Search for Beyond Standard Model signatures with phase-2 detectors with ATLAS and CMS

Fourth Italian Workshop on Physics at High Intensity

12th November 2025

Bari, Italy

Tiziano Pauletto for the ATLAS and CMS collaborations

Earth Science and Remote Sensing Unit, NASA Johnson Space Center

The name of the game

The Standard Model still leaves many questions unanswered.

Baryon asymmetry

No candidate to explain **Dark Matter**

Dark energy?

Strong CP problem

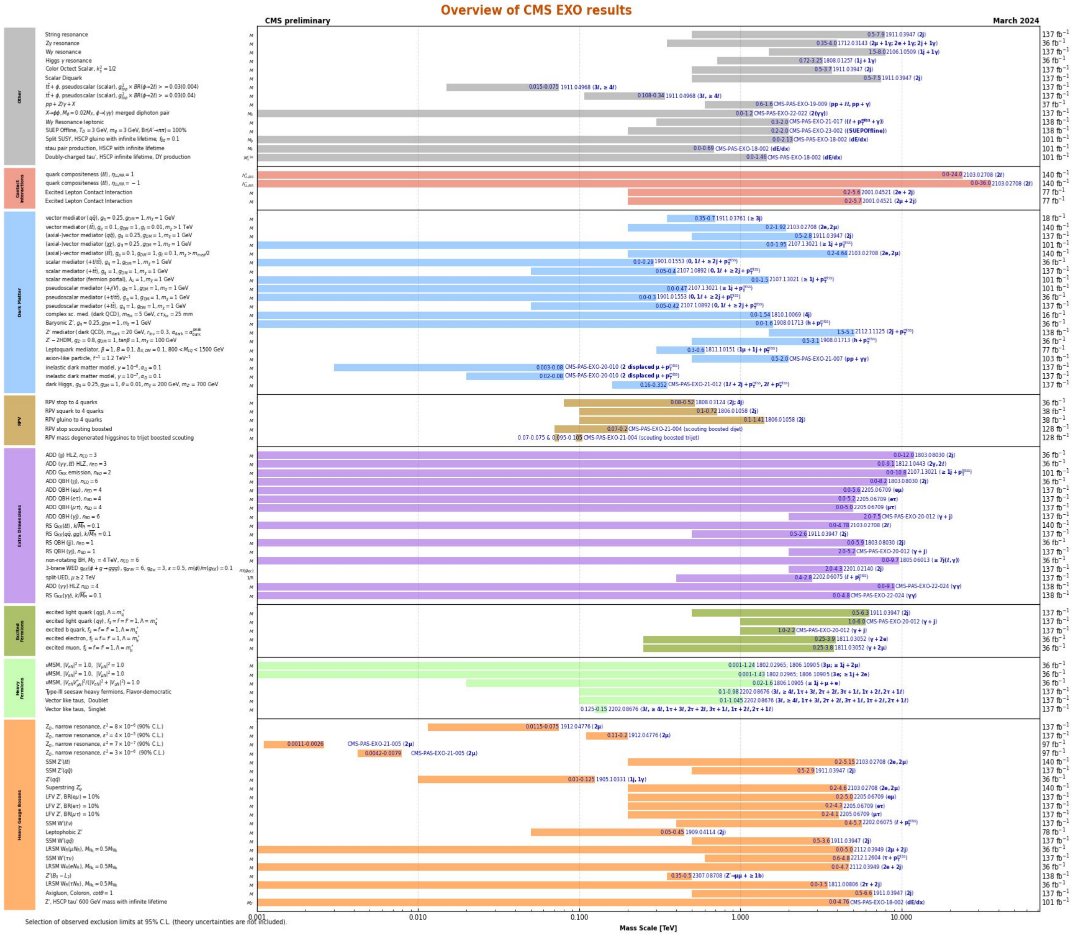
Naturalness? Fine tuning in the Higgs sector?

No gravity

Why three fermion generations?

The neutrino mass puzzle

What we are searching for



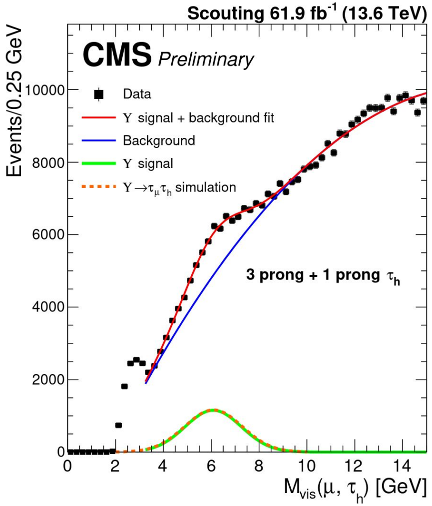
An **extensive physics program of searches**, from resonances to exotic signatures, both in ATLAS & CMS.

[CMS Exotica summary plots, ATLAS Summary Plots]

The state of the art: latest Run 3 results

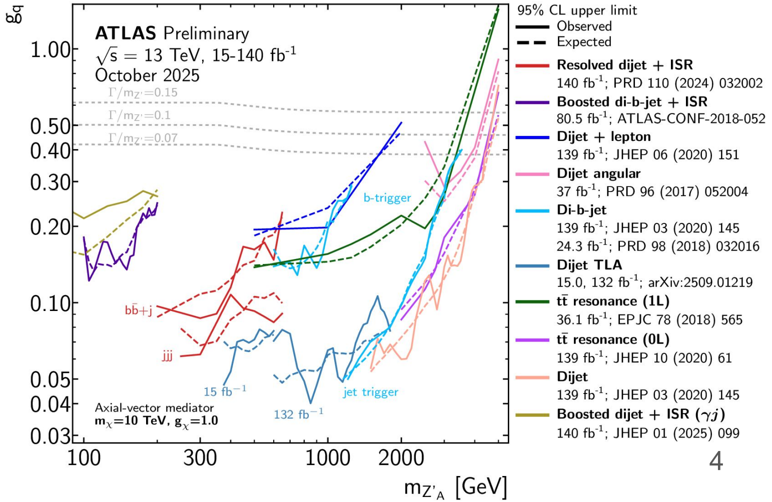
Hot off the press:

- CMS-PAS-EXO-24-012: Low mass scalar $\phi \rightarrow \tau\tau$ search.
  - **~100 pb limit** on pp$\rightarrow\phi \rightarrow \tau\tau$ in the whole mass range
  - Employing **data scouting** for this search
  - **First search w. hadronically decaying tau at a collider** probing 20-60 GeV mass range



- ATL-PHYS-PUB-2025-041: Constraints on axial-vector dark sector mediator [2509:01219]
  - Employing **Trigger Level Analysis** (TLA)
  - Up to **27 KHz data stream** (vs 1.2 KHz "main")
  - From 1500 GeV constraints on dijet resonances $\rightarrow$ **down to 400 GeV** with this strategy

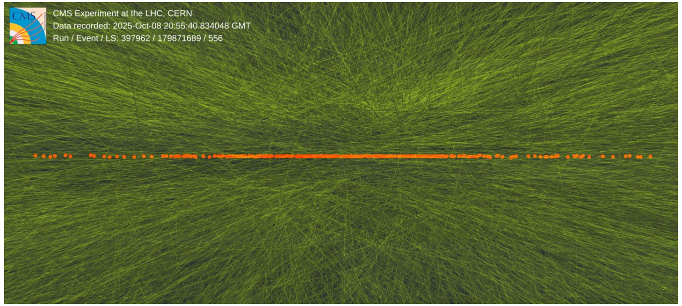
See **G. Maineri's talk**!



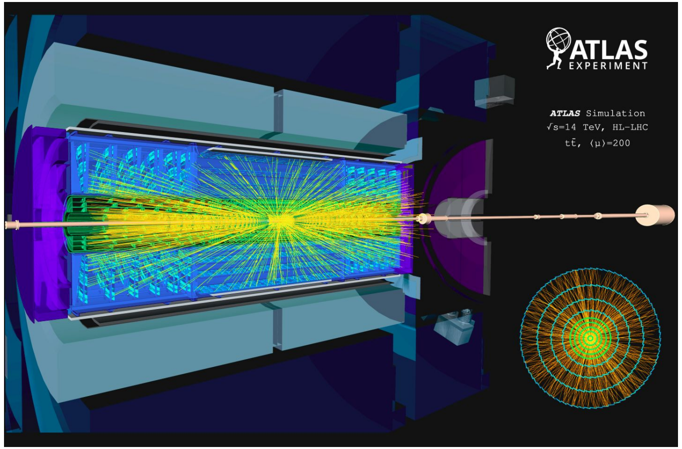
The High-Luminosity LHC

From mid-2026: LHC shutdown to prepare for **High Luminosity** (HL).

- HL-LHC starting operations in 2031
- **3/4-fold increase in instantaneous luminosity** w.r.t. to nominal LHC ops, pileup <μ>=140-200
- Reaching **3000-4000 fb^{-1} of delivered lumi** to ATLAS & CMS at end of operations
- **Ambitious detector upgrade program** for the experiments
- Challenges in detector design, event reconstruction, computing infrastructure
- … but a lot of opportunities for BSM physics



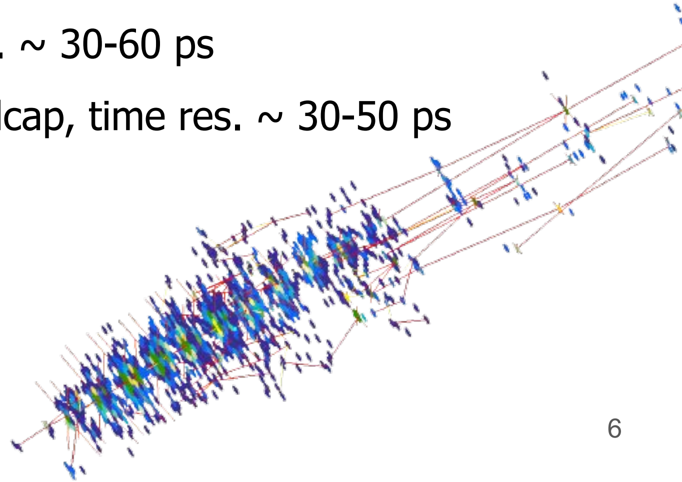
206 reconstructed primary vertices in CMS [CMS-PHO-EVENTS-2025-023]



[ATLAS prepares for High-Luminosity LHC]

Some of the detector improvements in ATLAS & CMS

- ATLAS: **installation of Inner TracKer (ITk)**, reaching coverage $|\eta|$ ~ 4 and r ~ 1 m, much finer granularity → **gain in acceptance** for large range of physics phenomena
- CMS: **tracker upgrade** reaching coverage $|\eta|$ ~ 4, trigger at L1
- CMS: Replacement of endcap calorimeters with **High Granularity CALorimeter** (HGCAL) → **reconstruct shower shape in space and time**, sizeable **gain in energy a resolution**.
- CMS: **MIP Timing Detector** (MTD), charged track time res. ~ 30-60 ps
- ATLAS: **High Granularity Timing Detector** (HGTD) in endcap, time res. ~ 30-50 ps
- ATLAS: Upgrade of muon detectors, replacement of electronics and Monitored Drift Tubes in trigger
- Not an exhaustive list…



A reconstructed 400 GeV photon shower in HGCAL
[ACAT 2022, W. Redjeb, F. Pantaleo]

A bright future ahead

Detectors:

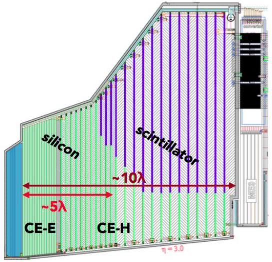
- Extended **coverage of trackers** & increase in granularity
- Upgrade of **calorimeters**, **muon detectors**, overhaul of electronics of existing detectors
- Addition of **timing detectors**

Data acquisition:

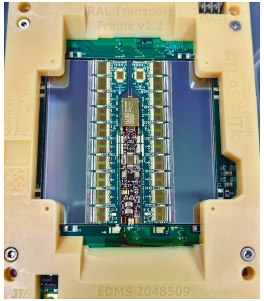
- Increase in **trigger rate**
- Dedicated **data streams**: **scouting**, parking, Trigger Level Analyses (TLAs)
- L1 **Track trigger** in CMS
- **New triggers** targeting exotic signatures
- Hardware track reconstruction

Reconstruction & data analysis:

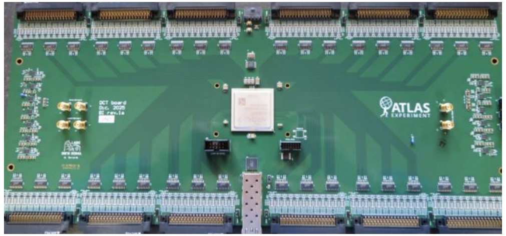
- **Heterogeneous computing** used in event reconstruction
- Novel **analysis techniques**
- Improvements in **flavour tagging**
- Probing unexplored signatures
- …



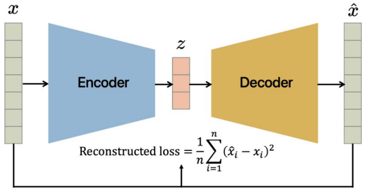
CMS-TDR-019



A. Hoecker/ATLAS Collaboration



ATLAS Muon Detectors upgrades for High Luminosity LHC, M. Sessa



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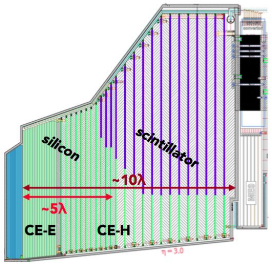

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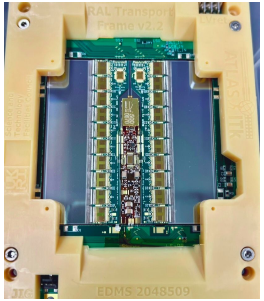

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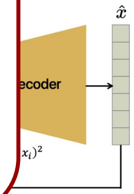
ATLAS Muon Detectors upgrades for High Luminosity LHC, M. Sessa



This talk will focus on some **physics cases** related to the **highlighted topics**

L1 scouting

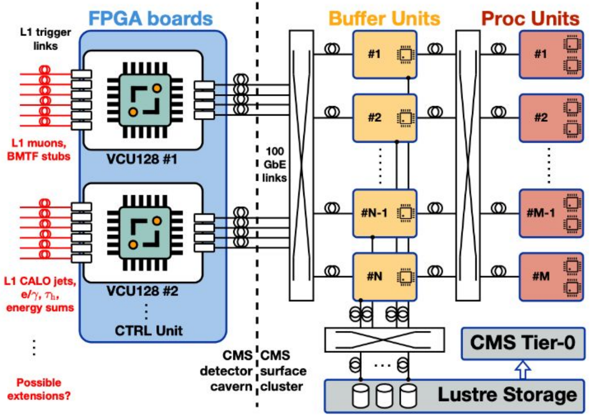
L1 Scouting at CMS

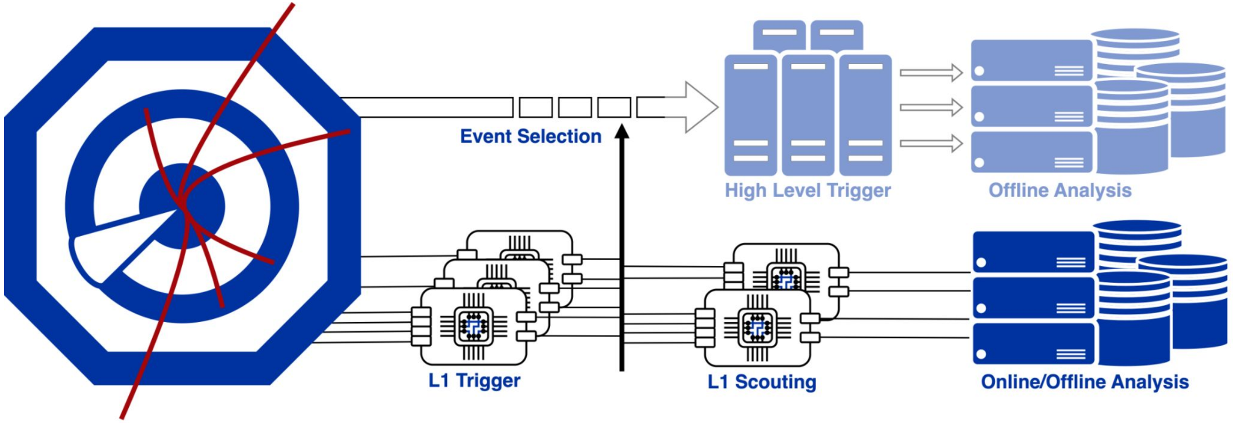
Collision rate of 40MHz → L1 trigger selects ~ 100 kHz → HLT selects ~ O(kHz)

Did we reject new physics hints due to our trigger selections?

New strategy: save L1 events at a rate of 40 MHz → **triggerless readout**

- **Demonstrator added to CMS in 2024 and collecting data**
- **O(kB) event size compared to 7.5 MB full event**





R. Ardino, M. Migliorini

CMS L1 Data Scouting for HL-LHC, L. Sieder

Opportunity for HSCPs: an example of L1 scouting

L1 scouting opens windows on:

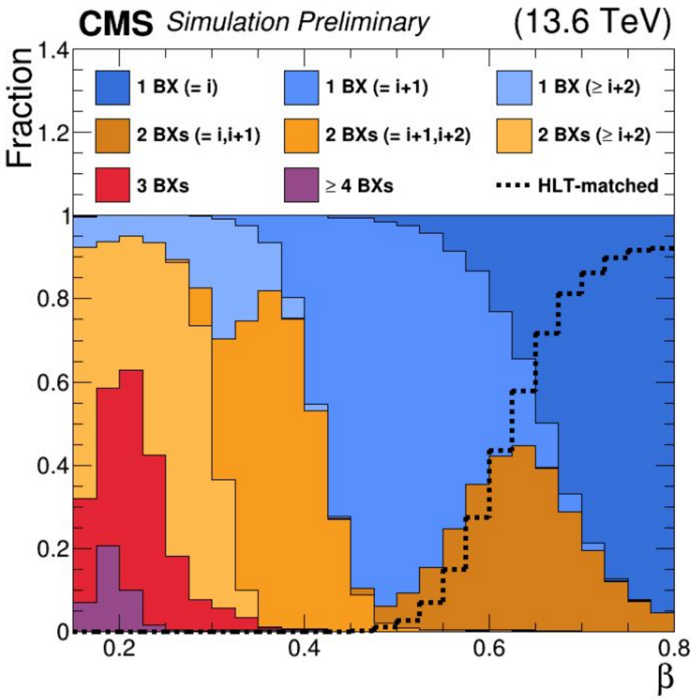
- Soft objects
- Low couplings
- Analyses requiring complex selections not possible at L1
- **Correlation between bunch crossings** (BX)

The latter ideal to probe very slow Heavy Stable Charged Particle (HSCP) signatures:

- Massive (m $\gtrsim$ 200 GeV),
- |Q| > 0
- Long lived (> detector length)

→ **Slow moving**, highly ionizing

Predicted in several SUSY, GMSB, and superstring models.

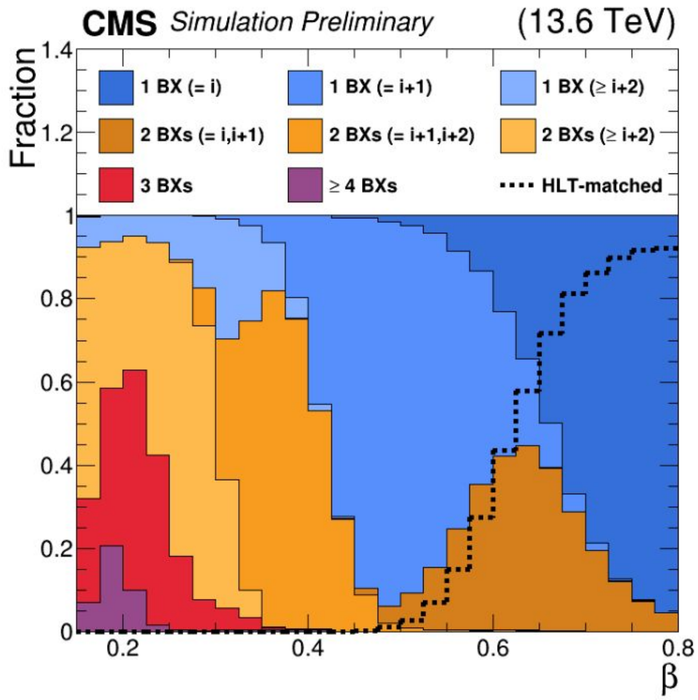


Search for heavy stable charged particles with L1 Scouting data at the CMS experiment, C. Caillol

Opportunity for HSCPs: an example of L1 scouting

L1 scouting analysis [CMS PAS EXO-25-010]:

- Time-based HSCP analyses probe β > 0.5
- Looking at BX correlations → going to β ~ 0.2
- Exploiting 3.7 fb^{-1} of data, **put limits on cross-section at fb-pb level in β ~ 0.2-0.8 range**



Very slow HSCPs can be detected over > 2 BXs

Search for heavy stable charged particles with L1 Scouting data at the CMS experiment, C. Caillol

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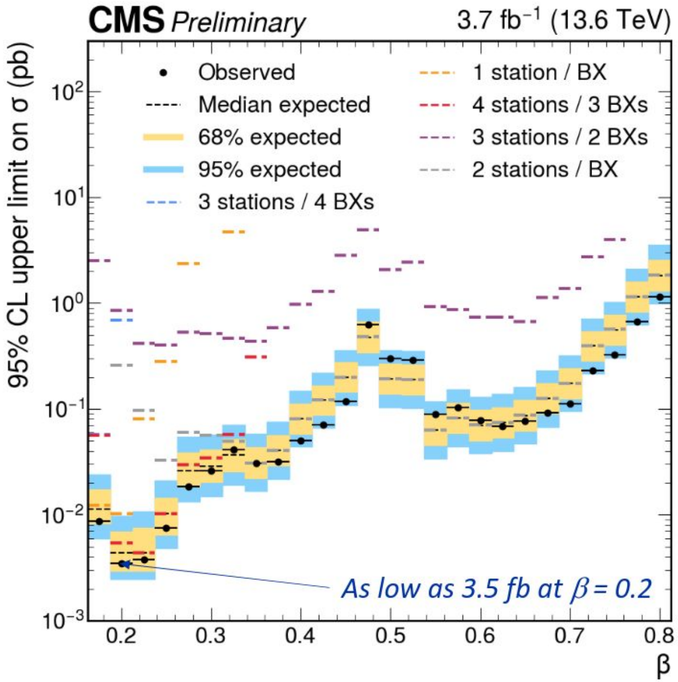


[Search for heavy stable charged particles with L1 Scouting data at the CMS experiment, C. Caillol](#)

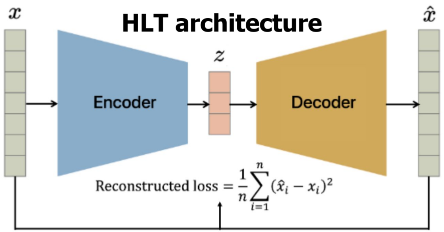
Anomaly detection at trigger level

Online Anomaly Detection: GELATO

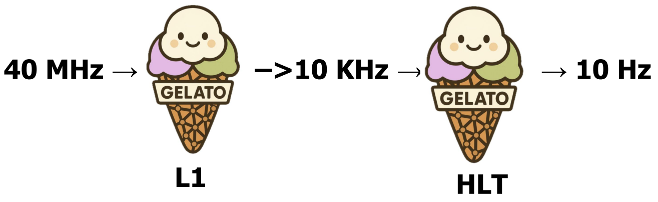
The Generic Event-Level Anomalous Trigger Option for ATLAS (GELATO) is an anomaly detection (AD) framework that **triggers at L1** (hardware) and **at HLT** (software).

- **GELATO L1**:
  - VAE-GAN architecture on FPGAs
  - 45 features: (p_T,η,φ) of 6 jets, 4 taus, 4 muons + MET
- **GELATO HLT**:
  - AE architecture, implemented on HLT CPUs
  - 47 features: from 6 jets, 3 electrons, 3 muons and 3 photons + MET

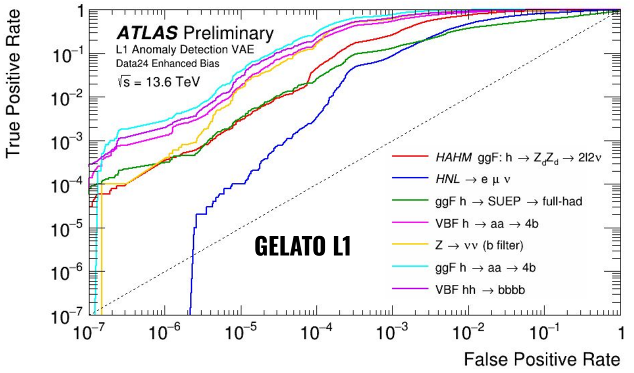
Trained on Enhanced Bias data, **shows significant discriminating power** in several models. Testing in early 2025, prescaled data-taking started in June.

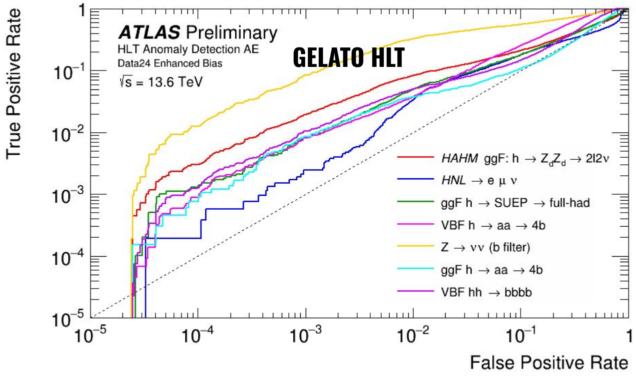


[GELATO: A Generic Event-Level Anomalous Trigger Option for ATLAS in LHC Run 3, K. Sugizaki]



In CMS similar effort: AXOL1TL





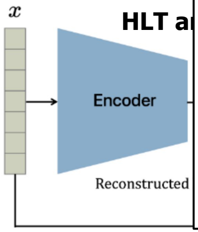
[Public Combined Plots For Trigger Data, ATLAS]

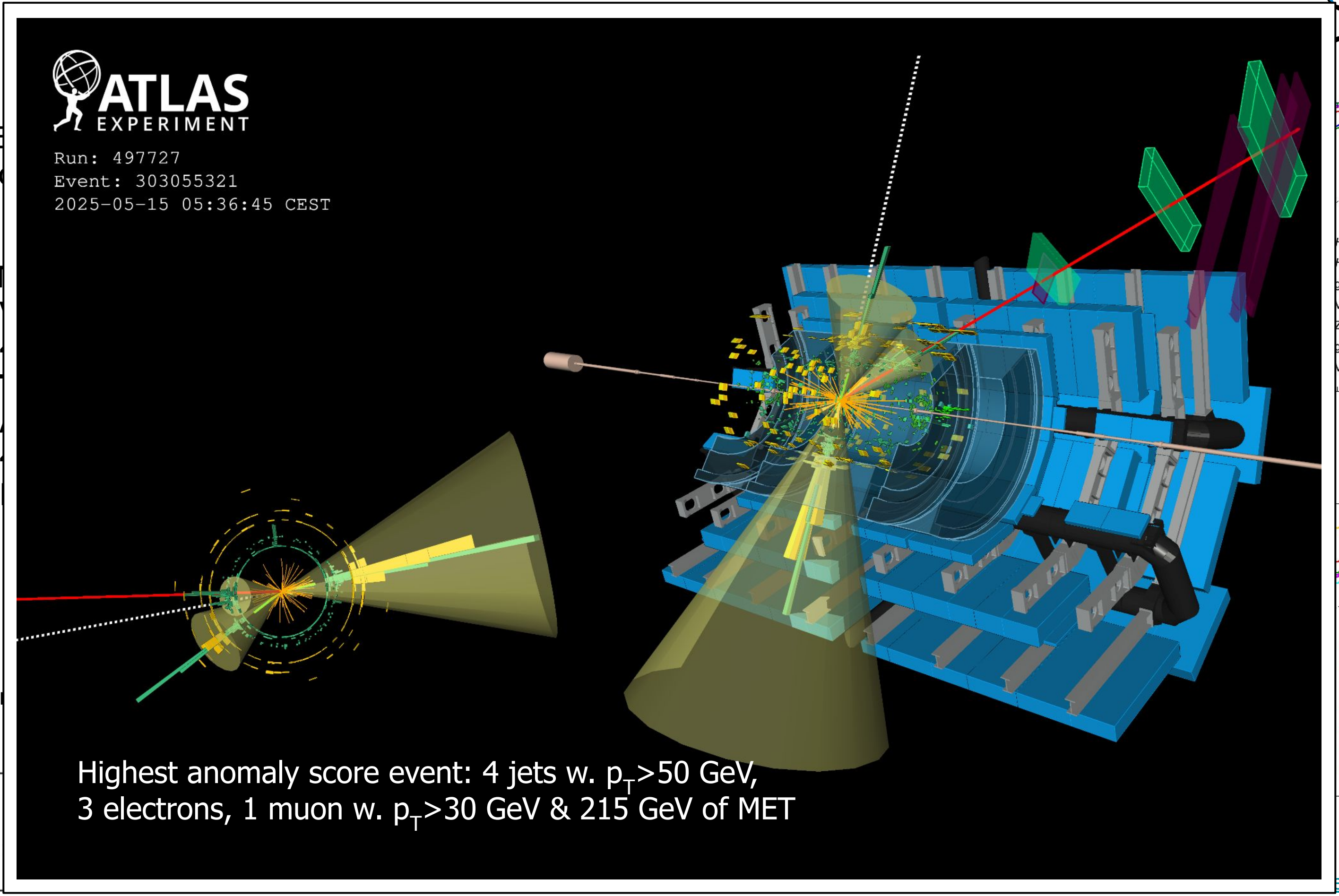
Online

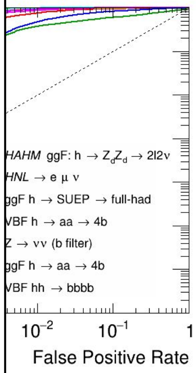
The Generic E
anomaly dete
(software).

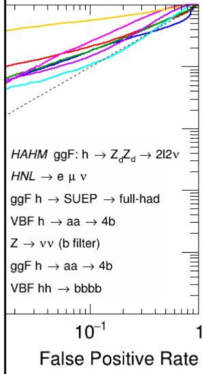
- **GELAT**
  -
  -
- **GELAT**
  -
  -

Trained on En
several model









er Data, ATLAS]

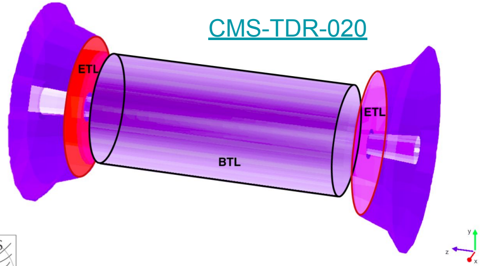
[GELATO: A Generic Event-Level Anomalous Trigger Option for ATLAS in LHC Run 3, K. Sugizaki]

In CMS similar effort: AXOL1TL

A new dimension for searches: time

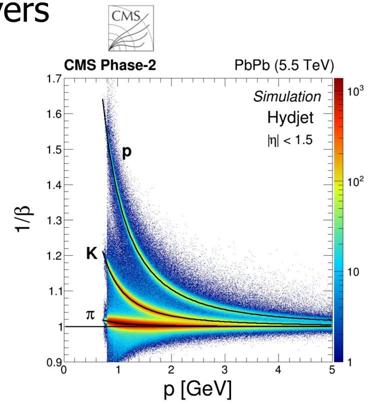
The timing detectors: MTD and HGTD

CMS-TDR-020



The **MIP Timing Detector** (MTD) will be installed in CMS:

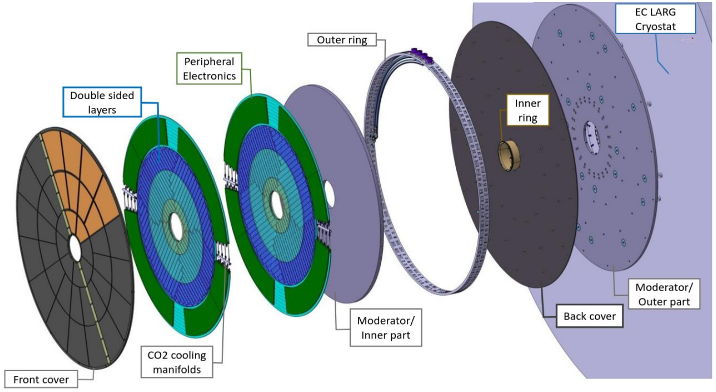
- Made of Barrel (BTL, $|\eta|<1.5$) and Endcap (ETL, $1.6<|\eta|<3.0$) Timing Layers
- LYSO:Ce scintillators in the barrel and LGADs in the endcap
- Track time resolution of **~30-60 ps**
- Assignment of vertex time:
  - ↳ Possibility to **measure Time-of-Flight** → $\boldsymbol{\beta}$
  - ↳ In combination with p measurement → **estimate mass**



ATL-TDR-031

The **High Granularity Timing Detector** (HGTD) will be installed in ATLAS:

- Composed of two instrumented double layers of LGADs
- Covering $2.4<|\eta|<4.0$
- Time resolution **~ 30-50 ps**
- Recovers current pileup rejection in forward detectors



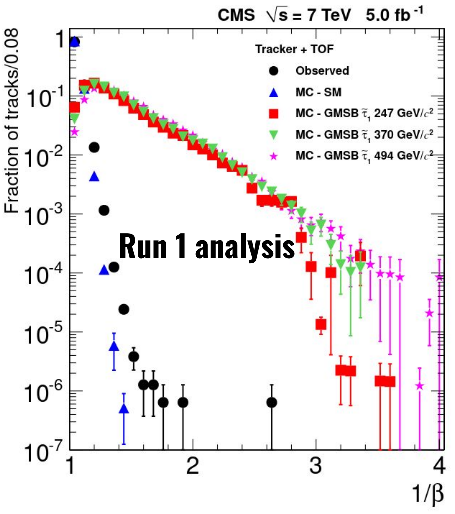
Hunting HSCPs with MTD

Returning to HSCPs → possible to search for them using a **Time-of-Flight** (ToF) **signature.**

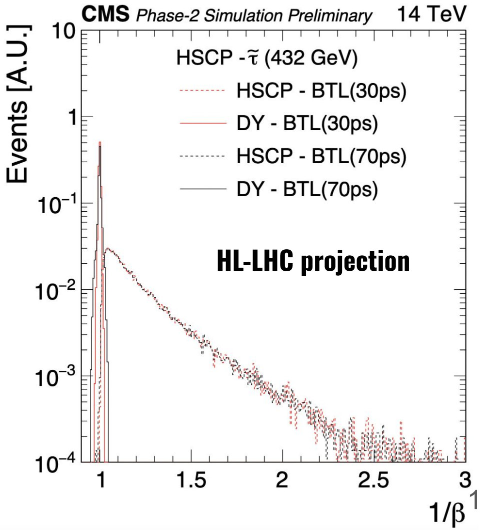
Now ToF given by CMS muon system. During HL-LHC → MTD can be exploited.

MTD will change the landscape of HSCP searches:

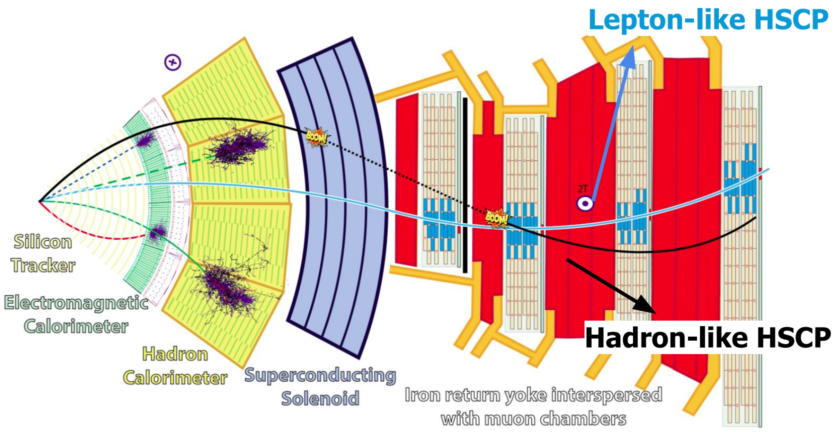
- Going from **~1.5 ns** track time resolution in muon system **(now)** to **~30-60 ps** **(MTD)**



arXiv:1205.0272



CMS-DP-2022-25

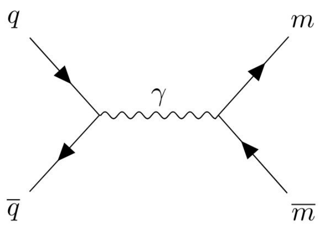


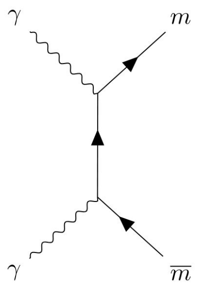
Triggering on magnetic monopoles with HGTD

Magnetic monopoles → highly charged particles leaving large energy deposits in detector.

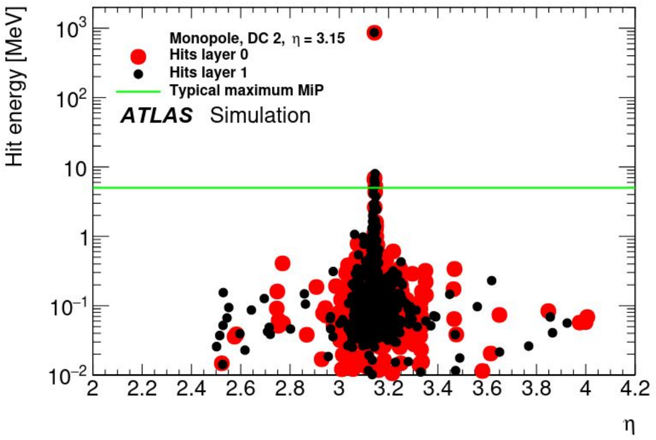
Already searched for in calorimeters & tracker [2308.04835] , HGTD **sensitive to an unprobed mass range m < 200 GeV**.

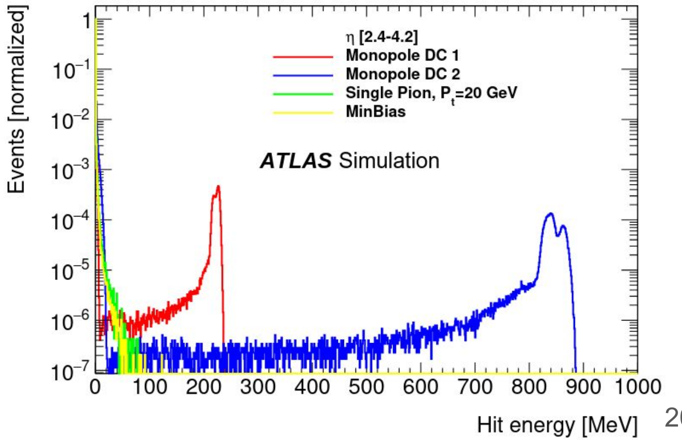
- Monopole charge is multiple of Dirac Charge (DC) ~ 68.5 e





- **Large energy deposition in HGTD** → well separated **from MIP deposits**
- Explored possibility to use HGTD to **recognize candidates online** & **use information to trigger**
- Scenario would require a modification of readout electronics → case under study



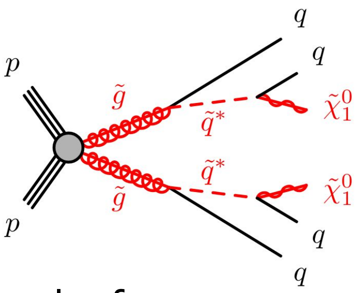


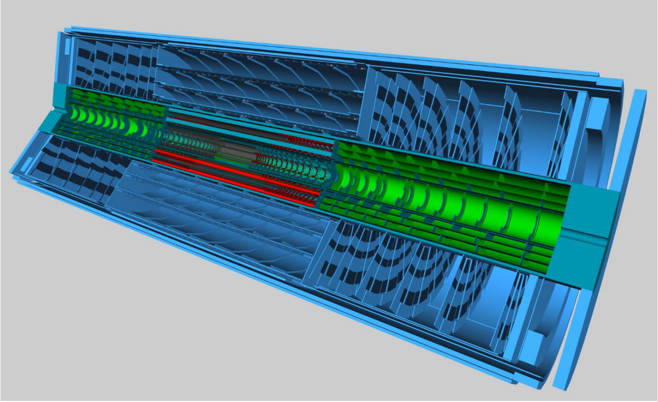
Tracking improvements

Displaced vertex signature

New Inner TracKer (ITk) design:

- All-silicon tracker: pixel (inner part) and strips (outer region)
- Improved coverage $|\eta|<2.5 \rightarrow |\eta|<4.2$
- 165 m^2 active area and 5 B / 60 M channels of pixels/strips

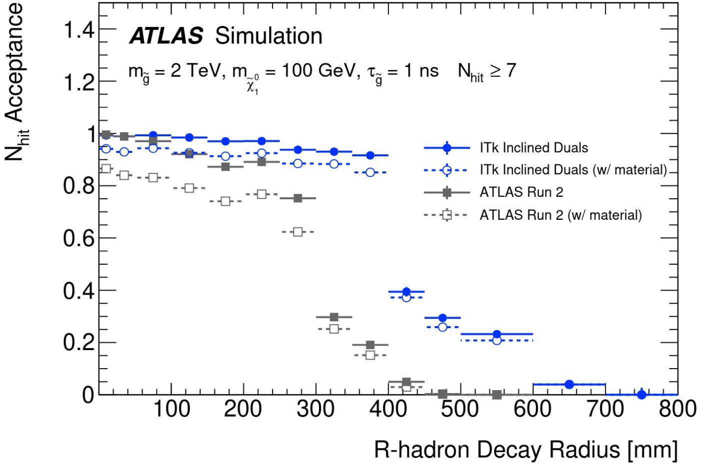




ATL-TDR-030

BSM particles with lifetime ~ 10 ps - 10 ns can decay inside the tracker volume.

⏩ e.g. particles from Hidden Valley, R-parity violating and split SUSY models, that arise from SUSY scenarios with large squark mass

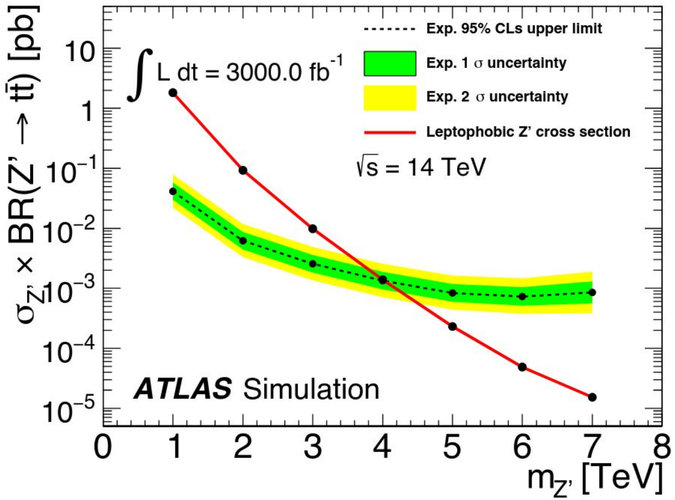


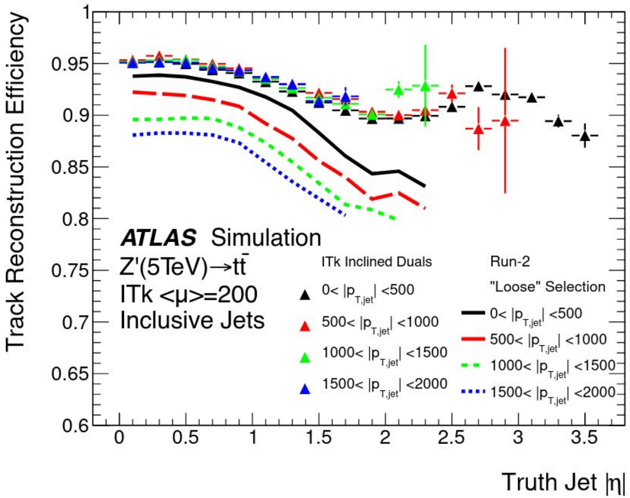
Efficiency on displaced vertices is greatly increased with ITk, especially at ~ 300-400 mm, extending reach up to 550 mm.

Bonus: heavy resonances decaying to top quark pairs

There are some models in which resonances decay preferably to top quarks. Considering here a leptophobic topcolour-assisted technicolour Z’.

- Run 3 analyses exclude **$m_{Z'}$< 3.2 TeV**
- For higher masses, **boosted ttbar topology**, b-jets with p_T > 600 GeV
- Tracking system crucial to disentangle high-density track environment





ATL-TDR-030

Sizeable **increase in track reconstruction efficiency** in large η range

Expected to probe **4 TeV mediator mass** in this model

Outlook

Outlook

- **ATLAS and CMS gearing up for the HL-LHC**, ambitious upgrade program ongoing
- HL-LHC will deliver an unprecedented amount of integrated luminosity to the experiments & **unlock discovery possibilities in many models**
- In this presentation: overview of some of the **improvements on detecting capabilities** & their **impact on the discovery potential** of ATLAS & CMS
- **The quest for new physics is ongoing, stay tuned**
- Many upgrade topics not covered here, open to discussion


THE TRUTH IS OUT THERE

Thanks for listening