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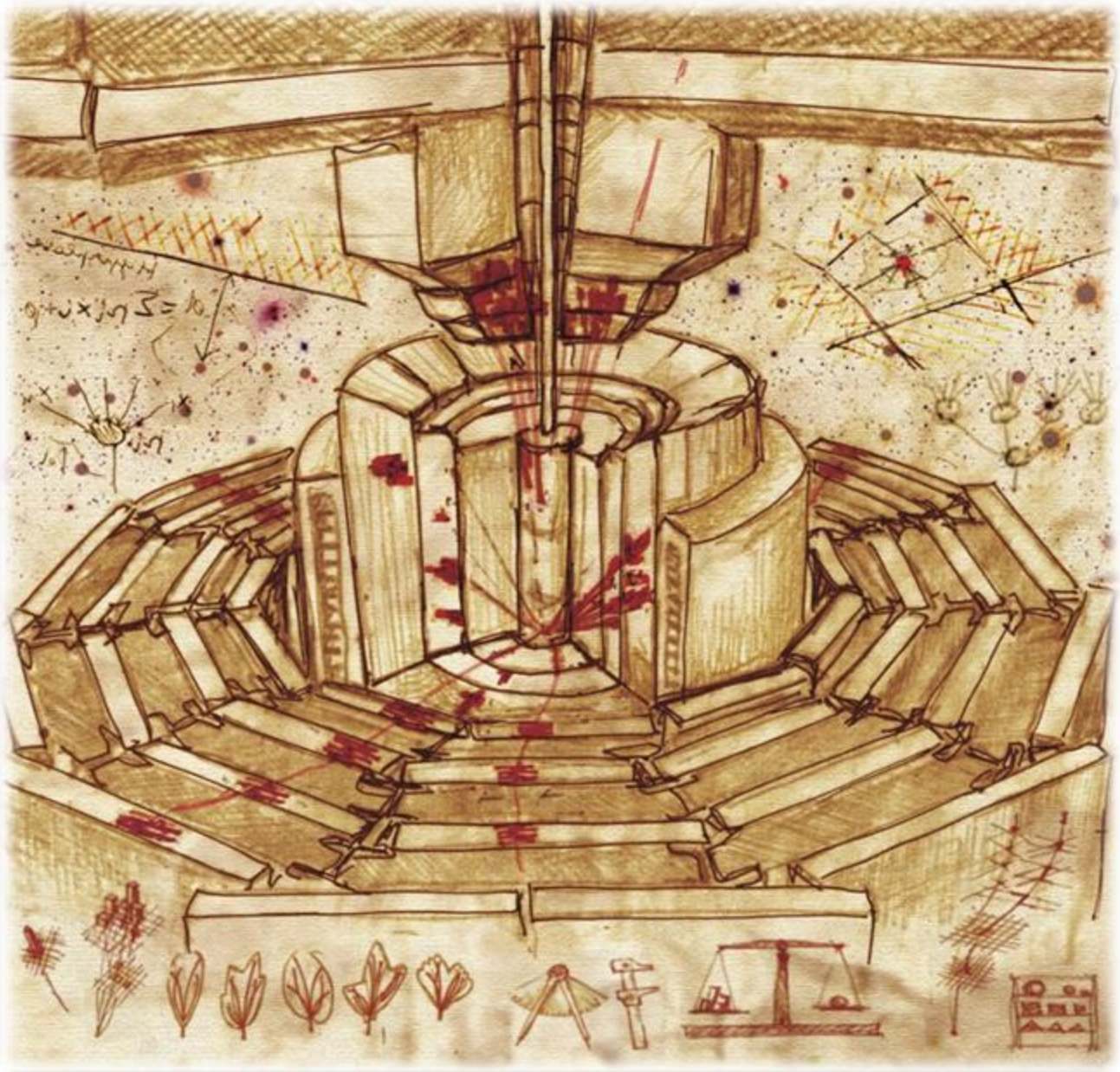
# INnovative TRiggEr techniques for beyond the standard model PhysIcs Discovery at the LHC

TWO YEAR JOURNEY



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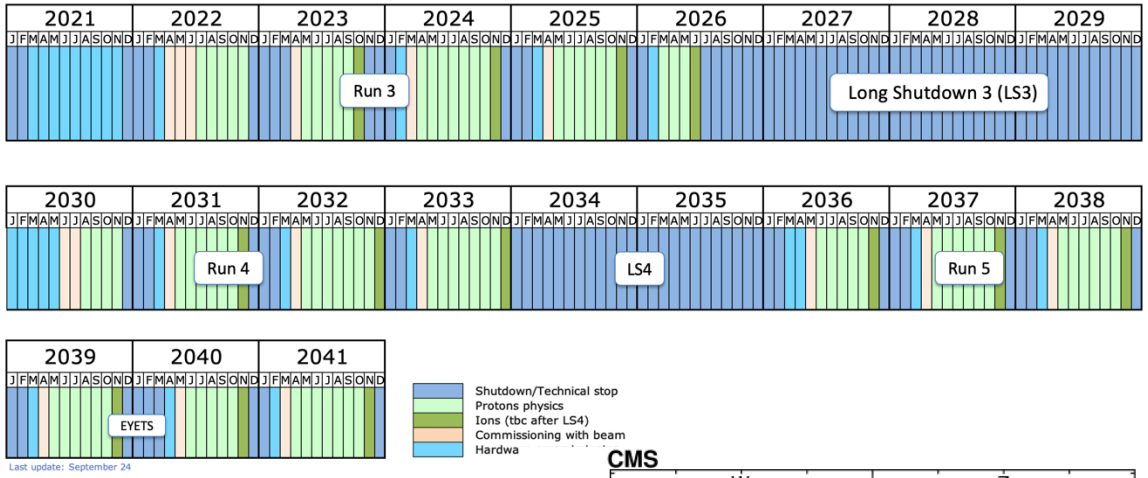
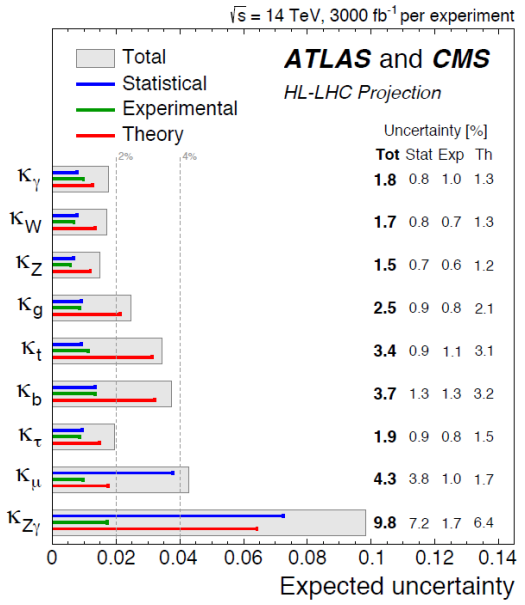
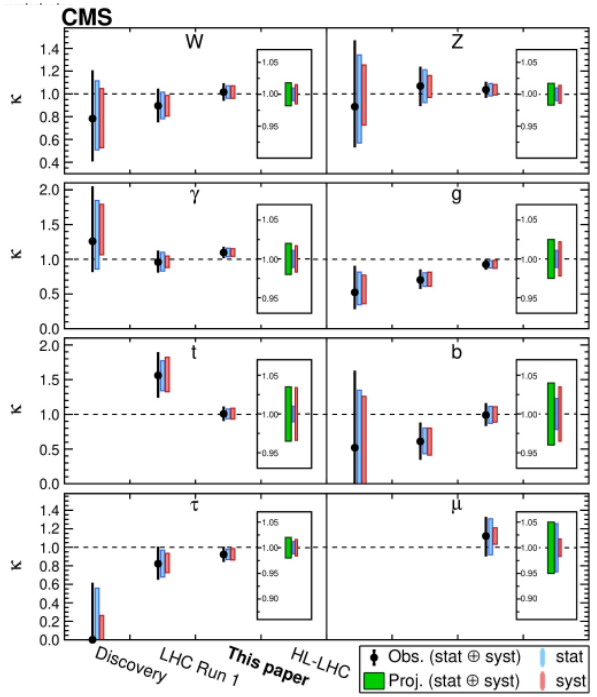
# Towards the HL-LHC

- Preparing for the big upgrade of the LHC detectors, starting 2026.
- HL-LHC upgrade offers an unprecedented opportunity to explore uncharted lands and achieve scientific progress.
  - 8 times more data to what we will have by the end of Run 3 will facilitate a rich physics program.
- 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.
  - Search for deviations at high momenta (i.e. Effective Field Theories) or
- Extend reach of new physics searches: unexplored signatures (LLPs, HSCPs… ) or regions of the phase-space will be within reach.




Nature 607, 60–68 (2022)

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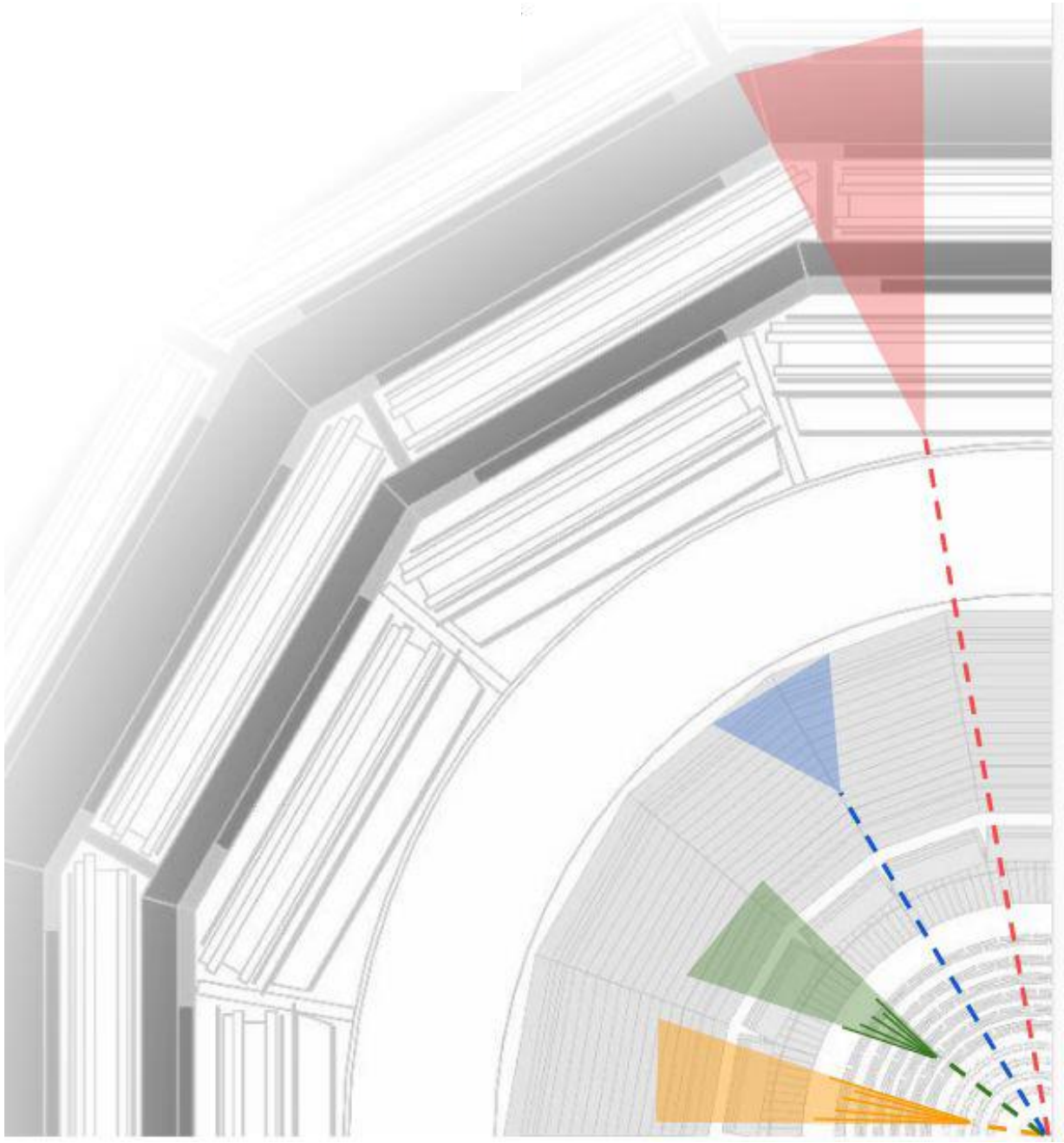
# Yes but…

- Prompt-Optimized Triggers Miss LLPs: Current (Phase-1) L1 trigger system has been designed to select prompt objects from the primary vertex.
  - Searches are (mostly) limited for the L1 acceptance and they need to rely on inclusive triggers such as MET or cross-triggers. Some displaced muon trigger exist in Run-3
- Many models predict the existence of **long-lived particles** (LLPs)
  - Many Exotic scenarios not envisioned when the trigger system was being designed!
- LLPs transit layers at later times, timing information
- LLPs decay far from the interaction point and show displaced signatures
  - Dedicated trigger paths exploiting unique features
  - Displaced jets in the tracker, calorimeters, or muon systems
- Run 3 is the perfect benchmark for "crazy" ideas for HL-LHC



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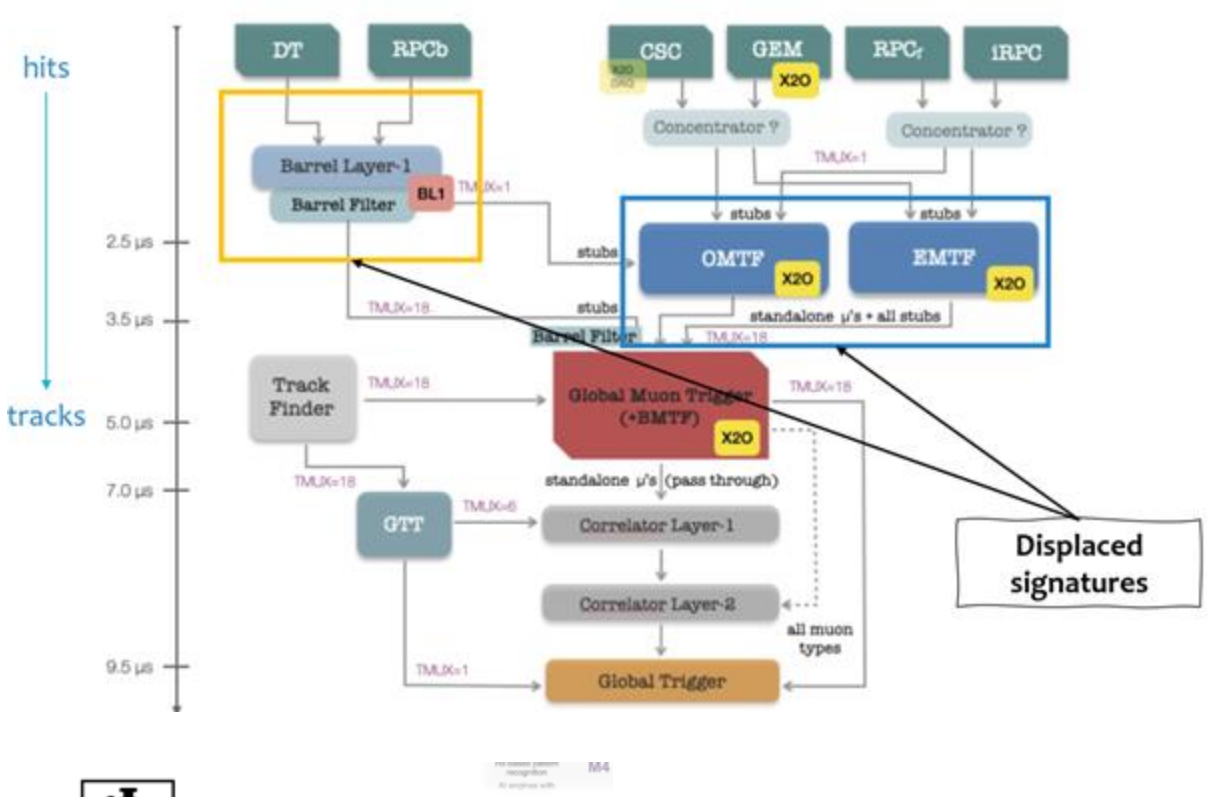
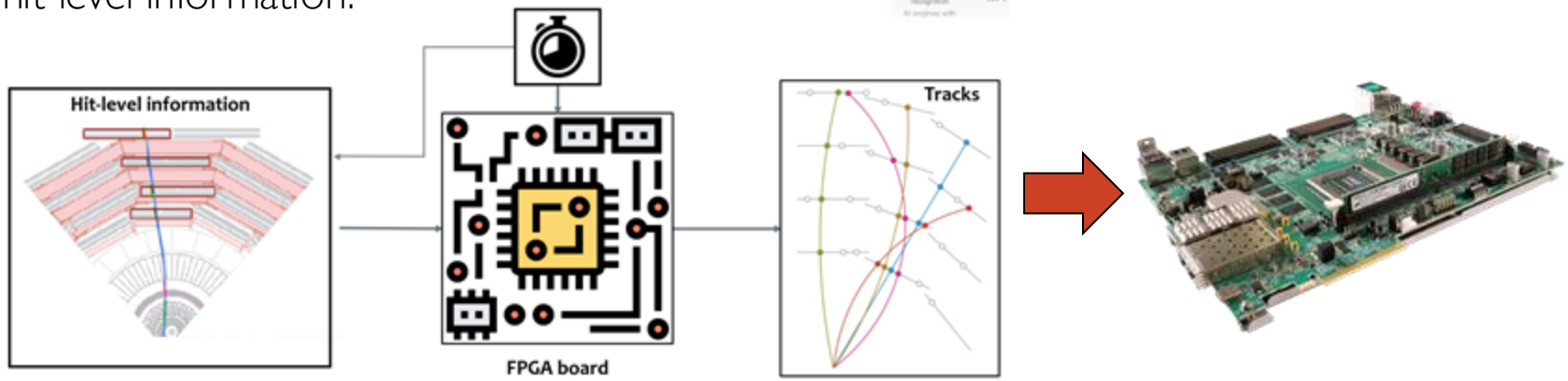
# What are the goals?

- LLP signals might be easily missed or misinterpreted in LHC data.
- Optimizing the techniques within the current architecture to improve detection efficiency without requiring significant hardware upgrades.
- Explore alternative technologies and ideas which could not be otherwise investigated that could potentially lead to a significant breakthrough.
  - Can we profit from using hit-level information?
  - Use of 7nm technology?

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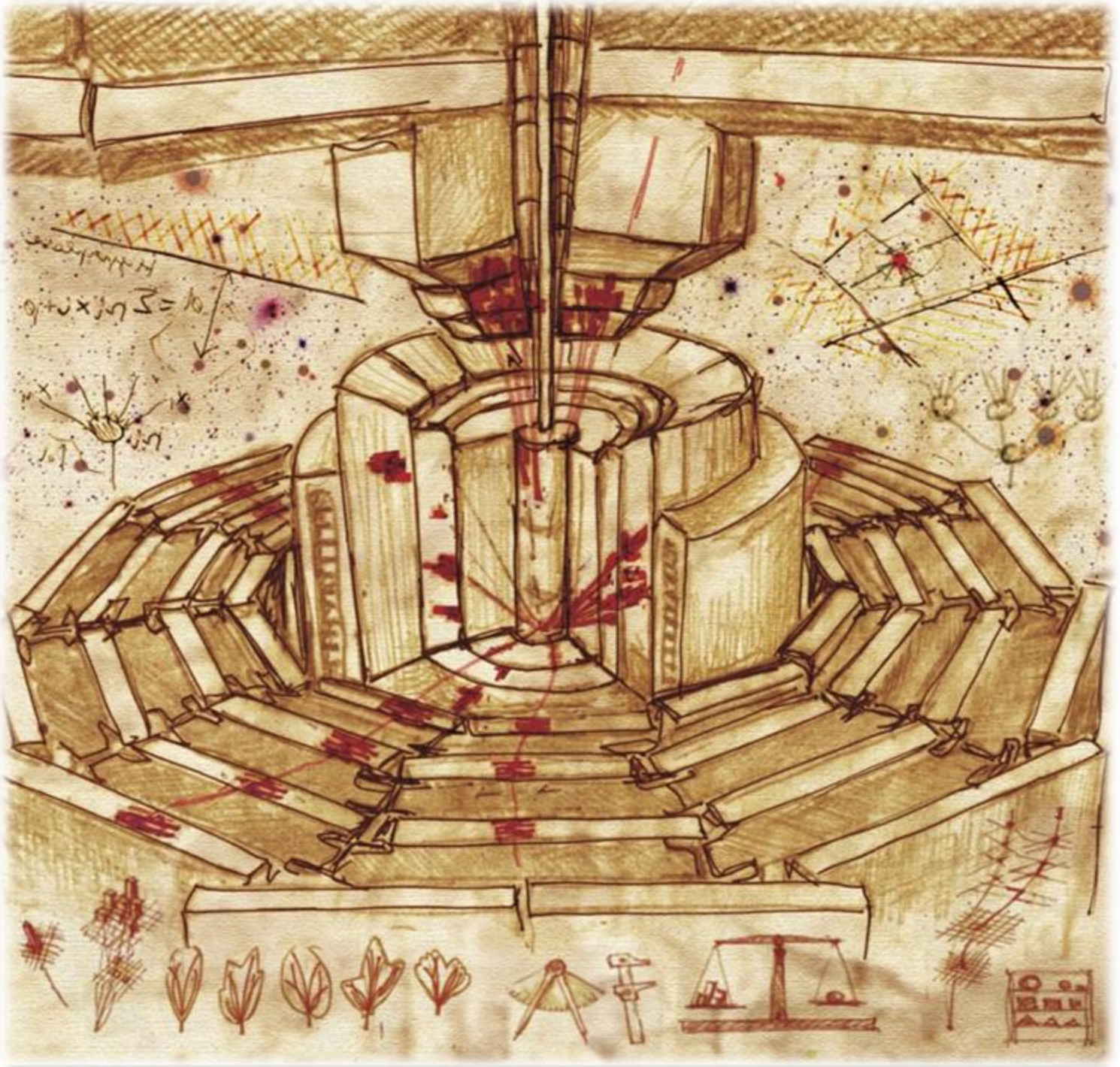
# Using existing architecture



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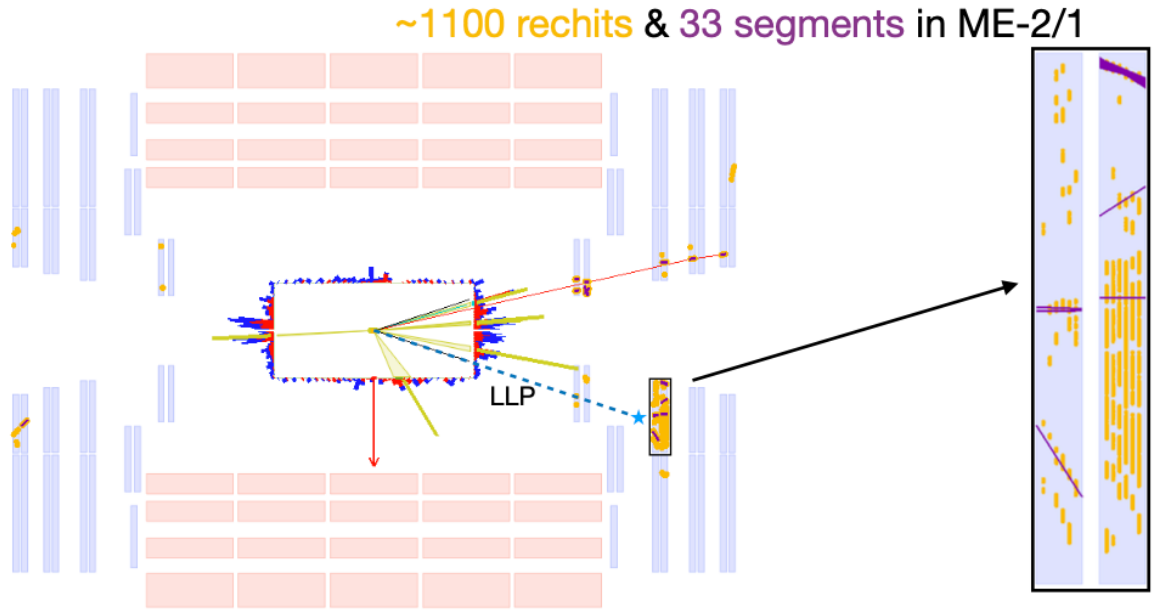
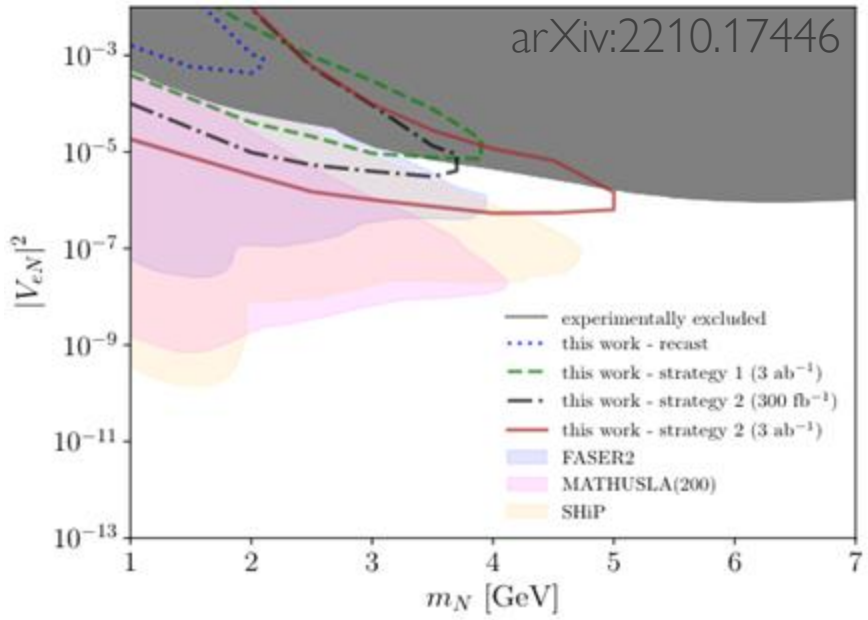
# Displaced jets in the muon system

- 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

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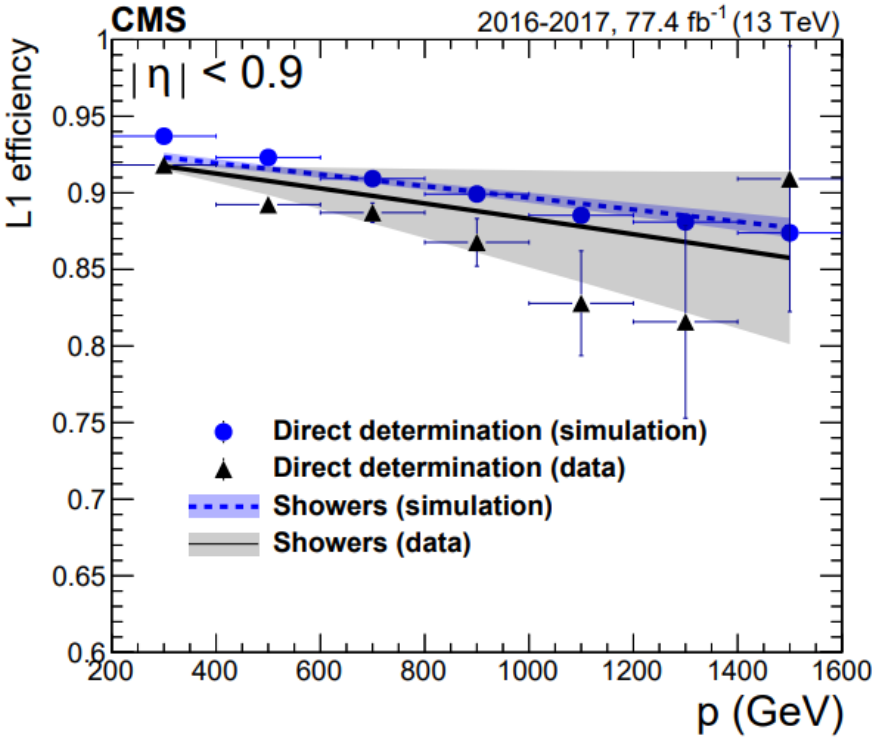
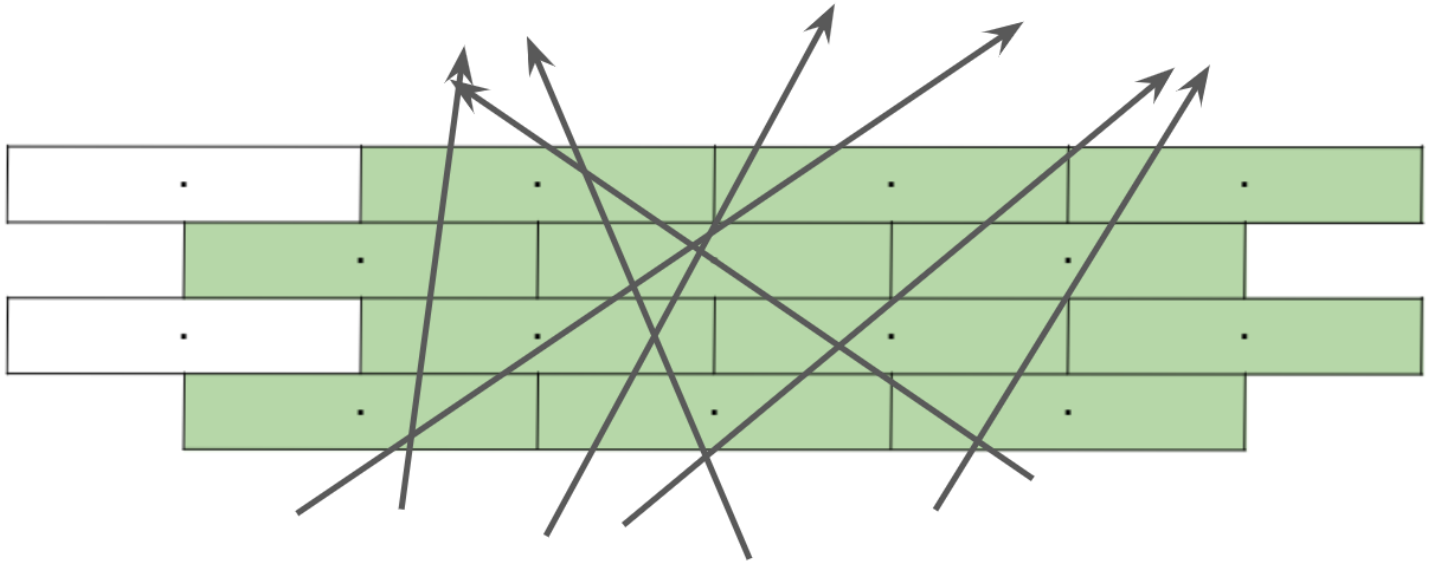
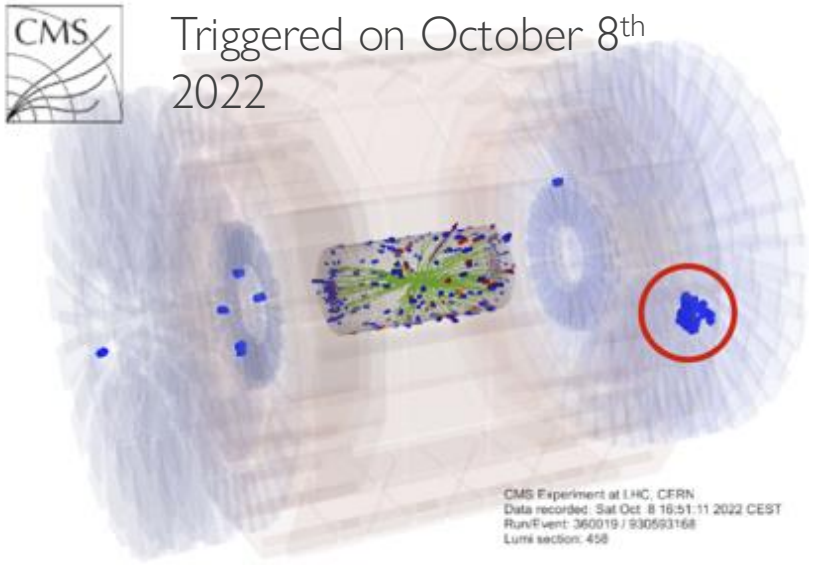
# Triggering on muon showers

- 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 $c\tau \sim (1 - 10\ m)$
- Working algorithm on the CSC (right) and extending it on the barrel for phase-2



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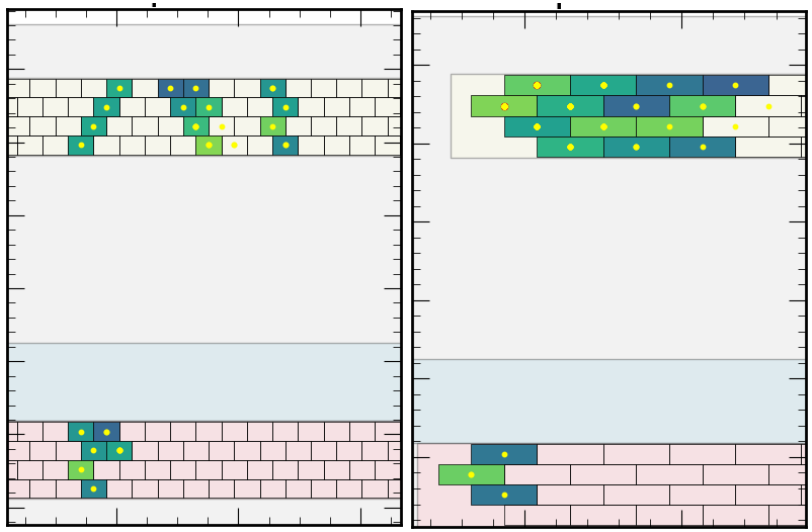
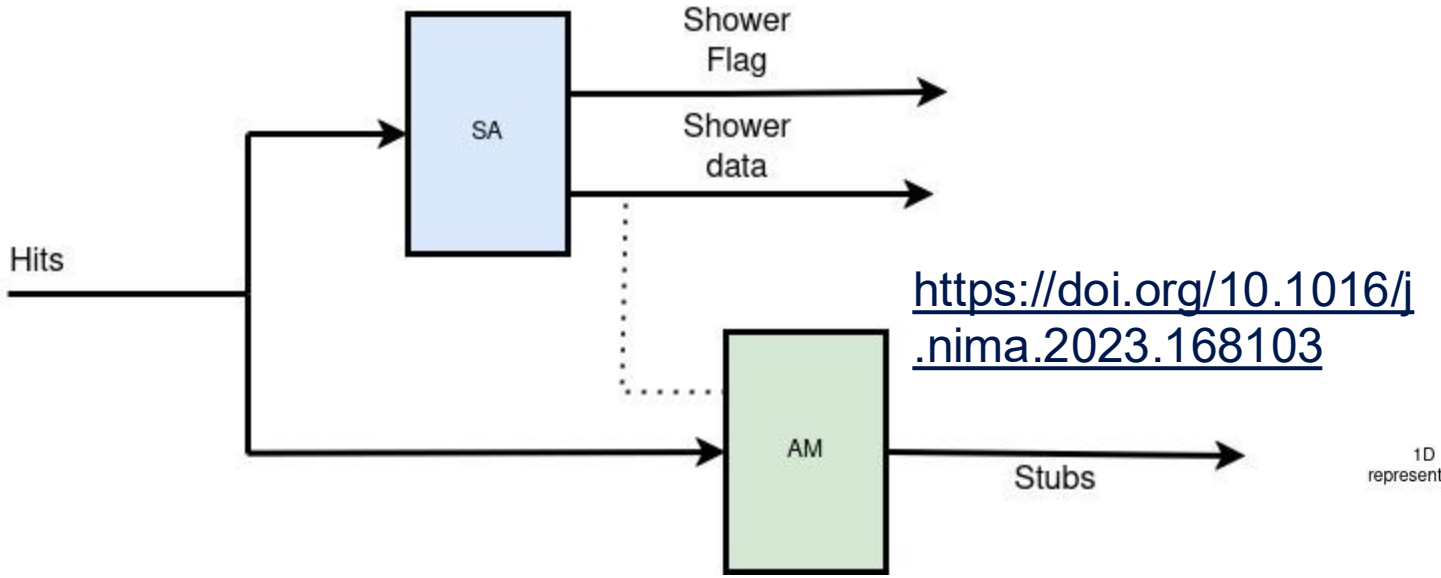
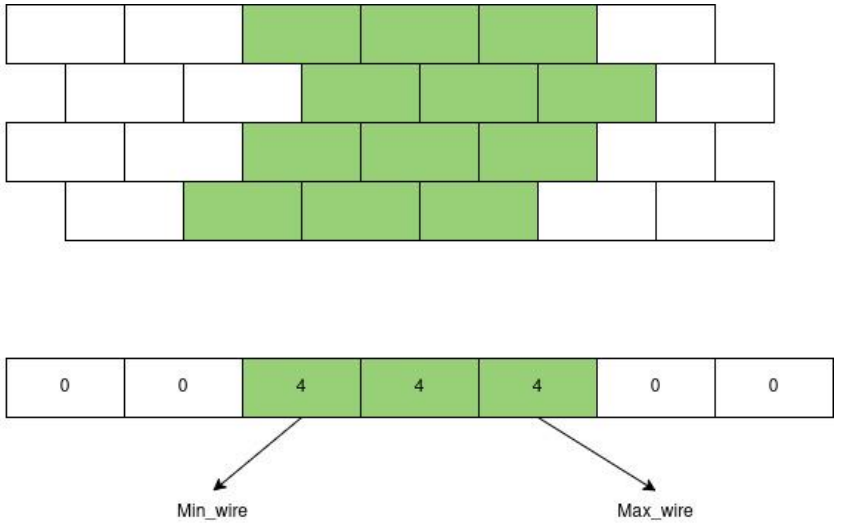
# Triggering on muon showers

- Each hit is stored for 16BXs (400ns) to account for their drift times
- Above the threshold, hits are stored, and the station is labeled as a shower: BX, widtdh, and 1D representation of n° hits.






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

https://doi.org/10.22323/1.476.0930 (ICHEP 2024)

https://iopscience.iop.org/article/10.1088/1748-0221/20/03/C03024/pdf

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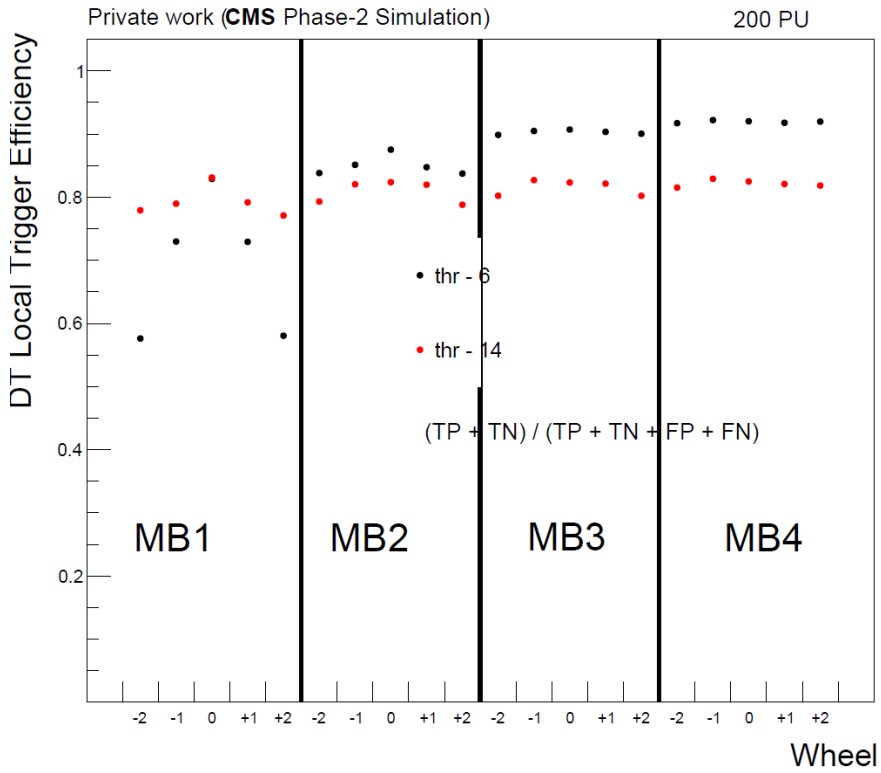
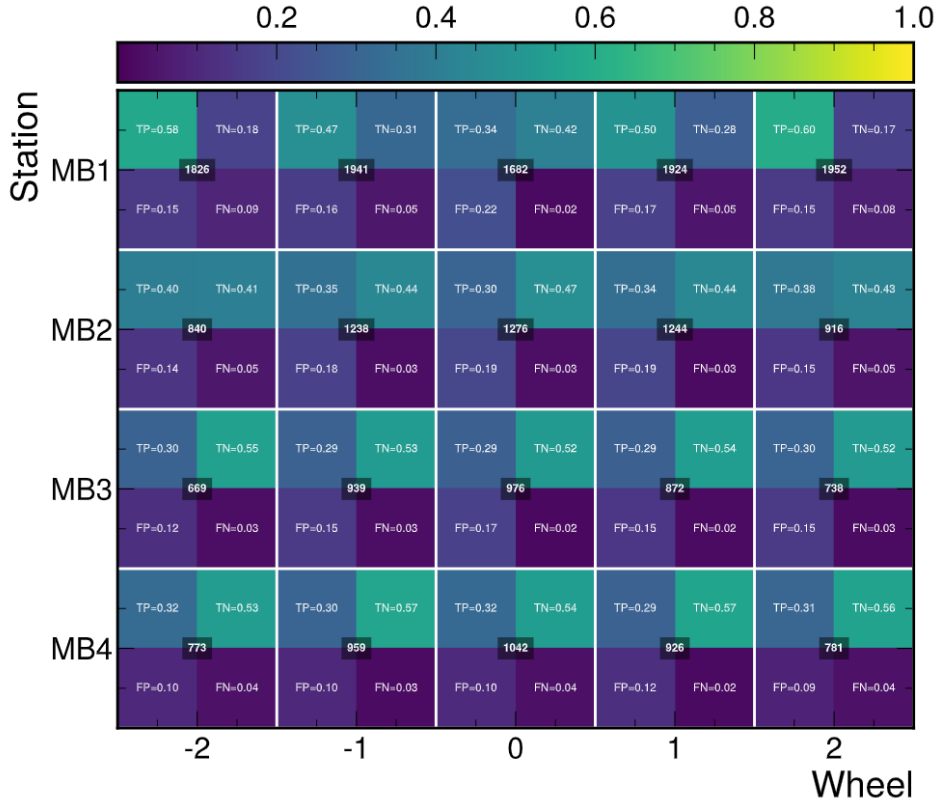
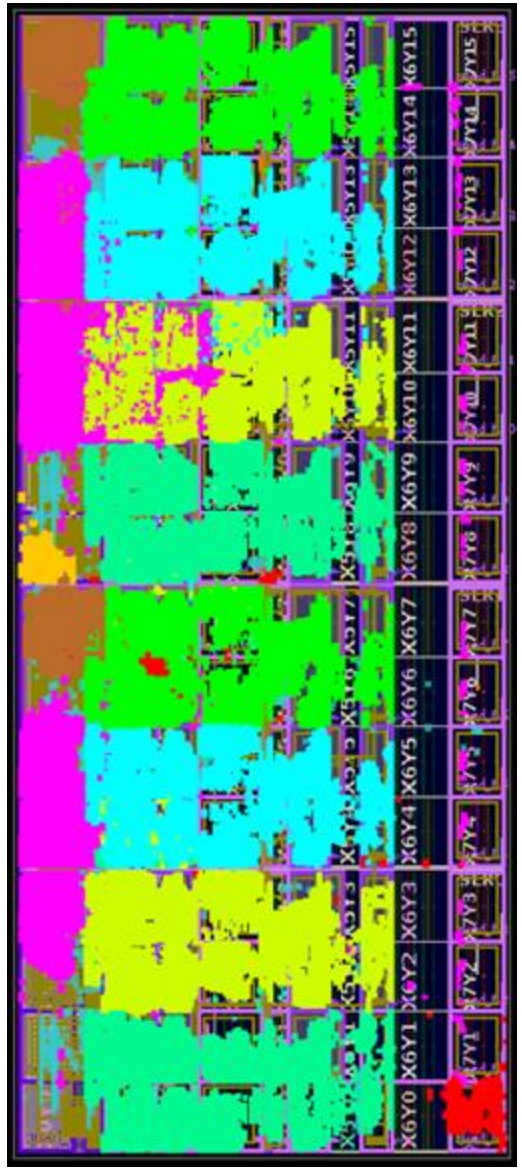
# Triggering on muon showers

- A preliminary firmware algorithm has been developed, with less than 3K LUTS and less than 3K registers for each SuperLayer @480MHz
- Working with CIEMAT to integrate the algorithm with the current firmware and test in on the slice test this year.



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# Contributing to the X20 manufacturing

- Gaining expertise in hardware assembly and testing to provide long-term support to the project.
- Javier Prado is now at UFL helping to assemble the first X20 batch.

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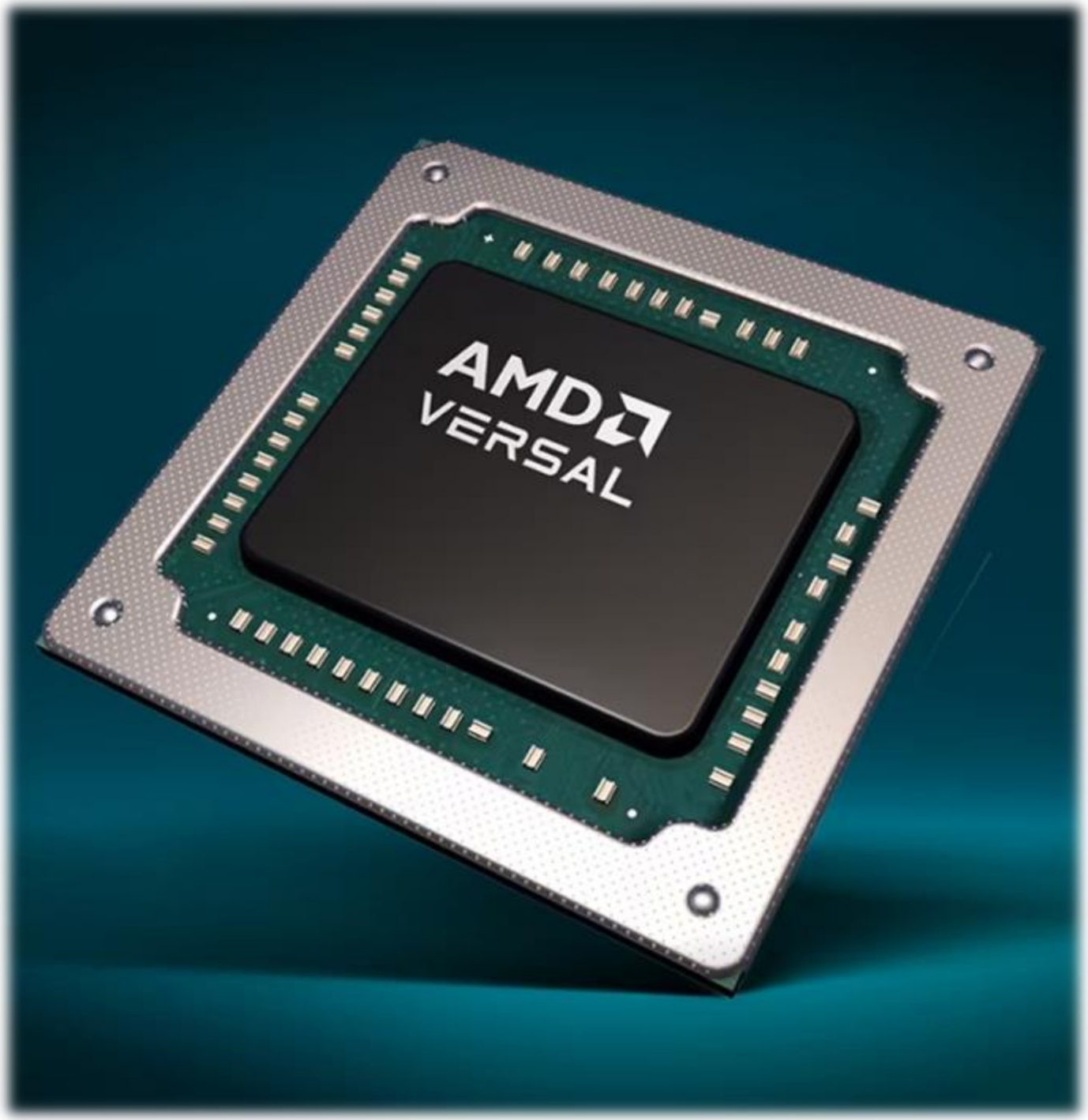
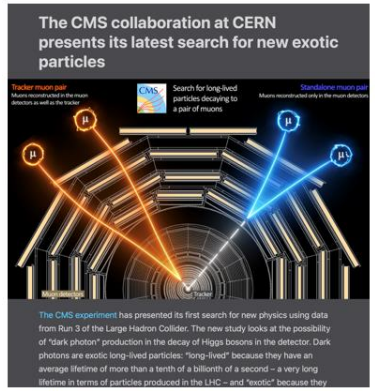
# What else we can do?



# Displaced muons

- Muon detector are located 4-10m away from the interaction point. Unique signature to search for new physics.
- First result in Run-3 data (13.6 TeV) with a strong Spanish contribution.

## 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:

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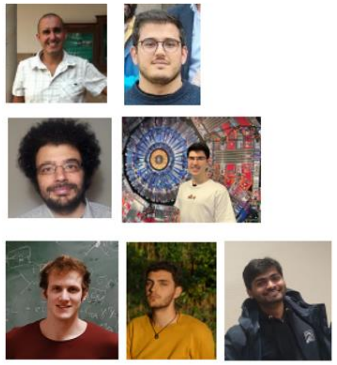
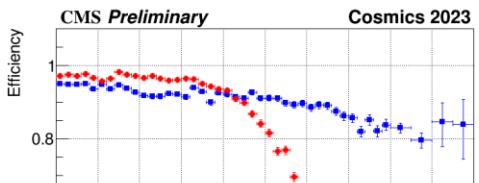
IFCA Instituto de Física de Cantabria

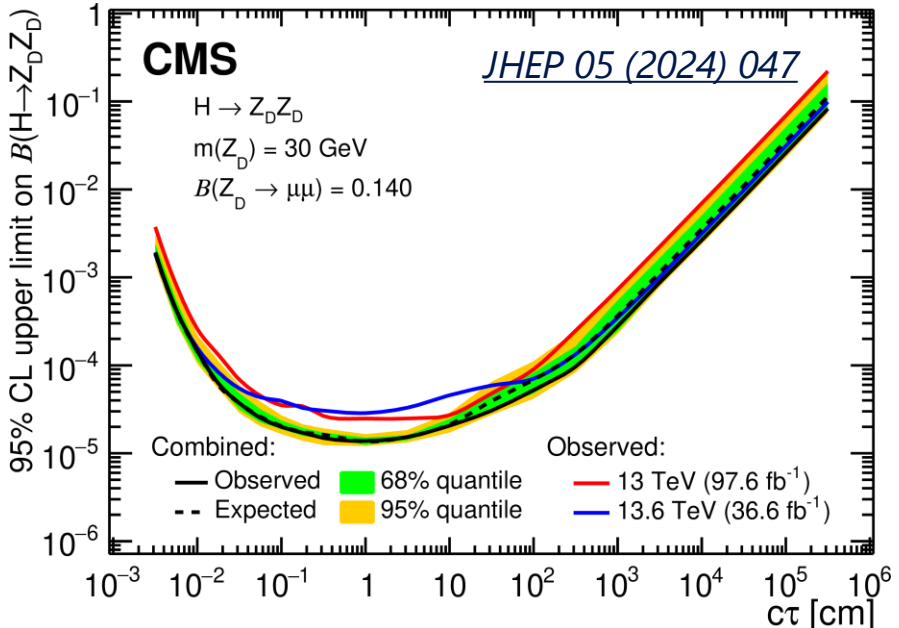
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

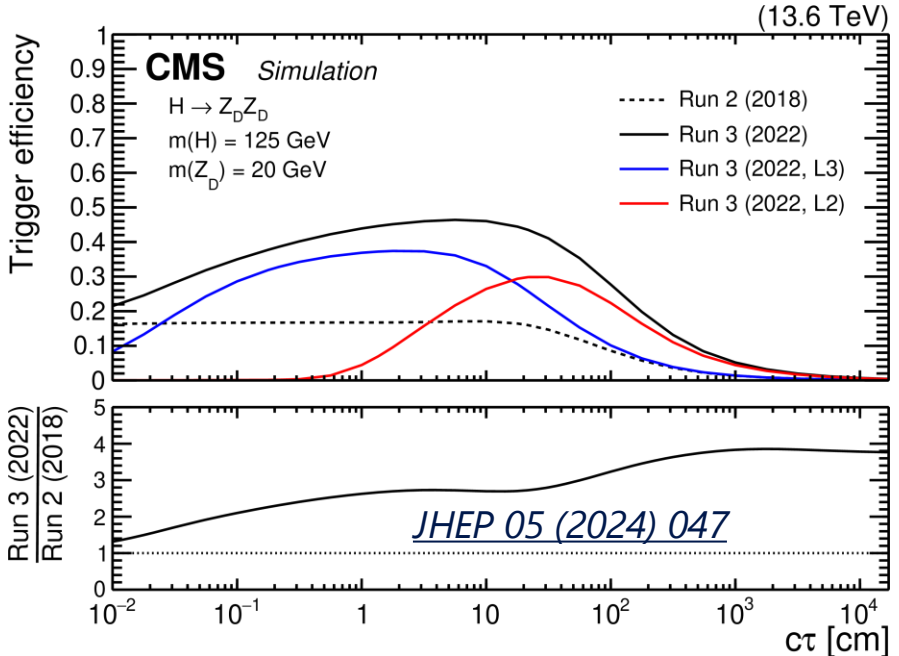














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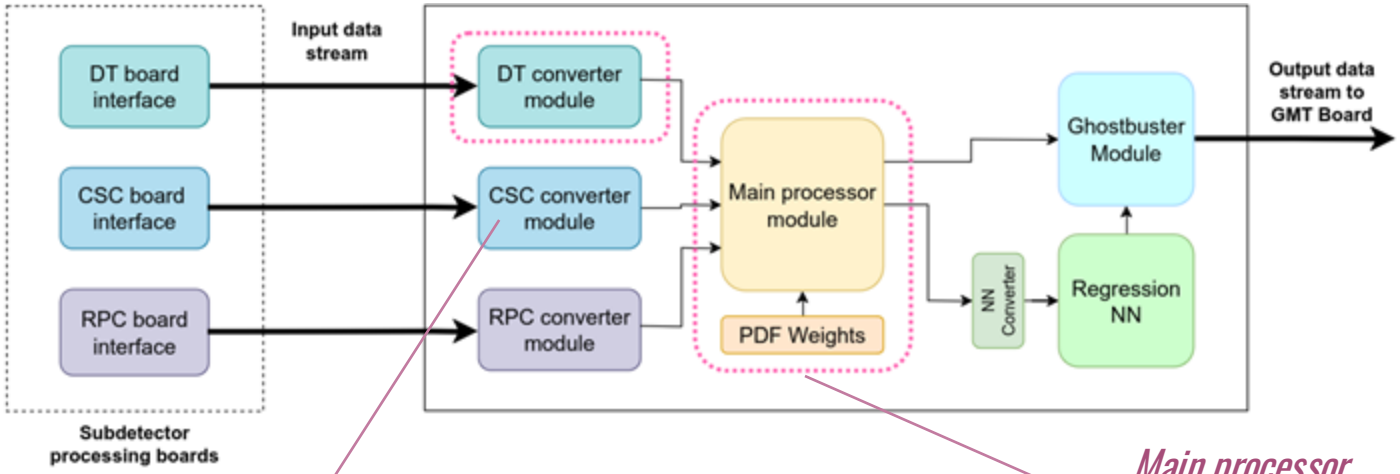
https://doi.org/10.3389/fdest.2024.1502834

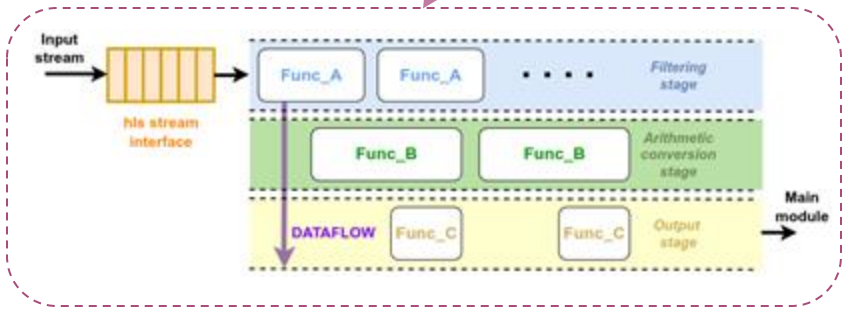
# Firmware development

- Reduction of data load by implementing a zero-suppression approach (Batch processing instead of storing all the possible input data for each single event)
- We take advantage of the streamed inputs coming from the different subdetectors.

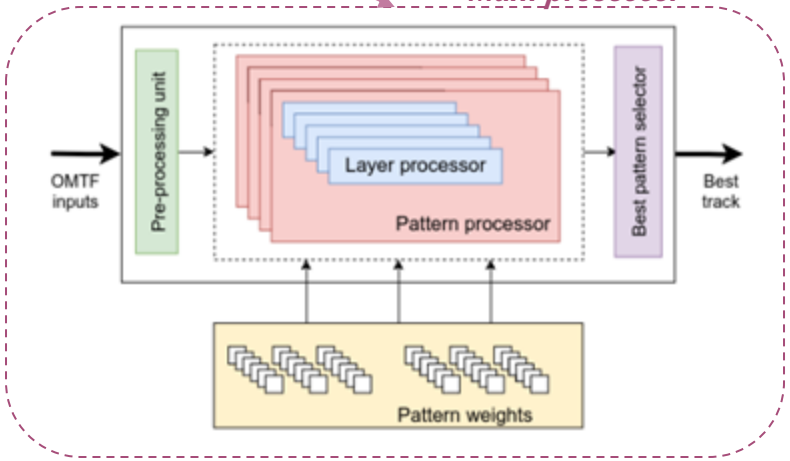
*General scheme*




*Input converting modules*




*Main processor*




> Manage streamed data.

> Parse data frames.

> Parallel “golden pattern” processing.

> Stored weights reshaped for simultaneous availability.

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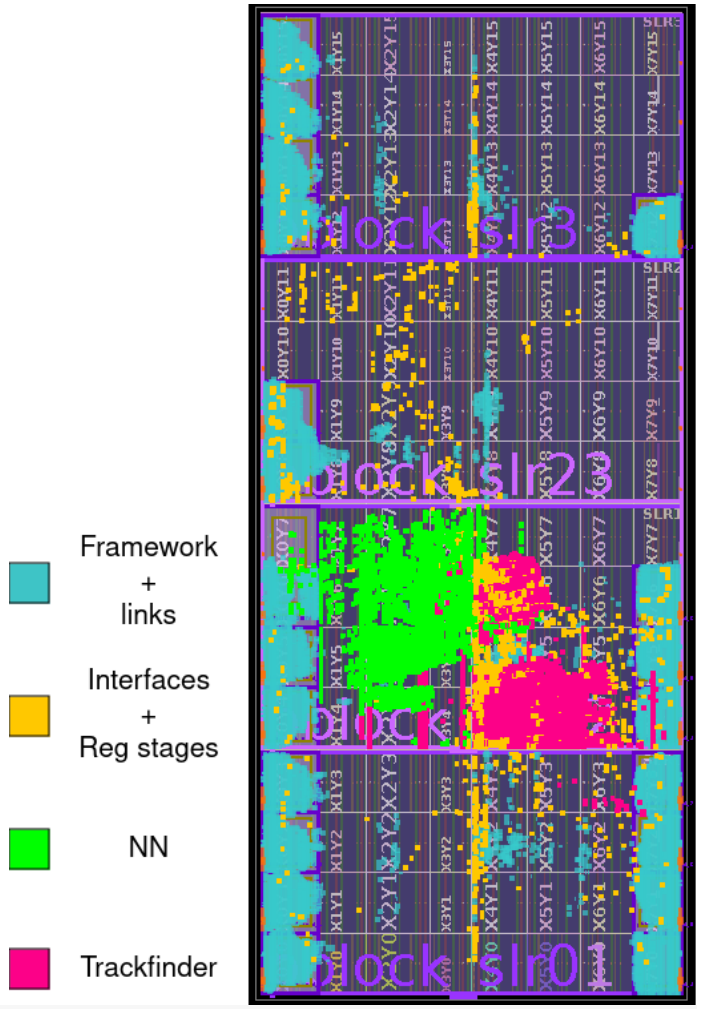
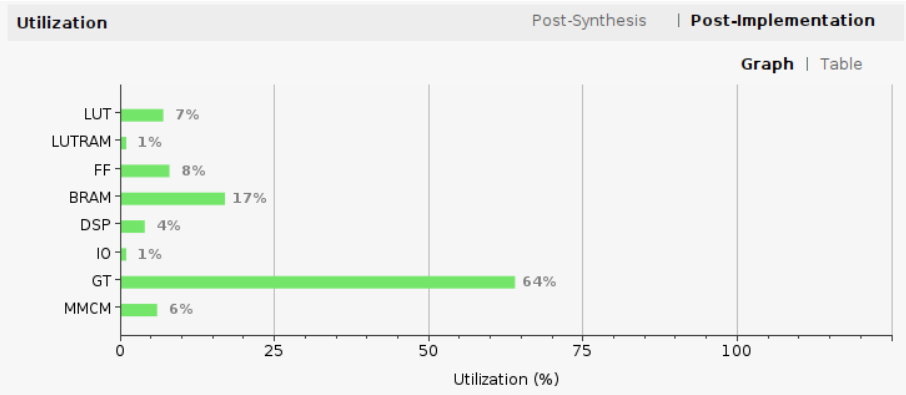
# Firmware development

- Latest implementation of the OMTF Phase-2 firmware on VU13P, including the 65 CSC links + 15 DT instantiated.
- No module is forced to be placed in a particular region
- Getting ready to do Slice tests at 904




| Resource | Utilization | Available | Utilization % |
|---|---|---|---|
| LUT | 113848 | 1728000 | 6.59 |
| LUTRAM | 4522 | 791040 | 0.57 |
| FF | 280379 | 3456000 | 8.11 |
| BRAM | 447.50 | 2688 | 16.65 |
| DSP | 450 | 12288 | 3.66 |
| IO | 2 | 448 | 0.45 |
| GT | 82 | 128 | 64.06 |
| MMCM | 1 | 16 | 6.25 |

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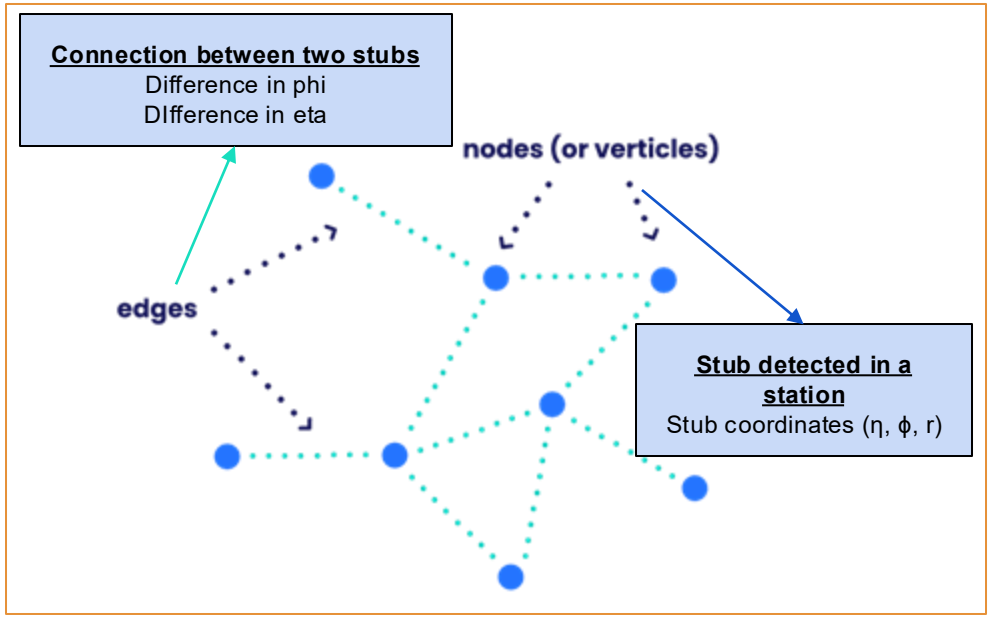
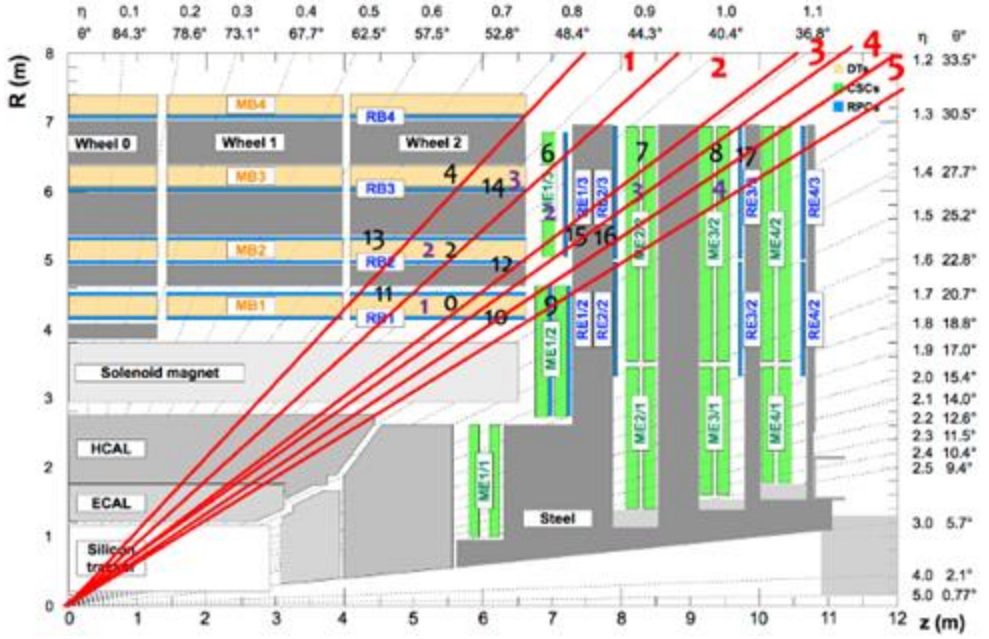
# Conceptual design

Designing a basic network:

- Each node is a stub on a detected layer (DT, RPC, CSC).
  Edges represent the difference in η-ϕ between stubs.
- For now only regress momentum, either q·pT or q/pT
- Target OMTF as it has the most complex detector topology

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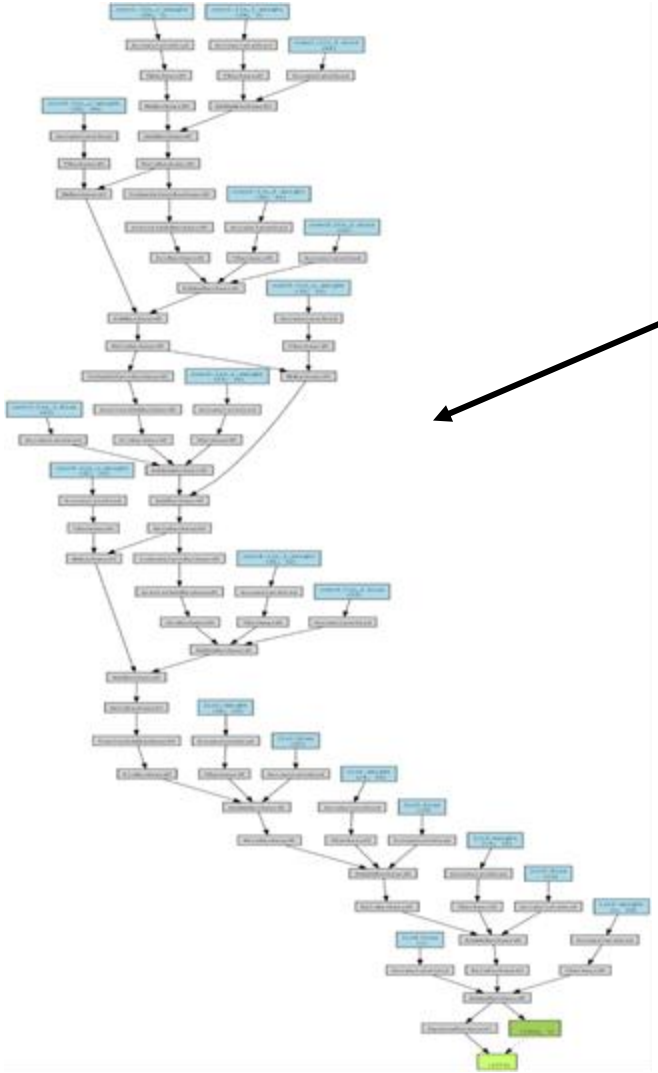
# Model configuration. Designing a “basic” network



```
GraphSAGEModel(
  (conv1): SAGEConv(3, 128, aggr=mean)
  (conv2): SAGEConv(128, 64, aggr=mean)
  (conv3): SAGEConv(64, 64, aggr=mean)
  (conv4): SAGEConv(64, 64, aggr=mean)
  (lin1): Linear(in_features=64, out_features=64, bias=True)
  (lin2): Linear(in_features=64, out_features=32, bias=True)
  (lin3): Linear(in_features=32, out_features=32, bias=True)
  (lin4): Linear(in_features=32, out_features=1, bias=True)
)
MPLNNRegressor(
  (conv1): MPL()
  (conv2): MPL()
  (conv3): MPL()
  (conv4): MPL()
  (lin1): Linear(in_features=128, out_features=128, bias=True)
  (lin2): Linear(in_features=128, out_features=16, bias=True)
  (lin3): Linear(in_features=16, out_features=16, bias=True)
  (lin4): Linear(in_features=16, out_features=1, bias=True)
  (lin5): Linear(in_features=128, out_features=128, bias=True)
  (lin6): Linear(in_features=128, out_features=16, bias=True)
  (lin7): Linear(in_features=16, out_features=16, bias=True)
  (lin8): Linear(in_features=16, out_features=1, bias=True)
  (global_att_pool1): AttentionalAggregation(gate_nn=Sequential(
    (0): Linear(in_features=64, out_features=1, bias=True)
  ), nn=None)
  (global_att_pool2): AttentionalAggregation(gate_nn=Sequential(
    (0): Linear(in_features=64, out_features=1, bias=True)
  ), nn=None)
)
```

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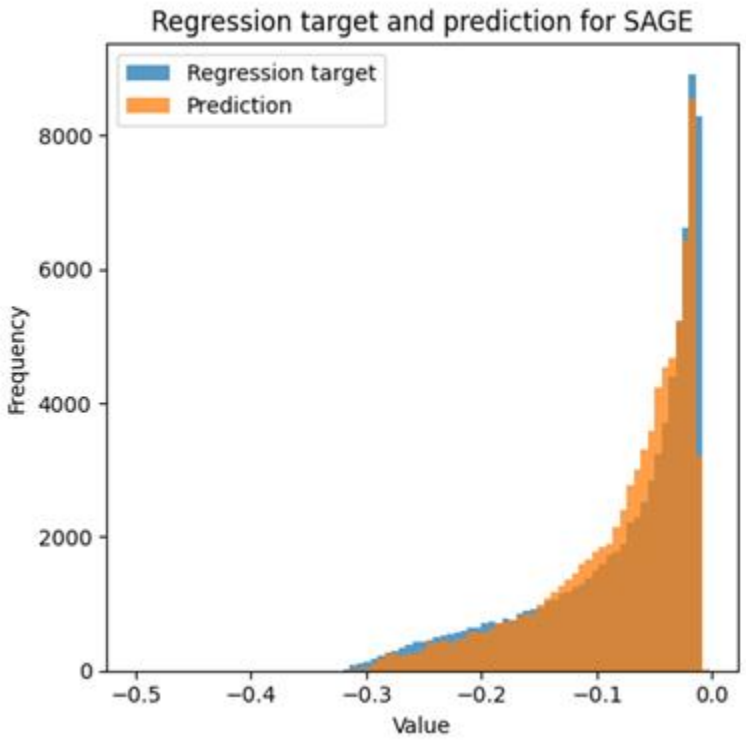
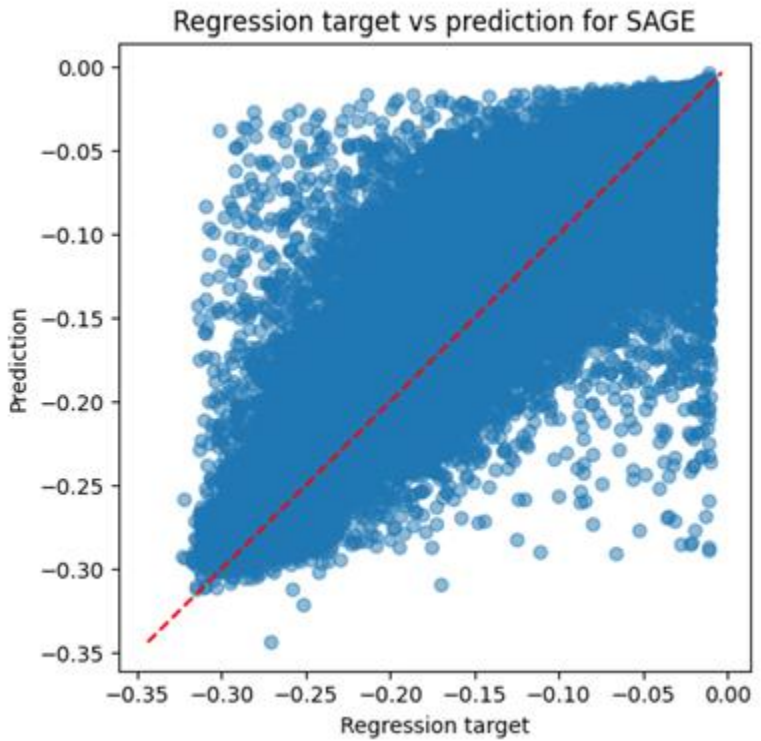
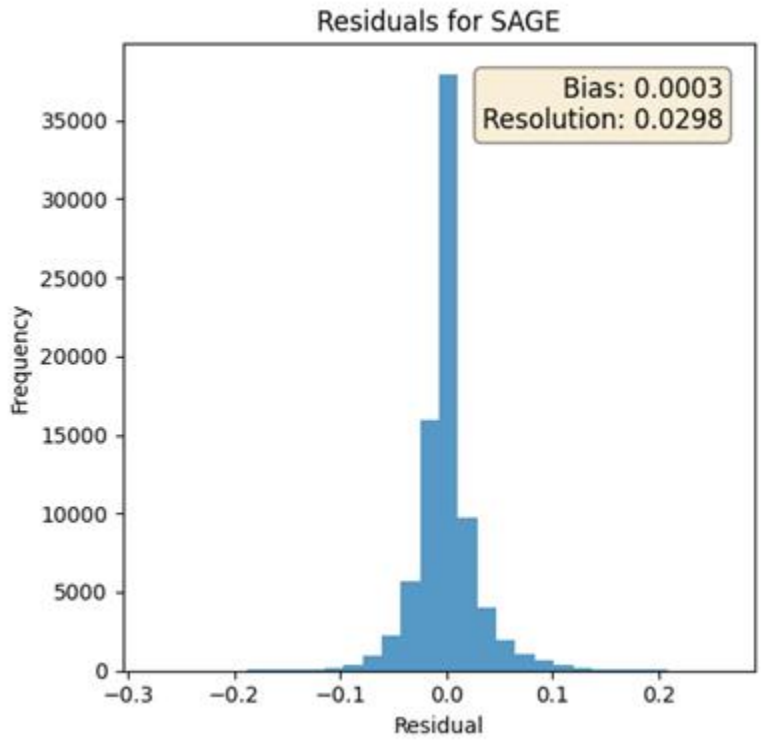
# Results

- Trained with a reduced sample (~1M events) in 20 epochs (model converges in 10 or so) with all possible connections in place
- Different configuration tested for now, early stopping, and dropout layers are now in place.
- Re-training with displaced samples and with flat-pt prompt samples to avoid favoring higher $p_T$ estimation.

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# GNN

## Status

- Things achieved:
  - All modules defined
    - Message Passing (Mean & Sum agg)
    - Linear
    - Normalizer
    - ReLu
    - SAGE
    - Mean Pool
  - Behavior tested against SW Python/C++ implementation
- Ongoing work:
  - Complete synthesis
  - Implementation in versal aie cores

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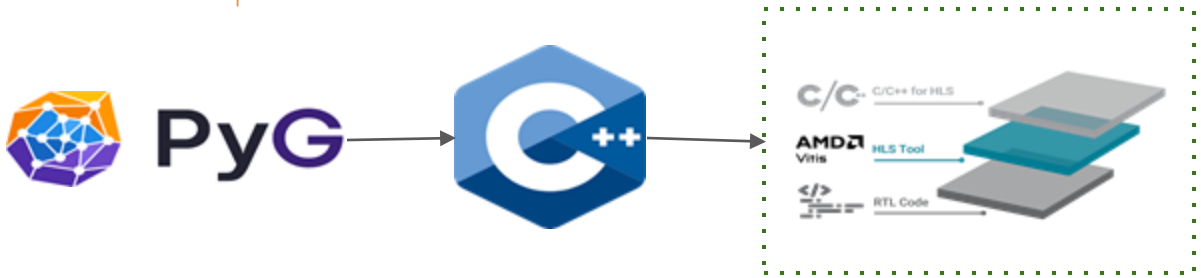
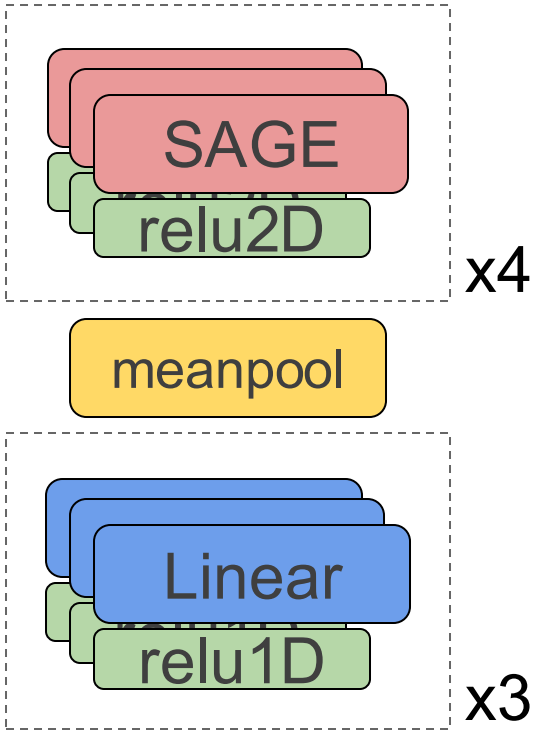



- Python implementation and test
- C++ conversion and testing of Python modules
  - Unitary test for each layer/function to match behavior
- HLS translation
  - Static definition of input parameters
  - Based on the expected net size

- Development of own library for Oviedo NN acceleration
  - Python, C++ and HLS src/tests
- Designed following HLS4ML methodology
  - Template and parameter definition
  - Full partitioned (minimum latency)





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# Prospects for the future

- Explore alternative technologies and ideas which could not be otherwise investigated that could potentially lead to a significant breakthrough.
  - Both in the present architecture of the CMS experiment and beyond
- Using muons as probes for new physics, as they 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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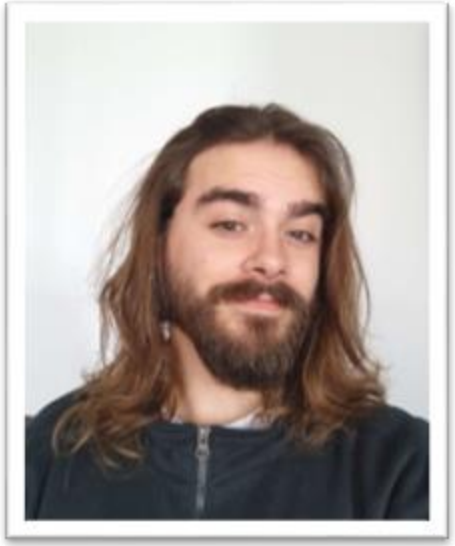
# Backup

# Who are we?

Daniel Estrada

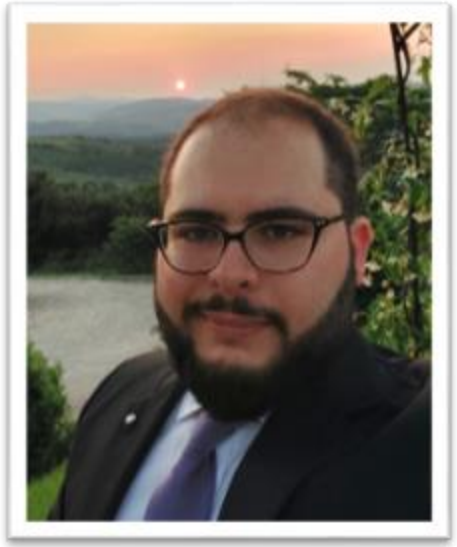
PhD. Student.
Physicists



Pelayo Leguina

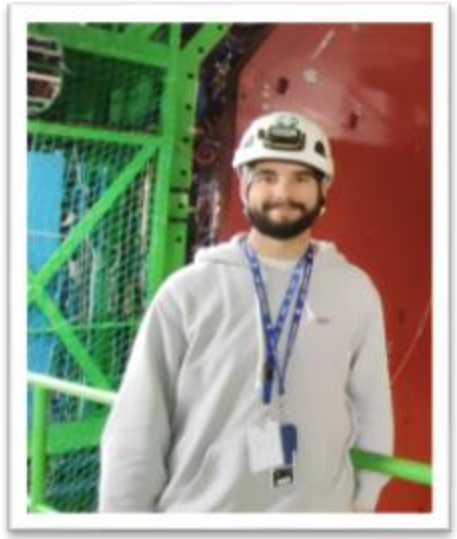
PhD. Student.
Engineer

Santiago Folgueras



Andrea Cardini

Postdoc.
Physicist.



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