ATLAS
Trigger & Data Acquisition
Upgrades for the High Luminosity LHC

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On behalf of the ATLAS Collaboration

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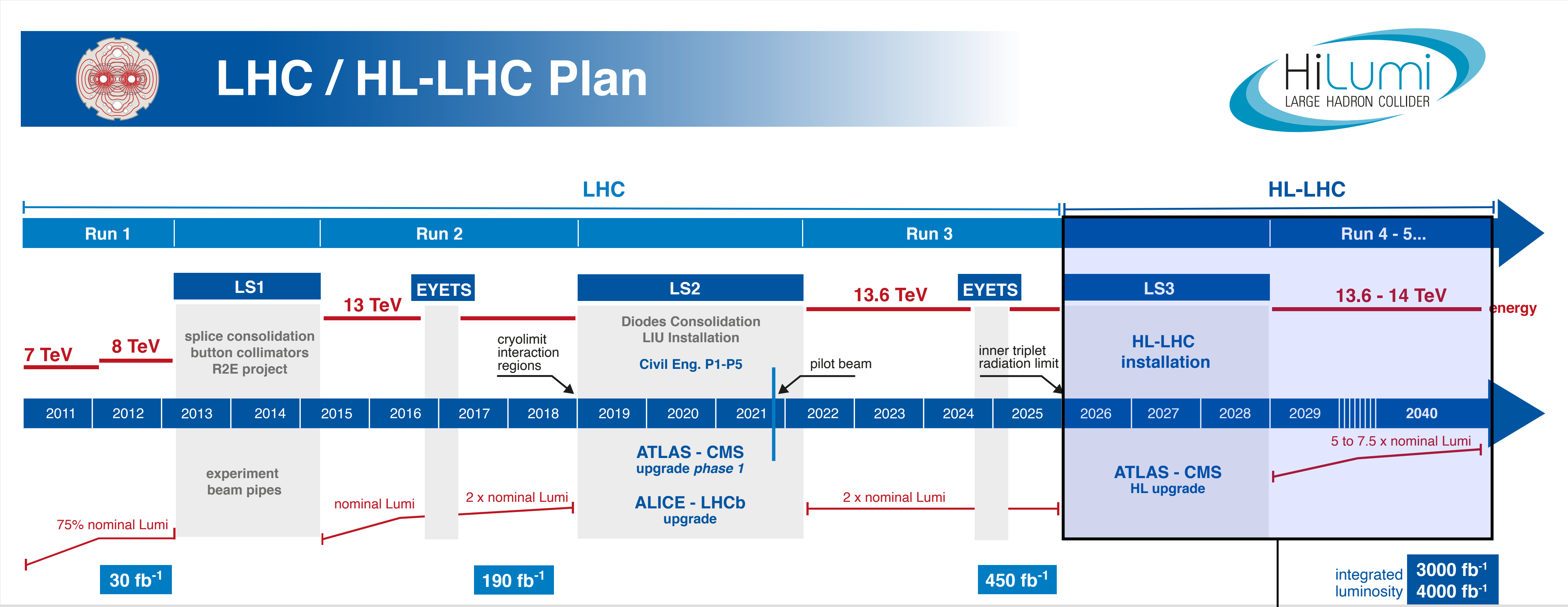
for the help in preparing this talk

Outline:

- HL-LHC implications
  - ATLAS
  - TDAQ (Trigger & Data AcQuisition (DAQ)) →
- TDAQ Phase-II
  - Operational model
  - Subsystems

"This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC0010120"

HL-LHC schedule



- Up to 200 events per pp bunch-crossing
- total pp-dataset of up to $4000\ fb^{-1}$

ATLAS in the HL-LHC

- ATLAS preparations for the HL-LHC:
  - *New sub-detectors are being introduced: Inner Tracker (ITk) and High Granularity Timing Detector (HGTD) and a small number of Muon chambers*
  - *Electronics-only upgrades for other sub-detectors*

	* Detector system	Upgrade scope
New inner tracker	ITk Pixel Detector	Sensors, modules, mechanics, FE electronics
	ITk Strip Detector	Sensors, modules, mechanics, FE electronics
Extra pile-up mitigation	HGTD	Low gain avalanche detector technology
Higher radiation tolerance, providing full granularity data to the triggers	LAr Calorimeter	FE and BE electronics
	Tile Calorimeter	Mechanics, FE and BE electronics
Improved trigger coverage	Muon Spectrometer	FE electronics Inner Barrel MDT chambers Inner Barrel RPC stations
Discussed in this presentation	TDAQ	On-detector readout and trigger electronics

*Other forward detectors (LUCID, ZDC, AFP/ALFA) are not mentioned here, yet are included in the ATLAS upgrade plan

Implications on TDAQ

Detector system	Upgrade scope
ITk Pixel Detector	Sensors, modules, mechanics, FE electronics
ITk Strip Detector	Sensors, modules, mechanics, FE electronics
HGTD	Low gain avalanche detector technology
LAr Calorimeter Tile Calorimeter	FE and BE electronics Mechanics, FE and BE electronics
Muon Spectrometer	FE electronics Inner Barrel MDT chambers Inner Barrel RPC stations
TDAQ	On-detector readout and trigger electronics

- High luminosity & pileup ($\langle\mu\rangle \sim 200$ vs 60)
  - → *need to 'scan' more complex events*
- Accommodating the new subdetectors: ITk, HGTD
  - → *support the sub-detectors electronics constraints (e.g. no. of channels to read-out)*
- Full granularity to the L0Trigger provided by the detectors (LAr, Tile, Muon System)
  - → *exploiting the data for better triggering while dealing with bigger event sizes (4.6 vs 2 MB)*
- Identification of low pT objects is still required
  - → *maintaining low pT threshold in the trigger menu*
- Would need to deal with an order of magnitude higher data volume through the system
- → *maintaining low trigger rates in order to keep only relevant events*

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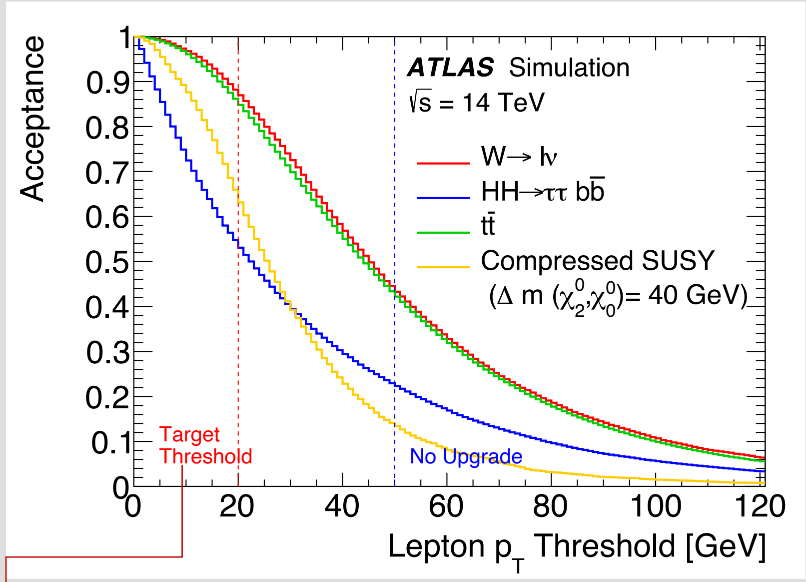
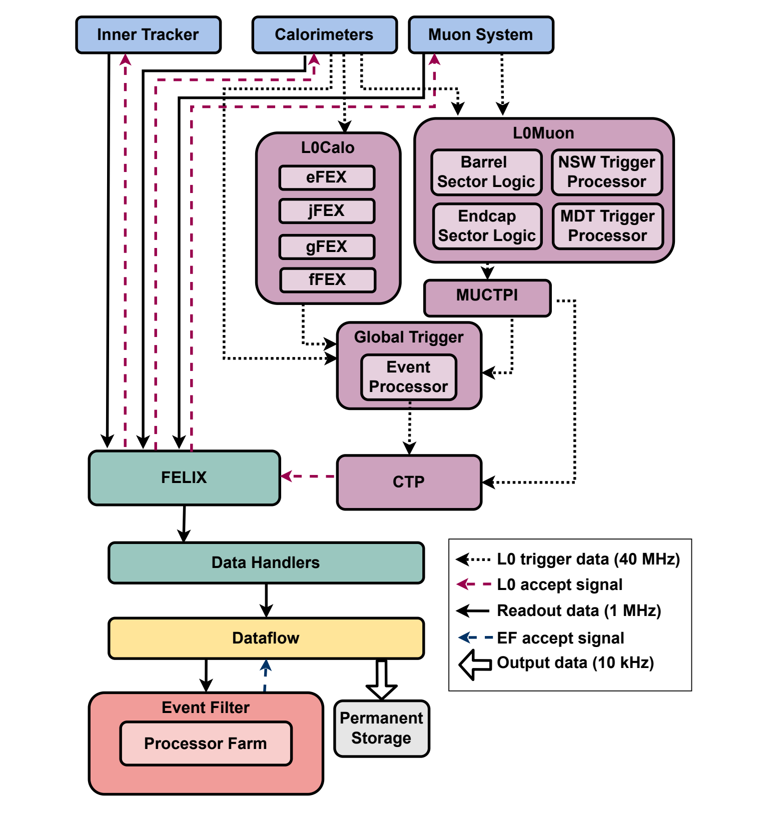


The Phase-II TDAQ upgrade would enable lowering the single lepton Level-0 threshold to 20 GeV from 50 GeV (the projected threshold without the upgrade).

TDAQ Phase-II

Operation model:

- 3 systems:
  - *Level-0 Trigger*
  - *DAQ (Readout & Dataflow)*
  - *Event Filter*

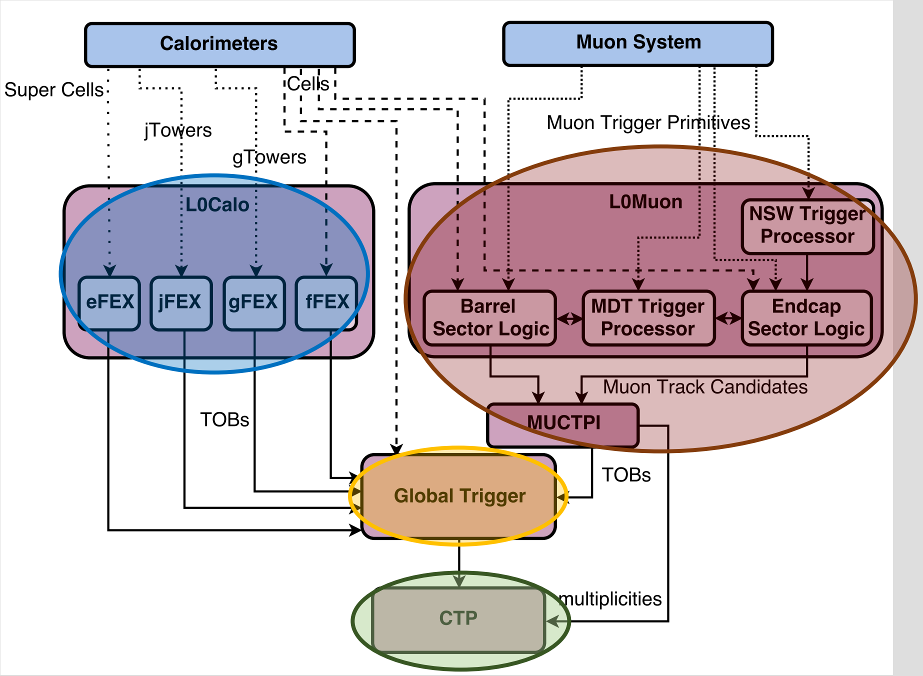


- Data flow **from the detectors** and **into the L0Trigger** systems – *at 40 MHz*
- The **L0Trigger:** *within 10 μs (2.5 μs today)*
  → **identifies** physics objects and **calculates** event-level physics quantities
  → **forms** Trigger Objects (**TOBs**)
  → **makes** trigger decision - **L0Accept** (L0A)
  → **sends back** to the **detectors** L0A – signals
- Complete event-data **from** the **detectors** & **triggers** are then **transmitted** through the **Readout** & **Dataflow** systems for formatting & buffering, etc… and eventually **into** the **Event-Filter** – *at 1 MHz (100 kHz today)*
- The **Event Filter** performs **reconstruction & selection** of the events. The events that passed the **Event Filter** trigger decision *(4.6 MB vs 2 MB today)* will be **transferred** to **permanent storage** of the ATLAS offline computing system – *at 10 kHz (3 kHz today)*

L0 Trigger

Composed of 4 main systems:

- *L0Calo*
- *L0Muon & MUCTPI*
- *Global trigger*
- *Central Trigger Processor (CTP)*



- **ATCA-based architecture:**
  - ***FPGAs*** *used for running algorithms*
  - *Data I/O Via* ***optical links*** *at 9-25 Gb/s*

- **Functionality:**
  - ***Identifying*** *physics objects (e, γ, τ, jets)*
  - ***Calculates*** *physics quantities (e.g. E_T^{miss})*

Form Trigger Objects (TOBs)

L0Calo

Composed of 4 main systems:

- L0Calo
- L0Muon & MUCTPI
- Global trigger
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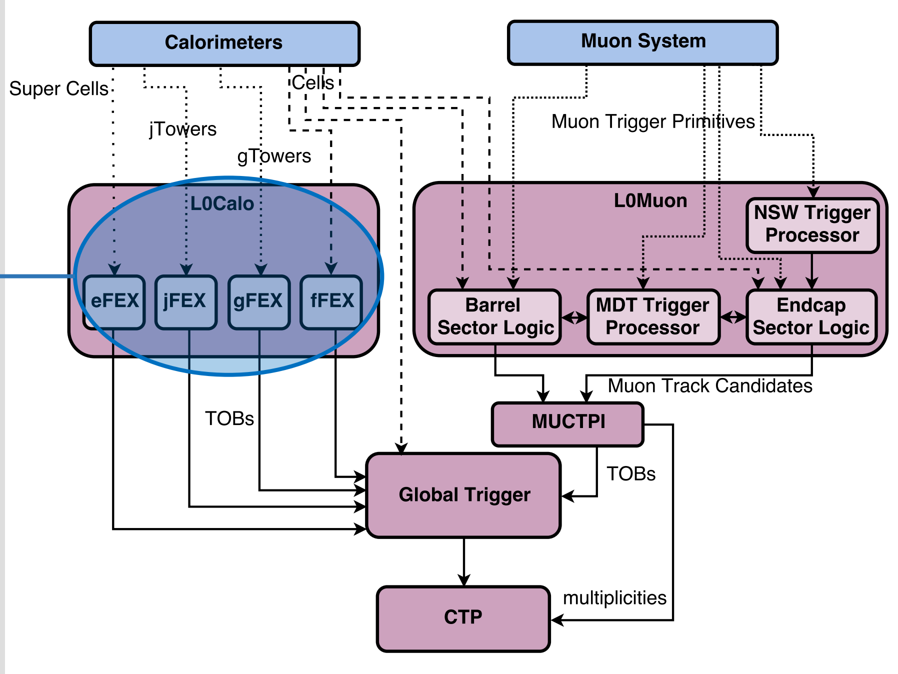

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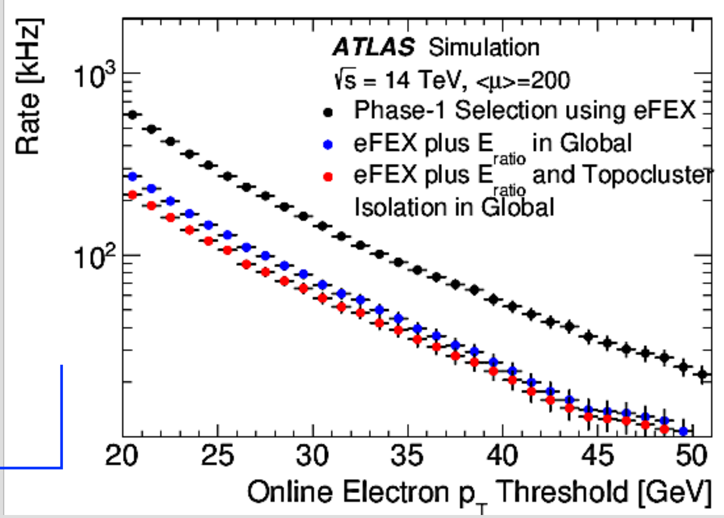
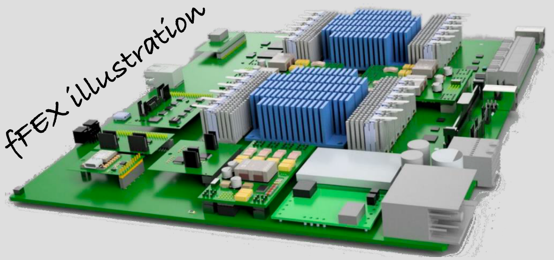


fFEX illustration



Combined selections of **eFEX** and Global reduces the trigger rates for the essential low p_T thresholds

L0Calo

- **Composed of** 4 **Feature EXtractors** (FEXs)
  - *electron-**FEX** (eFEX), **j**et-**FEX** (jFEX), **g**lobal-**FEX** (gFEX) and **f**orward-**FEX** (fFEX)*
- *Mostly **Phase-I legacy**:
  - *Upgraded firmware for phase-II algorithms*
  - **Additional trigger coverage – fFEX*
- *Use **coarse-granularity calorimeter** data — Inputs to the algorithms
  - **The fFEX will use full-granularity*
- **Identify** physics objects (e, γ, τ, jets) and **calculate** E_T^{miss}
- Final **Trigger Objects** are **sent to the Global Trigger** for further processing

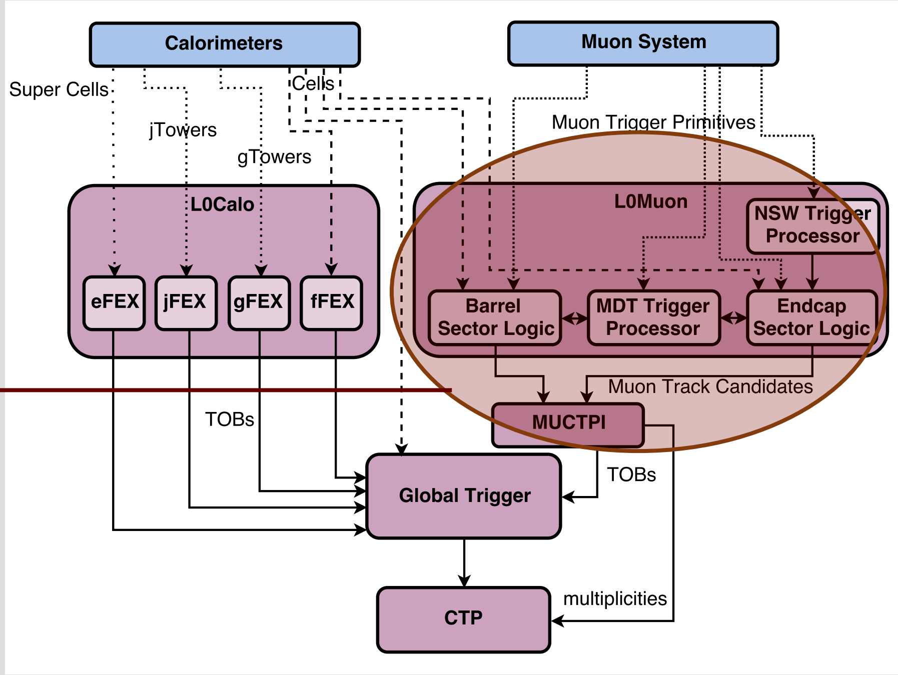
Subsystem	Trigger Object	Approximate Granularity	Coverage $\|\eta\|$
eFEX	e, γ, τ	Super Cells (10 in 0.1 × 0.1)	< 2.5
jFEX	τ, jet, E_T^{miss}	0.1 × 0.1 0.2 × 0.2 0.4 × 0.4	< 2.5 2.5 – 3.2 3.2 – 4.9
gFEX	Large-R jet, E_T^{miss}	0.2 × 0.2 0.4 × 0.4	< 4.9 3.2 – 4.9
fFEX	e, γ jet	Full detector EMEC, HEC, FCal Full detector FCal	2.5 – 4.9 3.2 – 4.9

L0Muon & MUCTPI

Composed of 4 main systems:

- *L0Calo*
- *L0Muon & MUCTPI*
- *Global trigger*
- *Central Trigger Processor (CTP)*

MDT-TP Command Module



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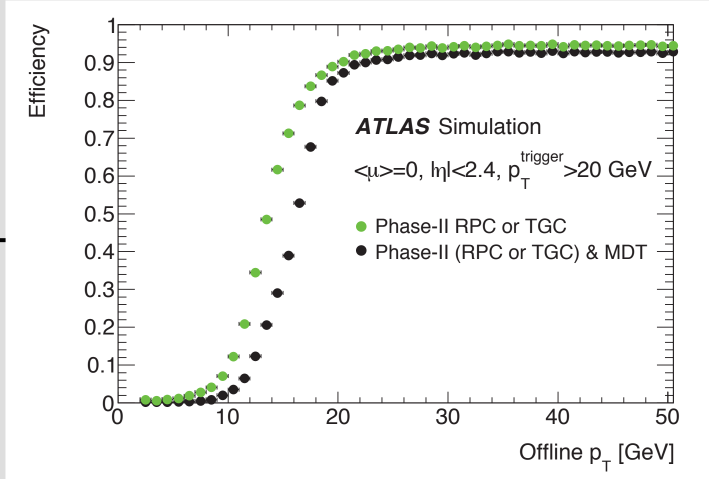


Including MDT info in the Muon triggers:

- provides better sensitivity to muon candidates
- while still keeping the trigger eff. high

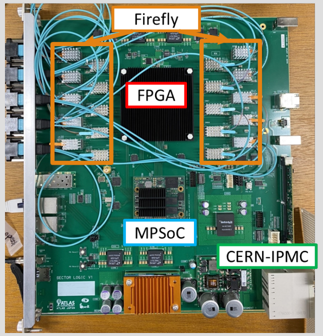
L0Muon + MUCTPI

- *Upgraded **muon** trigger system, **composed of 4 trigger-processors** (TP)
  - *RPC (Resistive Plate Chambers) Sector Logic (SL), TGC (Thin Gap Chambers) SL, NSW (New Small Wheel) TP as legacy, with new design*
  - **MDT (Monitored Drift Tube) are the precision muon chambers, their TP is a new addition to L0Muon (further details in G. Loustau's poster)*
- Receive **full granularity data** inputs from:
  - *all Muon subsystems*
  - *subset of Tile data*

Subsystem	Granularity	Coverage $\|\eta\|$
NSW processor	Full NSW detector	1.3 – 2.4
MDT processor	Full MDT detector	< 2.4
Barrel Sector Logic	Full RPC and Tile, MDT	< 1.05
Endcap Sector Logic	Full TGC, Tile, RPC, NSW, MDT	1.05 – 2.4

- **Higher quality** trigger **candidates** due to:
  - ***Increased detector acceptance*** *(additional RPC chambers providing further hits)*
  - ***Additional processing of the MDT data****, seeded by both barrel & end-cap information, forming pattern recognition & tracking*
- The **MUCTPI** (**Mu**on to **CTP I**nterface) **combines information** for final refined selection
  - *Legacy hardware with upgraded firmware (additional blade for Phase-II is being considered)*
  - *Forming final TOBs sent to the Global Trigger for further processing*

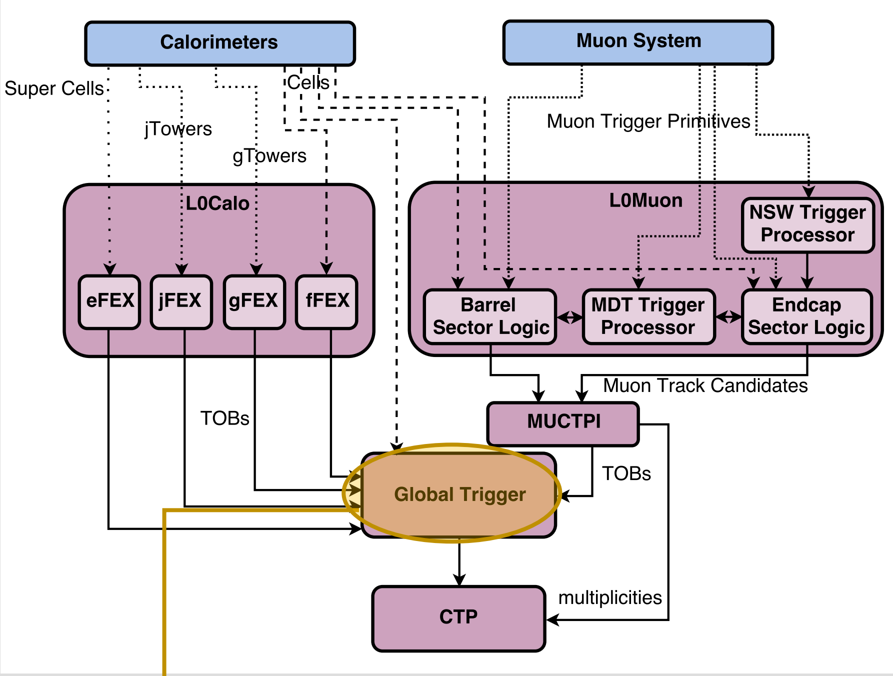
Sector-Logic prototype



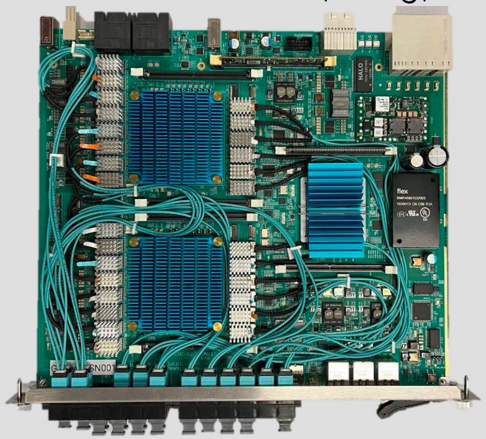
Global Trigger

Composed of 4 main systems:

- *L0Calo*
- *L0Muon & MUCTPI*
- *Global trigger*
- *Central Trigger Processor (CTP)*



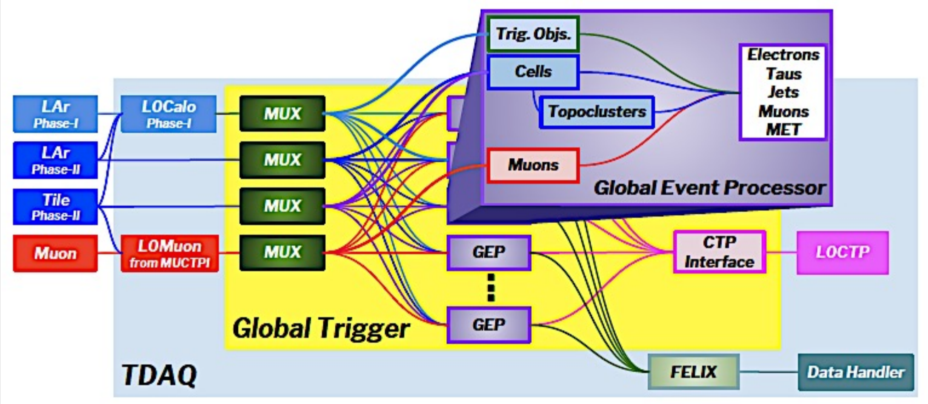
GCM (Xilinx US+) prototype



Global

- **Receiving** information from the Calorimeters, L0Calo and MUCTPI at a total **input rate of 50 TB/s**
- **Composed** of 3 main components, (same hardware platform):

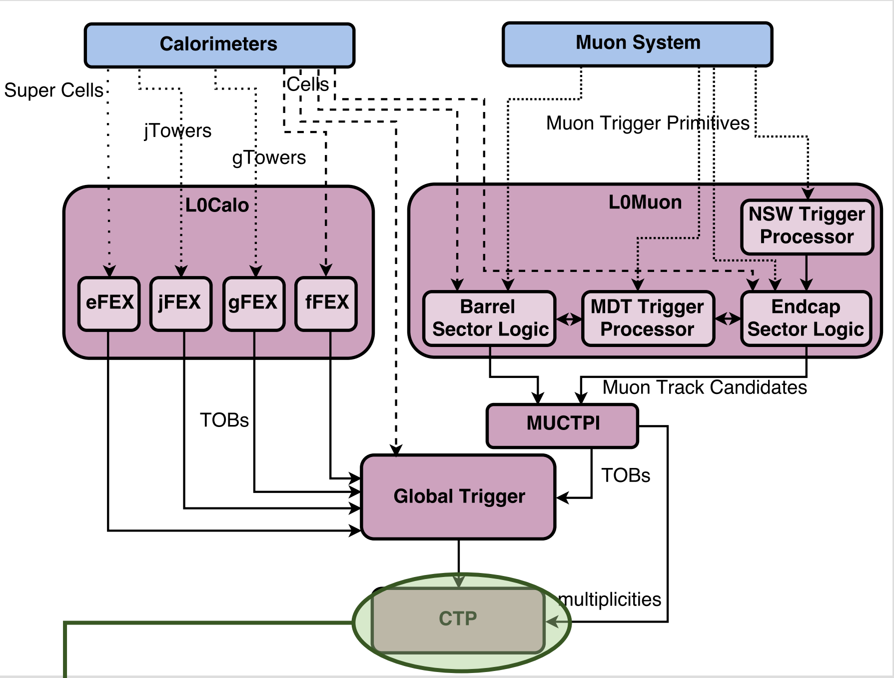
- ***MUX*** *– time* ***multiplexing*** *serial* ***inputs****:*
  - ***L0Calo*** *systems*
  - ***Calorimeter*** *pre-processors*
  - ***MUCTPI***
- ***GEP*** *(Global Event Processor) – execute "offline-like"* ***processing algorithms****, running on state-of-the-art Xilinx Versal Premium FPGAs :*
  - ***Topological*** *clustering*
  - *Sophisticated pileup subtraction*
  - *Anti-kT jet finding*
  - *Machine Learning techniques usage*
  - *Refined candidate (e, γ, τ, jets)* ***identification***
  - ***Topological*** *selections to TOBs*
- ***CTP interface*** *- routes the results to the CTP and generates TTC signals (see next slide)*



Central Trigger

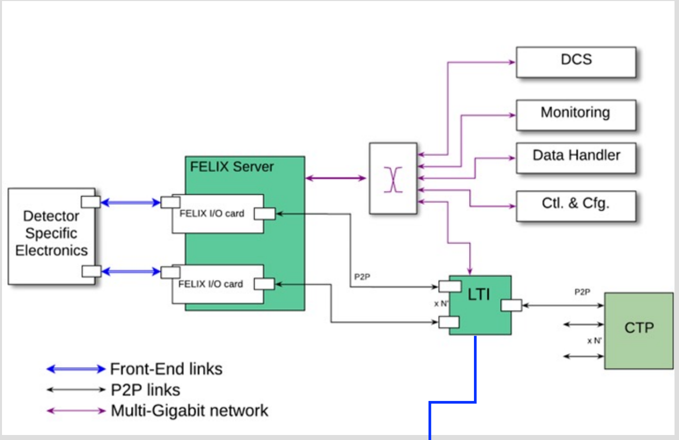
Composed of 4 main systems:

- *L0Calo*
- *L0Muon & MUCTPI*
- *Global trigger*
- ***Central Trigger** **P**rocessor (CTP)*



CTP

- **The last step** of the L0 processing chain
- Interface with the LHC for reception the **beam timing signals**
- Receive **inputs** from:
  - ***Global*** *trigger*
  - ***MUCTPI***
  - *Various* ***forward detectors***
- **Functionality**:
  - ***Align & combine*** *digital trigger inputs (1024 vs 512 now)*
  - *Makes final* ***L0Accept decision*** *(considering trigger menu configuration, prescale factors and dead-time)*
- **Transmits** to the ATLAS subdetectors **via** the **T**rigger, **T**iming and **C**ontrol system (**TTC**):
  - *The 40 MHz* ***beam synchronous clock***
  - ***The L0A*** *signal with fixed latency*

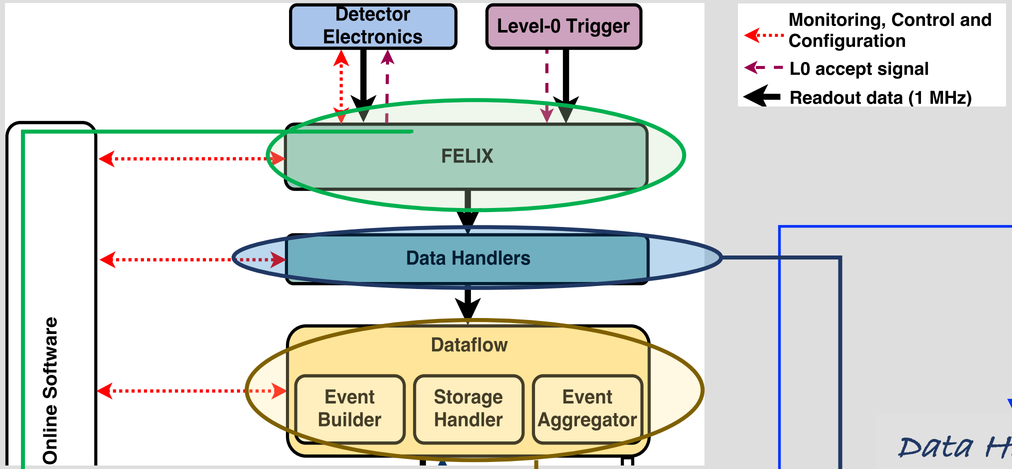


The Local Trigger Interface (LTI) provides an interface for the TTC signals between the CTP and subdetector front-end electronics via FELIX (see next slide)

DAQ: Readout & Dataflow

Composed of 3 main systems:

- *FELIX*
- *Data Handlers*
- *Dataflow*



Commodity PC servers

FELIX (FLX-182) prototype

Data Handlers

- **Receive** the data from the subdetectors over the network at 1 MHz
- Total bandwidth of 4.6 TB/s
- Performs **data formatting** before sending to the dataflow system
- Subdetector-**specific data preparation**

FELIX

- Front-End LInk eXchange (FELIX):
  - *provides common **interface** between the subdetectors and the DAQ system*
- **Composed** of:
  - ***PC** hosting custom **FPGA** I/O cards*
- **Functionality**:
  - ***Propagating trigger & command** signals (i.e L0A, TTC) to the subdetectors*
  - ***Transmits** the full detector data up to the DAQ system*

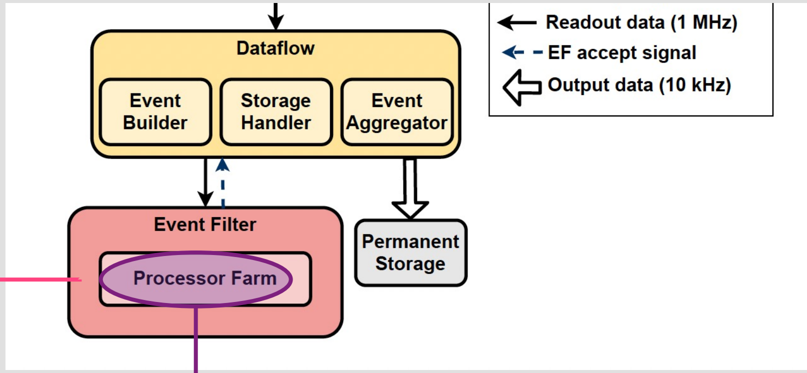
Dataflow

- **Buffers**, **transports**, **aggregates** & **compress** event data
- Data buffering before/while/after Event-Filter decision
- Provides **access** to the **event data**
- **transfers** data to permanent **storage**

Event Filter

Event Filter system:

- *Processor Farm*



Processor Farm

Event Filter (EF)

- Recent change in strategy: **moved from custom-hardware tracking to a full commodity solution**
- A **heterogeneous system** integrating multiple types of computational units
  - **Commodity CPU-server farm with accelerators** (FPGAs, GPUs) is being considered
  - **Final technology choice** (CPU/FPGA/GPU) will be made **in 2025** after a program of demonstrators
- **1 MHz data input** rate from the DAQ system
- **Runs event reconstruction algorithms** (~ offline reconstruction quality)
  - Integration with **A** **C**ommon **T**racking **S**oftware (**ACTS**)
- **Examples for potential reconstruction elements under study**:
  - EF tracking: track reconstruction using ITk seeds and extrapolation of hit patterns using Neural Network
  - EF Calo: topological clustering using accelerators and machine-learning algorithms
  - EF Muon: muon reconstruction using machine-learning based algorithms on NSW information
- **Final event selection** (according to the trigger menu) should be at maximum **10 kHz rate**

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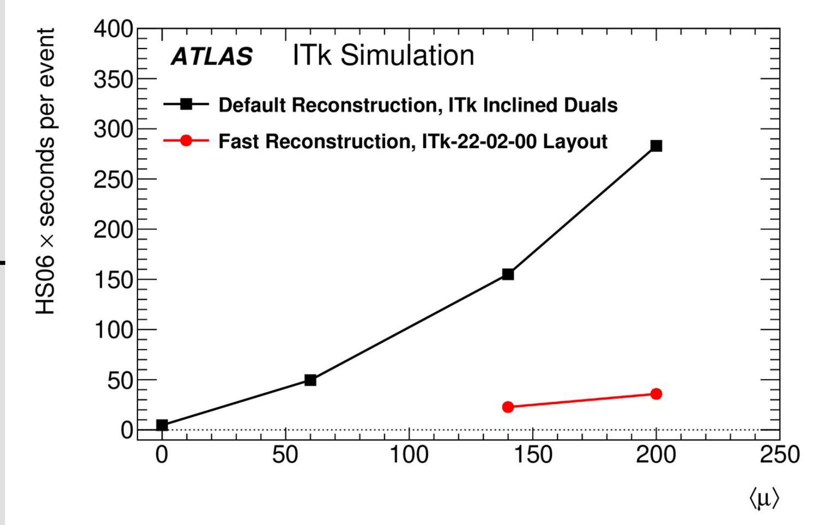
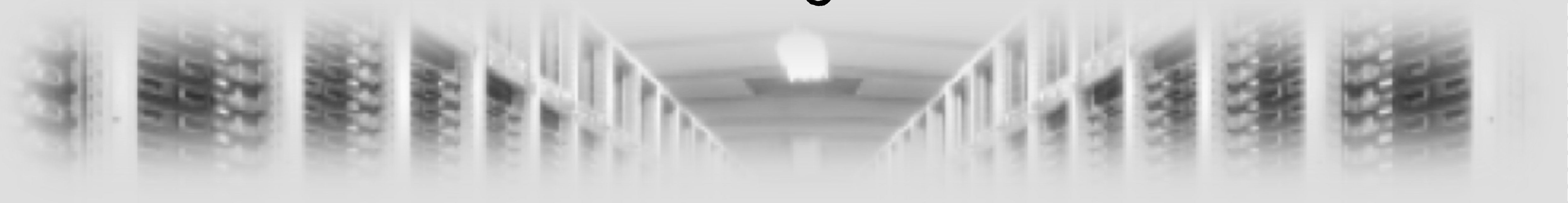


CPU-usage comparison for track reconstruction as a function of average pile-up, using: the tracking software available at the beginning of Phase-II planning (2017) vs upgraded software prototype (2022)

Summary

Summary:

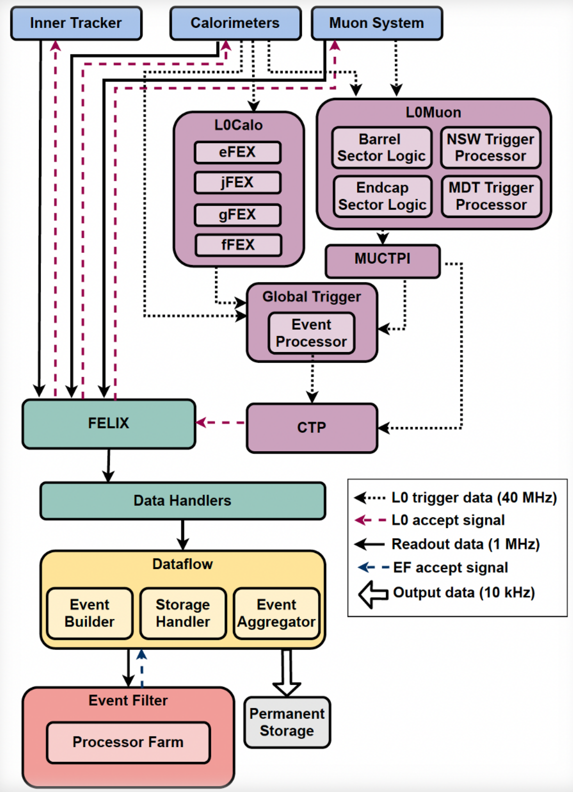


TDAQ is being extensively upgraded to enable the ATLAS HL-LHC physics program:

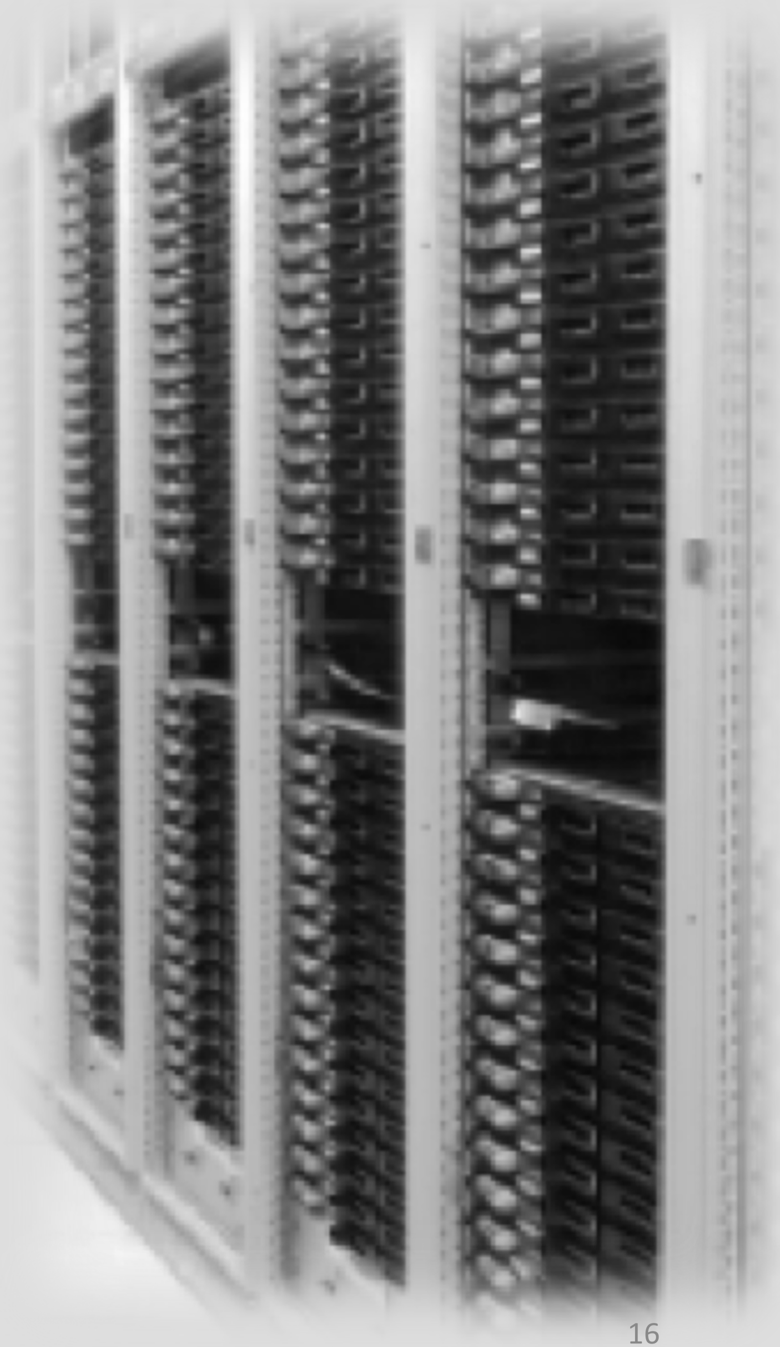
- Benefit from conclusions deduced from previous runs along with the current Phase-I upgrade experience
- Combine information with the L0Global trigger for refined selection and trigger rate reduction
- Implement sophisticated algorithms for better triggering & reconstruction
- Improve reconstruction and reducing event rates by:
  - *Increase detector coverage and high granularity data events (e.g. RPC, fFEX)*
  - *Including more subdetectors information at the trigger level (e.g. MDT, NSW)*
  - *Heterogeneous commodity system allowing usage of advanced technologies for high performance reconstruction (e.g. EF)*

Status & Plans:

- All requirements on TDAQ have already been evaluated and the developments are in advanced stages
- Prototypes hardware produced for ~all systems. More advanced versions on the way
- Firmware development well advanced
- Beginning integration tests between systems



Backup...



ATLAS in the HL-LHC

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Annotation	* Detector system	Upgrade scope	CDS Reference
New inner tracker	ITk Pixel Detector	Sensors, modules, mechanics, FE electronics	CERN-LHCC-2017-021
	ITk Strip Detector	Sensors, modules, mechanics, FE electronics	CERN-LHCC-2017-005
Extra pile-up mitigation	HGTD	Low gain avalanche detector technology	CERN-LHCC-2020-007
Higher radiation tolerance, providing full granularity data to the triggers	LAr Calorimeter	FE and BE electronics	CERN-LHCC-2017-018
	Tile Calorimeter	Mechanics, FE and BE electronics	CERN-LHCC-2017-019
Improved trigger coverage	Muon Spectrometer	FE electronics Inner Barrel MDT chambers Inner Barrel RPC stations	CERN-LHCC-2017-017
Discussed in this presentation	TDAQ	On-detector readout and trigger electronics	CERN-LHCC-2017-020 CERN-LHCC-2022-004

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Single electron trigger rates as a function of leading electron p_T

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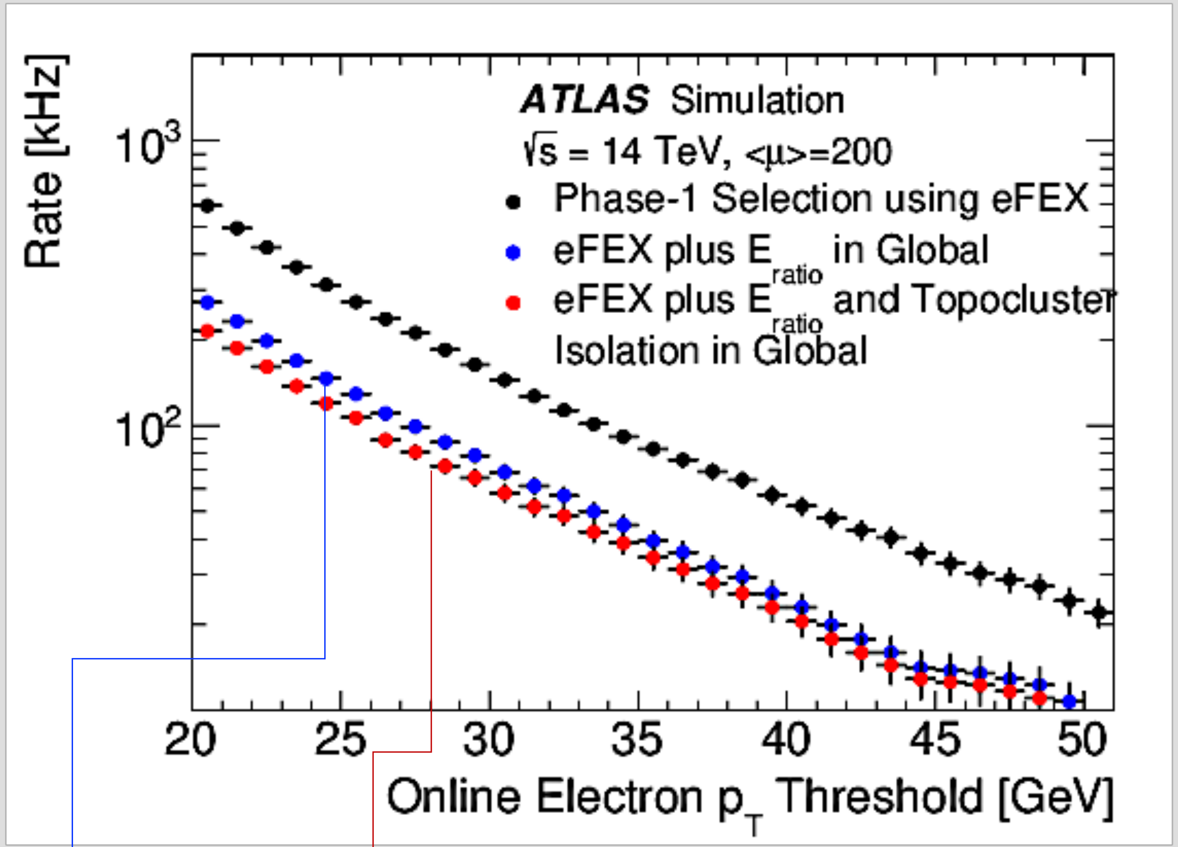

- E_{ratio} - usage of the 1st layer of the LAr, that is not available in eFEX but will be available in Global

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

Including E_{ratio} reduces the rate by 50% at 20 GeV

Including E_{ratio} + topocluster isolation reduces the rate by ~70% at 20 GeV