Overview of trigger/DAQ in CMS

ICNFP 2024

Crete, Greece

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On behalf of the CMS collaboration

CMS trigger/DAQ is a very broad topic

Impossible to discuss all of it in 20 minutes. So I made a choice...

DAQ = Data acquisition

The mainstream

- Core triggers. They have been there since the beginning.
- Example: single/double electron, Jet H_T, MET, single/double muon
- Serves a broad spectrum of physics analyses. Very **important** for CMS physics program.
- These triggers are performing in a **robust**, **stable** and **efficient** way (they always have).
- I will speak less about this.

Less mainstream / not-at-all mainstream

- Triggers aiming for experimentally **challenging**, **exotic** signatures.
- Innovative ideas, smart use of modern machine learning techniques.
- Things that you may find odd, extraordinary, **novel** or debatable!
- Will speak mostly about these.

Focus of this talk

So, this is not meant to be exhaustive. But will give a glimpse of the cool things we are doing at trigger-level.

CMS trigger system (Run3)

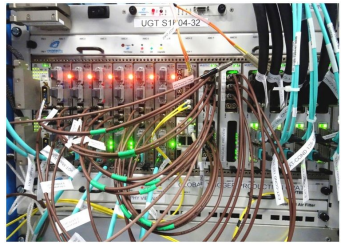
Events not selected by trigger system are lost. Forever.

Proton-proton collision at LHC

Up to 40 MHz

~4 μs time to take a decision

Level 1 Trigger (L1)
Coarse granularity, Only muon systems and calorimeters, hardware-based



~110 kHz

High Level Trigger (HLT)
Full granularity, all subsystems are used, software-based (CPU/GPU)

~2 kHz

Standard stream
Quick offline reconstruction, full event information

~4-5 kHz

Parking stream
Delayed[*] offline reconstruction, full event information

~25 kHz

Scouting stream
No offline reconstruction, reduced event information

[*] If resource is available, parking data is reconstructed as promptly as the standard data

CMS trigger system (Run3)

Events not selected by trigger system are lost. Forever.

Proton-proton collision at LHC

Up to 40 MHz

Level 1 Trigger (L1)
Coarse granularity, Only muon systems and calorimeters, hardware-based

~110 kHz

Few hundred ms average time to take a decision

High Level Trigger (HLT)
Full granularity, all subsystems are used, software-based (CPU/GPU)

~2 kHz

~4-5 kHz

~25 kHz

Standard stream
Quick offline reconstruction, full event information

Parking stream
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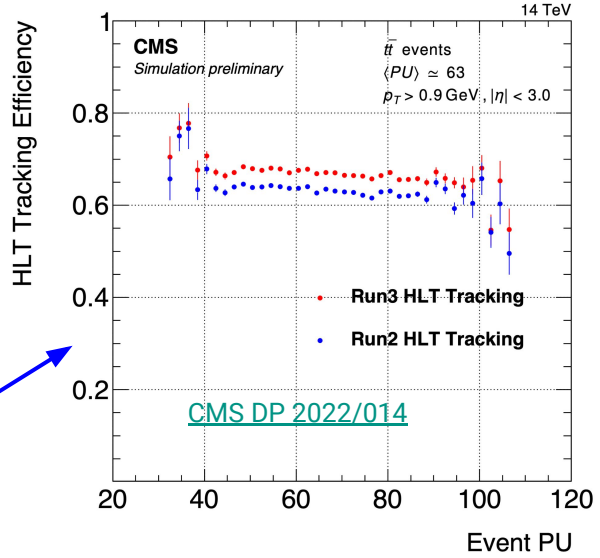
HLT Scouting stream
No offline reconstruction, reduced event information

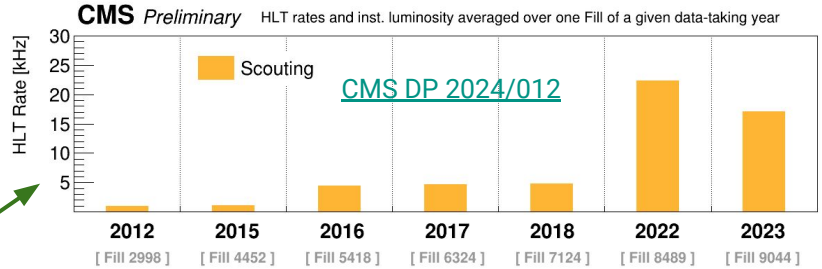
[*] If resource is available, parking data is reconstructed as promptly as the standard data

Bringing heterogeneity to CMS trigger

- CPU evolution can't cope with CMS's computing demand.
- CMS HLT already using GPUs in Run 3.
  - GPUs are more cost efficient & energy efficient.
- Specific coding styles or API are required for GPUs.
  - CMS's choice: Alpaka (portability library).
  - Same code able to run on multiple hardware (eg. AMD, Intel)

- Pixel, HCAL, ECAL and particle-flow reconstruction code already ported to GPU.
  - While re-engineering the existing code for parallelisation, we gained in physics performance.
- More computing power allows CMS to:
  - invest in accurate methods of reconstruction (better quality physics objects at HLT)
  - extend the physics program (running HLT scouting at much higher rate than Run 2).





The standard stream

Standard stream
Quick offline reconstruction, full event information

Parking stream
Delayed [*] offline reconstruction, full event information

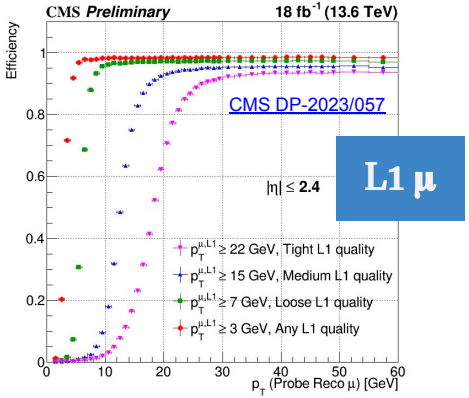
HLT Scouting stream
No offline reconstruction, reduced event information

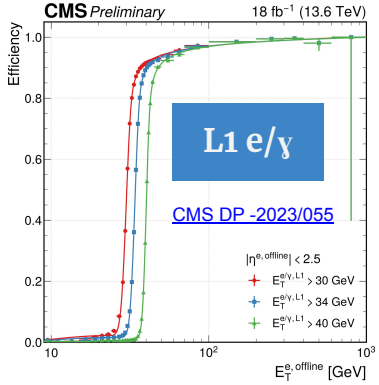
- Majority of high level triggers (often called HLT paths) belong to this category.
- Few hundred HLT paths collecting data for **varied purposes**
  - Alignment and calibration of detector components
  - Generic HLT paths used in various physics analysis (precision measurements, BSM searches)
  - Dedicated HLT paths for targeted physics analysis (often experimentally challenging)
    - Example: dedicated **triggers for long-lived particle (LLP) searches**
  - Dedicated triggers to catch any anomalous event which could be BSM (**anomaly finder**)

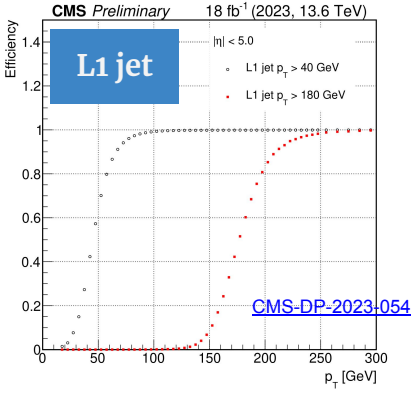
The mainstream in HLT

[*] If resource is available, parking data is reconstructed as promptly as the standard data

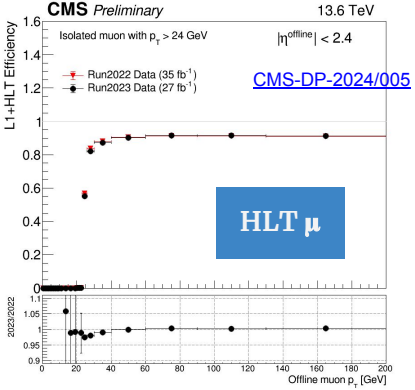
Mainstream is robust & efficient, as always

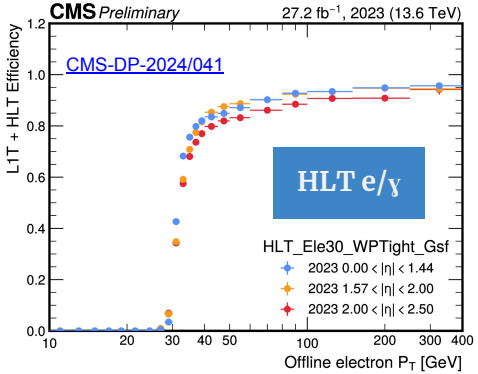


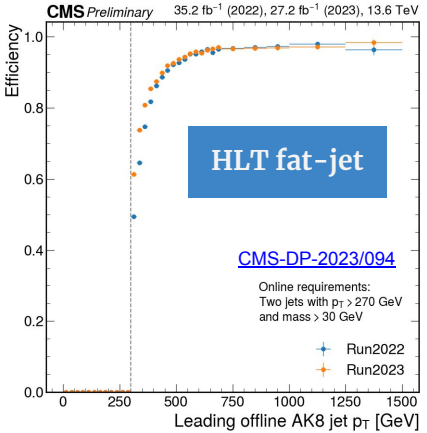




[Link to L1T results](#) & [Link to HLT results](#)







Parking and scouting at HLT

Standard stream
Quick offline reconstruction, full event information

Parking stream
Delayed [*] offline reconstruction, full event information

HLT Scouting stream
No offline reconstruction, reduced event information

[*] If resource is available, parking data is reconstructed as promptly as the standard data

Novel trigger strategy

Can't fit your trigger in the standard stream budget?

Move it to parking or scouting streams

Ref:
https://cms.cern/news/same-lhc-same-cms-more-physics

arXiv:2403.16134

The parking stream at HLT

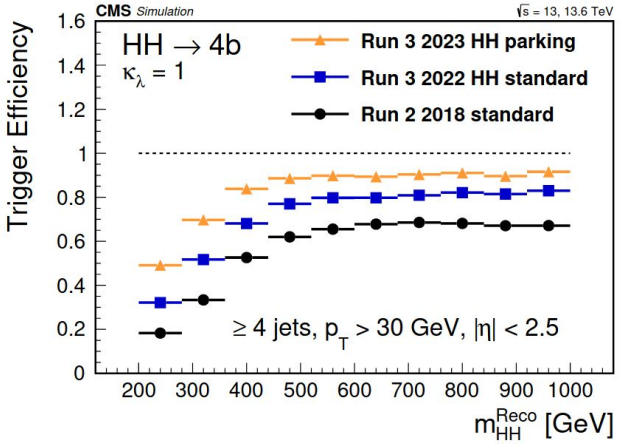
~~**Standard stream**~~
~~Quick offline reconstruction, full event information~~

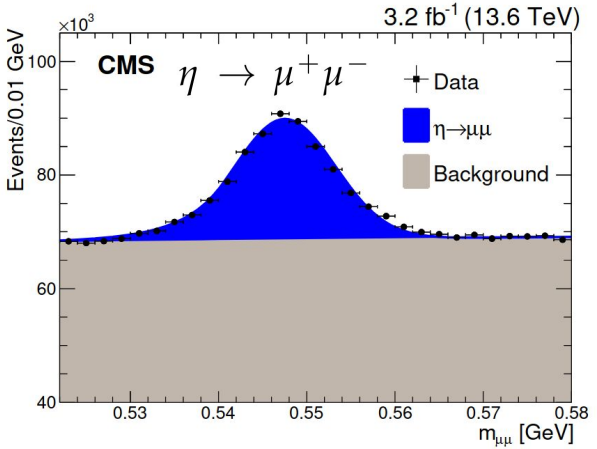
Parking stream
Delayed [*] offline reconstruction, full event information

[*] If resource is available, parking data is reconstructed as promptly as the standard data

Novel trigger strategy

- Parking strategy is flexible according to physics needs.
- Currently CMS has dedicated parking triggers for **LLP, di-Higgs,** and **VBF Higgs production** signatures.
- Double muon, single muon, and double electron parking triggers for **B-physics**.





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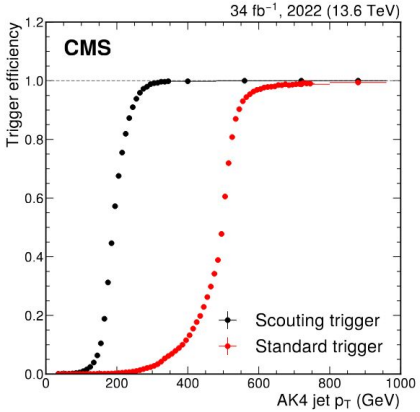
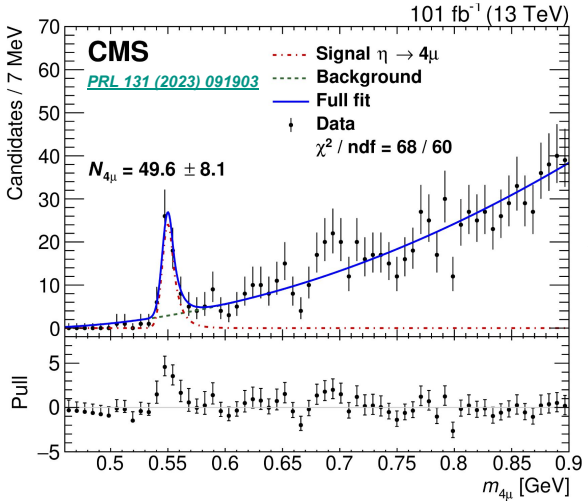
arXiv:2403.16134

$D^0 \to \mu^+\mu^-$ $B^+ \to K^+e^+e^-$ $B^0 \to J/\psi K^0_S$ $B^0_s \to \mu^+\mu^-$

The scouting stream at HLT

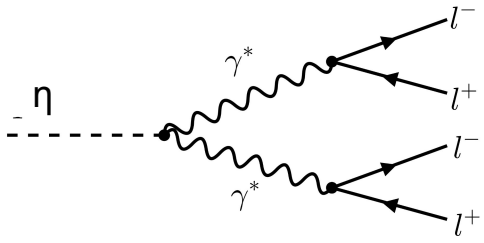
Novel trigger strategy





HLT Scouting stream
No offline reconstruction, reduced event information

- HLT scouting strategy improved over time.
  - For example: In Run 3 we run particle-flow in HLT scouting at >20 kHz, much higher rate than in Run 2.
- Crucial for very low-mass bump-hunt searches.
- Also useful for
  - LLP searches (long-lived dark photon decaying to dimuon). JHEP 04 (2022) 062
  - B-physics analyses (first observation of η meson decaying into four muons)



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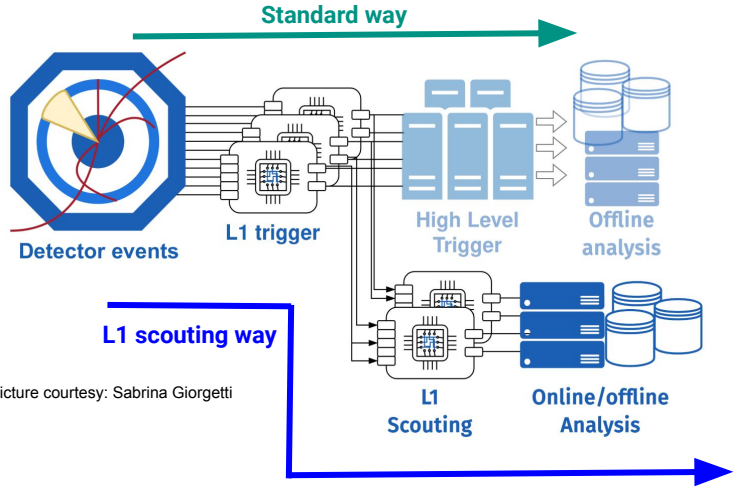
L1 scouting (40 MHz scouting)



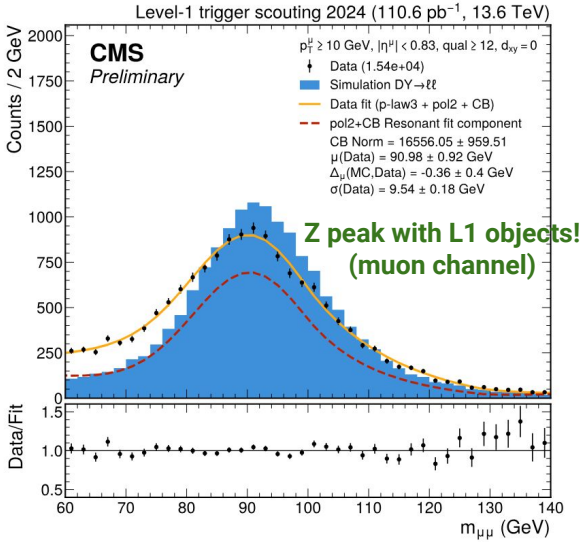
Picture courtesy: Sabrina Giorgetti

- Standard L1 rejects 99.75% events. L1 scouting will allow us to have a look at those events
- Tremendous capability. Enables studies of otherwise inaccessible region of phase space.
- Next step: Properly identify all potential signatures unreachable through standard trigger and let L1 scout those events.

CMS DP -2024/056

- Idea: Store **trigger-less data** with limited resolution before L1 decision.
- L1 trigger data Scouting is being developed for high-lumi LHC.
- A **demonstrator** has been operational since the start of Run 3.

L1 scouting in Run 3: a proof of concept



L1 scouting rack

LLP signatures at trigger level

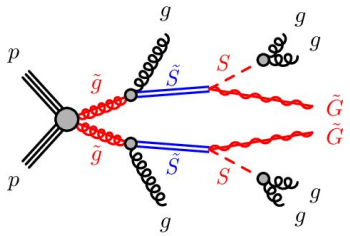
Long-lived particles in BSM

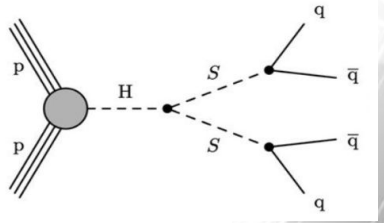
Very exotic signature.

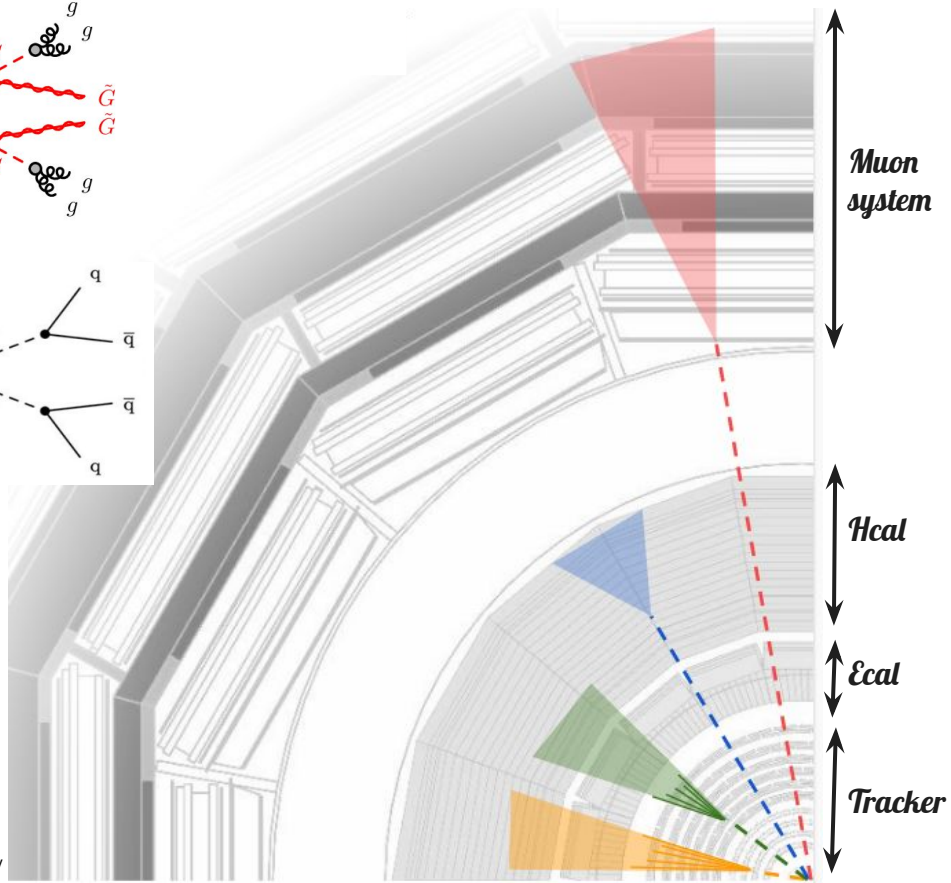
Often needs dedicated trigger strategy.

Displaced jet

- Hadronically decaying LLP is a viable BSM scenario.
- Several **displaced-jet triggers** to capture various detector signatures, depending of LLP's lifetime (decay length).
  - tracking-based
  - ECAL-based
  - HCAL-based
  - Muon system-based







Picture courtesy: Kiley Kennedy

Displaced jet trigger

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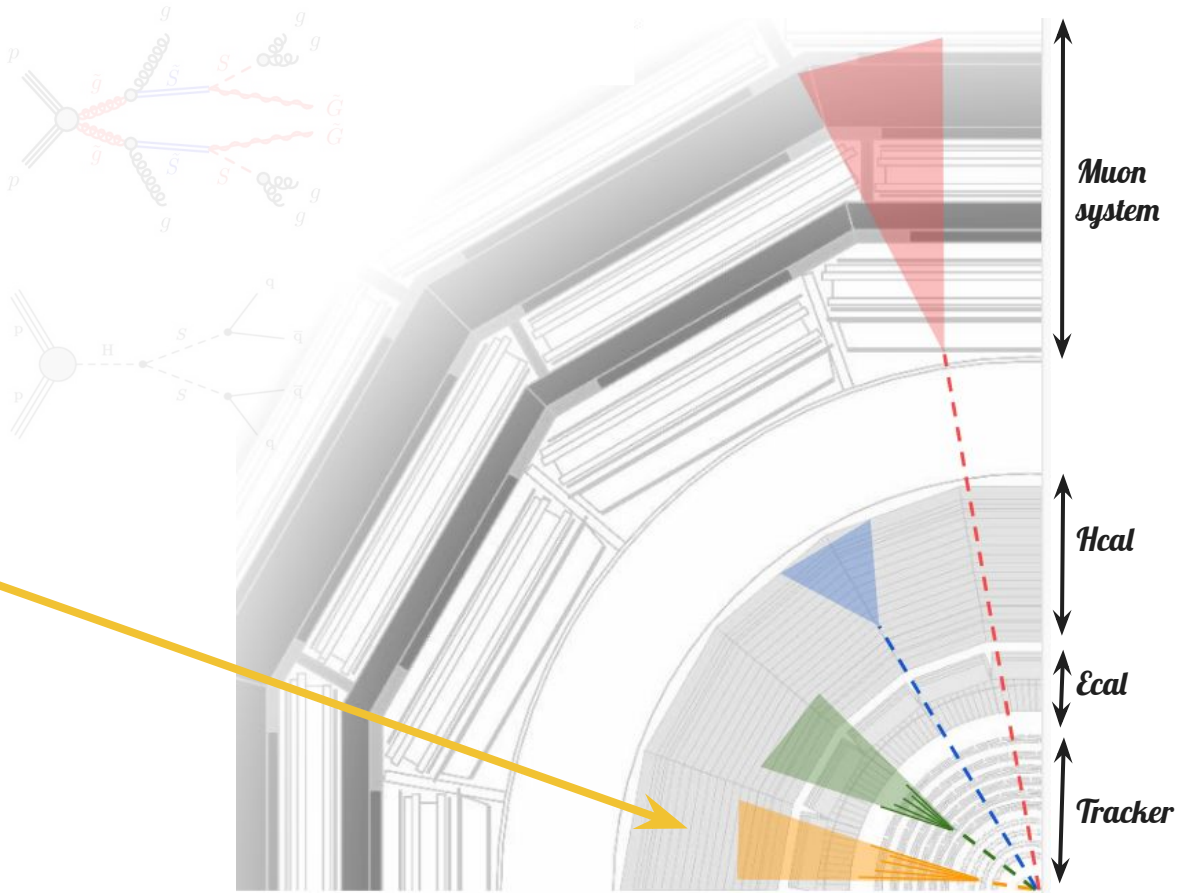
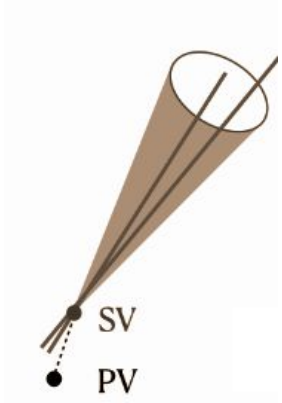


Tracking-based displaced jet trigger

- Trigger implemented in Run 2.
  - Displaced-jets search with full Run 2 data https://arxiv.org/abs/2012.01581 (Published in PRD)
- Run 3 trigger improved. Better than Run 2 by a factor of ~5-10
- L1 Strategy: H_T>430 GeV or (soft-muons with p_T>6 GeV and H_T>240 GeV).
  - Triggering on soft muon enables lower H_T thresholds and is sensitive to signatures with b-jets in the final state
- HLT strategy: Reconstruct displaced jets with displaced tracks. Prompt track veto
- Early Run 3 result already public, CMS PAS EXO-23-013 (2022 data)



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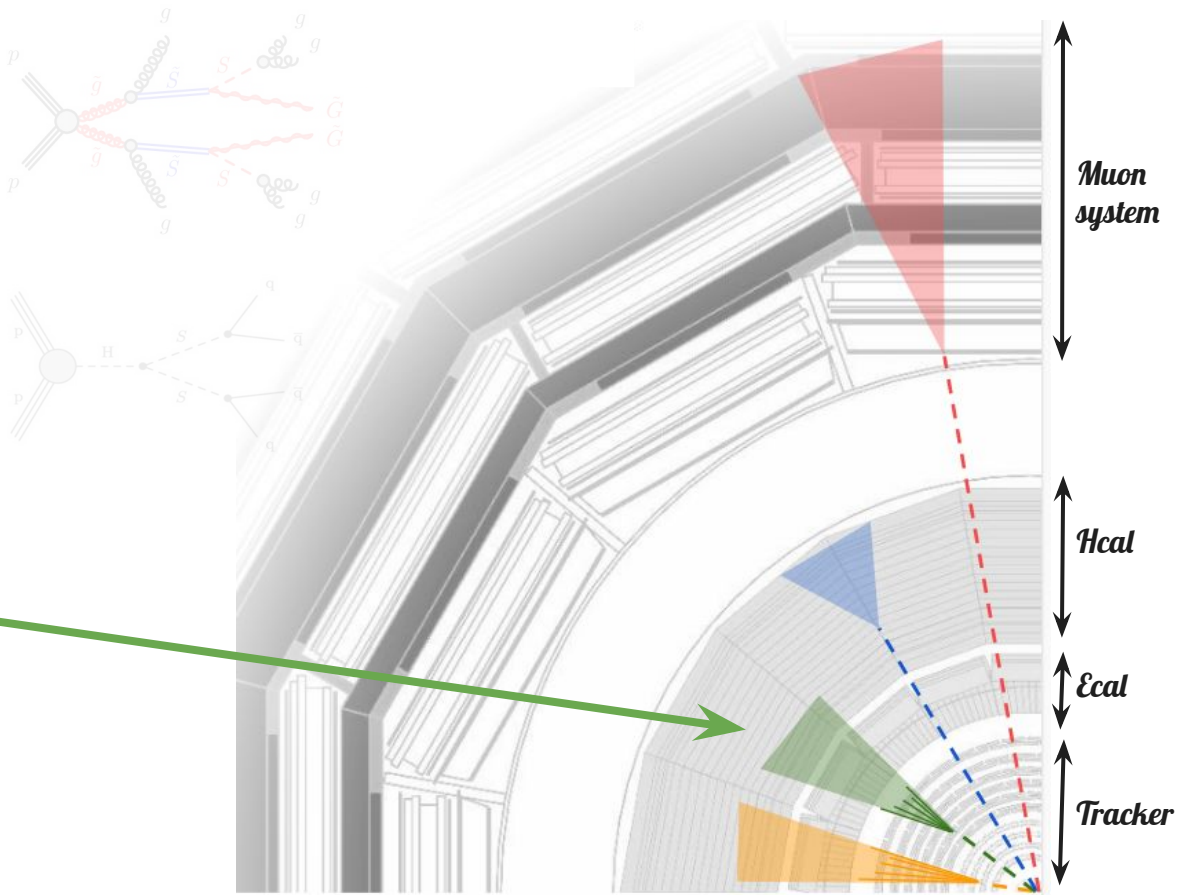
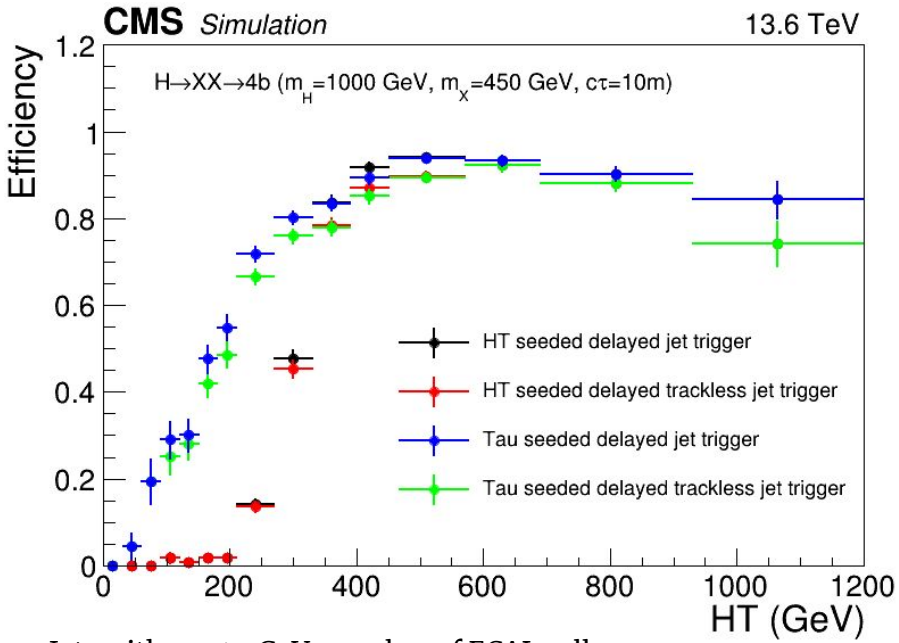


ECAL-based displaced jet trigger

ECAL measures arrival time of objects with precision of ~200 ps (for energy deposits >50 GeV)



Jets with p_T>40 GeV, number of ECAL cells>5, $|\eta|$<1.48 and jet timing>2 ns.

- **L1 Strategy**: H_T>430 GeV or (L1 Tau p_T>120 GeV and H_T>360 GeV)
  - L1 Tau seeds enable lower HT thresholds.
  - As LLPs become more massive and displaced, the resulting jets become collinear and can look like τ leptons
- **HLT strategy**:
  - Nominal jets (track matched to the jet) or trackless jets (no matched track).
  - Use ECAL timing information for jet timing.

Ref: https://cds.cern.ch/record/2865844

Exciting searches ongoing!

Displaced jet trigger

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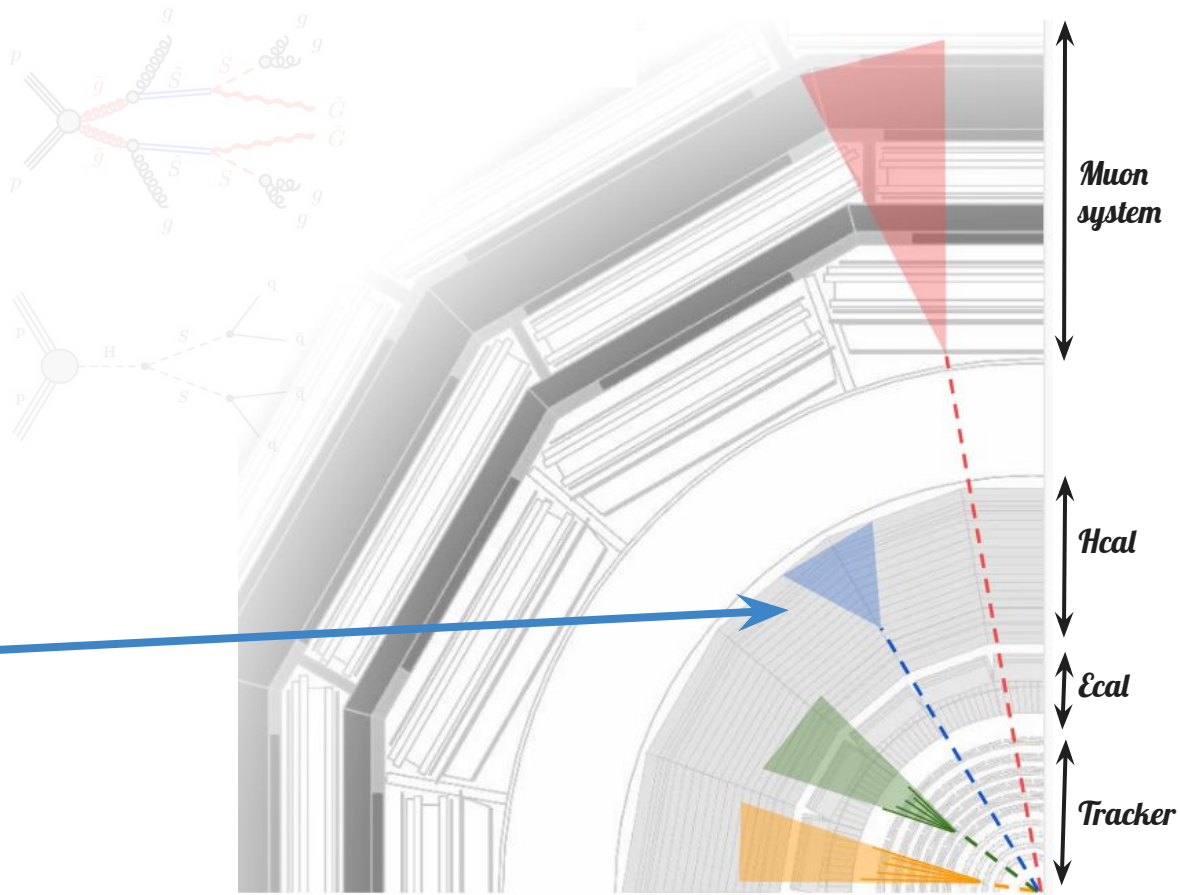
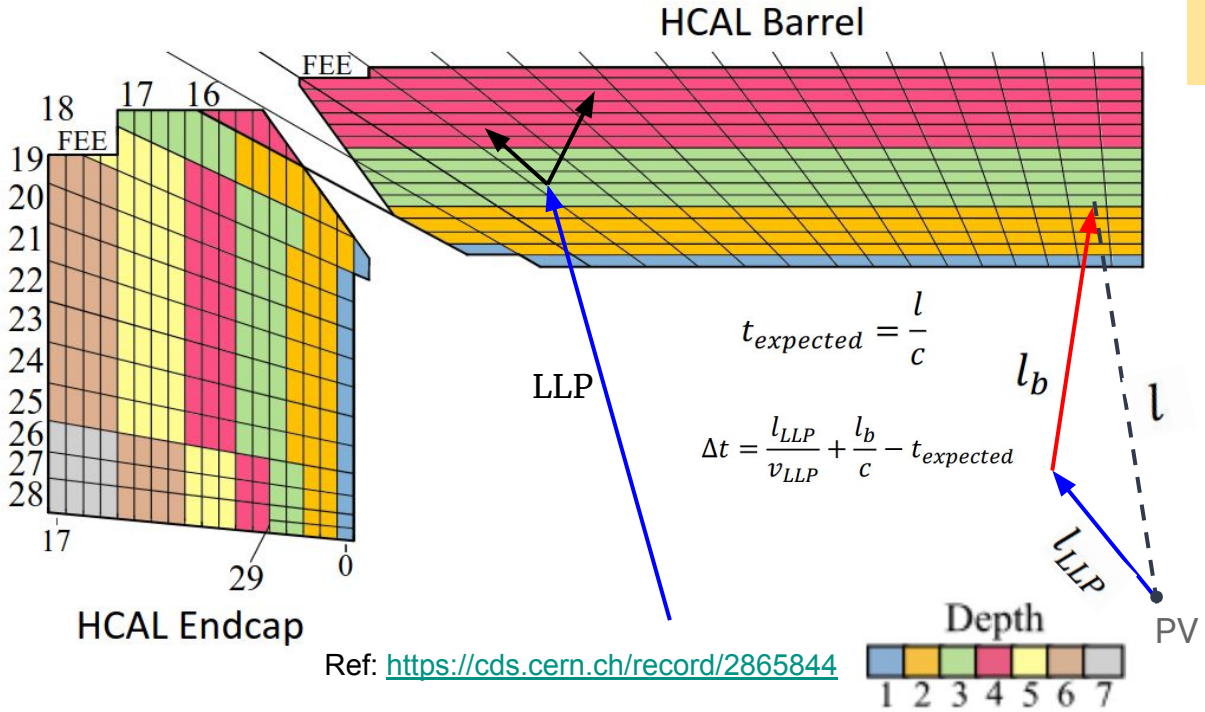


HCAL-based LLP triggers

HCAL depth segmentation + HCAL timing → excellent for LLP
Exploit these capabilities in L1 triggers (and subsequently in HLT)

2 scenarios considered @L1: Time-flagged & Depth flagged

1. **Use HCAL time information at the L1 trigger level to identify delayed jets (>6 ns). Prompt veto applied.**
2. **Trigger on minimal energy deposits in the first two layers and high energy deposits in the later layers**



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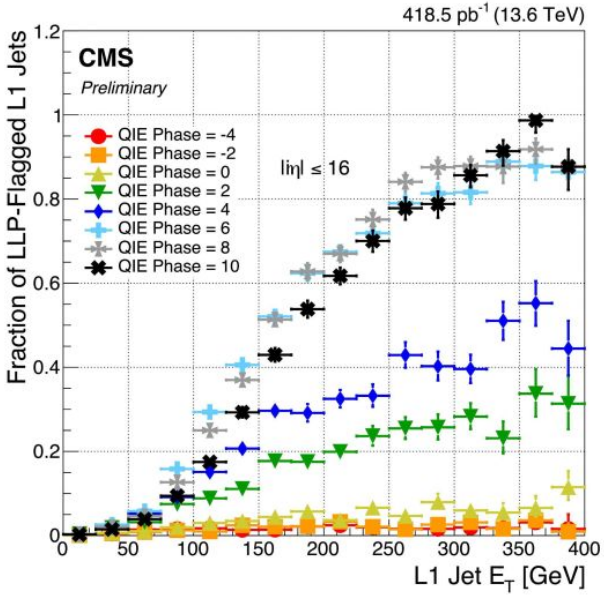

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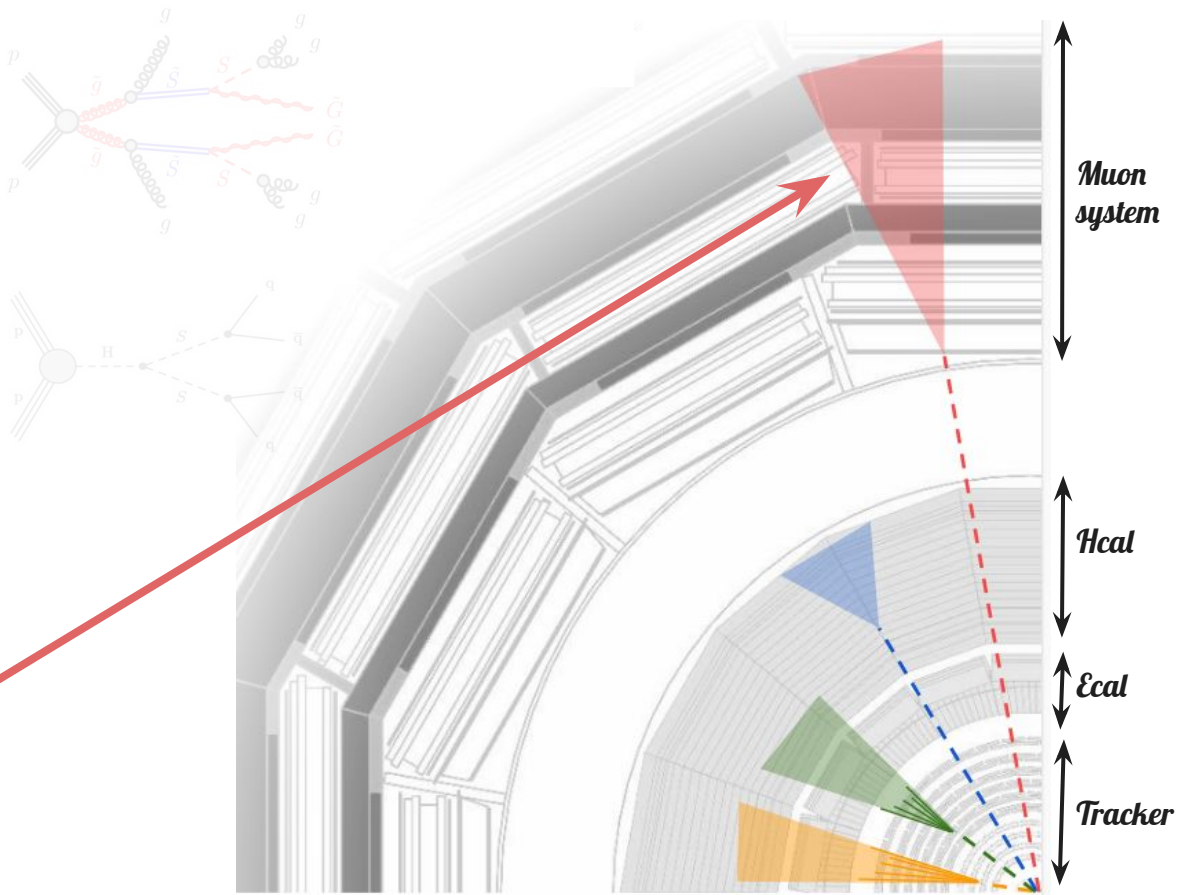
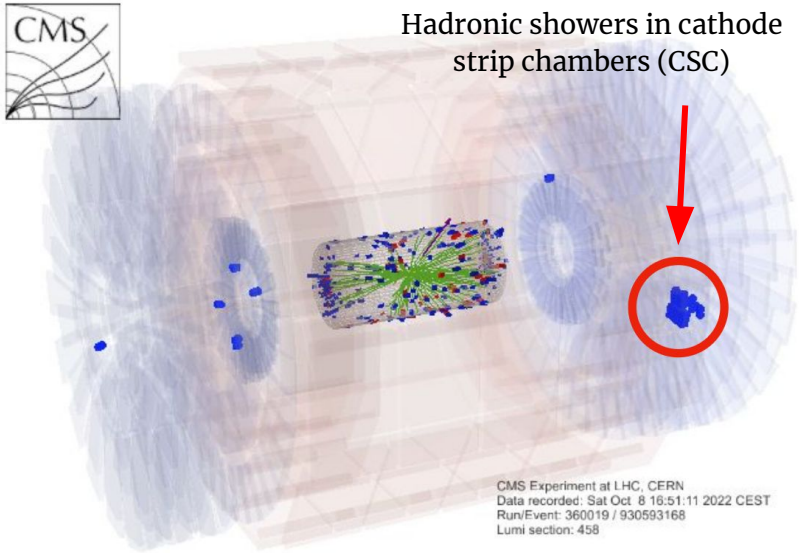


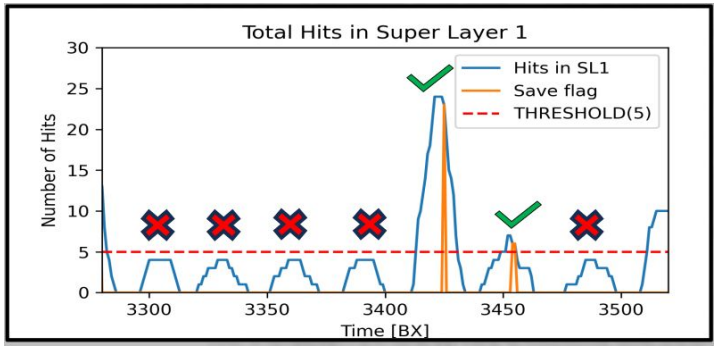
Muon system based displaced jet trigger

- Signature was studied in offline analysis already in Run 2, but no dedicated trigger strategy.
- Analysis with full **Run 2** data:
  - endcap-only (published in PRL)
  - endcap+barrel (submitted to PRD)
  - **Both triggered with MET.**
- In **Run 3**, improved the trigger strategy (in endcaps).



L1 strategy: Count hits in a given muon chamber. Event accepted if hit multiplicity is greater than some threshold (configurable).

HLT strategy: Reconstructed hits clustered using Cambridge-Aachen (CA) algorithm. Some selections applied on cluster properties.

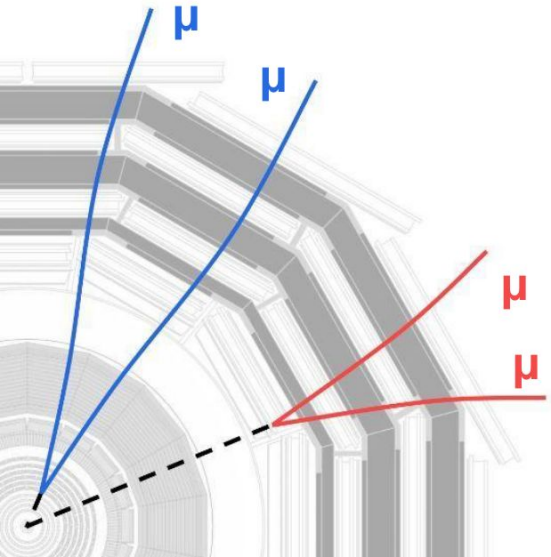


Ref: https://cds.cern.ch/record/2842376

There are many other LLP triggers in CMS

Displaced Dimuon

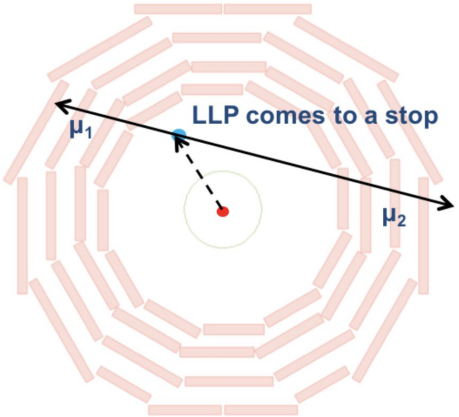
Already have public results with Run 3 (2022) data. EXO-23-014



Triggering on out-of-time objects

LLP can be stopped inside CMS, and decay later. Look for LLP decays during empty BX.

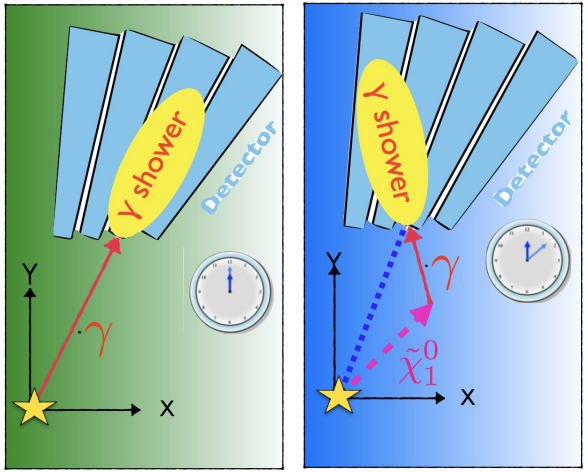
Published Run 2 results. Run 3 analysis underway.



Displaced/delayed Photon

(another use-case of ECAL-timing)

Published Run 2 results. Run 3 analysis underway.

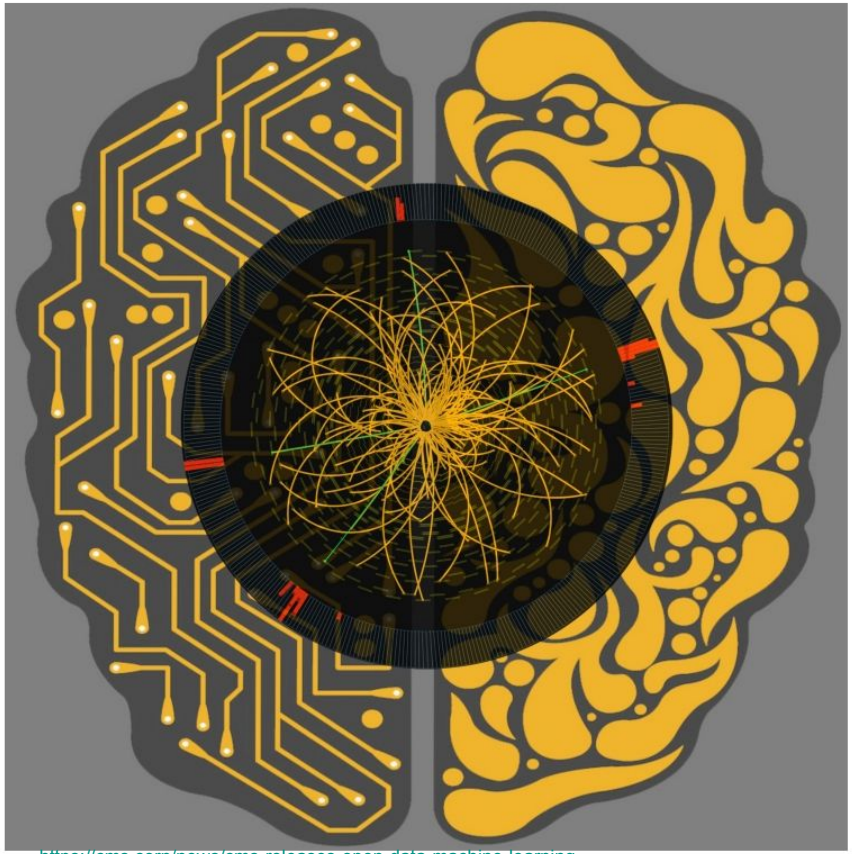


Picture courtesy: Livia Soffi

Machine learning at trigger level

ML is an essential and versatile tool that we use to

- ➔ improve existing approaches
- ➔ enable new approaches

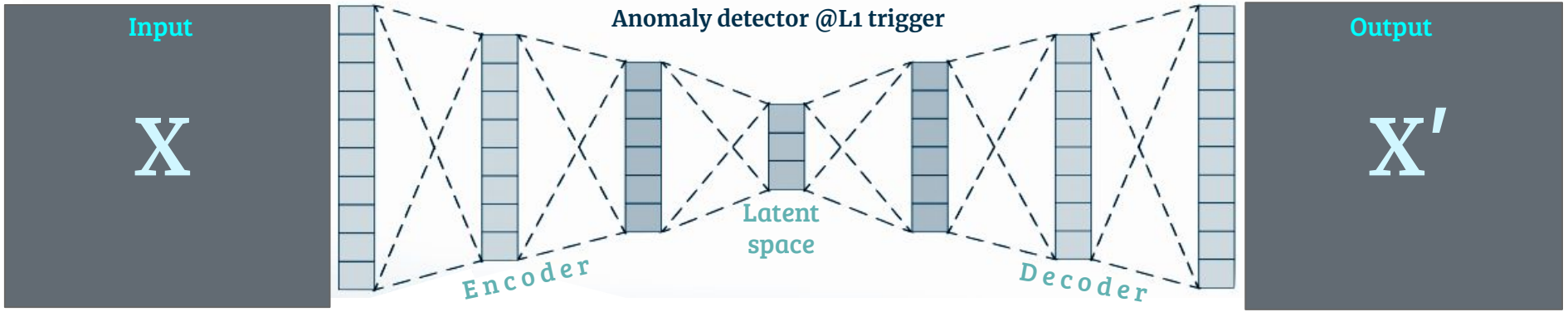


https://cms.cern/news/cms-releases-open-data-machine-learning

The unknown-unknown territory: how to approach it?

- If we knew the exact signature we are looking for, we'd build a trigger for it!
- In absence of that, what else can we do?

- Use of ML to learn the features of typical standard model events
- Then, pick events that are not typical, using **autoencoder** (AE)
- Train AE on typical events (ZeroBias data) and use reconstruction error (loss) as a metric for anomalous-ness



$$\mathcal{L} = || X - X' ||$$

Anomaly detector @L1 trigger in CMS

Two complementary approaches

AXOL1TL

Anomaly eXtraction Online Level-1 Trigger aLgorithm

Inputs: P_T, η, ϕ of Jets(x10) , e/γ (x4), μ (x4), and MET (from Calo layer-2 and Global Muon Trigger)

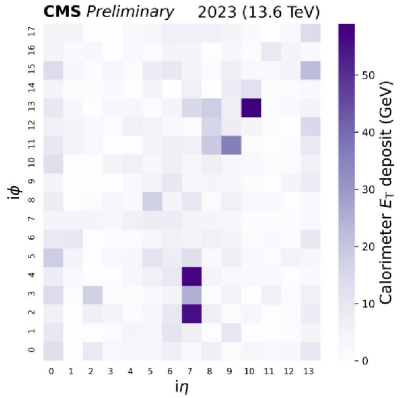
Ref: https://cds.cern.ch/record/2876546

CICADA

Calorimeter Image Convolutional Anomaly Detection Algorithm

Inputs: Low-level information (from Calo layer-1) in image format.

Ref: https://cds.cern.ch/record/2879816



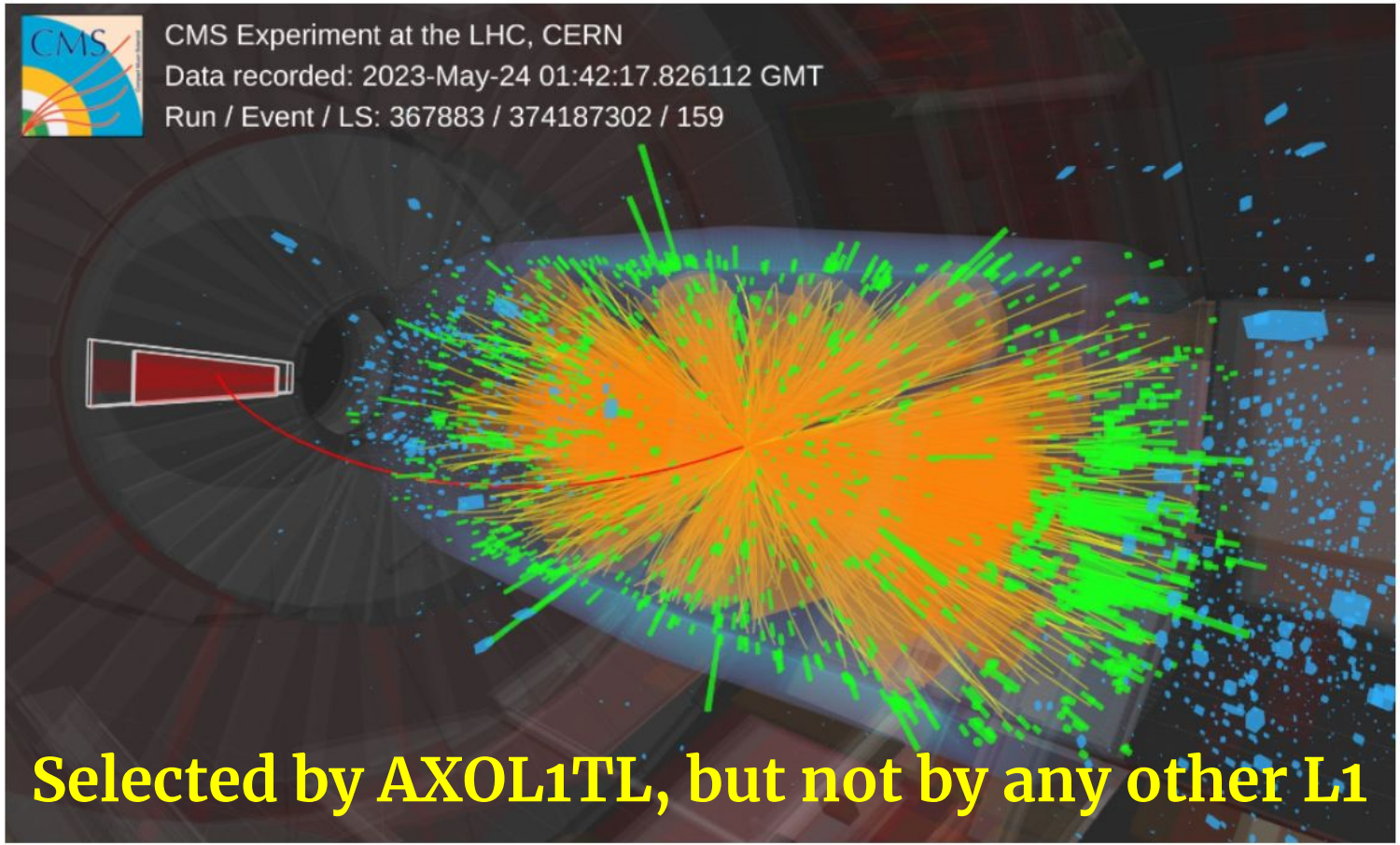
ML@L1 trigger becoming important. Tools for ML@FPGA developed.

- Neural Nets → HLS4ML (documentation)
- Boosted Decision Trees → Conifer (github, paper)

hls4ml

Conifer

An event selected by AXOL1TL



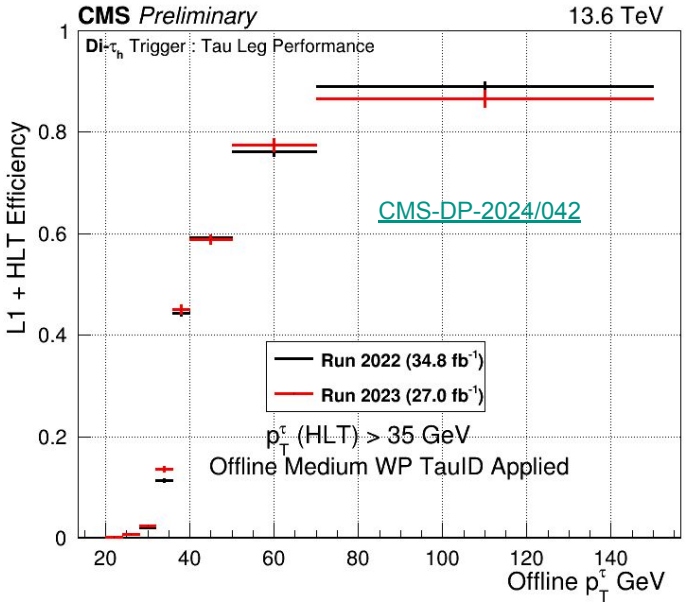
SUEP?

Emerging jet?

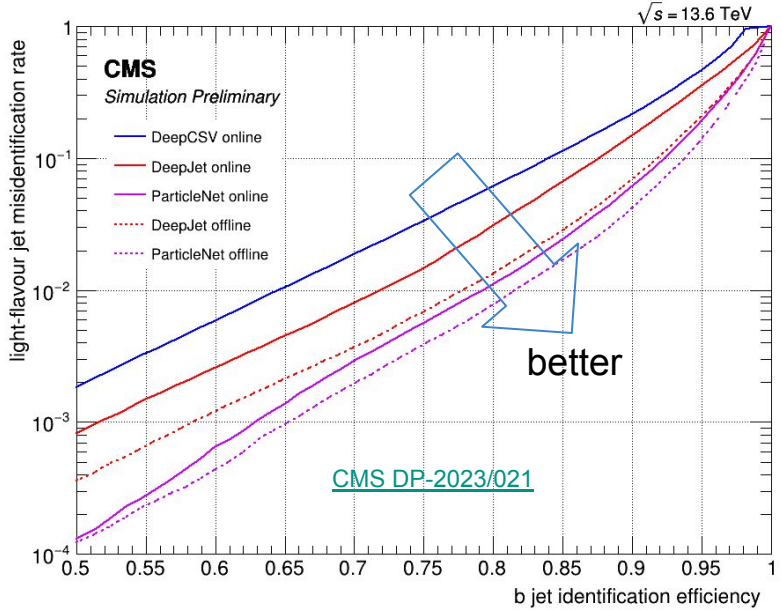
Or just normal QCD?

ML@HLT

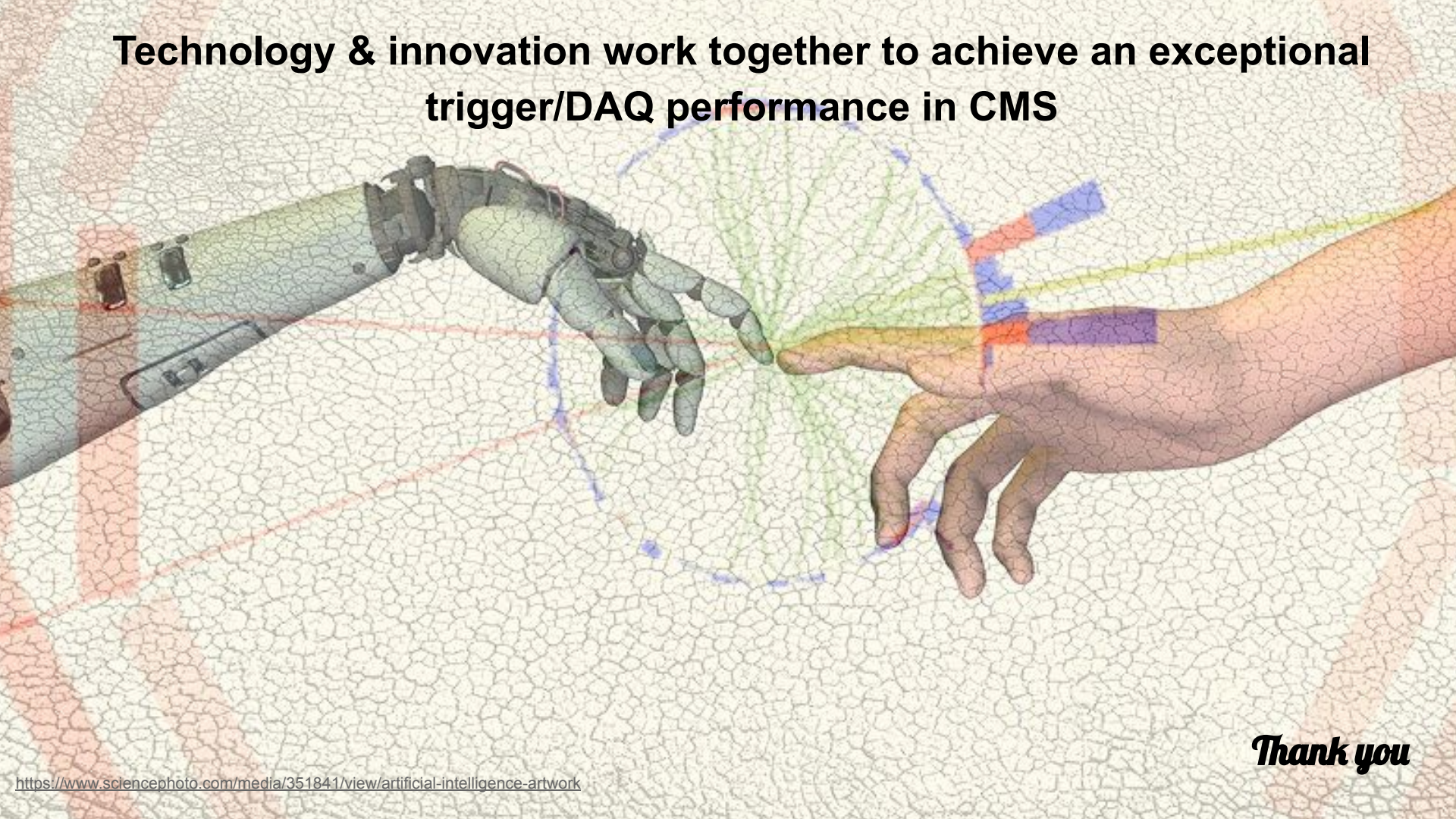
- Tau HLT
- Reconstruction: Hadron plus strip
- Identification: CNN+DNN based tagger (DeepTau)



- ParticleNet b-jet tagger@HLT. GNN-based.
- Jets treated as a permutation-invariant point cloud.
- Performance gain, specially for HH(4b), HH(2b2τ) and HHH(6b) processes, compared to Run 2.



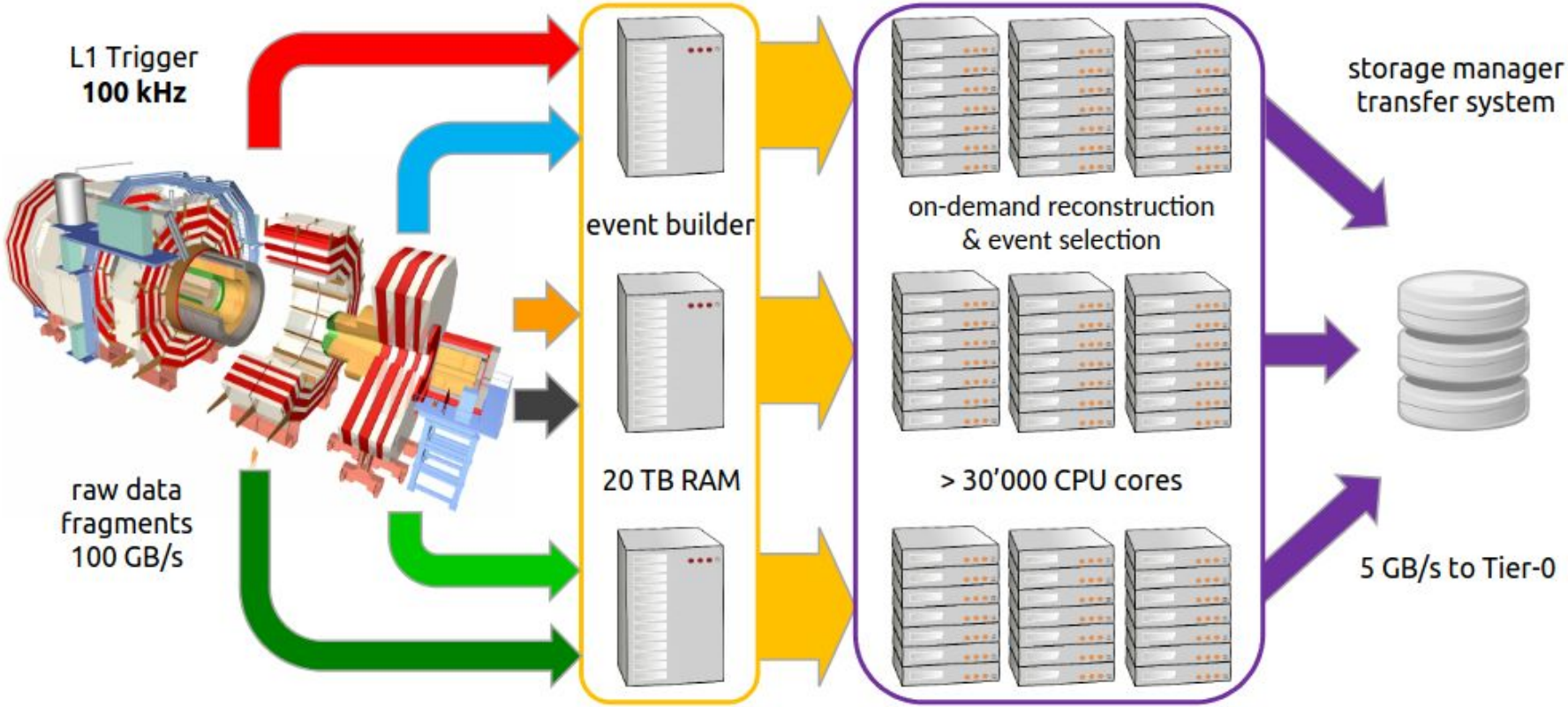
Technology & innovation work together to achieve an exceptional trigger/DAQ performance in CMS



Thank you

https://www.sciencephoto.com/media/351841/view/artificial-intelligence-artwork

Extra slides



Level 1 Trigger
- hardware based
- synchronous with LHC

Data Acquisition
- ADC converters
- event builder network

High Level Trigger farm
- software based
- multithreaded jobs

Storage Manager
- distributed filesystem
- transfer to Tier 0