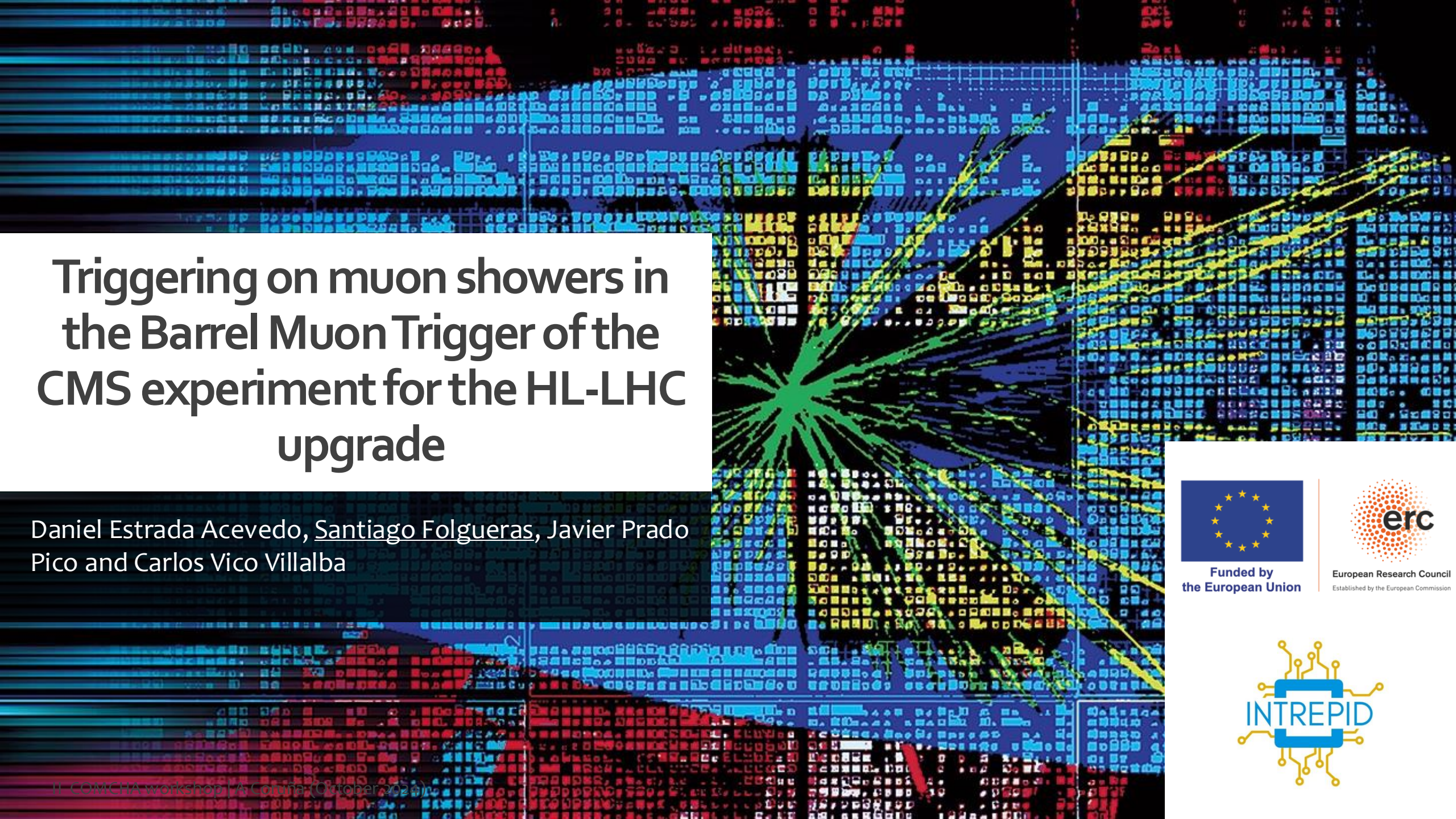


Triggering on muon showers in the Barrel Muon Trigger of the CMS experiment for the HL-LHC upgrade

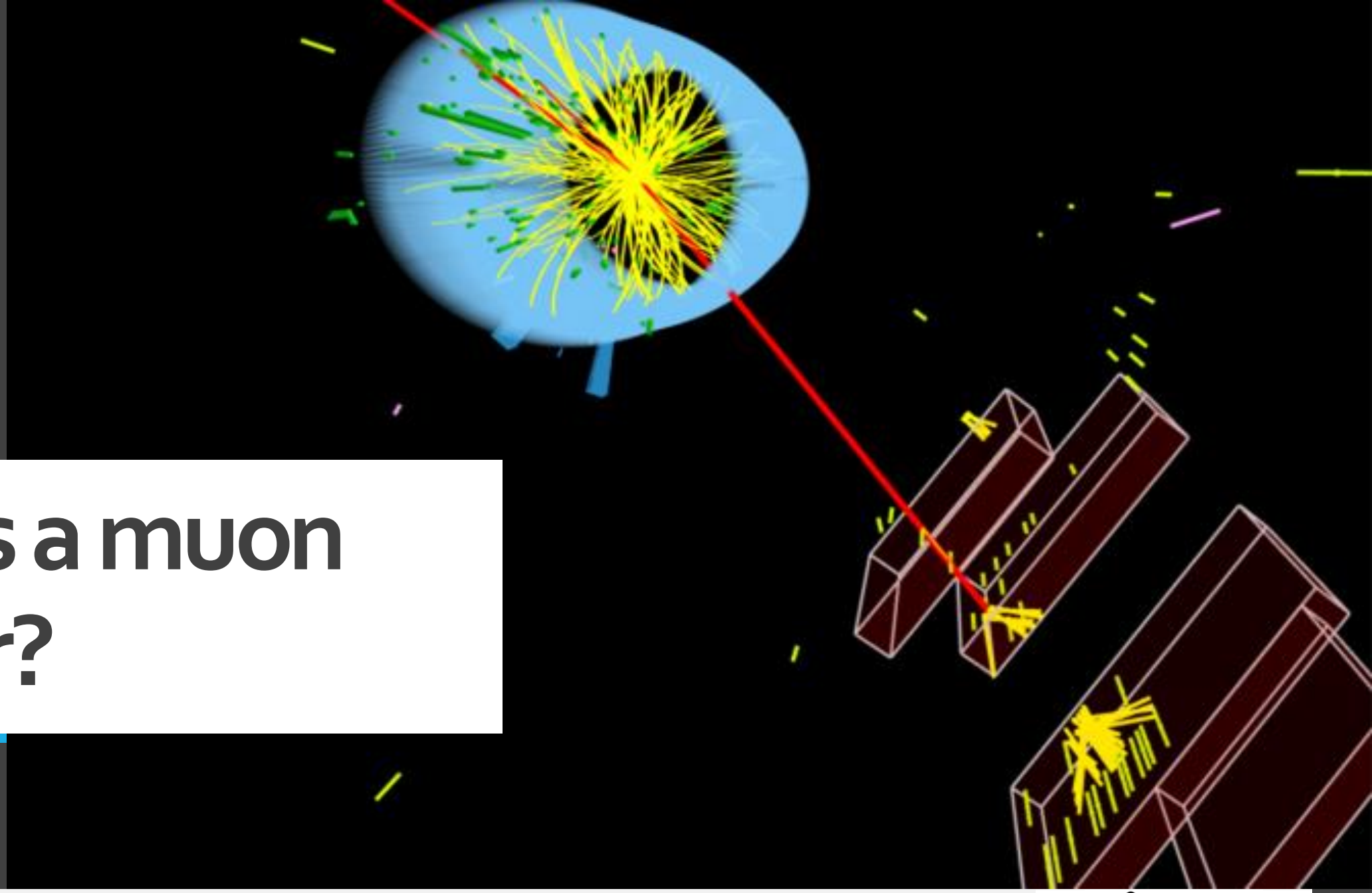
Daniel Estrada Acevedo, Santiago Folgueras, Javier Prado Pico and Carlos Vico Villalba

Funded by the European Union

European Research Council
Established by the European Commission

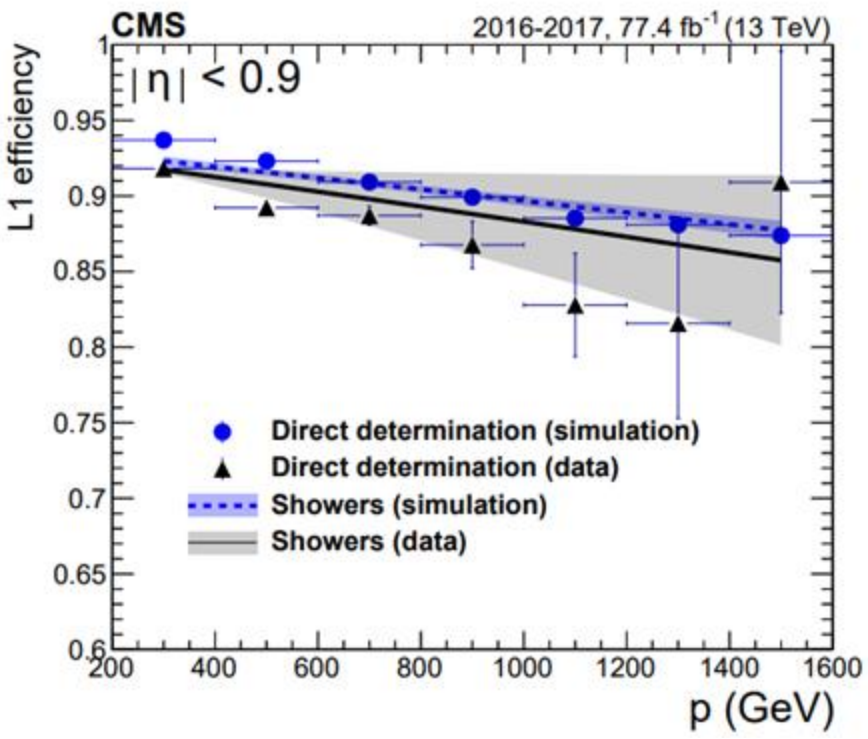
INTREPID

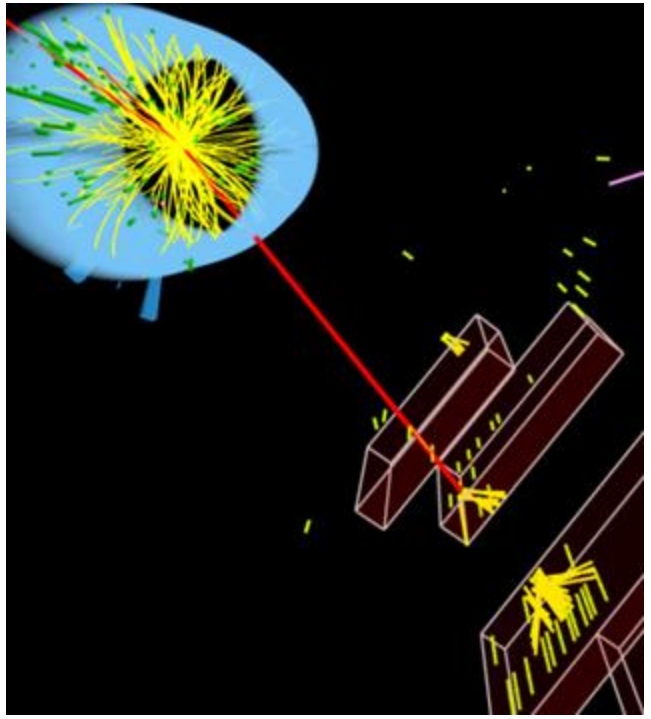
What is a muon shower?

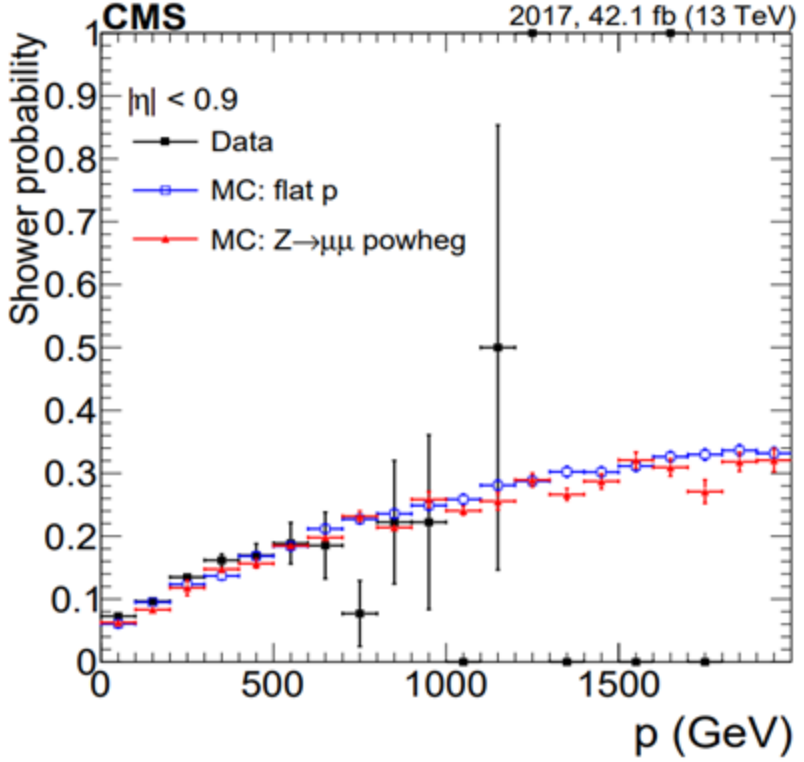


Motivation

- Muon showers appear naturally in events with high-momentum muons.
  - Above a certain energy, muons start to suffer strong radiative losses resulting into a large cascade of electromagnetic activity
  - Detected in the muon system as high-multiplicity events.
- Affect the reconstruction of muons: inefficiencies and/or momentum mismeasurements

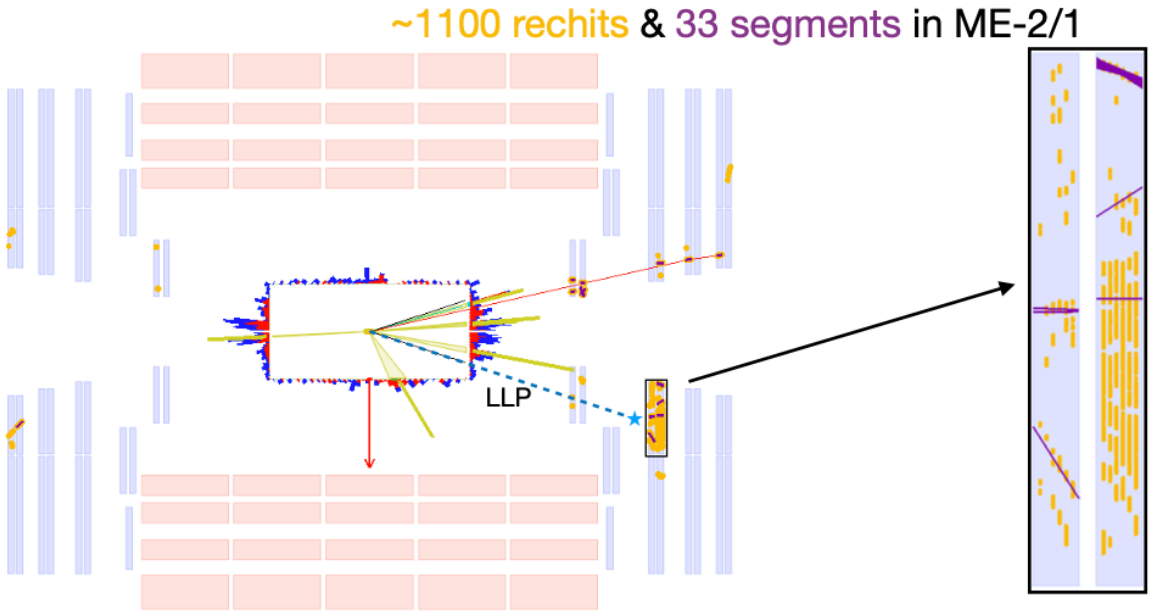


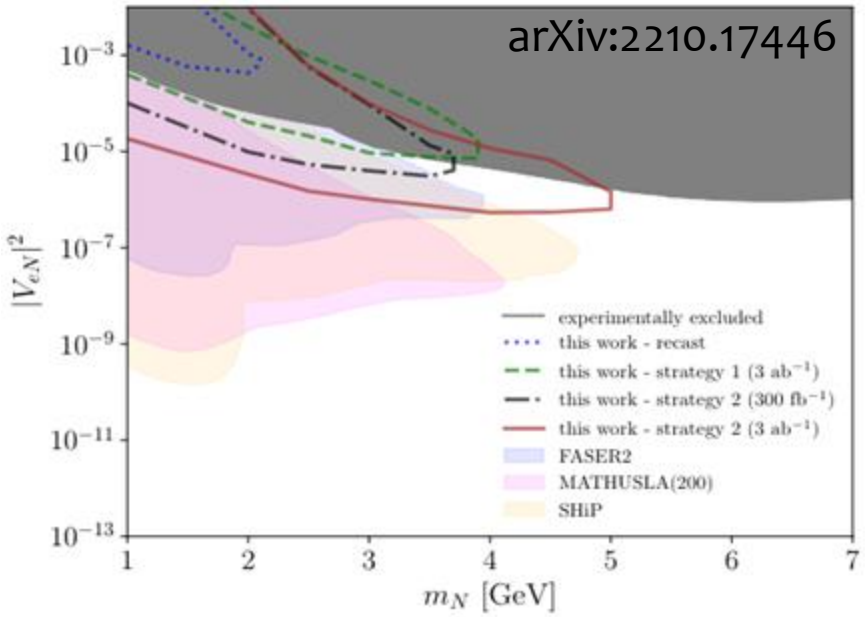




Motivation

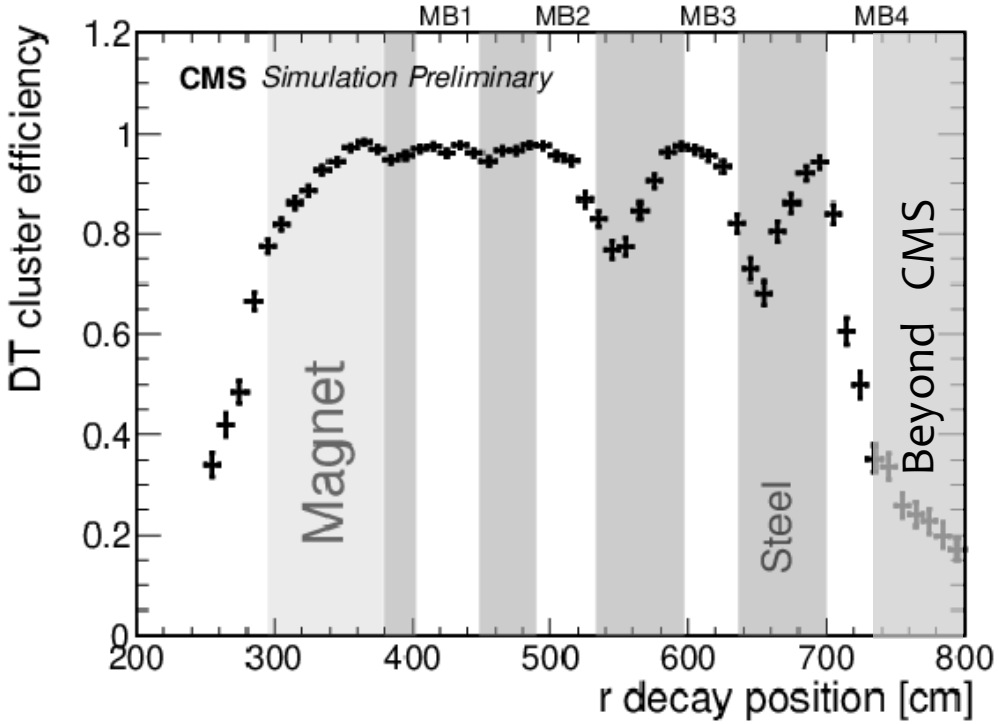
- Long-lived particles such as HNL could decay in the muon system if sufficient long lifetime (or low mass)
  - Hadronic showers in the muon system
  - Probe lower masses (< 10 GeV) or longer lifetimes O(1m) parameter space
- Nowadays this signatures escape detection due to reconstruction and trigger constrains
- **Unprecedented opportunity for new physics discovery**

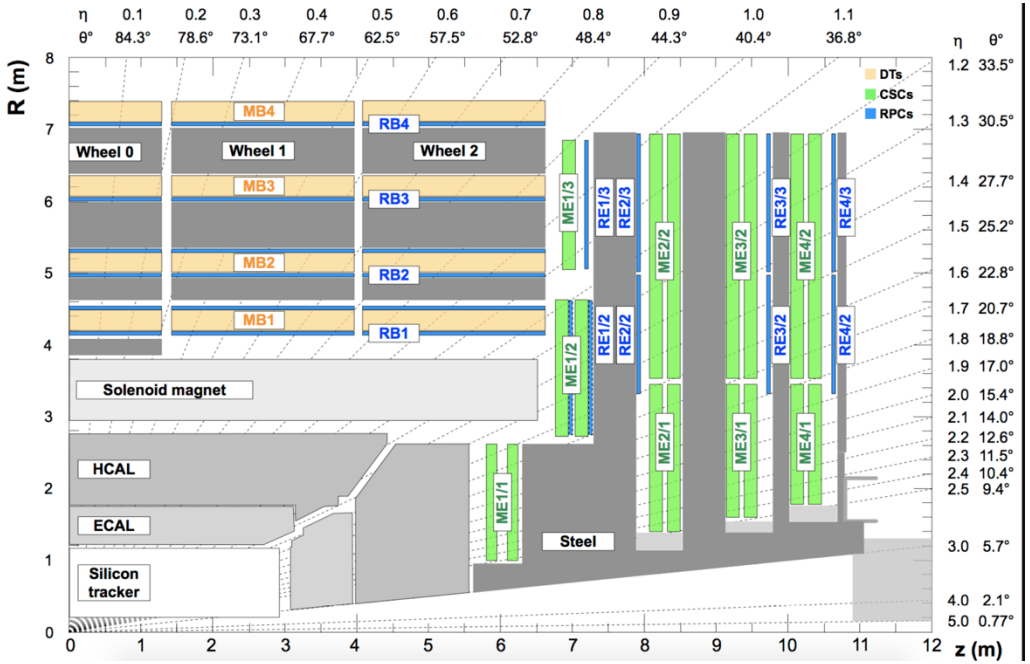




"Hacking" a particle detector

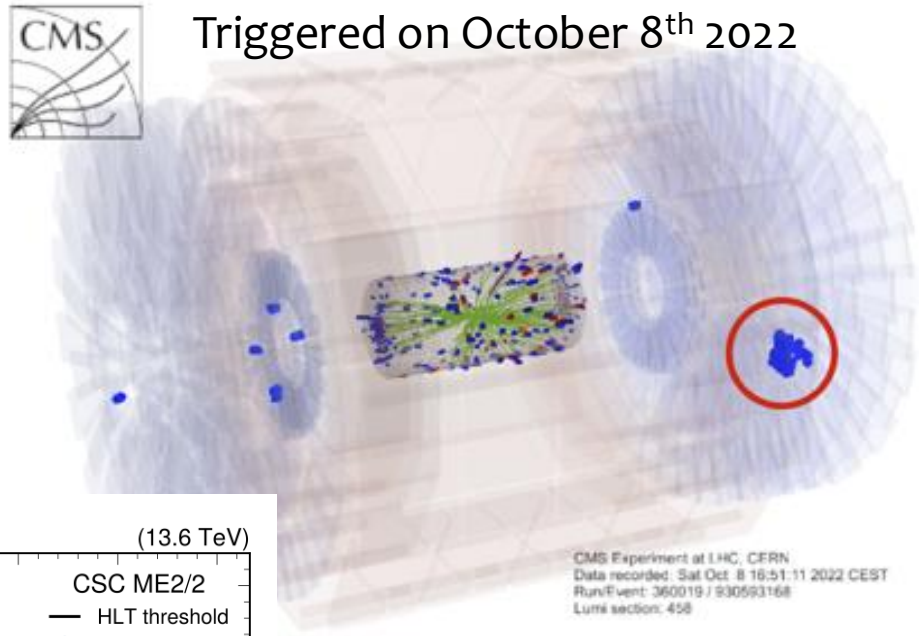
- Shower are detected as multiple hits in either the CSC or DT chambers
- Steel between muon stations can act as absorbers in a sampling calorimeter
  - Shielding of 12-27 interaction length (Background suppression factor ~10^7)
  - Unique feature of CMS muon system
- Sensitive to LLP with longer $c\tau \sim (1 - 10\ m)$

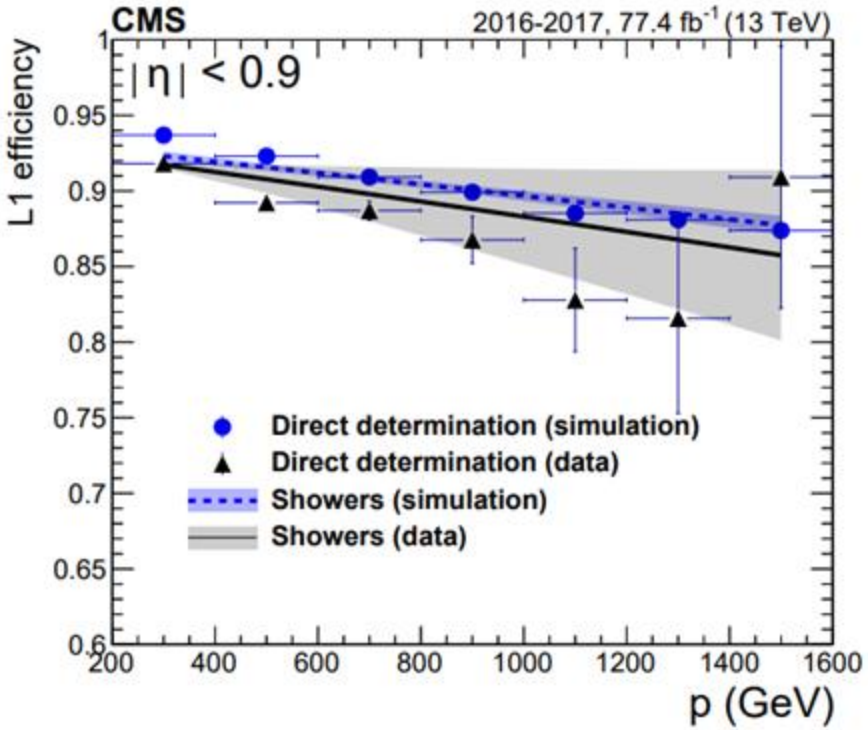


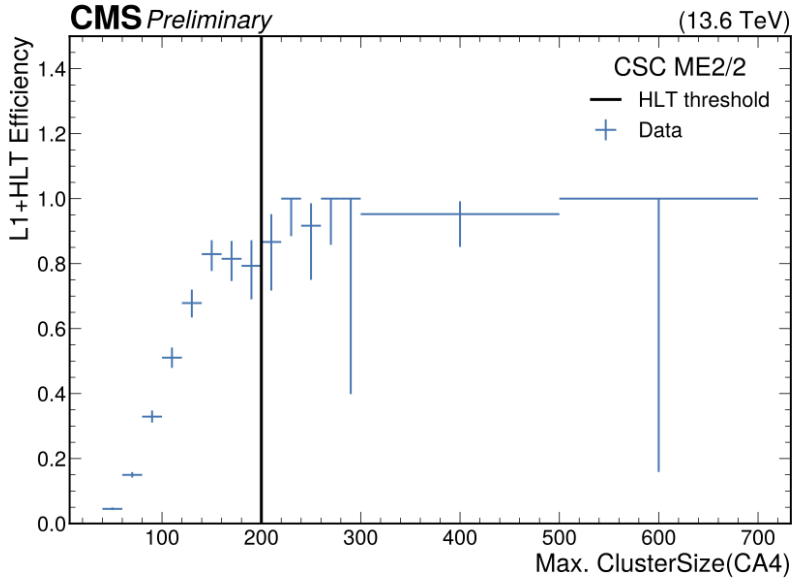


But you can only analyse the things that you saved…

- Trigger efficiency on high-pt muons drops ~10% due to radiative losses
- High-multiplicity events in the muon chambers clutter traditional reconstruction algorithms at trigger level and require different solutions.
  - During Run-3 a dedicated trigger to target high-multiplicity events in the CSCs.





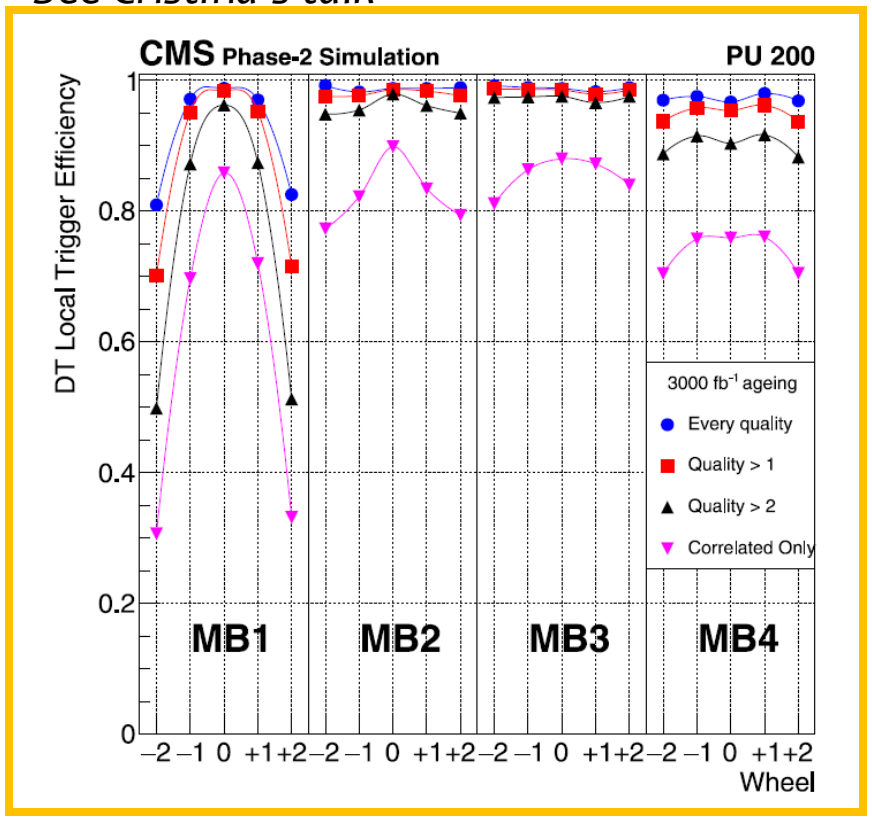


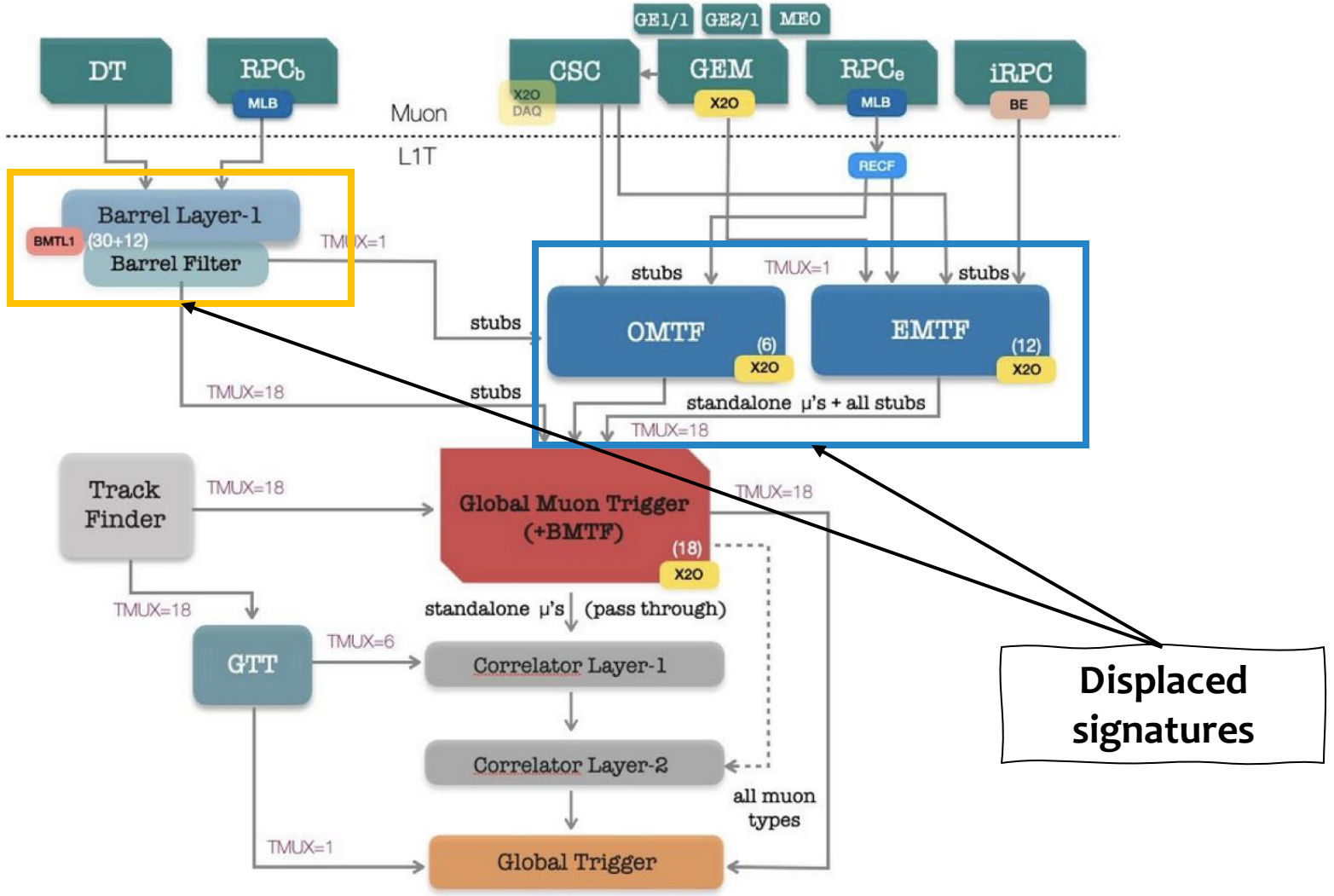
Main limitation is the hardware trigger!!

HighMultiplicityTriggerIn2022

The CMS L1T muon trigger system for the HL-LHC

See Cristina's talk



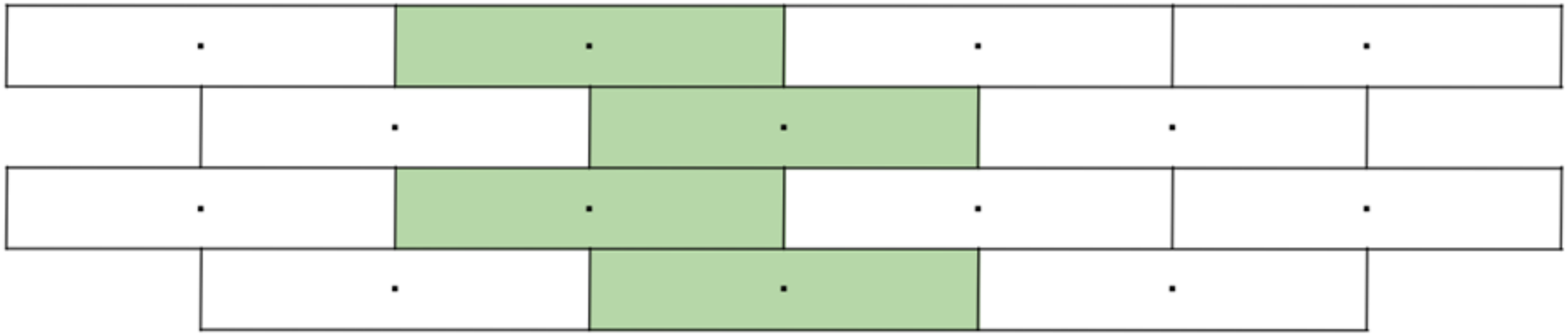


Universidad de Oviedo

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

UAM
Universidad Autónoma de Madrid

The Analytical method

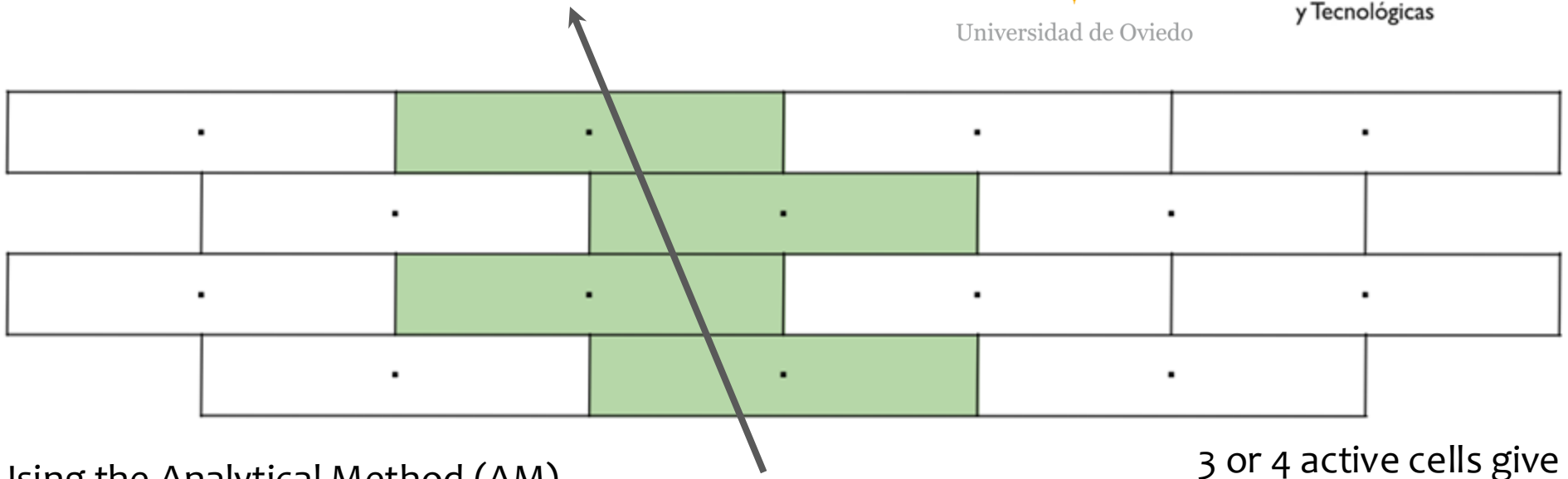


Using the Analytical Method (AM) developed by CIEMAT, UAM and University of Oviedo we can accurately reconstruct tracks

3 or 4 active cells give an unequivocal track of the particle.

https://doi.org/10.1016/j.nima.2023.168103

The Analytical method



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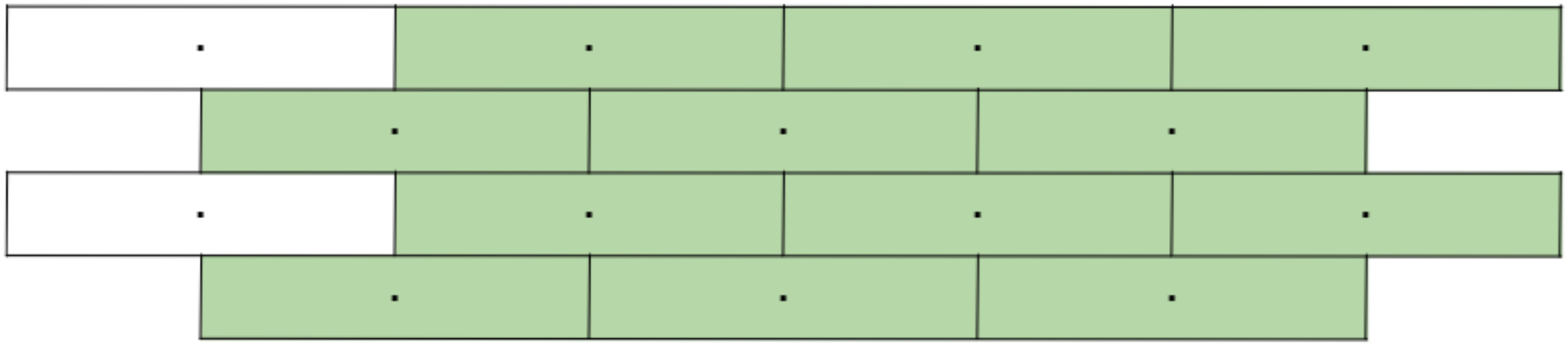
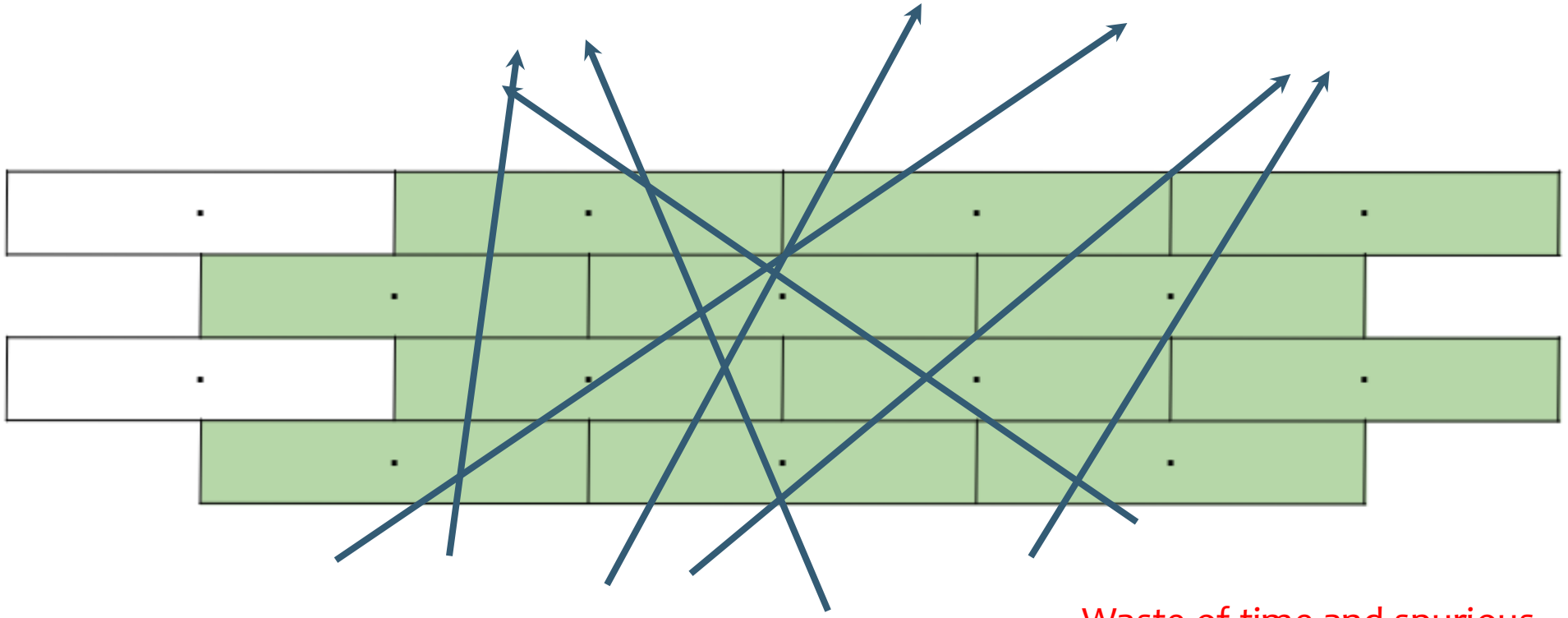
What happens if a muon radiates?



Many active cells

https://doi.org/10.1016/j.nima.2023.168103

What happens if a muon radiates?



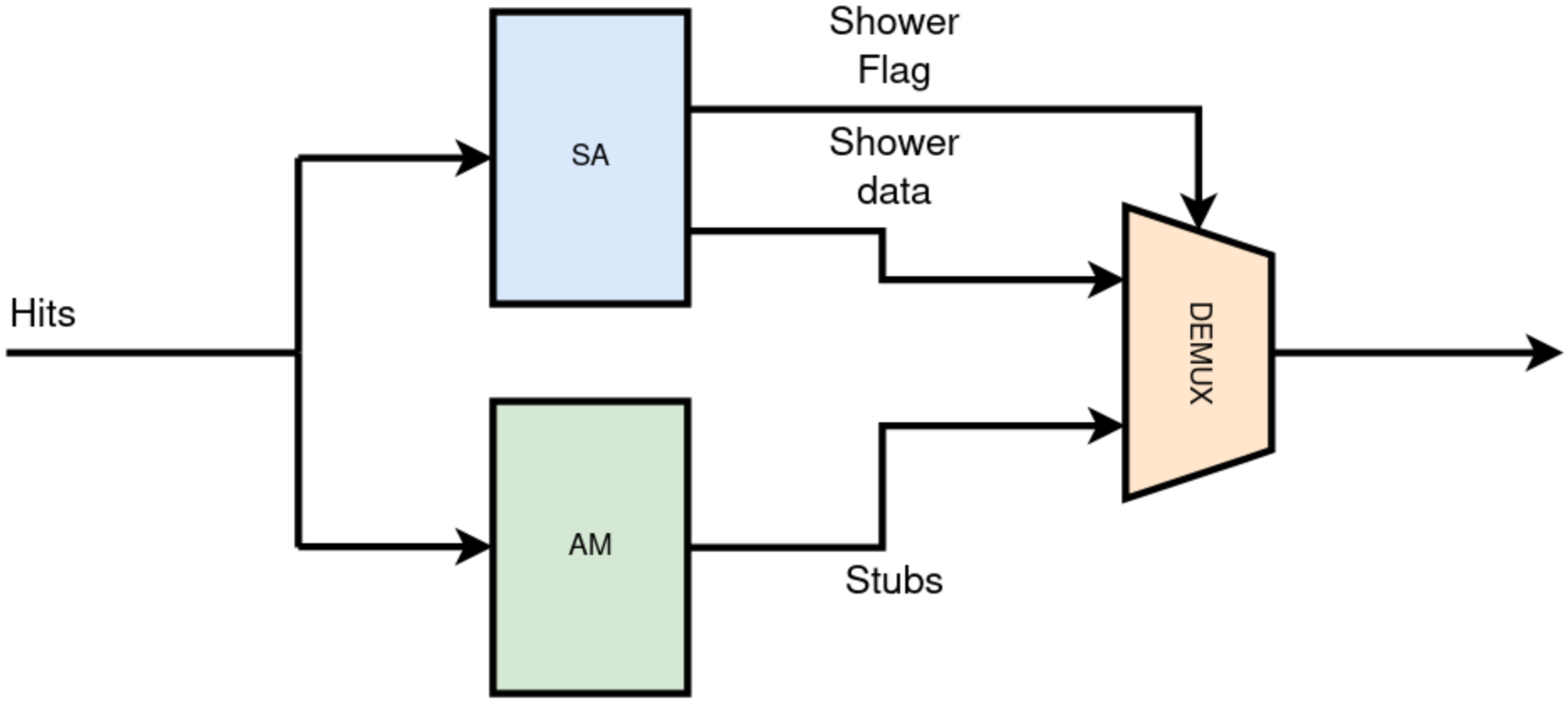
Many active cells

Many possible tracks to calculate!

Waste of time and spurious data

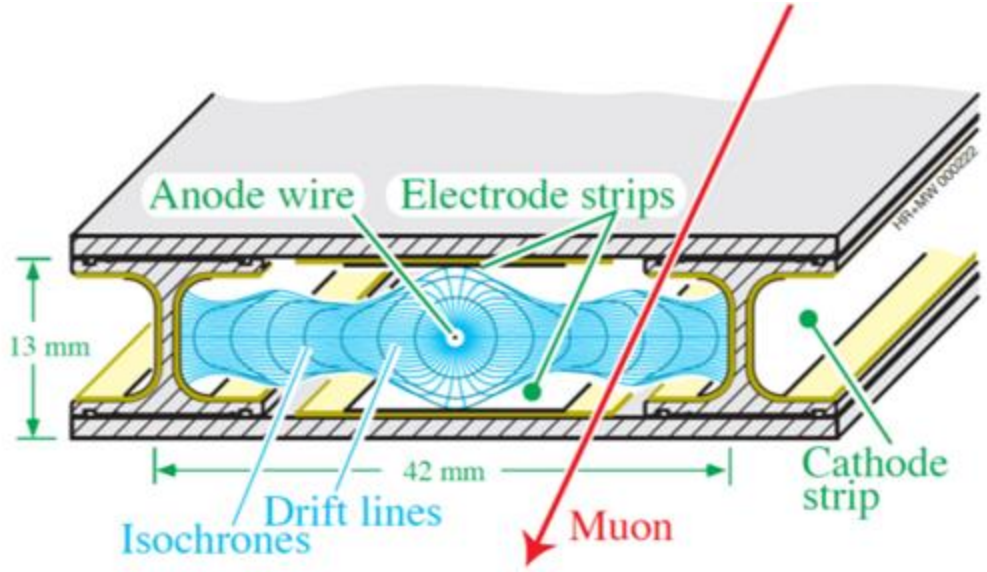
https://doi.org/10.1016/j.nima.2023.168103

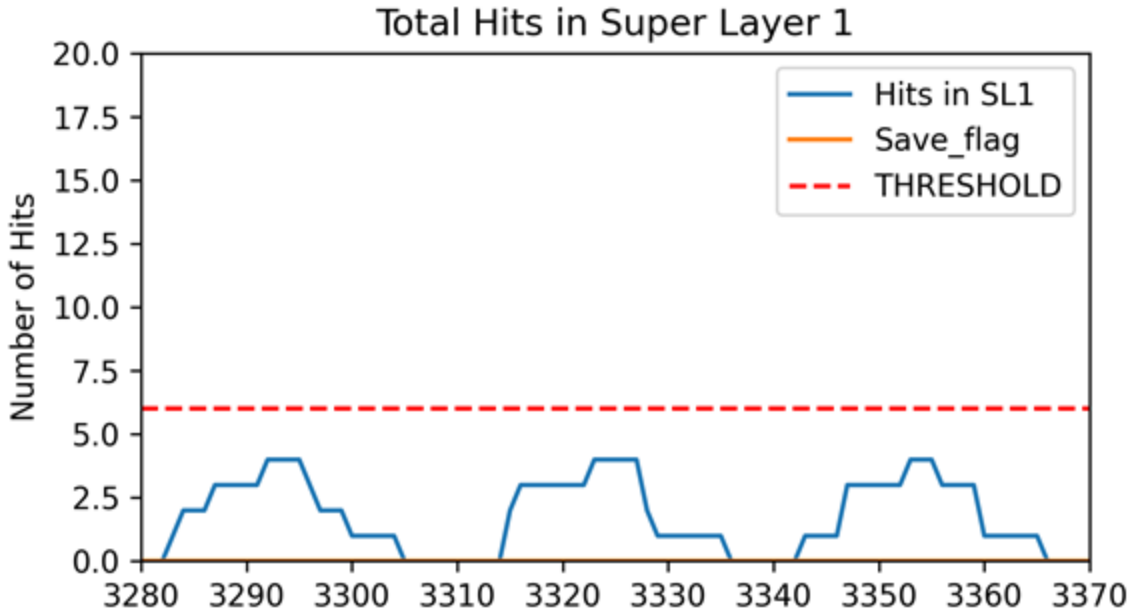
How can we solve this?

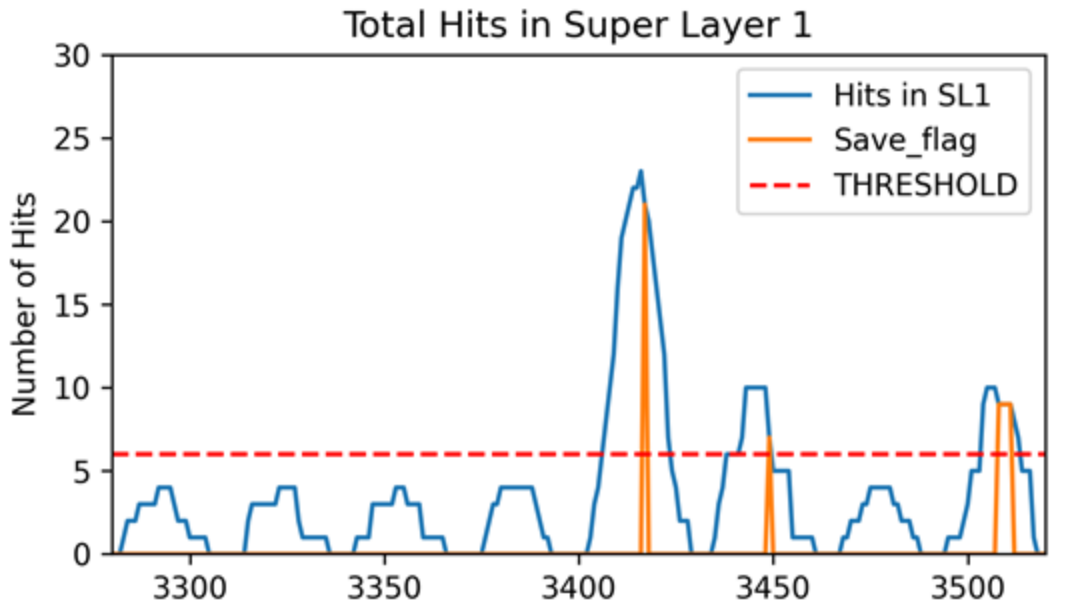


Shower identification algorithm

- Each hit is stored for 16 BXs (400ns) to account for their drift times
  - Hits are received serially
- We can represent the total amount of hits in a given superlayer over time
  - When the accumulated hits exceed a threshold, stop AM
  - When maximum detected, store hits to identify a shower (position, time,…)

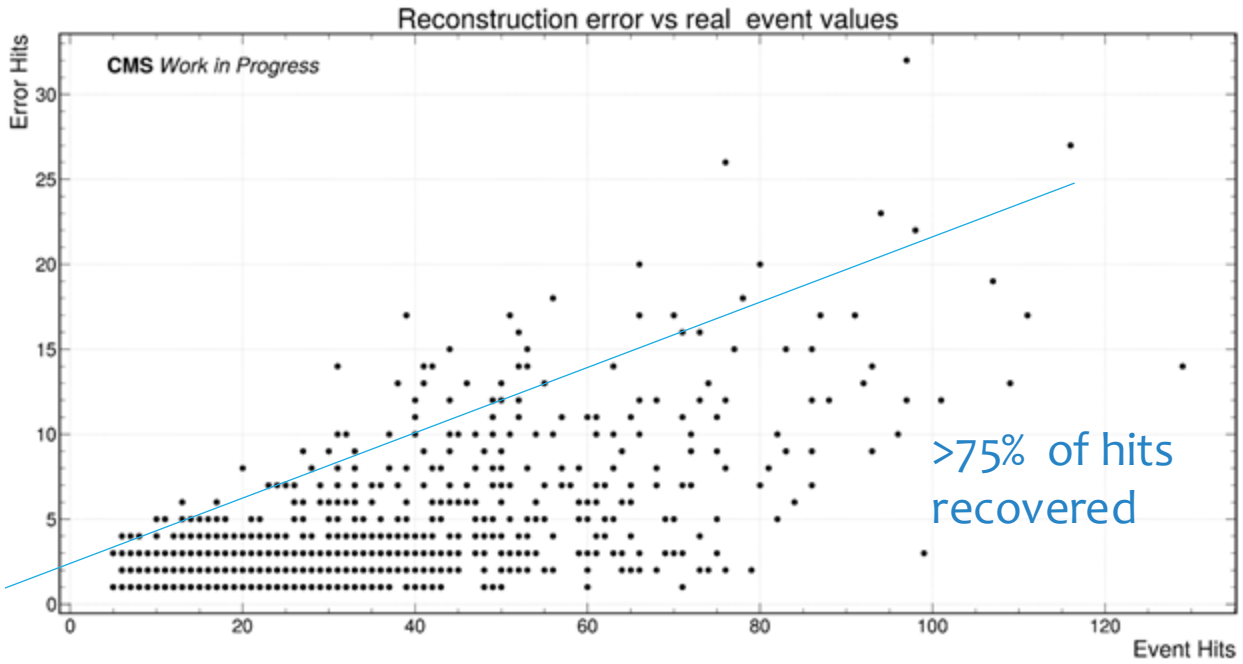


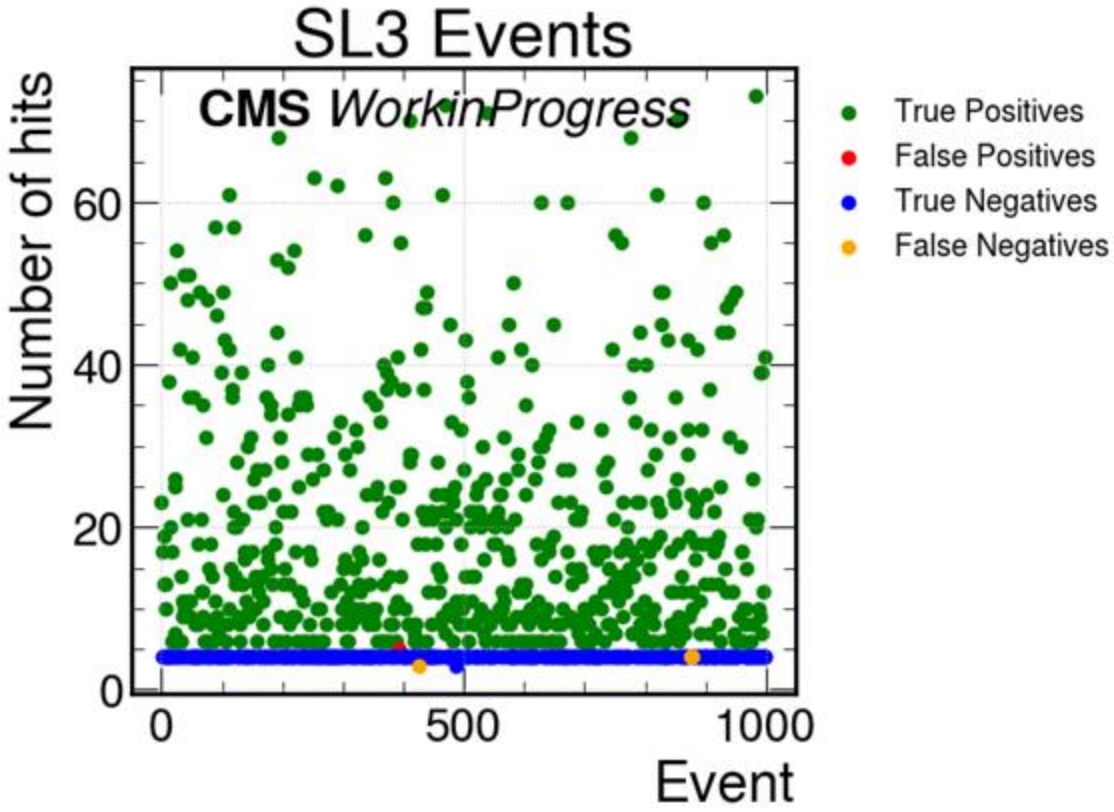




Algorithm performance

- Generated 1000 muons (2 TeV) on a custom Geant-4 simulator of a DT station.
  - > 99% of the events are correctly tagged
  - < 0,07% of the events are mis-tagged
- On average, 88% of the hits corresponding to a shower are recovered





Firmware implementation

Resource consumption with xcvu13p:

Site Type	Used	Available	Util%
CLB LUTs	7038	1728000	0.41
CLB Registers	9995	3456000	0.29
CARRY8	180	216000	0.08
F7 Muxes	72	864000	<0.01

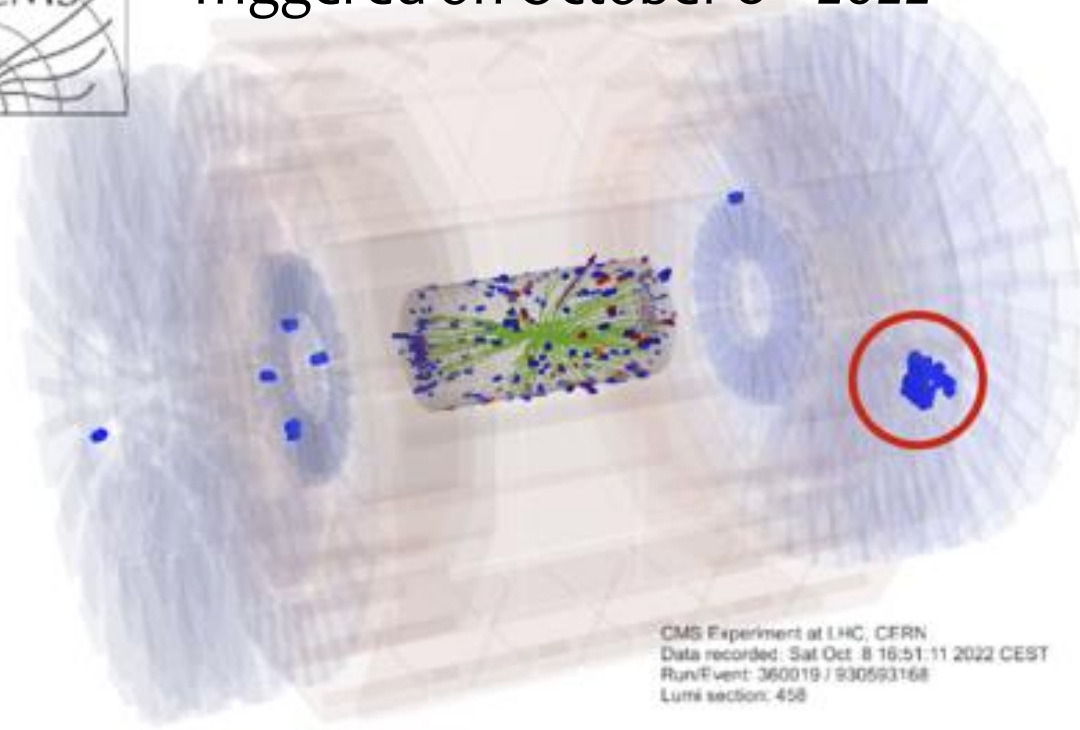
- Firmware implemented with 480MHz clock timing
- Comparisons with emulation in agreement.

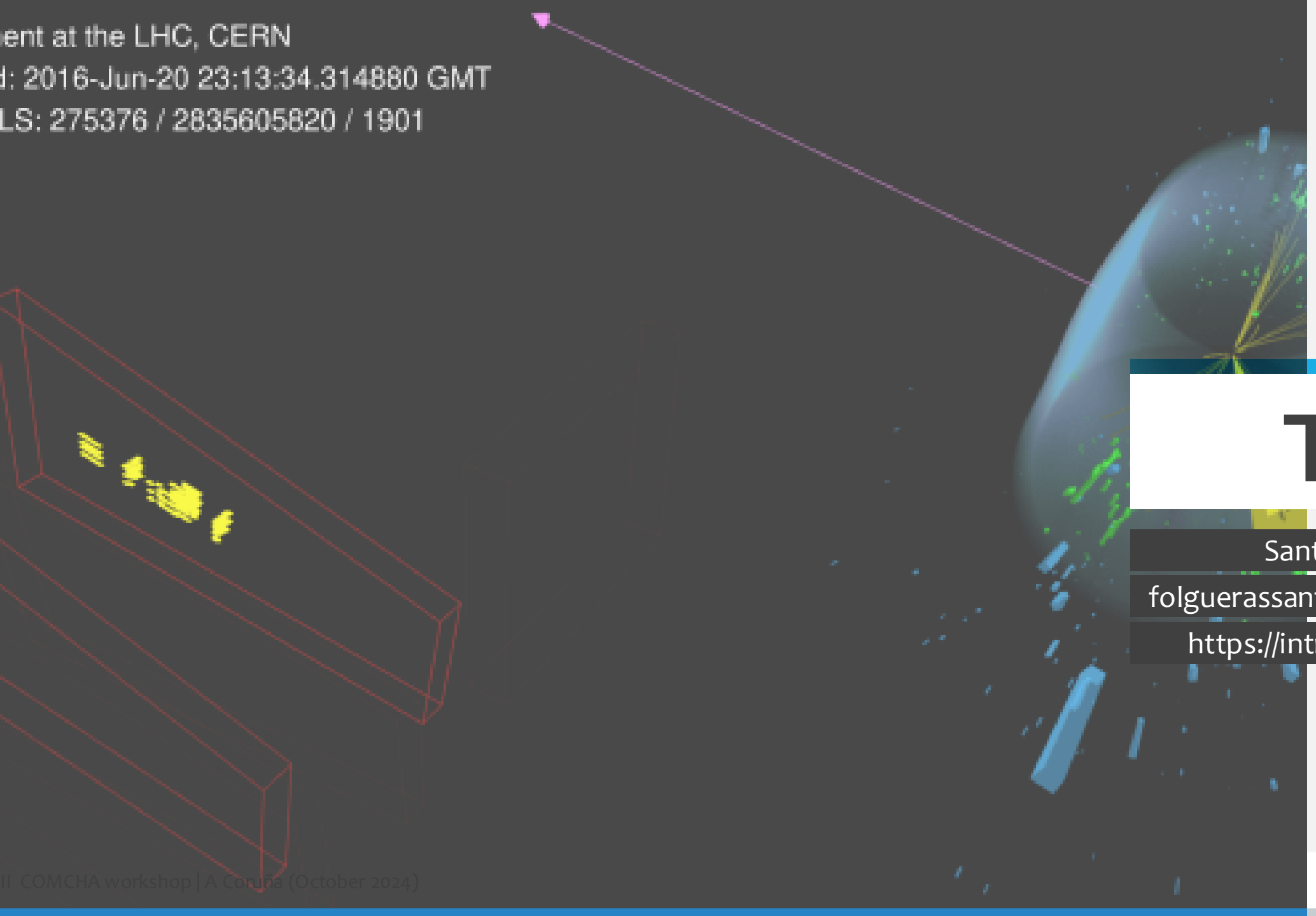
- Next steps:
  - Determine position and time
  - Integrate together with the AM on a single board and check performance

Conclusions

- Muon showers appear naturally in events with high-momentum muons and result into trigger inefficiencies. They could also appear as a hint of long-lived particles decaying far from the interaction point.
- Excellent opportunity or new physics discovery
- Such events will be missed by the trigger system unless we do something.
- We have designed a first version of such an algorithm that allows to tag showers with close to 100% accuracy.
- Work is being presented at TWEPP and was also shown at ICHEP 2024.

Triggered on October 8th 2022





Funded by the European Union

European Research Council
Established by the European Commission

INTREPID

Thanks!

Santiago Folgueras

folguerassantigo@uniovi.es

https://intrepid.uniovi.es/

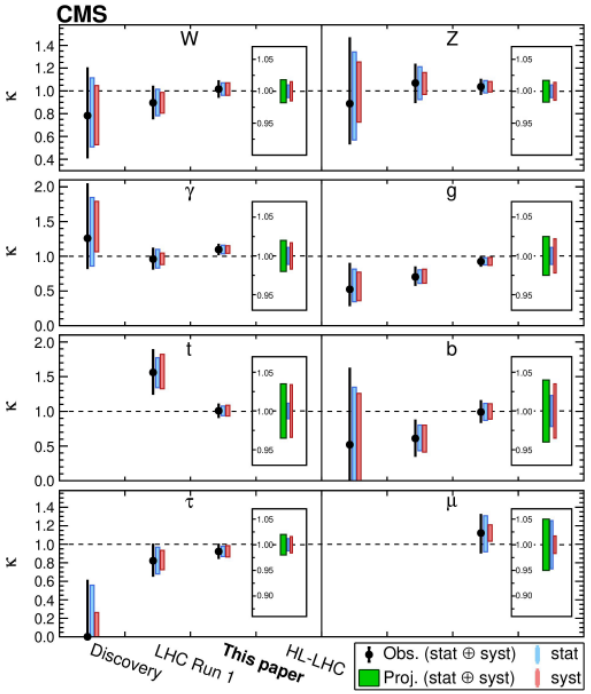
Where to look for new physics?

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

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

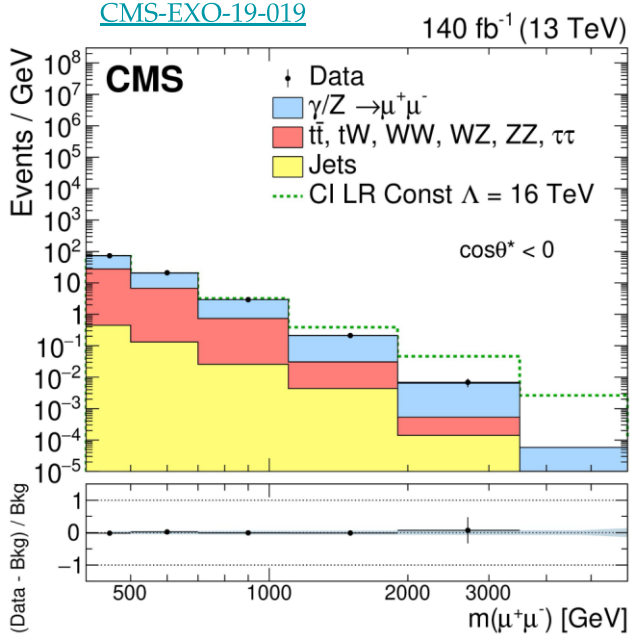
Search for deviations at high momenta (*i.e. Effective Field Theories*)

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

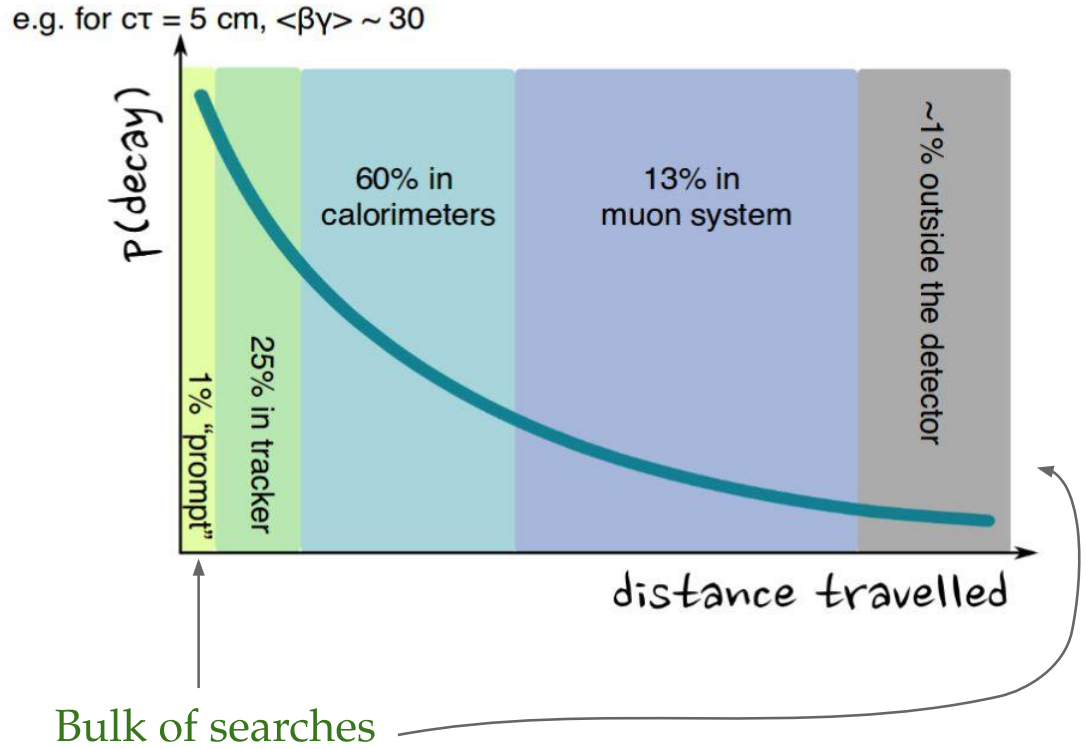


Nature 607, 60–68 (2022)

CMS-EXO-19-019



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



From A. Escalante @ICTEA Seminar

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

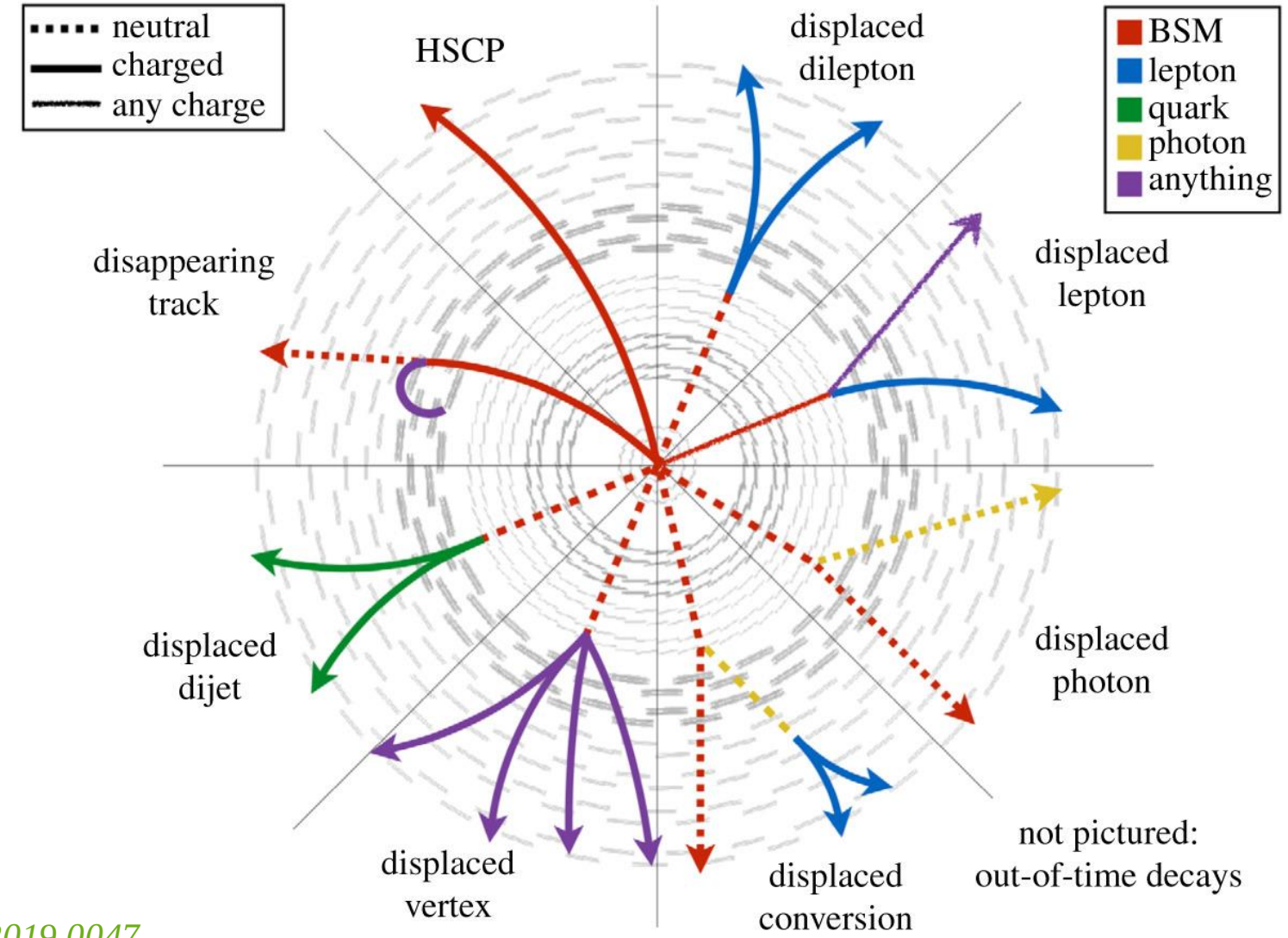
- Feebly (small) couplings
- Large mass hierarchies/ heavy mediators
- Small mass difference or "compressed spectra"

Three reasons why is hard

- Low rates
- Large energies (LHC inaccessible)
- Low efficiency (soft particles/limited object reconstruction)

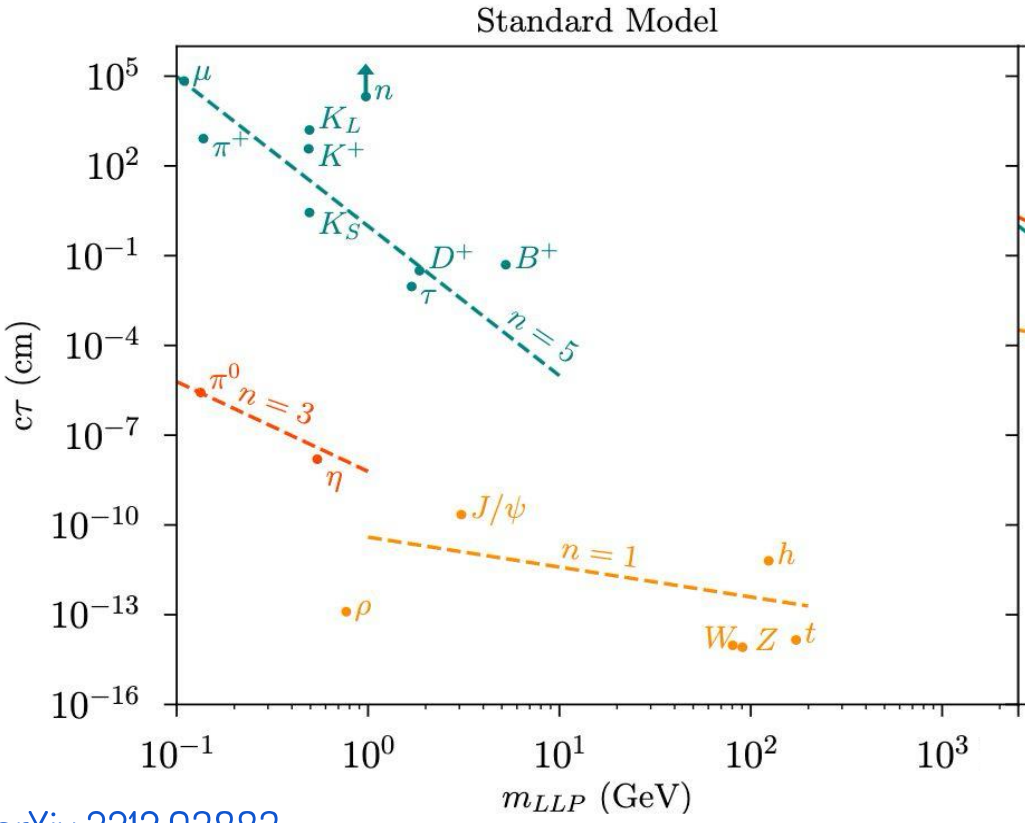
2

Experimental signatures of long-lived particles



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

Why long-lived particles?



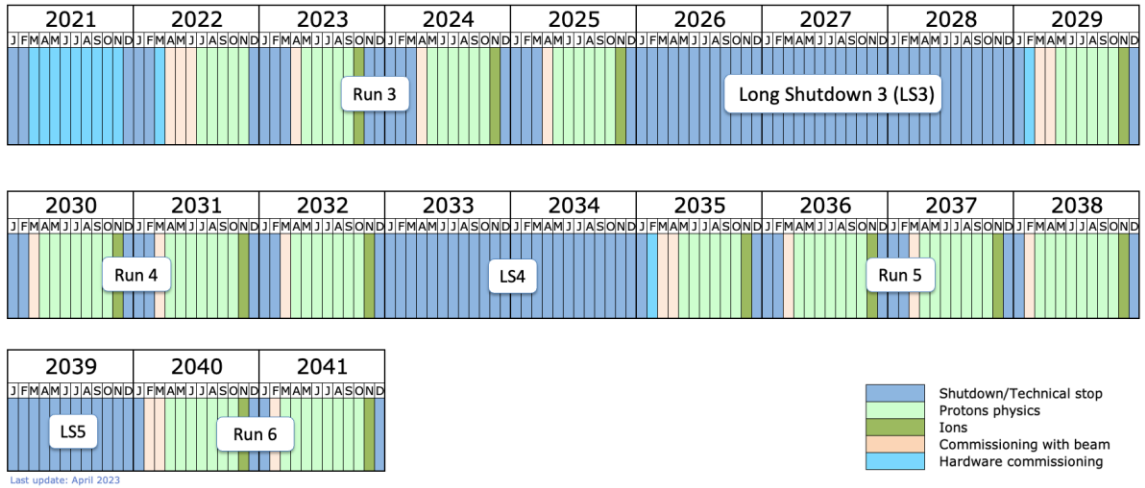
arXiv:2212.03883

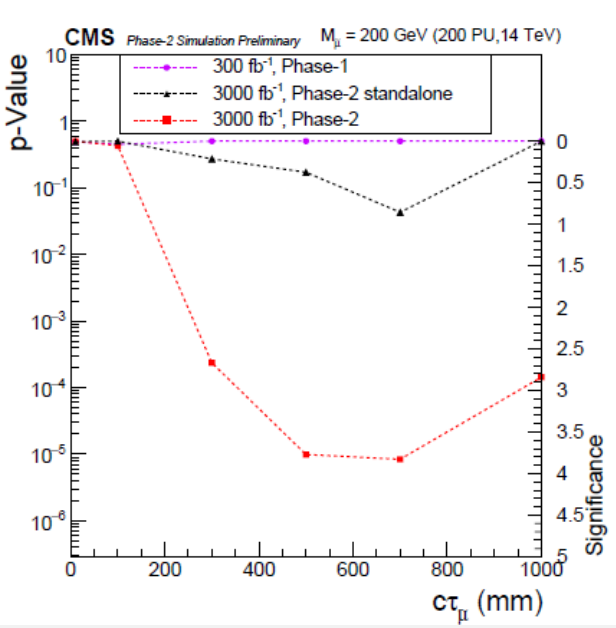
- The SM is full of LLPs:
  - muon ($\tau = 2.2\mu s$)
  - Kaon ($c\tau$(K+) = 3.71 m
  - Heavy flavour
    - $c\tau$(D+) = 311.78 μm
    - $c\tau$(B+) = 491.06 μm
- There is no reason to believe they won't be present on BSM theories.

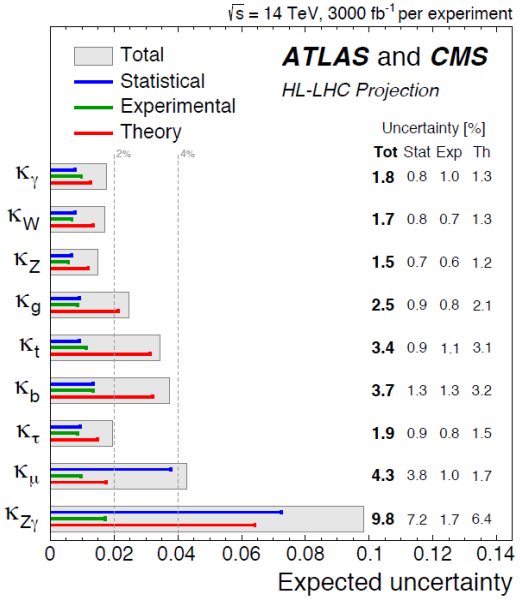
From A. Escalante @ICTEA Seminar

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 ($H \to \mu\mu$) or production modes (HH) previously unseen at the LHC.
- However, this physics program will have to overcome **significant challenges** to succeed.







Conclusions