



Long-Lived Particle searches at CMS



Thales Menezes de Oliveira
on behalf of the CMS Collaboration

31st International Symposium on Particles, Strings, and Cosmology
PASCOS 2026 · Sheffield, United Kingdom · 22-26 June 2026

- **Why Long-Lived Particles?**

- **Long lifetimes** appear naturally in SM and BSM;
- Small couplings, compressed spectra, hidden sectors;
- Connections to DM, neutrino masses, Higgs portals;

- **Why dedicated LLP strategies?**

- Signatures often evade standard prompt searches;
- Displaced, delayed, slow, or soft objects;
- **Unique challenges → Innovations;**

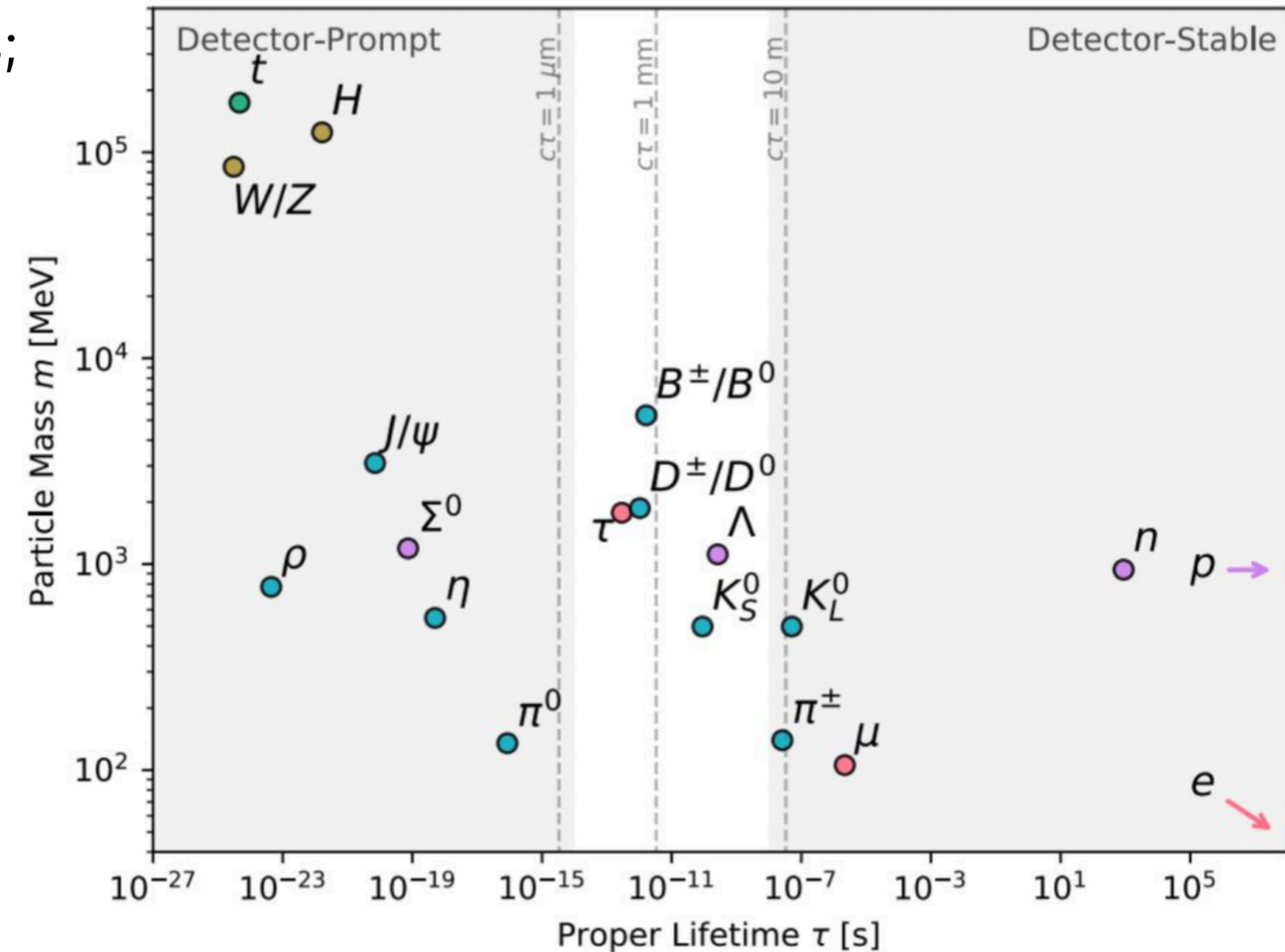
- **Run 3 tools at CMS:**

- Dedicated LLP triggers;
- L1 and HLT scouting streams;
- Displaced-object reconstruction and ML tools.

$$\tau^{-1} = \Gamma \sim y^2 \left(\frac{m}{\Lambda}\right)^n \Phi$$

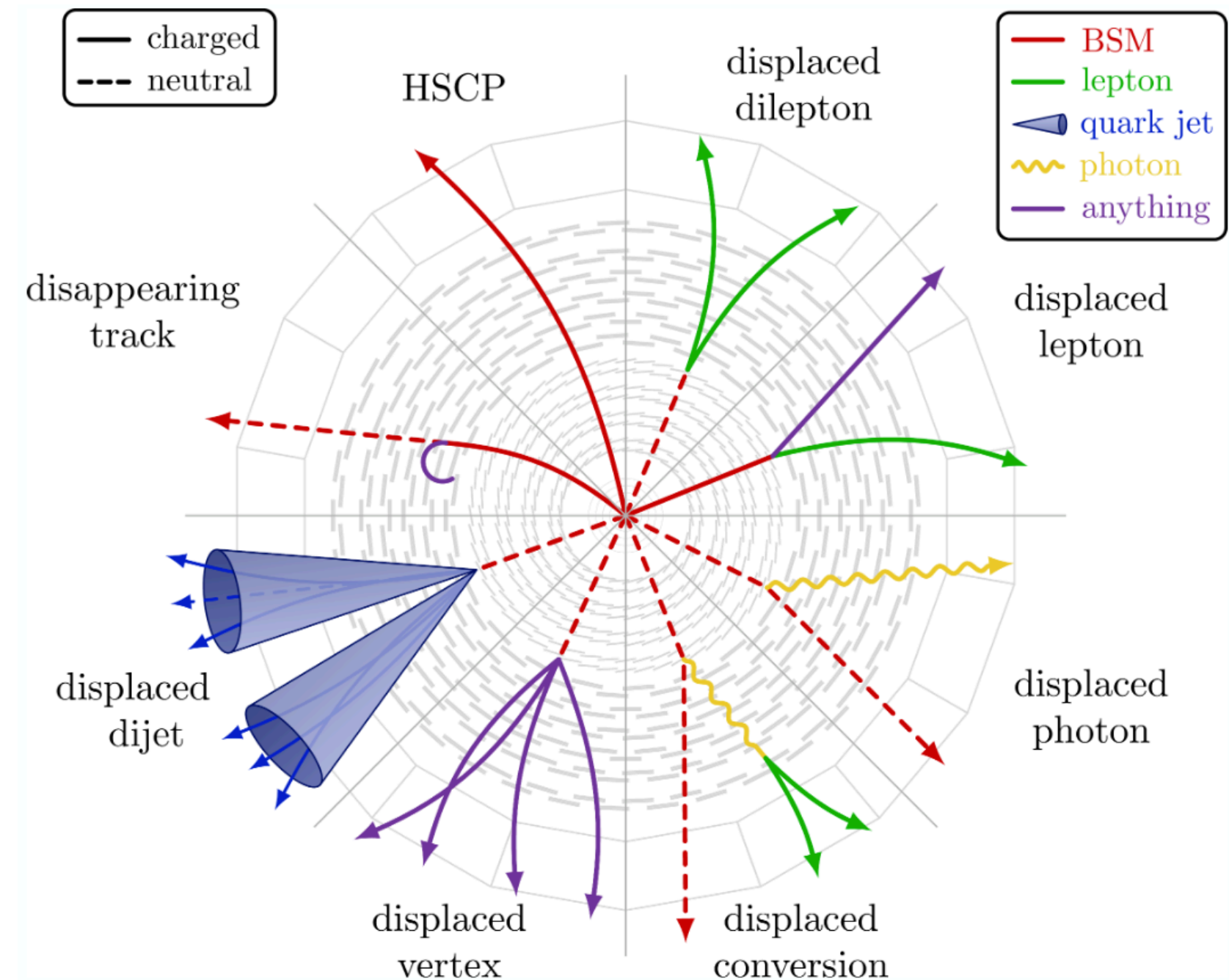
y – small coupling
 $m \ll \Lambda$ – scale suppression
 Φ – small phase space

[arXiv:1810.12602](https://arxiv.org/abs/1810.12602)



The CMS Experiment is expanding LLP sensitivity through dedicated triggers, scouting streams, and displaced-object reconstruction.

- **Run-3 LLP trigger program:**
 - Dedicated L1/HLT paths;
 - Complementary detector regions and signatures;
- **Physics impact of dedicated triggers:**
 - Muon detector showers, displaced jets and displaced (di)muons;
- **New data stream and reconstruction handles:**
 - HLT scouting for low-mass displaced dimuons;
 - L1 scouting for slow HSCPs;
 - Standalone displaced muons for long-lived HNLs.



(from Izaak Neutelings)

Representative public results in jets, dimuons, HSCPs, and HNLs.

- **The first comprehensive review of the CMS dedicated LLP trigger program in Run 3:**

- Strategies and Performance;
- Diversity and Complementarity;

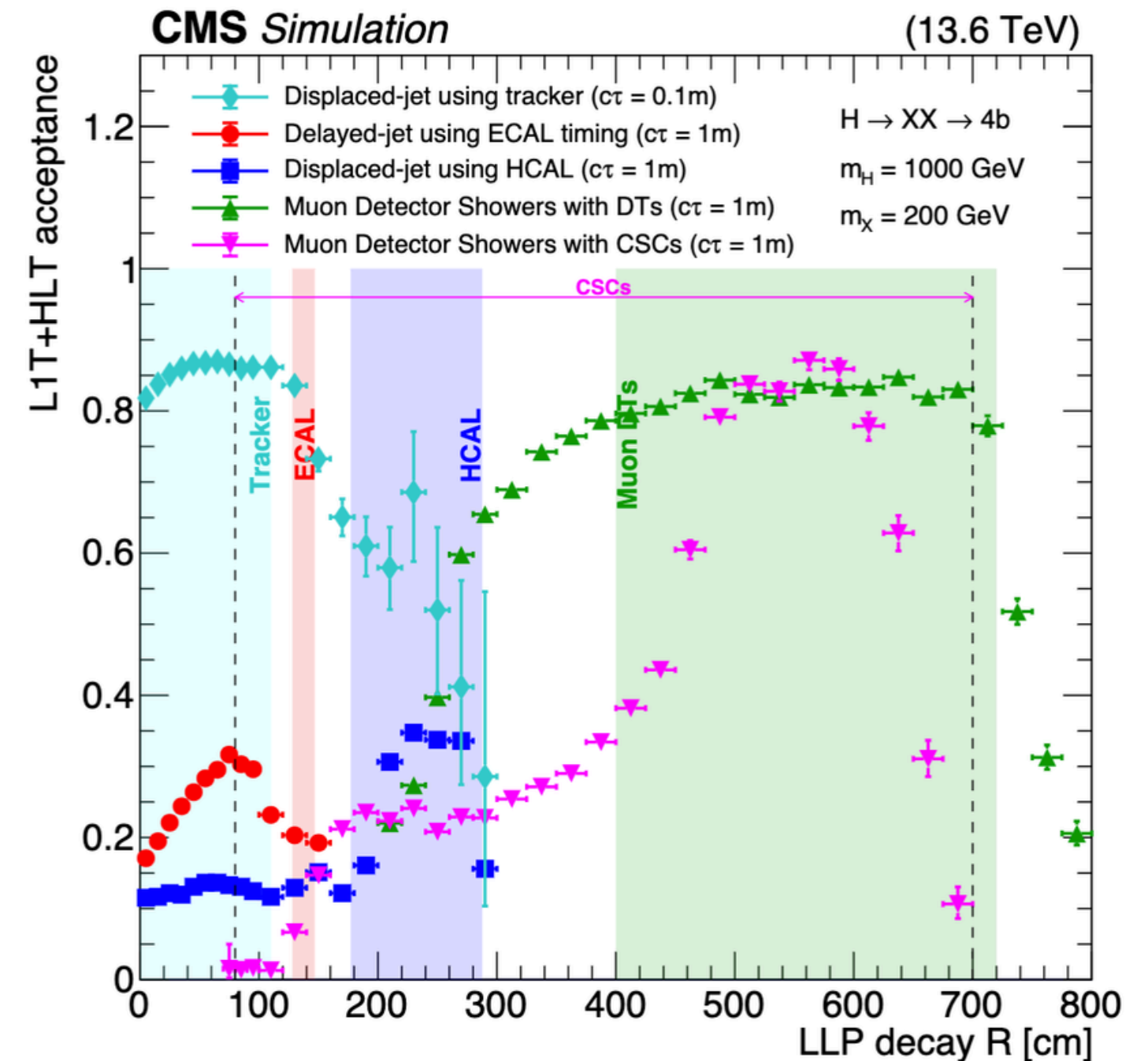
[arXiv:2601.17544](https://arxiv.org/abs/2601.17544)

- **Run 3 LLP Trigger Program:**

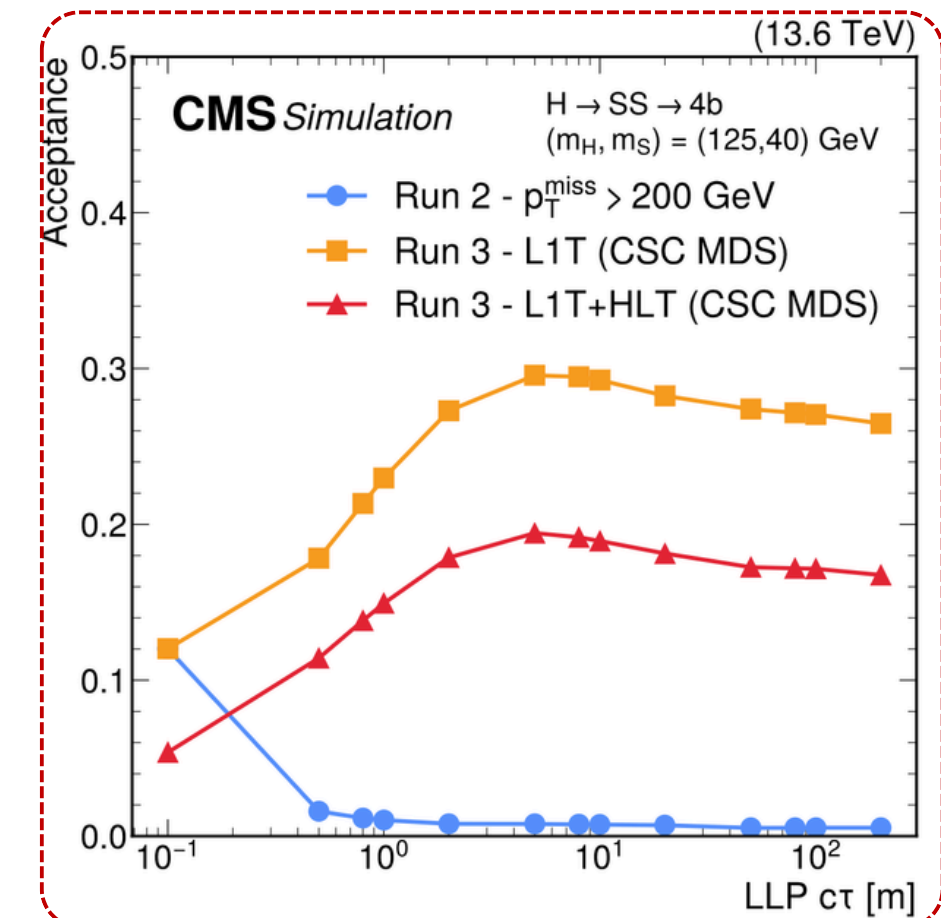
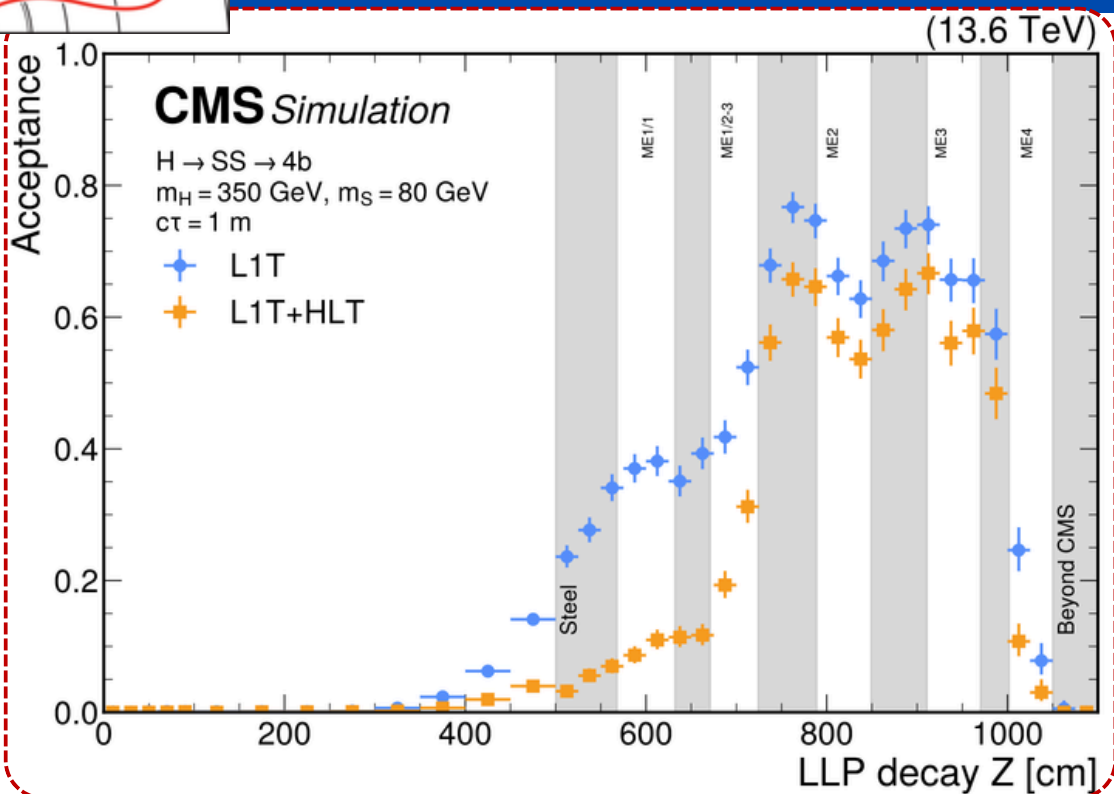
- **Motivation:** Unique signatures;
- Improved and expanded trigger menu for Run 3;
- New and refurbished L1/HLT paths;
- Additional HLT bandwidth allocated to LLP signatures;

- **Total of 15 dedicated LLP triggers:**

- **Tracker:** displaced jets and τ , disappearing tracks;
- **ECAL/HCAL:** delayed jets, delayed diphotons;
- **Muon:** displaced muons, MDS, L3 muon + photon;
- **Other:** Dimuon scouting, jet/muon no-BPTX.



The CMS Run 3 LLP dedicated triggers extend LLP sensitivity from the tracker to the muon system.



Muon Detector Showers at CMS (Run 3)

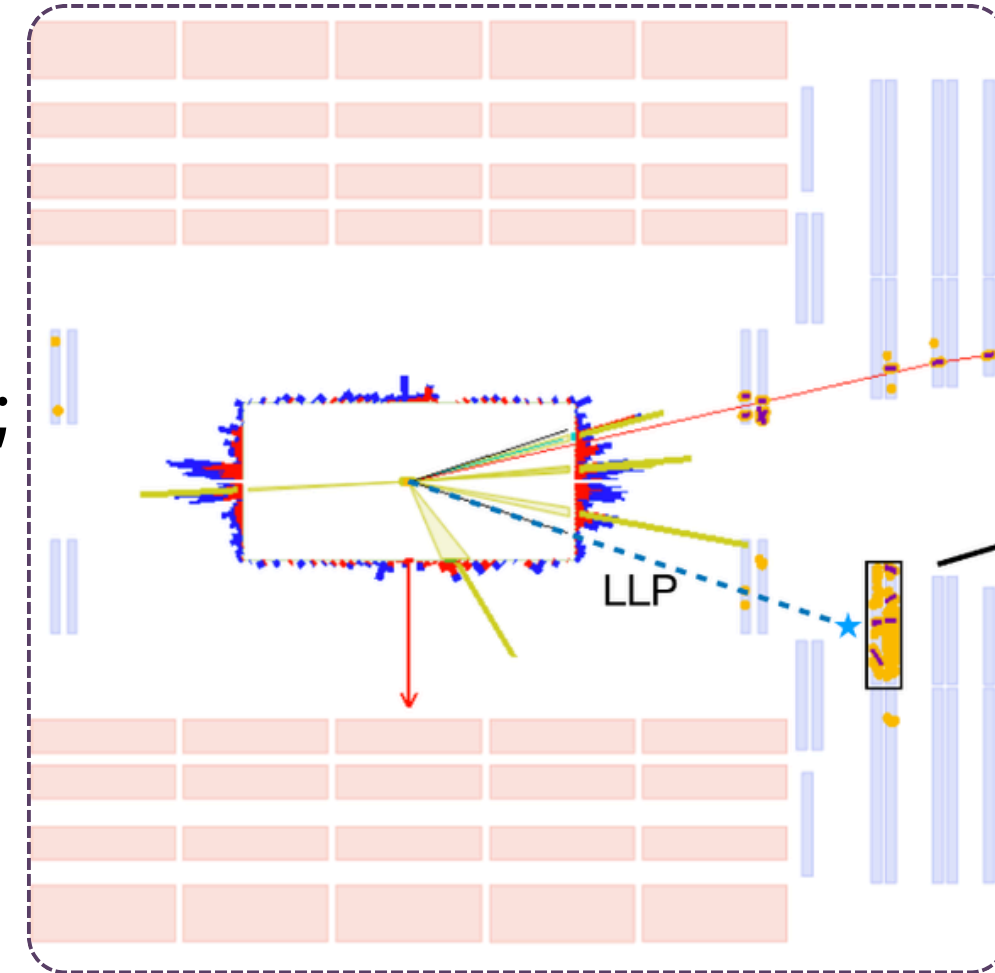
- **Signature: neutral LLP decays in the muon system**

[arXiv:2601.17544](https://arxiv.org/abs/2601.17544)

- Trackless CSC/DTs hit clusters;
- CSC and DT as sampling calorimeters;

- **Why powerful?**

- Low SM background from steel shielding;
- High hit multiplicity at L1 Trigger;



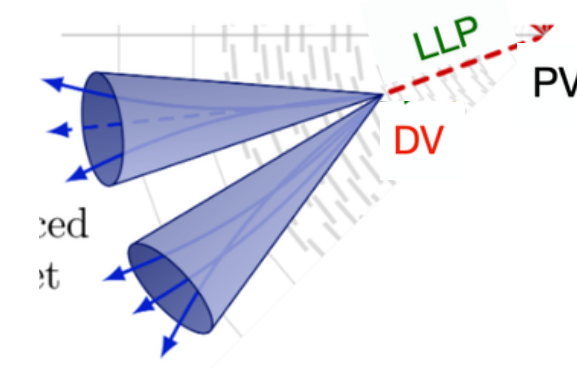
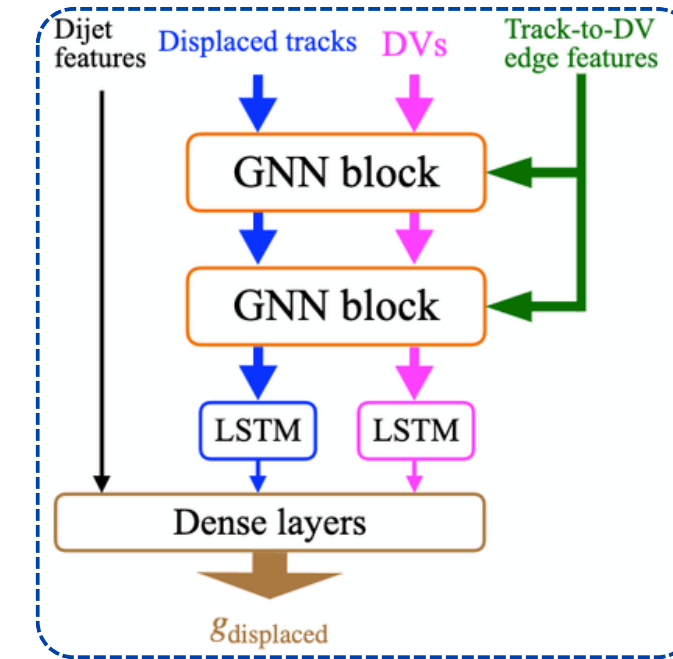
- **Run 3 Analysis:**

- Dedicated CSC and DT MDS triggers;
- **Extends acceptance for large decay radii;**
- Reduced reliance on MET-based Run-2 trigger strategies;
- Exploits the unique CMS muon-system geometry and shielding.

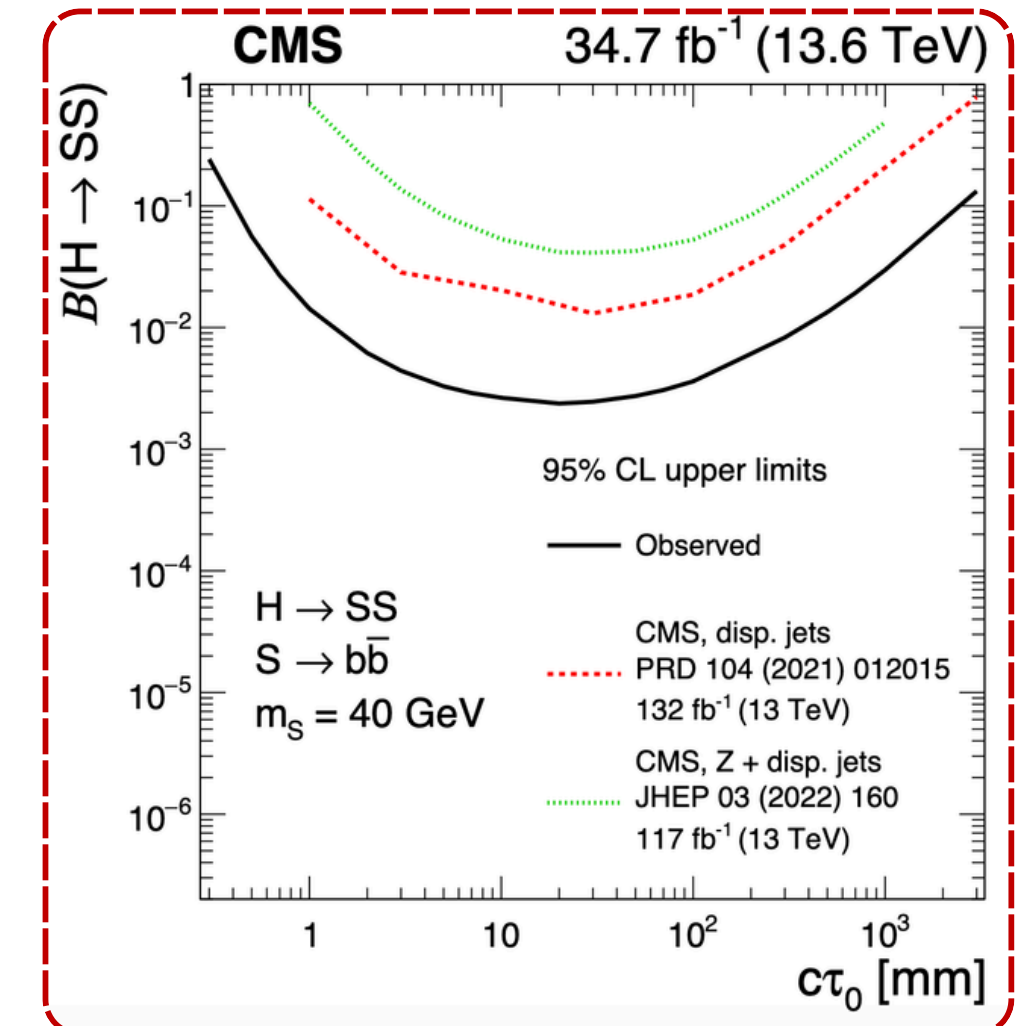
Dedicated MDS triggers extend CMS sensitivity to LLP decays in the muon system.

Search for long-lived particles using displaced jets with early Run 3 data.

- **Target:** low-mass LLPs decaying hadronically (up to 60 GeV);
 - Hidden Higgs portal and other BSM benchmarks;
 - Offline selection based on two LLP GNN taggers;
- **Run 3 Analysis:**
 - Displaced-jet triggers and displaced vertex reconstruction;
 - GNN taggers using displaced tracks, vertices, and dijet features;
 - ABCD data-driven for background estimation;
- **Results:**
 - No significant excess observed;
 - Improved sensitivity by up to an order of magnitude in key regions.



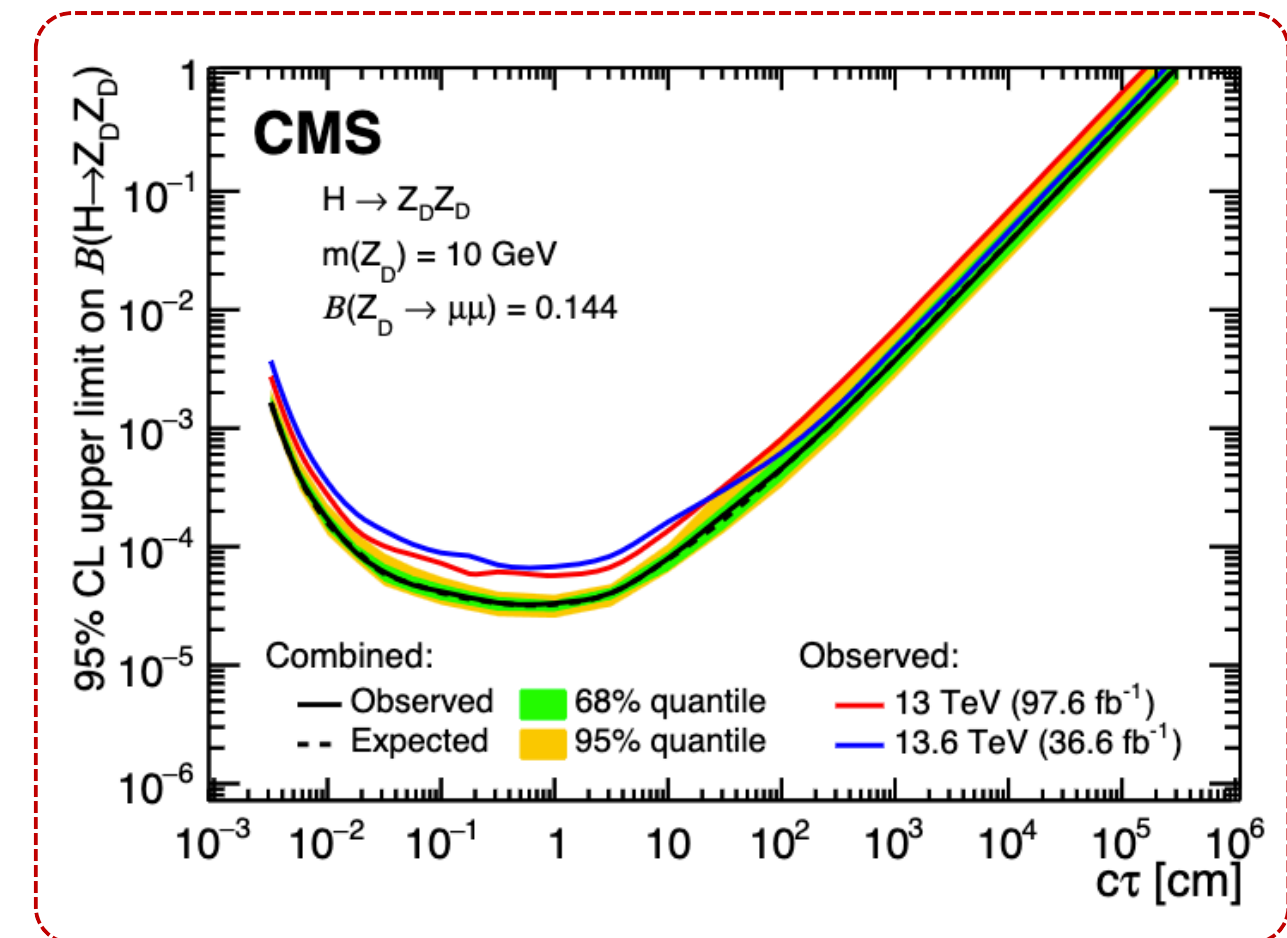
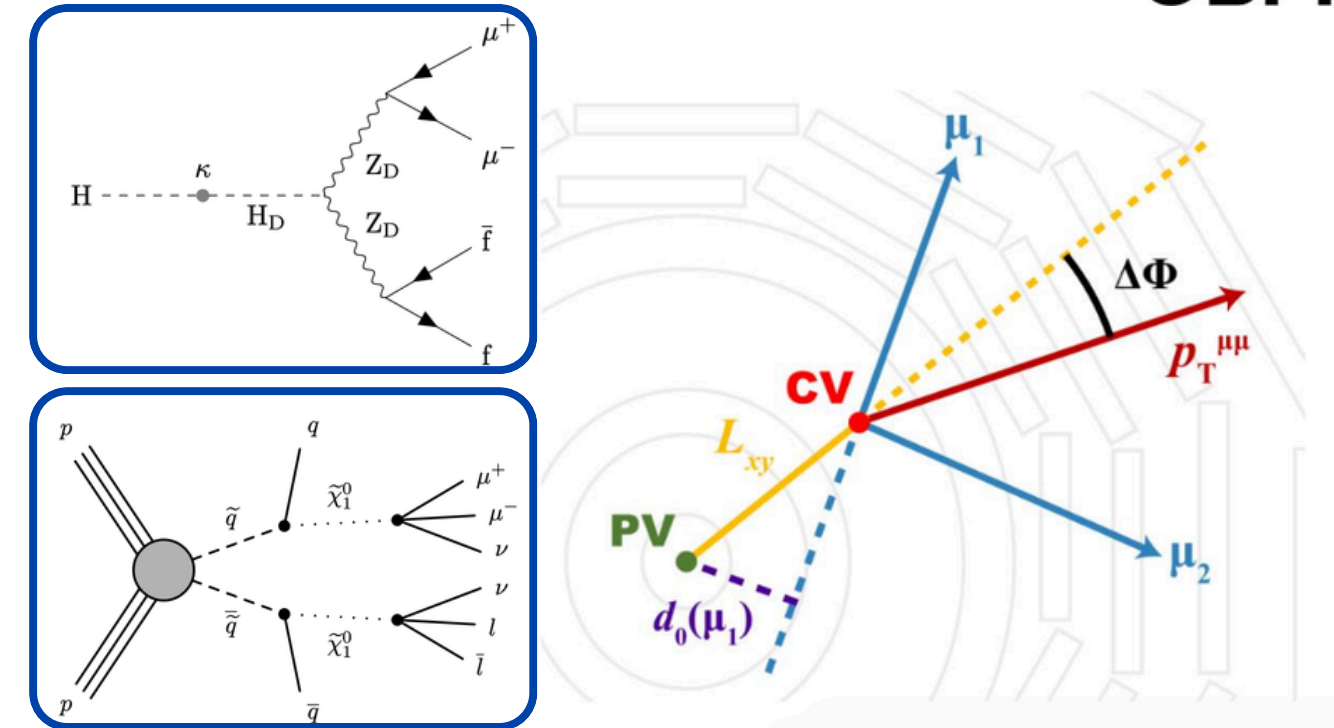
[arXiv:2409.10806](https://arxiv.org/abs/2409.10806)



Early Run-3 techniques already improve displaced-jet sensitivity; full Run 3 will further extend coverage.

Inclusive search for LLPs decaying in a pair of displaced muons

- **Target: LLP decays to a pair of displaced muons**
 - Inclusive search over a broad kinematic range;
 - Tracker-muon and muon-system only categories;
- **Benchmark models:**
 - Dark photon and RPV SUSY interpretations;
- **Run 3 Trigger Improvements:**
 - New L1 seeds and HLT paths for soft and displaced muons;
 - Factor of 2 to 4 gain in signal efficiency;
- **Results:**
 - Observation consistent with SM expectation;
 - Improved sensitivity with early Run 3 data (36.6 fb⁻¹).

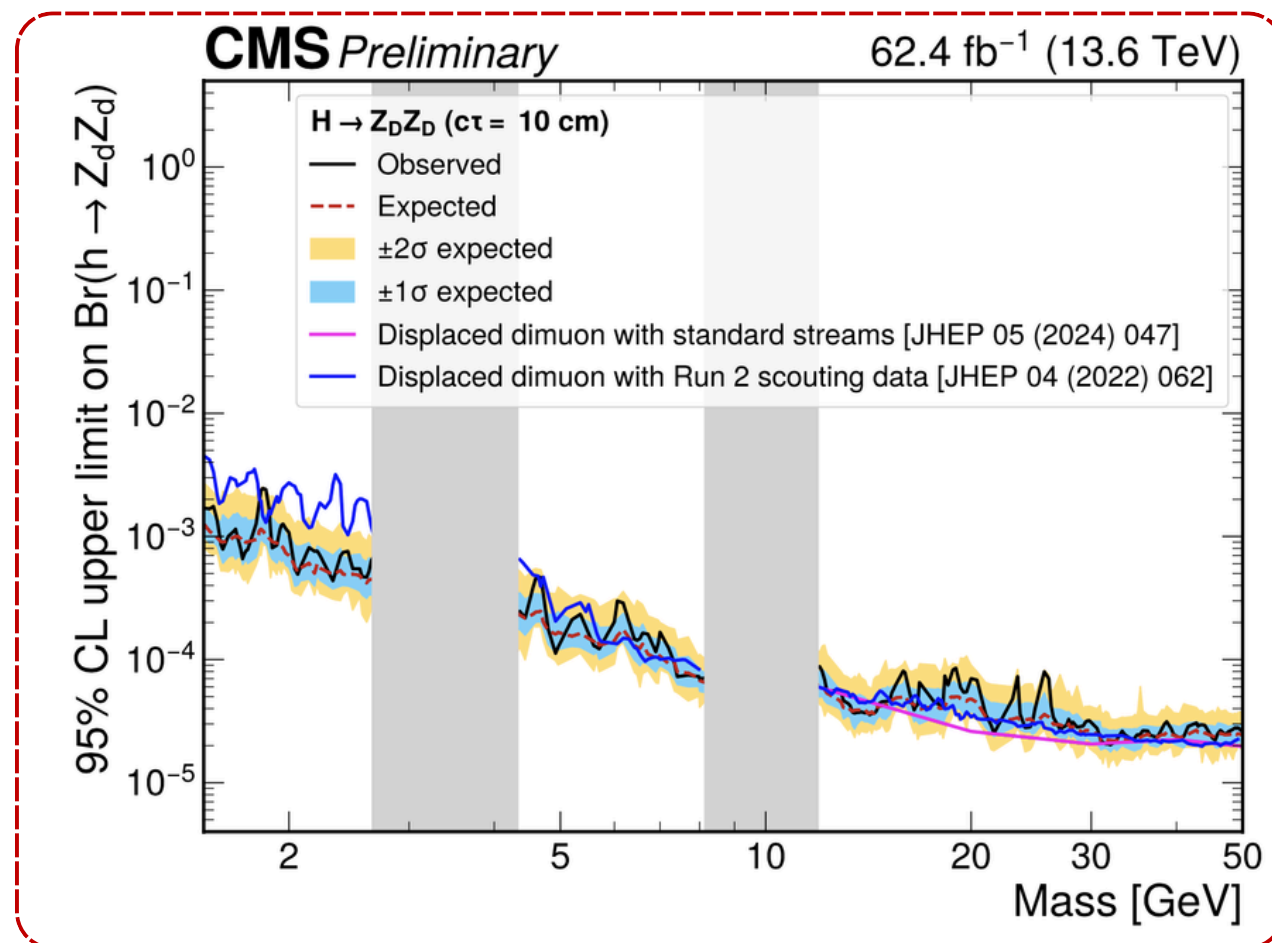


[JHEP 05 \(2024\) 047](https://arxiv.org/abs/2405.047)

Search for LLPs decaying into dimuons with data scouting

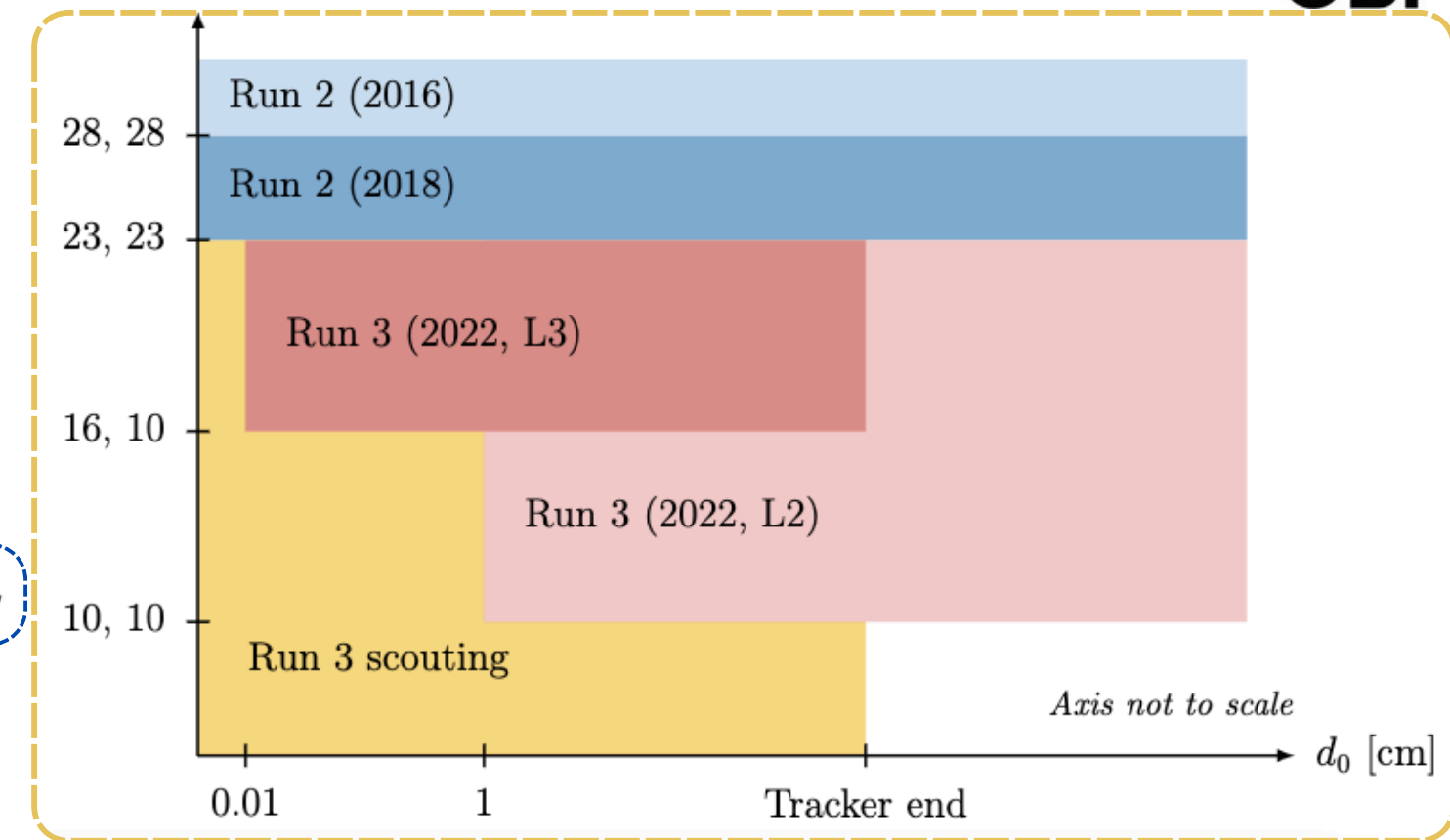
- **Target:** LLPs decaying to displaced dimuons;
 - Clean and low-multiplicity signature;
 - Dark-photon and dark-showers benchmarks;

[JHEP 04 \(2022\) 062](#); [JHEP 05 \(2024\) 047](#)



$$H \rightarrow \Psi\Psi \rightarrow \text{with } \pi_3 \rightarrow A'A' \rightarrow 4\mu$$

$$H \rightarrow Z_D Z_D \rightarrow 4\mu$$



Run 3 HLT scouting strategy:

- Dedicated dimuon scouting stream with reduced event content;
- Lower pT thresholds than standard streams;
- Displaced vertices up to 70 cm;

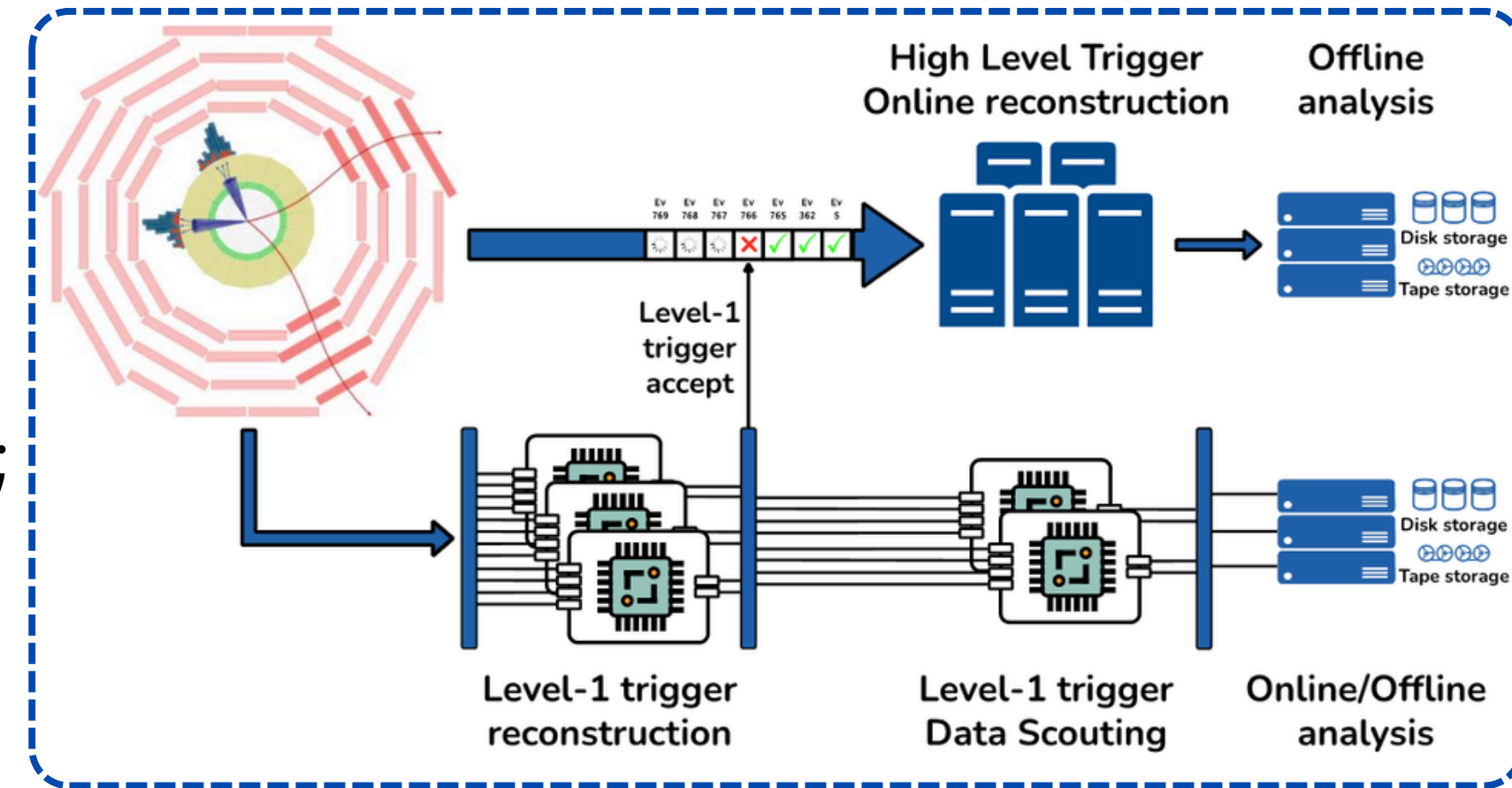
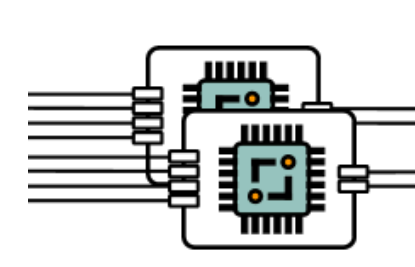
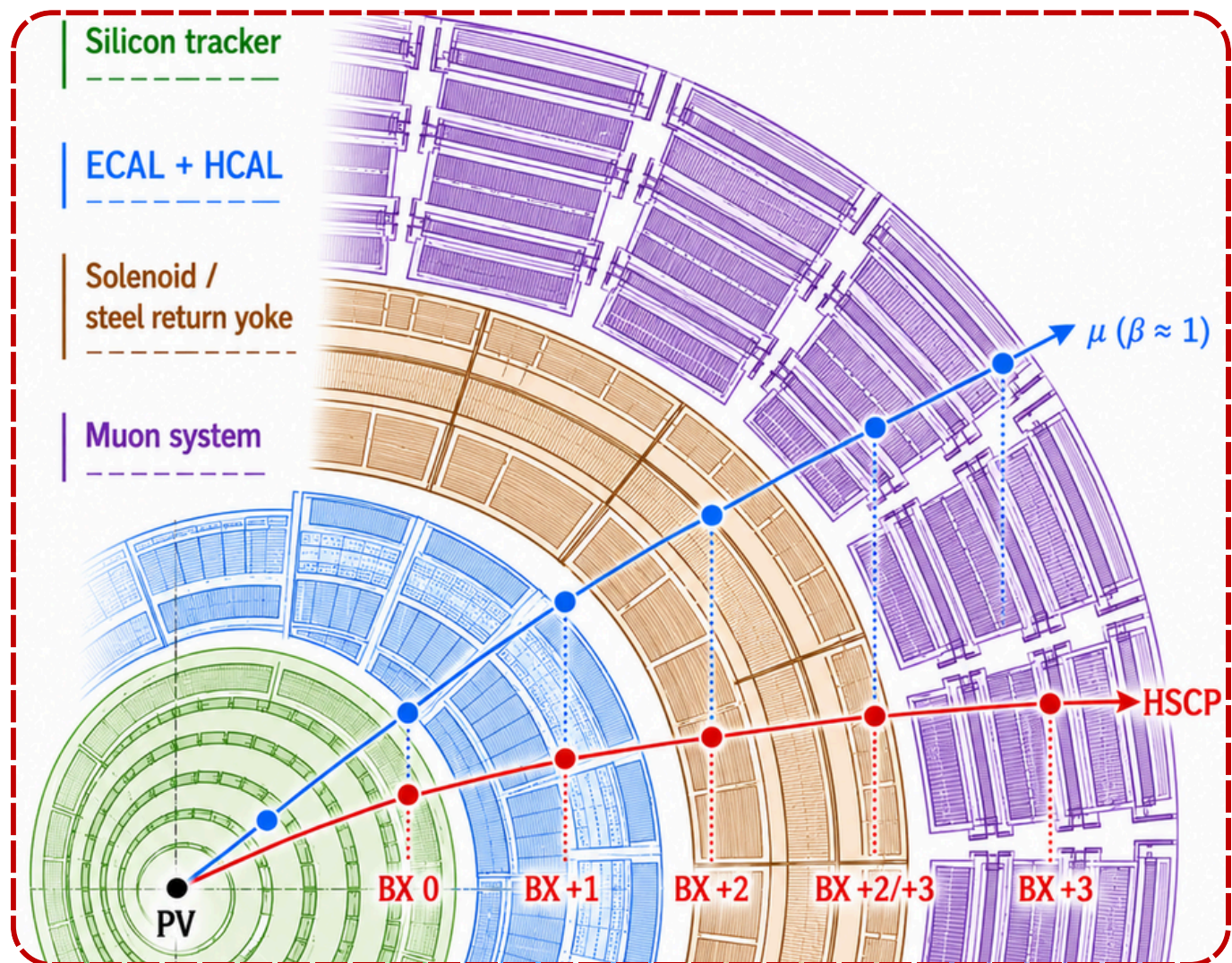
Results:

- No significant deviation from background prediction;
- Limits set in dark-photon and dark-shower models.

[CMS-PAS-EXO-24-016](#)

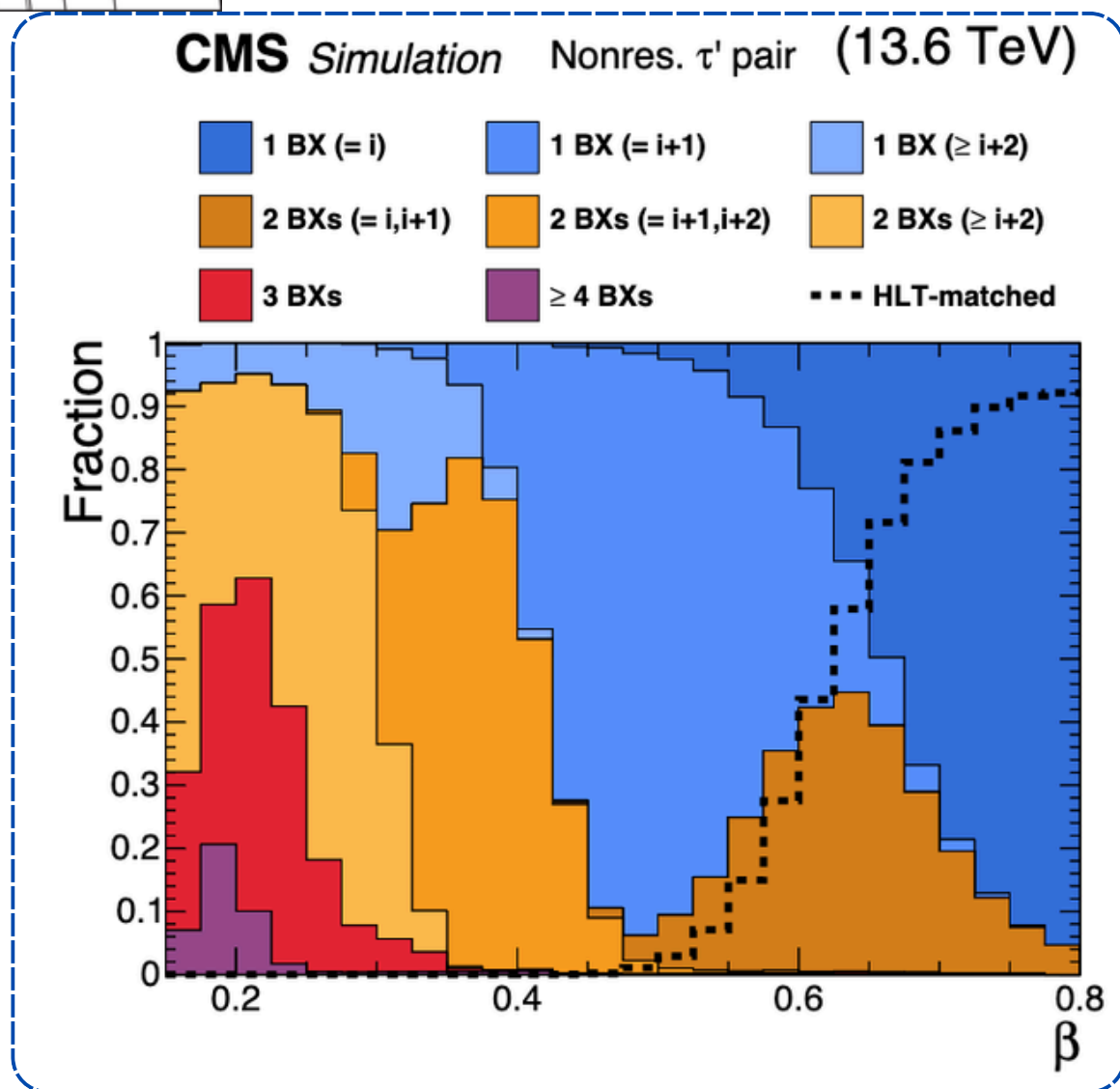
Run-3 HLT scouting extends sensitivity to lower masses and larger displacements.

- **Heavy Stable Charged Particles:**
 - Massive, charged, long-lived BSM particles;
 - Late arrival in the muon system, multiple BXs;
- **Challenges for standard triggering:**
 - Conventional L1 trigger assumes single-BX objects;



L1 Data Scouting Strategy:

- Store L1 trigger primitives without of trigger decision;
- Reconstruction of slow muon-like objects from RPC+DT;
- Access signatures missed by standard L1/HLT paths;
- Opportunity for triggerless analysis.

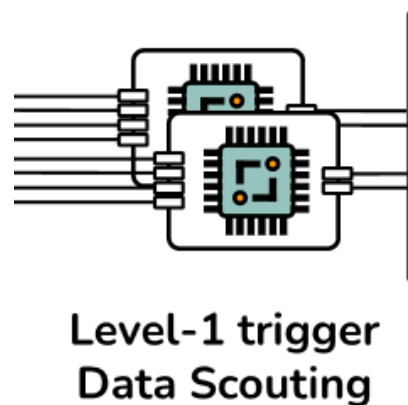


- **New approach for Run 3:**

- Targets high-mass, slow HSCPs: $m < 6.5$ TeV, $\beta \sim 0.3-0.6$;
- Effective luminosity of 3.7 fb^{-1} from Run 3 L1 Scouting data;

- **Multi-BX:**

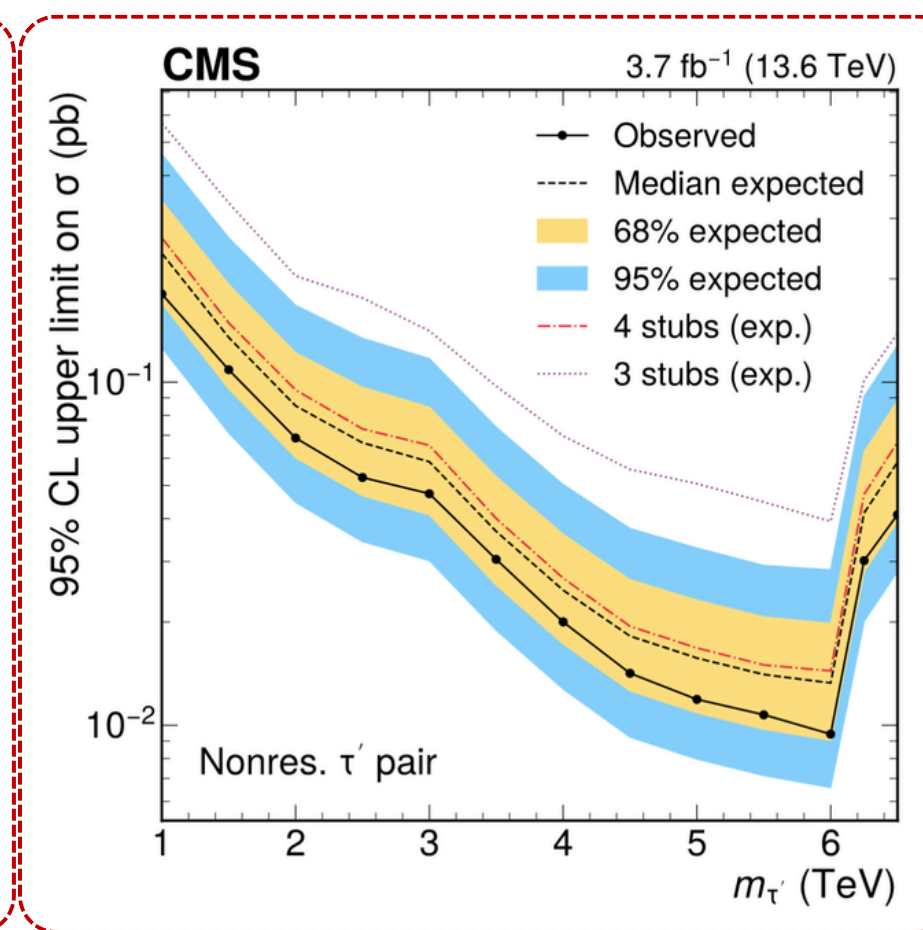
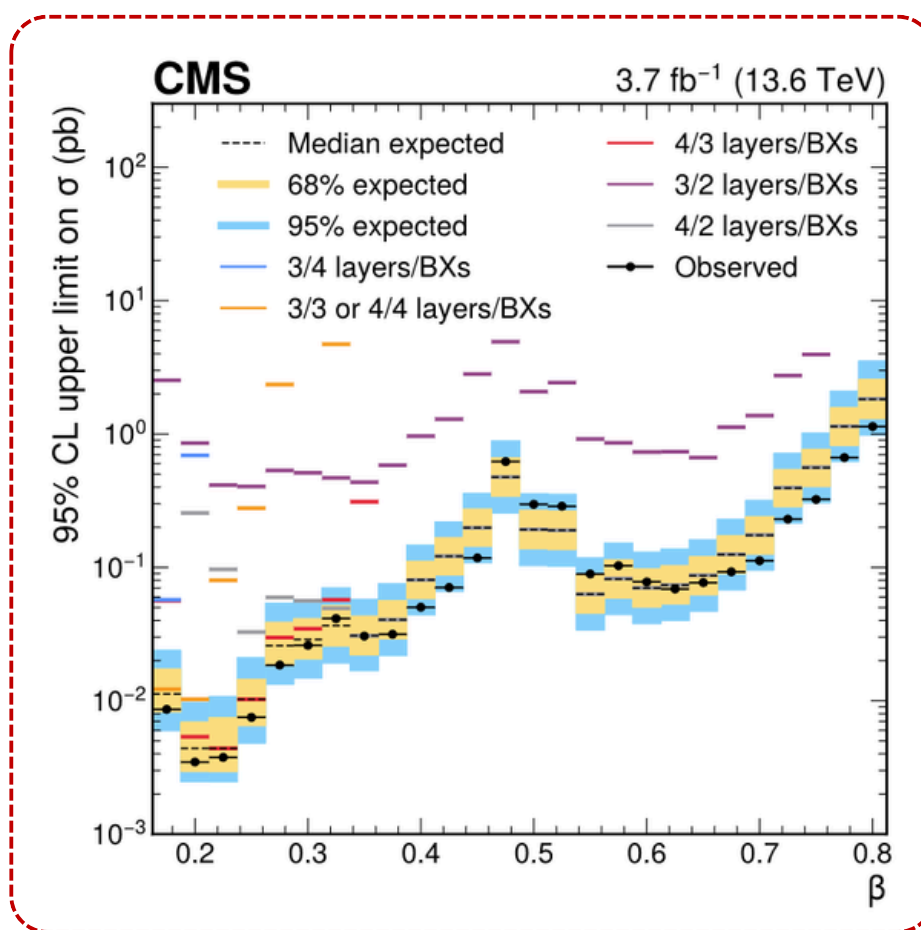
- kBMTF reconstructs tracks across multiple bunch crossings;
- Categories based on muon layers and BX patterns probe different β regimes;



[arXiv:2601.20063](https://arxiv.org/abs/2601.20063)

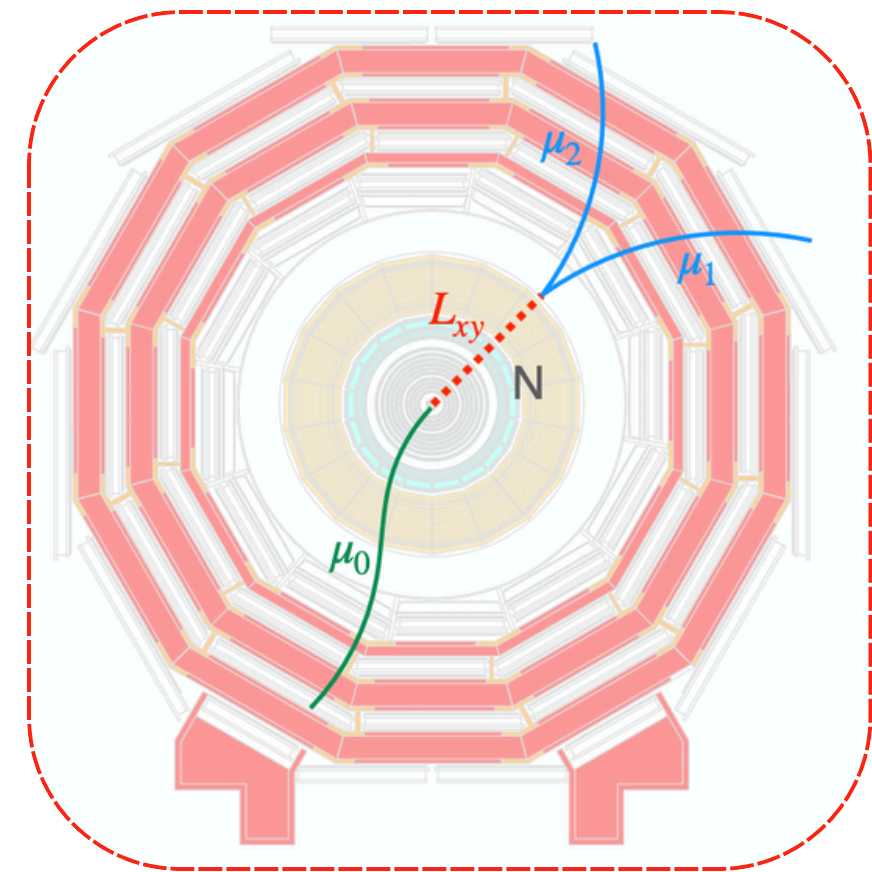
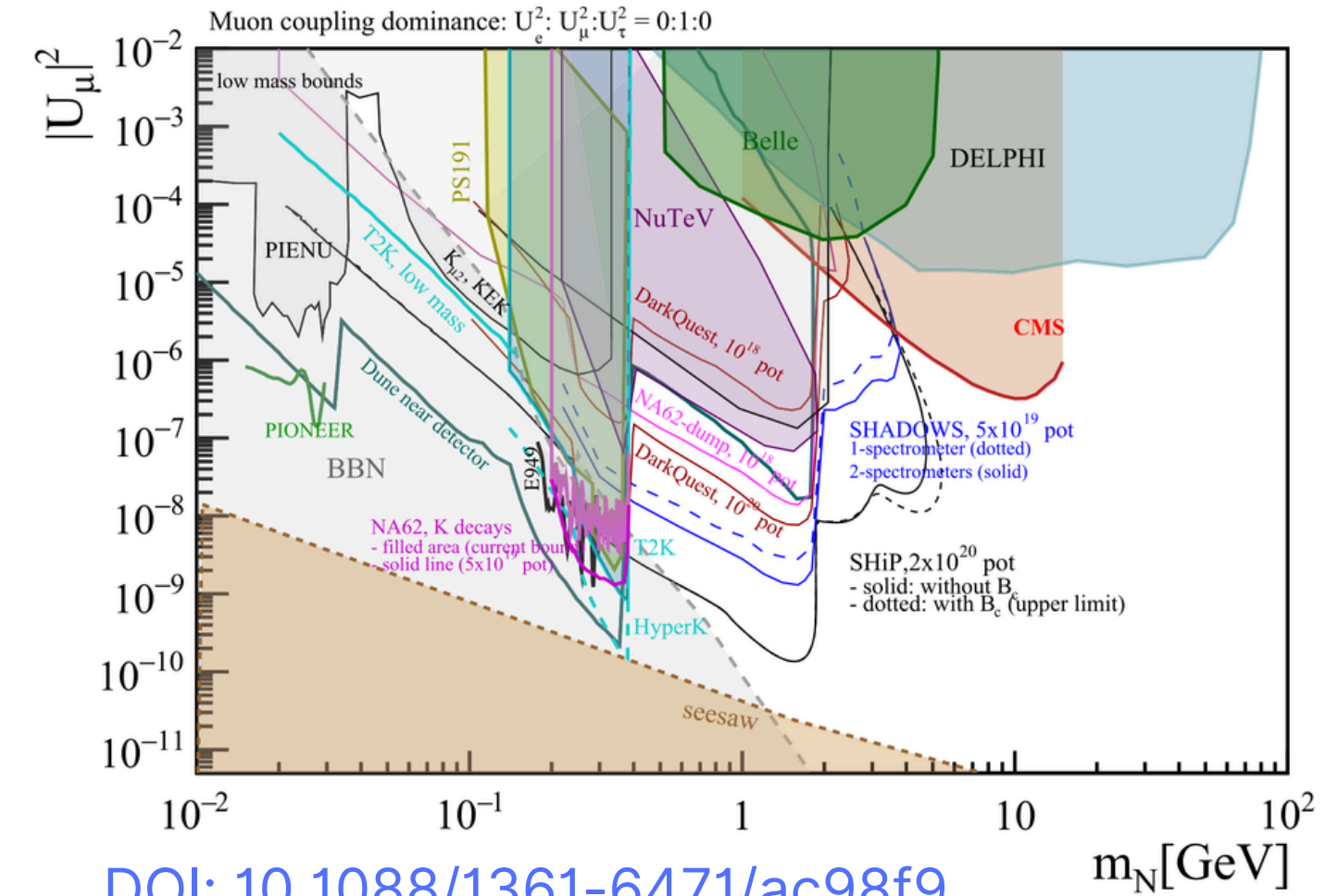
- **Results and impact:**

- No significant excess observed;
- Unique sensitivity for slow HSCPs.



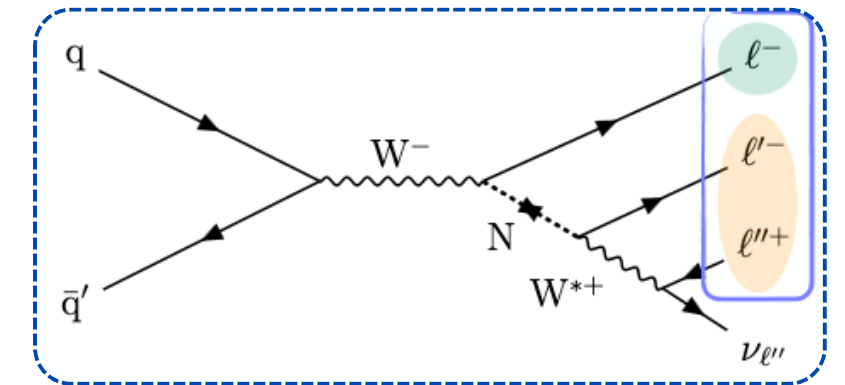
Proof of concept for L1 Scouting in LLP searches.

- **Final state: 1 prompt muon + 2 displaced standalone muons;**
 - Muons reconstructed only in the muon detectors;
- **Motivation:**
 - Origin of neutrino masses, Seesaw mechanism;
- **Inclusion of massive right-handed neutrinos (HNL):**
 - Almost sterile under SM (only neutrino mixing);
 - Interested on HNL mass and mixing angle;



$$\tau \propto (m_N)^{-5} \left(\sum_{\ell} |V_{N\ell}| \right)^{-2}$$

- **Signature:**
 - Fully leptonic decays, through W production;
 - Displaced standalone muons signature;
 - Access to low masses and couplings, longer ctau.

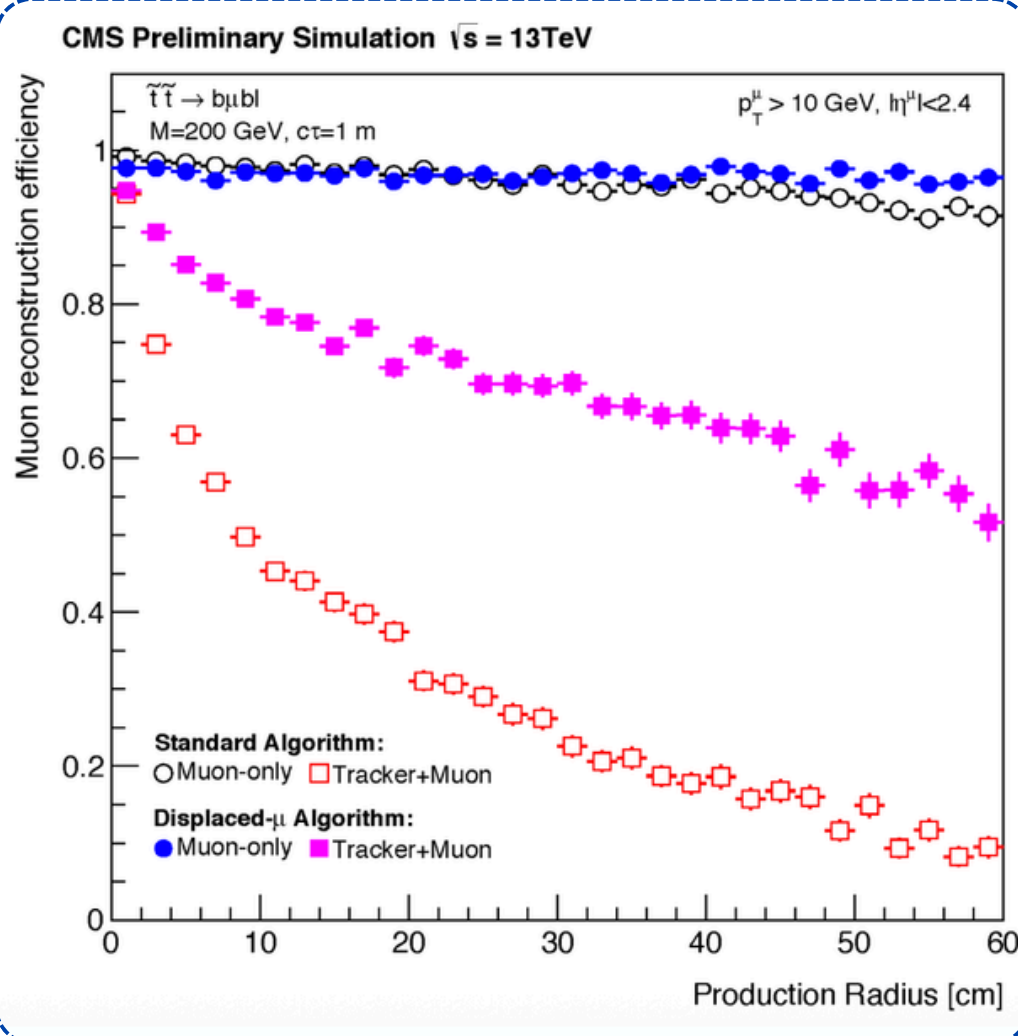
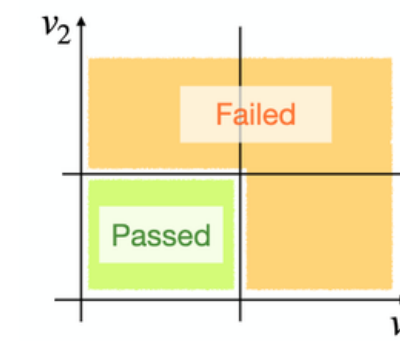


Long-lived HNLs as a benchmark for displaced-muon reconstruction.

[CMS-PAS-EXO-24-015](#)

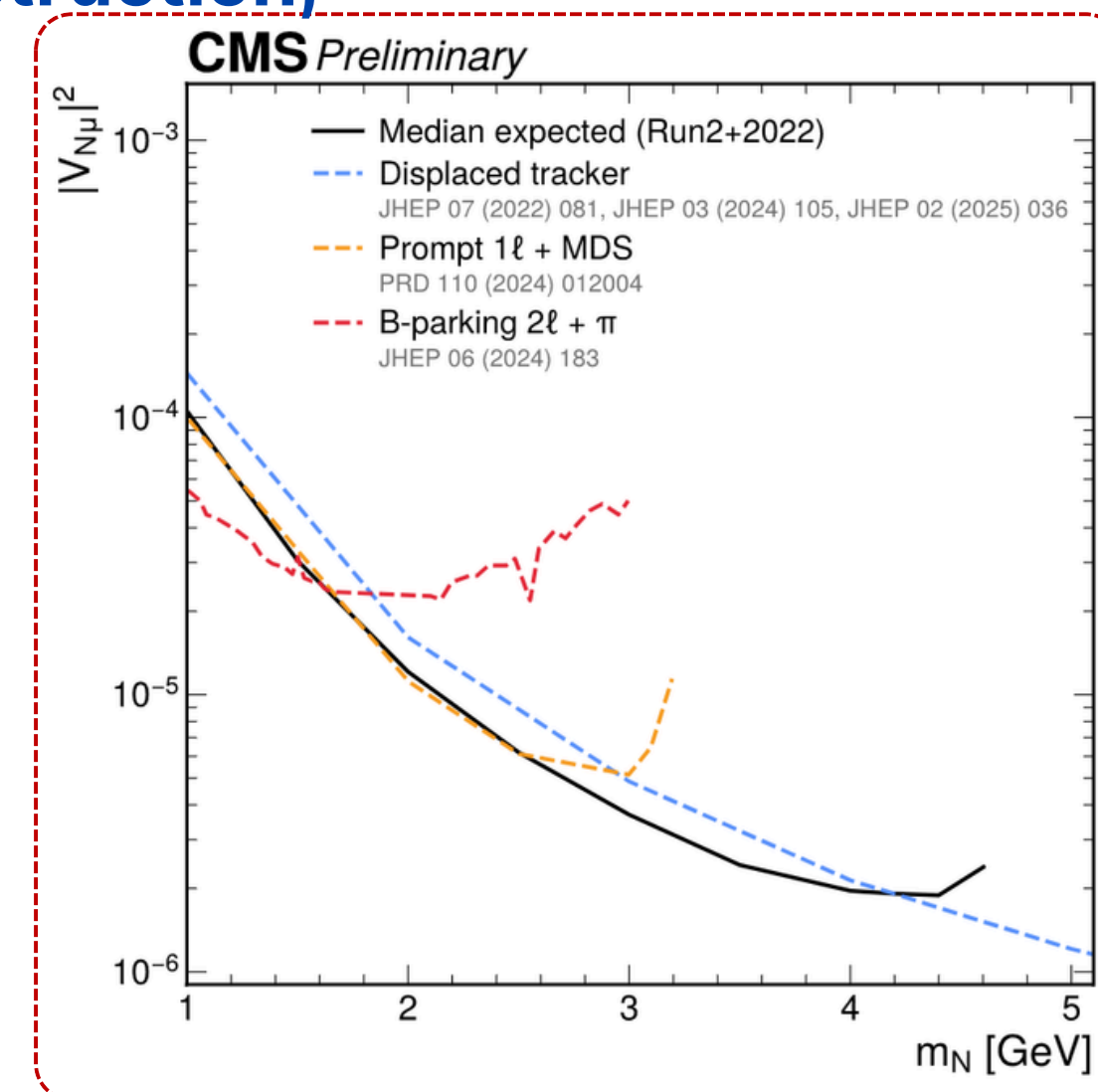
Run 3 Analysis Strategy:

- Signal regions based on decay length;
- Data-driven ABCD background estimation;
- New displaced muons collection (timing available);
- **Displaced StandAlone muon reconstruction;**
 - 20% gain in efficiency selection.



Dataset
Run 2 (138 fb⁻¹) + 2022 (34.6 fb⁻¹)
Results combined between the two periods

full $(m_N, |V_{N\mu}|^2)$ parameter space



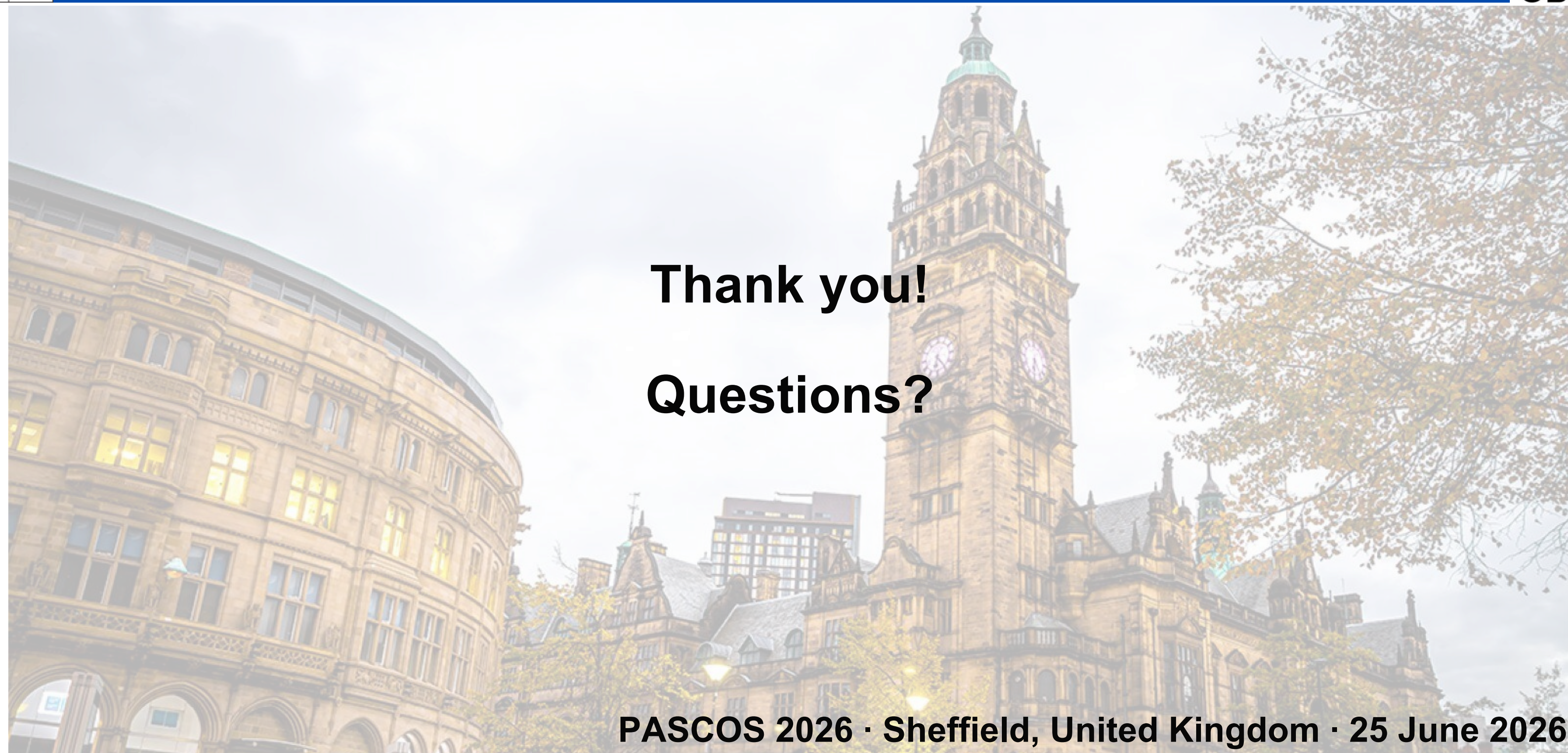
Results:

- First CMS HNL result including Run-3 data;
- Improved sensitivity in the low-mass regime;
- Best expected limits on $|V_{N\mu}|^2$ and $2.5 \leq m_N \leq 4.2\text{ GeV}$.

Standalone displaced muons extend the HNL reach beyond tracker-based approaches.

- **Dedicated LLP triggers are a central pillar of the CMS Run 3 LLP/BSM program.**
 - Complementary paths targeting displaced, delayed, slow, and low-pT signatures;
- **Run 3 techniques with physics impact:**
 - Improved sensitivity in displaced-jet and displaced-dimuon searches;
 - Displaced standalone-muon reconstruction extends the reach for long-lived HNLs;
- **Scouting opens new LLP phase space:**
 - HLT scouting probes low-mass displaced-dimuon signatures;
 - L1 scouting provides a new handle on slow HSCPs missed by standard trigger paths;
- **Outlook:**
 - Full Run 3 and HL-LHC to further expand the CMS LLP program;
 - Strong synergy with timing, L1 tracking, and upgraded trigger capabilities.

Run 3 is still delivering, with much more sensitivity expected from the full dataset and HL-LHC upgrades.



Thank you!
Questions?

PASCOS 2026 · Sheffield, United Kingdom · 25 June 2026



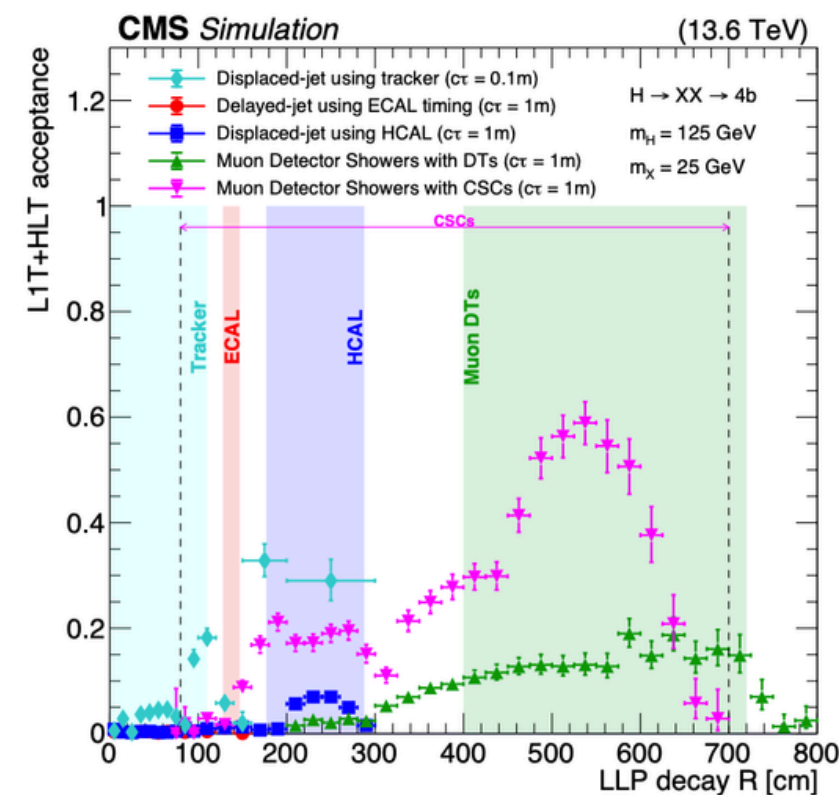
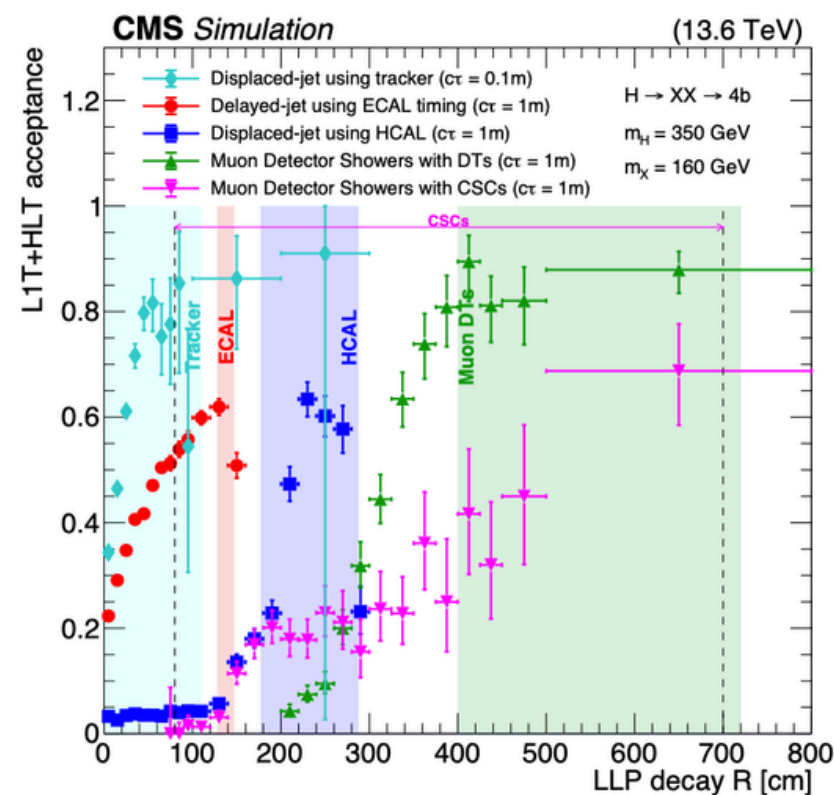
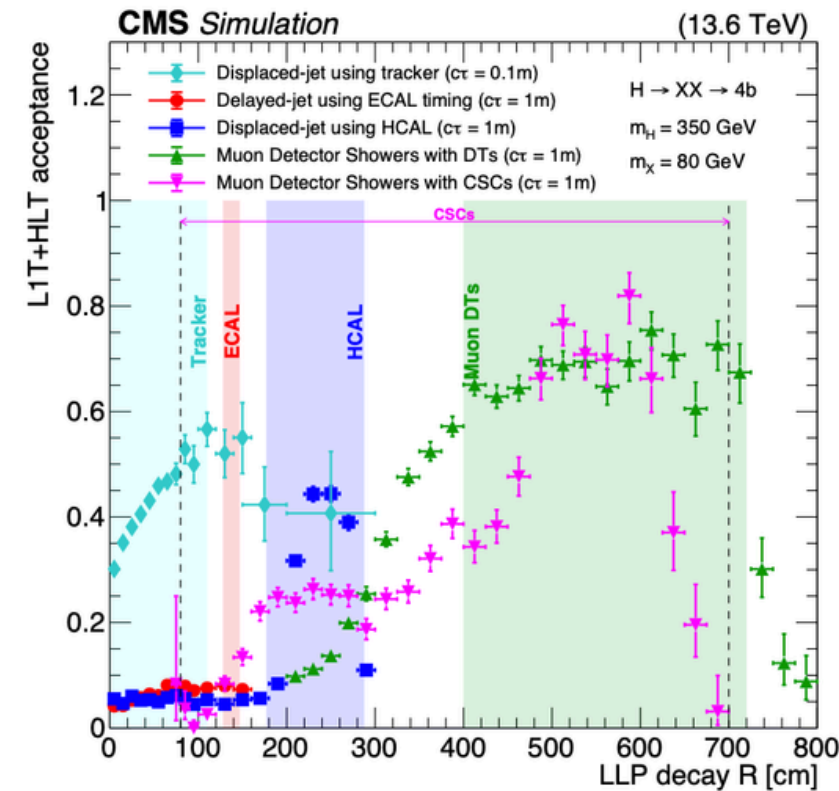
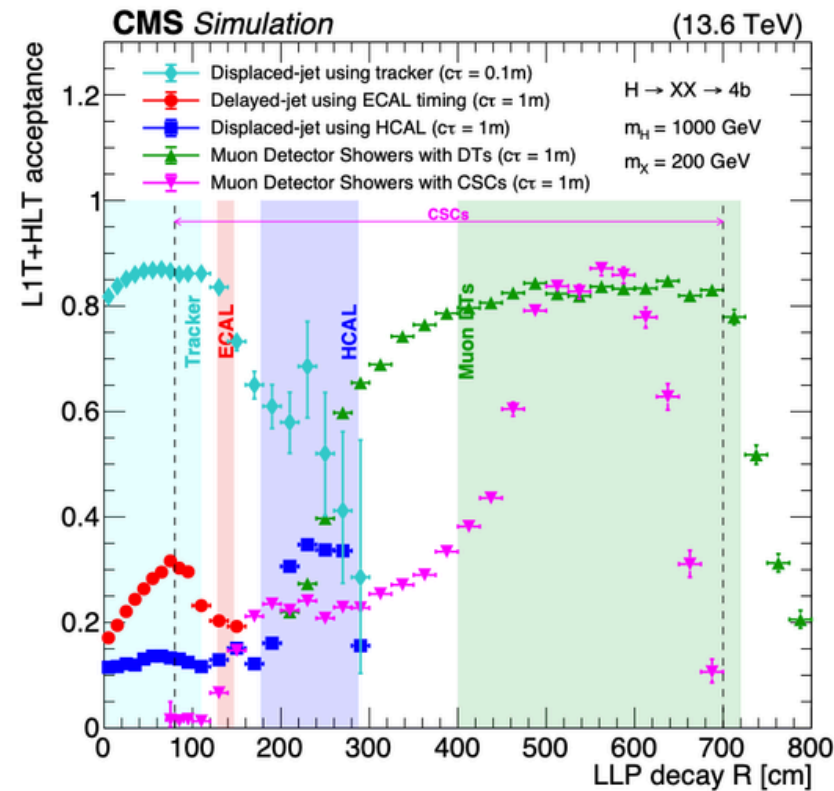
Backup



- LLP Triggers and their total **HLT rates in Run 3**, calculated from 2024 for an instantaneous luminosity of $2.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.
 - HLT rates and (parking rates);

Triggered signature	Trigger description	HLT rate [Hz]	Triggered signature	Trigger description	HLT rate [Hz]
Disappearing track	$p_T^{\text{miss}} > 105 \text{ GeV} + \geq 1 \text{ isolated track } (p_T > 50 \text{ GeV})$	4	Double disp. L3 muon	$\geq 2 \text{ L3 } \mu (p_T > 43 \text{ GeV})$	2
Disp. tau	$\geq 2 \text{ disp. } \tau_h (p_T > 32 \text{ GeV}, d_0 > 0.005 \text{ cm})^\dagger$	36	Disp. L3 muon + photon	$\geq 1 \text{ L3 } \mu (p_T > 43 \text{ GeV}) + \gamma (p_T > 43 \text{ GeV})$	5
	$\geq 1 \text{ disp. } \tau_h (p_T > 24 \text{ GeV}) + \geq 1 \mu (p_T > 24 \text{ GeV})^\dagger$			$\geq 1 \text{ L3 } \mu (p_T > 38 \text{ GeV}, d_0 > 1 \text{ cm}) + \gamma (p_T > 38 \text{ GeV})$	
	$\geq 1 \text{ disp. } \tau_h (p_T > 34 \text{ GeV}) + \geq 1 e (p_T > 34 \text{ GeV})^\dagger$			Dimuon scouting	$\geq 2 \text{ scouting } \mu (p_T > 3 \text{ GeV})$
Disp. jet	$\geq 2 \text{ jet } (p_T > 40 \text{ GeV}, \text{ inclusive tagging req.}) + H_T > 430 \text{ GeV}$	53 (163)	MDS in CSCs	$\geq 1 \text{ CSC cluster } (\geq 200/500 \text{ hits in outer/inner rings})^\dagger$	14
	$\geq 2 \text{ jet } (p_T > 40 \text{ GeV}, \text{ disp. tagging req.}) + H_T > 240 \text{ GeV} + \geq 1 \text{ L1 } \mu (p_T > 6 \text{ GeV})$		$\geq 2 \text{ CSC clusters } (\geq 75 \text{ hits})^\dagger$		
HCAL-based disp. and delayed jet	$\geq 2 \text{ jet } (p_T > 40 \text{ GeV}, \text{ displ. tagging req.}) + H_T > 170 \text{ GeV}^\dagger$	35	MDS in CSCs + X	$\geq 1 \text{ CSC cluster } (\geq 100 \text{ hits}) + \geq 1 e (p_T > 5 \text{ GeV})^\dagger$	14
	$\geq 2 \text{ jet } (p_T > 40 \text{ GeV}, \text{ inclusive tagging req.}) + H_T > 200 \text{ GeV}^\dagger$			$\geq 1 \text{ CSC cluster } (\geq 100 \text{ hits}) + \geq 1 \text{ L3 } \mu (p_T > 5 \text{ GeV})^\dagger$	
	$\geq 1 \text{ jet } (p_T > 60 \text{ GeV}, \text{ NHEF} > 0.7) + H_T > 200 \text{ GeV}^\dagger$			$\geq 1 \text{ CSC cluster } (\geq 100 \text{ hits}) + \geq 1 \tau_h (p_T > 10 \text{ GeV})^\dagger$	
ECAL-based delayed jet	$\geq 1 \text{ inclusive and trackless jet}^\dagger$	37 (77)	MDS in DTs	$\text{L1 } p_T^{\text{miss}} > 150 \text{ GeV} + \geq 1 \text{ DT cluster } (\geq 50 \text{ hits})^\dagger$	9
Delayed diphoton	$\geq 2 \text{ ECAL superclusters } (\text{time} > 1 \text{ ns})^\dagger$	15		$\geq 1 \text{ L1 CSC cluster} + \geq 1 \text{ DT cluster } (\geq 50 \text{ hits})^\dagger$	
Disp. photon + H_T	$\geq 1 \gamma (p_T > 60 \text{ GeV}) + \text{PF } H_T > 350 \text{ GeV}$	12	Jet No-BPTX	$\geq 1 \text{ out-of-time jet } (E > 60 \text{ GeV})$	1
Disp. single-muon and dimuon	$\geq 2 \text{ L2 } \mu (p_T > 10 \text{ GeV}, d_0 > 1 \text{ cm})^\dagger$	165	Muon No-BPTX	$\geq 1 \text{ out-of-time L2 } \mu (p_T > 40 \text{ GeV})$	7
	$\geq 2 \text{ L3 } \mu (p_T > 16, 10 \text{ GeV}, d_0 > 0.01 \text{ cm})^\dagger$				
	$\geq 2 \text{ L2 } \mu (p_T > 23 \text{ GeV})$				
	$\geq 1 \text{ L2 } \mu (p_T > 50 \text{ GeV}, d_0 > 1 \text{ cm})^\dagger$				
	$\geq 1 \text{ L3 } \mu (p_T > 30 \text{ GeV}, d_0 > 0.01 \text{ cm})^\dagger$				

[arXiv:2601.17544](https://arxiv.org/abs/2601.17544)



- **L1+HLT acceptances for various LLP triggers:**

- Different subdetectors;
- LLP decay, $H \rightarrow XX \rightarrow bbbb$ for 2023;

- **Signal points:**

- $m(X) = 200, 80, 160$ and 25 GeV;
- $m(H) = 1000, 350, 350$ and 125 GeV;

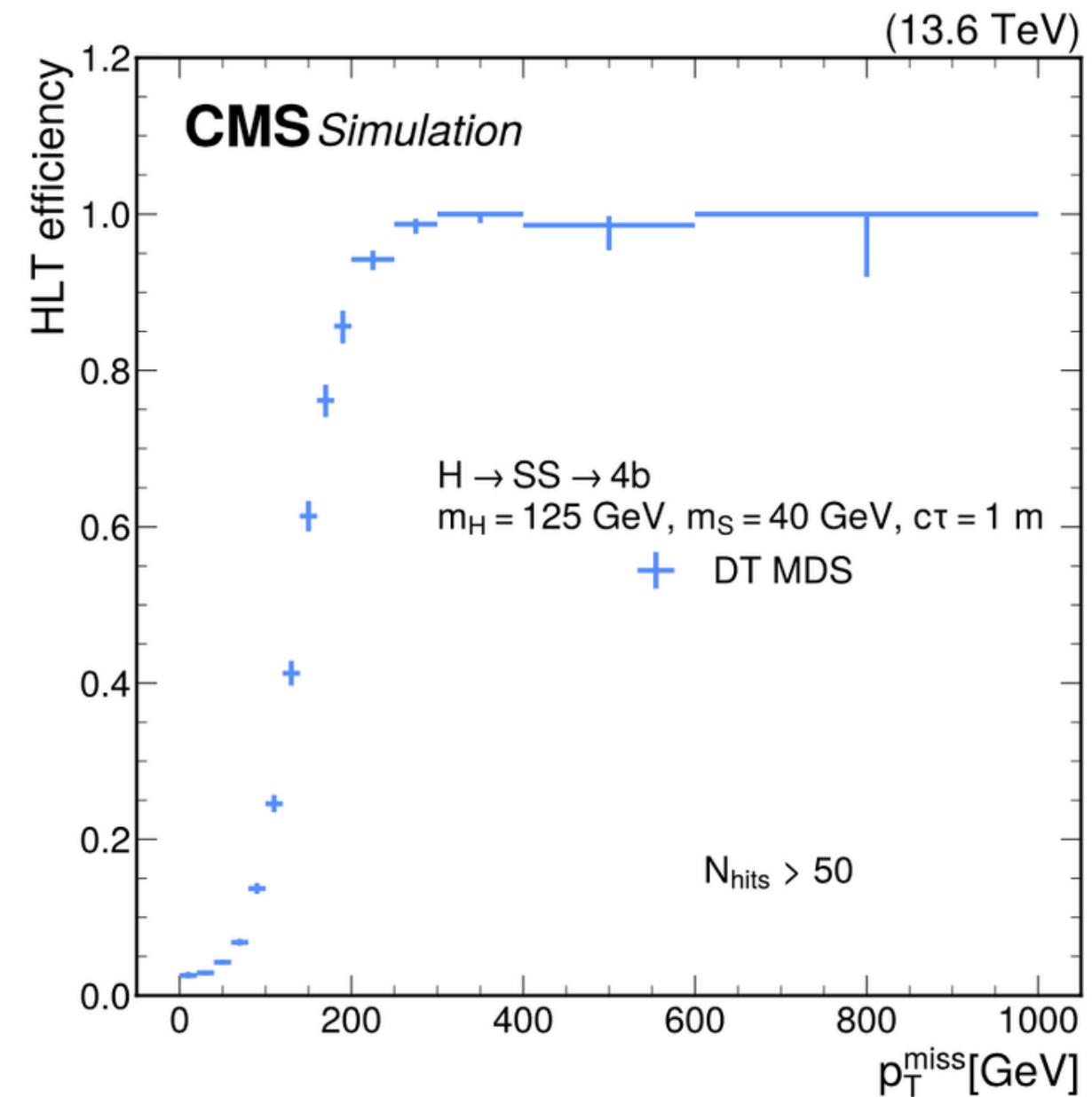
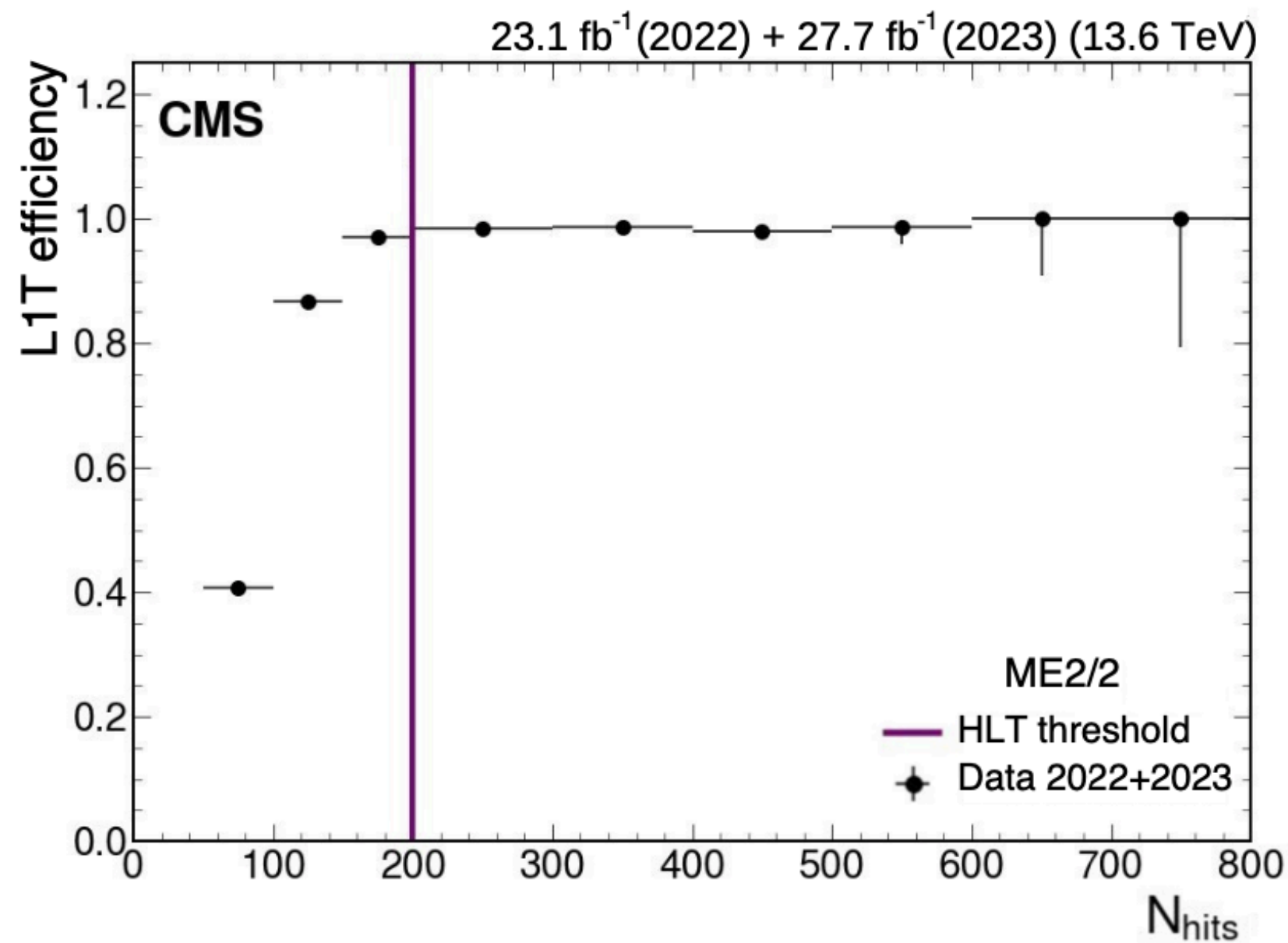
- **Acceptance:**

- Displaced-jet triggers with tracker (cyan);
- Delayed-jet triggers with ECAL (red);
- Displaced-jet triggers with HCAL (blue);
- MDS triggers with DTs (green);
- MDS triggers with CSC (pink).

[arXiv:2601.17544](https://arxiv.org/abs/2601.17544)

- **L1T efficiency** of the One-Nominal CSC MDS trigger with 2022+2023 data;
- **HLT efficiency** of the DT MDS triggers, simulated $H \rightarrow SS \rightarrow bbbb$;

[arXiv:2601.17544](https://arxiv.org/abs/2601.17544)

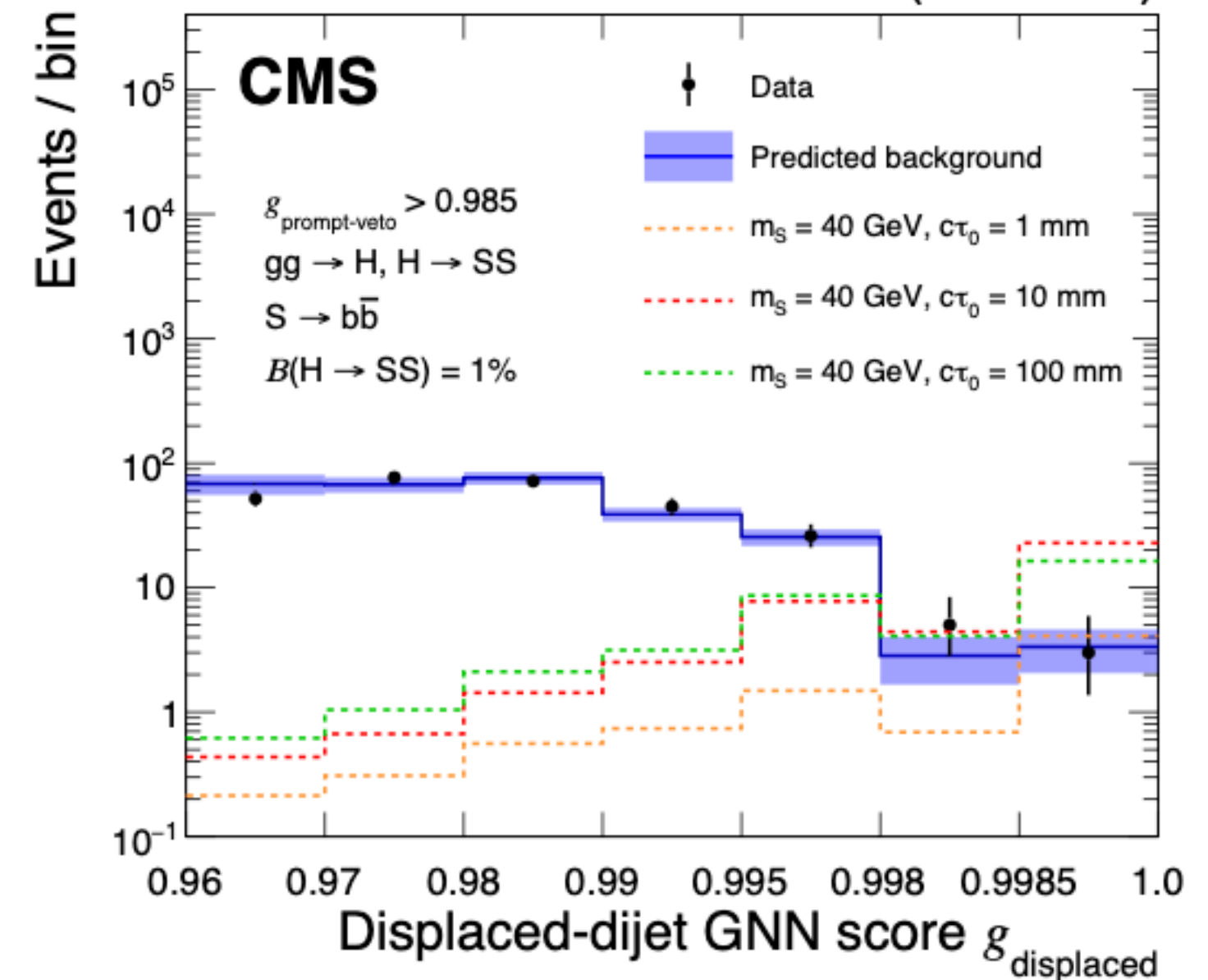


- **Signal efficiencies** scaled by a factor of 10^4 for the $H \rightarrow SS$ signature;
 - Different $m(s)$ and $c\tau$, **dependence on the mass**;
- **Predicted background yields** for different bins of the **GNN score**.

[arXiv:2409.10806](https://arxiv.org/abs/2409.10806)

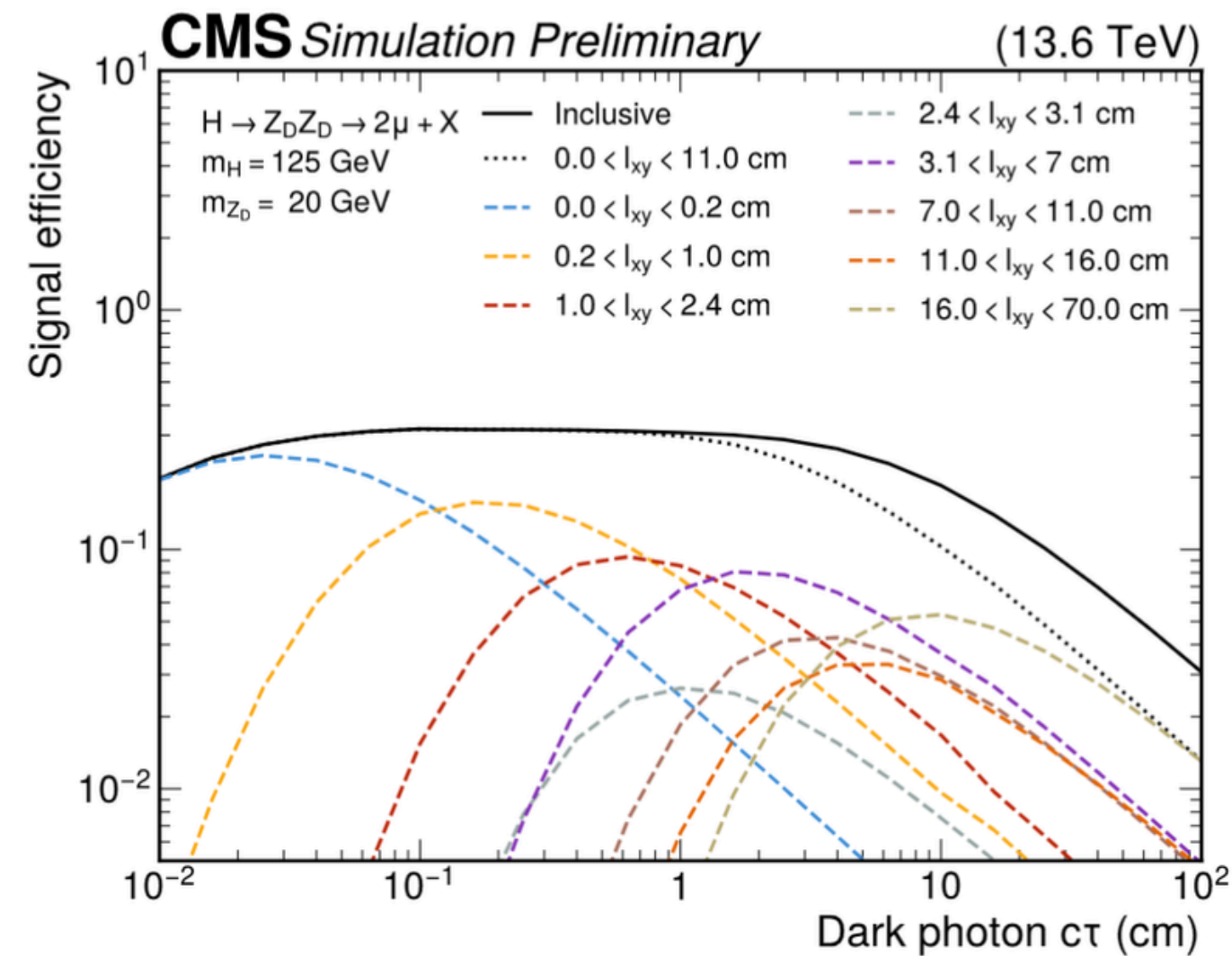
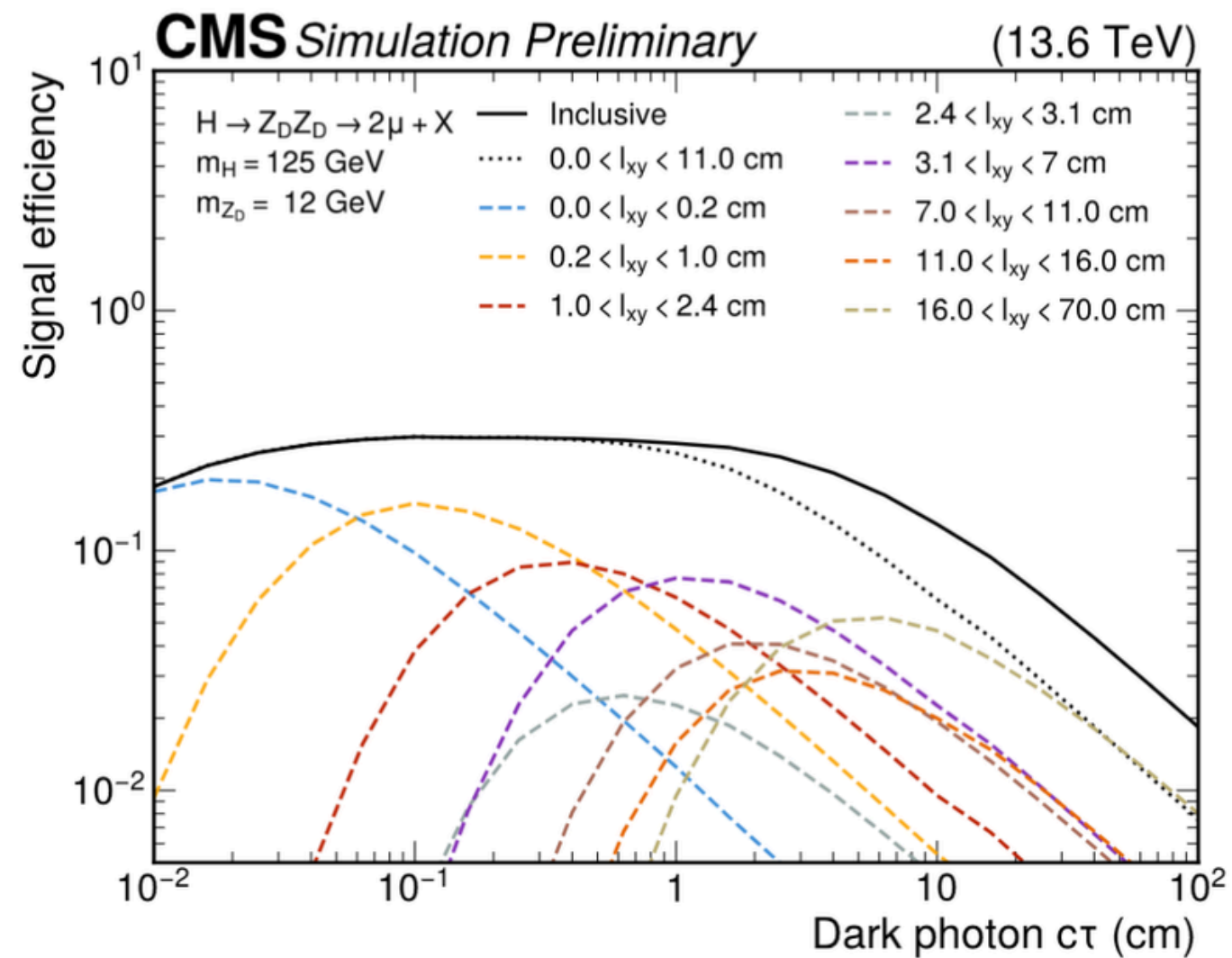
34.7 fb^{-1} (13.6 TeV)

Decay channel	m_S (GeV)	$c\tau_0$			
		1 mm	10 mm	100 mm	1000 mm
$S \rightarrow b\bar{b}$	55	2.82 ± 0.06	15.46 ± 0.14	12.52 ± 0.12	2.17 ± 0.05
	40	2.25 ± 0.05	11.96 ± 0.12	8.60 ± 0.10	1.06 ± 0.04
	23	0.48 ± 0.02	4.42 ± 0.07	2.71 ± 0.06	0.20 ± 0.01
$S \rightarrow d\bar{d}$	55	2.80 ± 0.06	12.48 ± 0.13	10.30 ± 0.11	1.89 ± 0.05
	40	2.47 ± 0.05	11.76 ± 0.12	8.13 ± 0.09	1.06 ± 0.04
	23	0.59 ± 0.03	5.14 ± 0.07	2.89 ± 0.06	0.19 ± 0.02
$S \rightarrow \tau\tau$	55	0.28 ± 0.02	2.17 ± 0.05	1.40 ± 0.04	0.24 ± 0.02
	40	0.23 ± 0.02	1.77 ± 0.05	1.08 ± 0.04	0.15 ± 0.01
	23	0.09 ± 0.01	0.75 ± 0.03	0.39 ± 0.02	0.023 ± 0.005



- Events with **one muon pair**; four-muon system from two **(un)resolved SVs**;
- Overall **signal efficiency** for representative mass points of Hidden Abelian Higgs Model;
- **Increased sensitivity** from the additional coverage [11.0, 70.0] across the entire mass range.

[CMS-PAS-EXO-24-016](#)



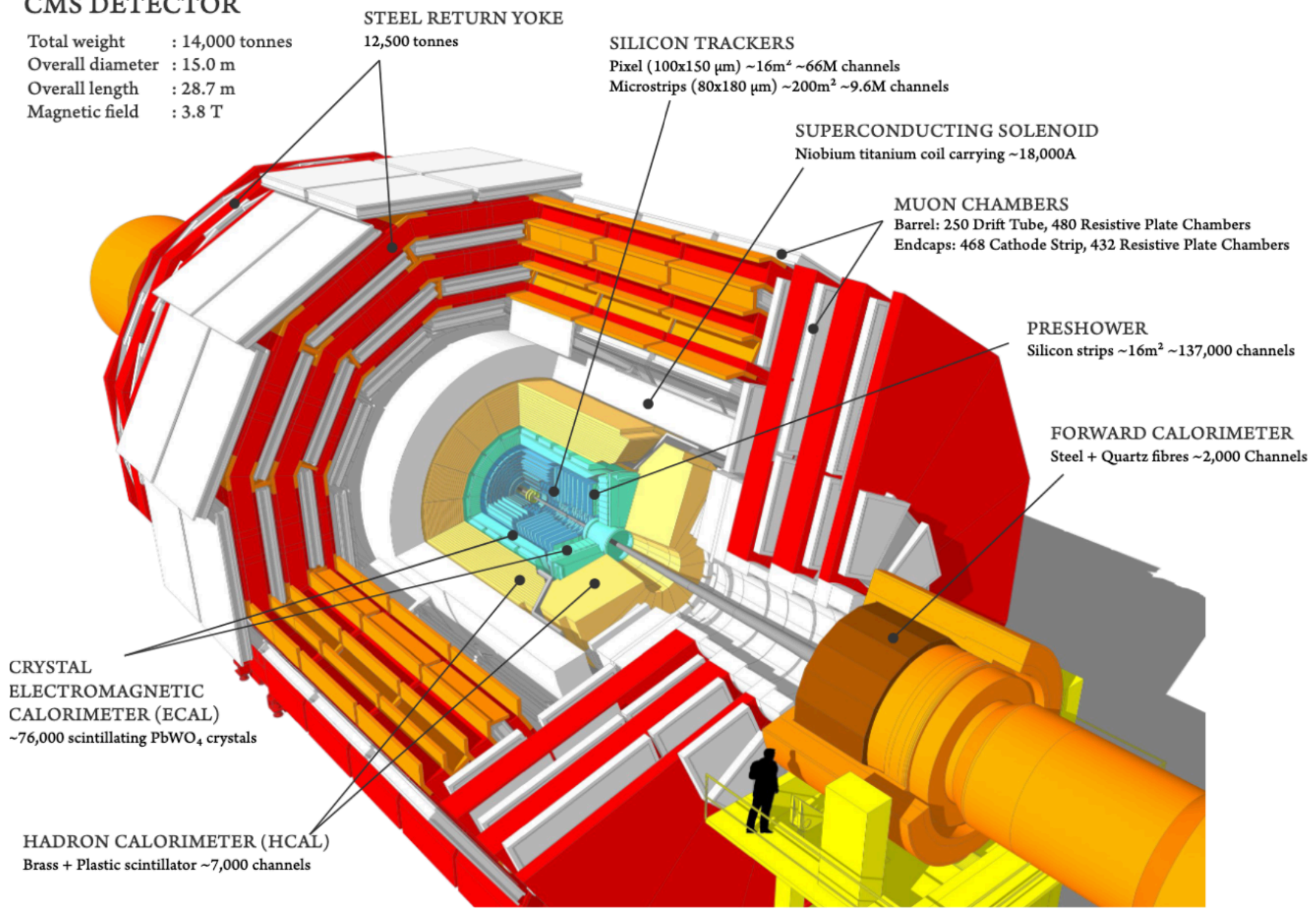
- **Categorisation and background:**

- Speed expressed as the number of crossed layers divided by the number of BXs spent;
- **BX1234**: 4-stub tracks within 4 consecutive BXs; **BX123**: 3-4 stubs across a 3-BX range;
- Estimation is verified in two orthogonal validation regions (VRs).

Stub config.	Layers / BXs				
	3/4	3/3 or 4/4	4/3	3/2	4/2
4 stubs	—	BX1234 BX124/134	BX123	—	BX1112 BX1122 BX1222
3 stubs, MB1 ⊕ MB4	BX124/134 slow	BX123 slow	—	BX112 slow BX122 slow	—
3 stubs, MB1 ∧ MB4	—	BX124/134 fast	BX123 fast	—	BX112 fast BX122 fast

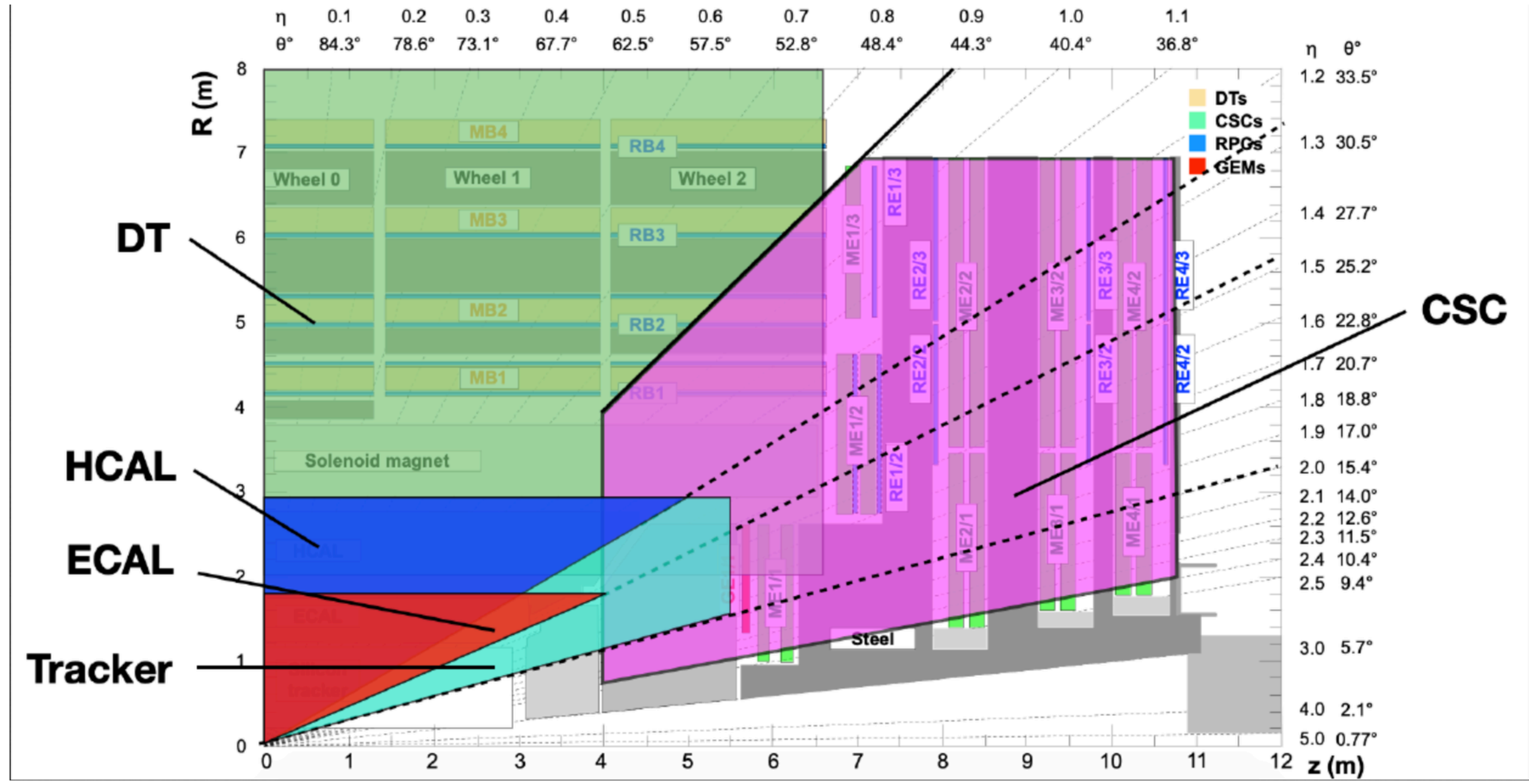
CMS DETECTOR

Total weight : 14,000 tonnes
 Overall diameter : 15.0 m
 Overall length : 28.7 m
 Magnetic field : 3.8 T



- **High-precision measurements** of LHC-produced particles;
- **Tracking:**
 - All-silicon detector;
 - High spatial resolution;
- **Electromagnetic calorimeter (ECAL):**
 - PbWO_4 crystals (homogeneous);
 - High granularity and fast response;
 - sFGVB for noise suppression;
- **Level-1 Trigger:** Hardware-based;
- **High-Level Trigger:** Software-based
- **Reconstruction:**
 - [ParticleFlow](#) for global event reconstruction/description.

Divided into barrel (central) and endcaps (forward).



[arXiv:2601.17544](https://arxiv.org/abs/2601.17544)

