Novel triggering strategies at High Luminosity LHC

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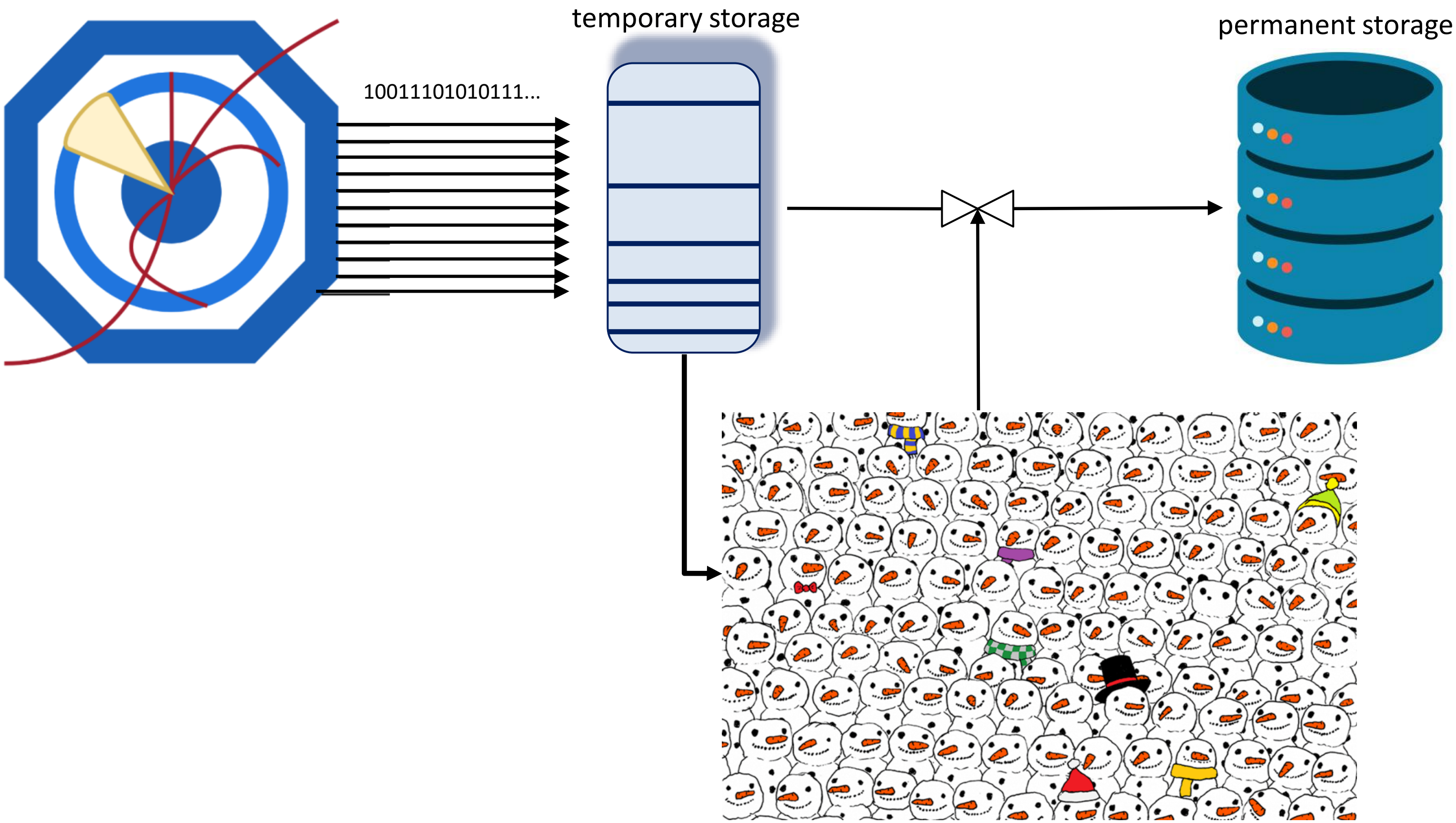
"Classical" Trigger systems

Target a set of predefined signals/topologies, run online algorithms that select them, reducing the event rate to disk to an amount manageable by offline computing and analysis



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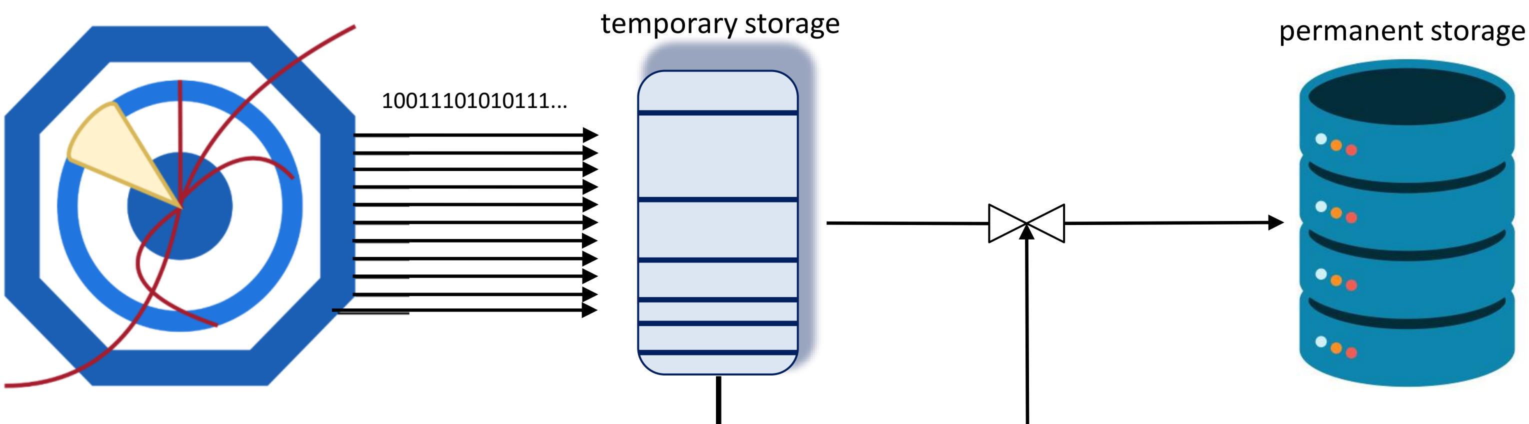

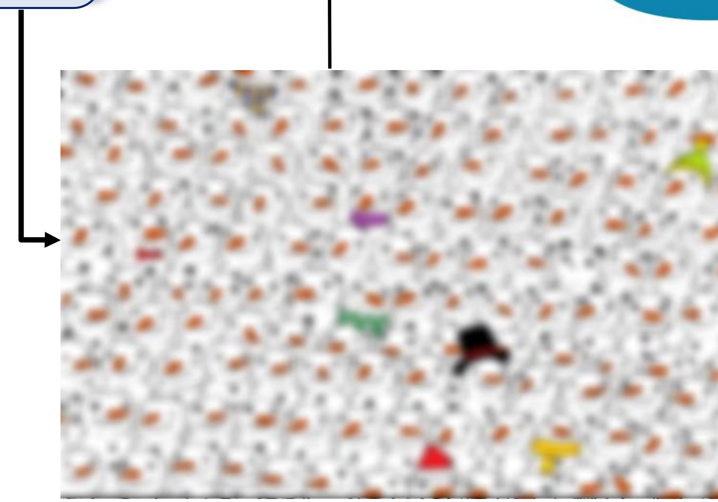

The main constrains:

> **Latency:** delay between the start of a process and the arrival of its results

> **Throughput:** the rate at which the process can start over

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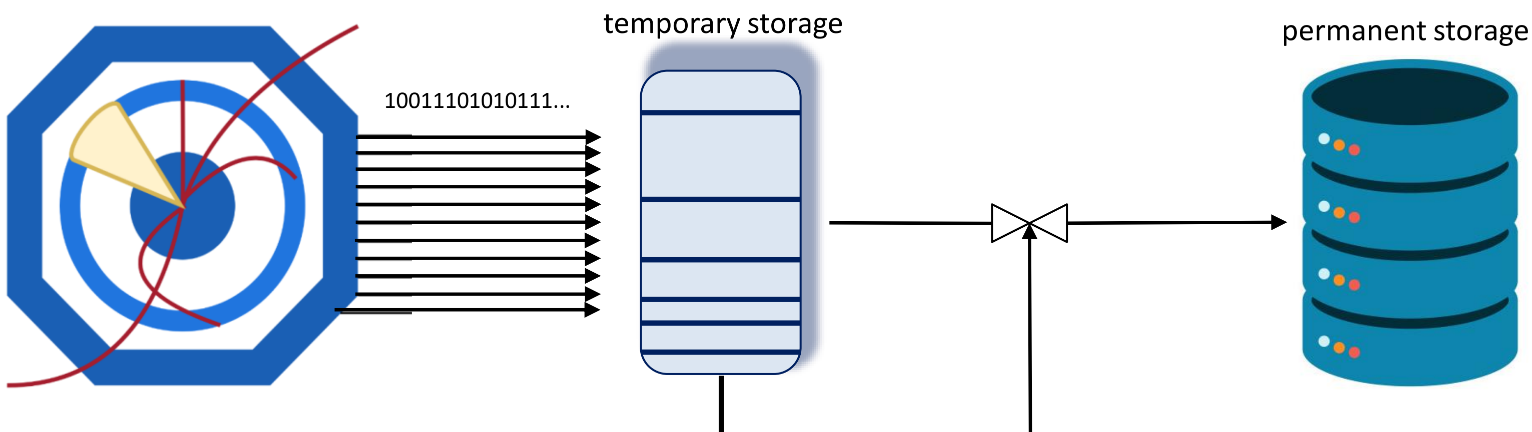
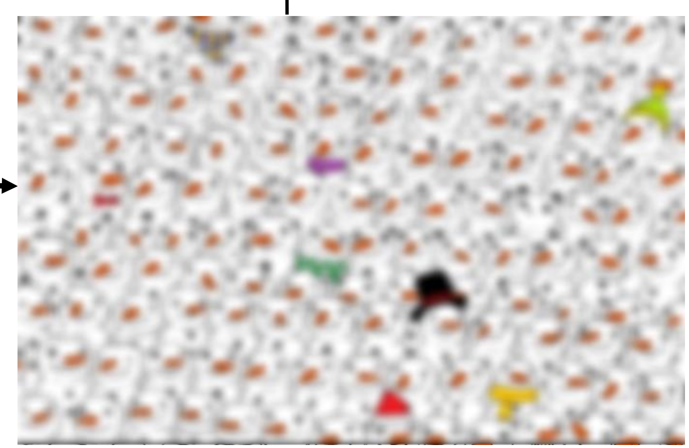


Typically "layered": 2 or more levels dealing with decreasing rate and increasing granularity/resolution



Leveraging Technology Advancements

Trigger systems have been and will be profiting from sensational advancements in Telecom, Computing, Electronics, Algorithms

NETWORKING

high speed – high capacity optical links of hundreds of Gbps

ALGORITHMS

complex Machine Learning models for classification, data compression, anomaly detection

MEMORY

fast access – high density memories allowing deep buffering (longer latencies)

USER FRIENDLINESS

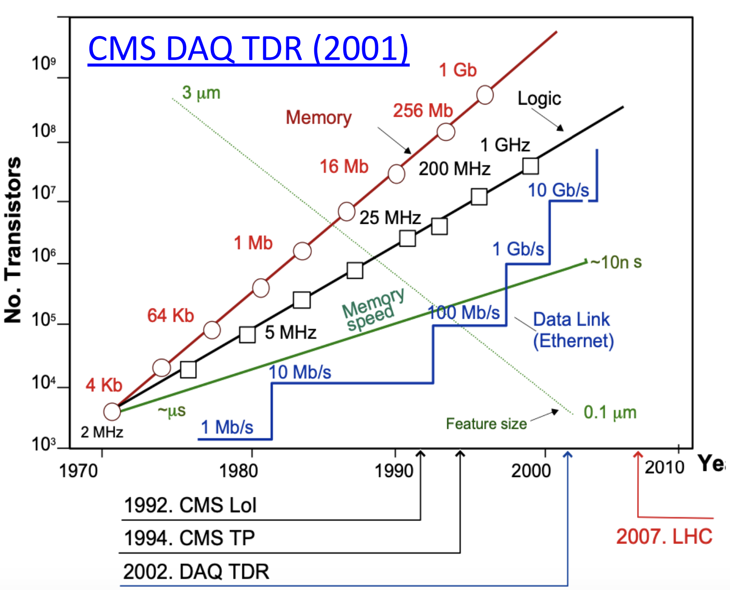
convenient tools, large communities, common standards: enabling development and deployment

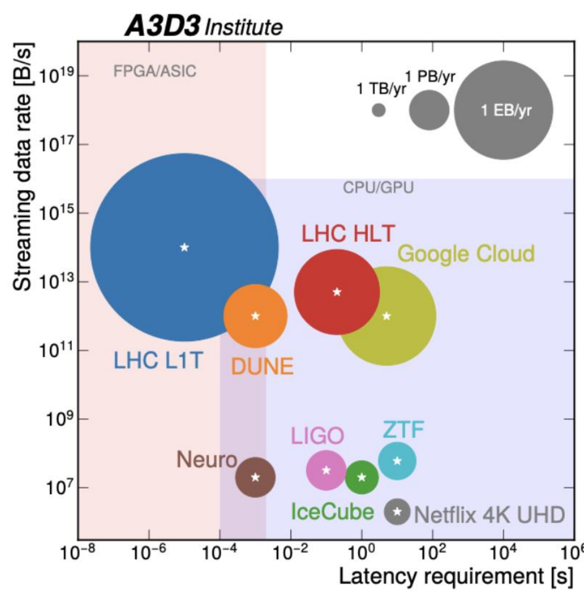
PROCESSING

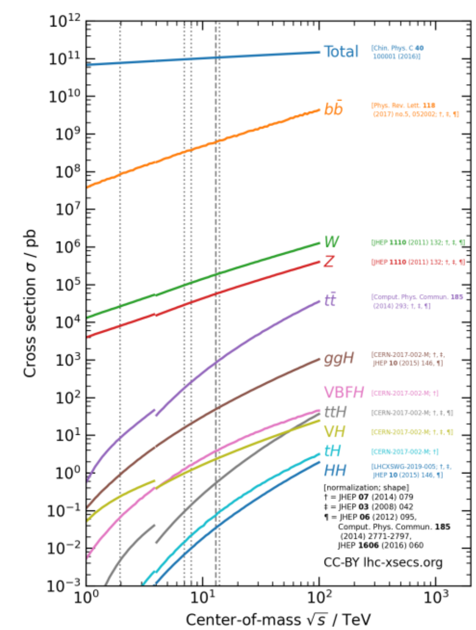
still improving CPUs; GPUs as boosted by AI revolution; FPGAs as new standard for high performance accelerator/processing unit; distributed computing

A word of caution

- 10+ years of LHC running ahead, may projections lead to reconsider the need of a trigger system?
- Trigger will evolve, but at least for omni-purposes experiments, it will still be playing a crucial roles
  - Among the biggest players (~50 TB/s), also considering commercial activities
  - We know a large portion of events are little interesting
  - Accurate Monte Carlo samples (with weight <1) corresponding to full stat impossible to produce







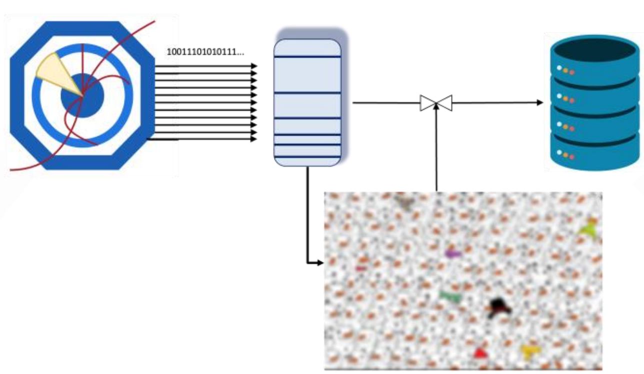
Objectives

New Trigger strategies are key to empower physics reach of experiments. That will especially the case for HL-LHC

More efficient selection for target signals/topologies

Extend phase space for interesting topologies (low p_T)

Reduce the bias! Deal with the unexpected (anomalies)



Strategies

Get a better "classical" trigger system

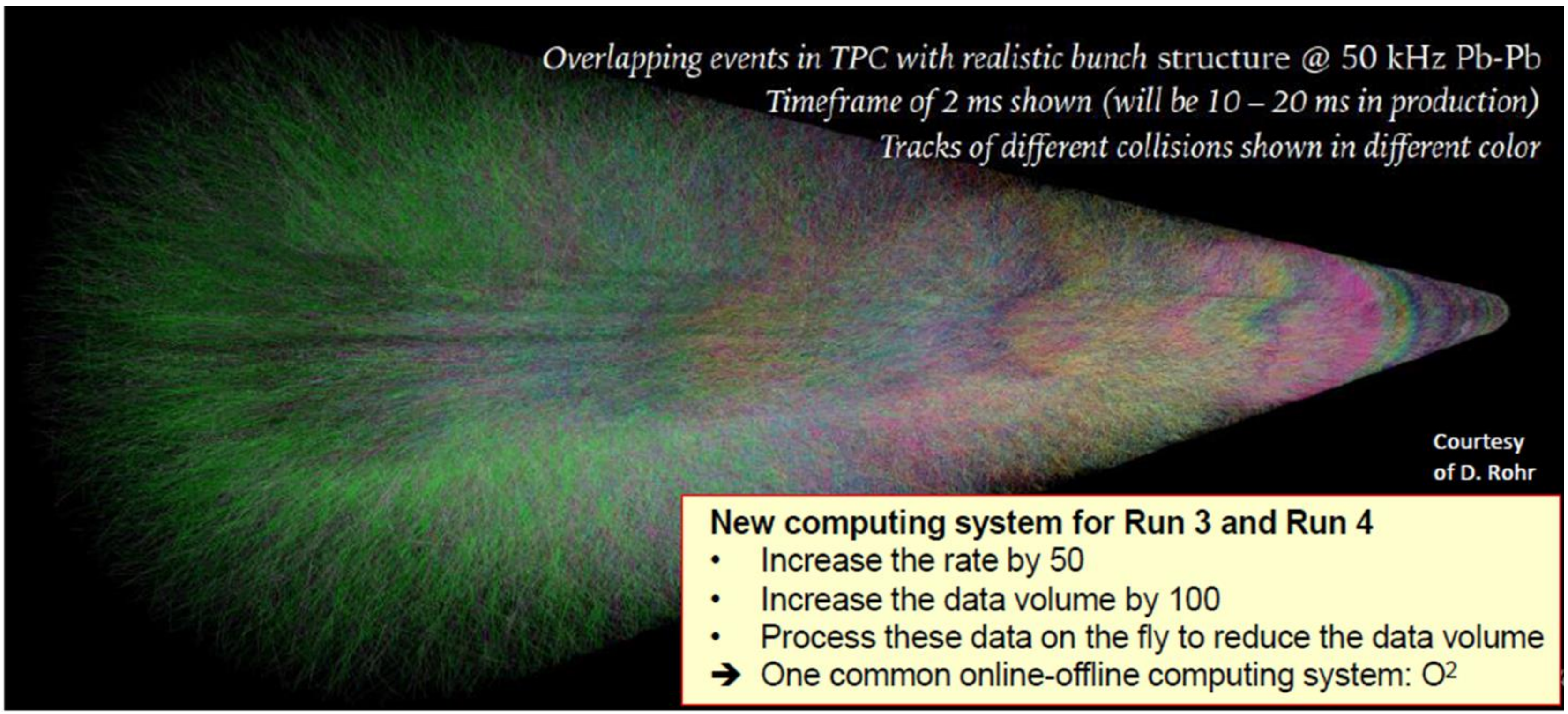
- More detectors participating to the trigger
- Increase latencies
- More complex offline-like algo, both in hardware and software: Machine Learning!
- Get rid of the hardware level
- Higher rate (of raw data) on disk

Profit from the event reconstruction / data reduction done by the trigger system

- Permanent store reconstructed objects, trading event size with event rate
- Enabled by fast online calibration procedures
- "Real Time Analysis" both online (producing aggregated results) and offline

ALICE continuos reading

- Heavy-Ions program entails very low S/B, online selection is essentially impossible → need large statistics!
- LHC will provide 50 kHz of min-bias Pb-Pb collisions (x100 w.r.t. run 2)
- Continuous read-out of all detector data, with reduced data volume to disk



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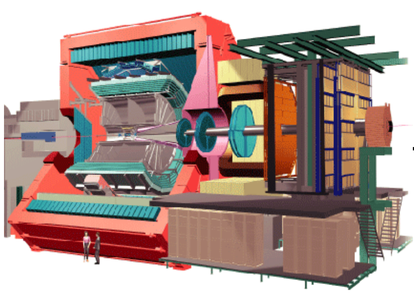
ALICE O^2 system

(common online-offline system)



3.5 TB/s
raw data

Baseline correction + zero suppression: Data reduction by cluster finder.
Compression factor ~6.6

0.5 TB/s

Data reduction by tracking. Only reconstructed data to storage.
Compression factor 5.5

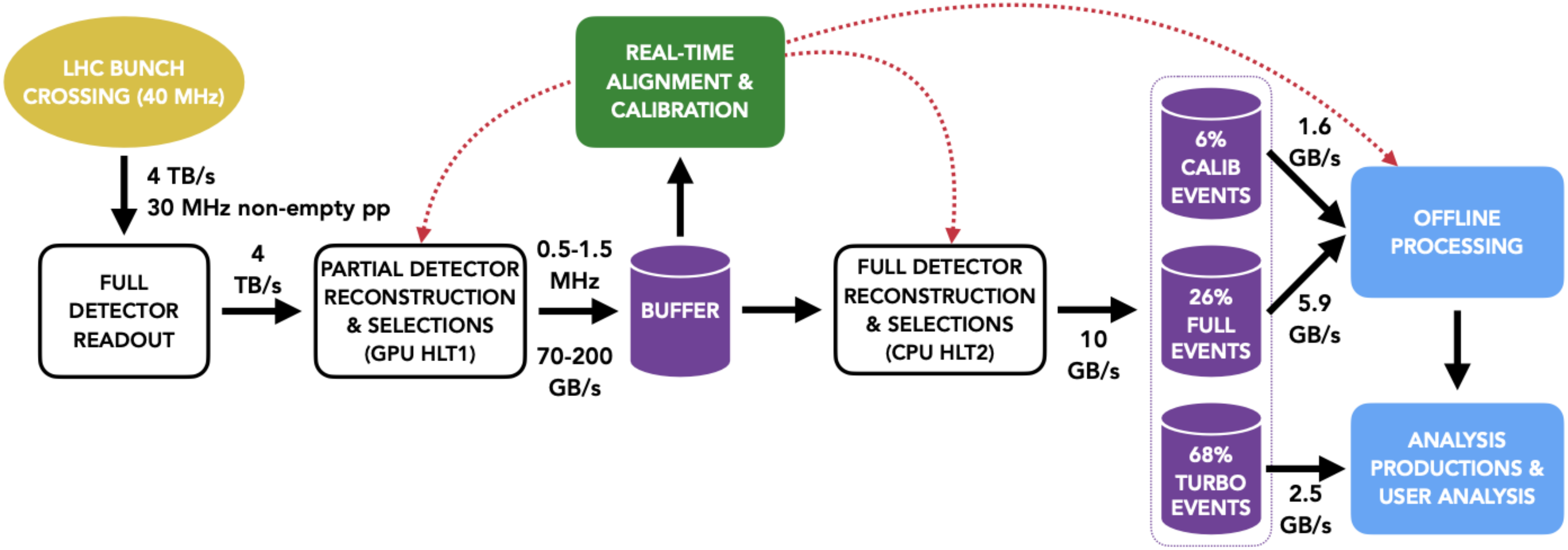
100 GB/s

Permanent storage.
(60PB/y)

Analysis facilities

asynchronous event reco w/ full calibration

LHCb Real Time Analysis

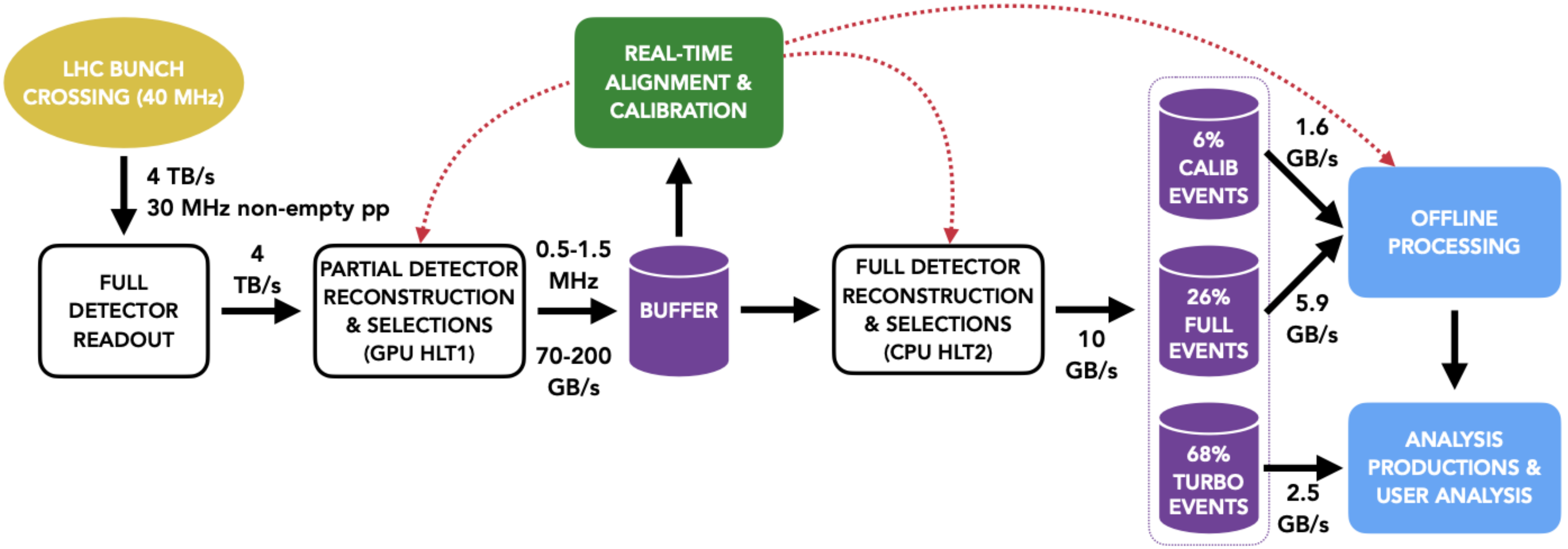


Hardware-based L0 would not allow profiting from higher luminosity → full detector readout (4 TB/s) + 2 levels of software-based trigger

HLT1

- performs a fast reconstruction to identify inclusive beauty and charm signatures as well as high p_T muons at 30 MHz
- partial event reconstruction (tracking) on GPUs hosted in the event-building servers
- select events with 2-tracks vertices, displaces single tracks, muons (configurable)
- Output rate ~1 MHz onto a ~30PB disk buffer (80h)

LHCb Real Time Analysis



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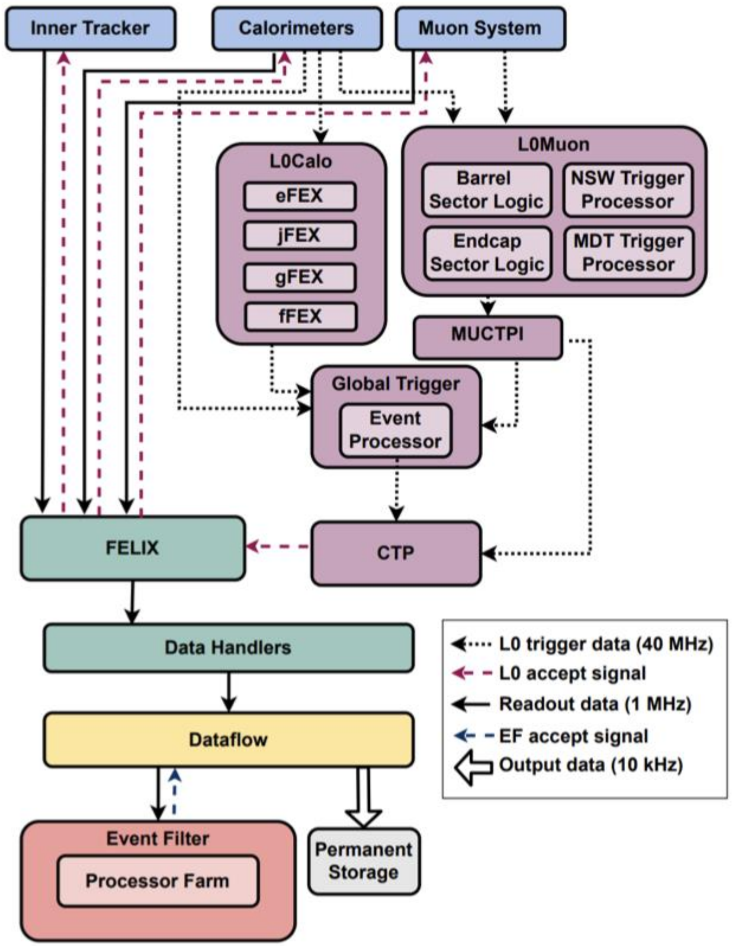
HLT2

- provided with real-time computed calibration constants, performs full event reconstruction on CPU and possibly on accelerators
- run O(1000) algorithms selecting relevant signal events and a few inclusive topologies
- outputs 10 GB/s, split into dedicated streams (majority to "Turbo", with high level event content)

ATLAS TDAQ for HL-LHC



L0

- 40MHz → 1MHz, latency of 10 μs
- Full granularity data from Calorimeters
- Data from all muon detectors
- Global Trigger: offline-like algorithms to combine/refine regional candidates running on farm of common HW

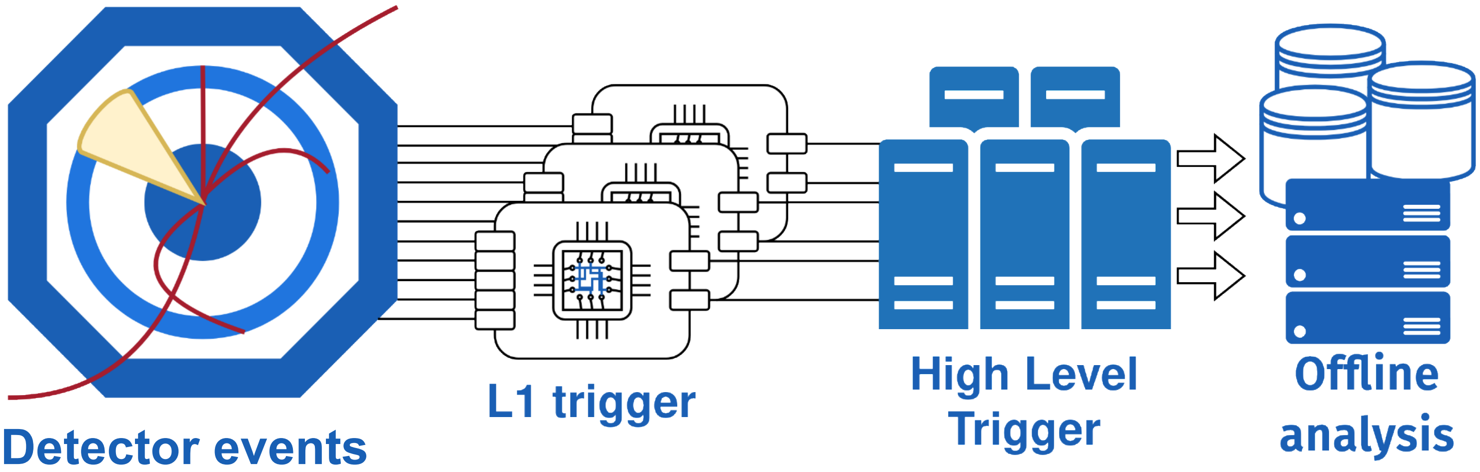
Event Filter Trigger

- 1MHz → 10kHz
- Full event building dealing with throughput of 5 TB/s
- Farm of heterogeneous commodities processors running offline-like algos on accelerators too (GPU/FPGA)

CMS Trigger for HL-LHC

- Maintain the 2 levels structure:
  - L1: custom FPGA boards (ATCA)
  - HLT: farm of servers with CPUs and GPUs
- Updated figures for rates, throughput, latency

CMS detector	LHC Phase-1	HL-LHC Phase-2	
Peak ⟨PU⟩	60	140	200
L1 accept rate (maximum)	100 kHz	500 kHz	750 kHz
Event Size at HLT input	2.0 MB [a]	6.1 MB	8.4 MB
Event Network throughput	1.6 Tb/s	24 Tb/s	51 Tb/s
Event Network buffer (60 s)	12 TB	182 TB	379 TB
HLT accept rate	1 kHz	5 kHz	7.5 kHz
HLT computing power [b]	0.7 MHS06	17 MHS06	37 MHS06
Event Size at HLT output [c]	1.4 MB	4.3 MB	5.9 MB
Storage throughput [d]	2 GB/s	24 GB/s	51 GB/s
Storage throughput (Heavy-Ion)	12 GB/s	51 GB/s	51 GB/s
Storage capacity needed (1 day [e])	0.2 PB	1.6 PB	3.3 PB



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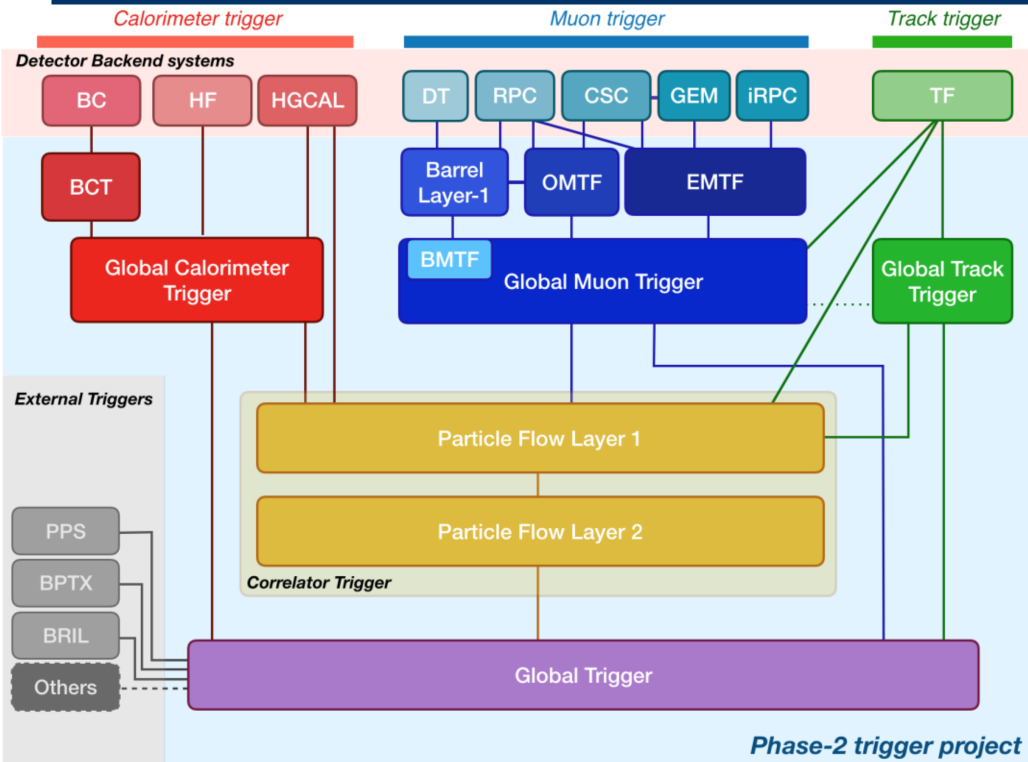
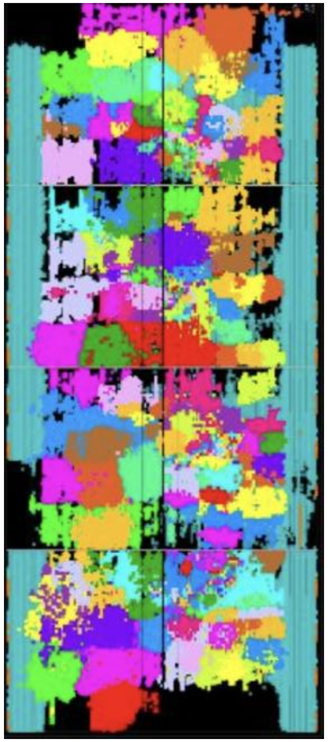


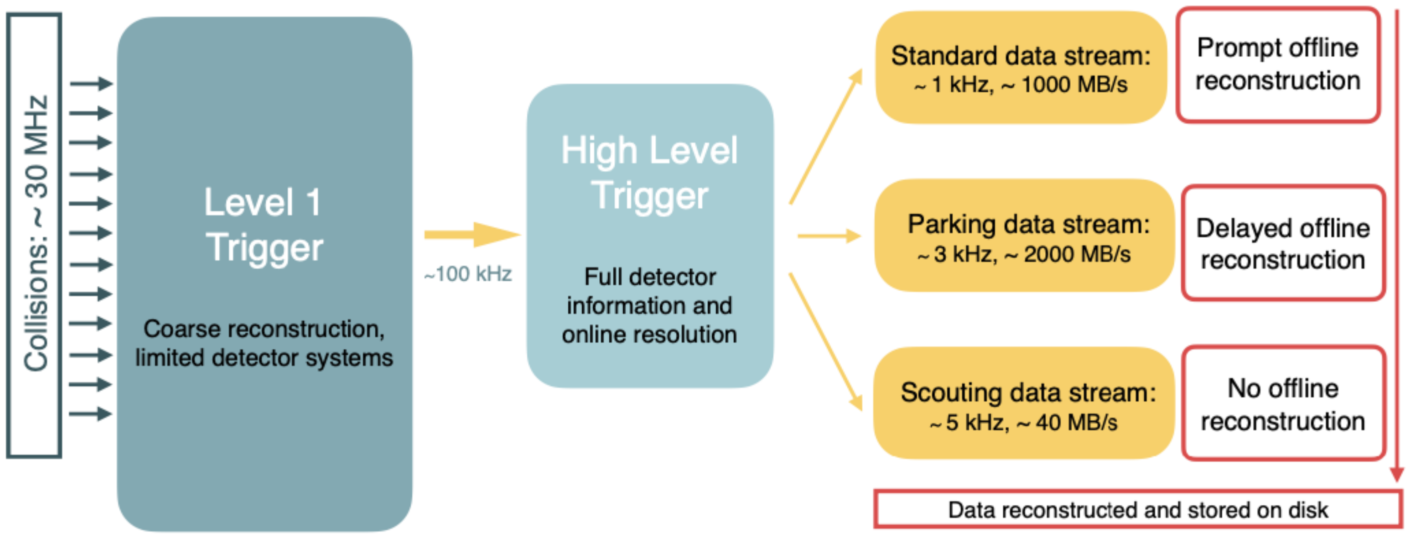


400 algos on 1 FPGA

- Major upgrade of the L1 system → all detectors (but silicon-pixel detector) participating in providing primitives!
- Information from subsystems combined in an offline-like fashion by the Trigger Correlator:
  - Particle Flow, PU mitigation; ubiquitous usage of ML
- Physics objects quality comparable to those of HLT/offline

Enriching the Physics Program

- Software-based trigger layers provide physics objects with accuracy comparable to offline → exploit those to extend phase space to regions filtered out by online selections
- Store dedicated data streams with high level info only
- Several measurements performed and published both by ATLAS and CMS



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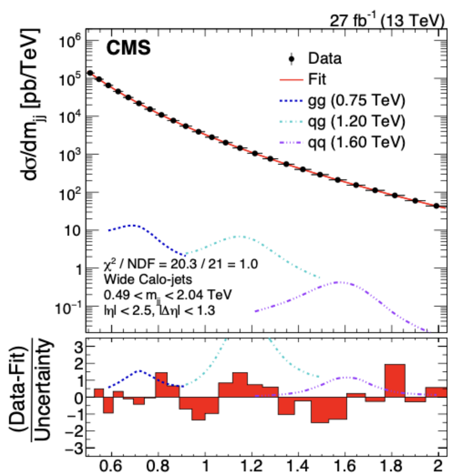
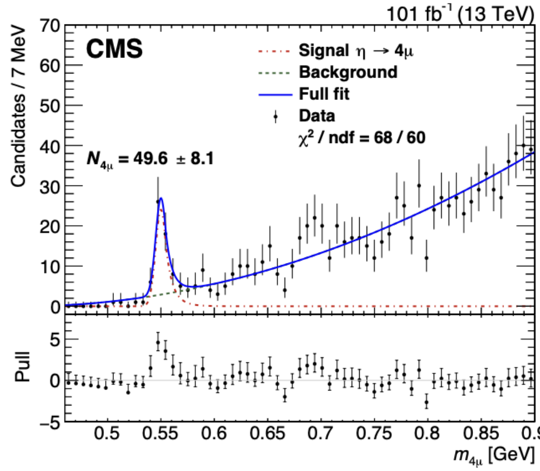
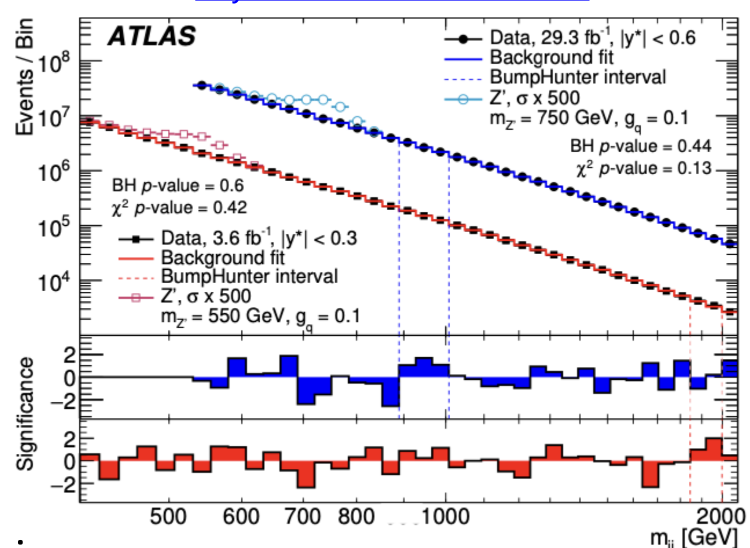
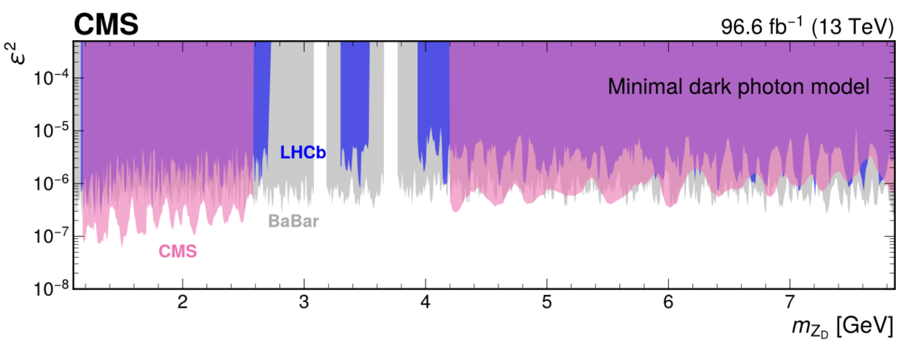




[Phys. Rev. Lett. 121, 081801](https://doi.org/10.1103/PhysRevLett.121.081801)

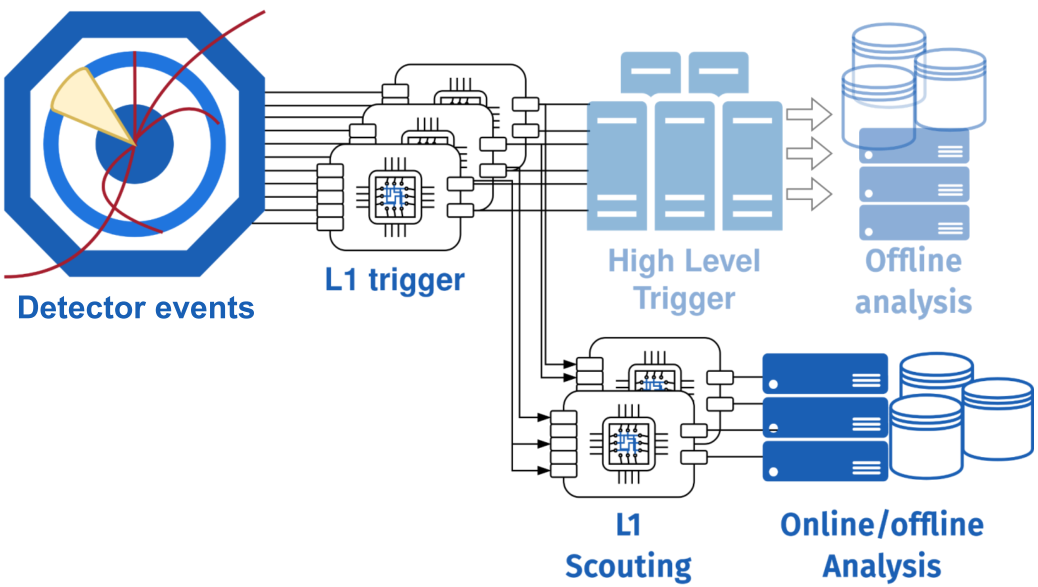




CMS review submitted to [Phys. Rept.]()

CMS L1 Scouting

- Push further this by gathering @ 40MHz L1 objects and use them for physics analysis → potentially unprescaled Zero Bias sample
- Tradeoff between rate and resolution. Proof of principle now in production
  - Interesting analyses could be addressed anyhow, e.g. dijet resonances
- Full potential of the system expected for HL-LHC w/ high resolution L1 objs
- Address both extensions to inaccessible topologies (e.g. $H \to \phi\phi \to 4K$, $W \to 3\pi$) and fully unbiased anomaly searches
  - Correlation with other bunch crossing also possible (looong lived particles)



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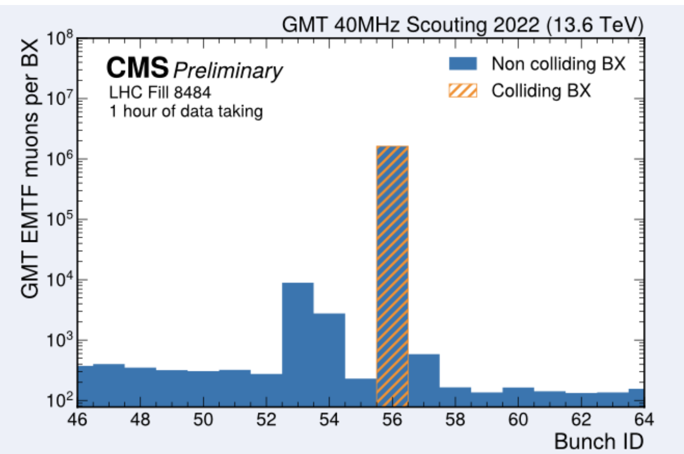
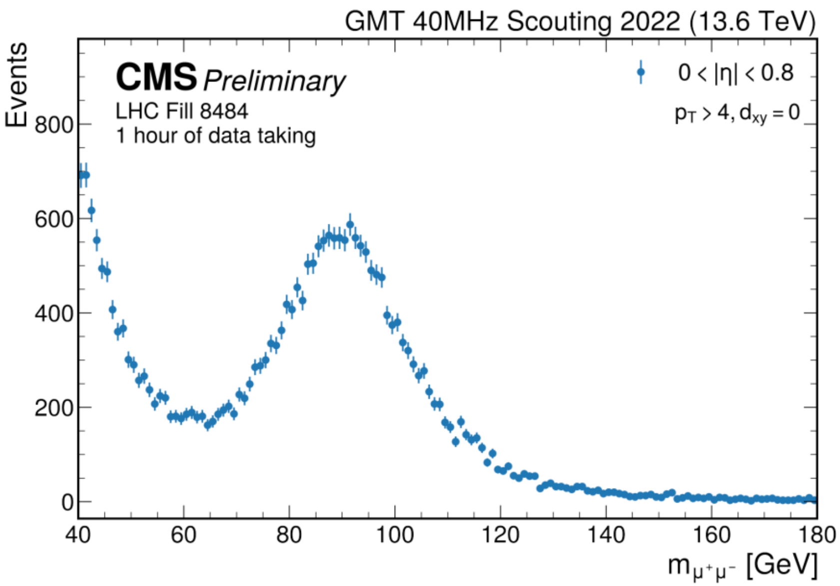


Global Muon Trigger (GMT) muons occupancy per bunch crossing (BX) within an LHC orbit for muons reconstructed by the Endcap Muon Track Finder (EMTF) in the BX range [46,64]. The single isolated colliding bunch (BX 56) is highlighted by the orange transversal lines [CMS-DP-2023-025].



Anomaly Detection, Data Compression

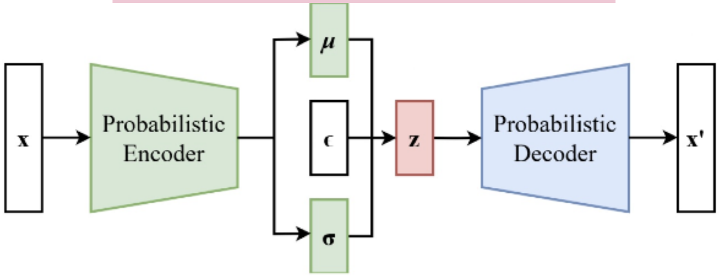
Courtesy of G. Grosso

Anomaly Detection (& Data Compression)

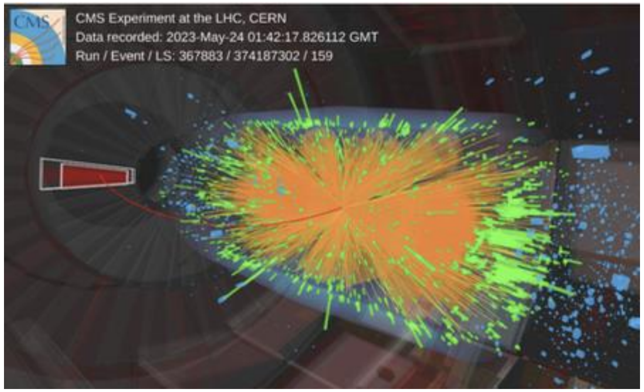
- Variational AutoEncoders used to "compress" input into a latent space; such representation can be used as metric to classify standard vs anomalous data
- AXOL1TL: use VAE to trigger on anomalous events

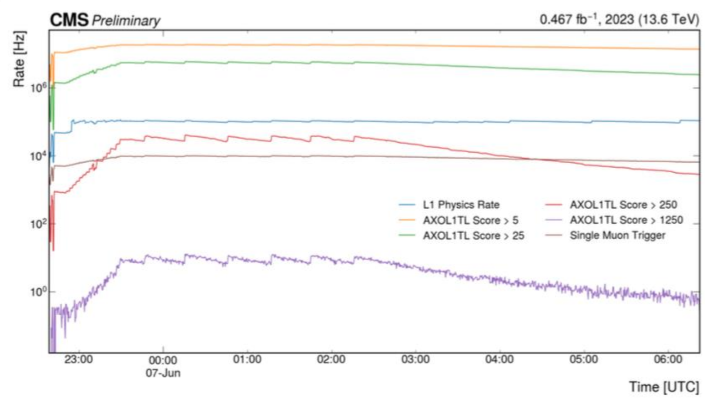
$$\mathscr{L} = (1-\beta)\,||x-\hat{x}||^2 + \beta\,\frac{1}{2}(\mu^2+\sigma^2-1-\log\sigma^2)$$

reconstruction latent representation



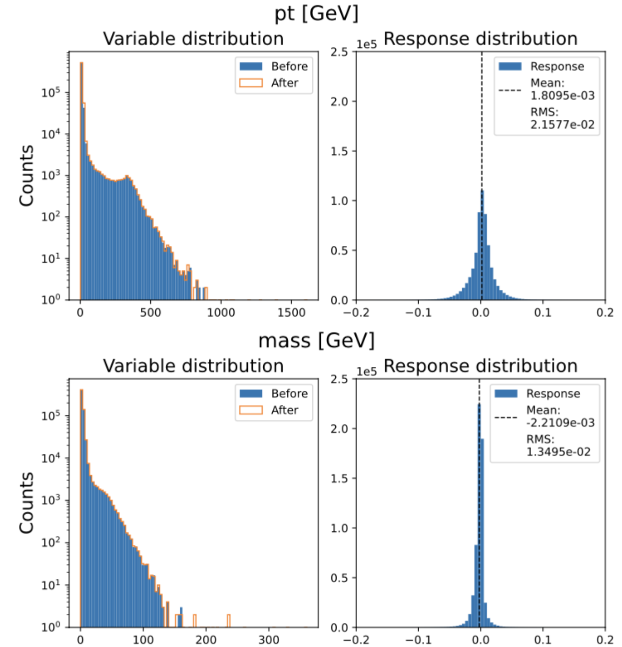
- Train the model on L1 objects in a large Zero Bias datasets
- It results that μ is the enough to discriminate anomalous events.
- In production at CMS since a couple of weeks!



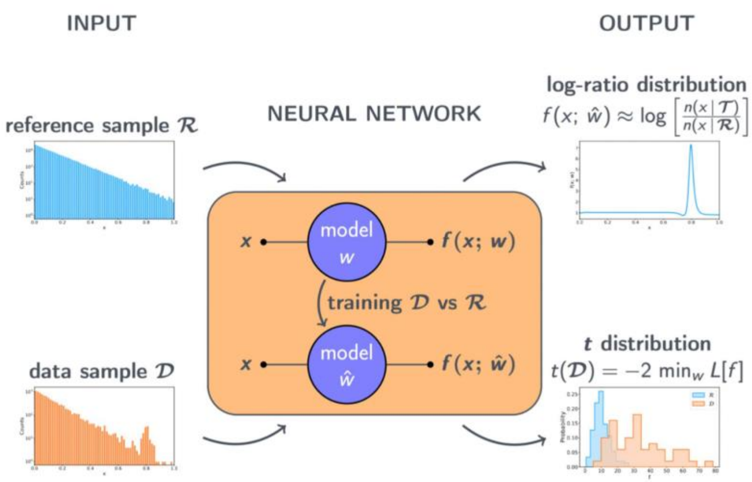


Anomaly Detection (& Data Compression)

- The (lossy) compression provided by VAE could be used as an efficient way to gain bandwidth to disk
- Attempts to evaluate faithfulness of the method are ongoing (e.g. Baler)



- In addition to seeking single anomalous events, statistical anomalies can be addressed
- Run anomaly detection algos on batches of data online (e.g. NPLM), storing statistics parameters to let potential anomalies building up



Summary

- Trigger systems are critical enablers of the LHC experiments' physics programs at the incoming High Luminosity phase
- Tremendous technological advancements in telecom, electronics, algoritms will allow processing huge data flows with offline-comparable accuracy
- Boost in sensitivity for most targeted signals, several ideas being developed for being prepared for the unexpected