Searches for Long-Lived Particles with the CMS Detector

Kiley Kennedy, Princeton University

DPF-PHENO, 14 May 2024

Where is BSM Physics Hiding?

Title Image Credit:
Michael Hoch
"CMS-The Art of Science"

Where is BSM Physics Hiding?

- Dark Matter
- Flavor Anomalies
- Neutrino Masses
- SUSY
- Hidden Sector
- Multiple Higgses

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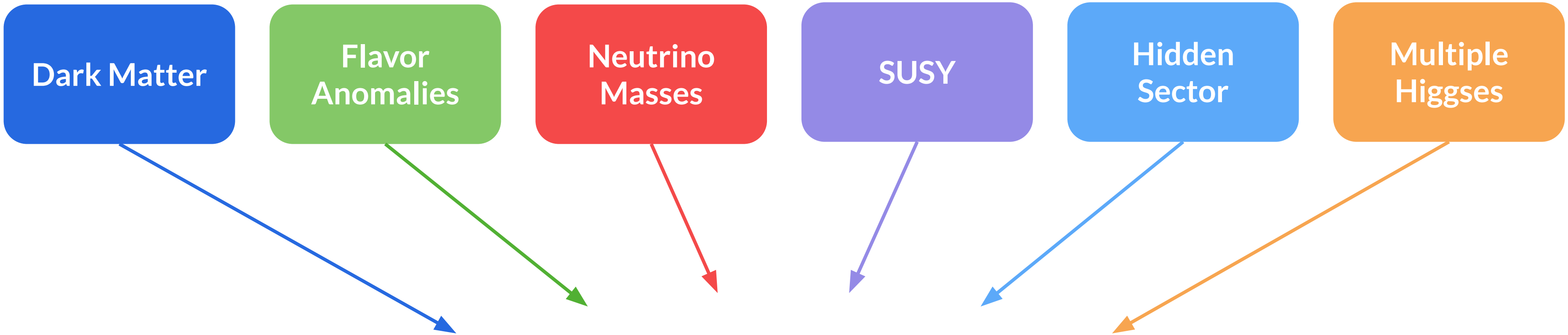
Where is BSM Physics Hiding?



Long-Lived Particles (LLPs):

➔ Small couplings

➔ Highly virtual intermediate states

➔ Small phase space (nearly degenerate masses)

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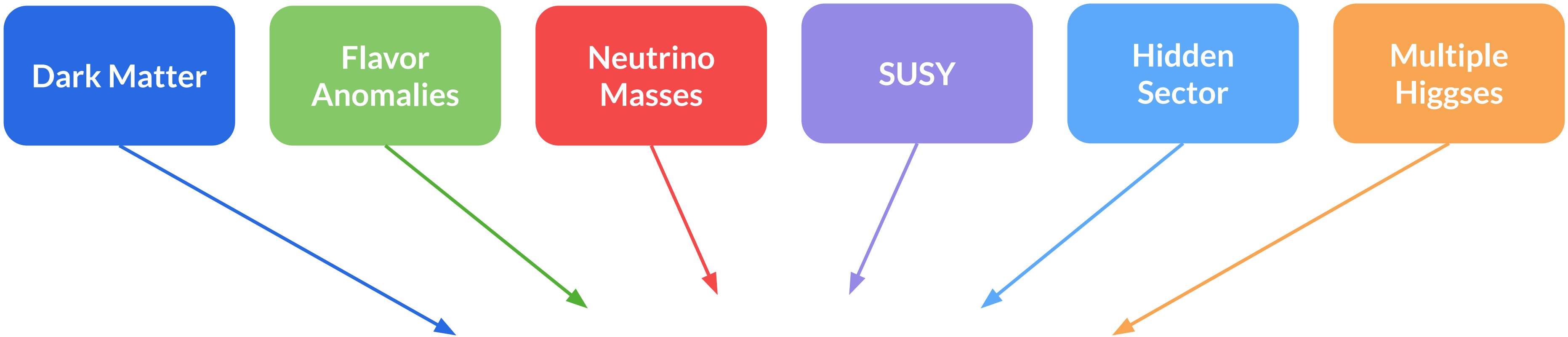

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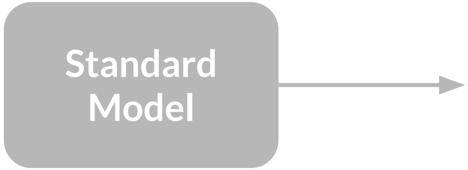

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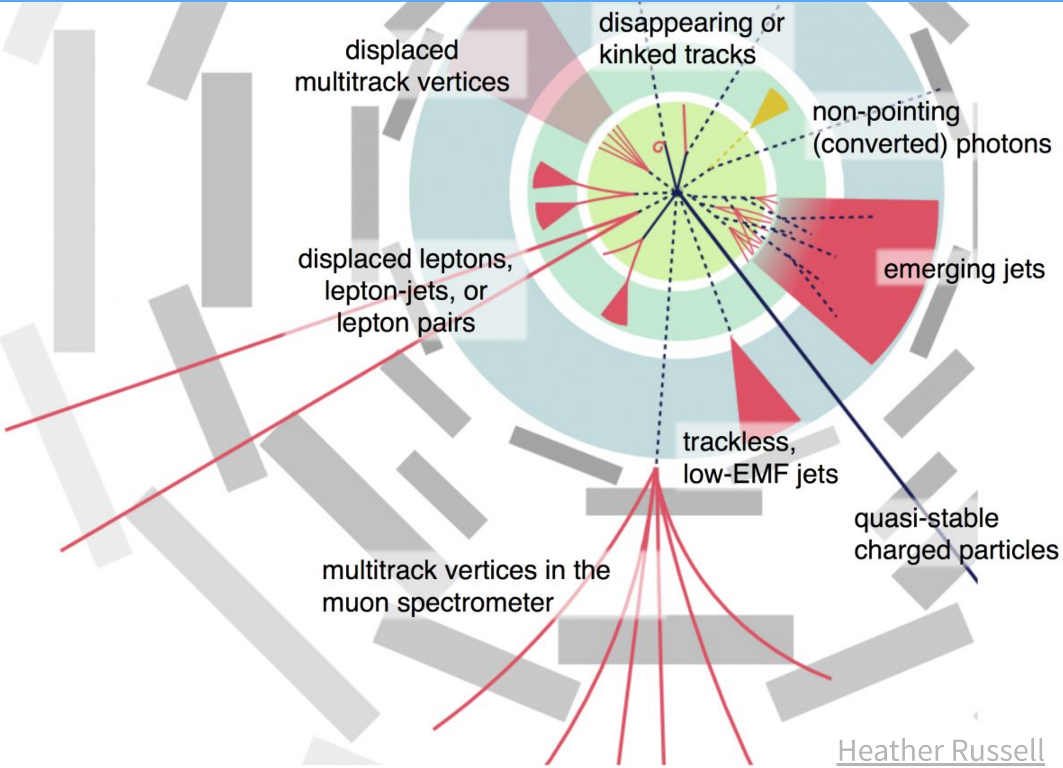
Key Challenges for LLP Searches at the LHC

Physics: Displaced and Delayed Decays

➔ E.g. displaced tracks, unusual energy patterns in ECAL/HCAL, decays in muon system



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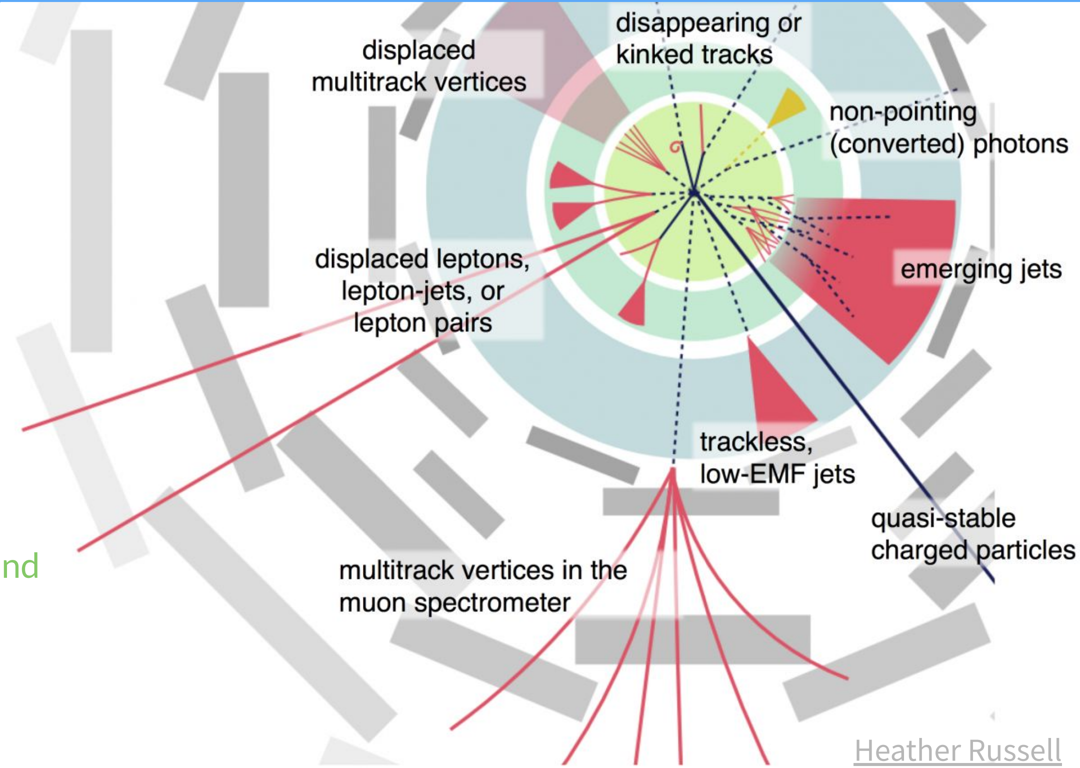

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Physics: Displaced and Delayed Decays

➔ E.g. displaced tracks, unusual energy patterns in ECAL/HCAL, decays in muon system

Reconstruction and Analysis

➔ E.g. dedicated triggers, custom reconstruction and calibrations, specialized simulation strategies

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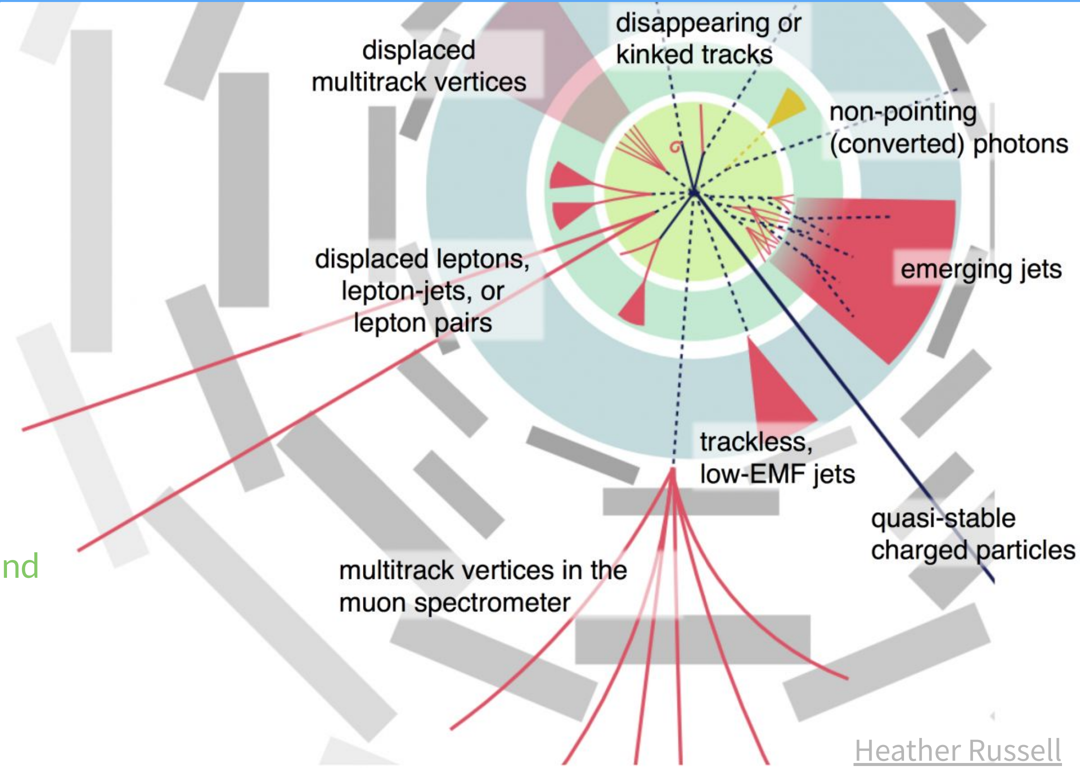

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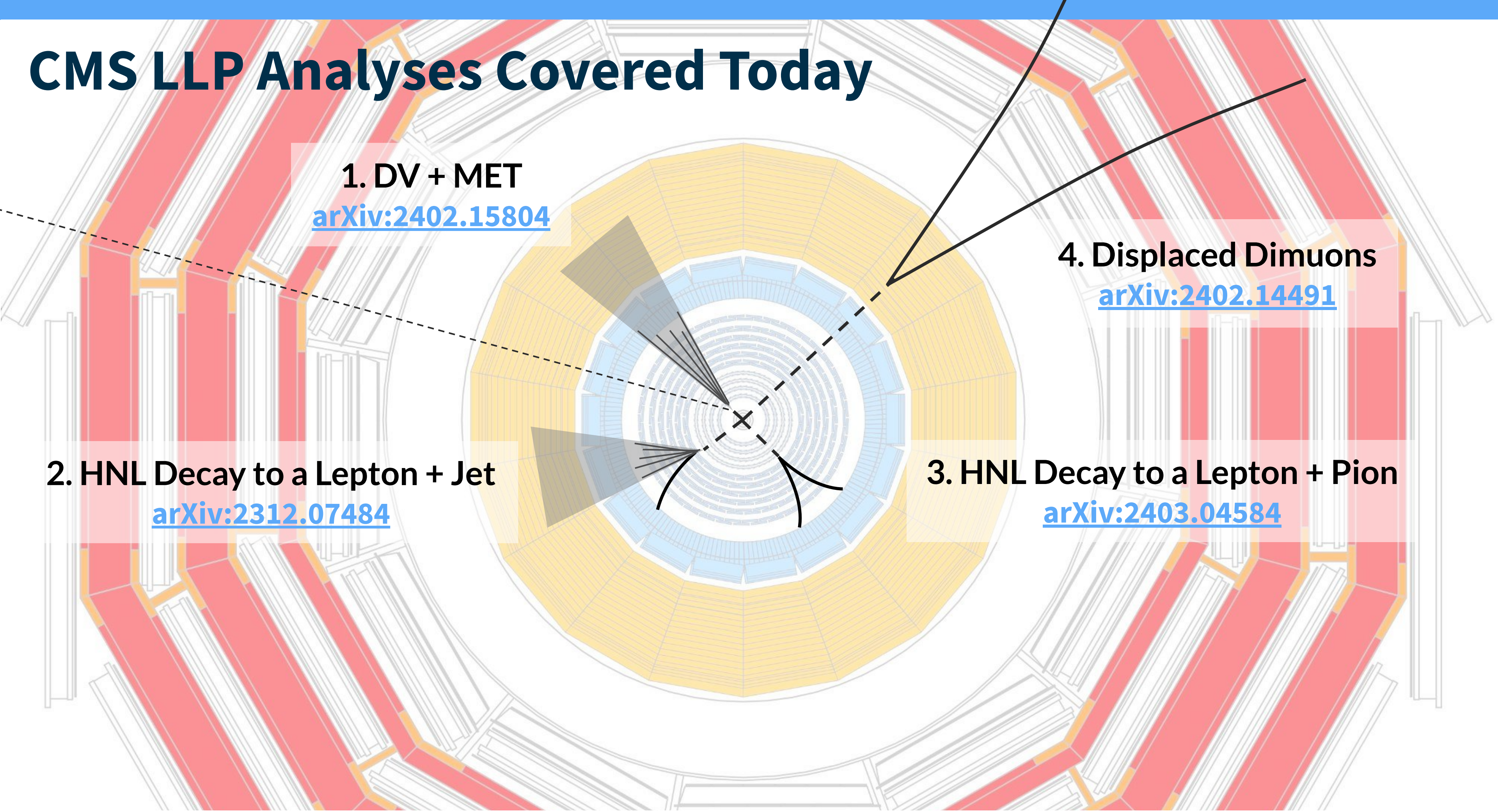
(Non-Standard) Backgrounds

- Long-lived SM backgrounds
- Cosmic rays
- Pileup (in- and out-of-time)
- Material interactions
- Accelerator backgrounds (satellite collisions, beam halo)

CMS LLP Analyses Covered Today



1. DV + MET
arXiv:2402.15804

2. HNL Decay to a Lepton + Jet
arXiv:2312.07484

3. HNL Decay to a Lepton + Pion
arXiv:2403.04584

4. Displaced Dimuons
arXiv:2402.14491

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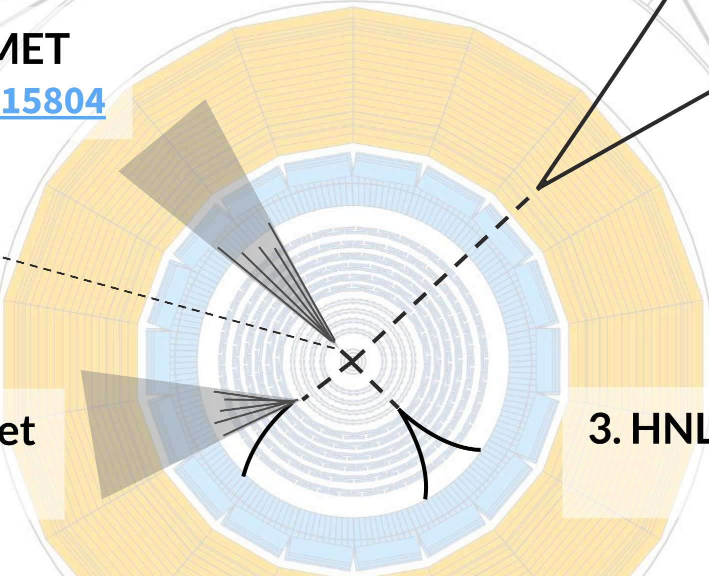

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Other CMS LLP Talks at DPF-PHENO:

- Emerging Jets (C. Savard) arXiv:2403.01556
- Long-Lived Charged Particles (P. Maksimovic) arXiv
- Displaced Jets in Run 3 (J. Luo) cds:2893044
- LLP Decays in the Muon System (D. Guerrero) arXiv:2402.01898, arXiv:2402.18658

1. Search for Displaced Vertices + MET

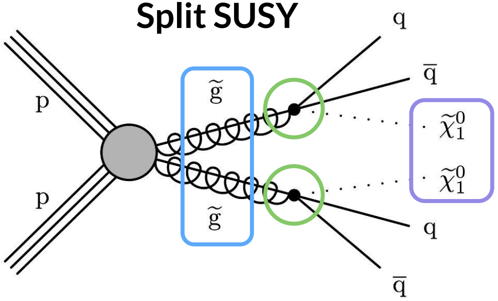
arXiv:2402.15804

Overview: Search for LLPs with at least one displaced vertex within the beam pipe and missing transverse energy

- ➔ Model-independent search interpreted in Split SUSY and SUSY GMSB
- ➔ Sensitive to softer final states (compressed, low ΔM's) than arXiv:2104.13474 and lower cτ values than arXiv:1710.04901
- ➔ Full CMS Run 2 dataset triggering on MET

Target: 1.4 GeV < m_{LLP} < 2.6 TeV , 10^{-5} < $c\tau_{LLP}$ < 1 m

Split SUSY



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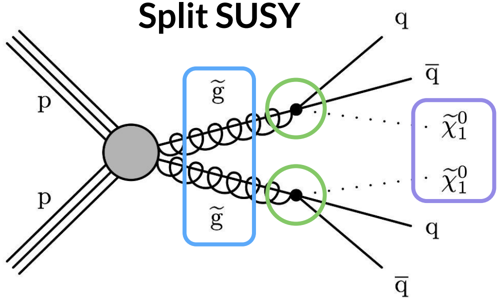
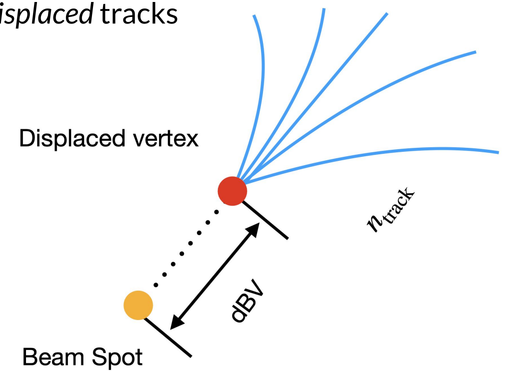


Reconstruct Displaced Vertices:

- ➔ Using *high-quality* and *displaced* tracks
- ➔ Categorize vertices by n_{track}



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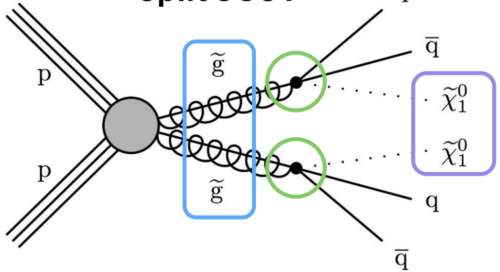

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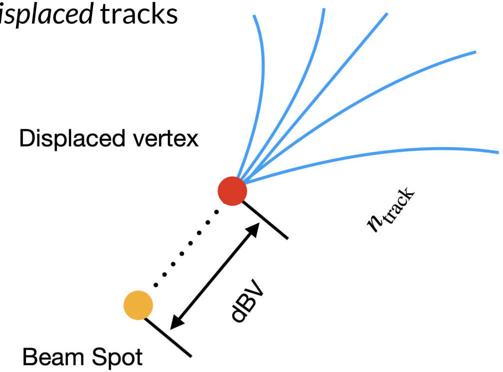

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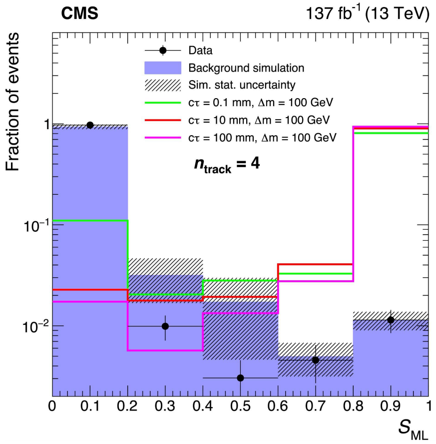
Interaction Network:

- ➔ Event-level GNN using tracks
- ➔ Categorize events by output, S_{ML}



1. Search for Displaced Vertices + MET

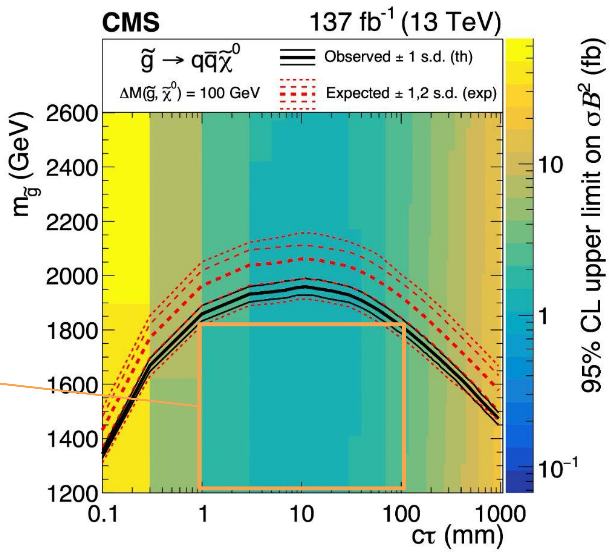
arXiv:2402.15804

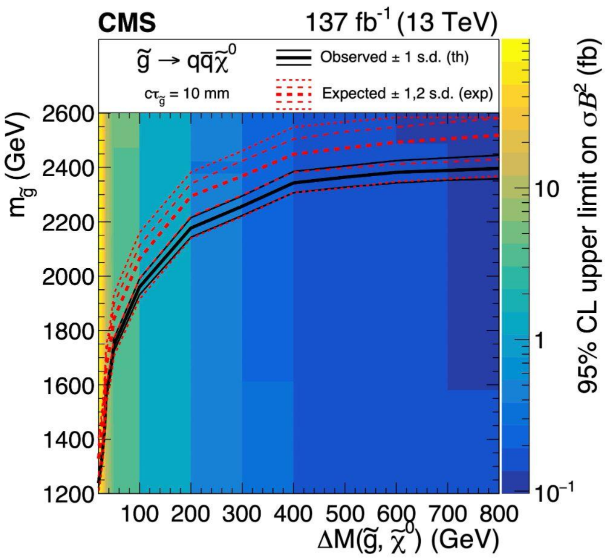
Background Estimation

- ➔ Strategy: Data-driven ABCD using n_{tracks} and S_{ML}
- ➔ Primary background: unrelated tracks randomly crossing

Results

- ➔ No significant excess observed
- ➔ Split-SUSY: excludes gluinos with cτ in the range 1–100 mm *(for M_g < 1800 GeV, $\Delta M_{g,\chi}$ = 100 GeV)*
- ➔ SUSY GMSB:
  - ◆ Cross section limits as low as 1 fb
  - ◆ Excludes gluinos with cτ in the range 0.3–100 mm *(M_g < 2240 GeV)*





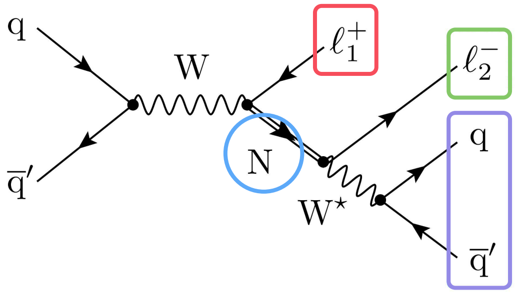
2. Search for Long-Lived HNLs in W-Decays

arXiv:2312.07484

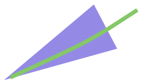
Overview: Search for long-lived HNLs decaying to a jet and a charged lepton in association with a prompt lepton

- ➔ Target both lepton flavor-conserving or violating decays
- ➔ Full CMS Run 2 dataset triggering on prompt lepton (e/μ)

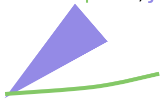
Target: $2 < m_{LLP} < 20$ GeV , $10^{-5} < c\tau_{LLP} < 1$ m



High mass (boosted):
Merged lepton, jet



Low mass (less boost):
Resolved lepton, jet



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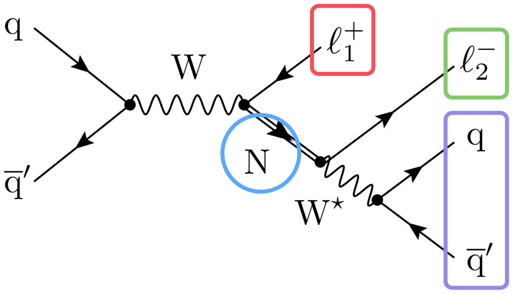

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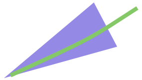

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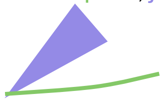

Displaced Jet Tagger

- ➔ Extended DNN tagger in arXiv:1912.12238 to include case where displaced lepton is inside the jet cone

Background Estimation

- ➔ ABCD method with m_{llj^*} and displaced jet tagger score

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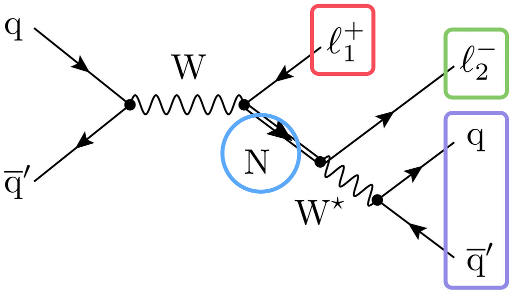

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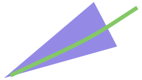

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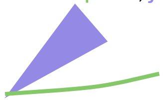

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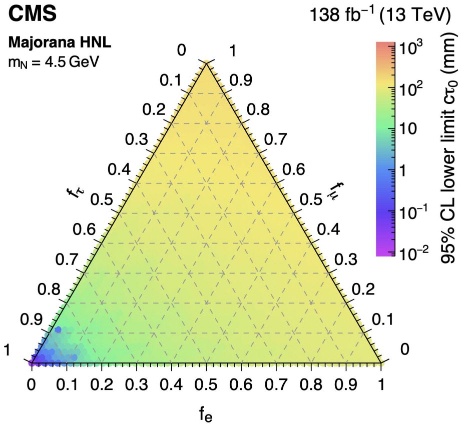
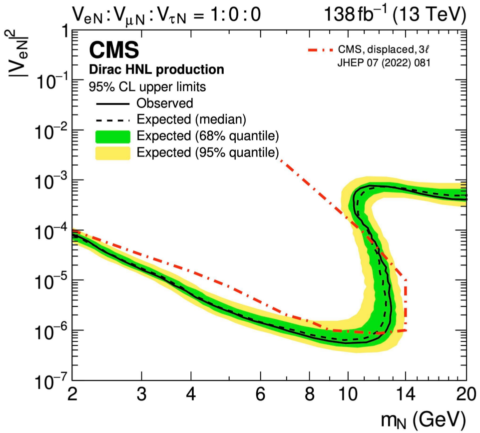
Results

- ➔ No significant excess observed
- ➔ First result involving a Dirac or Majorana HNL that couples to all three lepton generations (with $2 < m_N < 20$ GeV)
- ➔ Most stringent limits to date for the pure electron coupling scenario with $m_N \lesssim 4$ GeV





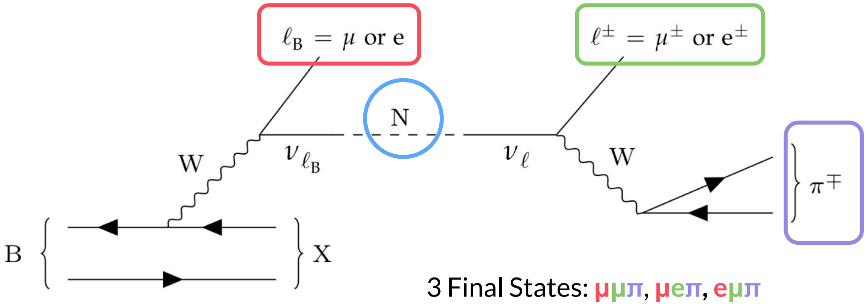
3. Search for Long-Lived HNLs in B-Decays

arXiv:2403.04584

Overview: Search for long-lived HNLs decaying to a charged lepton and charged pion in association with a prompt lepton

- ➔ B meson decays: sensitive to lighter HNL masses (complementary to W decays)
- ➔ CMS 2018 parking dataset with triggers targeting semileptonic B decay (higher luminosity than LHCb, Belle searches)

Target: $1 < m_{LLP} < 3$ GeV, $10^{-5} < c\tau_{LLP} < 10$ m



3 Final States: μμπ, μeπ, eμπ
2 Channels: muon only, mixed flavor

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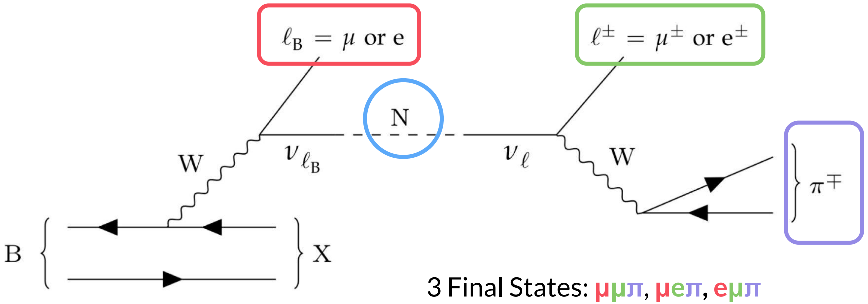

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Data Parking at CMS:

- ➔ Save raw data to be reconstructed later, enabling higher HLT rates
- ➔ 2018 "B-Parking" Dataset:
  - ◆ 41.6 fb^{-1}
  - ◆ ~12B BBbar enriched events

arXiv:2403.16134

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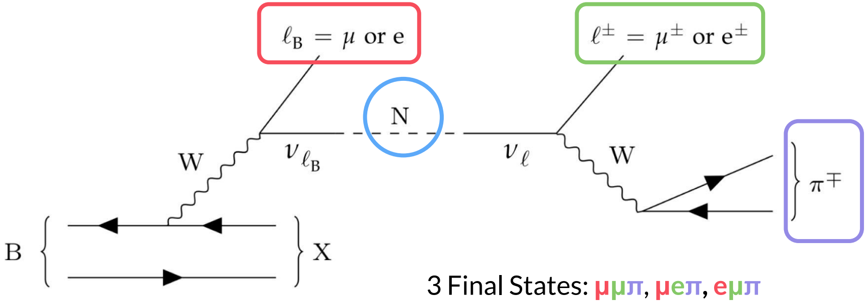

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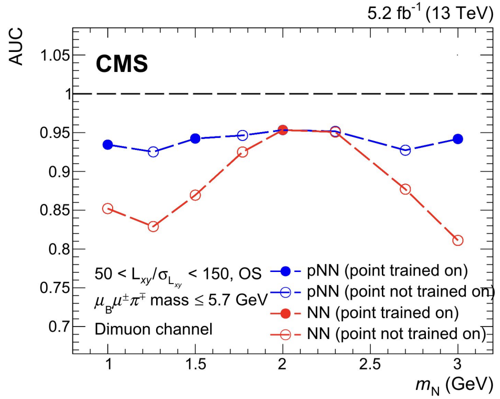
Analysis Strategy:

- ➔ Event selection via a parametric neutral network (**pNN**)
- ➔ Bump hunt performed in $m(l^\pm\pi^\mp)$



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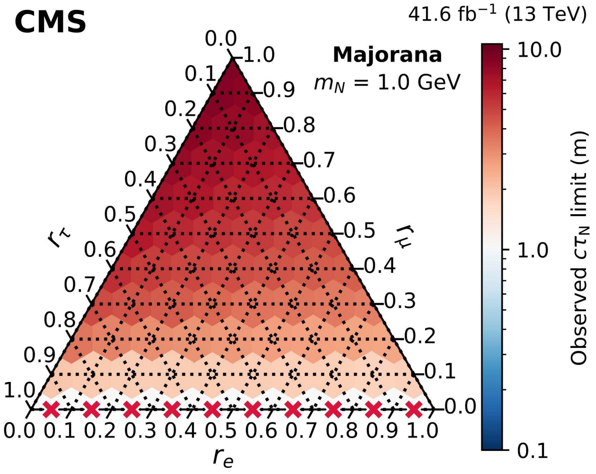
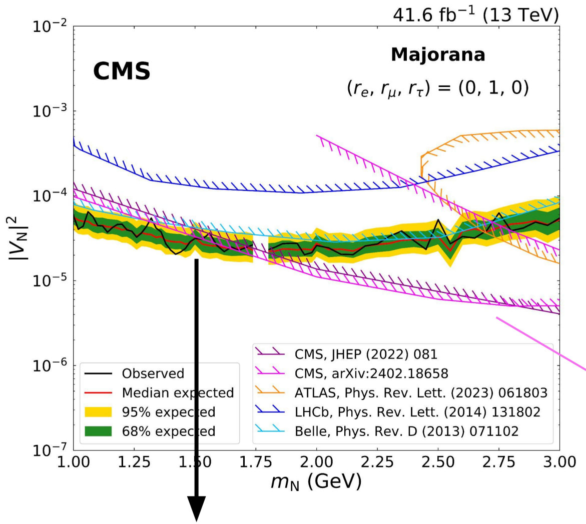
Results

- ➔ No significant deviation from the background prediction observed
- ➔ Set limits on both Majorana and Dirac-like HNLs



Limits on $c\tau_N$ given for 66 mixing scenarios for the first time for m_N = 1, 2 GeV



Most stringent upper limits on $|V_N|^2$ from a collider experiment

CMS search for long-lived HNLs decaying in the muon system (see D. Guerrero's talk)

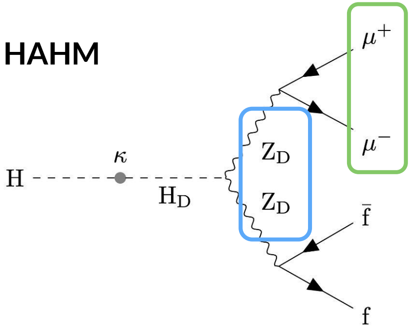
4. Search for Displaced Dimuons in LHC Run 3

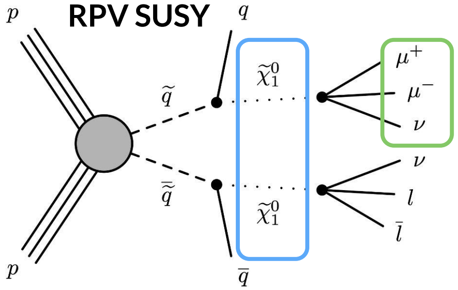
arXiv:2402.14491

Overview: Search for neutral LLPs with at least one displaced dimuon vertex

- ➔ Model-independent search, benchmarks: HAHM, RPV SUSY
- ➔ Uses CMS data collected during 2022 using dedicated displaced dimuon trigger

Target: 10 GeV < m_{LLP} < 1.6 TeV , 10^{-5} < $c\tau_{LLP}$ < 10^{4} m





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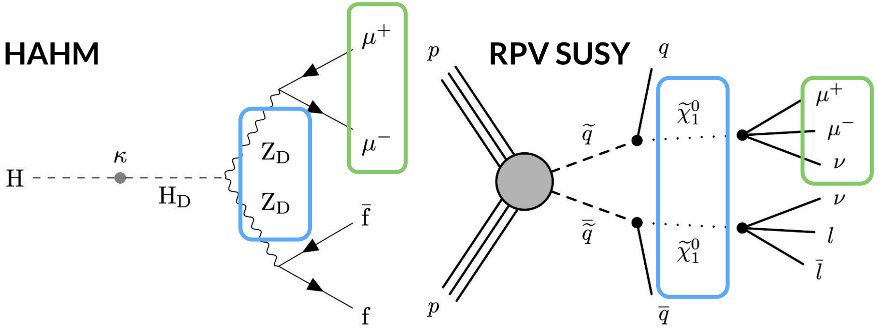
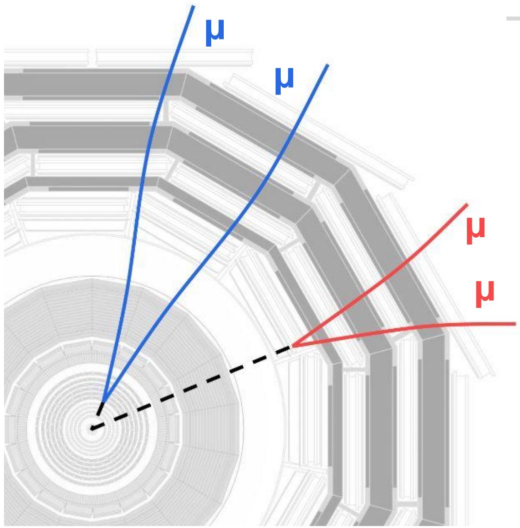
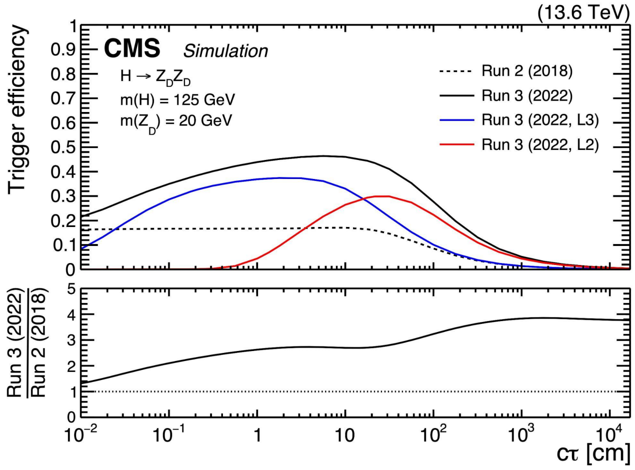




Displaced Dimuon Triggers in Run 3

- ➔ Custom L1 seeds and HLT paths enable lower p_T thresholds (e.g. 23 → 10 GeV)
- ➔ Improved efficiency for muons at high displacements
- ➔ Online and offline reconstruction with both the tracker and muon system (L3, TMS) or only the muon system (L2, STA)



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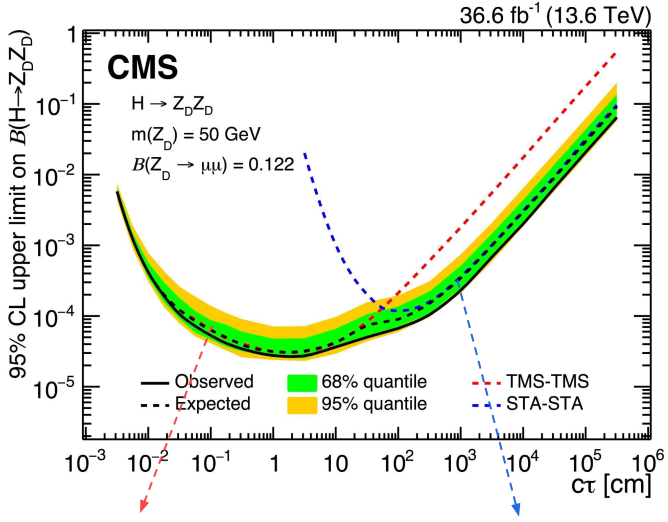
Results:

➔ Data-driven background estimation categorized by tracking + MS and MS-only muons

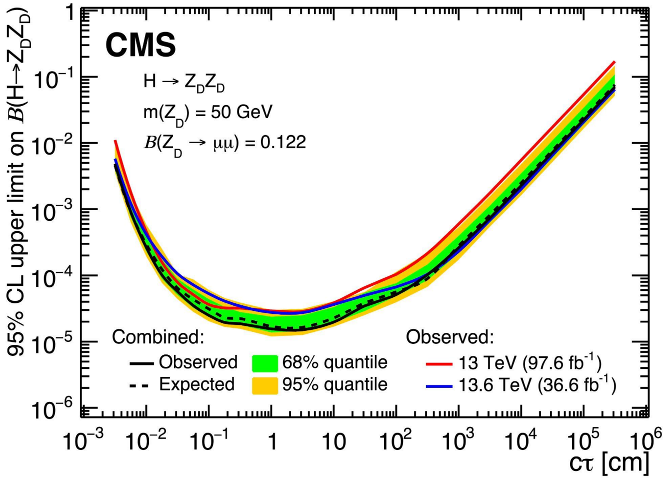
Complementary use of tracking and muon system



Reco with Tracker + MS dominates

Reco with MS only dominates

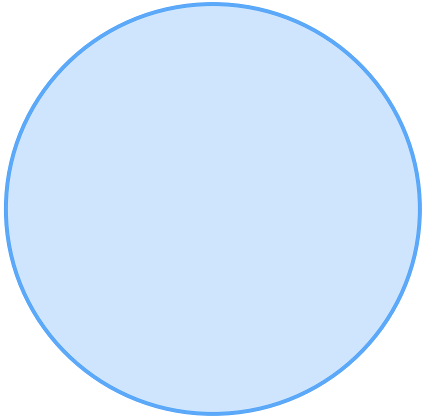
Achieved similar sensitivity to Run 2 result with only ~1⁄3 of the luminosity in 2022



Common Themes Across CMS LLP Searches

Broad coverage across models with LLPs

- ➔ SUSY, HNLs, dark photons, exotic Higgs decays, and more
- ➔ Model-independent interpretations



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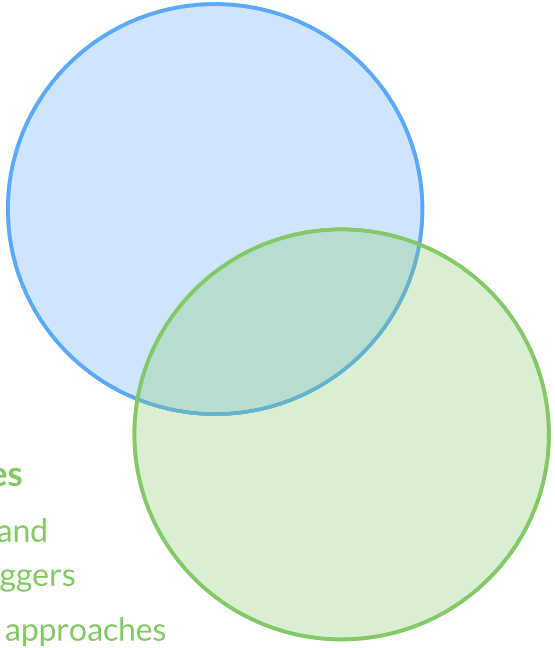

Creative analysis strategies

- ➔ Dedicated LLP triggers and clever use of existing triggers
- ➔ Novel machine learning approaches
- ➔ Improved taggers
- ➔ Shared tools

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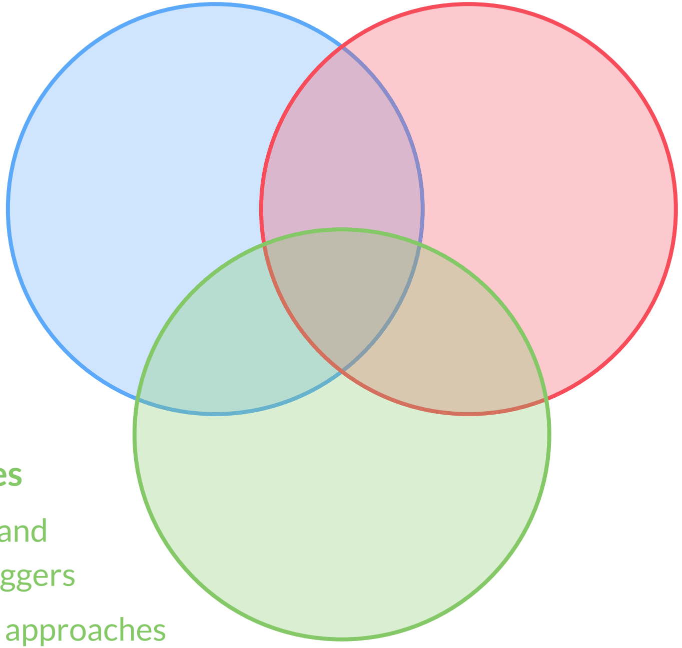


Complementarity across sub-detectors

- ➔ Measurements from different subsystems lead to improved cτ and final state coverage

E.g., dedicated talks on Thursday on displaced jet results using the tracker (10^{-3} < cτ < 1 m) and the muon system (0.1 < cτ < 100 m)

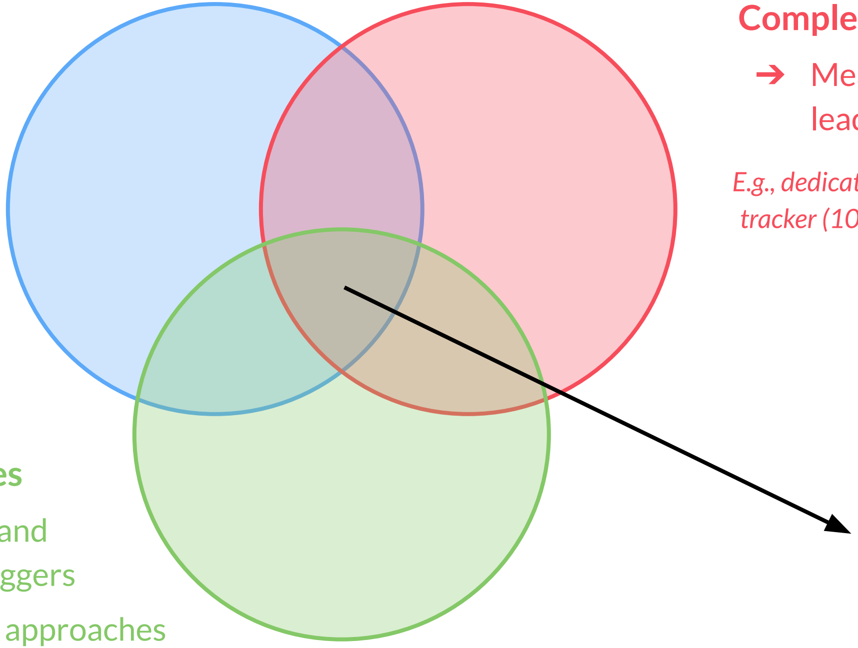
Creative analysis strategies

- ➔ Dedicated LLP triggers and clever use of existing triggers
- ➔ Novel machine learning approaches
- ➔ Improved taggers
- ➔ Shared tools

Common Themes Across CMS LLP Searches

Broad coverage across models with LLPs

- ➔ SUSY, HNLs, dark photons, exotic Higgs decays, and more
- ➔ Model-independent interpretations



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Robust and exciting LLP search program!

Outlook + Conclusions

➔ Presented 4 long-lived particle search results today – many more CMS LLP results presented throughout this week

➔ Many developments in trigger strategy, ML tools, and understanding of background processes continue to push the CMS LLP program forward

➔ Actively analyzing Run 3 data and anticipate many more exciting results in the coming years

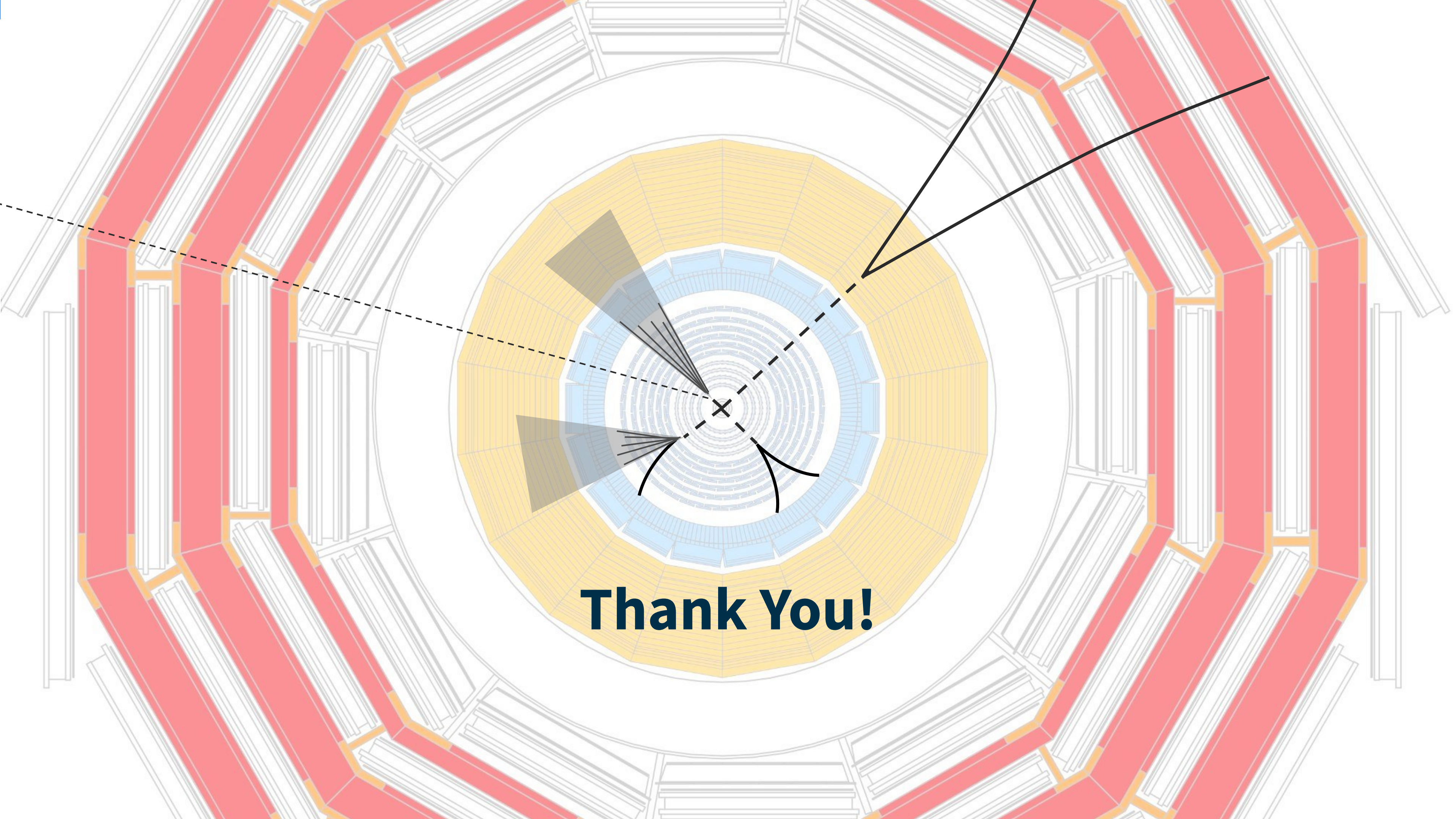
Keep an eye out for…

Search for emerging jets *(C. Savard)*

Search for long-lived charged particles using the CMS detector in Run 2 *(P. Maksimovic)*

Search for long-lived particles using displaced jets at CMS in Run 3 *(J. Luo)*

Searches for long-lived particles in the CMS muon system *(D. Guerrero)*

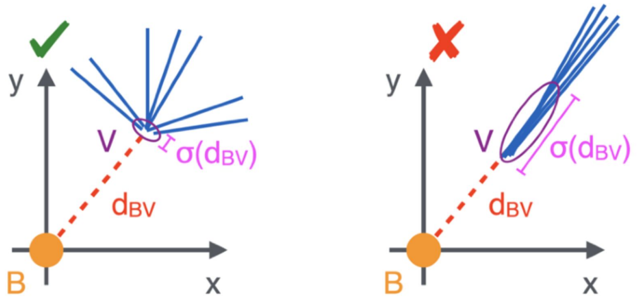

Thank You!

Backup

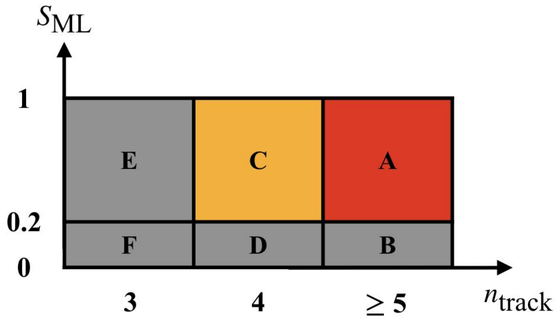
Search for Displaced Vertices + MET

arXiv:2402.15804

Vertex Reconstruction: Rejection of b jets



Control, Validation, and Signal Regions



Interaction Network

Validated on Neutralino → tbs, WH → SS → bbbb/dddd

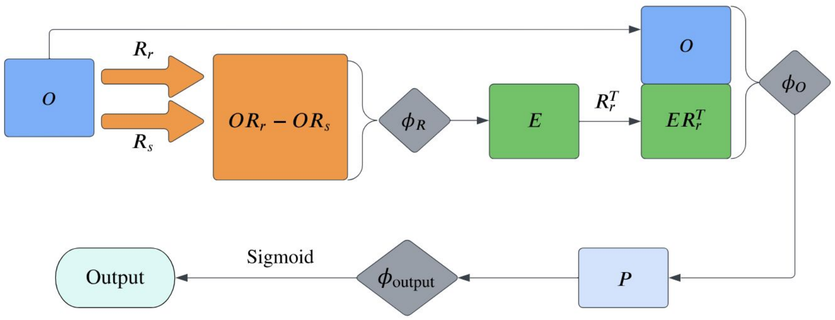
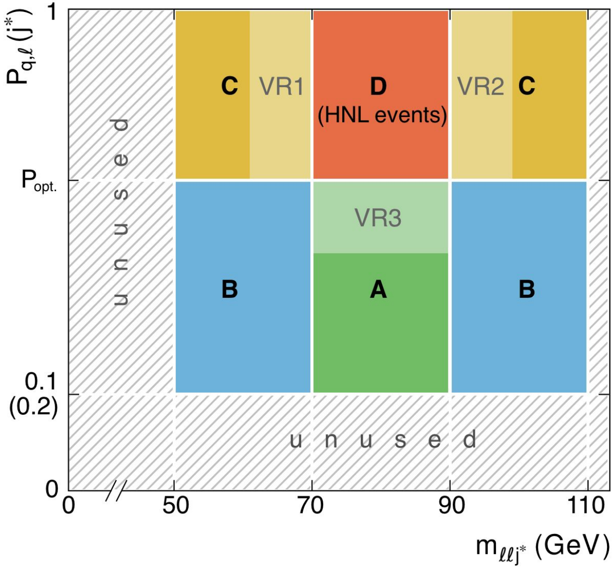


Figure 2: An illustration of the architecture of the IN, where the flow of data is indicated by arrows. Rectangular boxes represent data matrices, while diamonds represent multilayer perceptrons (MLPs). The original input information (O) is integrated with relation matrices (R_r and R_s) to form a graph that captures interactions between tracks. This graph is subsequently processed by an MLP (ϕ_R) to compute the effect (E) of the interactions. The effect is then combined with R_r and merged with the original input O. To assess the influence (P) of the effect on the original information, it undergoes further processing via another MLP (ϕ_O). Finally, the influence is passed through an MLP (ϕ_{output}) and a sigmoid function to produce the final output.

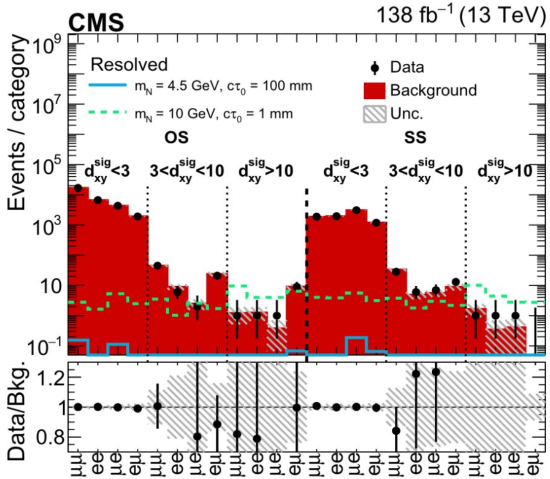
Search for Long-Lived HNLs in W-Decays

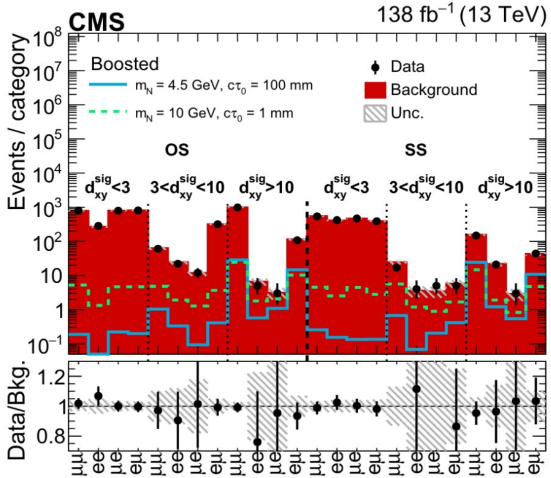
[arXiv:2312.07484](https://arxiv.org/abs/2312.07484)

ABCD Method



Signal Region Categories and Fit

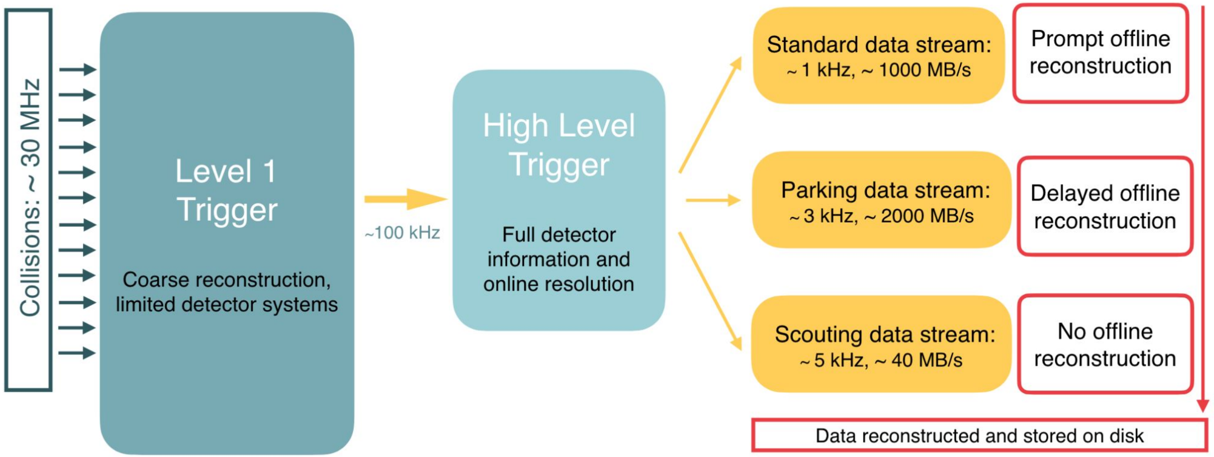




Data Parking and Scouting at CMS

arXiv:2403.16134

Data flow for a typical 2018 data-taking scenario



Single-muon trigger settings during a typical LHC fill

$\mathcal{L}_{inst}$ $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Pileup	L1 μ p_T [GeV]	HLT μ p_T [GeV]	HLT μ IP_{sig}	Peak L1 rate [kHz]	Peak HLT rate [kHz]	Purity [%]
2.0	54.0	—	—	—	—	—	—
1.7	45.9	12	12	6	20	1.5	92 ± 5
1.5	42.8	10	9	6	30	2.8	87 ± 4
1.3	35.1	9	9	5	32	3.0	86 ± 4
1.1	29.7	8	8	5	43	3.7	83 ± 4
0.9	24.3	7	7	4	53	5.4	59 ± 3

Search for Long-Lived HNLs in B-Decays

arXiv:2403.04584

Veto on SM Resonances

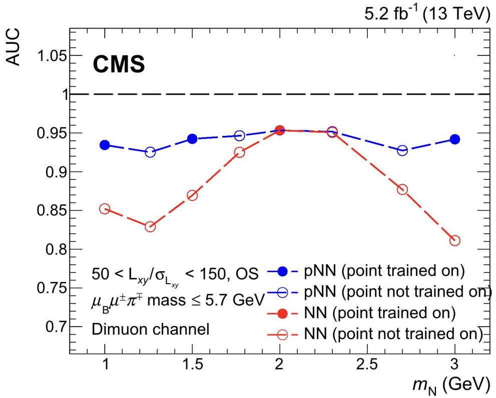
Mass spectrum	Process	Veto (GeV)	Categories	Misidentification
$m(\mu_B \mu^\pm)$	$\phi(1020) \to \mu\mu$	$\lvert m(\mu_B \mu^\pm) - 1.02\rvert > 0.01$	OS	0
	$J/\psi(1S) \to \mu\mu$	$\lvert m(\mu_B \mu^\pm) - 3.10\rvert > 0.15$	OS	0
	$\psi(2S) \to \mu\mu$	$\lvert m(\mu_B \mu^\pm) - 3.69\rvert > 0.08$	OS	0
$m(\mu_B \pi^\mp)$	$J/\psi(1S) \to \mu\mu$	$\lvert m(\mu_B \pi^\mp) - 3.10\rvert > 0.05$	SS	1 misid. π
	$D^0 \to K\pi$	$\lvert m(\mu_B \pi^\mp) - 1.76\rvert > 0.05$	SS	1 misid. μ
$m(e_B \pi^\mp)$	$J/\psi(1S) \to ee$	$\lvert m(e_B \pi^\mp) - 3.10\rvert > 0.05$	SS	1 misid. π
	$D^0 \to K\pi$	$\lvert m(e_P \pi^\mp) - 1.76\rvert > 0.05$	SS	1 misid. e
$m(\mu^\pm \pi^\mp)$	$D^0 \to K\pi$	$\lvert m(\mu^\pm \pi^\mp) - 1.77\rvert > 0.03$	all	1 misid. μ
$m(e^\pm \pi^\mp)$	$D^0 \to K\pi$	$\lvert m(e^\pm \pi^\mp) - 1.77\rvert > 0.03$	all	1 misid. e

24 Exclusive Signal Region Categories

Quantity	Label	Definition
$L_{xy}/\sigma_{L_{xy}}$	low $L_{xy}/\sigma_{L_{xy}}$	$L_{xy}/\sigma_{L_{xy}} < 50$
	medium $L_{xy}/\sigma_{L_{xy}}$	$50 < L_{xy}/\sigma_{L_{xy}} < 150$
	high $L_{xy}/\sigma_{L_{xy}}$	$L_{xy}/\sigma_{L_{xy}} > 150$
Relative lepton sign	OS	ℓ_B charge $\neq \ell$ charge
	SS	ℓ_B charge = ℓ charge
$\ell_B \ell^\pm \pi^\mp$ mass	low $\ell_B \ell^\pm \pi^\mp$ mass	$\ell_B \ell^\pm \pi^\mp$ mass $< 5.7\,\text{GeV}$
	high $\ell_B \ell^\pm \pi^\mp$ mass	$\ell_B \ell^\pm \pi^\mp$ mass $> 5.7\,\text{GeV}$
Flavour channel	dimuon	$\ell_B \ell = \mu\mu$
	mixed-flavour	$\ell_B \ell = (\mu e, e\mu)$

pNN

arXiv1601.07913, arXiv:2202.00424



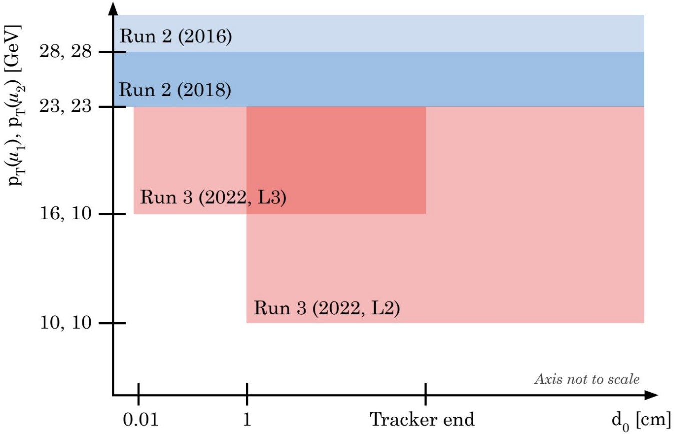
The pNN is trained using input variables that provide a good discrimination between signal and background. These variables, which are discussed in more detail below, are

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 [43, 46].

Search for Displaced Dimuons in LHC Run 3

arXiv:2402.14491

Dimuon Trigger Coverage in Runs 2 + 3

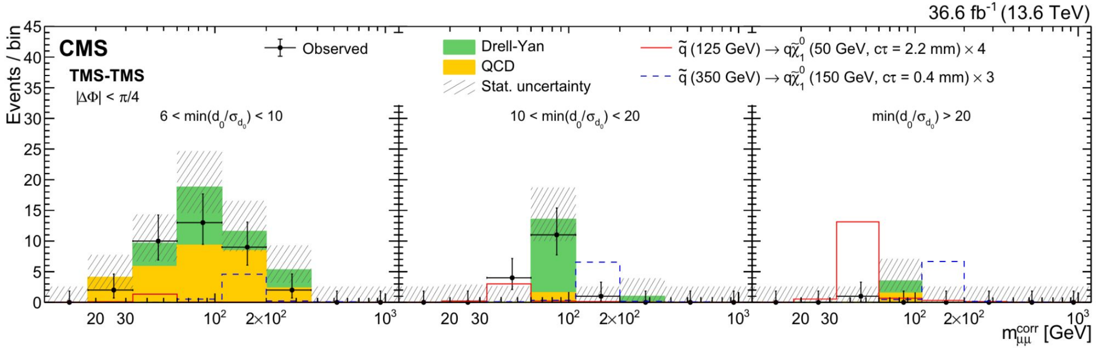


Dimuon Corrected Mass

$$m_{\mu\mu}^{\text{corr}} = \sqrt{m_{\mu\mu}^2 + p_{\mu\mu}^2 \sin^2\theta} + p_{\mu\mu}\sin\theta, \quad (1)$$

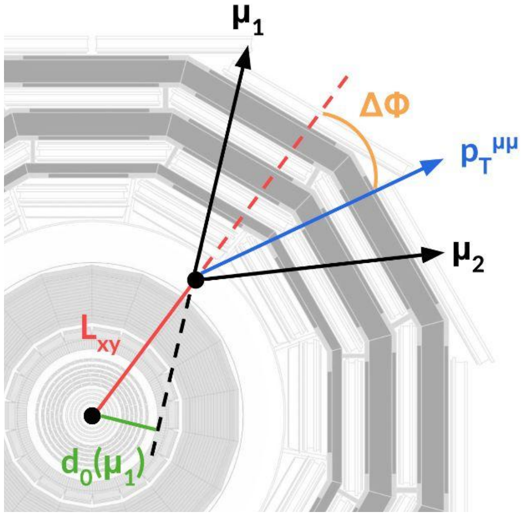
where $p_{\mu\mu}$ is the magnitude of the dimuon momentum vector $\vec{p}_{\mu\mu}$, and θ is the angle between $\vec{p}_{\mu\mu}$ and the vector connecting the PV with the CV.

Signal Region Fits



Search for Displaced Dimuons in LHC Run 3

arXiv:2402.14491



Key Observables:

- ➔ Transverse decay length, L_{xy}
- ➔ Impact parameters: $d_0(\mu_1)$ and $d_0(\mu_2)$
- ➔ Collinearity angle: ΔΦ *(small in signal)*
- ➔ Dimuon **mass** (μμ resonance) or "**corrected" mass** (μμν resonance)

Data Driven Background Estimation:

- ➔ Categorize: tracking + MS and MS-only muons
- ➔ Signal Region defined by muon isolation, opposite- vs same-sign, ΔΦ, binned in displacement
- ➔ Dedicated Control Regions for each source of background developed by inverting SR selections