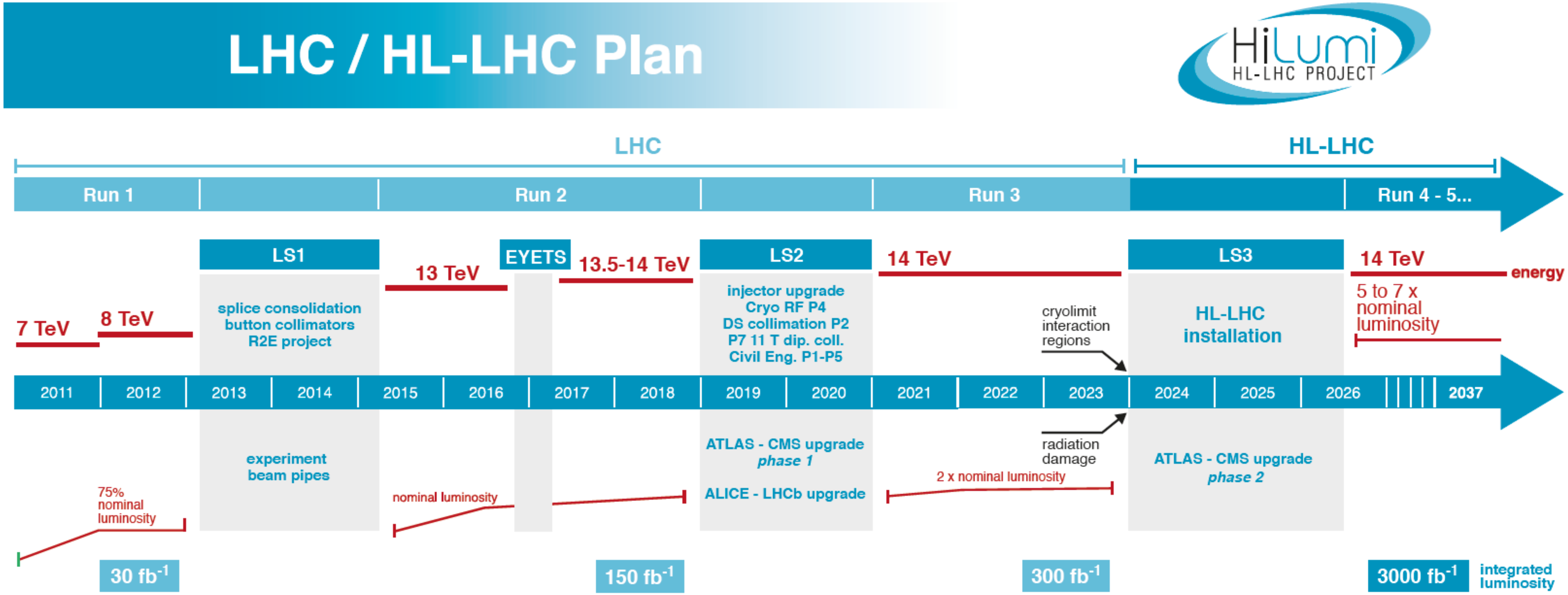
New TDAQ for HL-LHC and beyond

Samuel Silverstein, Stockholm University

- LHC upgrade
- Upgrades to Trigger/DAQ
- New and future systems

High-luminosity LHC upgrade

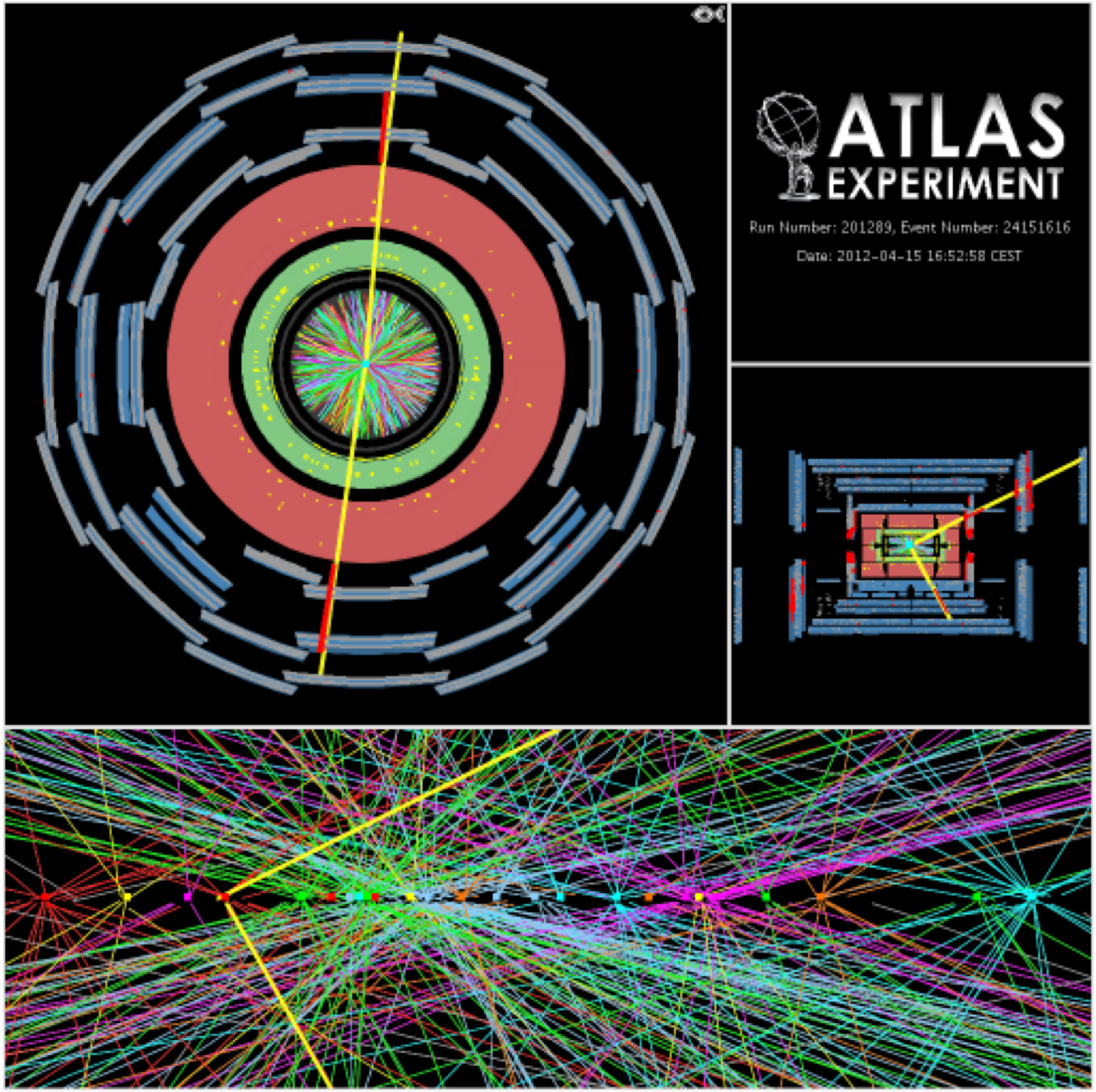


- HL-LHC upgrade ~ 2024-2026
- Aim to provide > 3000 fb-1 by 2039
- Mean of up to ~200 ”soft” collisions per event!

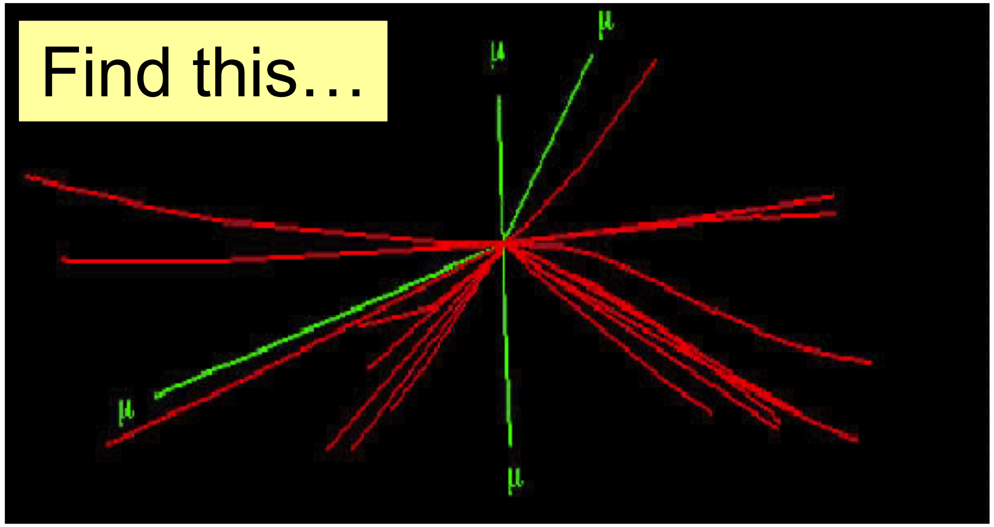
”Nominal” pileup event

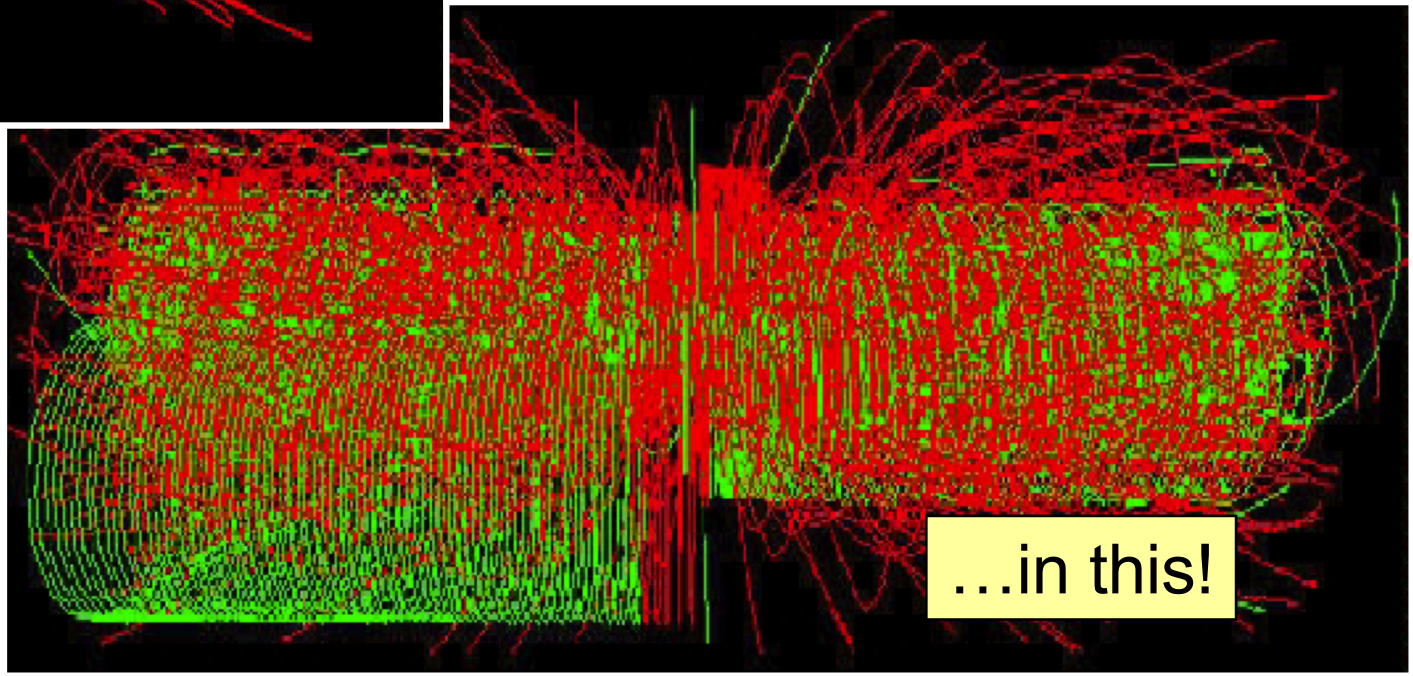
Z ➔μμ

plus 24 additional minimum-bias collisions



Physics at high luminosity…





Challenges at high lumi

- Increased pileup means many more unrelated particles on top of "interesting" physics events
- This degrades our trigger performace
  - Pattern recognition in trigger and tracker
  - "Isolated" particle recognition in calorimeter
  - "Missing energy" of neutrinos and other neutral particle
- Radiation damage also scales with luminosity
  - Front-end electronics need to be replaced with new, radiation-tolerant systems

High pileup conditions

- Many “soft” minimum-bias collisions overlaid on each “hard” physics event
  - More low-momentum tracks in inner detector and muon chambers
  - Low-energy calorimeter deposits surrounding and/or on top of interesting features
  - “Out of time” hits adversely affect BX identification and energy calculation

Single-object triggers

- Muon isolation particularly sensitive
- For calorimeter objects (e/γ/τ/had)
  - Isolation cuts must be higher (and thus less effective)
  - Pileup degrades E_T resolution of central clusters

Jets

- Minimum bias deposits contribute proportionally to jet window area
  - Larger jet windows affected more by pileup
  - Smaller jet windows “miss” more of the actual jet
- Jet algorithms often use sums of many calorimeter cells
  - Particularly sensitive to out-of-time energy deposits

Energy-sum algorithms

- Many low-E_T deposits distributed throughout the calorimeter
- Large pedestals added to sum-E_T calculations
- Missing-E_T measurements degraded

Implications for L1 trigger

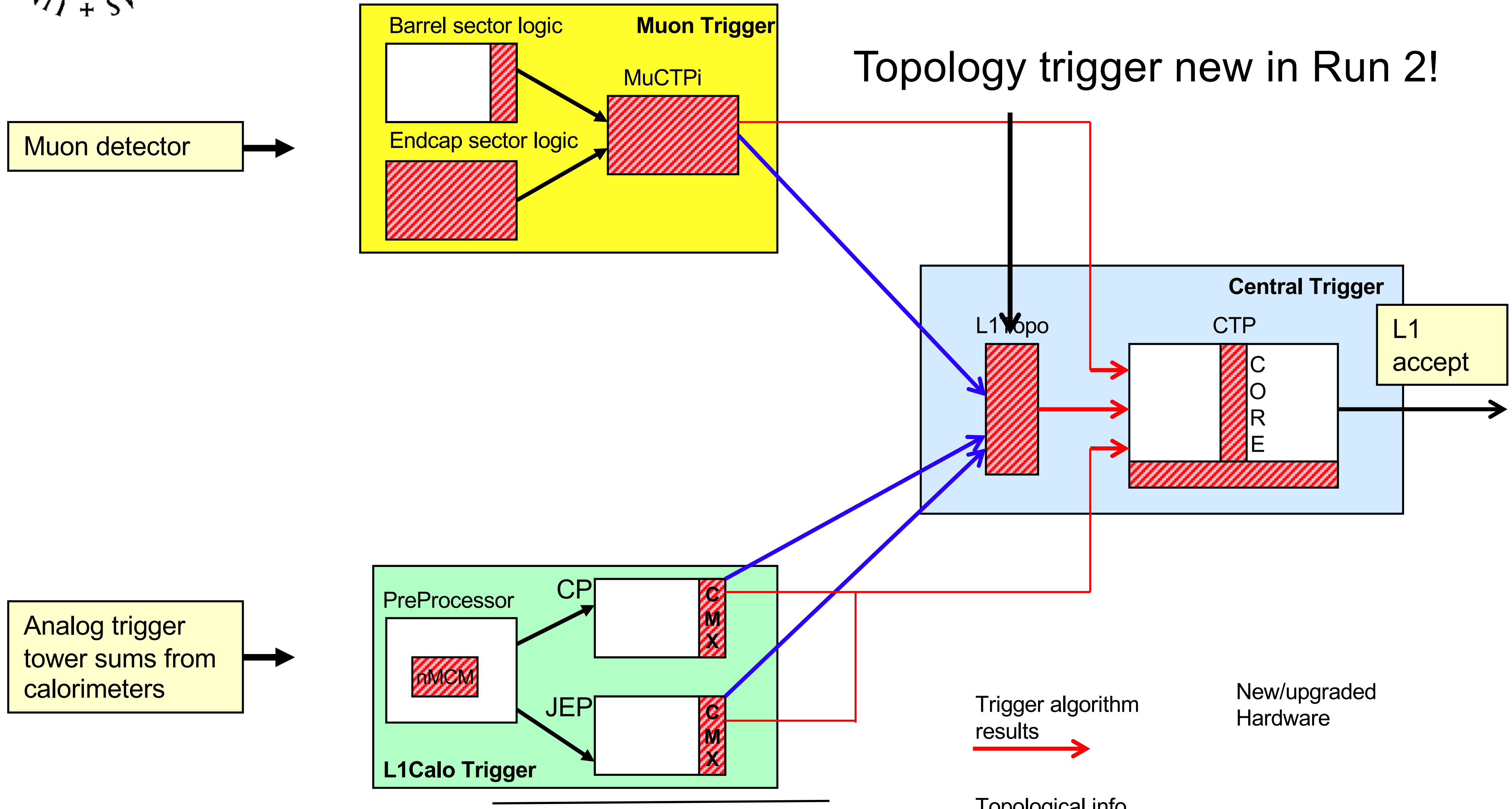
- Balance between rates and thresholds for single-object triggers
  - Higher thresholds ➔ lose physics
  - Higher rates ➔ dead time
- Strategies to reduce rates:
  - Pre-scaling low-threshold triggers
  - Multi-object triggers (2e + 2j)
  - Event topology
  - Track trigger
- Smaller objects have less pileup
  - Finer-granularity calorimeter trigger data

Event topology

- Original triggers were multiplicity-based:
  - Single electron > 40 GeV
  - 2 jets > 25 GeV
  - etc…
- ATLAS added a topology trigger for Run 2:
  - Add object coordinates to real-time data
  - Perform topology-based algorithms like:
    - E,g. two 25 GeV Jets, $0 < \Delta\varphi < 2.8$
    - Non-overlapping tau + Jet
    - Invariant M_T of two electrons

ATLAS Run-2 architecture

Topology trigger new in Run 2!

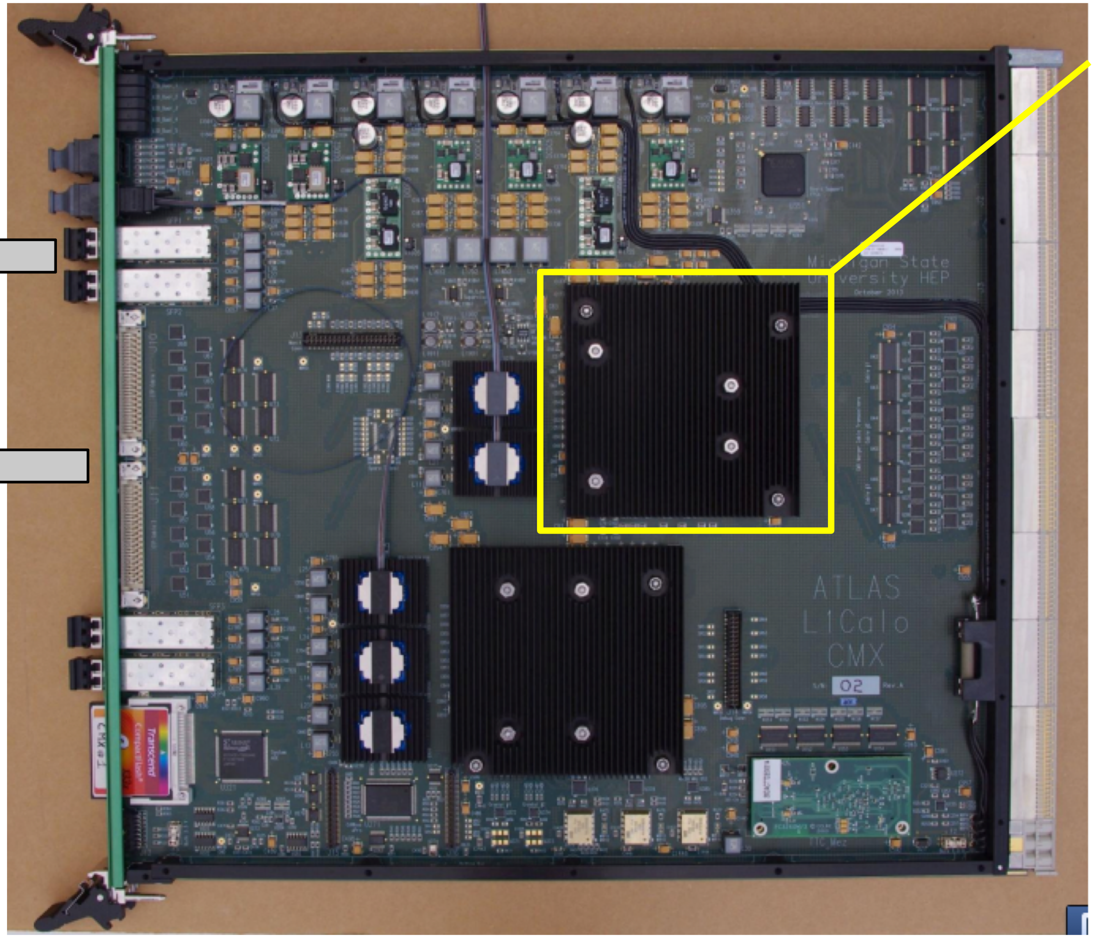


ATLAS topology upgrade

CMX: Merger module replacement in jet, cluster processors

Topology data (trigger objects) to L1Topo

Multiplicity results to the CTP

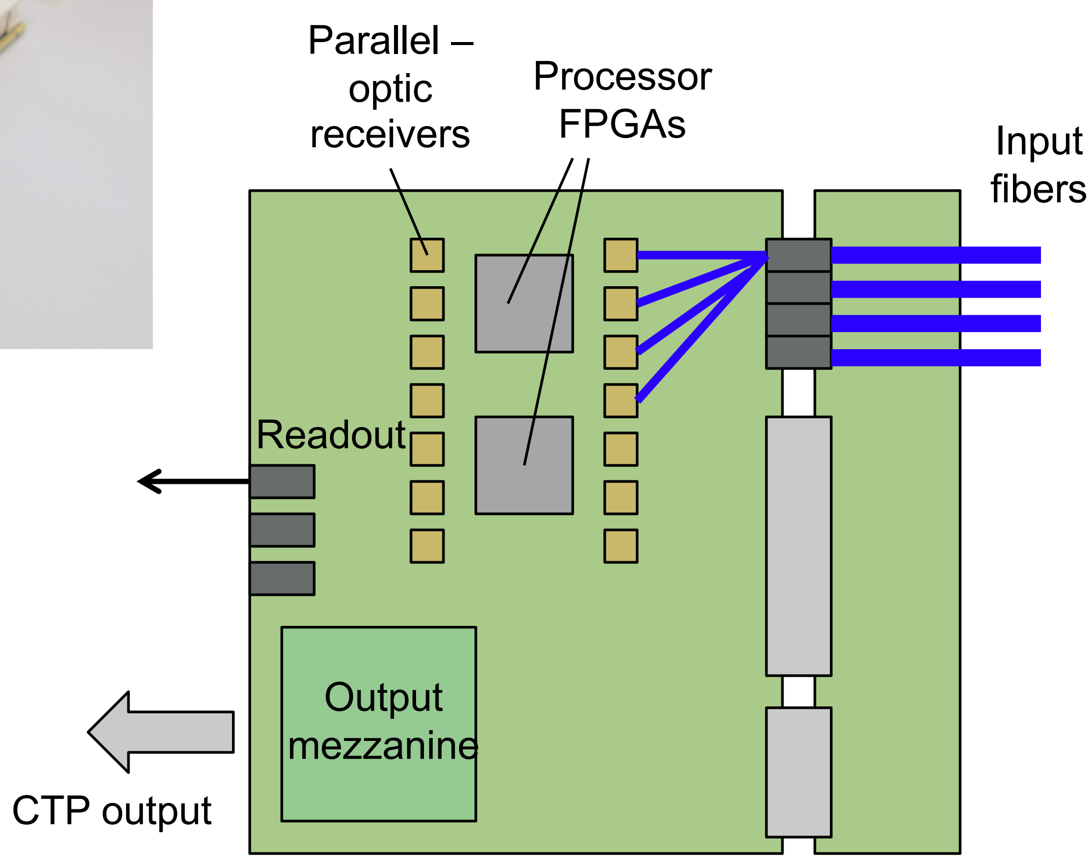


Large, fast FPGA does multiplicity-based algorithms, Sends trigger objects to L1Topo

Backplane input rate increased 4x for more bandwidth

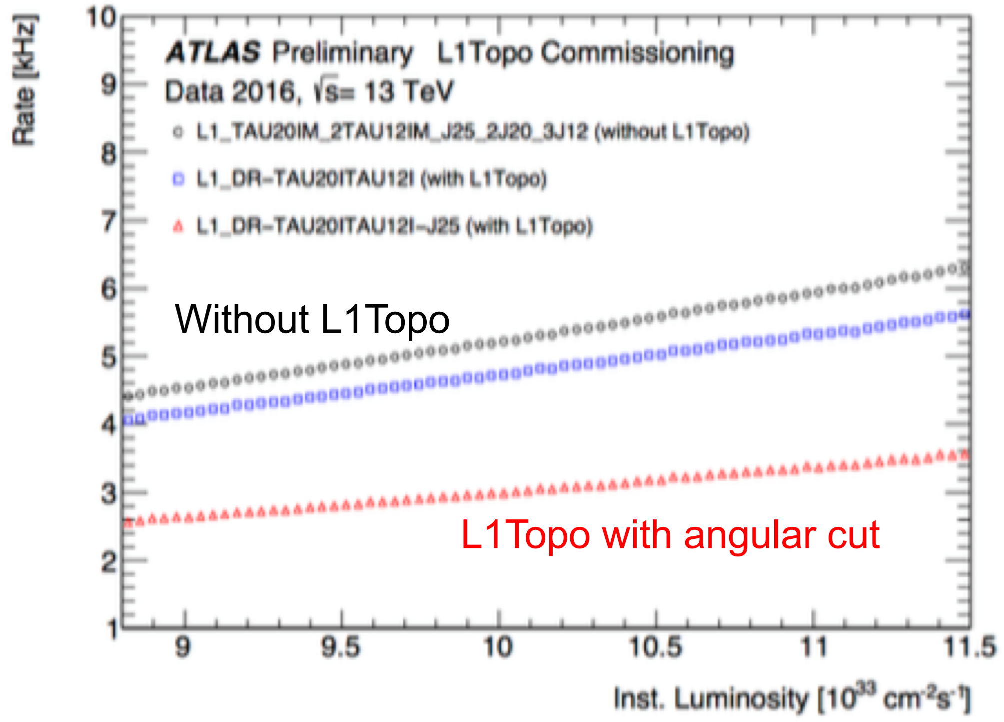
L1Topo processor module

- Two modules, 2 FPGAs each
- Each FPGA has 80 input links
  - Currently 6.4 Gbit/s
- Can receive full event topology
  - E/gamma/hadron clusters
  - Jets
  - Muons
  - Sum and missing ET
- Send up to 128 bits to CTP



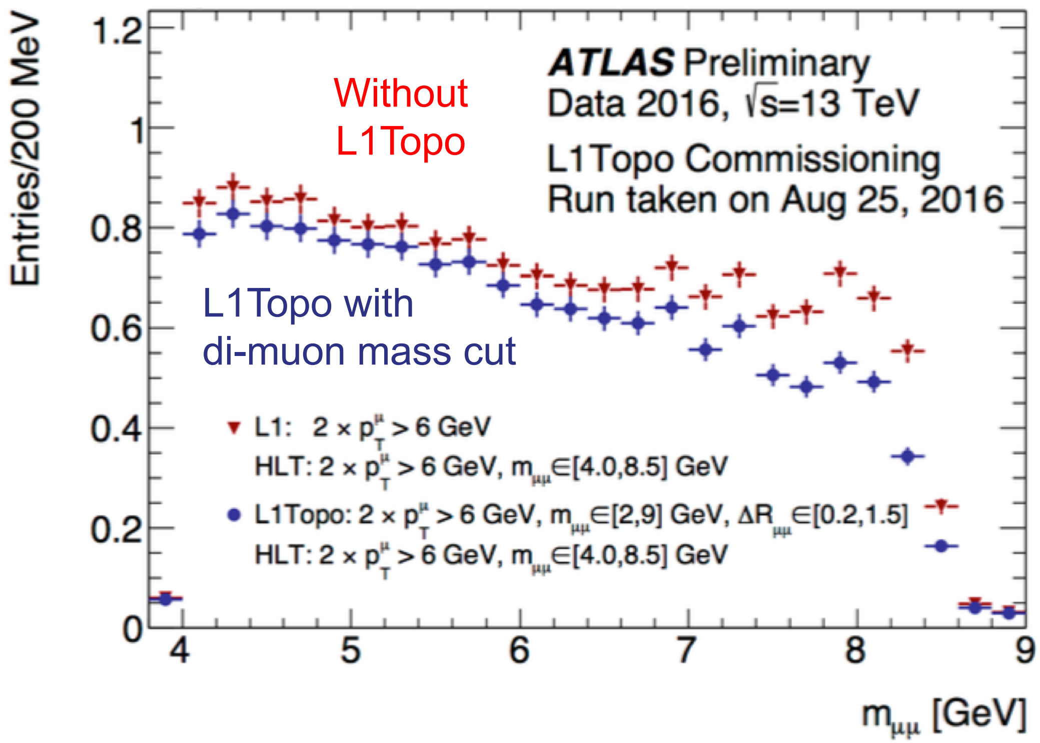
L1Topo commissioning

di-tau + jet(s)



Important Higgs trigger.
~2 rate reduction, with
no loss of efficiency

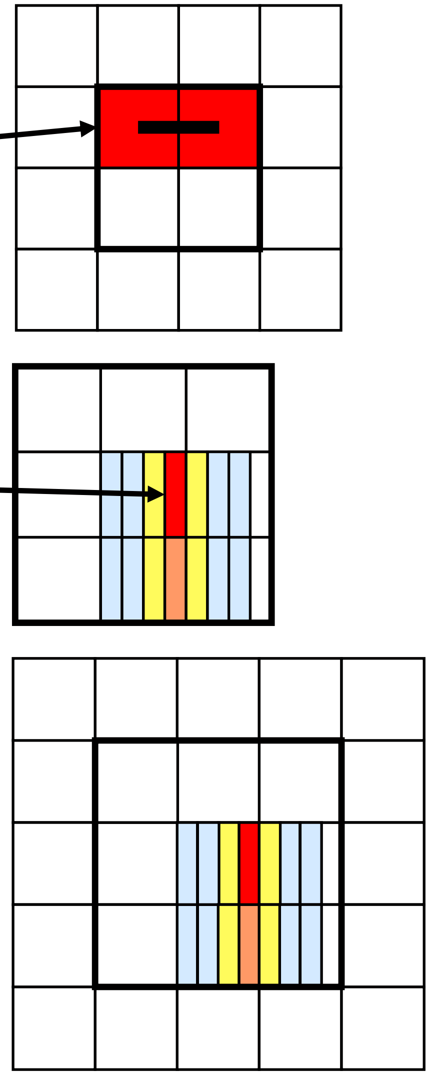
di-muon trigger



Important b-physics trigger…

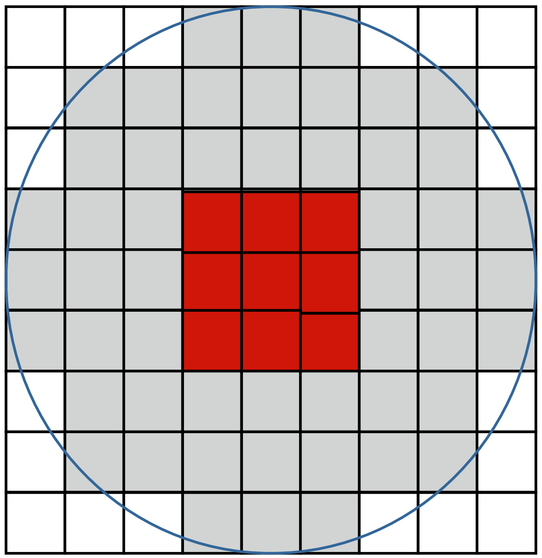
EM/Tau ID in jFEX

- Legacy EM/Tau algorithms
  - 0.1 x 0.2 ‘cluster’
  - 0.4 x 0.4 isolation window
- New EM algorithm
  - 0.1 x 0.025 ‘cluster’
  - 0.3 x 0.3 isolation window
  - hadronic veto
- New Tau algorithms
  - Up to 0.5 x 0.5 isolation window



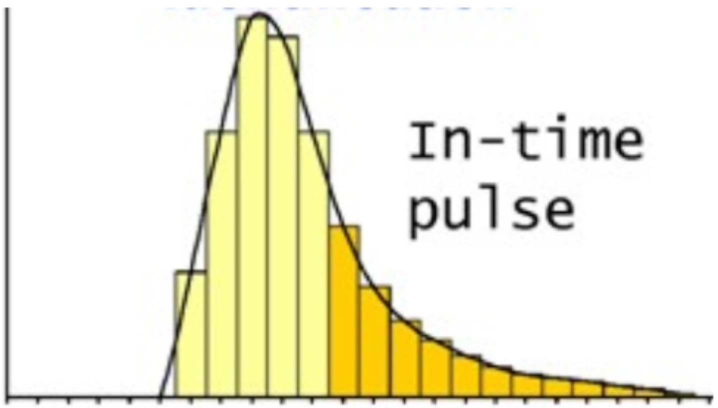
Jet ID in jFEX

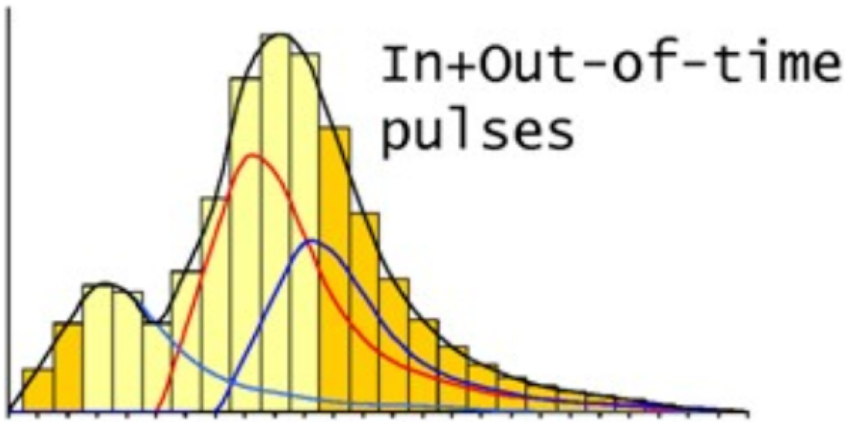
- Jet identification with 0.1x0.1 towers
  - Currently using 0.2x0.2
- Digital summing of towers reduces out-of-time pileup
- More sophisticated algorithms:
  - Assemble jets from higher-E_T 'clusters', "round" jets, Gaussian fit, etc..
- gFEX: "Fat" jets (R ~ 1)
  - For 'boosted' physics



‘Out-of-time’ pileup

- Calorimeter pulses are fit to an “ideal” shape to extract amplitude and time
  - Adding out-of-time pulses degrades measurements



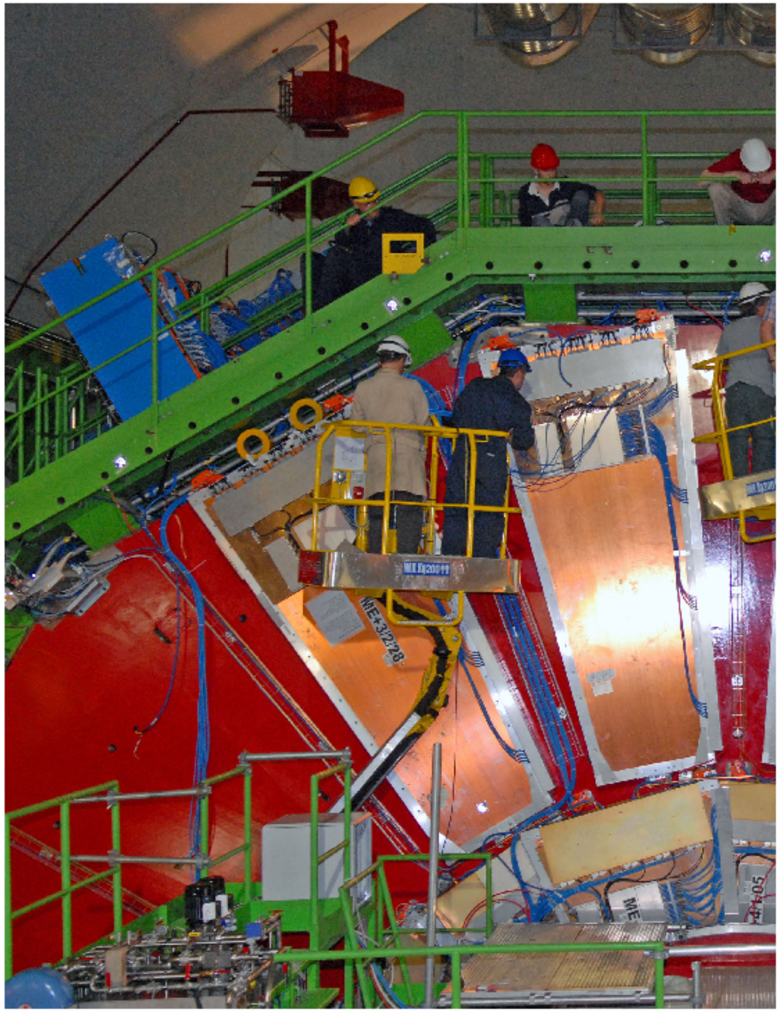


Single-object Triggers

Muons

- Muon particularly sensitive to pileup in forward regions of the detector
  - Low P_T particles from minimum bias
  - Cavern- and beam-related backgrounds
- To improve muon performance
  - Finer-granularity detectors in affected angular regions
  - More trigger layers
    - 4-fold coincidence better than 3-fold

CMS muon upgrade



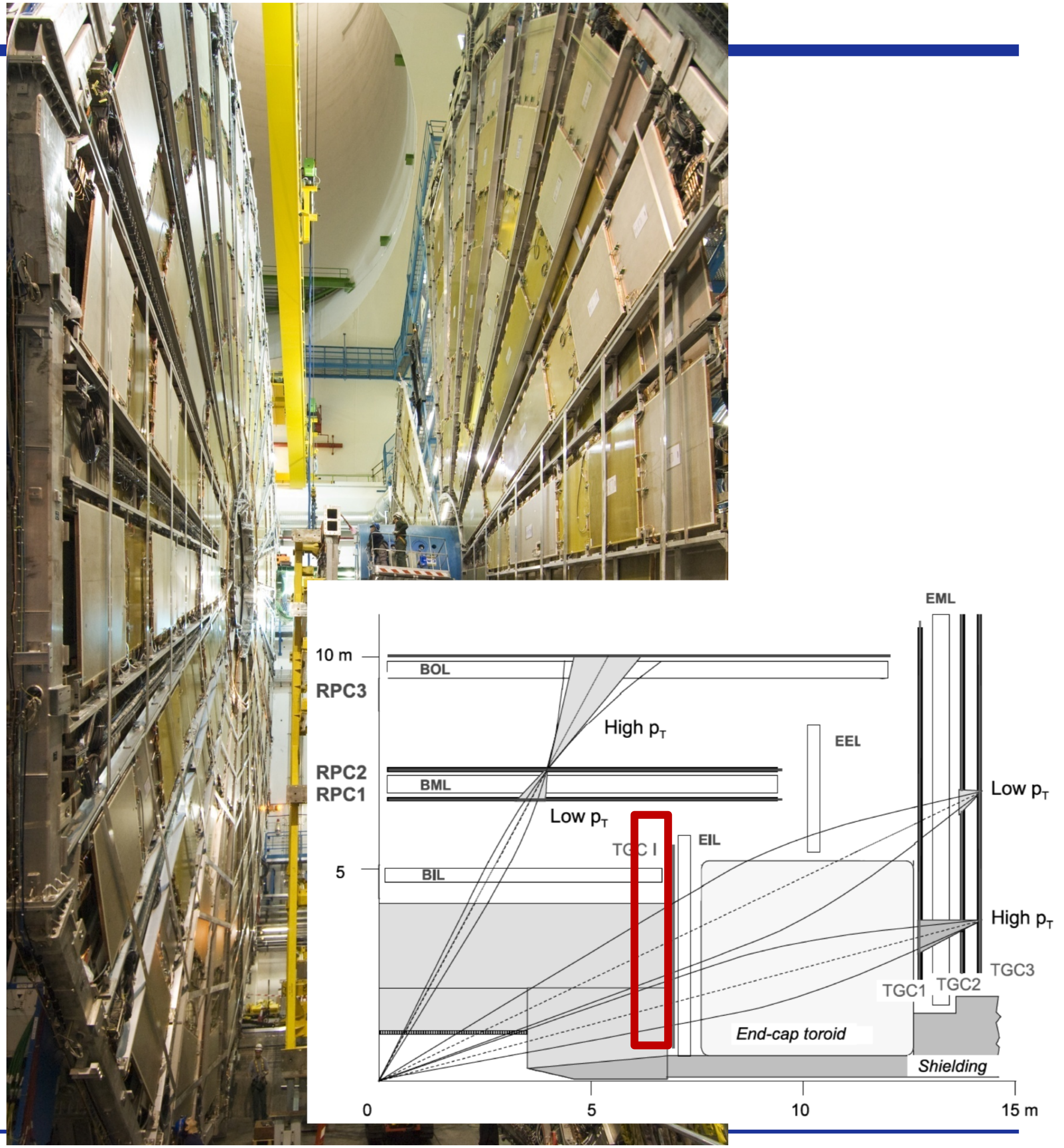
4th layer of forward muon chambers
(CSC & RPCs)

- better trigger robustness in range $1.2<|\eta|<1.8$
- preserve low p_T threshold

Long shutdown 1 2014-15

Atlas: new muon small wheel

- Replace "small wheel"
  - New chambers with σ<100 μm
  - Improved P_T resolution
- Provides 4th trigger layer
  - reduce fake rate
  - Level-1 track segments with 1 *mrad* resolution
- Installation in LS2

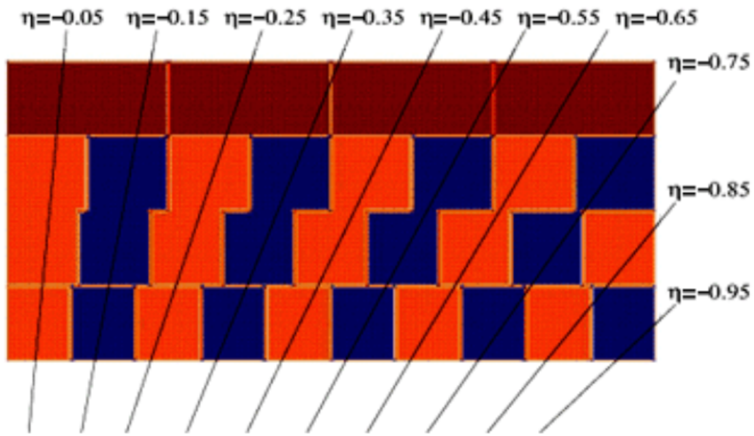


Isolated electrons/hadrons

- Finer-granularity isolated particle algorithms are less sensitive to pile-up
- Strategy
  - Upgrade front-end electronics (if necessary) to add finer EM tower segmentation to L1 data path
  - New L1 feature processors to receive and use the finer data
- Level-1 becomes more HLT-like

Better calorimeter trigger data is needed for Level-0

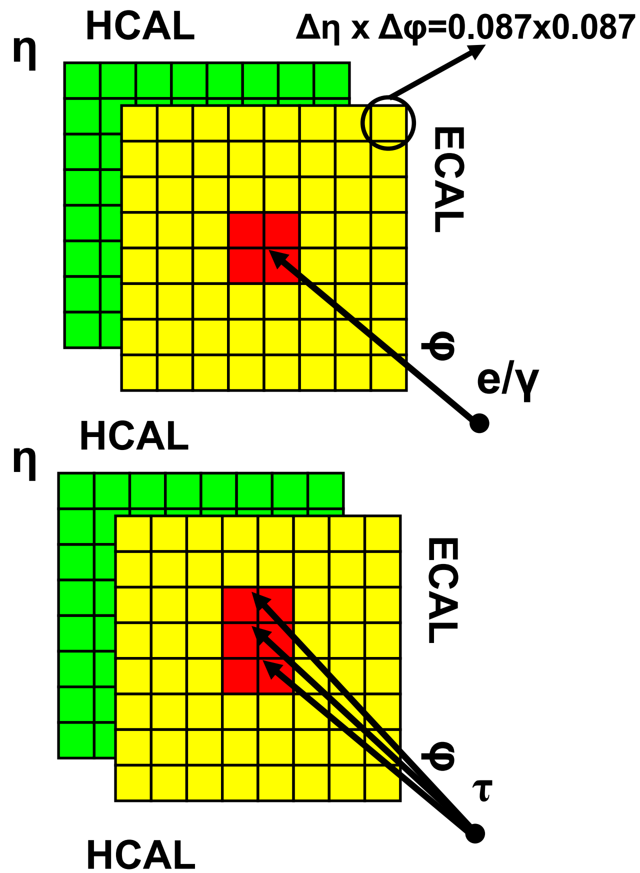
- Current trigger receives analog "trigger tower" sums of multiple channels (0.1 x 0.1)
  - Limited granularity
  - Vulnerable to pile-up
    - Nearby deposits
    - "out-of-time" pile-up



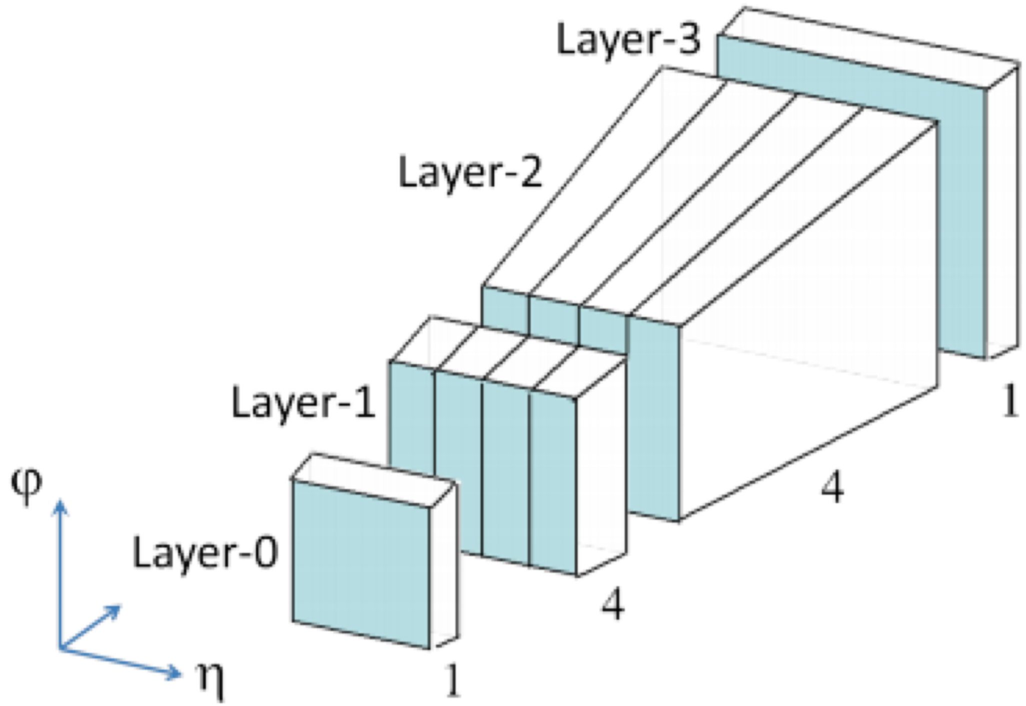
- Upgraded system:
  - Read out and digitally process each detector channel at 40 MHz (both amplitude and time)
  - Provide higher-granularity trigger data, with only <u>in-time</u> energy deposits

CMS single-particle algos

- Finer-granularity calorimeter towers
  - 0.087 × 0.087 instead of 0.1 × 0.1
- Smaller electron and tau candidates
  - 2 × 2 and 2 × 3 clusters
  - Calculate isolation deposits around clusters

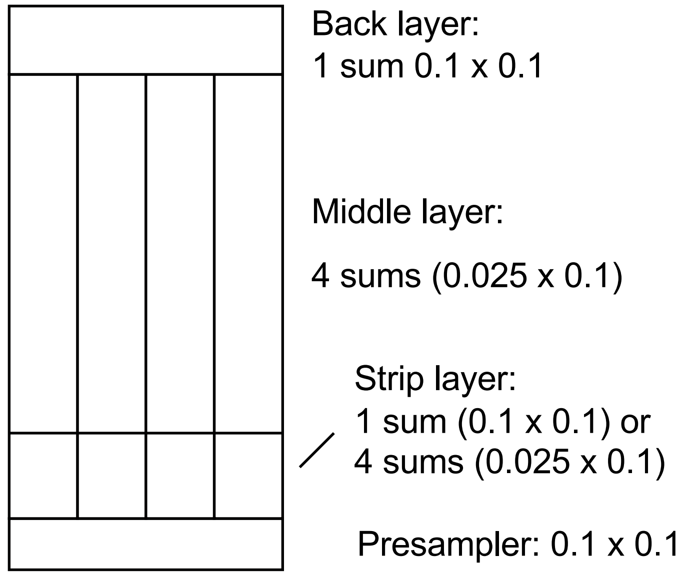


ATLAS: fine EM segmentation

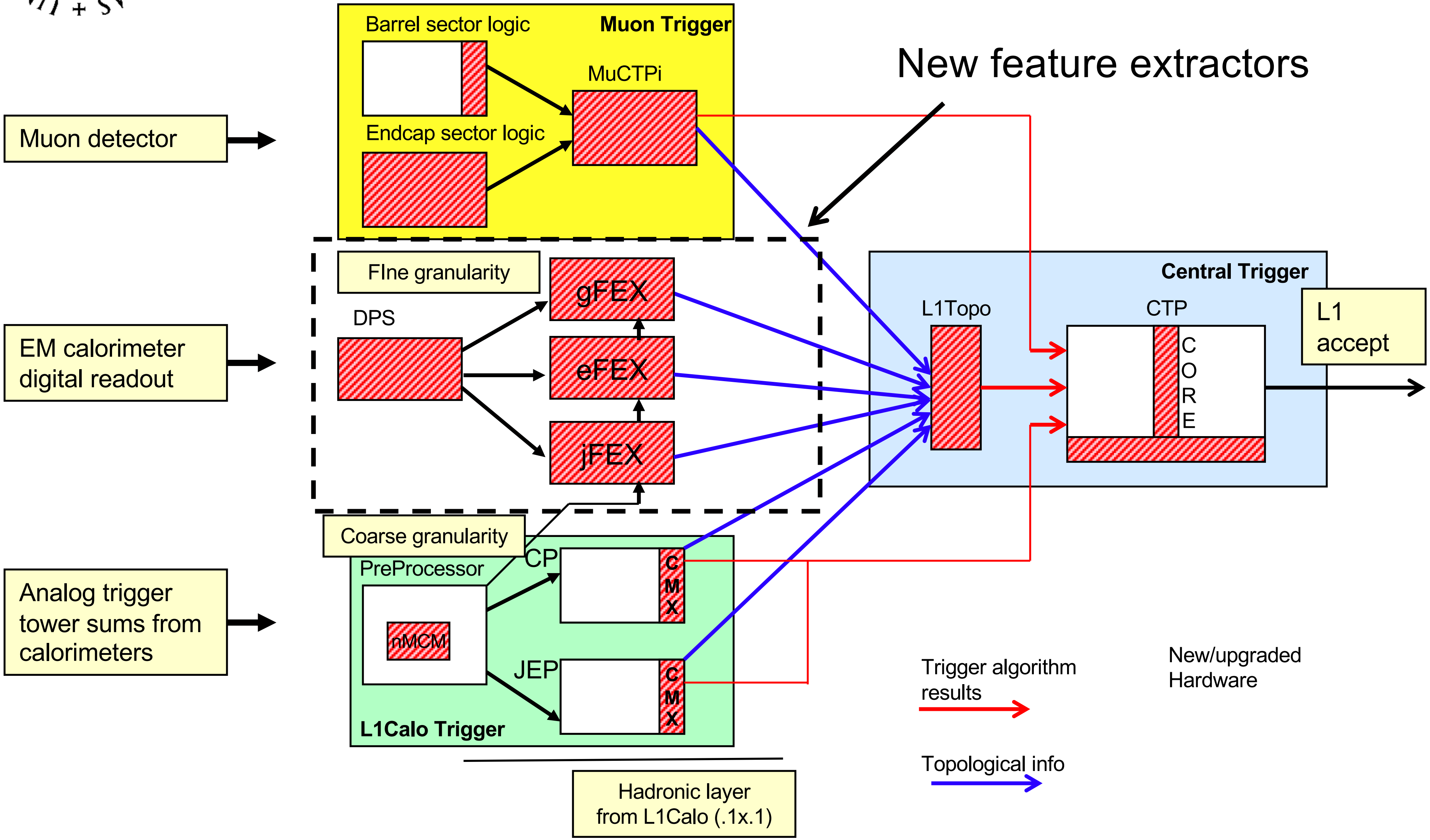


"1441"

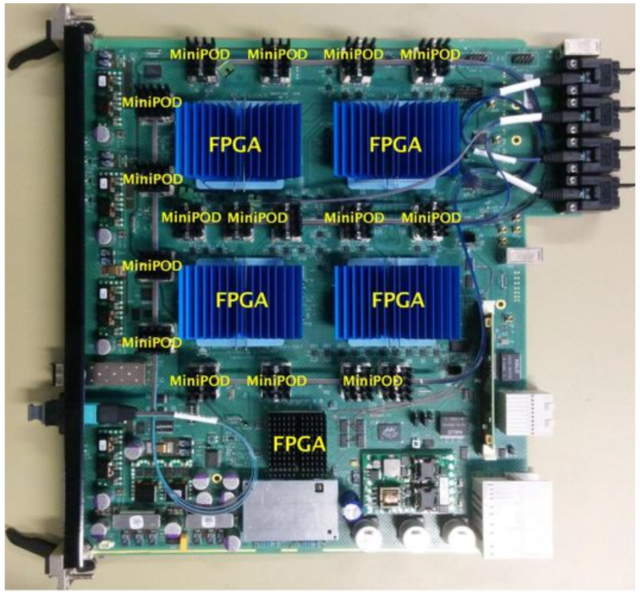
10 sums/tower



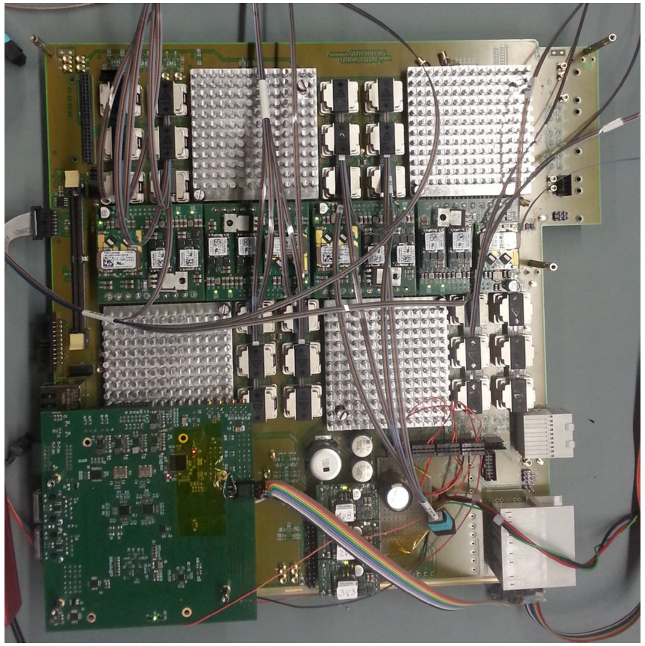
ATLAS Run 3 architecture



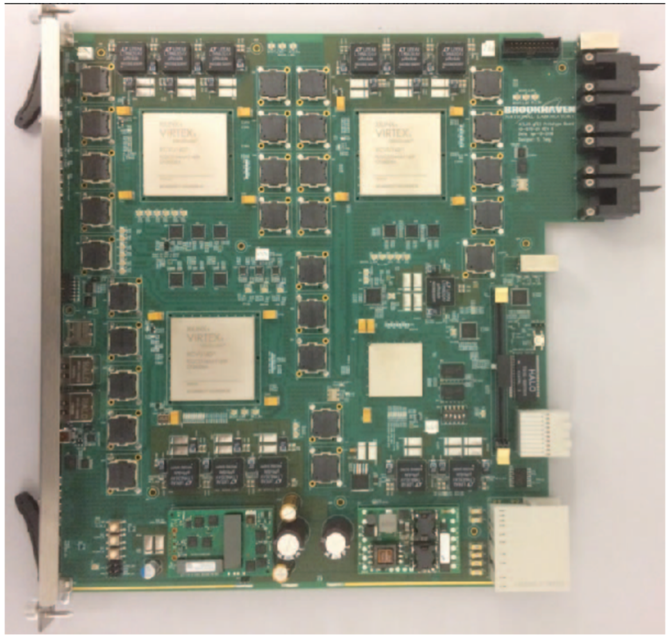
ATLAS feature extractors



eFEX



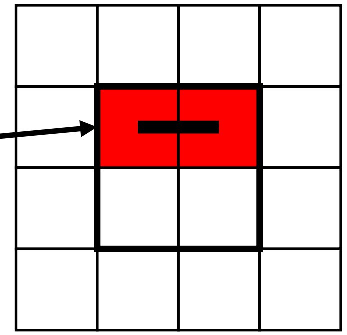
jFEX



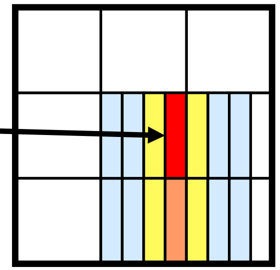
gFEX

EM/Tau ID in eFEX

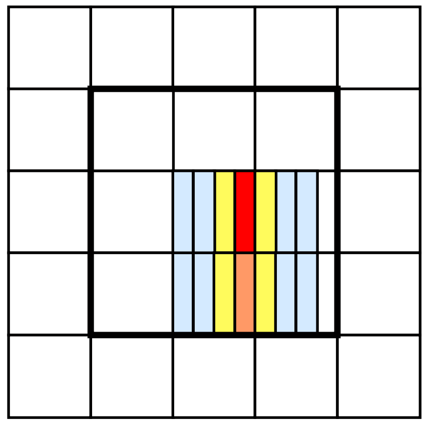
- Legacy EM/Tau algorithms
  - 0.1 x 0.2 'cluster'
  - 0.4 x 0.4 isolation window



- New EM algorithm
  - 0.1 x 0.025 'cluster'
  - 0.3 x 0.3 isolation window
  - hadronic veto

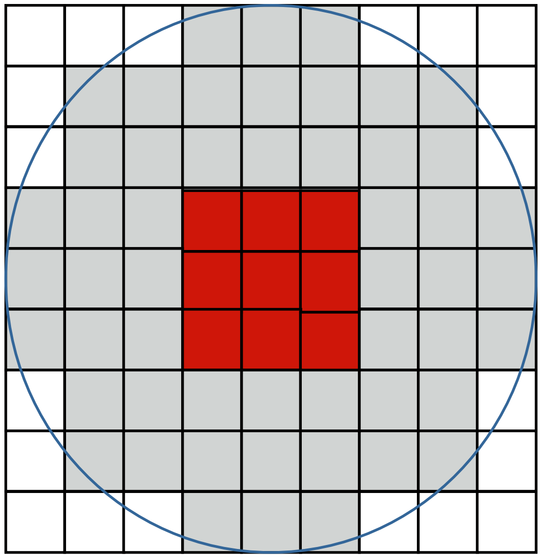


- New Tau algorithms
  - Up to 0.5 x 0.5 isolation window



Jets (jFEX and gFEX)

- Finer-granularity CAN help
  - Reduce effects of out-of-time pileup
- More sophisticated algorithms
  - Assemble jets from higher-E_T ‘clusters’
  - Round jets (vs. square)
  - HLT-like algorithms (Gaussian fit…)
  - gFEX: “Fat” jets (R ~ 1) for boosted physics
  - Global pile-up calculation and subtraction

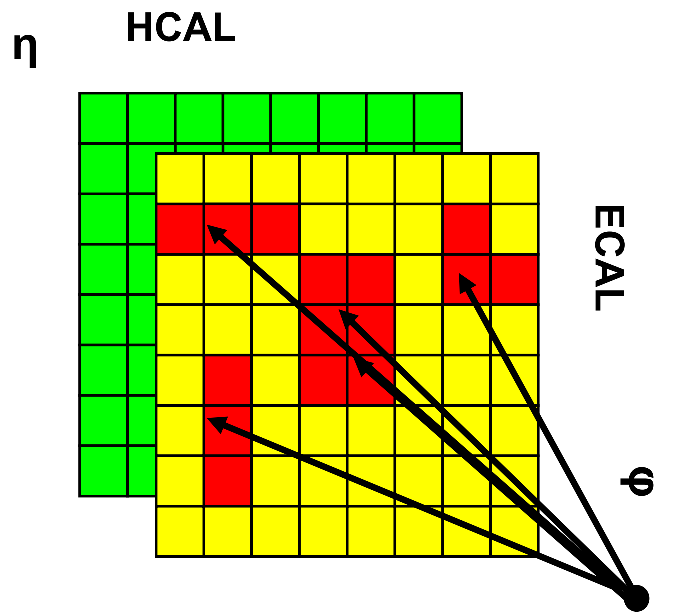


Energy-sum algorithms

- Sum from finer cell granularity
  - Reduce effects of out-of-time pileup
  - Combined benefit with jets
- Selective inclusion of cells in sums
  - CMS: ‘clusters’
  - ATLAS: possible to implement feature-based sums
    - For example, Jet missing E_T
- Improve signal processing

Using clusters

- Clusters reduce effect of low-energy minimum-bias deposits
- Useful for jets and energy-sums
- Works better than zero-suppression
  - Small deposits next to larger ones are still counted



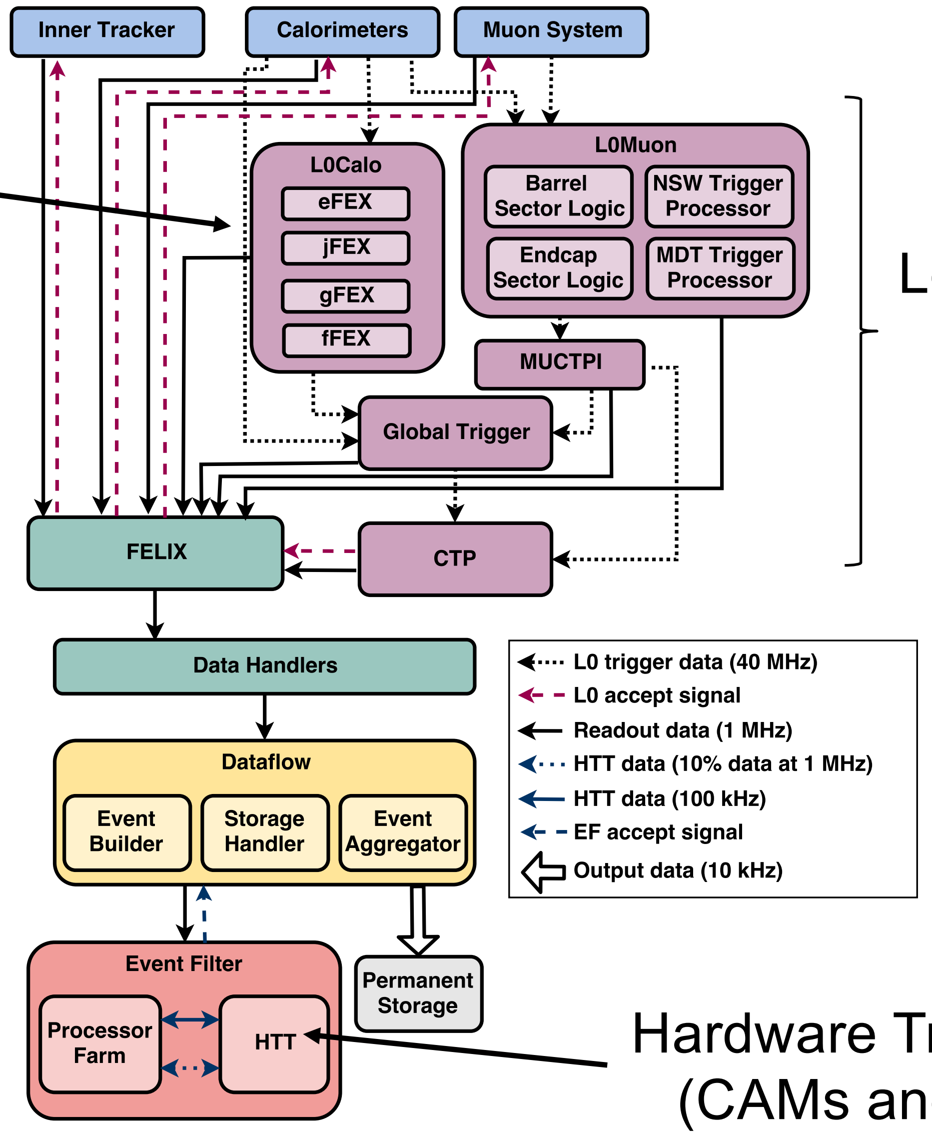
(CMS)

Tracking triggers

- Add tracking trigger to Level-1
  - Allows triggers like isolated electrons with matching high-pT track
- Challenging – millions of channels!
  - Millions of channels
  - On-detector: power and dead material
  - Off-detector: large bandwidth/latency
  - Need to reduce data to be processed
- Approaches
  - Seeded: L1Calo and L1Muon send object coordinates to guide L1Track processing (ATLAS)
  - Self-seeded: L1Track independently identifies and processes track candidates. (CMS…)

ATLAS trigger (HL-LHC)

Calorimeter feature extractors (FEX) (digital input data)



Level-0 (1 MHz) (hardware)

Level-1 (400 kHz) High-level trigger (10 kHz) (CPU based)

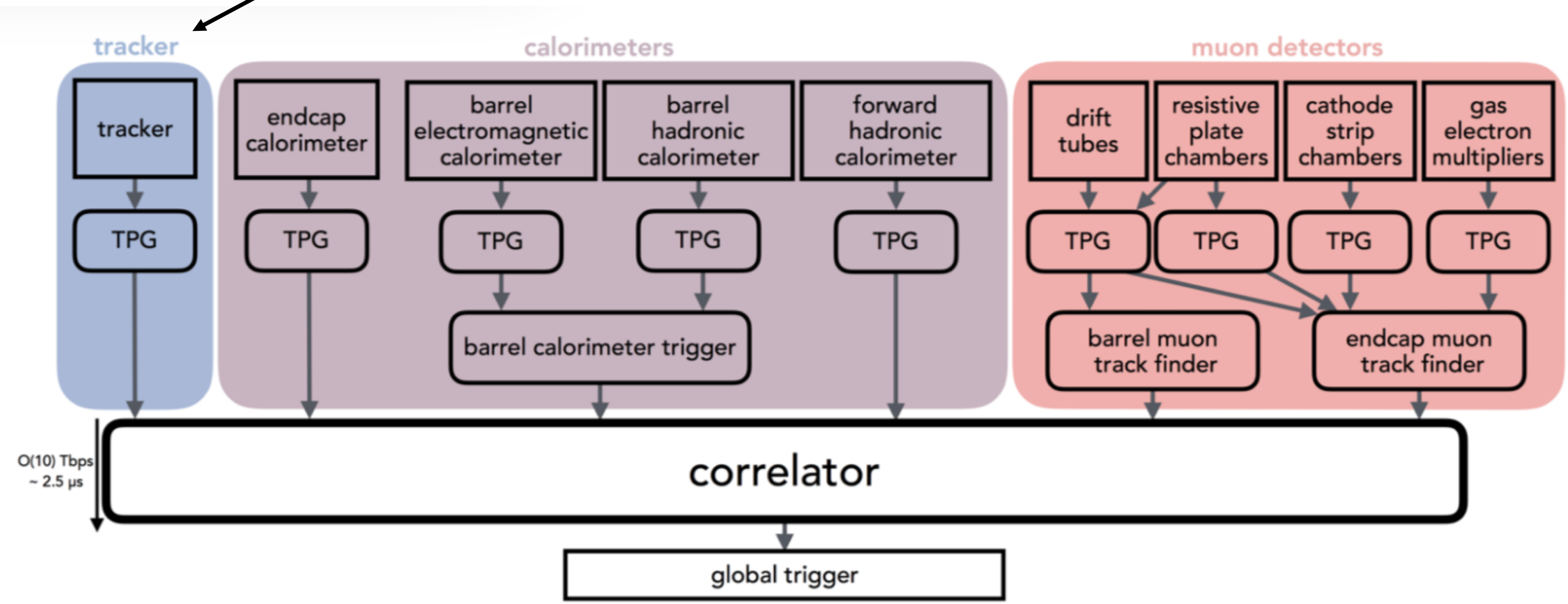
Hardware Track Trigger (CAMs and FPGAs)

ATLAS track trigger

- Hardware trigger (Phase-0) does not use tracking information
  - But 1 MHz L0 accept rate keeps more “interesting” events
- Event filter combines track information with calorimeter/muon objects
  - Guided by L0 Regions of Interest (RoI)
  - Interfaced with Hardware Track Trigger (HTT)
    - CAM/FPGA based

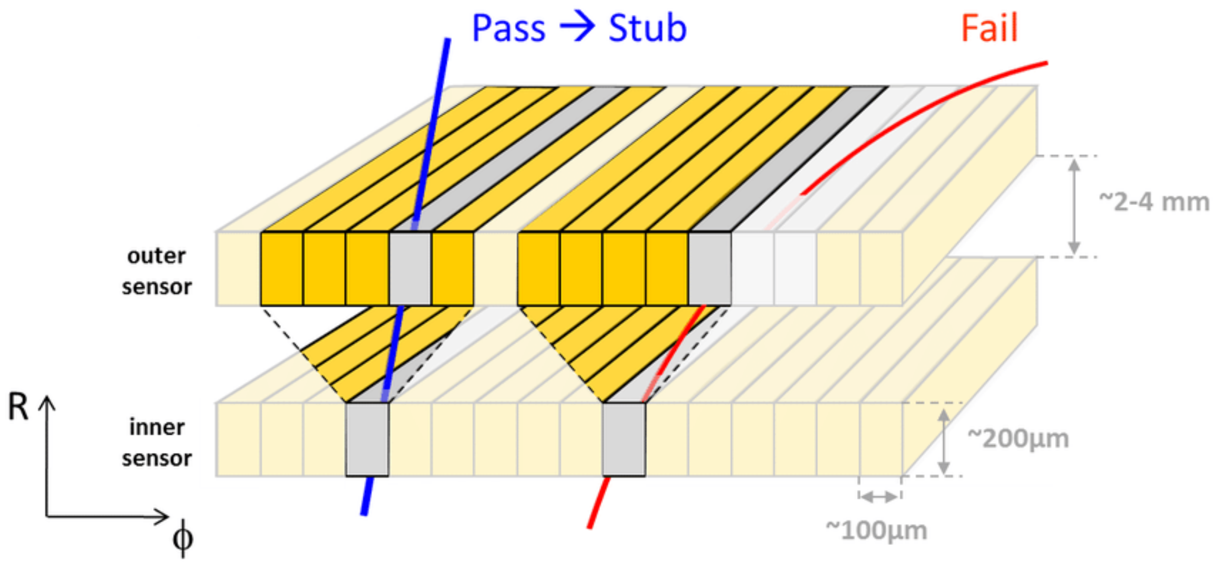
CMS L1 trigger (HL-LHC)

Tracker is part of Level-1 hardware trigger



CMS L1 track trigger

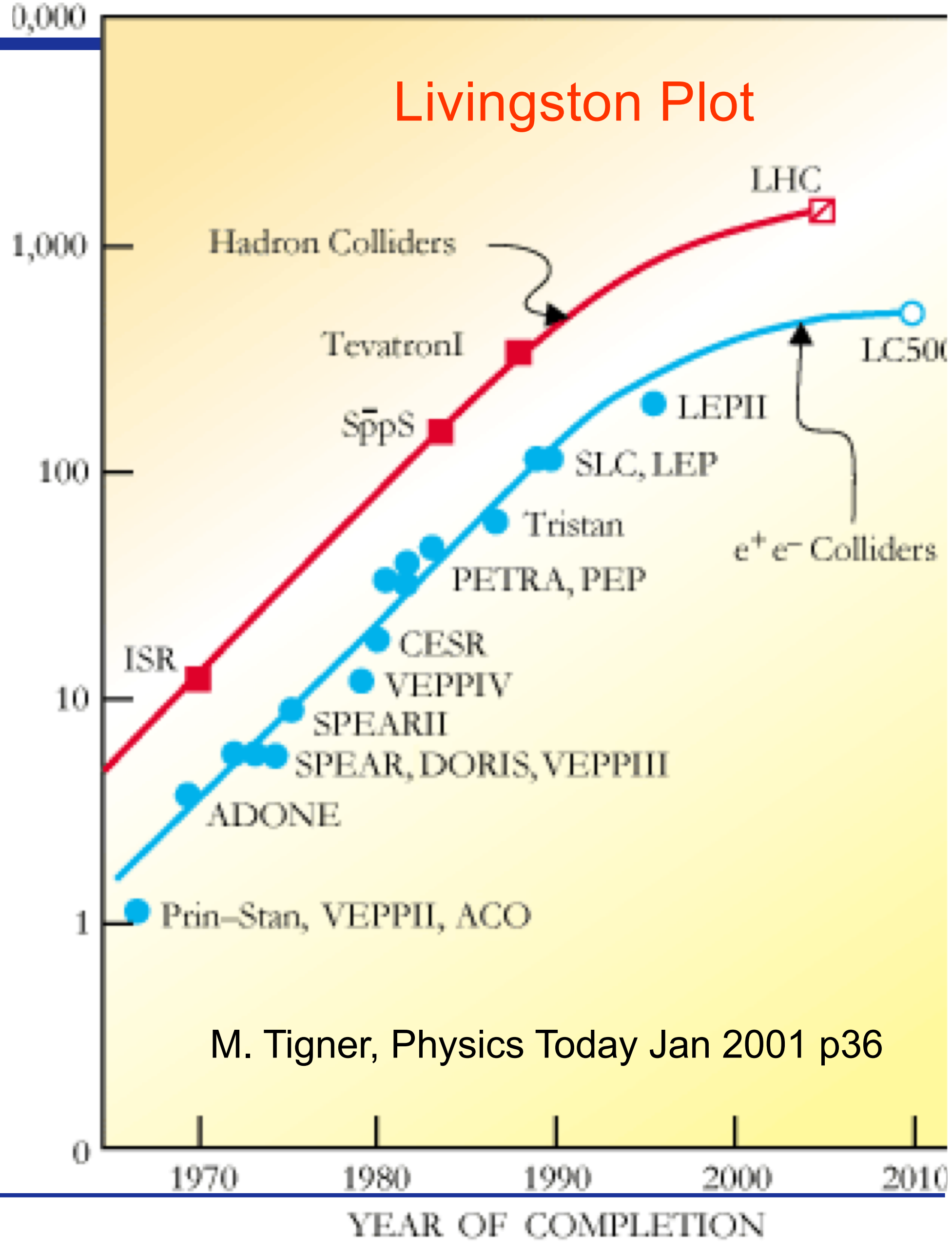
- Idea: High-PT tracks curve less than low-PT
- ‘Use two layers of strip detectors in strong B-field to select “straight” tracks
- Similar to how muon detectors work



Future directions

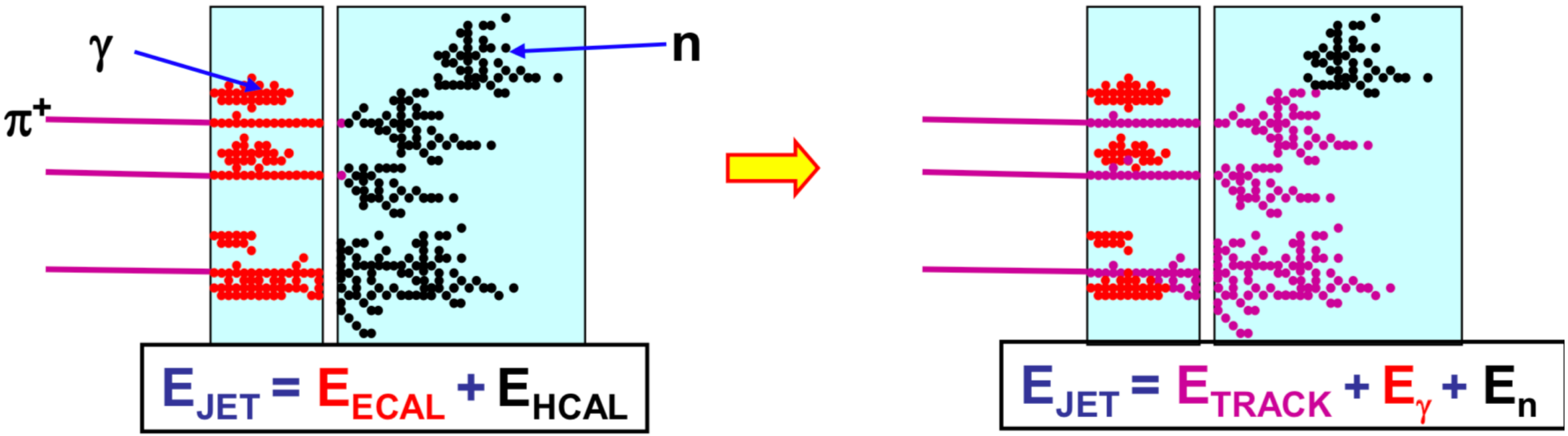
Future Accelerators

- Accelerator energy continues to grow
  - Rate of change decreasing?
- Processing power, bandwidth and storage media growing faster than luminosity
- Potential future machines?
  - Linear Collider (500-1000 GeV)
  - Super B-Factory (10^{36} /cm^{2}s)
  - Muon Collider?
  - FCC: pp up to 100 TeV?

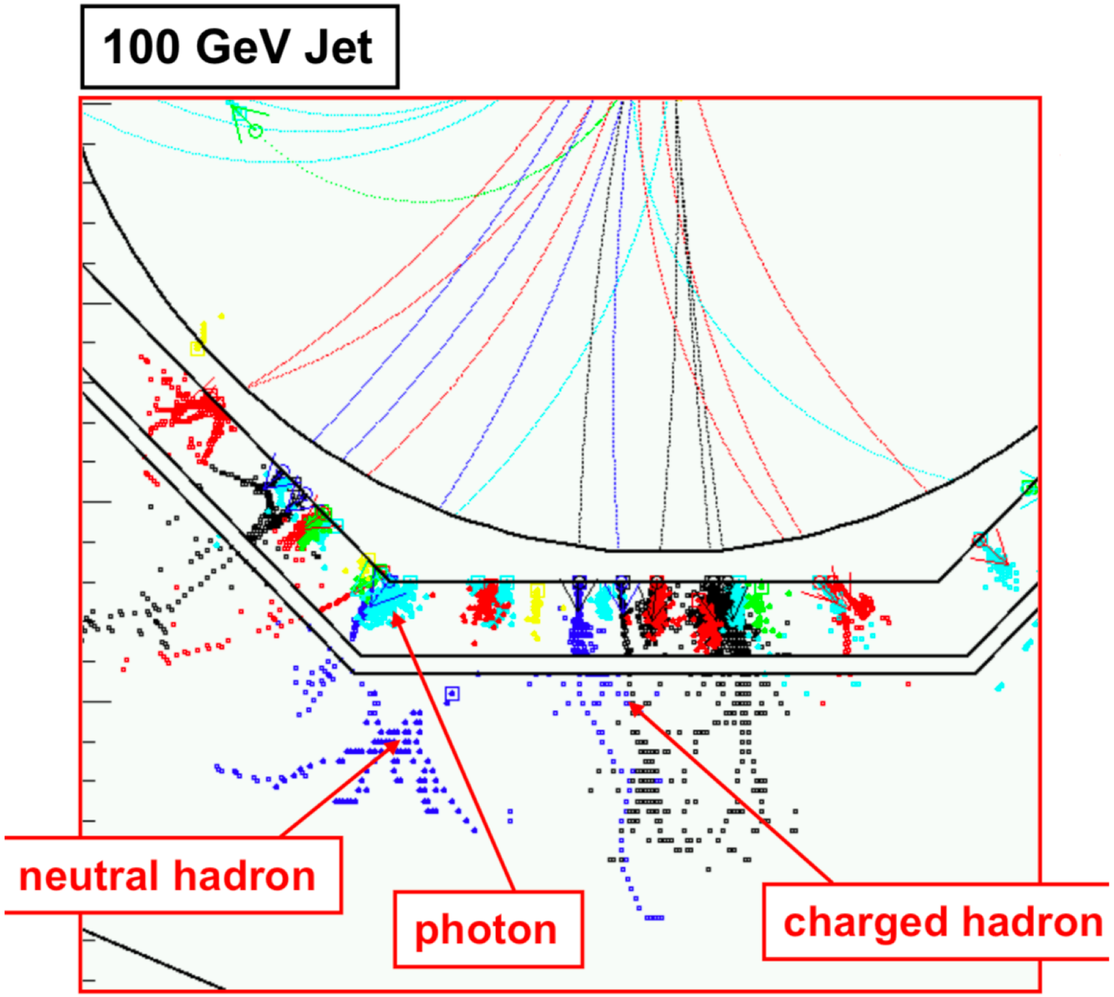


Particle Flow Calorimetry

- Traditional calorimetry (left) is limited by the lowest-resolution calorimeter (hadronic)
- By adding track information to identify the individual particles (right), resolution can be improved!

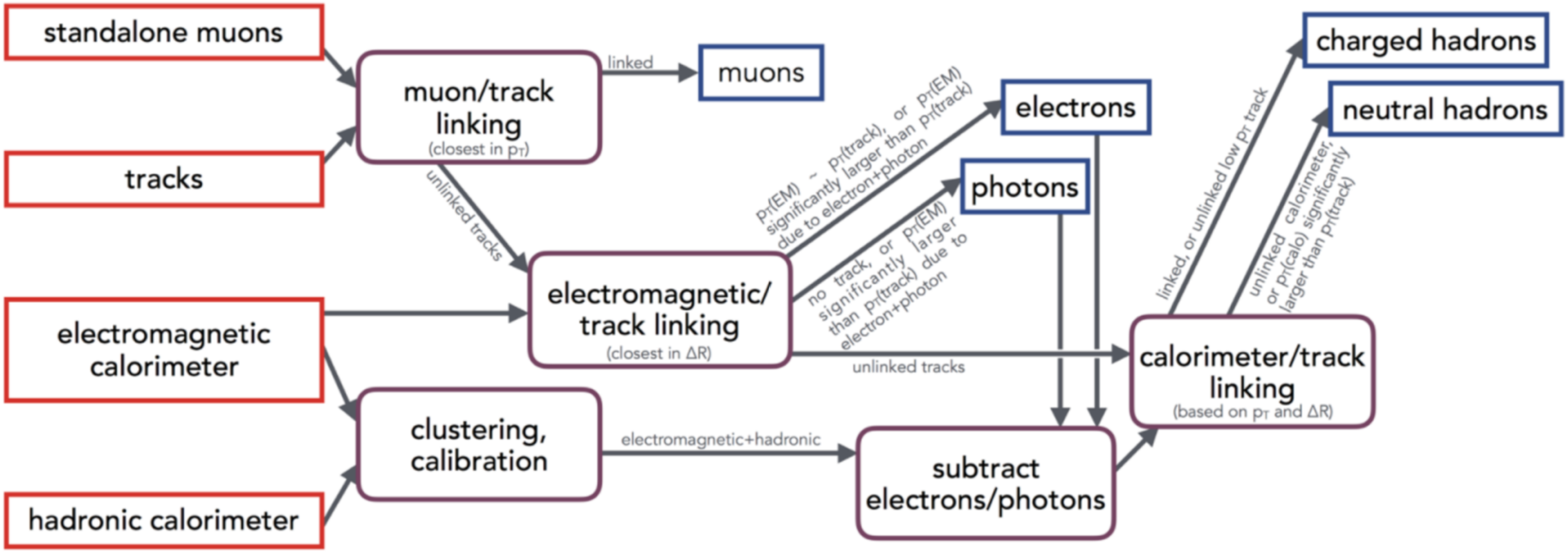


Particle Flow Calorimetry

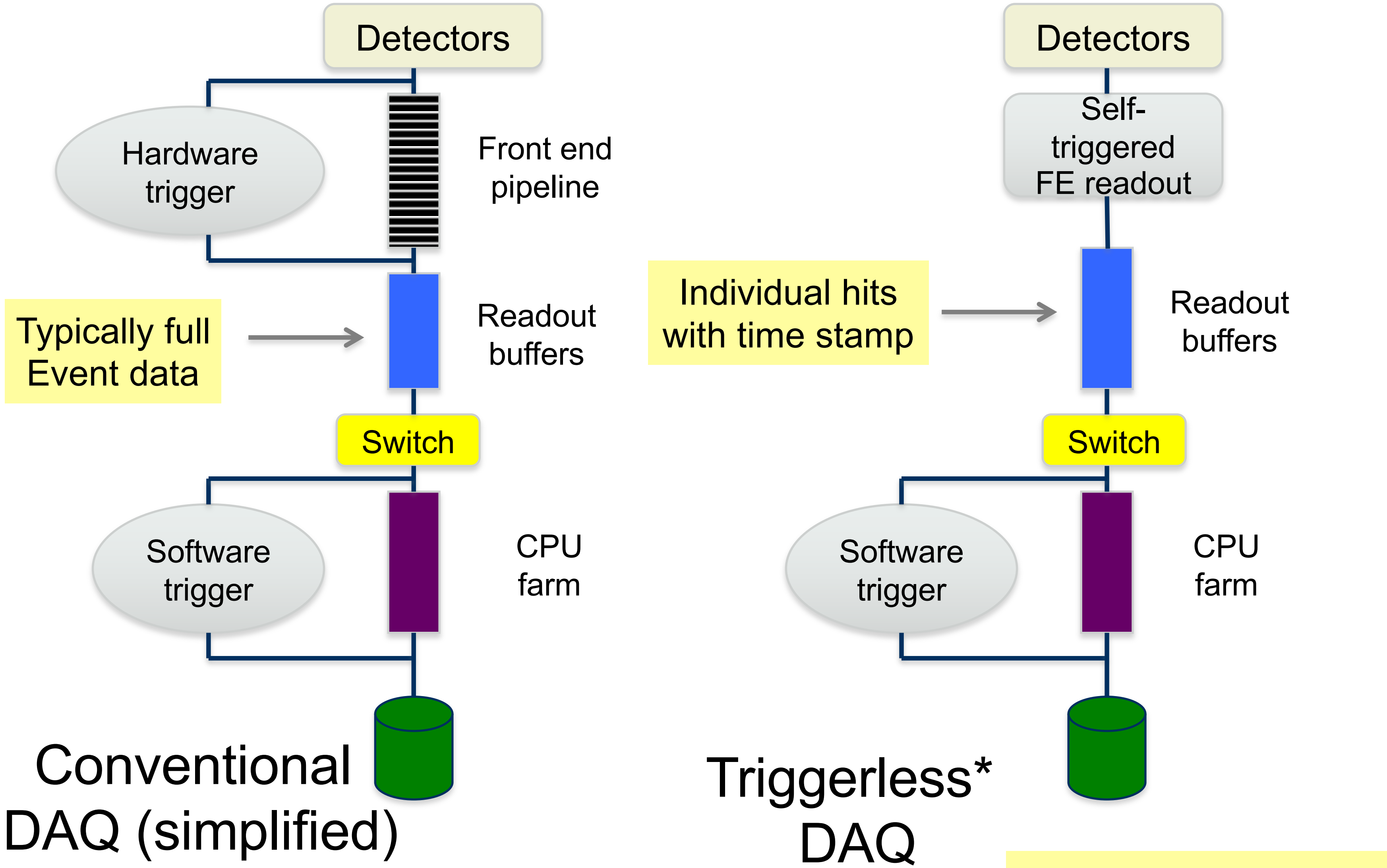


- Particle flow can be used to improve analysis of existing detectors
- Can be used in triggers with track info (CMS)
- Even better: trigger on high-granularity calorimeter data
  - “Triggerless” DAQ

Particle flow in CMS level-1

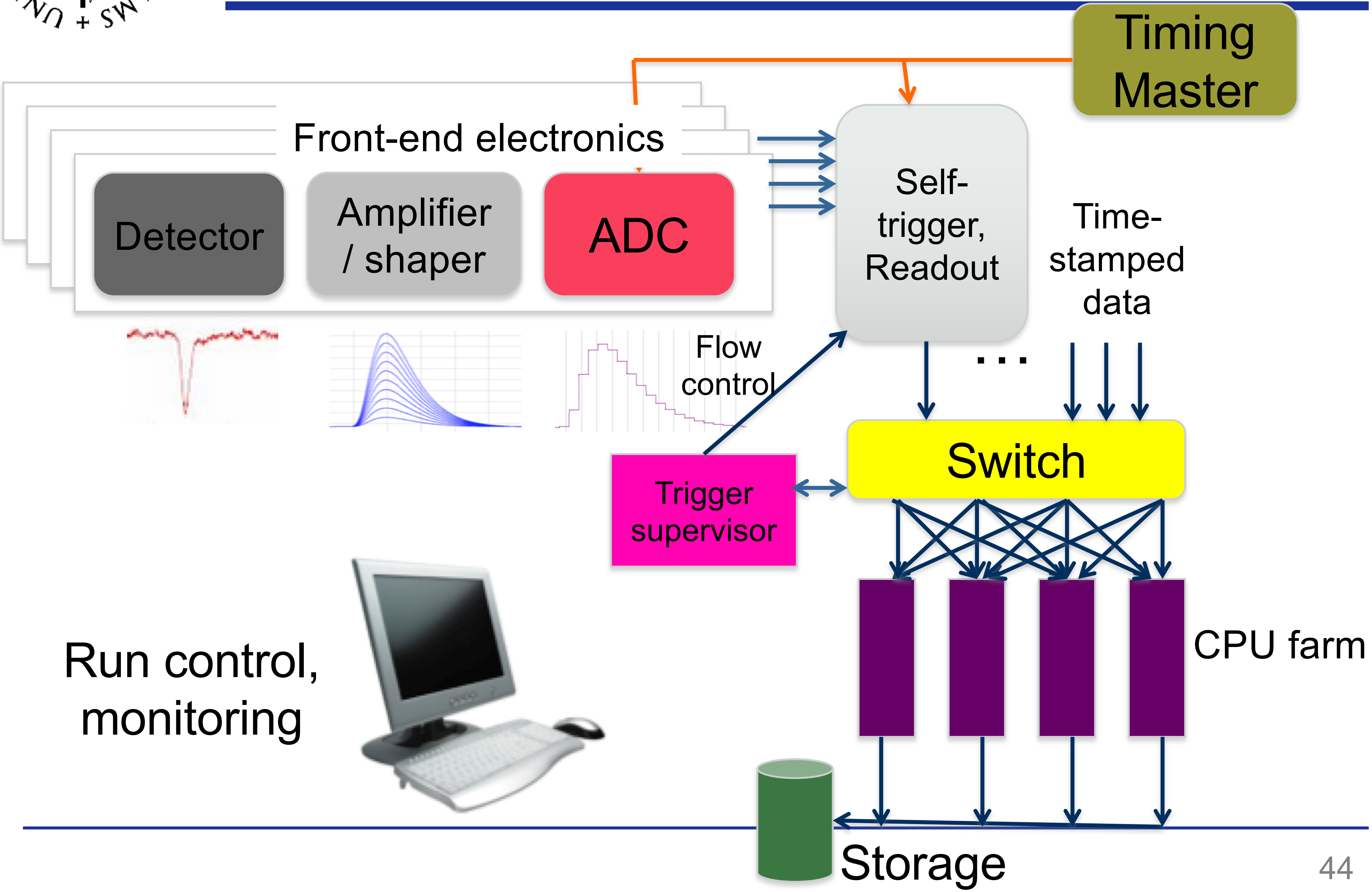


”Triggerless” DAQ



* Alternatively, “self-triggered”

Triggerless DAQ architecture



Summary

- Many approaches to dealing with trigger/DAQ challenges
- Influenced by:
  - Existing hardware constraints
  - Available technology
  - Previous experience of developers
- Future machines and detectors will be different from the ones today
  - But many fundamentals will remain