

The Phase-1 Upgrade of the ATLAS Level-1 Calorimeter Trigger

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Niklas Schmitt

on behalf of the ATLAS Collaboration

JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



Cluster of Excellence
PRISMA++



FSP ATLAS
Erforschung von
Universum und Materie

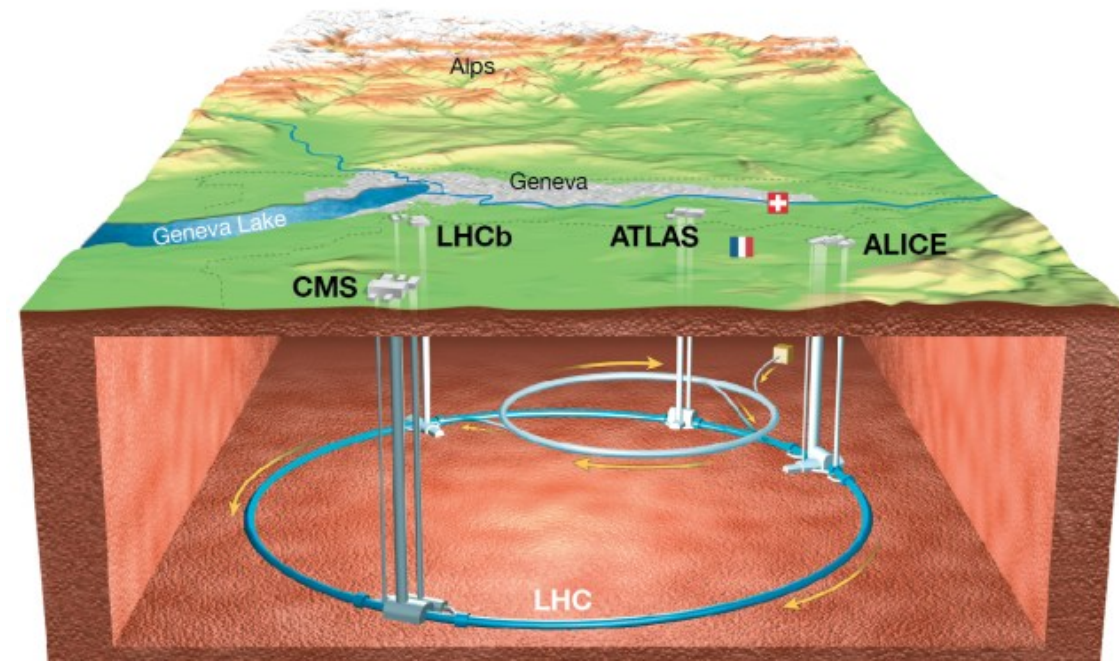
Gefördert durch:



Bundesministerium
für Forschung, Technologie
und Raumfahrt

The Large Hadron Collider (LHC)

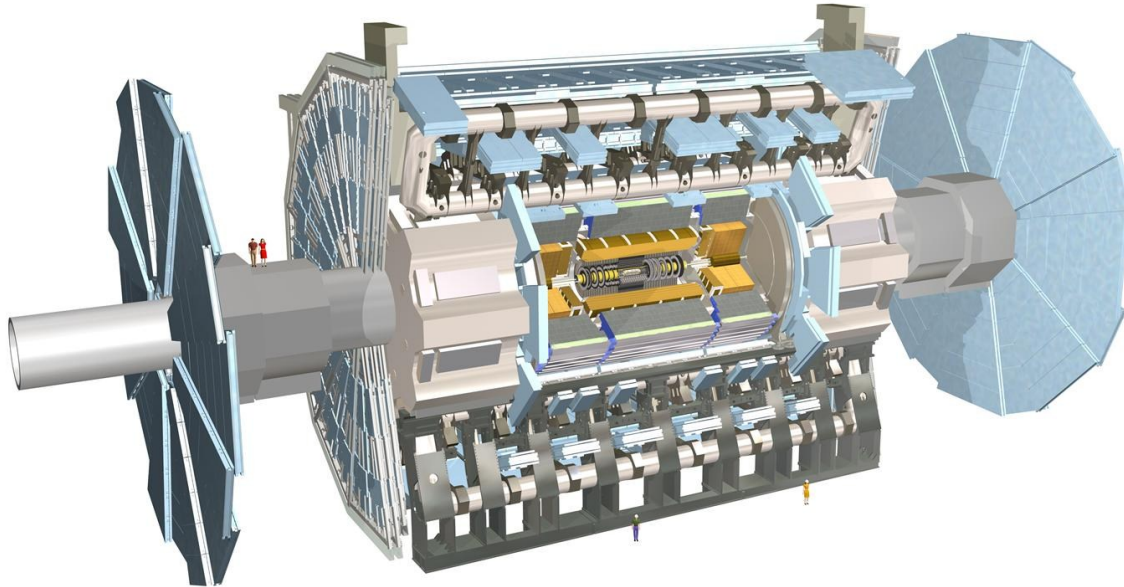
- most powerful particle collider of the world
 - accelerating bunches of protons
→ multiple collisions per bunch crossing
 - collisions every 25 ns (event rate of 40 MHz)
 - over periods of multiple hours without a break
- challenging data taking conditions for particle detectors



Mouche, Philippe [<https://cds.cern.ch/record/1708847>]

The ATLAS Detector after Phase-1

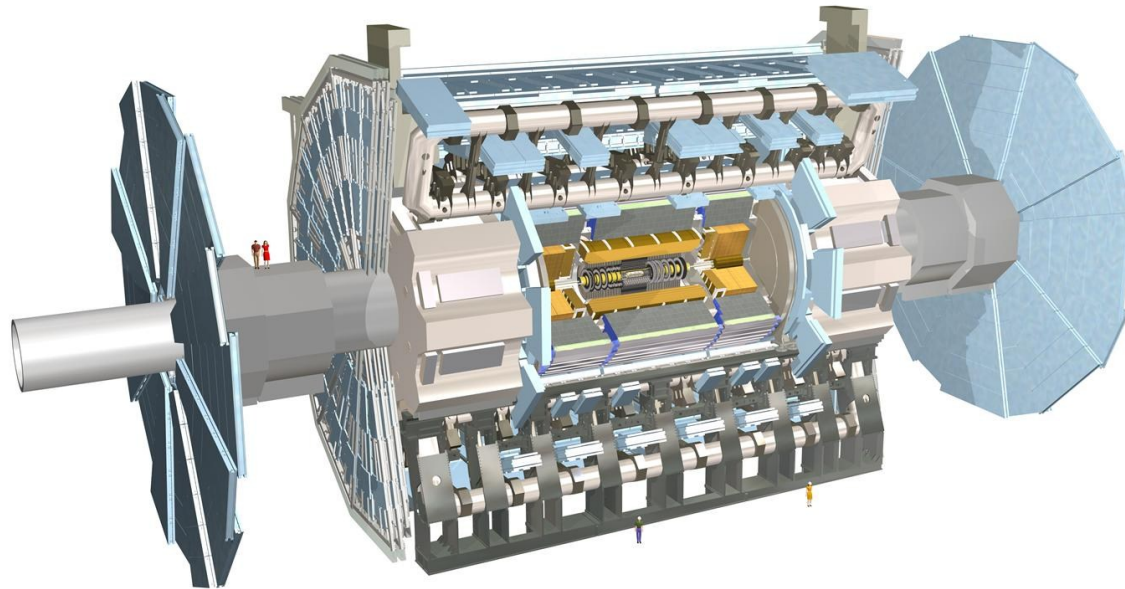
- general purpose detector at the LHC
- why did we need to upgrade?



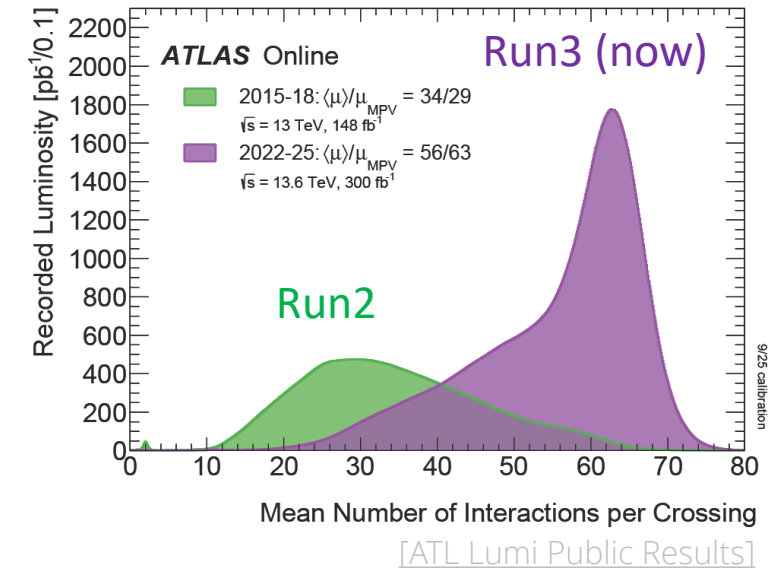
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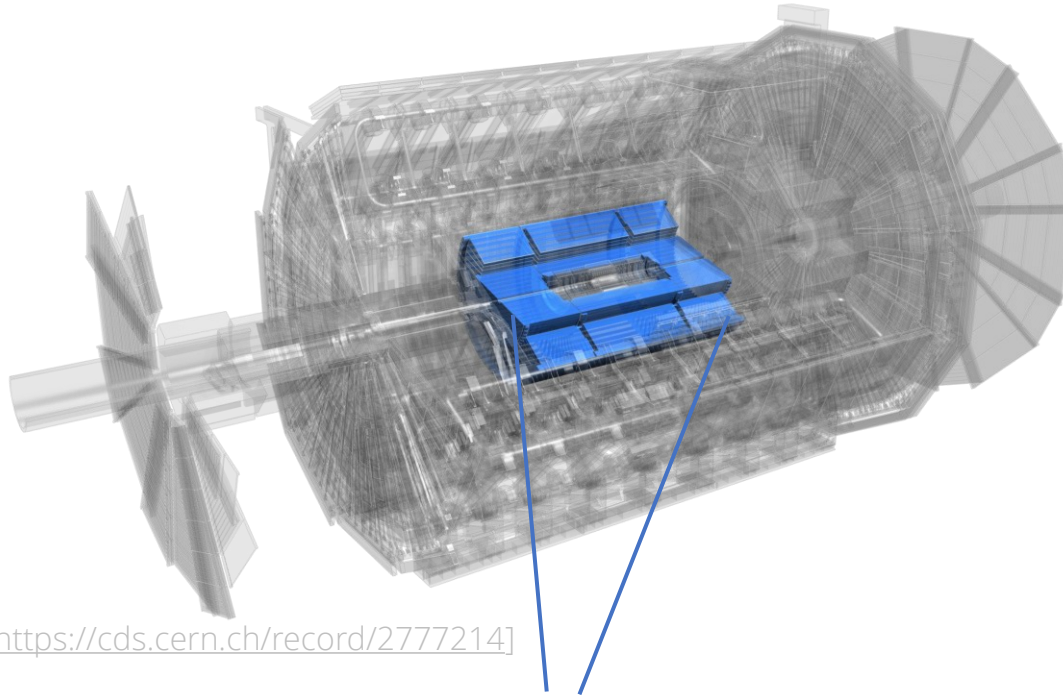
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- want to study rare processes
- more collisions = more data

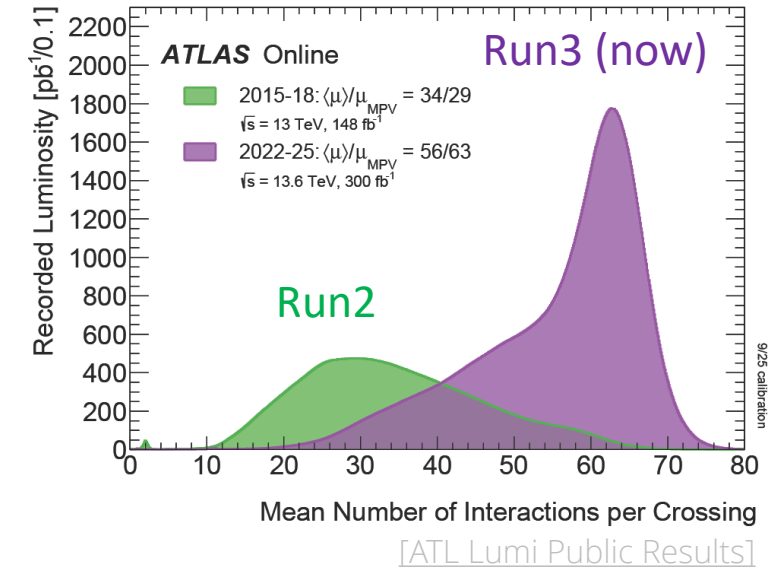
The ATLAS Detector after Phase-1

- ATLAS is evolving: some parts are still from day one, others are upgraded or even fully replaced



- calorimeter system:
upgraded readout
electronics

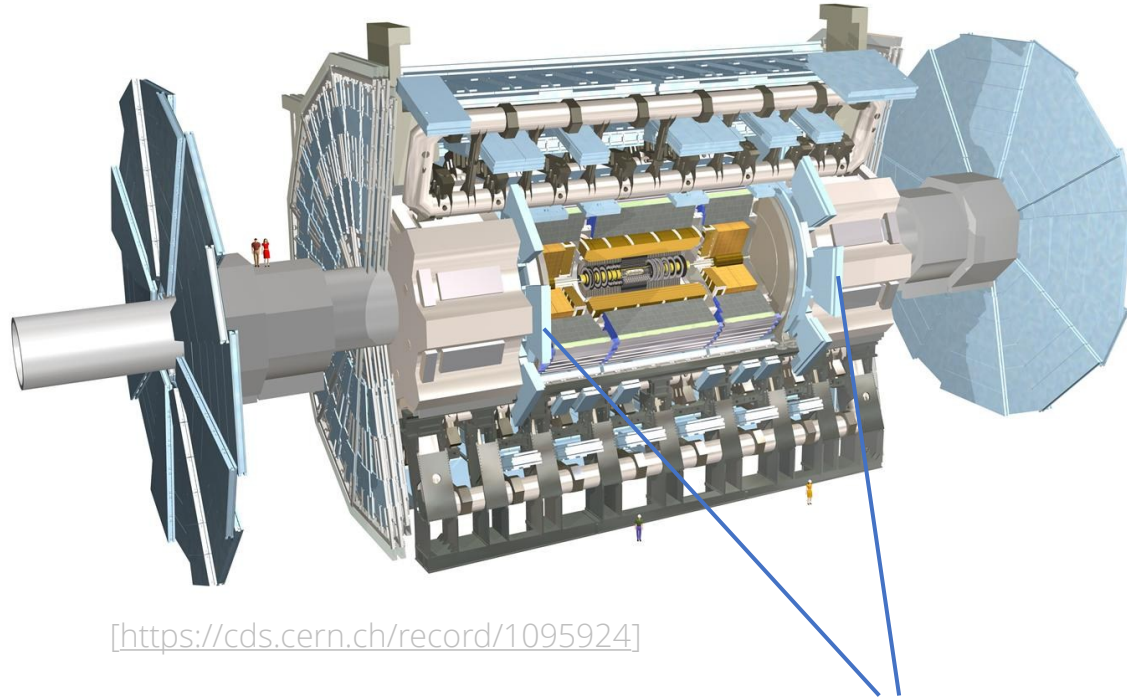
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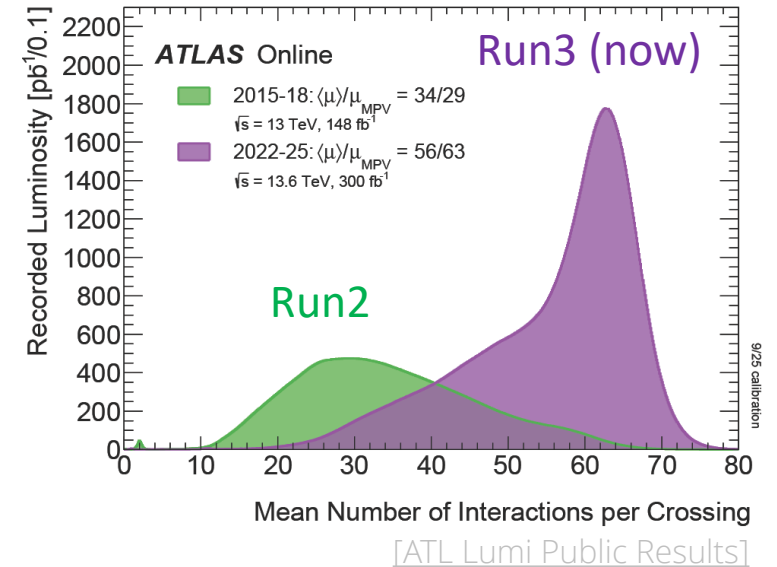
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- calorimeter system: upgraded readout electronics
- muon system: *New Small Wheels*

- why did we need to upgrade?



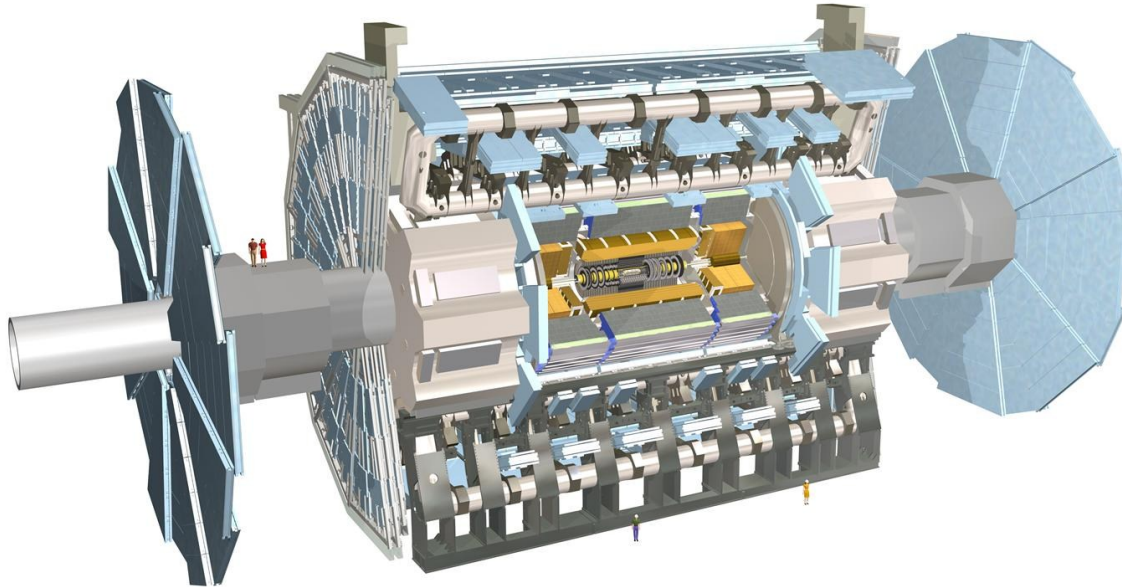
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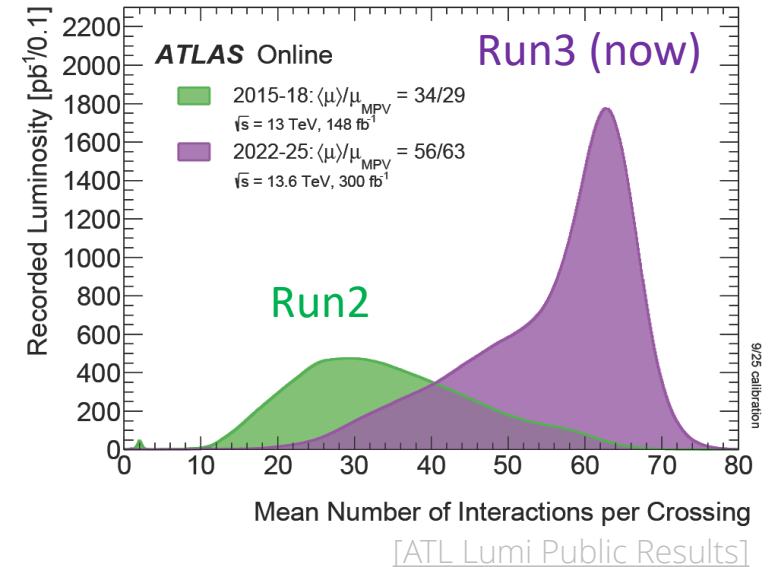
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- why did we need to upgrade?

- Level-1 Trigger System



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- this talk

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The ATLAS Trigger System

40 MHz – LHC Bunch Crossing Frequency

Level-1

100 kHz accepted

HLT

~ 3 kHz recorded

Motivation:

- unfiltered event rate $O(100 \text{ TB/s})$
- way too high to store all of it

Level 1 - Trigger

- custom hardware (FPGA based)
- handles real-time data
 - needs to be fast, fixed latency budget of $2.5 \mu\text{s}$
 - new data every 25 ns

High Level – Trigger

- software based @ ~60k CPU cores
- accesses more detector information, e.g. tracking
- analysis of the regions of interests spotted from Level-1 at full detector resolution, latency $O(1\text{s})$

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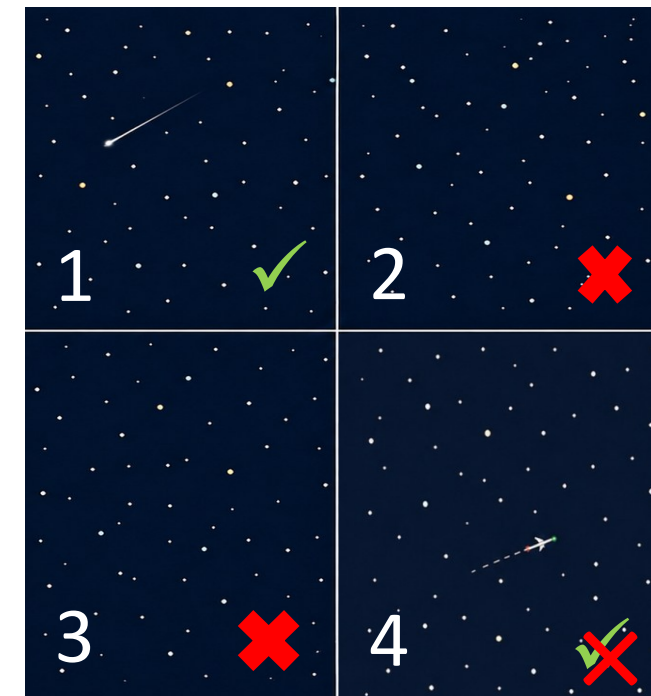
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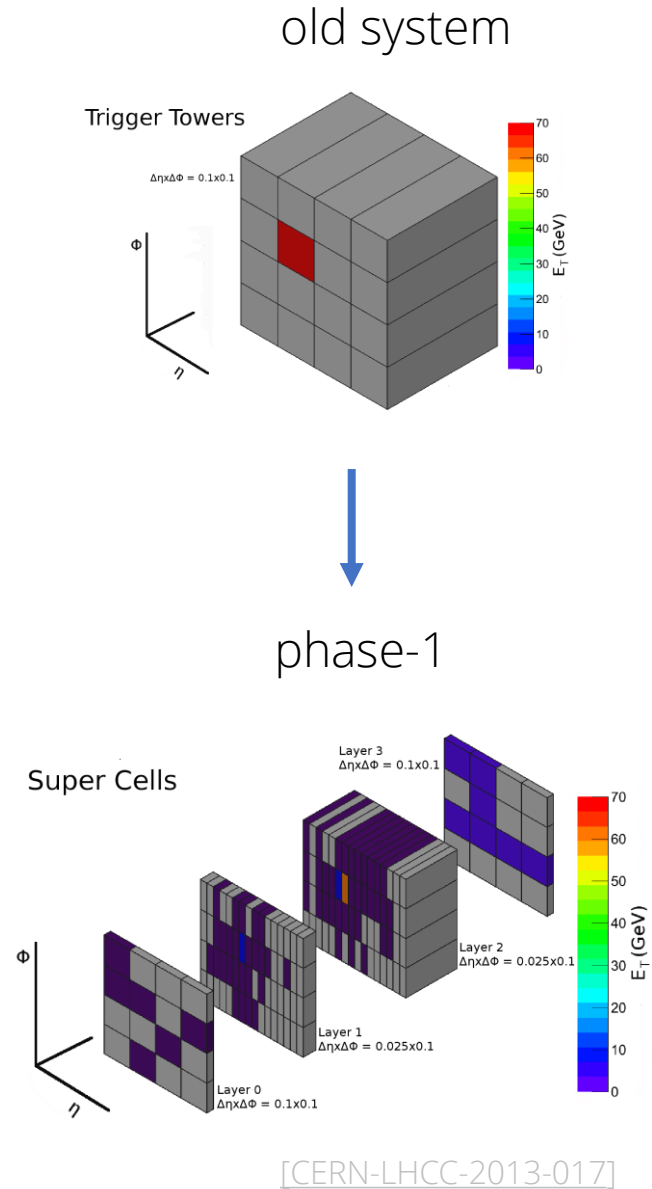
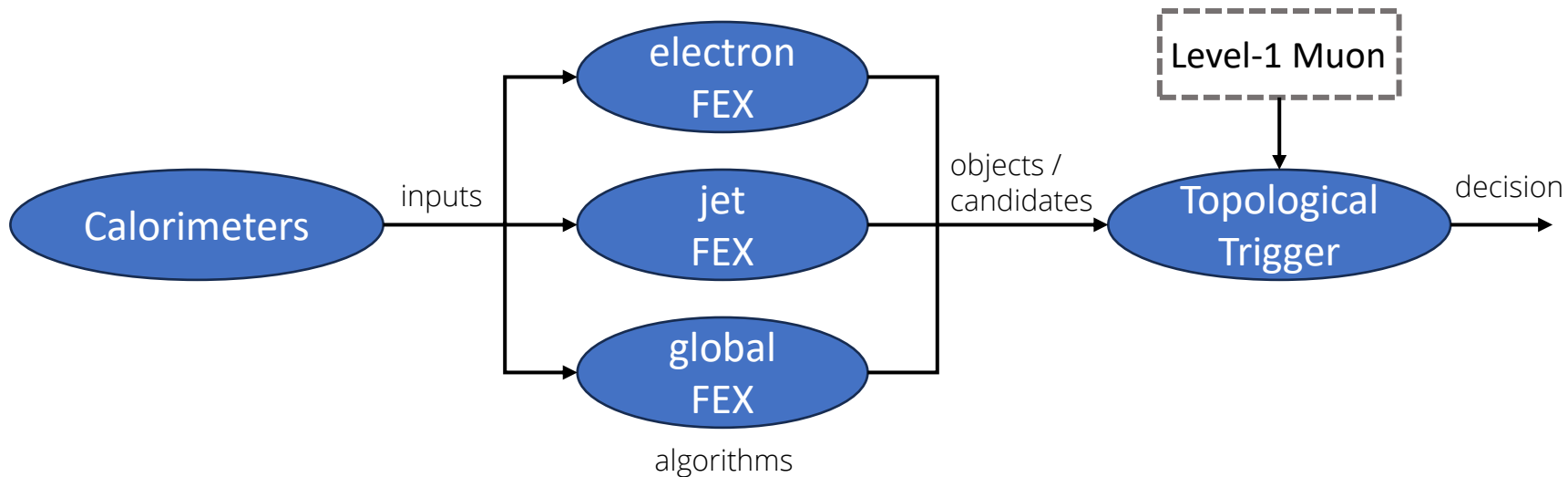
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after phase-1 upgrade closer to this

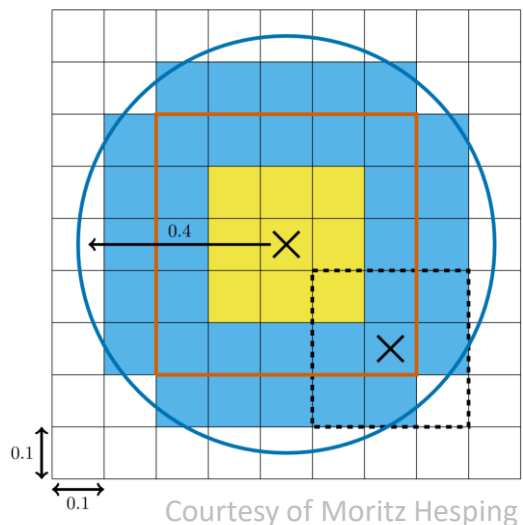
Level-1 Calorimeter Trigger

- receives digitized and calibrated inputs from calorimeters with improved granularity \rightarrow 3D grid of energy information
- system of three Feature EXtractors (FEXes) to reconstruct signatures of corresponding objects
- new Topological Trigger system for multi-object correlations



L1Calo Feature Extractors

example: jFEX jet algorithm

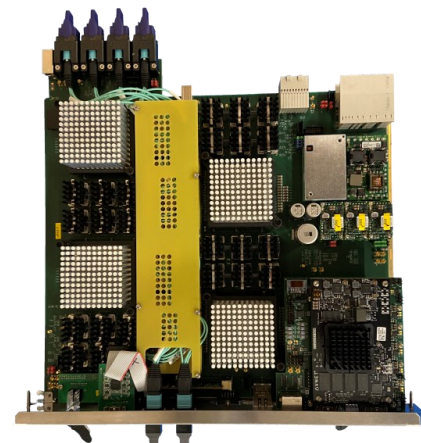


runs within 75ns

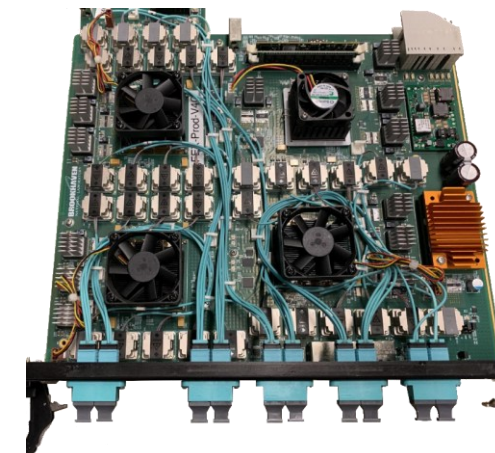
- >1 million LUTs/FPGA
- large input bandwidth



24 × eFEX
(electromagnetic)



6 × jFEX
(jets & more)

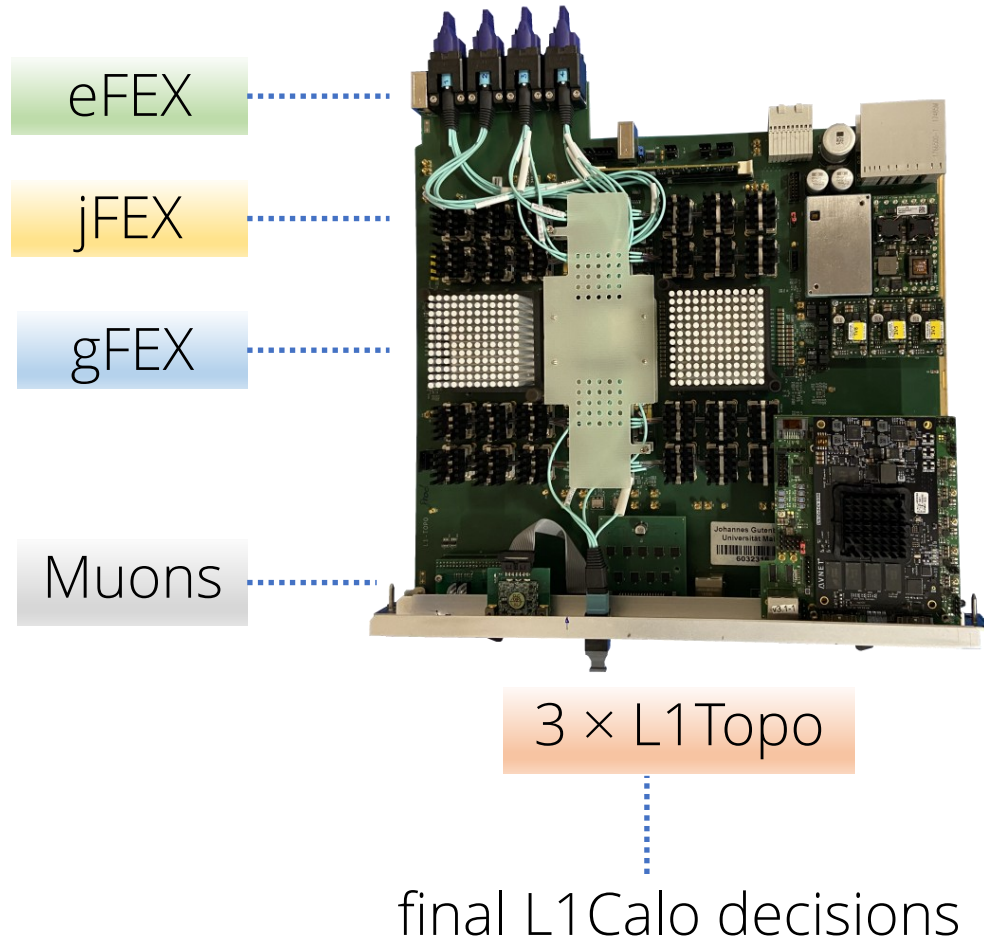


1 × gFEX
(global)

granularity	0.025 × 0.1	0.1 × 0.1	0.2 × 0.2
coverage	central detector	full detector	full detector
trigger objects (TOB)	$e/\gamma, \tau_{\text{had}}$	jets, $\tau_{\text{had}}, E_T^{\text{miss}}, \sum E_T, e/\gamma_{ \eta >2.5}$	large jets, $E_T^{\text{miss}}, \sum E_T, \rho$
main FPGAs	XC7VX550T ×96	XCVU9P ×24	XCVU9P ×3
#LUT/FPGA	346k	1 182k	1 182k
input bw/board	~ 1.4 Tbps (×24)	~ 2.2 Tbps (×6)	~ 3.4 Tbps (×1)

*with line rates of about 11.2 Gbps per link

L1 Topological Processor

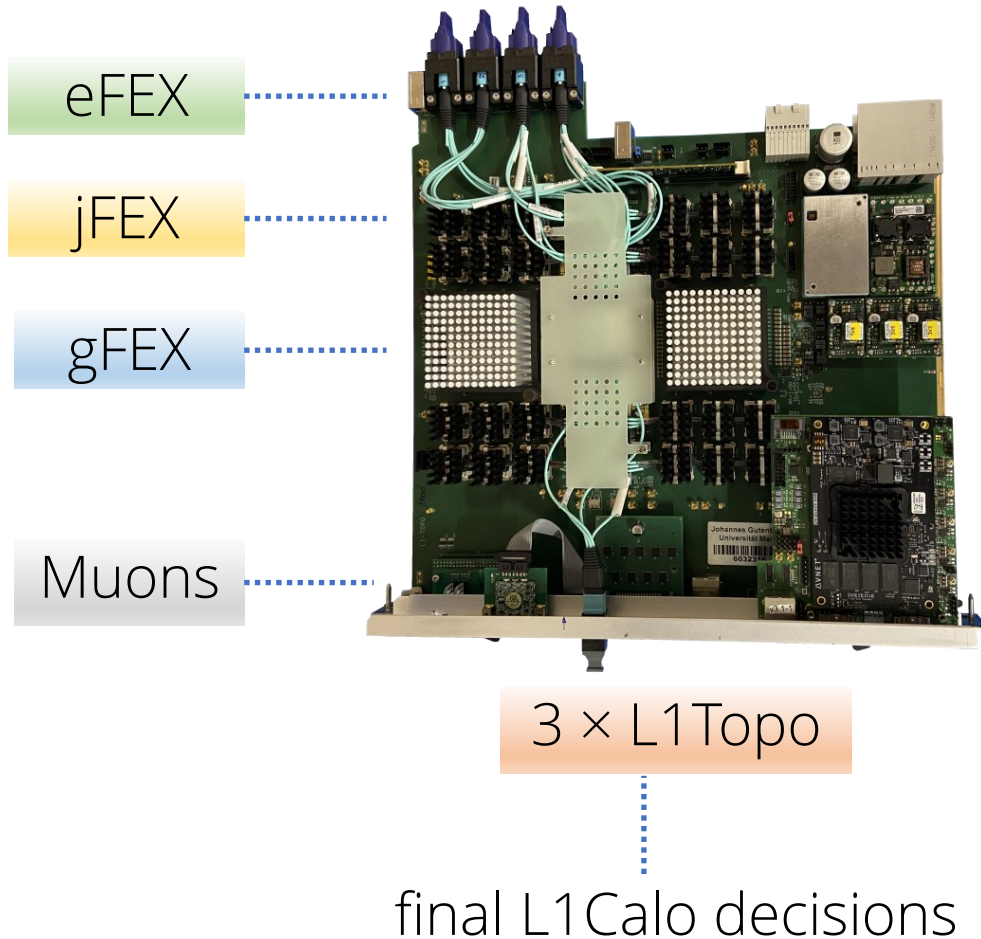


- 3 boards with 2 FPGAs, each
- inputs from several level-1 systems, runs multi-object algorithms (~200 decisions)

Examples:

- angular separation & invariant masses

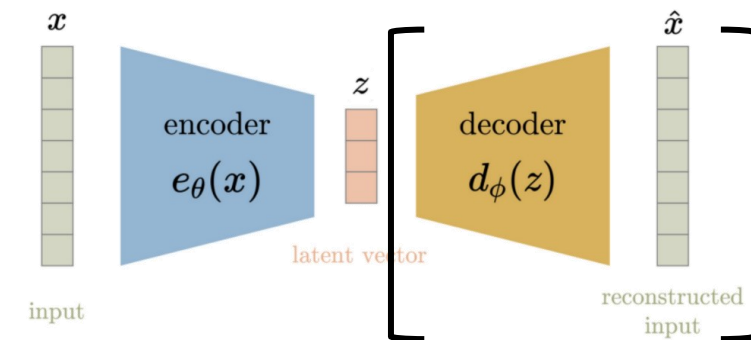
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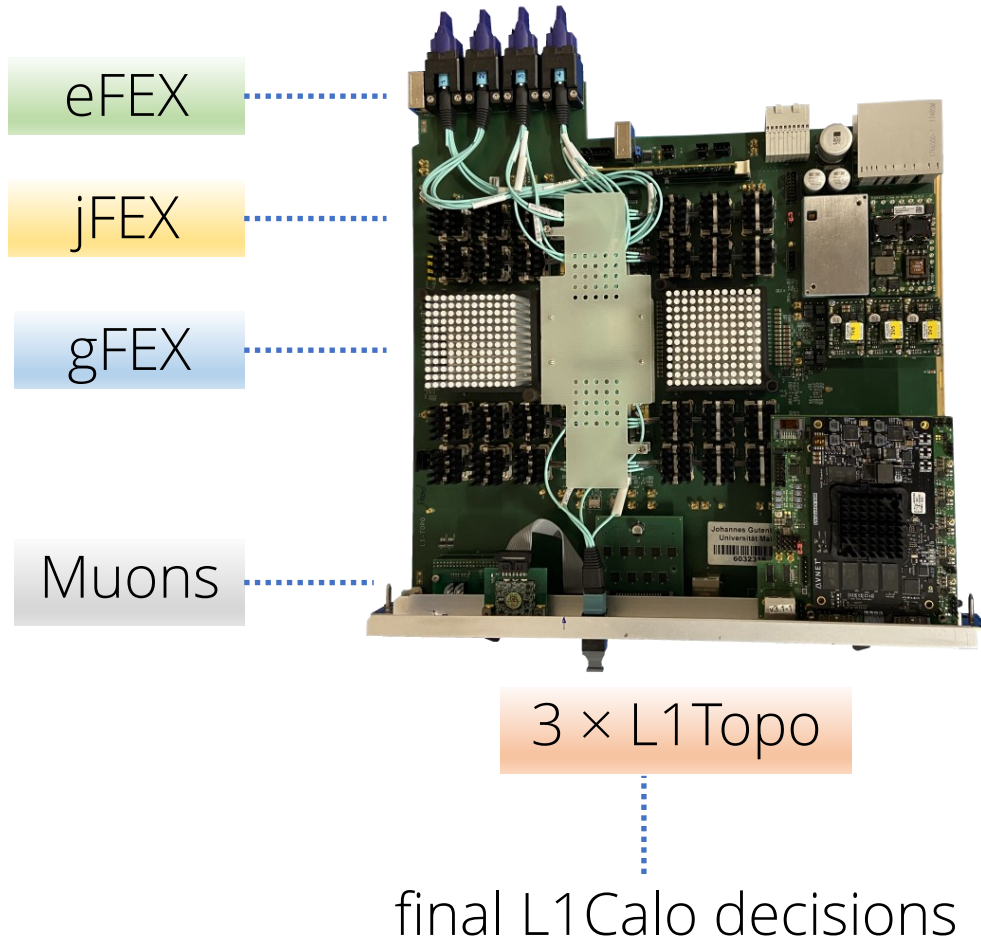
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Examples:

- angular separation & invariant masses
- variational autoencoder for anomaly detection
 - 3-layer MLP evaluated in 25 ns (details [here](#))



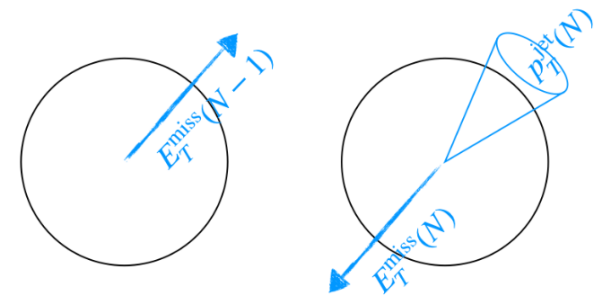
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Examples:

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 - 3-layer MLP evaluated in 25 ns
- correlate information from different bunch crossings (time-slices)
long-lived particles

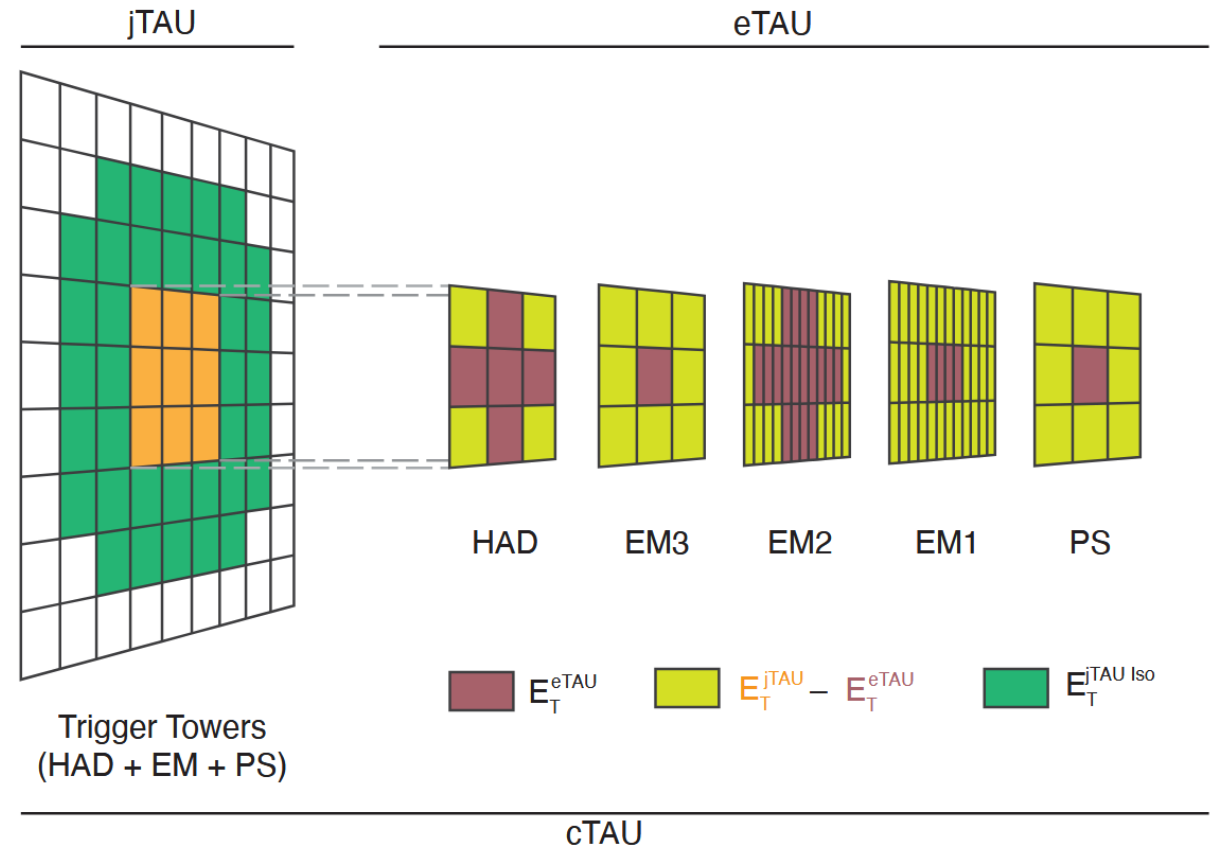


Event $N - 1$

Event N Gareth Bird

Algorithmic Examples: “combined” TAU

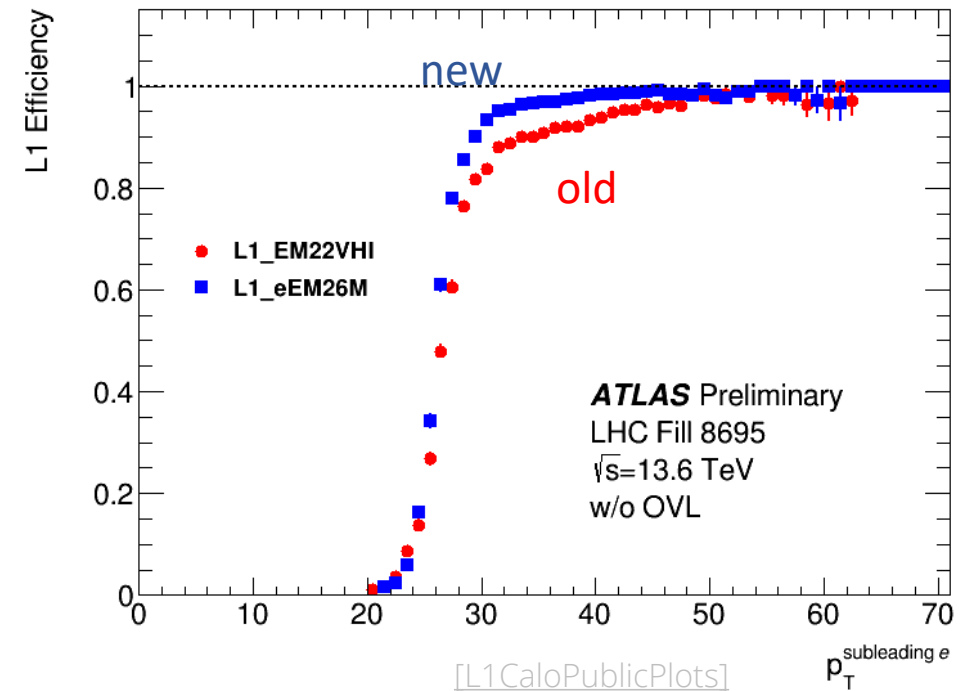
- eFEX – eTau: high granularity, small window per processor
- jFEX – jTau: moderate granularity, larger window per processor
- L1Topo – cTau: combination eTau + jTau = cTau, additional energy information in core & wide-area isolation from jFEX improves background rejection



Courtesy of Ralf Gugel

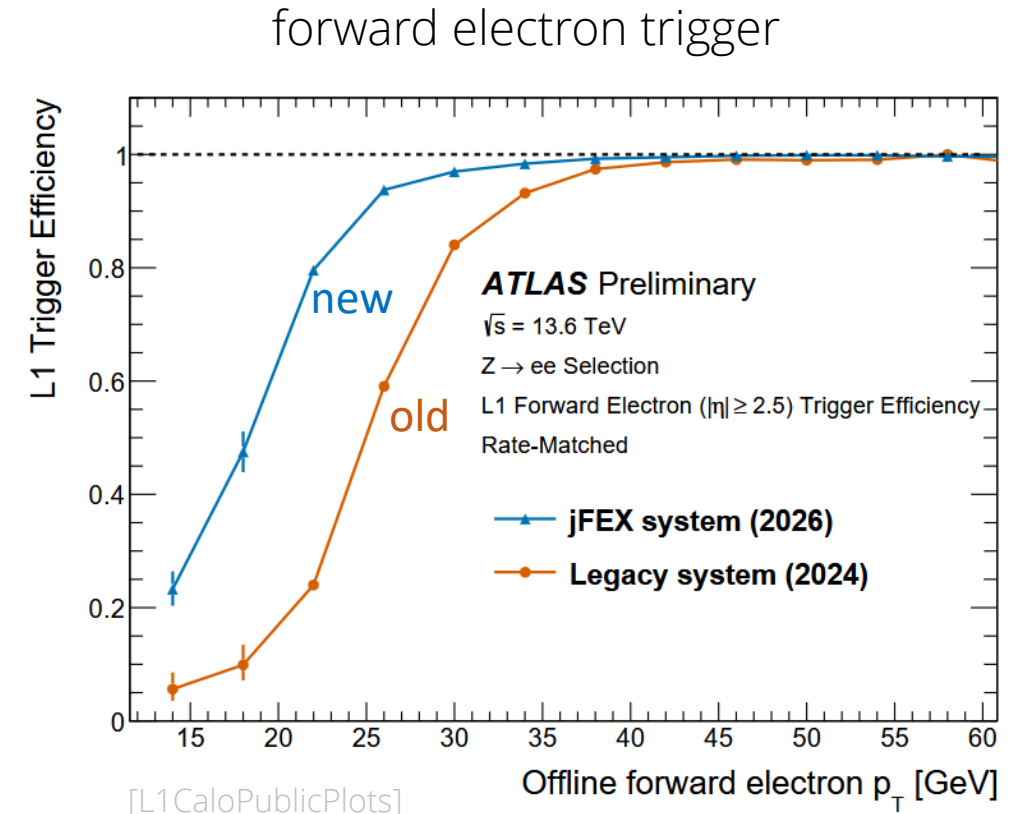
Performance: eFEX

- efficiency curve for EM trigger:
 - efficiency of finding and triggering the event at level-1
 - momentum threshold applied on the object
 - curve “turns-on” after the threshold
- eFEX turn-on curve (blue) reaches full efficiency much faster compared to old system (red)
- old system suffered from less efficient isolation requirements → slower towards plateau
- sizeable reduction in trigger rate with phase-1 system (~5 kHz)
 - better background rejection



Performance: eFEX & jFEX

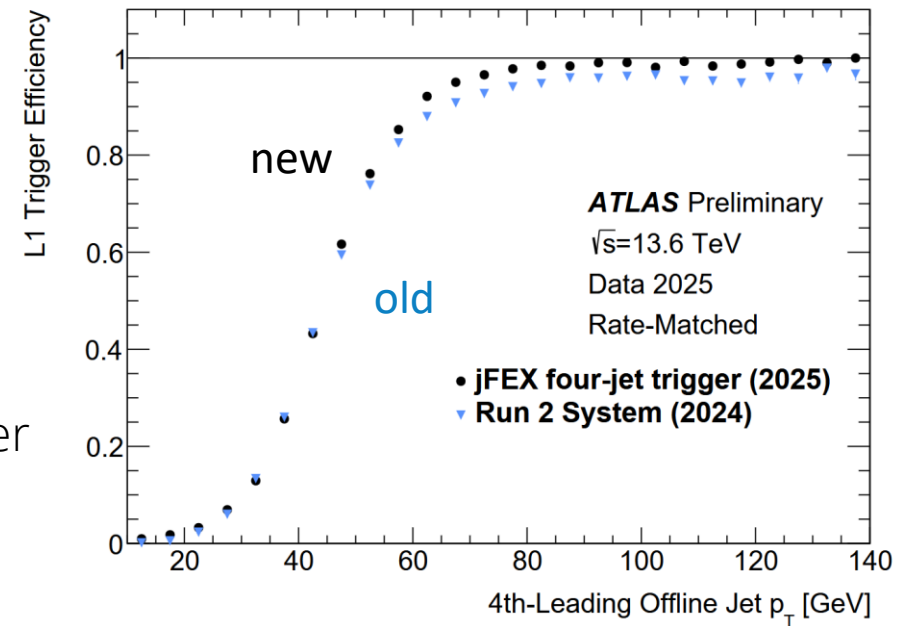
- trigger requires one electron in central part of the detector (eFEX) and one in the forward region (jFEX)
- new for phase-1, old system did not trigger on electrons in the forward region (used jets instead)
- jFEX trigger (blue) significantly outperforms the corresponding legacy item (orange)



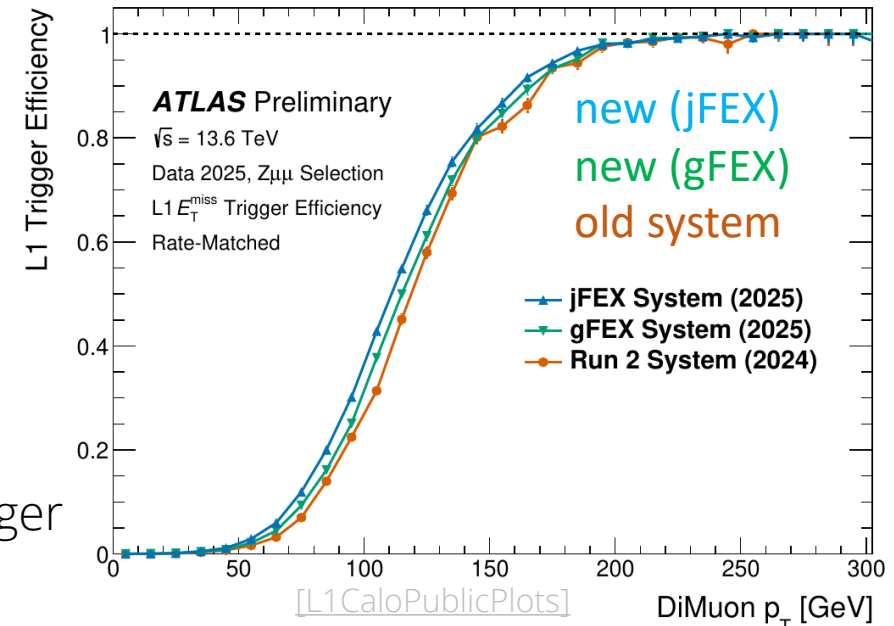
Performance: jFEX & gFEX

- jFEX turn-on (black) sharper compared to old system (blue) at the same trigger rate
- ability to resolve nearby jets overcomes inefficiency → reaches plateau at 1 not below!
- jFEX & gFEX E_T^{miss} trigger efficiencies outperform Run 2 system (orange)
- similar improvements for all FEXes across several signatures

4 jet trigger



missing energy trigger



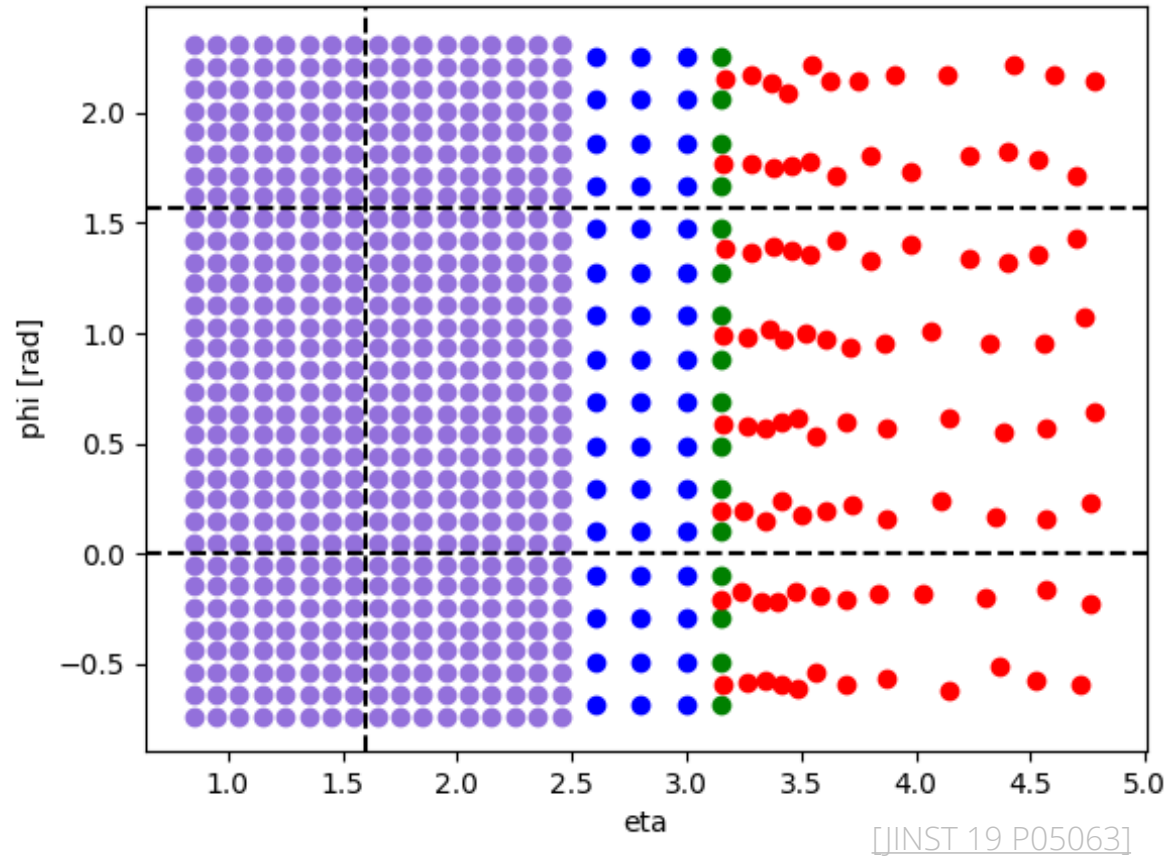
Summary & Outlook:

- level-1 calorimeter trigger does real-time event selection by running fast & efficient algorithms on customized hardware
- new and/or improved trigger algorithms were crucial for a successful data taking during LHC Run 3
- FEXes will remain an essential building block of Phase-2 upgrade, which provides additional improvements towards the *High Luminosity LHC* period, starting ~2030

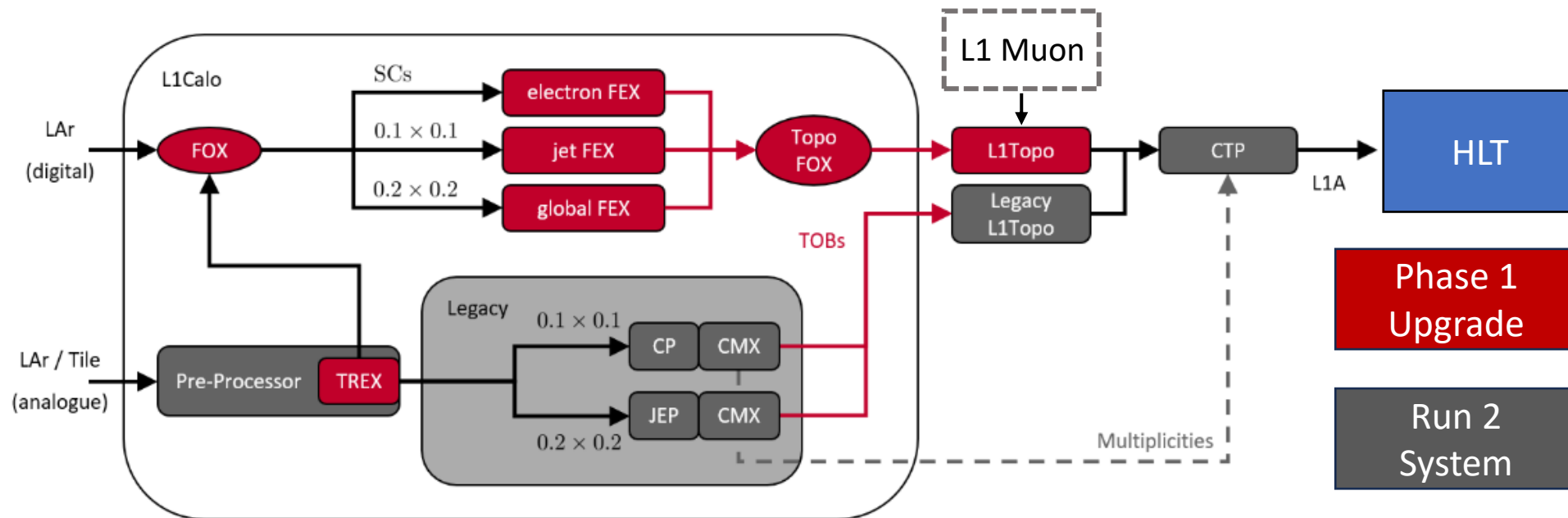


BACKUP

Backup: jFEX Input Granularity



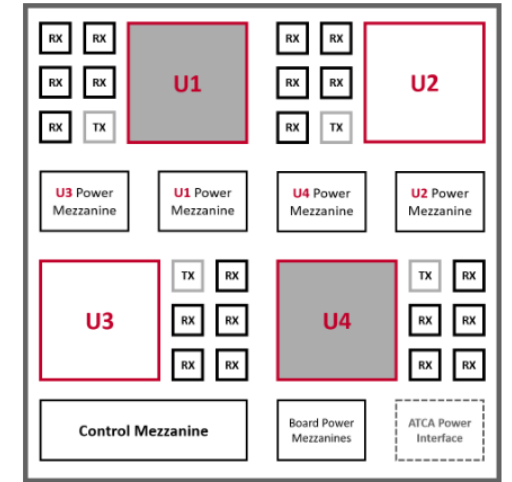
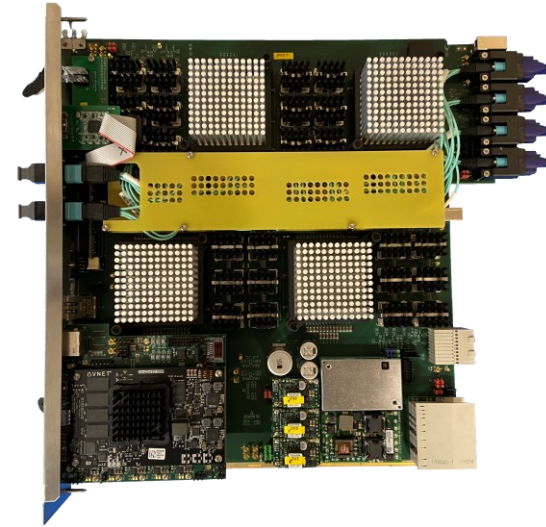
Backup: Overview Old vs. New System



[<http://doi.org/10.25358/openscience-6407>]

Backup: jFEX Hardware

- 24 high speed optical transceivers: Avago MiniPODs
 - RX: 240 fibres (5 x 12 x 4)
 - TX: 48 fibres (1 x 12 x 4)
- control mezzanine: XCZU7EV
 - slow control, configuration, monitoring
- power mezzanines
 - 4 FPGa power mezzanines & 3 board power mezzanines



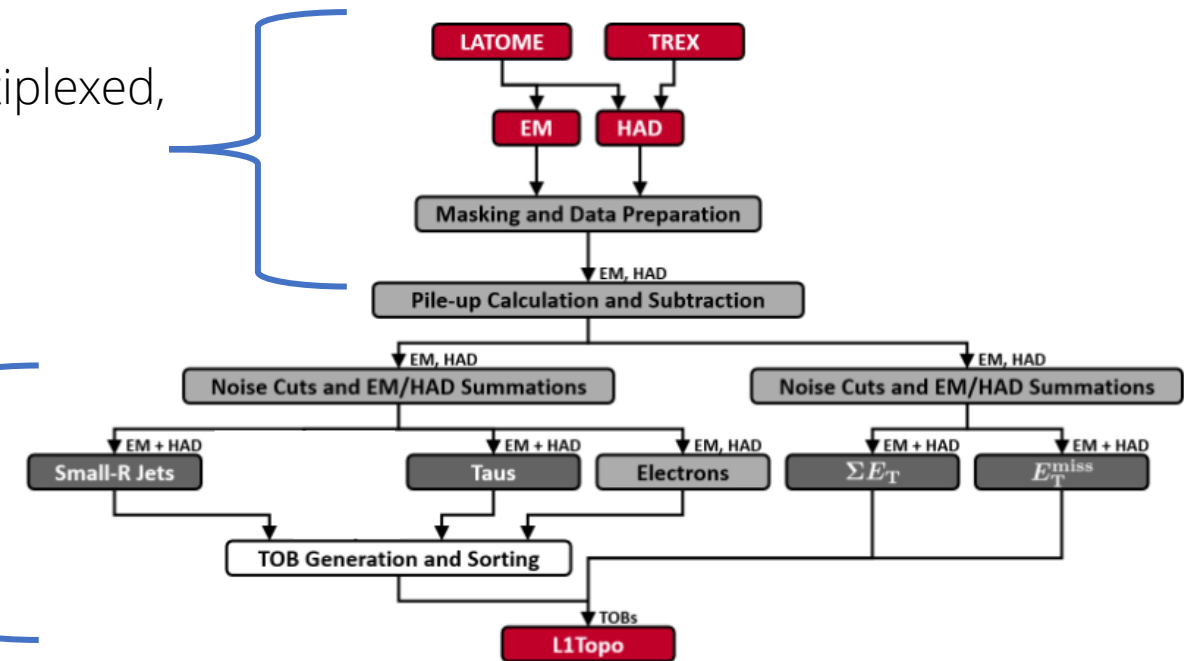
[\[http://doi.org/10.25358/openscience-64071\]](http://doi.org/10.25358/openscience-64071)

Backup: jFEX Firmware

- multi-linear energy encoding
- data preparation, time multiplexed
- algorithmic part, parallel
- sorting with *Batcher odd-even mergesort*

time multiplexed,
160 MHz

parallel,
40 MHz

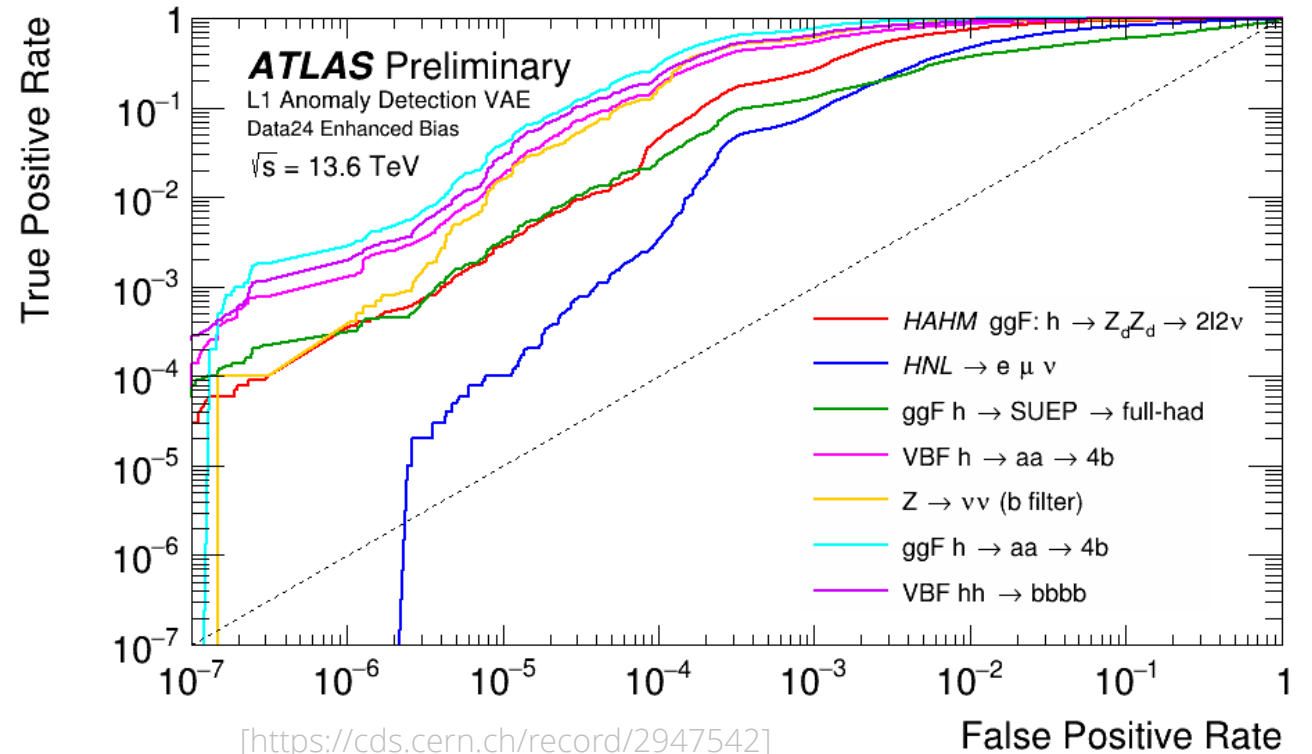
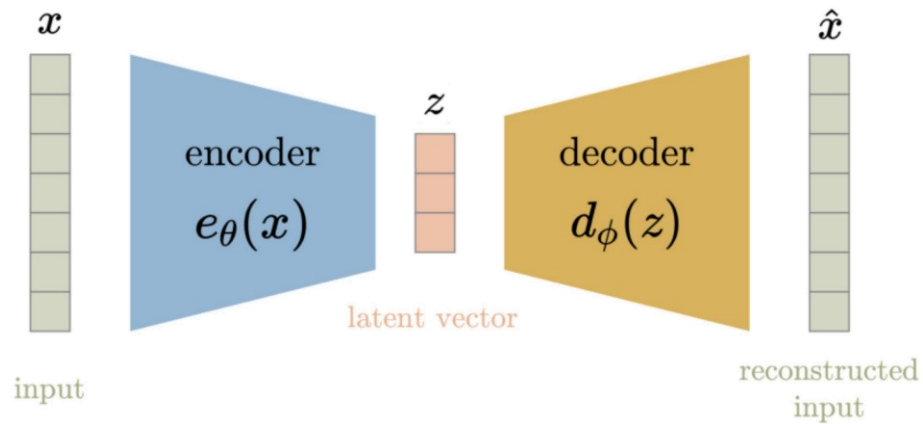


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Backup: Anomaly Detection (GELATO)

“Generic Event-Level Anomalous Trigger Option”

- variational autoencoder
 - evaluated based on latent space w/o decoder part
- inputs are objects from FEXes
- 3-layer MLP in 25 ns

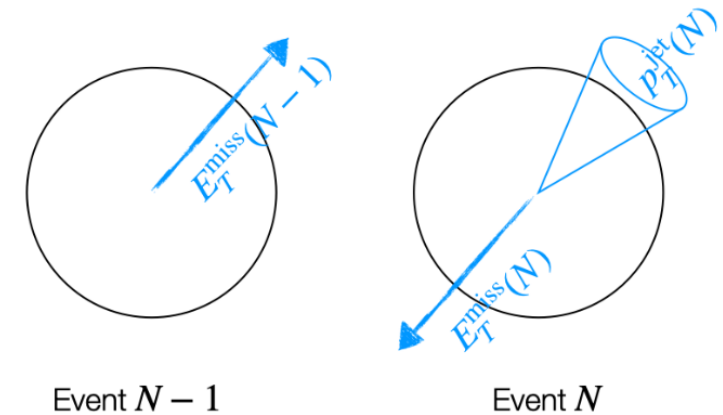


Backup: Long-Lived Particle Trigger

- long-lived \rightarrow does not decay immediately

Signature:

- missing energy (particle did not interact with detector yet)
- after the decay it produces daughter particles
 - jet in the same direction of missing energy but one bunch crossings (**25ns**) later
 - particle at speed of light travels about 7.5m in 25ns – less if its heavy
 - \rightarrow can still decay before / within calorimeter, but signal is delayed
- correlation of information from different time-slices
 - very interesting signature w.r.t. searches for new physics



Gareth Bird