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

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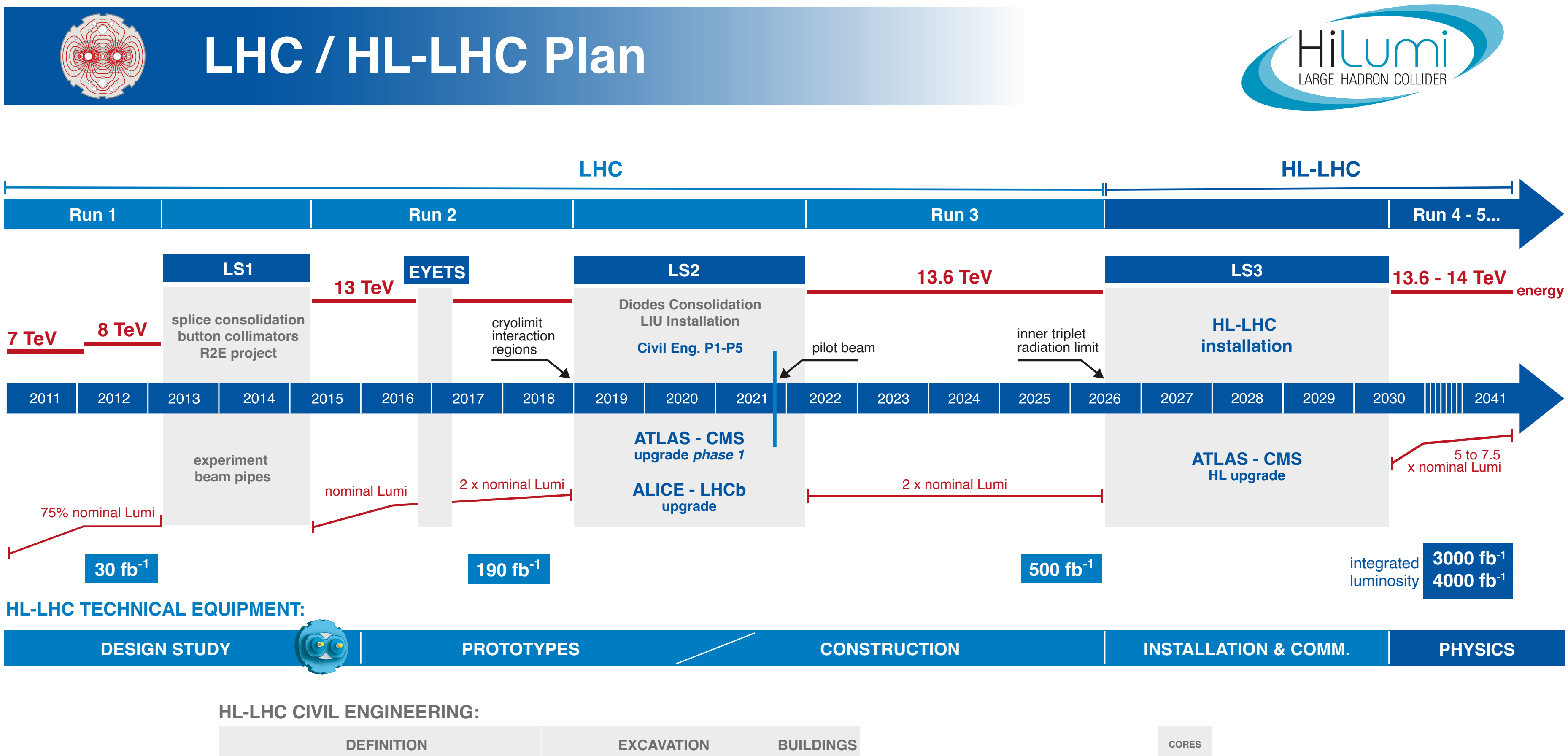
Outline

- Evolution of the TDAQ system towards HL-LHC
- Components of the hardware L0 trigger
- Challenges in the Event Filter (high-level trigger based on commodity resources)
  - Evaluation of technologies to provide computing resources for the EF farm (CPU, CPU+accelerators)

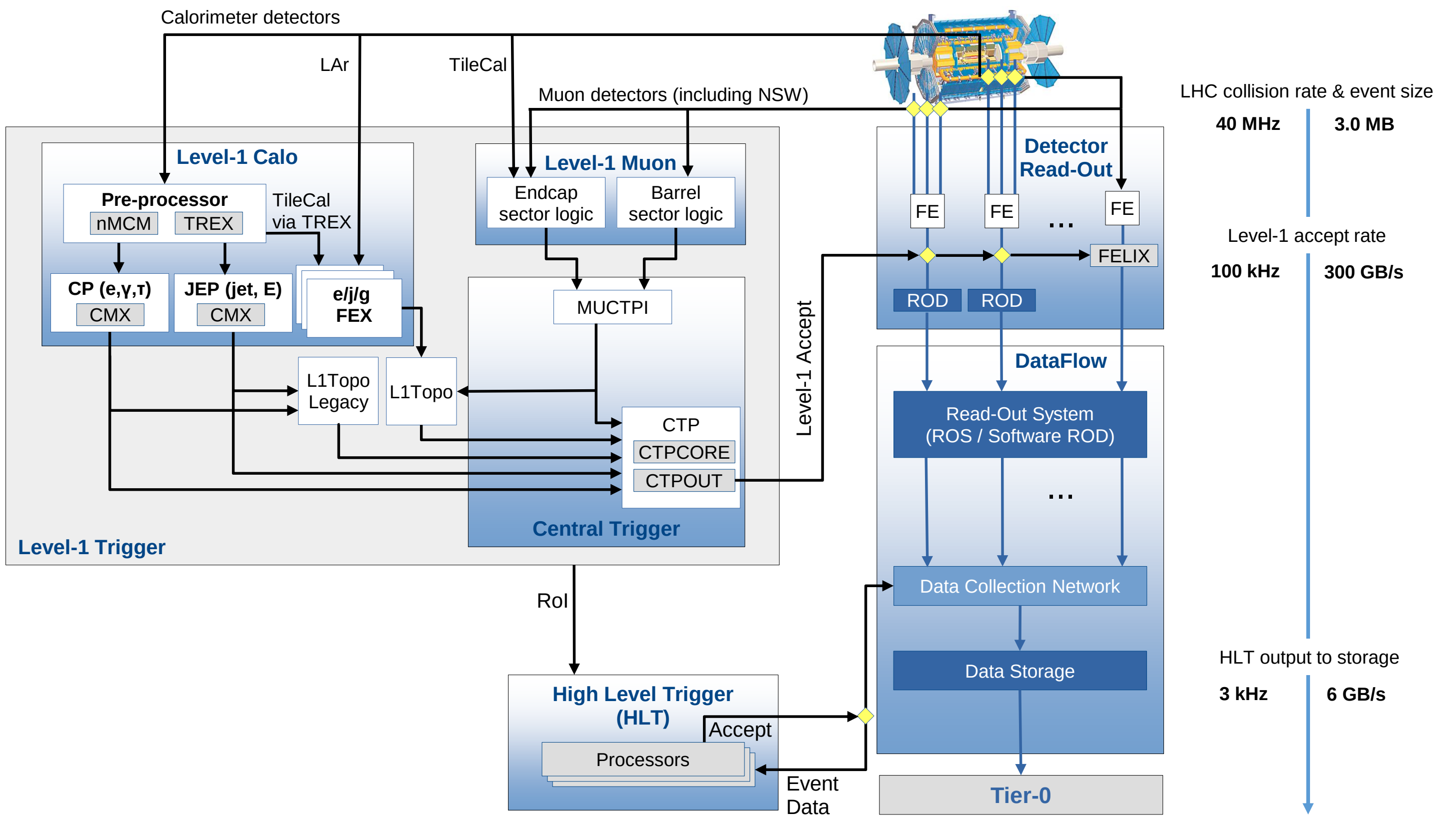
High Lumi LHC era



Run4 and Run5 to increase the instantaneous luminosity to 5-7.5x10^{34}cm^{-2}s^{-1} (from 2x10^{34}cm^{-2}s^{-1} in Run3) and record 3000fb^{-1} (500fb^{-1} in Run3)

ATLAS TDAQ system will be upgraded to deal with higher rates and pileup μ=140-200 (wrt μ~60 in Run 3)

Evolution of ATLAS TDAQ from Run 3

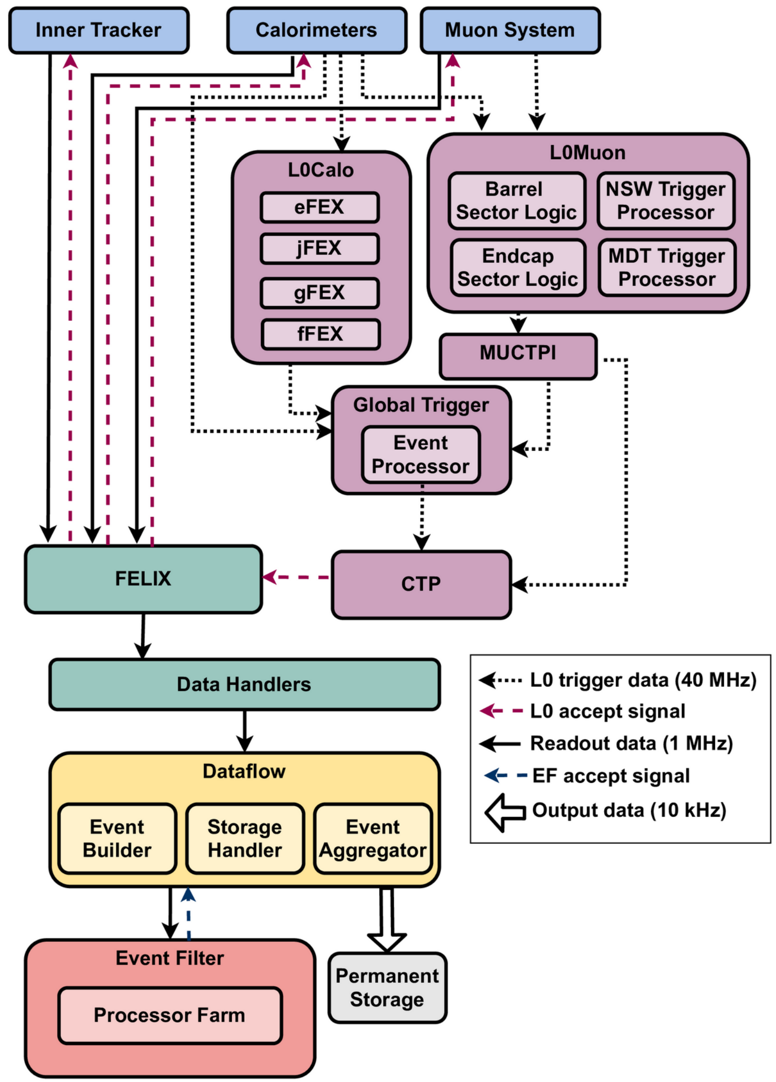


Hardware L1 + software HLT farm

L1 hardware trigger reduces rate from 40MHz to 100kHz and High-Level Trigger (HLT) from 100kHz to ~3 kHz (main+delayed streams, extra rate in partially built events).

Event building: request-driven access by RoIs (regions of interest) in HLT. Full-event building after HLT accept

ATLAS TDAQ for High-Lumi LHC

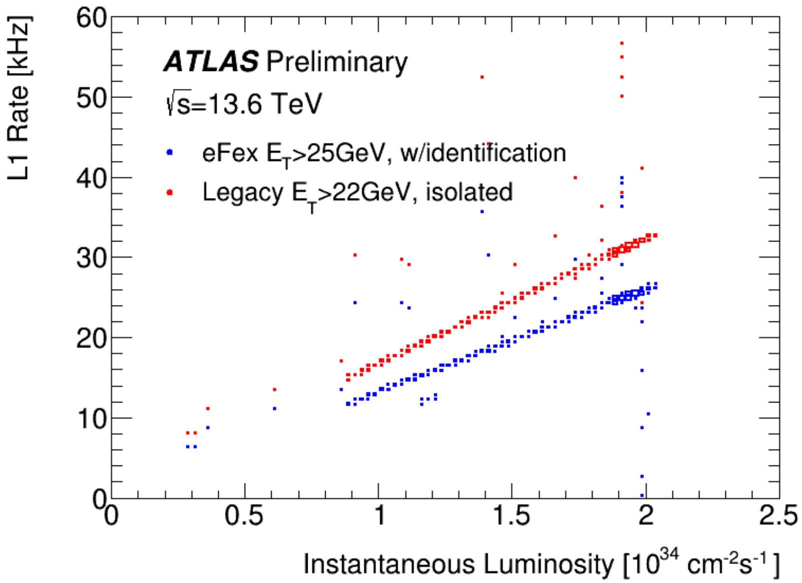


- ATLAS TDAQ system for High Lumi LHC
- More advanced initial level in Hardware (L0) refined by offline-like reco in the Event Filter (EF)
- 1 MHz of L0 output
  - Factor of 10 increase wrt Run 3
  - ~5TB/s, 20 times increase wrt Run 3
- 10kHz of EF output to the storage
- The EF is a farm of the commodity CPUs / commodity accelerators
  - Responsible for forming trigger decision after L0 accept
  - Regional + full detector reconstruction
- Event building different wrt Run 3
  - Full events streamed from detector after L0 accept and assembled by dataflow
  - High throughput system
  - Events available to the EF and sent to Permanent Storage after the trigger decision

ATLAS L0 Trigger @ HL-LHC

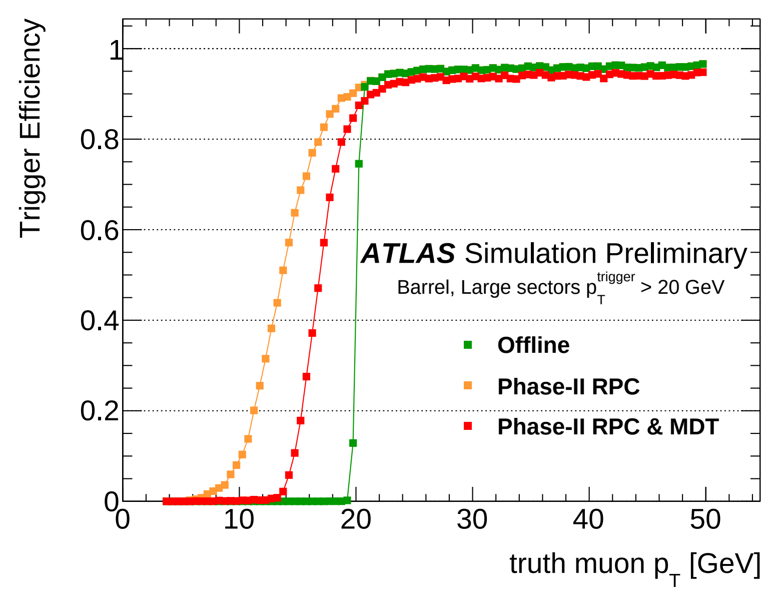
- HW trigger to reduce the rate from interaction rate to 1MHz
  - Low latency ATCA (Advanced Telecommunications Computing Architecture) and FPGAs
  - L0Calo, L0Muon, MUCTPI, Global Trigger and CTP
  - L0Calo uses a calo signals processed by Feature Extractors (FEX)
    - eFEX, jFEX, gFEX, fFEX specialised to calo signatures
    - Except of fFEX part of Phase1 Calo upgrade of Run 3
    - Calo granularity and algos upgraded in Run 3
  - L0Muon identifies muon candidates, MUCTPI processes them to CTP
  - Global Trigger takes output from L0Calo, L0Muon + extra calo info to combine them to topological info
    - New component in Run4
  - CTP forms the final decision to accept/reject event on L0 level

electron L1Calo



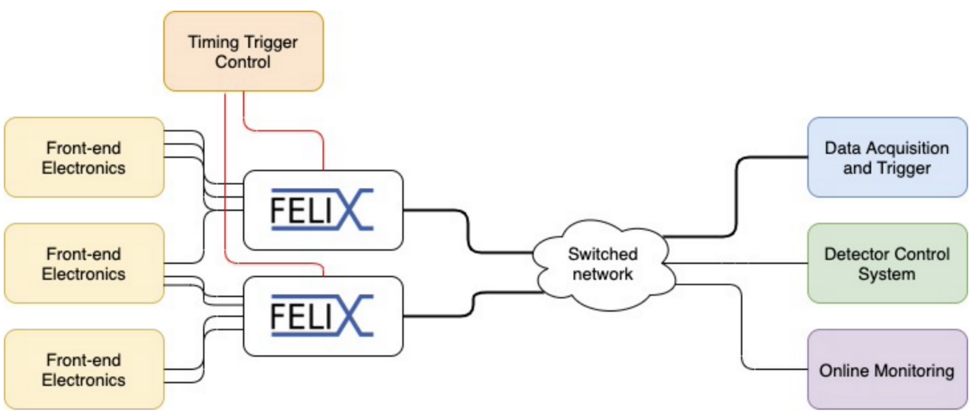
Thresholds legacy-eFex comparable

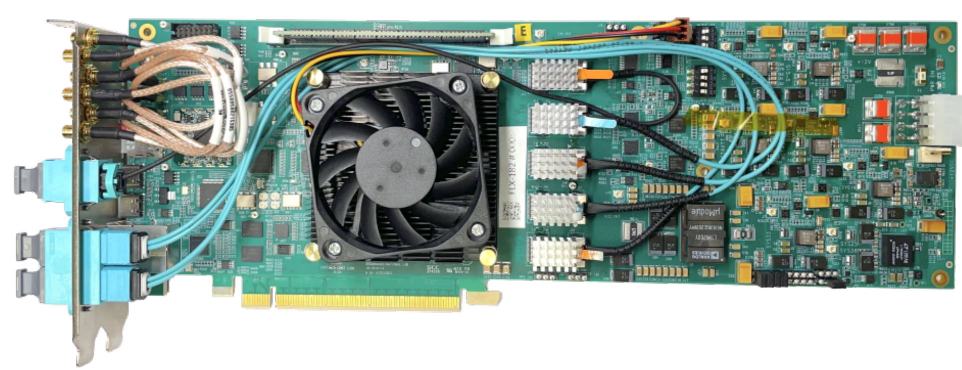
L0Muon efficiency



FELIX - read-out system

- Common readout via FELIX
  - FrontEnd Link Exchange will be used in all detector readout systems
  - Commodity servers with PCIe cards, large FPGAs and high-speed serial fiber transceivers
  - Scalable + flexible + uniform system replacing custom hardware from Run 3 (partial use of FELIX – L1Calo, Liquid Ar digital readout, New Small Wheel)
  - ~500 FELIX cards handling the stream of 5TB/s from the full detector





atlas-project-felix

Event Filter

- A CPU farm with resources to provide final acceptance/rejection using offline-quality reconstruction
- Majority of the resources of the CPU farm would be needed for track reconstruction
  - The possibility to use commodity hardware studied in the ATLAS TDAQ TDR Amendment
    - Demonstrated the feasibility of the CPU reconstruction and started the EFTracking project to evaluate other solutions (Fast-tracking prototype slide later)
    - GPU or FPGA reconstruction or possibly heterogeneous strategies being evaluated alongside the CPU baseline in the EFTracking project
      - Also different approaches to track reconstruction as GNN4ITk (Expected Tracking Performance of the ATLAS ITk GNN Track Reconstruction Chain)
- Accelerator solutions studied beyond tracking (topological clustering with topo-automaton)

ATLAS Trigger menu for Run 4

- A representative set of chains and their evolution from Run 1
  - Plan lower thresholds despite harsher conditions
  - Input rates lower thanks to updates of the L0 system
- Input to the EFTracking technology choice and computing resources needed

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	Offline p_T Threshold [GeV] 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.

Physics programme:
Precision studies of the Higgs boson, precision measurements of the SM processes, search for effects beyond SM

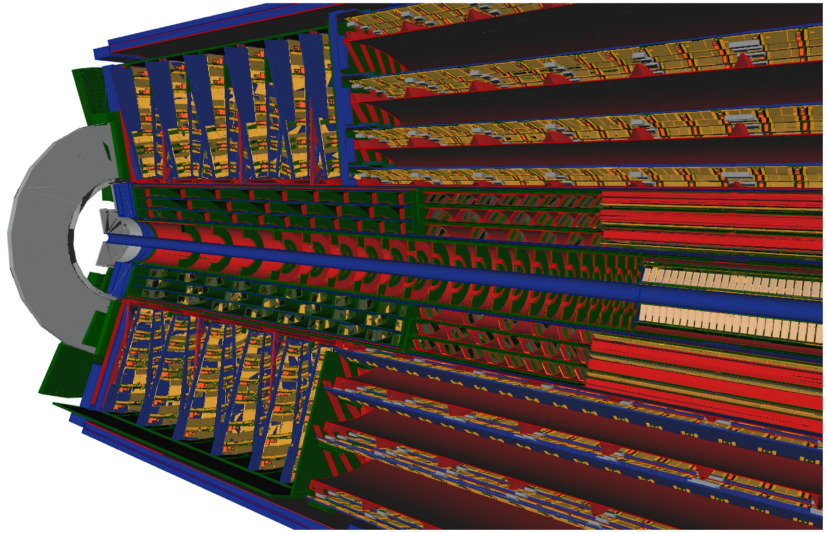
EF Tracking / design

- Use commercial system with CPUs and possibly accelerators, heterogeneous solution for tracking
- Optimize steps of the tracking reconstruction
  - ITk Data Preparation
  - Track Seeding & Pattern Recognition
  - Track Extension, Fitting & Ambiguity Resolution

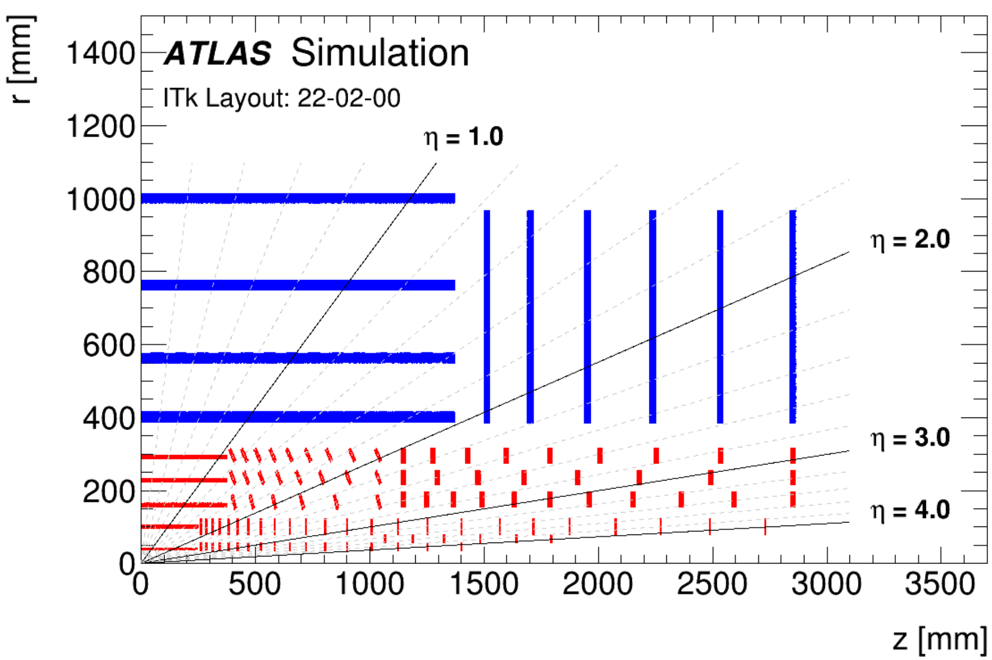
  in CPU / accelerator implementations
- Develop demonstrators for CPU/GPU/FPGA and present their performance in 2025Q3 followed by a decision of the technology
  - Fulfilling requirements on the tracking performance (efficiency, resolutions & fake rate)
  - Delivery of the physics menu
  - Power consumption constraints (accelerators may help)
  - Cost of the system

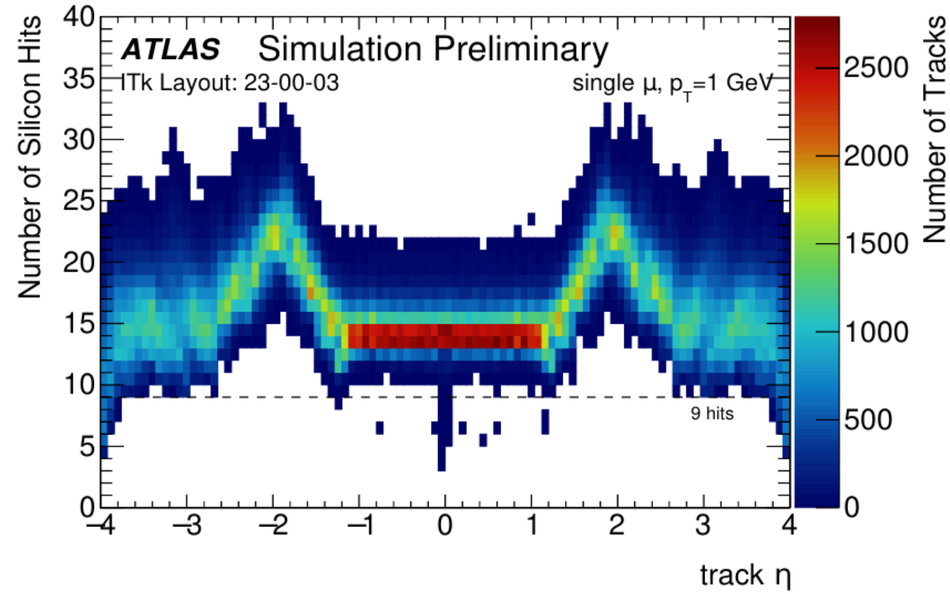
EFTracking and ITk detector

- ITk – silicon-only tracker for HL-LHC
- The design optimized substantially since TDAQ TDR
  - Simpler layout with ring design and inclined barrel sections optimized where to provide trajectory measurements and reduce CPU in reconstruction
  - Pixel detector with a minimum of 5 layers in eta gives sufficient redundancy for efficient & robust seeding



→ Foundation for a faster track reconstruction





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EFTracking / Fast-tracking prototype for CPU

$\langle\mu\rangle$	Tracking	Release	Byte Stream Decoding	Cluster Finding	Space Points	Si Track Finding	Ambiguity Resolution	Total ITk
140	default fast	21.9	2.2	6.4 6.1	3.5 1.0	31.6 13.4	43.4 -	87.1 22.7
200	default fast	21.9	3.2	8.3 8.1	4.9 1.2	66.1 23.2	64.1 -	146.6 35.7

CPU cost in HS06*s for ttbar MC sample

- Largest savings in track finding and omitting full scale Ambiguity Resolution
- Non-pattern steps non-negligible contribution to the total cost
- Factor of 8 speedup wrt default reco on earlier ITk layout

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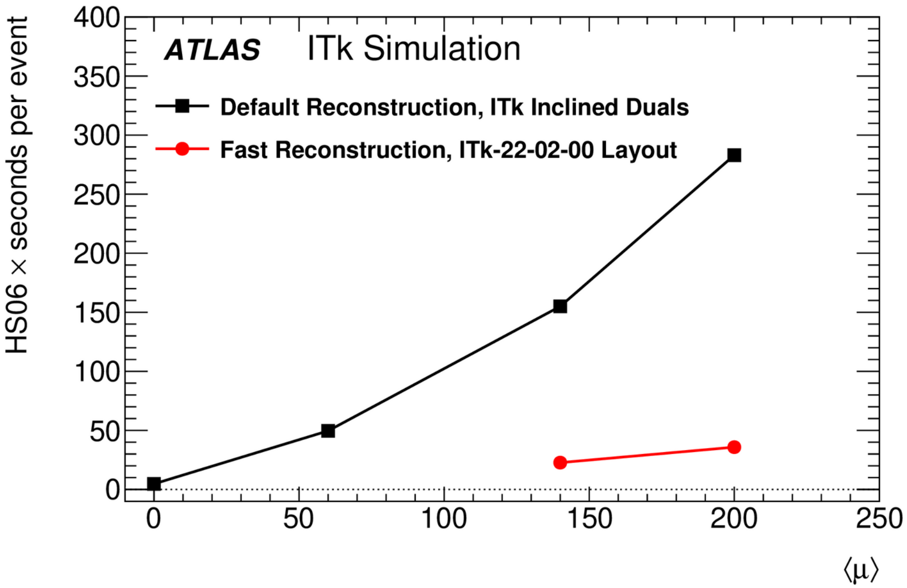
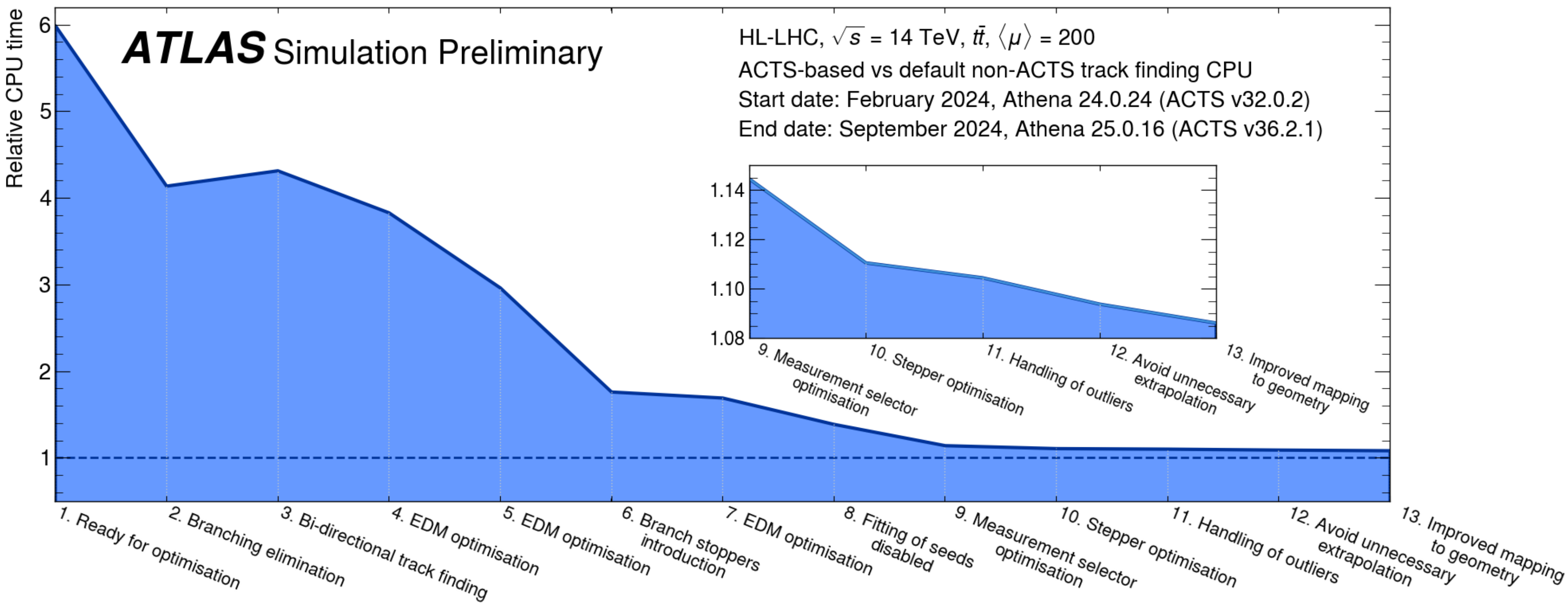


EFTracking + ACTS

A Common Tracking Software:

- an open-source github.com:acts-project, experiment-independent software toolkit for track reconstruction in high-energy physics (HEP) and nuclear physics
  - modern C++ code with better maintainability
  - building on the ATLAS and other clients experience
  - traccc subproject for GPU based reconstruction to ease integration of accelerators
- Recent optimizations reach the technical performance of the legacy fast reconstruction (dashed line below)



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EFTracking + GNN4ITk

GNN4ITk is an alternative to the standard track finding.

It uses graph neural networks to reconstruct track candidates

Graph is constructed of spacepoints, an edge represents a connection between them

GNN is taught to classify edges and score them to prioritize track-like connection over noise

GNN is a candidate for highly-parallel execution on accelerators (GPUs or FPGAs)

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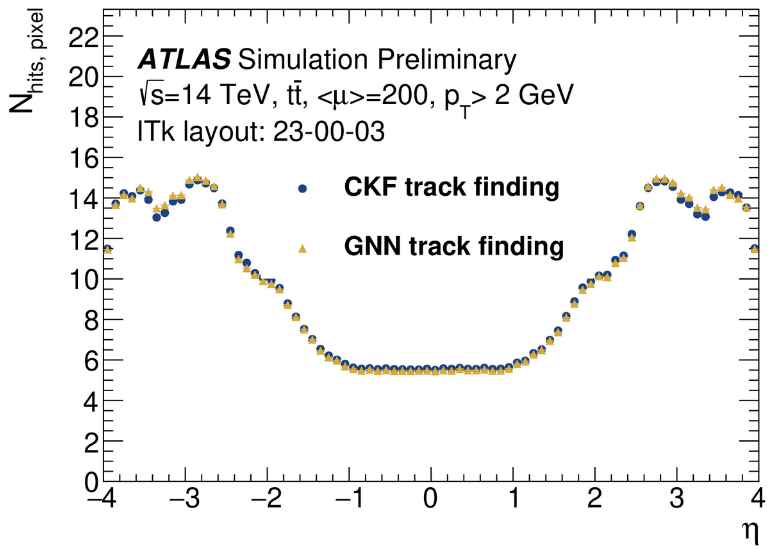

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Stage	**Pipeline**	
	Metric Learning (ms)	**Module Map (ms)**
1. Graph Construction	505	69
2. Edge Classification	108	323
3. Graph Segmentation	118	118
Sum	**731**	**510**

Other accelerator projects
Topo-automaton clustering

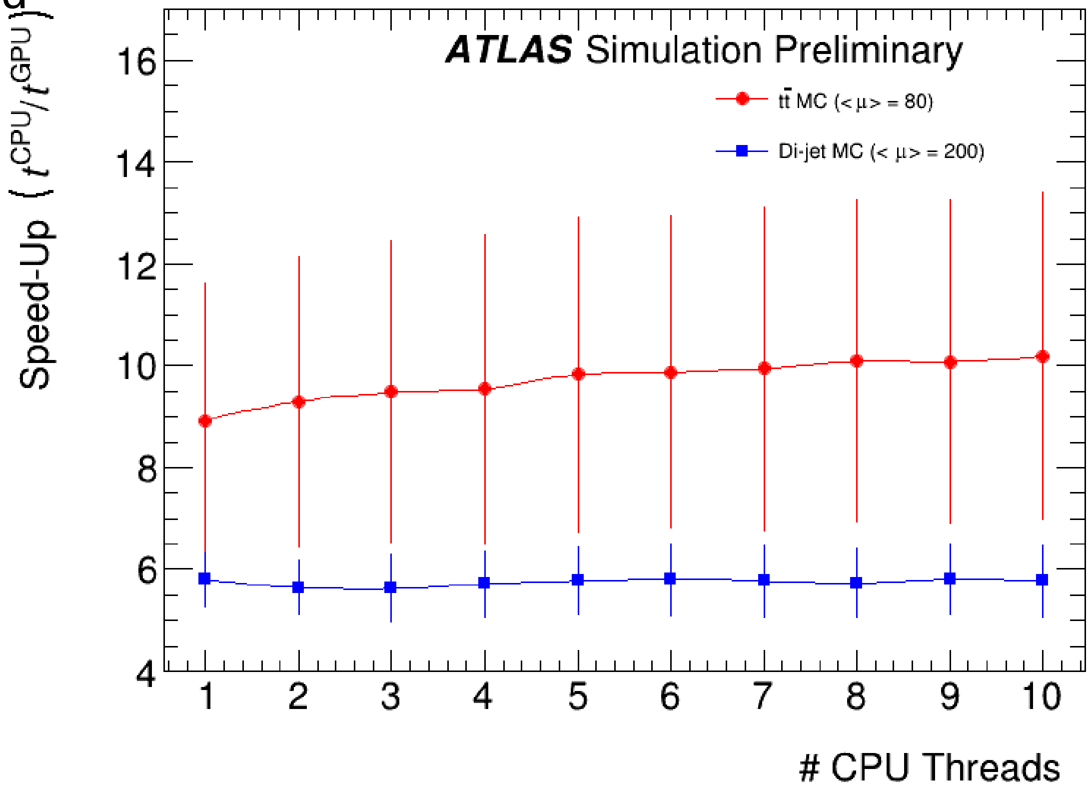
Computational demanding task not scaling well with high pileup is topological clustering in calorimeter
- Reconstruction of particle showers in calorimeter to form noise-suppressed 3d topological clusters from calorimeter cells

Topo-automaton is highly parallelizable and designed for GPU acceleration
- Using tags for cluster assignment in an atomic manner

In an advanced stage – fully validated in Run-3 data wrt CPU approach in trigger reprocessing of the raw data on grid

Factors 9 (6) speed up in ttbar (mu=80) and dijet (mu=200) samples respectively

Further improvements considered in data preparation and in the optimization of the EDM



Summary

- ATLAS TDAQ for HL-LHC designed to cope with unprecedented input rates and data transfers
  - More advanced L0 HW trigger to help the reduction of rate
  - DAQ upgrades to handle the full data rate at L0 decision
  - EF in the process of technology decision for the track reconstruction. Baseline is the CPU as demonstrated in the TDR amendment, demonstrators of technologies (CPU, GPU or FPGA) to be evaluated this year
    - Alternative approaches as GNN4ITk, traccc (GPU) or FPGA
  - Applications of accelerators studied beyond tracking (topo-automaton)
- Development of the Trigger/DAQ system well underway to provide an optimal data-recording in Run4+5 HL LHC collisions