Searches for BSM physics using long-lived signatures with the CMS detector

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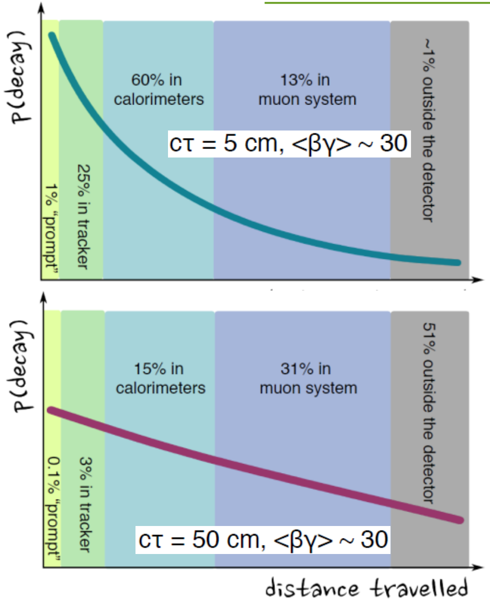
What are LLPs?

From H. Russell's Slides



- Particles that have relatively long lifetime (> $\mathbf{O}$(ns)), that travel significant distances before decaying (0.01 – 1 m)
- Naturally arise in many BSM scenarios like SUSY, dark matter models and hidden sector theories
- Main signature: displaced origin
  - may have other signature depending on the analysis

Why are they long-lived?

$$\frac{1}{\tau} = \Gamma = \frac{1}{2m}\int \mathrm{dLIPS}\,|\mathcal{M}|^2 \sim \frac{\varepsilon^2}{(8\pi)^{a-1}}\,\frac{m^n}{M^{n-1}}$$

arXiv:2212.03883

- ✓ Small couplings to SM → decay channels are suppressed
- ✓ Kinematics → small phase-space volume, suppressing decay
- ✓ Decays via Heavy Mediator → the decay width is suppressed by a factor of $(m/M)^p$

Trigger and Dataset

Custom Hardware processors

Farm of processors

Bunch crossing → (40 MHz) → Level-1 Trigger (L1) → (100 kHz) → High Level Trigger (HLT) → (1 kHz) → Standard dataset for offline reconstruction and analysis

High Level Trigger (HLT) → (5 kHz) ↓

B-parking dataset Run 2 (2018)

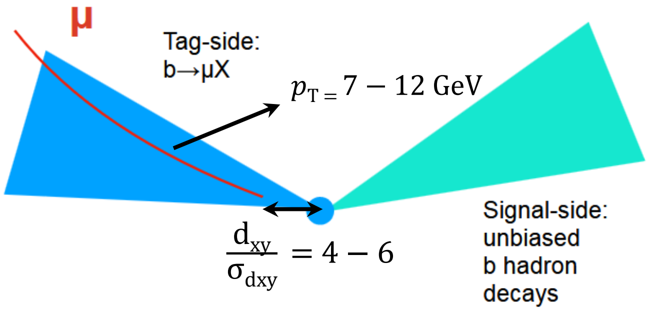


Figure from B-parking internal CMS performance note

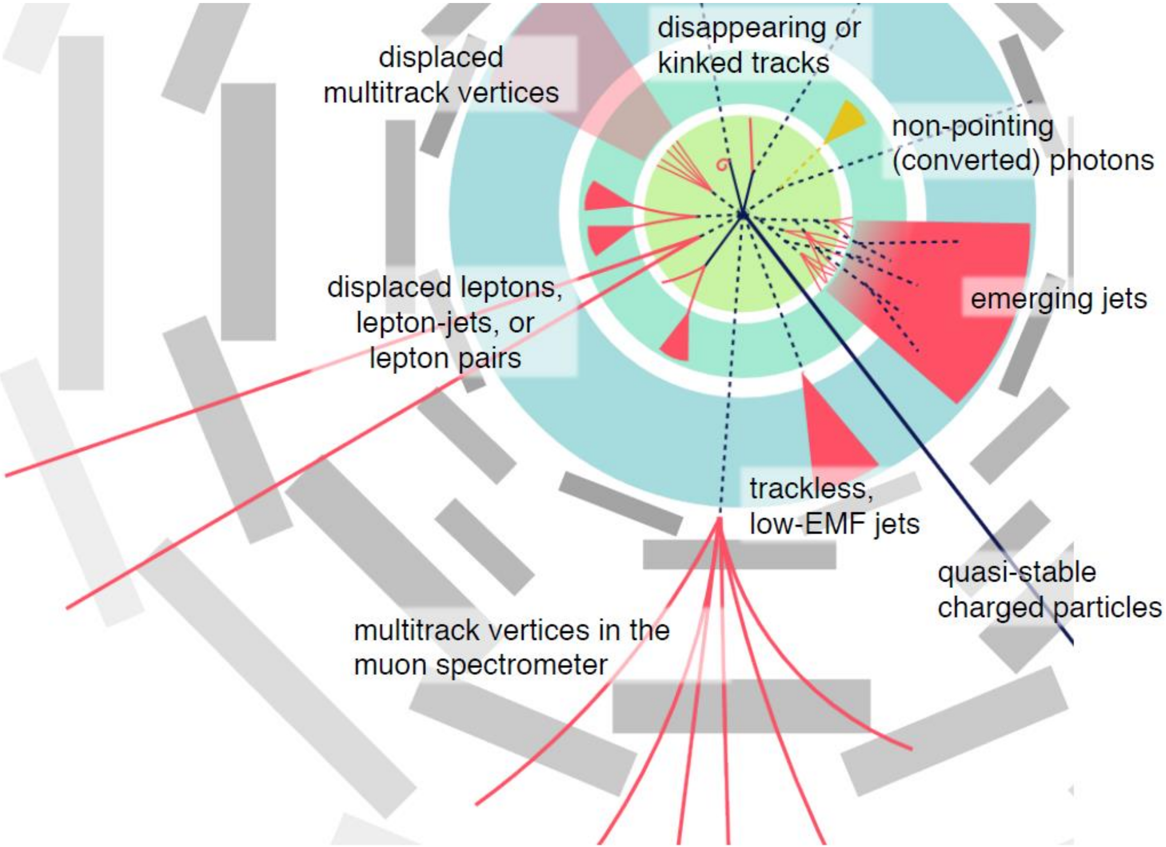
- Single muon triggers
  - Lower thresholds
- Integrated luminosity 41.6 fb^{-1}

LLP Searches at CMS

Many search analyses within CMS

- ✓EXO-23-013 (displaced jets)
- ✓EXO-22-019 (displaced lepton-jets)
- EXO-22-015 (emerging jets)
- EXO-22-017 (muon spectrometer)
- EXO-22-020 (displaced vertices)
- ✓EXO-21-008 (muon spectrometer)
- EXO-21-014 (trackless jets)
- ✓EXO-18-002 (stable charged particles)
- EXO-19-005 (delayed photons)

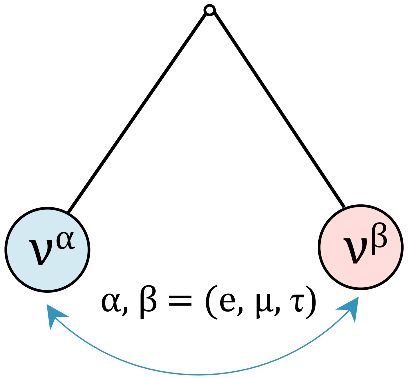
The full list of public results of BSM searches using LLP can be found here



From H. Russell's Slides

Heavy Neutral Lepton Search

EXO-22-019



Neutrino oscillations ⇒ Neutrinos are massive

Not explained by SM

Possible solution: **Extend SM to νMSM**

- Add right-handed sterile neutrinos ν_R
- Gets mass by Seesaw mechanism

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{\nu}_R^c\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M\end{pmatrix}\begin{pmatrix}\nu_L^c \\ \nu_R\end{pmatrix} + \text{h.c}$$

SM

νMSM

$$m_\nu = \frac{m_D^2}{M}$$

$$\nu \sim (\nu_L + \nu_L^C)$$

$$m_{HNL} = M$$

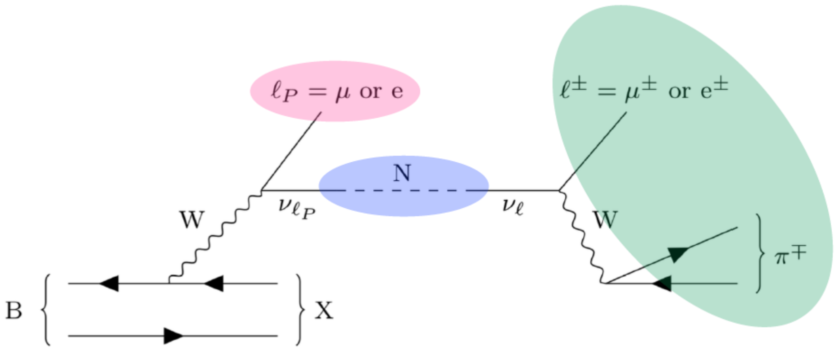
$$HNL \sim (\nu_R + \nu_R^C)$$

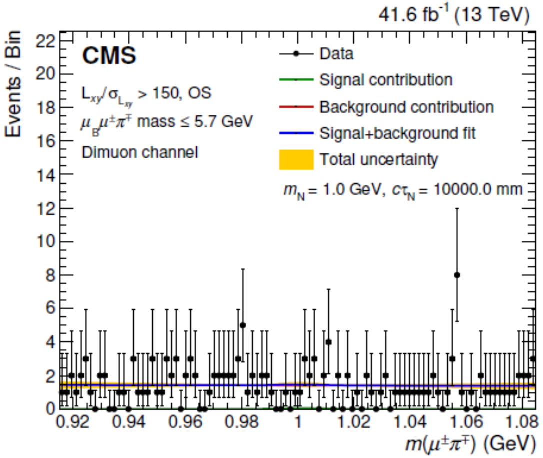
Outcomes:

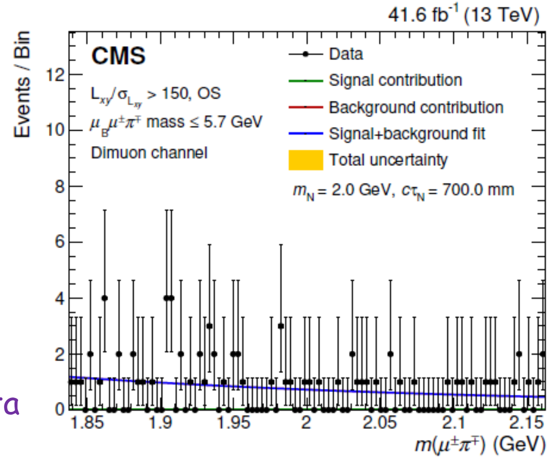
- Mass eigenstates N_1, N_2, N_3 (ordered in mass)
- Lightest neutrino N_1 serves as DM candidate
- N_2 and N_3 are LLPs

Heavy Neutral Lepton Search

EXO-22-019



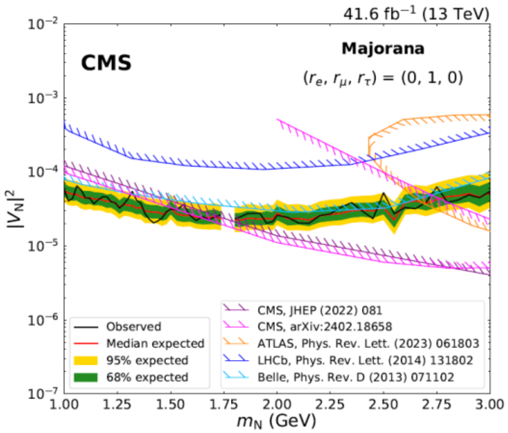


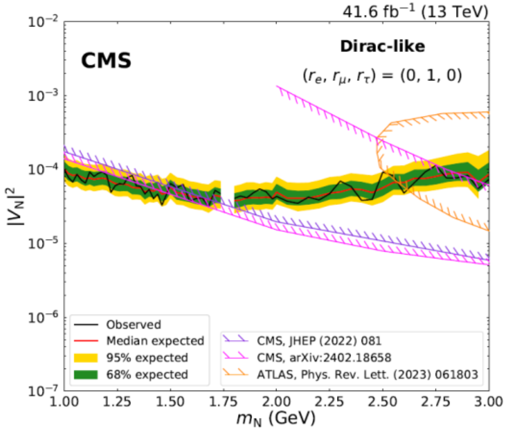


- Analysis performed using B-parking dataset
  - ✓ Triggered by muon
  - ✓ 3 flavor channels explored in the analysis: μμ, μe, eμ
- Strategy:
  - Reconstruct displaced vertex using $l^{\pm}$ and $\pi^{\pm}$ tracks
  - Bump hunt in $(l^{\pm}\pi^{\pm})$ mass spectrum
- Event selection using parametric neural network (list of variables)
- Background for training obtained by taking 1/1000 of events available in data

Heavy Neutral Lepton Search

EXO-22-019





- Signal rate = $F(m_N, V_N)$ (link)

$$|V_N|^2 \equiv |V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2$$

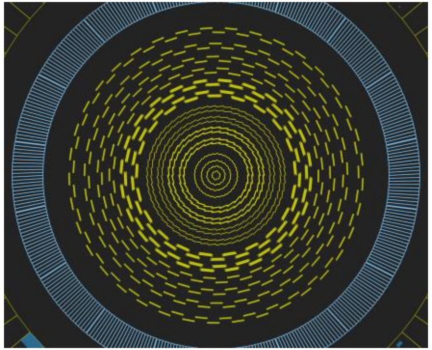
$$r_\ell \equiv |V_{\ell N}|^2 / |V_N|^2 \quad \ell = (e, \mu, \tau)$$

- The limits are calculated in terms of the mass m_N and mixing V_N
- The best limit is obtained for muon exclusive mixing $(0, 1, 0)$ at 95% CL

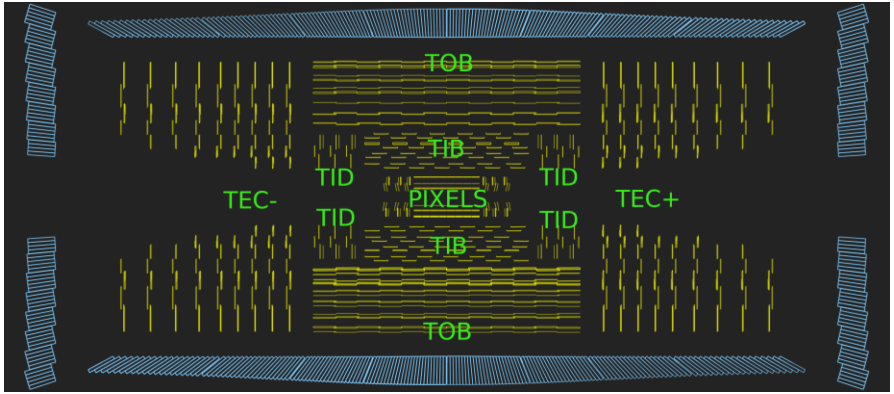
(r_e, r_μ, r_τ)	Scenario	$\lvert V_N\rvert^2$	Mass (GeV)
(0, 1, 0)	Majorana	2.0×10^{-5}	1.95
(0, 1/2, 1/2)	Majorana	4.0×10^{-5}	1.42
(1/2, 1/2, 0)	Majorana	3.3×10^{-5}	2.15
(1/3, 1/3, 1/3)	Majorana	5.0×10^{-5}	2.15
(0, 1, 0)	Dirac-like	3.2×10^{-5}	1.68
(0, 1/2, 1/2)	Dirac-like	6.5×10^{-5}	1.68
(1/2, 1/2, 0)	Dirac-like	5.7×10^{-5}	1.68
(1/3, 1/3, 1/3)	Dirac-like	8.5×10^{-5}	1.68

Heavy Stable Charged Particle Search

EXO-18-002



- Model independent search for HSCPs
- Main signature → **Isolated high p_T track** with Large energy loss per unit length (dE/dx)
- $m_{HSCP} > 100$ GeV ⇒ $\beta = v/c$ significantly smaller than 1
  - ✓ Distinguishable from ultra-relativistic SM particles
- Search performed using Run 2 data of 2017 and 2018 → Total luminosity $101\ \text{fb}^{-1}$



- Only barrel region of the tracker is used
  - 4 pixel detector layer (after upgrade in 2017) and 10 layers of strip detectors
  - Coverage: $|\eta| < 1.4$
  - Track resolution:

    p_T → 2.8% at 100 GeV

    position → 10(30) μm in transverse (longitudinal) IP

Heavy Stable Charged Particle Search

EXO-18-002

Observables

Ionization Method

- For Pixel detector

$$F_i^{\text{Pixels}} = 1 - \prod_{j=1}^{n} P_j' \sum_{k=0}^{n-1} \frac{[-\ln(\prod_{j=1}^{n} P_j')]^k}{k!}$$

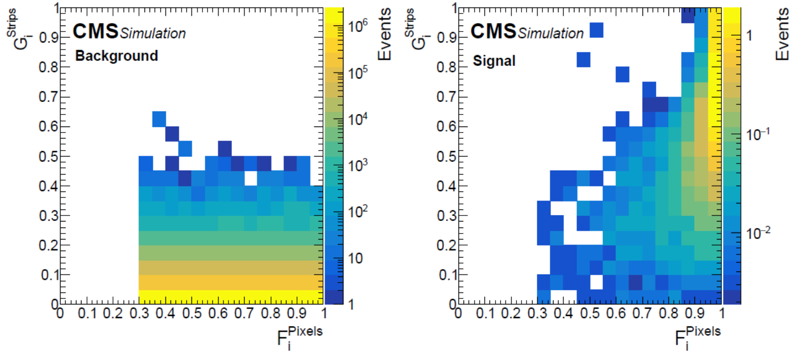
$P_j \longrightarrow$ MIP hit probability $n \longrightarrow$ number of pixel hits (excluding layer 1)

- For Strip detector

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

$P_j' \longrightarrow$ MIP hit probability to produce charge equal or less than j^{th} measured charge

$N \longrightarrow$ number of hits



Mass Method

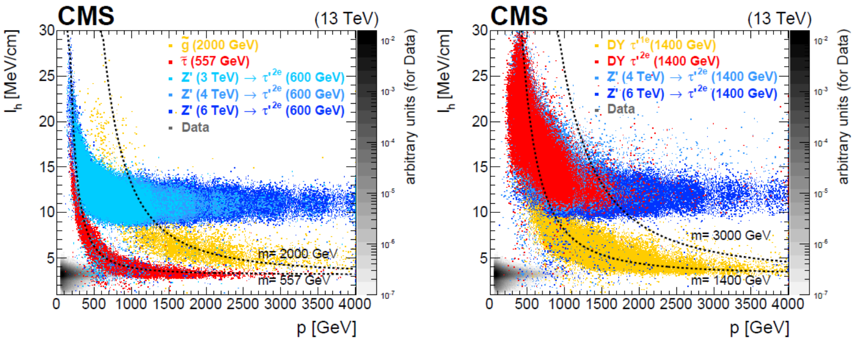
- Ionization Estimator

$$I_h = \left(\frac{1}{N}\sum_{j}^{N}(dE/dx_j)^{-2}\right)^{-1/2}$$

- Mass of HSCP $\quad I_h = K\frac{m^2}{p^2} + C$

$m \rightarrow$ mass
$p \rightarrow$ momentum

- Constants K and C are determined from a sample of low-momentum particles (link)
- Equation is inverted to calculate the mass of the candidate particle from dE/dx measurement

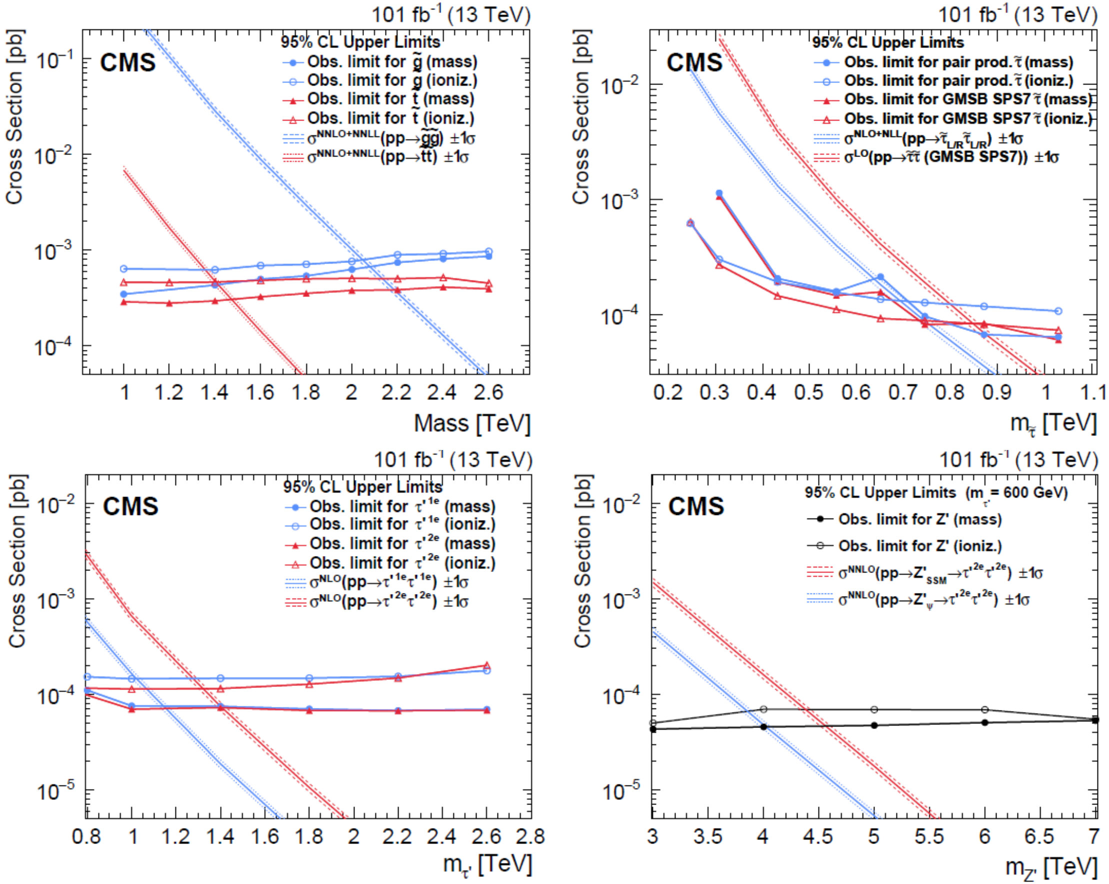


Heavy Stable Charged Particle Search

EXO-18-002

Results

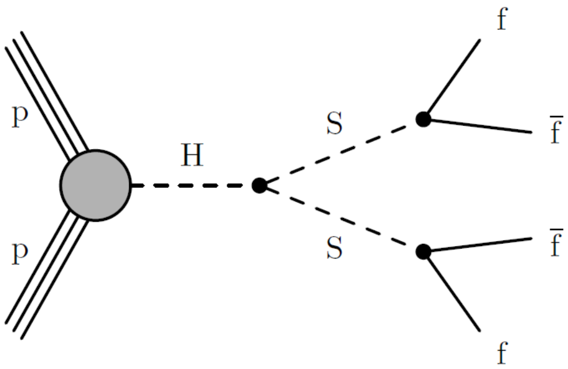
- ABCD method used to estimate background in SR by defining CR for both the methods
- Results interpreted based on many signal production scenarios
- Limits calculated for production cross-section vs. mass of HSCP at 95% CL

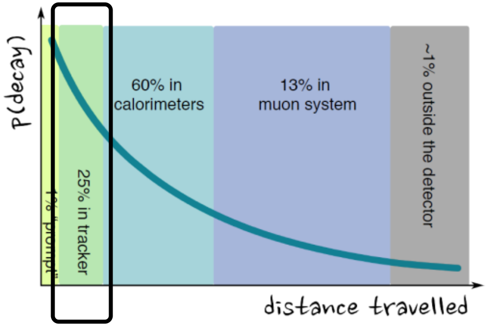


LLP Search with Displaced Jets

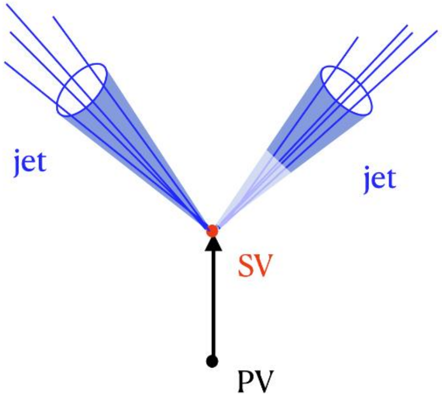
EXO-23-013

From H. Russell's Slides





- Search for LLPs decaying to hadronic final state
- Focusing on low mass LLP :
  $m_{LLP} = 10 – 60$ GeV
  $c\tau = 1 – 1000$ mm



- Main signature → displaced-jet vertex (DV) and tracks
- Benchmark Model → Higgs portal to hidden sector
- Search performed using Run 3 data of 2022 (13.6 TeV)
  → Total luminosity 34.7 fb^{-1}
- Dedicated displaced-jet triggers used to collect data

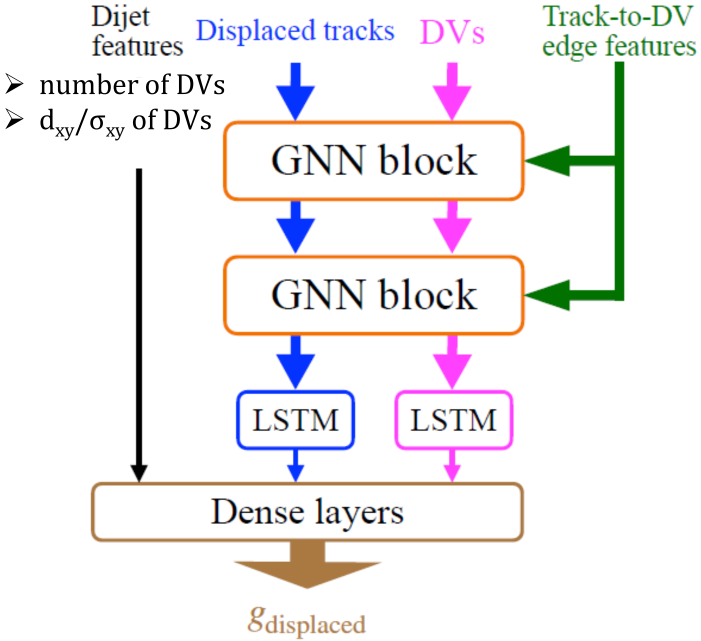
LLP Search with Displaced Jets

EXO-23-013

Two GNN-based Taggers

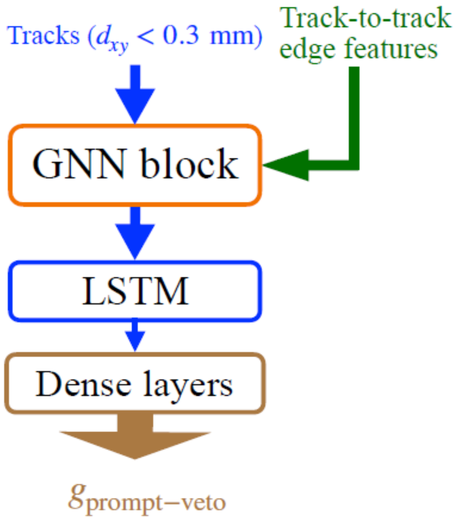
Displaced Tagger

✓ Learns presence of displaced activities



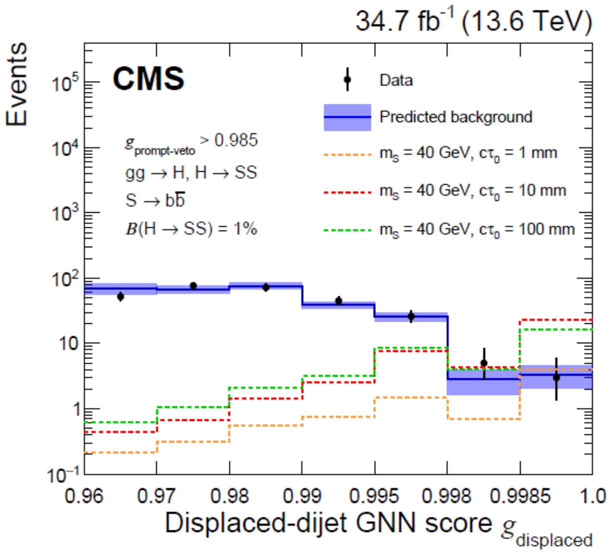
Prompt Tagger

✓ Learns absence of prompt activities



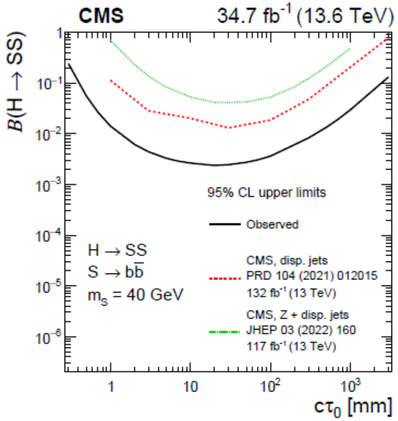
LLP Search with Displaced Jets

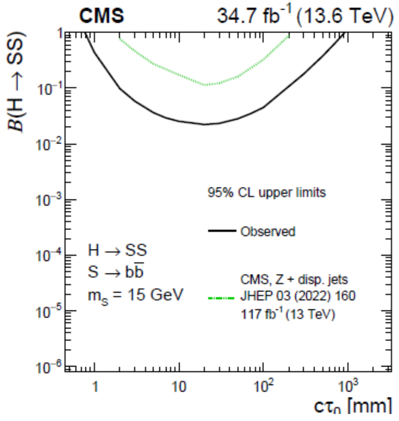
EXO-23-013



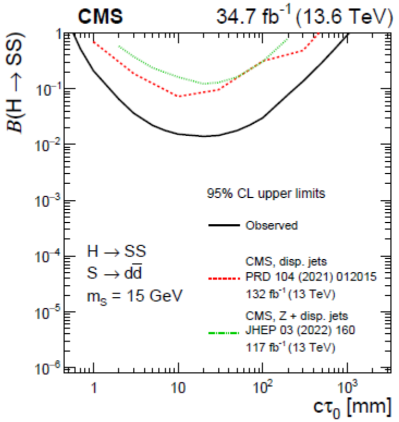
The tagger scores are used as variables for the ABCD method to estimate the background in SR.

Results





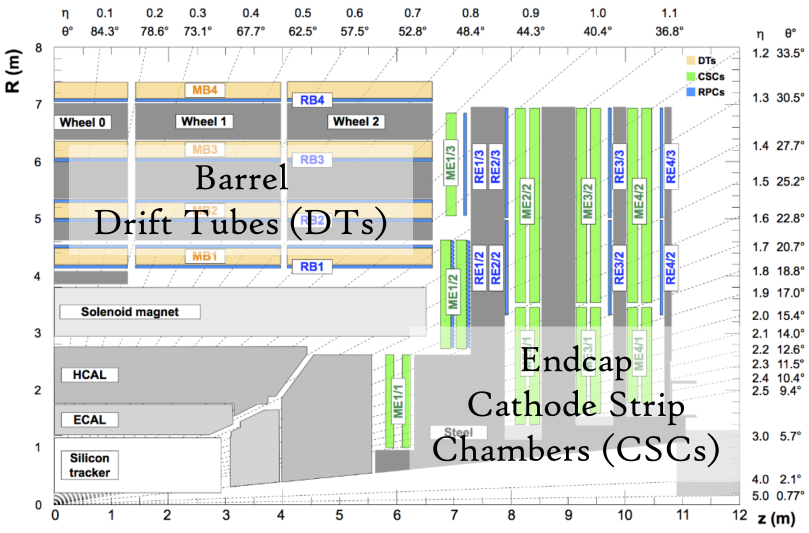
- Results interpreted with signal models with varying mass of S
- Limits calculated for BR of H → SS vs. $c\tau_0$ of S at 95% CL

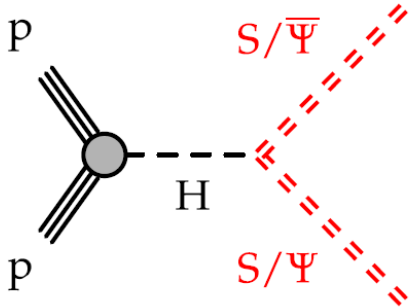


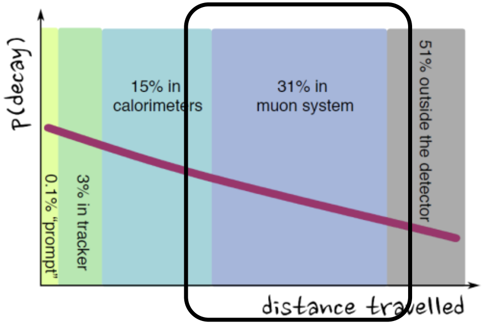
LLP Search with Muon System

EXO-21-008

From H. Russell's Slides





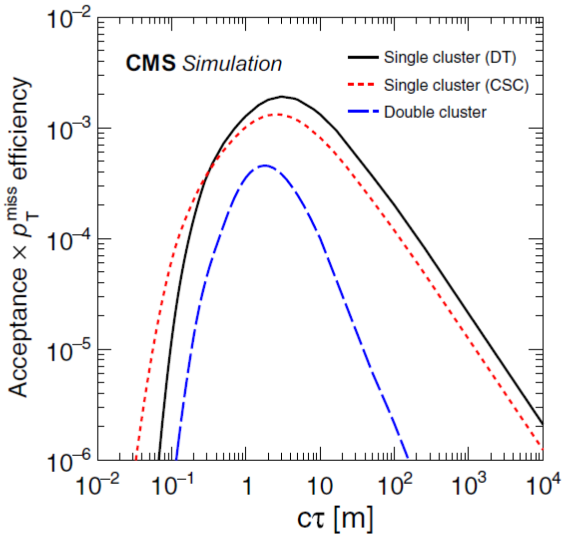


- Search for LLPs producing shower in the muon system
- Main signature → Cluster of hits in the muon system in the direction of missing transverse momentum (MET or $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$)
- Benchmark Model → Twin Higgs and Dark Shower Model
- Search performed using full Run 2 data (13.6 TeV)

  → Total luminosity 138 fb^{-1}
- Events selected based on MET
  - ✓ MET > 120 GeV HLT
  - ✓ MET > 200 GeV in offline selection

LLP Search with Muon System

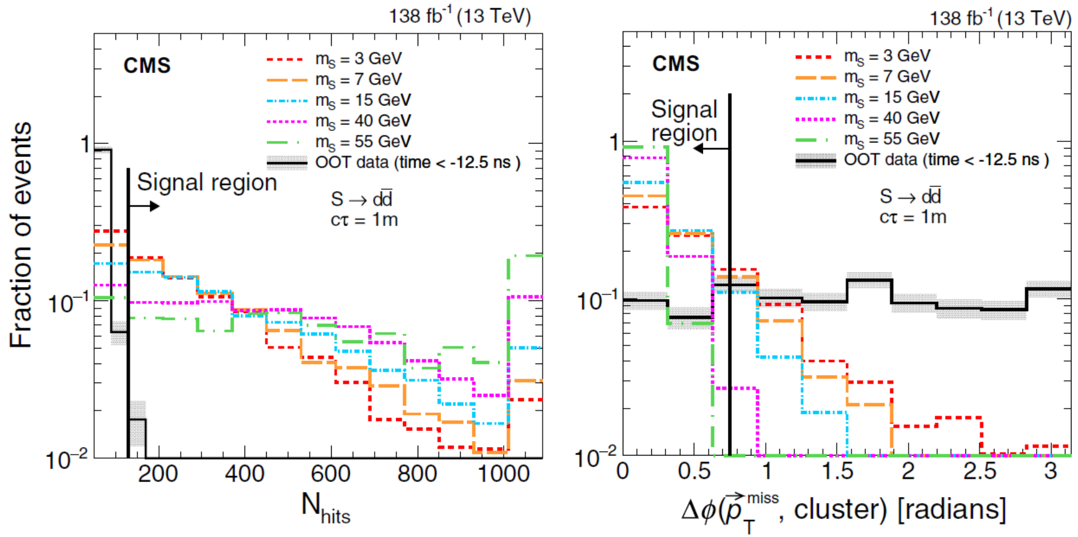
EXO-21-008



3 mutually exclusive search categories:

- Double Clusters: CSC-CSC, DT-DT and CSC-DT
- 1 DT Cluster
- 1 CSC Cluster

Observables

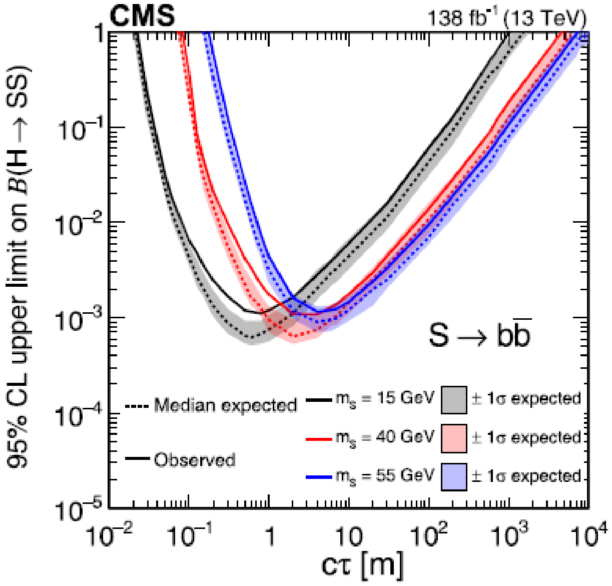


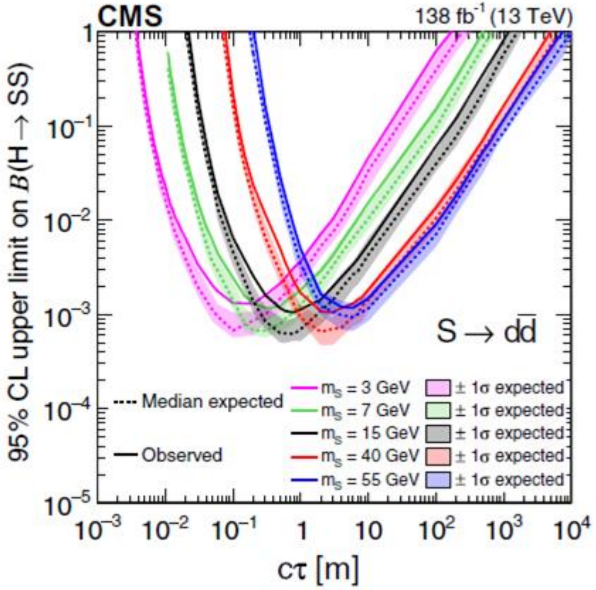
- ➢ Two discriminating variables defined for the analysis
  - N_{hits} → Number of hits in the cluster
  - $\Delta\phi(\vec{p}_T^{miss}$, cluster) → Angular separation between MET and the cluster
- ➢ These are correlated for signal and uncorrelated for background. So, ABCD method employed to estimate background in SR

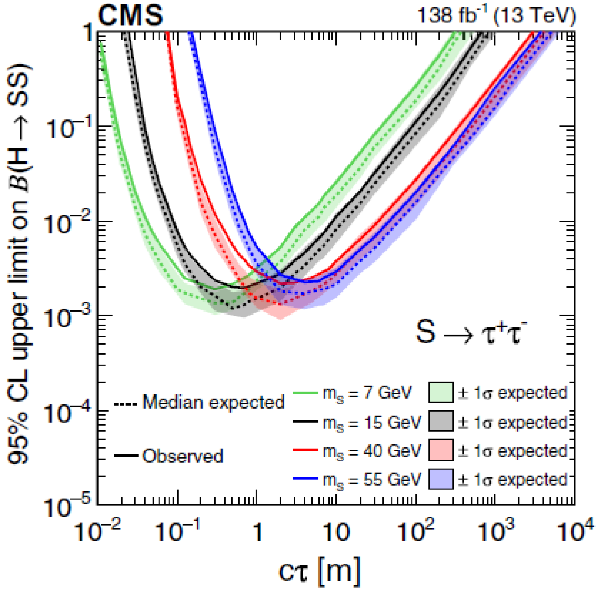
LLP Search with Muon System

EXO-21-008

Results





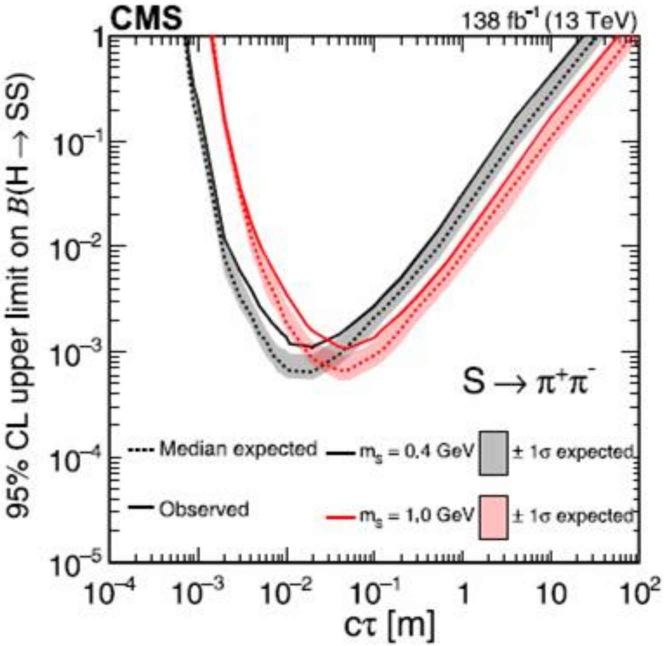


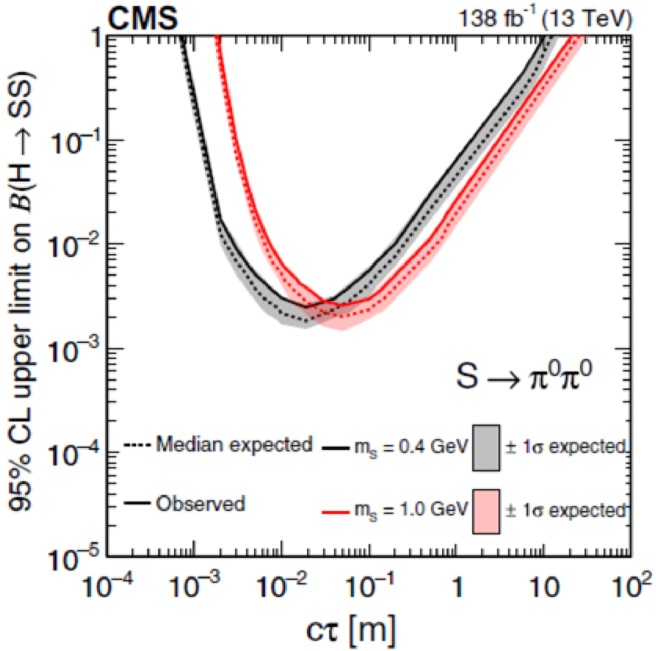
- Results interpreted with signal models with varying mass of S
- Limits calculated for BR of H → SS vs. cτ of S at 95% CL

LLP Search with Muon System

EXO-21-008

Results





- Results interpreted with signal models with varying mass of S
- Limits calculated for BR of $H \rightarrow SS$ vs. $c\tau$ of S at 95% CL

Future Outlook

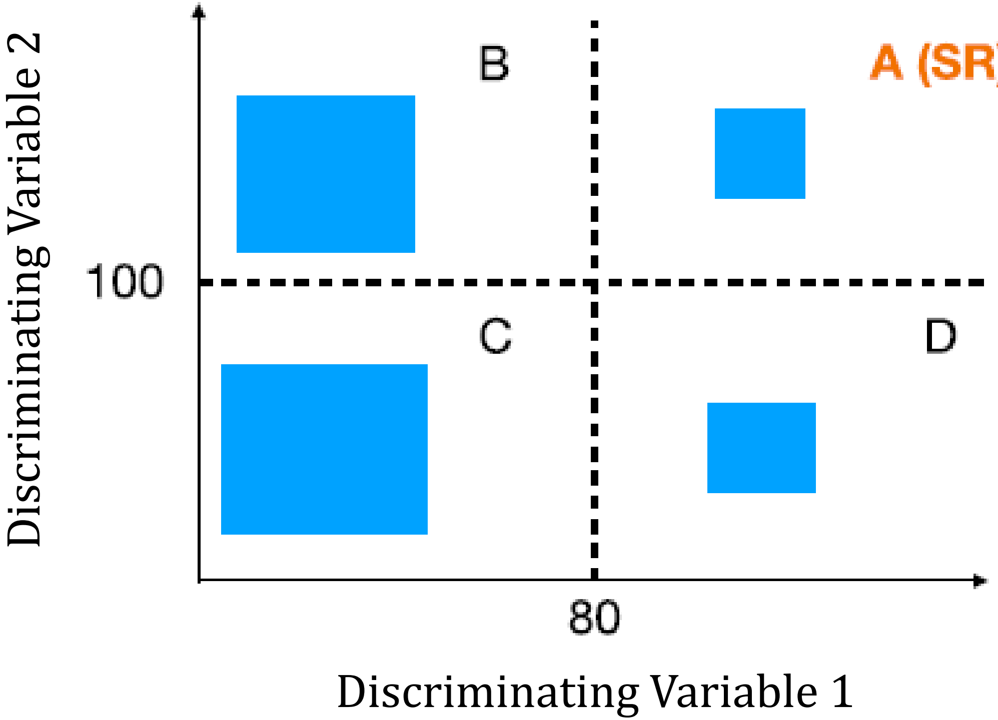
- New ML triggers
  - Auto-encoder based AXOL1TL trigger for selecting anomalous events
  - CNN based calorimeter trigger CICADA
- Inclusion of tracker information at L1 trigger → improved selection efficiency for events with displaced vertices
- Proposed detector upgrades at CMS like Massive Timing Hodoscope for Ultra Stable neutraL pArticles (MATHUSLA), a surface based dedicated detector for neutral LLPs

More LLP searches coming-up, STAY TUNED!

Thank you for your attention!

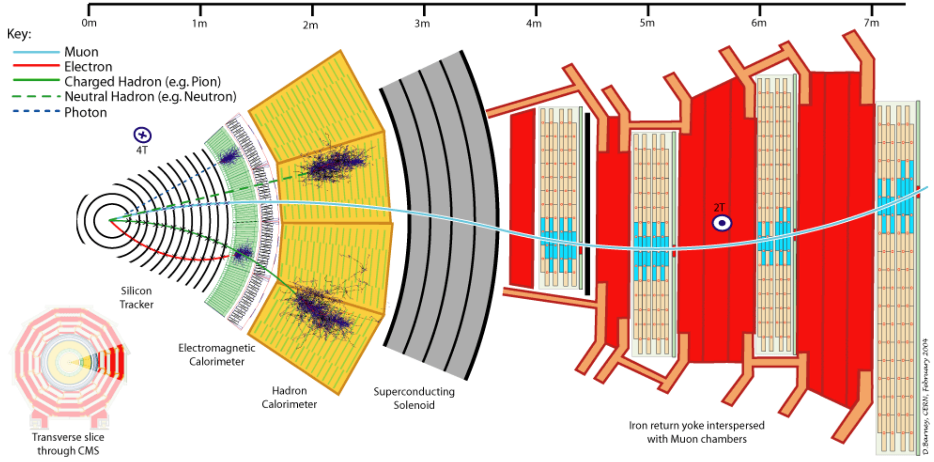
BACKUP

ABCD Method



$$N_{bkg}(A) = \frac{N(B)N(C)}{N(D)}$$

CMS Detector



Bunch crossing

40 MHz

Custom Hardware processors

Level-1 Trigger (L1)

100 kHz

Farm of processors

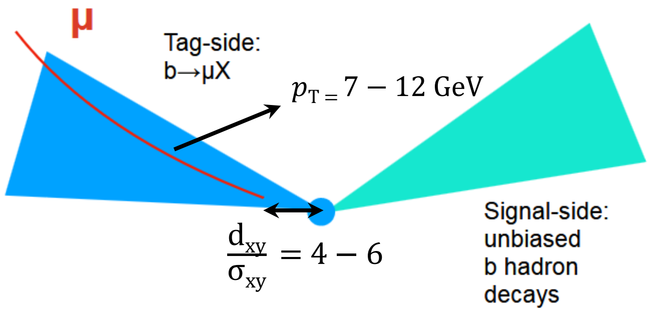
High Level Trigger (HLT)

5 kHz

1 kHz

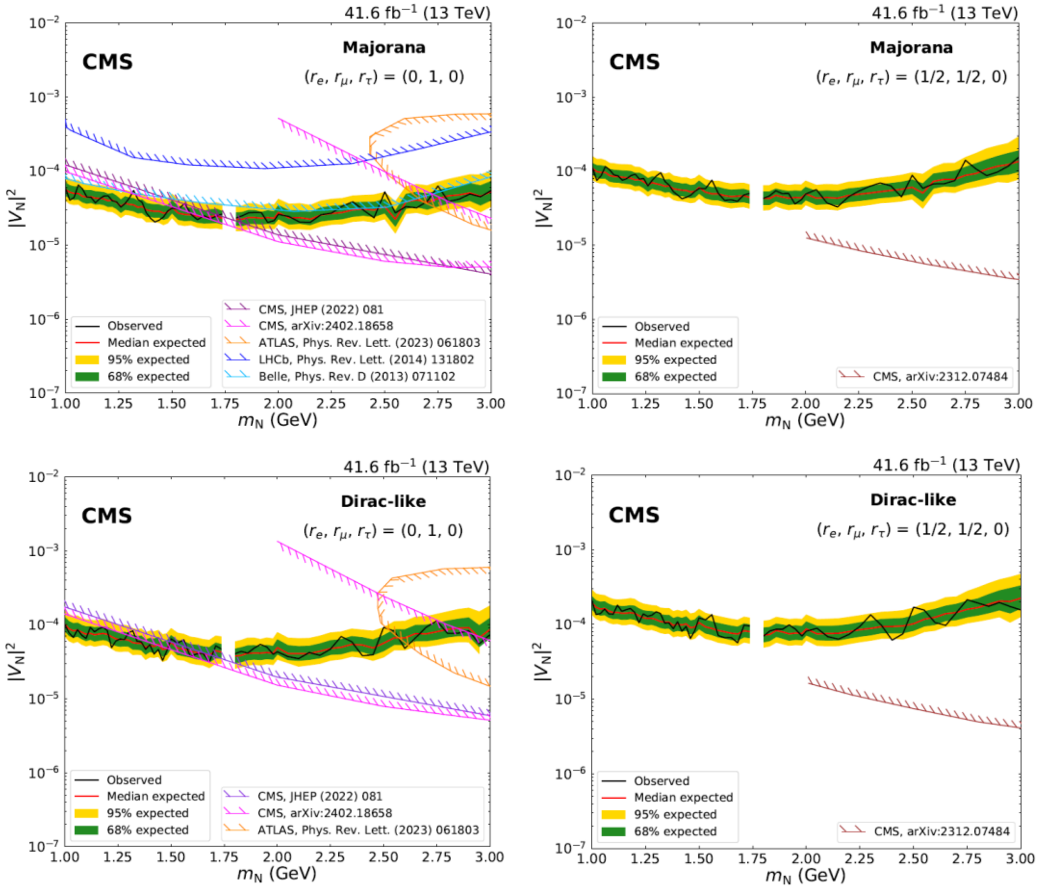
Standard dataset for offline reconstruction and analysis

B-parking dataset Run 2 (2018)



- Single muon triggers
  - ➢ Lower thresholds
- Integrated luminosity 41.6 fb^{-1}

Heavy Neutral Lepton Search



- Signal rate = $F(m_N, V_N)$

$$|V_N|^2 \equiv |V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2$$

$$r_\ell \equiv |V_{\ell N}|^2 / |V_N|^2 \quad \ell = (e, \mu, \tau)$$

- The limits are calculated in terms of the mass m_N and mixing V_N
- The best limit is obtained for muon exclusive mixing $(0, 1, 0)$ at 95% CL

$$|V_N|^2 > 2.0 \times 10^{-5} \text{ at } m_N = 1.95 \text{ GeV}$$

Majorana-like case

$$|V_N|^2 > 3.2 \times 10^{-5} \text{ at } m_N = 1.68 \text{ GeV}$$

Dirac-like case

Heavy Neutral Lepton Search

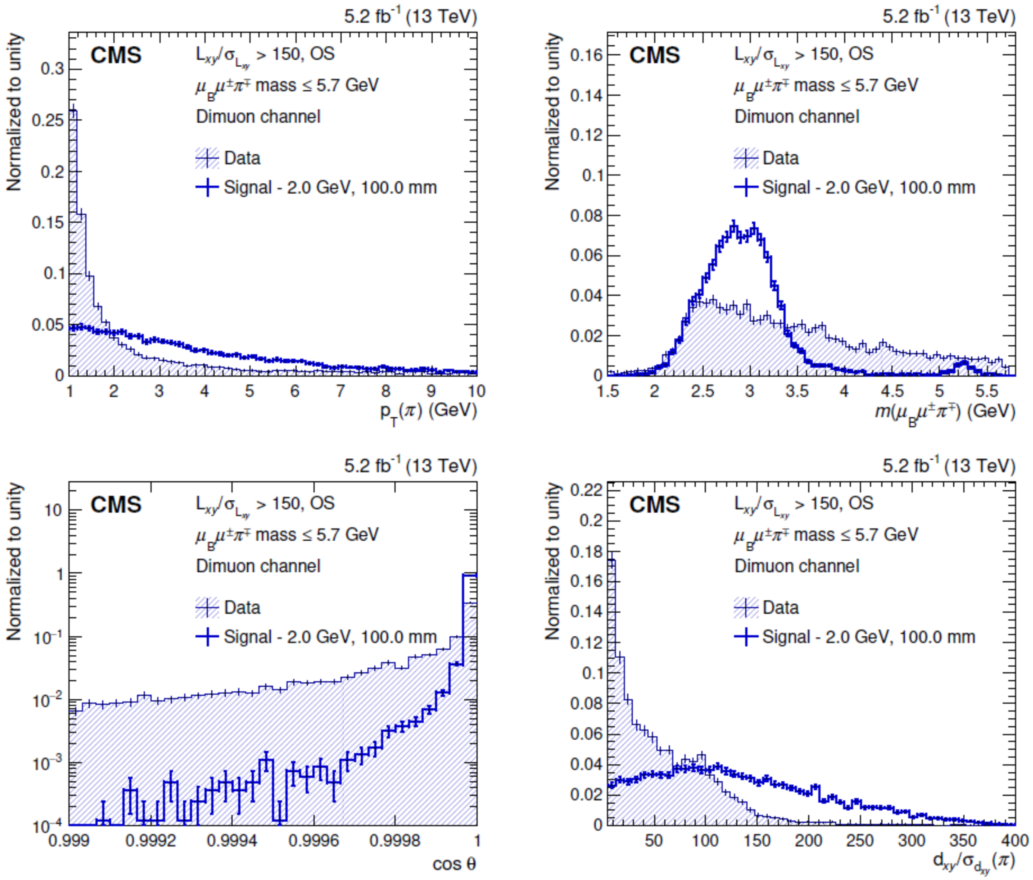
List of Input Variables for pNN

1. Transverse momenta: $p_T(\ell_B)$, $p_T(\ell^{\pm})$, $p_T(\pi^{\mp})$.
2. Invariant-masses: $m(\ell_B\pi^{\mp})$, $m(\ell_B\ell^{\pm})$, $m(\ell_B\ell^{\pm}\pi^{\mp})$.
3. Track separation in the η-φ space (where φ is the azimuthal angle) $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$: $\Delta R(\ell_B, \ell^{\pm})$, $\Delta R(\ell_B, \pi^{\mp})$
4. Displaced vertex properties: $\cos\theta$, fit p-value.
5. Displacement-related quantities: $L_{xy}/\sigma_{L_{xy}}$ and $d_{xy}/\sigma_{d_{xy}}$ of the pion.
6. Track-related information: number of layers of the CMS silicon pixel and strip tracker traversed by the lepton(s) and pion from the DV.
7. Lepton isolation, defined in a cone of ΔR smaller than 0.3 around the lepton momentum vector

back to main

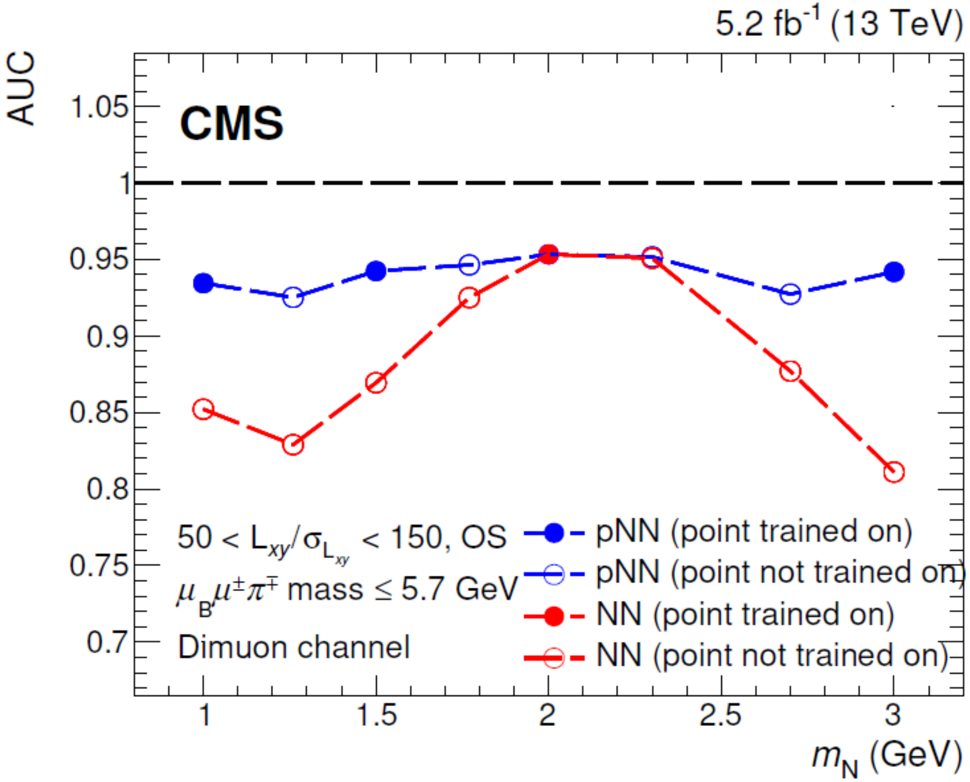
Heavy Neutral Lepton Search

Input Variable Distribution



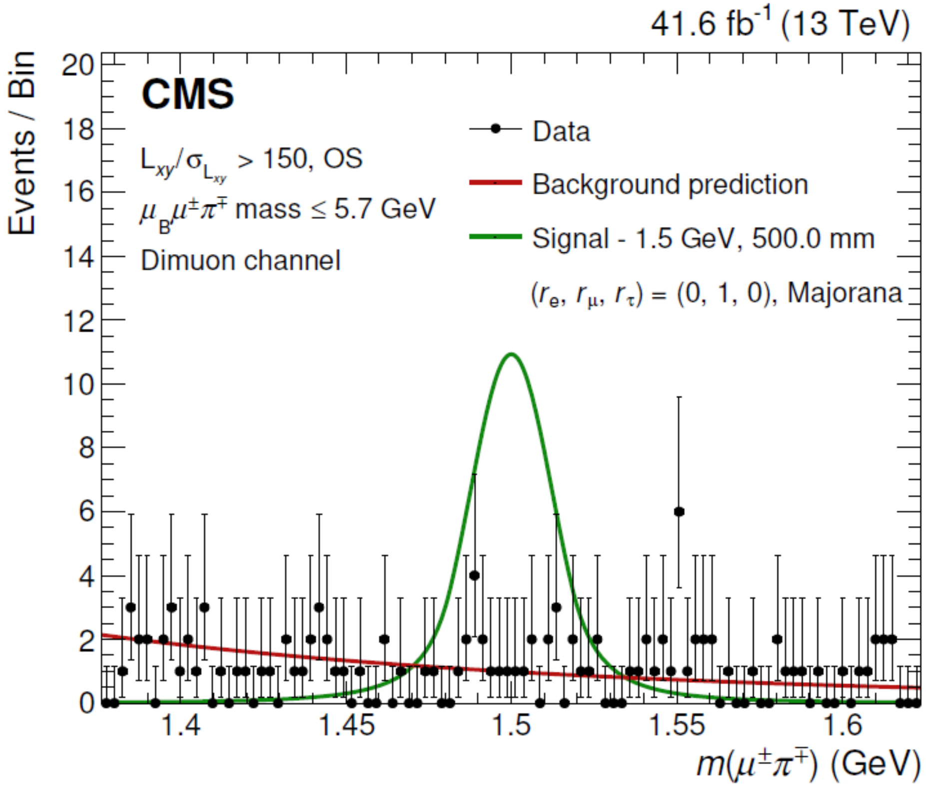
Heavy Neutral Lepton Search

pNN Validation



Heavy Neutral Lepton Search

Invariant Mass distribution



Heavy Neutral Lepton Search

Estimation of Signal Events

$$N_{\text{sig}}\left(\ell_{\text{B}}\ell, m_{\text{N}}, c\tau_{\text{N}}, \vec{r}\right) = \frac{\sigma^{\text{eff}}_{\text{B}^{\pm}}}{f_u}\mathcal{L}\sum_{\text{q}} F^{\text{q}}_{\text{N}}\left(\ell_{\text{B}}\ell, m_{\text{N}}, c\tau_{\text{N}}, \vec{r}\right)\epsilon^{\text{q}}_{\text{sig}}\left(\ell_{\text{B}}\ell, m_{\text{N}}, c\tau_{\text{N}}\right)$$

$$F^{\text{q}}_{\text{N}}\left(\ell_{\text{B}}\ell, m_{\text{N}}, c\tau_{\text{N}}, \vec{r}\right) = \underbrace{\sum_{\text{X}_{\text{b}}} f_{\text{q}}\frac{\widetilde{\Gamma}(\text{B}_{\text{q}} \to \ell_{\text{B}}\text{N}\text{X}_{\text{b}})}{\Gamma(\text{B}_{\text{q}})} r_{\ell_{\text{B}}}|V_{\text{N}}|^2}_{\text{N production}} \underbrace{\frac{\widetilde{\Gamma}\left(\text{N} \to \ell\pi\right)}{r_{\text{e}}\widetilde{\Gamma}_{\text{e}}\left(\text{N}\right) + r_{\mu}\widetilde{\Gamma}_{\mu}\left(\text{N}\right) + r_{\tau}\widetilde{\Gamma}_{\tau}\left(\text{N}\right)} r_{\ell}}_{\text{N decay}}$$

$$\frac{1}{c\tau_{\text{N}}} = |V_{\text{N}}|^2\left(r_{\text{e}}\widetilde{\Gamma}_{\text{e}}\left(\text{N}\right) + r_{\mu}\widetilde{\Gamma}_{\mu}\left(\text{N}\right) + r_{\tau}\widetilde{\Gamma}_{\tau}\left(\text{N}\right)\right)$$

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Heavy Stable Charged Particle

Control Region and Signal Region for Mass Method

control region A defined as $G_i^{\mathrm{Strips}} < 0.018$ and $55 < p_T < 70\,\mathrm{GeV}$

control region B defined as $G_i^{\mathrm{Strips}} > 0.22$ and $55 < p_T < 70\,\mathrm{GeV}$

control region C defined as $G_i^{\mathrm{Strips}} < 0.018$ and $p_T > 70\,\mathrm{GeV}$

signal region D is defined as $G_i^{\mathrm{Strips}} > 0.22$ and $p_T > 70\,\mathrm{GeV}$.

$$N_{bkg}(D) = \frac{N(B)N(C)}{N(A)}$$

Heavy Stable Charged Particle

Determining constants K and C

Parameter (MeV/ cm)	Data 2017	Data 2018	Simulation 2017	Simulation 2018
K	2.54 ± 0.01	2.55 ± 0.01	2.50 ± 0.01	2.49 ± 0.01
C	3.14 ± 0.01	3.14 ± 0.01	3.18 ± 0.01	3.18 ± 0.01

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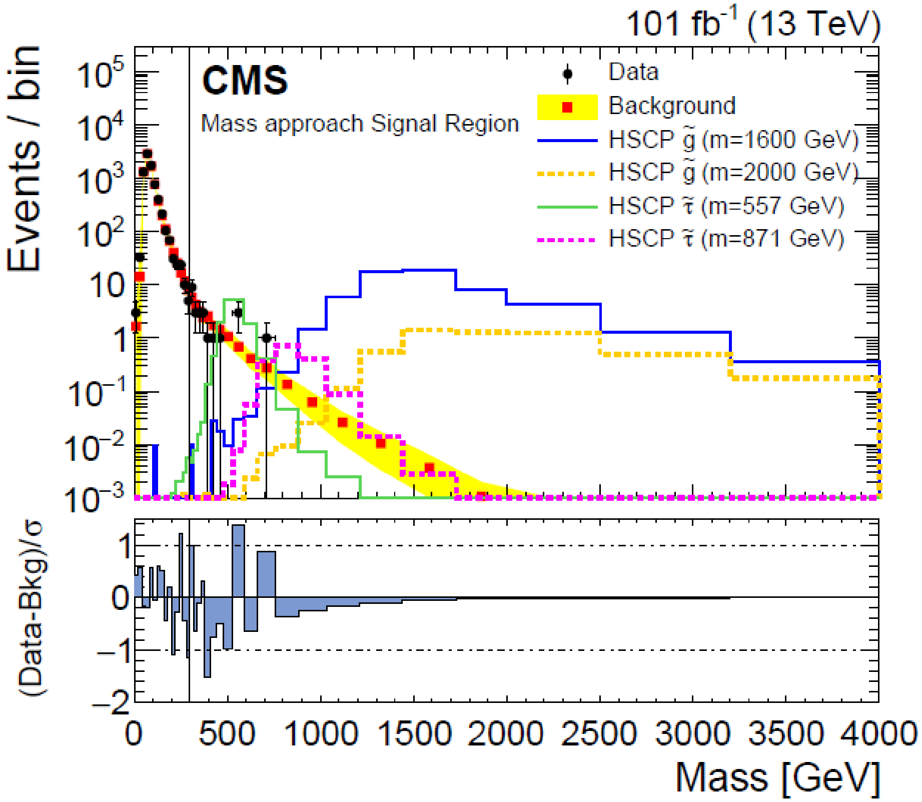
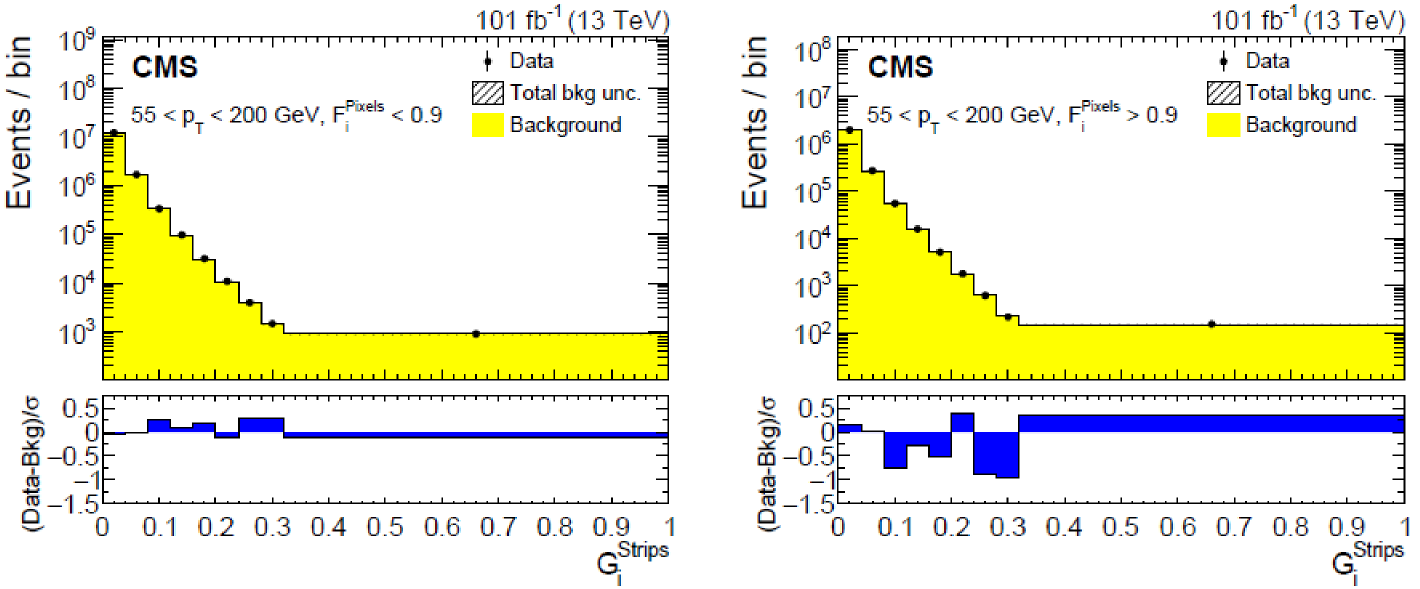
Heavy Stable Charged Particle

Mass Spectrum



Heavy Stable Charged Particle

Pass and Fail Region for Ionization Method



$$N^{\mathrm{bkg}}_{\mathrm{PASS}}(j) = R_{\mathrm{P/F}}(j)\, N^{\mathrm{bkg}}_{\mathrm{FAIL}}(j),$$

Heavy Stable Charged Particle

Exclusion Limits

Model	Ionization method		Mass method	
	Exp. (TeV)	Obs. (TeV)	Exp. (TeV)	Obs. (TeV)
$\tilde{g}$	2.06 ± 0.06	2.06	2.08 ± 0.02	2.08
$\tilde{t}$	1.43 ± 0.05	1.40	1.47 ± 0.02	1.47
GMSB SPS7 $\tilde{\tau}$	0.86 ± 0.07	0.85	0.87 ± 0.05	0.85
pair-prod. $\tilde{\tau}_R$	0.53 ± 0.03	0.52	0.50 ± 0.07	0.51
pair-prod. $\tilde{\tau}_L$	0.66 ± 0.04	0.64	0.67 ± 0.06	0.61
pair-prod. $\tilde{\tau}_{L/R}$	0.71 ± 0.04	0.69	0.75 ± 0.08	0.64
τ' ($Q = 1e$) from DY prod.	1.05 ± 0.05	1.02	1.14 ± 0.03	1.14
τ' ($Q = 2e$) from DY prod.	1.35 ± 0.05	1.32	1.41 ± 0.02	1.41
$Z'_\psi \to \tau'\tau'$	3.99 ± 0.21	3.95	4.03 ± 0.01	4.03
$Z'_{SSM} \to \tau'\tau'$	4.53 ± 0.23	4.38	4.56 ± 0.01	4.57

LLP Search with Displaced Jets

Control Region and Signal Region

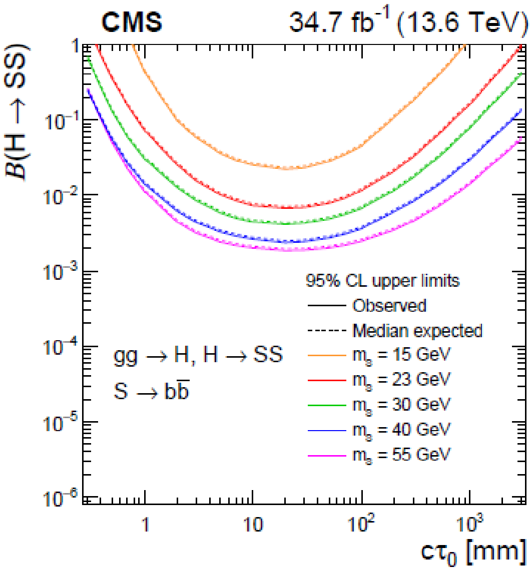
- Region A: events with $0.95 < g_{\text{displaced}} < 0.9985$, $0.95 < g_{\text{prompt-veto}} < 0.985$;
- Region B: events with $0.95 < g_{\text{displaced}} < 0.9985$, $0.985 < g_{\text{prompt-veto}} < 1.0$;
- Region C: events with $0.9985 < g_{\text{displaced}} < 1.0$, $0.95 < g_{\text{prompt-veto}} < 0.985$; and
- Region D, the signal region (SR): events with $0.9985 < g_{\text{displaced}} < 1.0$, $0.985 < g_{\text{prompt-veto}} < 1.0$.

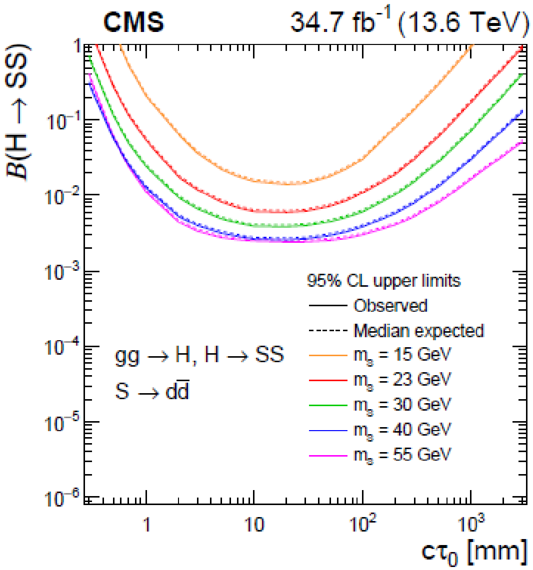
$g_{\text{displaced}}$	Predicted background	Observation	Z-value
(0.96, 0.97)	68.39 ± 12.60	52	-1.06
(0.97, 0.98)	67.55 ± 9.46	77	0.80
(0.98, 0.99)	76.18 ± 8.95	72	-0.27
(0.99, 0.995)	38.82 ± 5.08	45	0.84
(0.995, 0.998)	25.41 ± 3.87	26	0.22
(0.998, 0.9985)	2.83 ± 1.17	5	1.25
(0.9985, 1.0)	3.34 ± 1.28	3	0.19

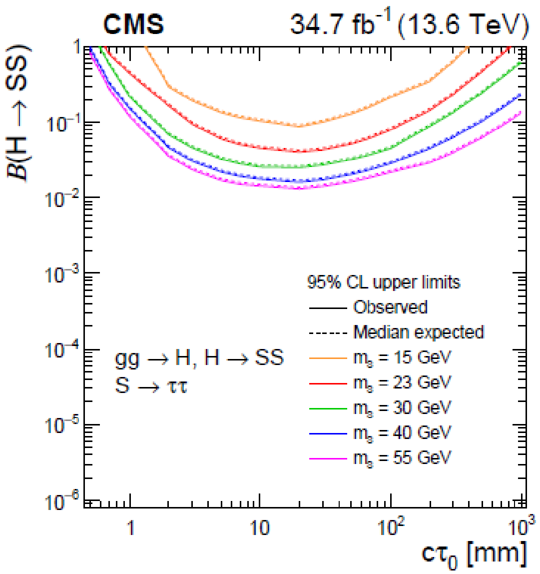
$g_{\text{prompt-veto}} > 0.985$

LLP Search with Displaced Jets

Exclusion Limit Plots

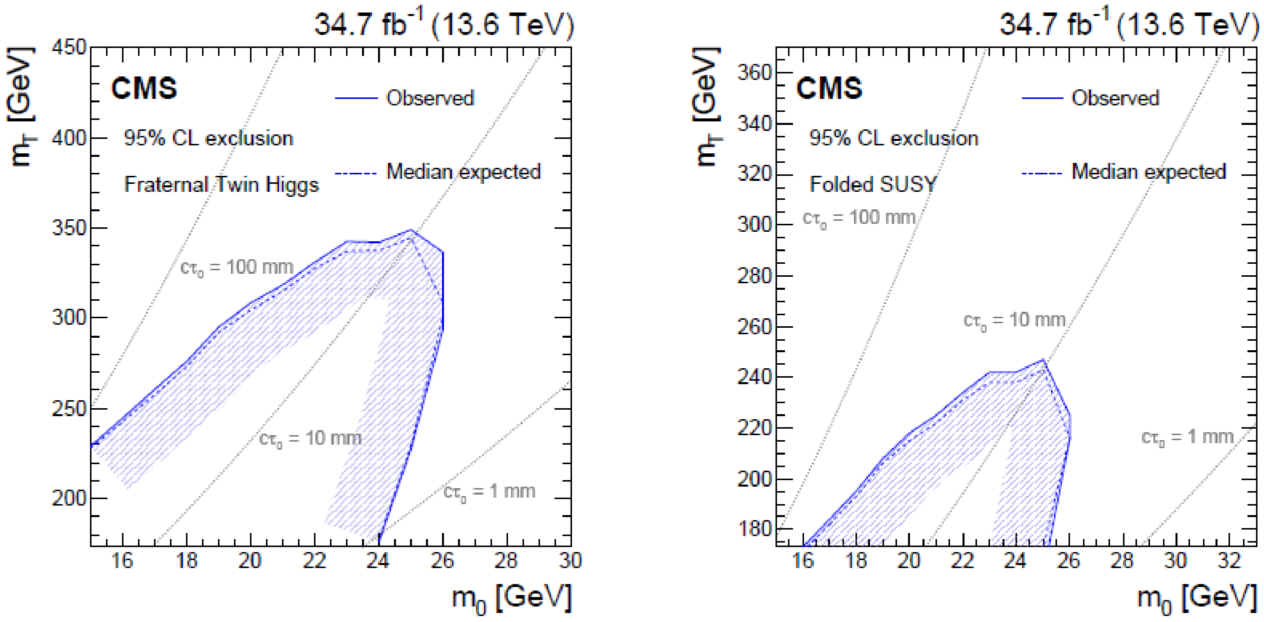




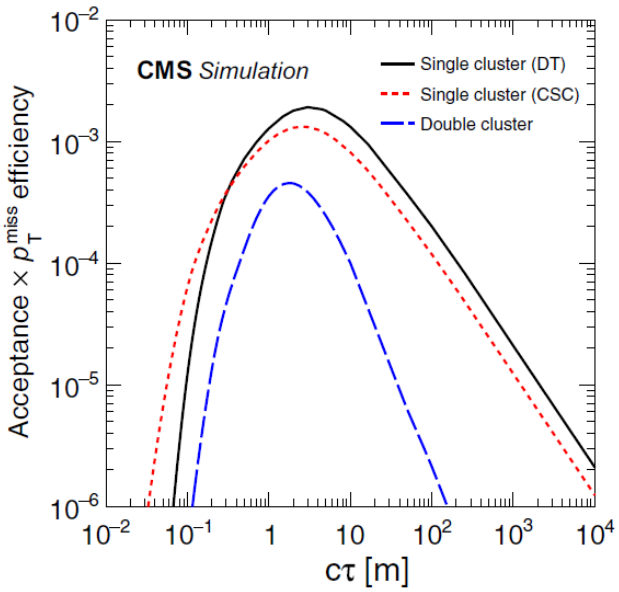


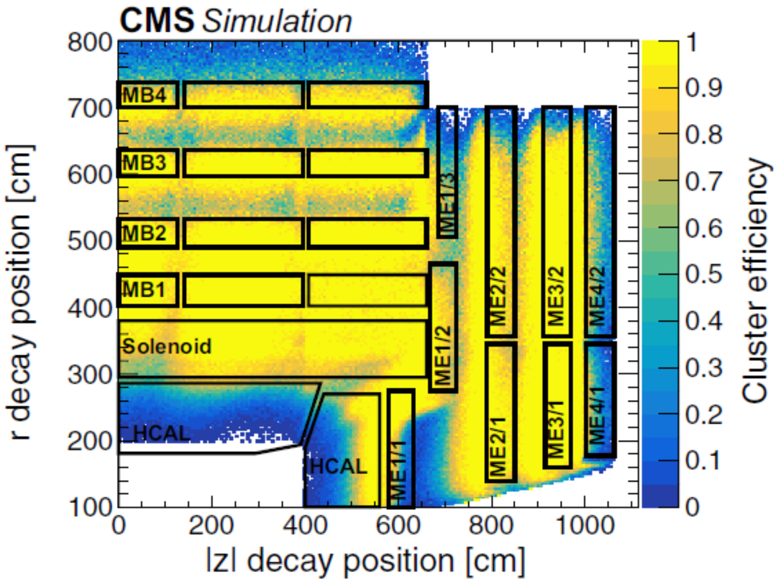
LLP Search with Displaced Jets

Exclusion Limit Plots



LLP Search with Muon System





3 mutually exclusive search categories:

- Double Clusters: CSC-CSC, DT-DT and CSC-DT
- 1 DT Cluster
- 1 CSC Cluster

LLP Search with Muon System

Control Region and Signal Region

Double Clusters

Bin A includes events with the CSC cluster with $N_{\text{hits}} > 100$ and the DT cluster with $N_{\text{hits}} > 80$;

Bin B includes events with the CSC cluster with $N_{\text{hits}} > 100$ and the DT cluster with $N_{\text{hits}} \leq 80$;

Bin C includes events with the CSC cluster with $N_{\text{hits}} \leq 100$ and the DT cluster with $N_{\text{hits}} \leq 80$;

Bin D includes events with the CSC cluster with $N_{\text{hits}} \leq 100$ and the DT cluster with $N_{\text{hits}} > 80$.

Category	Validation region	N_B	N_C	N_D	N_{BD}	λ_A	N_A
DT-DT	Inverted $\Delta\phi(\vec{p}_T^{\text{miss}}, \text{cluster})$	⋯	11	⋯	1	$0.02 + 0.05$	0
	Inverted N_{hits}	⋯	2	⋯	1	$0.12 + 0.27$	0
CSC-CSC	Inverted $\Delta\phi(\vec{p}_T^{\text{miss}}, \text{cluster})$	⋯	8	⋯	2	$0.12 + 0.18$	0
	Inverted N_{hits}	⋯	4	⋯	2	$0.25 + 0.38$	0
DT-CSC	Inverted $\Delta\phi(\vec{p}_T^{\text{miss}}, \text{cluster})$	0	19	3	⋯	$0 + 0.3$	0
	Inverted N_{hits}	2	11	1	⋯	$0.18 + 0.23$	0

Single Clusters

Bin A includes events with $\Delta\phi(\vec{p}_T^{\text{miss}}, \text{cluster}) < 0.75$ and $N_{\text{hits}} > 130$;

bin B includes events with $\Delta\phi(\vec{p}_T^{\text{miss}}, \text{cluster}) \geq 0.75$ and $N_{\text{hits}} > 130$;

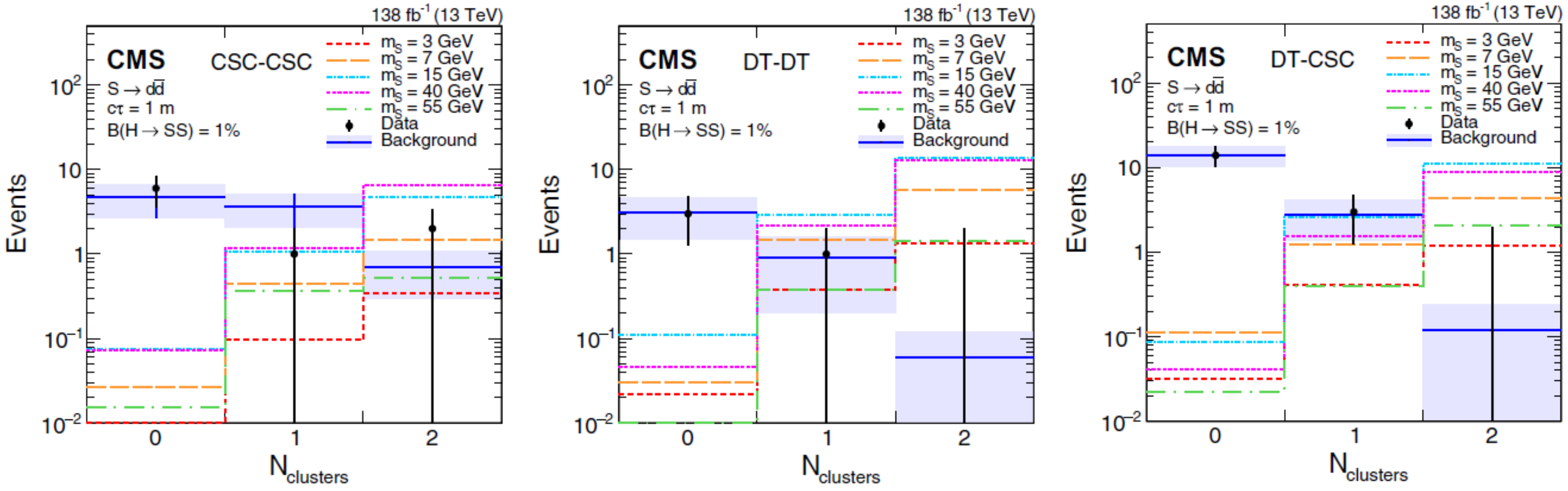
bin C includes events with $\Delta\phi(\vec{p}_T^{\text{miss}}, \text{cluster}) \geq 0.75$ and $N_{\text{hits}} \leq 130$;

bin D includes events with $\Delta\phi(\vec{p}_T^{\text{miss}}, \text{cluster}) < 0.75$ and $N_{\text{hits}} \leq 130$.

Validation region	N_B	N_C	N_D	λ_A	N_A
Out-of-time region	8	442	121	$2.2 + 0.8$	3
In-time region	8	317	87	$2.2 + 0.8$	2

LLP Search with Muon System

Double Cluster Results



LLP Search with Muon System

Single Cluster Results