The upgrade of the ATLAS Trigger and Data Acquisition system for the High Luminosity LHC

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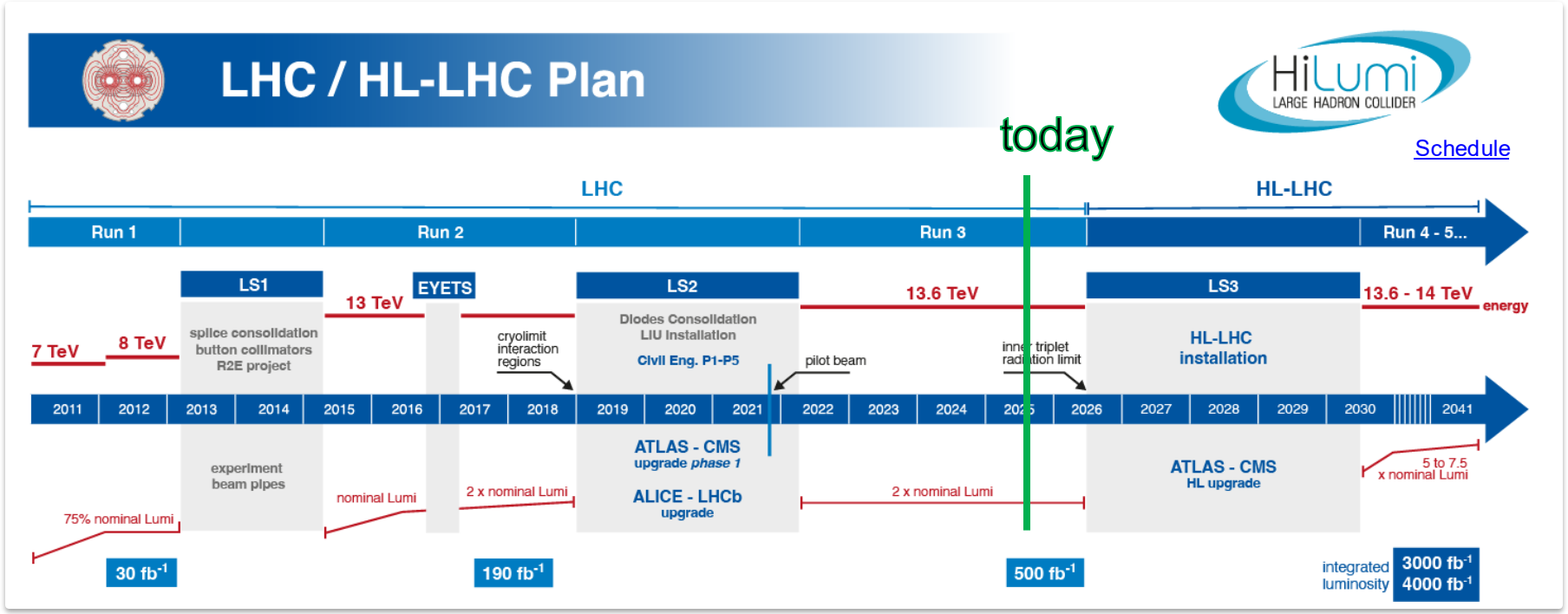
on behalf of the ATLAS Collaboration

The HL-LHC upgrade

A massive project !

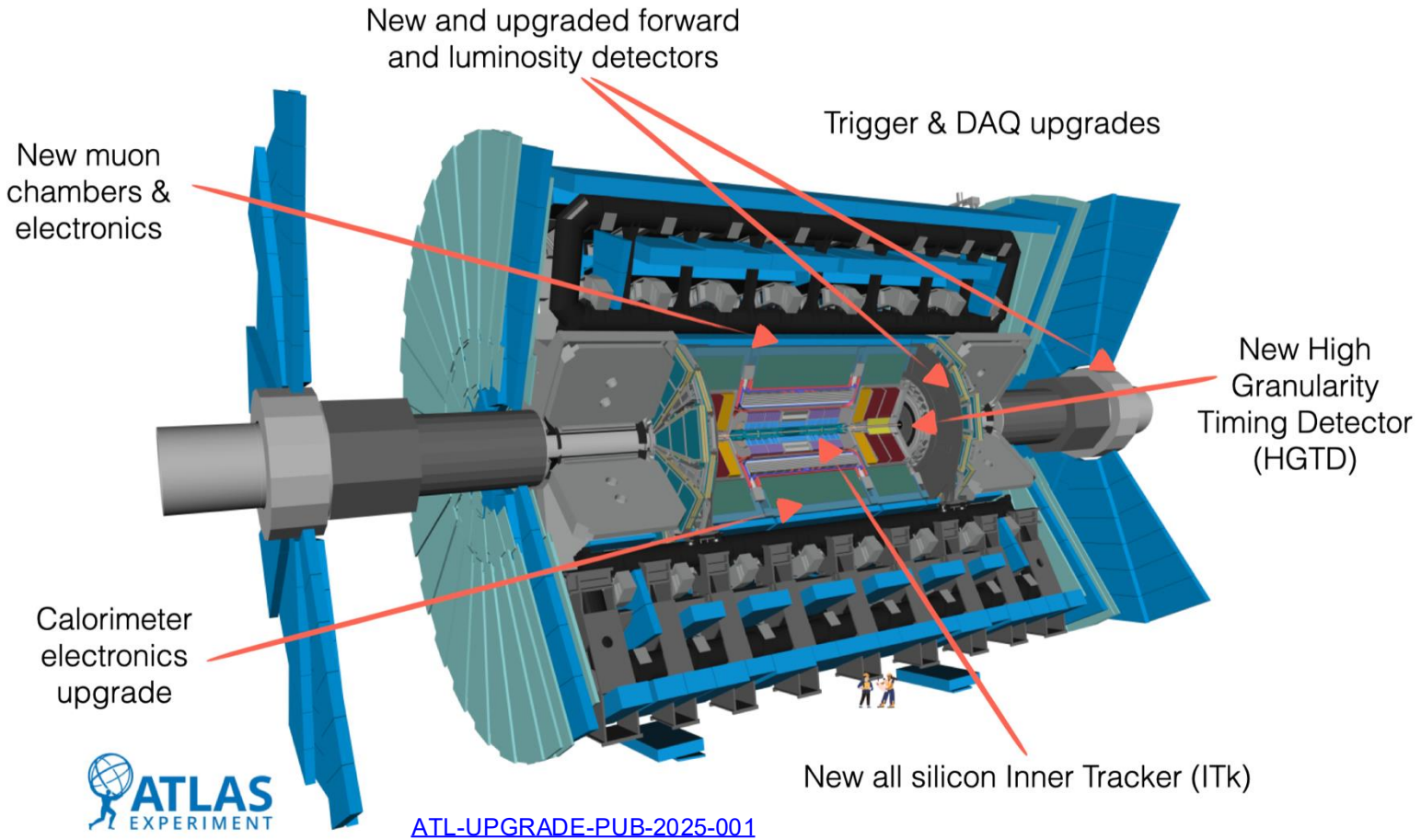
- Both for accelerator and experiments
- Top priority for the coming years
- Technological challenge on precision, data rates, storage, processing, radiation levels, etc.



ATLAS upgrades for Run-4

- Detector upgrades
  - New silicon inner detector (ITk) with coverage to $|\eta| < 4$
  - New muon detectors in barrel and endcap inner regions
  - High Granularity Timing Detector in forward region
  - Calorimeters and muon system front-end readout at 40 MHz
- TDAQ electronics upgrades
  - L0 hardware trigger fed by upgraded detector front-ends
  - New common read-out boards for all systems
  - Upgraded Event Filter processing farm

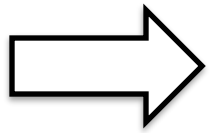
Maintaining good physics performance and acceptable trigger rates at low p_T requires major upgrades



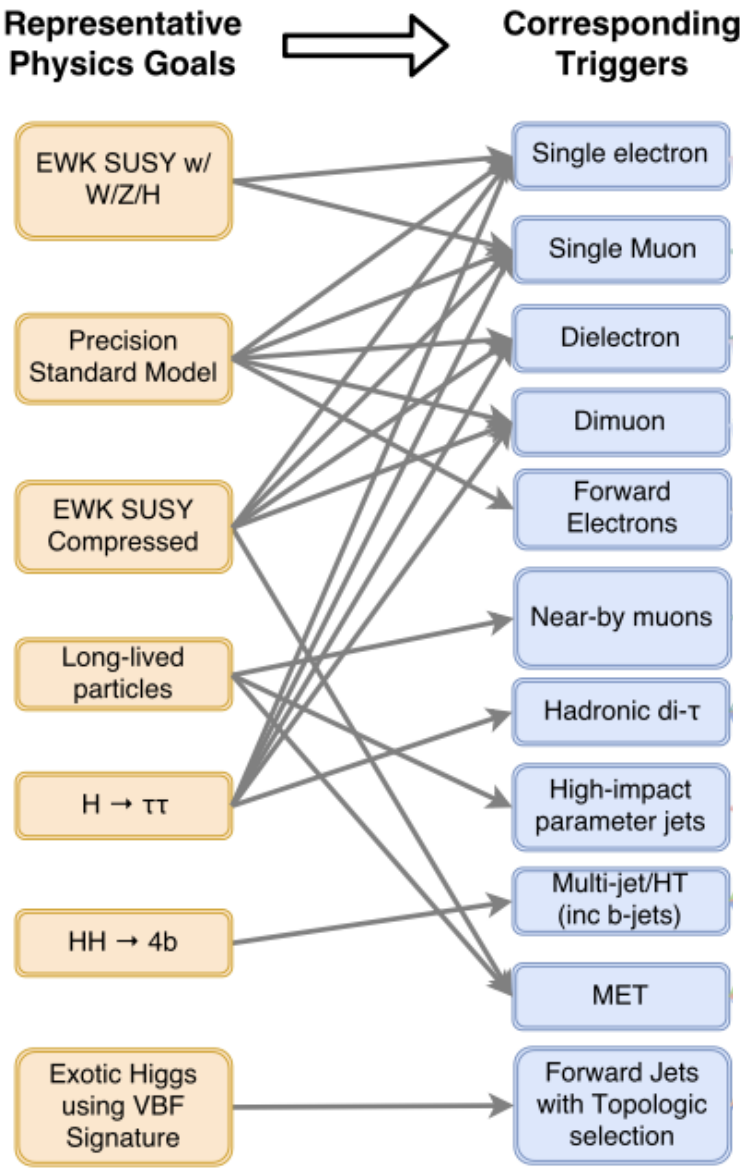
ATL-UPGRADE-PUB-2025-001

Physics Drivers of the upgrade …

- Precision measurements of Higgs boson properties
  - H → bb/μμ/$\tau\tau$, ttH
  - Self-coupling HH → 4b/bb$\tau\tau$/bb$\gamma\gamma$
- Other precision SM measurements
  - Z → ee/μμ
  - VBS, WWjj, WZjj
  - Top physics
- Flavour physics
  - Lepton flavour
- BSM searches
  - New vector bosons, DM, LLP
- Heavy Ion physics



ATLAS-TDR-029



… translated to a trigger menu*

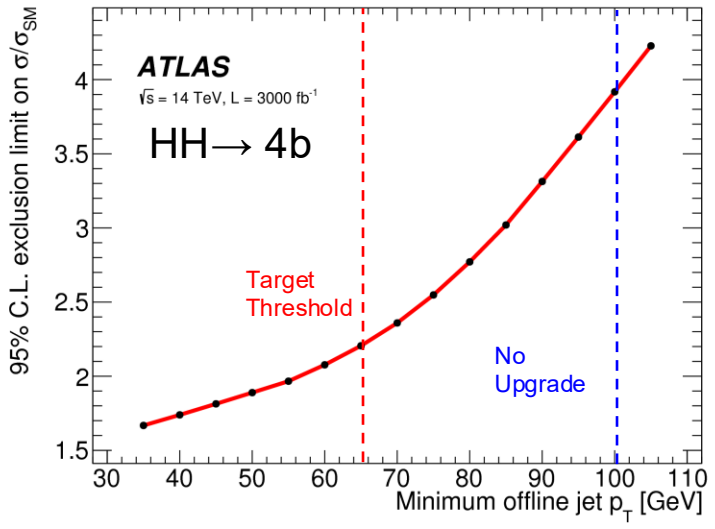
* i.e. set of criteria for selecting interesting collision events

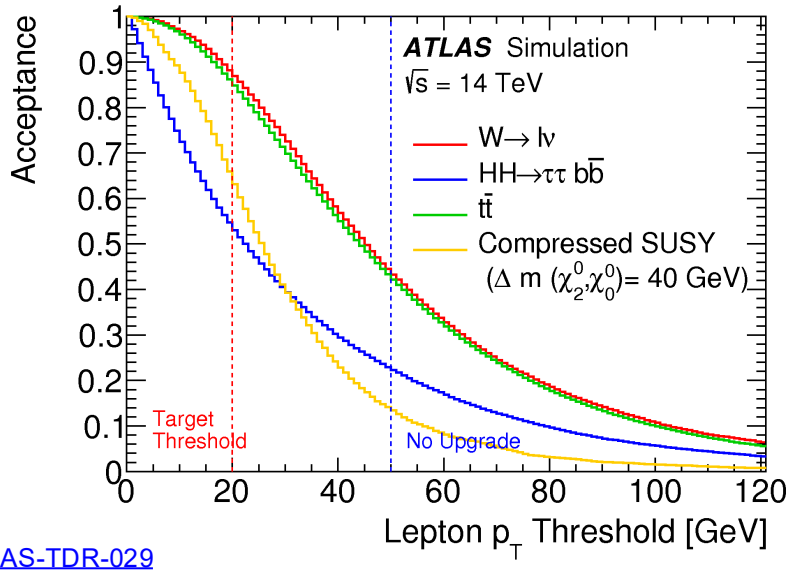
link

Trigger Selection	Offline p_T Threshold [GeV] Run 1	Run 2 (2017)	Planned HL-LHC Offline p_T Threshold [GeV]
isolated single e	25	27	22
isolated single μ	25	27	20
single γ	120	145	120
forward e			35
di-γ	25	25	25,25
di-e	15	18	10,10
di-μ	15	15	10,10
$e-\mu$	17,6	8,25 / 18,15	10,10
single τ	100	170	150
di-τ	40,30	40,30	40,30
single b-jet	200	235	180
single jet	370	460	400
large-R jet	470	500	300
four-jet (w/ b-tags)		45† (1-tag)	65(2-tags)
four-jet	85	125	100
H_T	700	700	375
E_T^{miss}	150	200	210
VBF inclusive			2x75 ($\Delta\eta > 2.5$ & $\Delta\phi < 2.5$)
B-physics††			
Support Triggers			

Despite the much more challenging conditions thresholds need to remain low to keep acceptance

- Aim to keep thresholds as low as in previous runs or even lower
- Impossible with Run-3 TDAQ system at Run-4 conditions





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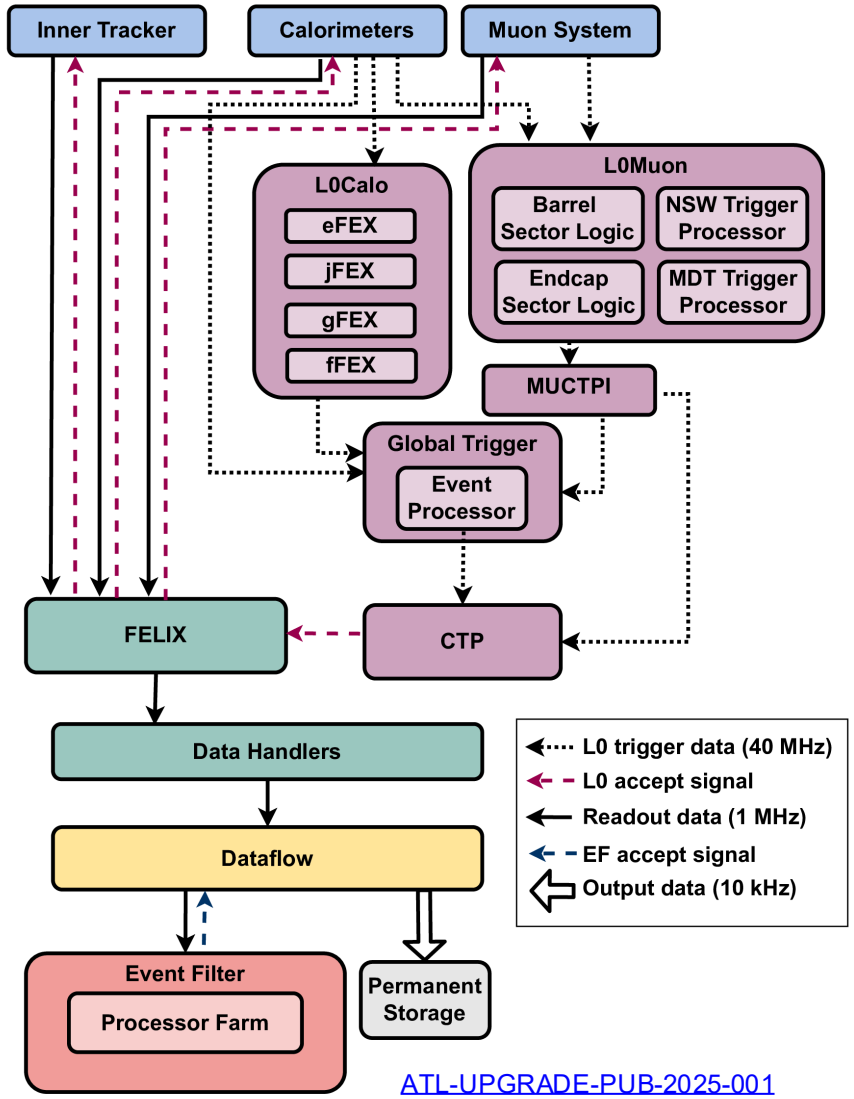
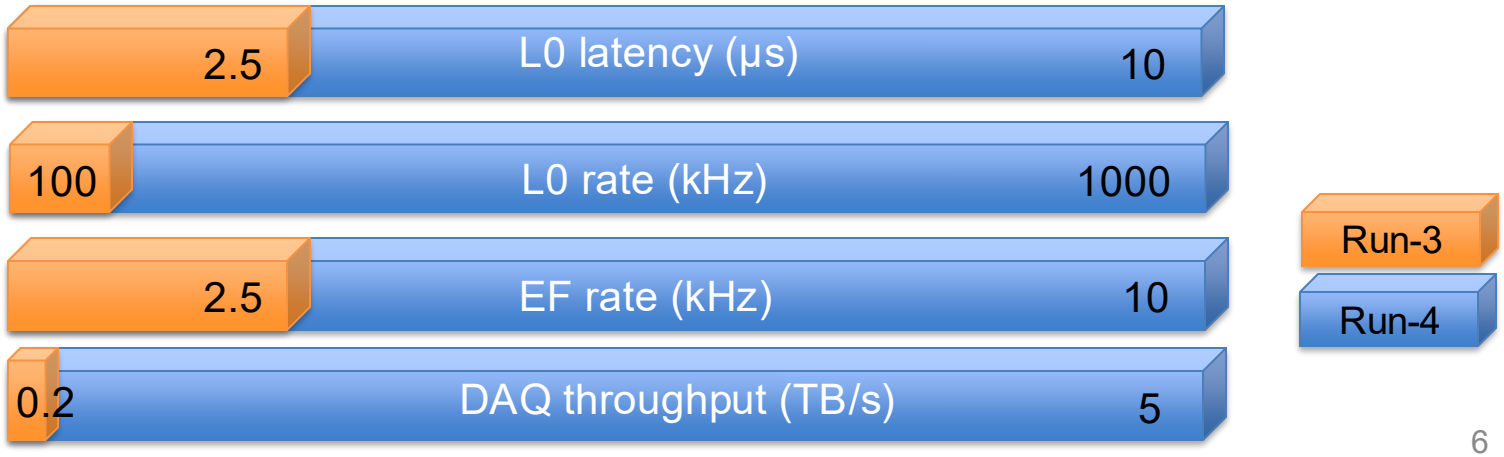
TDAQ changes for Run-4 (overview)

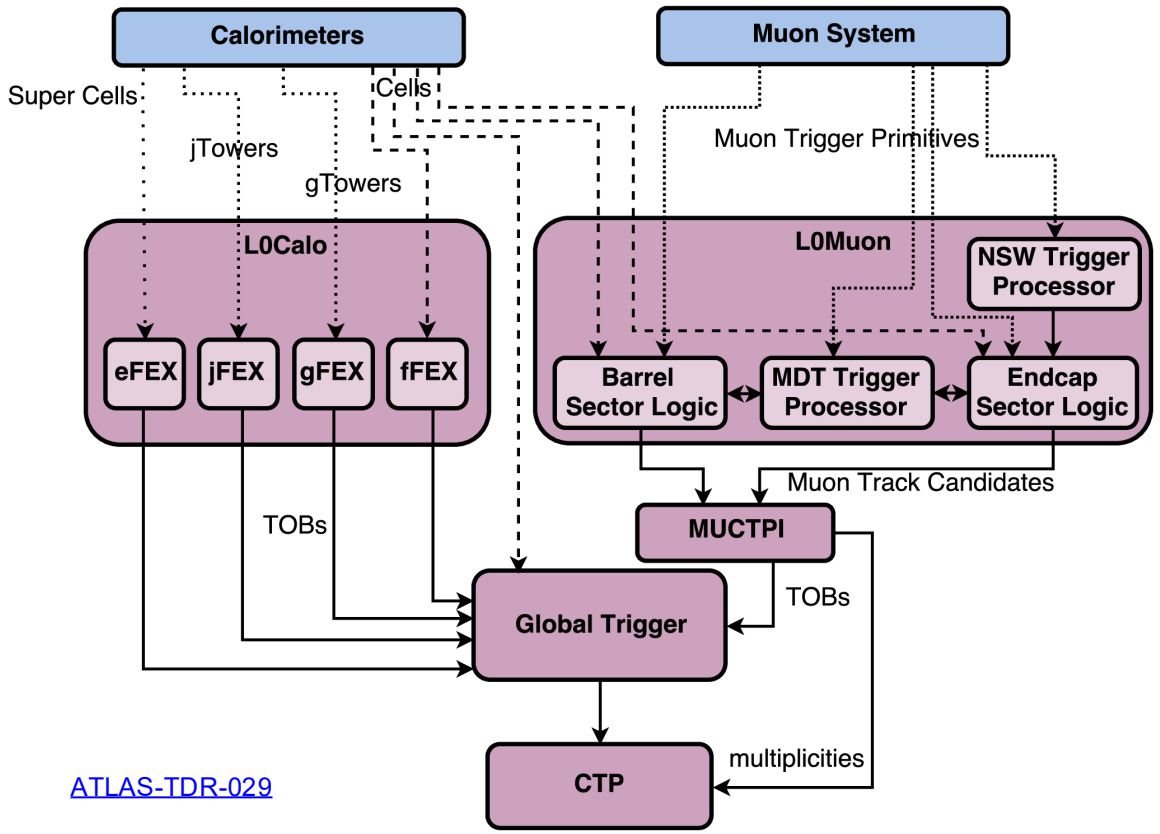


ATL-UPGRADE-PUB-2025-001

- Single level hardware trigger (L0)
  - ATCA boards, FPGAs, high speed links
  - Extended latency and increased bandwidth
- Event filter
  - Commodity-hardware based processing farm
  - Option of hardware accelerators
- DAQ system
  - Upgraded to cope with higher event rate and size
  - Custom r/o board with commodity servers/network

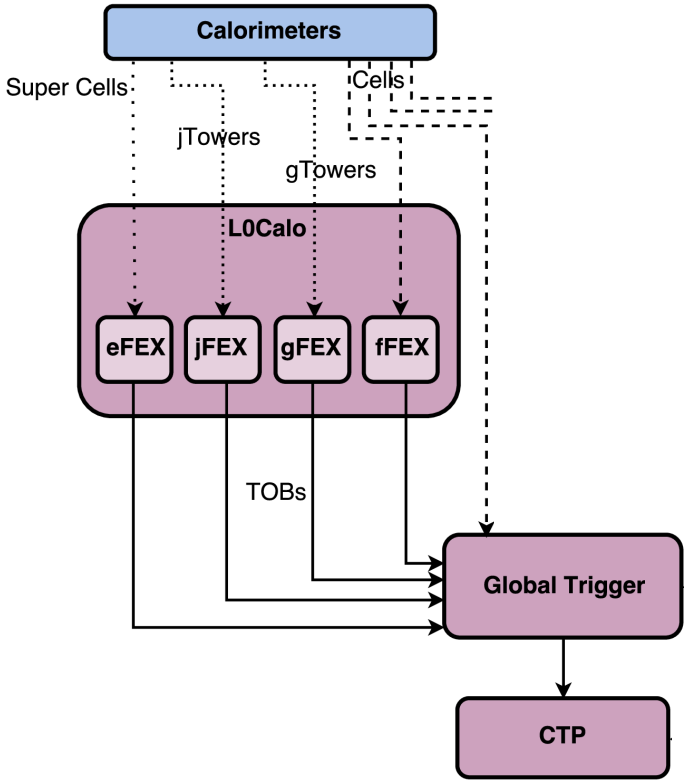


L0 Trigger system



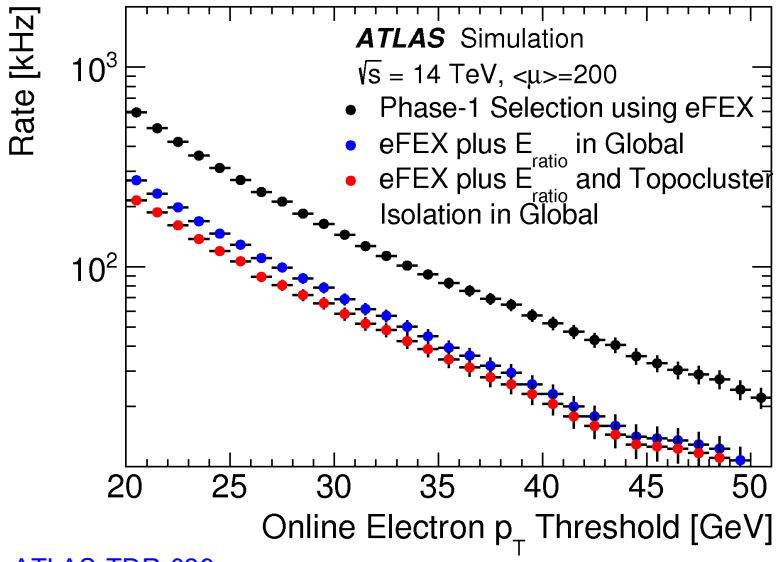
- Hardware trigger system working in real time
  - Reduces 40 MHz input rate to a maximum of 1 MHz output
- Based on inputs from muon system and calorimeters (no tracking information here)
  - Trigger objects are collected in the Global Trigger (new for Run-4)
- Global Trigger also receives full granularity information from calorimeters
  - Offline-like reconstruction at 40 MHz
- Central Trigger Processor (CTP)
  - Provides L0 trigger decision based on the selection menu
  - Timing master for all sub-systems

L0 Calorimeter Trigger



- Run-3 hardware with upgraded firmware
  - Feature Extractor boards (FEXs) provide trigger objects for e/γ/τ (eFEX), jets and missing ET (jFEX) and large R jets (gFEX)
- New fFEX added for forward region (objects $|\eta| > 2.5$)
  - high granularity information from calorimeters
- Improved performance
  - Increased latency budget → upgraded firmware algorithms

fFEX Prototype



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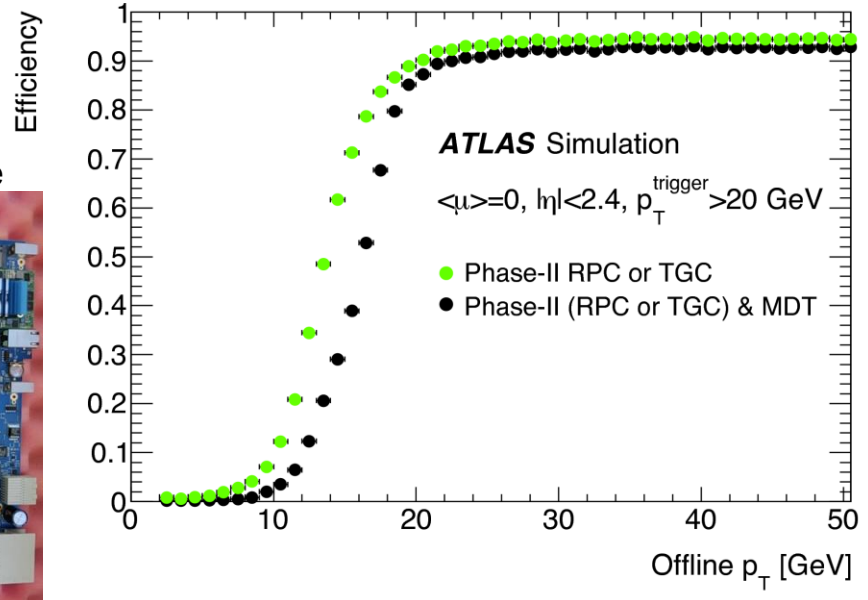
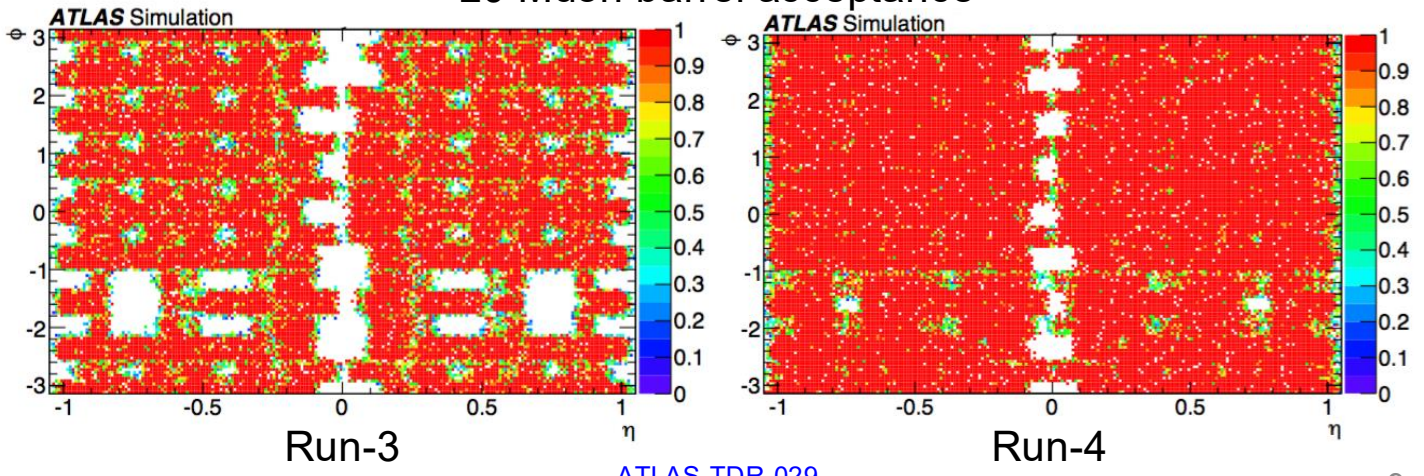
L0 Muon Trigger

- RPC (barrel), TGC and NSW (endcap) Run-3 detectors complemented by new RPC inner layer and MDT trigger
  - Loosen RPC trigger selection due to additional trigger layers – barrel geometrical acceptance from ~70% to ~95%
- MDT chambers included in the L0 trigger for the first time via dedicated trigger processor
  - Matching MDT hits with RPC/TGC seeds
  - Sharpen turn-on curve, increase rejection power
- New Trigger Processor for the New Small Wheel (NSW)
  - NSW: Endcap region inner station
  - Reduce endcap fake trigger rate

MDT TP Prototype



L0 Muon barrel acceptance



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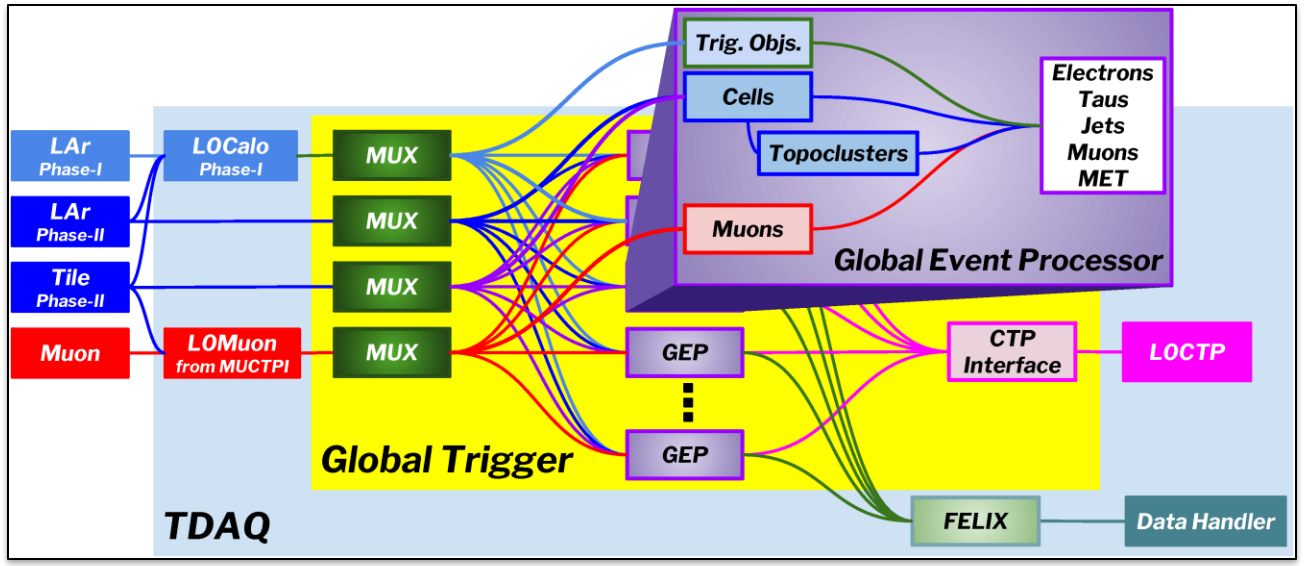
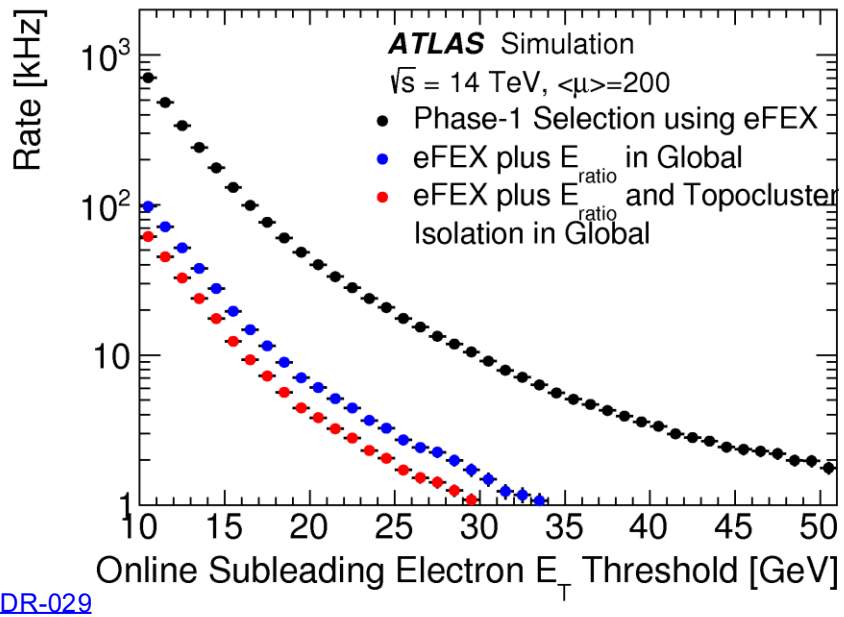
L0 Global Trigger

- Receives L0 Trigger objects and high granularity calorimeter data
  - Offline-like algorithms for muons, EM, jets, E_T-miss, topological triggers, refines trigger objects and adds new trigger lines
- FPGA based processing boards performing different functions in firmware
  - MUX: data aggregation and time multiplexing
  - GEP: Global Event Processing
  - gCTPi: demultiplexing and data transfer to Central Trigger Processor





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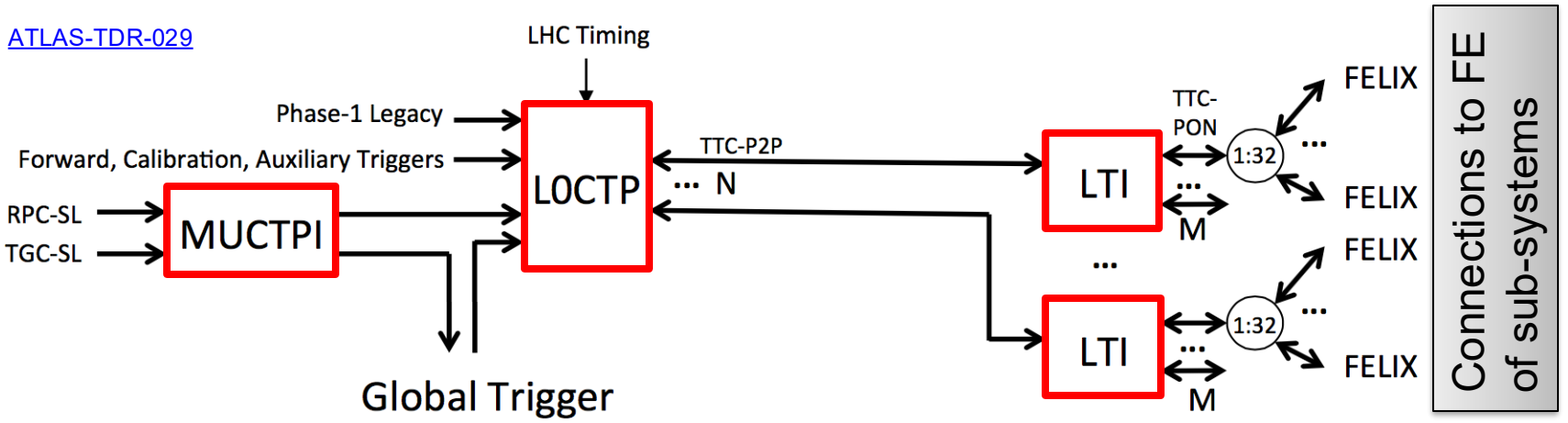
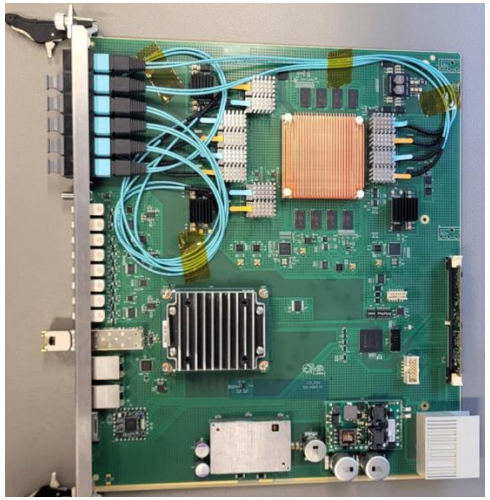
L0 Central Trigger and Timing



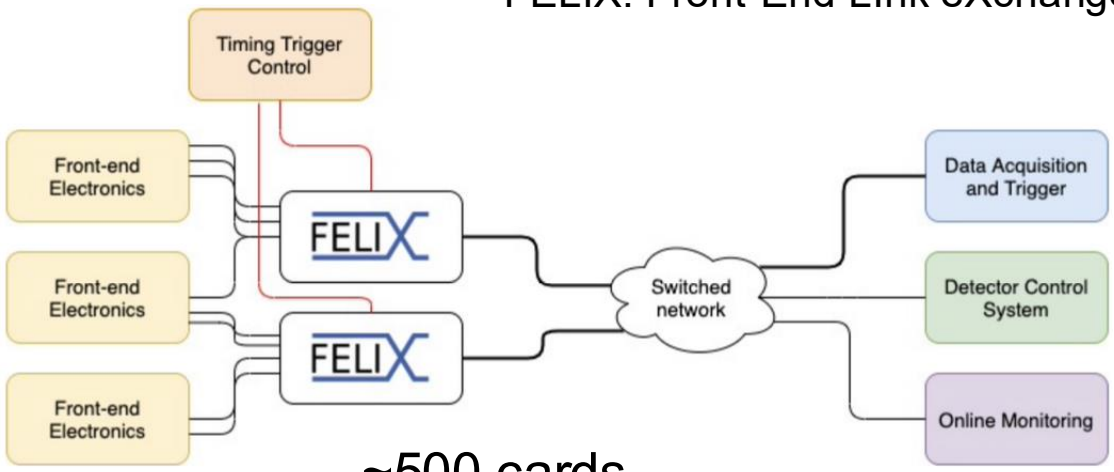


- Provides final L0 Trigger decision based on the selection menu and received inputs
  - New Central Trigger Processor (**L0CTP**) Board, now 1024 (before 512) possible input bits
    - Higher bandwidth, more complex selections possible, more partitioning, bunch matching, per-bunch monitoring
  - Muon to CTP Interface (**MUCTPI**): Combines barrel and endcap trigger candidates
    - Common hardware with the new CTP board with different firmware
- Trigger, Timing and Control (TTC) signals via new Local Trigger Interface (**LTI**)
  - Distribution of LHC timing, trigger accept and synchronisation signals to the sub-systems
  - Clock phase stability < 30 ps, provides standalone operation for sub-system tests

Readout, Dataflow and Networking

- New common readout via FELIX board
  - PCIe cards with single FPGA, custom optical links for front-ends, partially used in Run-3
  - Receives readout data and distributes timing signals from LTI
- Dataflow
  - Aggregates data from readout to the Event Filter (EF) and to storage
  - Full event building at 1 MHz and 5 MB event size requires 5 TB/s to EF
  - EF output rate of 10 kHz requires 50 GB/s to transient storage
- Online software: config./control, monitoring
  - Prototype based on Kubernetes as farm orchestrator

FELIX: Front-End LInk eXchange



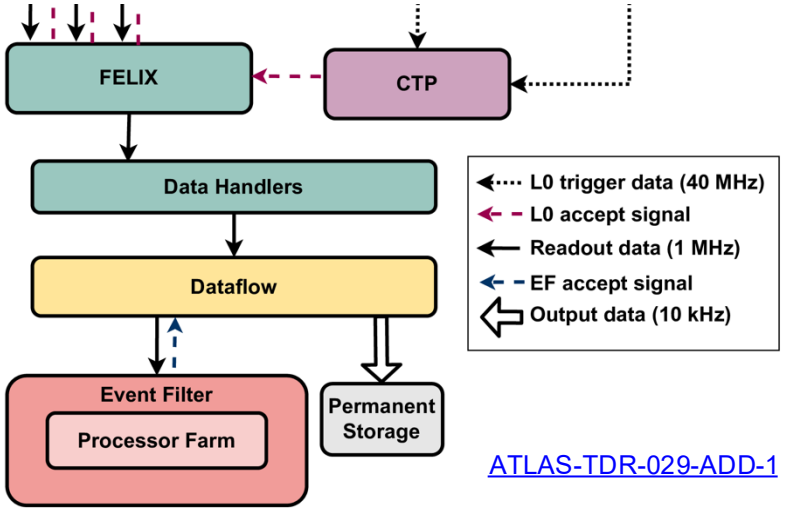
~500 cards

Felix FLX-182 prototype

FELIX Project

Event Filter

- Second stage event selection on asynchronous processing farm
  - Software trigger with full event building at 1 MHz
  - Refine L0 Trigger decision through inclusion of tracking information and higher precision algorithms
- Farm of commodity processors with off-line like algorithms, including ML
  - Initial plans to include custom hardware track trigger changed due to major improvements in reconstruction speed and the emergence of CPU with significant lower power consumption
    - Enables a farm with sufficient processing power within the constraints of the computing infrastructure
- Option of using GPU / FPGA hardware accelerators
  - Evaluation under way, to conclude towards end of 2025



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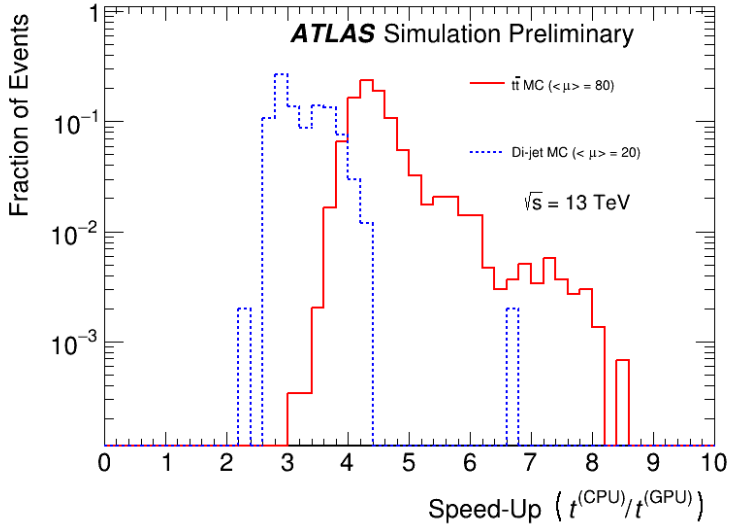


Speed-up of topo-clustering in ttbar events with GPU

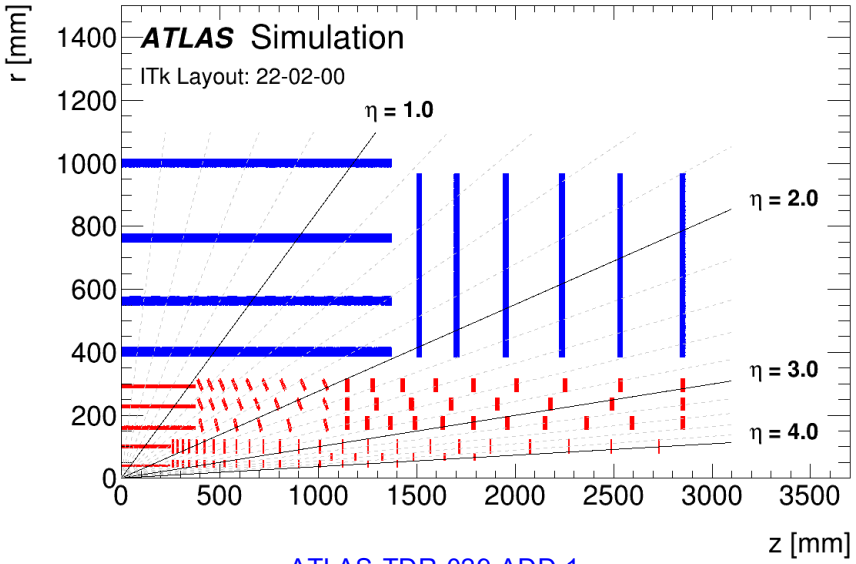
ATL-DAQ-PROC-2022-002

Event filter tracking

- Track reconstruction uses the majority of resources of the EF farm
  - Driver for the technology decision
  - Optimisation of the track reconstruction on CPU using the final layout of the ITk led to much faster processing
- Several avenues of using commodity accelerator cards currently under investigation
  - Fully CPU based processing
  - Fully or partially GPU based processing
  - Fully or partially FPGA based processing
  - Exploring track finding alternatives: Graph Neural Networks → candidate for highly parallel execution on GPU/FPGA

See talk by M. Neubauer

- Interface to ATLAS software via ACTS
  - **A** **C**ommon **T**racking **S**oftware ATCS Project
  - Experiment independent toolkit for tracking



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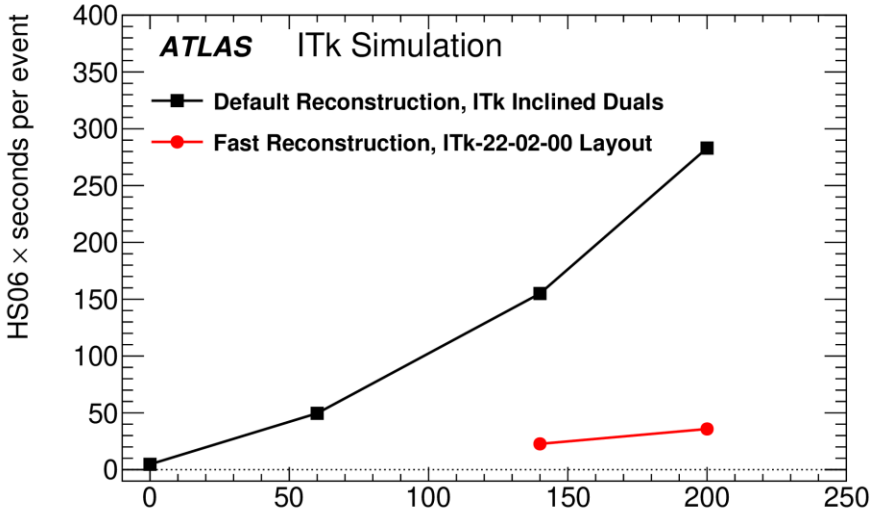
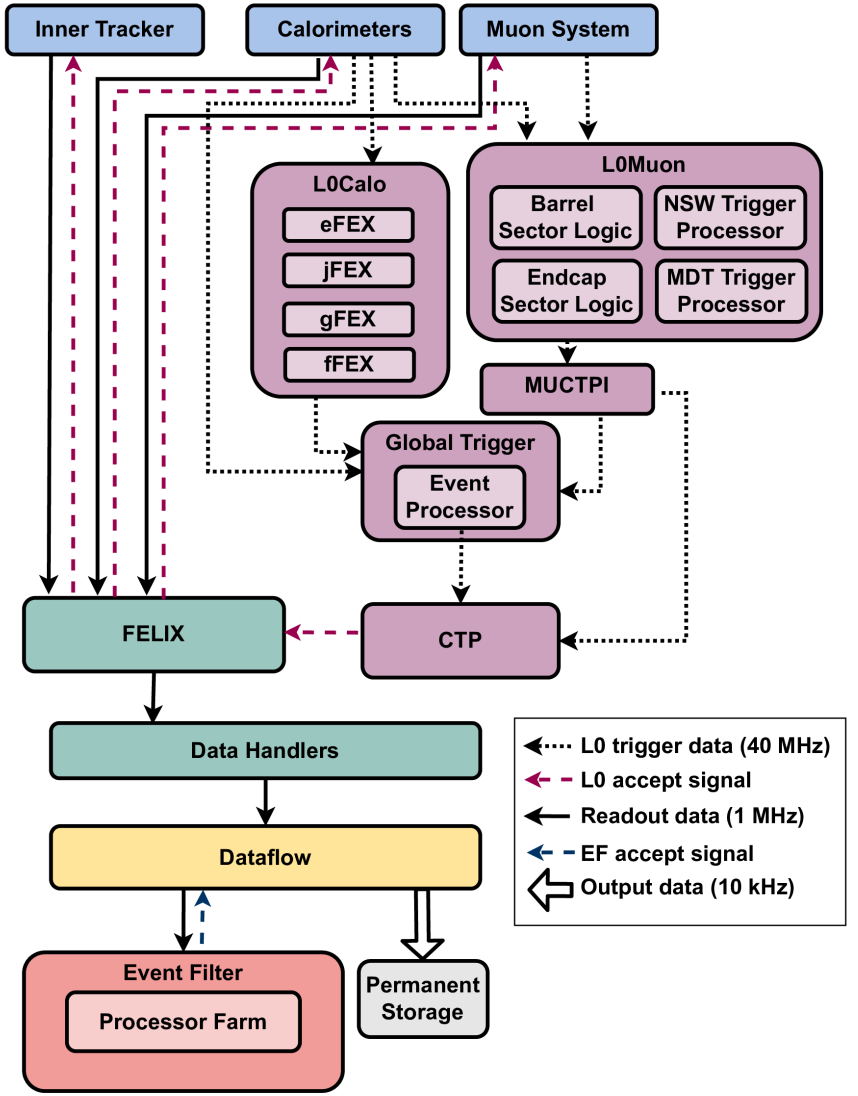


Summary

- ATLAS is undertaking very significant changes to its TDAQ system for Run-4
  - Needed to take full advantage of the higher luminosity provided by HL-LHC
- Prototypes are available already for many components
  - The focus is increasingly on integration and production
- Purchases of commodity hardware will be done as late as possible to profit from latest developments
  - Provides time for example to investigate use of hardware accelerators in the EF farm or components of the data transfer networks
- Much work is still to be done, but the project is proceeding well



Backup

Example Run-4 trigger menu with trigger rates

Table 2.1: *Representative trigger menu for 1 MHz Level-0 rate. The offline p_T thresholds indicate the momentum above which a typical analysis would use the data.*

Trigger Selection	Offline p_T Threshold [GeV] Run 1	Run 2 (2017)	Planned HL-LHC Offline p_T Threshold [GeV]	L0 Rate [kHz]	After regional tracking [kHz]	Event Filter Rate [kHz]
isolated single e	25	27	22	200	40	1.5
isolated single μ	25	27	20	45	45	1.5
single γ	120	145	120	5	5	0.3
forward e			35	40	8	0.2
di-γ	25	25	25,25		20	0.2
di-e	15	18	10,10	60	10	0.2
di-μ	15	15	10,10	10	2	0.2
$e-\mu$	17,6	8,25 / 18,15	10,10	45	10	0.2
single τ	100	170	150	3	3	0.35
di-τ	40,30	40,30	40,30	200	40	0.5†††
single b-jet	200	235	180	25	25	0.35†††
single jet	370	460	400			0.25
large-R jet	470	500	300	40	40	0.5
four-jet (w/ b-tags)		45†(1-tag)	65(2-tags)	100	20	0.1
four-jet	85	125	100			0.2
H_T	700	700	375	50	10	0.2†††
E_T^{miss}	150	200	210	60	5	0.4
VBF inclusive			2x75 ($\Delta\eta > 2.5$ & $\Delta\phi < 2.5$)	33	5	0.5†††
B-physics††				50	10	0.5
Support Triggers				100	40	2
Total rate				1066	338	10.15

† In Run 2, the 4-jet b-tag trigger operates below the efficiency plateau of the Level-1 trigger.
†† This is a place-holder for selections to be defined.
††† Assumes additional analysis-specific requirements at the Event Filter level

ATLAS-TDR-029-ADD-1

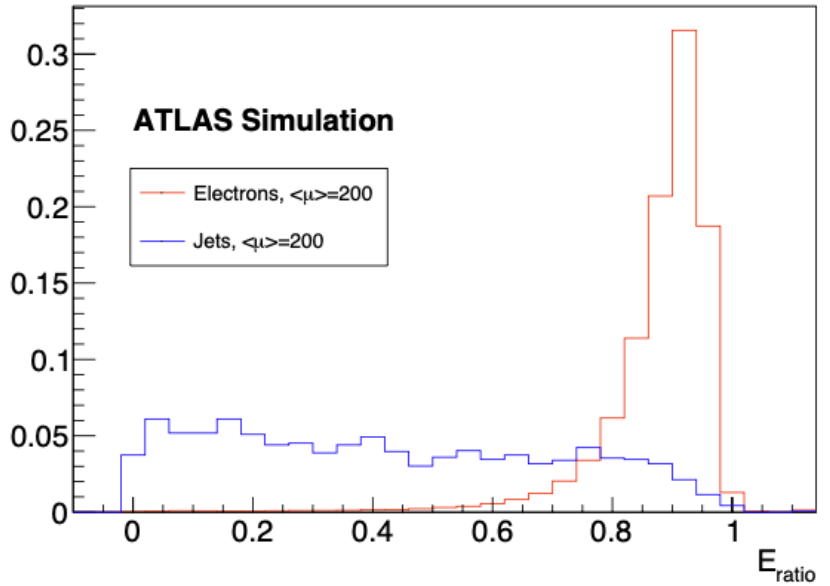
E_{ratio} variable in the L0 Trigger

$$E_{ratio} = \frac{E_{\text{highest energy cell}} - E_{\text{2nd local maximum energy cell}}}{E_{\text{highest energy cell}} + E_{\text{2nd local maximum energy cell}}}$$

$E_{\text{highest energy cell}}$: energy in the cell with the largest energy deposit associated with the electron

$E_{\text{2nd local maximum energy cell}}$: energy in the next largest local maximum (in a window of typically 0.0625 in η)

- discriminates between dominant background from $\pi^0 \rightarrow \gamma\gamma$ showers (whose maximum and second-maximum energy depositions would be balanced) and isolated electrons or photons (whose E_{ratio} is close to 1).



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(a) *Distribution of E_{ratio} variable.*