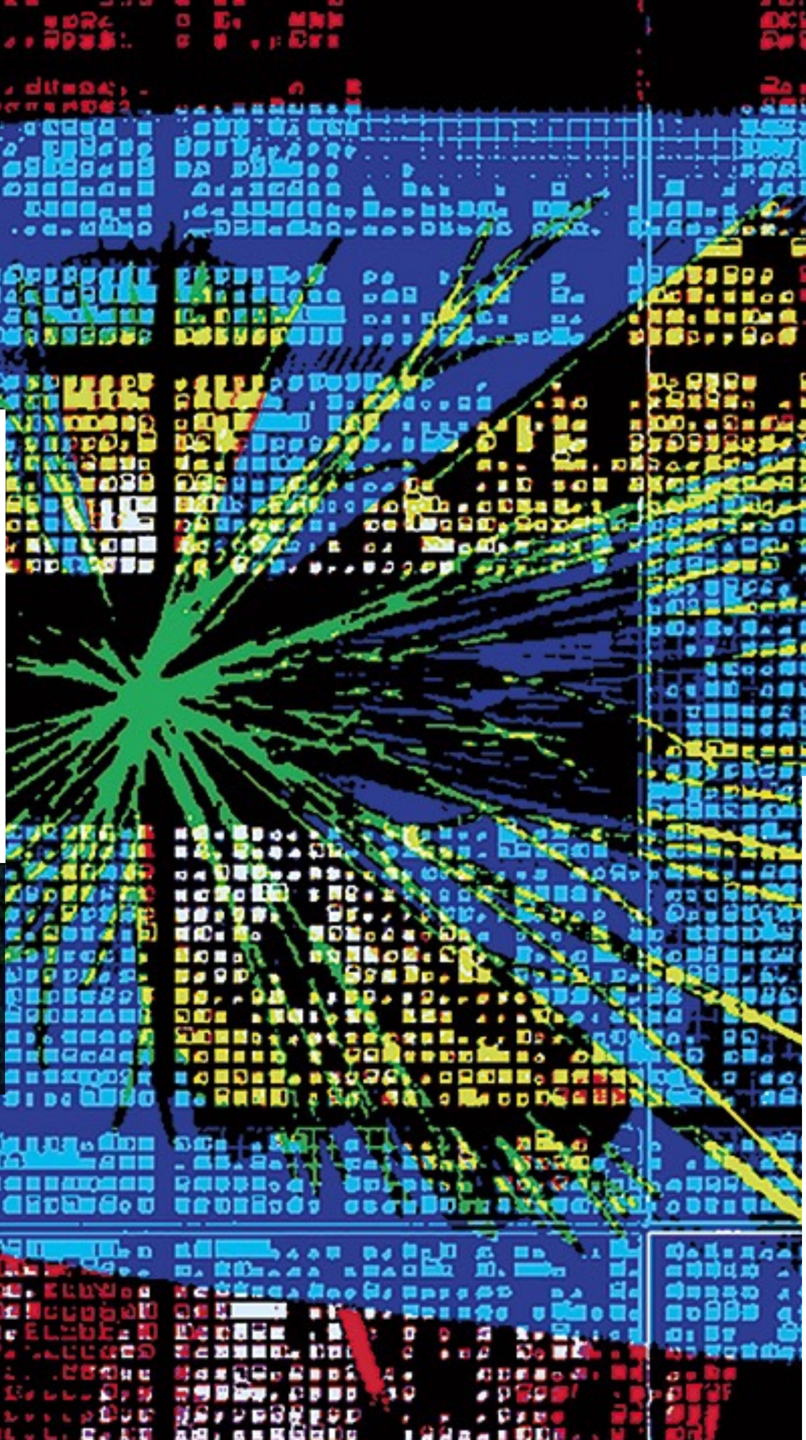
INnovative TRiggEr techniques for beyond the standard model PhysIcs Discovery at the LHC

INTREPID | ERC-StG2023

Santiago Folgueras



Funded by the European Union

European Research Council
Established by the European Commission

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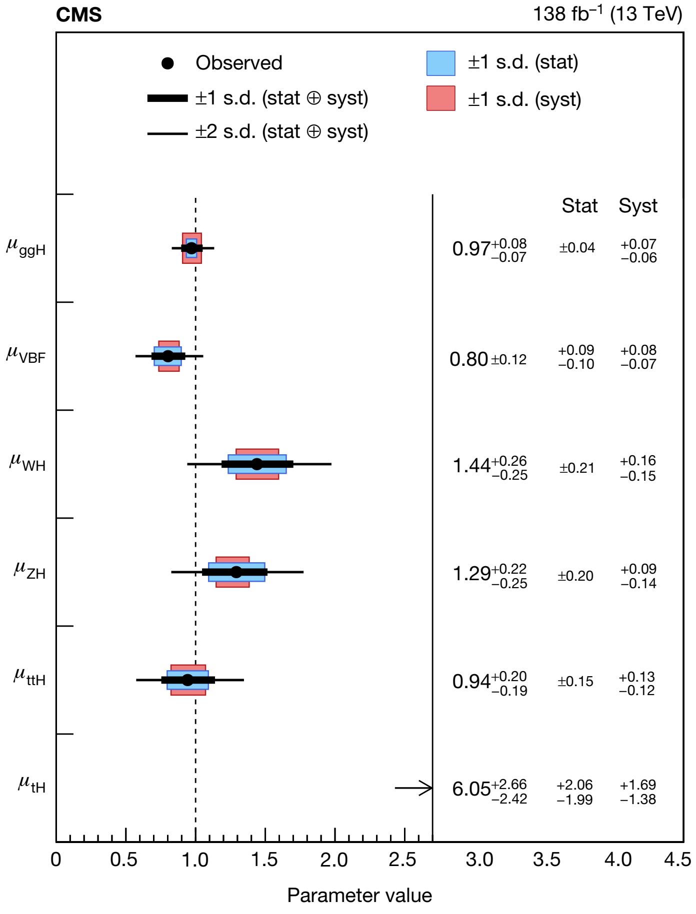
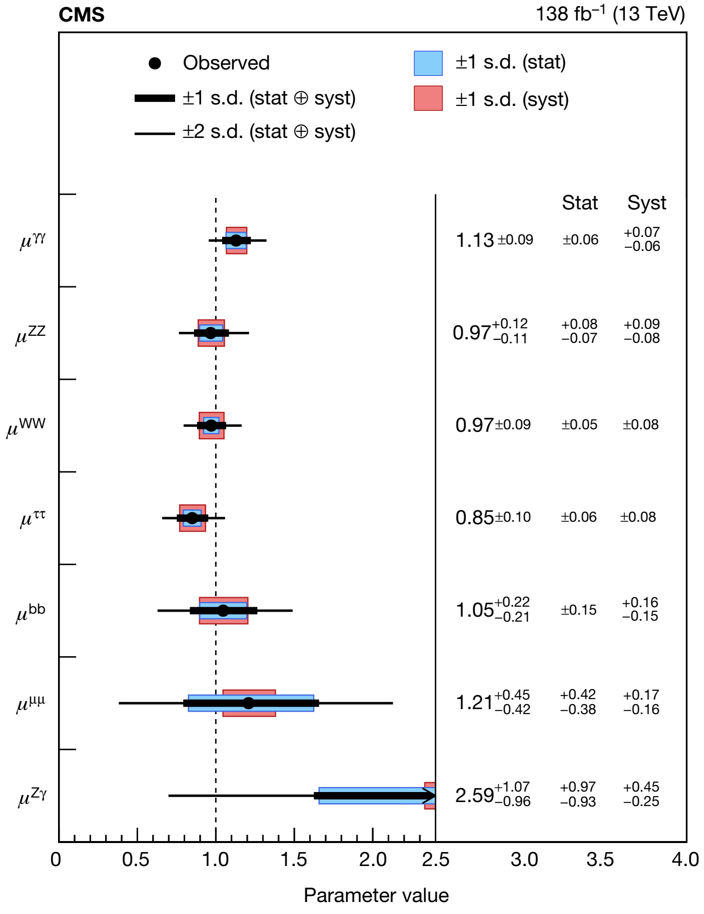
Higgs boson discovery

What's next?

Nature 607, 60–68 (2022)





- After the discovery in 2012, many studies to characterize the Higgs boson nature:
  - Decay channels, production modes, couplings…

What's next?

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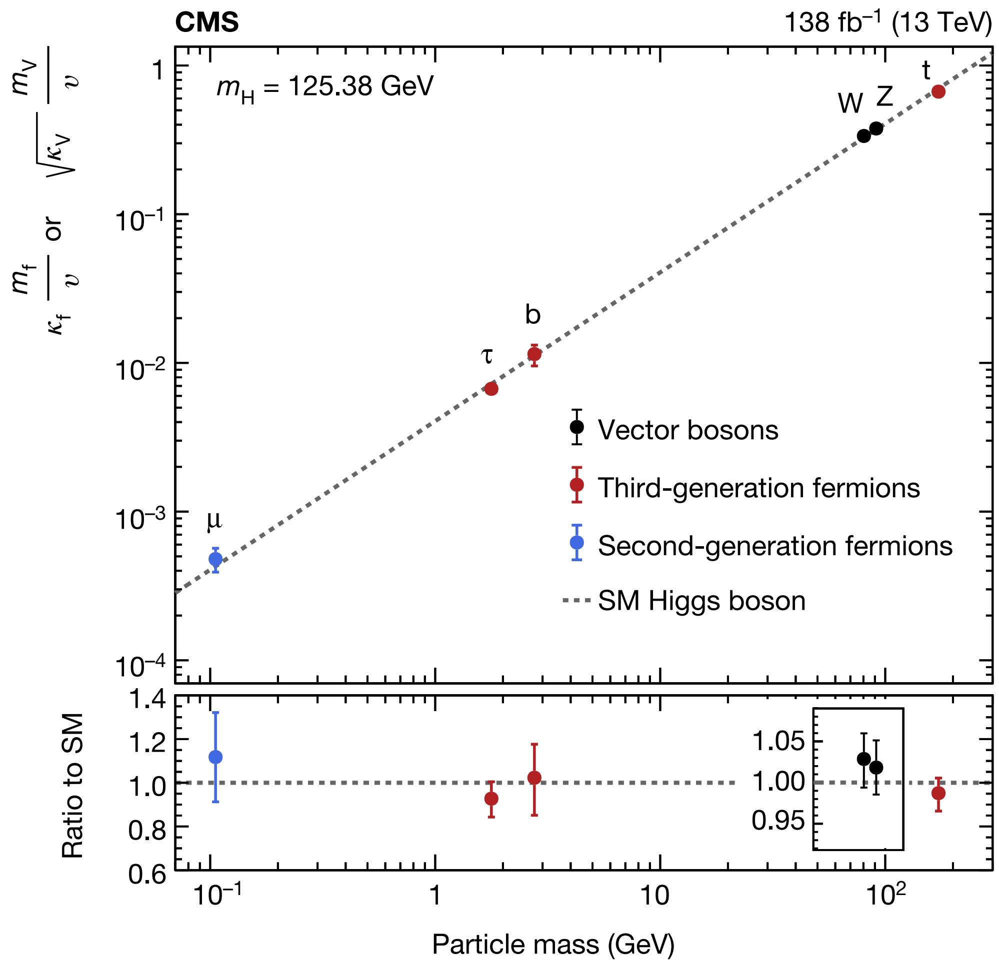


- After the discovery in 2012, many studies to characterize the Higgs boson nature:
  - Decay channels, production modes, couplings…
- As of today, coupling to the W, Z and γ bosons, coupling to the **3rd generation of fermions (t, b, τ)** and first **evidence to a 2rd generation fermion (μ)**, have been observed.

A solution to the
hierarchy problem

Baryon asymmetry
in the Universe

Nature of
dark-matter

Nature of
neutrino masses

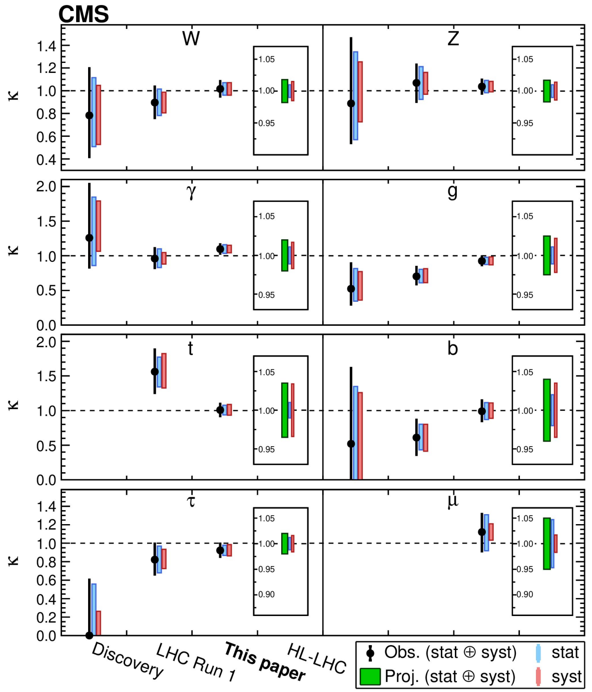
How to look for new physics?

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

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

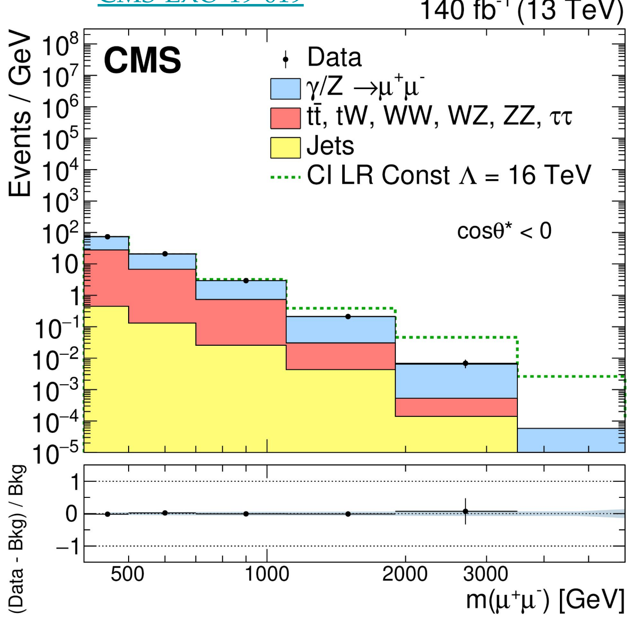
Search for deviations at high momenta (*i.e. Effective Field Theories*)

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



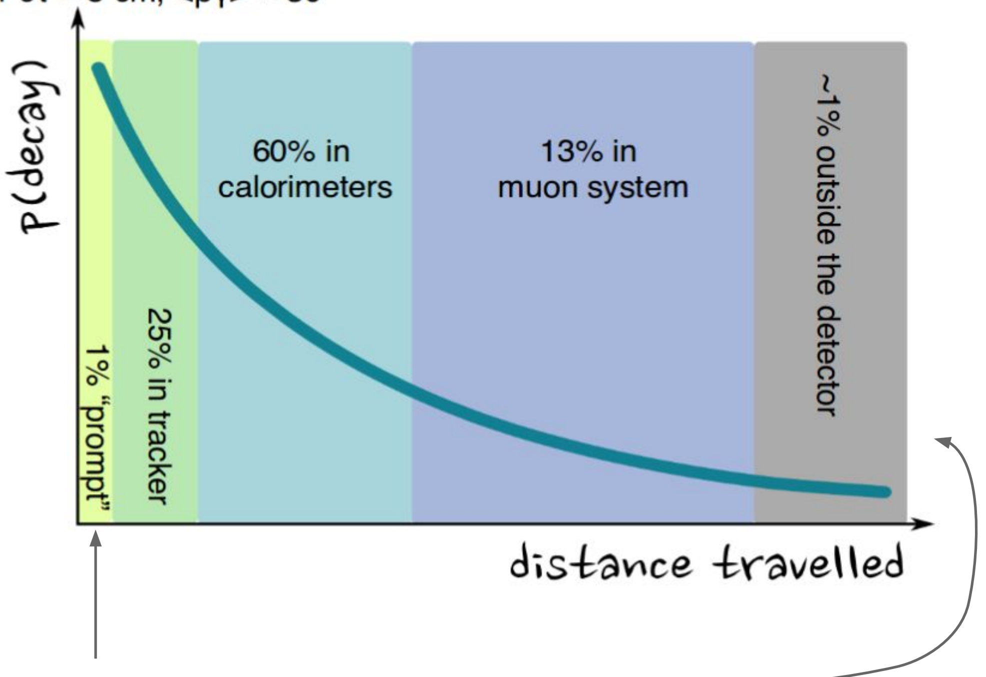
Nature 607, 60–68 (2022)

CMS-EXO-19-019



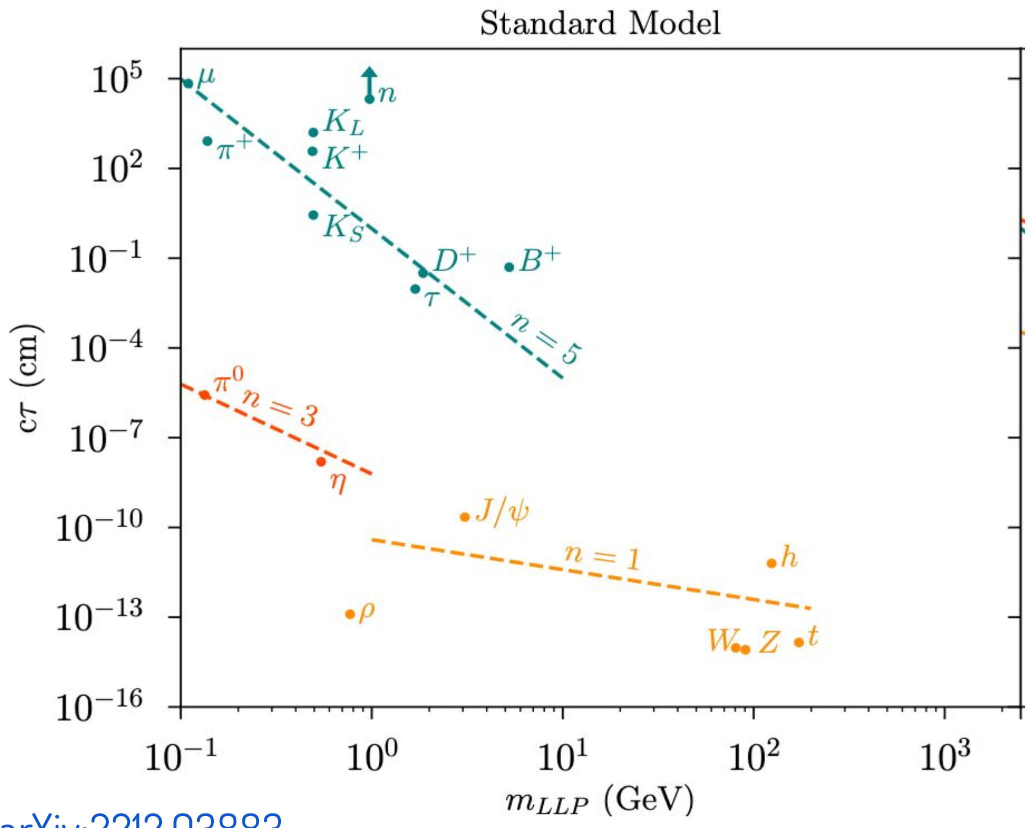
$$\mathcal{L}_{eff} = \mathcal{L}_{SM}^{(4)} + \sum \frac{C_x}{\Lambda^2} O_{6,x} + h.c.$$

e.g. for cτ = 5 cm, <βγ> ~ 30



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

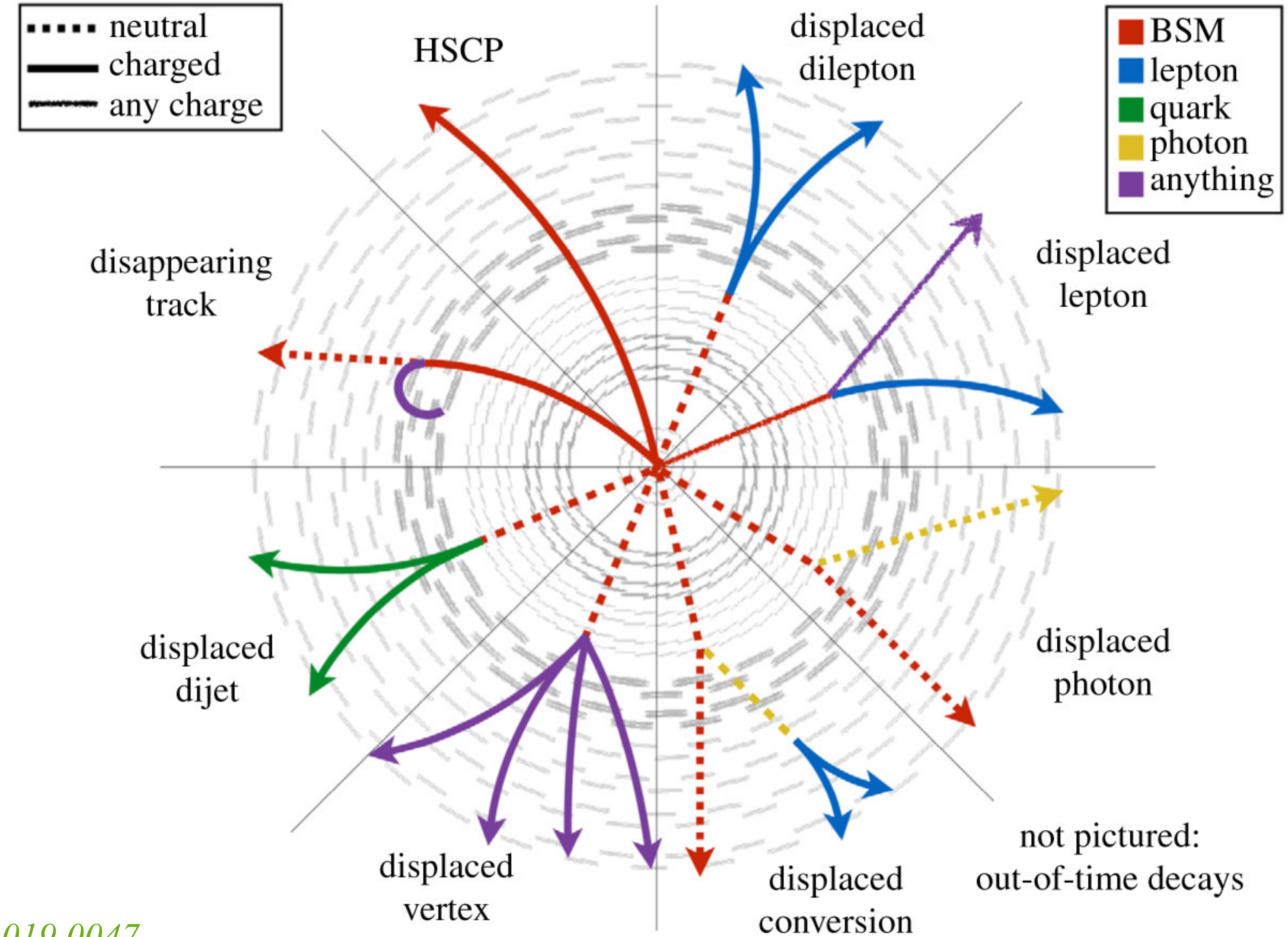
$$\Gamma \sim c^2 \left(\frac{\Delta m}{\Lambda}\right)^n \Delta m$$

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

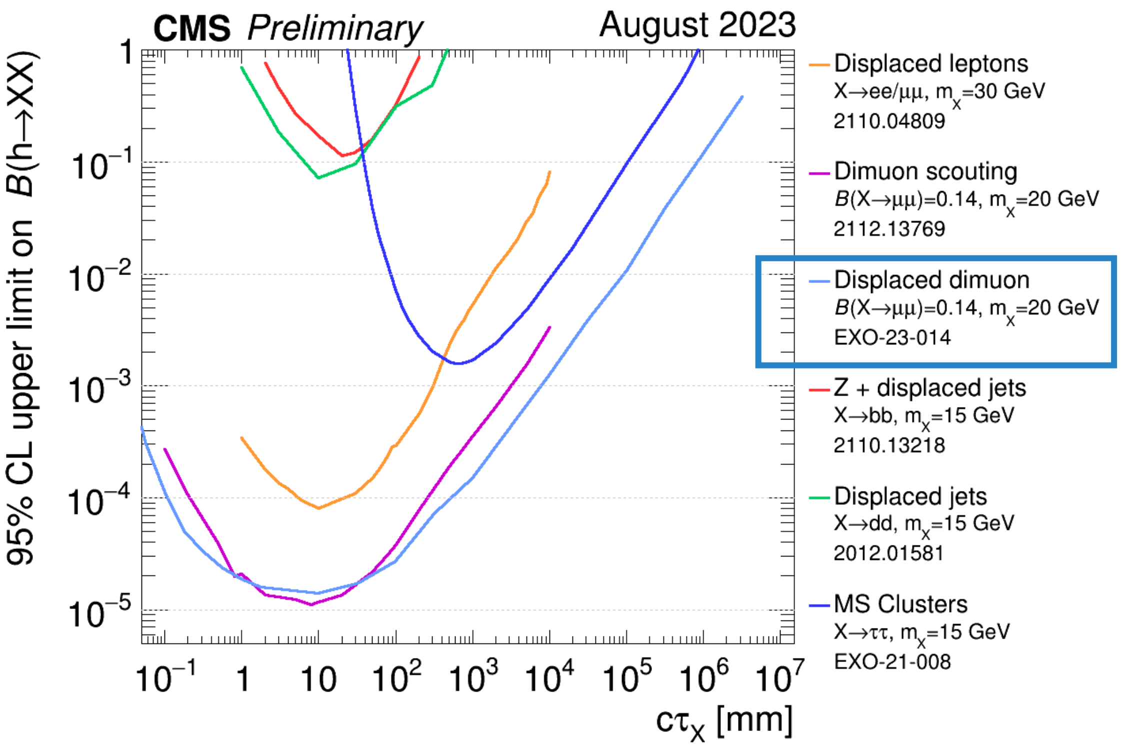
Experimental signatures of long-lived particles



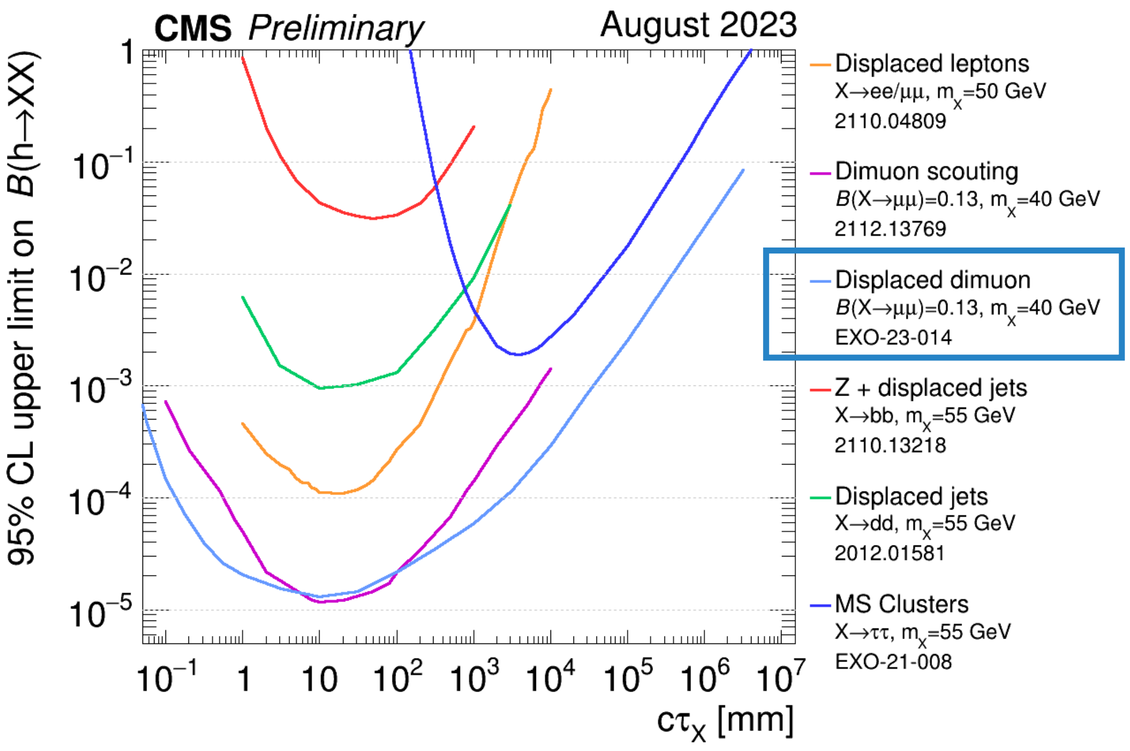
https://doi.org/10.1098/rsta.2019.0047

Searches for long-lived particles at the LHC

10 < m < 40 GeV



m > 40 GeV

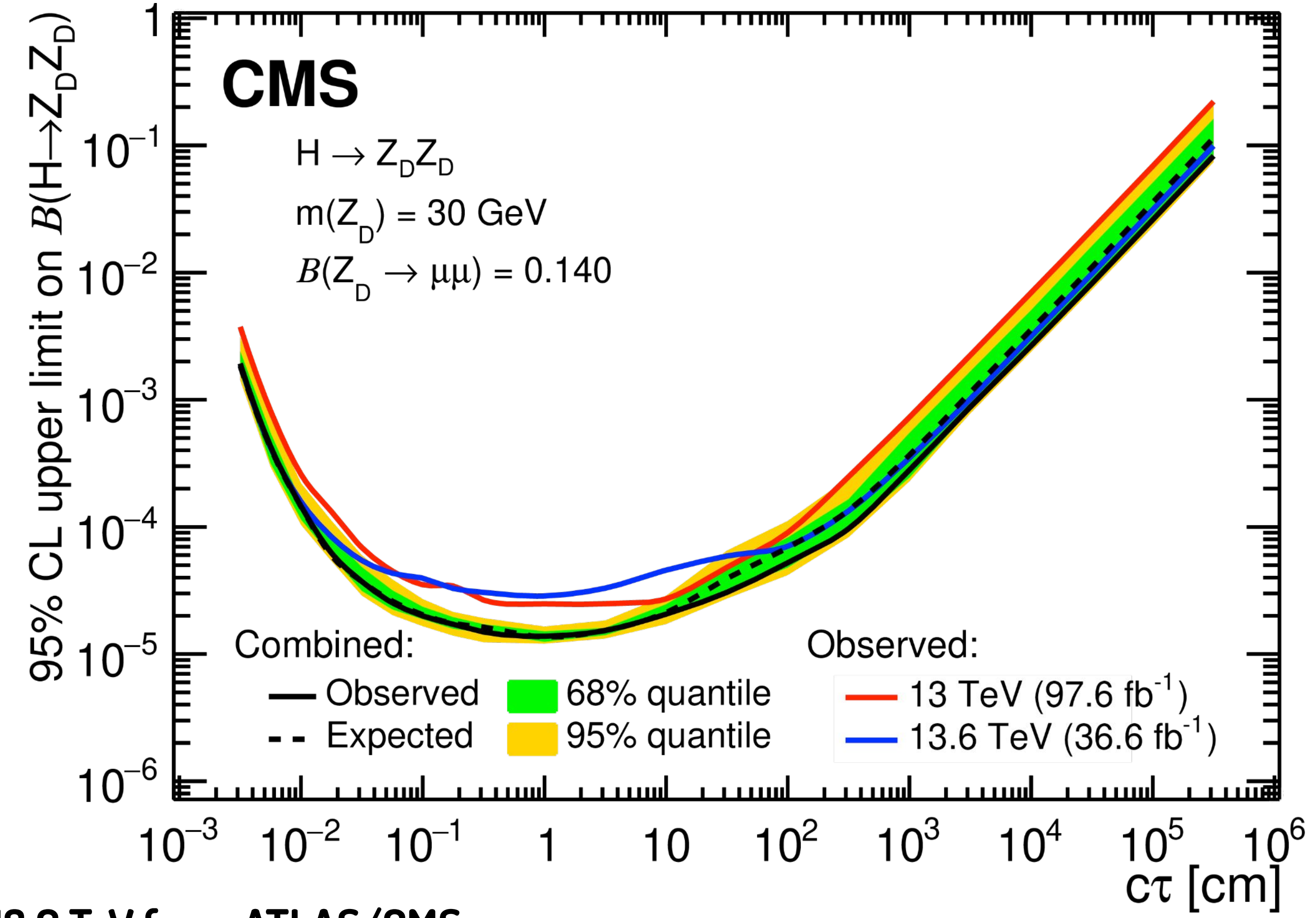


See Alejandro's talk yesterday

First successful story: Displaced dimuons at 13.6 TeV

EXO-23-014

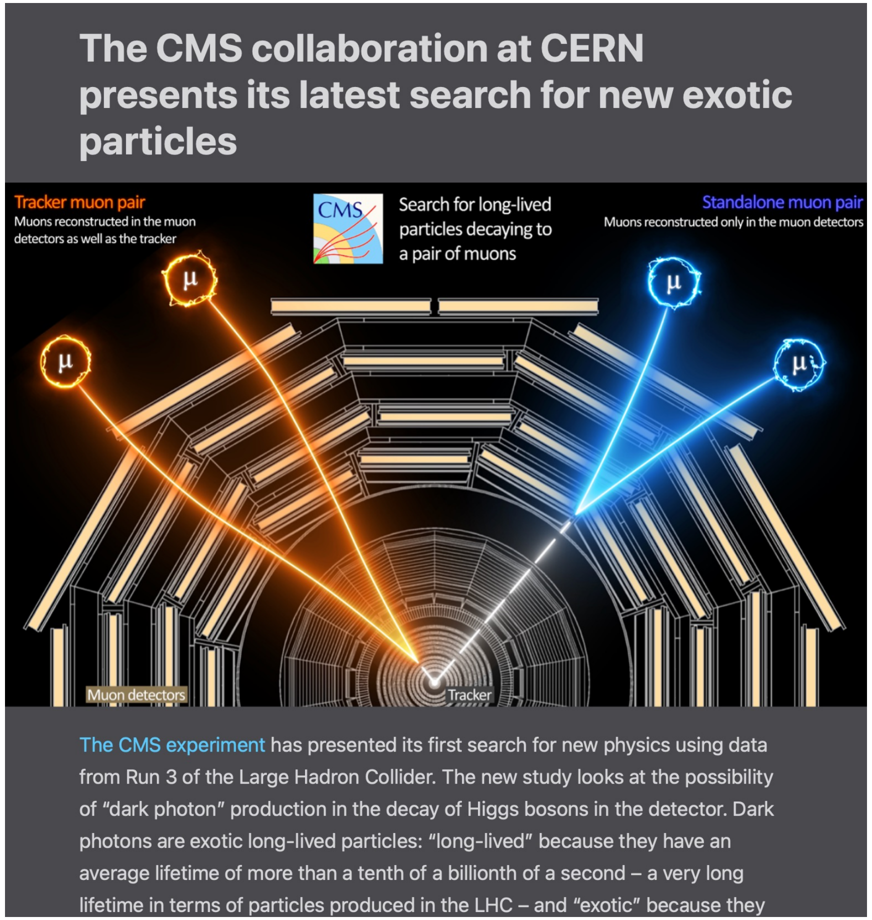
Despite about **2.5 smaller dataset**, comparable sensitivity w.r.t 13 TeV result, **thanks to trigger developments for Run 3**



A. Escalante @ICTEA Seminar

- **First search at 13.6 TeV from ATLAS/CMS**

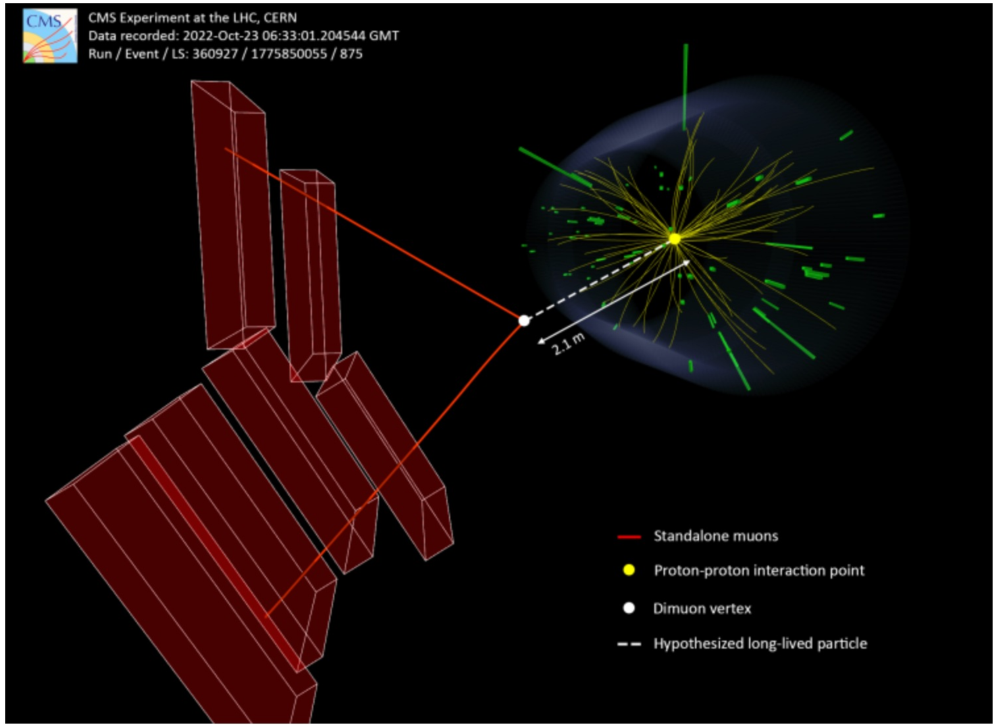
PRIMER RESULTADO DEL RUN-3


The CMS collaboration at CERN presents its latest search for new exotic particles

The CMS experiment has presented its first search for new physics using data from Run 3 of the Large Hadron Collider. The new study looks at the possibility of "dark photon" production in the decay of Higgs bosons in the detector. Dark photons are exotic long-lived particles: "long-lived" because they have an average lifetime of more than a tenth of a billionth of a second – a very long lifetime in terms of particles produced in the LHC – and "exotic" because they

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

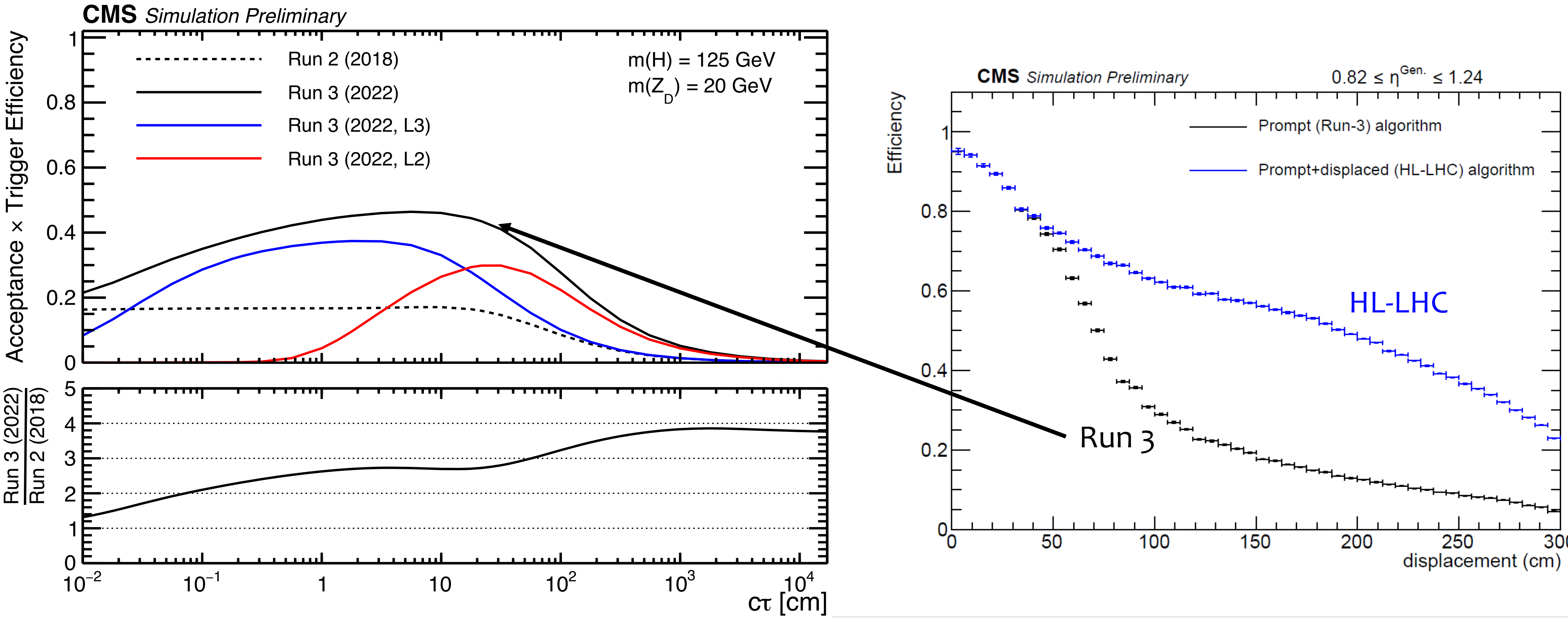
By CMS Collaboration



The first search for new physics using LHC data collected in Run 3 has been presented by CMS. It was shown during this year's EPS conference in Hamburg and relied on both the new data and refinements of the trigger system made for Run 3. It marks the first of many upcoming physics results to benefit from Run 3. The LHC Run 3 started in July 2022 and has a higher instantaneous luminosity than previous runs, meaning there are more collisions happening at any one moment for researchers to analyse.

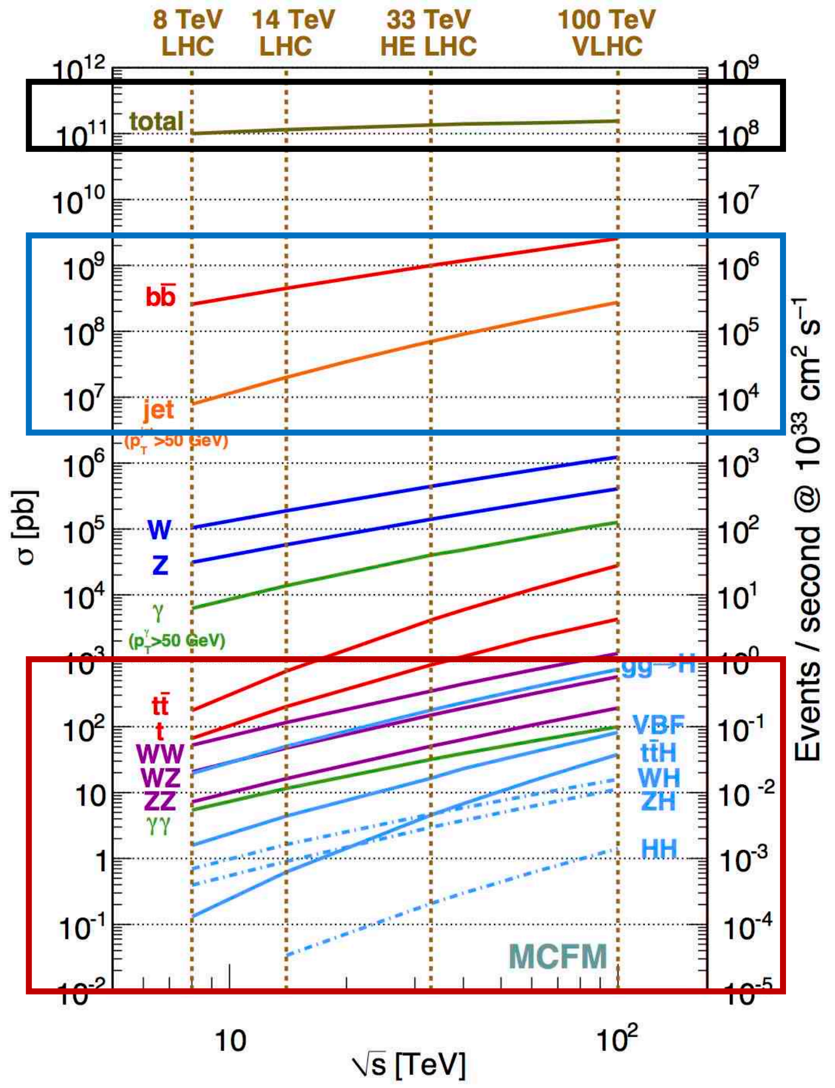
https://cms.cern/news/long-lived-particles-light-lhc-run-3-data

But we have not seen LLPs (yet)…



The limitation of the trigger system

- 40M of collisions/events per second (Tb/s) need to be reduced to 1-2k events per second (Gb/s)
- We don't know how the new physics will manifest itself. The trigger system must be UNIVERSAL, EFFICIENT but also SELECTIVE.
- **Keep as many good events as possible:**
  - Better momentum resolution
  - Vertex position determination
  - Precise particle identification
  - Anomaly detection
  - …
- Keep the general physics program (i.e. prompt physics) and yet keep our eyes open to the new physics (i.e. LLPs)



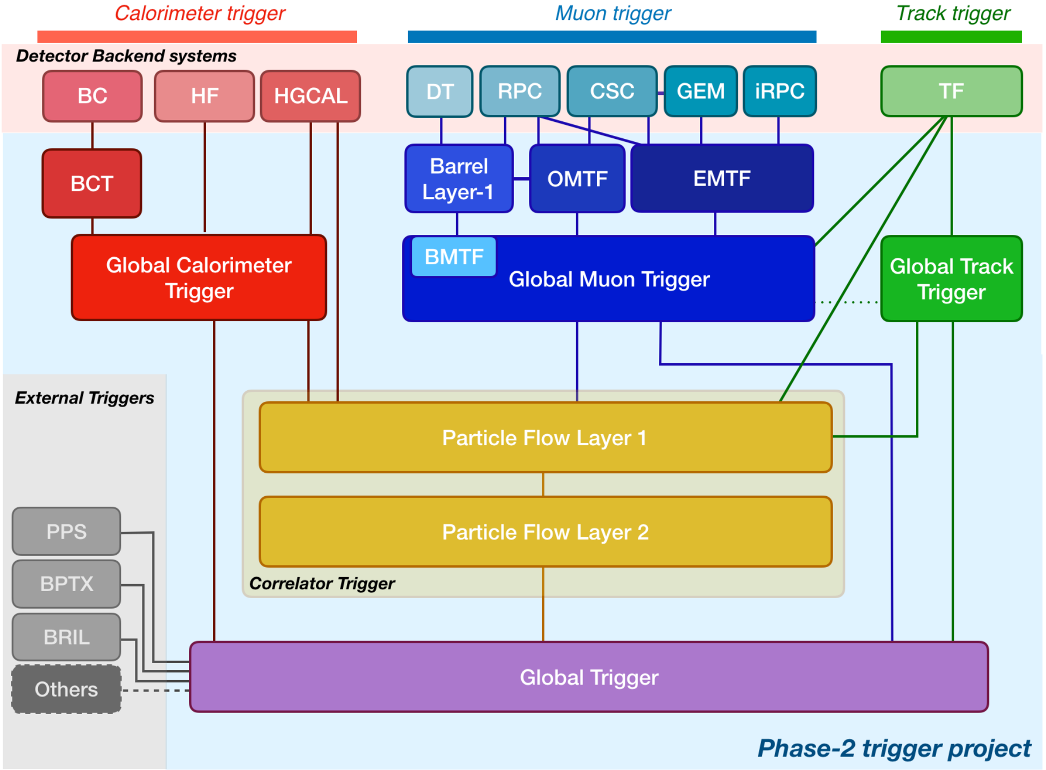
Universidad de Oviedo

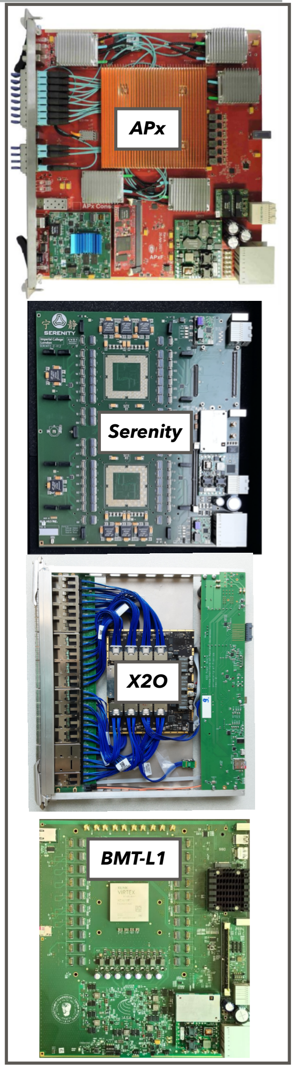
The arquitecture of a trigger system

ICTEA 2024 A. ZABI

CMS L1 TRIGGER @ HL-LHC 32

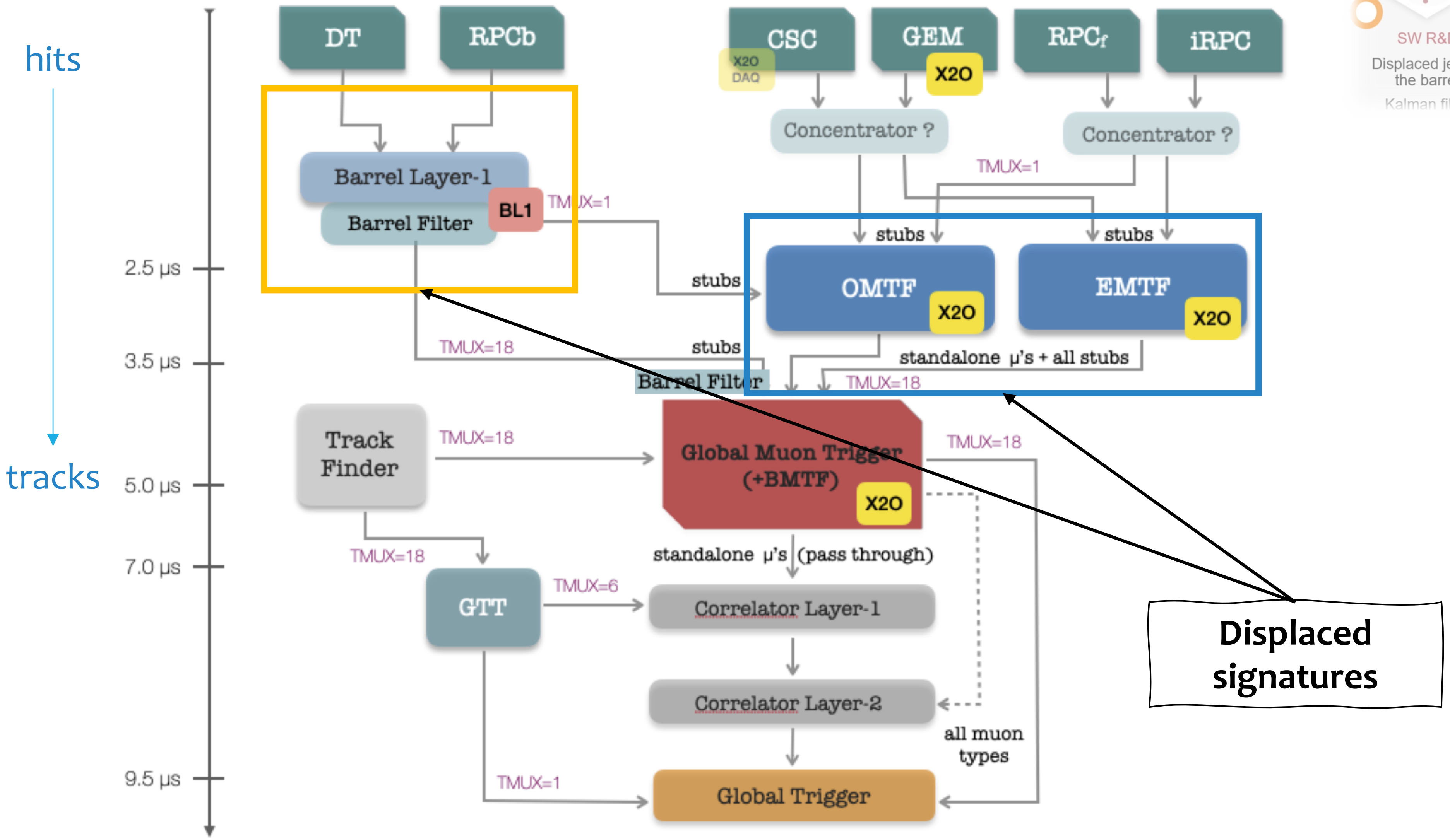
LEVEL-1 PHASE II TRIGGER UPGRADE SYSTEM

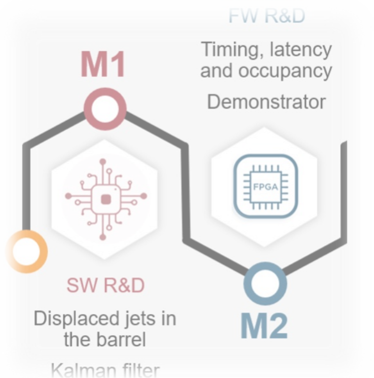




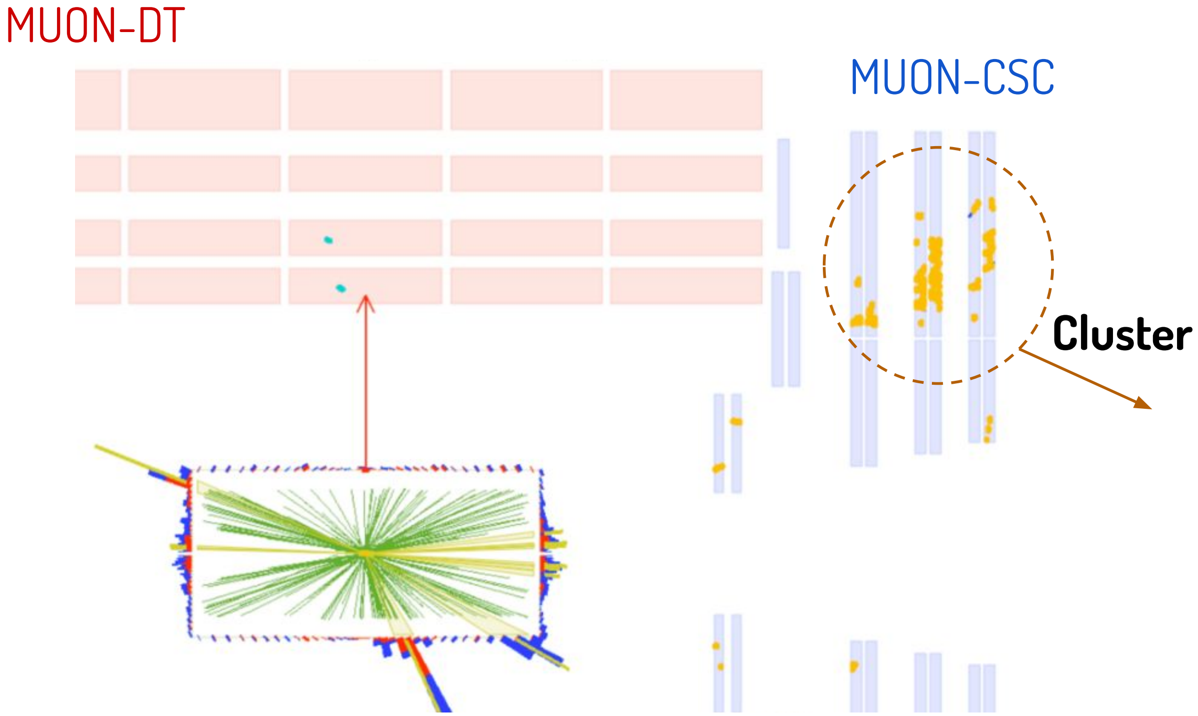
- **Level-1 Architecture:** Efficient distribution and processing of trigger primitives, provision appropriate resources and interconnections, retain enough headroom future flexibility & Robustness
- **Level-1 technological choices:** generic processing engines (inspired from Phase-1 upgrade)
- **Key design feature:** Correlator Trigger. Collects all inputs and feed sophisticated algorithms
- **Design Constraints :** HW processors > 100 links , FPGA resources < 50 %, Latency (< 9.5 us (keep 20%) while HGCAL/TF~5us)

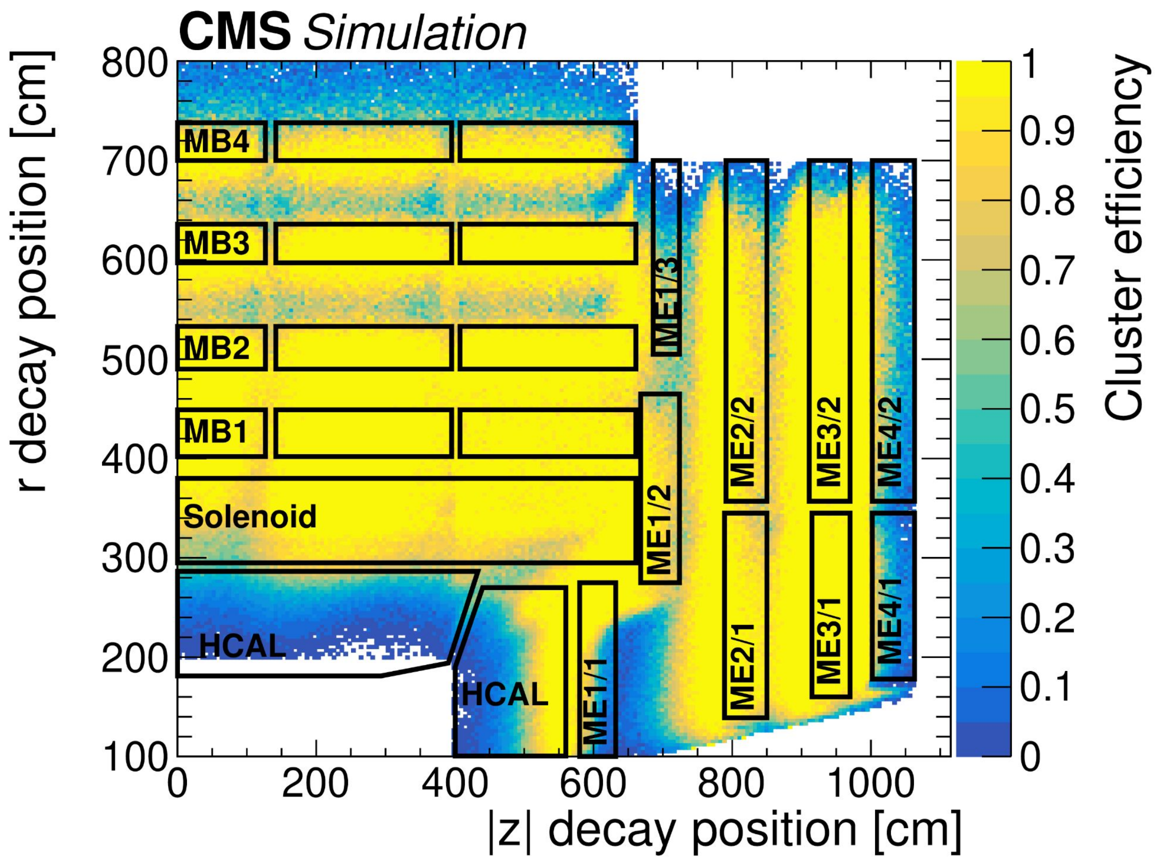
The arquitecture of a trigger system





Reconstruction of muon showers



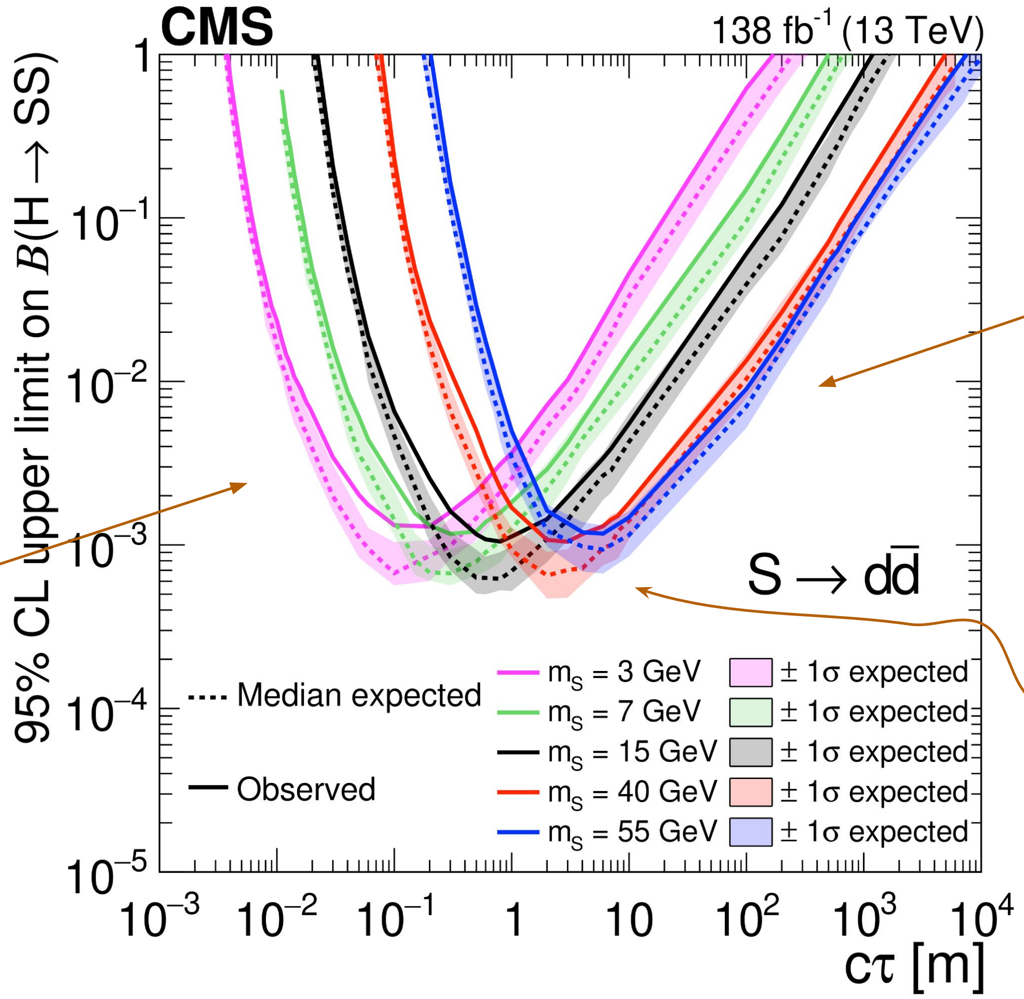


Use N_{hits} in the cluster as discriminant variable

A. Escalante @ICTEA Seminar

Reconstruction of muon showers

LLP decays before reaching Muon Detectors



LLP decays beyond CMS

Fails trigger

(no enough E_T^{miss} in event)

A. Escalante @ICTEA Seminar

See talk by Javier Prado

Reconstruction of muon showers

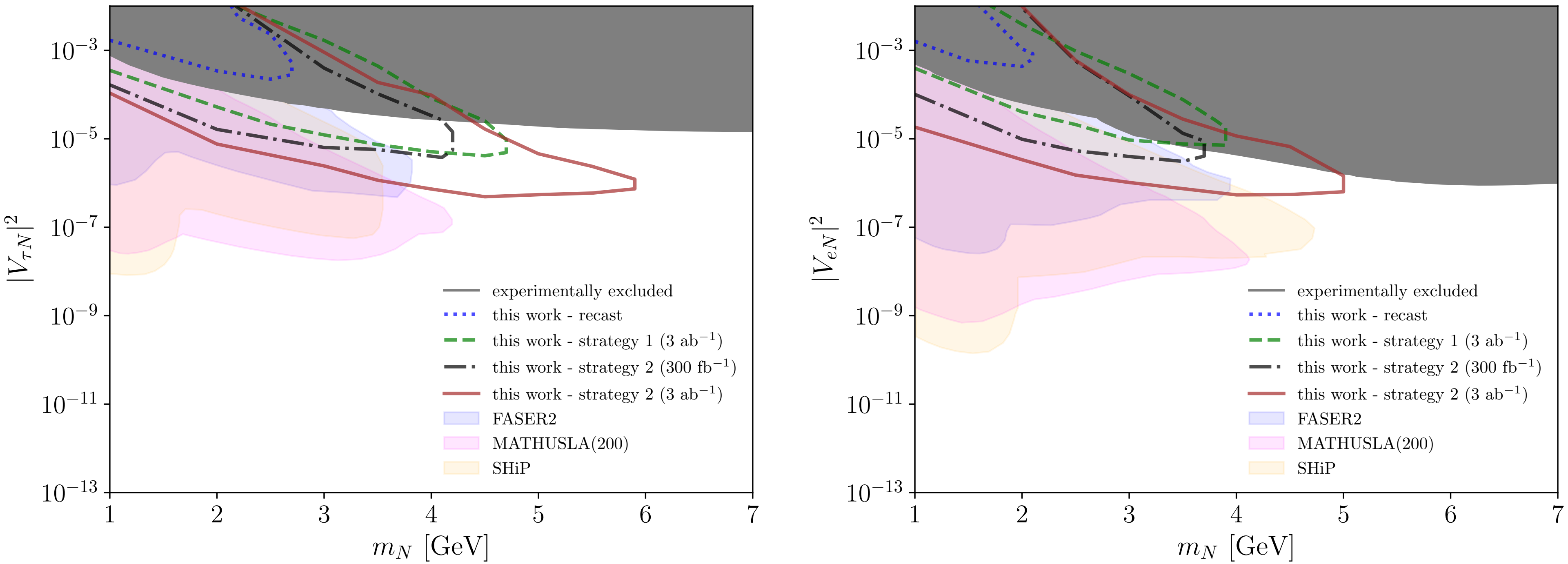
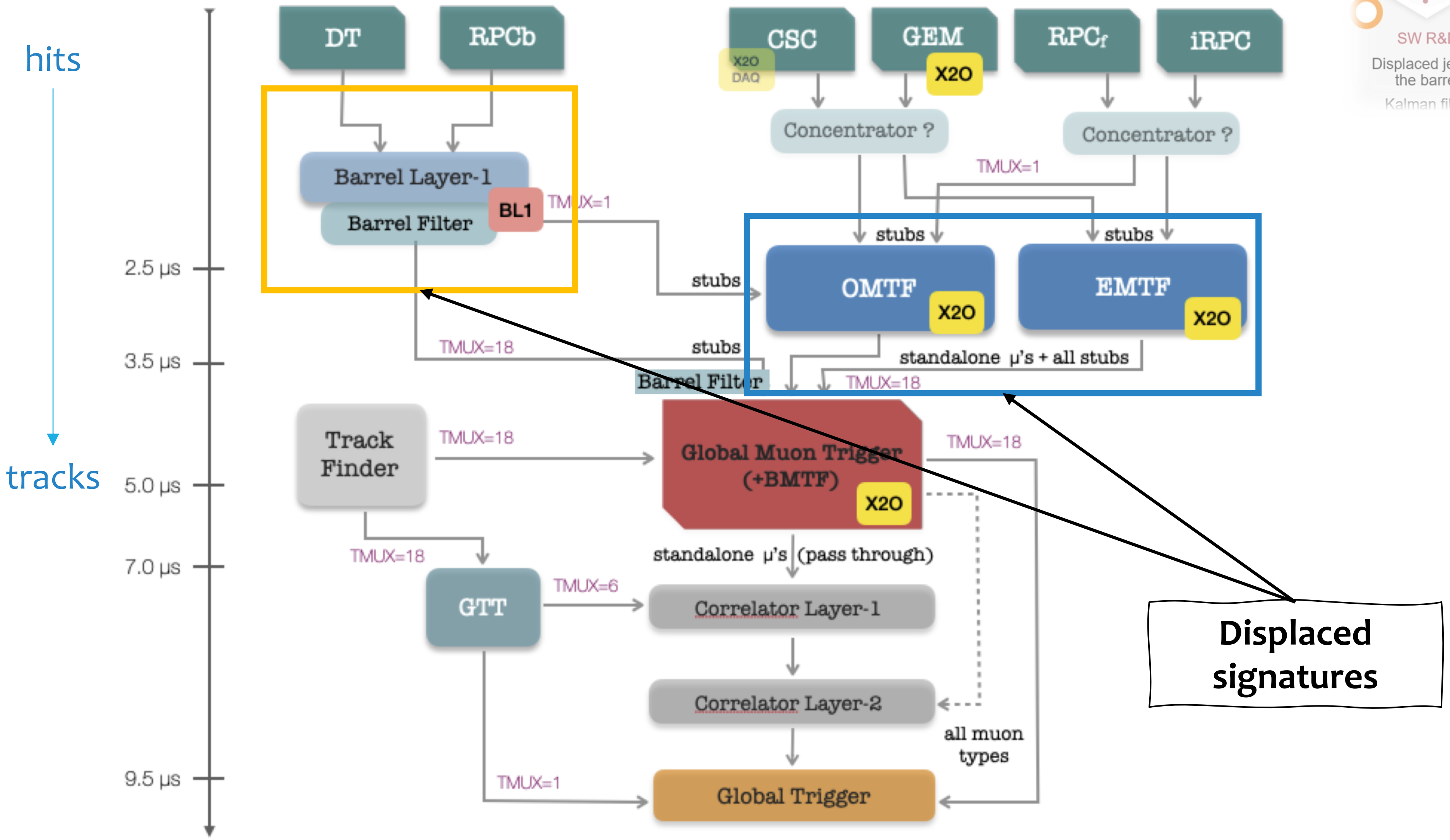
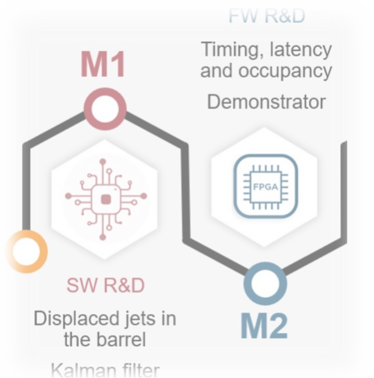


Figure 2. Projected sensitivity of the different proposed search strategies with a displaced shower signature in the CMS muon system. The minimal HNL scenario is considered with mixings in the τ and electron sectors, shown in the left and right panel, respectively.

JHEP 02 (2023) 011; arXiv:2210.17446

Beyond current trigger system





Beyond current system. Upgrading the upgrade?

- *Explore **alternative technologies** and ideas which **could not be otherwise investigated** that could potentially lead to a **significant breakthrough**.*
  - Both in the present architecture (BMTL1 and OMTF) and beyond
- Project focuses on muons, but ideas can be ported elsewhere.
- If ideas are successful, we may want to have a small-scale system running in parallel to our future HL-LHC system to validate it (beyond the scope of the grant) .

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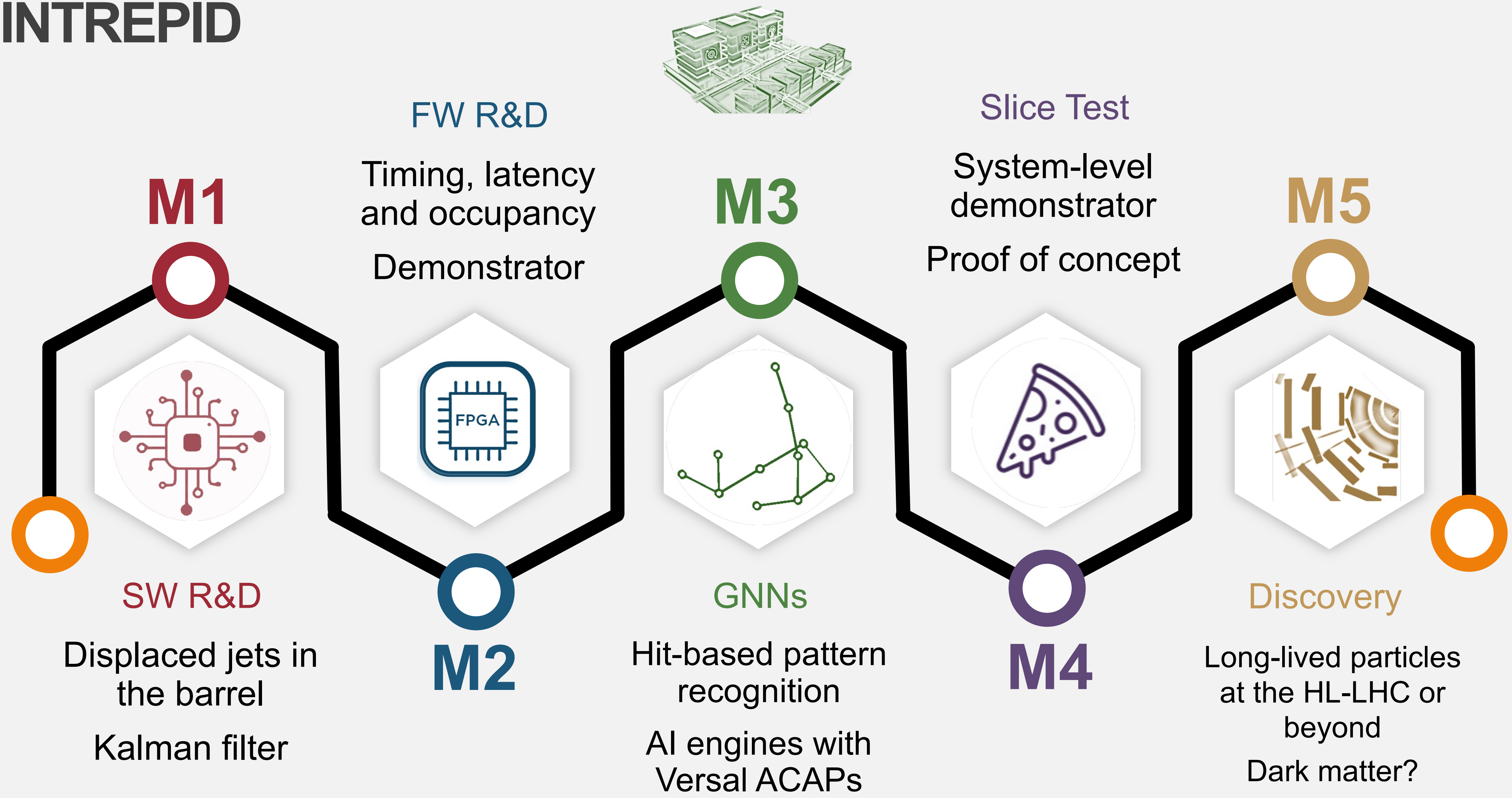
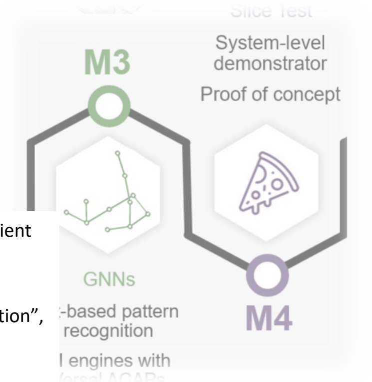

M1
SW R&D
Displaced jets in the barrel
Kalman filter
M2
FW R&D
Timing, latency and occupancy
Demonstrator
FPGA
M3
GNNs
Hit-based pattern recognition
AI engines with Versal ACAPs
M4
Slice Test
System-level demonstrator
Proof of concept
M5
Discovery
Long-lived particles at the HL-LHC or beyond
Dark matter?

Graph Neural Networks for particle reconstruction

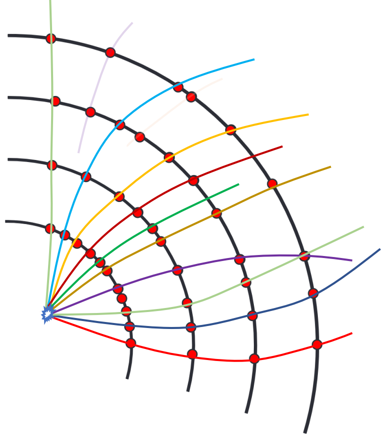


Representing tracking data using graphs

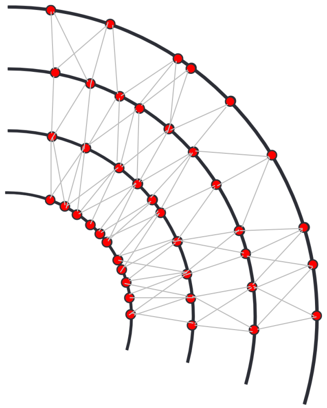
F. Siklér, “Combination of various data analysis techniques for efficient track reconstruction in very high multiplicity events”, *Connecting the Dots* conference 2017 (link)

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



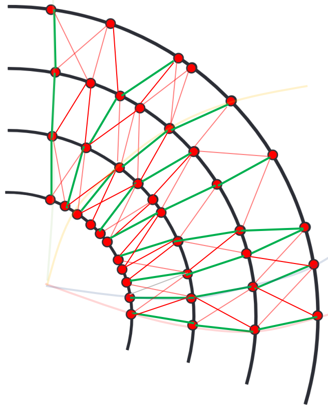
Represent the data using a graph



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

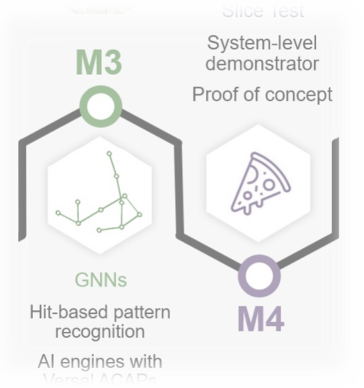
Goal:
classify the edges of the graph



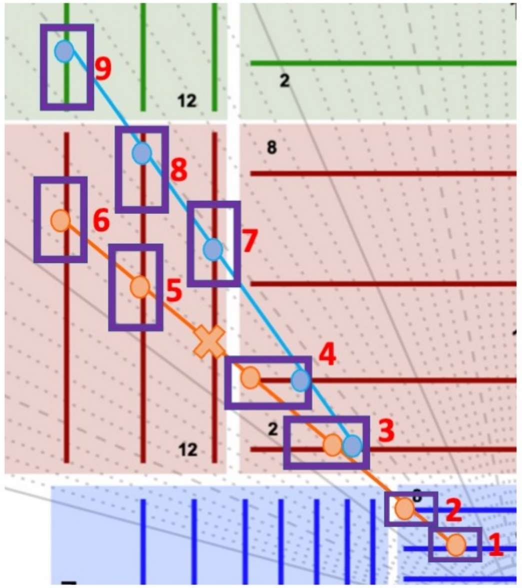
High classification score
=> **high probability** that the edge is part of a track

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

Graph building techniques

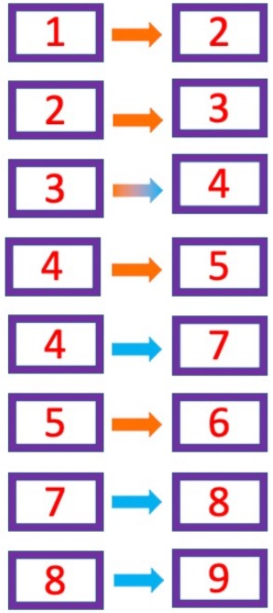


Particles leaving hits



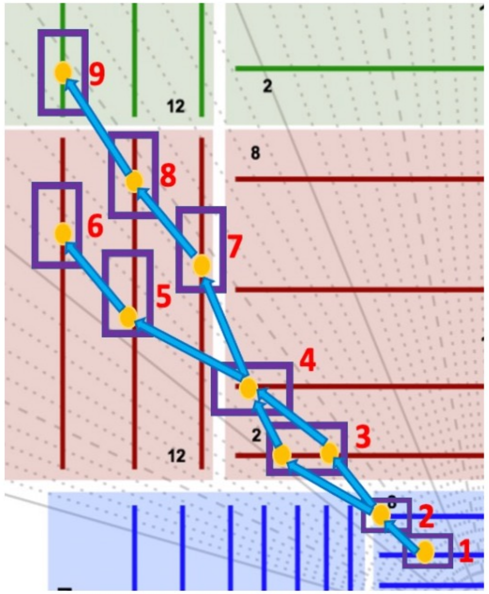
Done once

Module map creation

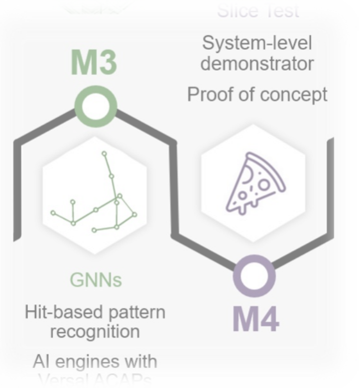


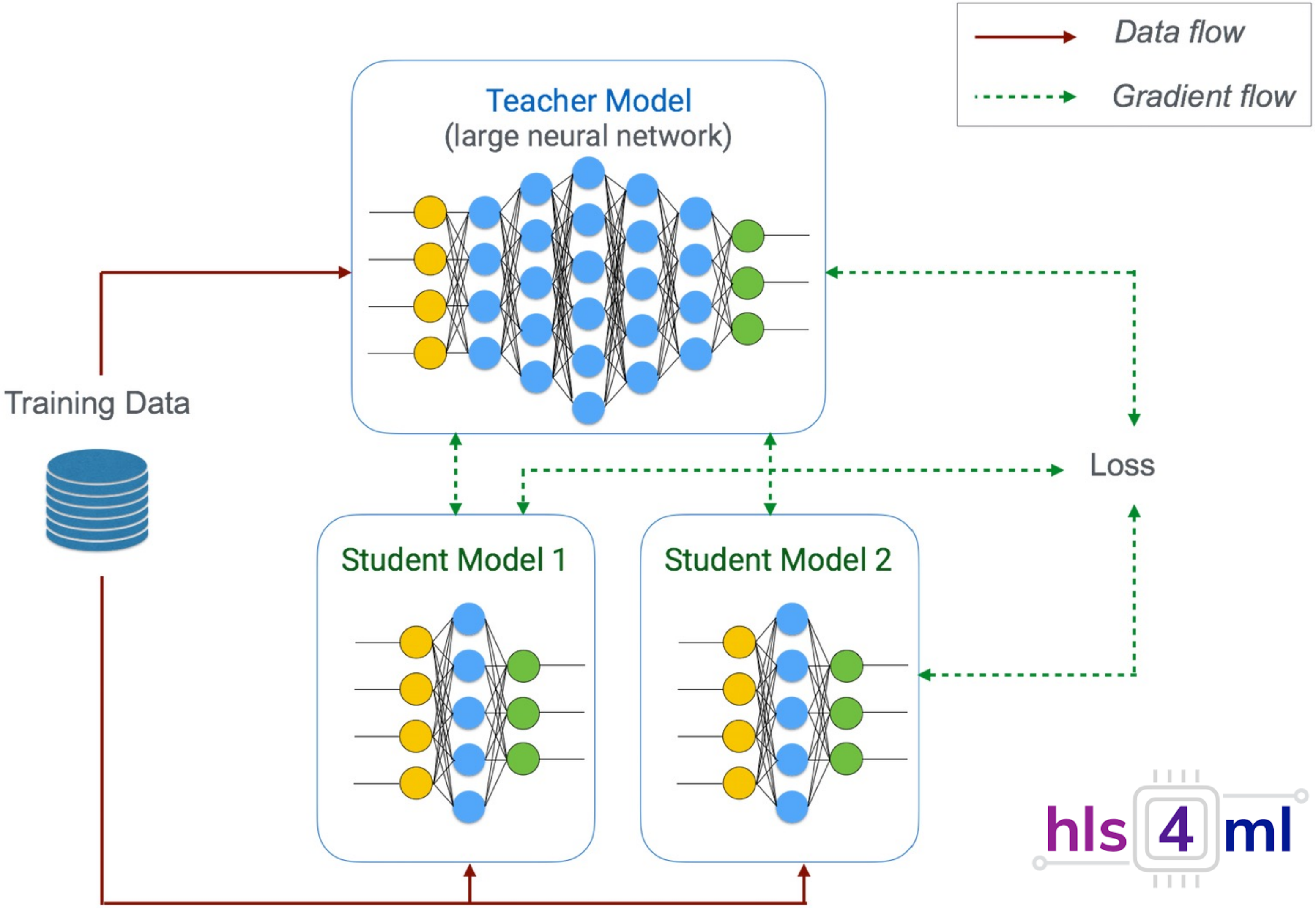
For event reconstruction

Graph creation



Graph Neural Networks for real-time muon reconstruction

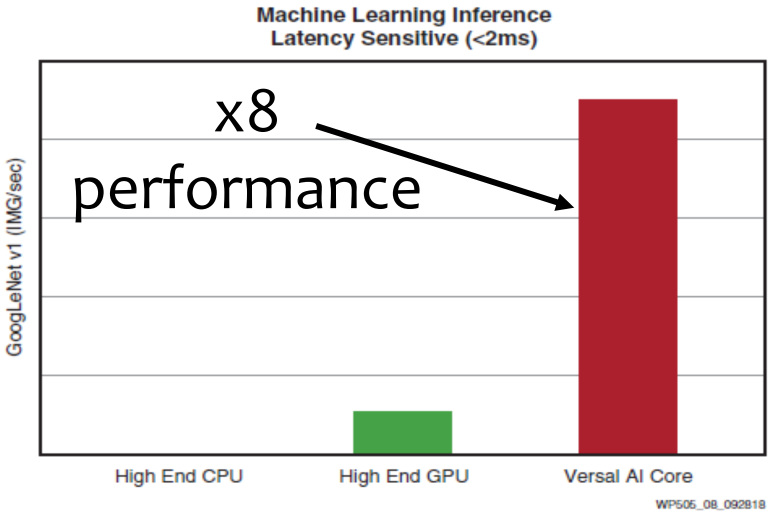


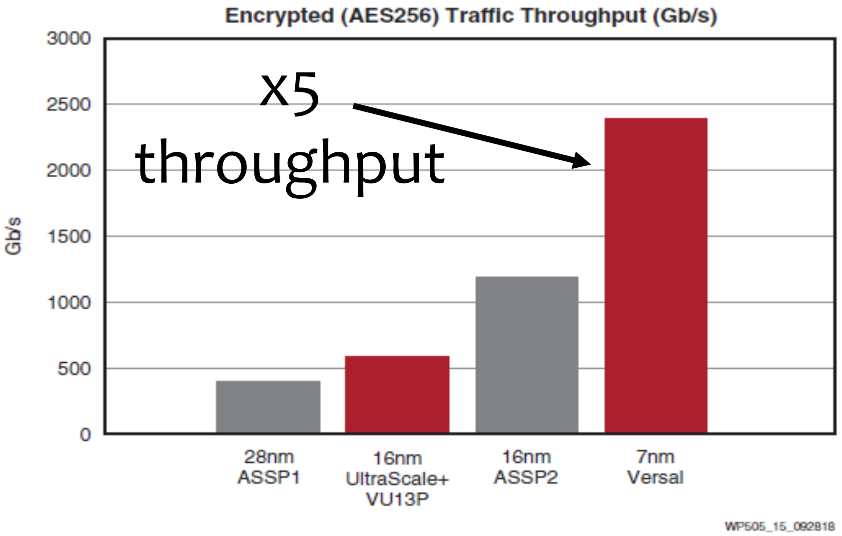


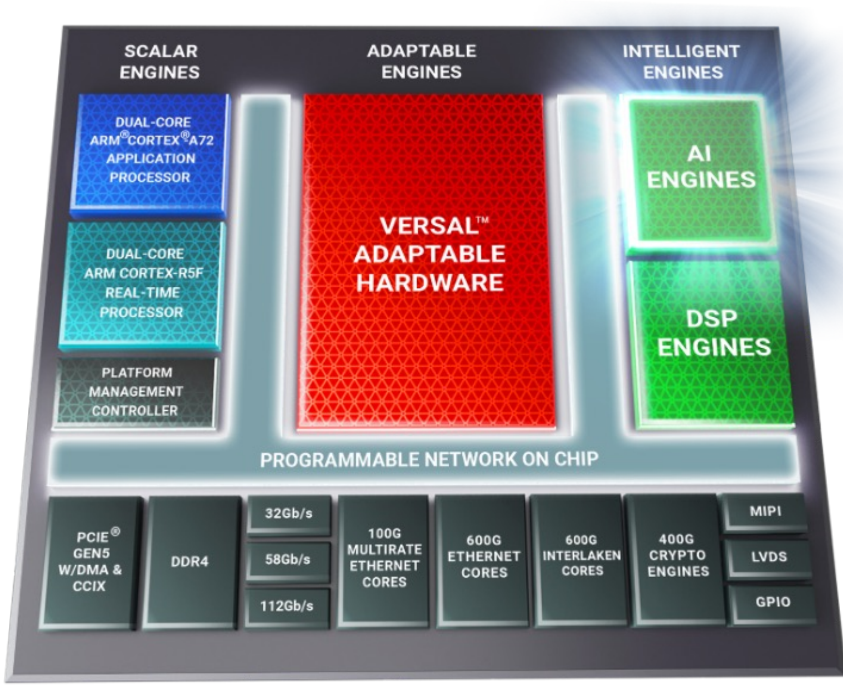
hls4ml

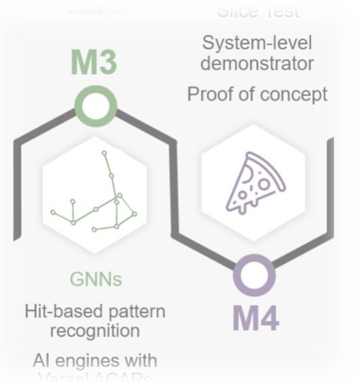
Explore capabilities of AI-engines

Provide the necessary throughput and latency for triggering?







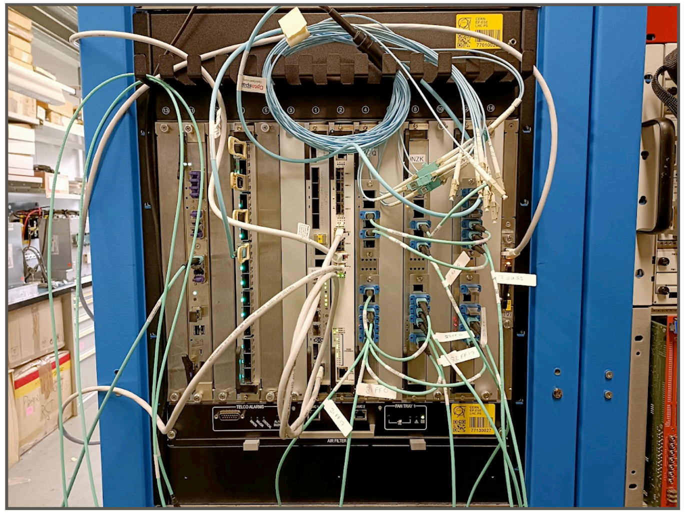


Our demonstrator

TESTING AND SYSTEM DEMONSTRATION

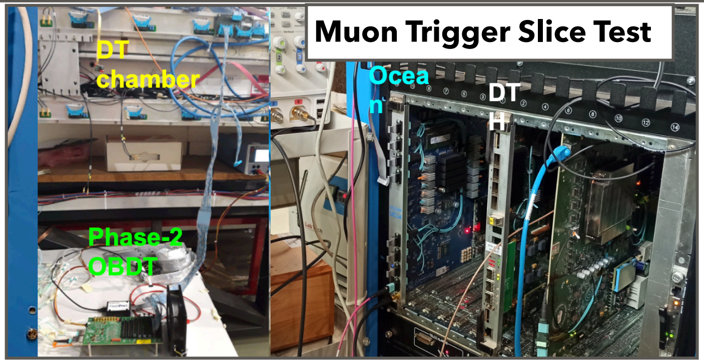
Phase-2 Level-1 Trigger system demonstration

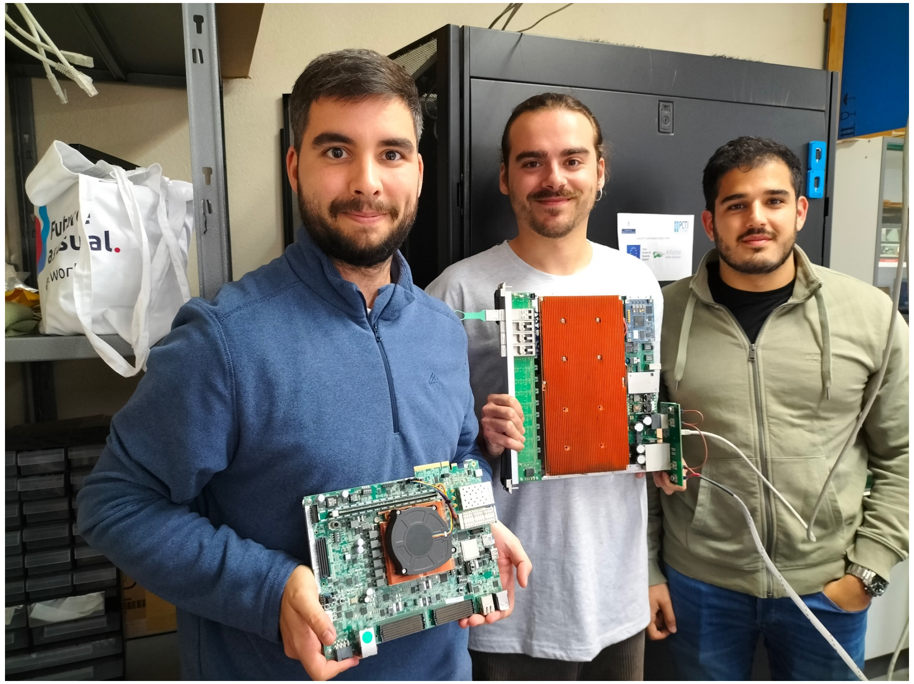
- Single-board and multiple board tests performed
- Integration centers across the globe: larger scale integration @ CERN (904). Multiple flavour board tests.
- Slice test in Muon Barrel Trigger during Run-3. Installation @P5: DT–>BMT–>GMT–>GT
- **Board interconnection: protocol**
  - Links (asynchronous) 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

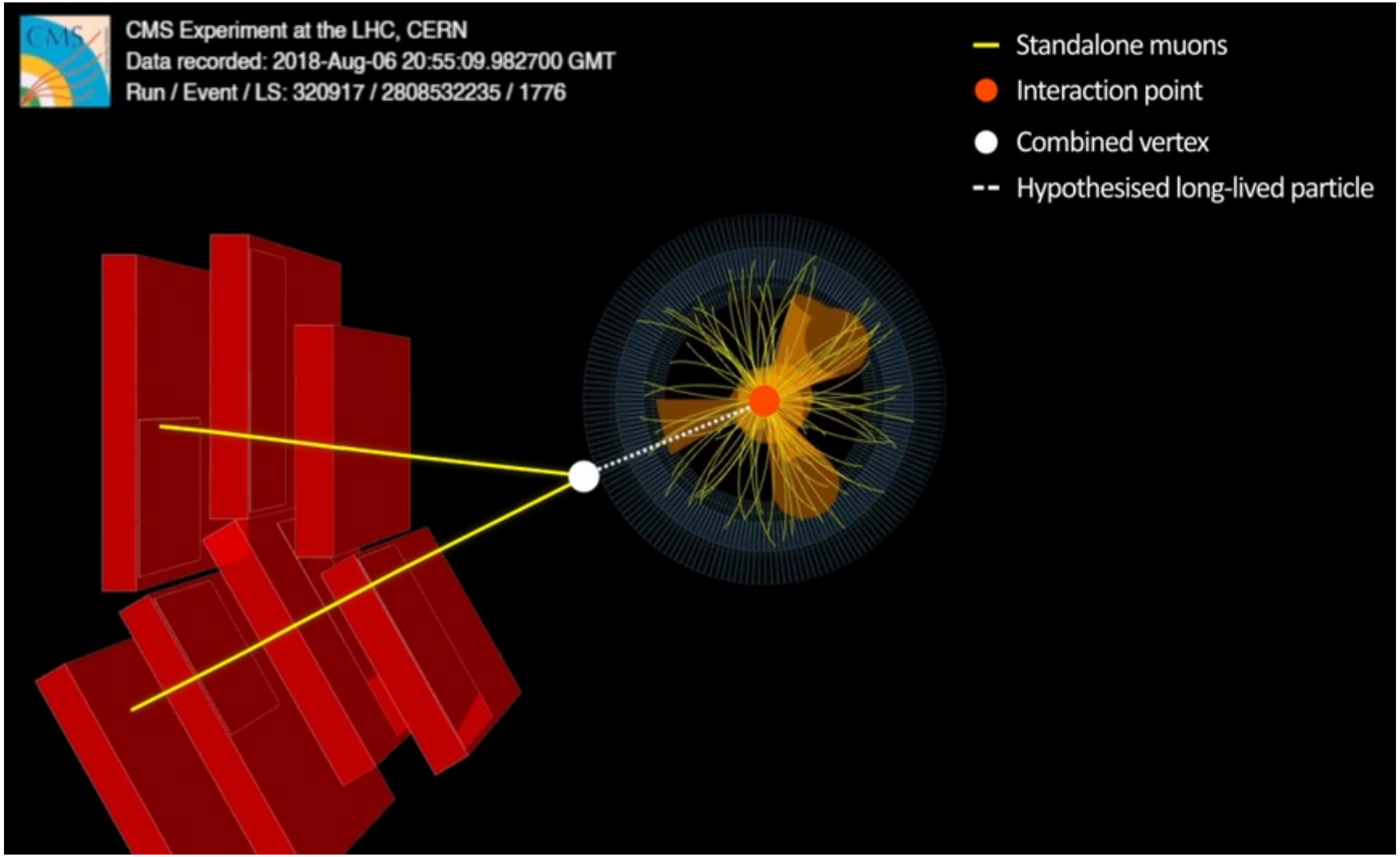


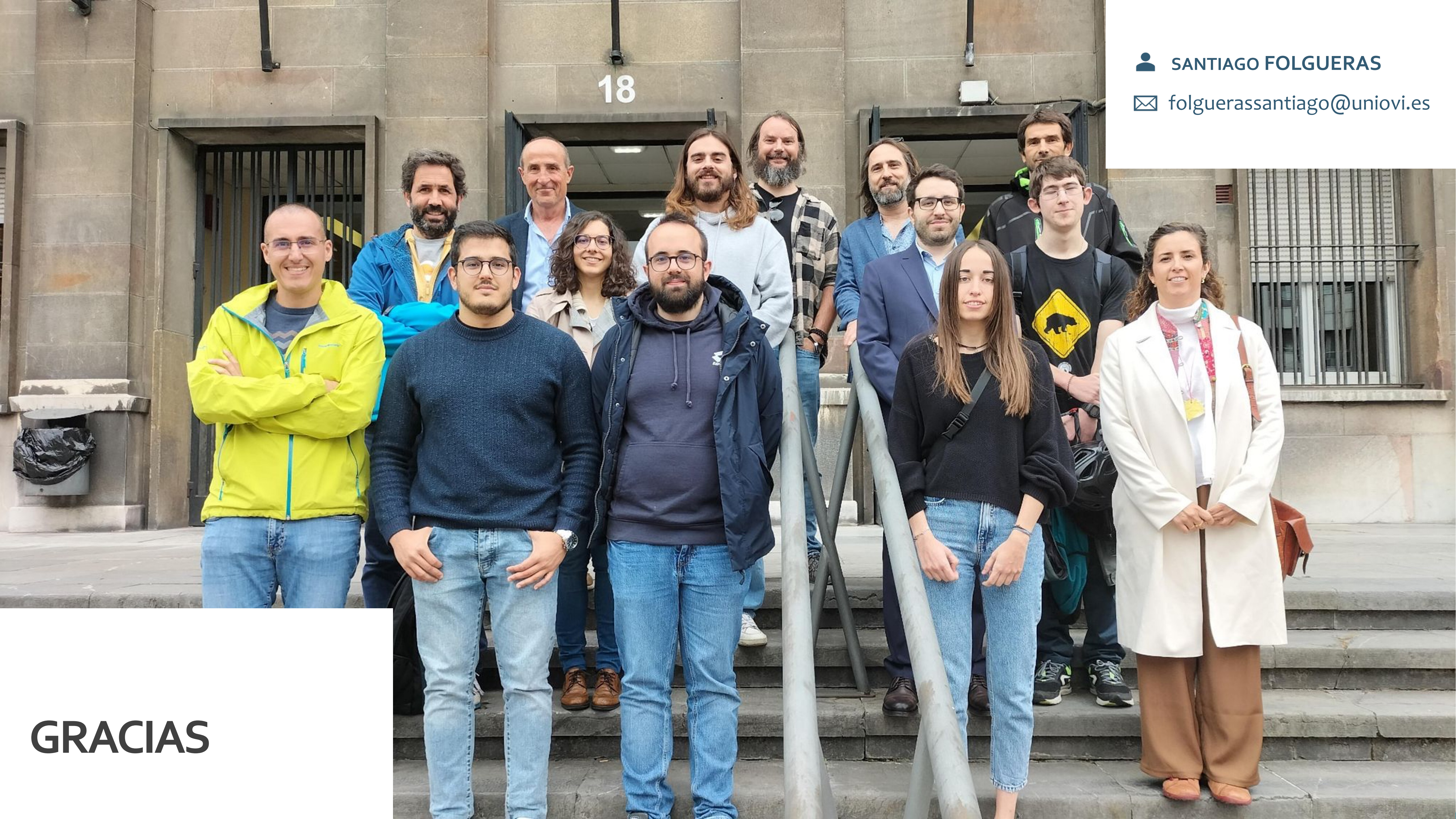


Thanks for listening!

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

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





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