The ATLAS Trigger System

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on behalf of the Trigger Operations Team

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Overview

- The ATLAS Trigger System
  - L1 Trigger Overview
  - High Level Trigger (HLT) and Data Flow
- HLT Physics Signatures & Streams
- Trigger Menu and Configuration
- Simple and Complex Dead-time
- LHC Bunch Structure and Bunch Groups

Inputs to this talk:

- Trigger Expert Training (https://indico.cern.ch/event/333628/):
  - https://indico.cern.ch/event/333628/contribution/3/material/slides/1.pdf
  - https://indico.cern.ch/event/333628/contribution/0/material/slides/0.pdf
- Various talks:
  - https://cds.cern.ch/record/1712900/files/ATL-DAQ-SLIDE-2014-373.pdf
  - https://cds.cern.ch/record/1609564/files/ATL-DAQ-SLIDE-2013-831.pdf
  - https://cds.cern.ch/record/1609597/files/ATL-DAQ-SLIDE-2013-837.pdf
  - https://indico.cern.ch/event/323425/session/7/contribution/7/material/slides/0.pdf
  - https://cds.cern.ch/record/1670926/files/ATL-COM-DAQ-2014-013.pdf
  - https://www.masse-spektrum-symmetrie.de/events/blockcourse_10_11/23_2011-10_zurneddenmartin.pdf
- ATLAS TDAQ glossary:
  - http://atlas.web.cern.ch/Atlas/GROUPS/DAQTRIG/glossary.html

The ATLAS Trigger System

The ATLAS Trigger System

Job: Selection of a few hundred events of interest/second for permanent storage

- In Run 2: 40 MHz → ~1kHz => rejection factor of 40 000

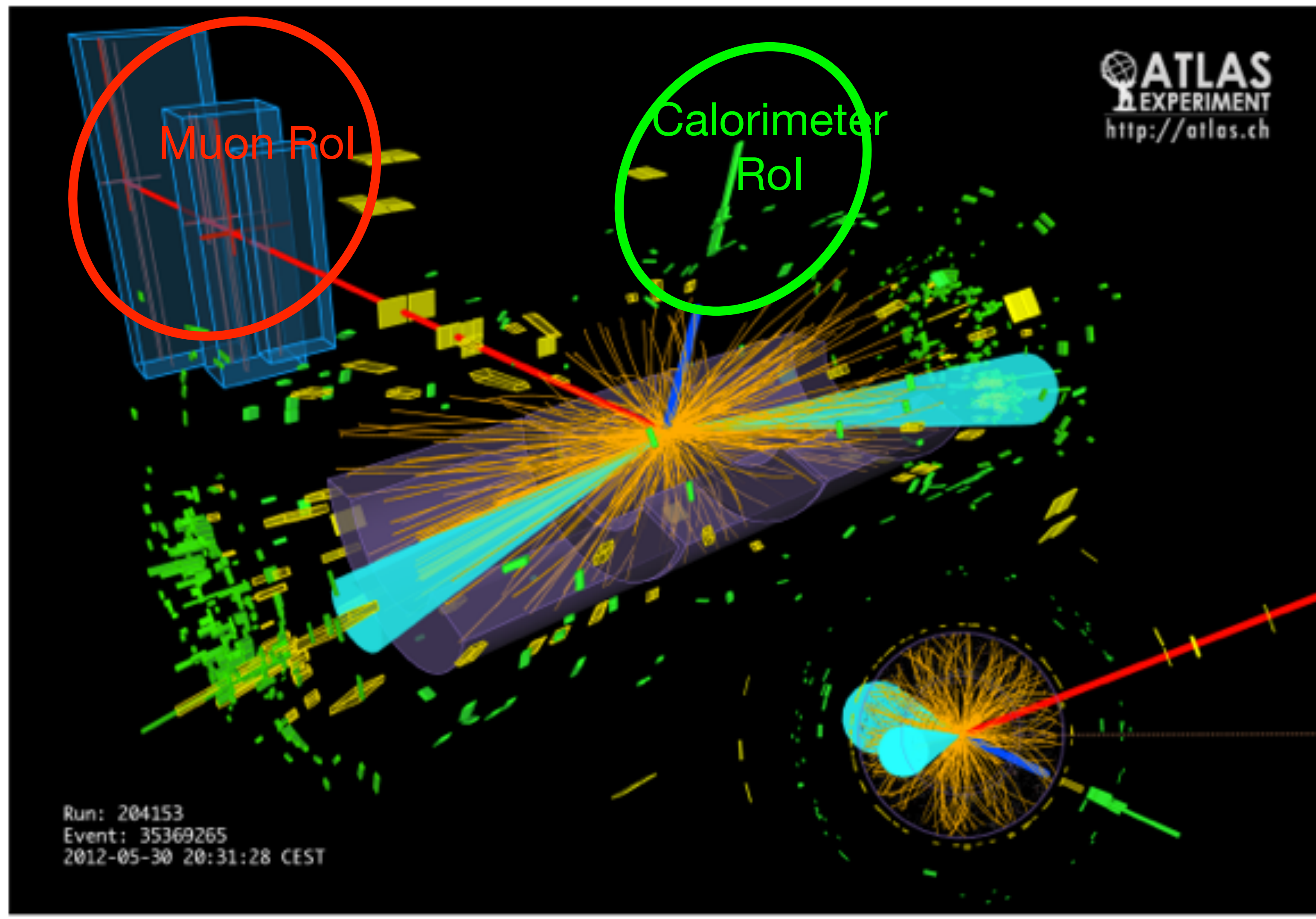
First level trigger (L1):

- Synchronous at 40 MHz with a fixed latency of 2.5 μs
- Identifies Region-of-Interest (RoI) in the muon spectrometer and/or in the calorimeter with coarse resolution

High Level Trigger (HLT):

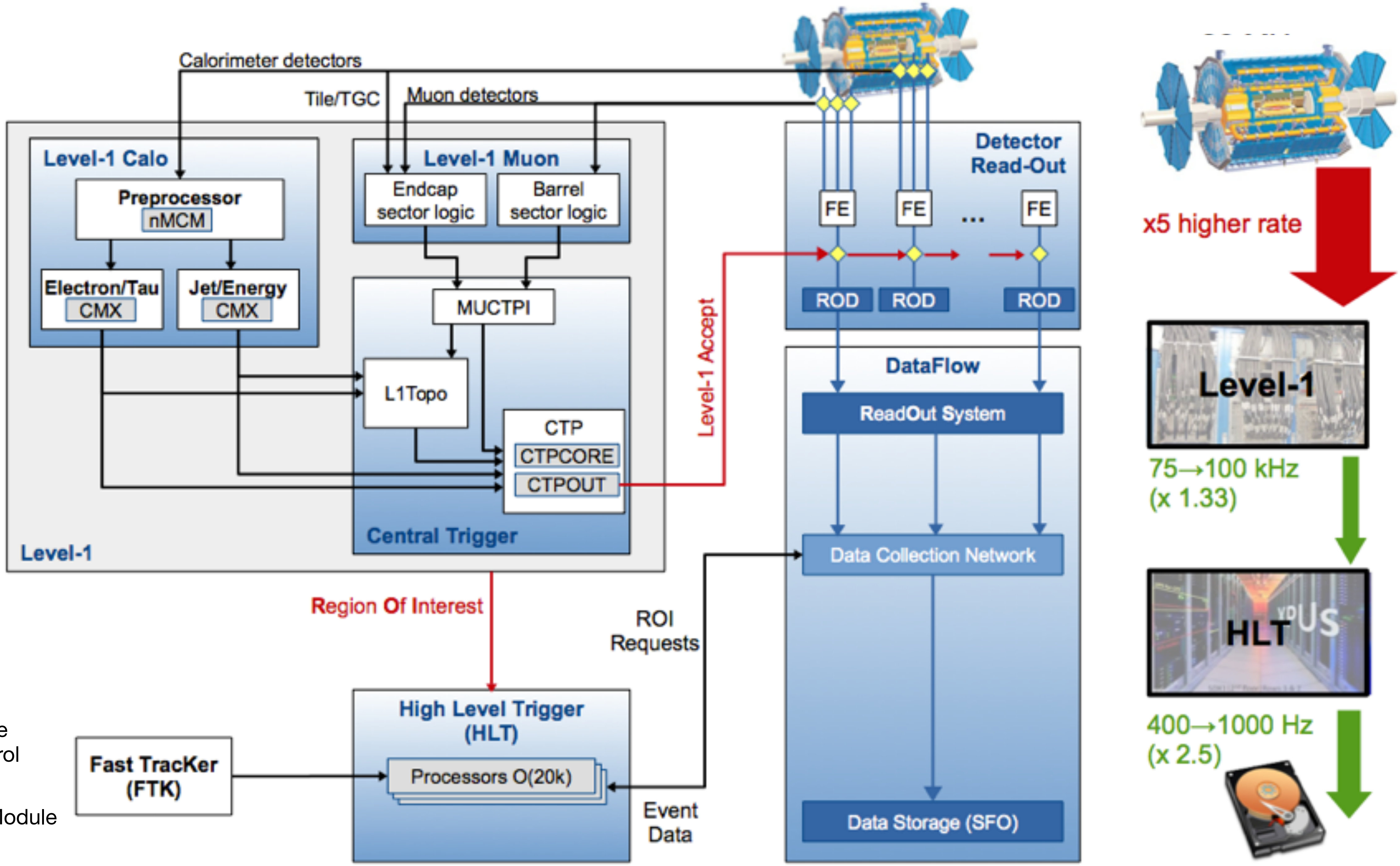
- Handles complexity with custom fast software on commercial CPUs
- Accessing the full resolution of all the detectors

Once HLT is passed, the event is accepted and recorded.



Then, offline software is run to reconstruct the objects (muons/electrons/jets/etc.) in the event. Trigger matching can be used to match offline reconstructed object with trigger object found by trigger software.

The ATLAS Trigger System



FE: Front End
ROD: Read Out Device
HW: HardWare
DC: Data Collector
RoI: Region of Interest
BE: Back End
ROS: ReadOut System
EB: Event Builder
SFO: SubFarm Output
MUCTPI: Muon to Central Trigger Processor Interface
TTC: Timing, Trigger Control

CPM: Cluster Processor Module
CMX: Common Merger eXtended Module
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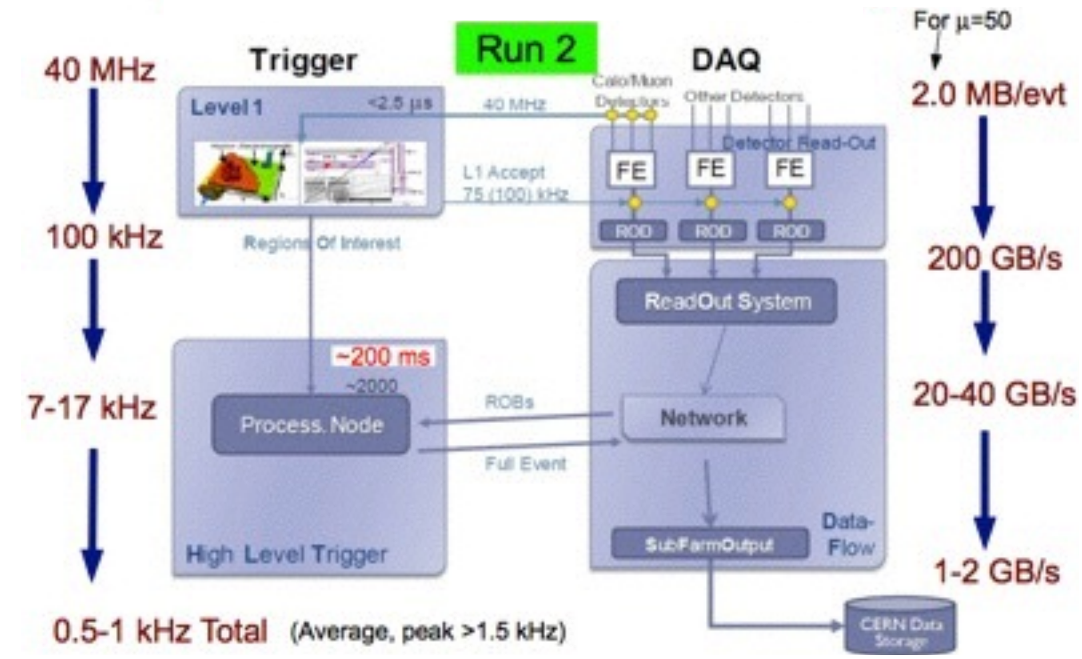
TDAQ System Upgrade

Changes in the TDAQ system to cope with Run 2 LHC conditions:

- Increase of output rate:
  - L1: from 75 kHz to 100 kHz
  - HLT: from ~200-400 Hz to ~ 500-1000 Hz on average per fill
    - limited by offline computing costs
- L1Calo and L1Muon upgrades
  - L1Calo: pile-up subtraction, more available thresholds
  - L1Muon: additional coincidences in endcap
  - Tile endcap trigger to reduce rate at 25ns
- Topological Trigger at L1
- Central Trigger Processor (CTP) upgrade:
  - more trigger items (256 → 512)) → more flexible menu
- Fast TracKer (FTK)
  - commissioning in 2015, full system available ~2016
  - offline-like tracks for all events passing L1
  - improvement of trigger performance in many areas, e.g. τ or b-jet triggers
- Merge of L2 and EF gives new opportunities for HLT
  - more flexibility in the order of selections and event building
  - even HLT farm loading (no fixed L2/EF allocation)
  - reduced ROS access (data retrieved only once)
    → 3rd gen. ROS would allow much more full-scan algorithms (but need to stay within CPU resources)

TDAQ System upgrades



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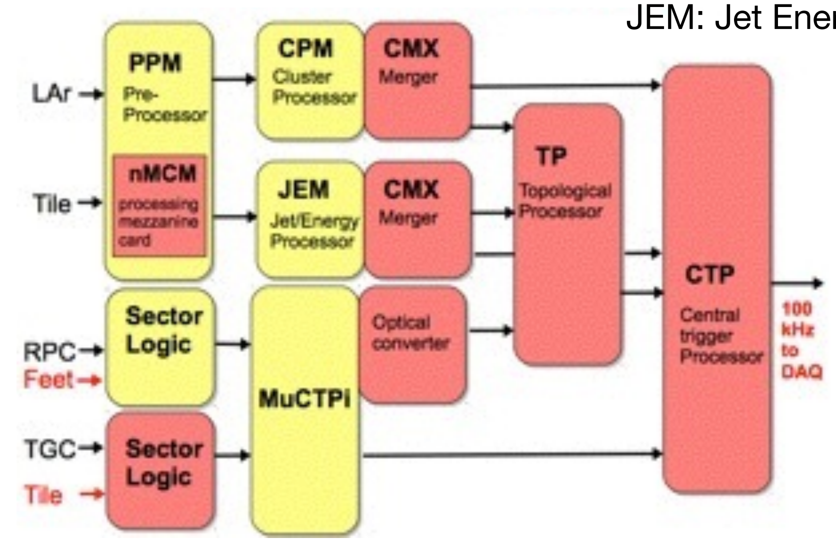
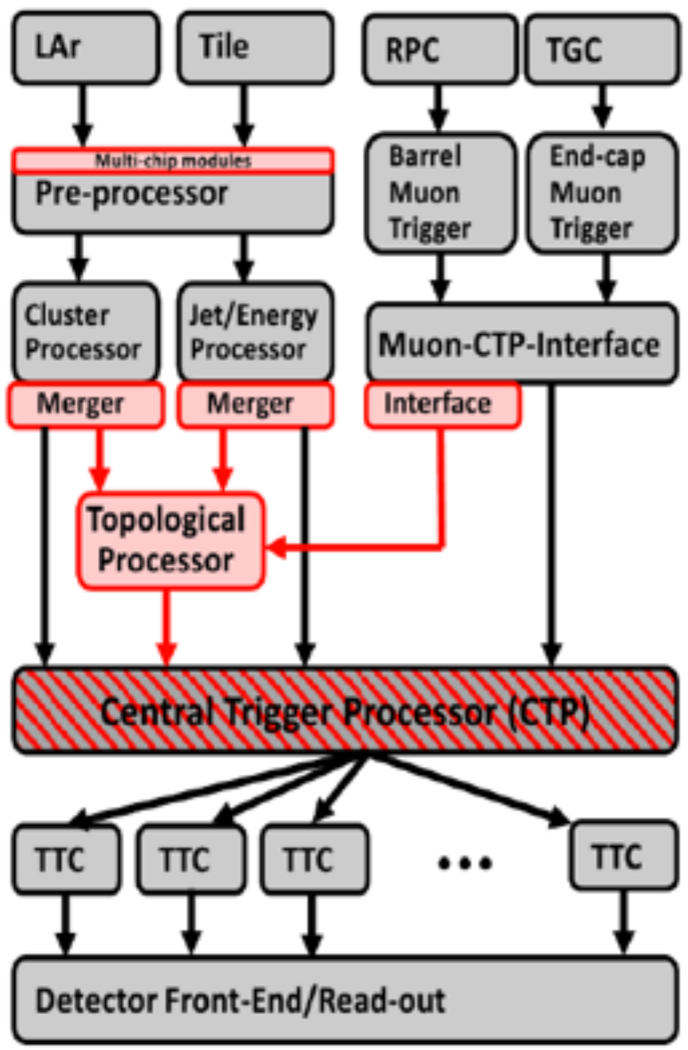
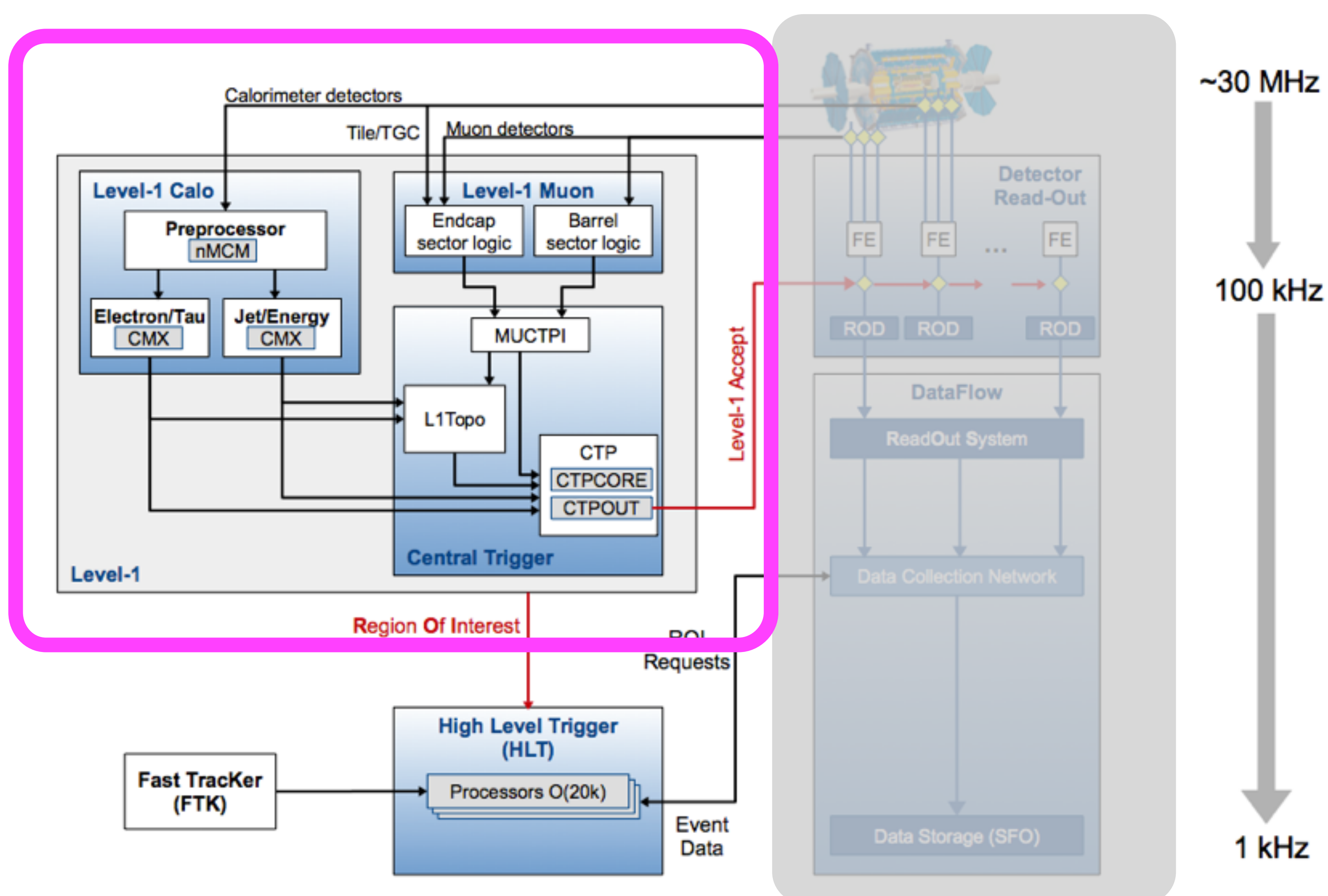
L1 upgrades



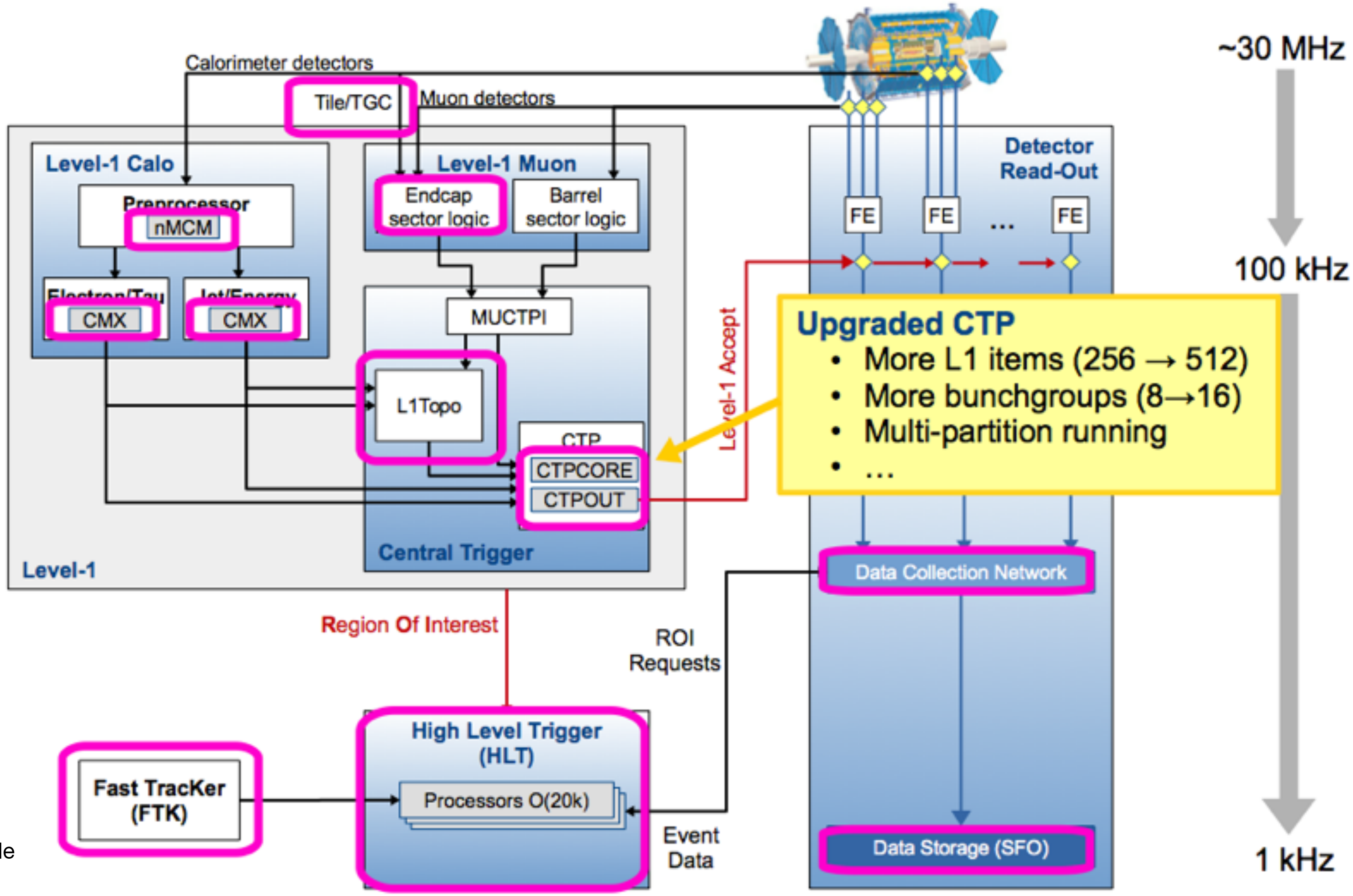
The L1 Trigger System





New/Improved L1 System - CTP

New/Improved



Upgraded CTP
- More L1 items (256 → 512)
- More bunchgroups (8→16)
- Multi-partition running
- …

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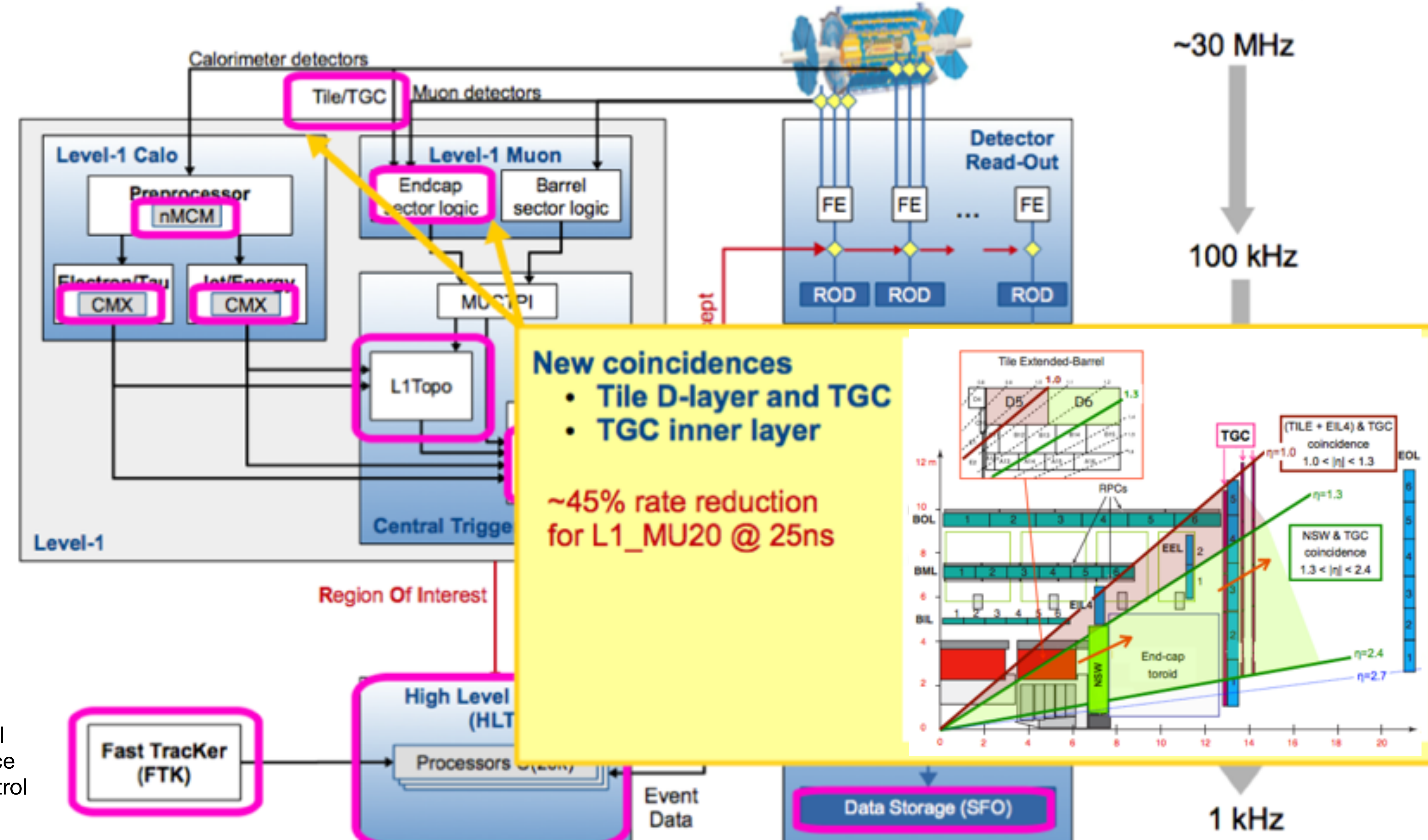
New/Improved L1 System - Tile TGC



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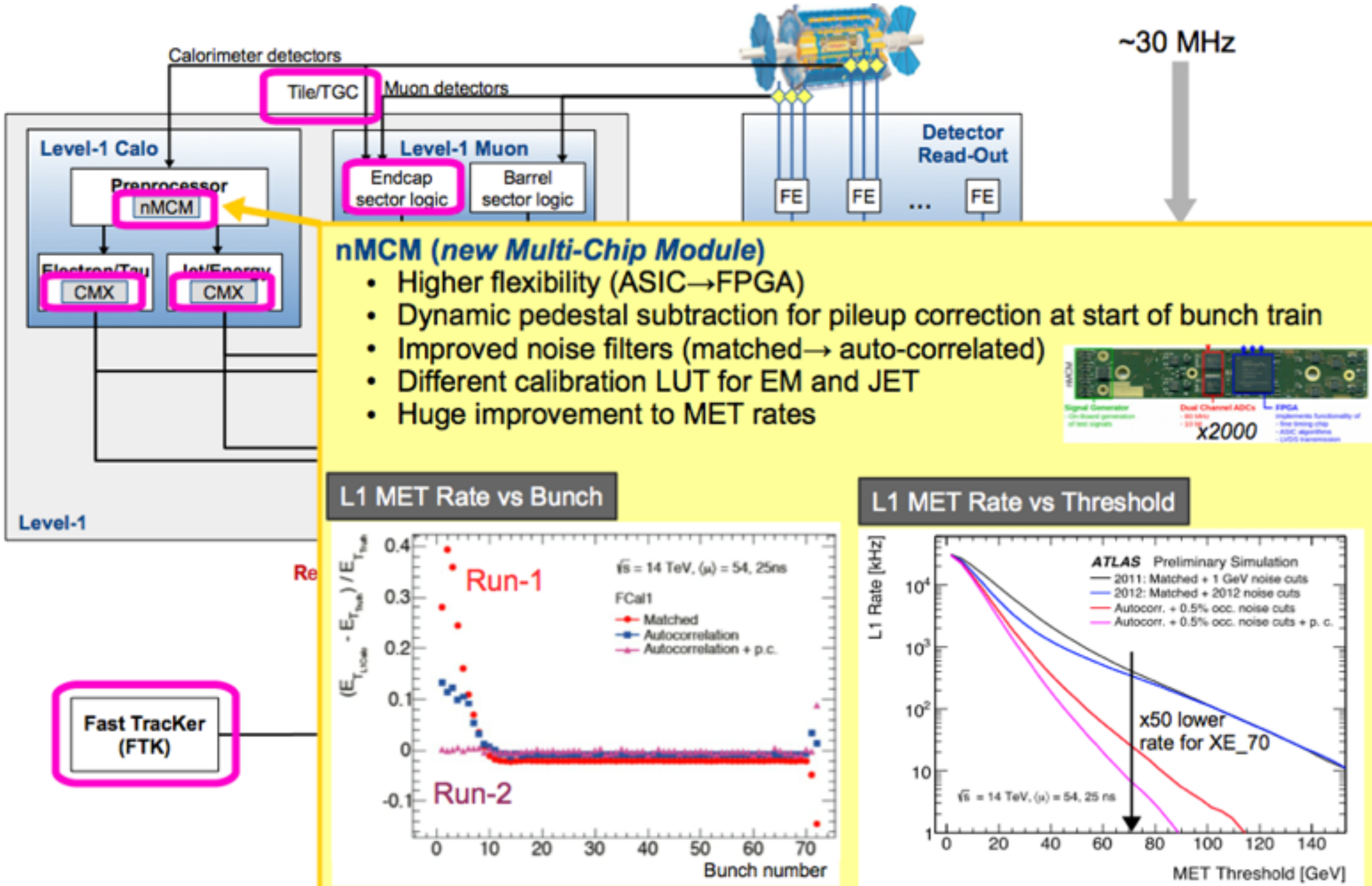
New/Improved L1 System



nMCM (*new Multi-Chip Module*)

- Higher flexibility (ASIC→FPGA)
- Dynamic pedestal subtraction for pileup correction at start of bunch train
- Improved noise filters (matched→ auto-correlated)
- Different calibration LUT for EM and JET
- Huge improvement to MET rates

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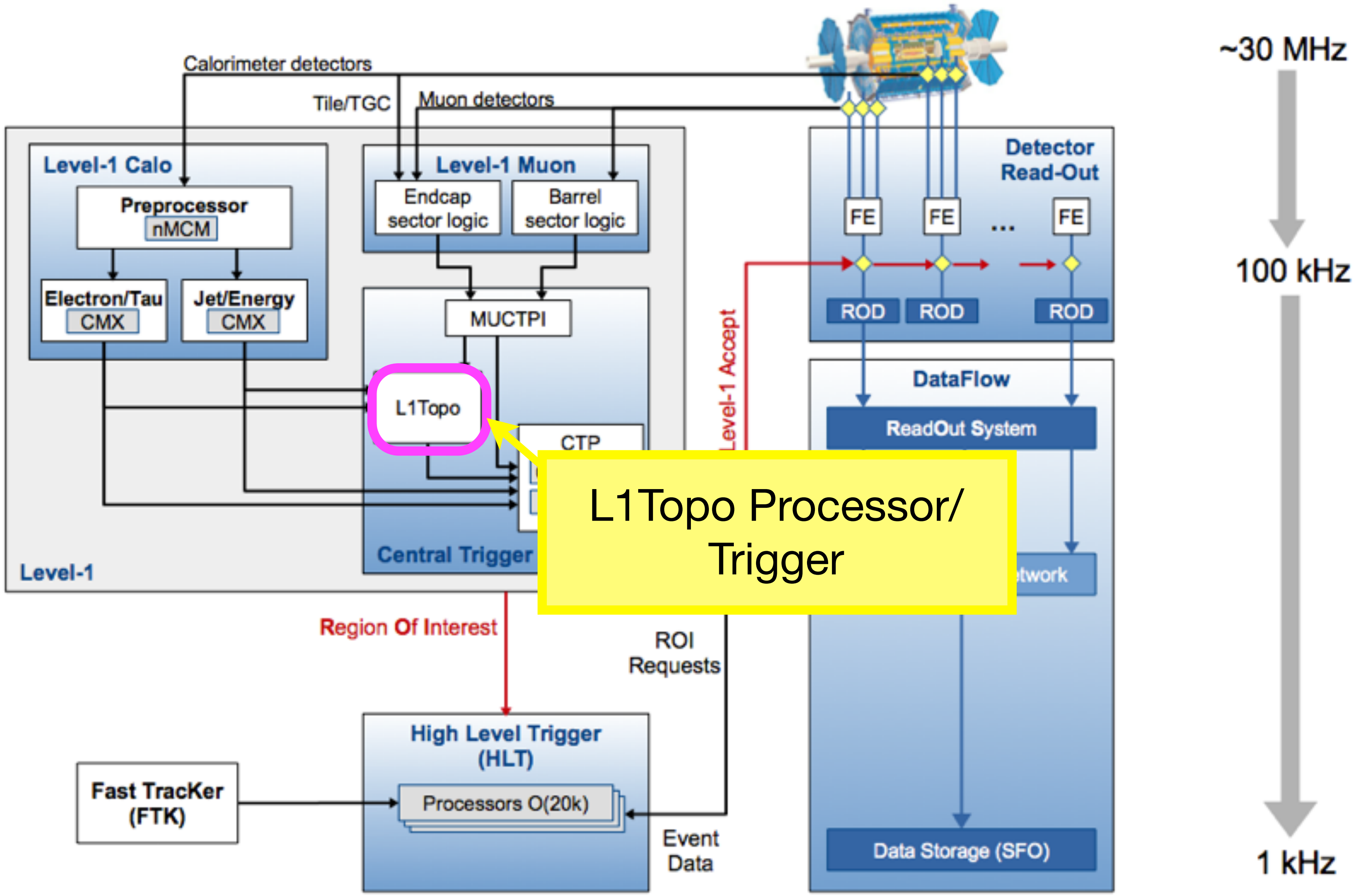
L1 Topological Processor/Trigger



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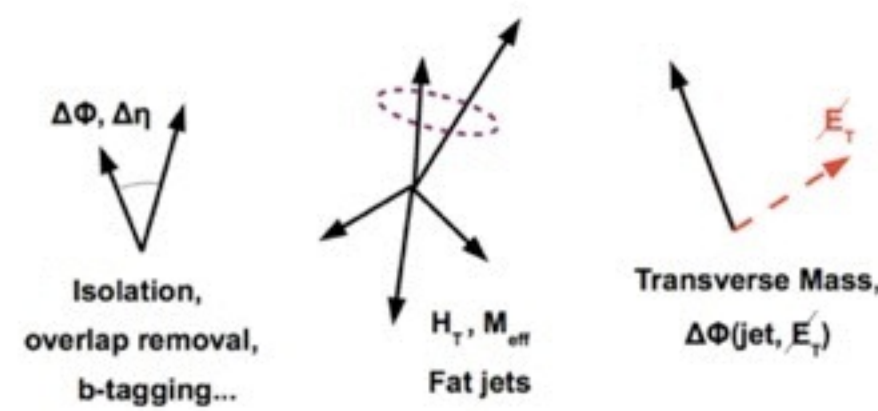
L1 Topological Processor/Trigger

- Completely new piece of L1 hardware
  - Programmable trigger selections (FPGA = Field-Programmable Gate Array)
  - Receives input from L1Calo and L1Muon
  - Applies selection on trigger objects



- Possible selections:
  - Angular cuts (ΔR, ΔΦ, Δη)
  - Invariant mass cuts
  - Object refinements
  - etc.

Objects	All List*	Abbreviated (9)	Sorted (6)
Muons	32	MU4	
Electrons	120	EM10, EM8I	
Taus	120	TAU12	
Jets 8x8	64	J15.0ETA26 J25.0ETA49	
Jets 4x4	-	-	-
MET	1	n/a	n/a

Input to

Angular Requirements

$\Delta\eta, \Delta\varphi, \Delta R^2, \Delta\eta + \Delta\varphi$

Mass Requirements

$M^2 = 2E_T^1 E_T^2 (\cosh\Delta\eta - \cos\Delta\varphi)$

$M_T^2 = 2E_T^1 E_T^{miss}(1 - \cos\Delta\varphi)$

$M_{CT}^2 = 2E_T^1 E_T^{miss}(1 + \cos\Delta\varphi)$

Event Requirements

$H_T = \sum p_T(jets)$

$H_{CT} = \sum p_T(central\ jets)$

$M_{eff} = H_T + MET$

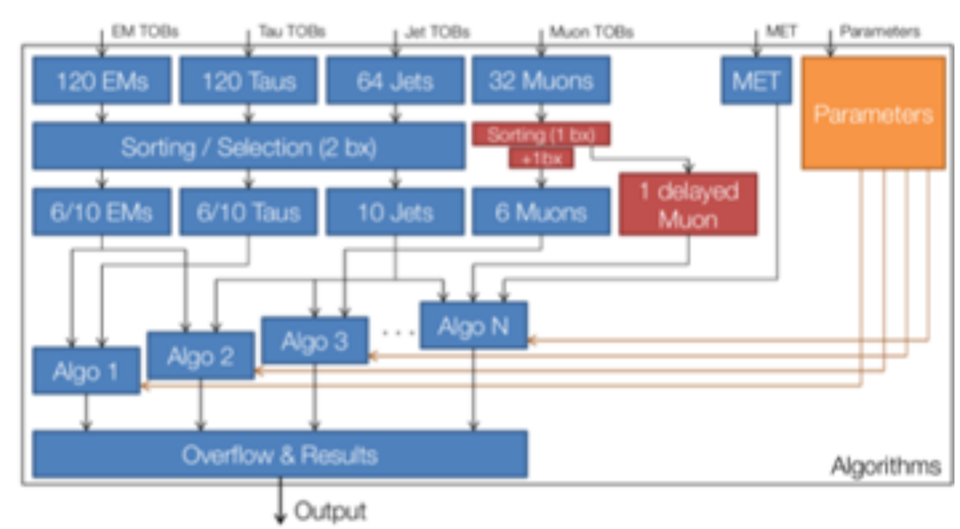
L1Topo MET

Dedicated Algorithms

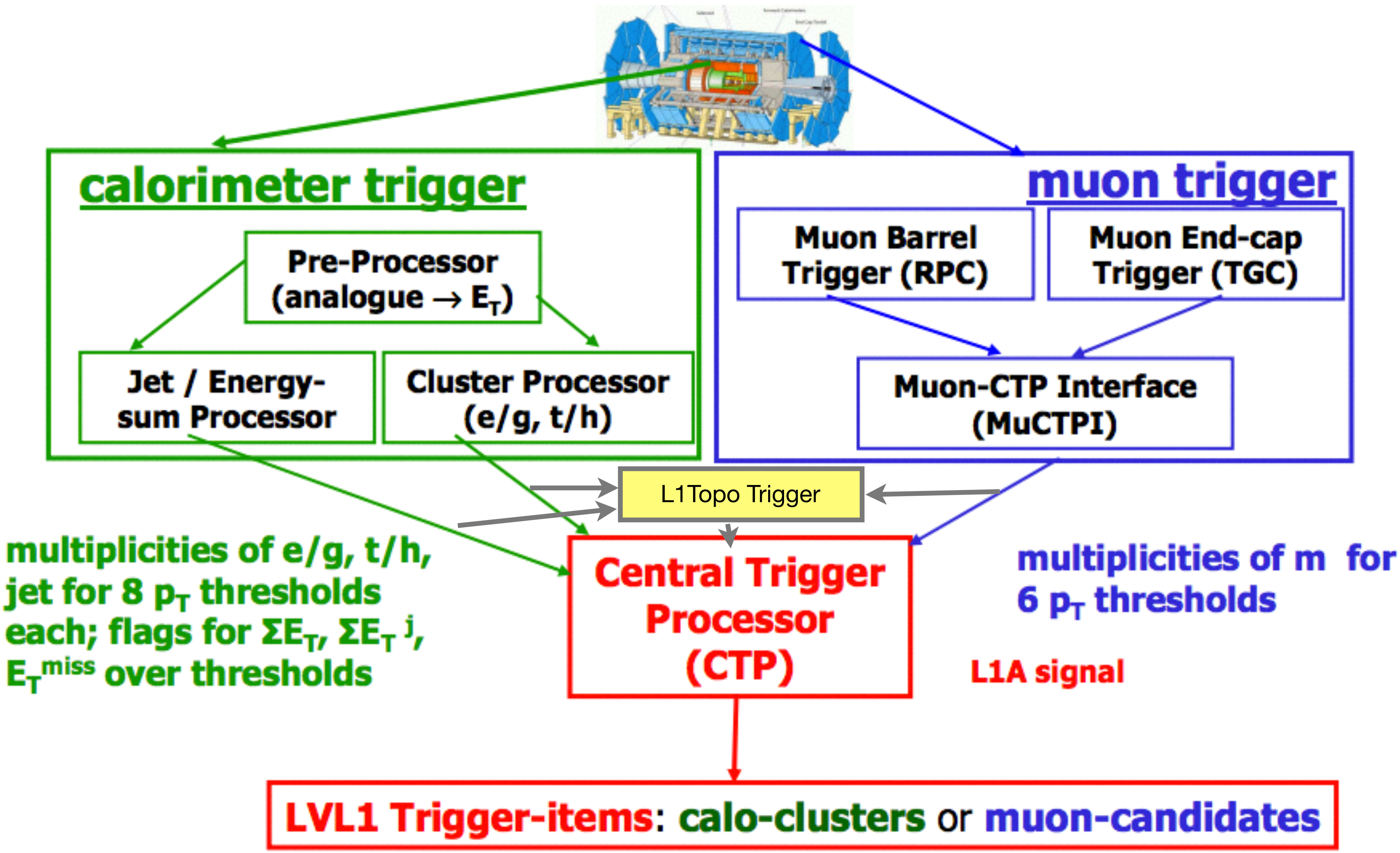
Calorimeter Ratio

Delayed Particles

- Constraints:
  - 128 L1Topo trigger items
  - Latency (algorithms) ≤ 3 BC (75 ns)
  - FPGA resources
  - Combinatorial constraints:
    most algorithms will be limited to work with top-N objects



L1 Trigger Items



Other L1 Items

Other triggers you might see during early running:

- L1_MBTS:
- L1_BPTX:
- L1_BCM:
- L1_LUCID:
- L1_ZDC:
- L1_TRT:
  Cosmic Track Trigger
- L1_CALREQ:
  Calo Calibration Triggers
- L1_RD0/L1_RD1

Minimum Bias Trigger Scintillators

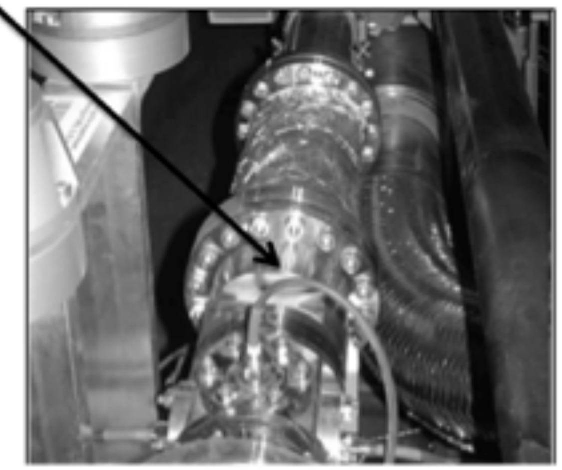
Beam Pickup Timing Experiment

Beam Condition Monitors

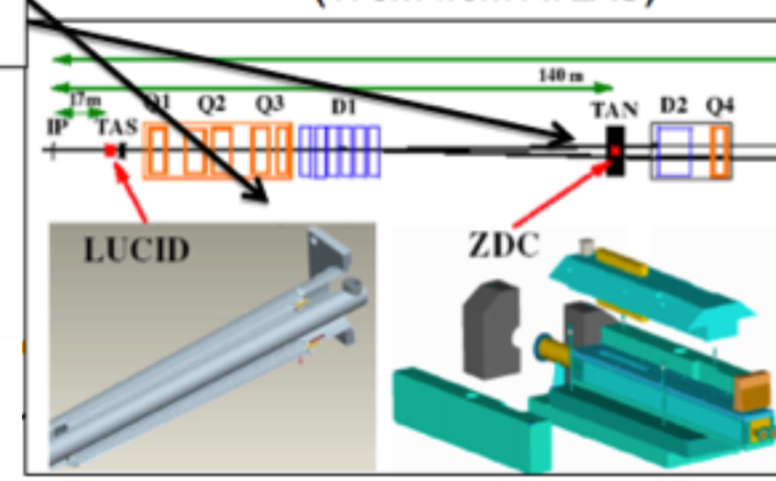
Luminosity Measurement with Cherenkov Integrated Detector

Zero Degree Calorimeter

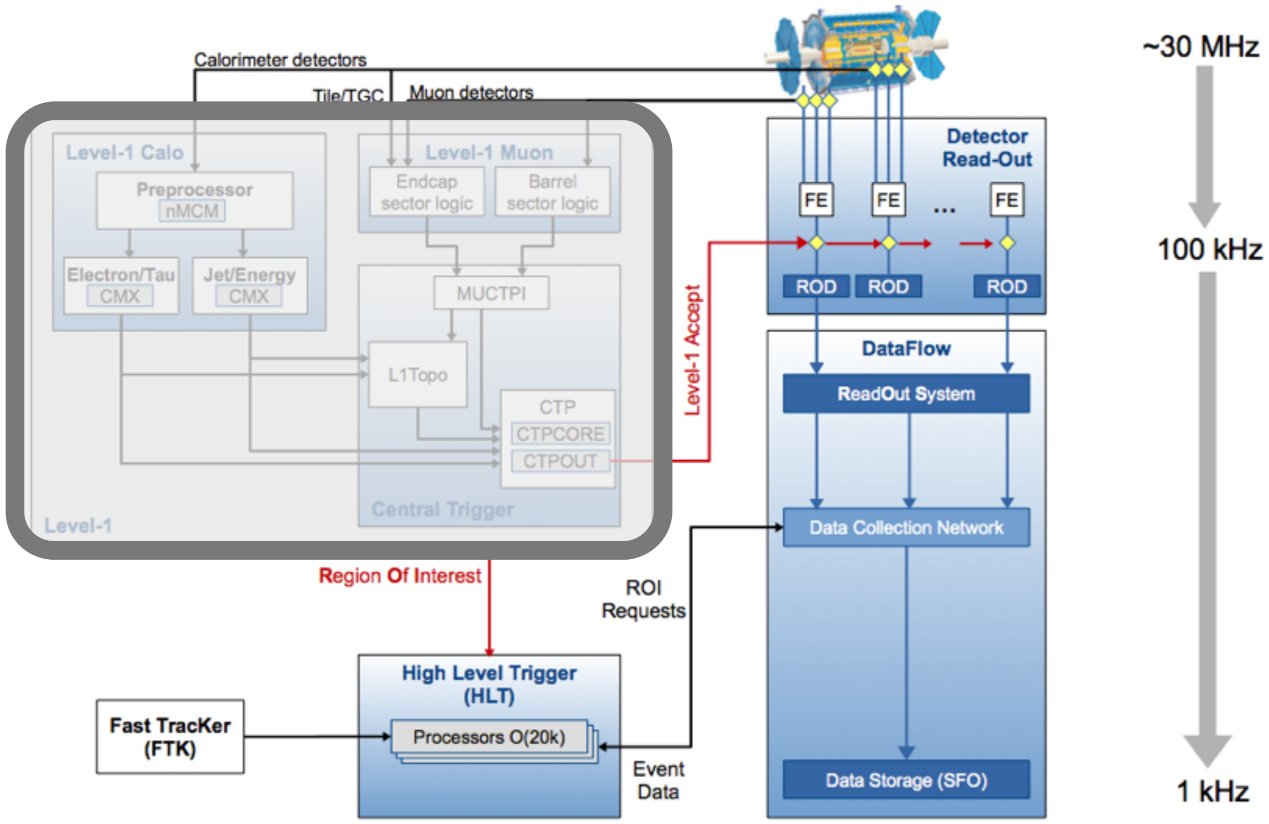
(between the end-cap calo & ID)



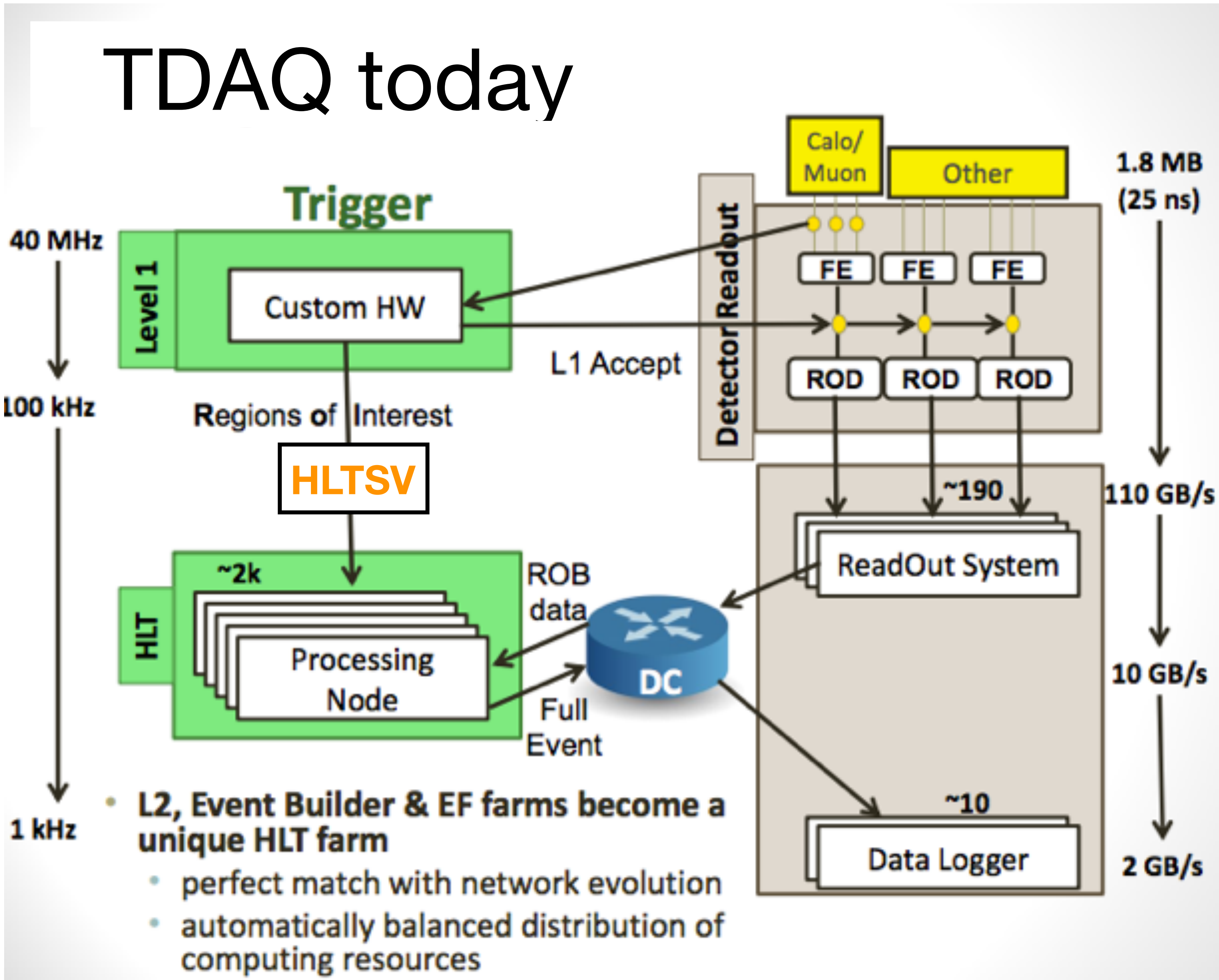
(175m from ATLAS)



HLT and Data Flow



Data Flow Architecture



Region of Interest Builder (RoIB)

- sends L1 result to HLT SuperVisor (HLTSV)

HLT SuperVisor (HLTSV)

- dispatches Regions of Interest (RoIs) to available HLT nodes

Data Collection Manager (DCM)

- data collection, caching, building
- assign fragments from ReadOut System (ROS) to HLTPU (HLT Processing Units)
  - HLTPUs: execute HLT algorithms
- sends accepted events to the Data Logger

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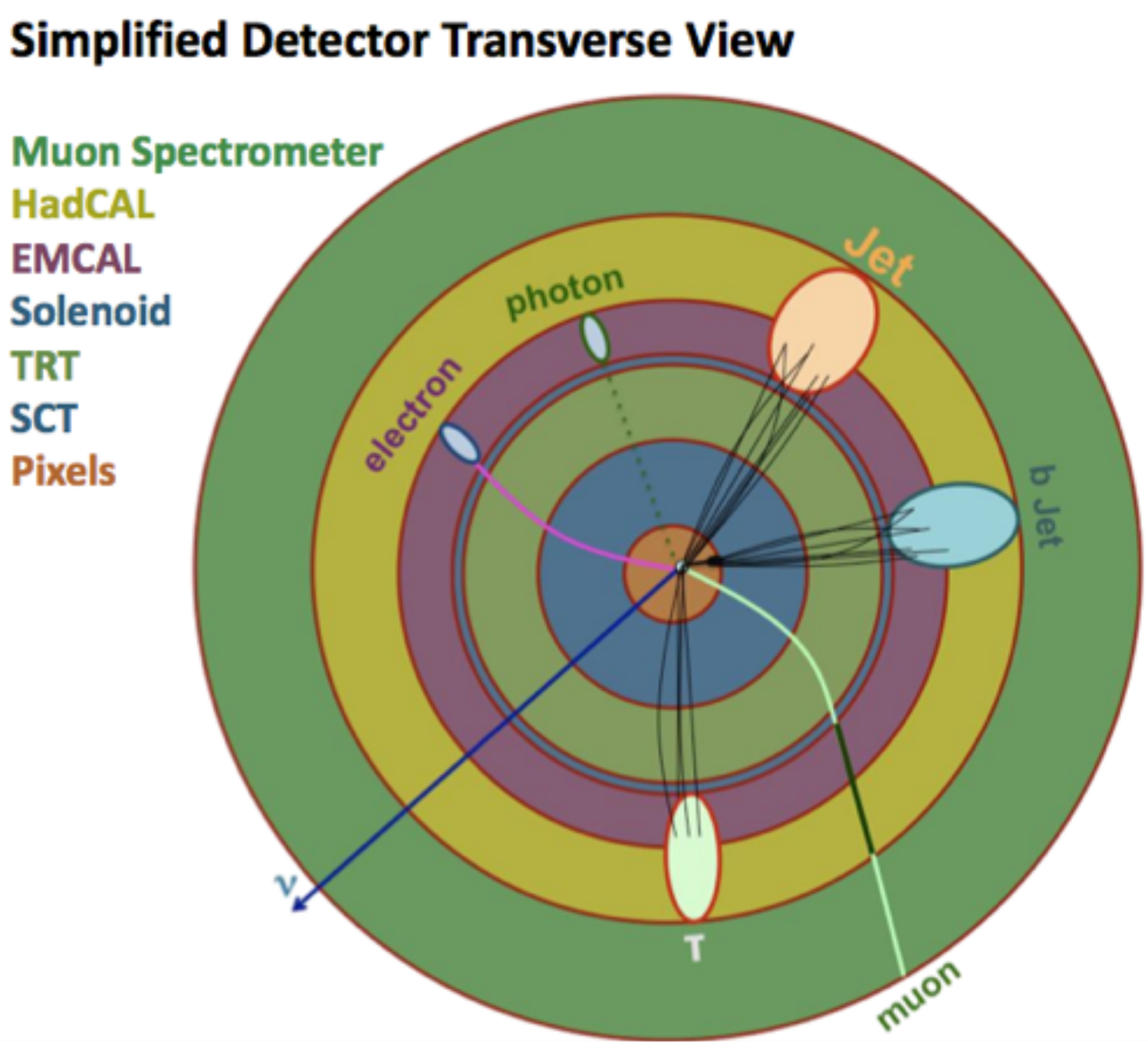
HLT Physics Signatures & Streams

HLT Physics Signatures

Physics signature:
- Defined as a group of closely related trigger chains, e.g. Muons, B-physics, Jets…
- Each Signature has primary, backup, supporting and monitoring chains



The different trigger signatures define the trigger physics streams (and corresponding trigger signature groups):

- **Electrons/photons**
- **Muons/B-physics,**
- **Jets/Met/taus**
- **Minimum Bias**

Data Streaming - Run 2

Stream: Collection of events or event fragments of related signatures in the same data set, overlap between streams is designed to be minimal

✓ Streaming is based on trigger decisions at the HLT
✓ The Raw Data physics streams are generated at the SFO
✓ All streams are inclusive, except the debug stream

One "Main" Physics stream
- Merge of Egamma, Muon, JetTauEtMiss
- Saves ~10% in computing/storage

Debug Streams
events without full trigger decision, due to failures in parts of the online system

offline shifter

One "Main "Physics Stream

~~Egamma~~
~~Muons~~
~~JetTauEtMiss~~
~~MinBias~~

Express Stream
Events for prompt reconstruction (calibration loop)

Datascouting Stream
Event stored in reduced data format

Calibration Streams
events delivering the minimum amount of information for detector calibrations at high rate

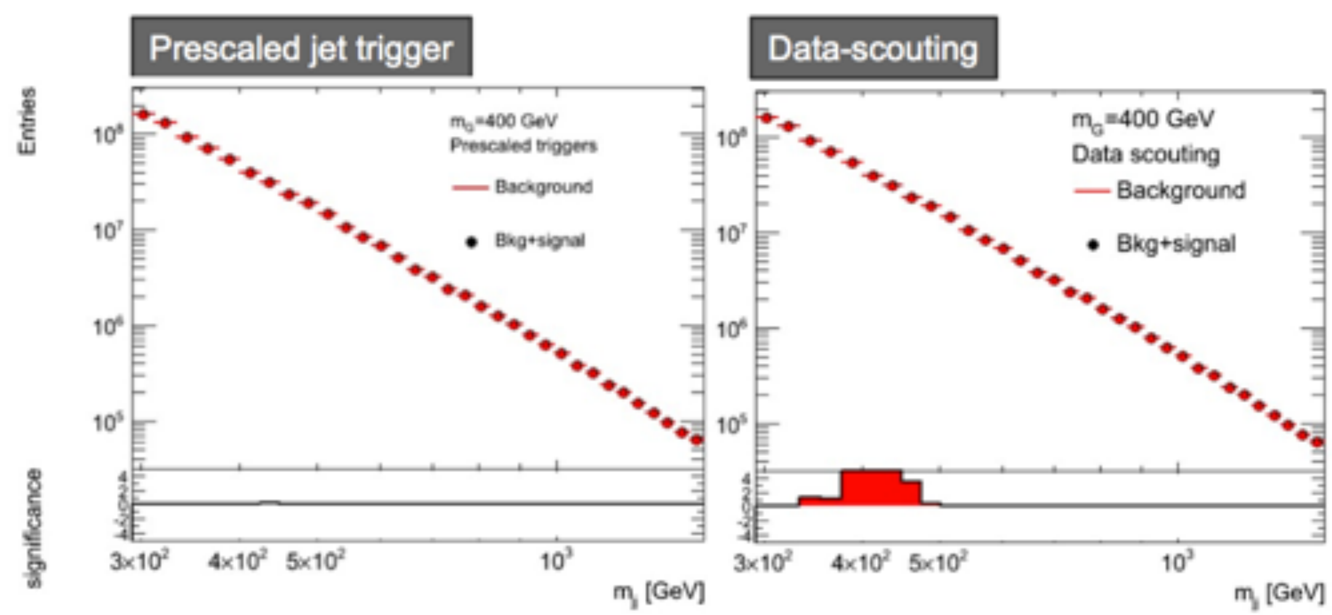
partial events

offline monitoring: 100% overlap to main stream

Data Scouting

DataScouting: write out data with reduced event content (i.e. store calo jets reconstructed during HLT only)

- New HLT/DAQ functionality
  - Store only HLT reconstructed objects in RAW data (not detector data)
  - Signal statistics increased by orders of magnitude
- Use-case: Di-jet resonance search
  - In Run-1 low-mass resonance searches limited by statistics
  - Due to limited output rate, had to rely on prescaled triggers
  - Run-2: Run and store HLT jet reconstruction on all L1_J100 triggered events
- Challenges
  - No detector data in RAW



Debug Stream

https://twiki.cern.ch/twiki/bin/view/Atlas/DebugStream

Debug sub-streams used to differentiate failures in the online system seen by the HLT:

Debug stream:

- a way to spot problems and weaknesses of the online system without loosing events
- presence of events in a timeout debug stream does not necessarily imply a bug in the online system
- timeouts ensure the system robustness

- `debug_DcmFetchRobsError`:
- `debug_DcmL1IdMismatchError`:
- `debug_HLTMissingData`: The event processing could not be started in the PU because some data was missing (very rare)
- `debug_HLTSVForceAccept`:
- `debug_HltError`: Severe algorithm errors which abort the event processing
- `debug_LateEvents`: Events that didn't make it to the SFO at the LB boundaries. The SFO has closed the "right" file, so it writes the late events to the debug_LateEvents stream.
- `debug_PUCrash`: PUCrash
- `debug_PUTimeout`: Event processing timeout where the steering was able to abort the event processing in time

Other debug streams:

- `debug_LateEvents`: Events that didn't make it to the SFO at the LB boundaries. The SFO has closed the "right" file, so it writes the late events to the debug_LateEvents stream.
- `debug_duplicated`: *Possibly* duplicated events, due crashes/communication failures in the DF system. Duplication can take place in DFM, SFI and EFD.
- `debug_DISCARD`: This is the "default" stream of some chains, e.g. xe chains running on all L1 TEs, that should never be included int he run, but executed only in *rerun* mode. This stream should never be seen. If it is, there has been a mistake in the online trigger configuration.

Trigger Menu & Configuration

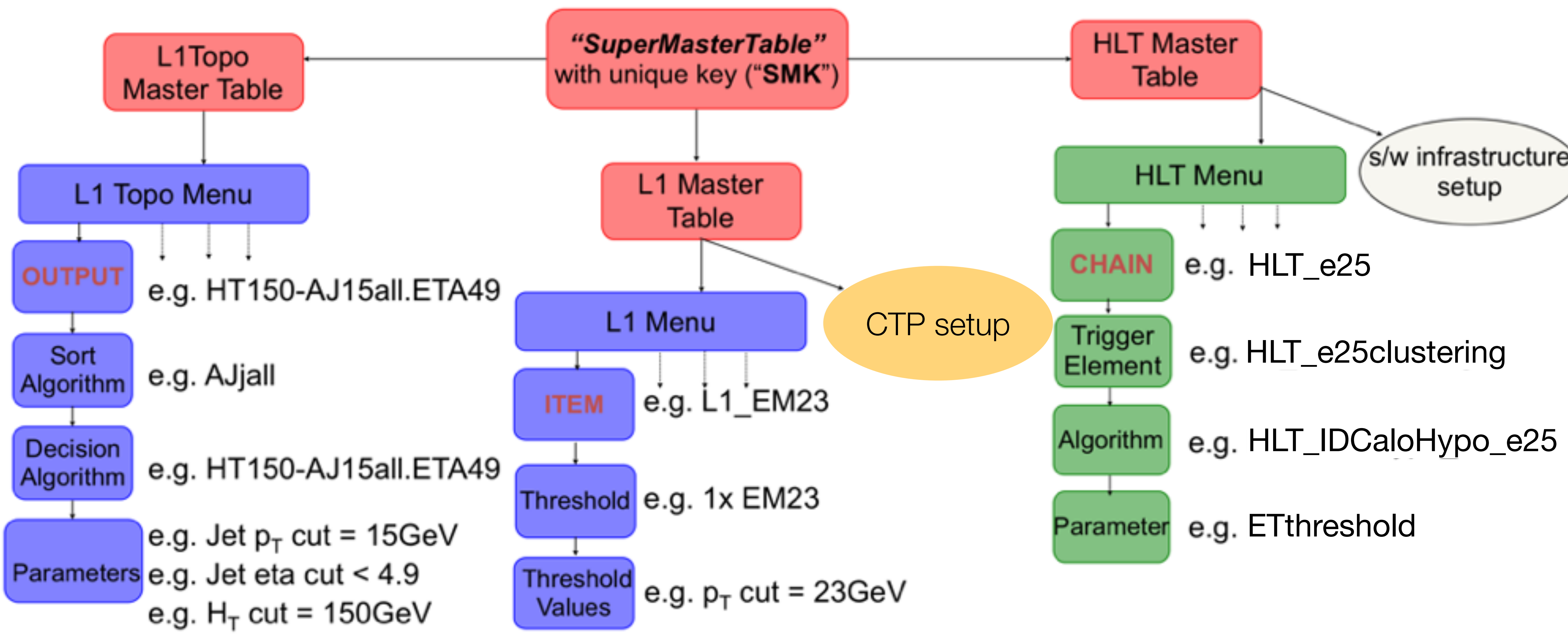
Trigger Menu Terminology

https://cds.cern.ch/record/1632445/files/ATL-DAQ-SLIDE-2013-893.pdf

- **Chain**: one full L1 → L2 → EF (Run 1) or L1 → HLT (Run 2) selection sequence
  - e.g. e24i chain = single electron trigger with ET>24GeV, seeding off L1_EM15
  - each chain is organised in steps (Trigger Elements), at any step it can be rejected
  - each step: execution of a sequence of algorithms, typically Feature Extraction (FEX) and hypothesis testing algorithms (Hypo)
  - if surviving till the last step → event accepted
- **Menu:** full set of chains and prescale factors
  - A typical menu contains several hundreds of chains (~500 in Run 1) to meet a large variety of physics goals at the LHC and also to contain sufficient supporting triggers, backup triggers and monitoring triggers
    - in general, all events passing the **primary chains** are kept (unprescaled) → for physics signals, should have the highest efficiency
    - **backup chains** have higher thresholds and are used in case of unexpected luminosity increases
    - **supporting chains** are used for maintaining or to support a physics analysis (e.g. to extract background in a data driven way)
    - **monitoring chains** are used to monitor the data qualities (e.g. to check the performance of tracking by the inner detectors)
  - Menu can be categorised corresponding to its purpose and LHC beam conditions, e.g. LS1 menu, Physics menu, MC menu, HI menu
  - Prescale factor = reduction factor to issue a trigger (e.g. a prescale factor on chain X of 5 means that every 5th event that is accepted by the chain is also recorded, all others are discarded)

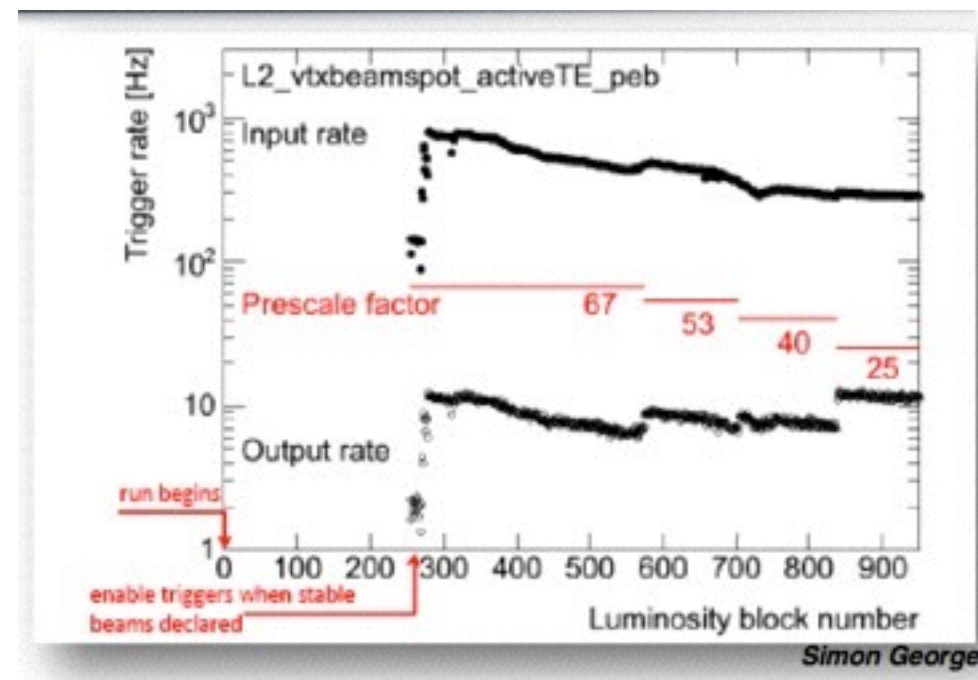
Trigger Configuration

- The Trigger DB stores the L1 and HLT Menus and the setups (= configurations of L1 hardware and HLT software)
  → Configuration = trigger menu + setup
- The TriggerTool (TT) is the user interface to TriggerDB



Trigger Menu Configuration Keys

- To completely specify the trigger configuration, three keys are required:
  - **SuperMaster Key (SMK)**: chooses one unique configuration (menu, configuration, dead-time settings, etc.)
  - **L1 and HLT Prescale Set key (PSK)**: can be changed (prescale, enable, disable triggers) during the run at the luminosity block boundaries
    - Cosmics Prescales: for cosmic data-taking (used in M-weeks)
    - Standby Prescales:
      - No beam or un-stable beams (before warm start)
      - Detectors in SAFE mode, high voltage off (low) for inner detector and muon systems
      - Only a few L1 triggers needed for detectors to measure background levels
    - Physics Prescales:
      - Stable beams, all detectors in physics mode
      - Data for physics analysis, all triggers in, HLT rejection
      - Prescale sets for different luminosities
    - Special Prescales:
      - High Rate tests
      - Special sub-detector tests



- Additionally there is a L1 Bunch Group Set (BGS) key which defines the LHC fill pattern for the Central Trigger Processor (CTP):
  - in data-taking period generated during ramp
  - can create user specified BGS

Simple & Complex Deadtime

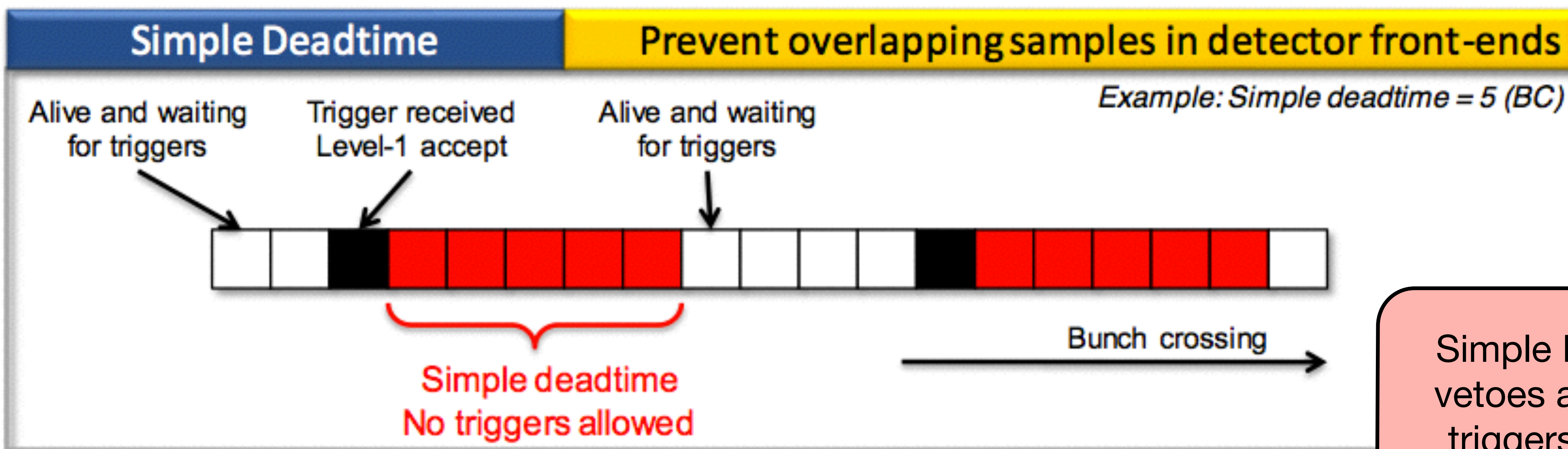
Simple Dead-time

http://cds.cern.ch/record/1300249/files/ATL-DAQ-PROC-2010-036.pdf

Preventive dead-time introduced by CTP to stop the front-end buffers from overflowing (processing time for a L1 accept).
Calculated in two ways: simple and complex dead-time

Simple dead-time:

- programmable number of bunch crossings after each L1A
- e.g. used to avoid overlapping readout windows



Simple Deadtime = vetoes a number of triggers after a L1 accept

Complex Dead-time

Complex Deadtime | **Protect readout buffers from trigger bursts**

Example: Complex deadtime = 4/570

Leaky bucket algorithm: to emulate the front-end buffer

- Bucket is filled with L1A tokens at constant rate up to bucket size
  (e.g. 1 token every 570 BC until 4 tokens in bucket)
- Every L1A takes one token out of the bucket
- If bucket is empty (no L1A tokens left), deadtime is applied

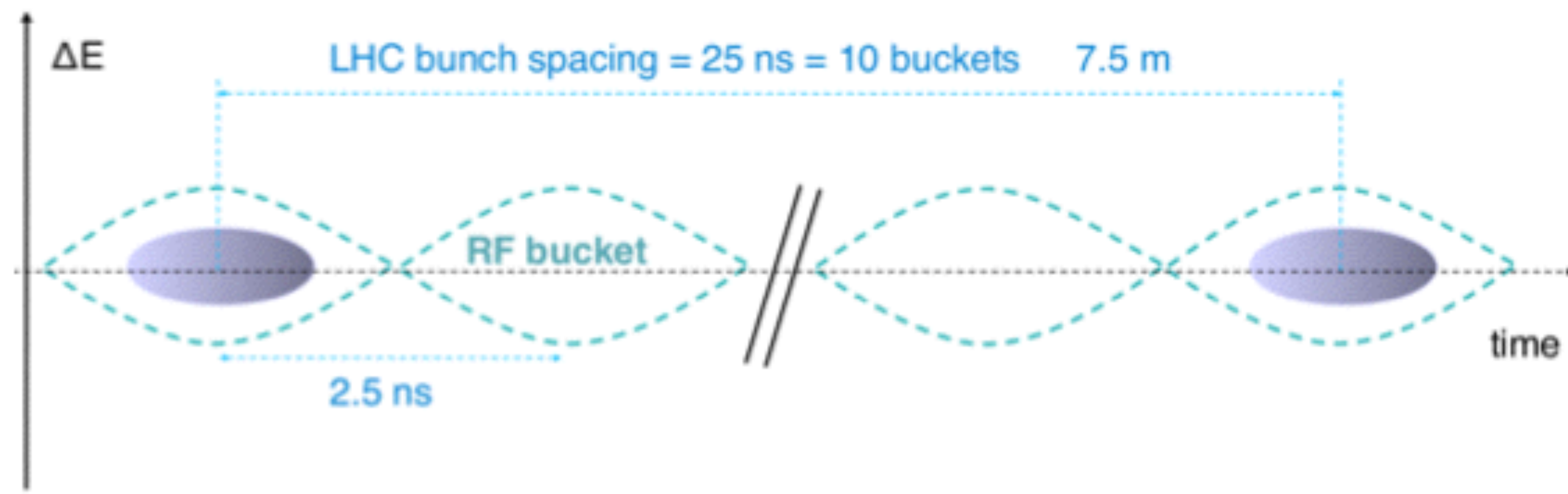
Complex Deadtime = restricts the number of triggers in a given period

Complex dead-time:

- defined by the size of the bucket X (in units of L1A) and the time it takes to leave one L1A, R (in units of BC)
- trigger rate is limited to X triggers in a time period of X x R bunch crossings

LHC Bunch Structure & Bunch Groups

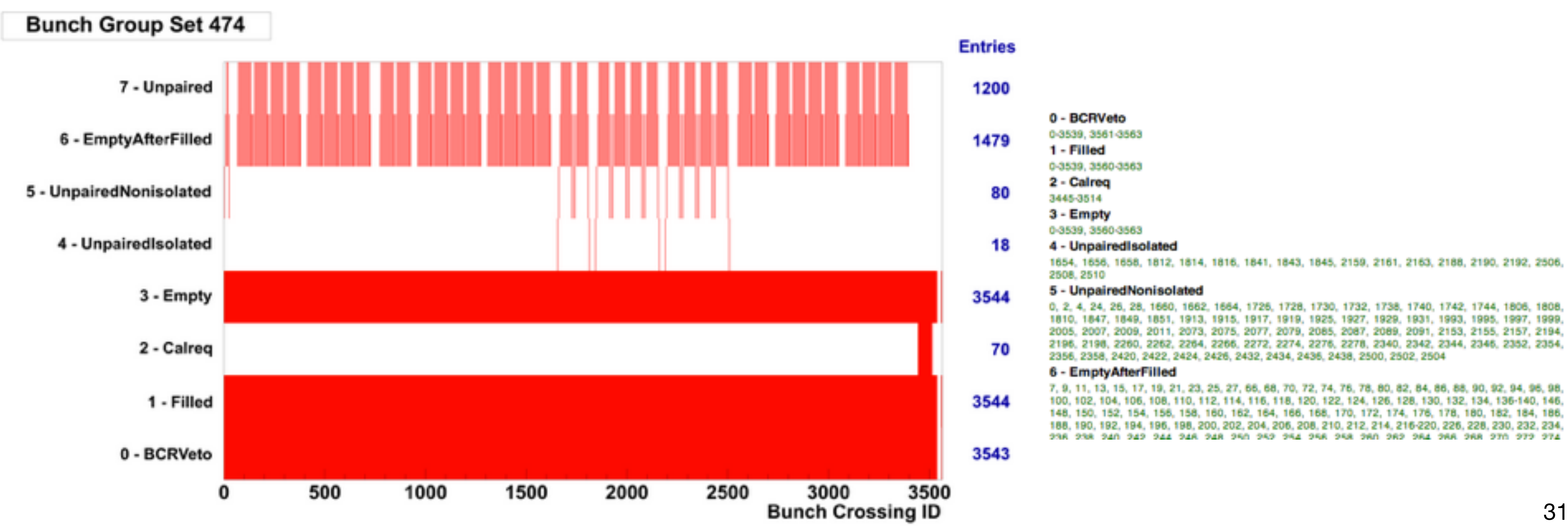
LHC Bunch Structure



- LHC bunch spacing = 25ns = 10 buckets
  → 2.5 ns RF buckets
- 3564 possible bunches in LHC identified by Bunch Crossing Identifier
  → BCID = 0,…., 3563
- A bunch can be filled or empty
  - 2 crossing bunches can be
    - "paired": both beams with protons
    - "unpaired": only one beam with protons
    - "empty": neither beam with protons
  - ATLAS defines additional crossings for special purposes

Bunch Groups & BGS

- A Bunch Group is a list of BCIDs, all 8 bunch groups form a Bunch Group Set:
  - 0) BCRVeto: Bunch Counter Reset (within abort gap), allows triggers everywhere but in a small region when the bunch counter reset is sent
  - 1) Paired/Filled: Colliding bunches in ATLAS
  - 2) Calreq: Calibration requests for TileCal (laser/charge injection) in the abort gap
  - 3) Empty: Two empty bunches crossing in ATLAS (for Cosmics, Noise)
  - 4) Unpaired Isolated: unpaired bunches separated by at least 3 BC from any bunch in the other beam
  - 5) Unpaired NonIsolated: unpaired bunches not in category 4)
  - 6) Empty after Filled: 3 empty bunches after paired bunch
  - 7) Unpaired: logical OR of 4) and 5)
- Look-up page for BGS: http://atlas-trigconf.cern.ch/bunchgroups?key=474



L1 trigger items and the Bunch Group

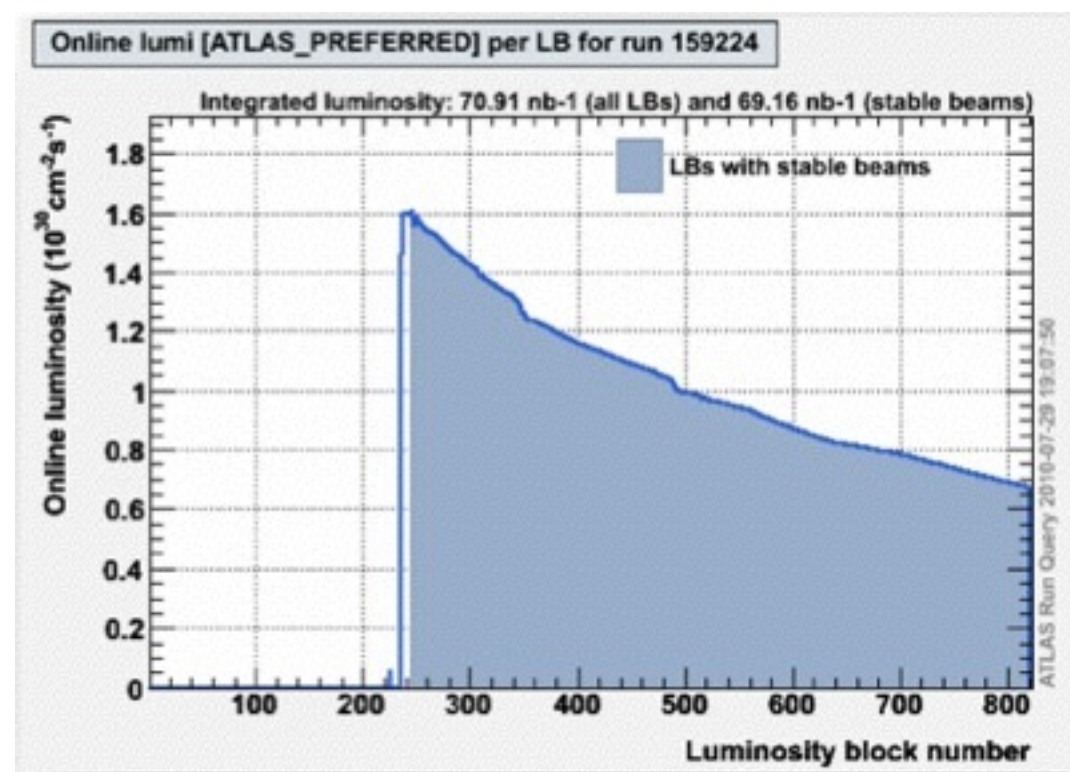
- All L1 trigger items have one or more explicit or implicit bunch group requirement
  - all triggers are ANDed with BCRVeto
  - Physics triggers (e.g. L1_J100): PAIRED is implicit
  - defined in TriggerMenu package
- Some triggers carry bunch group in their name:
  - e.g. L1_EM3_EMPTY, L1_TAU5_UNPAIRED
- Random triggers:
  - L1_RD0_EMPTY, L1_RD0_FILLED
  - L1_RD1_FILLED

ATLAS Data Taking Strategy

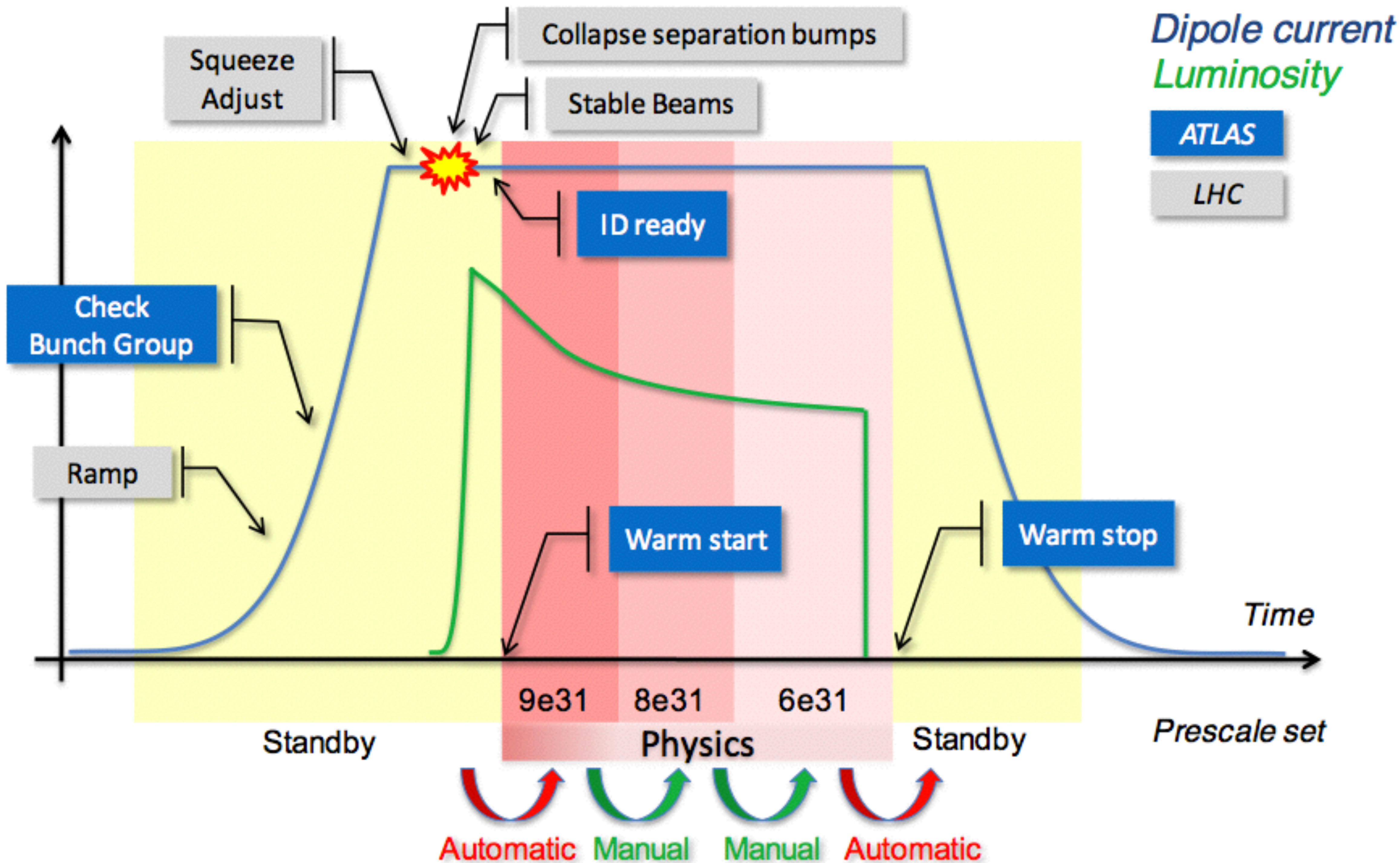
- Run:
  - Period of data taking with a fixed trigger configuration (SMK) and detector setup
  - Usually corresponds to one LHC fill (many hours)
  - Make sure the correct information is displayed on the TriggerWhiteBoard

- Luminosity Block (LB):
  - Luminosity, conditions and data quality are considered to be approximately constant
  - Time interval of about ~2min within a run

- Luminosity drops during a fill, meaning the trigger rates drop too. Ideally we'd like to take all data of interest and make use of the full bandwidth:
  - This is where prescale key changes come in which certain pre scales are released
  - Limitations imposed by detector and DAQ system (processing speed, buffer sizes, internal bandwidth), Tier0 and long-term storage capacities



Trigger during ATLAS running



The End!

Backup

ATLAS TDAQ Glossary

http://atlas.web.cern.ch/Atlas/GROUPS/DAQTRIG/glossary.html

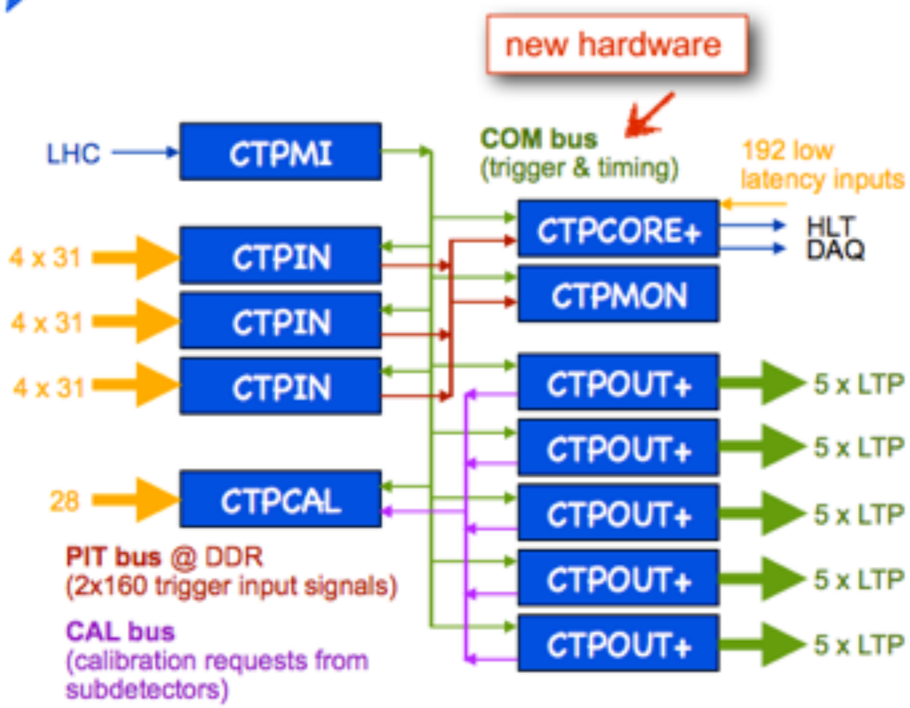
FE: Front End
ROD: Read Out Device
HW: HardWare
DC: Data Collector
RoI: Region of Interest
BE: Back End
ROS: ReadOut System
EB: Event Builder
SFO: SubFarm Output
MUCTPI: Muon to Central Trigger Processor Interface
TTC: Timing, Trigger Control

CPM: Cluster Processor Module
CMX: Common Merger eXtended Module
CTP: Central Trigger Processor
TP: Topological Processor
nMCM: new Multi Chip Module
PPM: Pre-Processor Module
JEM: Jet Energy sum Module
TCG: Thin Gap Chambers

CTP Upgrade

https://cds.cern.ch/record/1756906/files/ATL-DAQ-SLIDE-2014-658.pdf

Central Trigger Processor (CTP)



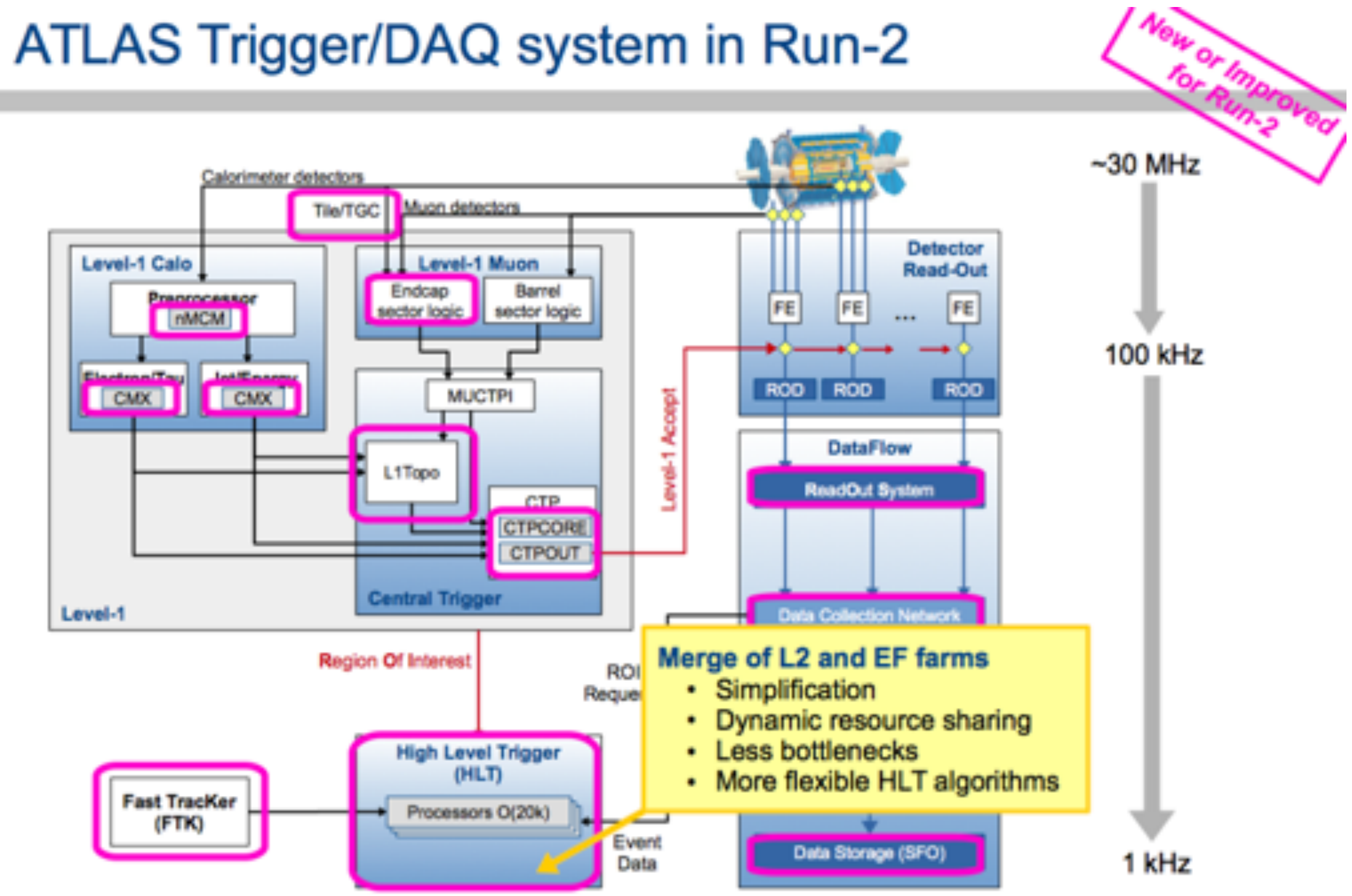
Why the upgrade?

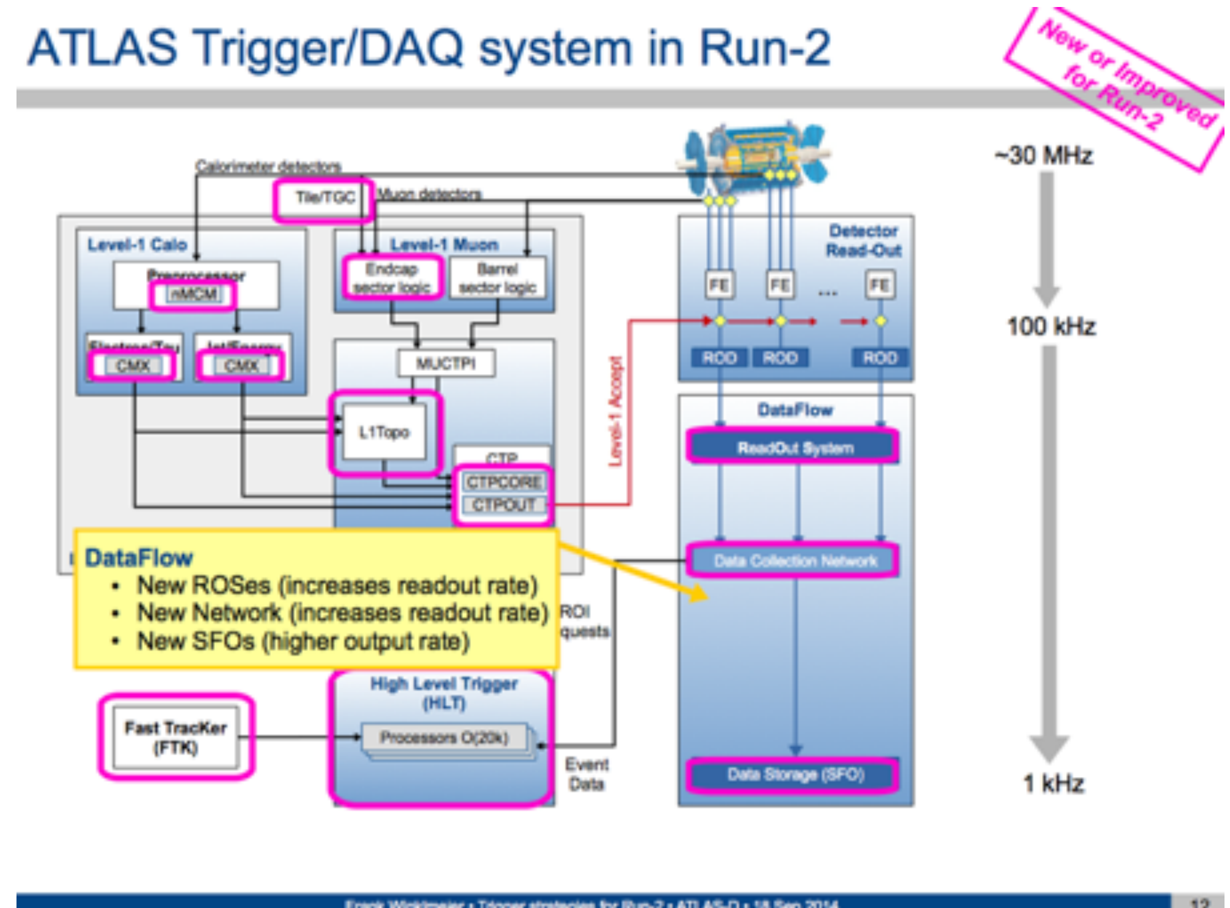
- more inputs: 160 → 512
- more outputs: 20 → 25
- more trigger items: 256 → 512 (logical combination of inputs)
- better monitoring

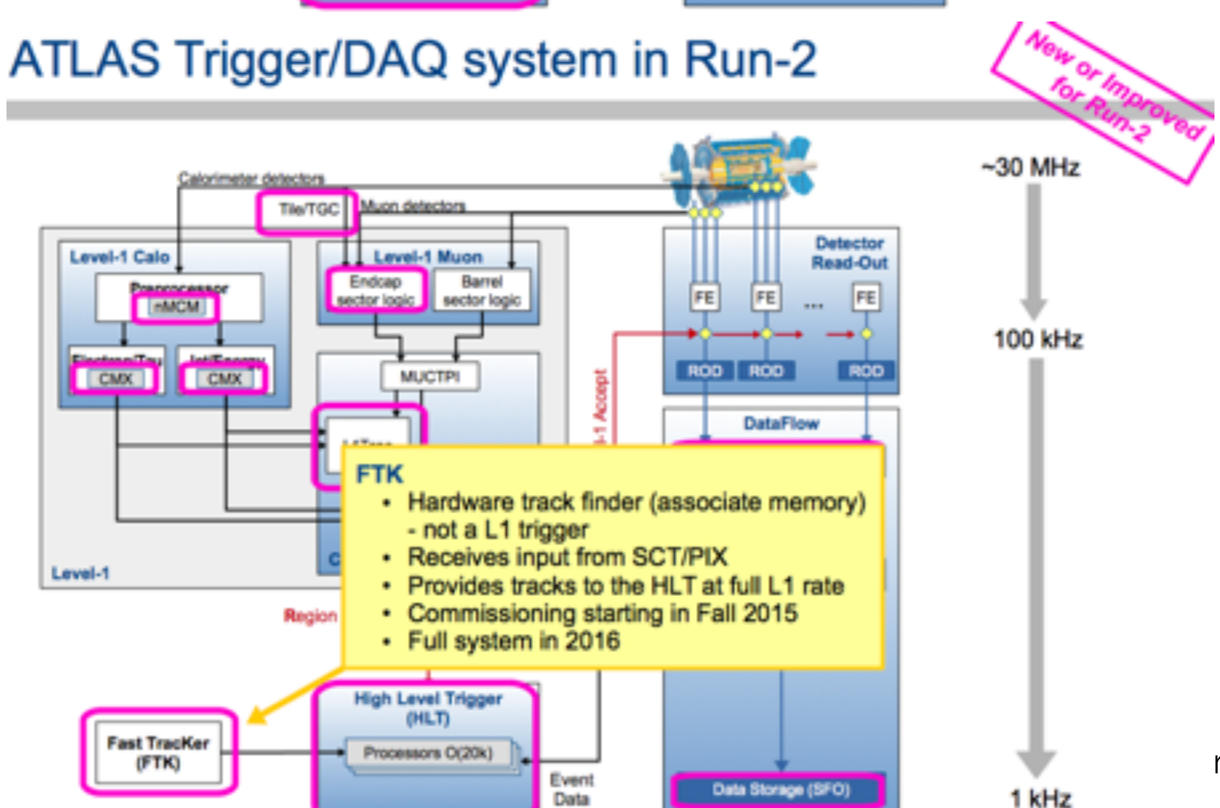
- CTPMI (machine interface)
  - receives timing signals from LHC
- CTPIN (input modules) — new firmware
  - trigger inputs from sub-detectors
  - synchronization / alignment / monitoring
- CTPCAL (calibration module)
- CTPCORE+ — new hardware
  - decision taking → L1 accepts (L1A)
  - dead time generation
  - generation of timing signals
  - summary information to HLT / DAQ
- CTPMON (monitoring module)
  - per bunch monitoring of trigger rates
- CTPOUT+ (output modules) — new hardware
  - distribute trigger & timing signals to sub-detectors
  - receives calibration requests

Kristof Schmieden TWEPP 2014 8

The ATLAS Trigger System







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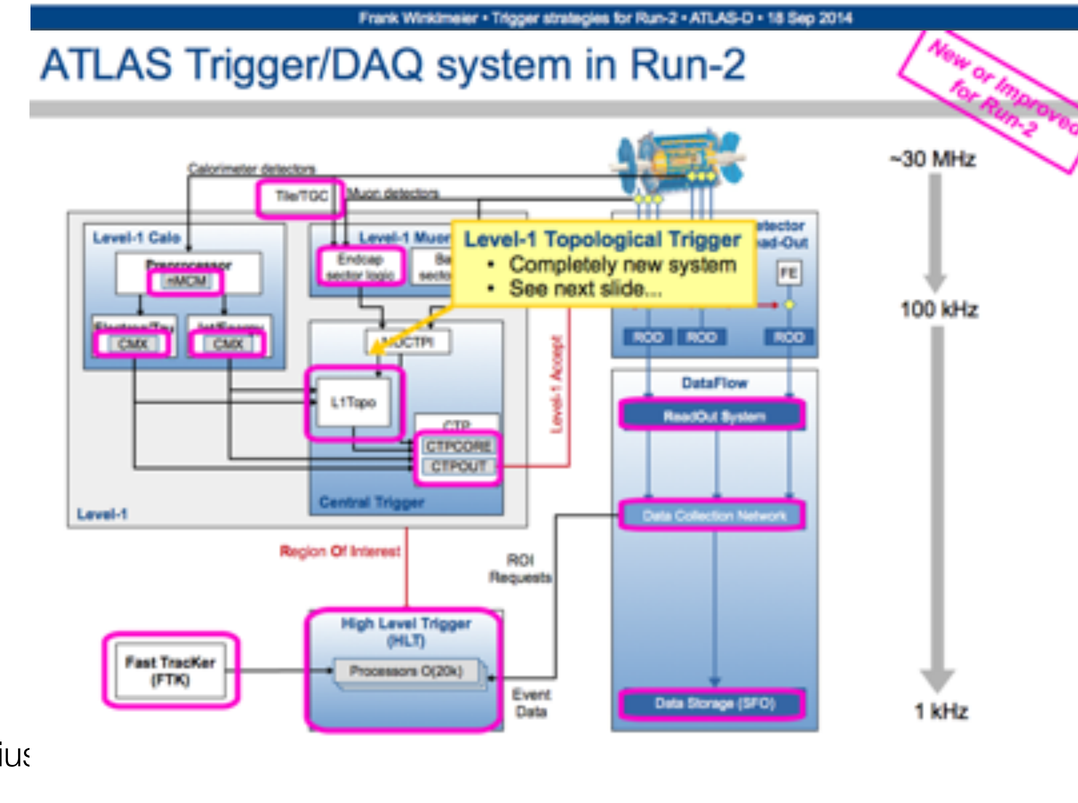


The ATLAS Trigger Configuration System

- sdf
  - sdf

- The Trigger DB – central source of the trigger configuration
  - DB & tooling designed to never overwrite any setting – only reuse

So far ~1500 trigger configurations stored

- Content
  - L1 system configurations - essentially the hardware settings
  - Trigger chains definitions o ~1k
  - Algorithm properties o ~4k
  - Prescale values ~1k for HLT, 256 for L1
    The prescale values are organized in sets and are managed independently

About 10k prescale value sets for L1 and 8k for HLT were used so far

https://cds.cern.ch/record/1609597/files/ATL-DAQ-SLIDE-2013-837.pdf

New HLT Design

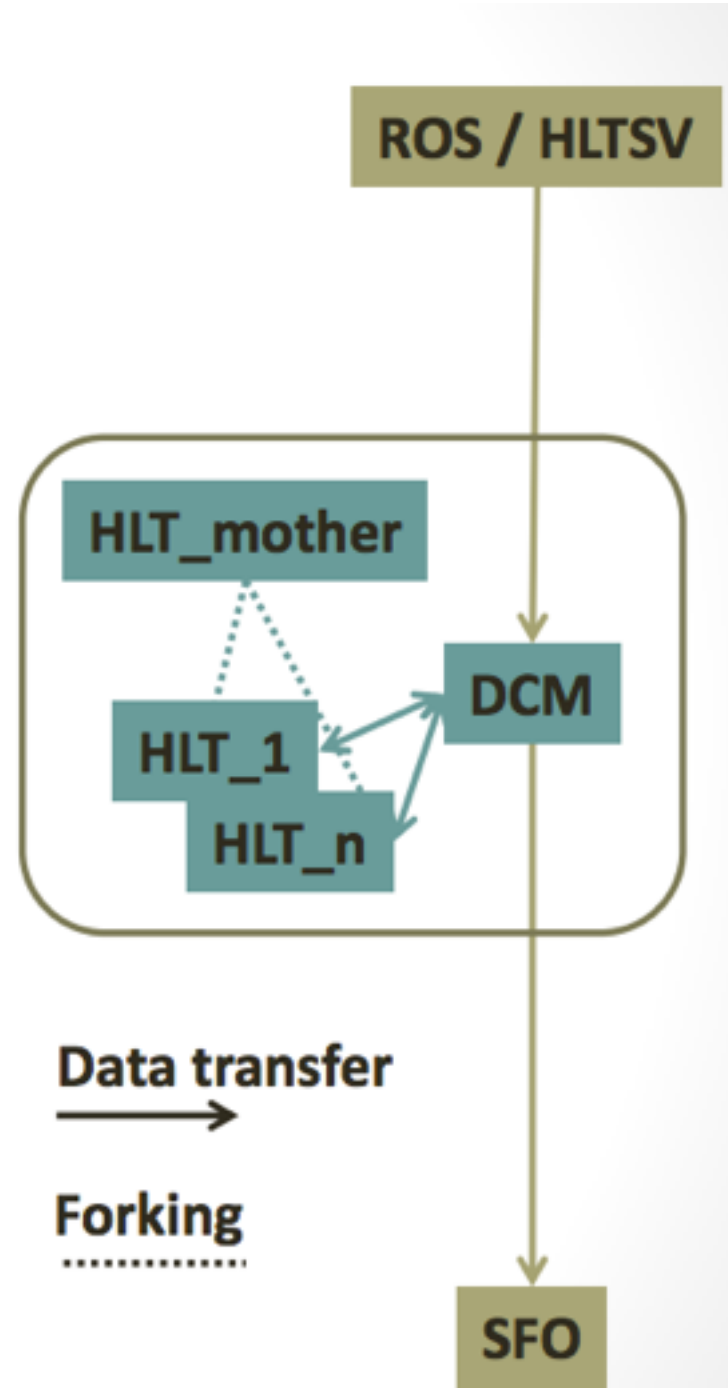
https://cds.cern.ch/record/1609564/files/ATL-DAQ-SLIDE-2013-831.pdf

Former L2 and EF algorithms ran in one process

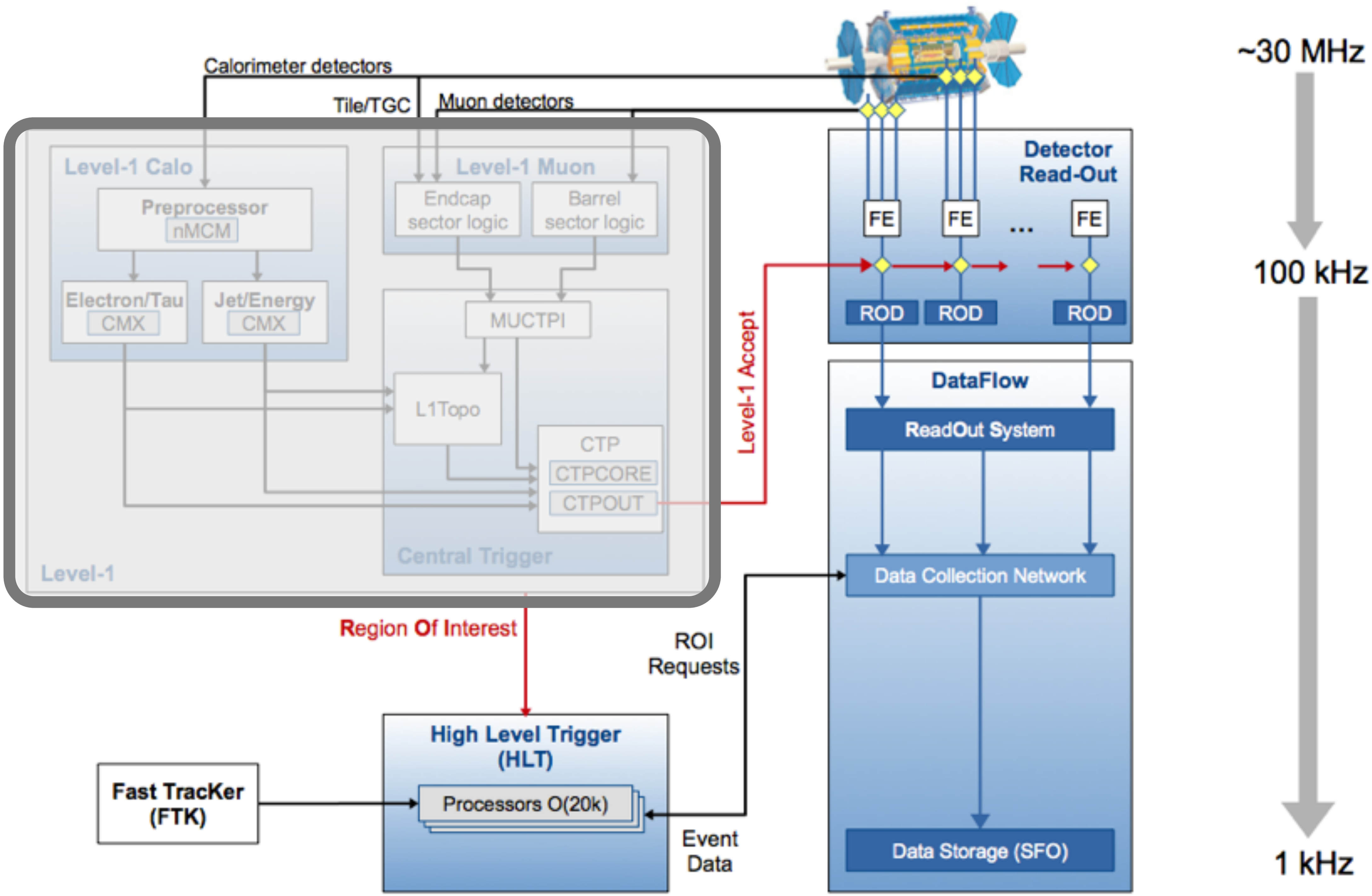
- Limited network transfer of data from L2 to EF algorithms replaced by unlimited in-memory transfer
- Data Collection optimization
- Flexible event building

Mother Process forks to exploit kernel's Copy on Write feature (CoW):

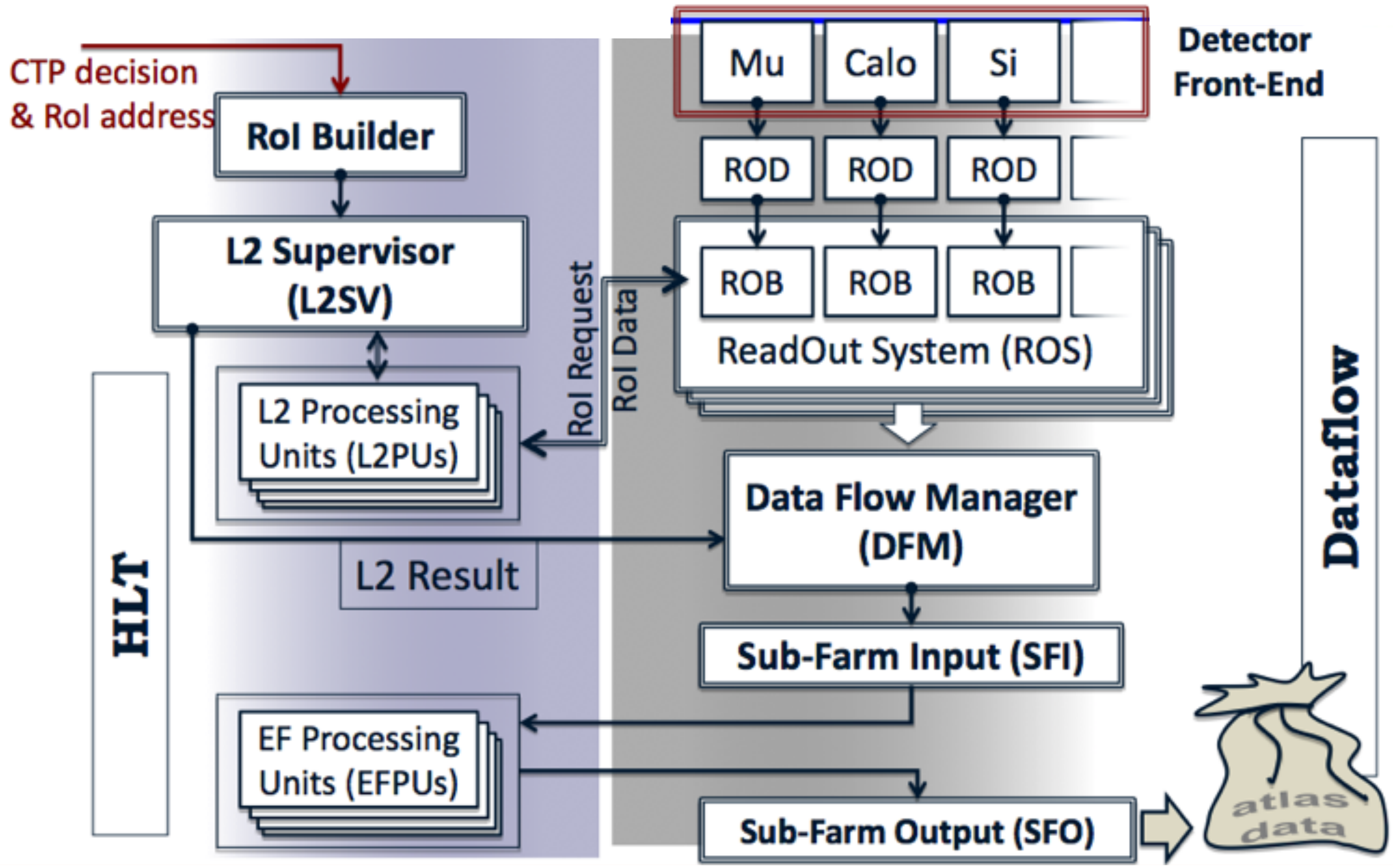
- HLT workers (multi-process HLT) created at start of data taking session
- Substantial amount of memory saving



Run 2 Data Flow



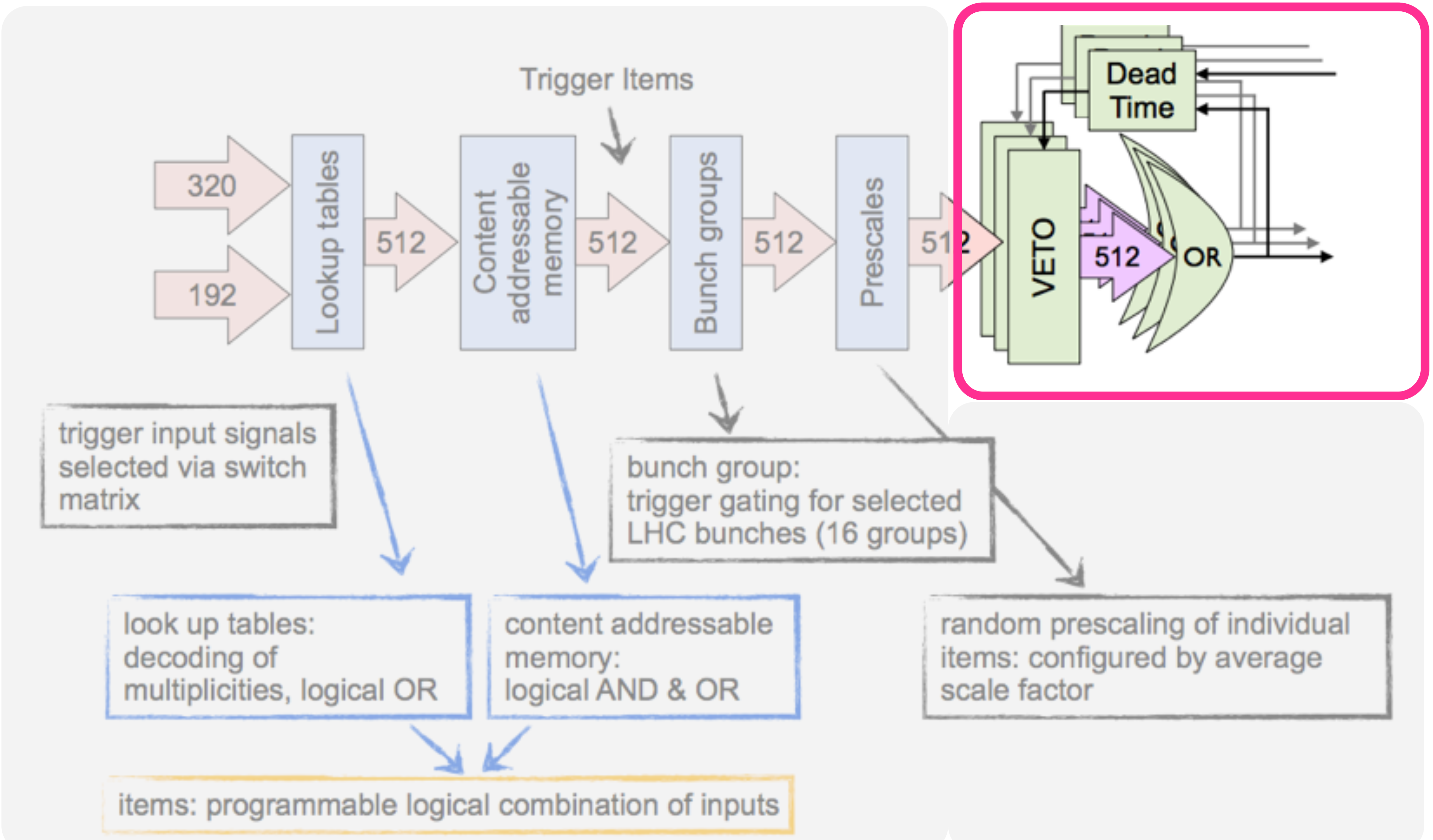
Run 1: HLT & Data Flow



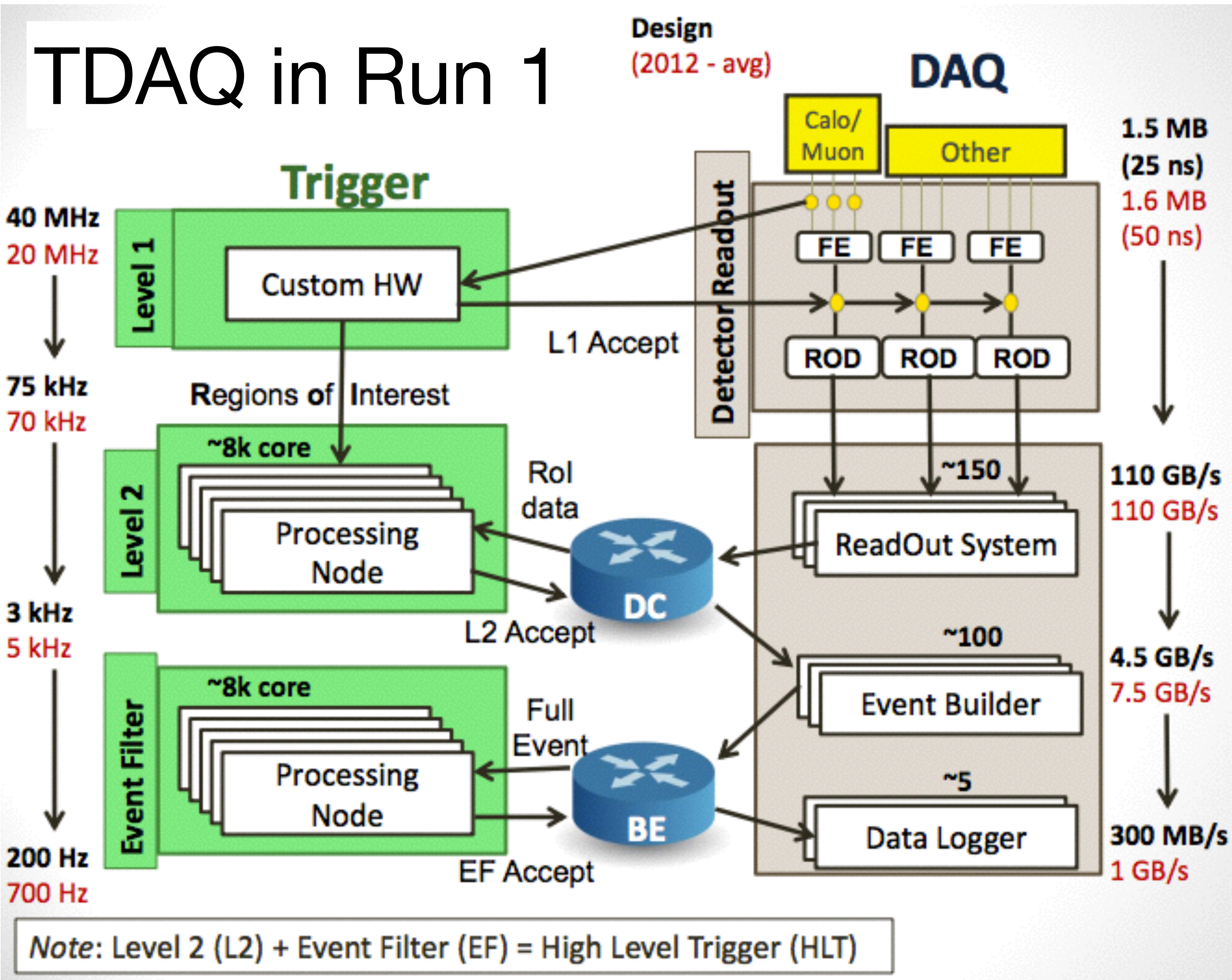
Trigger Path

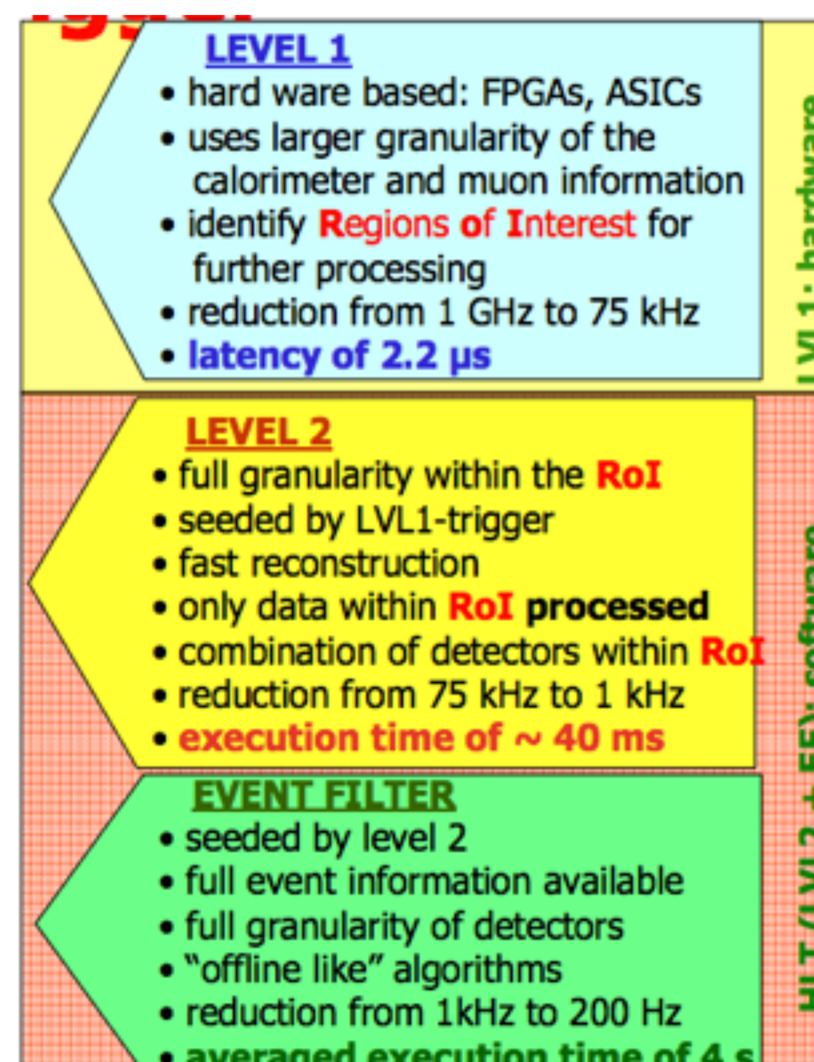
https://cds.cern.ch/record/1756906/files/ATL-DAQ-SLIDE-2014-658.pdf

- The way the deadtime is applies is shown in the following picture:



The ATLAS Trigger System in Run 1





FE: Front End
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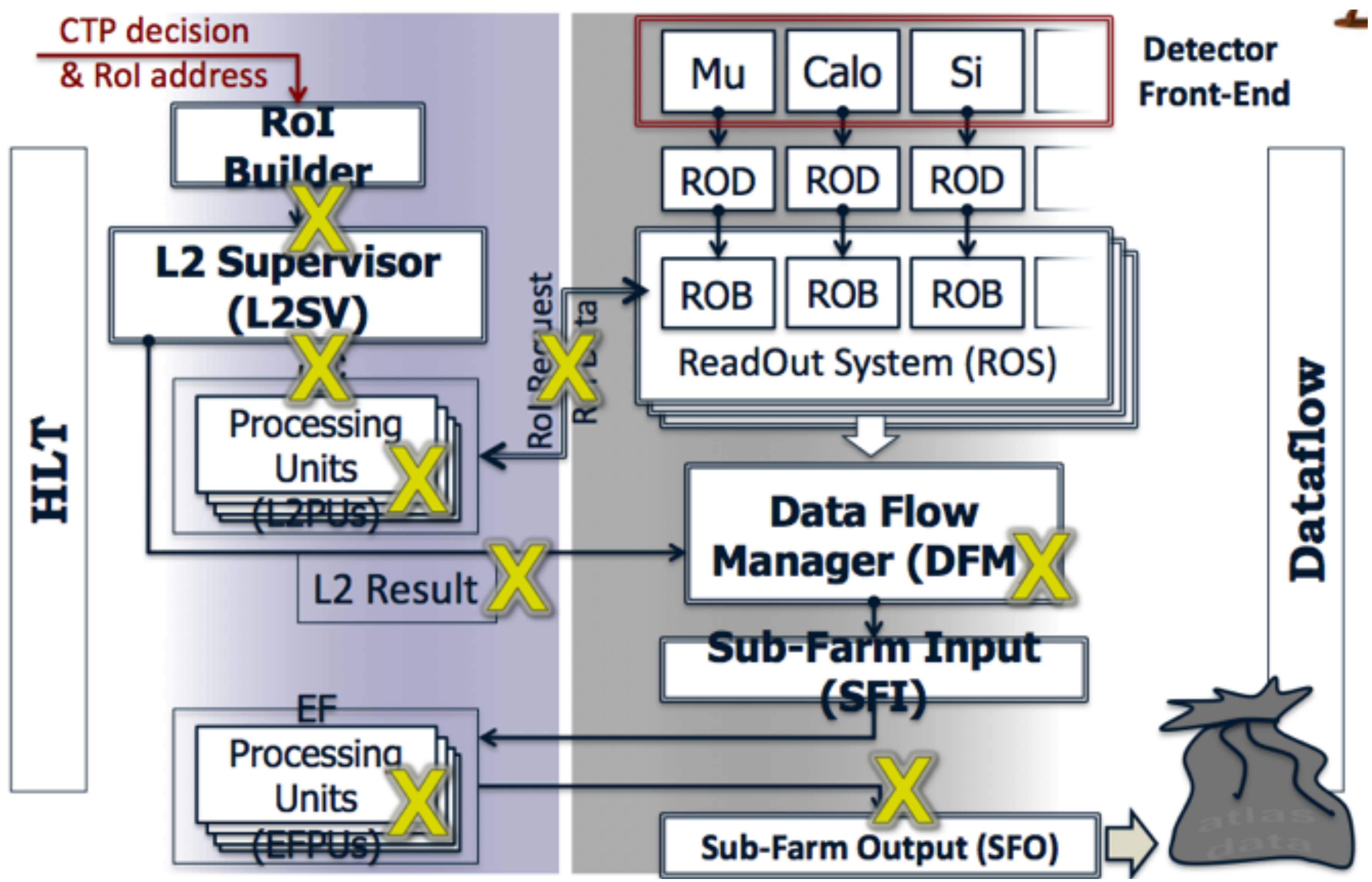
ROS: ReadOut System
EB: Event Builder

Debug Stream in Run 1

https://twiki.cern.ch/twiki/bin/view/Atlas/DebugStream

Debug stream:

- a way to spot problems and weaknesses of the online system without loosing events
- presence of events in a timeout debug stream does not necessarily imply a bug in the online system
- timeouts ensure the system robustness



Debug Stream in Run 2

Debug sub-streams used to differentiate failures in the online system seen by the HLT:

- debug_DcmFetchRobsError:
- debug_DcmL1IdMismatchError:
- debug_HLTMissingData: The event processing could not be started in the PU because some data was missing (very rare)
- debug_HLTSVForceAccept:
- debug_HltError: Severe algorithm errors which abort the event processing
- debug_LateEvents: Events that didn't make it to the SFO at the LB boundaries. The SFO has closed the "right" file, so it writes the late events to the debug_LateEvents stream.
- debug_PUCrash: PUCrash
- debug_PUTimeout: Event processing timeout where the steering was able to abort the event processing in time

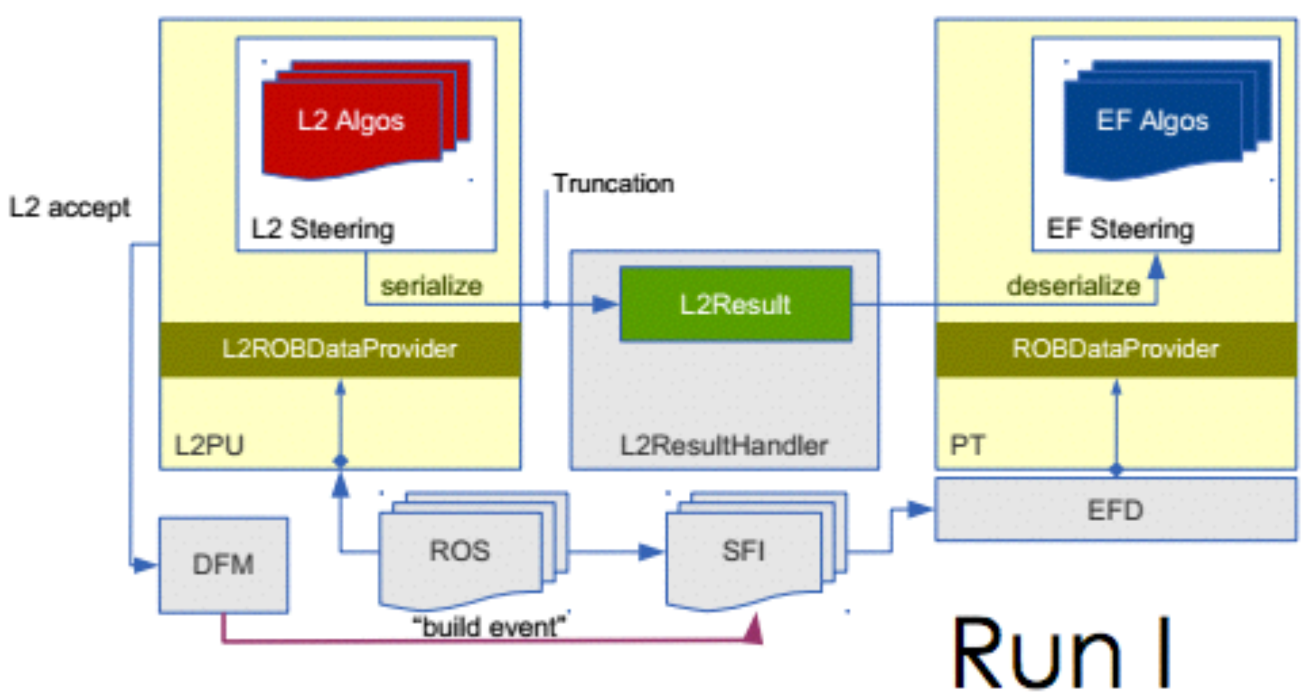
Other debug streams:

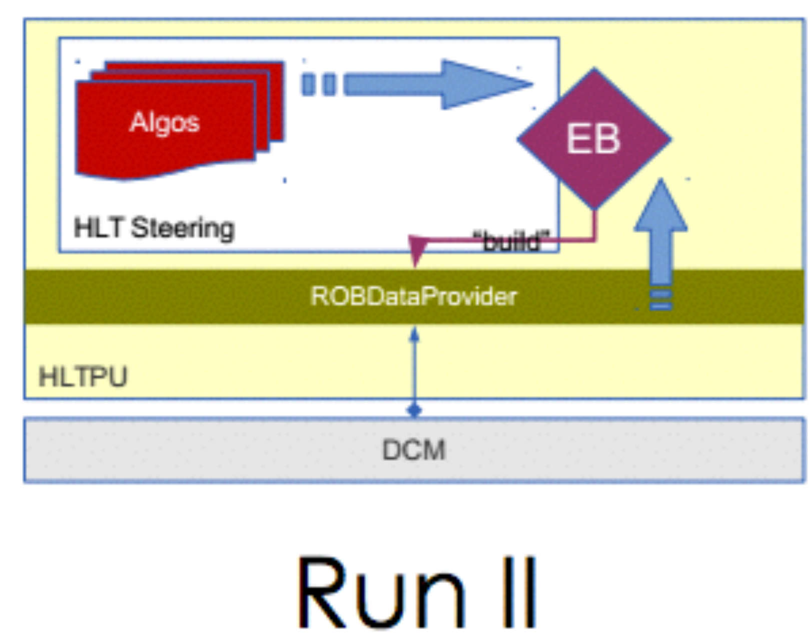
- debug_LateEvents: Events that didn't make it to the SFO at the LB boundaries. The SFO has closed the "right" file, so it writes the late events to the debug_LateEvents stream.
- debug_duplicated: *Possibly* duplicated events, due crashes/communication failures in the DF system. Duplication can take place in DFM, SFI and EFD.
- debug_DISCARD: This is the "default" stream of some chains, e.g. xe chains running on all L1 TEs, that should never be included int he run, but executed only in *rerun* mode. This stream should never be seen. If it is, there has been a mistake in the online trigger configuration.

https://twiki.cern.ch/twiki/bin/view/Atlas/DebugStream

Changes in HLT for Run 2

- Merged HLT Farm allows for flexible resource allocation in conjunction with combined network
- No need to read data from buffers multiple times, no network use for L2 → EF
  - No dedicated event building step → more flexibility
- Changes are accompanied by new software to exploit this merged design





Data Streaming - Run 1

Stream: Collection of events or event fragments of related signatures in the same data set, overlap between streams is designed to be minimal

- ✓ Streaming is based on trigger decisions at the HLT
- ✓ The Raw Data physics streams are generated at the SFO
- ✓ All streams are inclusive, except the debug stream

Debug Streams
events without full trigger decision, due to failures in parts of the online system

Physics Streams
data for physics analyses

Egamma
Muons
JetTauEtMiss
MinBias
...

Express Stream
Events for prompt reconstruction (calibration loop)

Calibration Streams
events delivering the minimum amount of information for detector calibrations at high rate

partial events