Austrian Roadmap Round Table Meeting

BSM searches at HL-LHC and beyond

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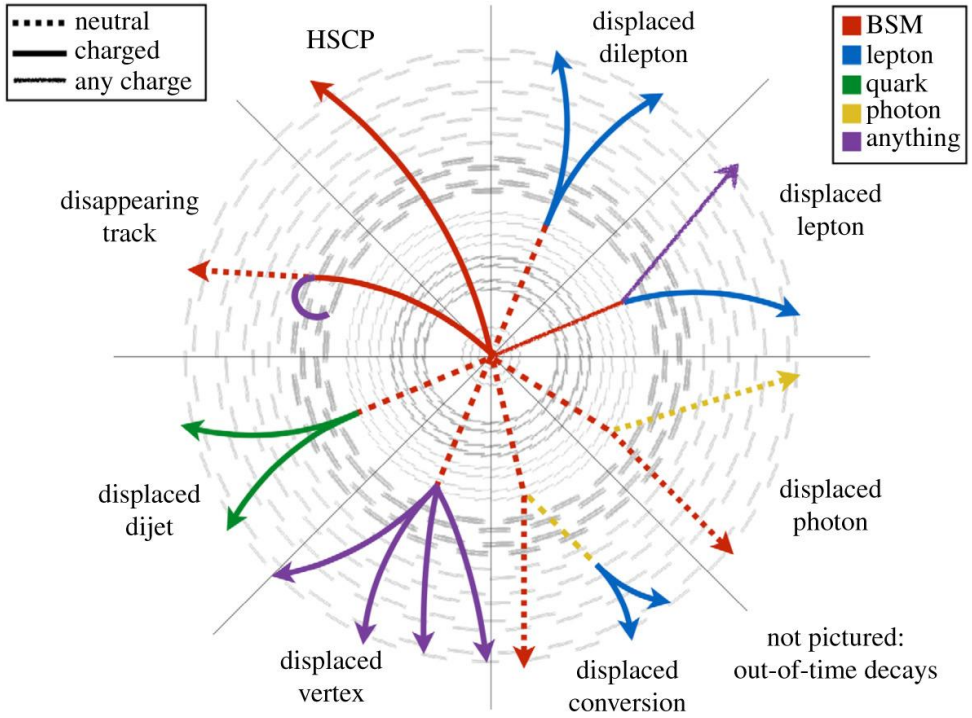
10 June 2024

BSM searches for long-lived particles @ CMS

- Long-lived particles (LLPs): most exciting searching frontier now!

- LLP searches are **challenging**
- But they give **unique opportunities** for R&D
- New ideas applied at **any level** (reconstruction, trigger, analysis techniques)

- Current activities: Run 2 + Run 3 LHC
- Mid-term activities: HL-LHC
- Long-term activities: Future colliders
- Synergies with other groups



J. Antonelli

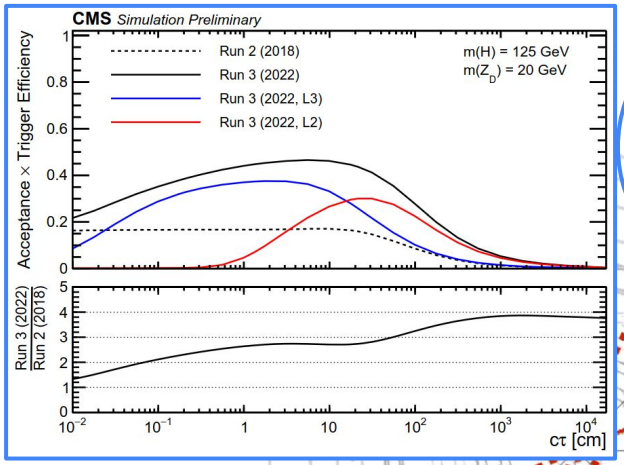
LLP searches: CMS current activities

Displaced dimuons

- Run 2 + first Run 3 search at CMS! http://dx.doi.org/10.1007/JHEP05(2024)047
- Significant improvements thanks to trigger expertise at HEPHY!
- **Synergy with CMS groups** (UCLA, Oviedo, IFCA Santander, BU, CIEMAT, Rice) and **AT theory** (Graz)

Soft displaced vertices

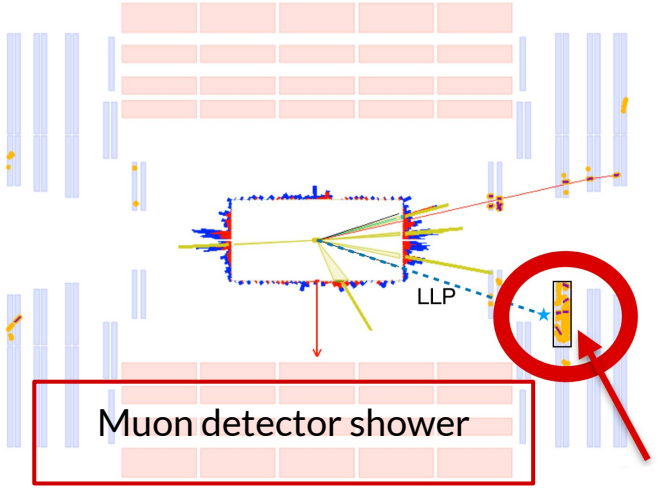
- Uncovered and challenging phase-space
- Advanced machine-learning techniques (graph networks and transformers) to cluster soft tracks and tag displaced vertices
- Working on Run 2 + Run 3 CMS data analysis
- **Synergy with US groups** (Virginia, Cornell, Rutgers) and **ML HEPHY** (C. Krause)



LLP searches: CMS current activities

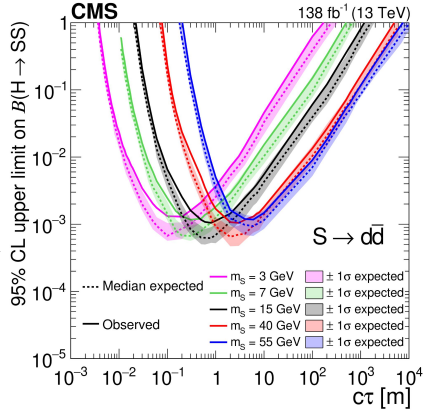
LLPs in the muon system (cτ > 1 m)

- CMS muon gas chambers + passive material act as sampling calorimeter
- Signature: high multiplicity of hits, **muon detector showers** (**MDS**)
- Sensitive to hadronic showers (bb, dd, K^+K^-, K^0K^0, $\pi^+\pi^-$), EM ($\pi^0\pi^0$, γγ, e^+e^-), or both ($\tau^+\tau^-$)
- Sensitive to sub-GeV LLP masses



- Run 3 (2022): **dedicated MDS trigger**!
  - x20 efficiency w.r.t. Run 2 unspecific trigger approach

- **Synergy with US-DE groups** (Fermilab, Caltech, UCSD, Hamburg)



Run 2 publications:
PRL.127.261804 (forward muon system)
https://arxiv.org/abs/2402.01898 (subm. PRD)

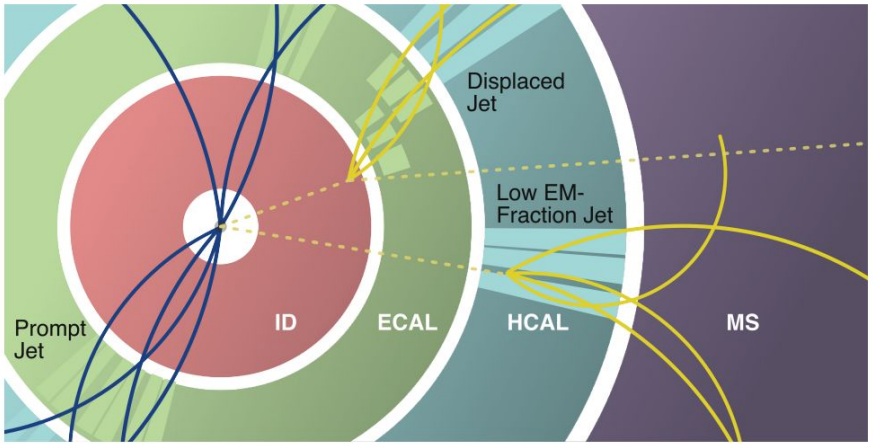
LLP searches: CMS current activities

Extend to displaced decays at radius ~ 1-3 m:

- **ECAL crystals** provide timing → measure **delay** wrt p-p collision
- **HCAL** provide time + **segmentation** → measure **shower** delay/**depth**

MDS, calorimeter and combinations:

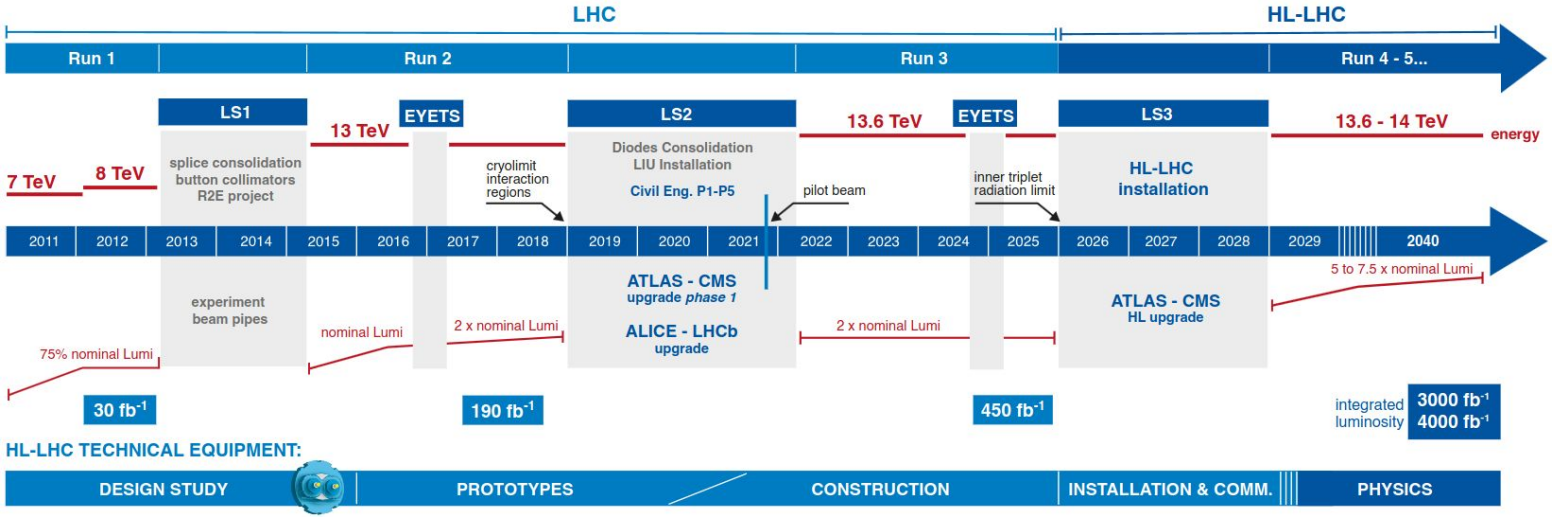
- Probe models with rich phenomenologies **not (fully) explored**!
  - Heavy Neutrinos in B-L models
  - Dark showers in QCD-like dark sector



- Use case for advanced ML techniques (**synergy with ML group C. Krause**)
- **Synergy with AT theory groups** (already established with S. Kulkarni in Graz + HEPHY, TU and UVie)

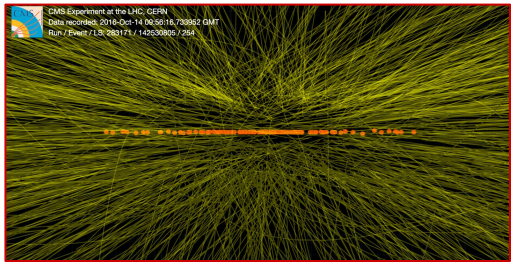
High Luminosity (HL) LHC project

https://home.cern/science/accelerators/high-luminosity-lhc



"HL-LHC aims to crank up the performance of the LHC to increase the potential for discoveries after 2029"

- Unprecedented luminosity up to 7.5 x 10^{34} $cm^{-2}s^{-1}$ (x7.5 wrt LHC)
- Expected 3000 fb^{-1} proton-proton (p-p) collisions for CMS
- Unprecedented challenges due to simultaneous p-p collisions (pileup, PU):
  - Run 3 (2023): PU 52; HL-LHC: PU 200!
  - Higher occupancy, trigger rates, detector irradiation
- Existing detectors require upgrades to cope with HL-LHC! (CMS Phase-II)



https://cds.cern.ch/record/2231915

CMS Phase-II: tracker & BSM opportunities

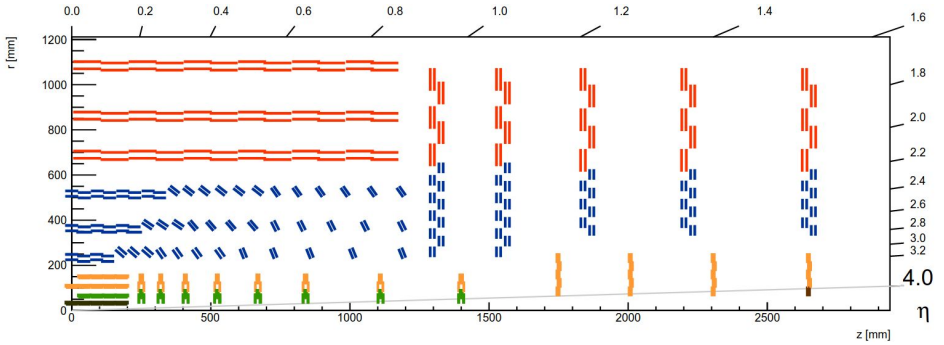
Complete exchange of Outer Tracker

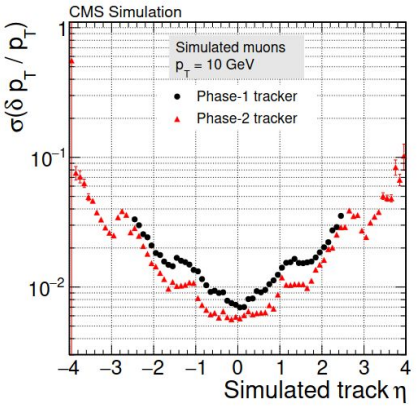
- Enhanced granularity, radiation tolerance
- Combined with inner tracker: enhanced discovery potential!
  - Extended coverage in endcaps
  - Reduced material budget
  - OT designed to be included in hardware level trigger

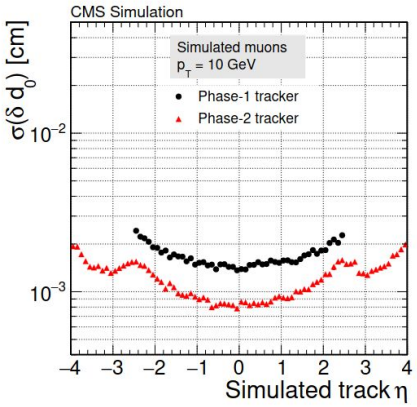
→ improved momentum/impact parameter resolution
→ impact on searches for LLPs!

HEPHY involvement:

- Concluded: development studies of the sensors; final design and wafer layout; procurement process
- Definition+supervision of Quality Assurance Campaign to produce ~29.000 sensors
- Sensor production ~95% (last shipments from HPK soon this summer)







http://cds.cern.ch/record/2272264

CMS Phase-II: HGCAL & BSM opportunities

https://cds.cern.ch/record/2311394

New Highly Granularity Calorimeter (HGCal) in endcaps

- 5D imaging calorimeter: position + energy + time (30 ps)
- Increased radiation tolerance, granularity
- Silicon modules (600 m^2 8” wafers) + scintillator tiles with SiPM

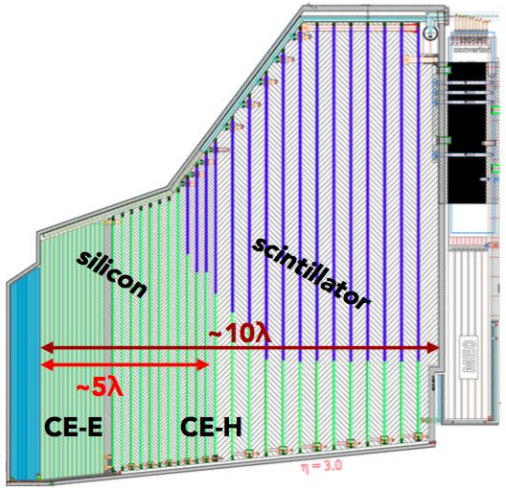
HEPHY involvement:

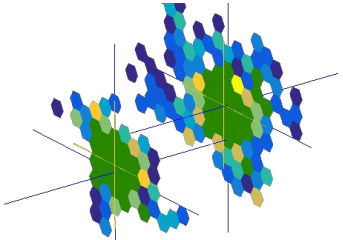
- Completed: development and prototyping of radiation hard silicon sensors
- Production at about 40%
- Participate in Quality Assurance campaign

HGCAL shower reconstruction:

- Challenging yet engaging task: heterogeneous detector, heterogeneous computing + machine learning
- Time resolution → new opportunities in calorimeter-based LLP signatures! (forward calorimeters not used so far!)

- **Synergy with detector group + ML group + Fermilab**





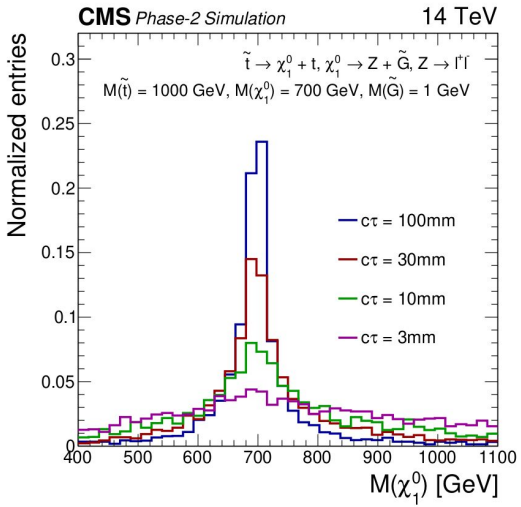
https://waredjeb.github.io/test-deploy/

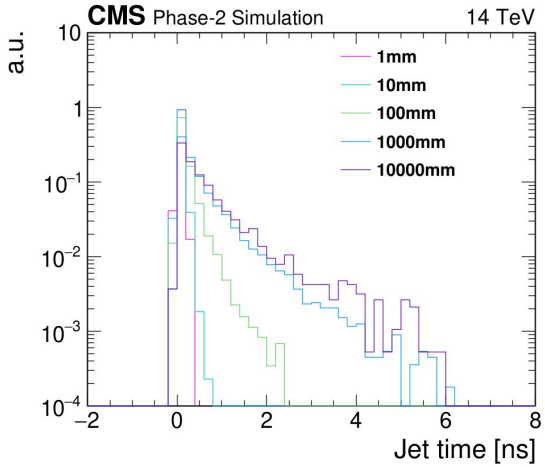
CMS Phase-II: MTD & new ideas

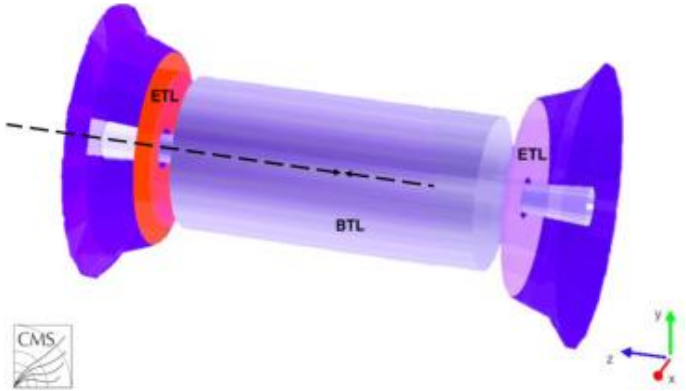
https://cds.cern.ch/record/2667167

MIP Timing Detector in the barrel:

- LYSO:Ce crystals with SiPMs: time resolution 30 ps
- Primary vertex + decay vertex time → particles time of flight (velocity) → infer LLP mass!
- Improve sensitivity to delayed objects (jets/photons)







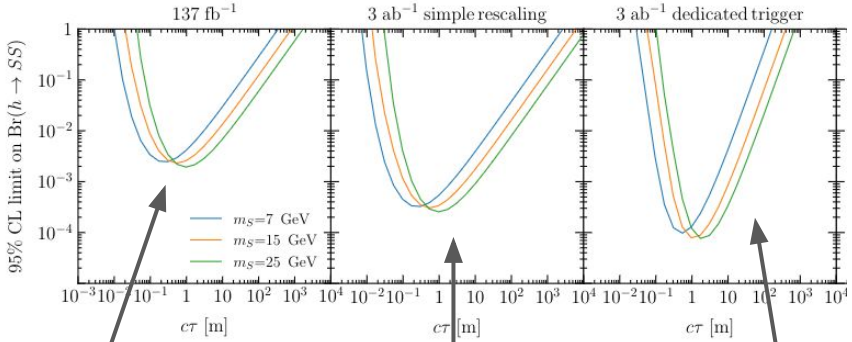
- MTD + HGCAL → full coverage of barrel and endcaps!

LLPs @ HL-LHC: sensitivity projections

https://arxiv.org/abs/2304.06109

- Much to gain from extending MDS and SDV at HL-LHC!

Higgs → SS (LLPs) with MDS in endcaps

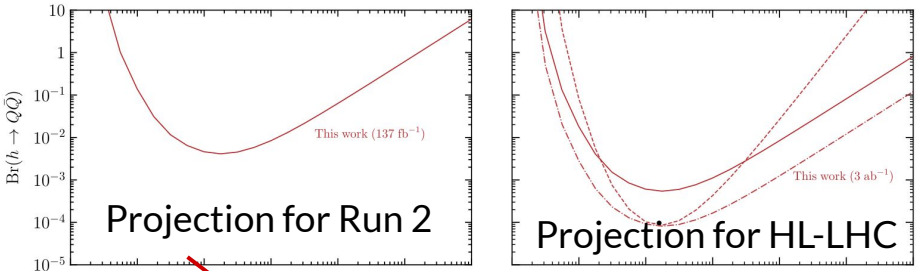


Run 2 analysis

Rescaled to HL-LHC

HL-LHC + new trigger (Run 3)

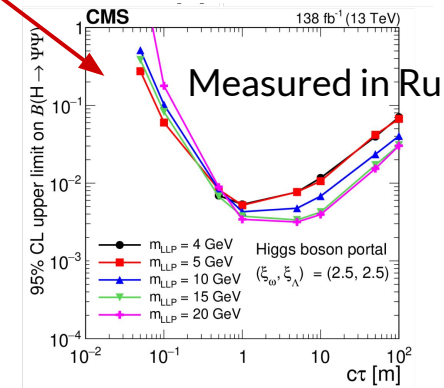
Dark showers with MDS in endcaps



Projection for Run 2

Projection for HL-LHC

Measured in Run 2



LLPs @ HL-LHC

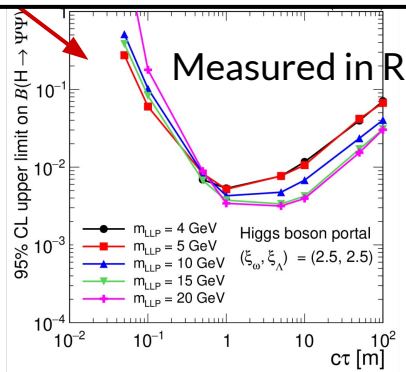
We need to fully exploit the HL-LHC!

Large effort still required to build and commission CMS Phase-II!

Run 2 analysis

Rescaled to HL-LHC

HL-LHC + new trigger (Run 3)



Measured in Run 2

LLPs @ future colliders

LLP priority list @ future colliders:

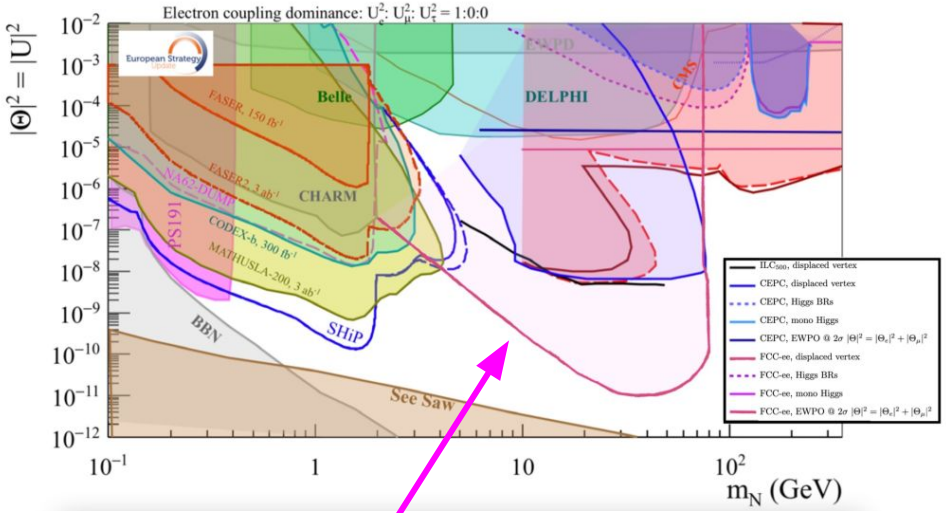
- Heavy neutral leptons
- Axion-like particles
- Exotic Higgs decays

We have the expertise to cover the entire phase-space:

- Displaced tracks and vertices
- Delayed objects with calorimeter timing
- Showers in the muon system, displaced muons

Synergies and perspectives:

- Reconstruction strategies → CMS legacy
- FCC-ee detector design → stronger focus on tracking → benefit from e^+e^- knowledge in **Belle II** group!
- Opportunity to expand searches in the Higgs sector (FCC-ee as Higgs factory) → **AT theory groups** (Graz, HEPHY, TU and UVie)



HNLs with **displaced vertices**!

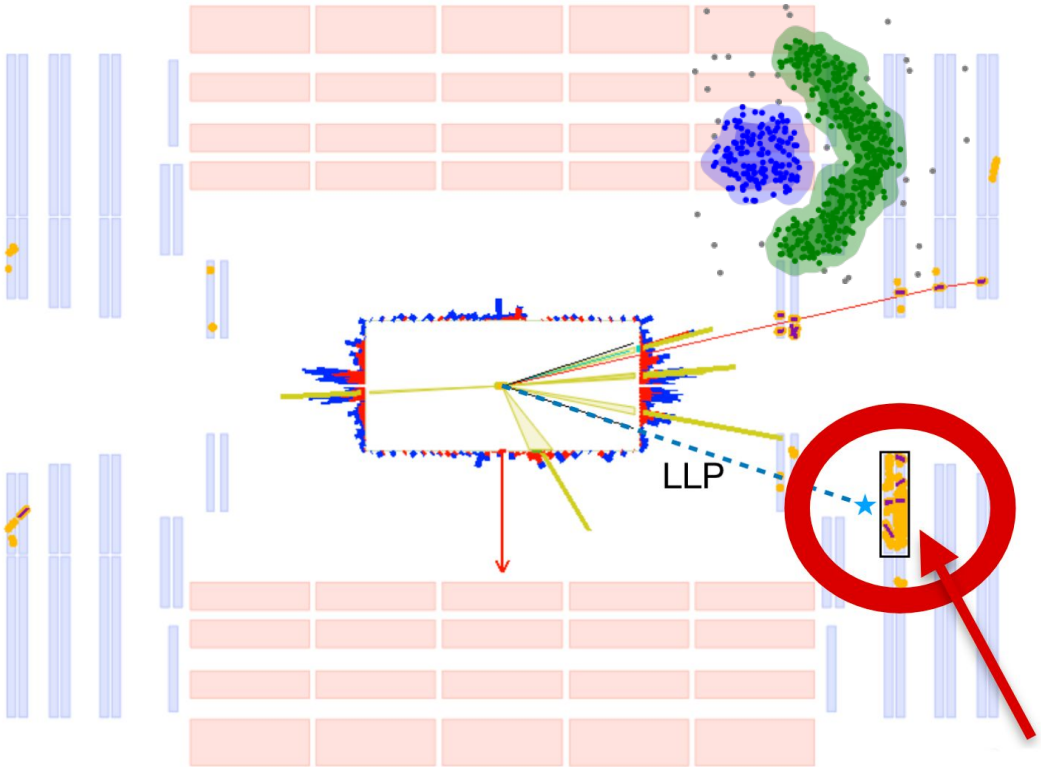
ECFA report https://arxiv.org/abs/2401.07564
LLP @ FCC-ee snowmass https://arxiv.org/abs/2203.05502

Backup

LLP decays in muon system

LB: PRL.127.261804 (CSC only)
https://arxiv.org/abs/2402.01898 (subm. PRD)

https://en.wikipedia.org/wiki/DBSCAN



- Neutral LLPs (cτ > 1 m) hadronic decays: no tracks, no jets, but showers in muon system
- Passive material (iron/steel) + muon chambers: sampling calorimeter → a shower develops
- Signature: high multiplicity of hits

New reconstructed object: **muon detector showers** (**MDS**)

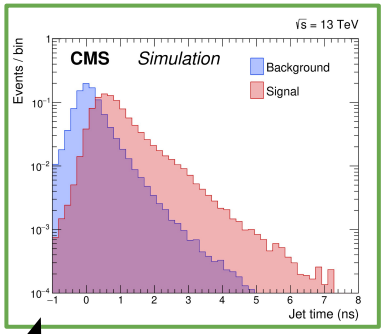
- Hits clustered with geometrical clustering algorithms: DBSCAN
- 1 cluster = MDS
- Hits are low-level information (RAW data format, non standard) → challenging to access!

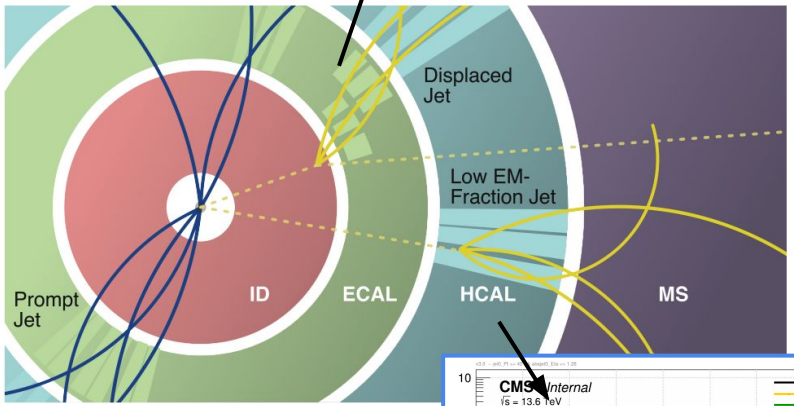
Muon detector shower

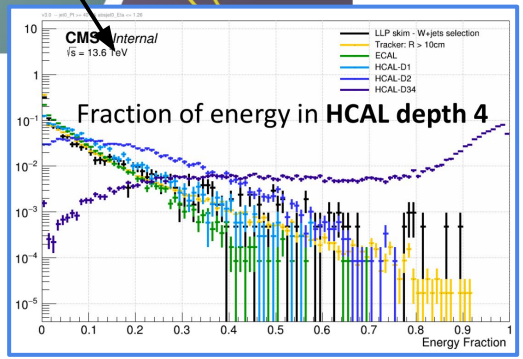
LLP decays in the calorimeters

Displaced decays at radius ~ 1-3 m:

- PBWO4 **ECAL crystals** provide timing → measure **delay** wrt p-p collision
- **HCAL** provide time + **segmentation** → measure **shower** delay/**depth**







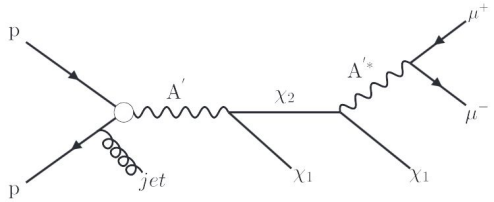
BSM discovery potential

https://arxiv.org/abs/2305.11649

Several exciting BSM **not (fully) explored**!

Inelastic dark matter

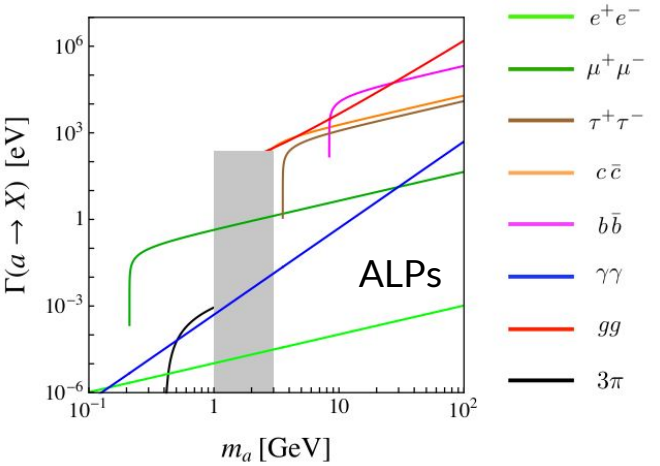
- Small mass splitting Δm(χ1, χ2), dark photon mediator A'
  Soft final state visible particles collimated to missing energy
- Only muons + missing energy probed at CMS so far



Inelastic DM

Axion-Like Particles (ALPs)

- Much phase-space to explore in h→ aa, h→Za, Z→aγ decays
- a→γγ, charged leptons and hadrons; below 1 GeV a→πππ
  - Not possible in inner detector at CMS!
- ALPs produced in exotic top decays → can be LL if m_a ~ few GeV

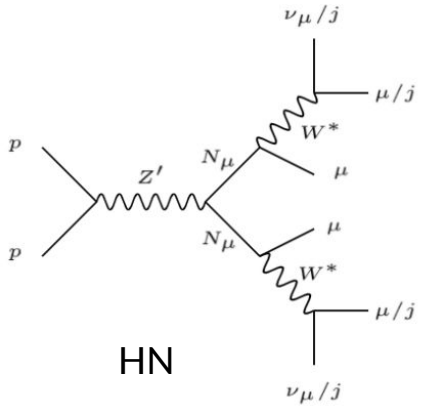


https://arxiv.org/abs/1708.00443

BSM discovery potential

Heavy Neutrinos (HNs) in B-L models

- $U(1)_{B-L}$: 3 HNs coupling to heavy Z' and heavy B-L charged Higgs X
- HNs produced from Z', X and SM H → m_{HN} up to > 100 GeV
- Rich phenomenology, interesting signatures in calorimeters



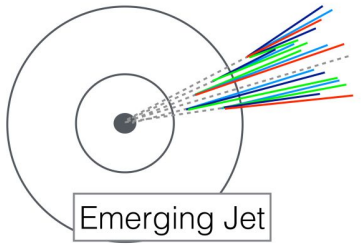
HN

https://arxiv.org/abs/2202.07310

Dark showers

- QCD-like dark sector
- Dark partons ψ through decay of massive mediator X → ψ$\bar{\psi}$
  X: new scalar/vector, Higgs boson, W/Z
- ψ hadronizes to dark mesons, that decay back to SM and can be LL
- Compelling signature explored at CMS as emerging jets (displaced tracks)
- Much unexplored phase-space accessible with MDS, calorimeter based methods and combinations

Dark showers

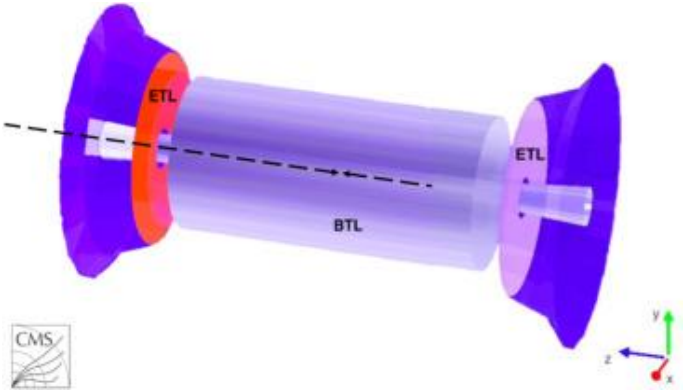


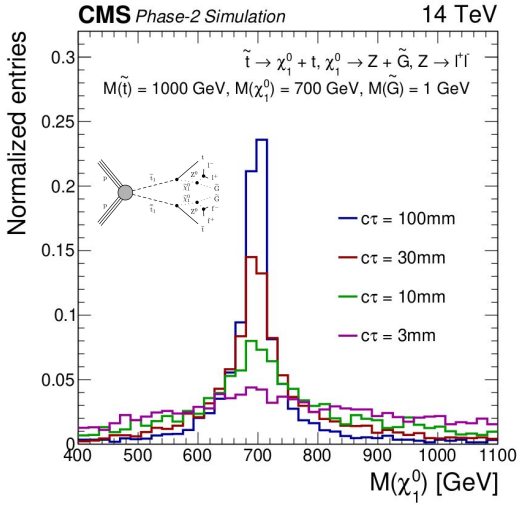
https://arxiv.org/abs/2203.09503

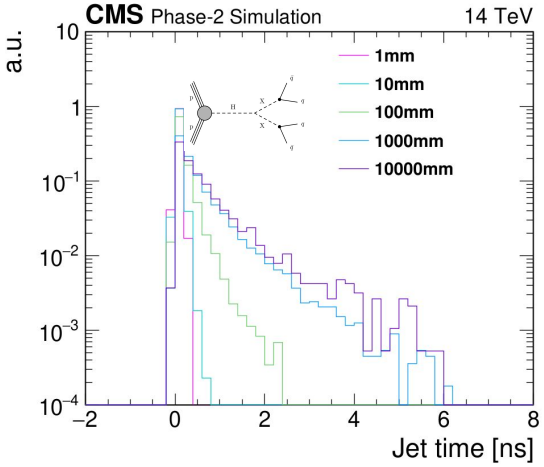
CMS Phase-II: MTD & new ideas

MIP Timing Detector: https://cds.cern.ch/record/2667167

- LYSO:Ce crystals with SiPMs: time resolution 30 ps
- Primary vertex + decay vertex time → particles time of flight (velocity) → infer LLP mass!
- Improve sensitivity to delayed objects (jets/photons)





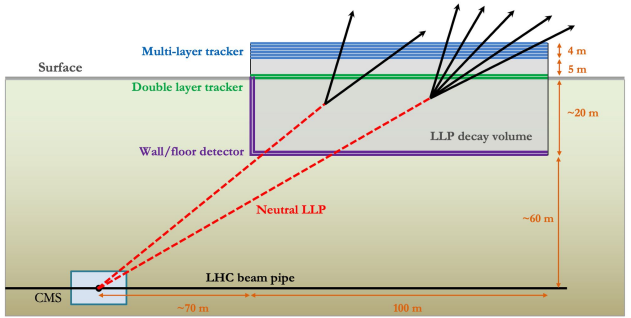


MDS trigger in the barrel:

- Currently only in forward muon system
- Electronics replacement: x2 acceptance

Correlated CMS-MATHUSLA analysis

- MATHUSLA can supply triggers to CMS
- Light particles/longer lifetimes



- MTD + HGCAL → full coverage of barrel and endcaps!
- **Synergy with Fermilab**

Run3 LLP new result: displaced dimuons

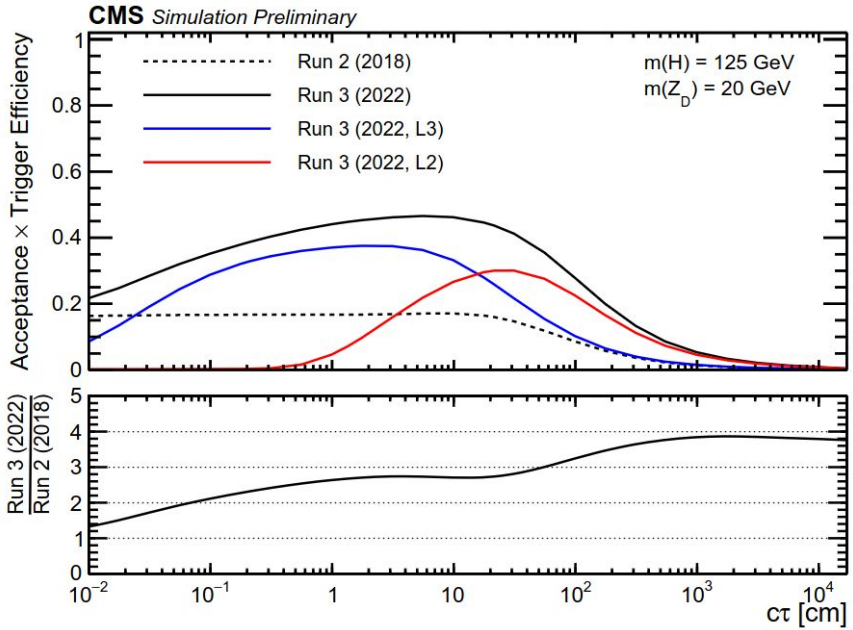
EXO-23-014
PAS-EXO-23-014

First Run3 CMS search!

Displaced dimuons (EXO-23-014)

- New L1T algo to assign p_T to μ from displaced vertex

- Improved HLT algos:
  - Recovers efficiency for tracker μ, x2 better @ cτ = 1 cm
  - Discard prompt μ → improves at larger displacement, x3 efficiency @ cτ = 1 m



Run3 LLP new result: displaced dimuons

EXO-23-014
PAS-EXO-23-014

Displaced dimuons reconstruction:

- As global μ (with tracker): better at lower displacement
- As standalone μ (muon system only): better at higher displacement

First CMS search with Run3 data!

- Achieved similar sensitivity to Run 2 data with only ⅓ of the luminosity in Run 3 (2022)