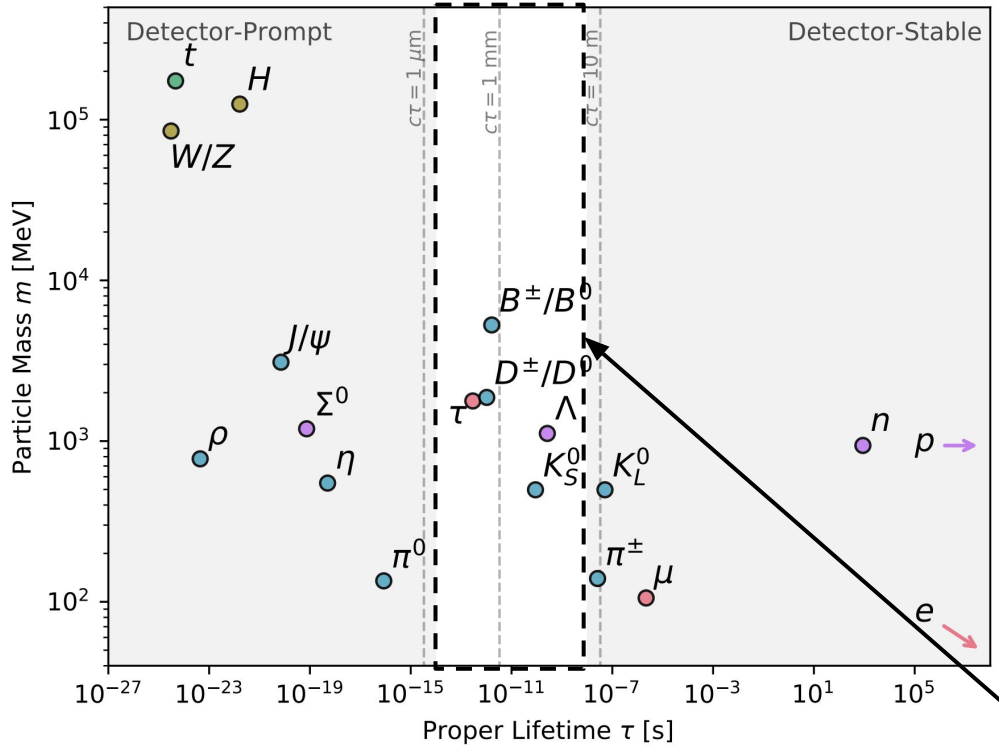
Searches for Long-Lived Particles and Unconventional Signatures with CMS

Gianfranco de Castro (Cornell) *on behalf of the CMS Collaboration*

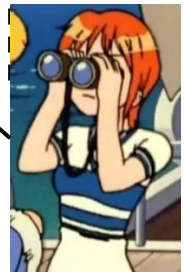
PHENO Symposium - 5/11/26

The Collider LLP Sweet Spot

arxiv.1810.12602



- Long lifetimes happen in nature.
  - μm for B mesons to km for muons.
- BSM models produce long-lived particles naturally!
- The CMS detector directly probes this regime.
  - ~100 μm cτ lower bound from tracker resolution.
  - 7m upper bound at the outer edge of the muon system.



Long-Lived Particle Signatures in CMS

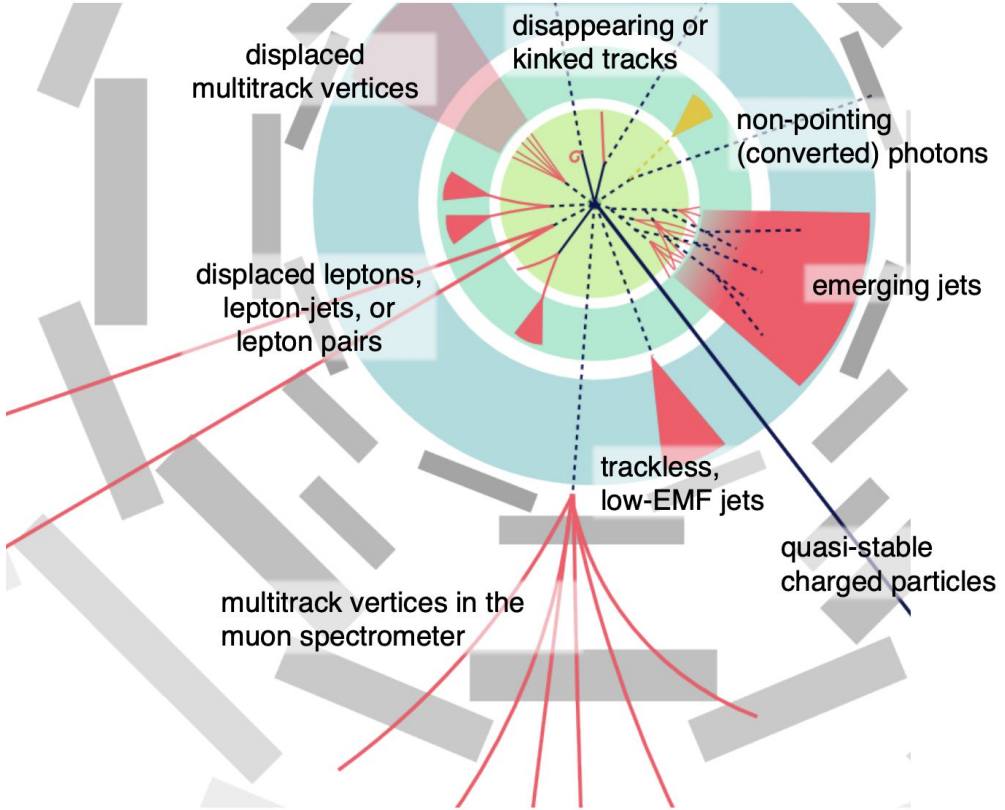
arxiv.1903.04497

In this talk, we will discuss the LLP signatures:

- HSCP L1 scouting (2026)
- Long-lived $\tilde{\tau}$ (2026)
- Non-prompt μμ (2025)
- Light scalars from B decays (2025)
- Soft DVs from SUSY coannihilation (2025)

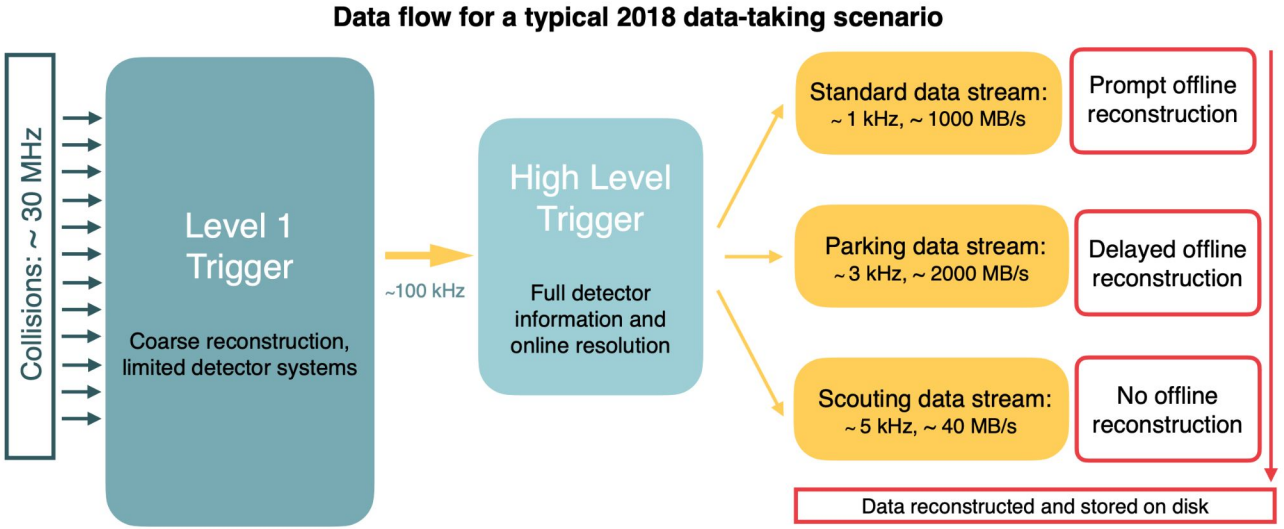
We also highlight some unconventional signatures!

- Black holes, string balls and sphalerons (2026)
- Fractionally charged particles (2025)



CMS Trigger Innovations

arxiv.2403.16134



The "*industry standard*"

+ More data, softer objects
- Highly targeted

+ Extremely low thresholds
- At the cost of resolution

- The image above covers Run 2 (2015-18) innovations!
- Run 3 (2022-26) extends this with more novel triggers (L1DS)…

Long-Lived Signatures

HSCP L1 scouting - arxiv.org:2601.20063 (2026) **NEW!**

Long-lived $\tilde{\tau}$ - arxiv.org:2601.17576 (2026) **NEW!**

Non-prompt $\mu\mu$ - arxiv.org:2511.11888 (2025) **NEW!**

Light scalars from B decays - arxiv.org:2508.06363 (2025) **NEW!**

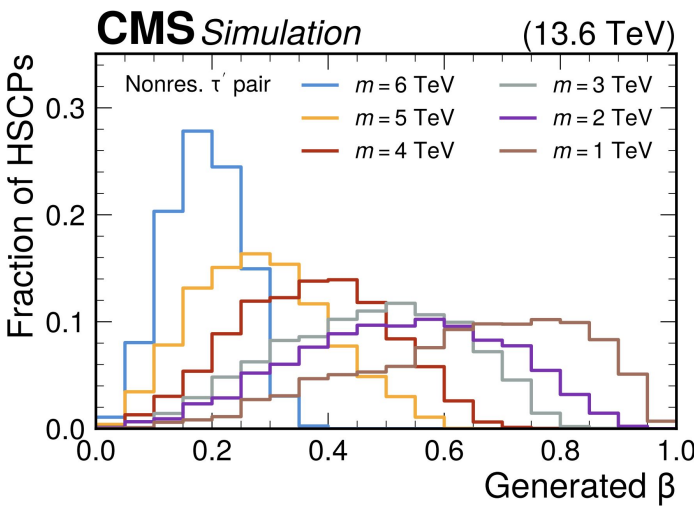
Soft DVs from SUSY coannihilation - arxiv.org:2511.08212 (2025) **NEW!**

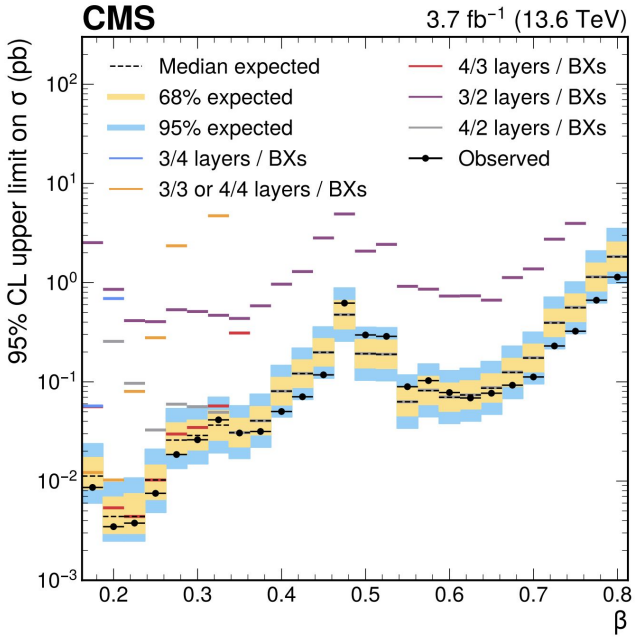
Heavy Stable Charged Particles (HSCPs) via L1 Scouting

arxiv:2601.20063

Signature: Pair-produced HSCPs, slow ($\beta \ll 1$), traversing muon system across multiple BXs
Trigger: L1 Data Scouting (***first CMS analysis!!***) - 40 MHz BX-rate readout, no trigger filter
Bkg. Estimation: Data-driven using signal-depleted, asynchronous stub orderings

τ' signal spans multiple BXs due to low β





No excess!

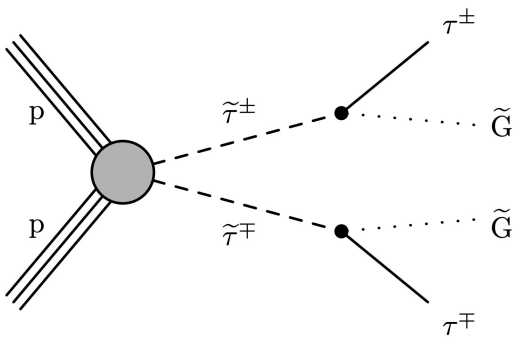
Fiducial limits placed on β

Results also interpreted in terms of τ' and gluino R-hadron masses

Long-Lived $\tilde{\tau}$

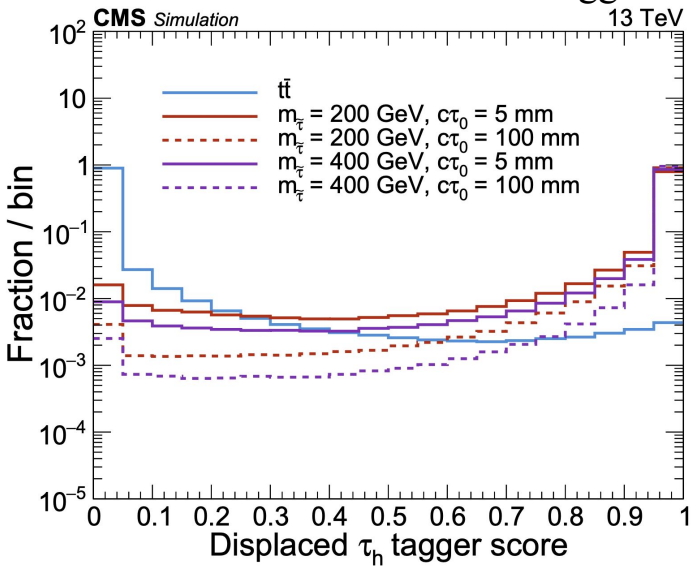
arxiv:2601.17576

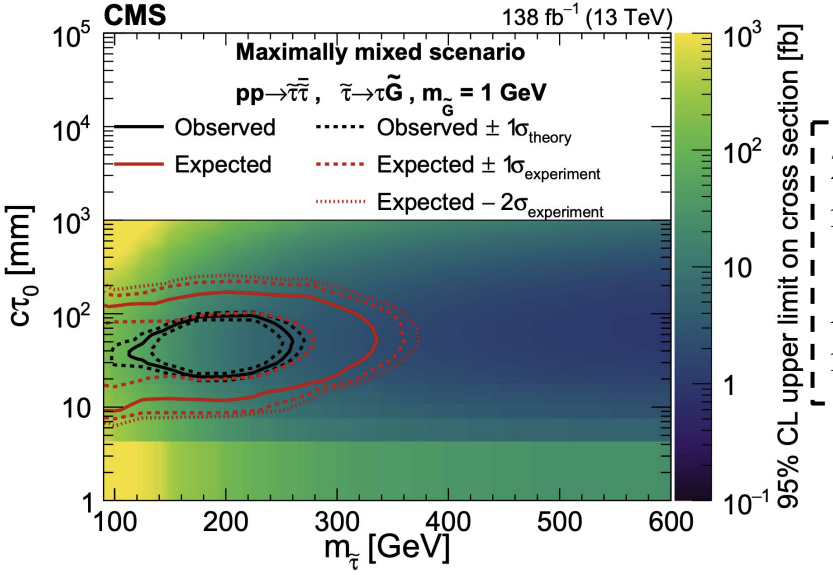
Signature: Pair-produced staus ($\tilde{\tau} \rightarrow \tau \tilde{G}$) within tracker.
Both τ decay hadronically → 2 displaced τ_h
Trigger: MET from the Gravitinos and τ_h decays
Bkg. Estimation: Data-driven τ_h mis-ID rates from CRs
Innovation! τ identification using DisTau GNN tagger



No excess!

Performance of the DisTau tagger





2D limits assuming maximal mixing

Also interpreted for mass degenerate case

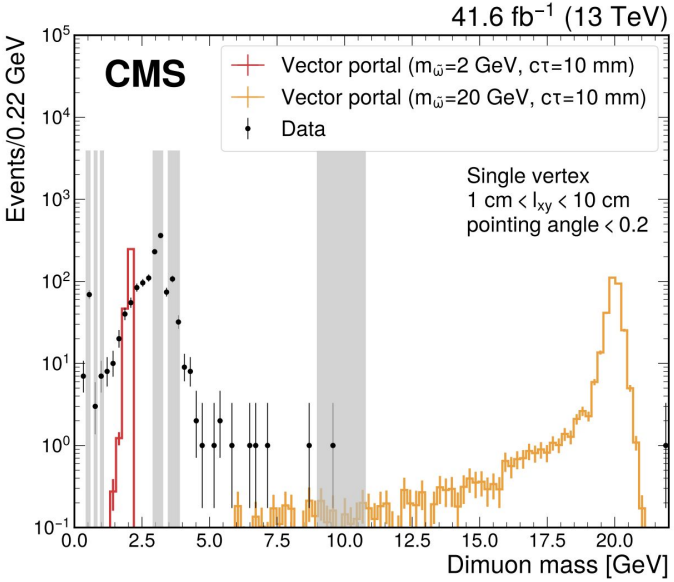
Non-prompt μμ

arxiv:2511.11888

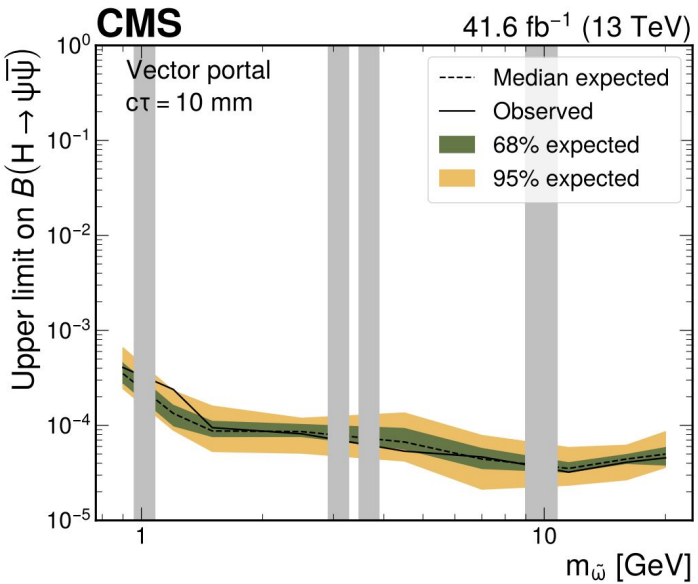
Signature: Displaced μμ vertices from dark showers!
Trigger: B-parking - non-prompt single-μ triggers
Bkg. Estimation: BDT against heavy-flavor QCD.
Final dimuon-mass fit in 12 categories with smooth envelope.

No excess!

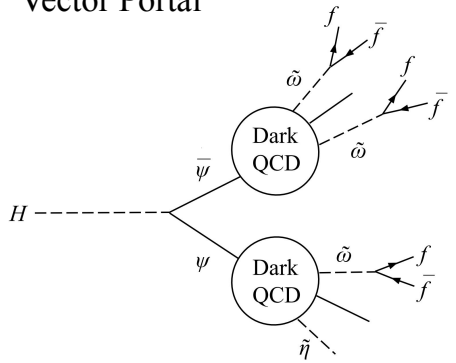
Representative single-vertex category



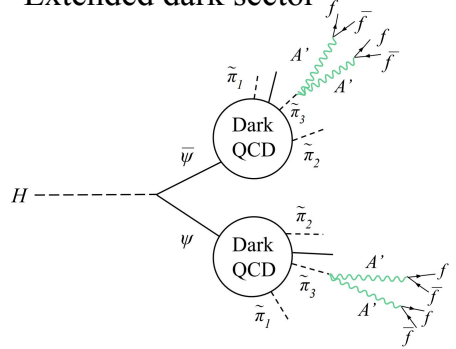
Limits on vector portal interpretation



Vector Portal



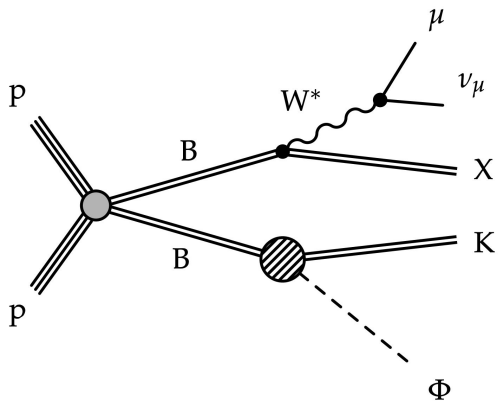
Extended dark sector



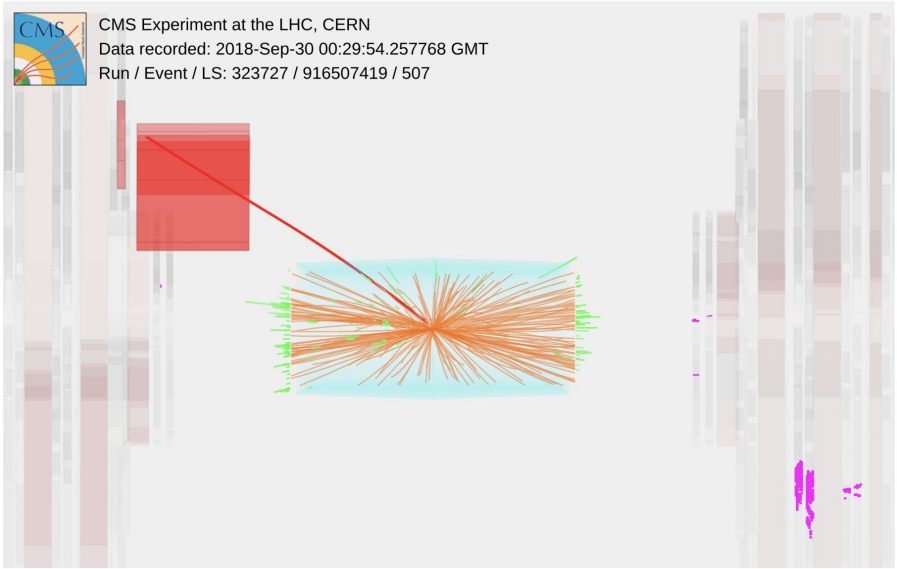
Light Scalars from B Decays

arxiv:2508.06363

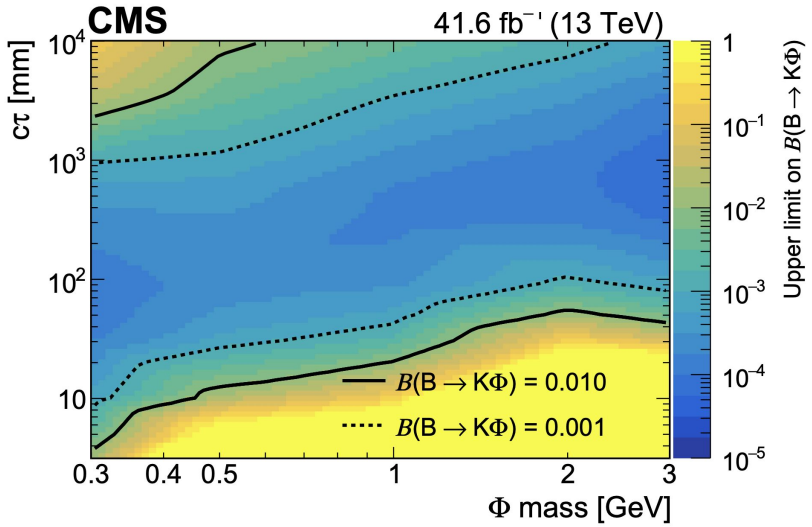
Signature: B → K + Φ ; Φ → hadrons → muon endcap shower cluster
Trigger: B-parking - same dataset as non-prompt μμ
Bkg. Estimation: ABCD in (N_hits, Δϕ) + jet mis-ID rate from CR



Candidate signal event



No excess!



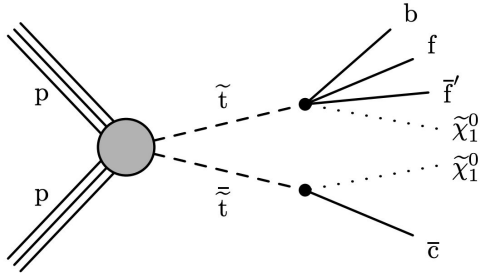
Soft DVs from SUSY Coannihilation

arxiv:2511.08212

Signature: Pair-produced LL $\tilde{t}$ or wino-like $\tilde{\chi}_2^0$ → Soft tracks + MET + ISR jet

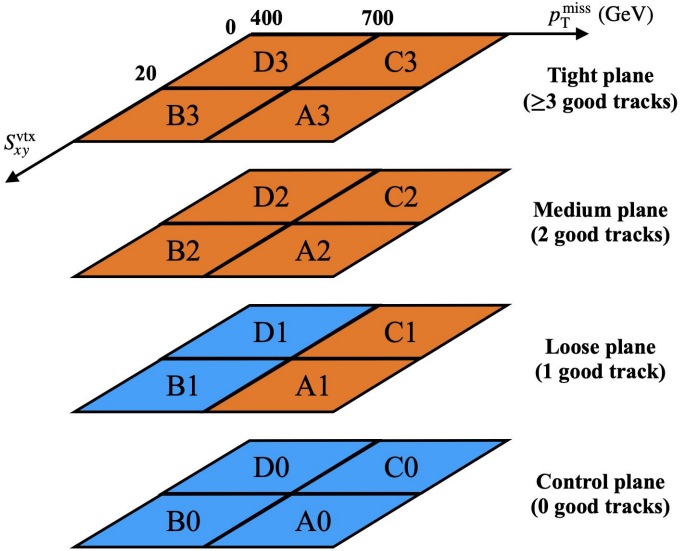
Trigger: MET from invisible LSPs $\tilde{\chi}_1^0$

Bkg. Estimation: Data-driven transfer factors from CRs

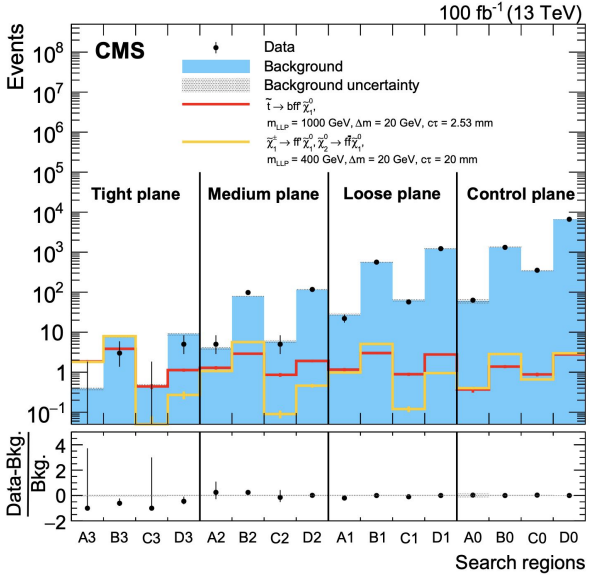


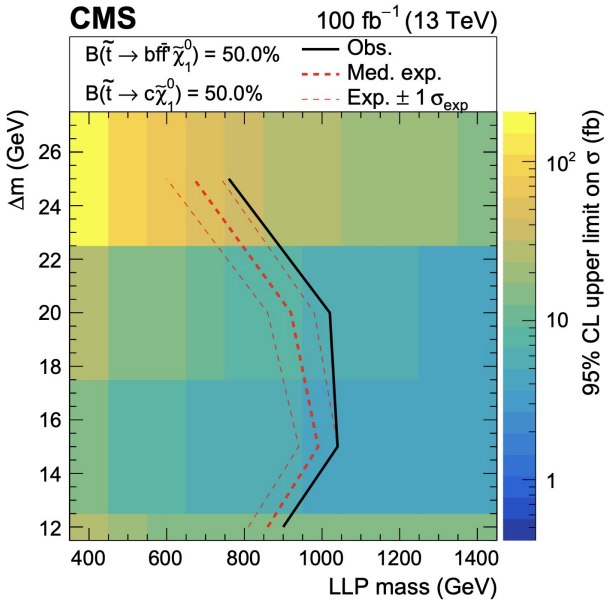
No excess!

Signal and control regions



Post-fit distribution





Unconventional Signatures

Black holes, string balls and sphalerons - arxiv:2604.10732 (2026) **NEW!**

Fractionally charged particles - arxiv:2402.09932 (2025)

Black Holes, String Balls, & Sphalerons

arxiv:2604.10732

Signature: High-multiplicity final states with energetic jets, leptons, and photons

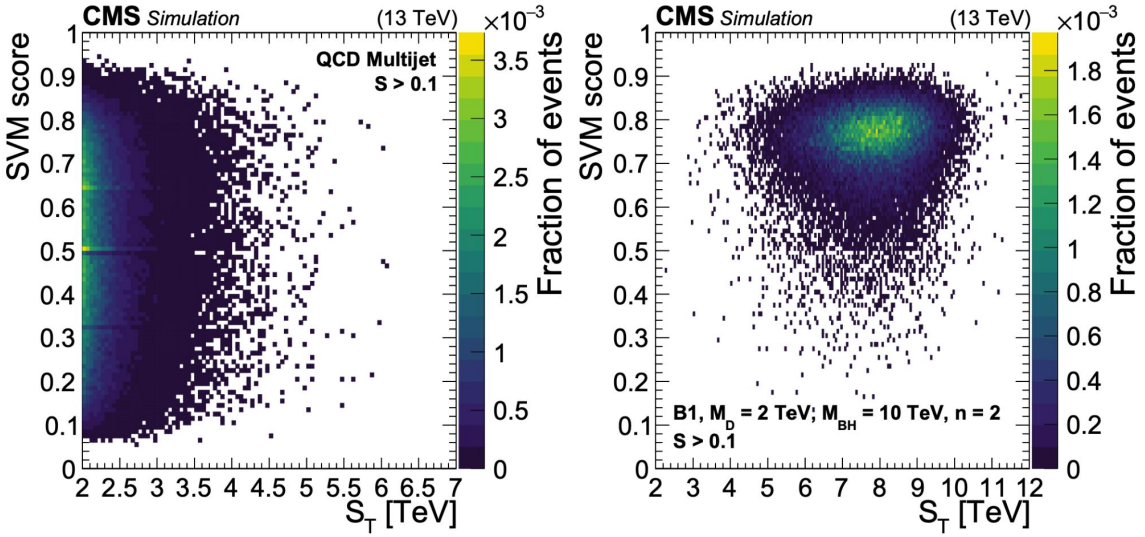
Trigger: On the scalar sum of jet pT in the event (HT)

Bkg. Estimation:

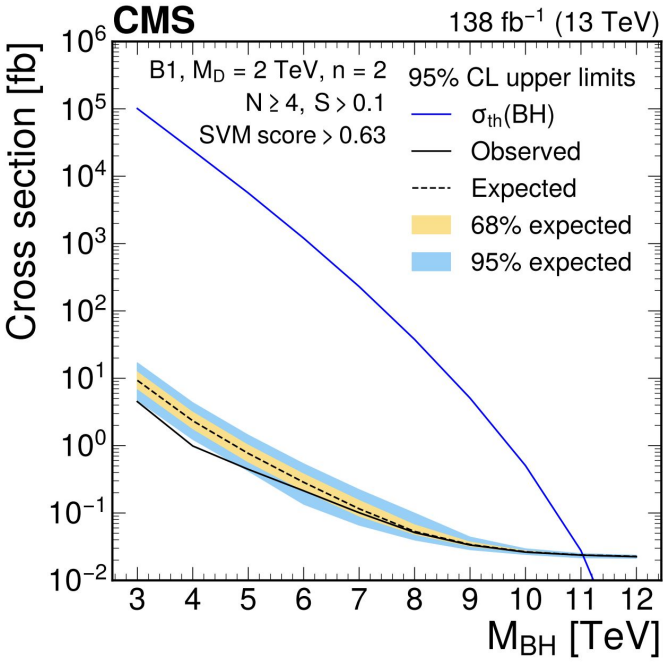
- Shape invariance of ST wrt to track multiplicity
- Phase space distance groups events by kinematic similarity

No excess!

Support Vector Machine classifier



Semiclassical nonrotating BH



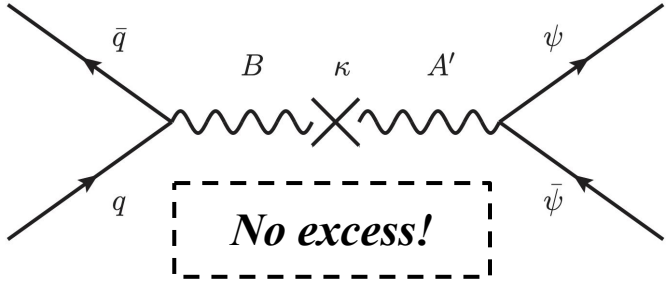
Fractionally Charged Particles

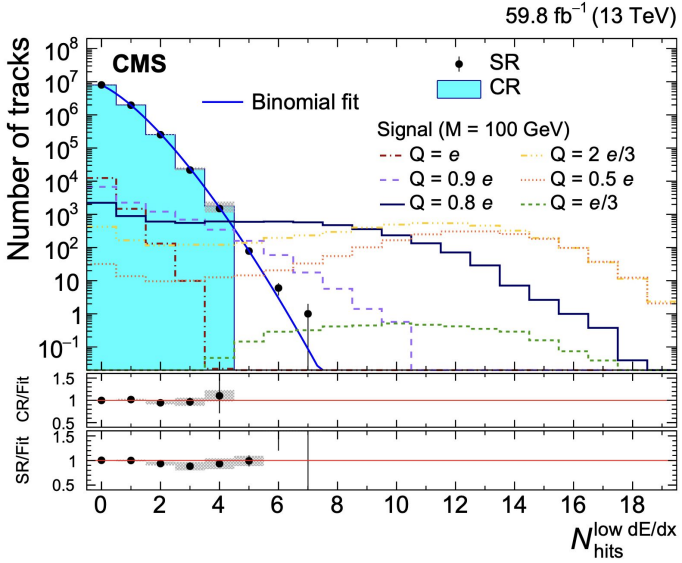
arxiv:2402.09932

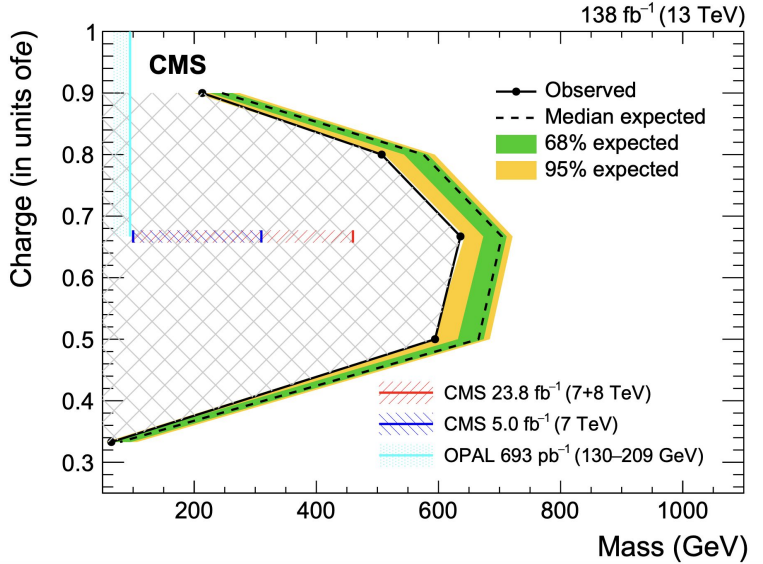
Signature: DY-like pair-produced FCPs with muon-like track with low dE/dx

Trigger: Single muon trigger

Bkg. Estimation: Fit the number of low dE/dx tracker hits in a CR and extrapolate to the SR

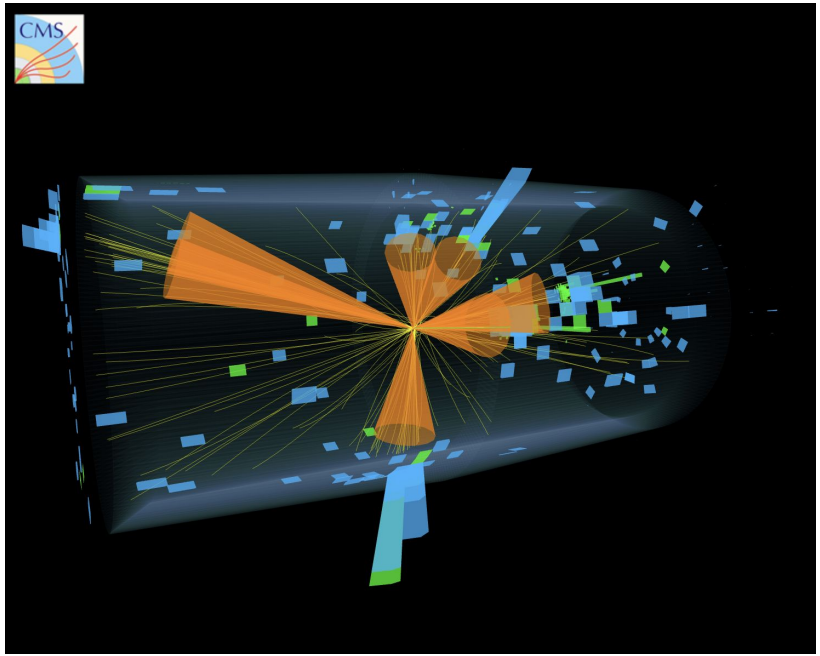




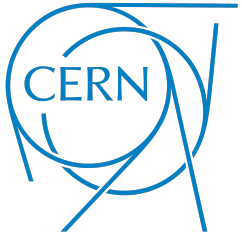
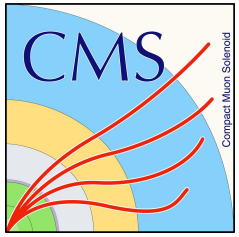
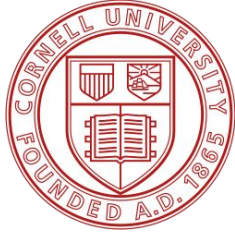


LLPs and Unconventional Signatures @ CMS - Summary

- CMS covers a wide variety of LLP signatures:
  - Tracker DVs, MS clusters, slow HSCPs…
- Trigger and reconstruction innovations:
  - L1 scouting, B-parking, DisTau GNN
  - Push into regimes prompt searches systematically miss
- Most stringent limits to date on multiple BSM models!



Are there quantum black holes that evaporate instantly?


CERN

CMS
Compact Muon Solenoid

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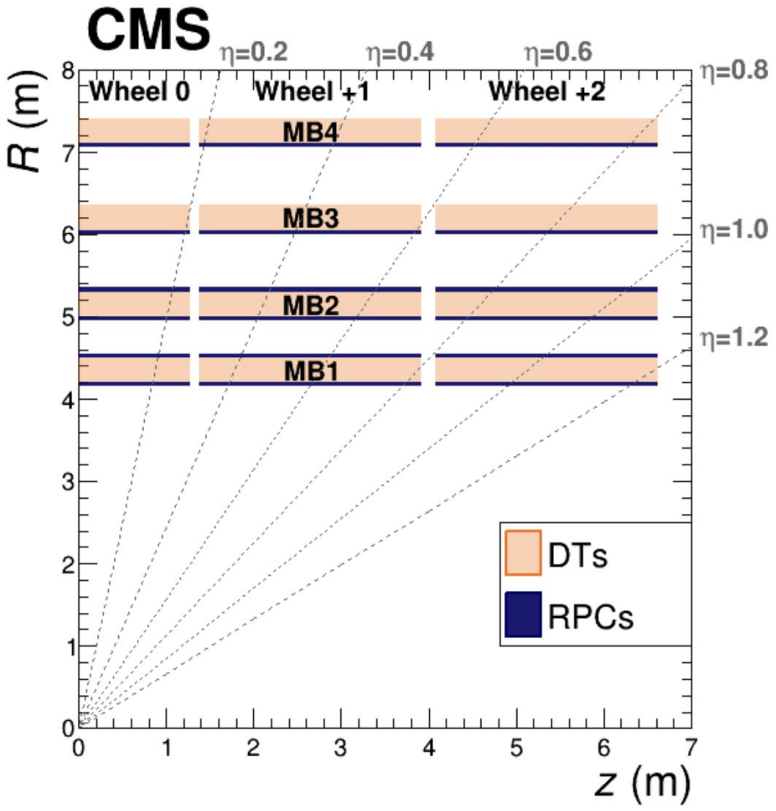
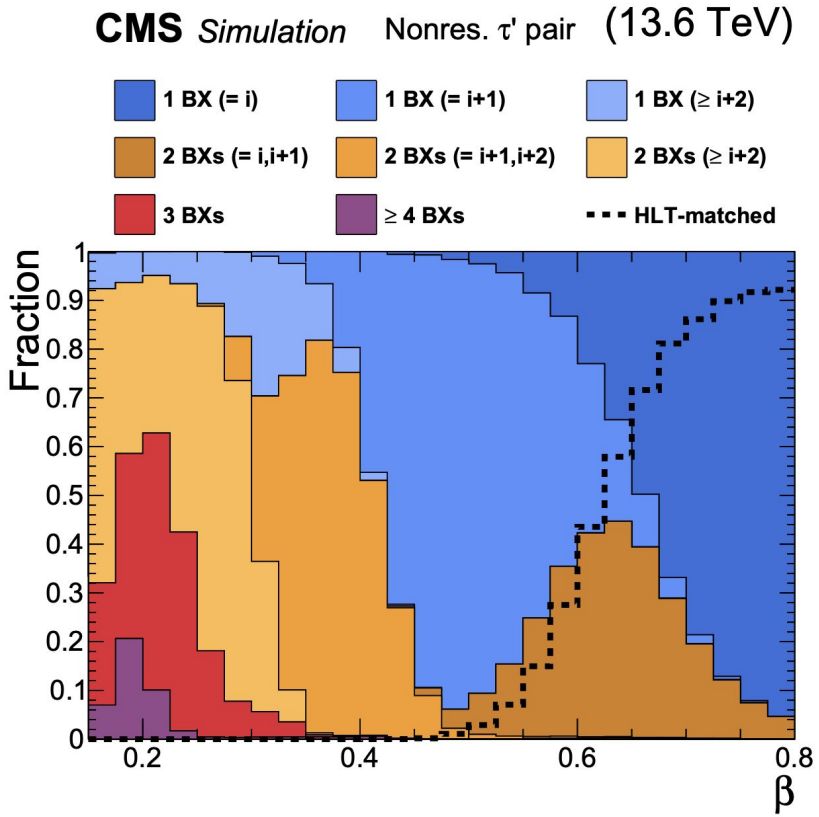
Backup!

HSCPs via L1 Scouting

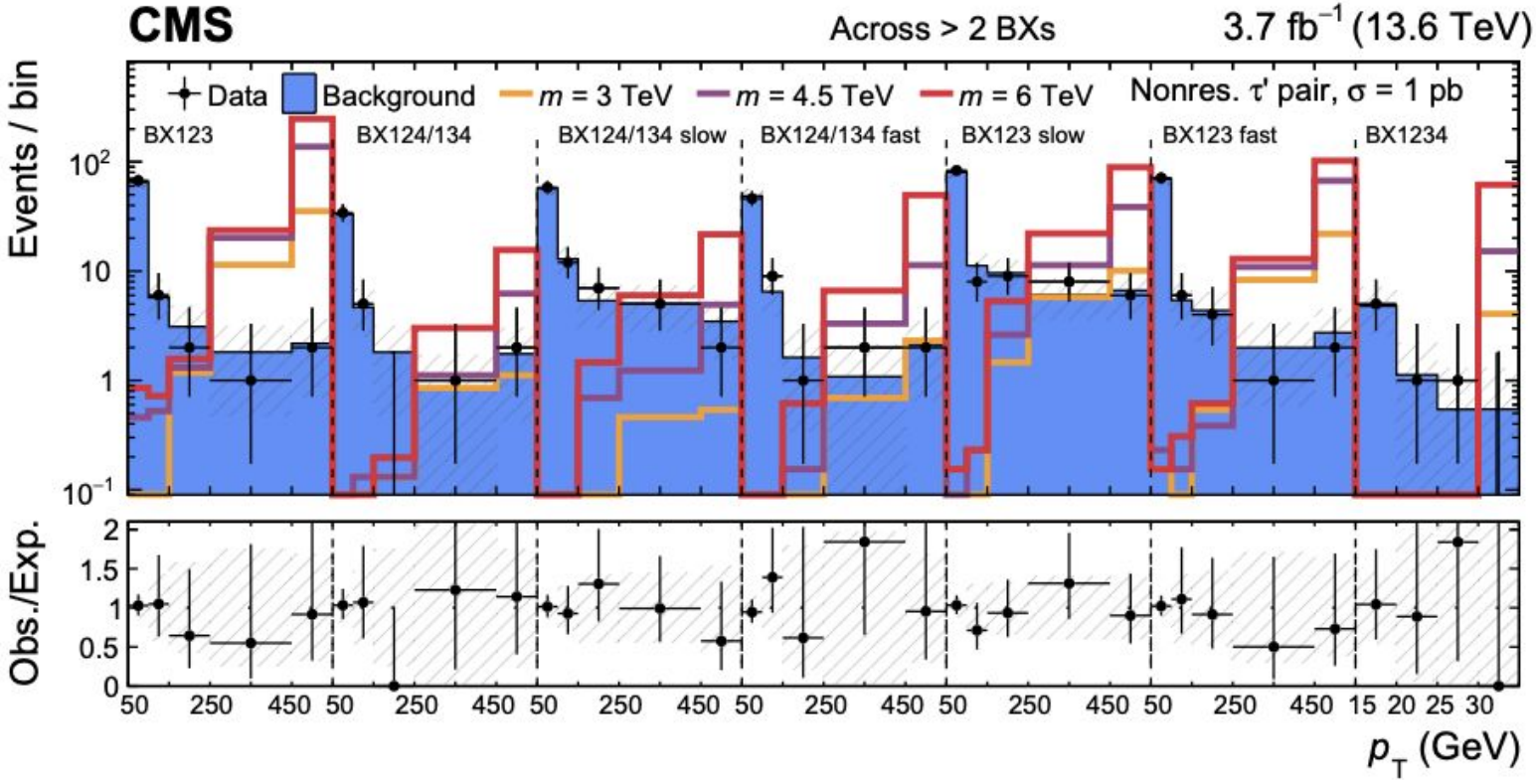
Search for heavy long-lived charged particles…, arxiv:2601.20063, Figs. 1 and 4





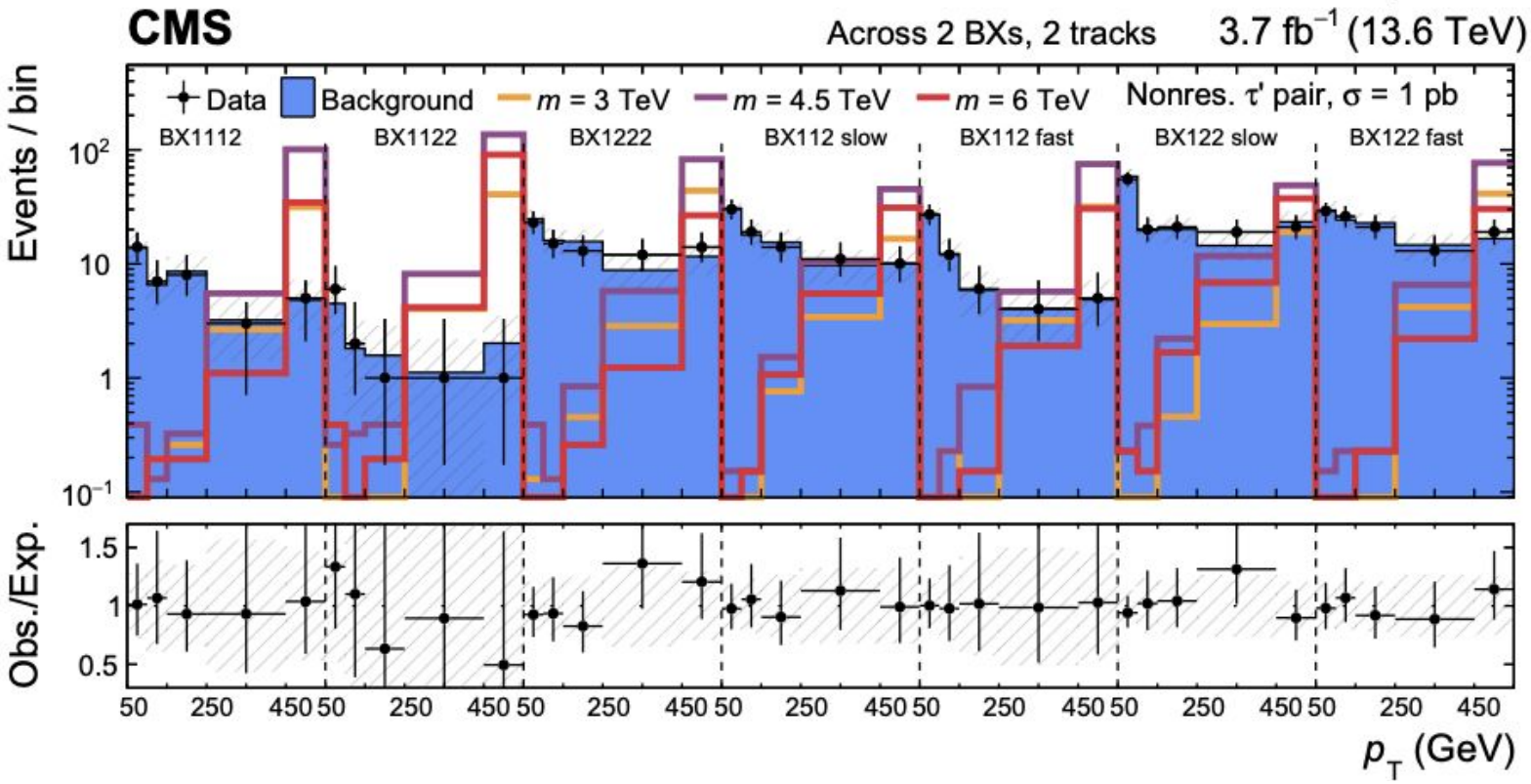
HSCPs via L1 Scouting

Search for heavy long-lived charged particles…, arxiv:2601.20063, Fig. 7



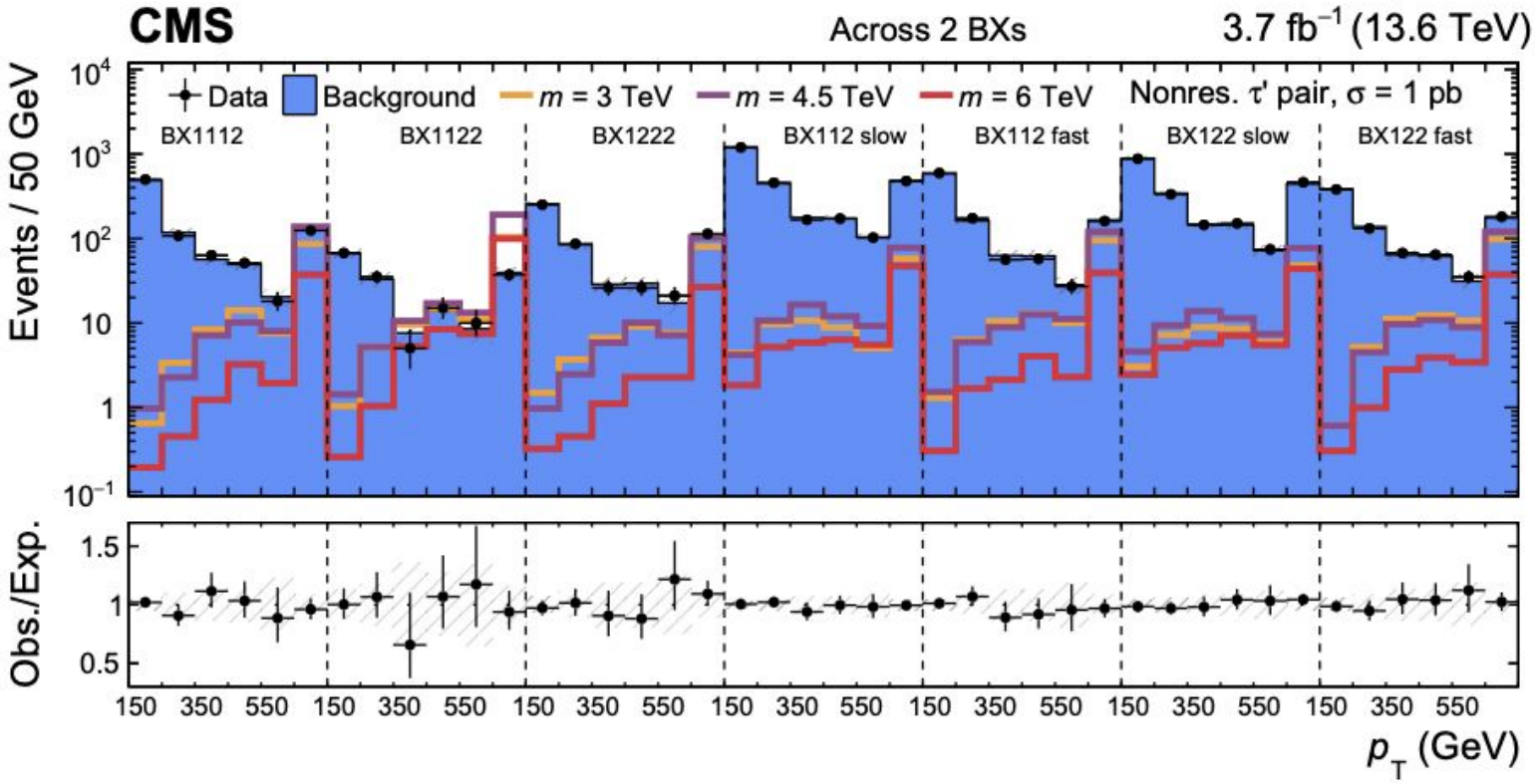
HSCPs via L1 Scouting

Search for heavy long-lived charged particles…, arxiv:2601.20063, Fig. 7



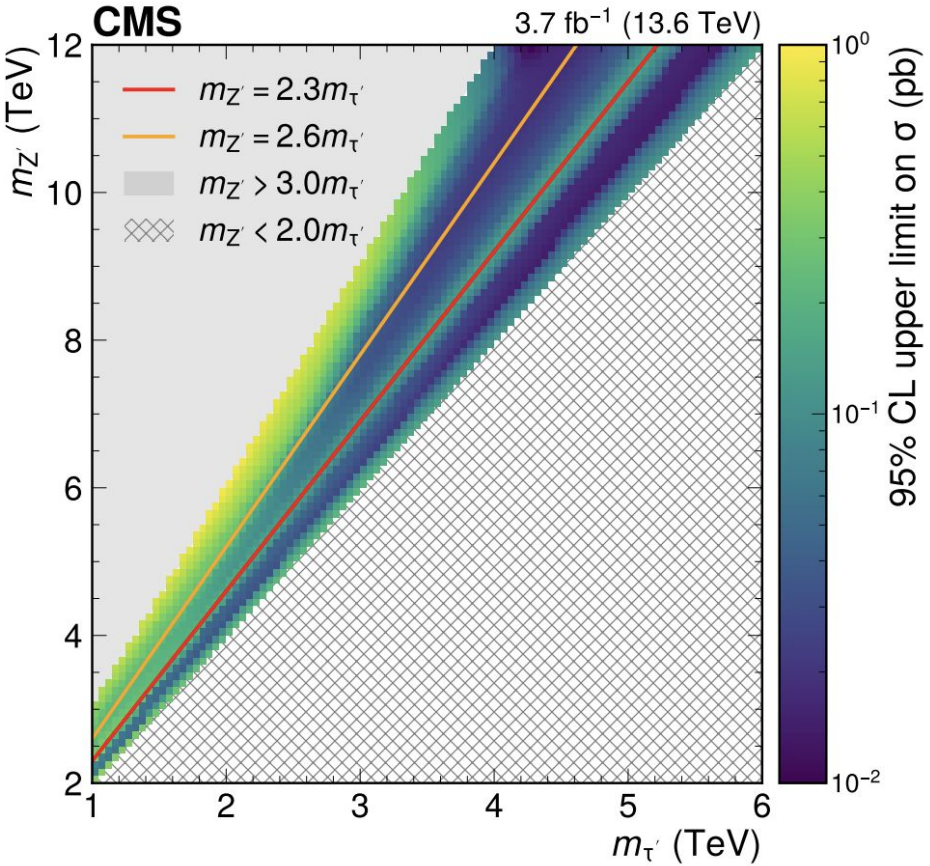
HSCPs via L1 Scouting

Search for heavy long-lived charged particles…, arxiv:2601.20063, Fig. 7



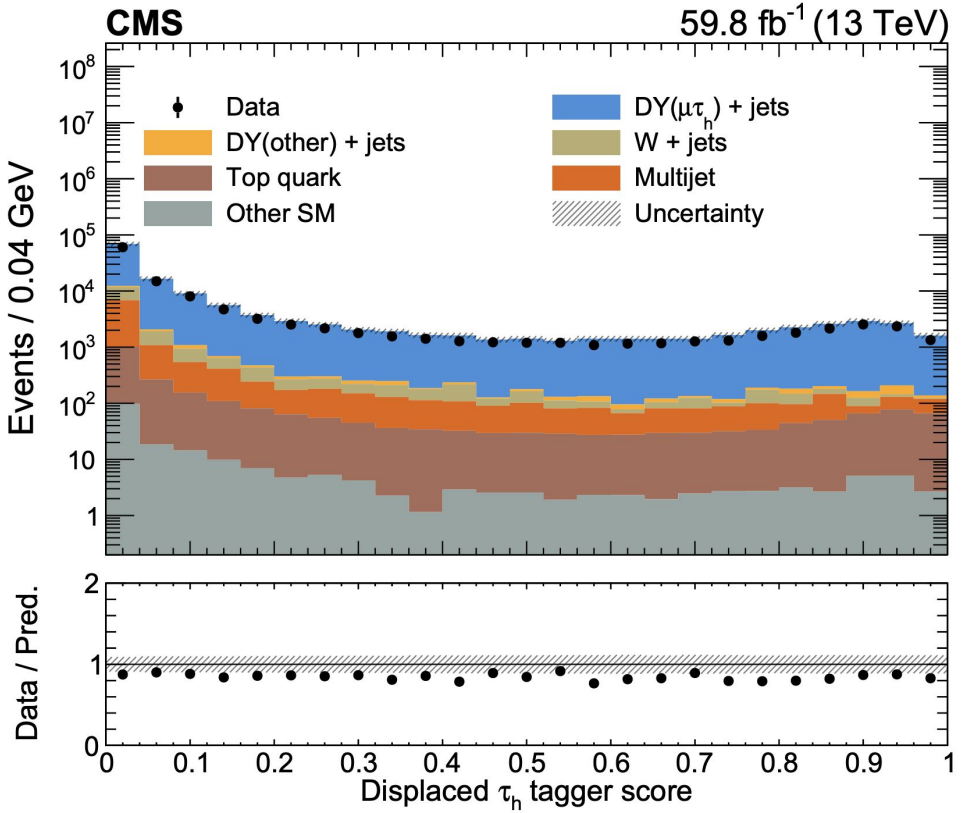
HSCPs via L1 Scouting

Search for heavy long-lived charged particles…, arxiv:2601.20063, Fig. 9



Long-Lived $\tilde{\tau}$

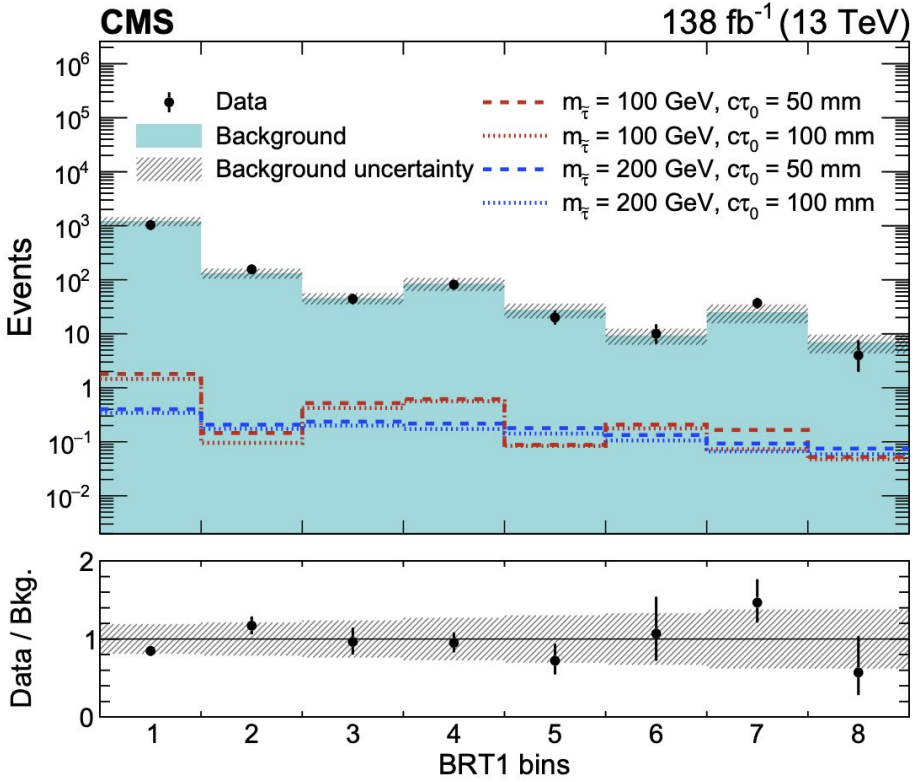
Search for the pair production of LL SUSY…, arxiv:2601.17576, Figs. 3



Long-Lived $\tilde{\tau}$

Search for the pair production of LL SUSY…, arxiv:2601.17576, Fig. 5 and Table 2

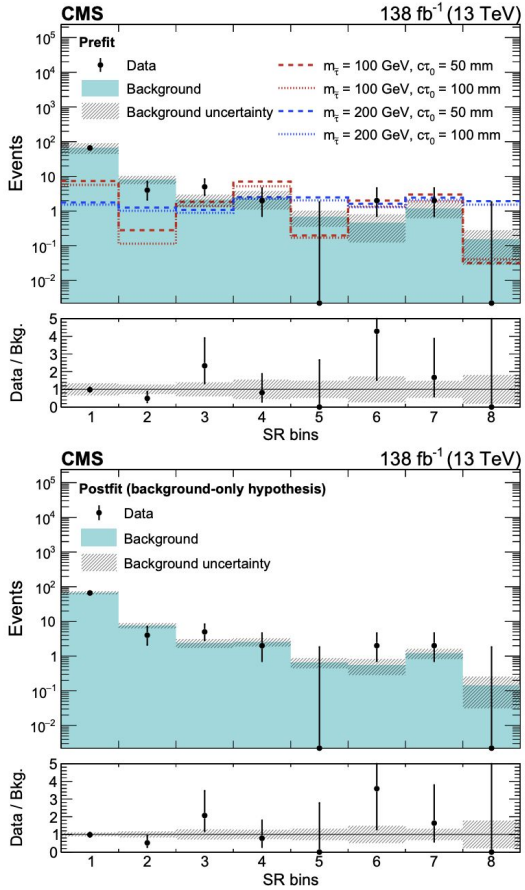
Bin no.	$p_{T,j2}$ [GeV]	p_T^{miss} [GeV]	m_{T2} [GeV]
1	30–50	120–250	<100
2	30–50	120–250	>100
3	30–50	>250	—
4	50–100	120–250	<100
5	50–100	120–250	>100
6	50–100	>250	—
7	>100	—	<100
8	>100	—	>100



Long-Lived $\tilde{\tau}$

Search for the pair production of LL SUSY…, arxiv:2601.17576, Fig. 6 and Table 3

Uncertainty source	Background	$m_{\tilde{\tau}}(100)$ $c\tau_0(50)$	$m_{\tilde{\tau}}(100)$ $c\tau_0(100)$	$m_{\tilde{\tau}}(200)$ $c\tau_0(50)$	$m_{\tilde{\tau}}(200)$ $c\tau_0(100)$
Parton distribution function	—	3.5, 3.8, 6	2.9, 4.2, 6.4	4, 4.6, 5.9	3.9, 4.4, 5.2
μ_R scale	—	<0.1, 0.29, 1.4	<0.1, 0.46, 1.3	<0.1	0.1
μ_F scale	—	0.62, 4.3, 7.1	1.3, 5.1, 7.1	0.63, 1.1, 2.9	0.65, 0.94, 2.8
Jet energy scale	—	0.83, 2.4, 7.4	0.68, 3.2, 10	0.39, 1.4, 2.5	0.47, 1.1, 2.5
Jet energy resolution	—	0.19, 0.54, 7.4	0.14, 0.82, 4.3	0.22	0.17
p_T^{miss} unclustered energy	—	0.26, 0.9, 7.4	0.31, 1.1, 8.9	0.28	0.33
Pileup	—	0.66, 1.2, 3.3	0.62, 0.98, 5.1	0.61	0.59
Integrated luminosity	—	1.7	1.7	1.7	1.7
p_T^{miss} trigger	—	1.6, 16, 20	1.6, 15, 20	1.7, 14, 16	1.6, 14, 16
DisTau identification	—	17, 18, 19	17, 18, 19	17	18
Misid. probability estimation region	11, 11, 13	—	—	—	—
Misid. probability sample size	15, 30, 57	—	—	—	—
Alternative bkg. prediction	8.5, 24, 53	—	—	—	—
Bkg. correction from BRT1	2.8, 5.2, 8.1	—	—	—	—



Non-prompt μμ

Search for low-mass hidden-valley dark showers…, arxiv:2511.11888, Fig. 1

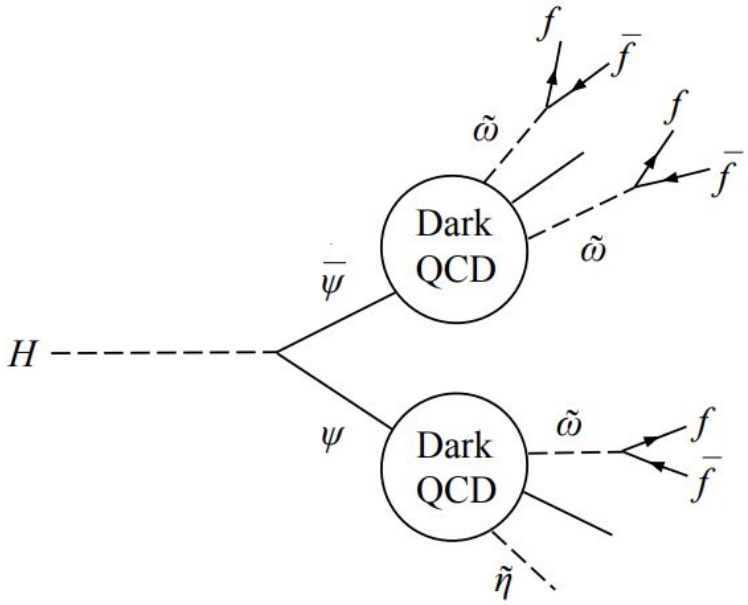


Figure 1: Diagram for the vector portal model. An SM Higgs boson decays to dark partons $\psi\bar{\psi}$, which then hadronise to form dark hadrons including dark vector mesons $\tilde{\omega}$ and dark pseudoscalar mesons $\tilde{\eta}$. The $\tilde{\omega}$ then undergoes displaced decay into SM fermions $f\bar{f}$.

Non-prompt μμ

Search for low-mass hidden-valley dark showers…, arxiv:2511.11888, Fig. 2

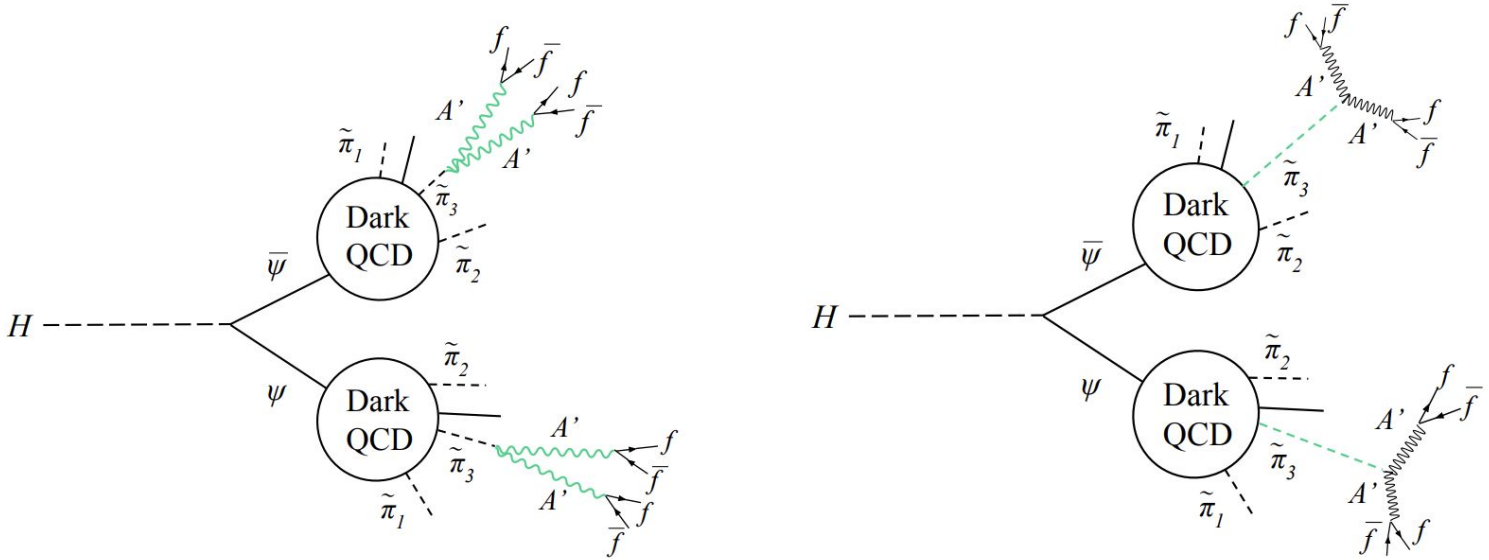
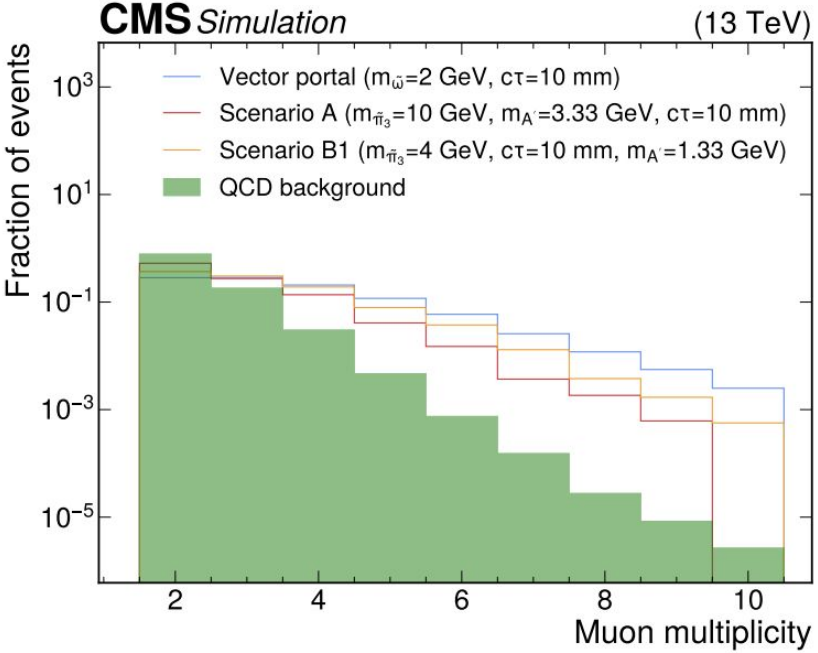
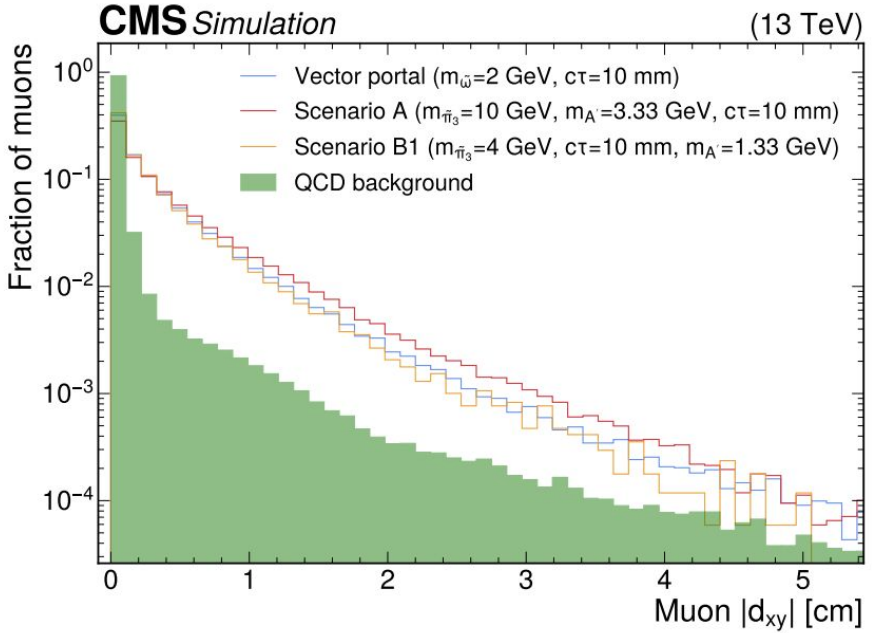


Figure 2: Diagrams for the Scenario A model (left) and the Scenario B1 model (right). In these extended models the dark hadronisation produces a spectrum of dark mesons, including the dark pions $\tilde{\pi}_1$, $\tilde{\pi}_2$ and $\tilde{\pi}_3$. The $\tilde{\pi}_3$ then decays into SM fermions $f\bar{f}$ through the dark photon A′. Green is used to indicate a long-lived particle. The A′ is a long-lived particle in Scenario A, while $\tilde{\pi}_3$ is a long-lived particle in Scenario B1.

Non-prompt μμ

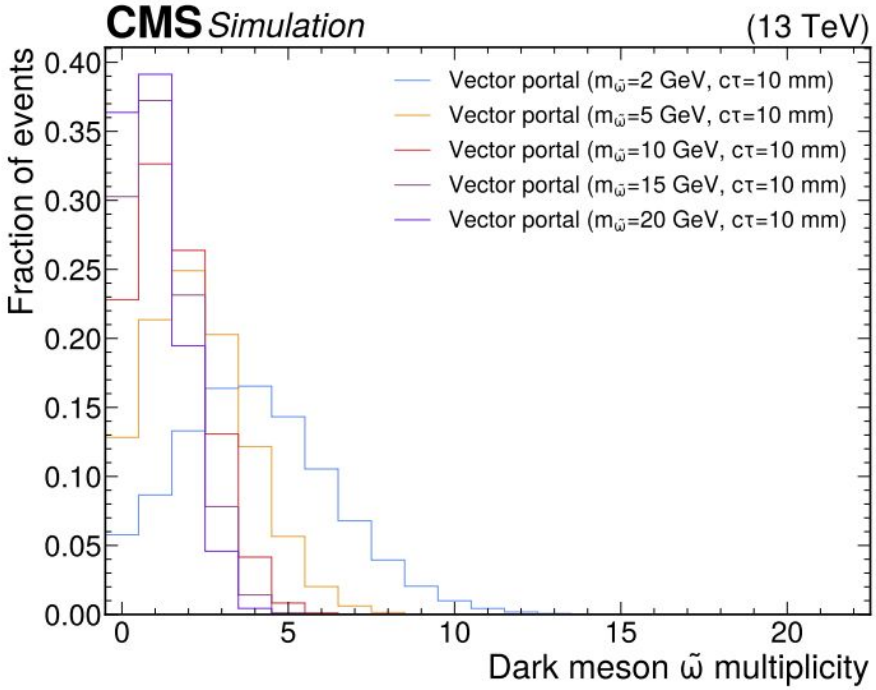
Search for low-mass hidden-valley dark showers…, arxiv:2511.11888, Fig. 3

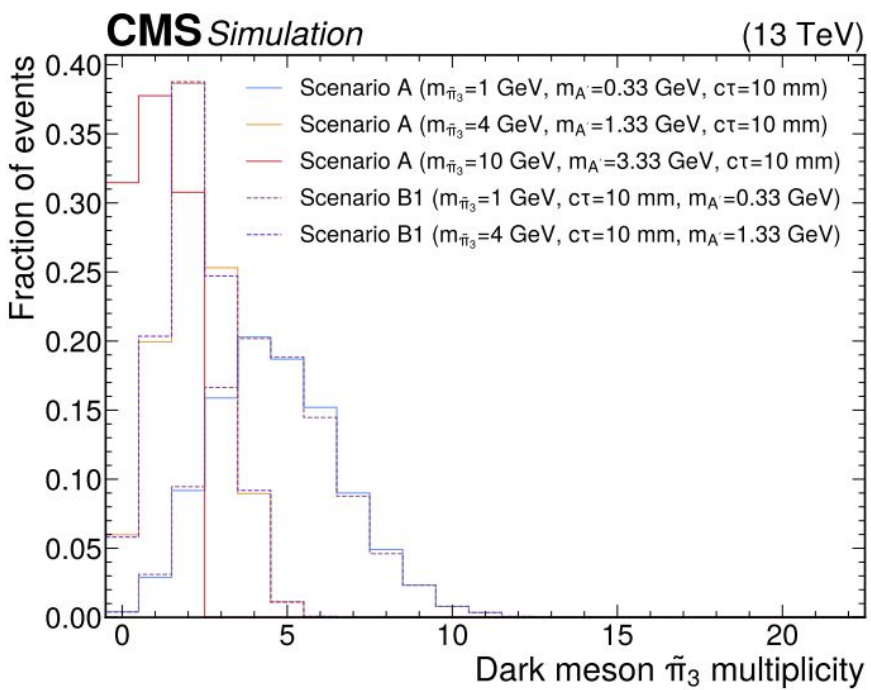




Non-prompt μμ

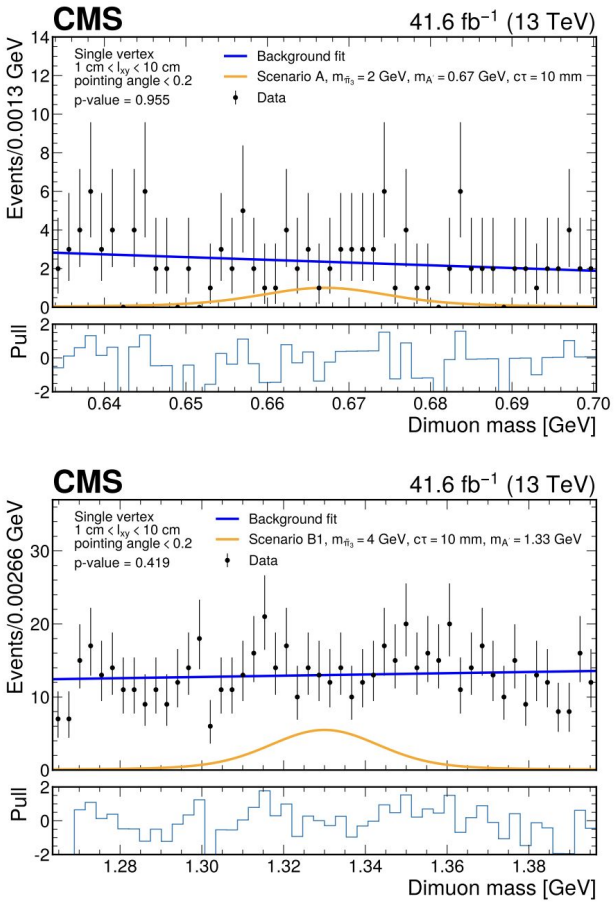
Search for low-mass hidden-valley dark showers…, arxiv:2511.11888, Fig. 4





Non-prompt μμ

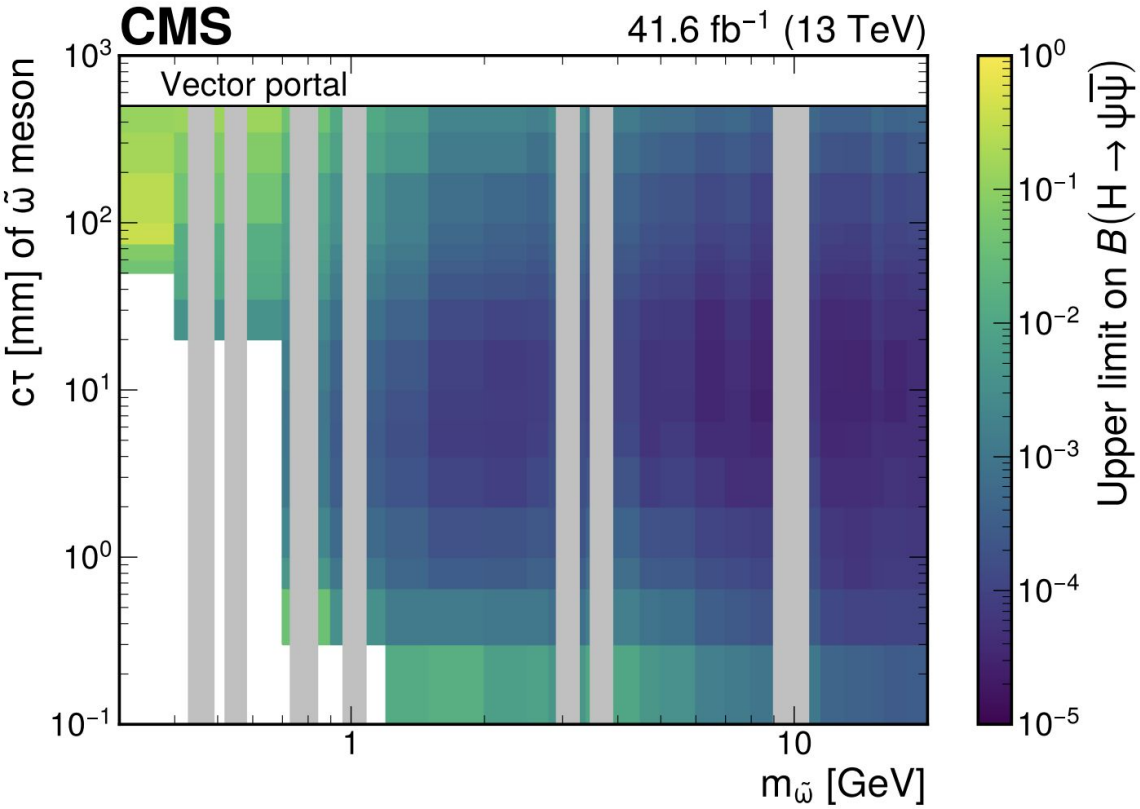
Search for low-mass hidden-valley dark showers…, arxiv:2511.11888, Fig. 7 and Table 3



Source	Systematic uncertainty [%]
Non-prompt muon identification	∼1–17
Trigger	∼1–2
BDT	10
Pileup	∼5
Theory uncertainty in ggF Higgs production	3.9
Strong coupling constant	2.6
PDF	1.9
Luminosity	2.5

Non-prompt μμ

Search for low-mass hidden-valley dark showers…, arxiv:2511.11888, Fig. 14



Light Scalars from B Decays

Search for b hadron decays to LLPs…, arxiv:2508.06363, Fig. 1

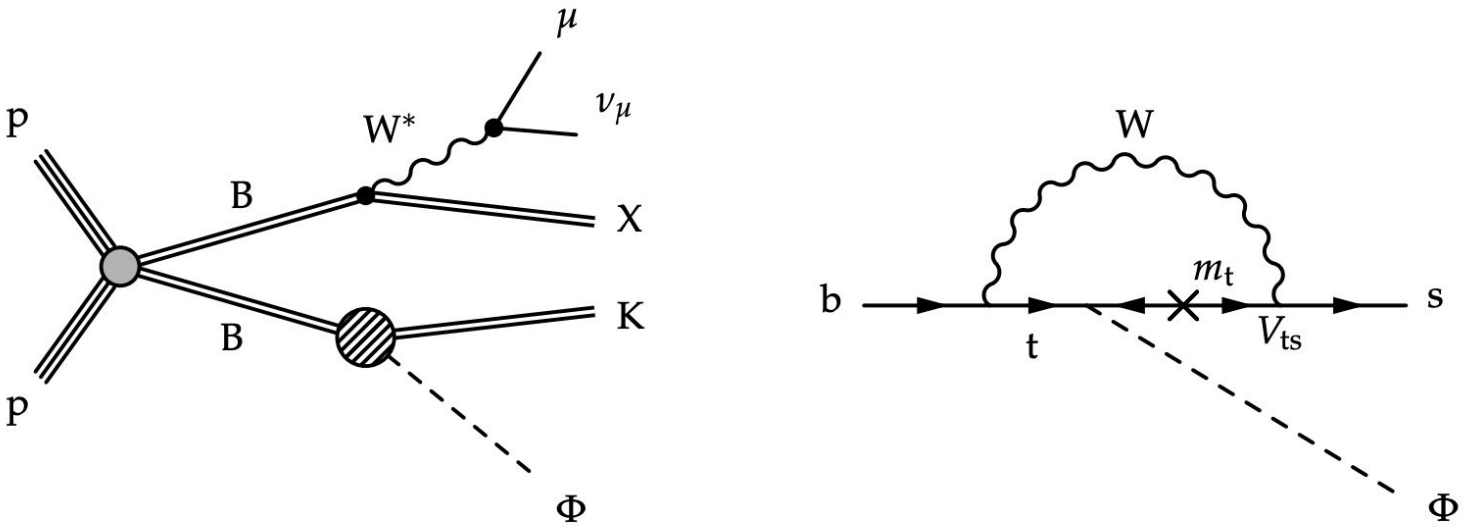
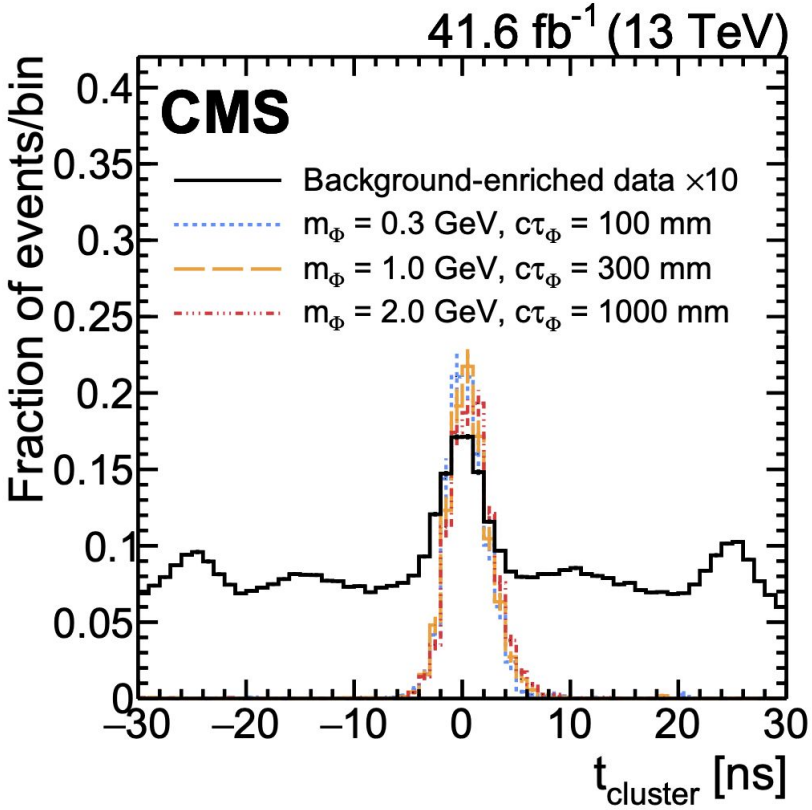
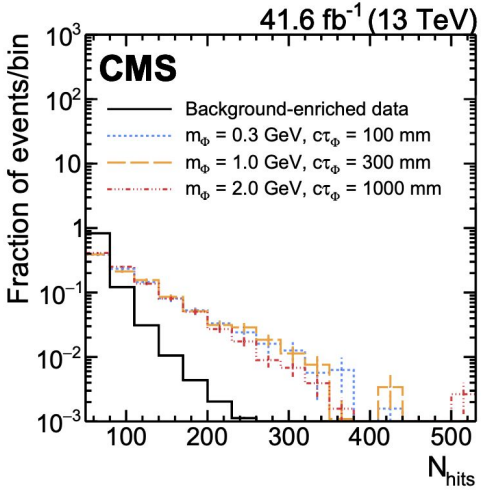


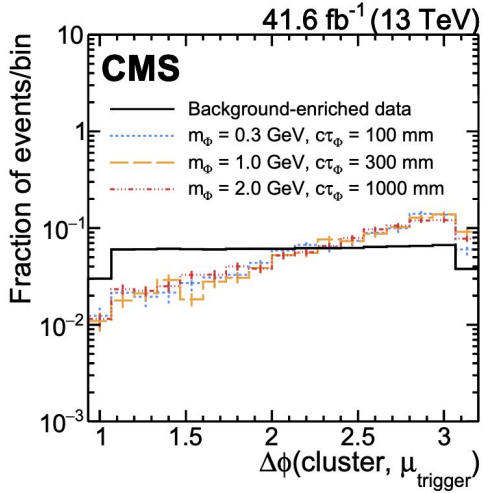
Figure 1: Example Feynman diagram for the production of a pair of B mesons, where one B meson decays to a muon, neutrino, and another hadron labeled X, while the other B meson decays to a kaon and the LLP Φ (left). Penguin diagram displaying the flavor-changing interaction which changes the flavor of the b quark to a s quark, producing the Φ particle (right). The interaction proceeds via a virtual top quark, denoted by the cross, which undergoes a chirality flip, denoted by the outward-pointing arrows on either side of the cross in the diagram.

Light Scalars from B Decays

Search for b hadron decays to LLPs…, arxiv:2508.06363, Figs. 3 and 4

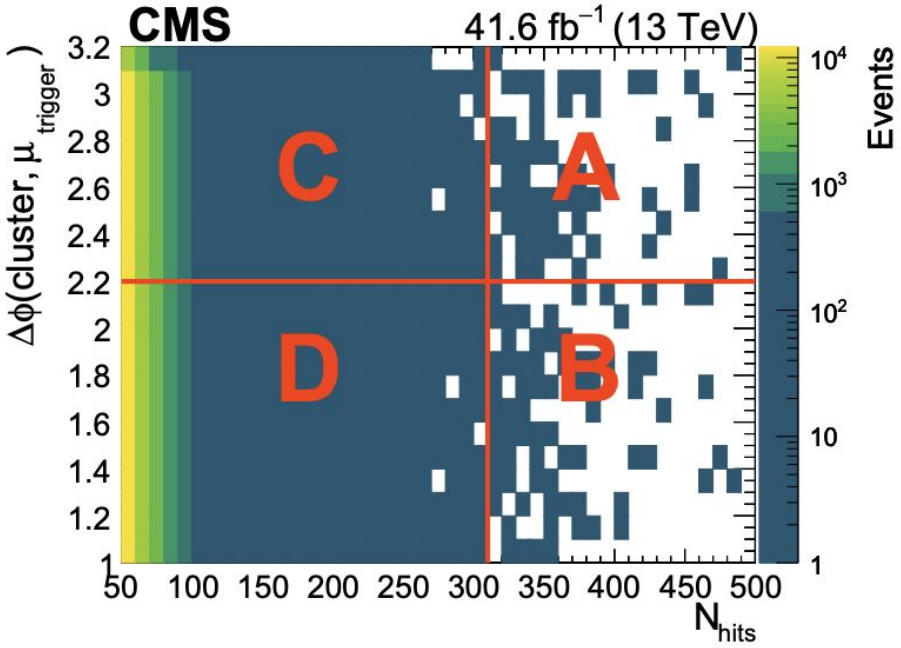






Light Scalars from B Decays

Search for b hadron decays to LLPs…, arxiv:2508.06363, Fig.5 and Table 2



Source	Uncertainty [%]
Integrated luminosity	2.5
Cross section	15
Muon ID scale factor	0.6
Simulated signal sample size	13–26
ME11/12 veto	2.2
RB1 veto	2.6
RE1 veto	0.7
MB1 segment veto	1.1
Muon bremsstrahlung veto	0.5
Cluster size correction	2.8
Cluster time	0.3
Cluster time spread	7.8
Total	22.0–31.5

Soft DVs from SUSY Coannihilation

Search for LLPs using DVs…, arxiv:2511.08212, Fig. 1

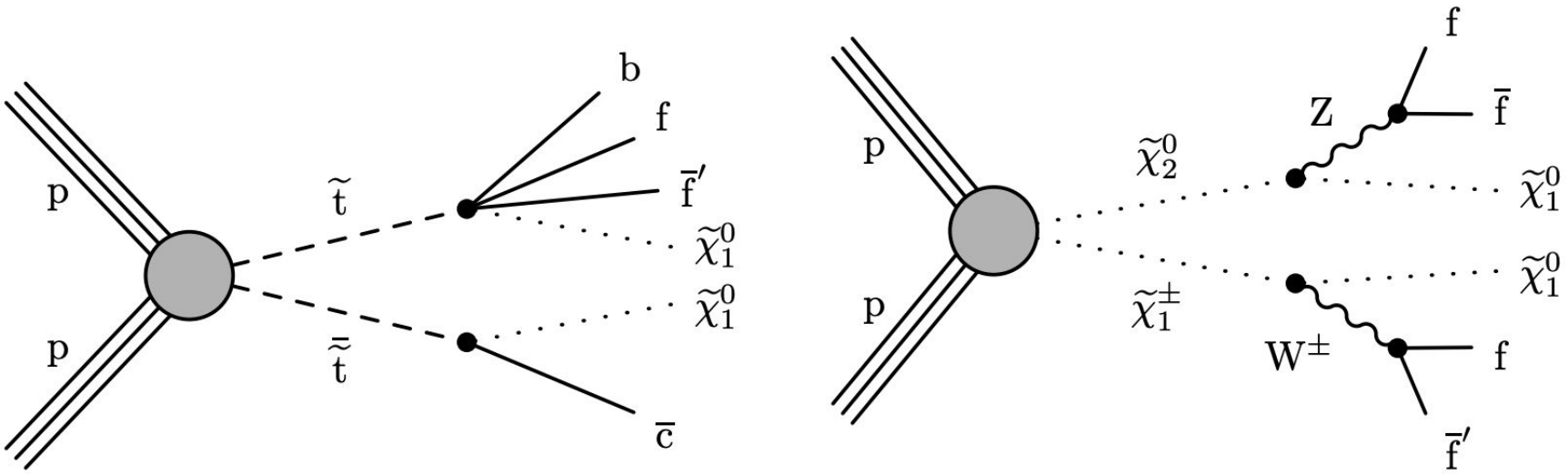


Figure 1: Feynman diagrams for the $\tilde{t}$ NLSP (left) and the bino-wino NLSP (right) production.

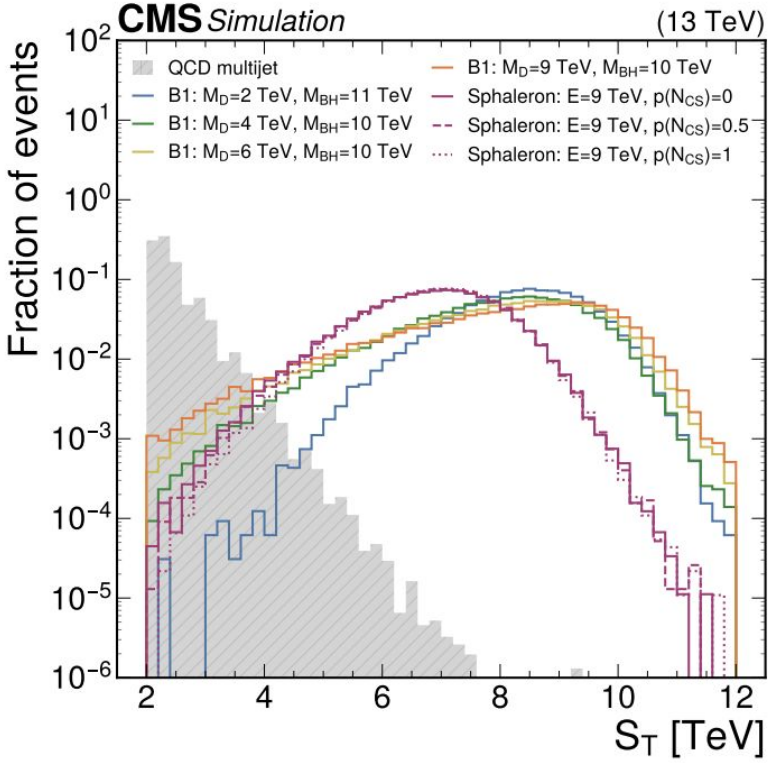
Soft DVs from SUSY Coannihilation

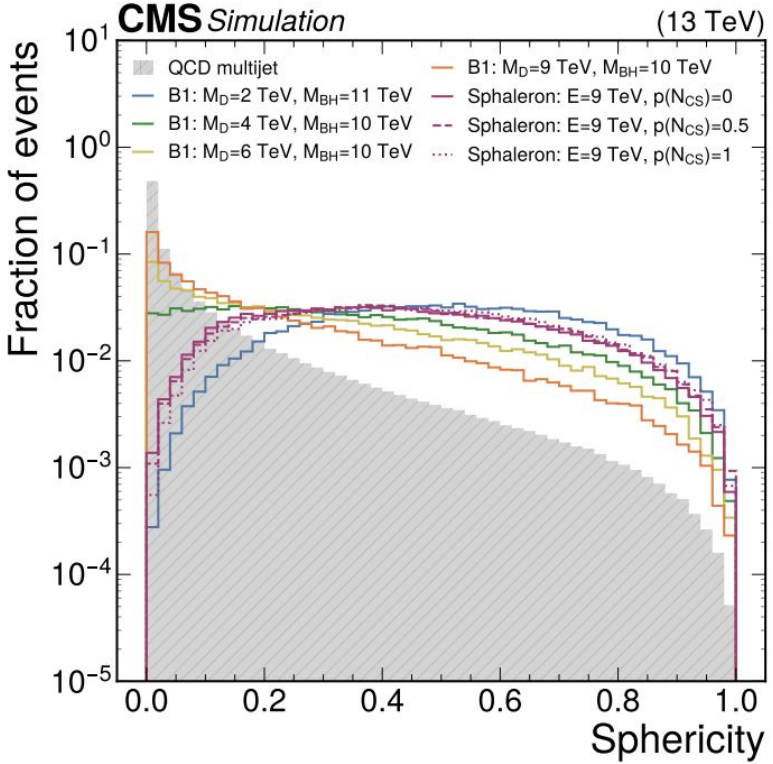
Search for LLPs using DVs…, arxiv:2511.08212, Table 1

Systematic uncertainty	Magnitude
Background estimate	<2%
Track/vertex reconstruction	10–11%
Material map veto	1–3%
Jet energy scale	2–4%
Jet energy resolution	1–2%
Unclustered energy	1–2%
Pileup	3–4%
Trigger	3%
Scale variations	1–5%
PDF variations	<1%
Integrated luminosity	2–3%
L1 trigger inefficiency	<1%

Black Holes, String Balls, & Sphalerons

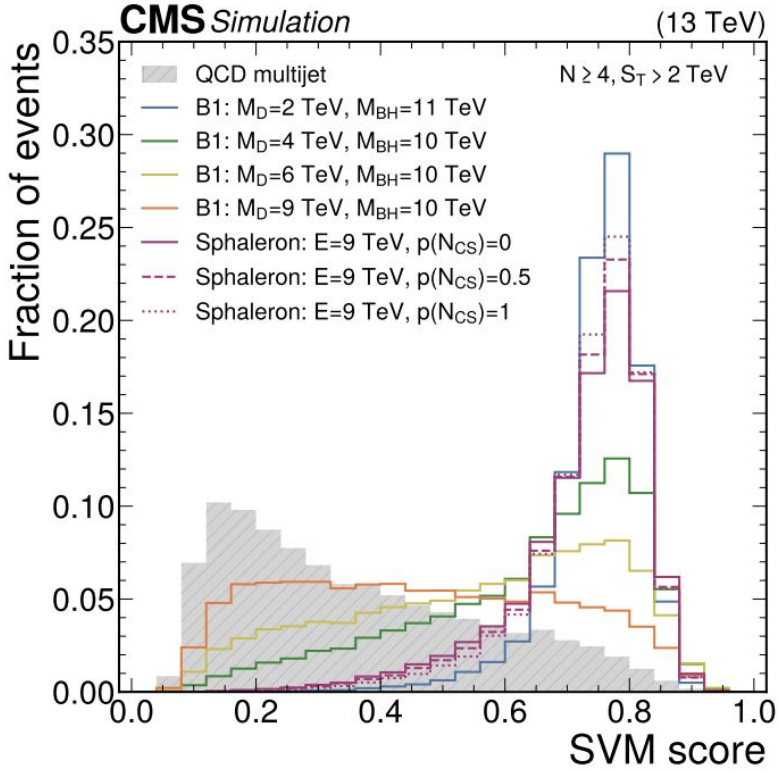
A search for microscopic BHs…, arxiv:2604.10732, Fig. 1

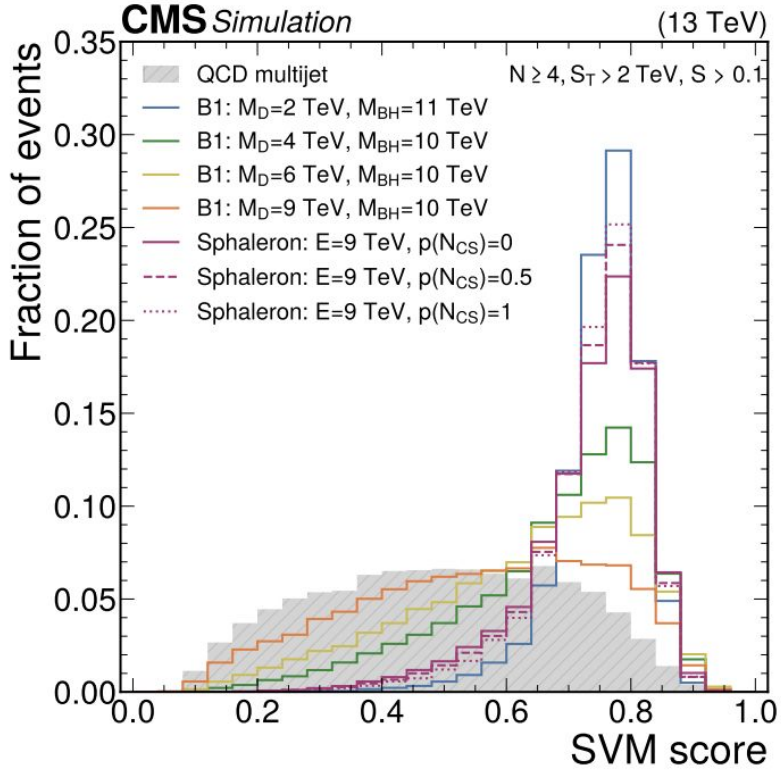




Black Holes, String Balls, & Sphalerons

A search for microscopic BHs…, arxiv:2604.10732, Fig. 2





Black Holes, String Balls, & Sphalerons

A search for microscopic BHs…, arxiv:2604.10732, Fig. 11

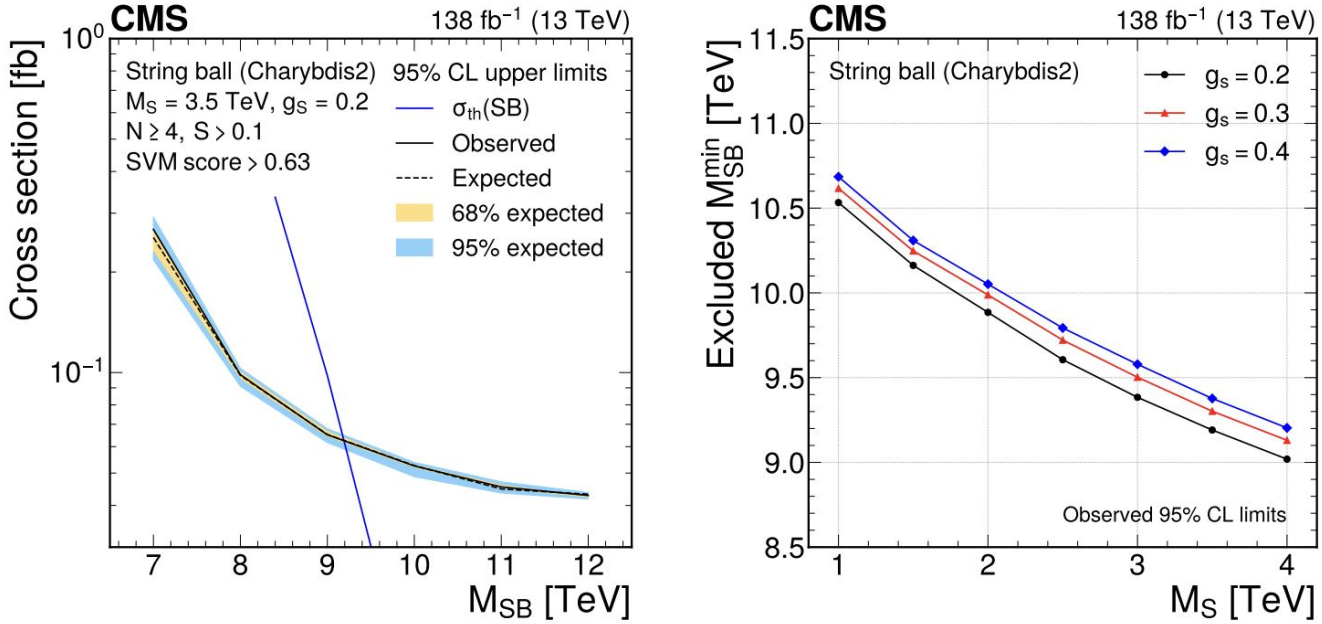


Figure 11: Expected and observed 95% CL upper limits for SB models with $M_S = 3.5\,\text{TeV}$ and $g_S = 0.2$ (left) and excluded SB mass values as functions of M_S at $g_S = 0.2, 0.3$, and 0.4 (right). The inner (outer) band represents the 68% (95%) quantile of the expected limit.

Black Holes, String Balls, & Sphalerons

A search for microscopic BHs…, arxiv:2604.10732, Fig. 12

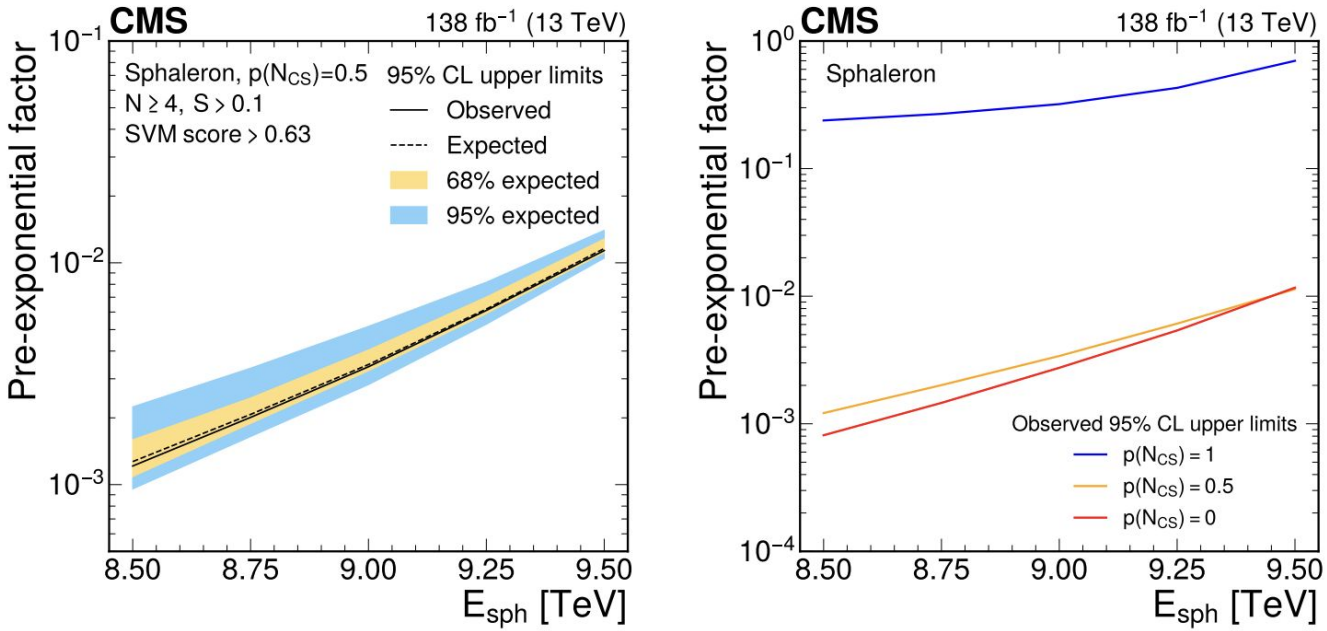


Figure 12: Expected and observed 95% CL upper limits on the pre-exponential factor for the sphaleron model with $p(N_{CS}) = 0.5$ (left), and observed limits with $p(N_{CS}) = 0$, 0.5, and 1 (right). The inner (outer) band (left) represents the 68% (95%) quantiles of the expected limit.

Fractionally Charged Particles

Search for fractionally charged particles…, arxiv:2402.09932, Fig. 2

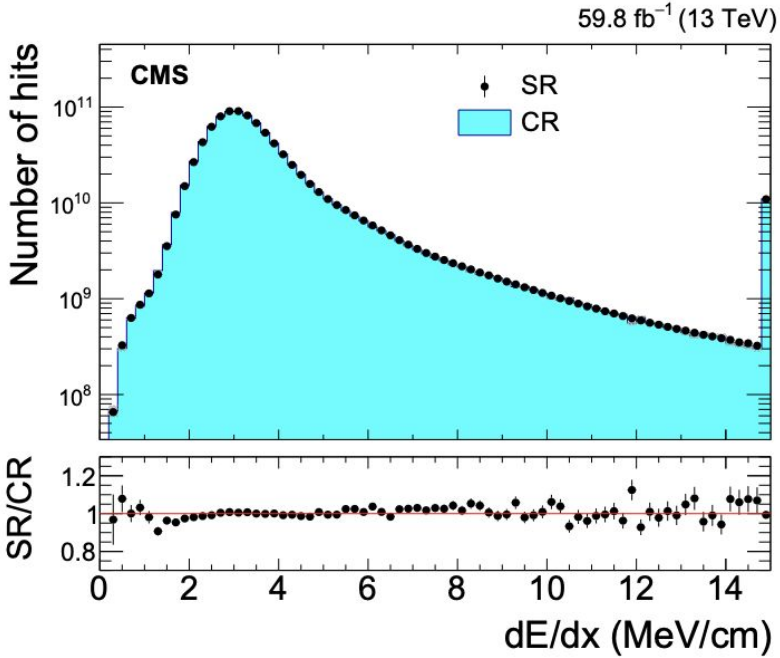


Figure 2: The dE/dx distribution for hits on candidate tracks in the CR and SR in 2018 data. The last bin is an overflow bin. The vertical bars and the shaded area correspond to the statistical uncertainty in the SR and the CR, respectively.