Search for Long-Lived Particles with CMS Experiment at the LHC

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on behalf of CMS collaboration

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Beyond Standard Model theories

- Beyond Standard Model (BSM) theories are introduced to explain shortcomings of SM.
- They extend the SM with new particles.
- Searches for BSM physics motivated by SM problems expect the new predicted particles to be prompt.
- This expectation has impacted the design of modern particle detectors, reconstruction and identification techniques.
- Further development of BSM models resulted in prediction of long-lived particles (LLPs).

Long-lived Particles (LLP)

- Requirements for the particle to be **long-lived**:
  - Small matrix element (coupling constant)
  - Limited phase space for the decay.
- Many theoretical models predict particles with macroscopic decay length.
  - Supersymmetric (SUSY) models
  - Seesaw models (HNL predicting models)
  - Higgs portal model
  - Hidden valleys
- For the detection of the LLPs new methods of particle detection and triggering are developed.

$$\tau^{-1} = \Gamma = \frac{1}{2m_X} \int d\Pi_f \, |\mathcal{M}(m_X \to \{p_f\})|^2$$

Mass of the particle

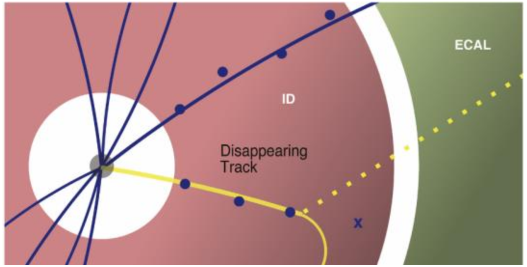
The decay products

Long-lived particle searches in CMS experiment

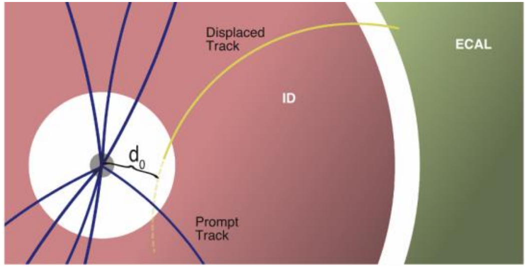
[[Collider searches for long-lived particles beyond the Standard Model](#)]

- The searches for LLPs can be performed via searching for a unique signature.
  - "Anomalous ionization".
  - Delayed detector signals.
- **Direct detection** (charged LLPs):
  - Disappearing tracks.
  - Anomalous-trajectory.
- **Indirect detection** (neutral LLPs):
  - Displaced decay vertex.
  - Displaced calorimeter deposits.
  - **Muon detector showers.**

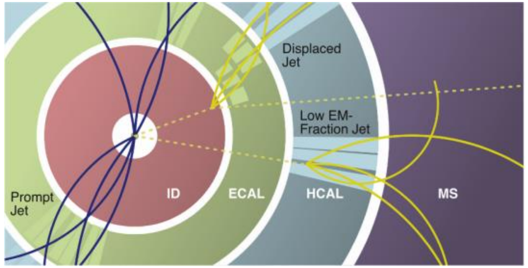
Disappearing tracks.



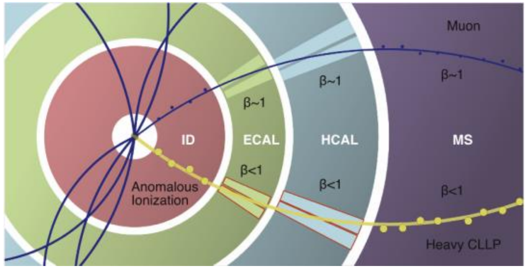
Displaced tracks.



Displaced decay vertex.



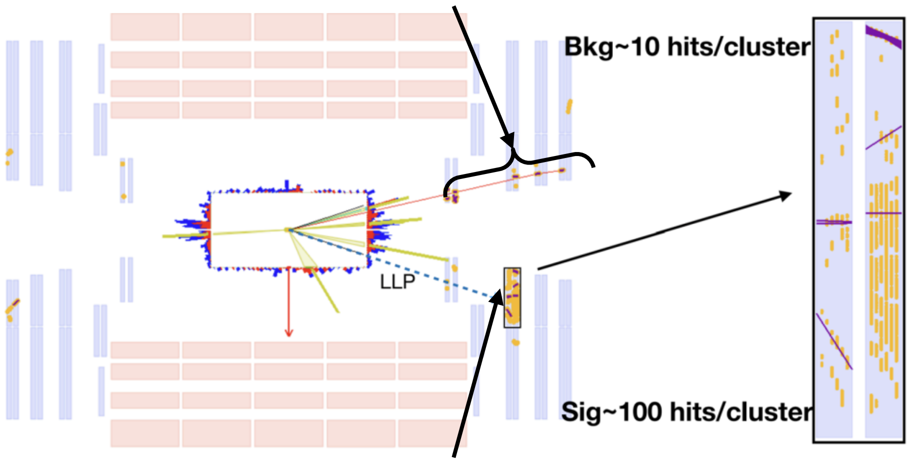
Heavy charged LLP (CLLP)



LLP searches in CMS Muon System (MS)

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

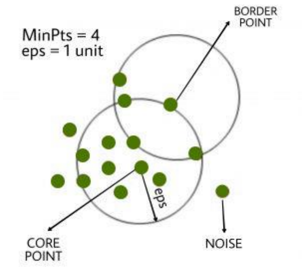
While **muons** only create a few hits



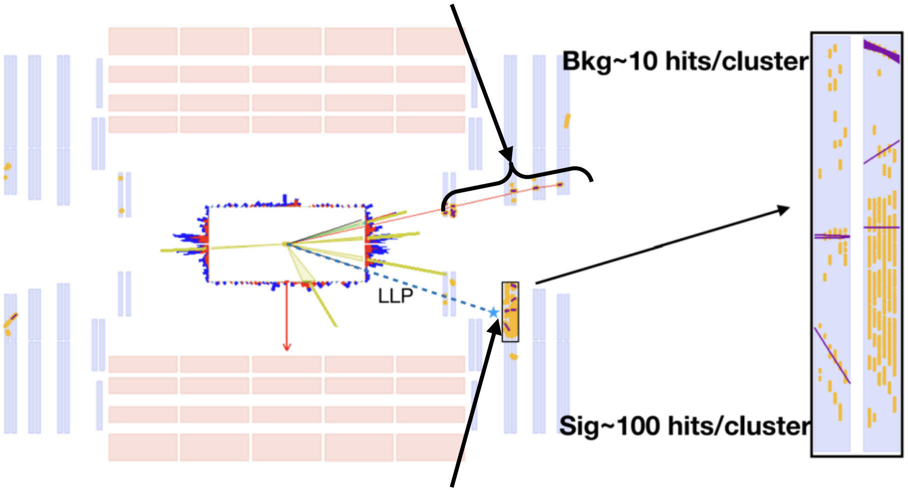
LLP decays produce high hit multiplicity clusters.

LLP signature in CMS Muon System

- The decay products of the LLPs produce electromagnetic or hadronic showers in MS.
- The hits in the MS are clustered using DBSCAN algorithm.
- The LLP signature will be a cluster with high multiplicity of hits in MS.
- Muons don't create high multiplicity clusters.



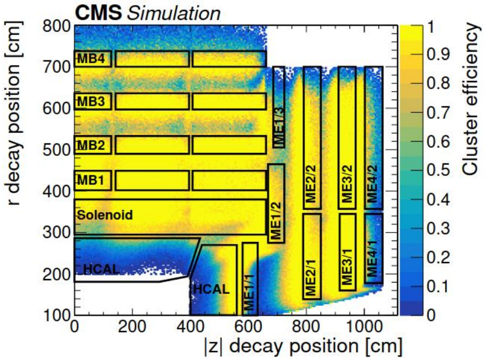
While **muons** only create a few hits

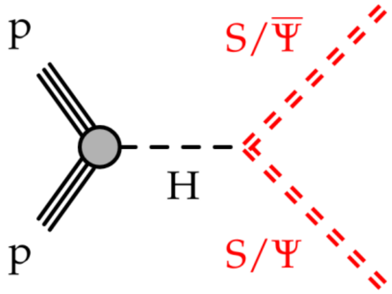


LLP decays produce high hit multiplicity clusters.

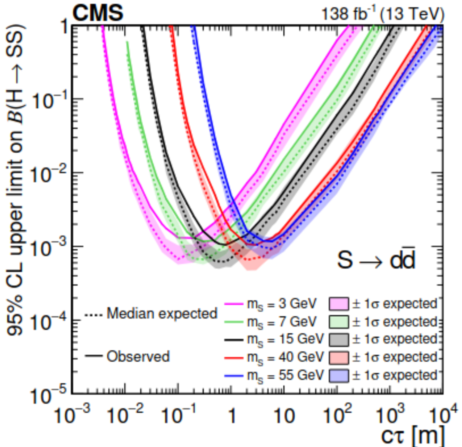
Long-lived particle (neutral) searches in CMS experiment

- High MET selection looks for boosted Higgs events.
- Selections
  - Offline $P_{T,\ miss}$> 200 GeV selection.
  - At least one jet with P_T > 50 GeV and |η| < 2.4.
  - 1 or 2 clusters passing cluster-ID
- Set stringent limits for ~1m proper decay lengths.





Dark-sector quarks: Ψ
LLP scalar: S



Cluster-ID

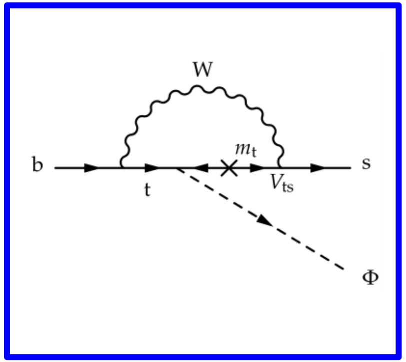
- |η| < 1.9 if $N_{stations}$ > 1,
- |η| < 1.8 if $N_{stations}$ = 1 and the cluster is in station 4,
- |η| < 1.6 if $N_{stations}$ = 1 and the cluster is in station 3 or station 2, and
- |η| < 1.1 if $N_{stations}$ = 1

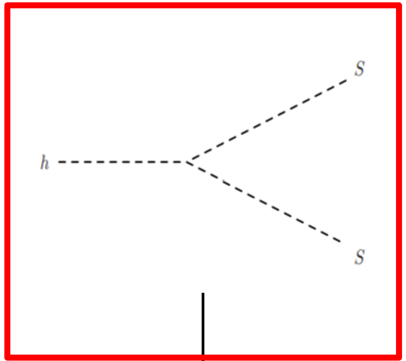
[EXO-21-008]

Higgs portal model

- A model with the minimum extension of the SM is used.
- An additional scalar is added to the SM.

$$\mathcal{L} \supset \boxed{A_S\, S H^\dagger H} + \boxed{\frac{\lambda}{2} S^2 H^\dagger H} + \cdots$$

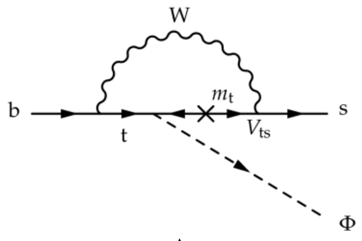




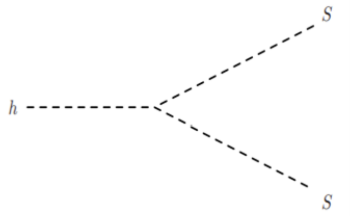
MET triggered
Well-excluded
First search with MDS

Ultra low-mass regime

- Left diagram will be the dominant production channel if LLP mass is smaller than b-mesons



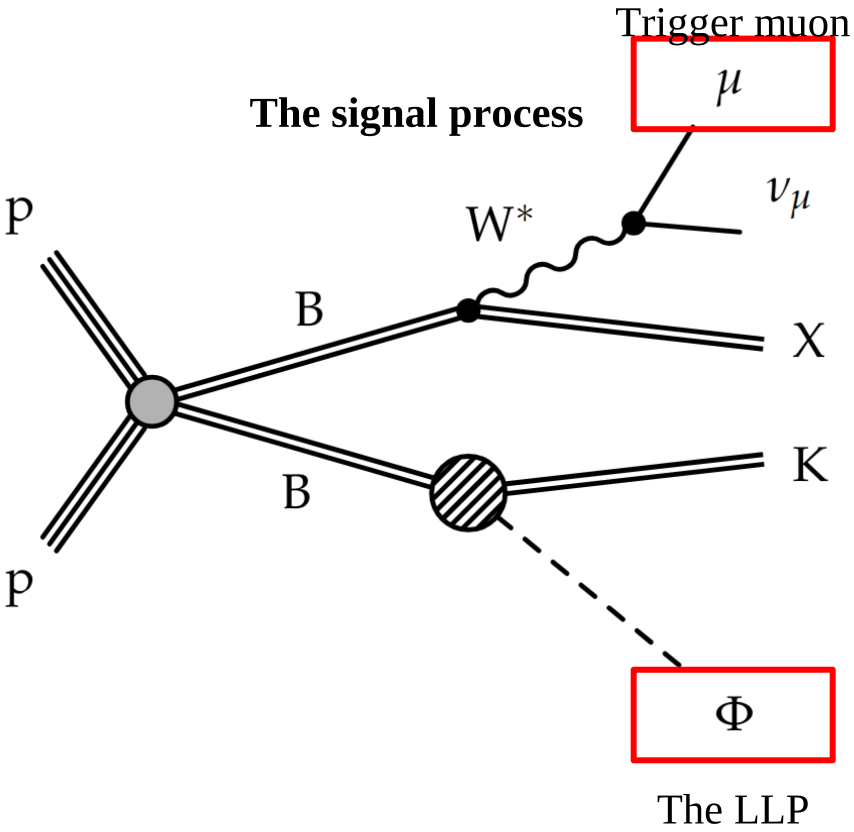
The process discussed in this talk



The process covered in EXO-21-008

- Use B-parking dataset to overcome the limitation from high MET analysis

The signal process

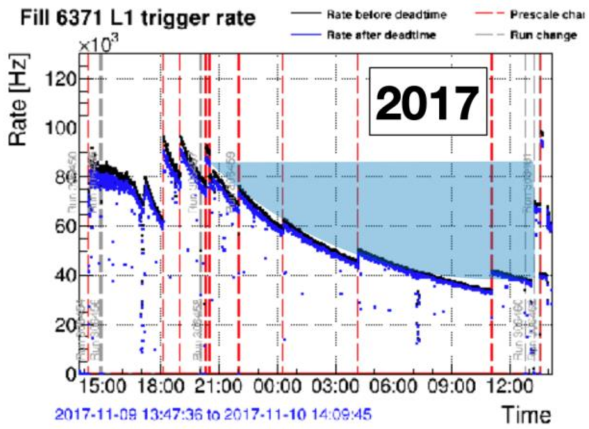


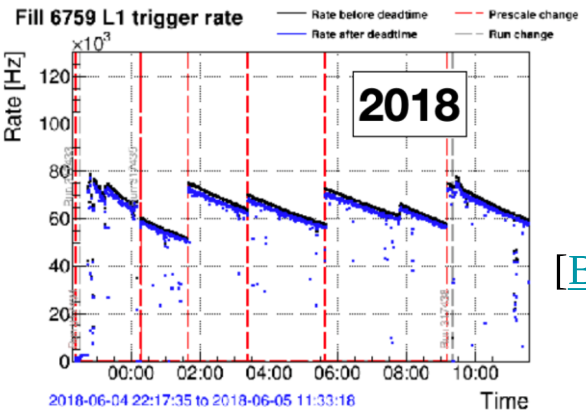
- One of the B meson decays to muons for triggering
- The other B meson decays to LLPs, which decay into oppositely charged pions that induce showers in the MS

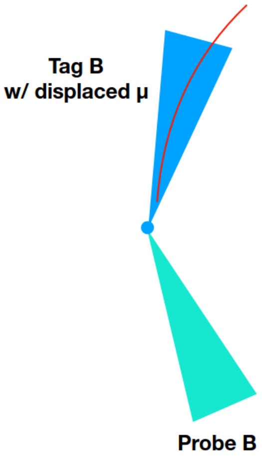
[CMS-PAS-EXO-24-004]

B-parking dataset

- B-parking dataset collected in 2018 will be used (41.6 fb^{-1})
- It consists of ~10 billion events each with a decay of a pair of B-mesons.
- As the luminosity drops, various single-muon $|\eta|$-restricted triggers are turned on, which allow to keep L1 rate constant and increase HLT rate toward the end of each fill.
- Tuned thresholds, while gaining experience; **HLT_Mu9_IP6,5,4** are the main triggers.
- A purity of 70-80% of the dataset was achieved.



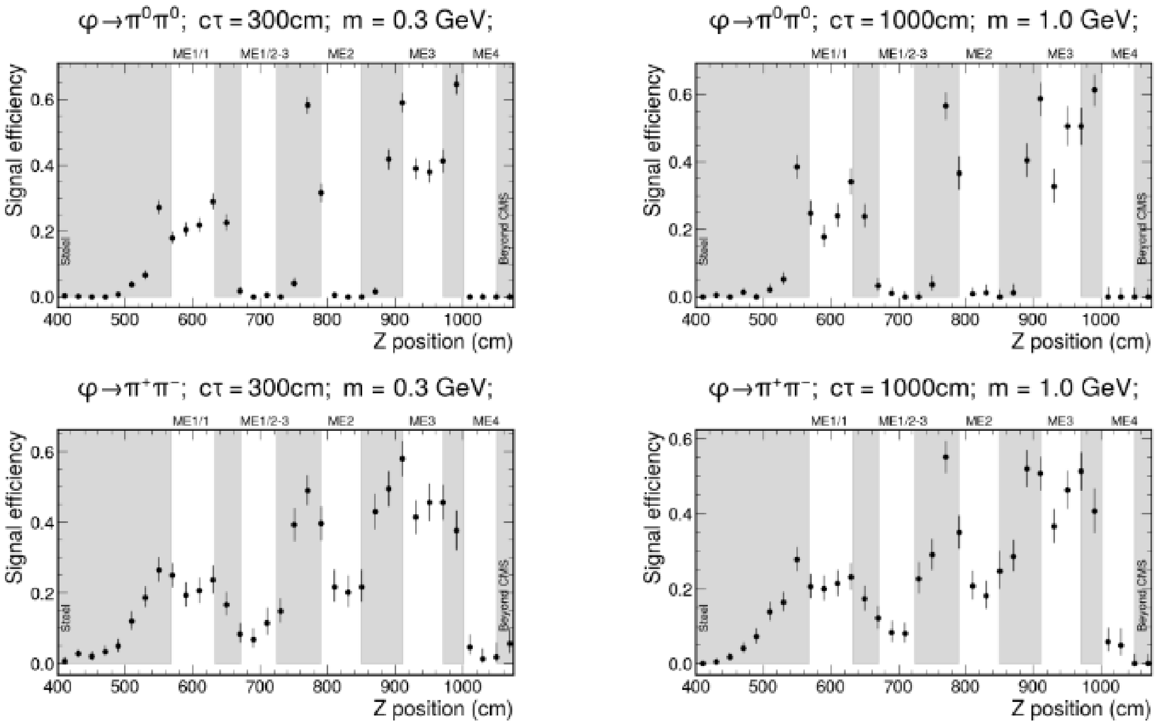




[B-Physics parking]

Muon detector shower reconstruction efficiency

- High reconstruction efficiency for $\pi^+\pi^-$ and $\pi^0\pi^0$ for B-produced LLPs



Analysis strategy: selection of the trigger muon

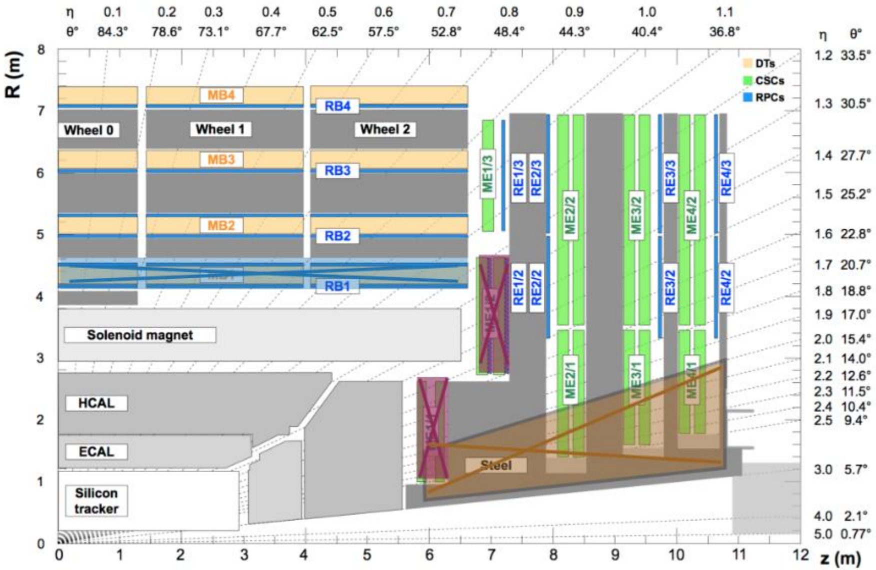
- Selections on the trigger muons:

  MuonPt > 7 GeV
  |MuonEta| < 1.5
  Muon fires a B-Parking HLT
  Soft muon ID

- Used B-Parking HLT triggers

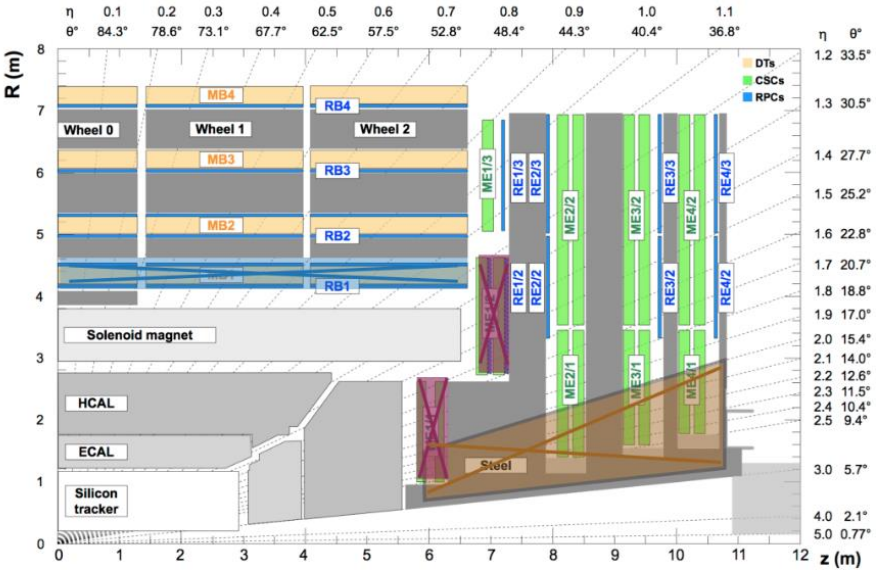
  HLT_Mu12_IP6
  HLT_Mu9_IP6
  HLT_Mu9_IP5
  HLT_Mu9_IP4
  HLT_Mu8_IP5
  HLT_Mu8_IP6
  HLT_Mu8_IP3
  HLT_Mu7_IP4

  (P_T > 7,8,9,12 GeV, d_{xy}/σ_{dxy} > 3,4,5,6)



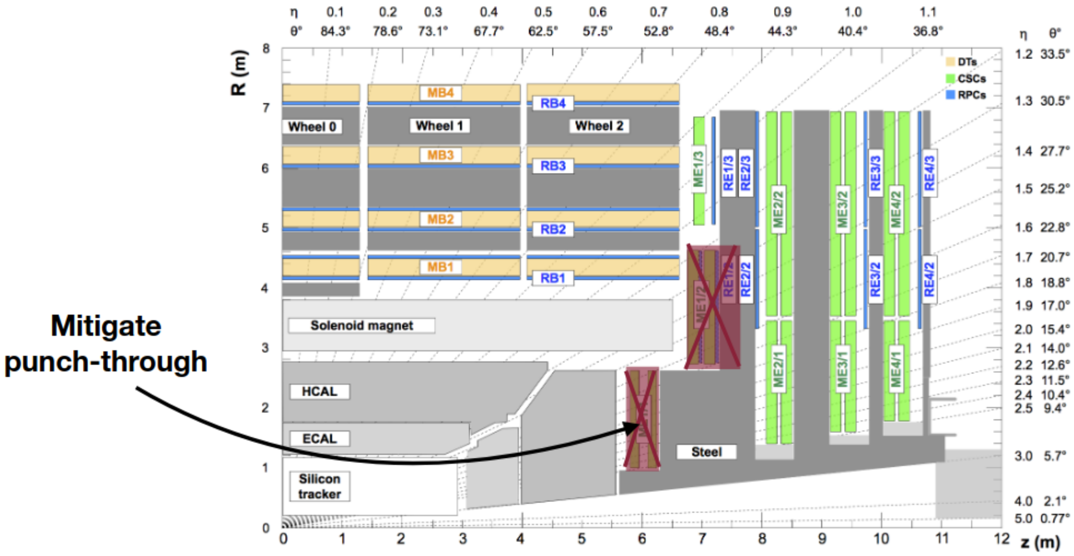
Analysis strategy: cluster selections

- Events of interest must contain at least one cluster the CSCs.
- Clusters pass quality checks to reduce the number of clusters coming from background.



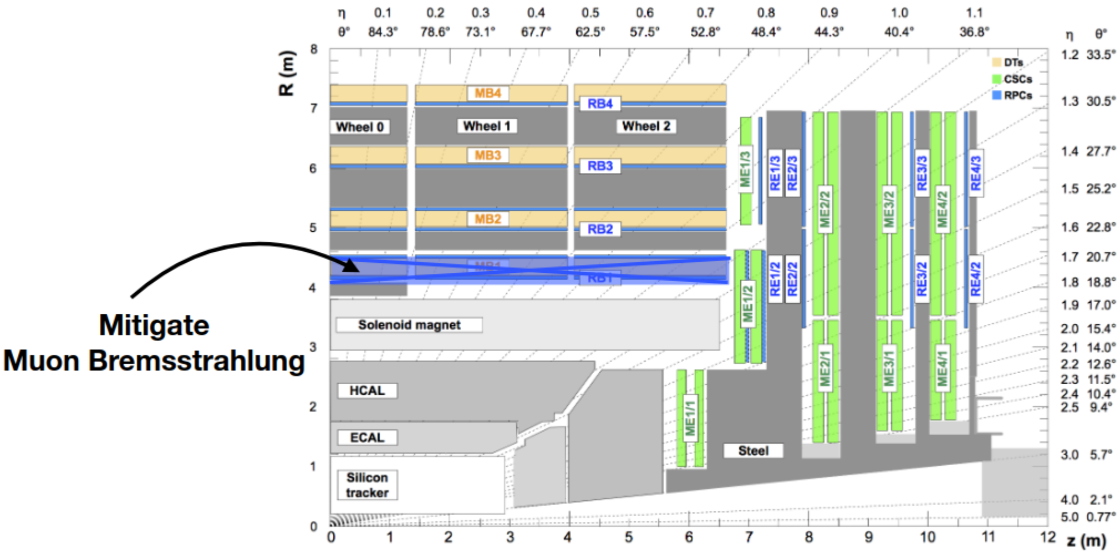
Analysis strategy: cluster selections

- Target background: punch through jets
- We veto clusters with hits in the first layer of the CSCs ME1/1 and ME1/2.
- An additional veto is applied to clusters matched to hits in RE1/2, the first RPC station after ME1/1 and ME1/2.



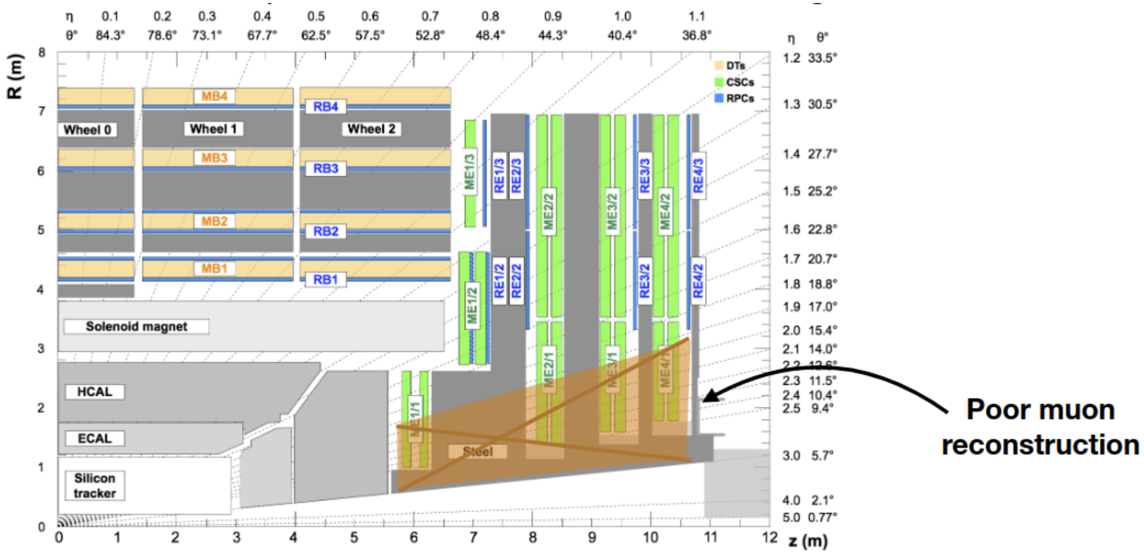
Analysis strategy: cluster selections

- Target background: clusters from muon bremsstrahlung
- Veto clusters matched to segments in the first barrel layers of the DTs (MB1) or RPCs (RB1).



Analysis strategy: cluster selections

- Target background: clusters from muon bremsstrahlung
- Veto clusters matched (<0.4) to muons with muon P_T >20 GeV
- Do not include clusters with > 1.9
  - Study in EXO-20-014 shows there is poor muon reconstruction in this region.



Expected background

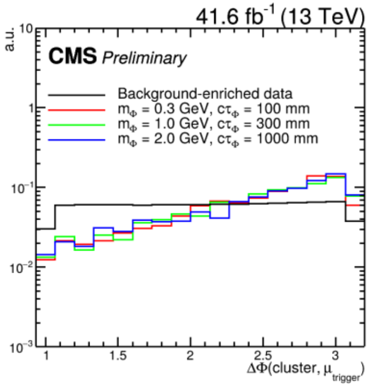
Two main classes of background

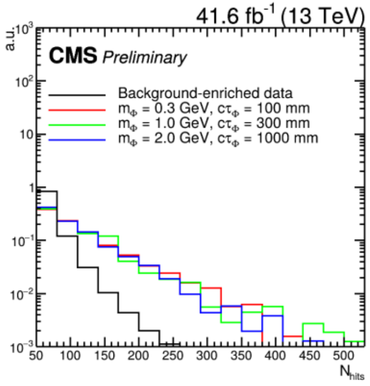
- **Reducible Background**
  - non-LLP objects making clusters. Examples: punch-through jets, muon bremsstrahlung, cosmic radiation.
  - Can be reduced with vetoes.
  - Estimate size via data-driven method.

- **Irreducible Background (jet-induced)**
  - Jets from SM long-lived particles (K^0_S, K^0_L, Λ, Σ^+, Σ^-, …).
  - Dominant source of background.
  - Measure size of this background via the fake rate method.

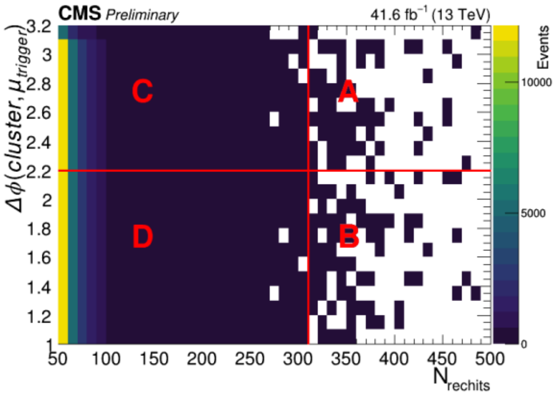
Background estimation

The reducible background is estimated using the ABCD method, based on the cluster multiplicity and $\Delta\Phi$(cls, muon).





[CMS-PAS-EXO-24-004]

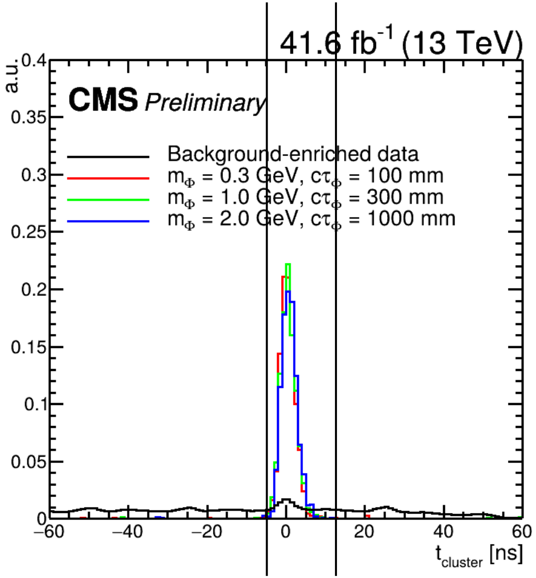


Background estimation validation

Clusters which are from primary interaction are used for the estimation of the background:

$^{\dagger}12.5 > |cscRechitClusterTime| > -5$ ns
$^{\dagger}cscRechitClusterTimeSpread < 20$ ns

Clusters which are not from primary interaction are used for the validation of the ABCD method.



Multiplicity	$\Delta\varphi$(cluster, μ_{lead})	B	C	D	A (Prediction)	A (Observed)
310	2.2	120	223594	283519	94.6±8.6	95

[CMS-PAS-EXO-24-004]

Fake rate estimation

To account for the possibility that SM jets could fake a CSC cluster, we measure and apply a fake rate.

- Create sample of W+jets events using Full Run 2 dataset
  - Req. 1 tight ID, tight ISO lepton
  - Veto jets matching ΔR<0.4 the lepton
  - MET > 30 GeV
- FakeRate measured and applied as a function of **jetPt** and matched **cluster multiplicity**.

$$N_{Fakes} = \Sigma_{p_T^j} \mathbf{FR}(p_T^j) \times N_{Jets}(p_T^j)$$

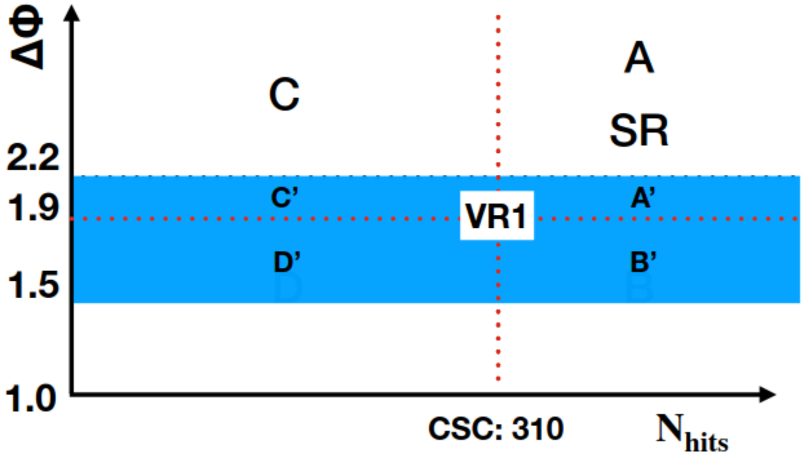
- Jets passing the cut on promoted to events with fake rate weight.
  - ~156 events to be included due to SM jets faking clusters.

P_T Bins [GeV]	Fake Rate
20.0-30.0	9.70978e-09 ± 4.34235e-09
30.0-40.0	3.45226e-08 ± 1.15075e-08
40.0-50.0	3.99186e-08 ± 1.62967e-08
50.0-60.0	6.25698e-08 ± 2.5544e-08
60.0-75.0	7.00959e-08 ± 2.86165e-08
75.0-200.0	1.15568e-07 ± 2.88919e-08
200.0-500.0	2.1248e-07 ± 1.22675e-07
500.0-1000.0	0 ± -

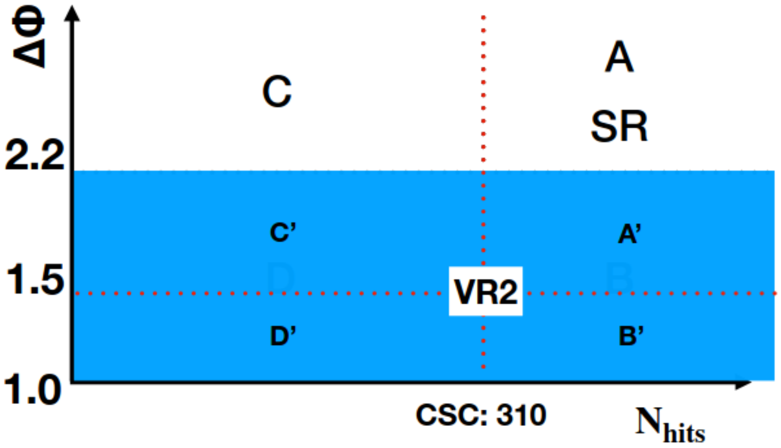
Region	Estimated irreducible background
A	155.86 ± 12.5
B	41.14 ± 6.41
C	16128.4 ± 127.0
D	5700.8 ± 75.5

Fake rate validation

- Defined two validation regions as subsets of main ABCD plane.
- Closure observed in both regions



	Prediction	Observation
ABCD′ Prediction	6.5 ± 3.9	–
Jet bkg Prediction	13.9 ± 3.87	–
Total	20.4 ± 5.4	18



	Prediction	Observation
Reducible bkg Prediction	8.8 ± 8.3	–
Irreducible bkg Prediction	27.3 ± 5.7	–
Total	36.1 ± 10.1	40

Simulation Modelling

- To study the systematic effect of applying our cluster level vetoes we apply a tag and probe selection (selection of the two best identified leptons) using a proxy process.
  - **Data: /SingleMuon/Run2017F-ZMu-17Nov2017-v1/RAW-RECO**
  - **MC: ZToMuMu_NNPDF31_13TeV-powheg_M50_120**
- Event Selection
  - Pass HLT_ISOMu27 (P_T > 27 GeV)
  - Muon selection
- **Tag:** Tight ID criterion / Isolation requirement on the muon
- **Probe:** Loose ID criterion / Isolation requirement on the muon
- $120 \le M_Z \le 800$ GeV

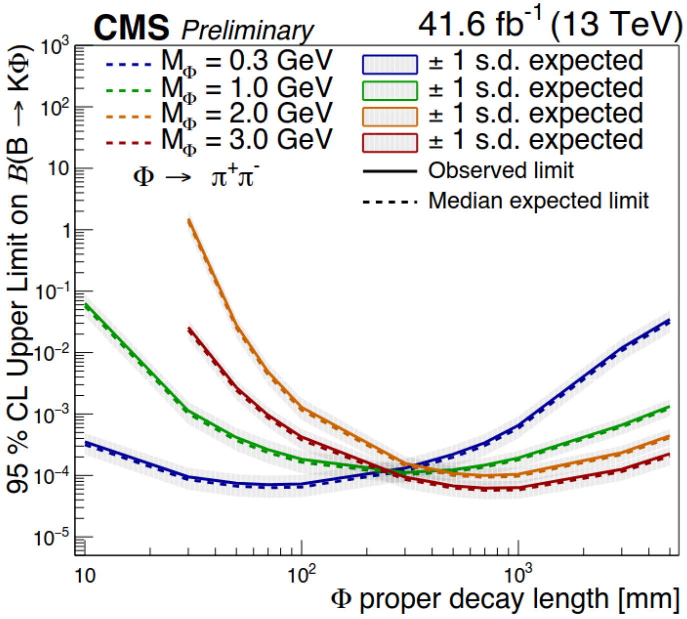
Summary of the systematic uncertainties

- Data uncertainties:
  - No uncertainties applied to the ABCD prediction.
  - Stat. unc assigned to the 156 events from the SM Jet fakes.
- MC
  - Summarized in table.
  - Also apply systematic unc. due to: lumi (~2.5%), PU (4.9%), TriggerSF (1.6%), MC Stat. (~19-32%)

Source	Uncertainty
Cross-section	0.9
Integrated luminosity	2.5
Cluster Efficiency	2.8
ME11/12 Veto	2.24
RE1 Veto	0.71
MB1 Segment Veto	1.1
RB1 Veto	2.56
Muon Veto	0.5
Muon ID scale factor	0.6
Cluster Time	0.3
Cluster Time Spread	7.79

Estimated limits

- First CMS result to search for this process.
- Computed limits on the Branching ratio B(B → KΦ) as a function of LLP decay distance cτ.
- Able to set limit on B(B → KΦ) at ~ 6×10^{-5} for decays to two charged pions.

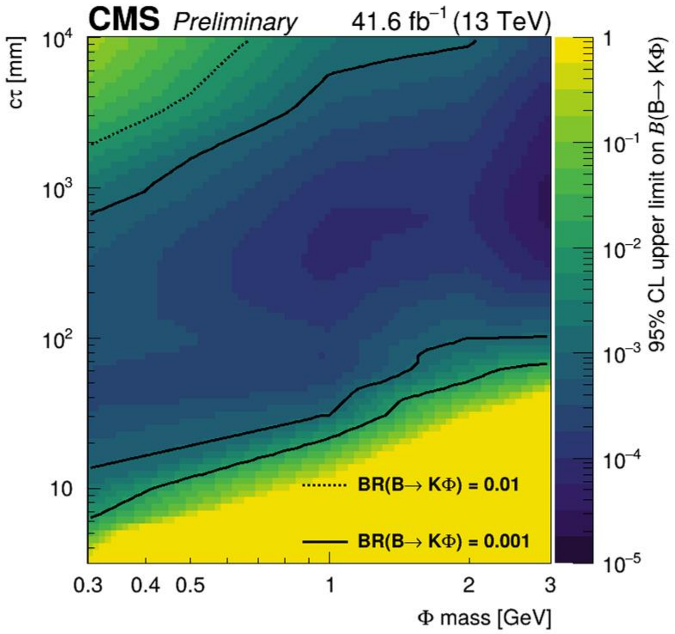


	B	C	D	A (SR)
Reducible background	19 ± 10	42632 ± 1240	51342 ± 490	16 ± 8
Irreducible background	41^{+10}_{-7}	16128^{+238}_{-230}	5701^{+93}_{-91}	156^{+31}_{-22}
Total background	60^{+14}_{-12}	58760^{+1263}_{-1261}	57043^{+499}_{-498}	171.52^{+32}_{-23}
Observed events	60	58760	57043	181

[CMS-PAS-EXO-24-004]

Estimated limits (2D)

- First CMS result to search for this process.
- Computed limits on the Branching ratio B(B → KΦ) as a function of LLP decay distance cτ.
- Able to set limit on B(B → KΦ) at ~ 6×10^{-5} for decays to two charged pions.



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[CMS-PAS-EXO-24-004]

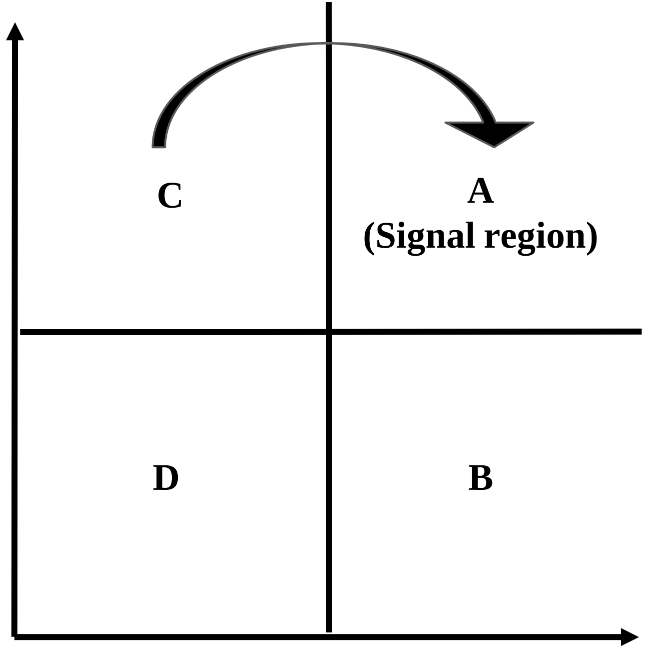
Summary

- The described analysis is only the 2nd LLP search done in B-parking dataset.
- Particularly sensitive to low-mass, low-P_T and LLP with longer lifetimes.
- An improvement in sensitivity by a factor of ~10 has been observed compared to the previous MDS analysis.
- The described analysis has been approved.

Thank you.

ABCD method for background estimation

- ABCD method requires two variables that are independent for background.
- Divides the phase space into four rectangular regions.
- For the background, the number of events in the region **A** is estimated based on **C**, **B** and **D** regions.



A = C * (B / D)

Long-lived particle (charged) searches in CMS experiment

- A single, well identified muon with $P_T > 50$ GeV trigger has been used to capture muon-like signals.
- The **LLP candidates** are required to match with a track reconstructed from hits in the silicon detectors.
  a. High-purity tracks are selected.
  b. Tracks must have a good fit: χ^2 / dof < 5.
- At least one LLP candidate with $P_T > 55$ GeV per event is required.
- The longitudinal and transverse impact parameters: $d_z < 0.1$ cm and $d_{xy} < 0.02$ cm.

$$I_\mathrm{h} = \left(\frac{1}{N}\sum_{j=1}^{N}\left(\frac{\mathrm{d}E}{\mathrm{d}x_j}\right)^{-2}\right)^{-1/2}$$
- Mean energy loss (summation over tracks)

$$I_\mathrm{h} = K\frac{m^2}{p^2} + C$$
approximated Bethe-Bloch formula in the nonrelativistic regime, K, C empirical parameters

pp→Gluino (G)
pp→STop
pp→STau
pp→Z′→l$^+$ l$^-$ (lepton charge is 2e)

$$G_\mathrm{i}^\mathrm{Strips} = \frac{3}{N}\left(\frac{1}{12N} + \sum_{j=1}^{N}\left[P_j\left(P_j - \frac{2j-1}{2N}\right)^2\right]\right)$$

$$F_\mathrm{i}^\mathrm{Pixels} = 1 - \prod_{j=1}^{n} P'_j \sum_{k=0}^{n-1}\frac{\left[-\ln\left(\prod_{j=1}^{n} P'_j\right)\right]^k}{k!}$$

←Discriminants

n - the number of measurements in the silicon pixel detector

P_j - probability for a MIP to produce a charge smaller or equal to that of the j-th measurement in the detector.

[CMS-PAS-EXO-18-002]

Long-lived particle (charged) searches in CMS experiment

[CMS-PAS-EXO-18-002]

- Two approaches of background estimation were used:
  a. **The ionization method:** ABCD method is used, and the signal region is selected based on G_i^{Strips} and F_i^{Pixels} distributions.

     (The signal region is defined by $F_i^{Pixels} > 0.9$, $G_i^{Strips} > 0.25$, and $P_T > 200$ GeV)

  a. **The mass method:** This method is based on searching for a new resonance in the mass spectrum of the LLP candidates using the ionization variable I_h and momentum p_{LLP}.
     i. the control region A defined as $G^{Strips}{}_i < 0.018$ and $55 < P_T < 70$ GeV,
     ii. the control region B defined as $G^{Strips}{}_i > 0.22$ and $55 < P_T < 70$ GeV,
     iii. the control region C defined as $G^{Strips}{}_i < 0.018$ and $P_T > 70$ GeV,
     iv. **and the signal region D is defined as $G^{Strips}{}_i > 0.22$ and $P_T > 70$ GeV.**

Long-lived particle (charged) searches in CMS experiment

[CMS-PAS-EXO-18-002]

- Two approaches of background estimation were used:
  a. **The ionization method:** ABCD method is used, and the signal region is selected based on G_i^{Strips} and F_i^{Pixels} distributions.

     (The signal region is defined by $F_i^{Pixels} > 0.9$, $G_i^{Strips} > 0.25$, and $P_T > 200$ GeV)

  a. **The mass method:** This method is based on searching for a new resonance in the mass spectrum of the LLP candidates using the ionization variable I_h and momentum p_{LLP}.
     i. the control region A defined as $G^{Strips}{}_i < 0.018$ and $55 < P_T < 70$ GeV,
     ii. the
     iii. the
     iv. **and**