ATLAS Trigger and Data Acquisition Upgrades for the HL-LHC

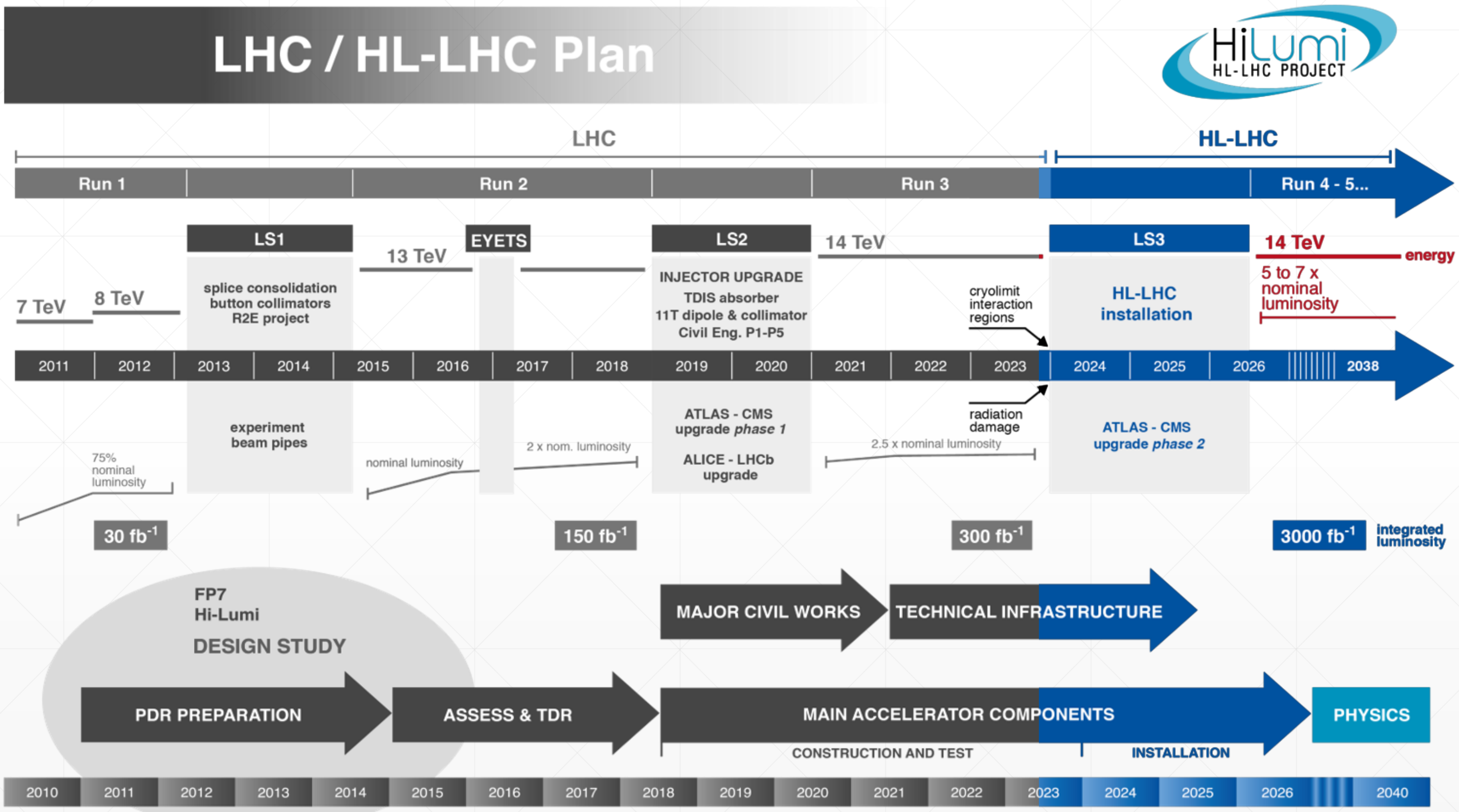
On behalf of the ATLAS Collaboration

Alessandra Camplani – University of Copenhagen
August 8^{th}, 2019

Overview

- LHC upgrade plan
- Upgrade physics motivation
- ATLAS Phase-II TDAQ upgrade
- TDAQ architecture and performance
  - L0 trigger system
  - Data Acquisition (DAQ) system
  - Event Filter (EF) system
- Trigger menu plans
- Conclusion

LHC schedule and upgrade plans



Challenges and physics motivation

High Luminosity consequences

- High pile-up up to 200 events per bunch crossing (<μ>~40 today)
- High granularity detectors that need to be read out
  - new subdetector: Inner Tracker (ITk)
  - front-end/back-end electronics updates
- Larger event size ~5.2 MB (~2 MB today)

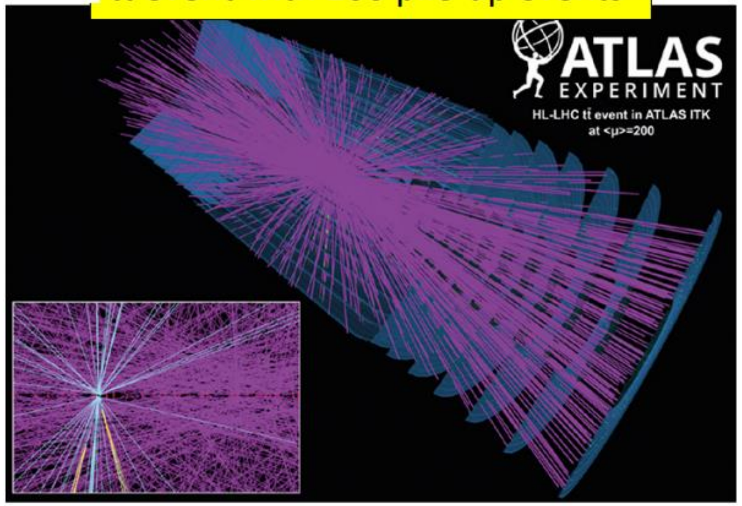
The **challenging and broad HL-LHC program** requires the pT of the various trigger objects as low as possible, e.g.:

- Electroweak scale requires low pT leptons
- Searches for new physics with low Δm
- HH measurements requires low pT jets /b-jets

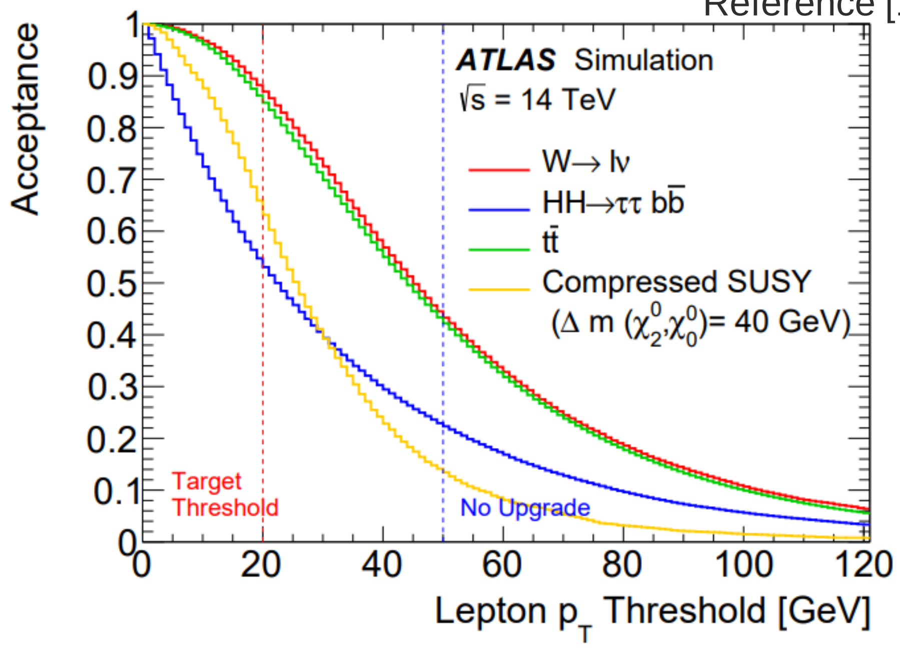
Operating points for ATLAS TDAQ:

- L1 latency increase to ~ 10 μs (~2.5 μs today)
- Readout rate increase to 1-4 MHz (100 kHz today)
- Rate to permanent storage ~ 10 kHz (~1 kHz today)

$t\bar{t}$ event with 200 pile-up events



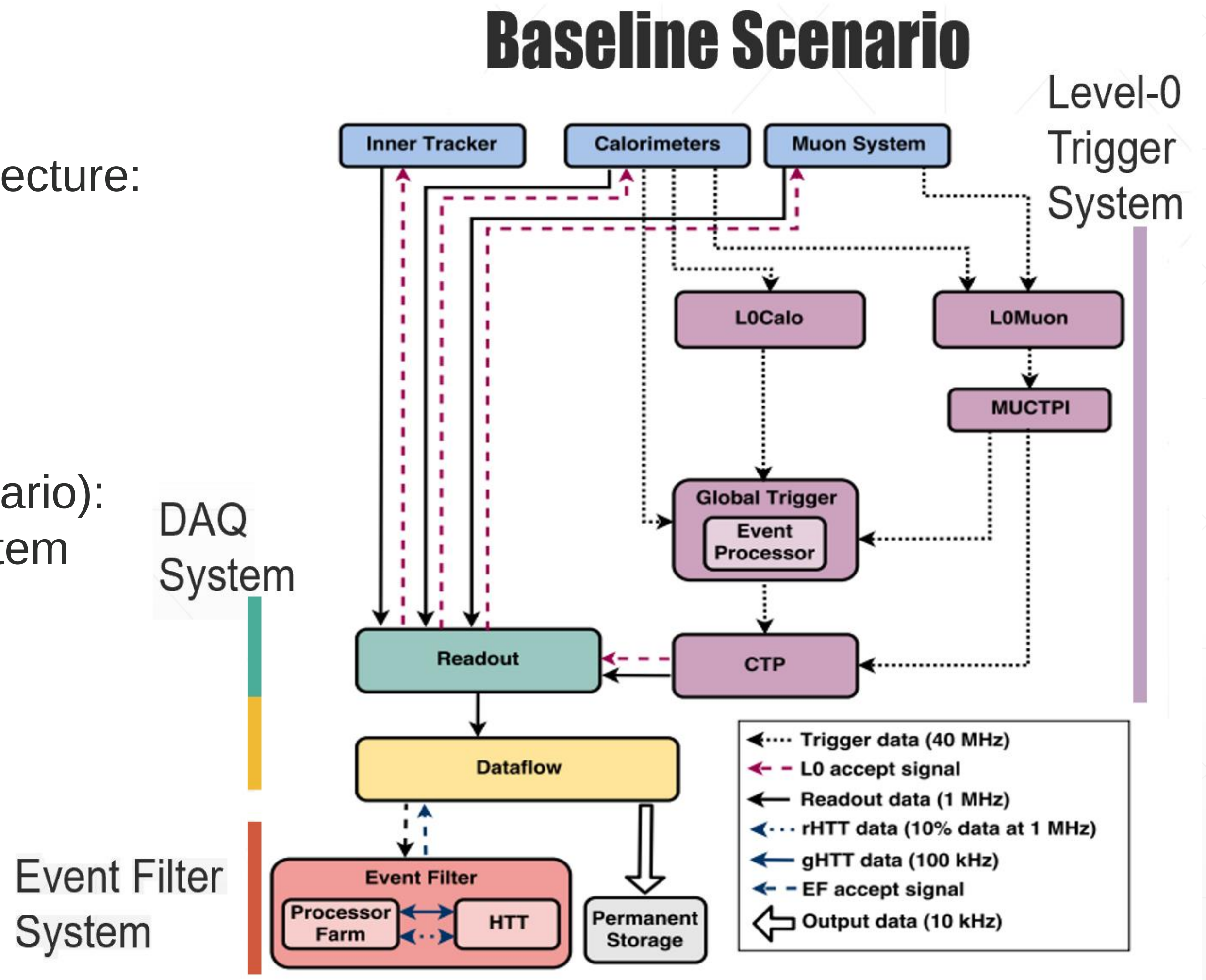
Reference [1]



Phase-II TDAQ upgrade

Three main systems of the TDAQ Phase-II upgrade architecture:
- Level-0 Trigger
- DAQ (Readout and Dataflow subsystems)
- Event Filter

Single-hardware-level trigger architecture (baseline scenario):
- ➢ capable of evolving into a two-level hardware trigger system (evolved scenario)



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Single-hardware-level trigger architecture (baseline scenario):
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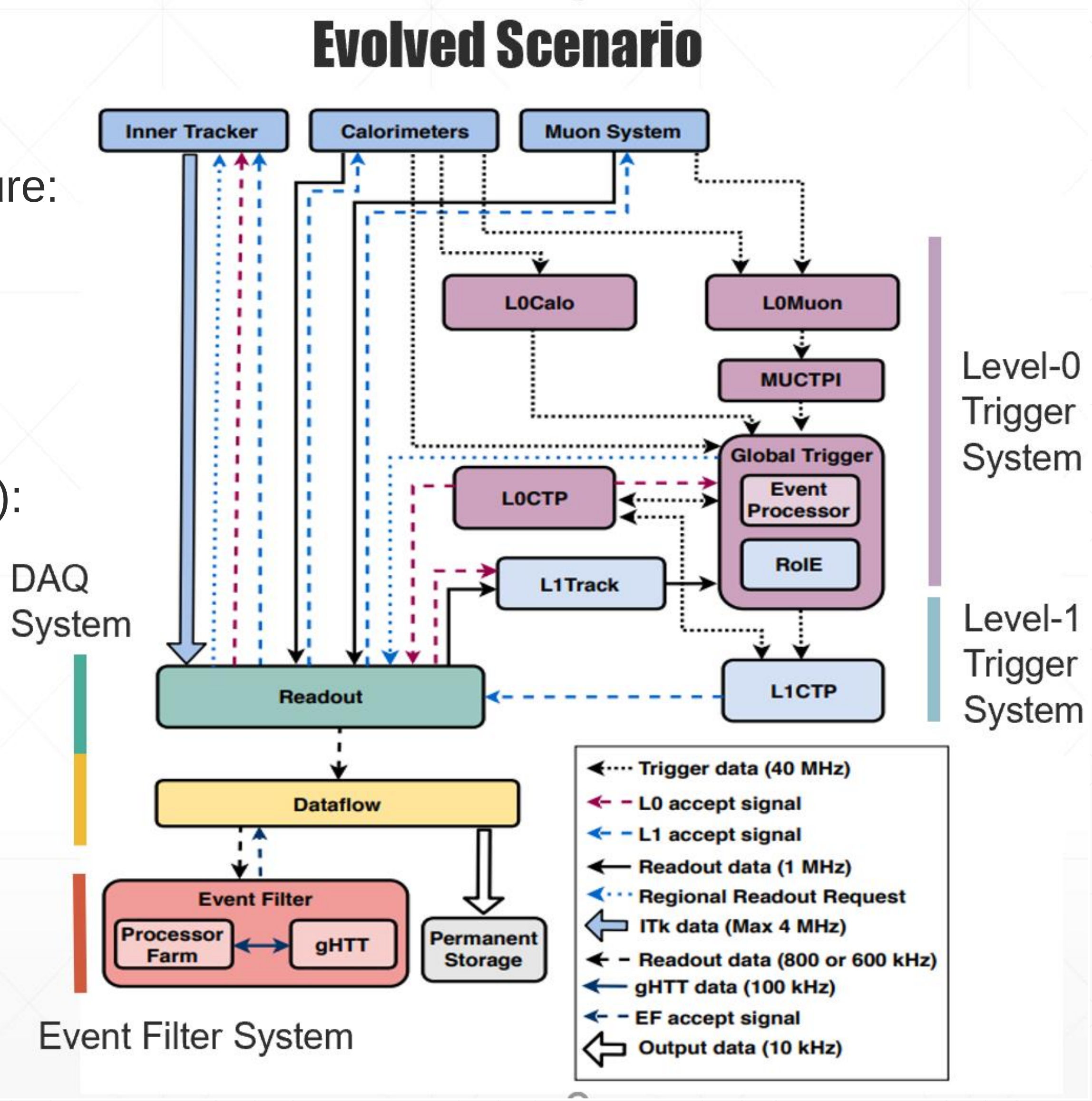
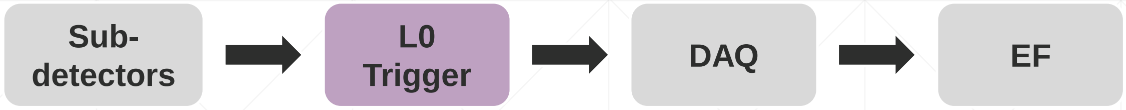
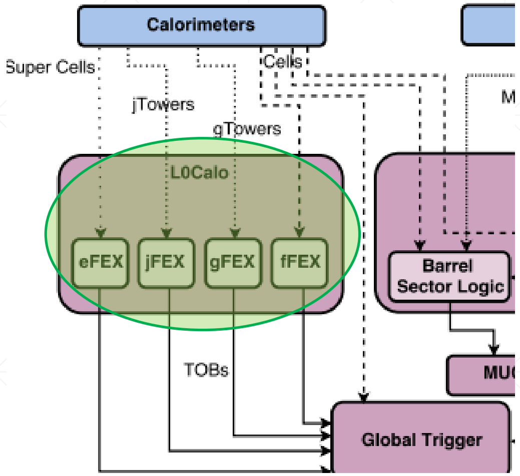
The two main **criteria for** an evolution to the **split-level hardware trigger** configuration:
- the hadronic trigger rates
- the inner pixel detector layer occupancies

If either or both are higher than expected, the baseline TDAQ architecture would restrict the trigger menu at the ultimate HL-LHC running conditions.





Level-0 Calo



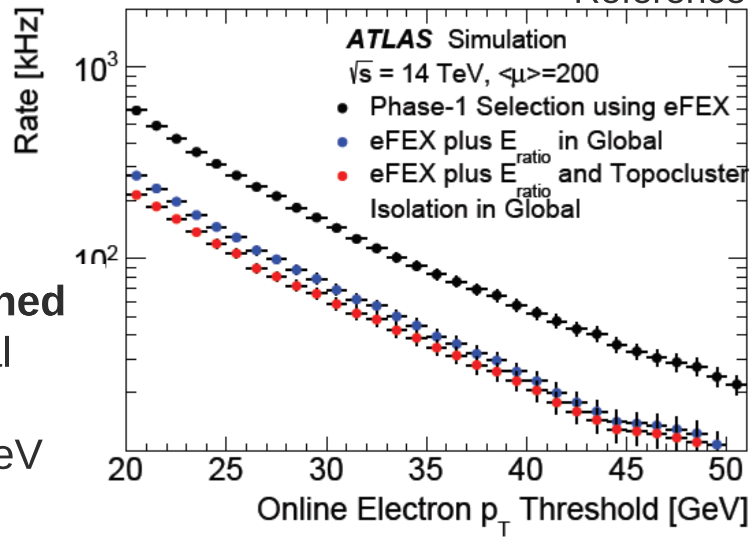
Calorimeters data with coarse granularity are sent to the Feature Extractors (FEXs).

- **eFEX**(1): electron and photon object identification
- **jFEX**(1): single jets identification
- **gFEX**(1): large-R (or multi-jet) triggers identification and global quantities calculation
- **fFEX**(2): forward electromagnetic (forward jet) trigger objects reconstruction at high η

The **Global Trigger refines the identification algorithm** by taking advantage of the transmission of fine-granularity cells

- trigger thresholds can be chosen reasonably low to cover the whole physics program

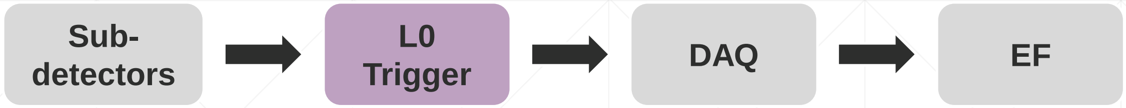
Reference [1]



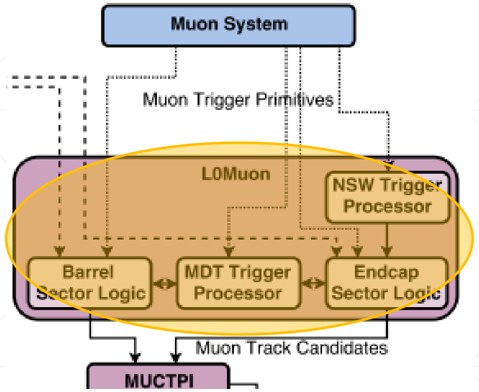
Subsystem	Trigger Object	Approximate Granularity	Coverage $\|\eta\|$
eFEX	$e/\gamma, \tau$	Super Cells (10 in 0.1×0.1)	< 2.5
jFEX	τ, jet, E_T^{miss}	0.1×0.1	< 2.5
jFEX	τ, jet, E_T^{miss}	0.2×0.2	$2.5 - 3.2$
jFEX	τ, jet, E_T^{miss}	0.4×0.4	$3.2 - 4.9$
gFEX	Large-R jet, E_T^{miss}	0.2×0.2	< 4.9
fFEX	e/γ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

The **performance of the combined system** (Level-0 Calo and Global Trigger) allows to set the single electron threshold at about 20 GeV

(1) Phase-I Upgrade hardware, firmware upgrade foreseen for Phase-II
(2) New Phase-II system



Level-0 Muon



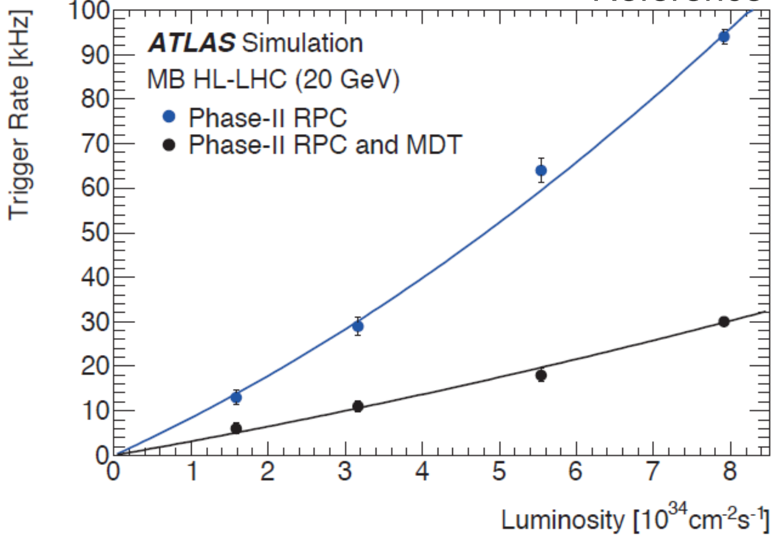
Based on the data of the upgraded muon spectrometer and the Tile calorimeter

- Improvements in trigger performance will be achieved by increasing
  - detector acceptance
  - momentum resolution (by including new MDT(3) chamber data)

Different detector technologies provide different angular coverage.

Subsystem	Granularity	Coverage $\|\eta\|$
NSW processor (1)	Full NSW detector	$1.3 - 2.4$
MDT processor (2)	Full MDT detector	< 2.4
Barrel Sector Logic (1)	Full RPC and Tile, MDT	< 1.05
Endcap Sector Logic (1)	Full TGC, Tile, RPC, NSW, MDT	$1.05 - 2.4$

Reference [1]



Rate of Level-0 single-muon trigger based on RPC only and RPC plus MDT for the barrel region $|\eta| < 1.05$.

Selectivity of the current Level-1 muon trigger is limited by the moderate spatial resolution of RPC (3) and TGC (3).

- MDT chambers will be included in L0 Muon and will provide:
  - better spatial resolution
  - pT resolution close to that of the offline reconstruction

(1) Phase-I hardware will be upgraded for Phase-II
(2) New Phase-II system
(3) RPC = Resistive Plate Chambers, TGC = Thin Gap Chambers, NSW = New Small Well, MDT = Monitored Drift Tube

Sub-detectors → L0 Trigger → DAQ → EF

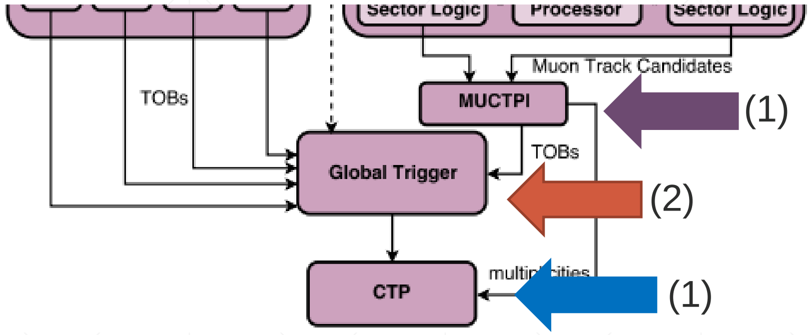
Level-0 Trigger to DAQ (in a nutshell)

MUCTPI (Muon CTP Interface):
- **Aggregates** and **merges** the trigger information from barrel and endcap muon systems
- **Sends it to the Global Trigger and the CTP**

Global Trigger:
- **Complements the L0Calo trigger** objects with additional high-granularity energy data
- **Applies topological selections** (such as angular requirements) to trigger objects

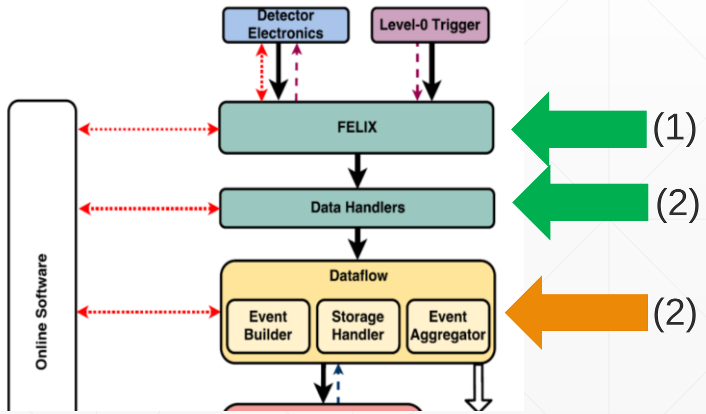
CTP (Central Trigger Processor):

Makes the final L0A decision:
- aligning and combining all the digital trigger inputs
- introducing preventing deadtime and applying prescales as required

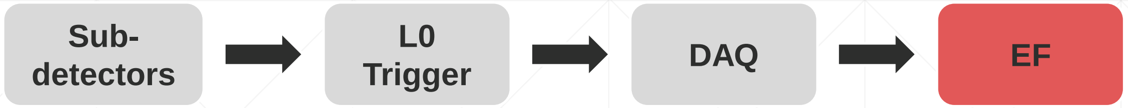


Readout:
- Receives **data from** the ATLAS detector **front-end** electronics
  - at the L0-trigger rate (1 MHz)
- **Performs data formatting**
- **Sends** them **to the Dataflow** system

Dataflow:
- **Buffers** data before, during and after the Event Filter decision
- Provides partial and full event access as needed and **transfers data to permanent storage**
- Managed by commodity software



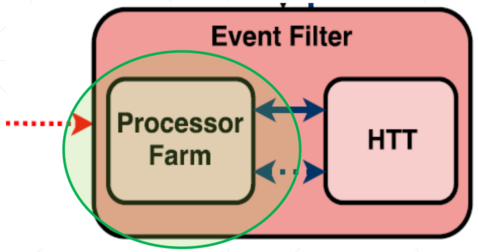
(1) Phase-I hardware/software/firmware will be upgraded for Phase-II
(2) New Phase-II system



Event Filter Farm

High pile-up conditions: higher occupancy of tracking detectors and reduced energy resolution in calorimeters. **This negatively affects** e.g.:

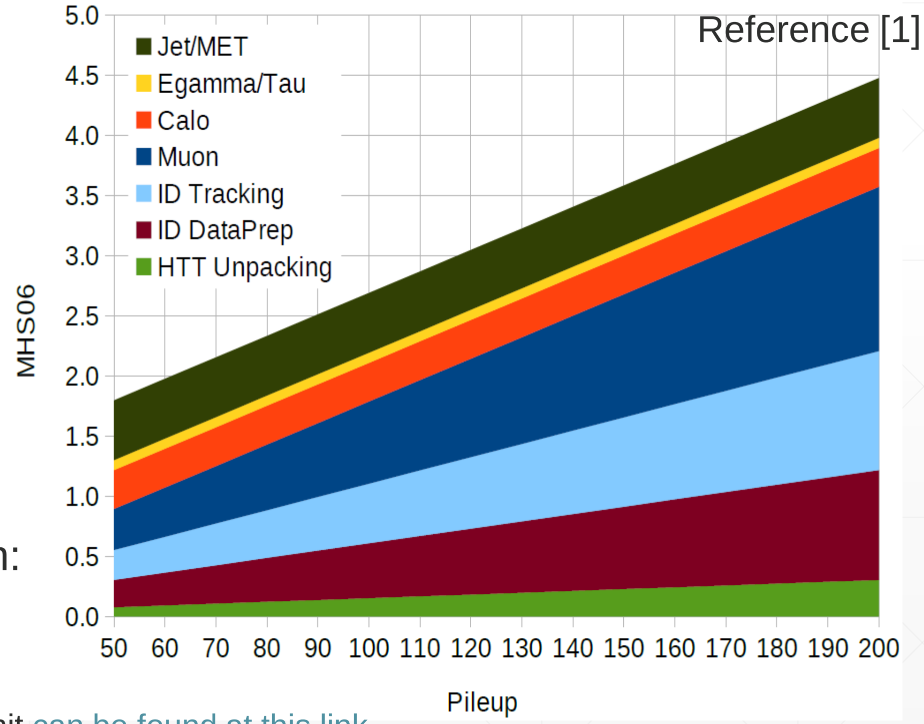
- the separation of electrons from background jets
- calculation of global event quantities like Et(miss)
- jet energy resolution



To maintain threshold similar to Run1:

- algorithms close to the offline reconstruction methods
- tracking to identify a primary vertex and associate reconstructed objects

CPU extrapolation versus event pileup



Processor Farm:

The current baseline assumption is that **CPUs will provide the required compute density** on the time-scale of Phase-II:

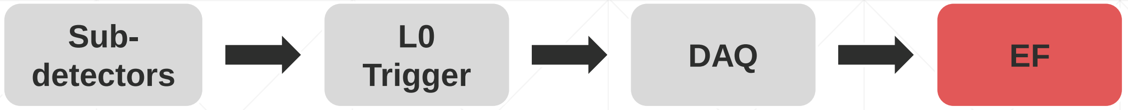
Current estimate of farm size:

- 4.5 MHS06(1) (+Hardware Track Trigger) to handle a L0 rate of 1 MHz

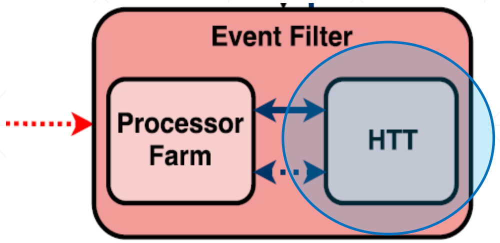
Under investigation commodity processors and accelerators (GPGPU & FPGA) with:

- optimized reconstruction software
- specialized fast algorithms
- machine learning techniques

(1) More about HEP-SPEC06 (HS06) unit can be found at this link



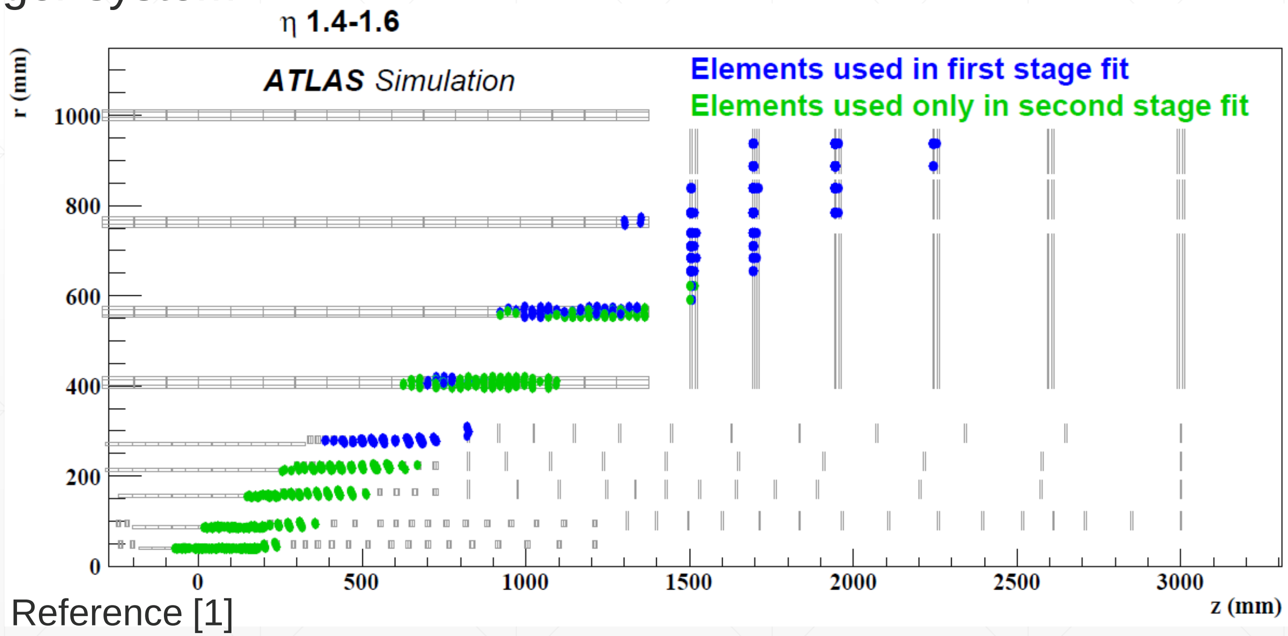
Event Filter HTT



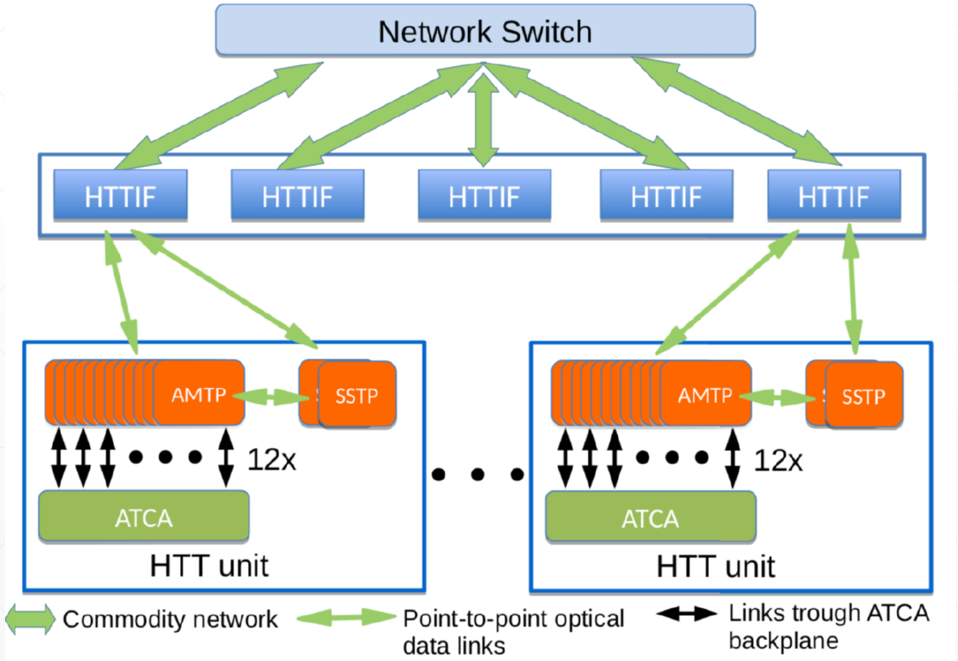
HTT (Hardware Track Trigger) : new massively parallel system, based on FPGA and custom Associative Memories (AM ASICs).

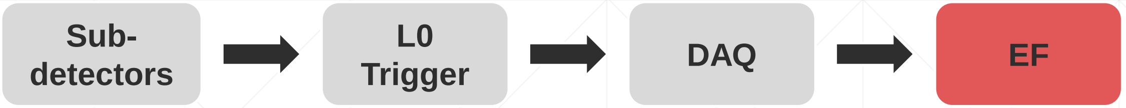
- Use hit information from ITk
- Provide fast hardware-based track reconstruction

Advantages: experience with the technology (from Fast Tracker project, Reference [2]), low power consumption, short latency, cost effectiveness and independence from the market, capability to evolve to two-level hardware trigger system.



Reference [1]





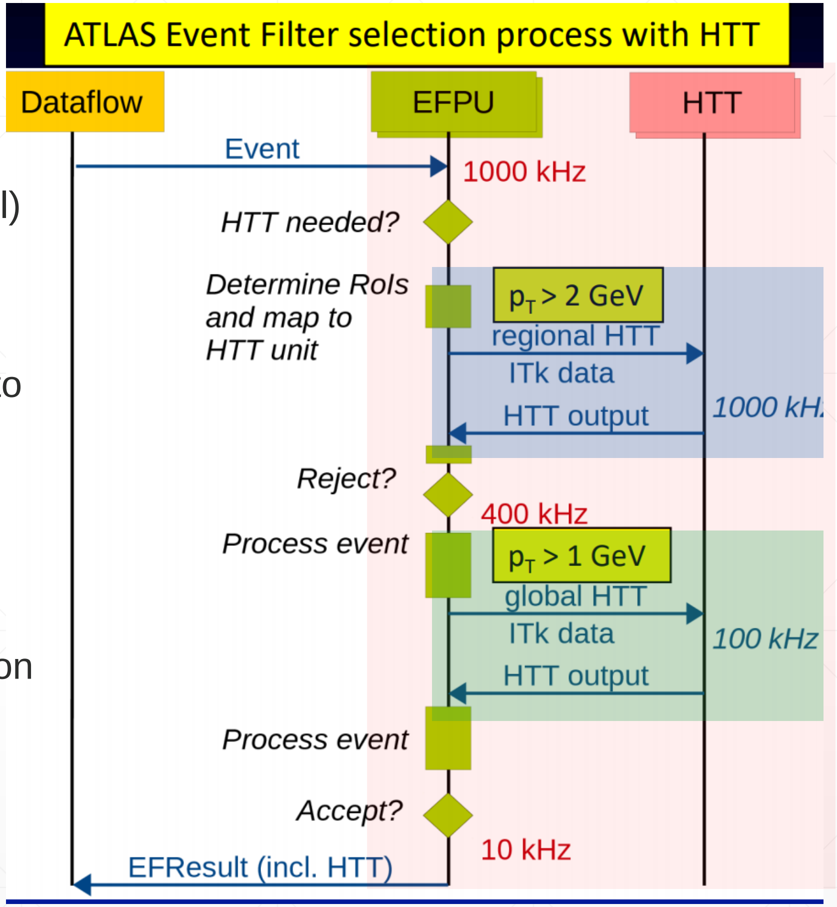
Two-step tracking in HTT

Regional HTT (rHTT)

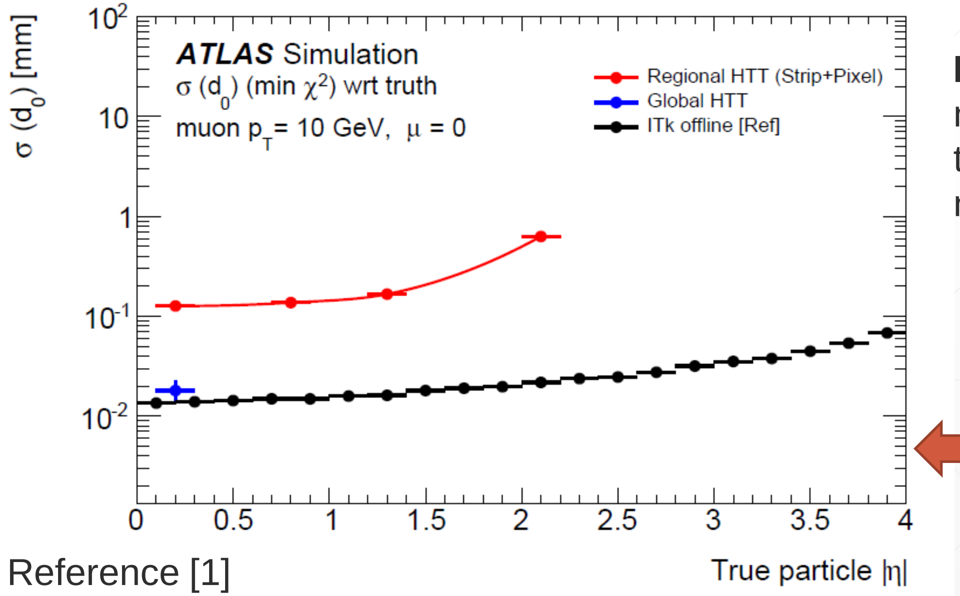
- **Event** from DAQ (Dataflow) to EF Processing Units (EFPU)
- **Partial tracker event** data (8 outermost layers) from EFPU to HTT (pT > 2 GeV)
- EFPU uses **rHTT tracks** in combination with Global Trigger objects to reduce the rate to **400 kHz**

Global HTT (gHTT)

- If required, **full hit data** (strip and pixel) from EFPU to HTT
- **Full tracking** (pT > 1 GeV) performed
- **EFPU uses gHTT tracks**, in combination with offline-like analysis, to the reduce the rate to **10 kHz**



In the Evolved Scenario, rHTT has moved to the Level-1 hardware-based trigger, with the associated event rejection now taking place before the EF.



Reference [1]

d0 resolution for 10 GeV muons as a function of η for the HTT first and second stage processing and offline tracking resolution.

Trigger menu

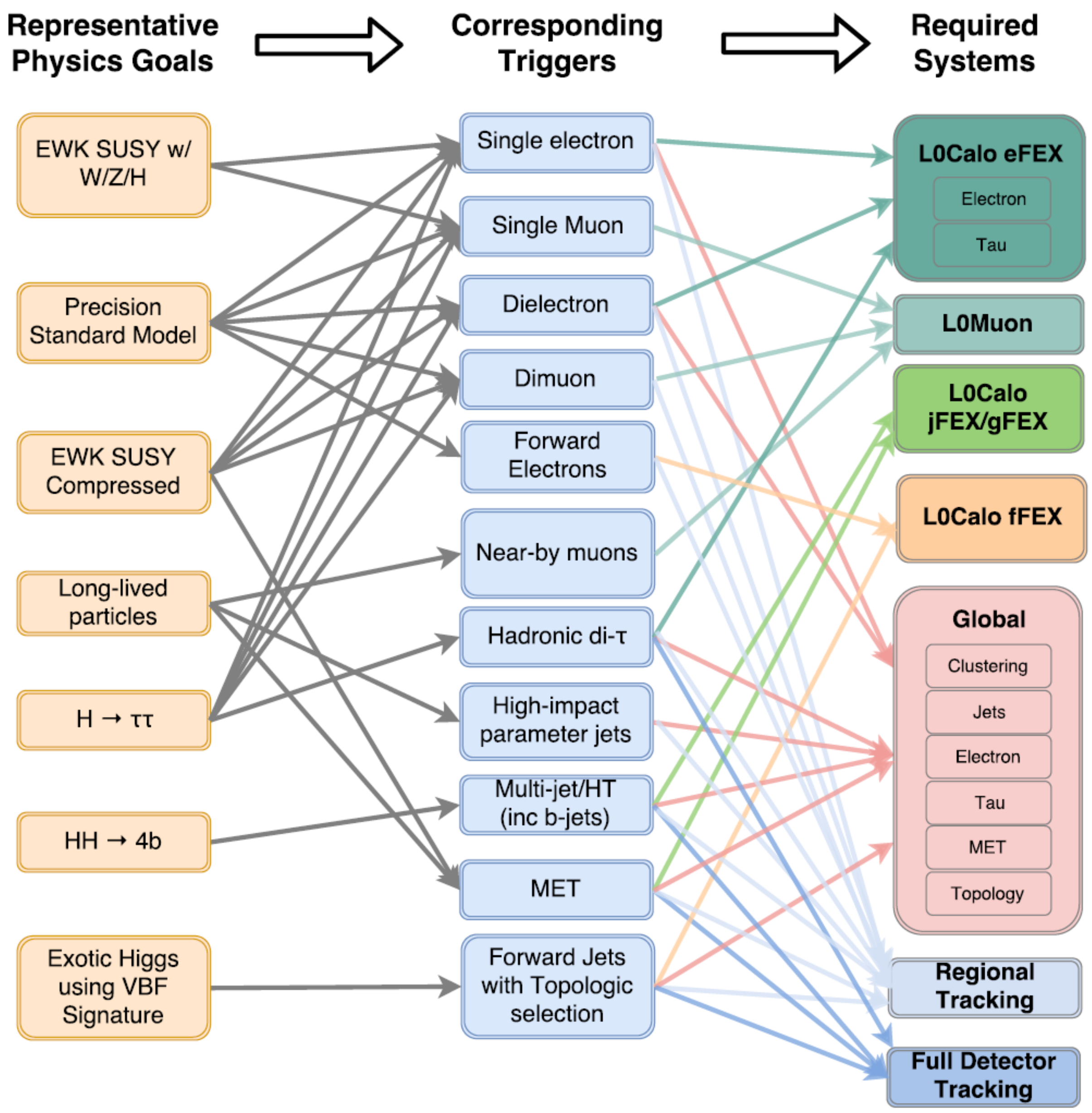
Schematic flow from the representative set of physics goals to the hardware systems needed to achieve them. The middle column lists the **corresponding triggers required.**

E.g.:

1. Global Trigger enables a low-pT electron trigger at Level-0 and then regional-tracking reduces the high rate early in the Event Filter processing.

2. Global Trigger enables low thresholds for multi-jet and Et(miss) triggers at Level-0, then regional tracking and full-detector tracking reduce the background acceptance rate while preserving the physics acceptance.

Definite plans for the Run 4 trigger menu will come towards the end of Run 3.



Conclusion

Plans for the ATLAS Trigger and Data Acquisition systems for the High-Luminosity Upgrades are detailed in a Technical Design Report.

TDAQ system will enable the broad physics program planned for the HL-LHC with a baseline scenario

- accommodate a possible evolution driven by high hadronic trigger rates and inner pixel detector layer occupancies.

Both L0 Trigger and DAQ systems rely on the knowledge gained during Run 1 and 2, as well as on Phase I experience

- some components need to be upgraded/added to sustain increased event size and trigger rates

HTT tracking information used to reduce event rates

- good flexibility and modularity to run as both regional and global
- capable to evolve to the two-level hardware trigger system, as part of L1 trigger

More details about Phase-II in the poster session

- ➢ The ATLAS Hardware Track Trigger design towards first prototypes - Ana Luísa Carvalho
- ➢ ATLAS Level-0 Endcap Muon Trigger for HL-LHC - Yuya Mino

Reference [1]: ATLAS Collaboration, “*Technical Design Report for the Phase-II Upgrade of the ATLAS TDAQ System*”, https://cds.cern.ch/record/2285584
Reference [2]: ATLAS Collaboration, “*Fast TracKer (FTK) Technical Design Report*”, https://cds.cern.ch/record/1552953

Thanks for your attention!

Evolved scenario

Table 14.7: *Comparison of specifications for the rHTT in the single-level trigger scheme and L1Track in the evolved design.*

Trigger	Latency requirement	Level-0 rate [MHz]	Trigger threshold [GeV]
rHTT	No	1	2
L1Track	6.0 μs	2–4	4

Criteria for evolution:

- Hadronic trigger rates higher than expected
  - projections for hadronic rates are extremely sensitive to the contribution from stochastic jets (accidental overlaps of uncorrelated particles)
  - a reasonably small underestimate of the stochastic jet contribution can result in a large increase in the four-jet trigger rate.
- Inner Itk pixel occupancy higher than expected
  - The maximum data rate of 5.12 Gb/s per front end chip
    - If the innermost pixel occupancy (number of hits per chip) is dramatically higher than predicted by simulation at the start of Run 4, the event size would increase and the data rate could exceed that value
  - Furthermore, the development of the 5.12 Gb/s serial output of the pixel detector aggregator chip carries a moderate technical risk

Table 14.13: *Summary of hooks put into the baseline design in order to accommodate a potential evolution and additional hardware and firmware needed for the evolved system.*

System Component	Hooks for Evolved System	Additional Hardware/Firmware Needed for Evolved System
Level-0 Calo Level-0 Muon	sufficient FPGA resources	minor firmware changes
Global Trigger	extra transceivers	additional MUX modules to receive information from L1Track; extra GCM modules configured as RoIEs; extra GCM module for L1CTP interface; additional GEP firmware
Central Trigger	extra optical connectivity	add L1CTP plus additional patch panels and fibres
Readout	none	additional FELIX I/O Cards, servers, and Data Handlers; new FELIX/Data Handler firmware and software; low-latency links to L1Track;
Dataflow	none	larger bandwidth requirements
Event Filter	none	significant increase in computing power
HTT	rHTT hardware and firmware must meet L1Track latency requirement	separation of regional and global functionality; additional AMTPs; new firmware

Reference [1]

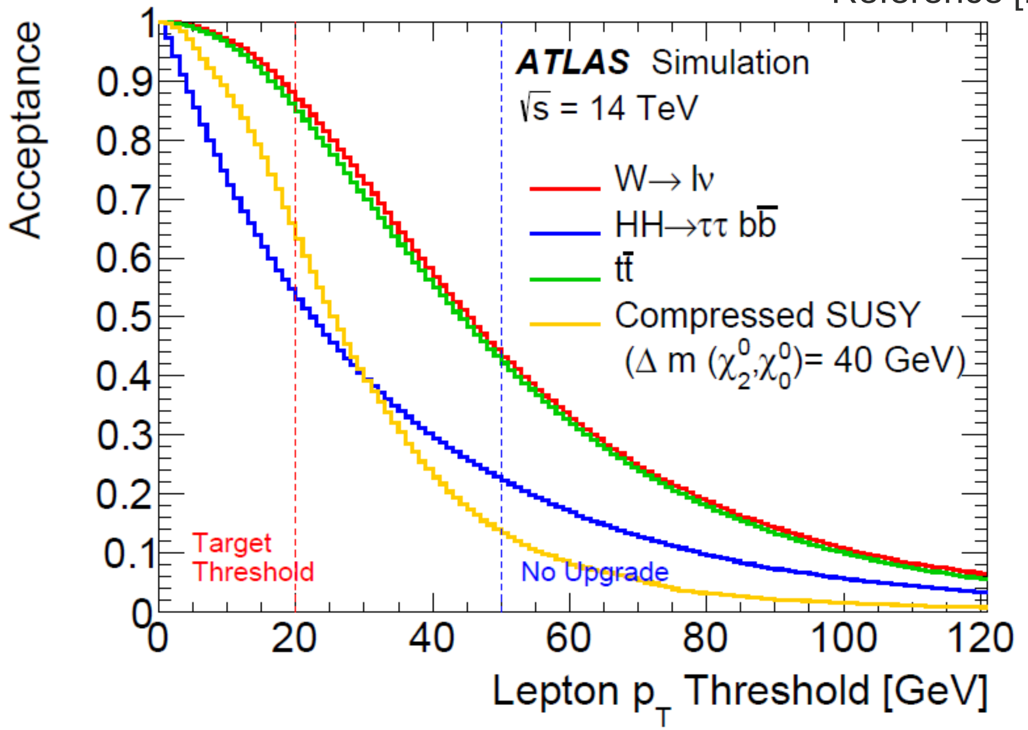
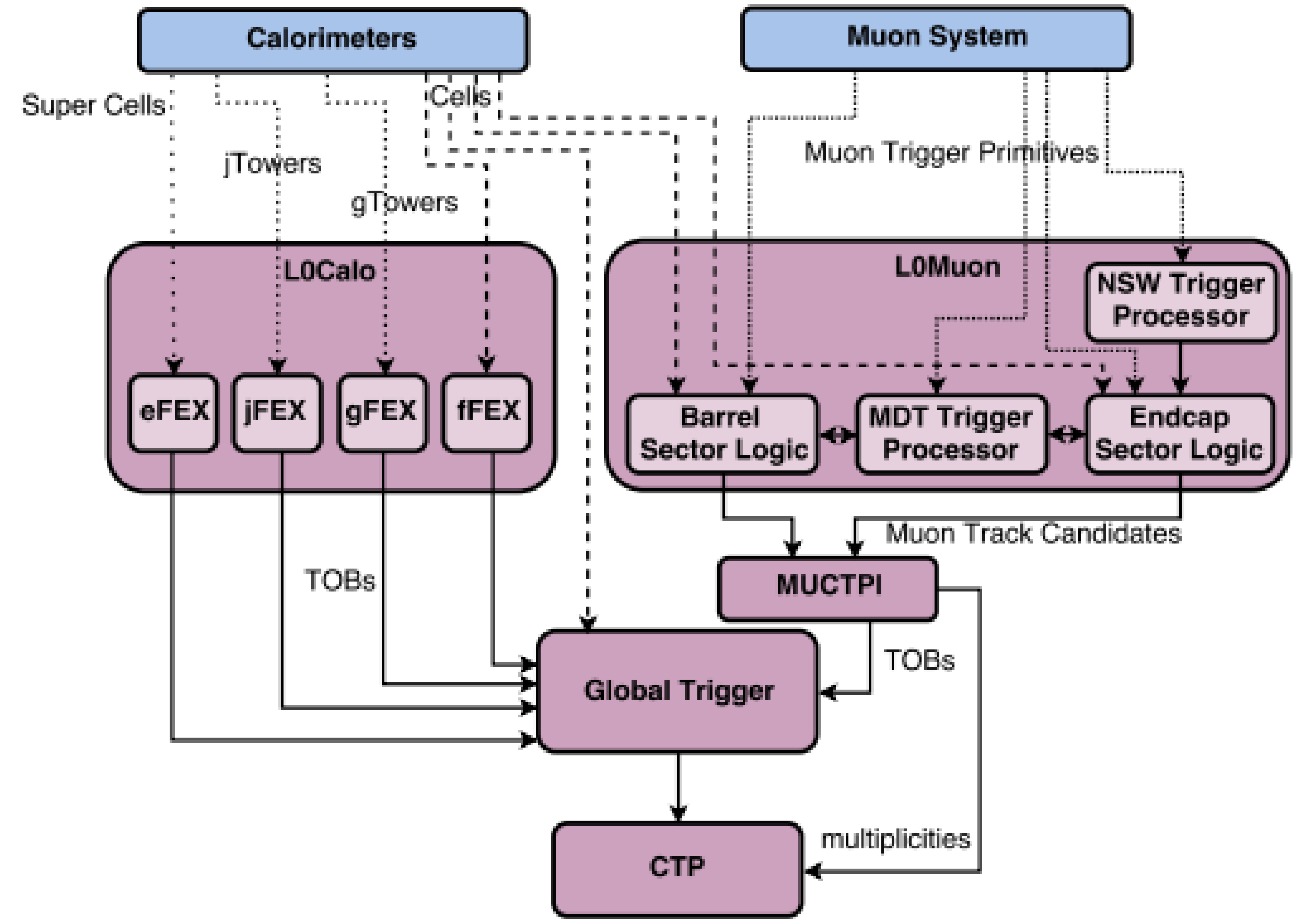
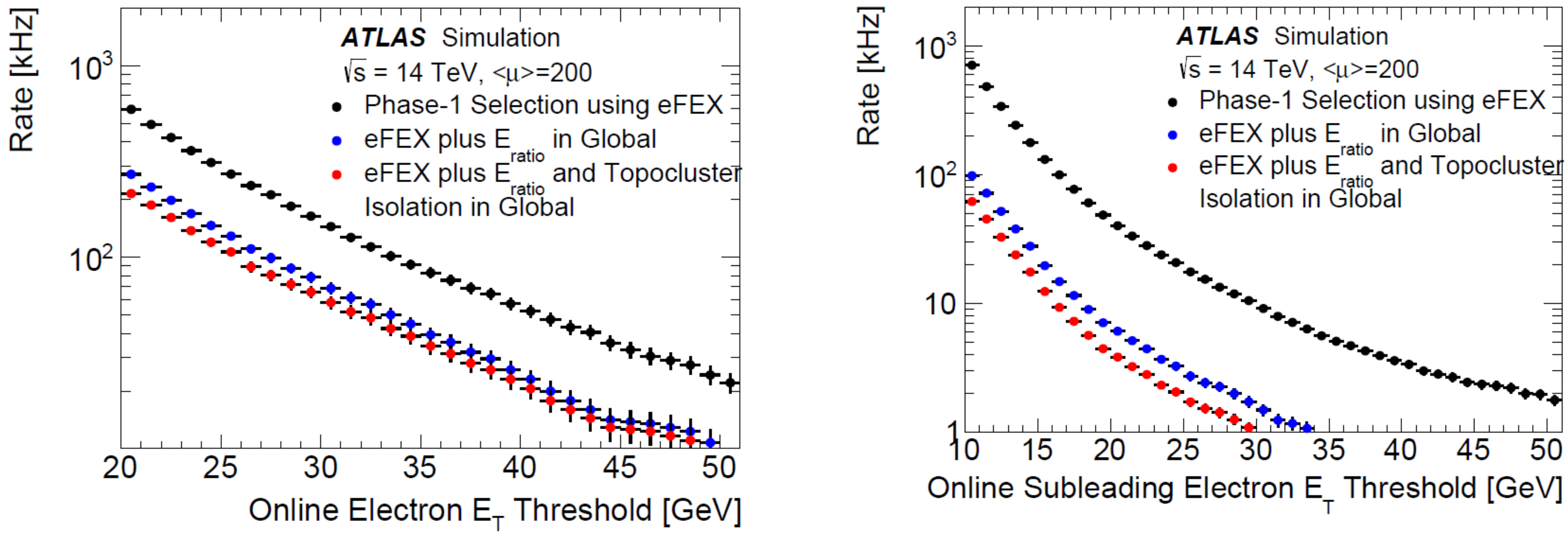


Figure 2.2: *The integrated acceptance as a function of the single lepton p_T threshold for four representative channels: $W \to \ell\nu$, $H \to \tau\tau b\bar{b}$, $t\bar{t}$, and a compressed spectrum SUSY model relevant for "Well-tempered Neutralino" motivated models. The Phase-II TDAQ upgrade would enable lowering the single lepton Level-0 threshold to* 20 GeV *from* 50 GeV*, the projected threshold without the upgrade.*


Calorimeters
Muon System
Super Cells
Cells
jTowers
gTowers
Muon Trigger Primitives
L0Calo
L0Muon
NSW Trigger Processor
eFEX
jFEX
gFEX
fFEX
Barrel Sector Logic
MDT Trigger Processor
Endcap Sector Logic
Muon Track Candidates
TOBs
MUCTPI
TOBs
Global Trigger
multiplicities
CTP

Reference [1]



(a) *Single-electron trigger rates as a function of leading lepton p_T*

(b) *Di-electron trigger rates as a function of sub-leading lepton p_T*

Figure 6.3: *The Level-0 rate as a function of leading p_T for the single-electron/photon triggers and sub-leading p_T for dielectron/diphoton triggers. Three levels of selection are shown solely from the eFEX, eFEX plus a requirement on E_{ratio}, and after a topocluster-based isolation requirement.*

Reference [1]

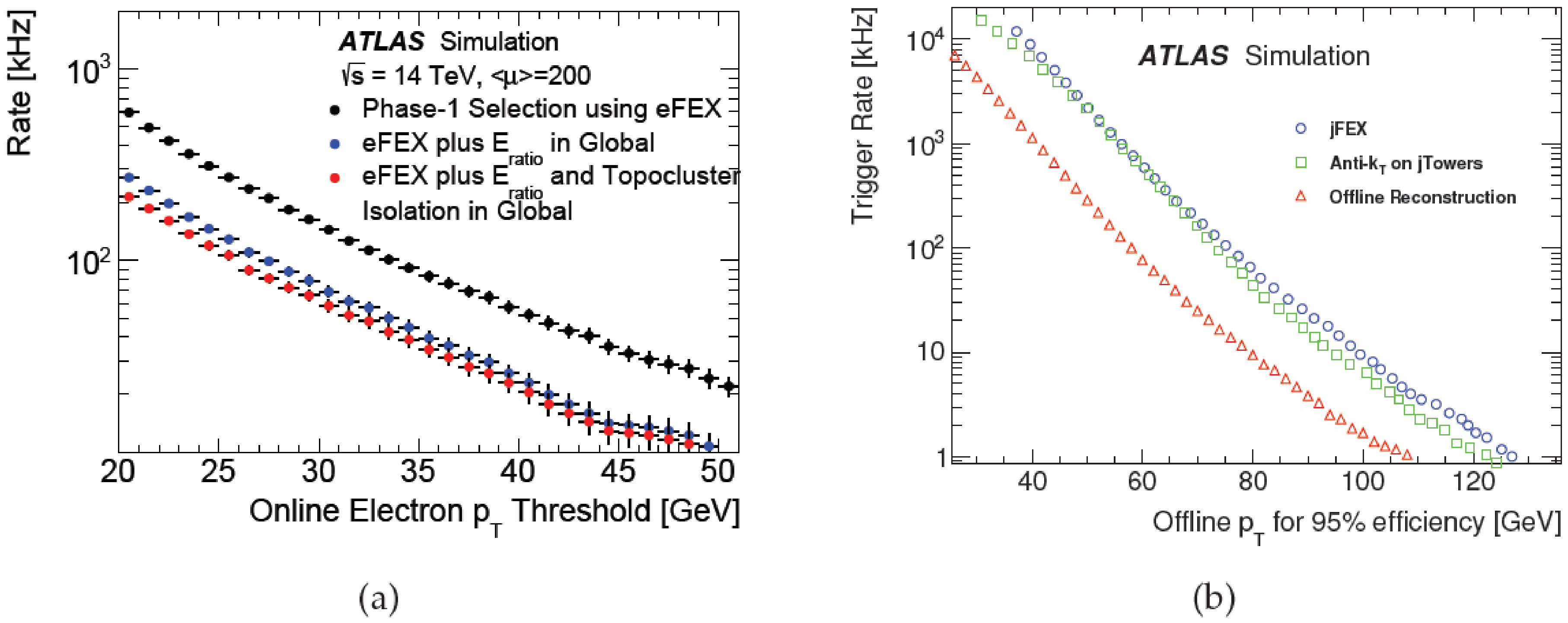


Figure 7.1: *a) Level-0 trigger rates for electrons. The different curves are for the successive application of veto conditions. b) The forward ($|\eta| > 3.2$) single-jet trigger rate vs. offline p_T thresholds for jets reconstructed in the jFEX. The efficiency is evaluated using $HH \to bbbb$ signal events, and the trigger rate is evaluated based on minimum bias background events at $\langle\mu\rangle \simeq 200$. The jFEX algorithm, the offline anti-k_t algorithm (run over $\eta \times \phi = 0.1 \times 0.1$ towers), and the full offline reconstruction are compared.*

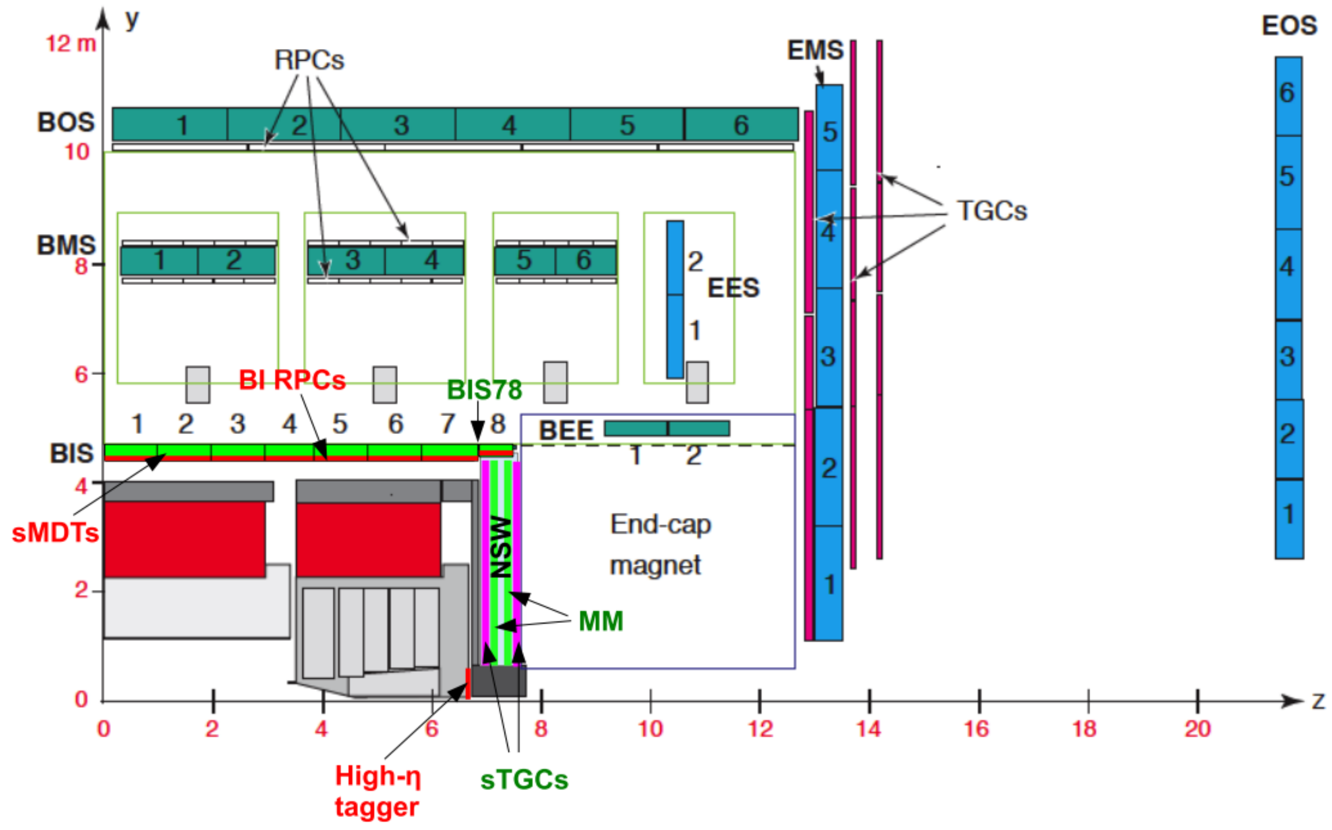
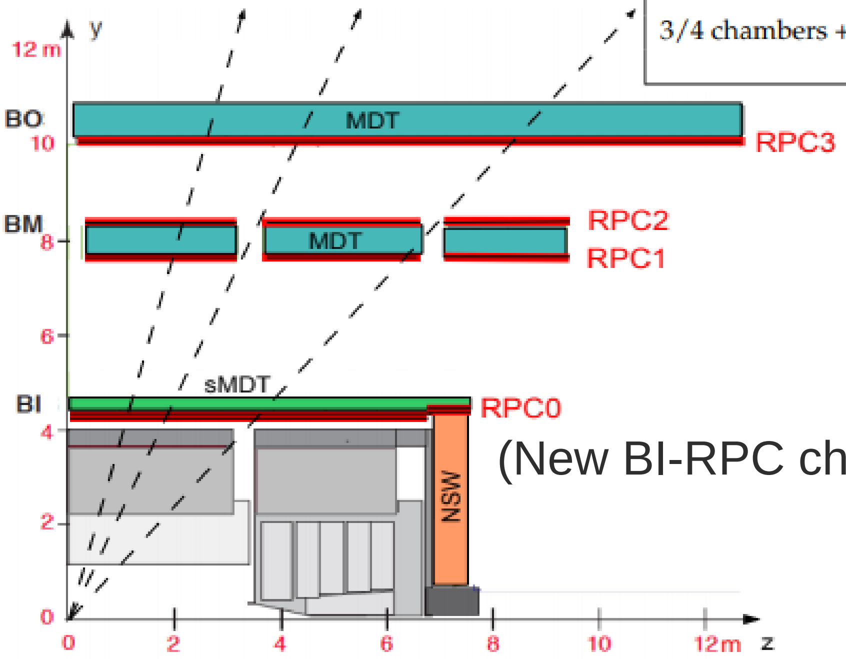


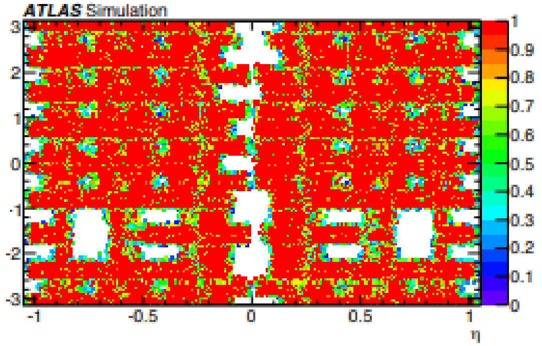
Figure 8.1: *Cross-sectional view of the Phase-II ATLAS muon spectrometer layout, showing a so-called small sector, one of the azimuthal sectors that contain the barrel toroid coils. The drawing shows the new detectors to be added in the Phase-II upgrade (red text: BI RPC, sMDT, high-η tagger), those to be installed during Long Shutdown 2 (green text: Micromegas and sTGC in the NSW and BIS78 RPC and sMDT), and those that will remain unchanged from the Run 1 layout (black text). In the so-called large sectors, which are the sectors in-between the barrel toroid coils, the TGCs and MDT chambers in the endcap inner station covers the η-φ range of the BIS78.*

Requirement	RPC0	RPC1	RPC2	RPC3
3/3 chambers	–	3 out of 4		1 out of 2
3/4 chambers	–	3 out of 4		1 out of 2
	2 out of 3	3 out of 6		
3/4 chambers + BI-BO	–	3 out of 4		1 out of 2
	2 out of 3	3 out of 6		
	2 out of 3	–	–	1 out of 2

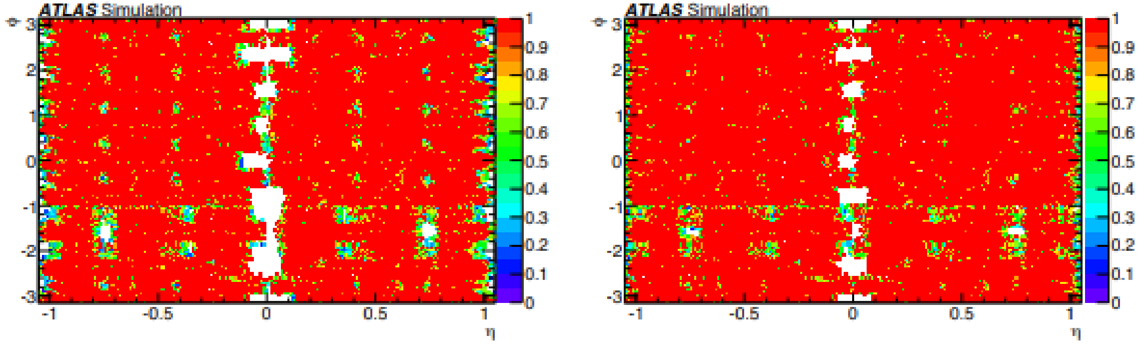


(New BI-RPC chambers)

Figure 8.5: *Sketch of a transverse section of the barrel region. The four groups of RPC chambers (red) are shown as well as the MDT chambers (green and cyan) on the BI, BM, and BO stations. The three dashed lines represent muon trajectories traversing four, two, and three RPC chambers. The drawing represents one of the sectors that contain a barrel toroid coil and its support structures which cause the holes in the chamber coverage of the BM station.*



(a)



(b)

(c)

Figure 8.7: *Geometrical acceptance of the Level-0 barrel muon trigger with respect to reconstructed muons with $p_T = 25$ GeV in the η-ϕ plane. The plots are obtained by assuming 100% hit efficiency and no pile-up. Figures (a), (b), and (c) show the acceptance for the different trigger coincidence logic "3/3 chambers", "3/4 chambers", and "3/4 chambers + BI-BO", respectively. The white areas correspond to zero acceptance.*

Reference [1]

Reference [1]

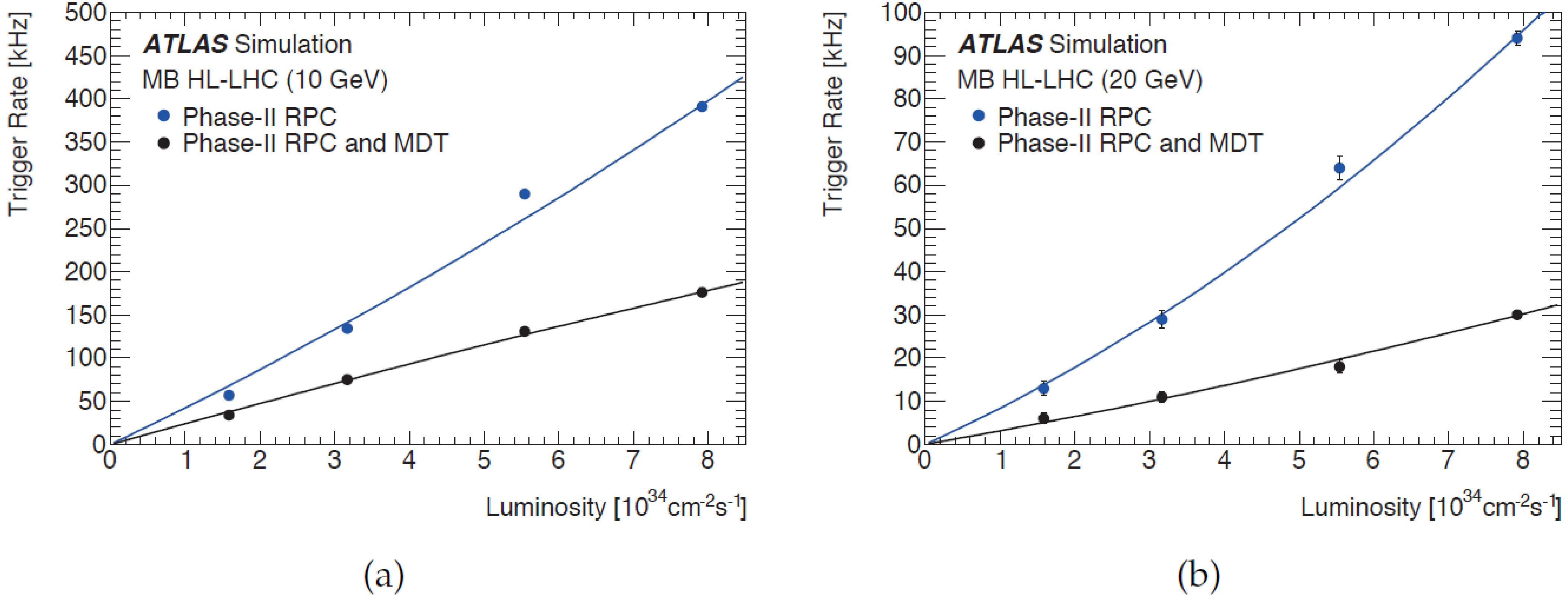


Figure 8.28: *The estimated rate of the Level-0 single-muon trigger based on RPC only and RPC plus MDT for the barrel region* $|\eta| < 1.05$. *The dots with error bars show the values estimated from MC samples with the* $\langle\mu\rangle$ *values corresponding to various luminosity scenarios. The curves show the result of the fit by a second-order polynomial.*

Global Trigger

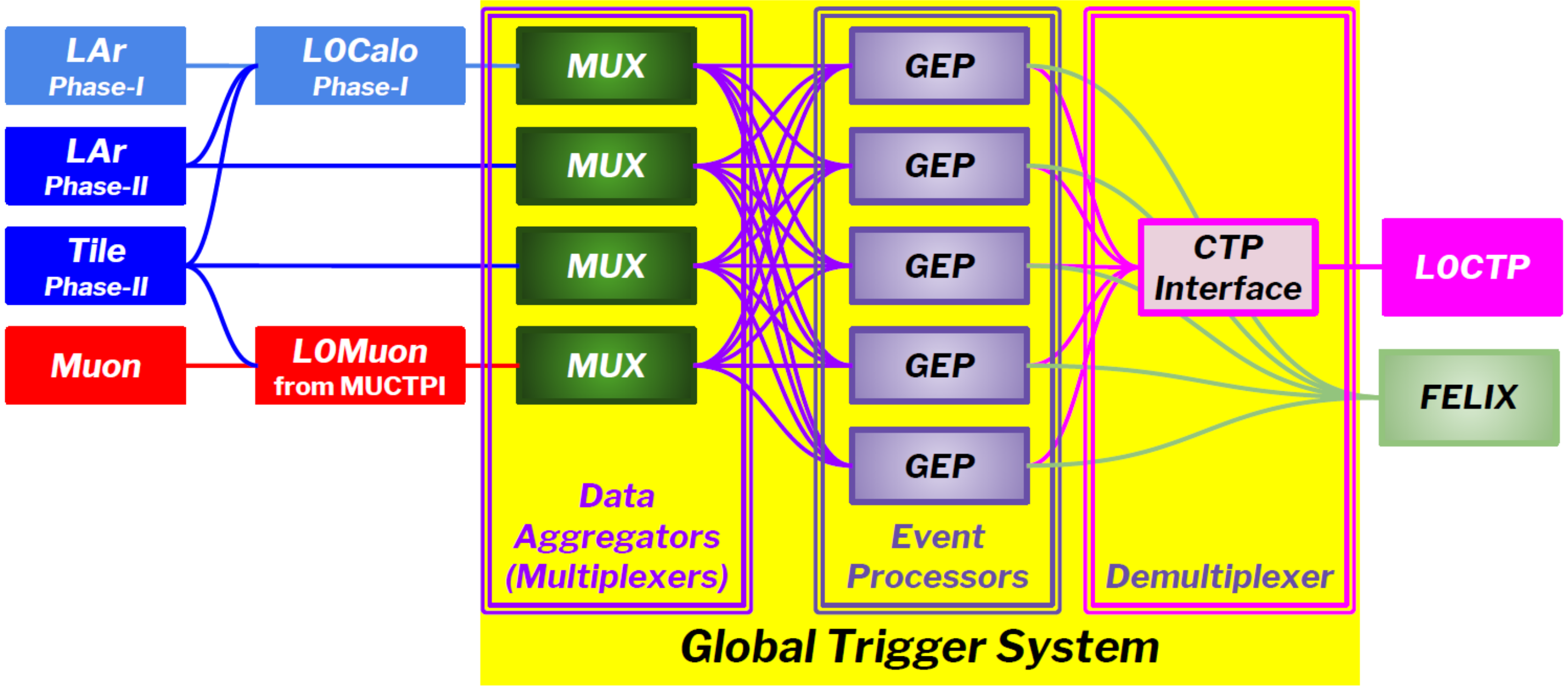
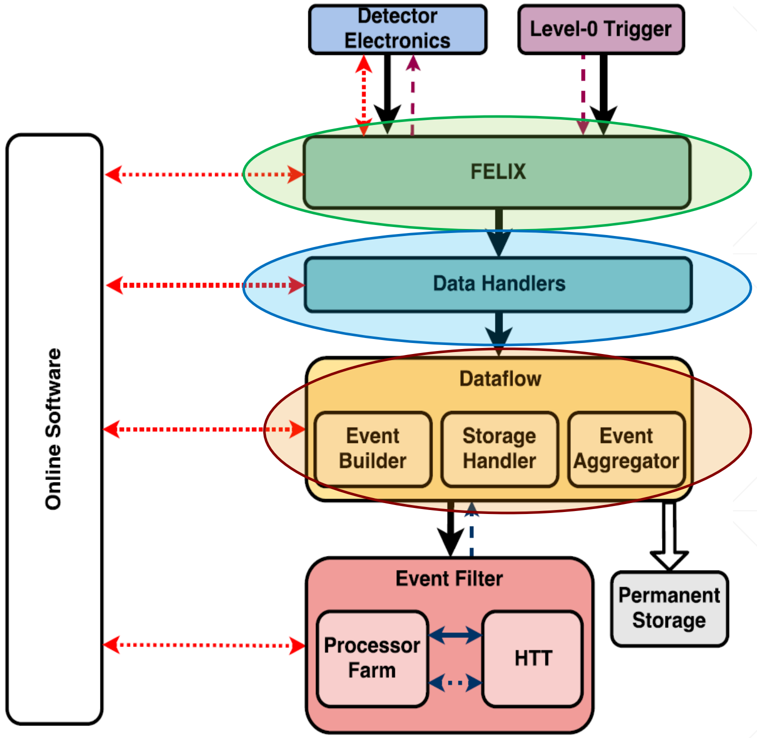


Figure 9.3: *The functional design of the Global Trigger system, illustrating the detector inputs, multiplexing MUX layer, multiplexed event-processing GEP layer, demultiplexing CTP Interface, and connections to other systems.*

DAQ details



Readout:

- receives data from the ATLAS detector front-end electronics
  - at the L0-trigger rate (1 MHz)
- performs basics processing
- sends them to the Dataflow system

FELIX (Front-End LInk eXchange):

- Custom cards PCIe based
- The new interface to detector-specific electronics including limited detector-specific firmware

Data Handlers:

Servers running a software application that :

- receives event fragments from FELIX
- performs detector-specific formatting and monitoring tasks:

Dataflow:

- Buffers data before, during and after the Event Filter decision
- Provides partial and full event access as needed and transfers data to permanent storage
- Managed by commodity software

Storage Handler

- buffering event data before and during Event Filter processing

Event Builder

- interface of the dataflow to Data Handlers and Event Filter

Event Aggregator

- receives the selected events from the Event Filter and groups/compress them before sending them to Tier-0

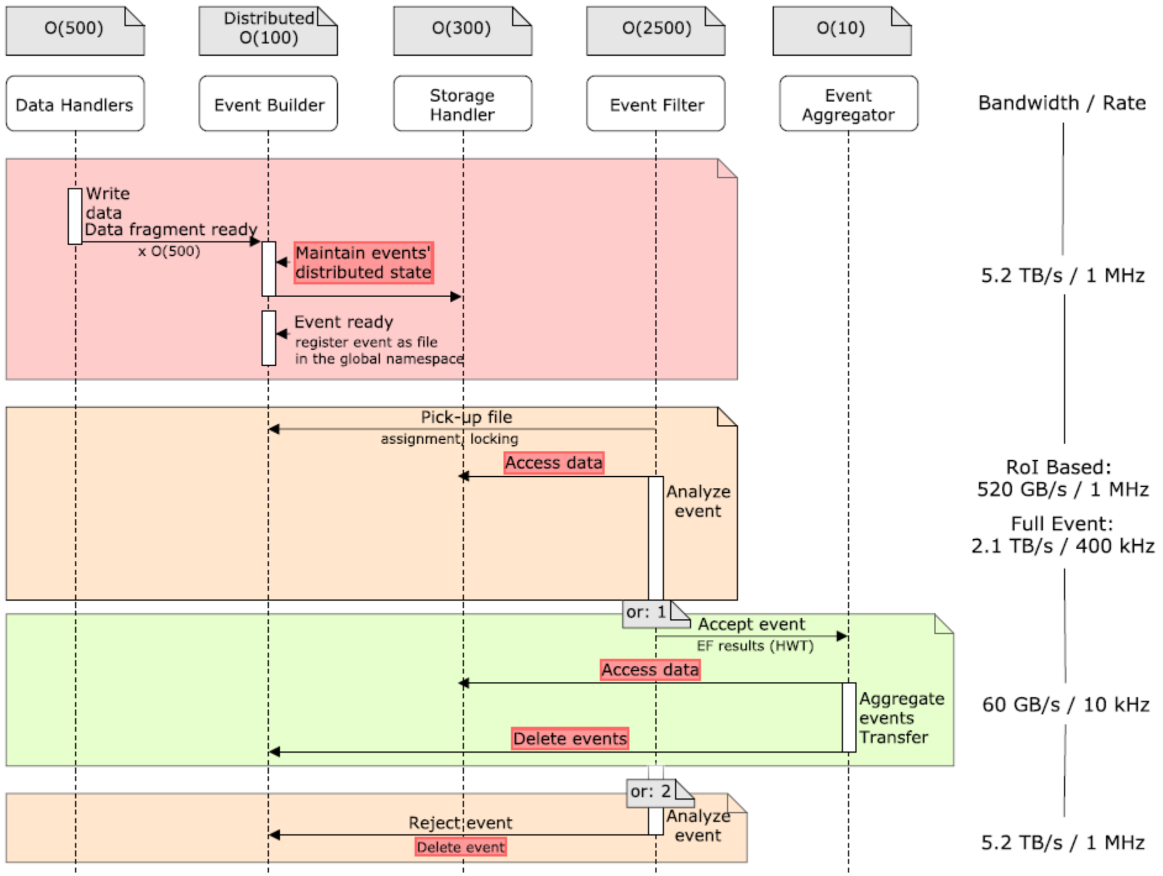


Figure 11.6: *Logical communications between different components of the Dataflow system. The red boxes show the communications involving inter-slice traffic, the dashed Vertical lines indicate the logical component responsible for each action. The arrows represent all communication between components, including the initial message (indicated by arrow direction) as well as any response and follow up high bandwidth traffic if present. The Event Builder serves as an interface for both the Data Handler to write data to the storage volume and the Event Filter Processing Units reading data from the storage volume.*

Reference [1]

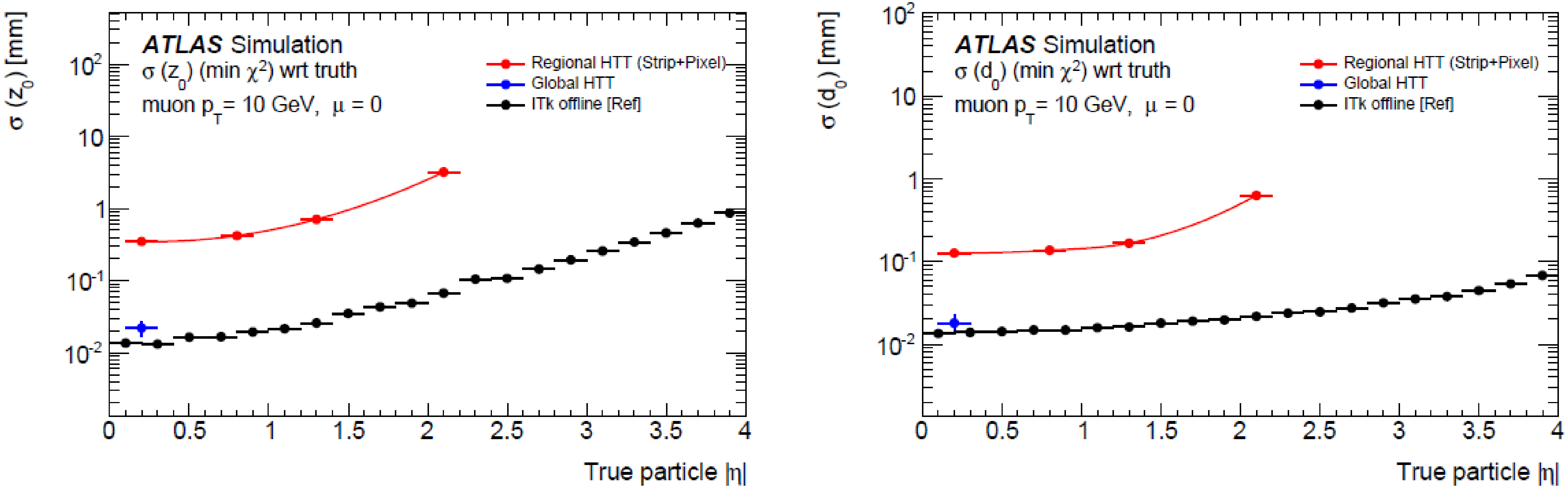


Figure 13.9: *Comparison of the z_0 (left) and d_0 (right) resolution for first- and second-stage fitting and offline.*

Table 6.4: *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	Run 1 Offline p_T Threshold [GeV]	Run 2 (2017) Offline p_T Threshold [GeV]	Planned HL-LHC Offline p_T Threshold [GeV]	L0 Rate [kHz]	After regional tracking cuts [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	$0.5^{\dagger\dagger\dagger}$
single b-jet	200	235	180	25	25	$0.35^{\dagger\dagger\dagger}$
single jet	370	460	400			0.25
large-R jet	470	500	300	40	40	0.5
four-jet (w/ b-tags)		$45^{\dagger}$(1-tag)	65(2-tags)	100	20	0.1
four-jet	85	125	100			0.2
H_T	700	700	375	50	10	$0.2^{\dagger\dagger\dagger}$
E_T^{miss}	150	200	210	60	5	0.4
VBF inclusive			2x75 w/ ($\Delta\eta > 2.5$ & $\Delta\phi < 2.5$)	33	5	$0.5^{\dagger\dagger\dagger}$
B-physics††				50	10	0.5
Supporting Trigs				100	40	2
Total				1066	338	10.4

† 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 requires at the Event Filter level

The Phase-II Event Filter menu can be compared to the current Run 2 menu scaled by luminosity. The current Run 2 menu operates at 1500 Hz for a luminosity of $\mathcal{L} = 2.0 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Scaled to $\mathcal{L} = 7.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, this gives 6.6 kHz. The majority of the additional rate in the Phase-II menu comes from these sources:

- Level-0 seeded large-R jets, 0.5 kHz additional rate
- Forward electrons, 0.2 kHz additional rate
- Inclusive VBF triggers, 0.5 kHz additional rate
- Lower single-lepton p_T threshold, 0.9 kHz additional rate
  - For comparison, this 30% higher rate gives acceptance gains of 16% for inclusive W and $t\bar{t}$ production, 28% acceptance gain for $HH \to bb\tau\tau$ with one τ decaying to leptons, and 47% for the "Well-tempered neutralino" compressed SUSY model introduced in Section 2.1.
- Lower dilepton p_T thresholds, 0.25 kHz additional rate
  - This leads to 70% more VBF $H \to \tau\tau$ acceptance and $\approx$ 3 times more acceptance for the SUSY model shown in Fig. 2.4
- More inclusive di-τ trigger, 0.15 kHz additional rate