Long lived particle searches with the CMS experiment. Present and future

S. Folgueras with input from M. Alcaide, A. Escalante, P. Martínez Ruiz del Árbol, R. López, and A. Soto.

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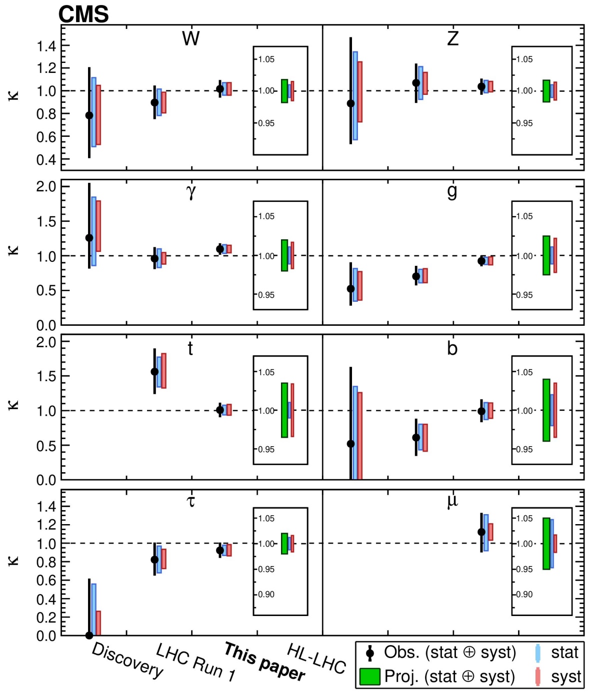
Where to look for new physics?

Improve precision of SM tests (*i.e. Higgs couplings,* m_W)

Target unobserved SM processes (*i.e.* $H \to HH$; $H \to cc$)

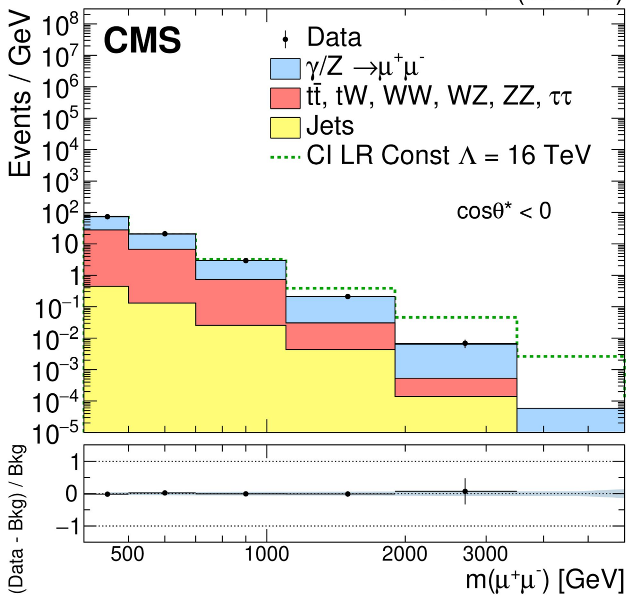
Search for deviations at high momenta (*i.e. Effective Field Theories*)

Probe new phase space (*i.e. Long-lived particles*)

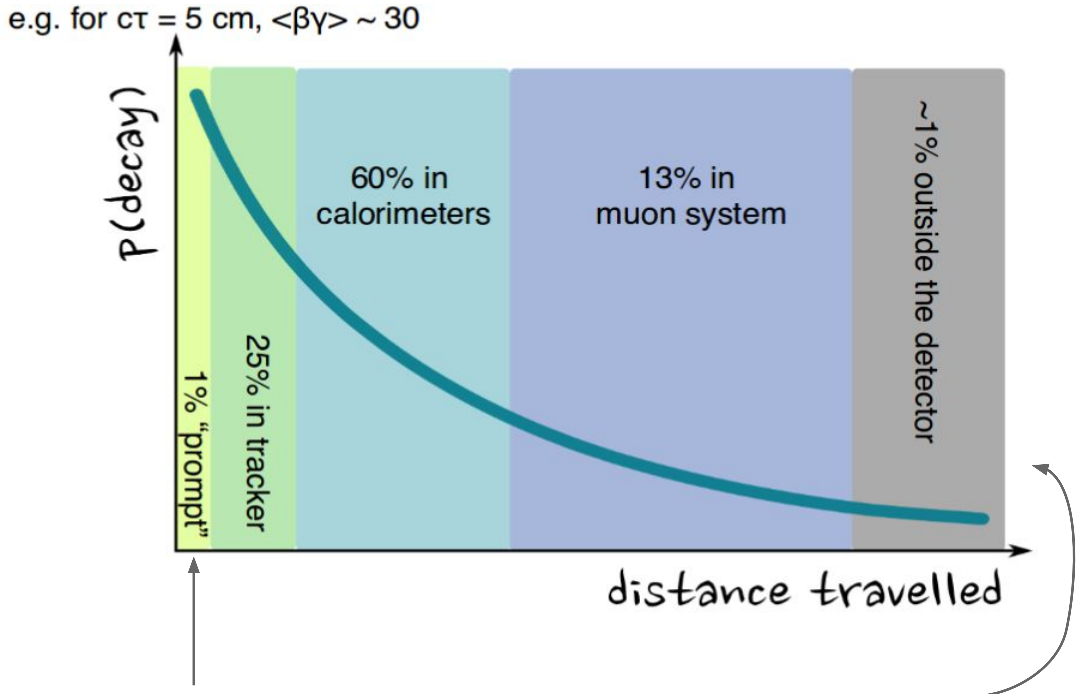


[Nature 607, 60–68 (2022)]

[CMS-EXO-19-019]

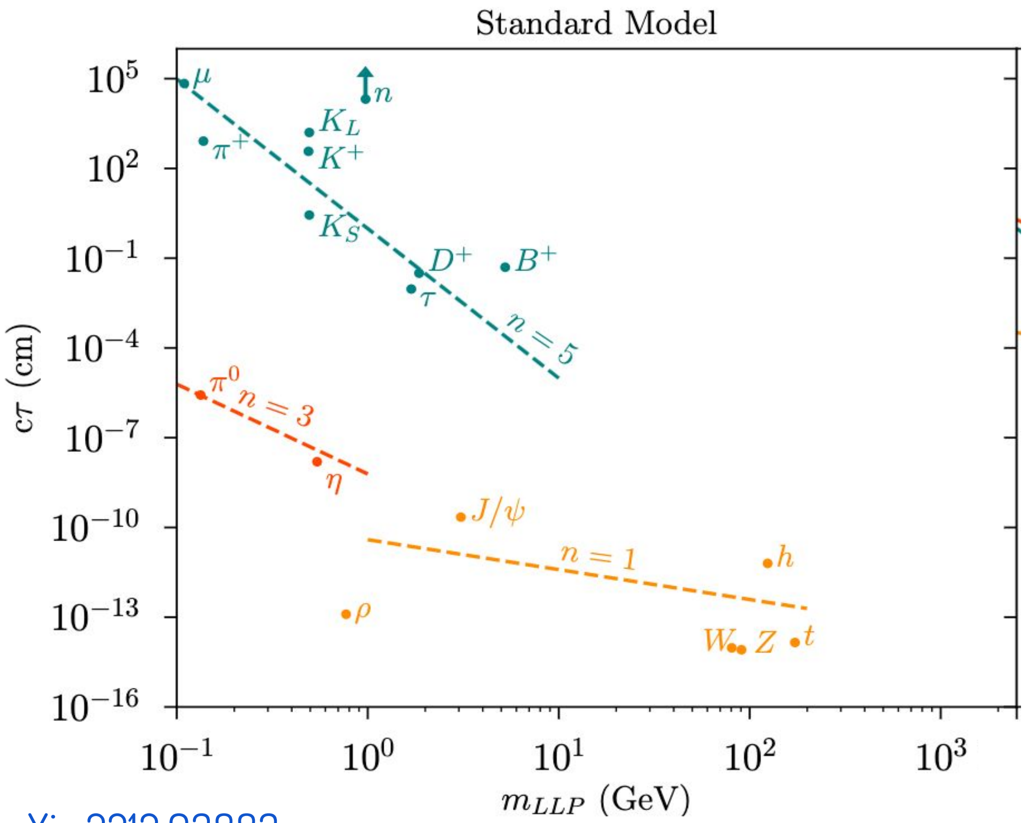


$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \sum \frac{C_x}{\Lambda^2} O_{6,x} + h.c.$$



Bulk of searches

Why long-lived particles?



arXiv:2212.03883

- The SM is full of LLPs:
  - muon ($\tau = 2.2\mu s$)
  - Kaon ($c\tau$(K+) = 3.71 m
  - Heavy flavour
    - $c\tau$(D+) = 311.78 μm
    - $c\tau$(B+) = 491.06 μm
- There is no reason to believe they won't be present on BSM theories.

New physics may be so *feebly* coupled to our Standard Model that their signatures may have been overlooked or miss identified by LHC searches not dedicated to LLPs

LLP?

$c\tau \sim \Gamma^{-1} \gtrsim 0.001$ [mm]

arXiv:2212.03883v1

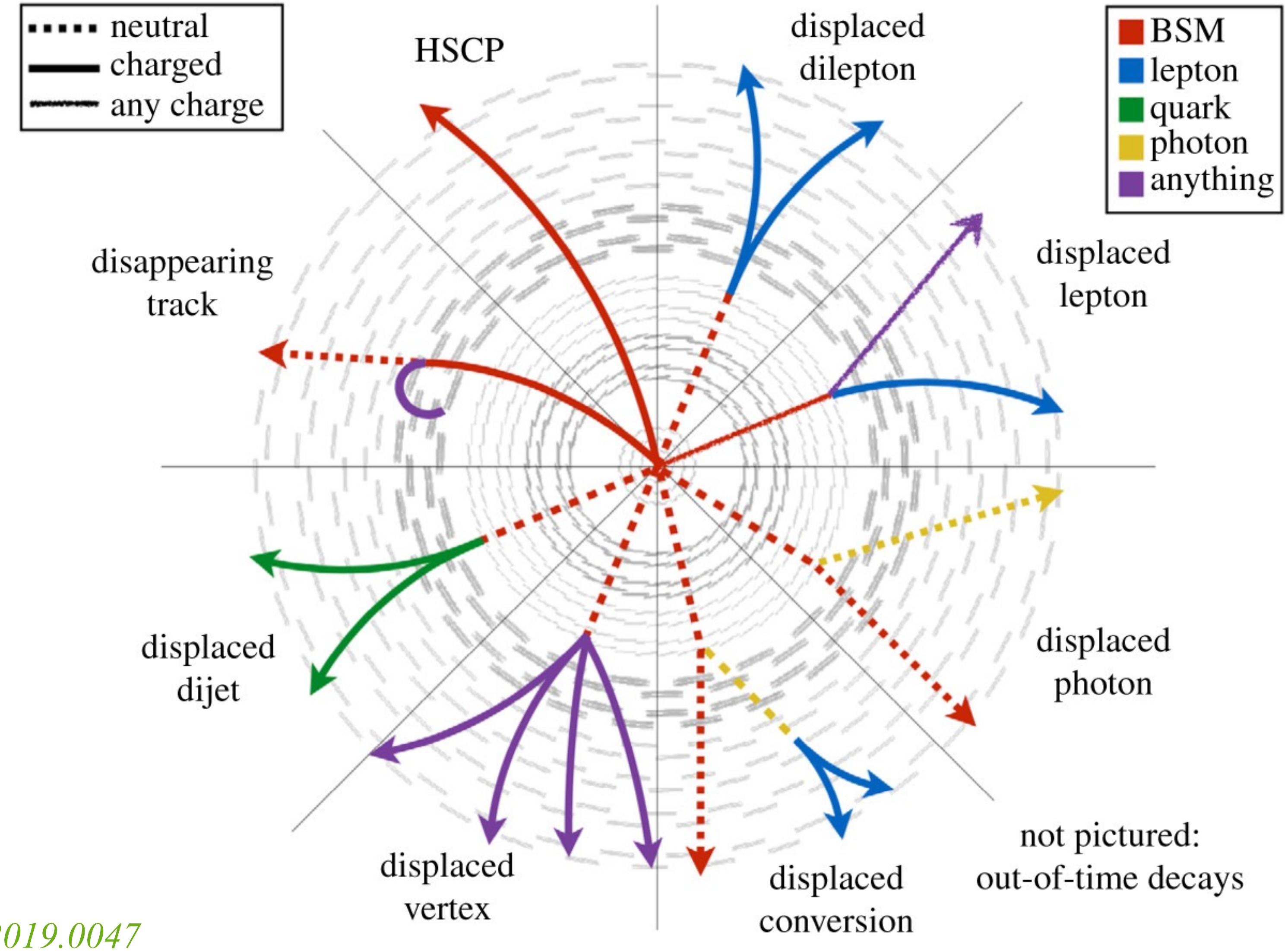
$$\Gamma \sim c^2 \left(\frac{\Delta m}{\Lambda}\right)^n \Delta m$$

G. Cottin @LHCP 2023

Three reasons why	Feebly (small) couplings	Large mass hierarchies/ heavy mediators	Small mass difference or "compressed spectra"
Three reasons why is hard	Low rates	Large energies (LHC inaccessible)	Low efficiency (soft particles/limited object reconstruction)

2

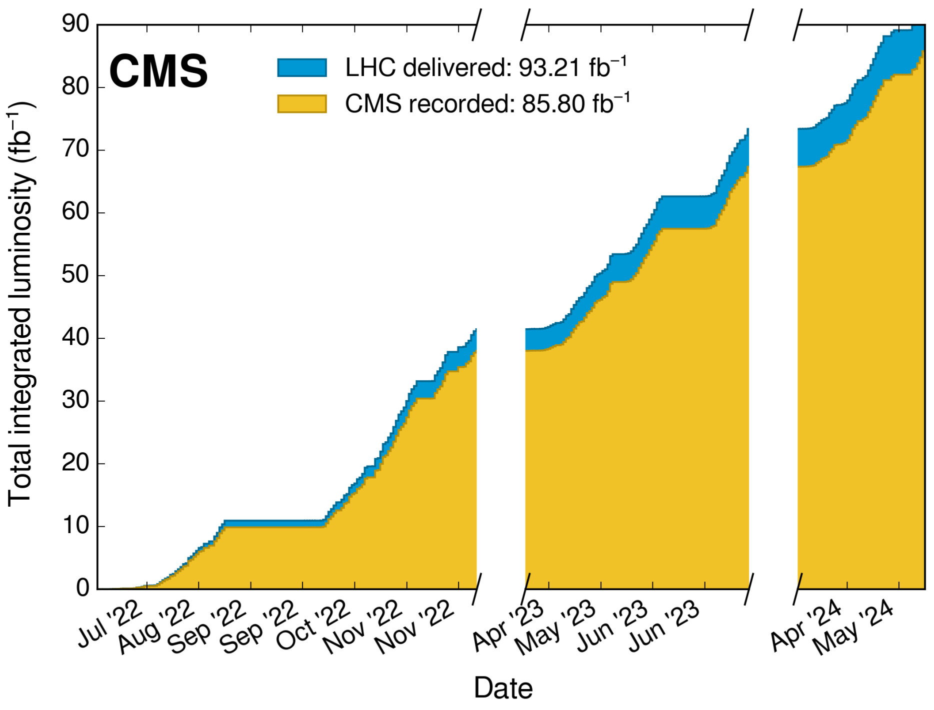
Experimental signatures of long-lived particles

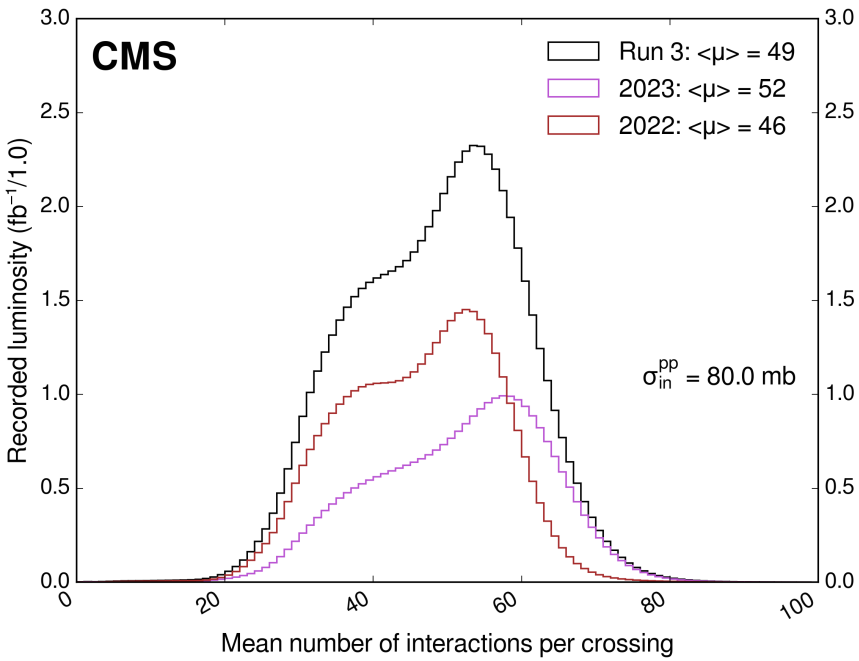


https://doi.org/10.1098/rsta.2019.0047

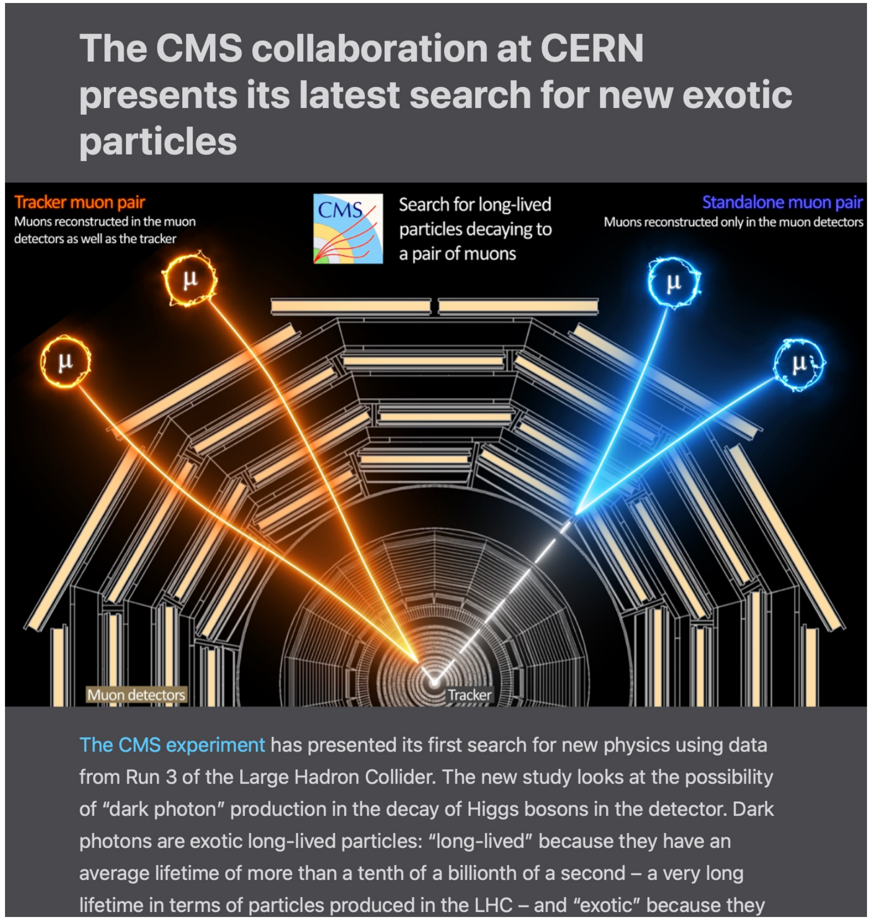
Run 3

- After the short data taking year in 2023, LHC is performing well
- 85.5 fb-1 recorded in CMS in 2022+2023+2024 at 13.6 TeV
- Improved trigger strategy!





First Run 3 result: Displaced dimuons at 13.6 TeV



https://cms.cern/news/long-lived-particles-light-lhc-run-3-data

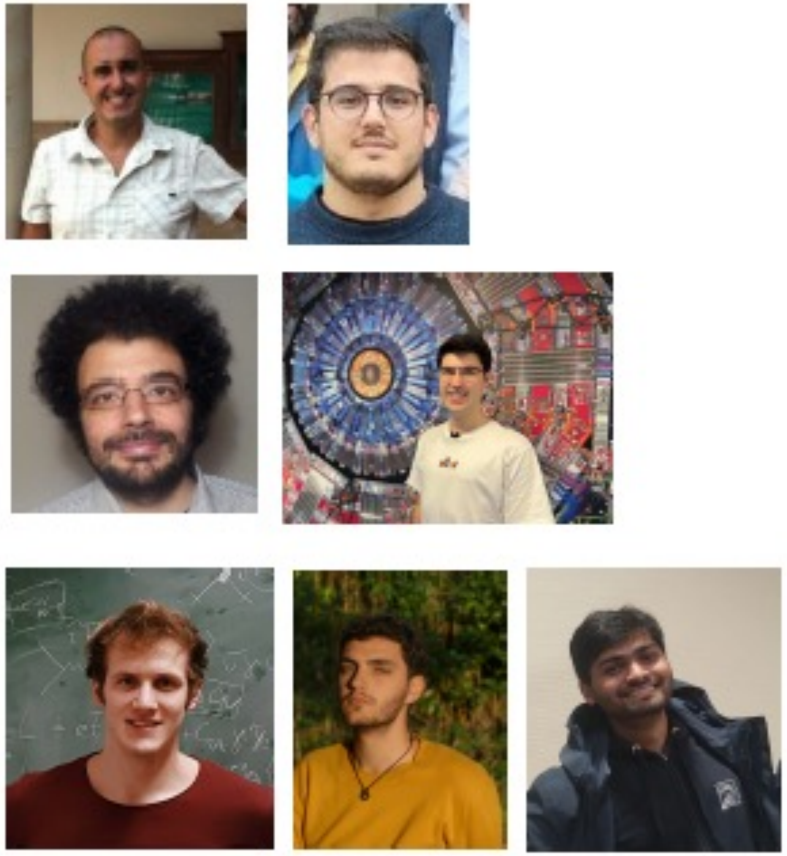
https://home.cern/news/news/physics/cms-collaboration-cern-presents-its-latest-search-new-exotic-particles

With a strong Spanish contribution:

Universidad de Oviedo

IFCA
Instituto de Física de Cantabria

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

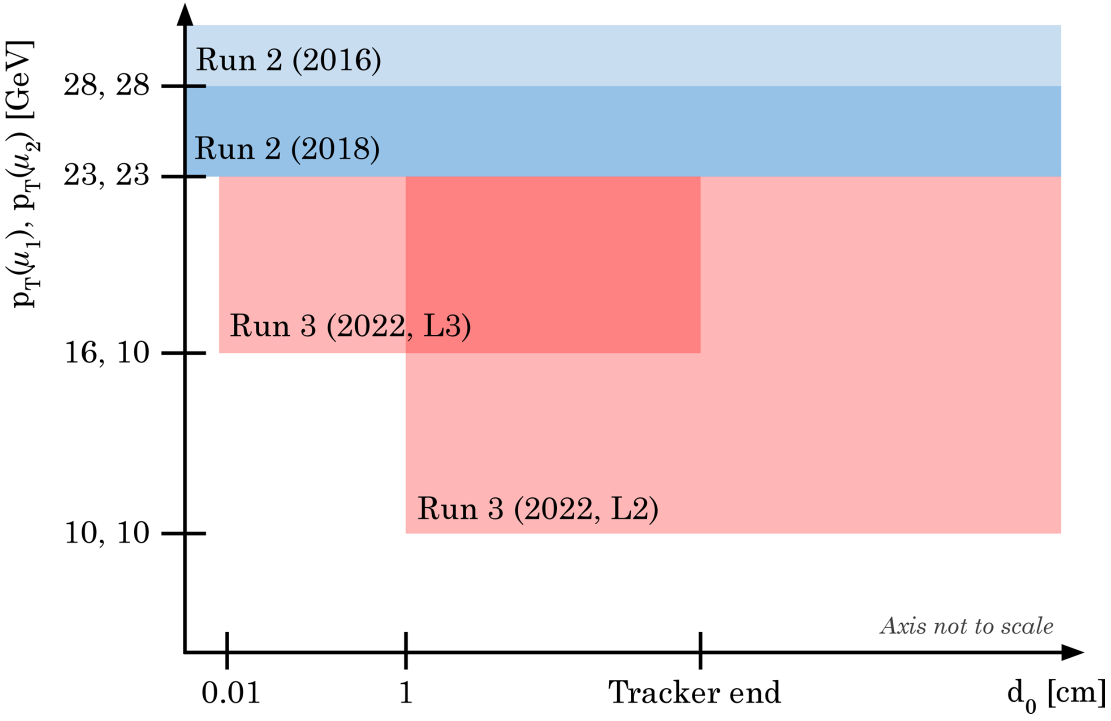


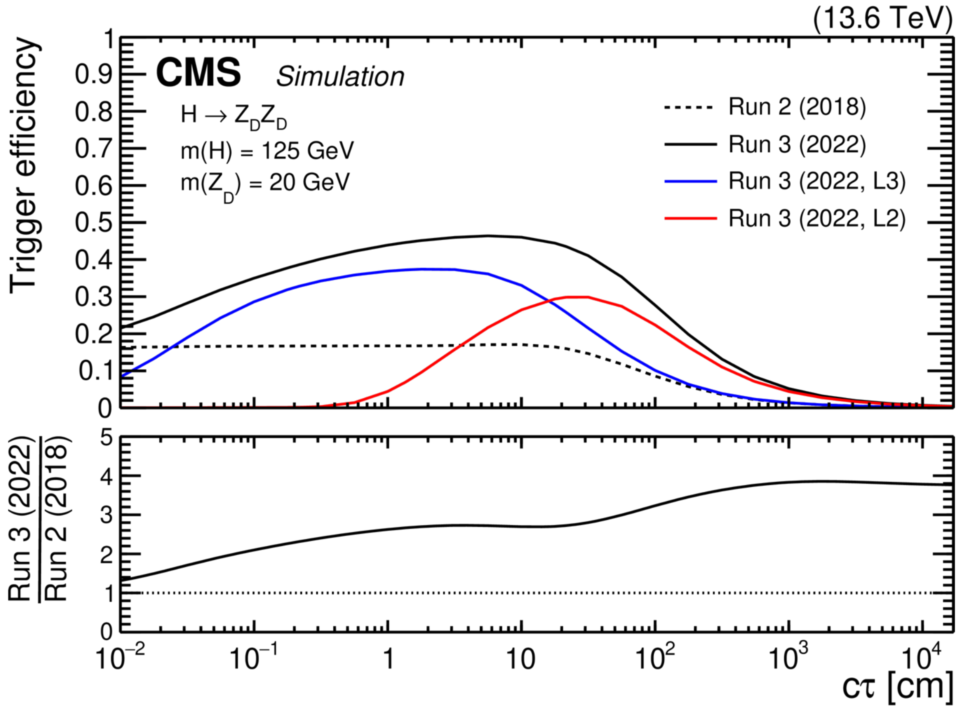
From A. Escalante @ICTEA Seminar

JHEP 05 (2024) 047

Displaced dimuons at 13.6 TeV. New triggers

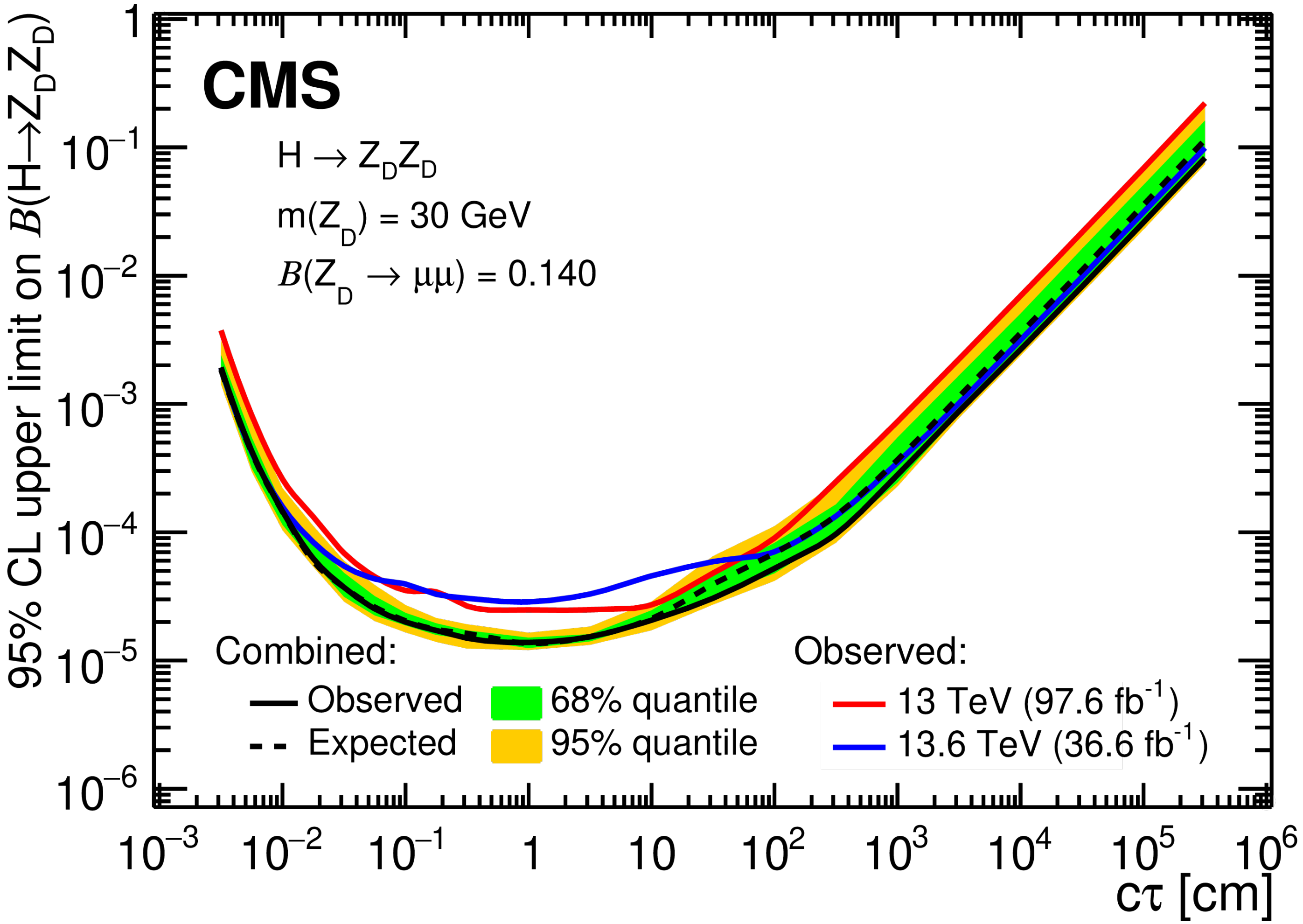
- Use the 2022 dataset (**36.7 fb^{-1}**) recorded with **new LLP triggers** with thresholds **down to $p_T(\mu)$ > 10 GeV**
  - Re-optimized L1 triggers, including p_T without beam spot constraint, and new reconstruction algorithms.
  - Use d_{xy} information at trigger level to control the background rate.
- **Factor 2-4 more signal efficiency**





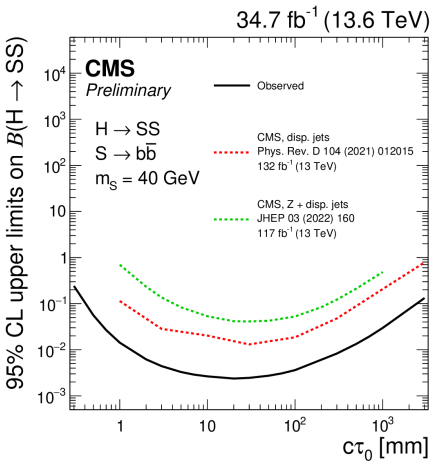
Displaced dimuons at 13.6 TeV

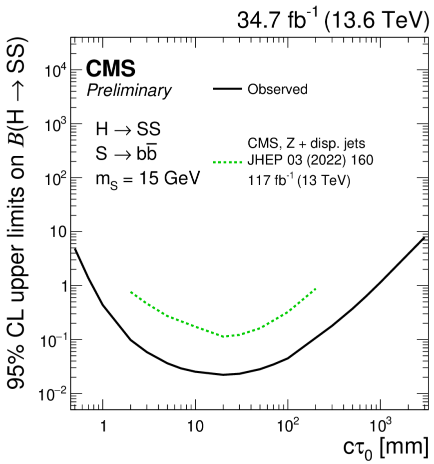
Despite **2.5 smaller dataset**, comparable (or better) sensitivity w.r.t. 13 TeV result.

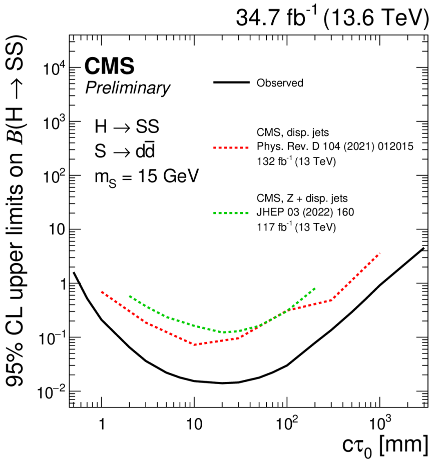


Displaced jets at 13.6 TeV

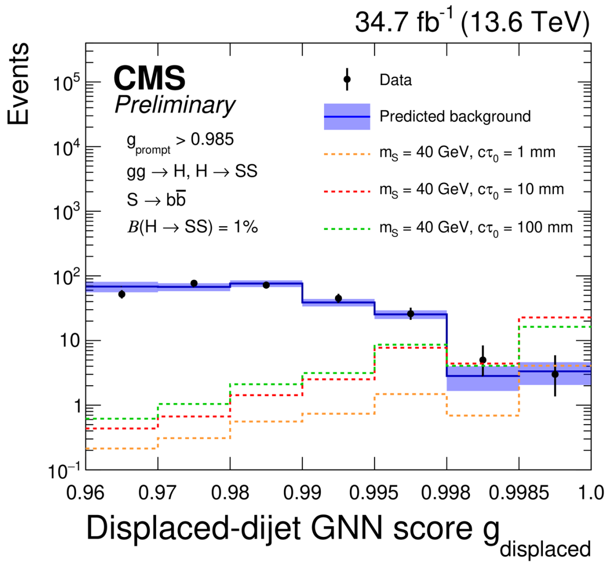
Despite **2.5 smaller dataset**, up to factor 10 improvement.







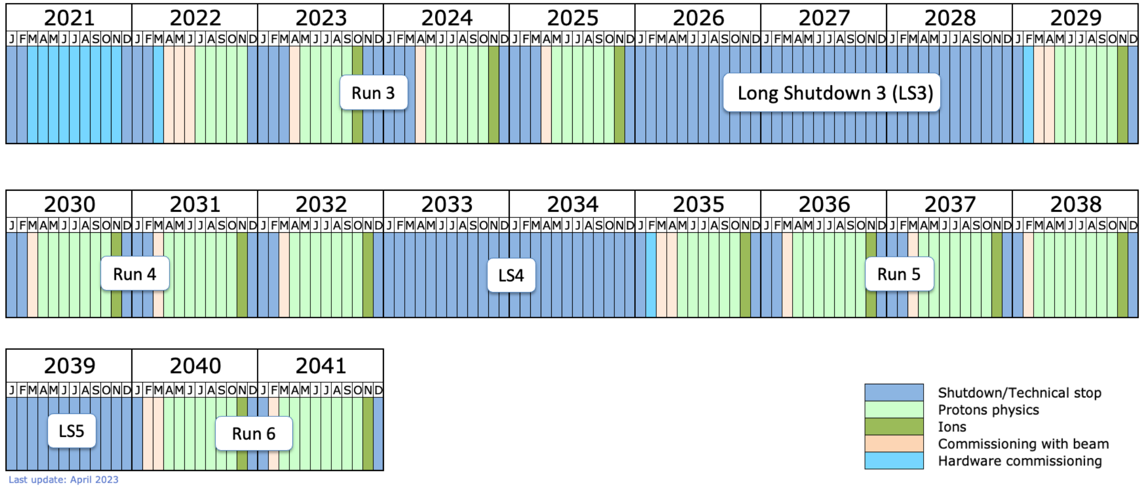
- **Improved trigger strategy:** 4-17 times larger signal acceptance
- **Improved analysis strategy,** using GNNs as taggers to identify dijets arising from LLP decays
  - Using displaced track features and info from the displaced vertex
  - the displaced tagger achieves a background rejection factor of 10^4 when the signal efficiency is ~55%

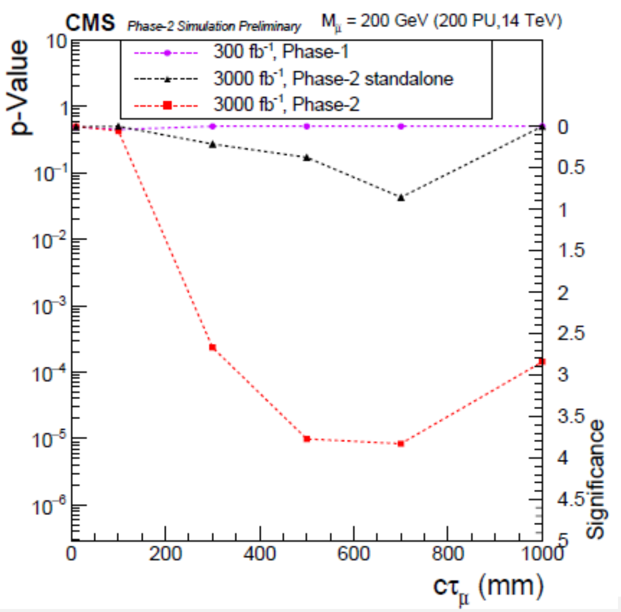


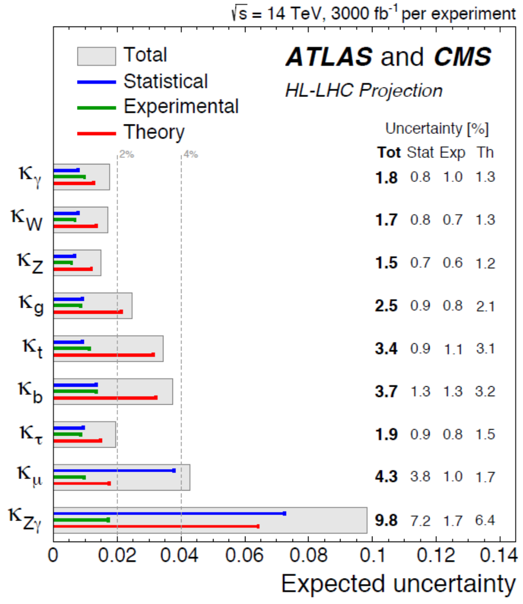
[CERN–LPCC–2019–01]

Towards the HL-LHC

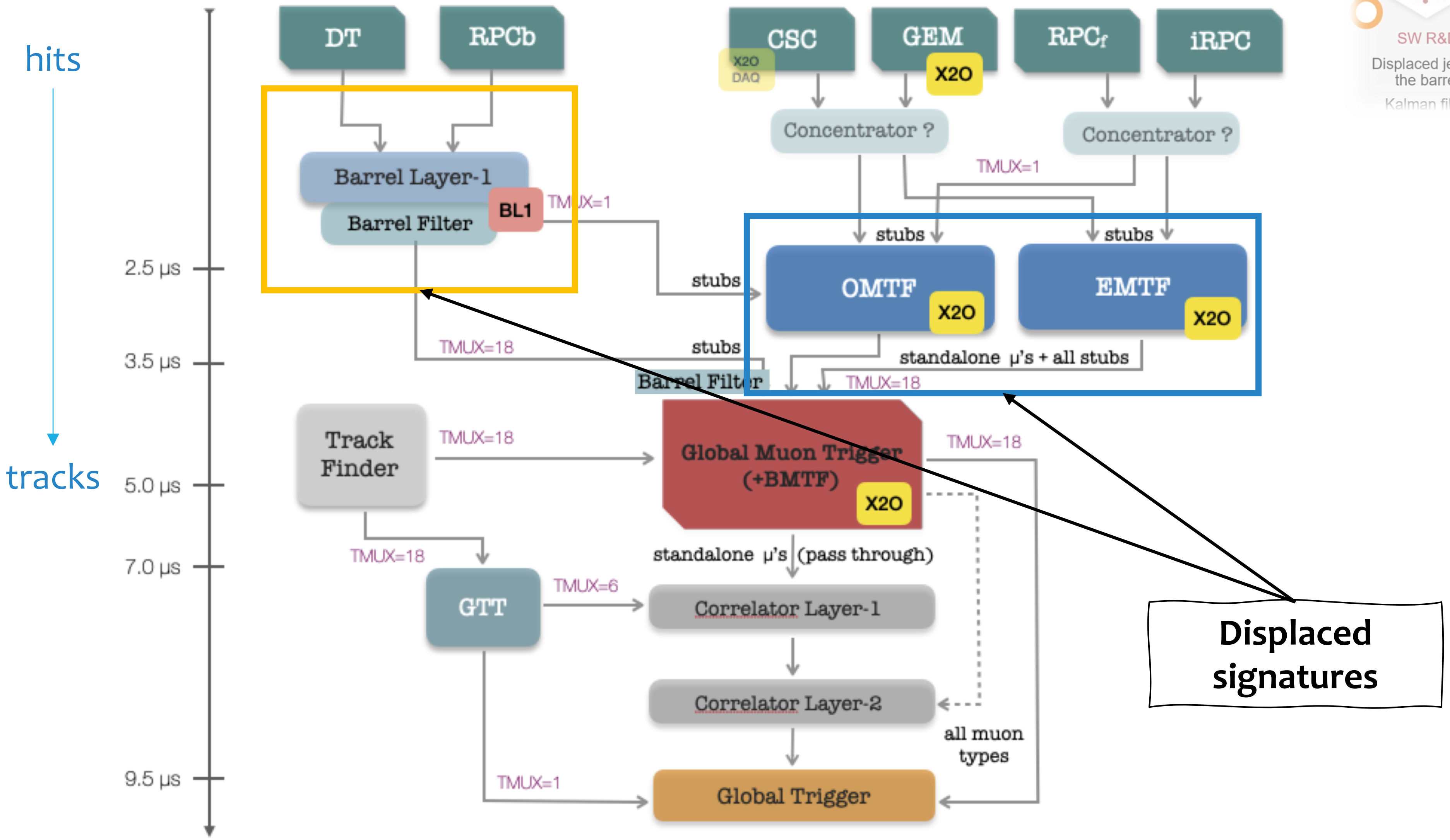
- **Preparing for the big upgrade** of the LHC detectors, starting 2029.
- HL-LHC upgrade offers an **unprecedented opportunity** to explore uncharted lands and achieve scientific progress.
- 10 times more data to what we will have by the end of Run 3 will facilitate a rich physics program.
- **Extend reach of new physics searches**: unexplored signatures (LLPs, HSCPs…) or regions of the phase-space will be within reach.
- **Improve current understanding of the SM and Higgs** sector by improving existing precision measurements and accessing rare decays ($H \rightarrow \mu\mu$) or production modes (HH) previously unseen at the LHC.
- However, this physics program will have to overcome **significant challenges** to succeed.

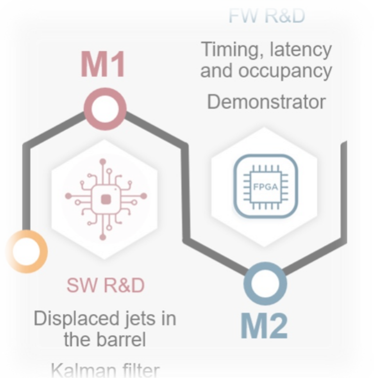






Improve muon triggers using the existing architecture





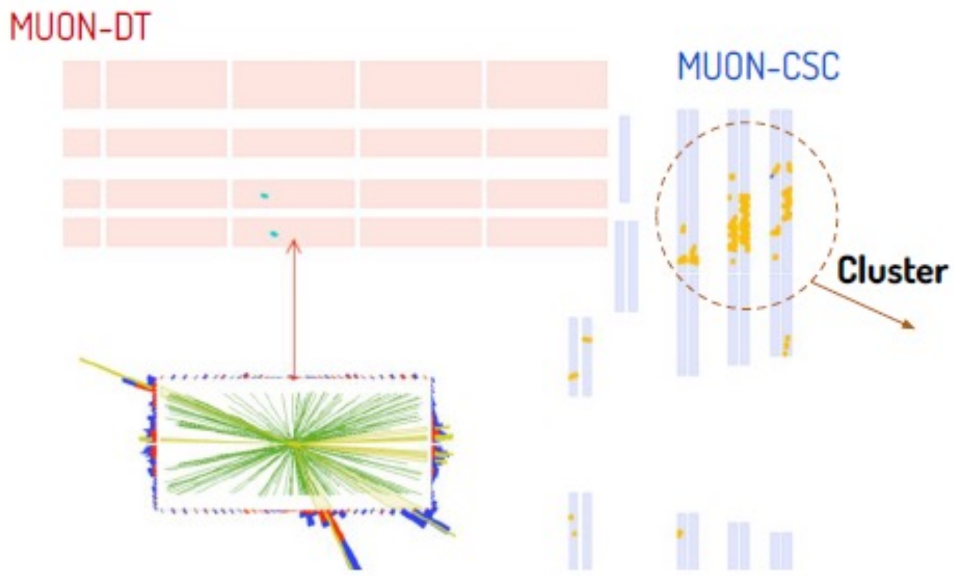
Extending LLPs coverage (yet in Run-3)

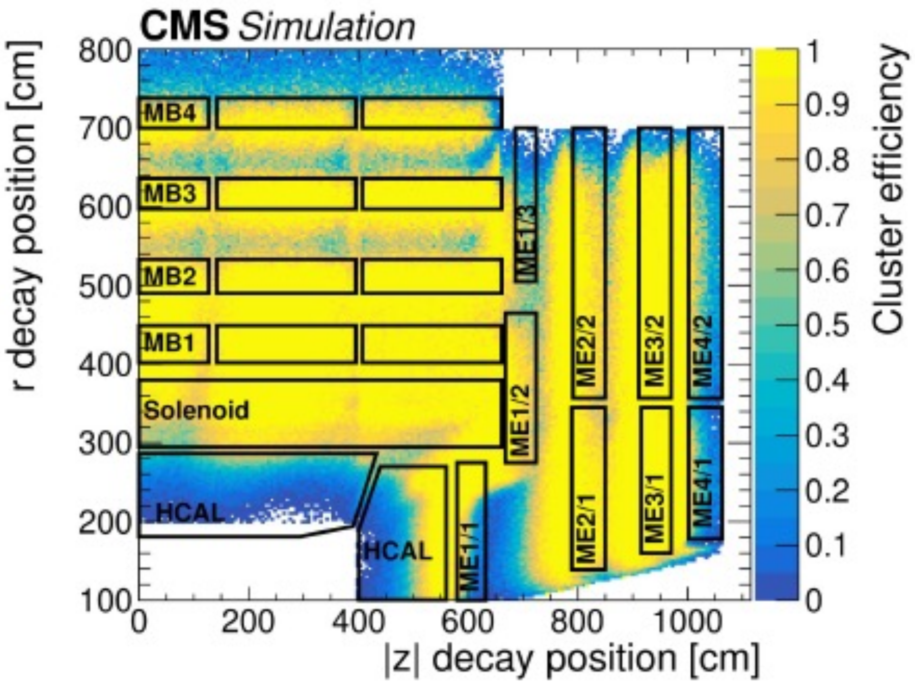
Hadronic showers in muon detectors

EXO-21-008

Target hadronic LLP decays in the muon system

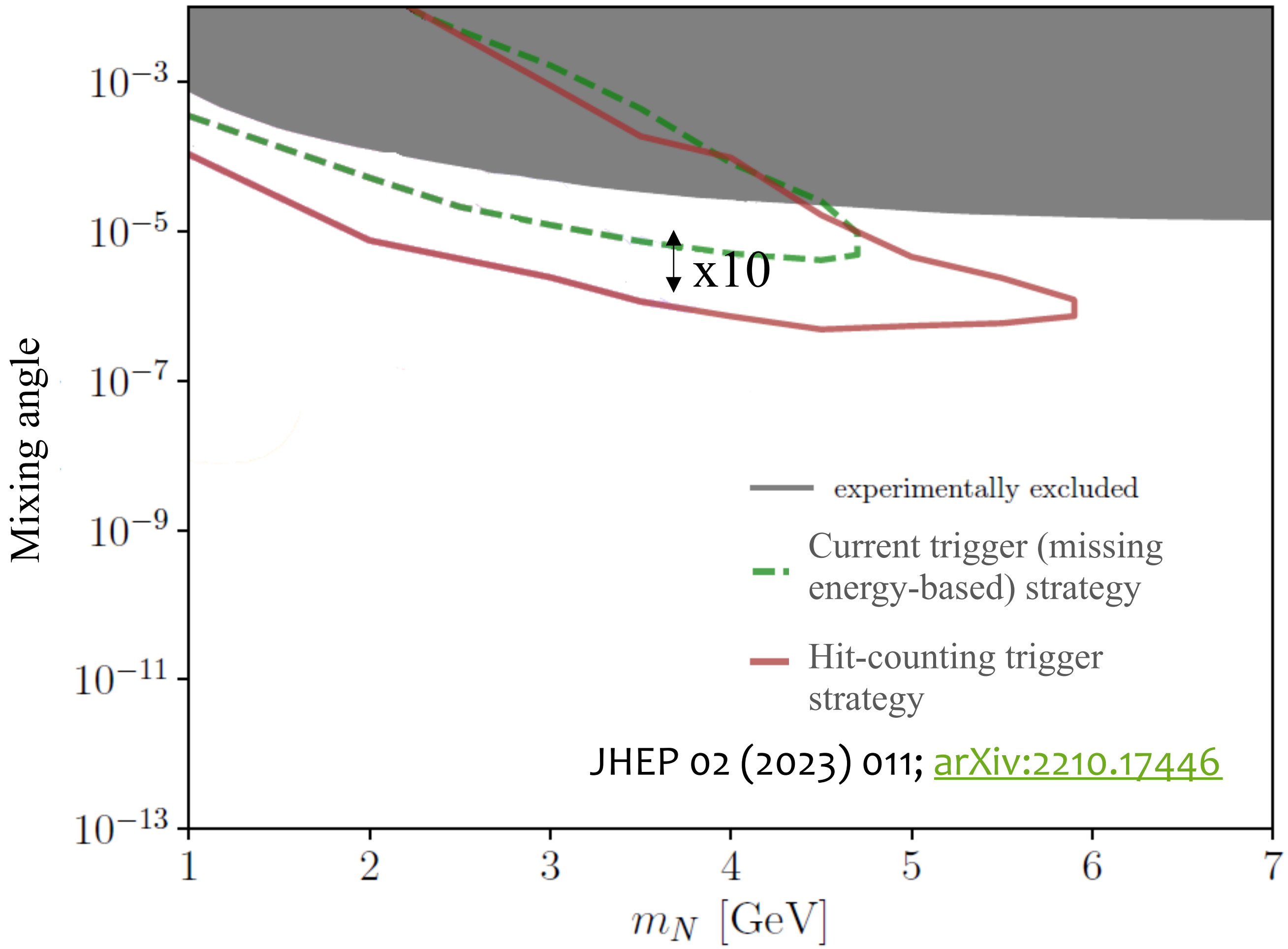
- **Large hit multiplicity in DT or CSC**



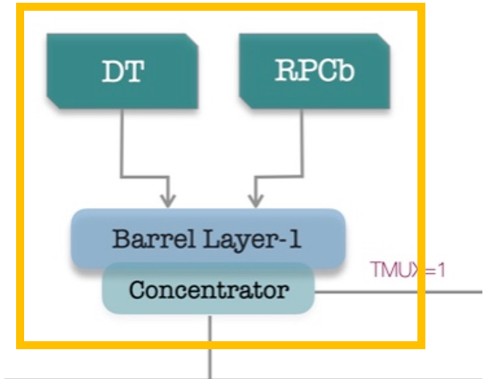


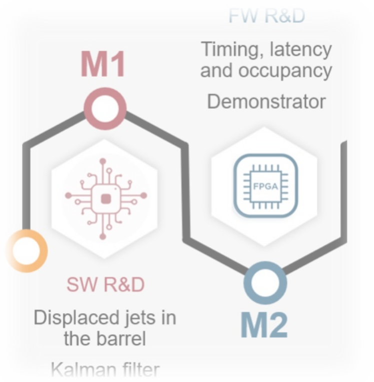
Use N_{hits} in the cluster as discriminant variable

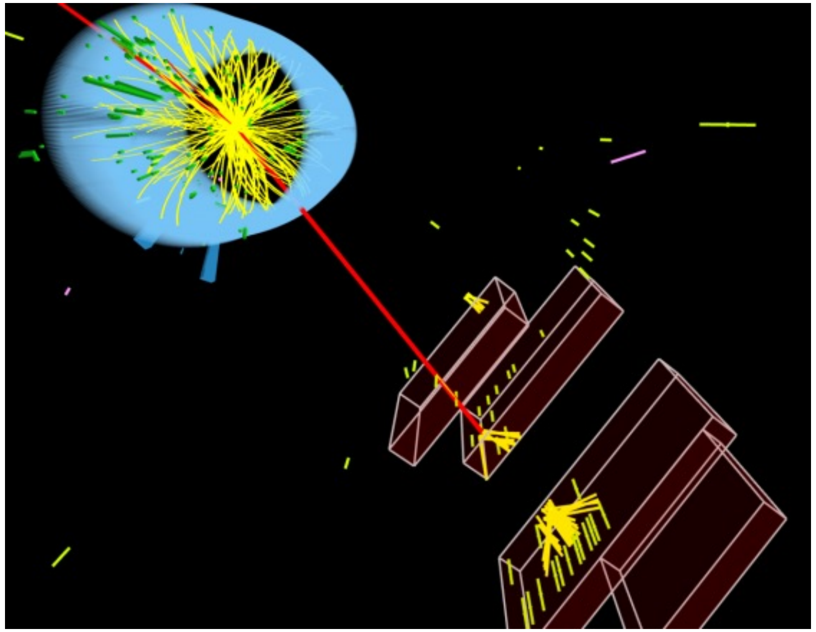
Reconstruction of muon showers



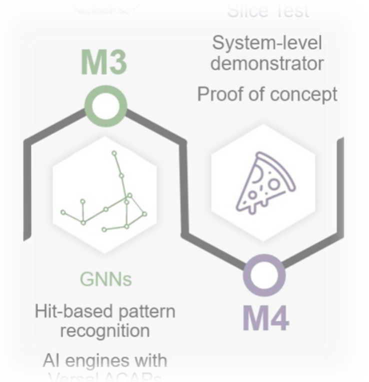
JHEP 02 (2023) 011; arXiv:2210.17446

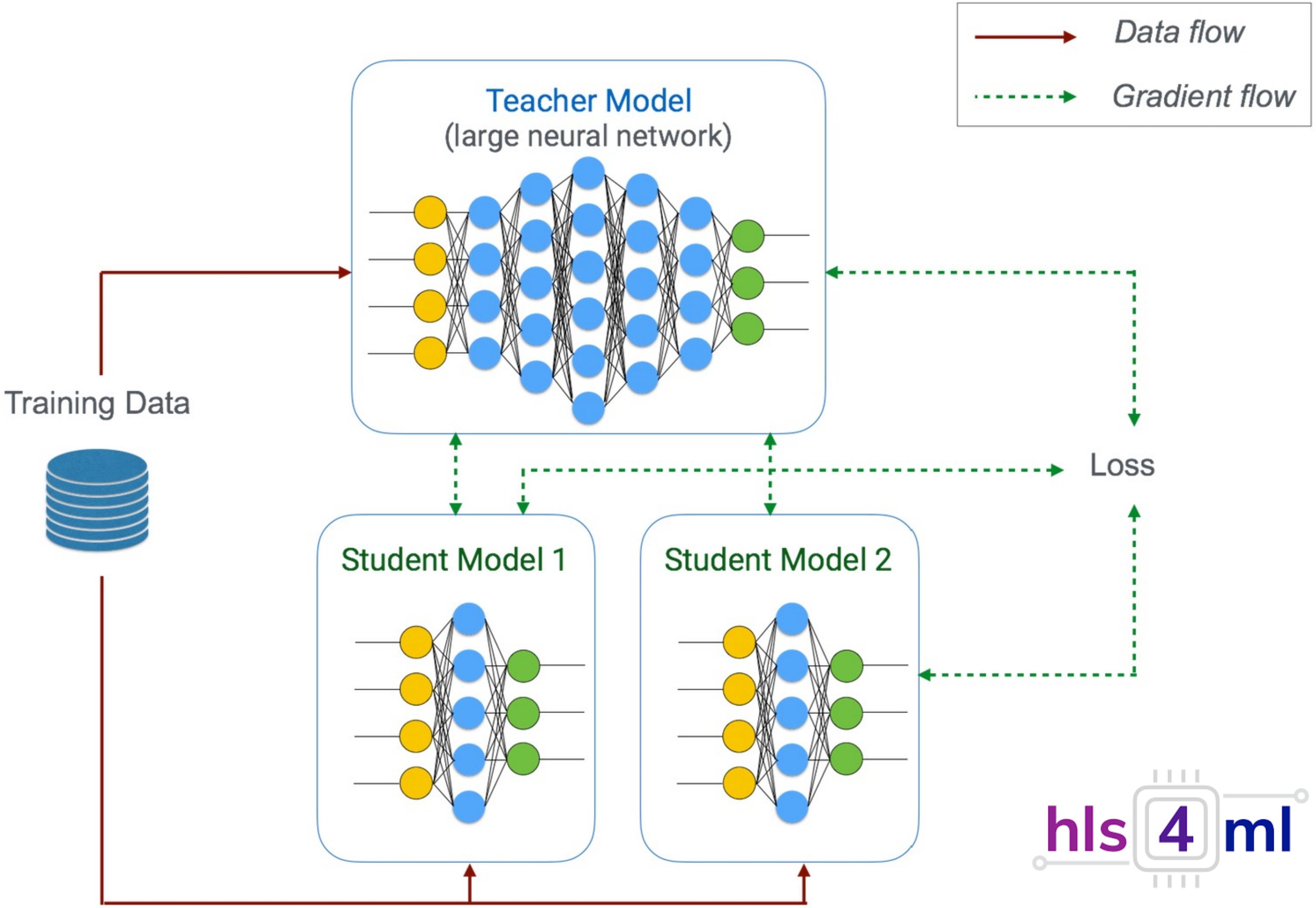




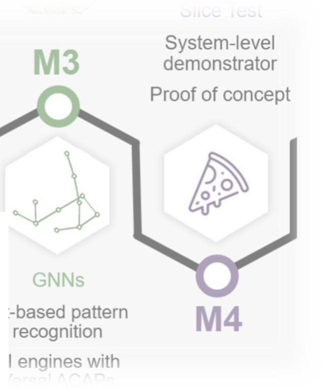


Graph Neural Networks for real-time muon reconstruction





Graph Neural Networks for particle reconstruction

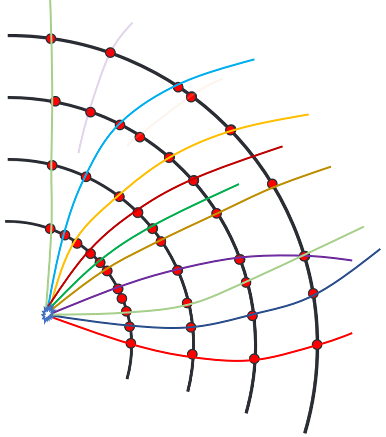


Representing tracking data using graphs

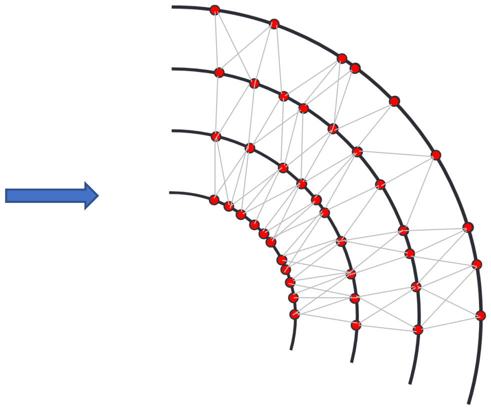
F. Siklér, "Combination of various data analysis techniques for efficient track reconstruction in very high multiplicity events", *Connecting the Dots* conference 2017 (link)

S. Farrell *et al.*, "Novel deep learning methods for track reconstruction", proceedings of *Connecting the Dots* conference 2018 (link)

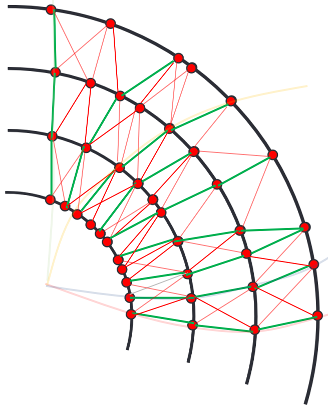
Charged particles leave hits in the detector



Represent the data using a graph



Goal:
classify the edges of the graph



High classification score
=> **high probability** that the edge is part of a track

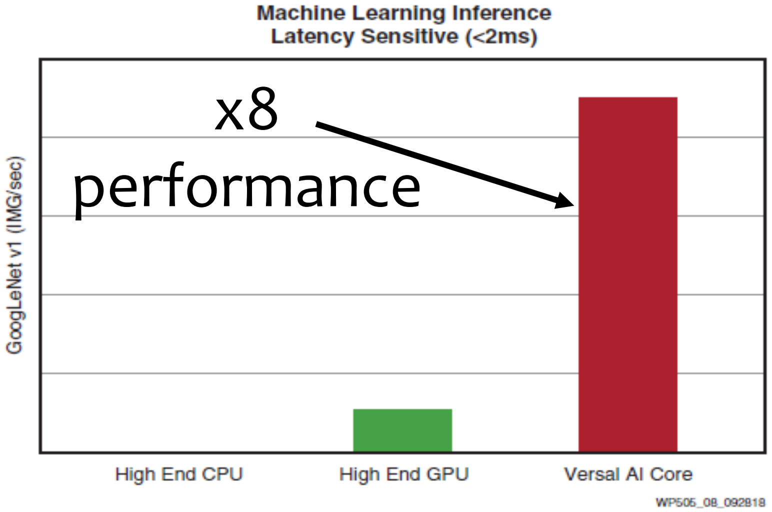
Low classification score
=> **low probability** that the edge is part of a track

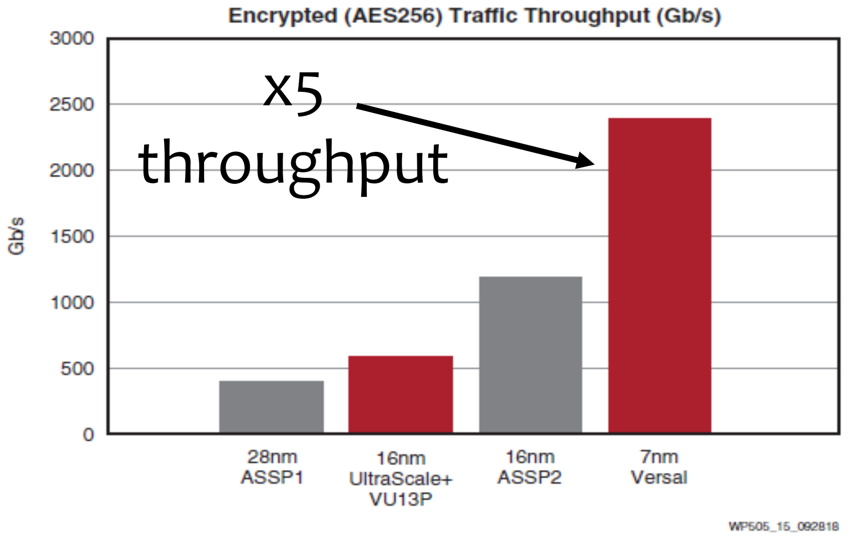
One node of the graph = one hit in the detector

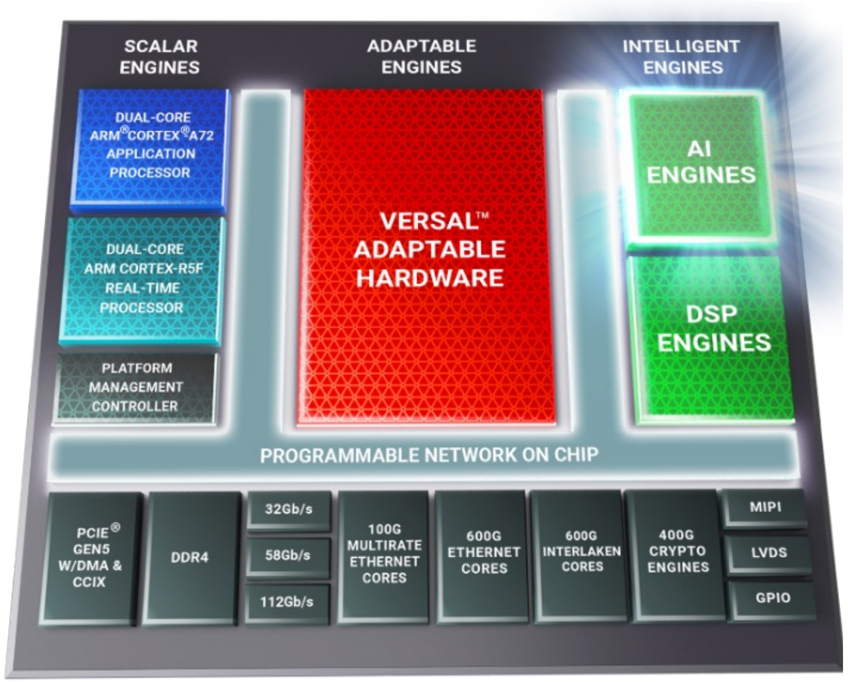
Connect two nodes using an edge
if "it seems possible" that the two hits are two (consecutive) hits on a track

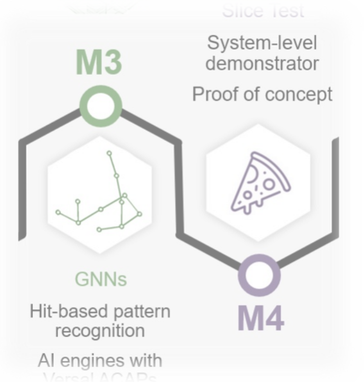
Explore capabilities of AI-engines

Provide the necessary throughput and latency for triggering?





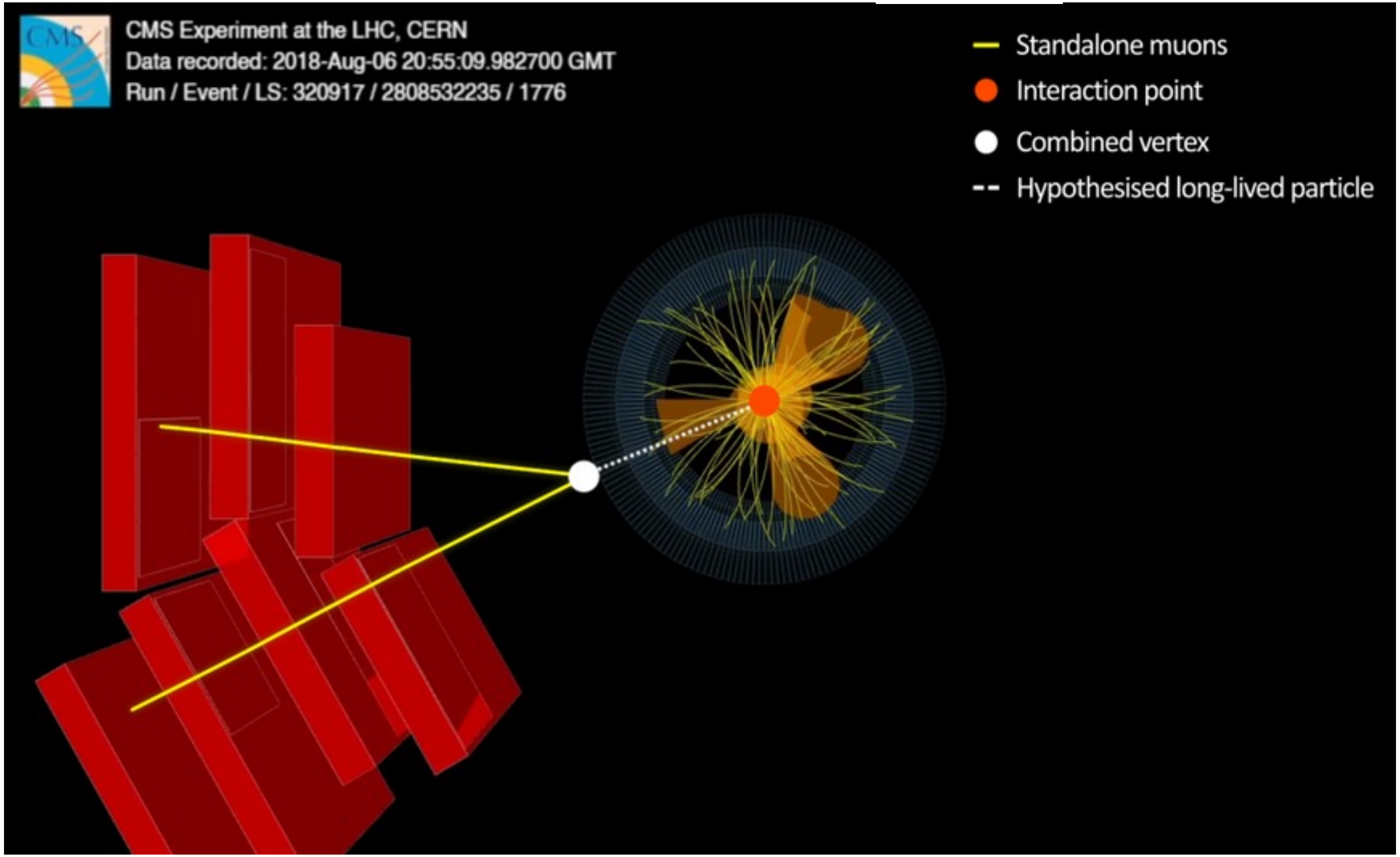




Thanks for listening!

Foreseen **improvements** on detection efficiency and **triggering** might allow the **discovery of BSM physics.**

Provide an **answer to fundamental questions of nature.**



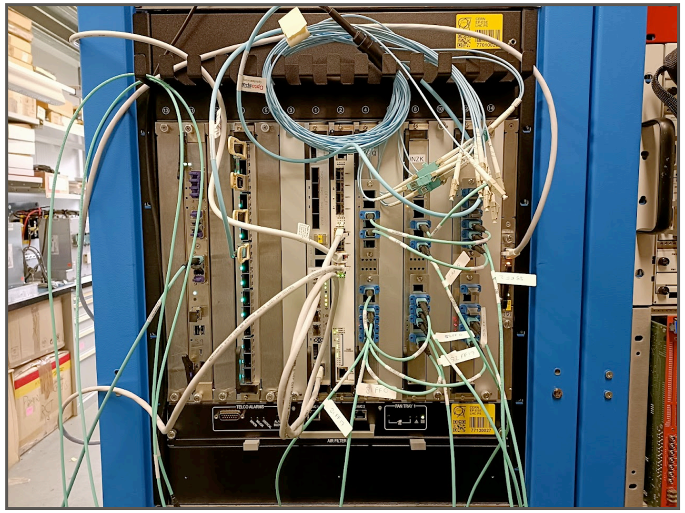
backup

Our demonstrator

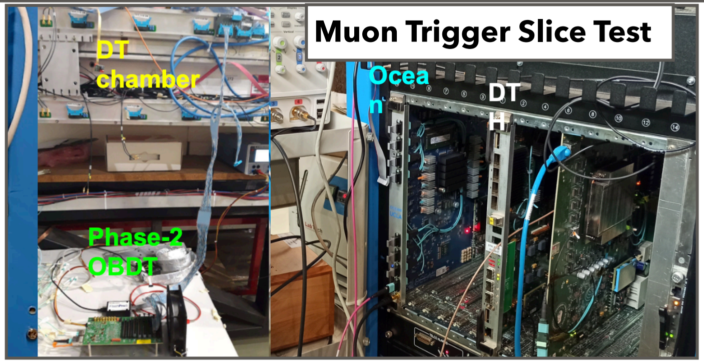
TESTING AND SYSTEM DEMONSTRATION

Phase-2 Level-1 Trigger system demonstration

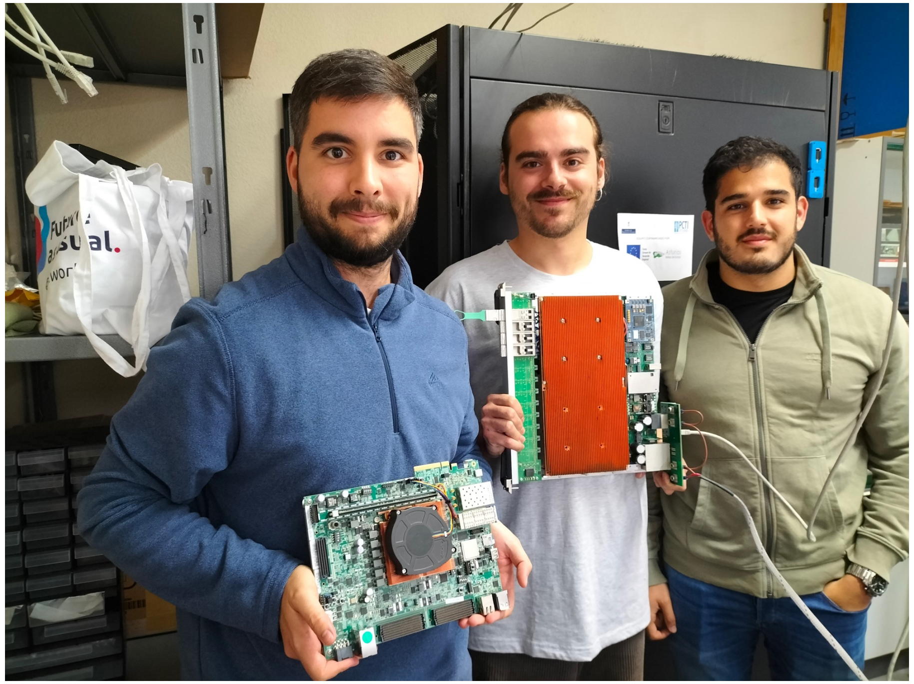
- Single-board and multiple board tests performed
- Integration centers across the globe: larger scale integration @ CERN (904). Multiple flavour board tests.
- Slice test in Muon Barrel Trigger during Run-3. Installation @P5: DT–>BMT–>GMT–>GT
- **Board interconnection: protocol**
  - Links (asynchronous) operation @ 25.78 Gb/s
  - L1 Trigger boards sending packets only once (no retransmission) → error proof
  - Protocols (64/66b or 64/67b) encoding achieved low error rate, validated recovery mechanism etc.



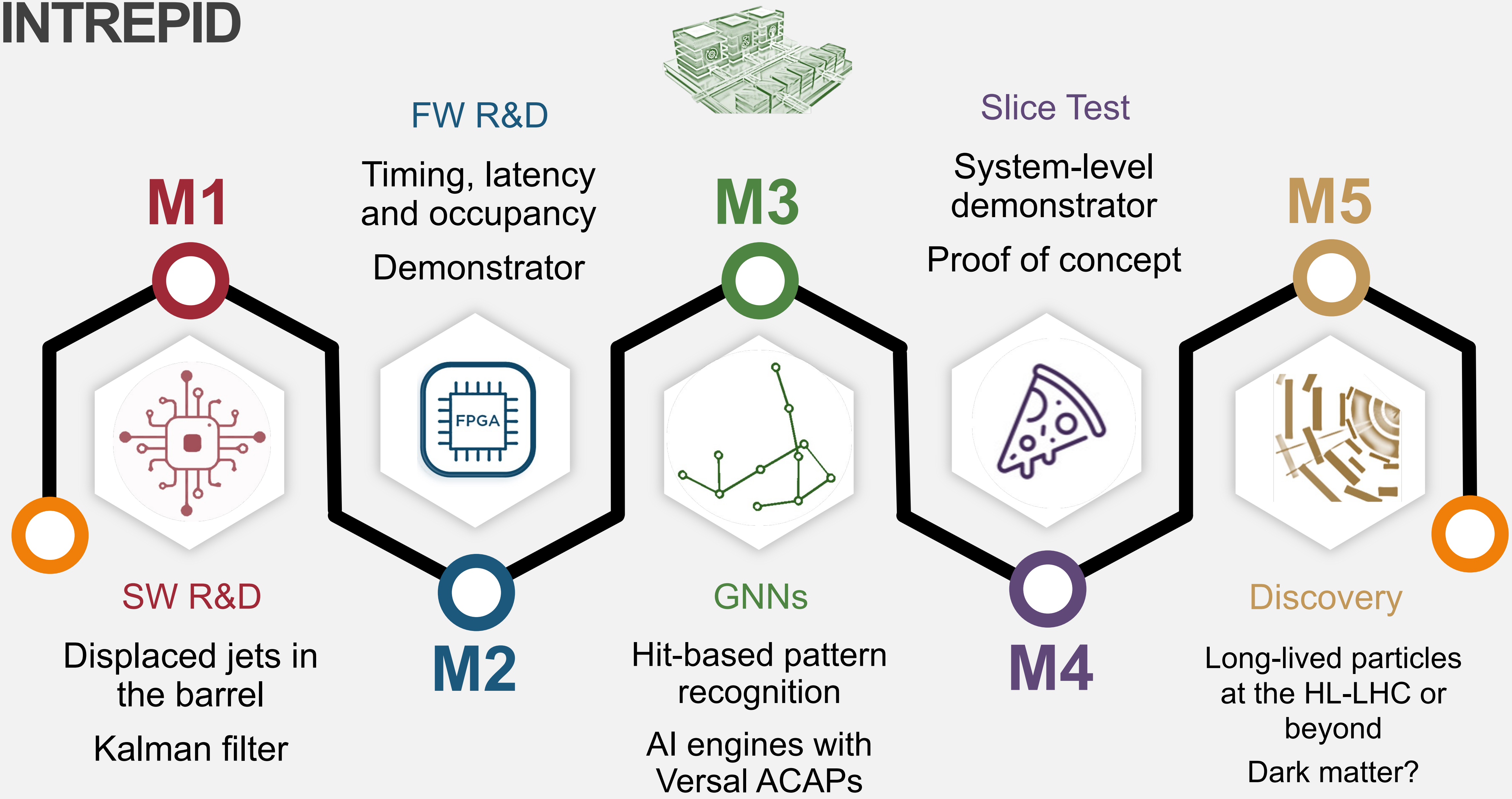
Building 904 @ CERN



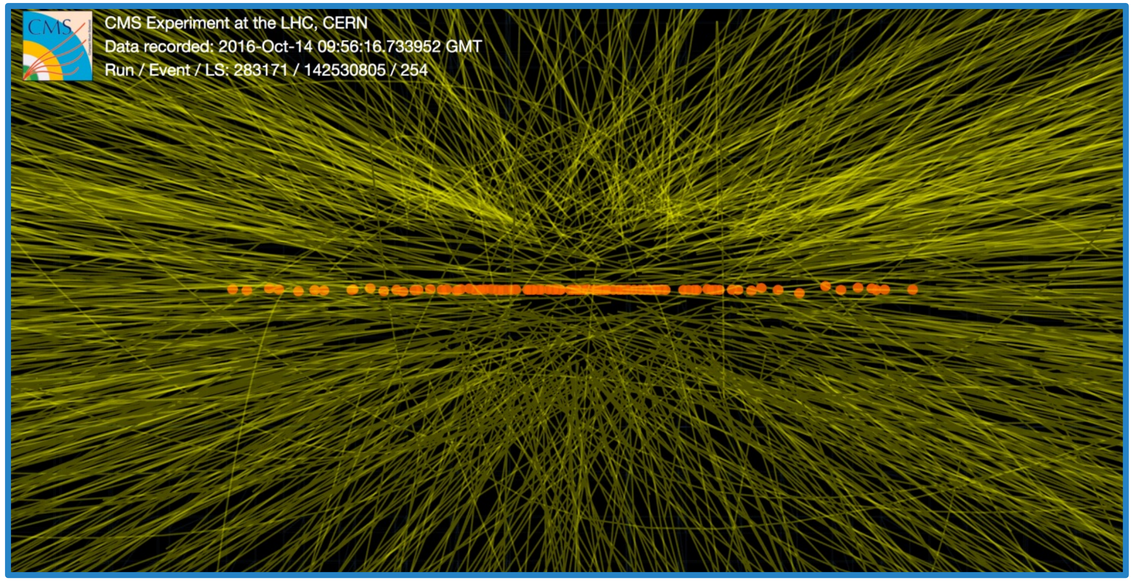
Muon Trigger Slice Test

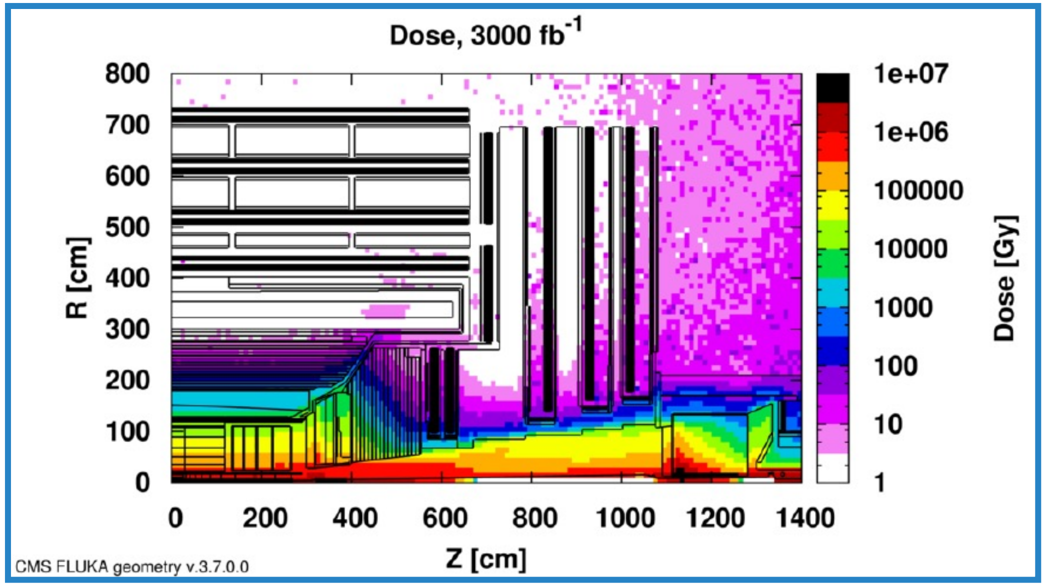


INTREPID


M1
SW R&D
Displaced jets in the barrel
Kalman filter
FW R&D
Timing, latency and occupancy
Demonstrator
FPGA
M2
M3
GNNs
Hit-based pattern recognition
AI engines with Versal ACAPs
Slice Test
System-level demonstrator
Proof of concept
M4
M5
Discovery
Long-lived particles at the HL-LHC or beyond
Dark matter?

HL-LHC: challenges

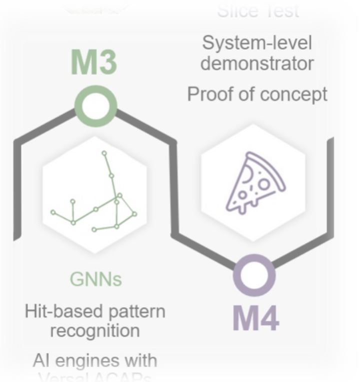




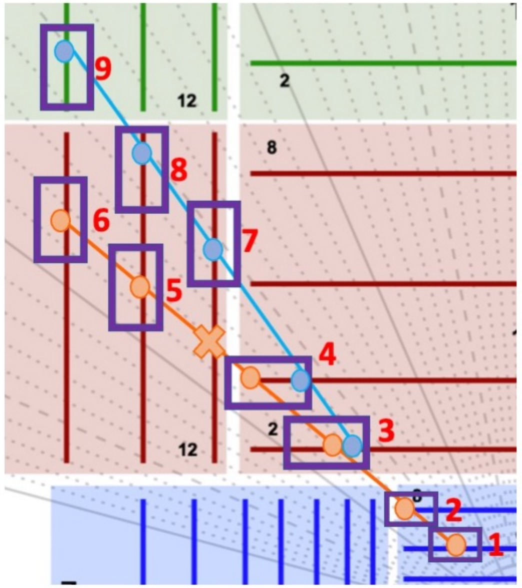
- **Expected pileup** (PU): ~140 (nominal HL-LHC lumi)
- Motivates/requires:
  - Improved granularity wherever possible
  - Novel approaches to in-time Pile Up mitigation: Precision Timing detectors (30ps)
  - A complete renovation of the Trigger and DAQ systems for better selectiveness, despite the high PU.

- **Radiation damage / accumulated dose** in detectors and on-board electronics may result in a progressive degradation of the performance.
- Maintain detector performance in harsh conditions:
  - The complete replacement of the Tracker and Endcap Calorimeter systems.
  - Major electronics overhaul and consolidation of the Barrel Calorimeters and Muon systems

Graph building techniques



Particles leaving hits



Done once

Module map creation

- 1 → 2
- 2 → 3
- 3 → 4
- 4 → 5
- 4 → 7
- 5 → 6
- 7 → 8
- 8 → 9

For event reconstruction

Graph creation