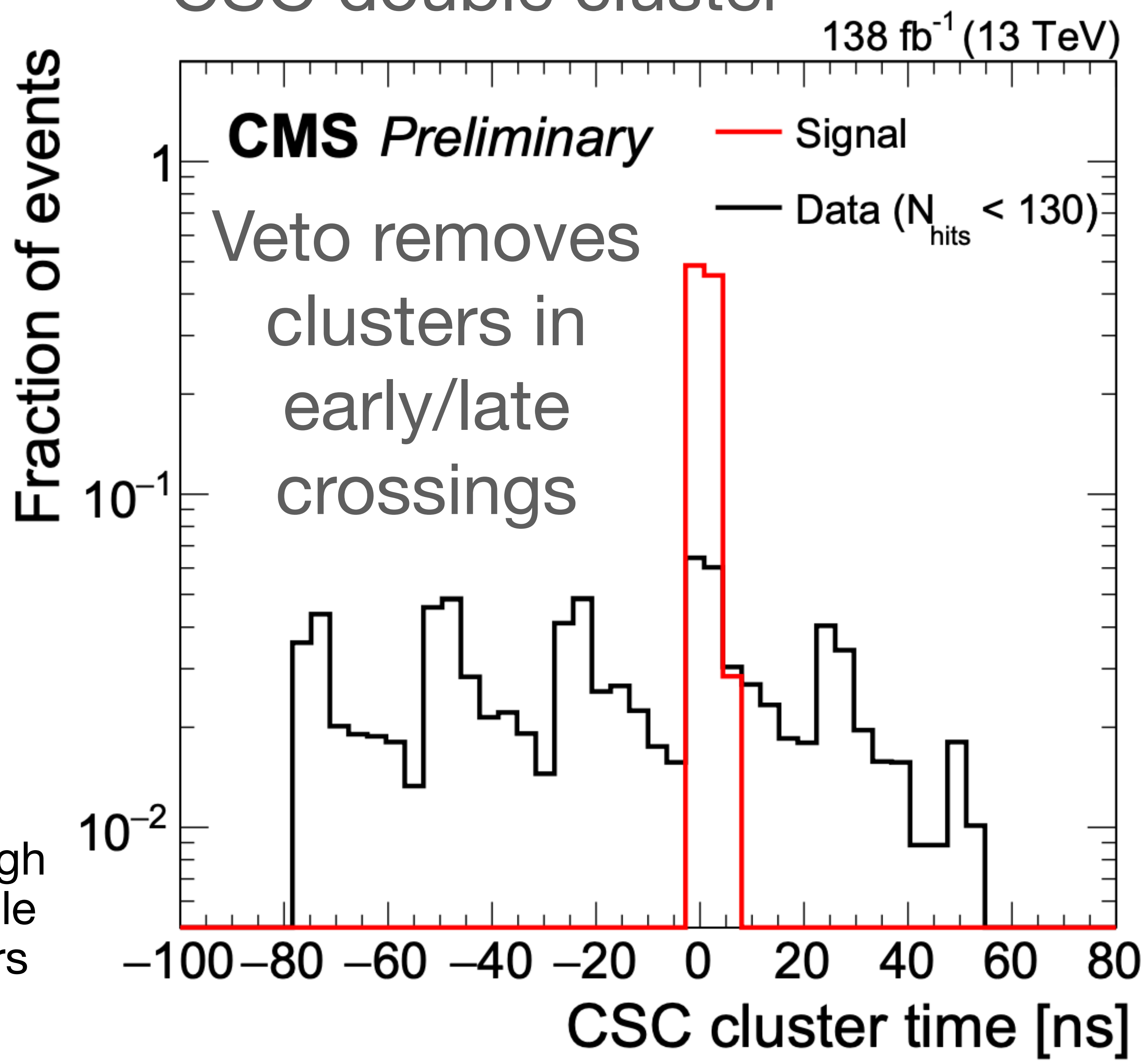
Example DT single cluster cosmic shower event



Example DT double cluster cosmic muon event



CSC double cluster



Veto removes clusters in early/late crossings

* Background histogram obtained through a control sample of small clusters

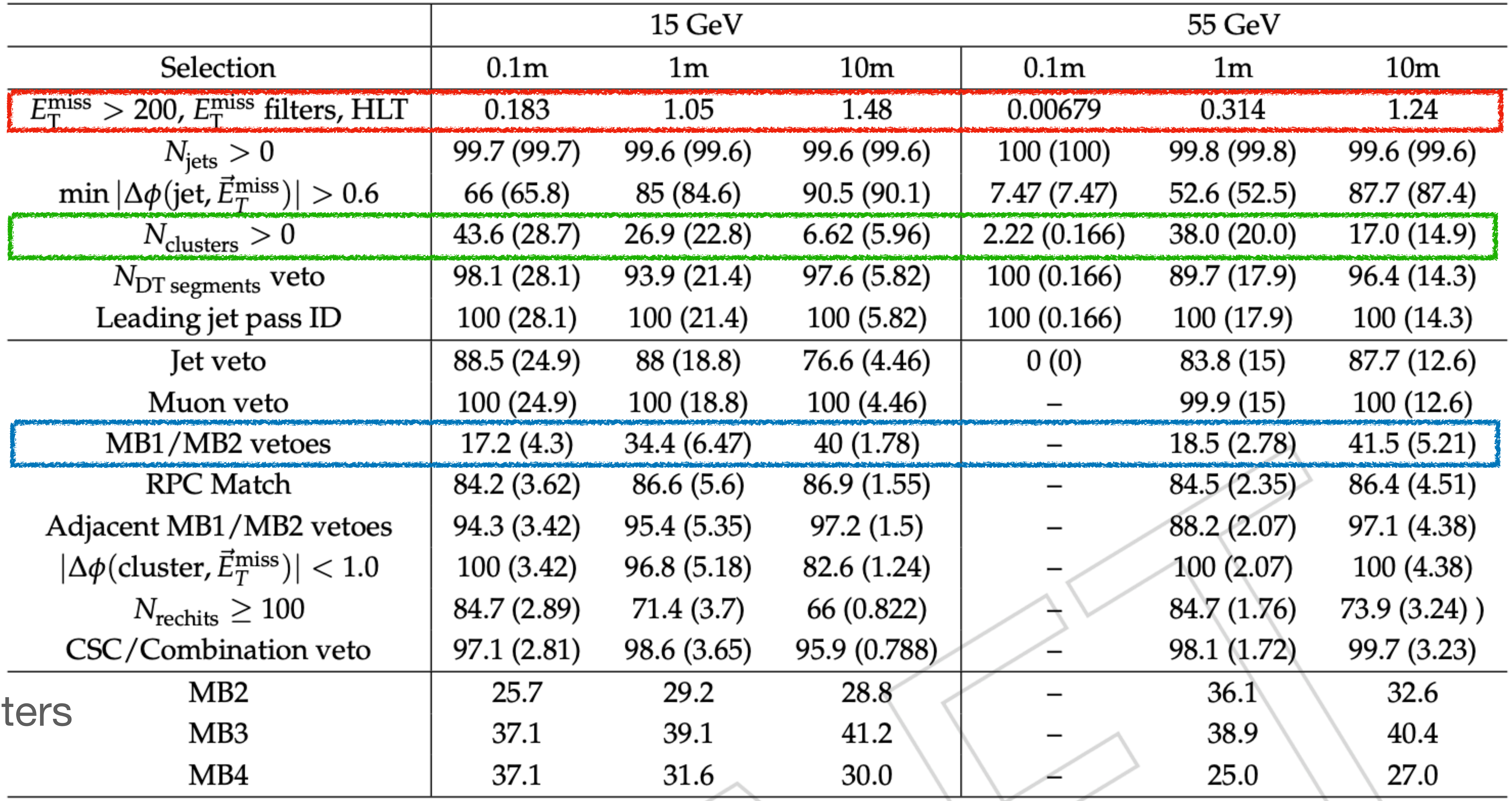
Require CSC cluster time is **between -5 and +12.5 ns** and the **rms spread is less than 20 ns** to remove out-of-time clusters

Signal Yield Corrections/Uncertainty

- **Clusters from muon bremsstrahlung** in dimuon events are used as a proxy for signal and random sampling of detector positions is used to study veto efficiencies to **compare simulation and data**
- 10% corrections necessary to account for muon veto modeling (single CSC), both MB1 and RPC rechit modeling (single DT)
- 3% (double DT) and 15% (single DT) uncertainties derived for DT cluster size modeling
- Uncertainty on single CSC cluster efficiency dominated by clustering/ID efficiencies (8%)
- 10% (double CSC) and 5% (CSC-DT) uncertainties due to CSC cluster time spread
- Other simulation-related uncertainties are all O(1%)
- Higher order corrections to Higgs pT shape, uncertainties on the cross section for each Higgs production method, and uncertainty on the parton distribution functions lead to ~10-20% theory uncertainty on the signal yields

Signal Efficiency

DT single cluster



	15 GeV			55 GeV		
Selection	0.1m	1m	10m	0.1m	1m	10m
$E_{\mathrm{T}}^{\mathrm{miss}} > 200$, $E_{\mathrm{T}}^{\mathrm{miss}}$ filters, HLT	0.183	1.05	1.48	0.00679	0.314	1.24
$N_{\mathrm{jets}} > 0$	99.7 (99.7)	99.6 (99.6)	99.6 (99.6)	100 (100)	99.8 (99.8)	99.6 (99.6)
$\min\lvert\Delta\phi(\mathrm{jet}, \vec{E}_T^{\mathrm{miss}})\rvert > 0.6$	66 (65.8)	85 (84.6)	90.5 (90.1)	7.47 (7.47)	52.6 (52.5)	87.7 (87.4)
$N_{\mathrm{clusters}} > 0$	43.6 (28.7)	26.9 (22.8)	6.62 (5.96)	2.22 (0.166)	38.0 (20.0)	17.0 (14.9)
$N_{\mathrm{DT\ segments}}$ veto	98.1 (28.1)	93.9 (21.4)	97.6 (5.82)	100 (0.166)	89.7 (17.9)	96.4 (14.3)
Leading jet pass ID	100 (28.1)	100 (21.4)	100 (5.82)	100 (0.166)	100 (17.9)	100 (14.3)
Jet veto	88.5 (24.9)	88 (18.8)	76.6 (4.46)	0 (0)	83.8 (15)	87.7 (12.6)
Muon veto	100 (24.9)	100 (18.8)	100 (4.46)	–	99.9 (15)	100 (12.6)
MB1/MB2 vetoes	17.2 (4.3)	34.4 (6.47)	40 (1.78)	–	18.5 (2.78)	41.5 (5.21)
RPC Match	84.2 (3.62)	86.6 (5.6)	86.9 (1.55)	–	84.5 (2.35)	86.4 (4.51)
Adjacent MB1/MB2 vetoes	94.3 (3.42)	95.4 (5.35)	97.2 (1.5)	–	88.2 (2.07)	97.1 (4.38)
$\lvert\Delta\phi(\mathrm{cluster}, \vec{E}_T^{\mathrm{miss}})\rvert < 1.0$	100 (3.42)	96.8 (5.18)	82.6 (1.24)	–	100 (2.07)	100 (4.38)
$N_{\mathrm{rechits}} \geq 100$	84.7 (2.89)	71.4 (3.7)	66 (0.822)	–	84.7 (1.76)	73.9 (3.24))
CSC/Combination veto	97.1 (2.81)	98.6 (3.65)	95.9 (0.788)	–	98.1 (1.72)	99.7 (3.23)
MB2	25.7	29.2	28.8	–	36.1	32.6
MB3	37.1	39.1	41.2	–	38.9	40.4
MB4	37.1	31.6	30.0	–	25.0	27.0

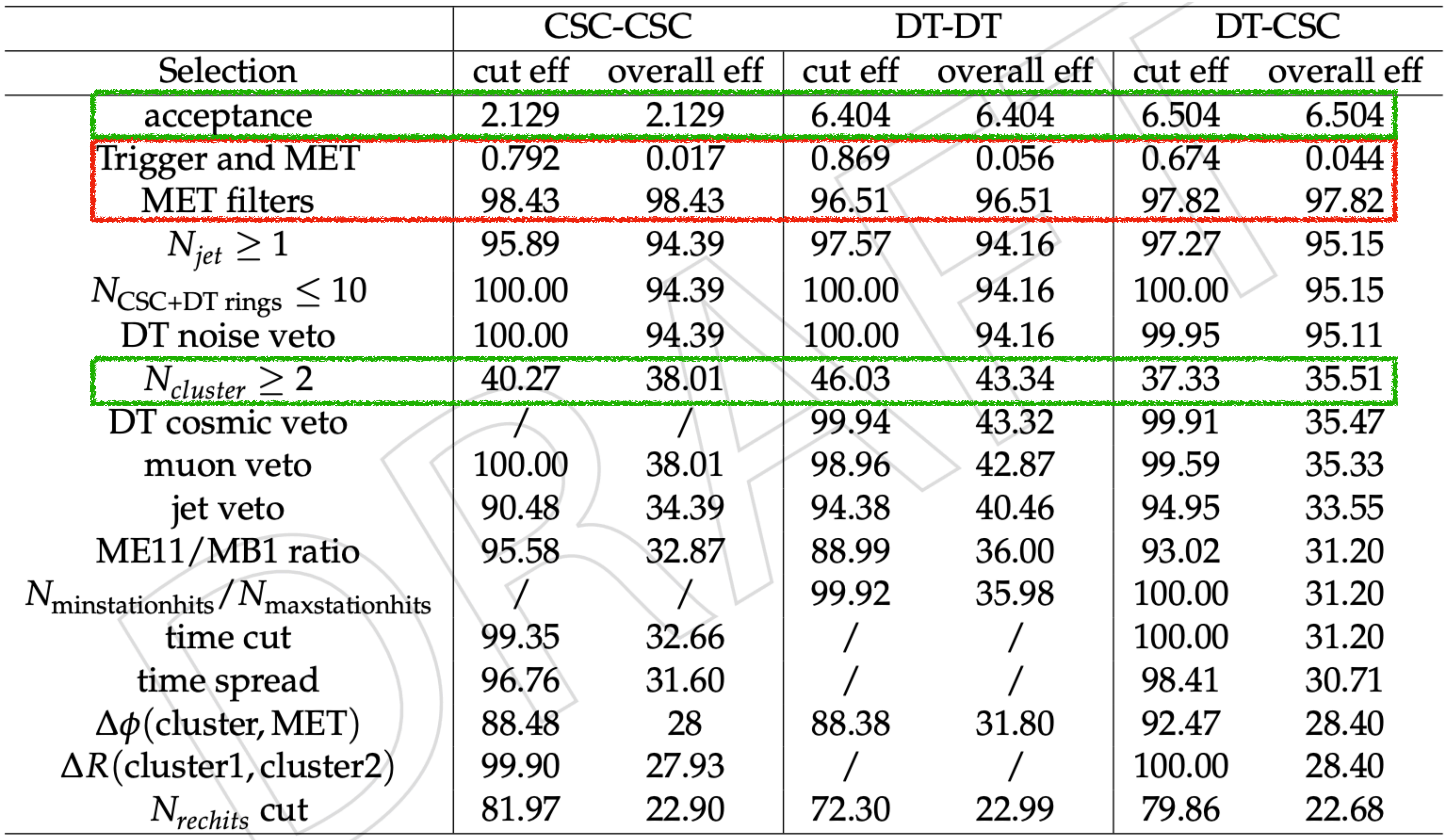
Overall efficiency relative to Trigger/ MET cut

Percentage of clusters in each station

Largest inefficiencies come from MET requirements, acceptance/clustering, and MB1/MB2 vetoes

Signal Efficiency

Double cluster, m_S=55 GeV, cτ=1m



	CSC-CSC		DT-DT		DT-CSC	
Selection	cut eff	overall eff	cut eff	overall eff	cut eff	overall eff
acceptance	2.129	2.129	6.404	6.404	6.504	6.504
Trigger and MET	0.792	0.017	0.869	0.056	0.674	0.044
MET filters	98.43	98.43	96.51	96.51	97.82	97.82
$N_{jet} \geq 1$	95.89	94.39	97.57	94.16	97.27	95.15
$N_{\text{CSC+DT rings}} \leq 10$	100.00	94.39	100.00	94.16	100.00	95.15
DT noise veto	100.00	94.39	100.00	94.16	99.95	95.11
$N_{cluster} \geq 2$	40.27	38.01	46.03	43.34	37.33	35.51
DT cosmic veto	/	/	99.94	43.32	99.91	35.47
muon veto	100.00	38.01	98.96	42.87	99.59	35.33
jet veto	90.48	34.39	94.38	40.46	94.95	33.55
ME11/MB1 ratio	95.58	32.87	88.99	36.00	93.02	31.20
$N_{\text{minstationhits}}/N_{\text{maxstationhits}}$	/	/	99.92	35.98	100.00	31.20
time cut	99.35	32.66	/	/	100.00	31.20
time spread	96.76	31.60	/	/	98.41	30.71
$\Delta\phi$(cluster, MET)	88.48	28	88.38	31.80	92.47	28.40
ΔR(cluster1, cluster2)	99.90	27.93	/	/	100.00	28.40
$N_{rechits}$ cut	81.97	22.90	72.30	22.99	79.86	22.68

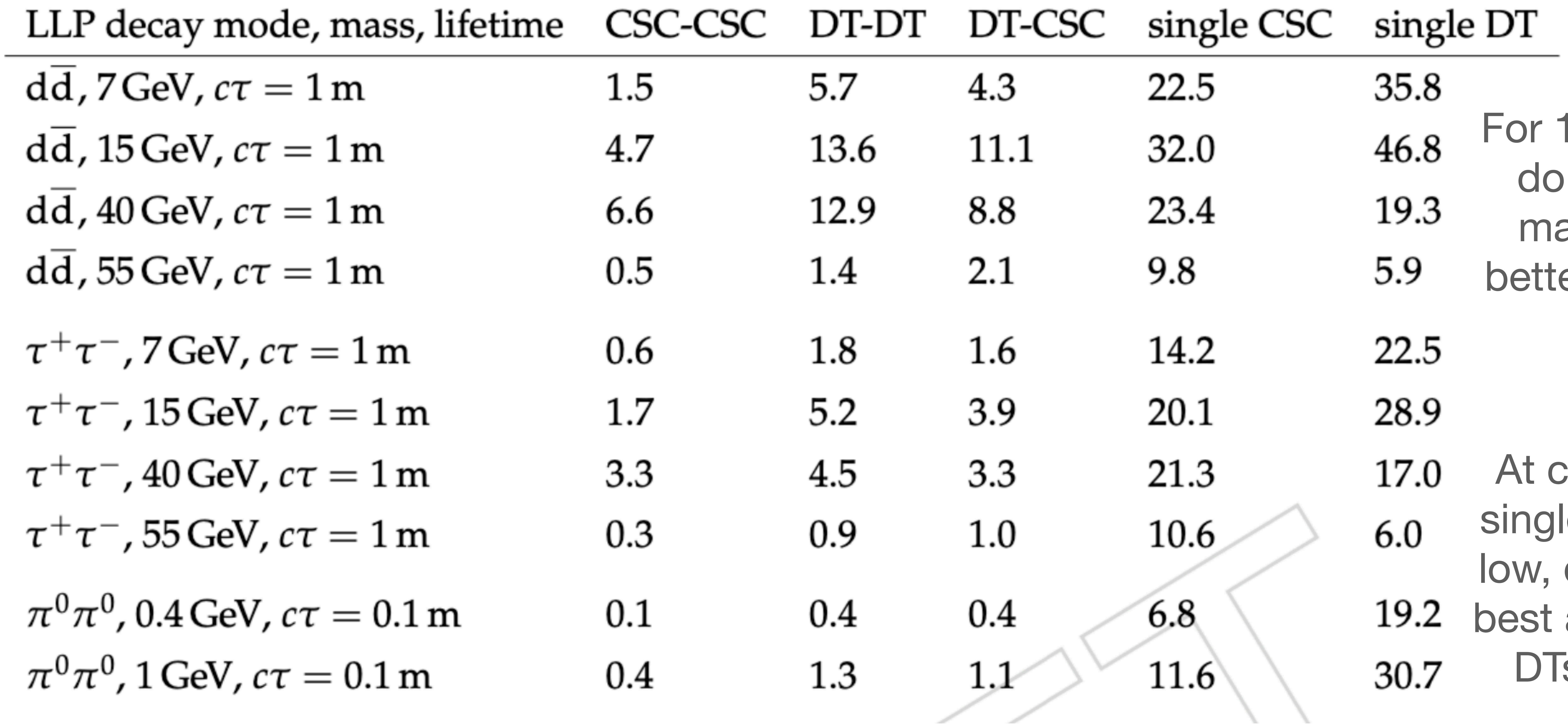
Overall efficiency relative to Trigger/MET cut

Largest inefficiencies come from MET requirements and acceptance/clustering

Signal Yields

Assuming BR(H→SS) = 1%

High yield for showers from a variety of final state particles

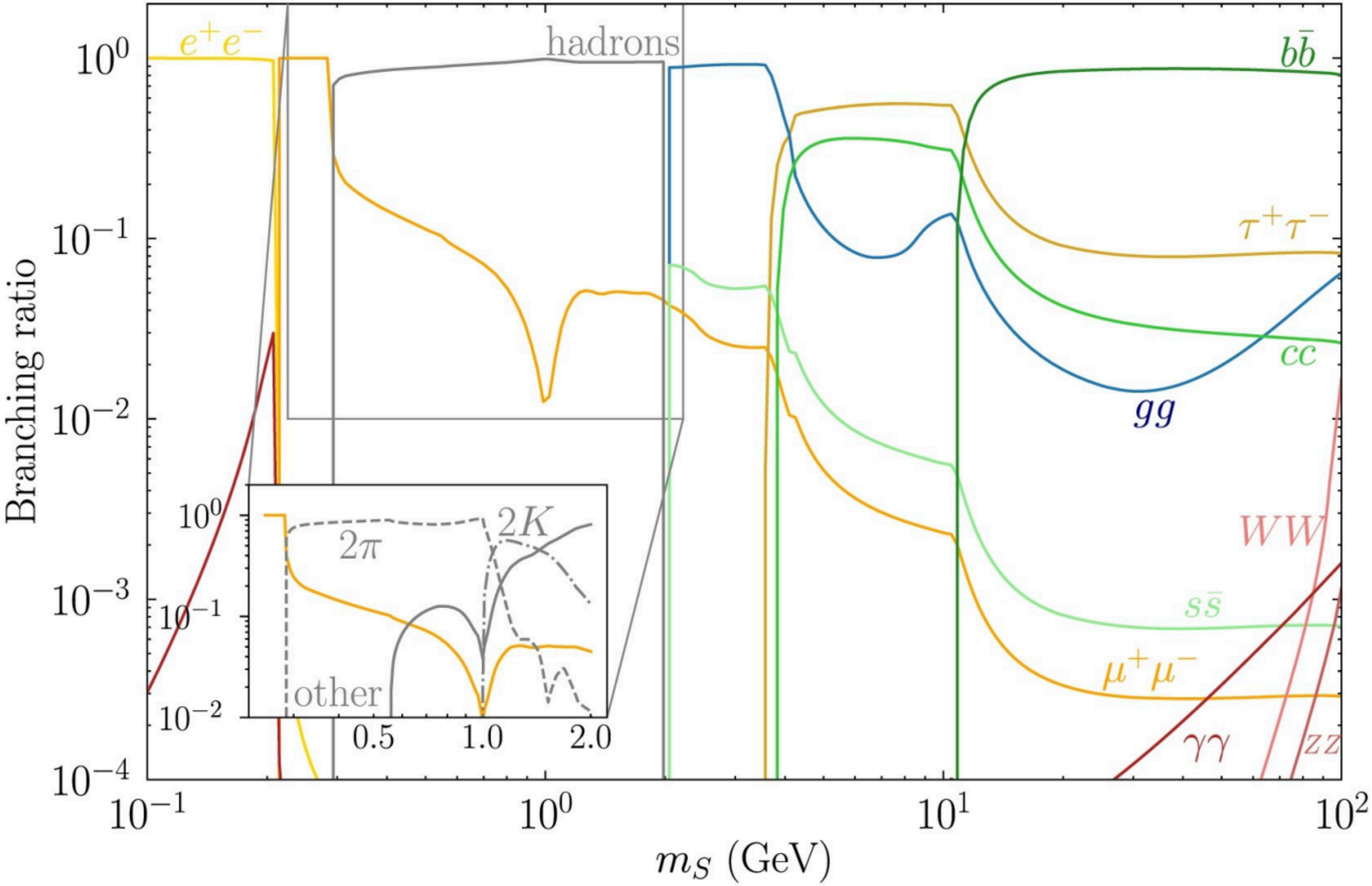


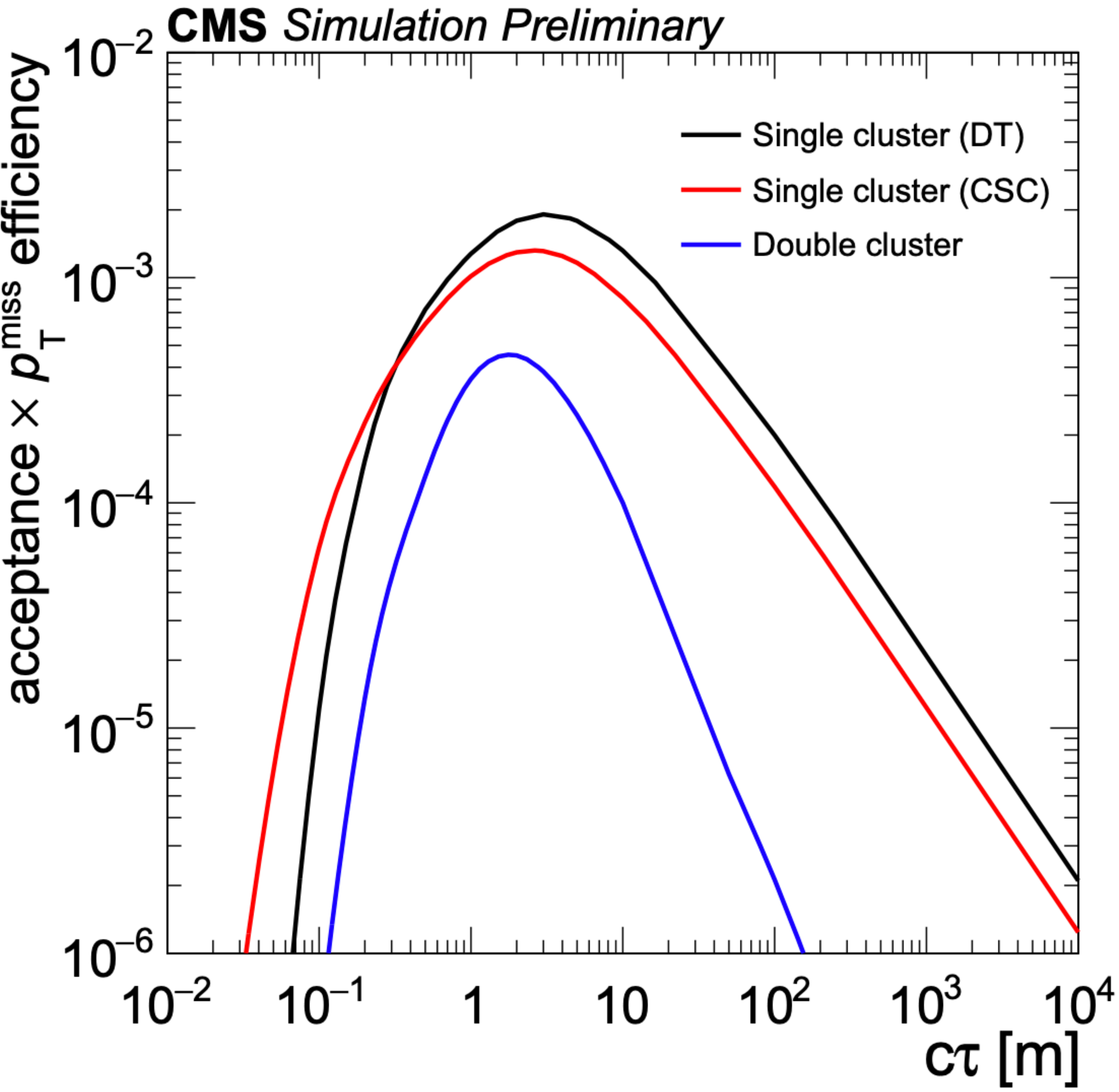
LLP decay mode, mass, lifetime	CSC-CSC	DT-DT	DT-CSC	single CSC	single DT
$d\bar{d}$, 7 GeV, $c\tau = 1\,\mathrm{m}$	1.5	5.7	4.3	22.5	35.8
$d\bar{d}$, 15 GeV, $c\tau = 1\,\mathrm{m}$	4.7	13.6	11.1	32.0	46.8
$d\bar{d}$, 40 GeV, $c\tau = 1\,\mathrm{m}$	6.6	12.9	8.8	23.4	19.3
$d\bar{d}$, 55 GeV, $c\tau = 1\,\mathrm{m}$	0.5	1.4	2.1	9.8	5.9
$\tau^+\tau^-$, 7 GeV, $c\tau = 1\,\mathrm{m}$	0.6	1.8	1.6	14.2	22.5
$\tau^+\tau^-$, 15 GeV, $c\tau = 1\,\mathrm{m}$	1.7	5.2	3.9	20.1	28.9
$\tau^+\tau^-$, 40 GeV, $c\tau = 1\,\mathrm{m}$	3.3	4.5	3.3	21.3	17.0
$\tau^+\tau^-$, 55 GeV, $c\tau = 1\,\mathrm{m}$	0.3	0.9	1.0	10.6	6.0
$\pi^0\pi^0$, 0.4 GeV, $c\tau = 0.1\,\mathrm{m}$	0.1	0.4	0.4	6.8	19.2
$\pi^0\pi^0$, 1 GeV, $c\tau = 0.1\,\mathrm{m}$	0.4	1.3	1.1	11.6	30.7

For 1m signals, DTs do better at low mass, CSCs do better at high mass

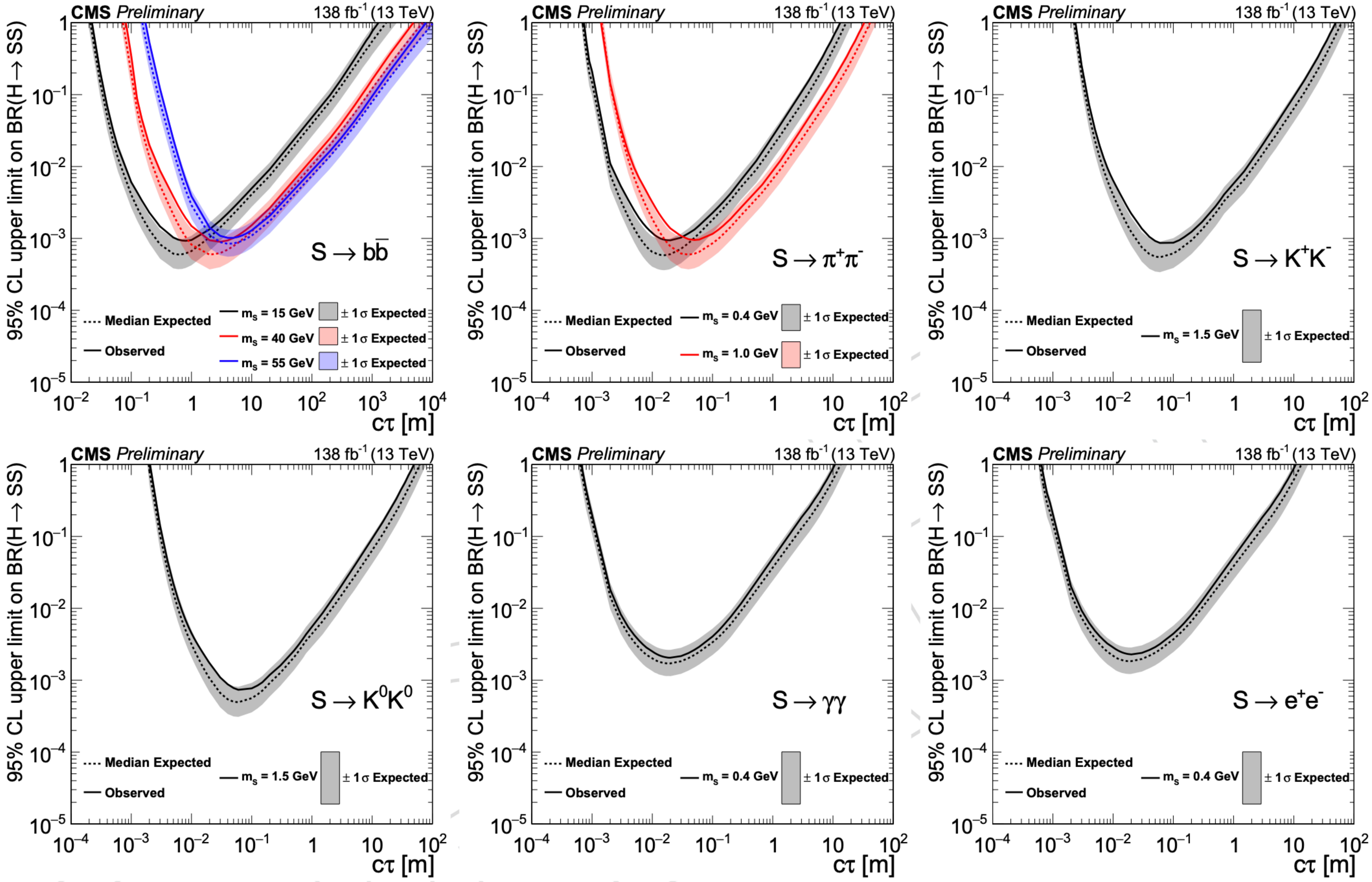
At constant mass, single CSCs best at low, double clusters best at intermediate, DTs best at high lifetimes

Across all tested signals, total yields range from ~20-100 events https://arxiv.org/pdf/2012.07864.pdf



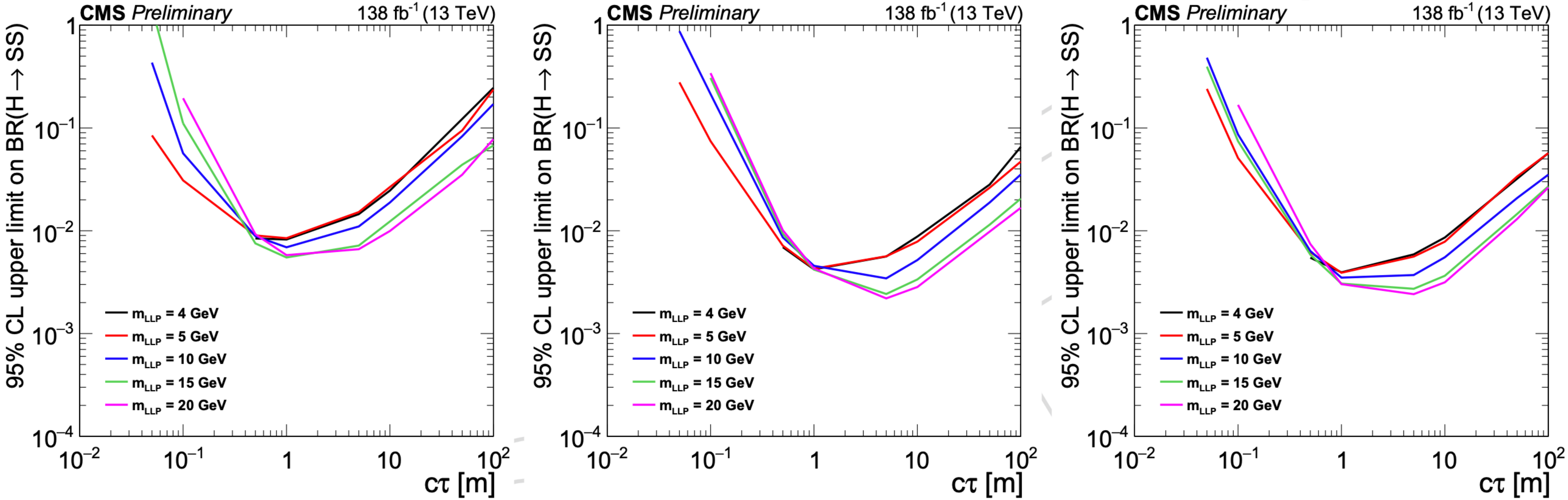

CMS Simulation Preliminary
acceptance × p_T^{miss} efficiency
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Single cluster (DT)
Single cluster (CSC)
Double cluster
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
cτ [m]

Observed Limits



Observed Limits

Higgs portal



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

- First interpretation of **dark shower model coupled to Higgs**
- Sensitive to **various LLP masses and lifetimes** with **different phenomenologies**

Observed Limits