An introduction to ATLAS trigger

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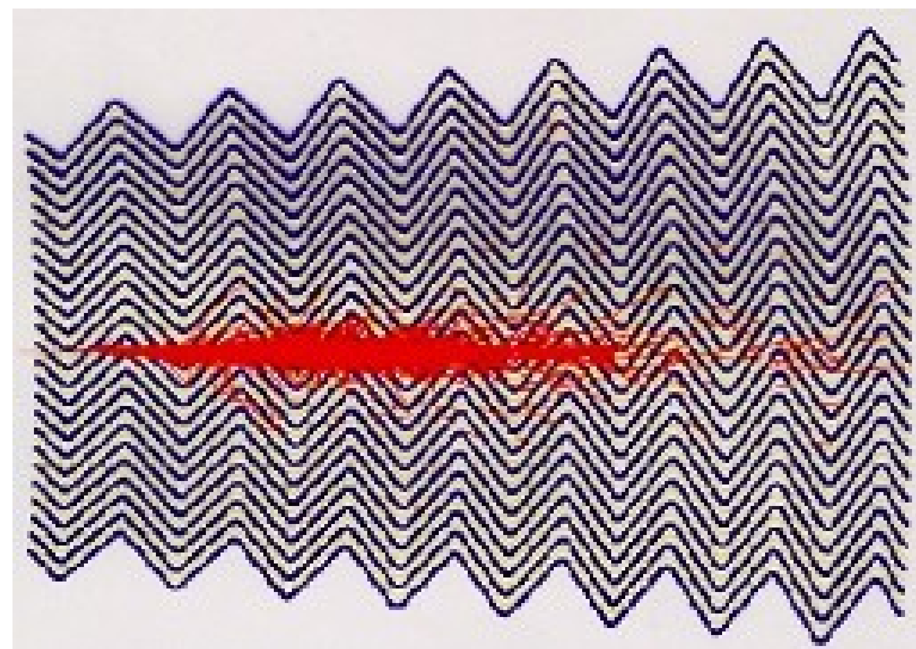
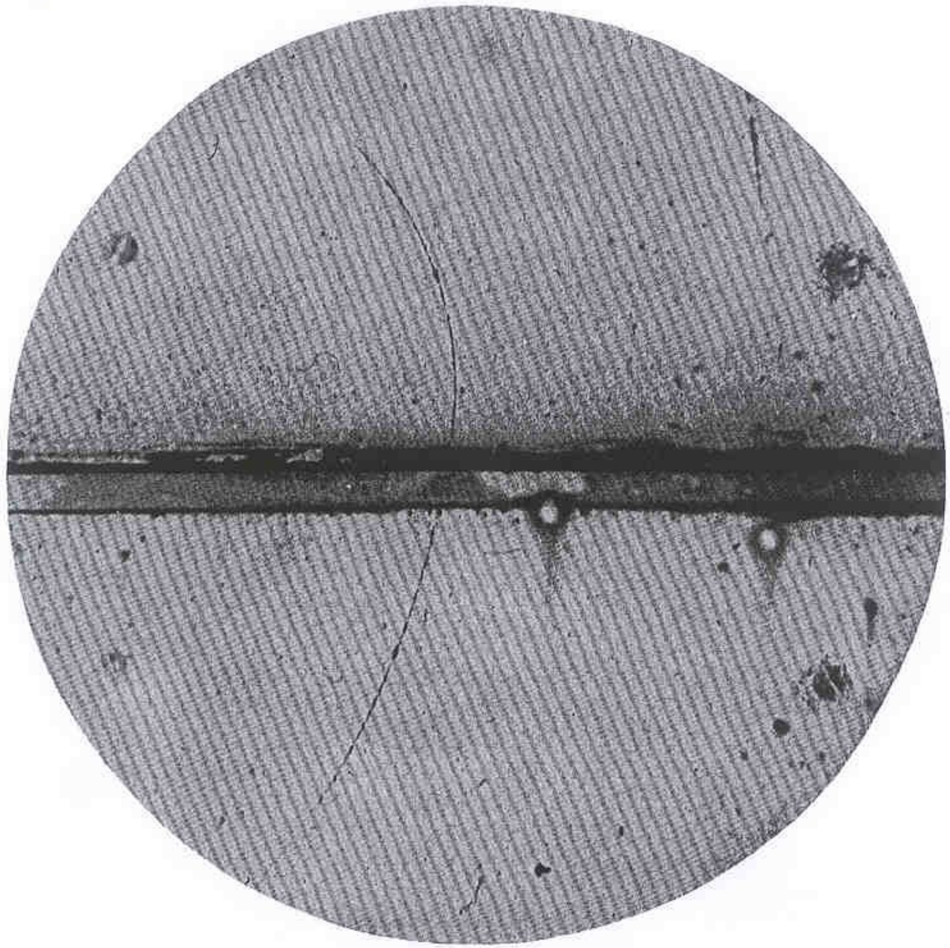
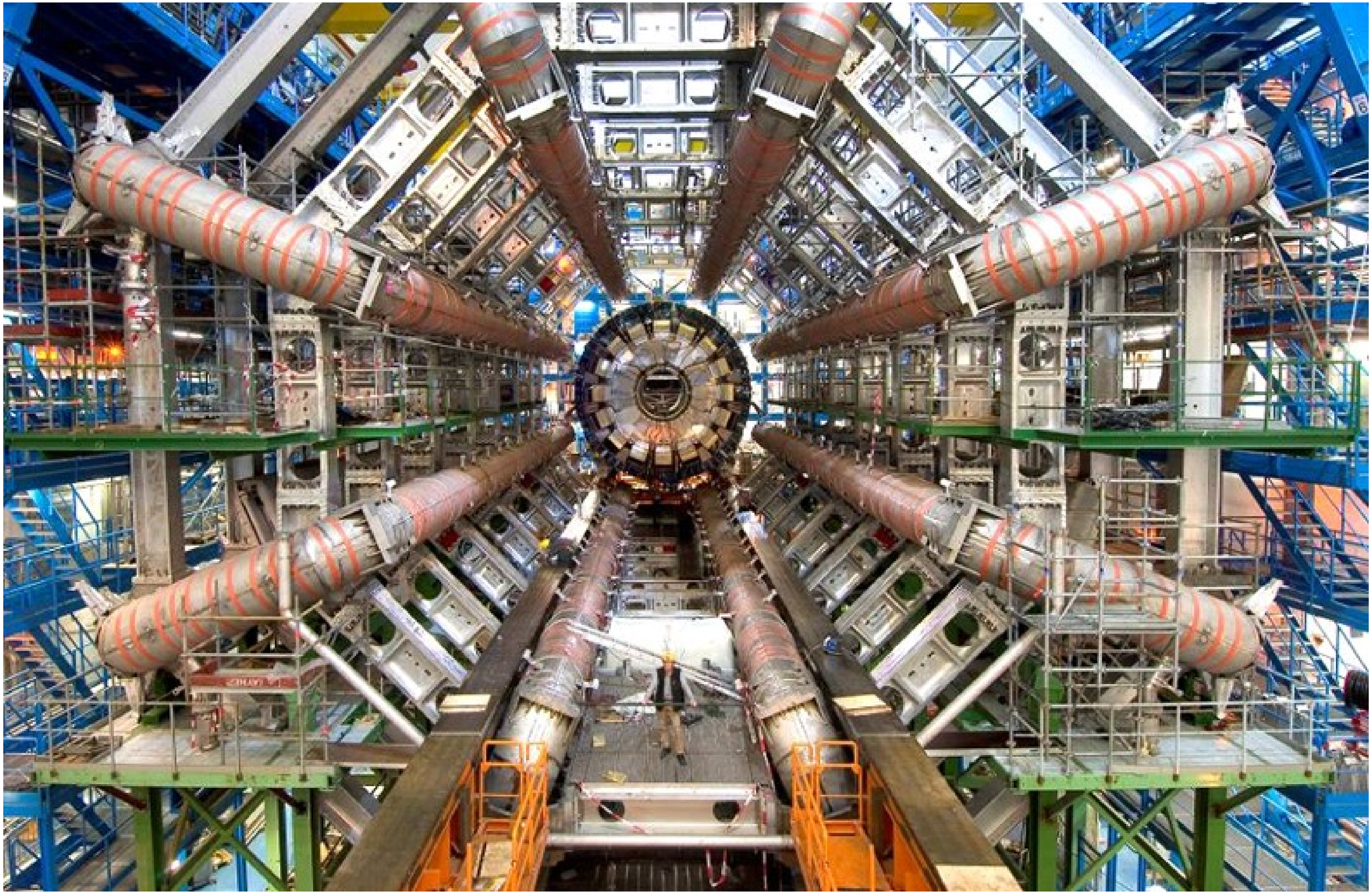


Introduction



Discovery of positron

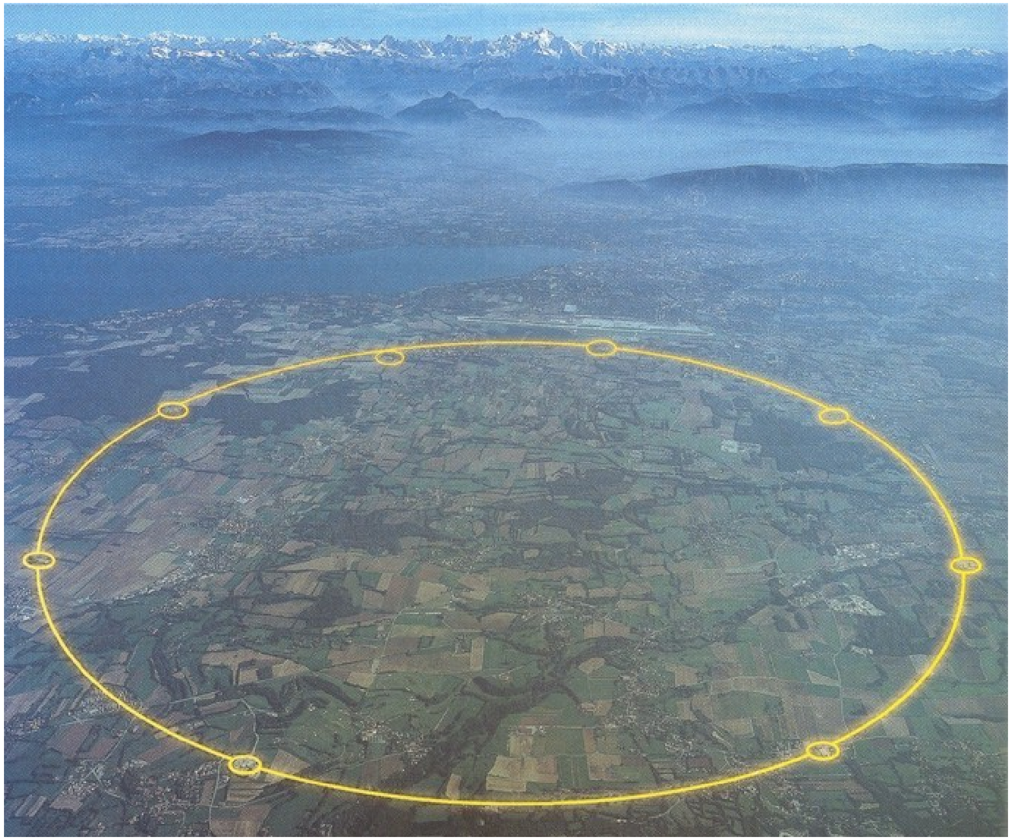


What are these lectures going to be? (maybe ...)

- Structure of the talk:
  - An introduction to the LHC and ATLAS detector
    - emphasis on triggering
  - ATLAS trigger, architecture and performance
  - More detailed look at L1 Calorimeter Trigger, its evolution and recent upgrades
    - This is what I work on, sorry...

LHC and ATLAS

Large Hadron Collider, design parameters

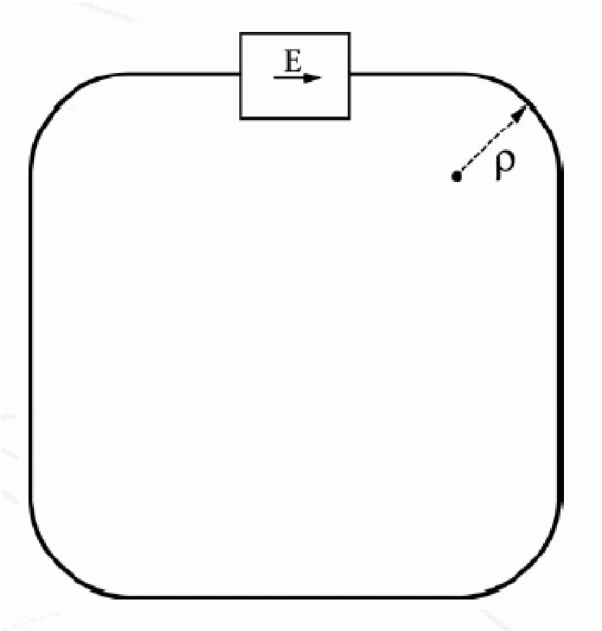


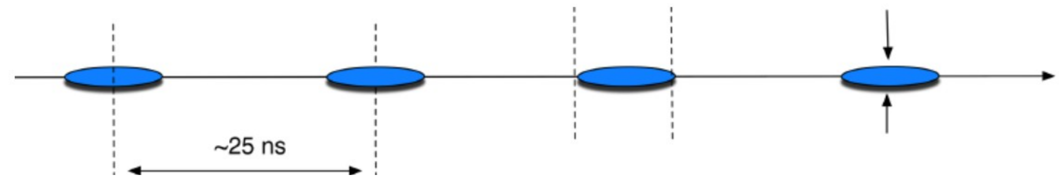
LHC nominal parameters

at collision energy

Particle type	p, Pb
Proton energy E_p at collision	7000 GeV
Peak luminosity (ATLAS, CMS)	1×10^{34} $cm^{-2}s^{-1}$
Circumference C	26 658.9 m
Bending radius ρ	2804.0 m
RF frequency f_{RF}	400.8 MHz
# particles per bunch n_p	1.15×10^{11}
# bunches n_b	2808

LHC beam,bunch structure

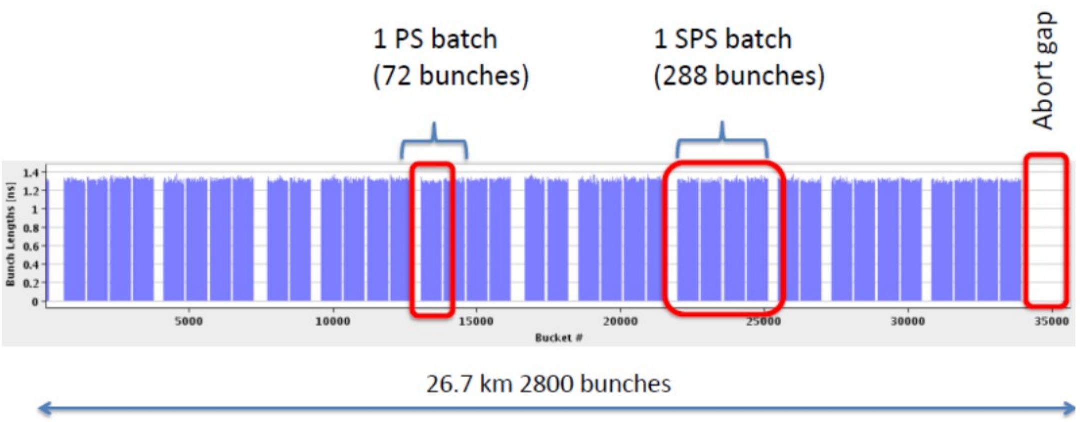


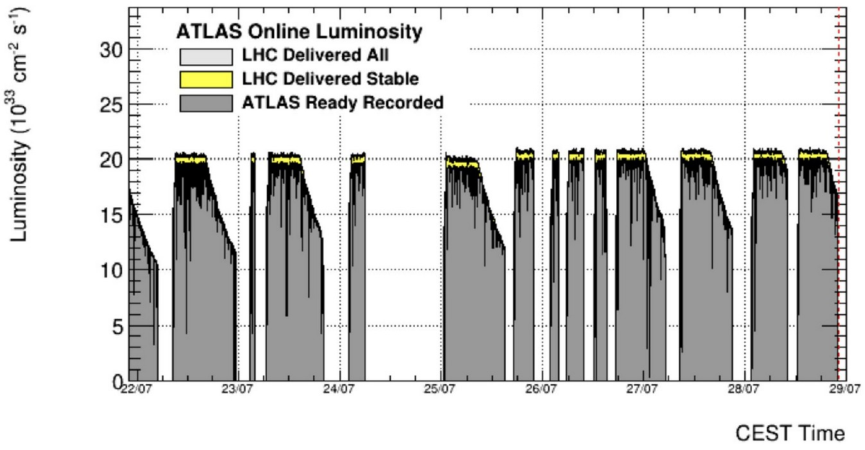


- LHC is a synchrotron, acceleration power provided by RF cavities
    - Beam need to be organised into bunches
  - Bunch length ~10cm
  - Transversal dimensions much smaller (~100 μm at collision points)
- time between bunches (1/ LHC clock frequency) is 25 ns

LHC beam, bunch trains and levelling

- Complicated structure of bunches:
  - 3564 full number
  - Around 2800 filled
    - Reflecting pecularities of beam injection and dumping
- Data taking revolves around LHC fills:
  - Injection, acceleration, bring beams to collision
  - Flat (levelled) part of the fill, constant luminosity
    - Using both separation and β* levelling
  - Then exponential decay

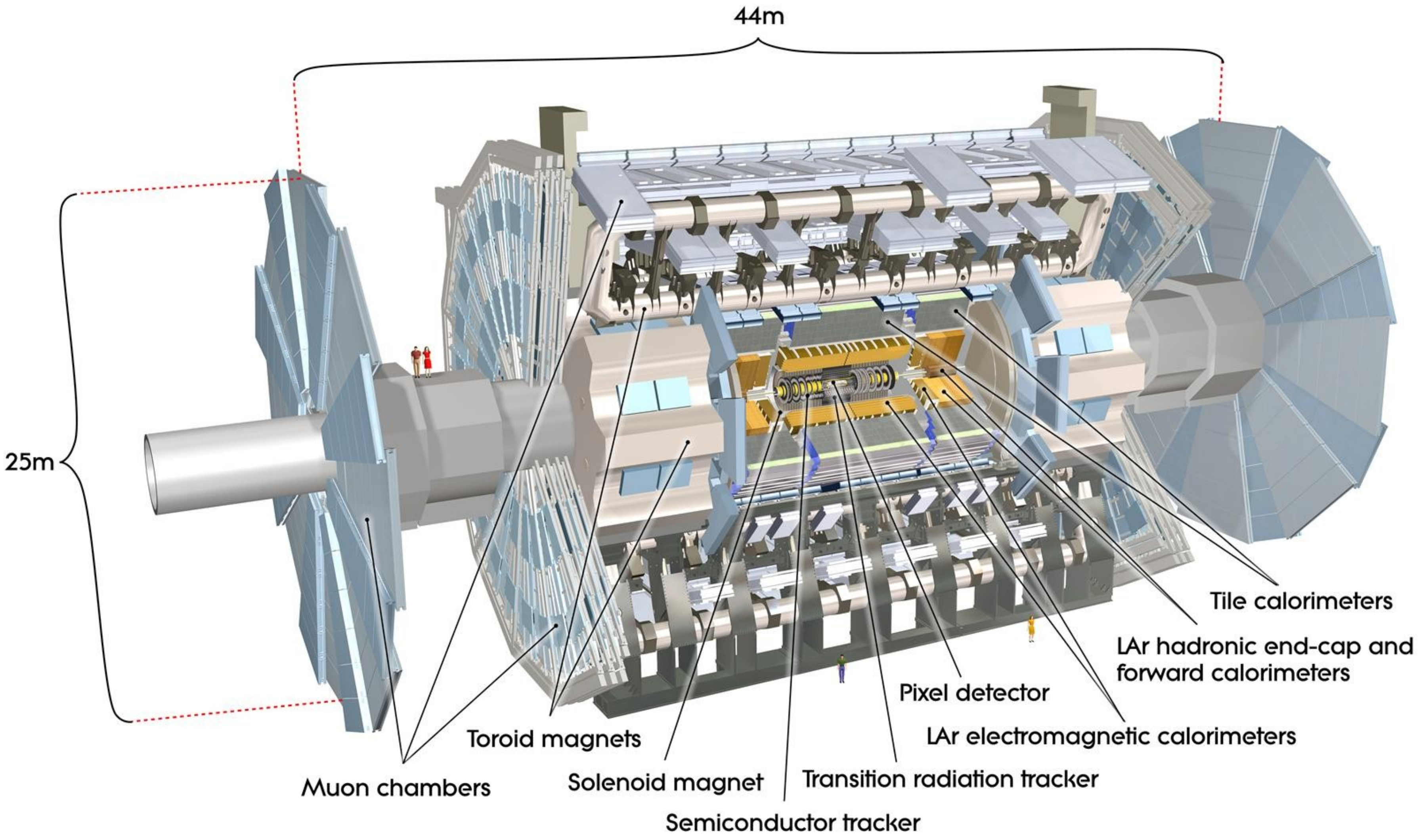




Phases of ATLAS data taking ...

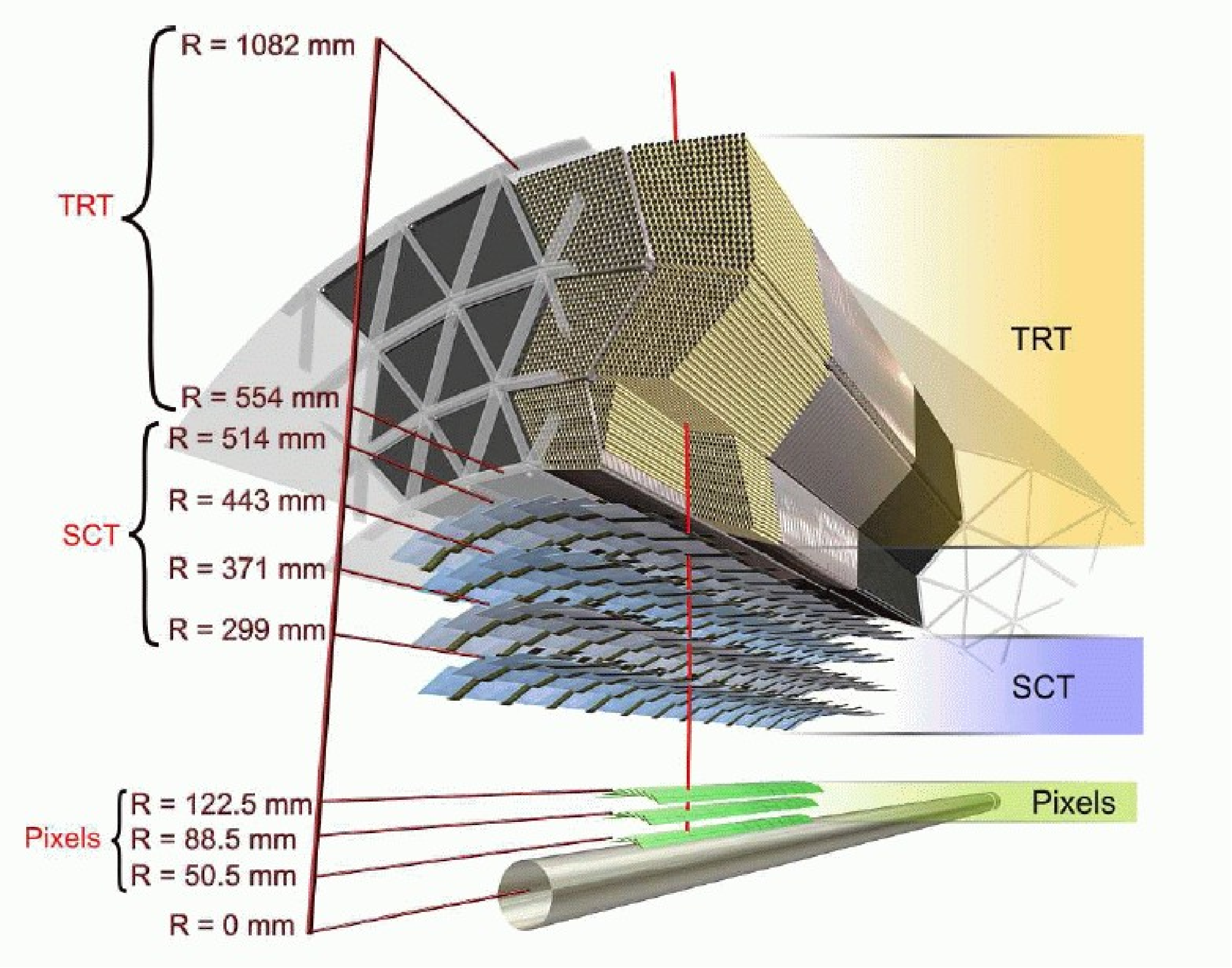
- Run 1 (2009-2013):
  - $\sqrt{s}$ up to 8 TeV, L up to 0.77×10^{34} $cm^{-2}s^{-1}$, <μ> ~ 21 BC^{-1} (peak <μ> ~ 40 BC^{-1})
- Phase 0 upgrade (LS1, 2013-2015)
- Run 2 (2015-2018):
  - $\sqrt{s}$ = 13 TeV, L ~ 2×10^{34} $cm^{-2}s^{-1}$, <μ> ~ 60 BC^{-1} (levelled)
- Phase 1 upgrade (LS2, 2018-2022)
- Run 3(2022-2026):
  - L ~ 2-3 $\times10^{34}$ $cm^{-2}s^{-1}$, <μ> ~ 60-70 BC^{-1} (levelled)
- Phase 2 upgrade (2026-2030)
- Run 4 (2030-2033)
  - L up to 7.5×10^{34} $cm^{-2}s^{-1}$, <μ> up to 200 BC^{-1}
- ...

ATLAS detector

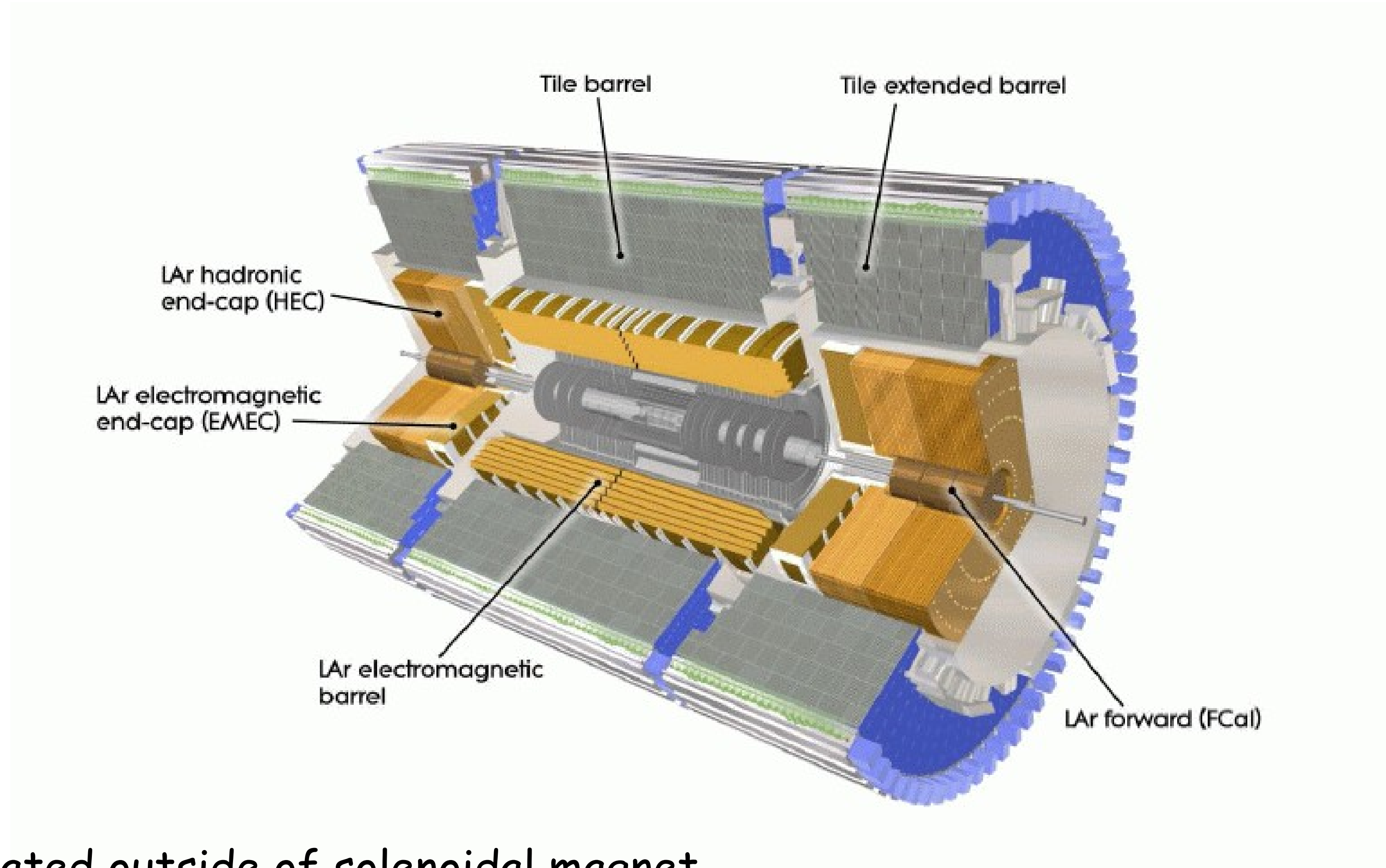


ATLAS tracking (Run 1)

- Low radius – pixels (3 layers in Run 1, another layer inserted in 2015)
- Then strips (SCT)
- At larger radius, additional detector – TRT (transition radiation tracker)

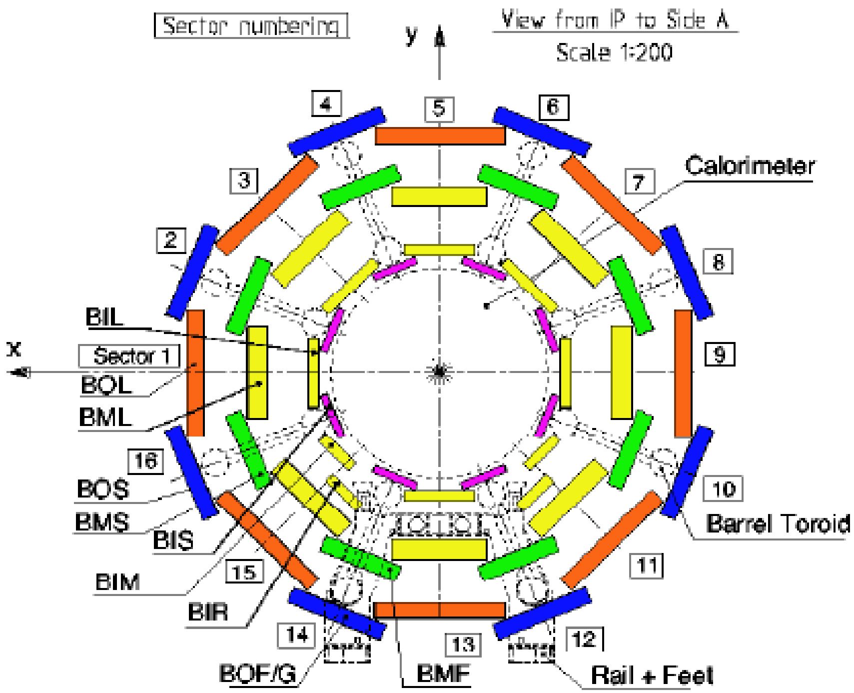


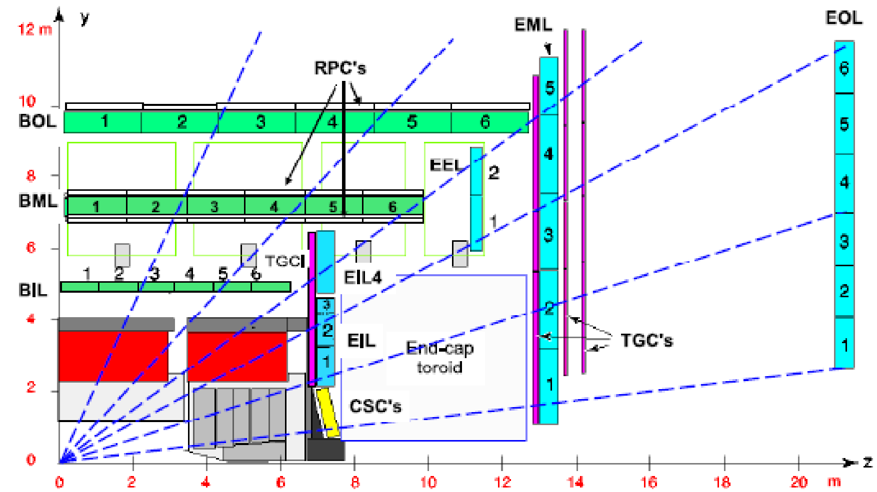
ATLAS calorimetry



- Located outside of solenoidal magnet
  - Mostly based on LAr technology
  - In hadronic barrel Iron+Scintilation tiles (TileCal)

ATLAS muon system (Run 1)



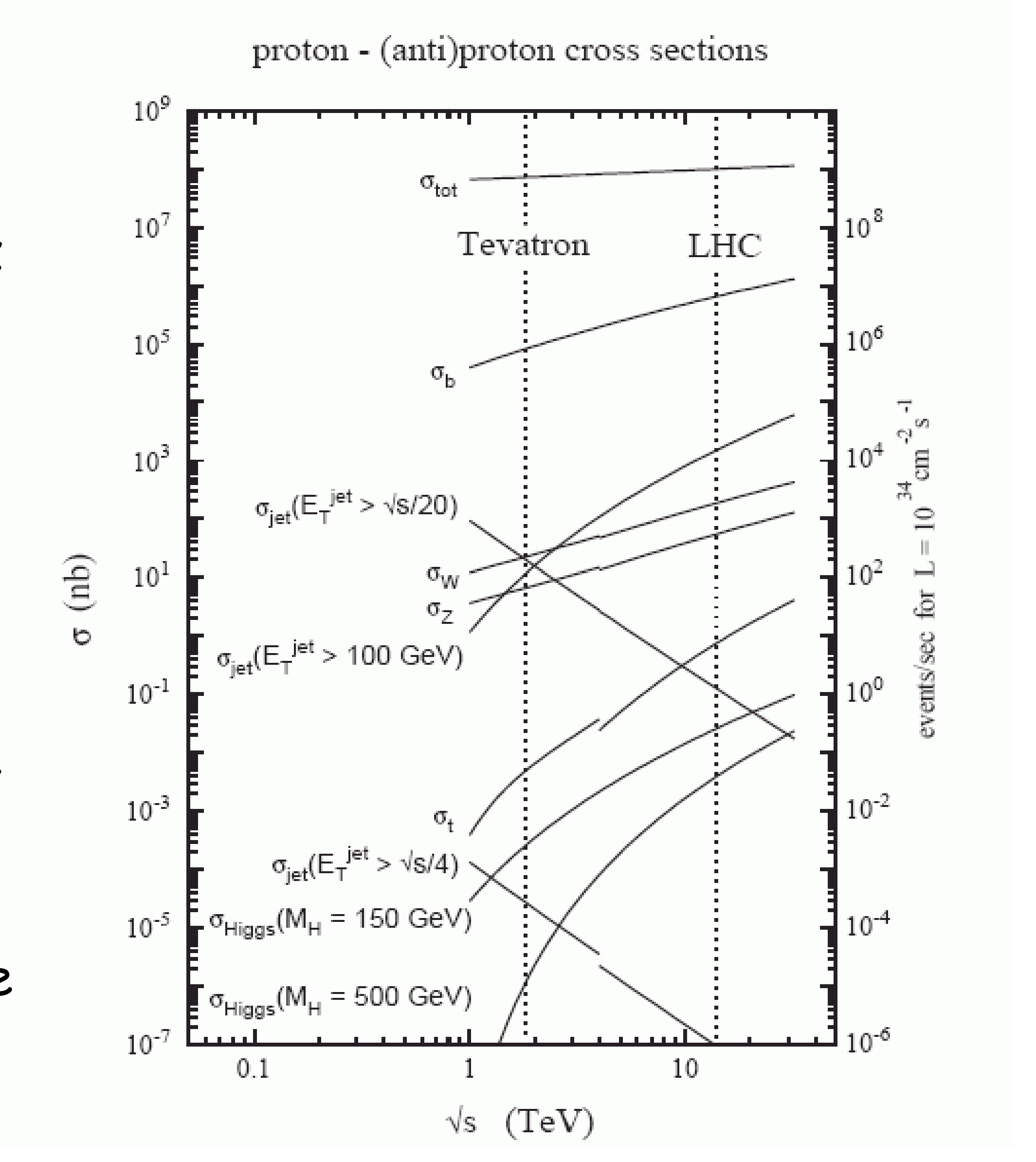


- Reasonable quality of tracking over huge volume of non-uniform magnetic field:
  - Gas drift chambers for precision position measurement (MDT's and CSC's in forward region)
  - Dedicated fast chambers for triggering (RPC's and TGC's in forward region)

ATLAS trigger, design and performance

Triggering ...

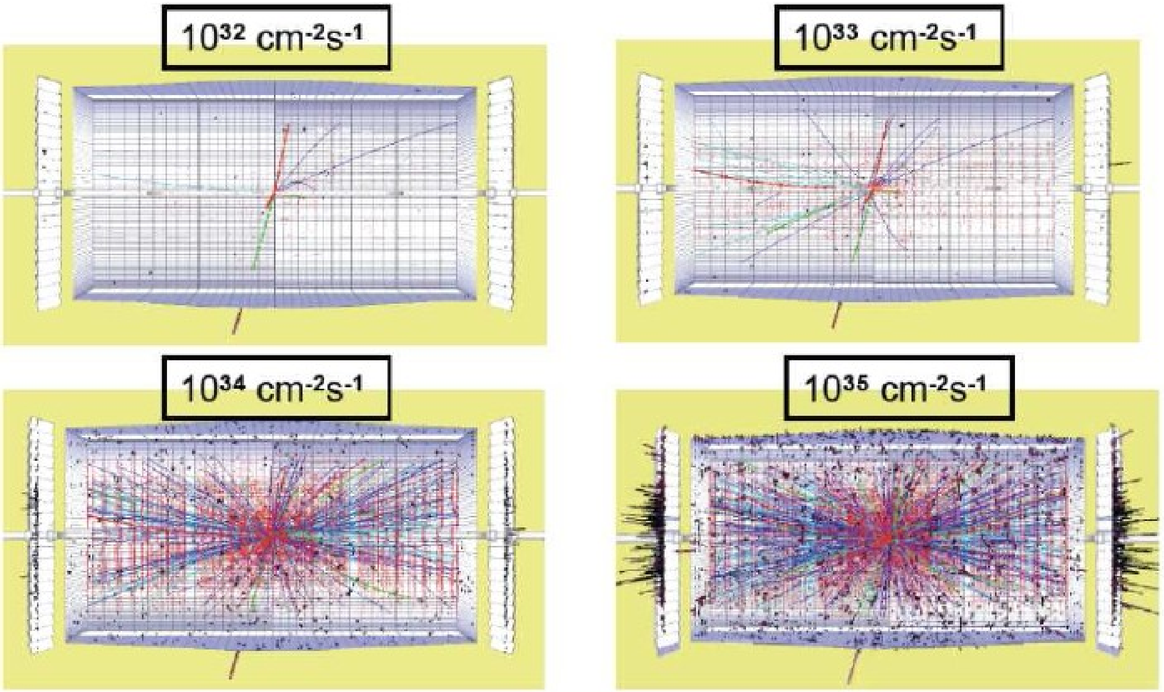
- At full LHC luminosity, huge event rate
  - Each bunch crossing at 40 MHz results in many (reaching ~65 in 2024) inelastic collisions
- ATLAS has around 100 Million electronics channels to be read out
  - Event size typically 1-2 MB
- Possible data recording rates are of the order of 1kHz
  - Need on-line filter (trigger) deciding which events should be saved on disk



Trigger signatures

Typically search for signatures like:

- high-p_T muons
- high-p_T electrons and photons
- High-p_T taus and jets
- Large missing E_T



Want to retain as many as possible events for:

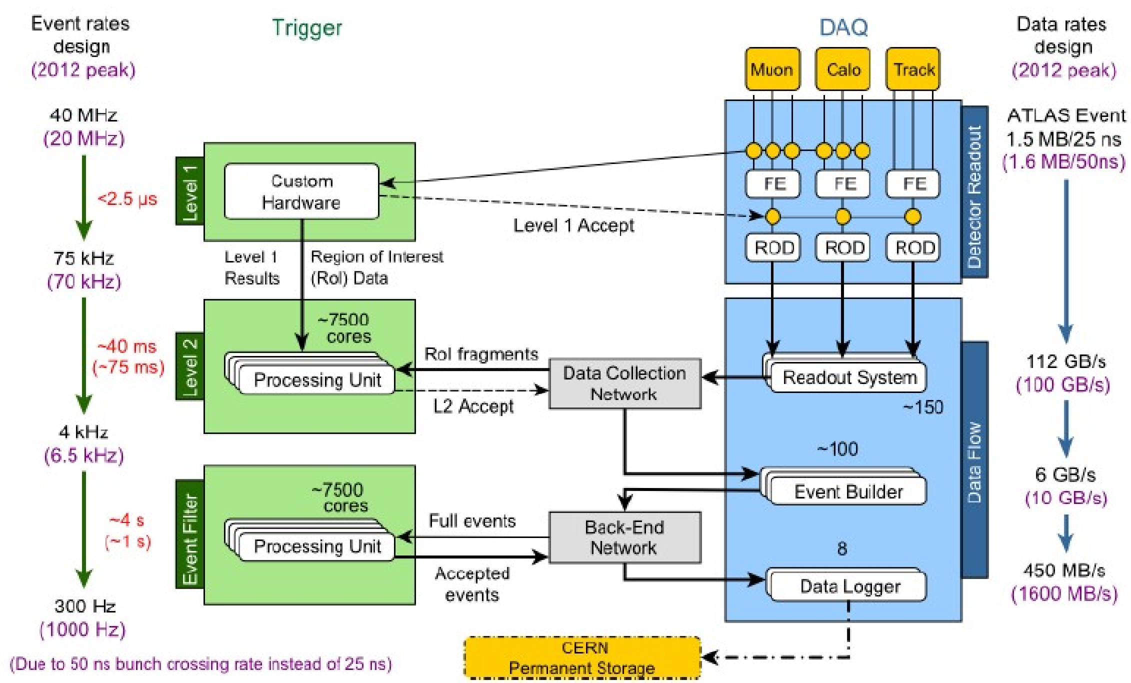
- Higgs physics
- SUSY searches
- Searches for any new physics
- Precision physics studies

Multi-level trigger

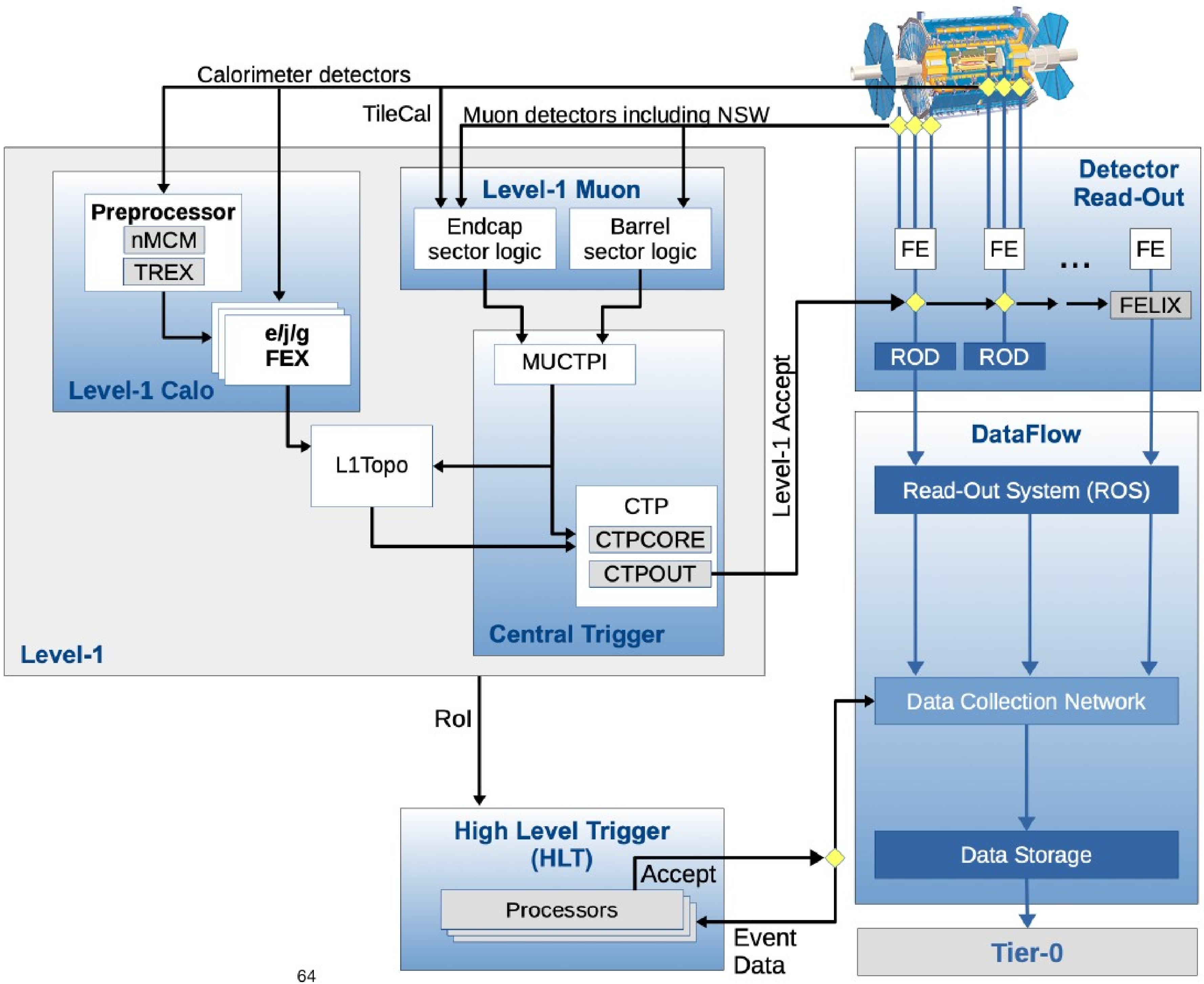
ATLAS trigger during Run1

Multilevel triggers are used everywhere!

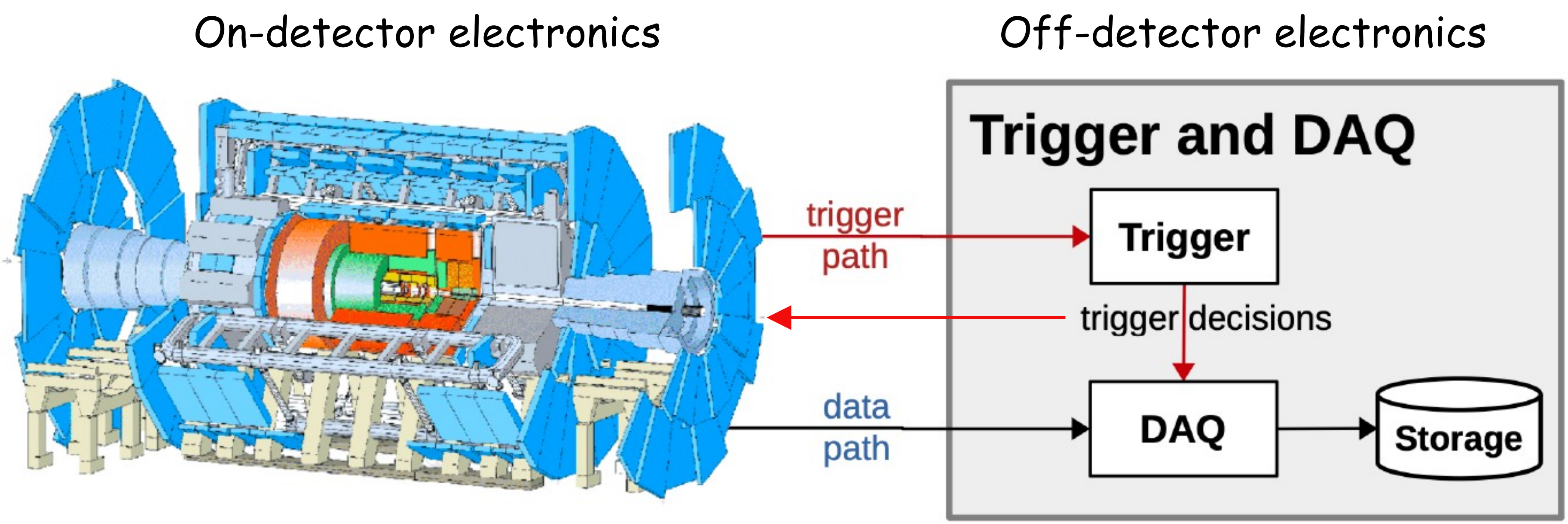
- Rapid rejection of high-rate backgrounds without too much of a dead time
- High overall rejection power



- First-level trigger – custom electronics
- Level-2 and Event Filter (L3) – built using computers (Linux PCs) and networks
- In Run 1 L2 and L3 were separate objects, now logic separation only


Calorimeter detectors
TileCal
Muon detectors including NSW
Level-1 Calo
Preprocessor
nMCM
TREX
e/j/g
FEX
Level-1 Muon
Endcap
sector logic
Barrel
sector logic
MUCTPI
L1Topo
CTP
CTPCORE
CTPOUT
Central Trigger
Level-1
Level-1 Accept
Detector
Read-Out
FE
FE
...
FE
FELIX
ROD
ROD
DataFlow
Read-Out System (ROS)
Data Collection Network
Data Storage
Tier-0
RoI
High Level Trigger
(HLT)
Accept
Processors
Event
Data
64

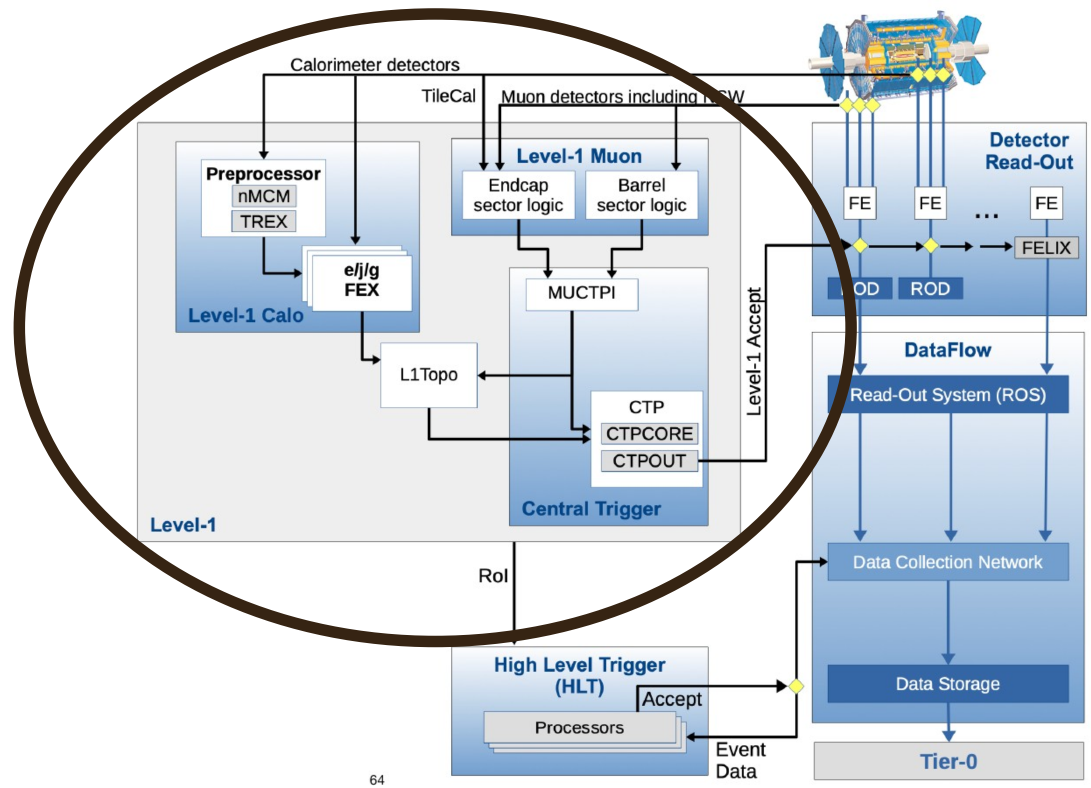
Trigger and Data Acquisition



- Two data paths
  - Low latency: Trigger path
    - Dedicated detectors or reduced granularity information
    - Mainly used by L1 trigger and seeding of High Level Trigger
  - Slower, large latency, precise: Data path
    - Used by High Level Trigger and for precision analysis

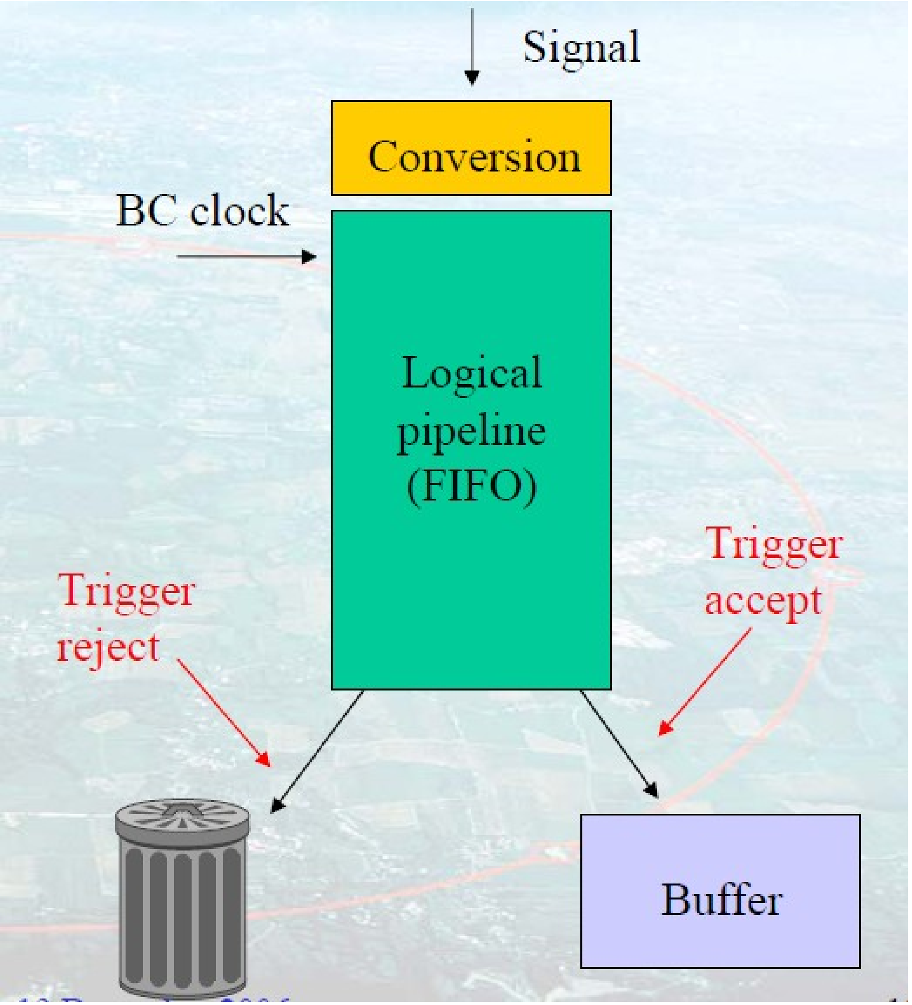
Level 1 trigger I

- Dedicated hardware
- Inputs from:
  - Dedicated detectors (RPCs and TGCs) for muons
  - reduced granularity calorimeter information
  - No tracking information used
- Main components:
  - L1Muon system (muons)
  - L1Calo (EM, TAU, Jets, E_{Tmiss})
  - L1Topo (multiplicities cuts and topological conditions)
  - Central Trigger (clock distribution, prescales, combination of triggers, busy logic, ...



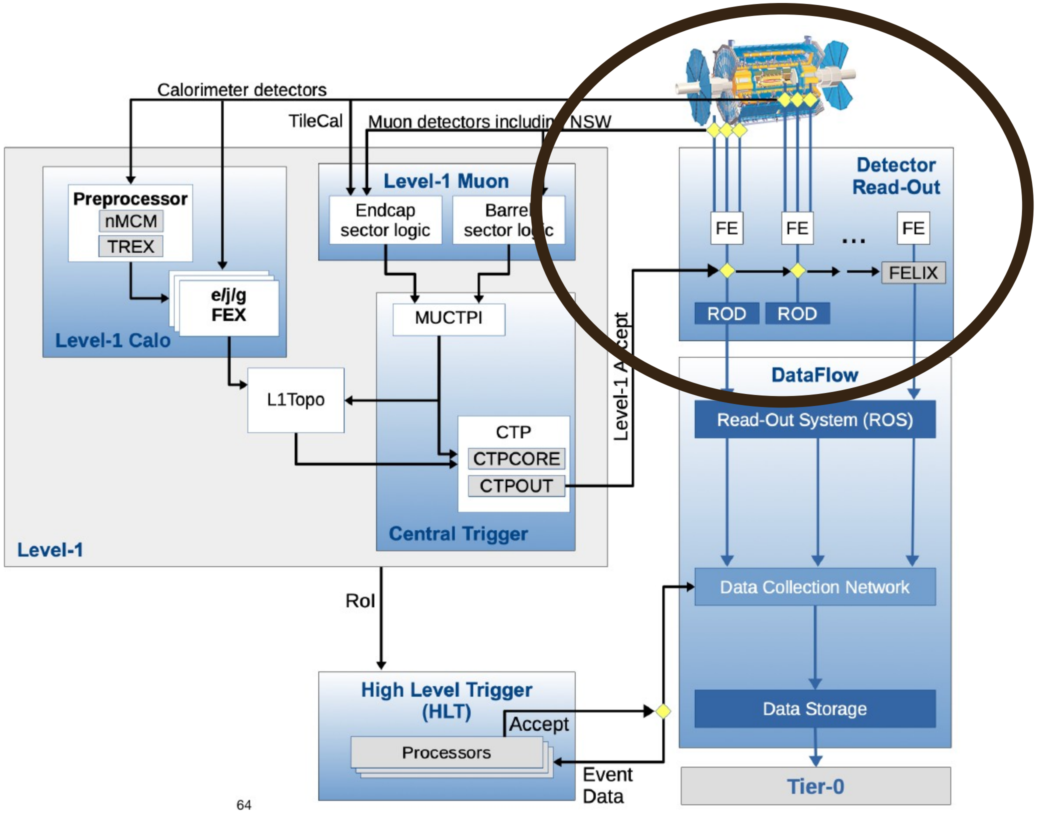
Level 1 trigger II

- Fixed latency, pipelined system:
  - Processes each bunch-crossing
  - During fixed latency time (2.5 μs) detector data stored in 'pipeline memories' on detector itself
  - The triggered data is taken out from pipeline at a fixed time
  - When L1 trigger accepts an event, data is sent to de-randomiser buffers off detector
  - Selects about 1 in 500 events
  - Also flags Regions-of-Interest (RoIs)



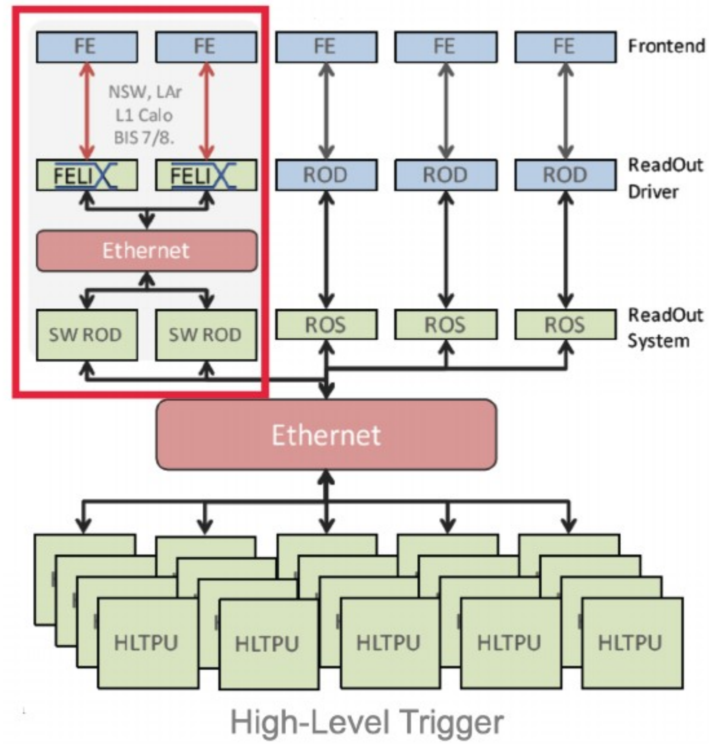
When L1 accepts ...

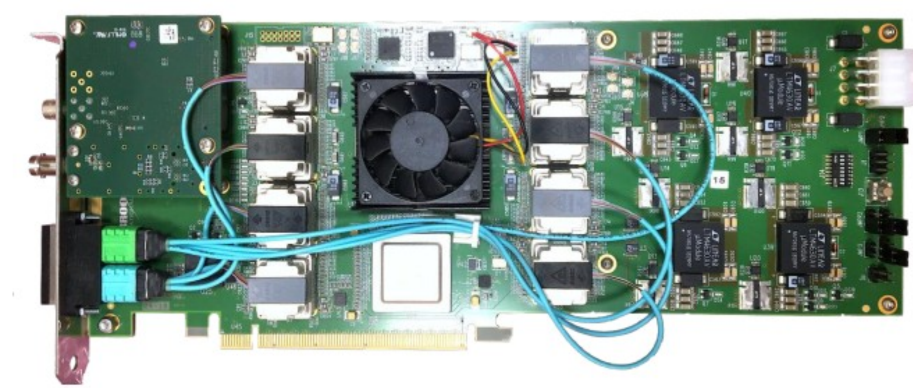
- In case of positive decision by L1 trigger:
  - Central Trigger (CT) sends signal (L1A) to all detector front-ends
  - This initiates read-out
    - Data from all pipe-lines are copied into Read-Out Buffers
- In the case of negative decision:
  - No dedicated signal
  - Pipe-lines are eventually overwritten with new data



ATLAS readout system

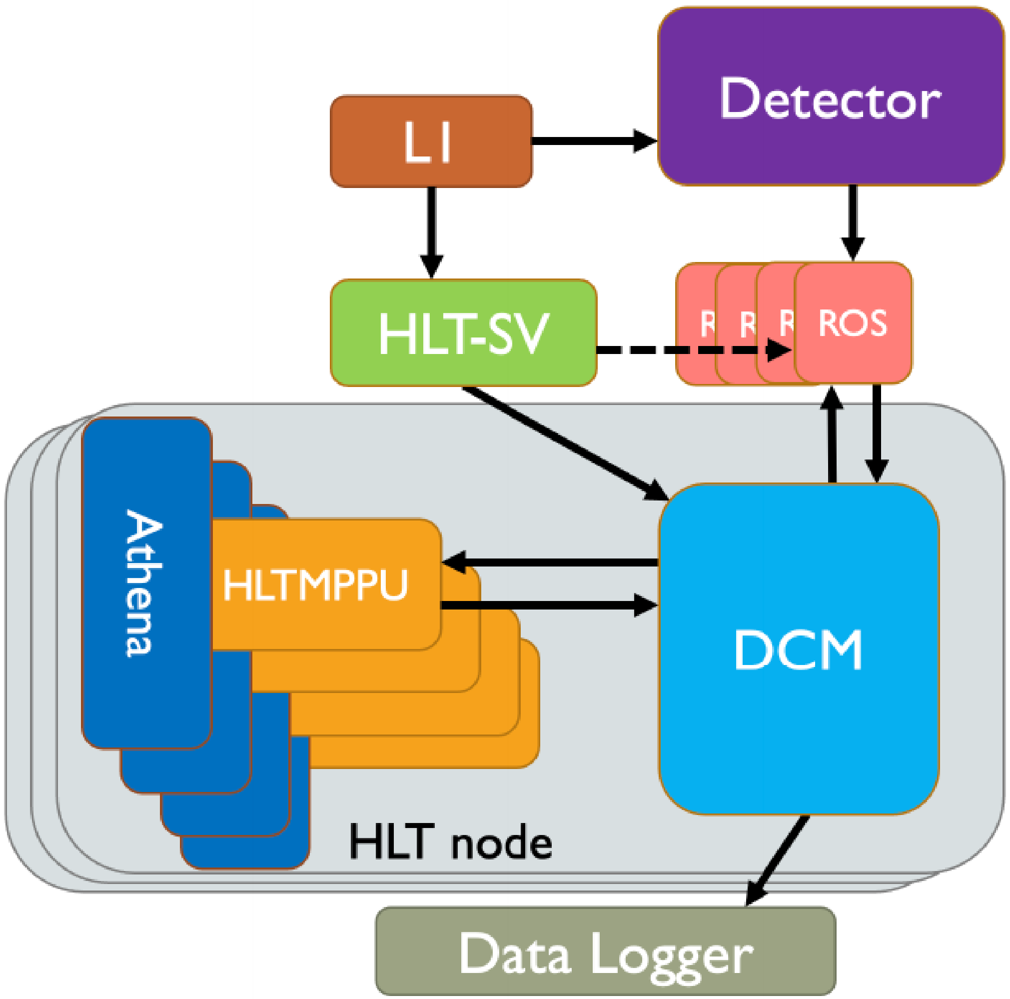
- Original architecture:
  - RoD
    - System specific card, usually VME
    - About dozen types
    - Connected to RoS
  - Commodity computers hosting ROBin cards
    - Storing data fragments and transfering them to HLT
    - About 100 servers in USA15 cavern
- Upgraded architecture:
  - FELIX
    - Custom PCIe card hosted in commercial servers
    - Currently ~100 cards in ~60 servers in USA15
  - Software RoD
    - Software running on a PC
    - Currently 33 servers in USA15





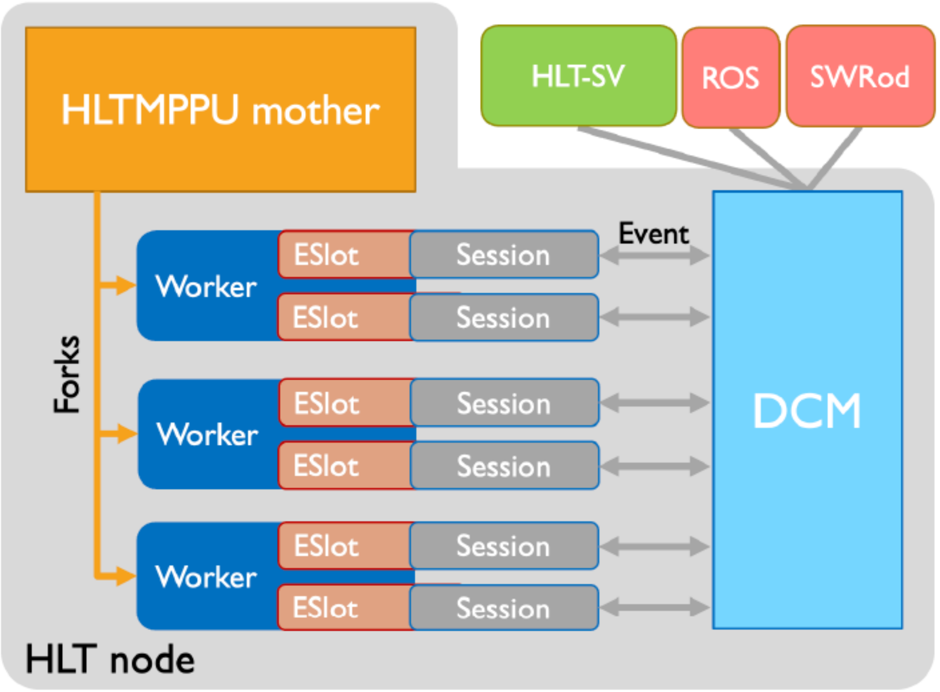
High Level Trigger – infrastructure I

- Highly parallel multi-core architecture:
  - HLT_SV (High-Level Trigger Supervisor):
    - One unique application
      - Assigns event to HLT nodes
      - Responsible for distributing L1 RoI information
  - DCM (Data Collection Manager)
    - Interface between HLT processing units and the rest of DAQ
      - Retrieves RoIs from HLTSV and event fragments from readout system, provides them to Processing Units (PUs)
      - Performs event building for selected events
      - Sends full event to the Data Logging System
    - One application running on each HLT processing note
      - Single thread
      - Communication with PU through shared memory



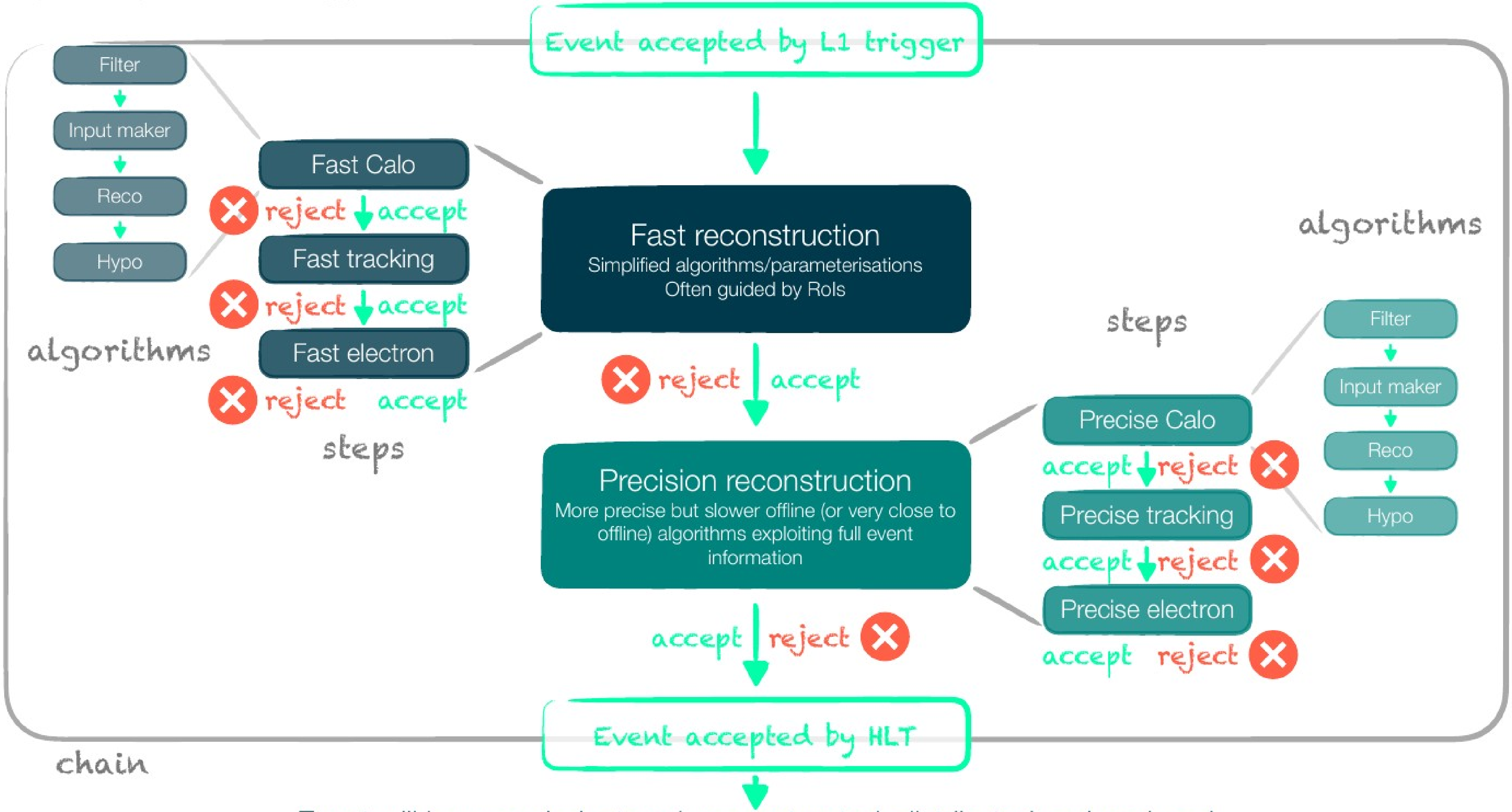
High Level Trigger – infrastructure II

- One mother process per HLT node (HLTMPPMU mother)
  - Forks n child processes (workers) and monitors them
- Workers:
  - Are in charge of event processing
  - Each of them can run multiple threads typical setup in 2024:
    - Processing slot == core on computer
    - 32 slots/node each running 2 threads
- Minimal nr. of nodes determined by event rate and processing time:
  - <Input rate> * <processing time> = <min nr of nodes>
  - 100 kHz input rate, 500 ms average processing time (to be compared with 2.5 μs fixed L1 latency)
    - >50 000 HLT processing nodes



HLT: Chains, Steps & Algorithms

example: simple electron trigger chain



Event will be recorded, stored, reconstructed, distributed and analysed

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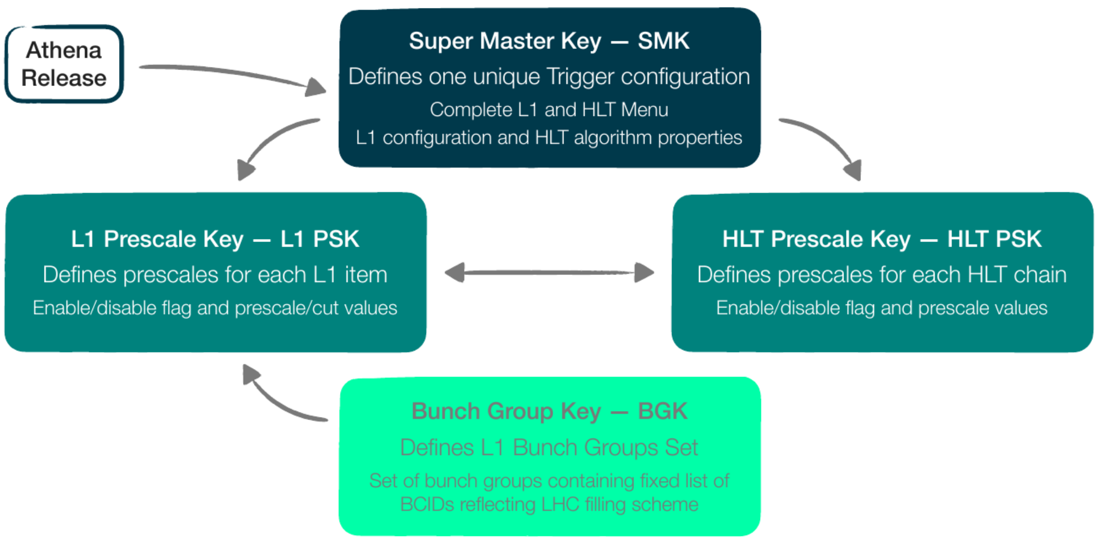
ATLAS HLT farm in SDX1
52 racks, 32 servers each,
over 55k physical cores
AMD EPYC 7302

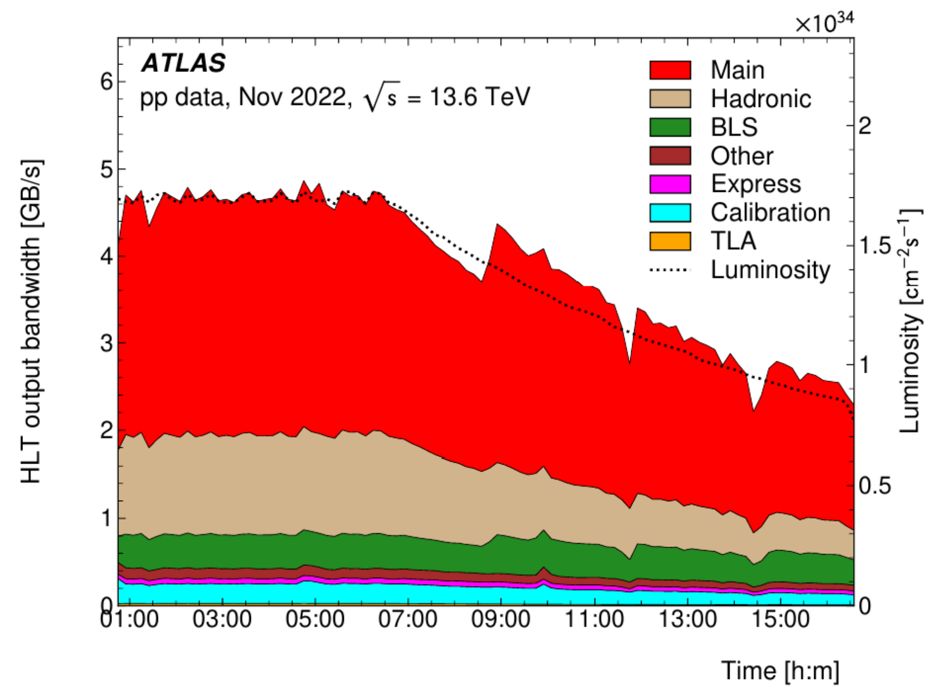
Data Logging System

- Stores events accepted by HLT and transfers data files to Offline Storage Systems
  - Decouples ATLAS data-taking from offline world
    - 48 hours of storage in case of connection problems
  - Implemented in 10 servers (SFOs) with directly attached storage systems (240 hard drives)
    - 8 GB/s writing (O(1) kHz of events)
  - Fully redundant system for high reliability
  - No data loss in more than 10 years!

Trigger settings adjustment during fill

More details here



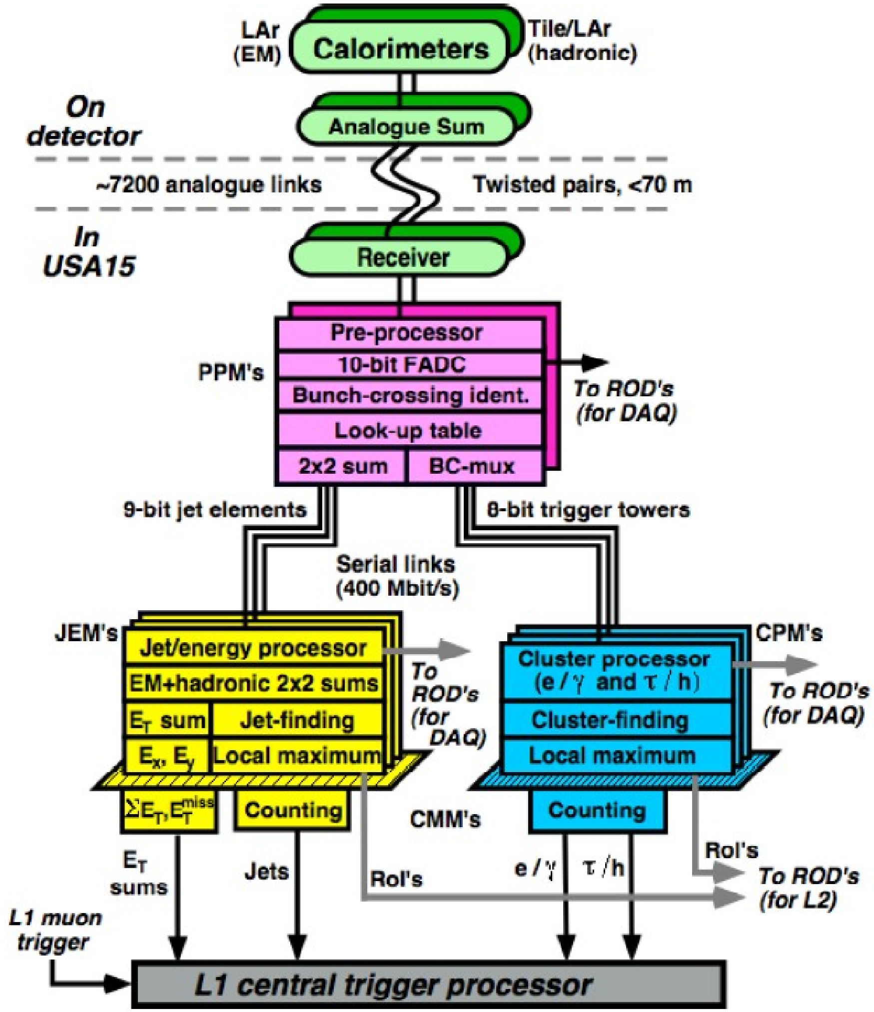


- For each fill fix basic trigger configuration (SMK)
  - Stay with the same L1 and HLT prescale keys during levelling stage
  - Update prescale keys at predefined points during exponential luminosity decay phase

More detailed look at L1Calo and its evolution

Level 1 Calorimeter Trigger (L1Calo during Run1)

- Synchroneous pipelined hardware trigger with fixed latency
  - Implemented as custom electronics (mainly VME, FPGAs, few ASICs)
  - Input are pre-summed analogue signals from all ATLAS calorimeters
- Pre-processor:
  - Digitization and conditioning of input signals
- Cluster processor:
  - looks for isolated energy maxima corresponding to electrons and taus
  - Counts their multiplicities
- Jet processor:
  - Finds Energy maxima – jets, count multiplicity
  - Calculates Global sums – E_{Tmiss}, E_{Ttot}
  - Compares with loaded thresholds
- Processors send their outputs to Central Trigger



L1Calo trigger during Run 1

(Half of) Receivers and PreProceccors

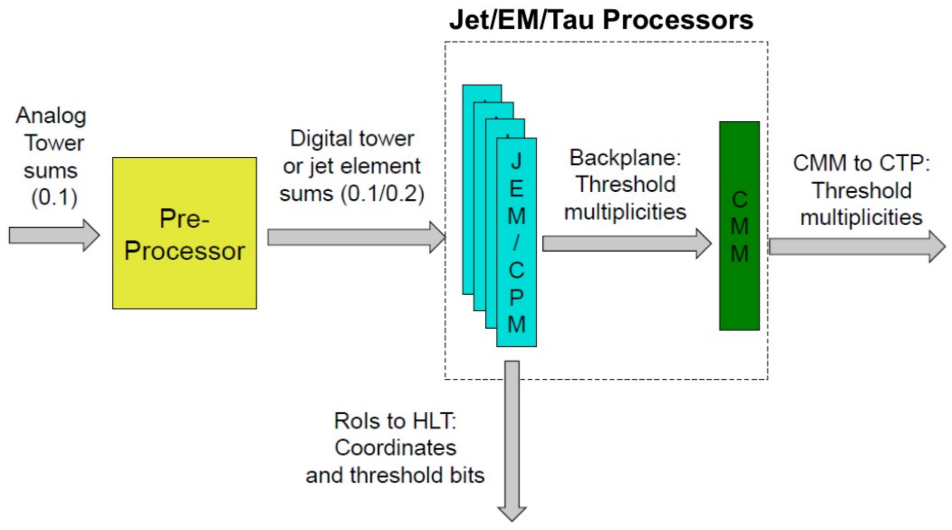
Processors

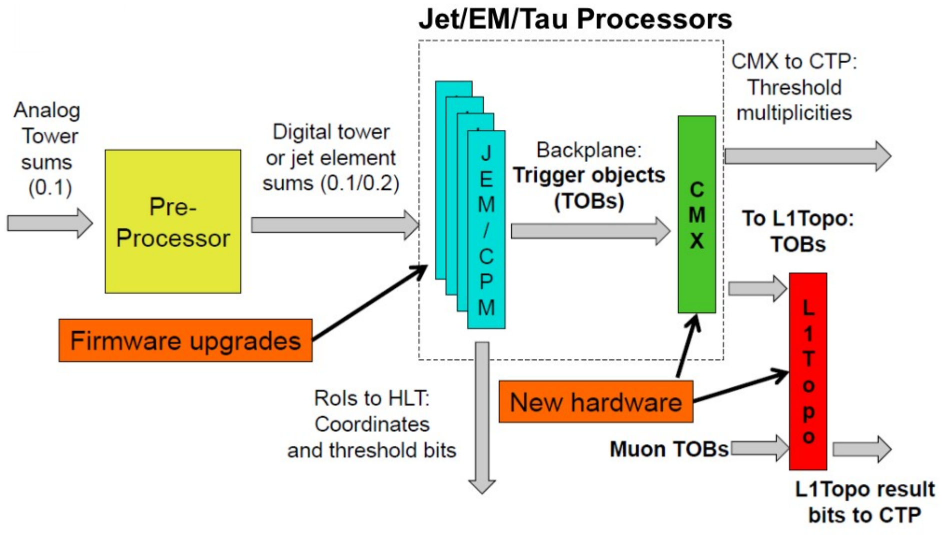
Readout Drivers

- ~300 VME modules of 10 types housed in 17 VME crates

Phase 0 upgrades of L1 trigger

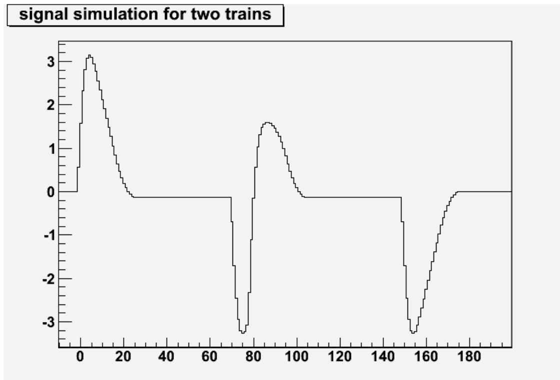
- Major upgrade of L1 Calorimeter trigger:
  - Improved treatment of input analogue pulses
    - nMCM (Multi Chip Module) upgrade in Preprocessors
  - Different definition of trigger objects:
    - Firmware update of processors and new merger (CMX) boards
    - Improvements to trigger algorithms
      - For example new calculation of electron isolation
  - New topological trigger (L1Topo)

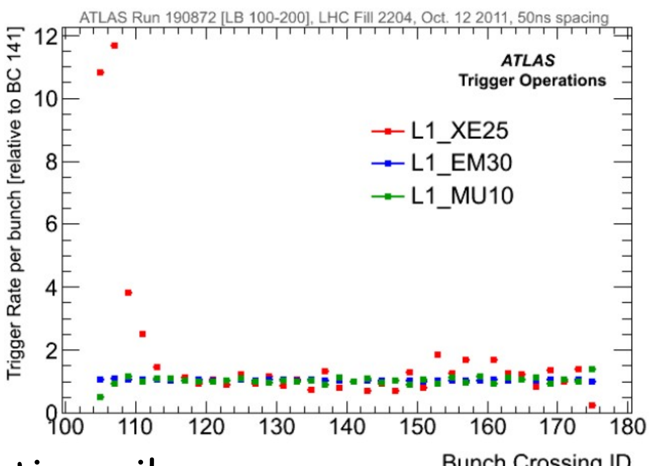


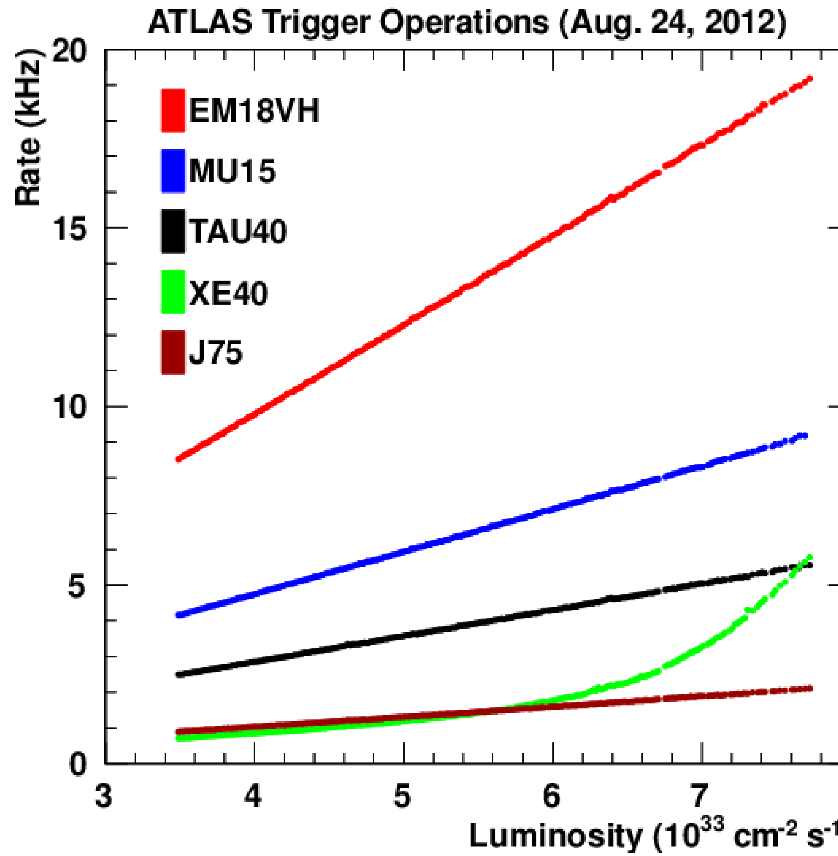


Out of time pileup and effect on baseline

More details here

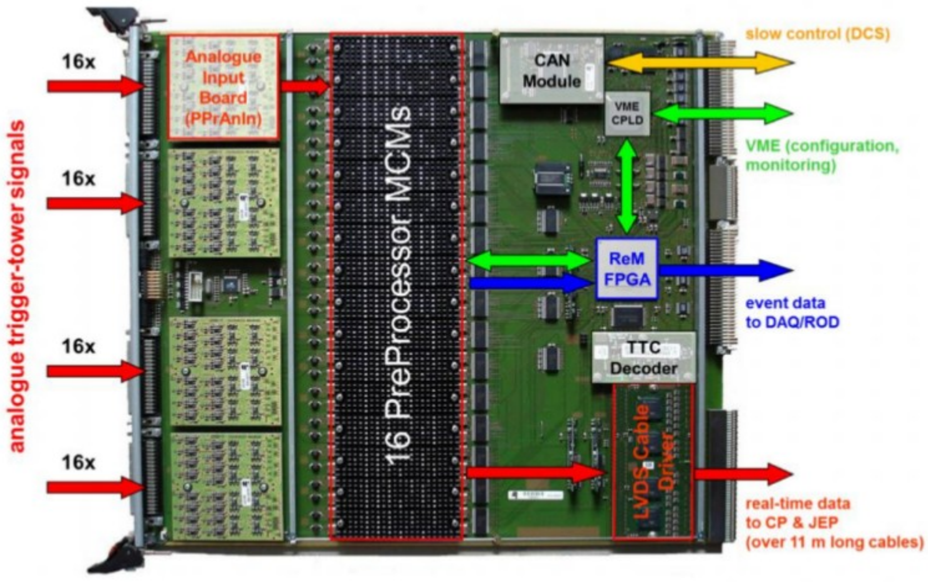


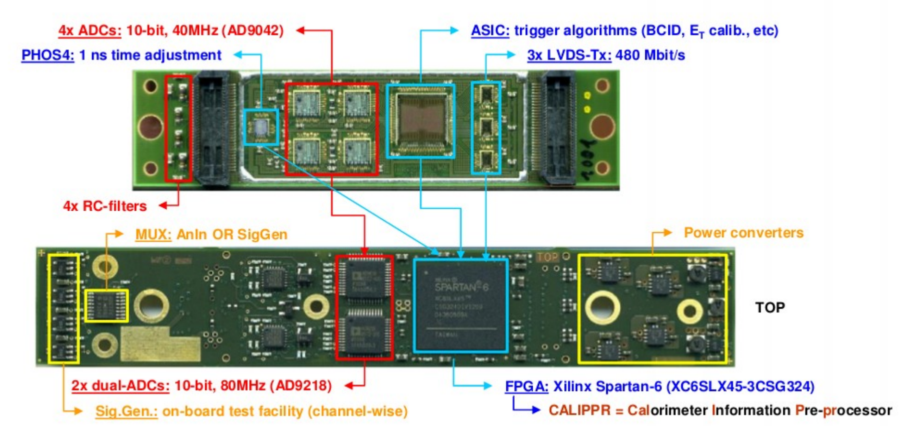




- Out of time pile-up
  - Signals from LAr are bi-polar and extend over several bunch crossings
  - In combination with LHC bunch train structure leads to shifts of base-line at the beginning and end of bunch trains
    - Seen as non-linear component of trigger rates

Upgrade of PP Multi Chip Modules

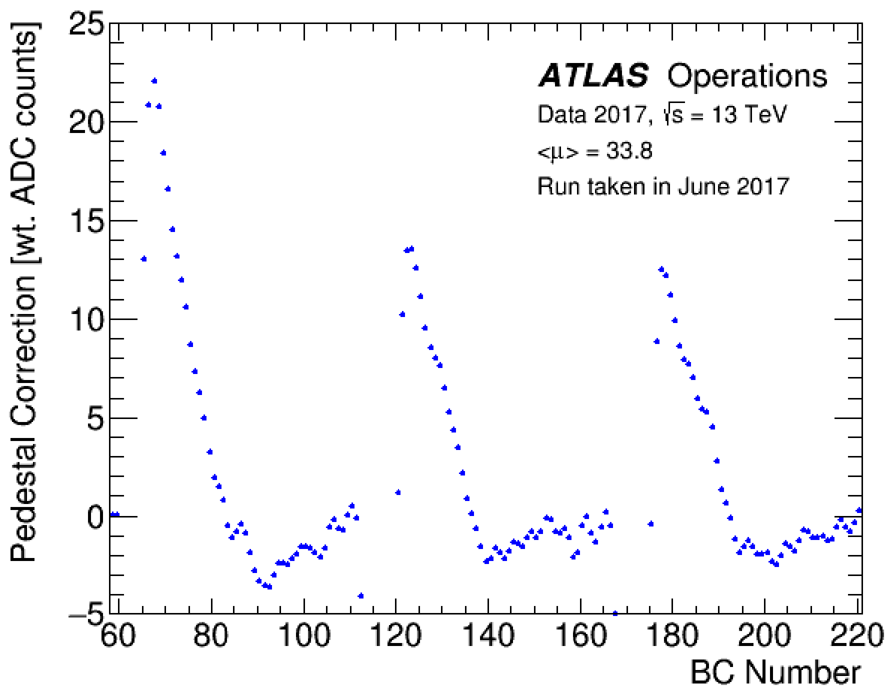


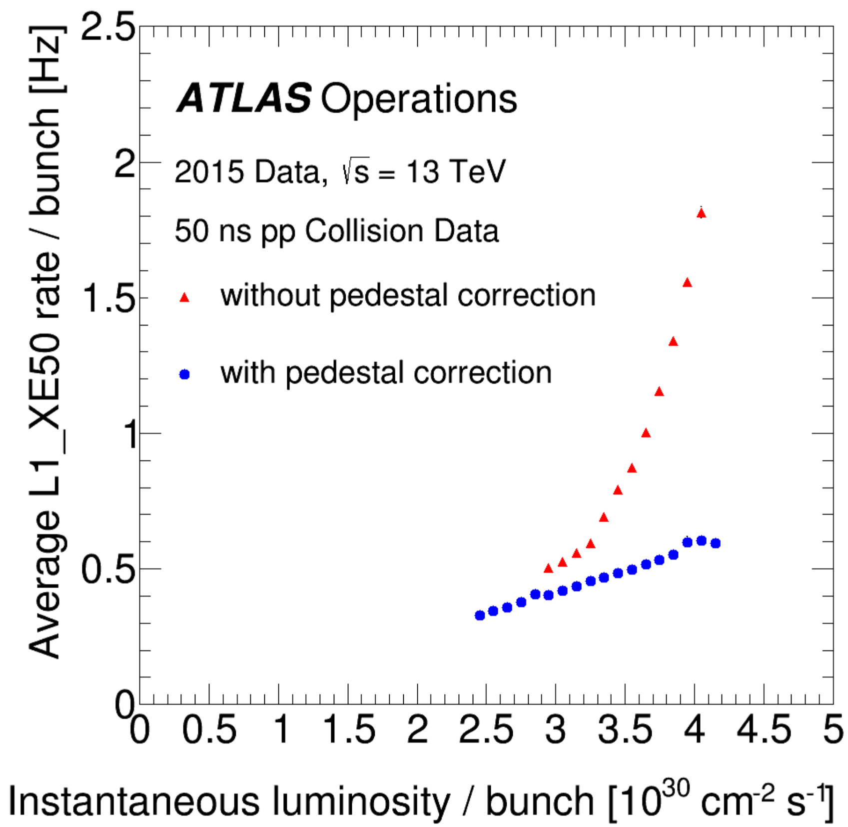


- Input signal conditioning, digitization and filtering done in PreProcessor daughterboards – Multi-chip-modules (MCMs)
- All being replaced by new FPGA oriented design (nMCM):
  - Better signal conditioning
  - Better pile-up filtering, taking into account pileup autocorrelation matrix
  - Better BC identification for saturated pulses
  - Dynamic baseline correction!!!

Overall improvement in L1 triggering

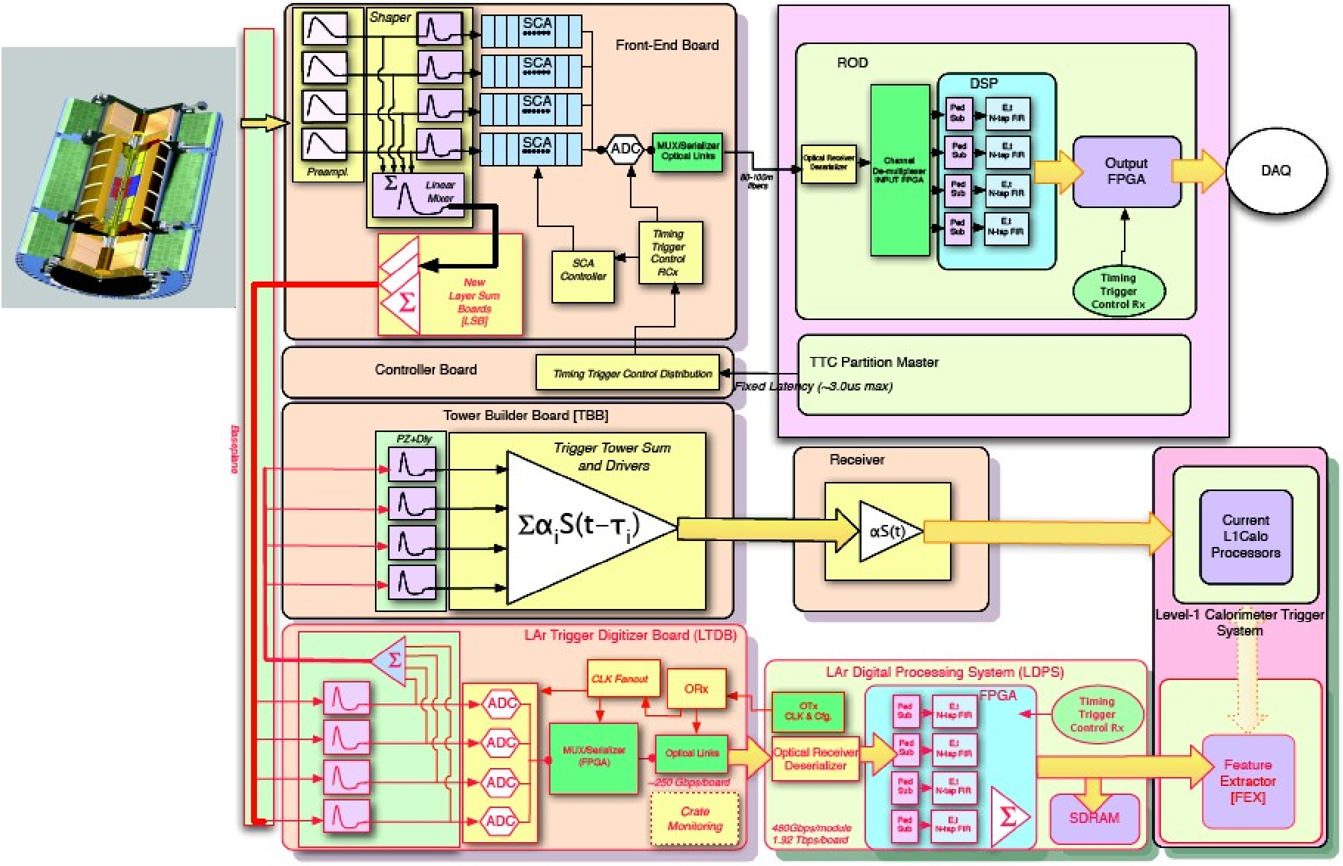
More details here





- Baseline (pedestal) correction calculated for each BC
- Average correction calculated over history of 65536 LHC orbits (~6s)
  - Subtracted from FADC counts before the tower energy is sent to digital processors
- Major improvements of global and multi-object rates!

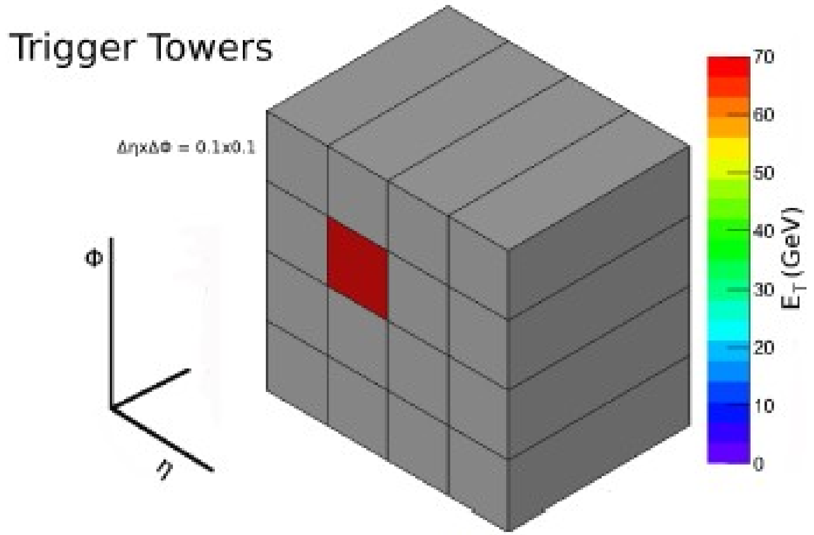
Phase I upgrade – Long Shutdown 2



- Major upgrade of LAr front-end electronics during LS2 (2018-2022)
  - Keeping old (legacy) analogue path untouched (almost)
  - New digital path
    - Digitisation of trigger signals on detector, improved granularity
    - Trigger Towers to SuperCells
    - Same latency of 2.5 μs as before Phase I upgrade

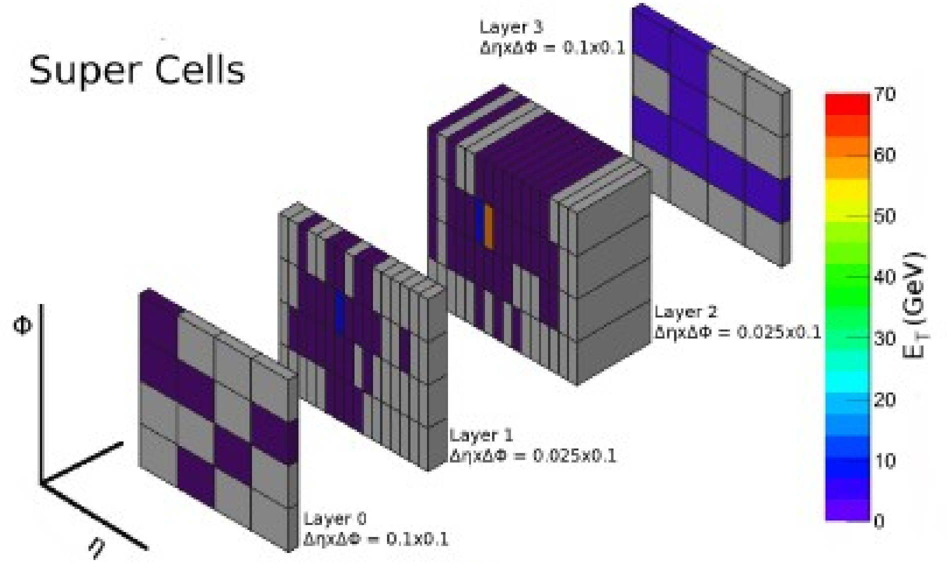
Phase I, changes to input signal granularity

Granularity of trigger signals before Phase 1 upgrade



(a)

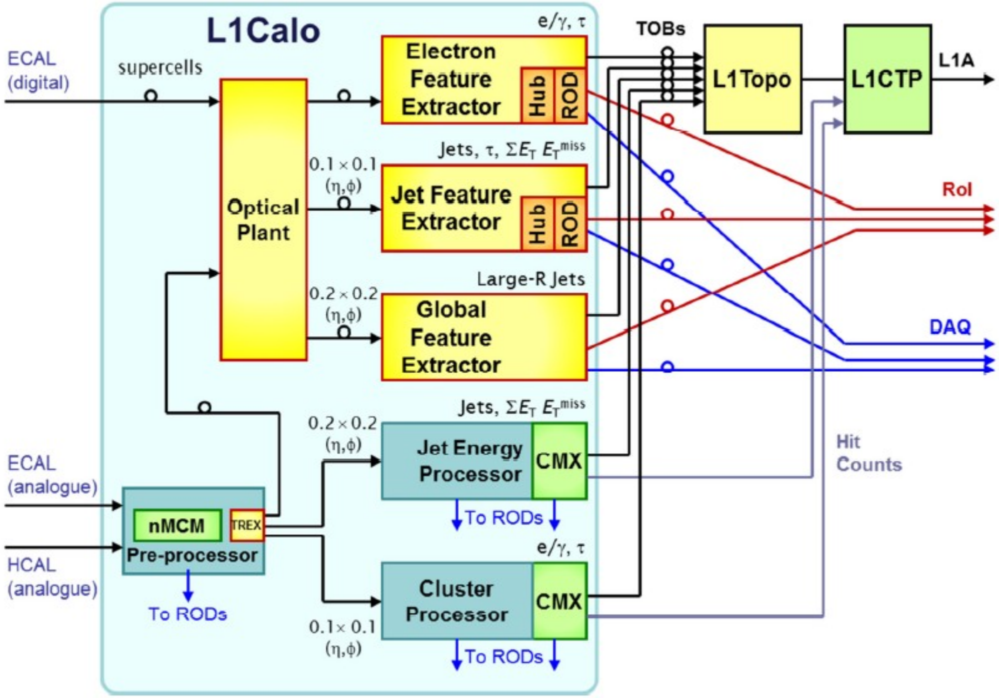
Granularity of trigger signals after Phase 1 upgrade



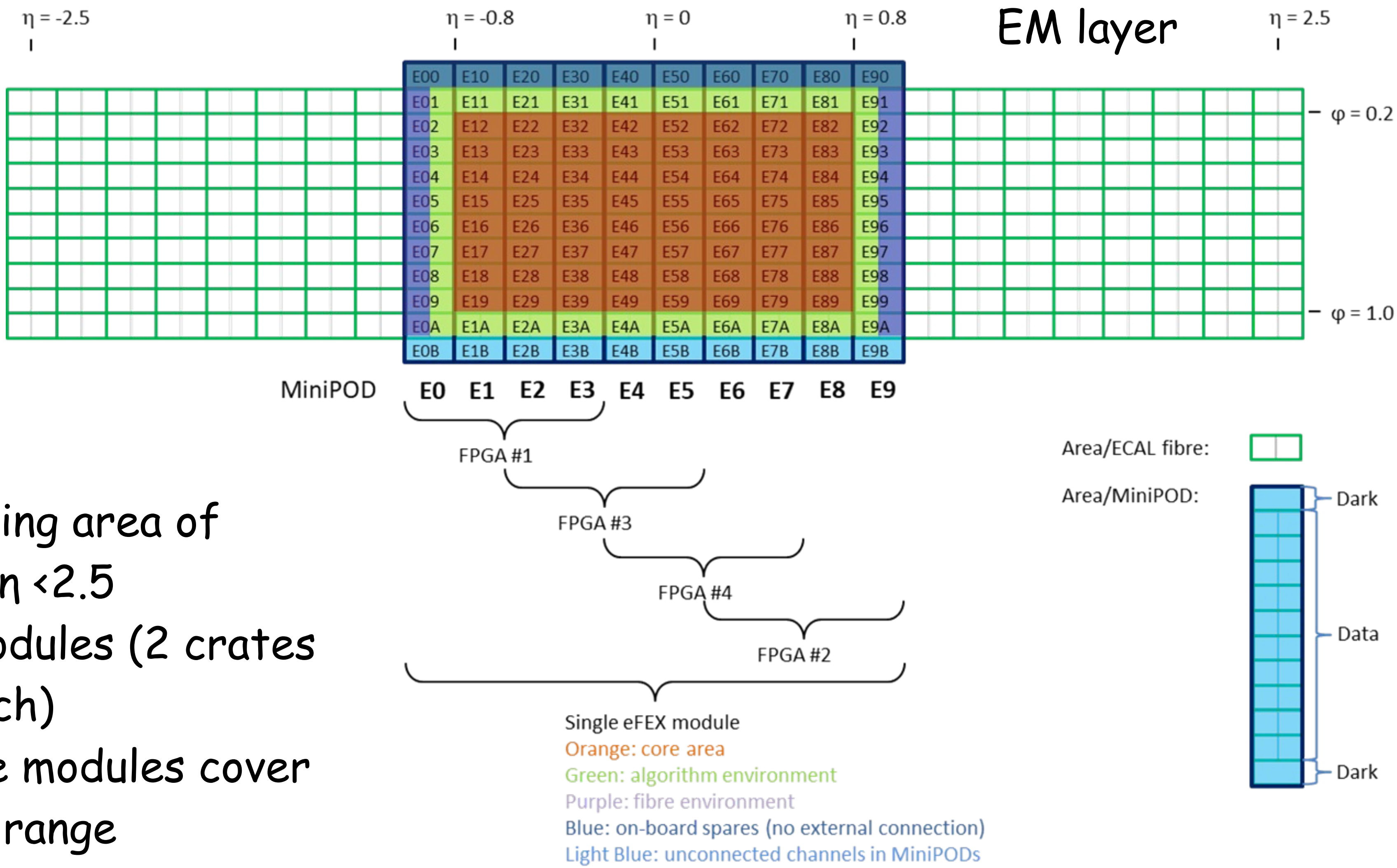
(b)

Phase 1 upgrades of L1Calo trigger

- To fully benefit from digital trigger signals from Lar new digital trigger processors built
  - Efex – electrons, photons and hadronic taus
  - Jfex - jets, forward electrons and global sums
  - Gfex – wide jets and global sums
- Gradual move from old to new system:
  - At the beginning of Run3 used legacy
  - In 2023 started to switch over
  - Migration finished in 2024, legacy system not used any longer
    - In next slides will focus on eFex

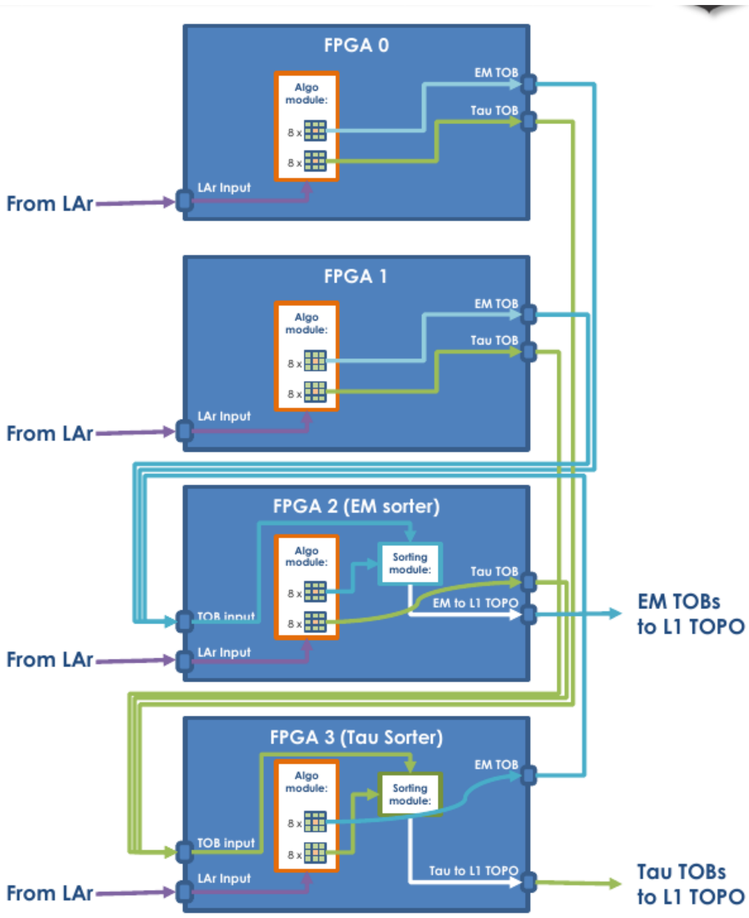


The eFex system, basic geometry



- Covering area of -2.5 <η <2.5
- 24 modules (2 crates 12 each)
- Three modules cover full η range
- Eight modules cover full Φ range

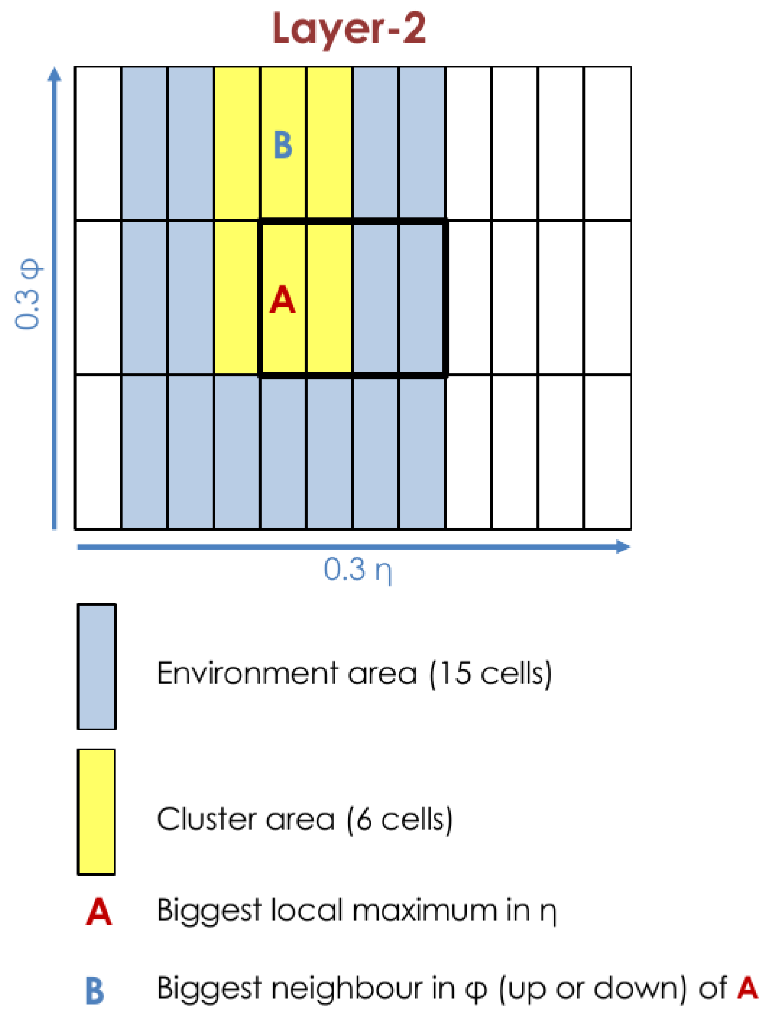
Efex board design



- Four processor FPGAs
- Two of them merge results (one em/gamma, one tau) before sending output into L1Topo

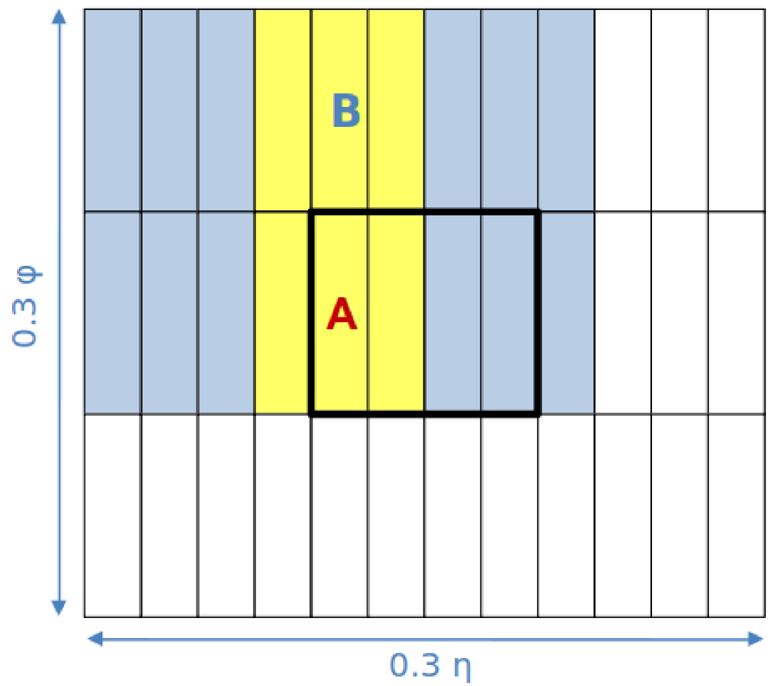
EM algorithm

- Electron algorithm:
  - Find seed (local maximum and biggest SC in TT in Layer 2) and direction of the cluster
  - Sum-up layers, calculate cluster (ToB) energy
  - Calculate isolation variables:
    - R_η
    - W_s
    - R_{had}
  - Compare each isolation variable with three thresholds, calculate "isolation bits"
  - Re-calibrate ToB energy, send to Topo and readout
- Parameters:
    - Minimum ToB energy threshold
    - Maximum ToB energy to apply isolation
    - R_η (x3), W_s(x3),E_{had}(x3) thresholds
  - All coming from trigger menu!

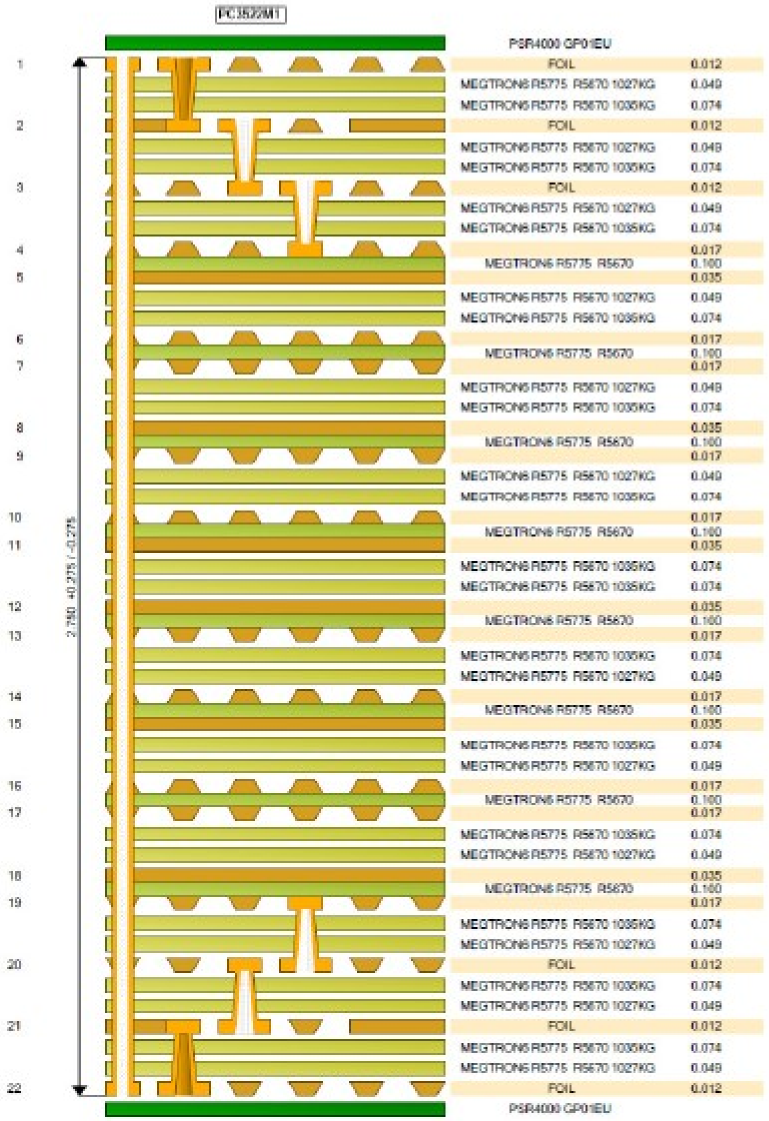


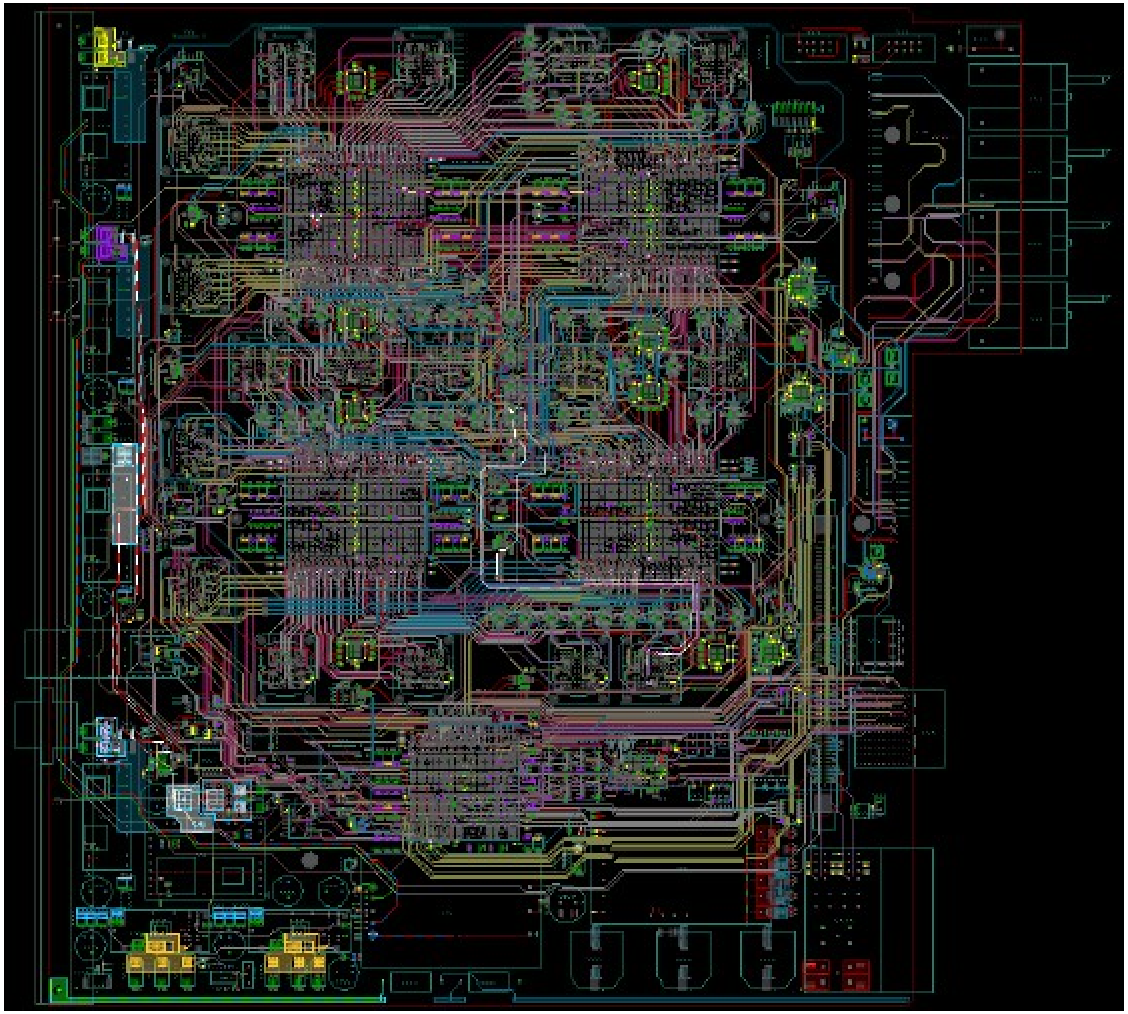
TAU algorithm

- Tau algorithm:
  - Find seed (two seed finders, biggest TT and SC in TT) and the direction of the cluster
  - Sum-up layers, calculate cluster (ToB) energy
  - Calculate isolation variables:
    - Jet Veto (like R_η but different size)
    - Frac (like E_{had} but different layers, long-lived particles)
  - Compare each isolation variable with three thresholds, calculate "isolation bits"
- Parameters:
    - Minimum ToB energy threshold
    - Maximum ToB energy to apply isolation
    - JetVeto (x3), Frac(x3) thresholds
  - All coming from trigger menu!

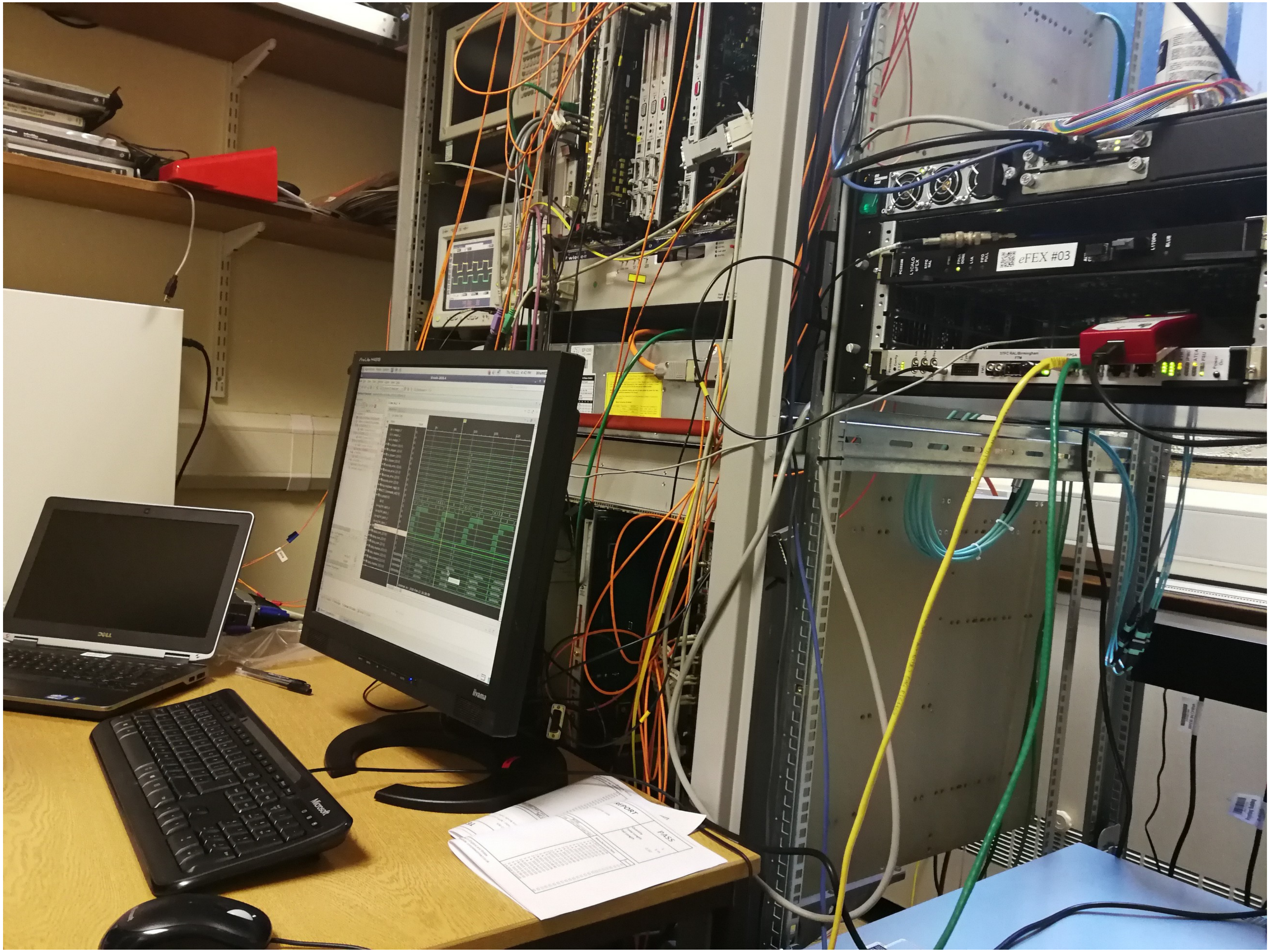


eFEX PCB design



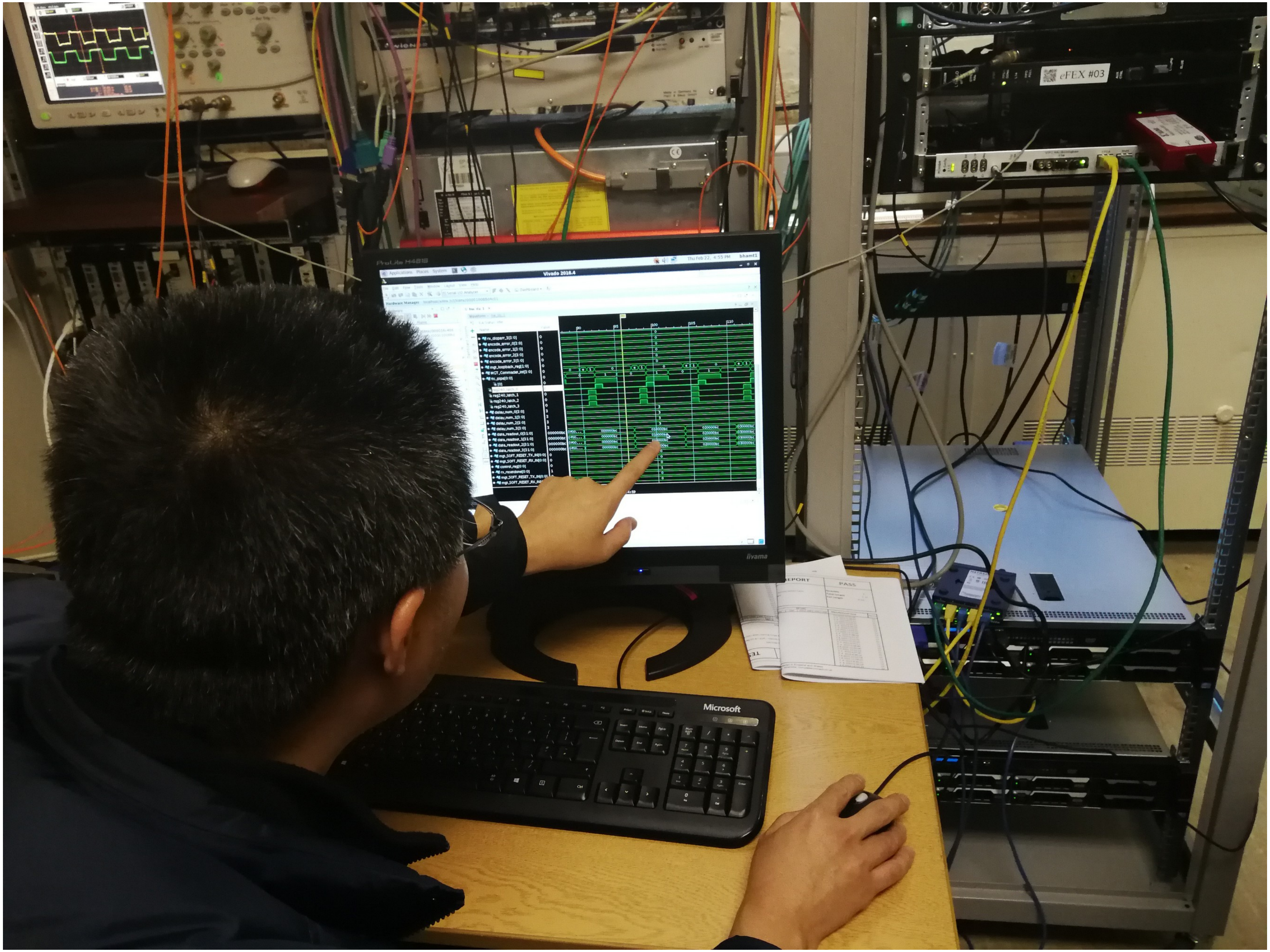


Early eFEX prototype board and firmware tests I

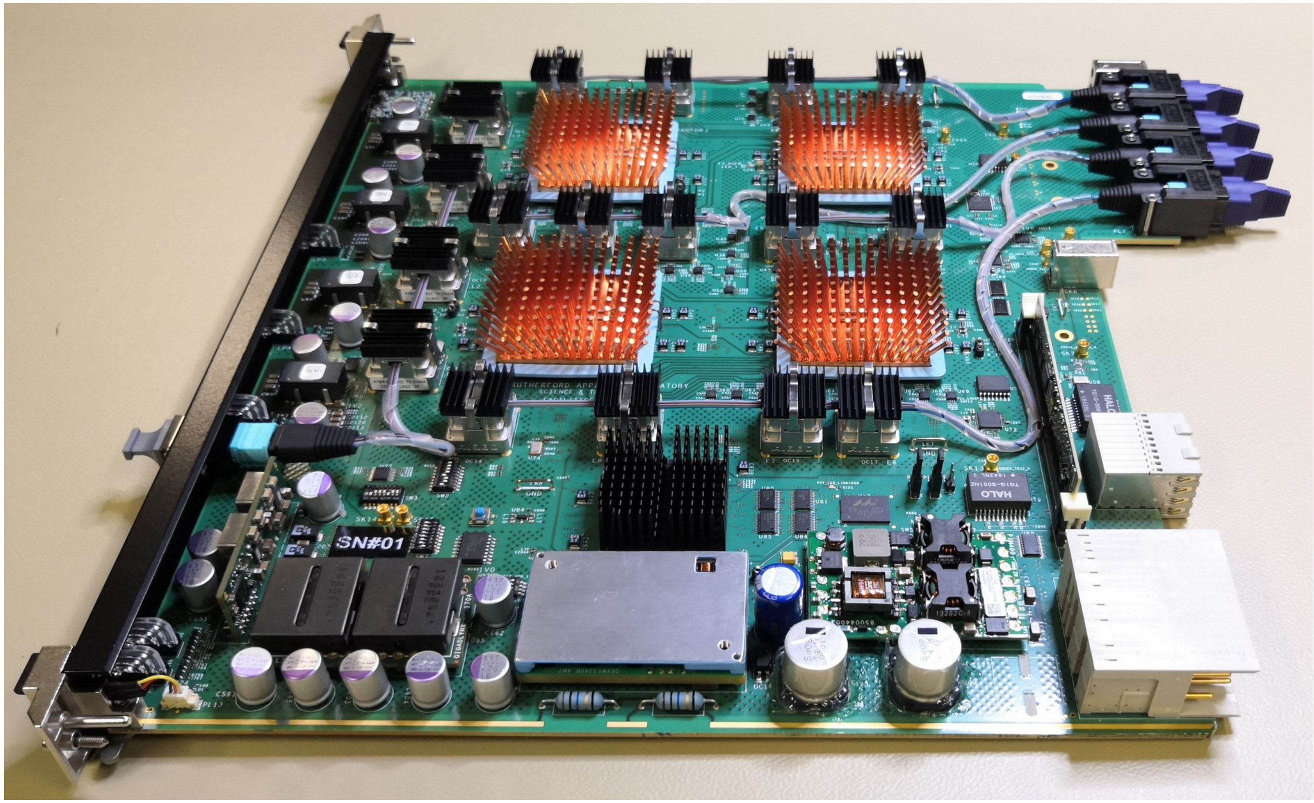


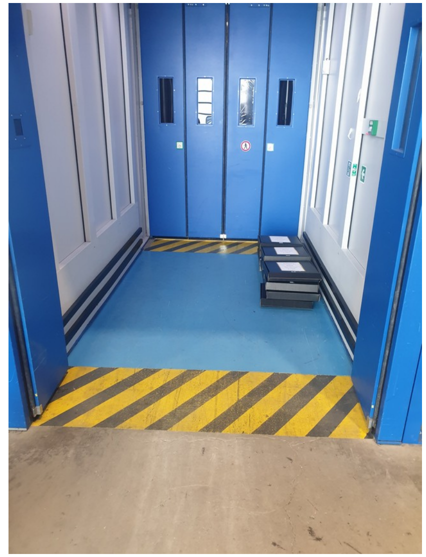
Early eFEX board and firmware tests II

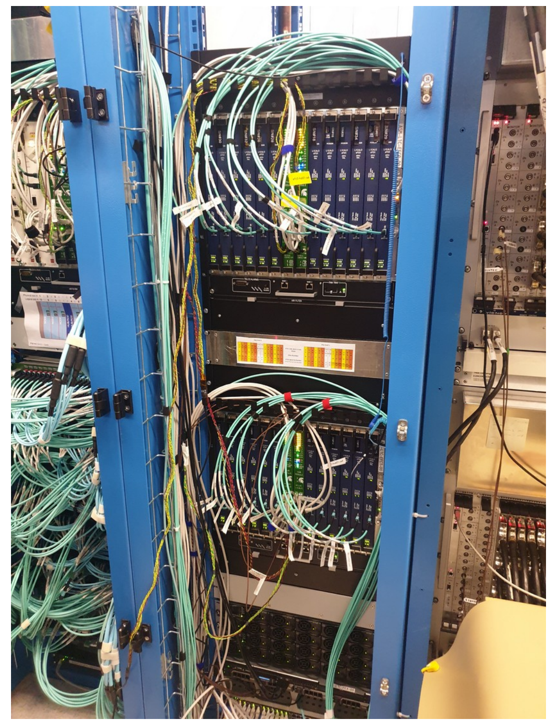
Early eFEX board and firmware tests III



eFEX -production board






Final system installation in Sep 2022

One of new processors (eFex) in numbers

Data flow through the system (eFex):

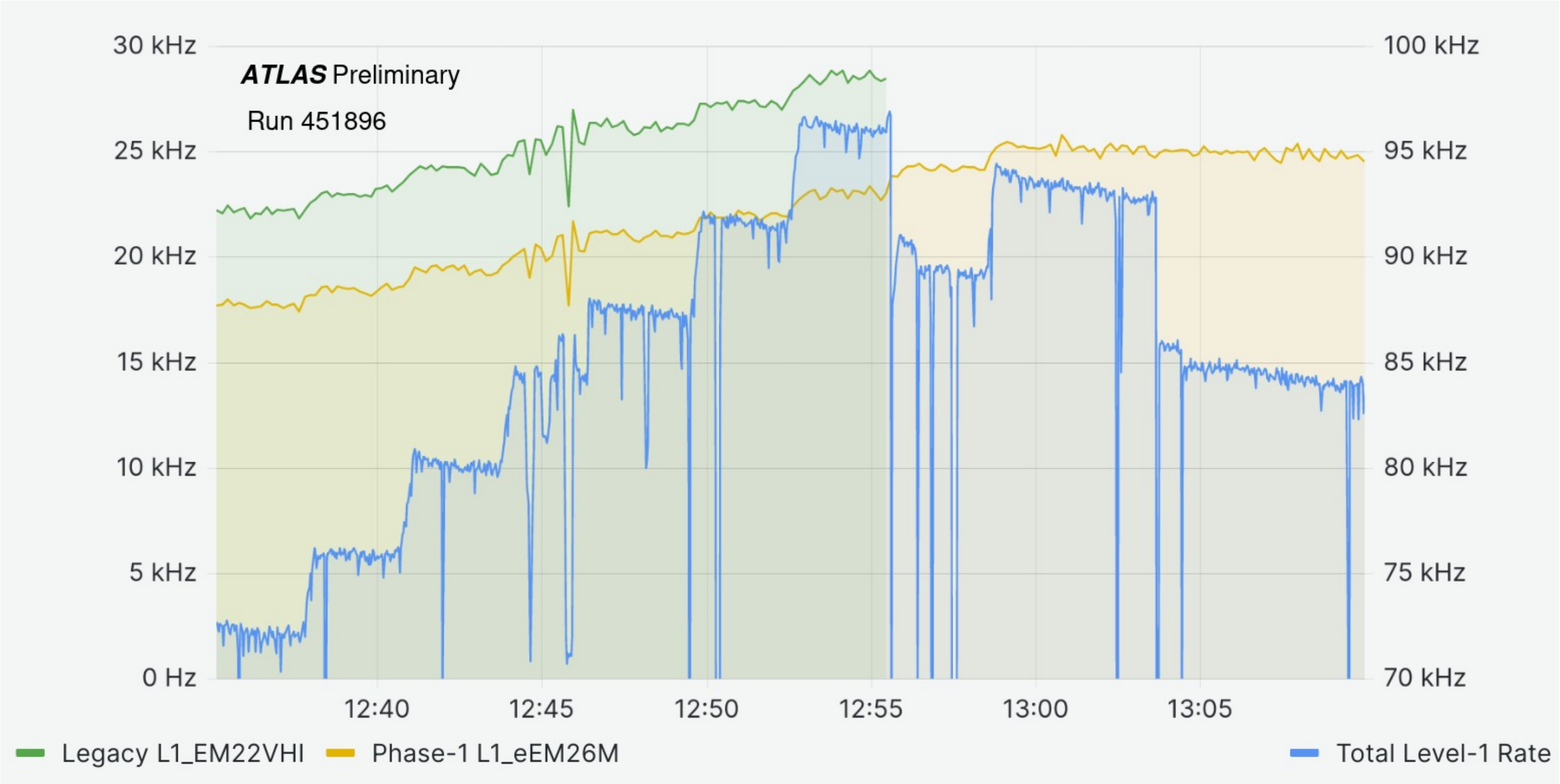
- 24 electronic modules
- 4 programmable FPGA chips on each module
- 58 optical fibres/FPGA
- 20 useful data words/LHC tick
- 10 bits/data word
- 40 MHz LHC collision frequency (25 ns is LHC tick)
- After multiplication we get ~40000 Gb/s

Typical phone chat (mobile phone or WhatsApp):

- 100 kbit/s

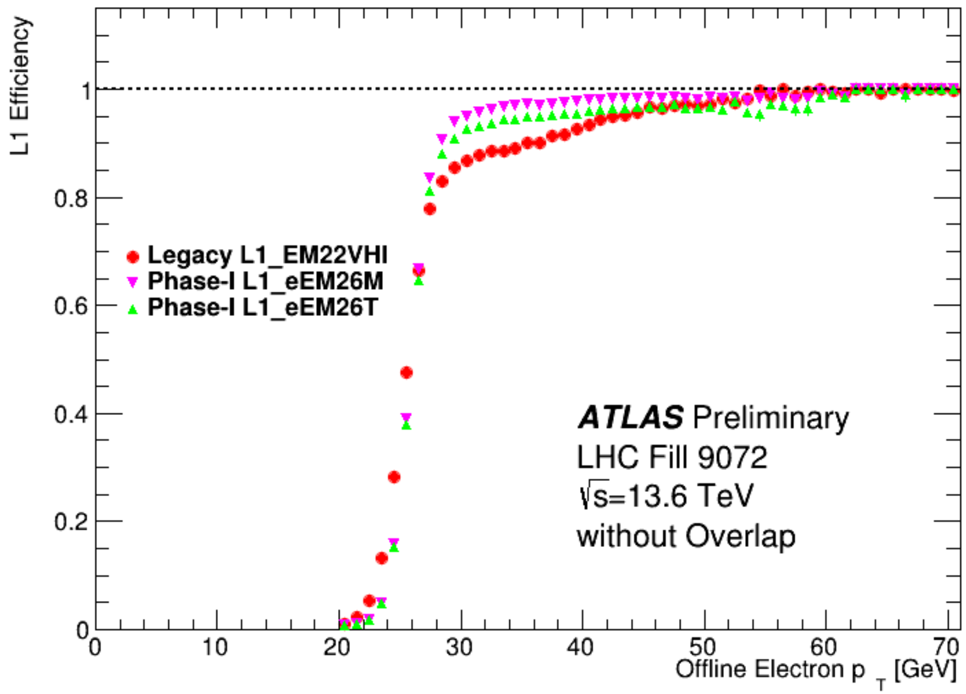
~ 400 M phone chats, all of them routed and processed by a system that is as big as average bookshelf

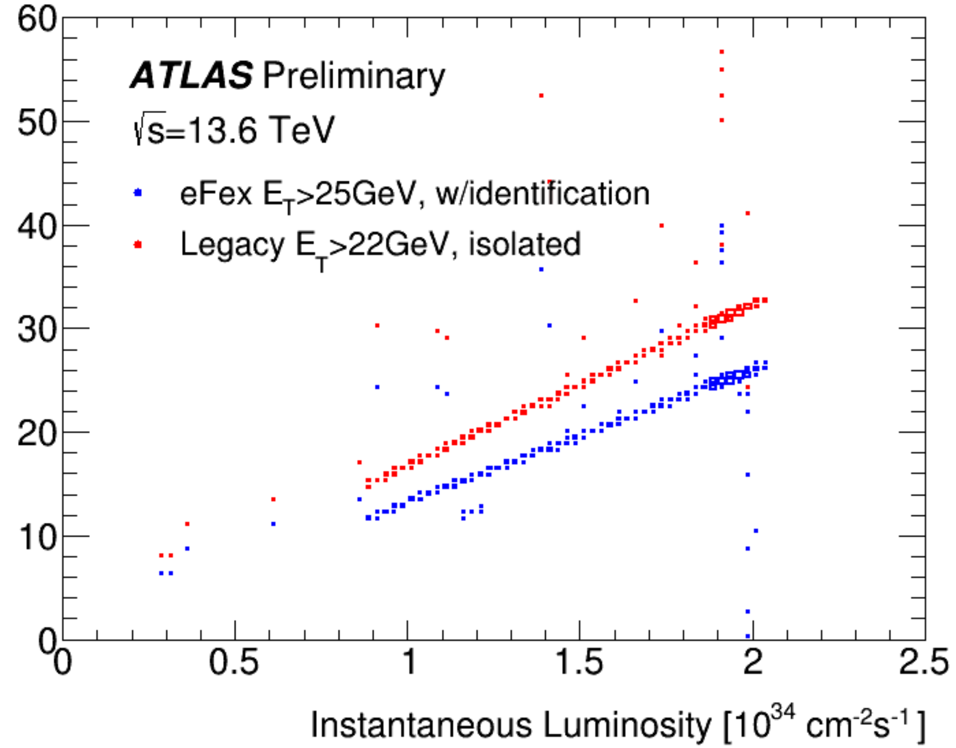
eFEX electron trigger performance I



Switch over from main legacy electron trigger to Phase 1 system (more details here)

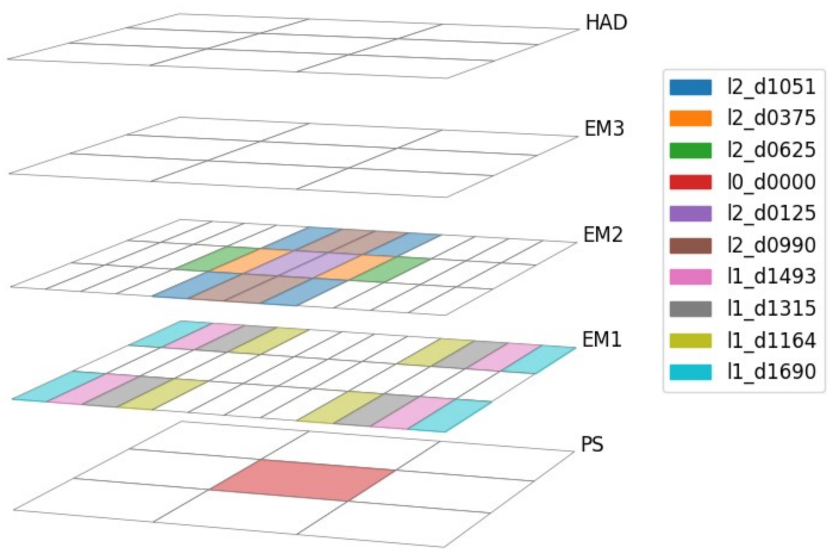
eFEX electron trigger performance II

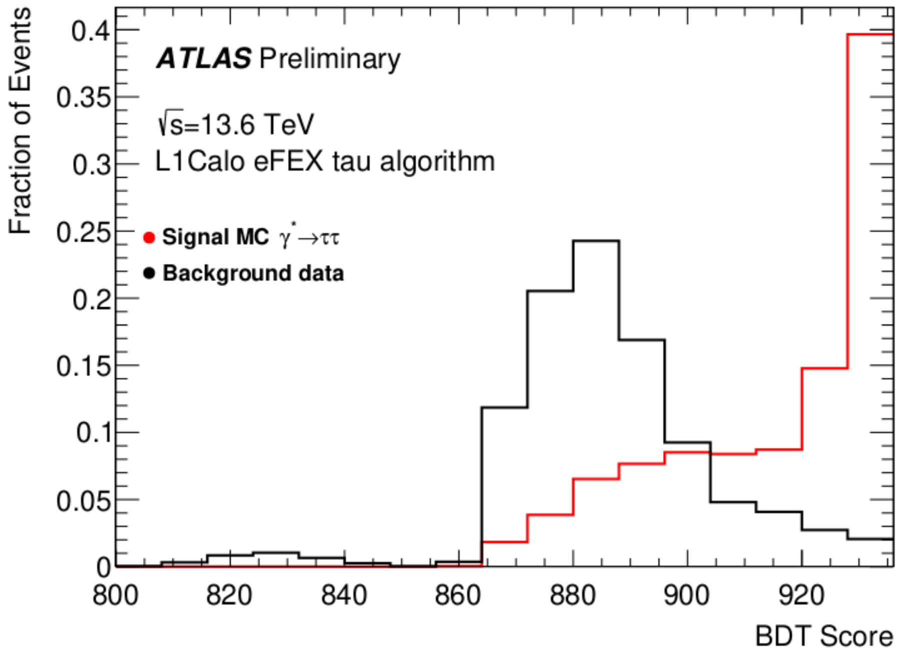




- Comparison of legacy electron trigger with Phase I trigger more details
  - This is first, not very well tuned eFex trigger (several calibrations updated in the mean time)
  - Better (lower) trigger rate
  - Better efficiency

Upgrades of eFex tau trigger





- In 2024 switched from heuristic tau trigger algorithm described before to ML based algorithm
  - Find local cluster
  - Then run Boosted Decision Tree to identify isolated taus
    - After several re-tunings performs better than heuristic algorithm
    - Hope to benefit fully in 2025
    - More details here

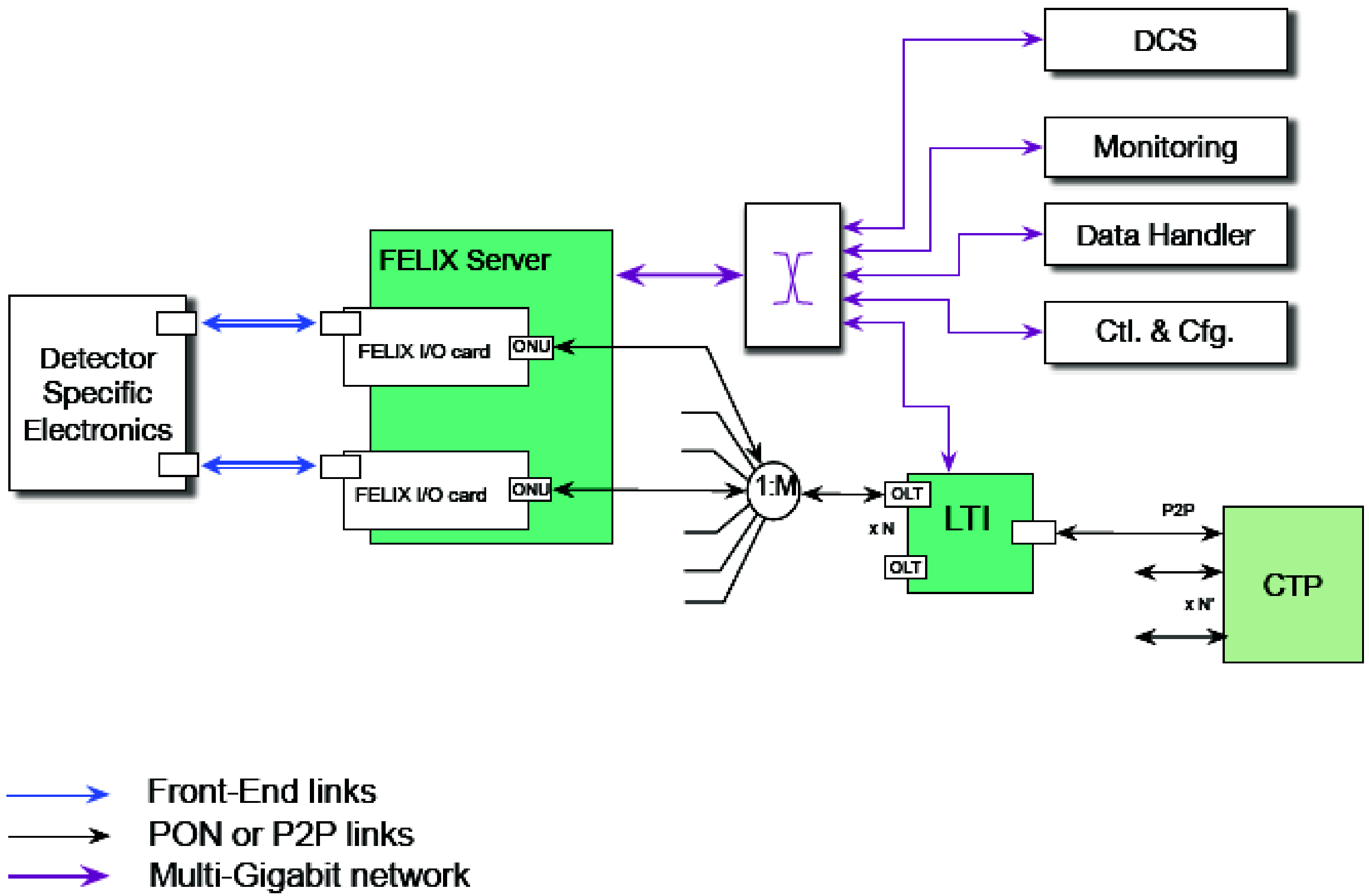
Conclusions

Conclusions

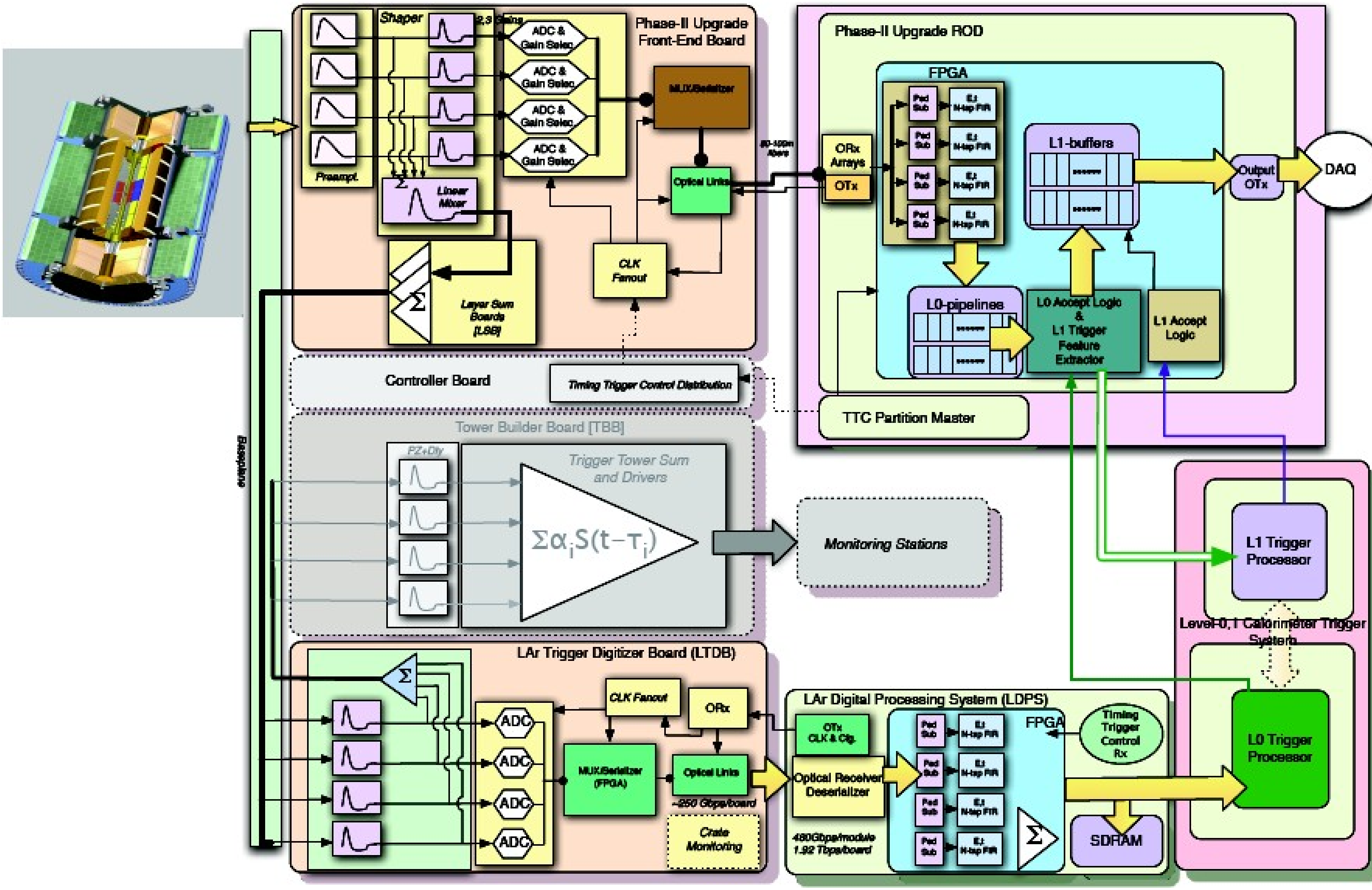
- To fully benefit from LHC capabilities, ATLAS has developed a sophisticated, multi-level trigger
- Extensive upgrades whenever possible
  - (parts of) detectors
  - (most of) electronics
  - Combination of small adiabatic changes and revolutionary architectural modifications allow to cope with increasing luminosity and pile-up and fully exploit ATLAS physics potential

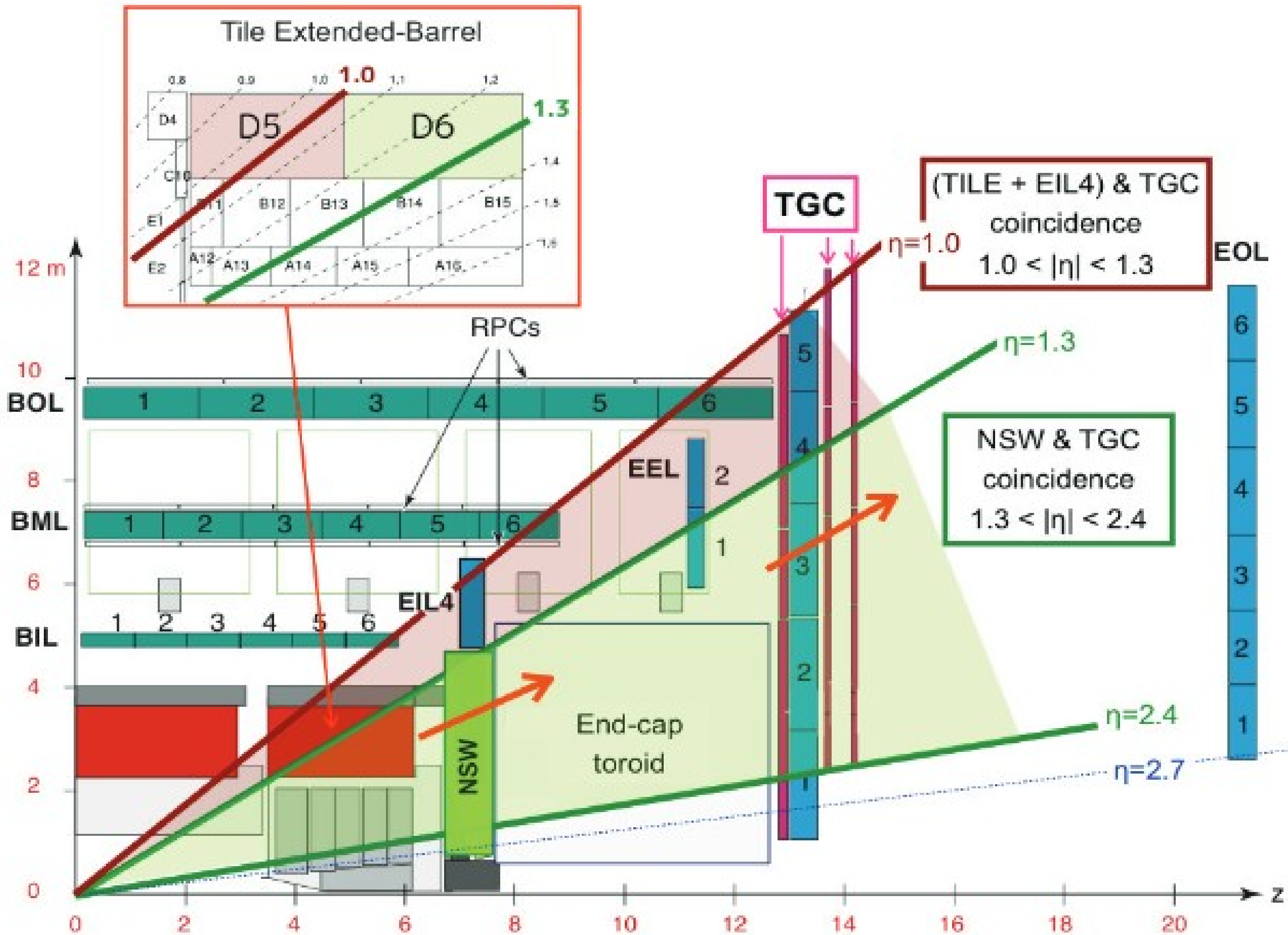
Slides that weren't good enough to make it into the talk

FELIX as TTC interface



Phase 2 LAr front-end

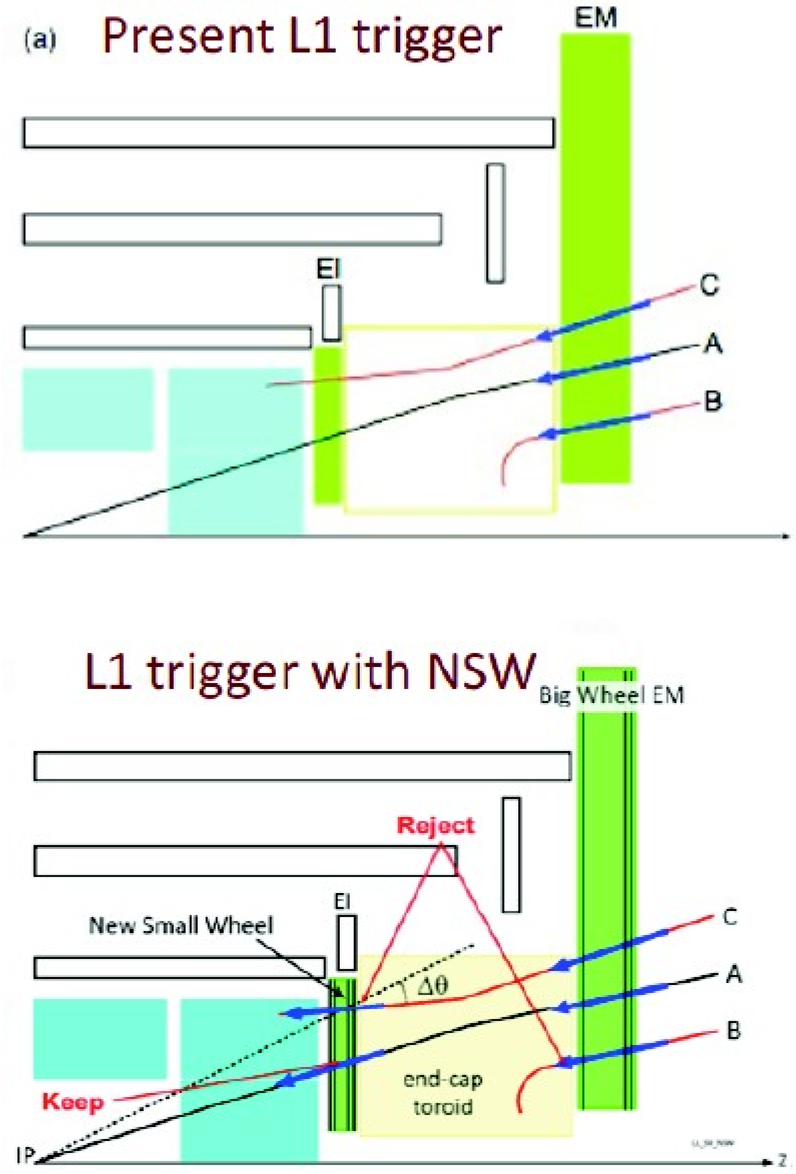




Tile Extended-Barrel
1.0
1.3
D5
D6
TGC
(TILE + EIL4) & TGC
coincidence
1.0 < |η| < 1.3
η=1.0
EOL
η=1.3
RPCs
BOL
BML
BIL
EEL
EIL4
NSW & TGC
coincidence
1.3 < |η| < 2.4
NSW
End-cap
toroid
η=2.4
η=2.7
12 m
z

Phase 1 upgrades of L1 trigger I

- Muon trigger rate in forward region dominated by fakes
- New muon detector in the forward area – New Small Wheel:
  - Detector technologies:
    - Micromegas
    - Small-strips Thin Gap Chambers (sTGC)
  - New sector logic and interface to Central Trigger

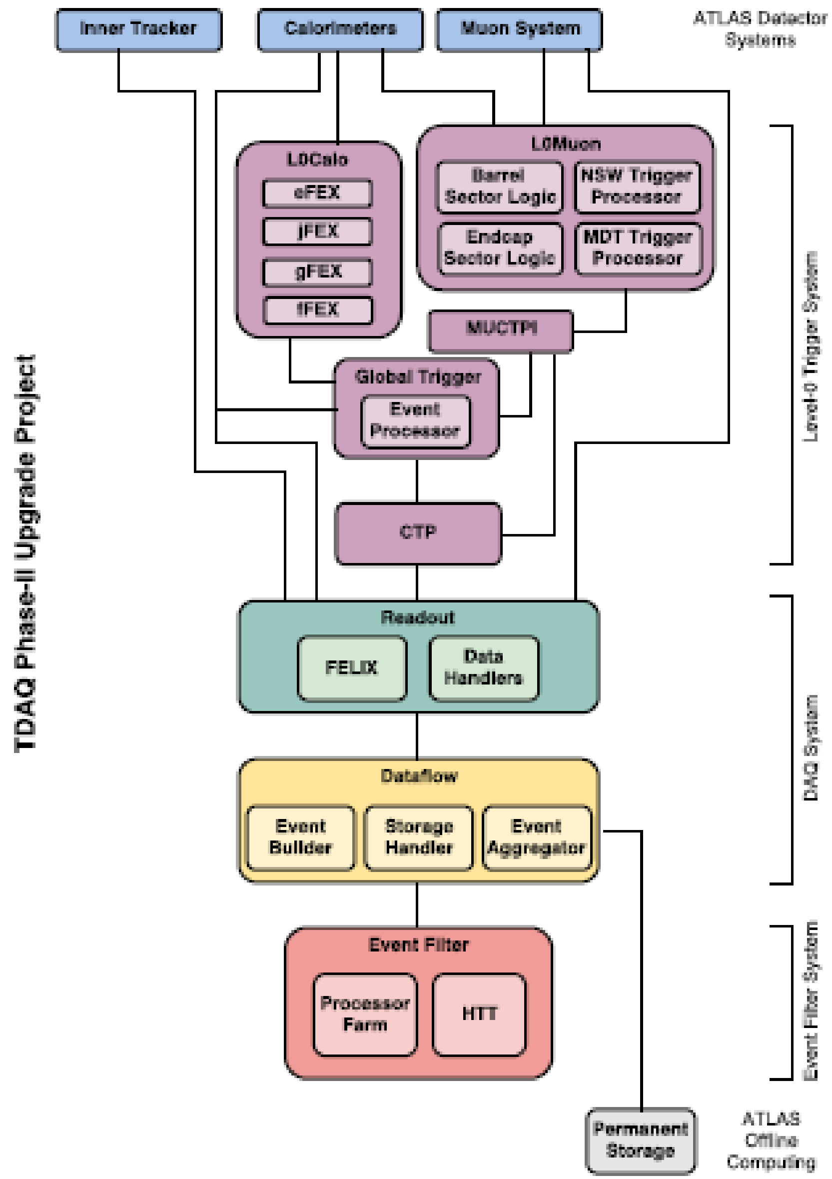


Phase 2 upgrades of ATLAS trigger

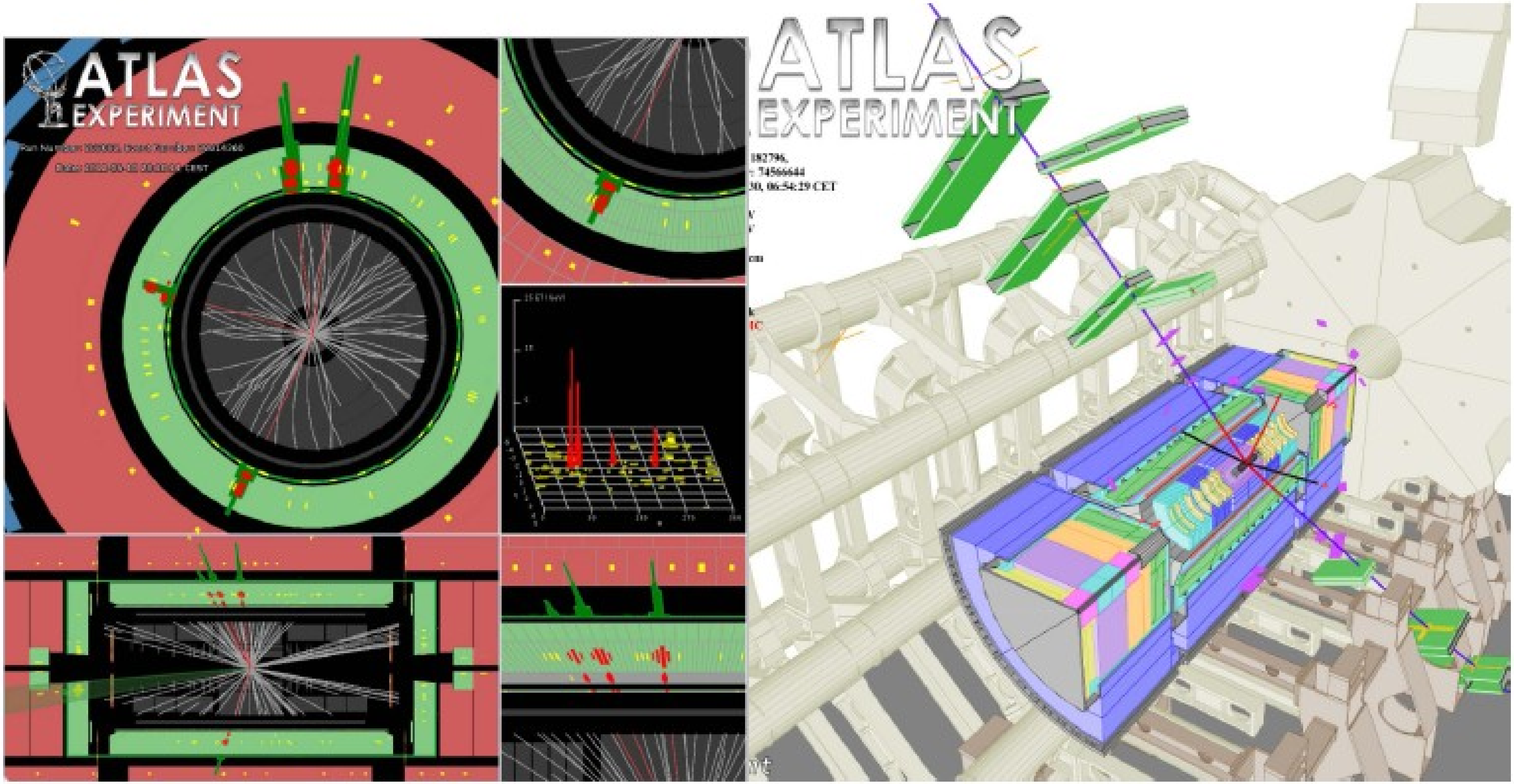
- Keep one HW and one SW level architecture
- Both levels see changes!

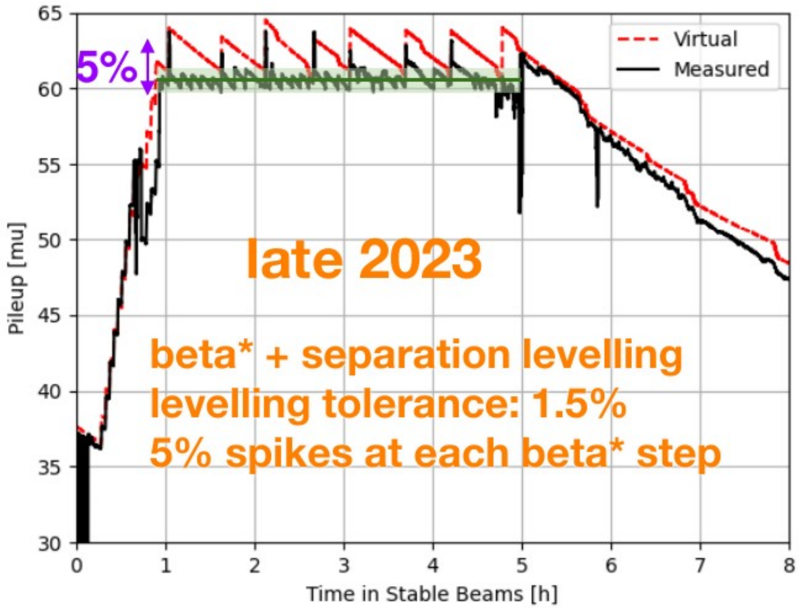
Hardware level:

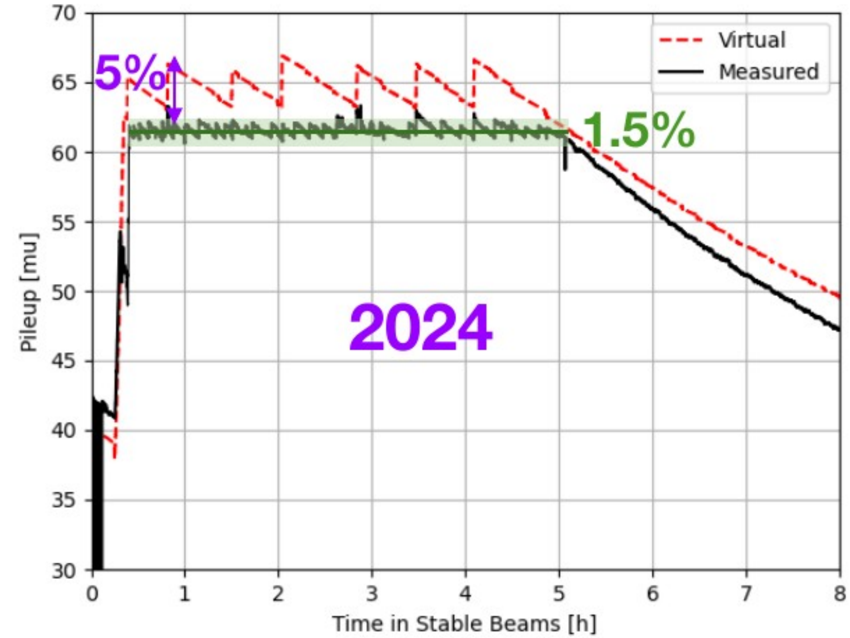
- Changes name (L1 to L0 :-))
- New Global trigger processor
  - Time multiplexed architecture
- (possible) new Timing Detector (High Granularity Timing Detector, HGTD)
- Muon Drift Tube (MDT) information added to trigger
- New Resistive plate chambers in the barrel to improve muon triggering



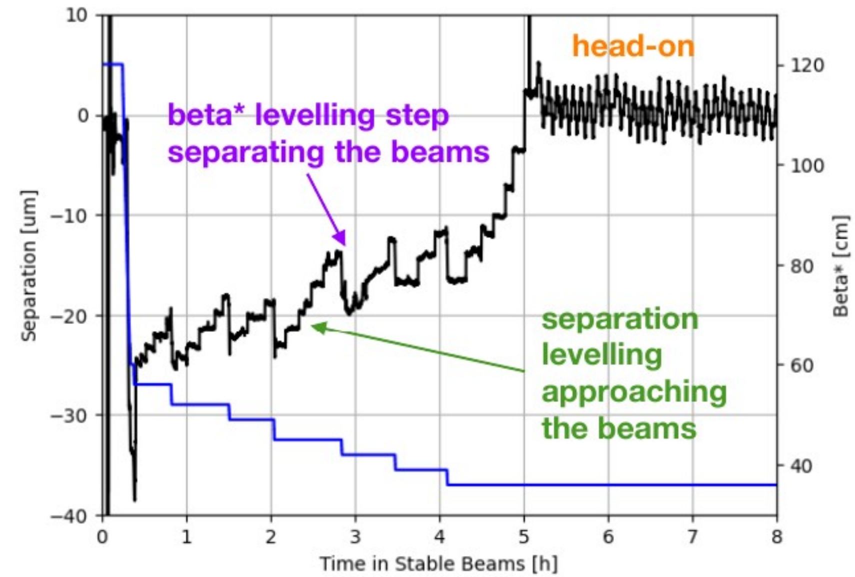
Regions of Interest (RoIs)

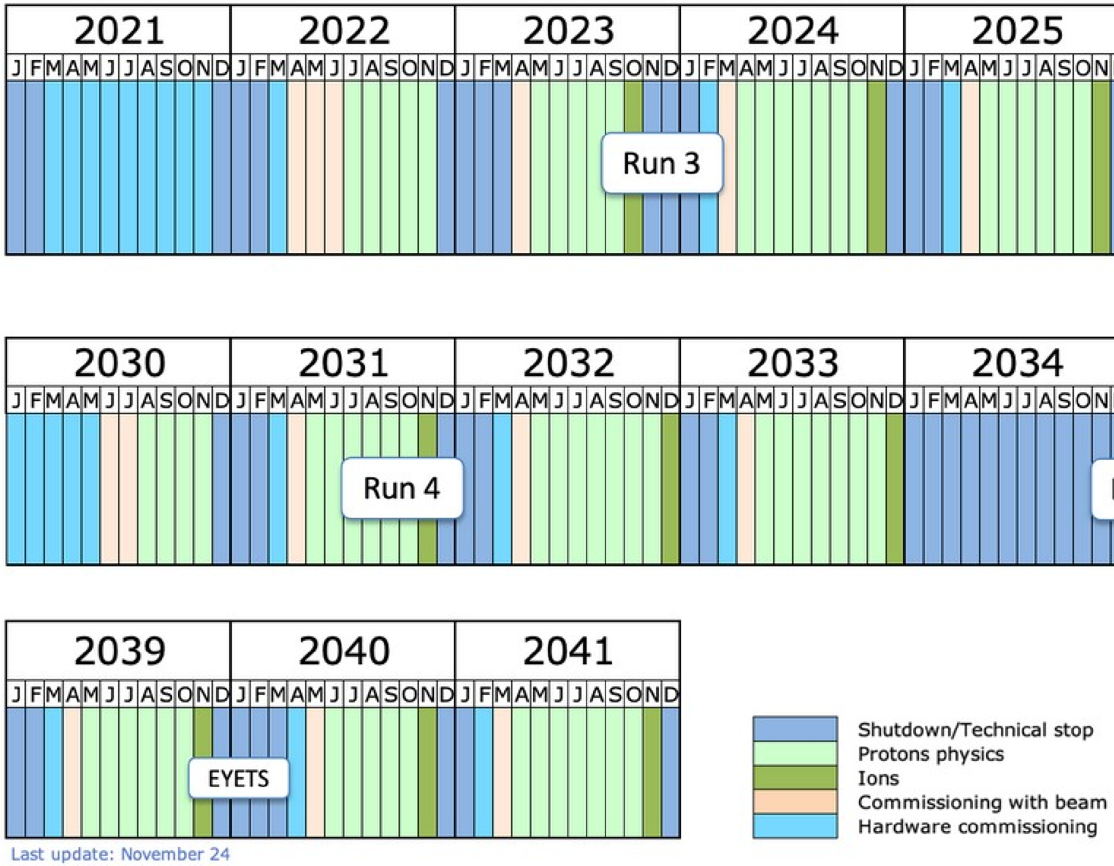




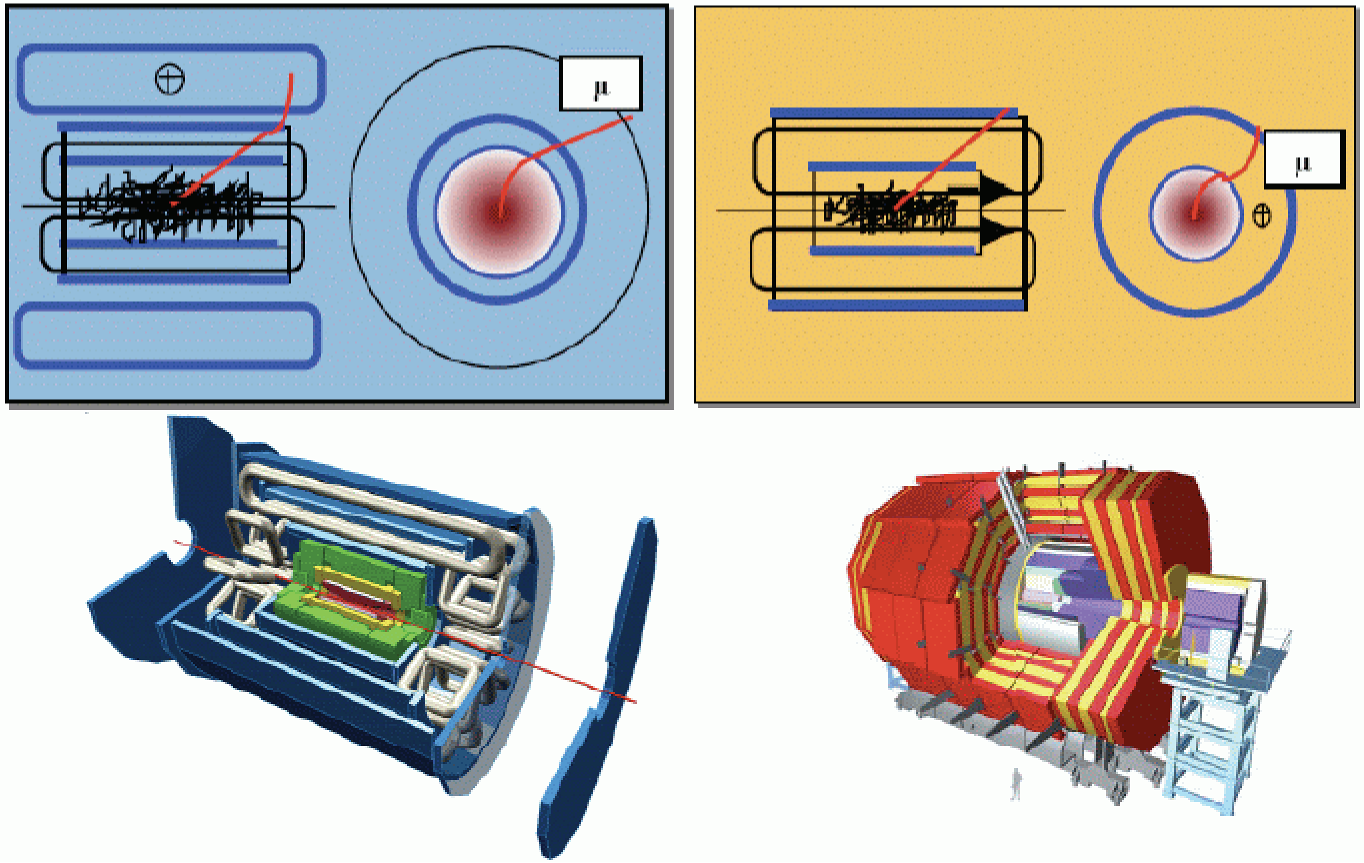


- Levelling strategy developing over time
- Recently combination of two effects
  - Separation of beams
  - β* separation

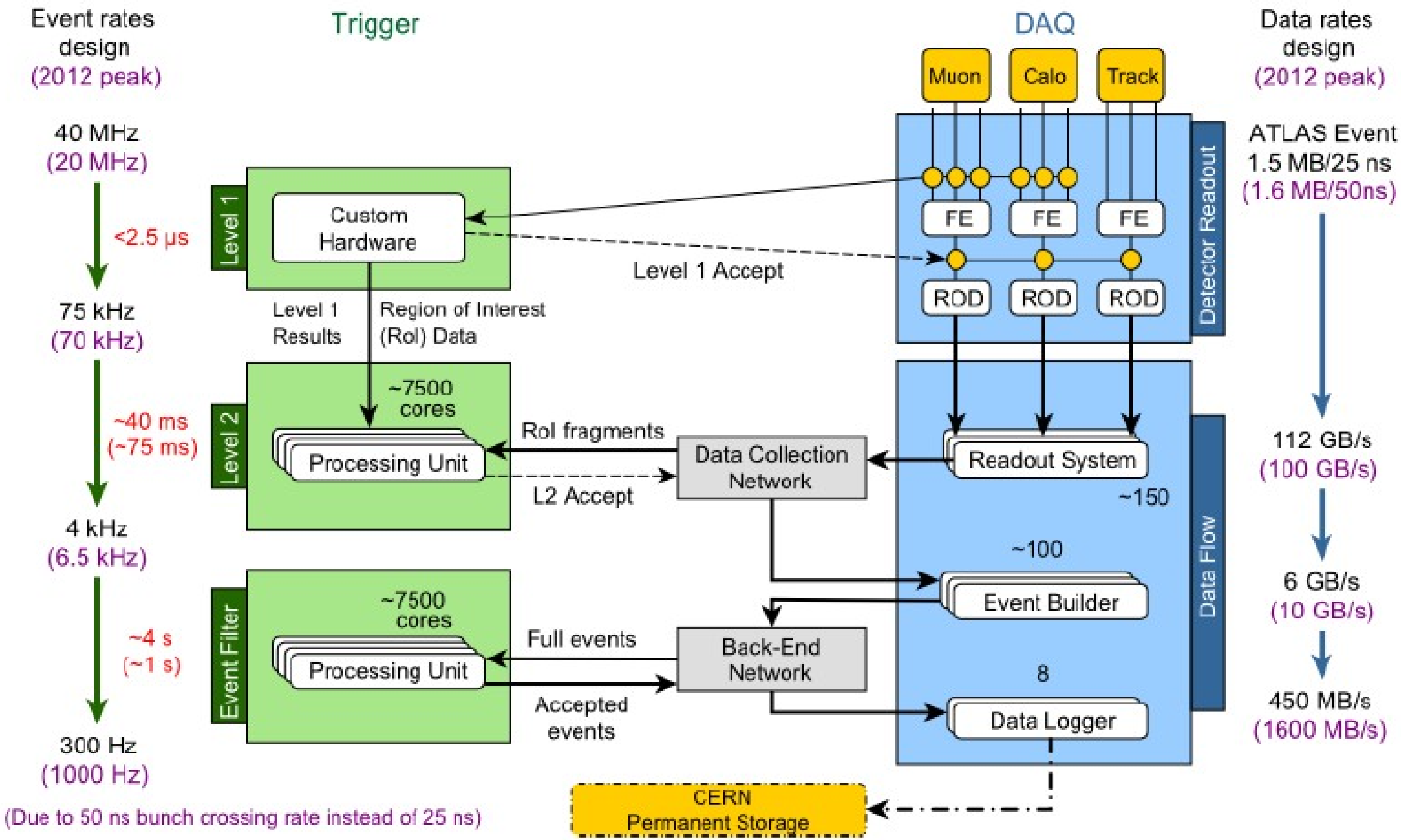



2021
2022
2023
2024
2025
2026
2027
2028
2029
Run 3
Long Shutdown 3 (LS3)
2030
2031
2032
2033
2034
2035
2036
2037
2038
Run 4
LS4
Run 5
2039
2040
2041
EYETS
Last update: November 24
Shutdown/Technical stop
Protons physics
Ions
Commissioning with beam
Hardware commissioning

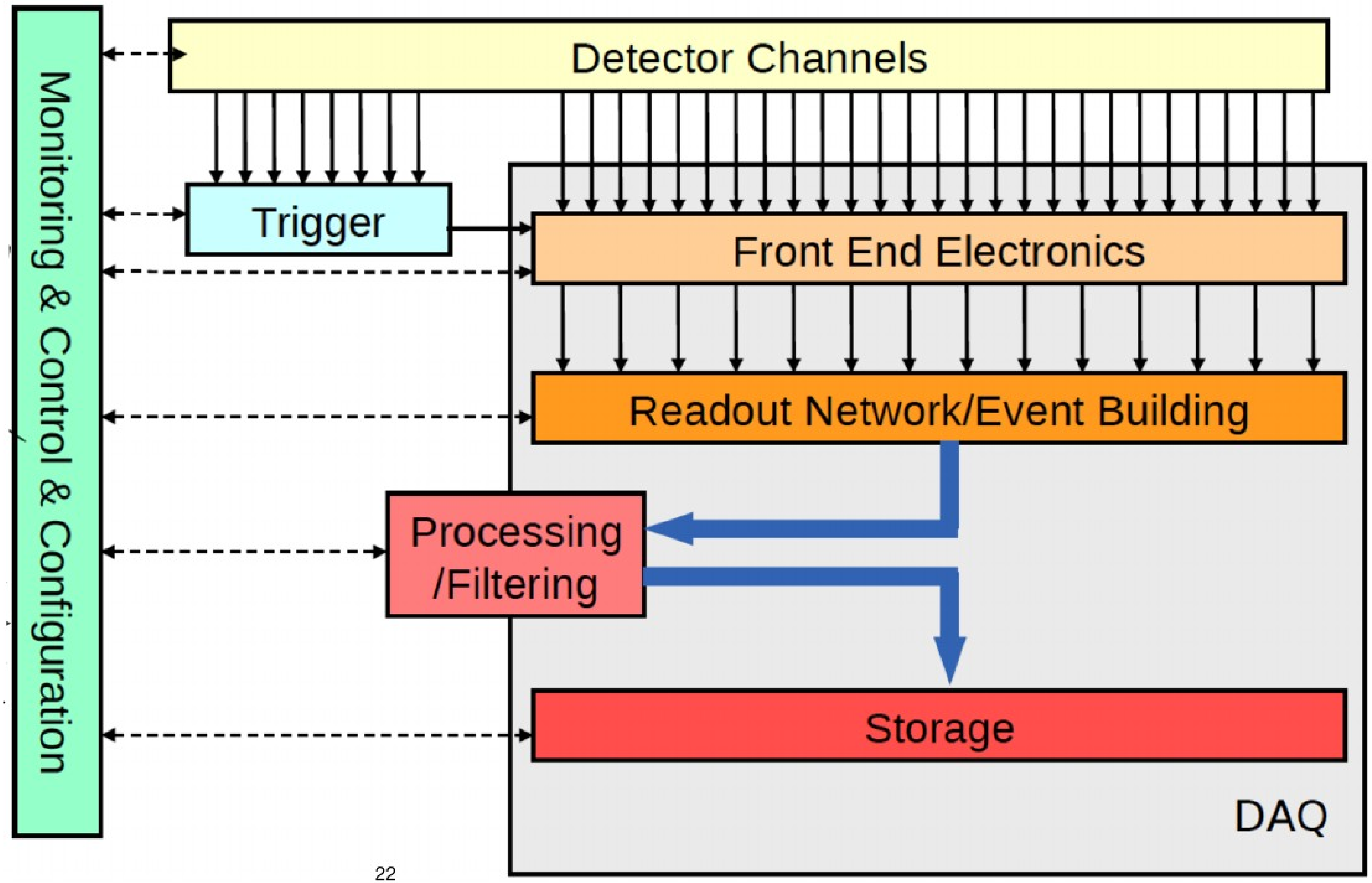
A Toroidal LHC ApparatuS | Compact Muon Solenoid



High Level Trigger during Run1

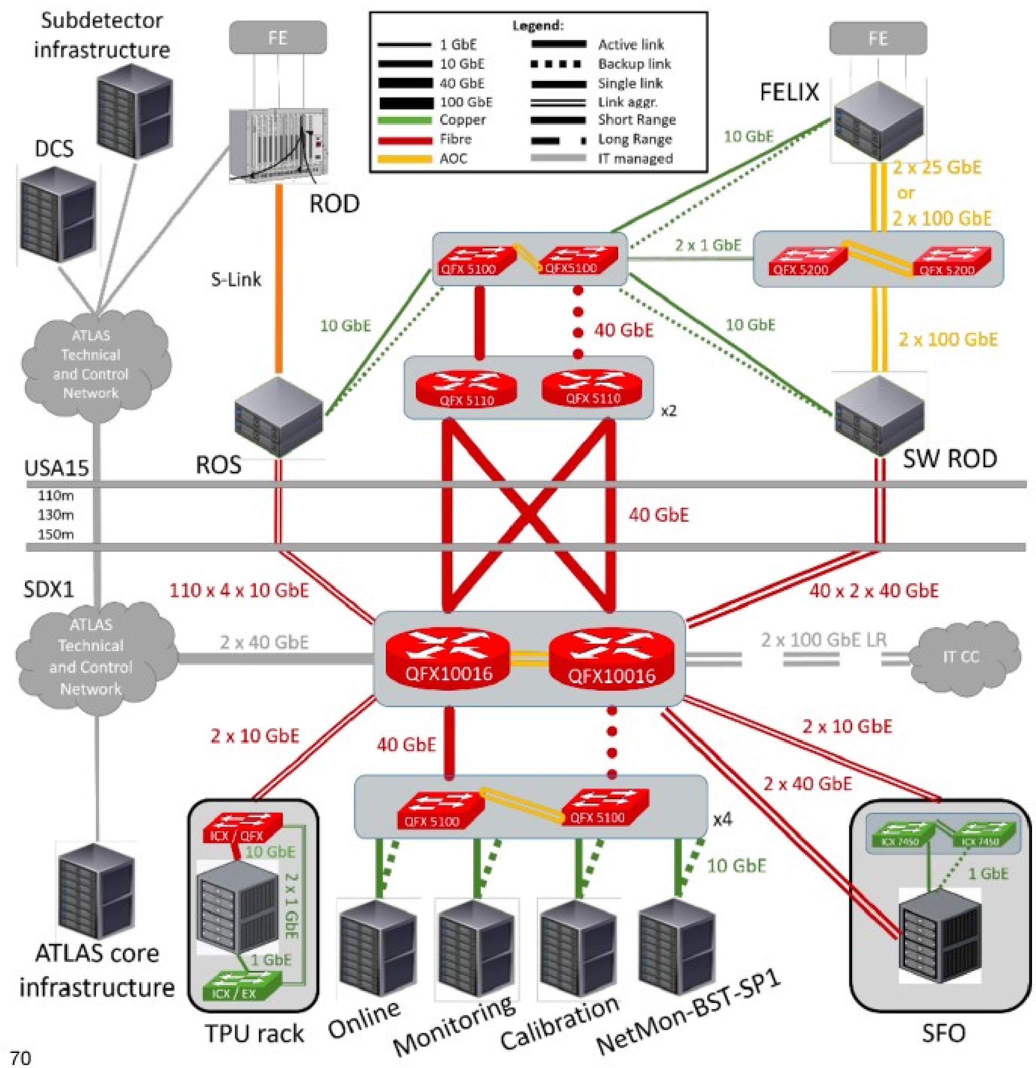


High Level trigger

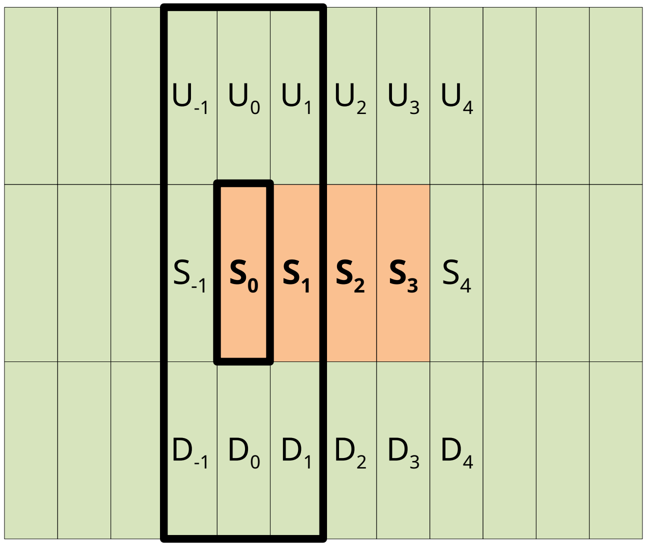


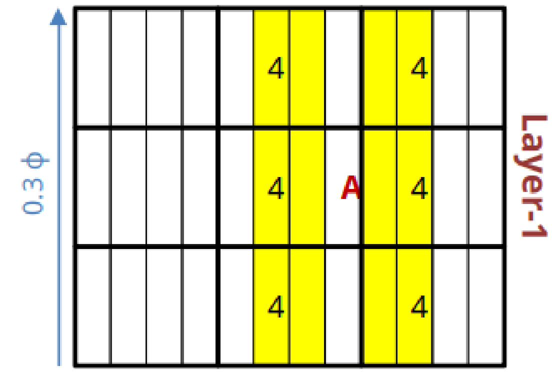
The DAQ network

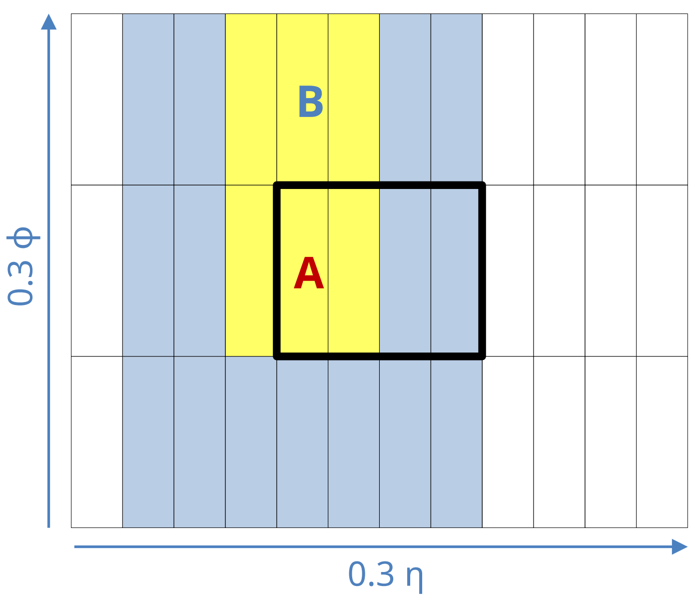
- The network system is the backbone of the ATLAS DAQ system
  - Multi-gigabit per second Ethernet infrastructure
  - Focus on high availability and performance
- Spans from USA15 to SDX1
  - Hundreds of > 150m long fibers
- Different virtual networks are provided
  - Main ones are DAQ control network for TDAQ control traffic and DAQ data network for Physics data traffic
  - Great degree of redundancy, can cope with all foreseeable single-component faults

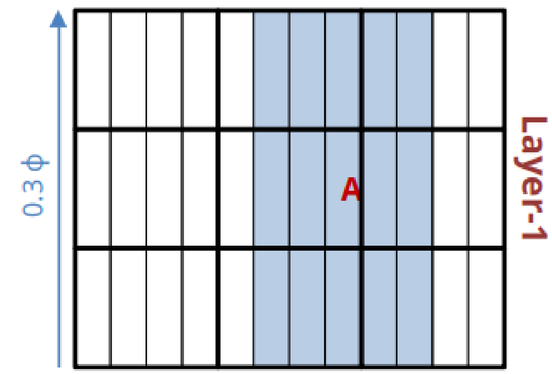


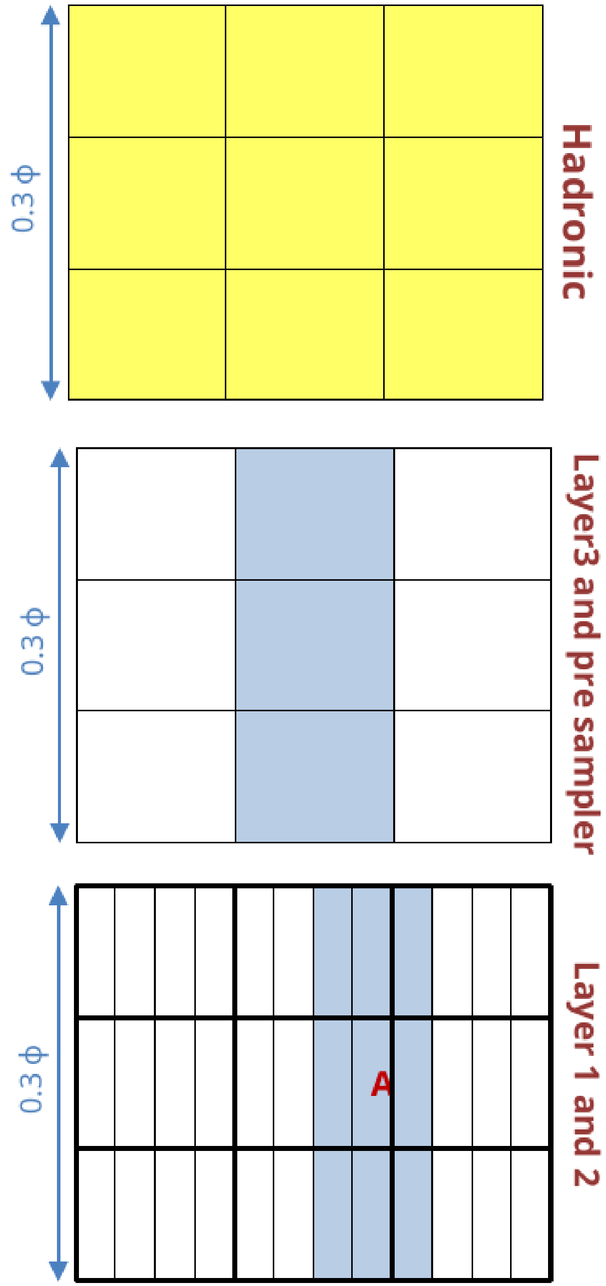
eFEX electron finding algorithm



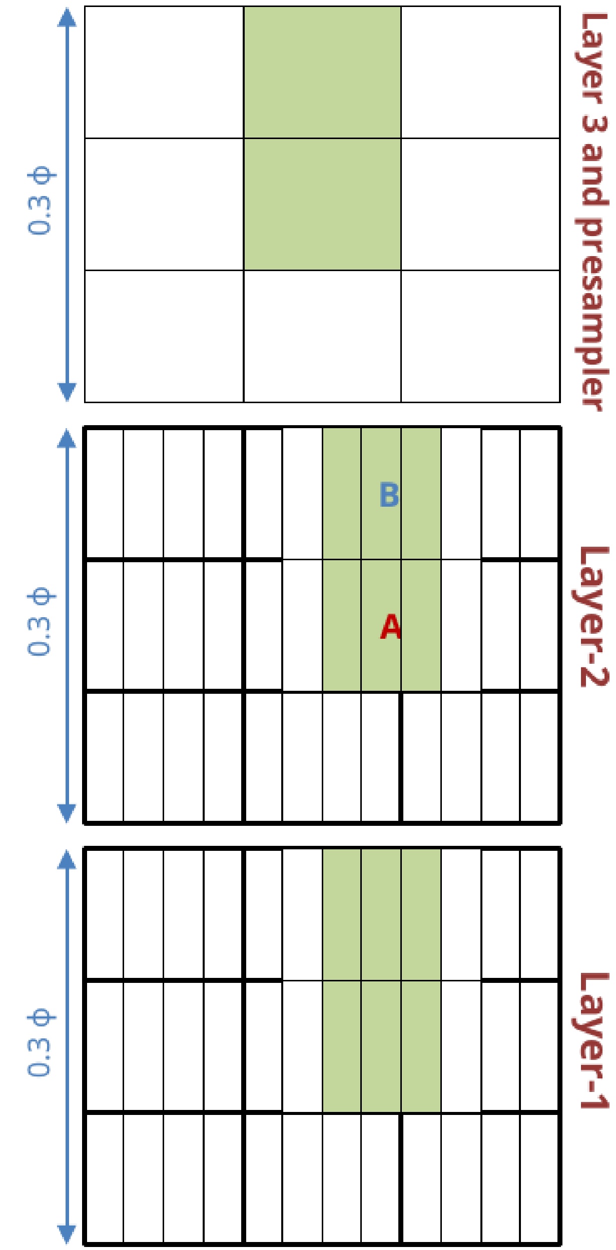








Hadronic veto



Cluster energy