Imperial College London

Data Taking at CMS

21st September 2021
CMS Induction

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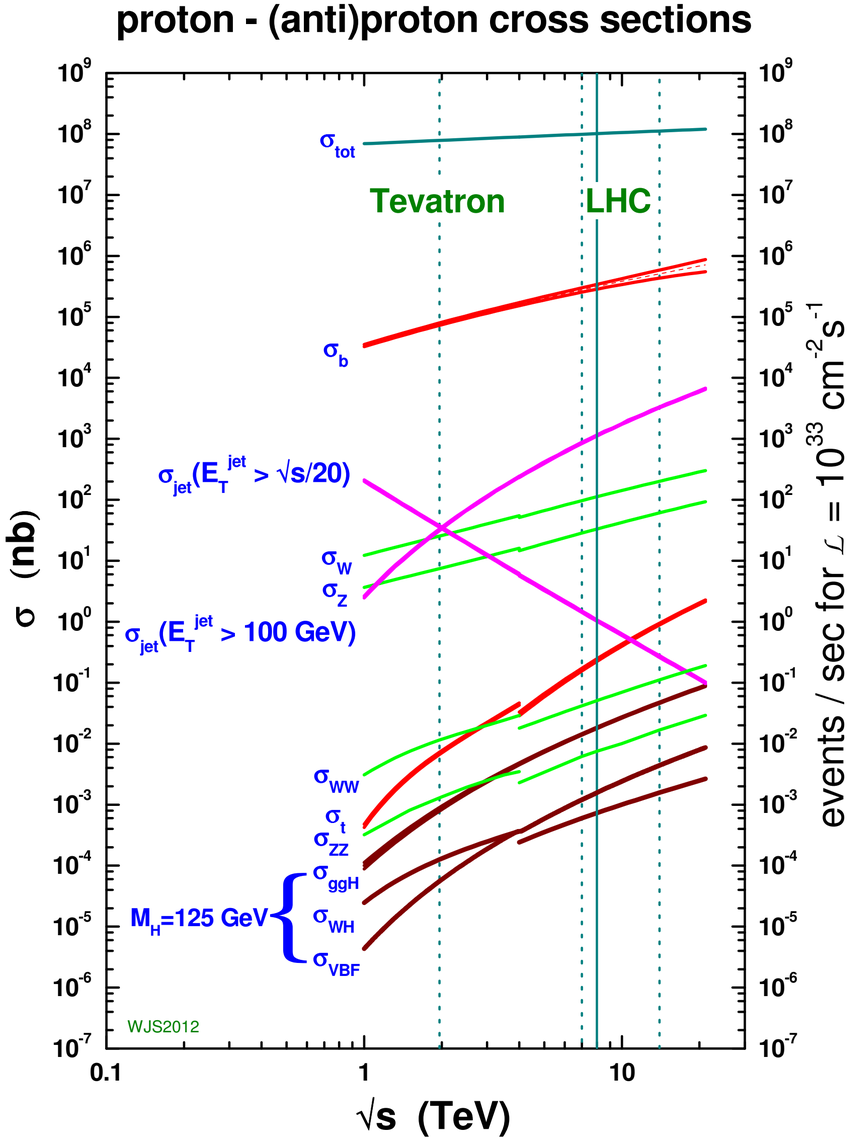
Premise

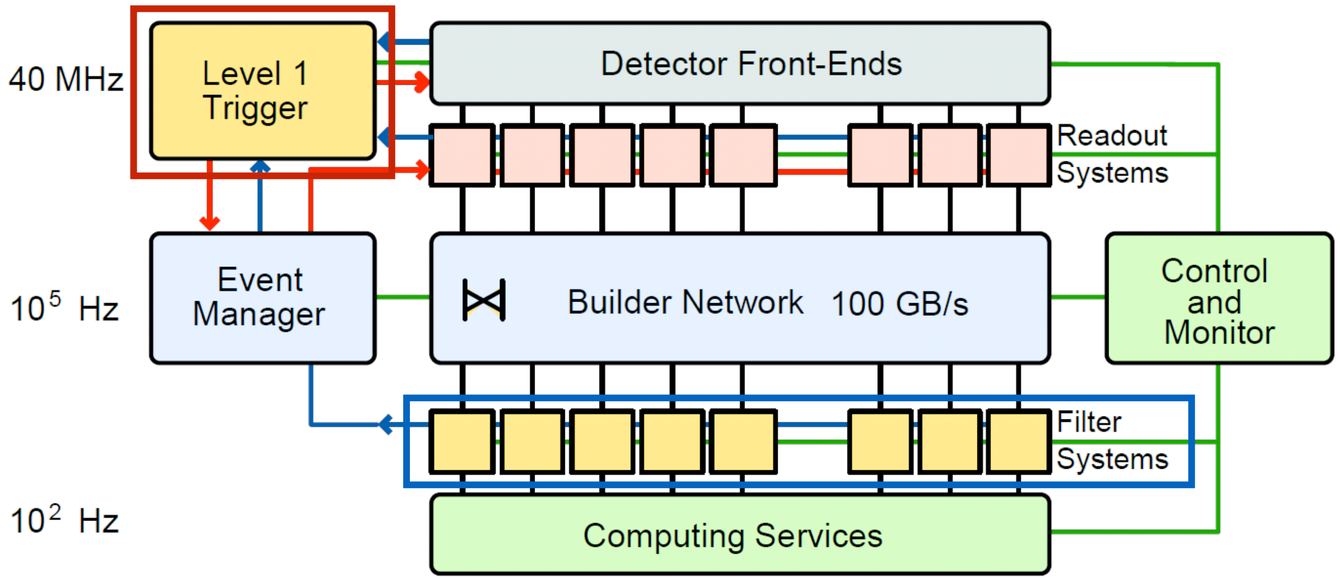
- The LHC collides bunches of protons at 40 MHz*
  - We cannot readout all of the collisions (Zero-supressed data would be ~30TB/s)
  - Only some of these collisions will be of interest
- We need a way to filter out the interesting collisions to analyse
  - 2 level trigger system based on hardware and software respectively



*If all bunches are filled

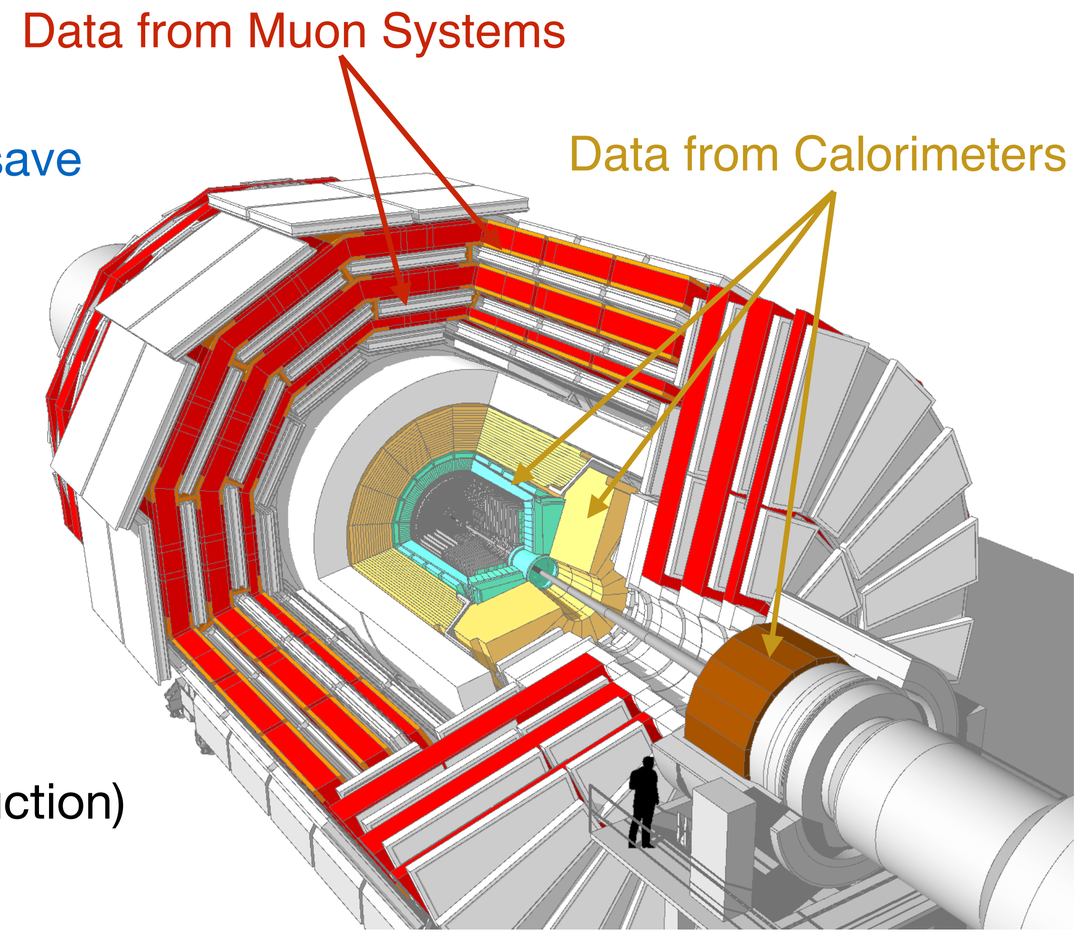
CMS Trigger System

- The trigger selects events which are of predetermined interest → allows us to perform our physics goals
  - 2 level trigger system based on hardware and software respectively
  - Level 1 trigger (L1T) → rate down to ~100kHz
  - High Level Trigger (HLT) → rate down to ~1kHz

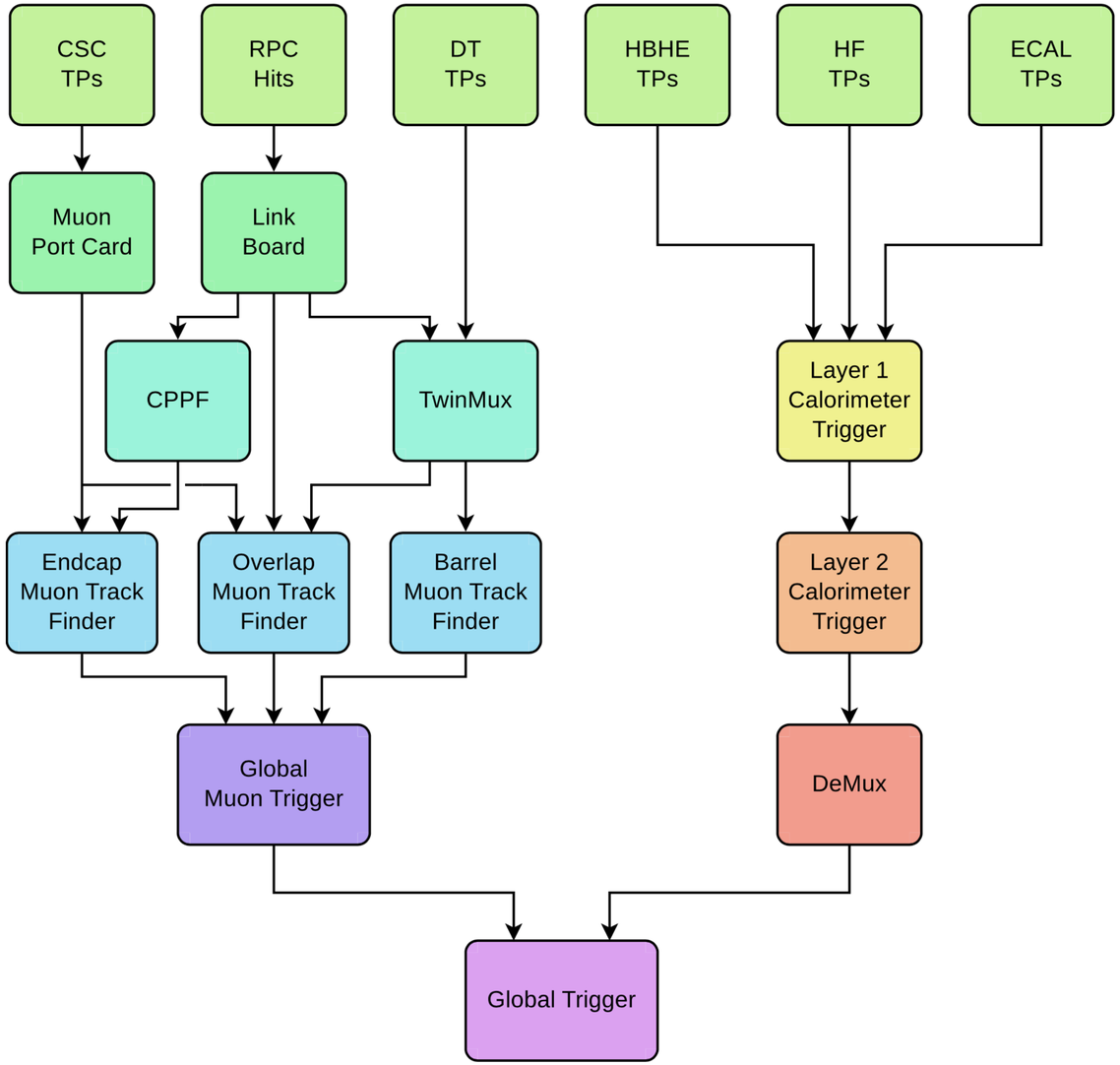


Level 1 Trigger at CMS

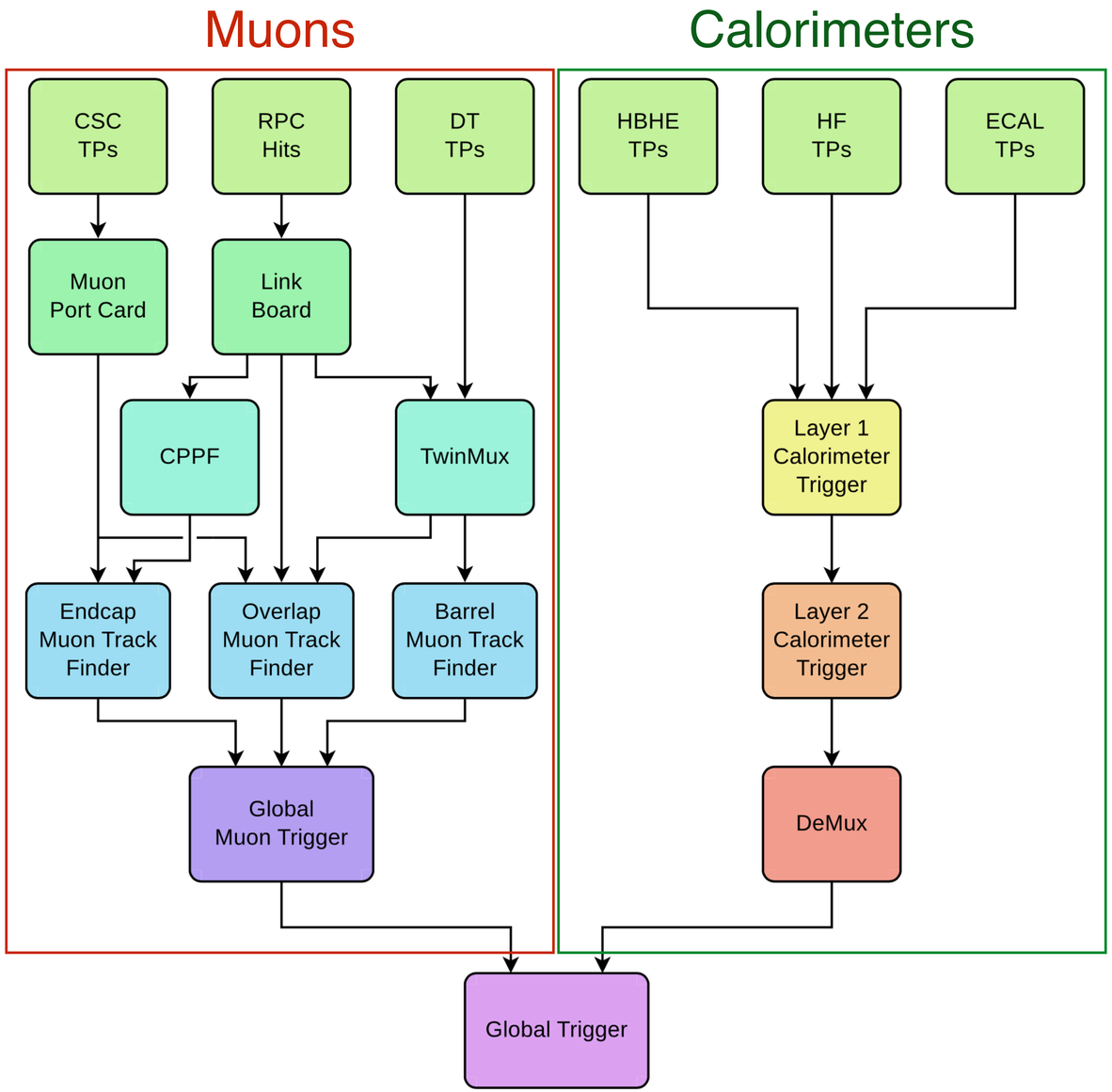
- The L1T receives data with coarse granularity from:
  - Calorimeters (ECAL, HCAL, HF)
  - Muon systems (CSC, DT, RPC, GEM)
- Data from all the detectors is buffered locally for < 4μs
  - Trigger works in a pipeline fashion to make the decision to save this data or not
  - Each event examined in a fixed time
  - Use custom electronics
- Implemented in hardware
  - Mostly with Field Programmable Gate Arrays (FPGAs)
  - Operates synchronously to the LHC clock (40 MHz)
- Read-out decision based on programmable algorithms
  - Maximum detector readout possible is ~100 kHz (x400 reduction)



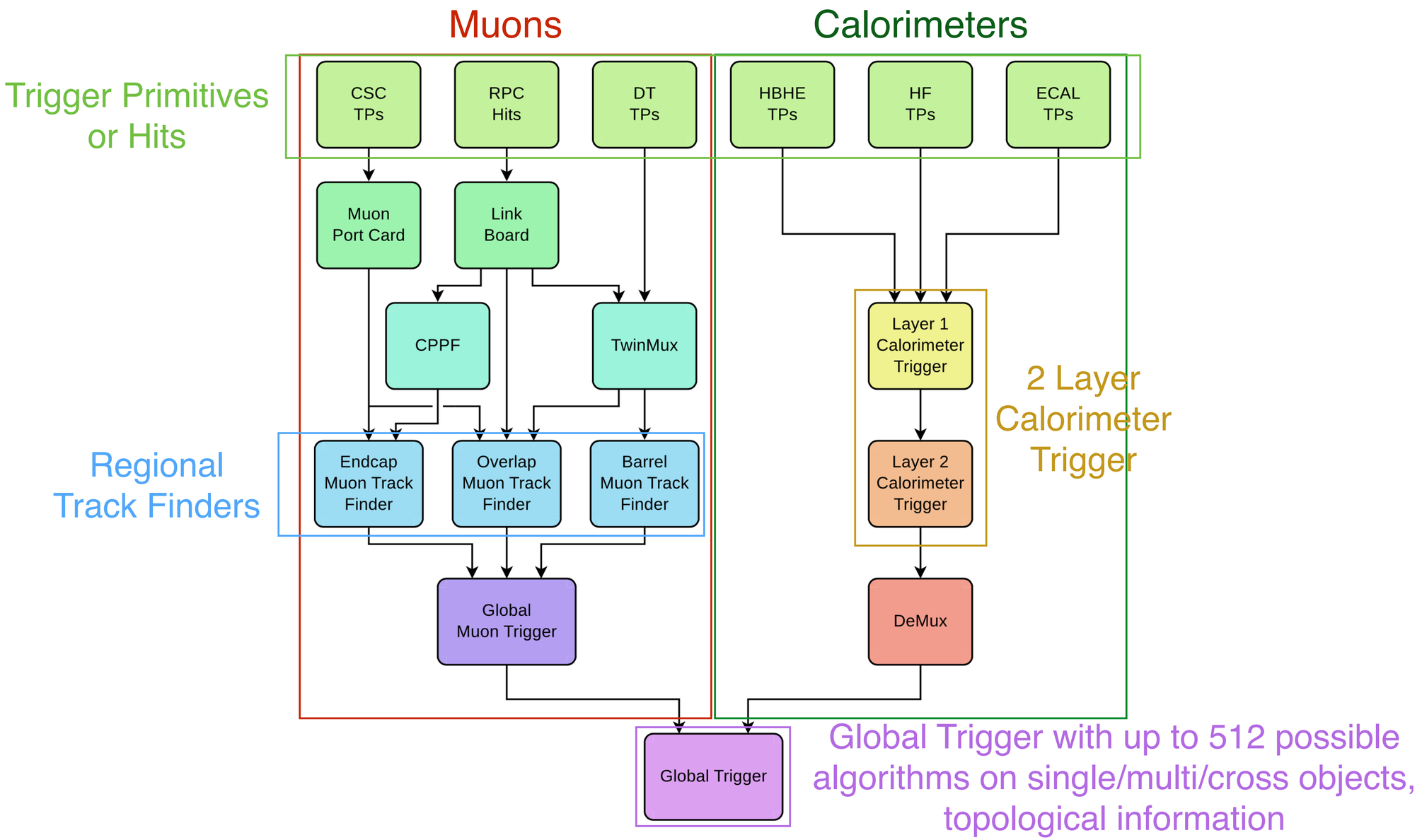
L1 Trigger Diagram



L1 Trigger Diagram

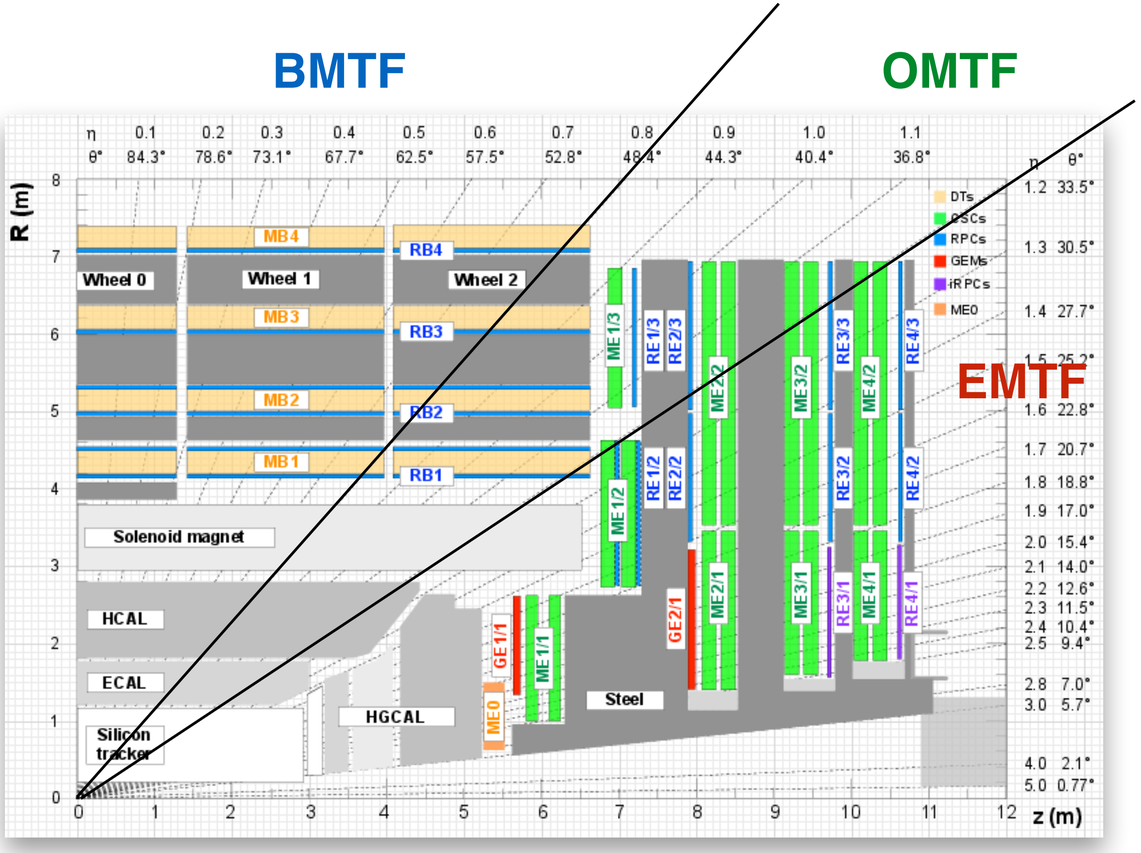


L1 Trigger Diagram



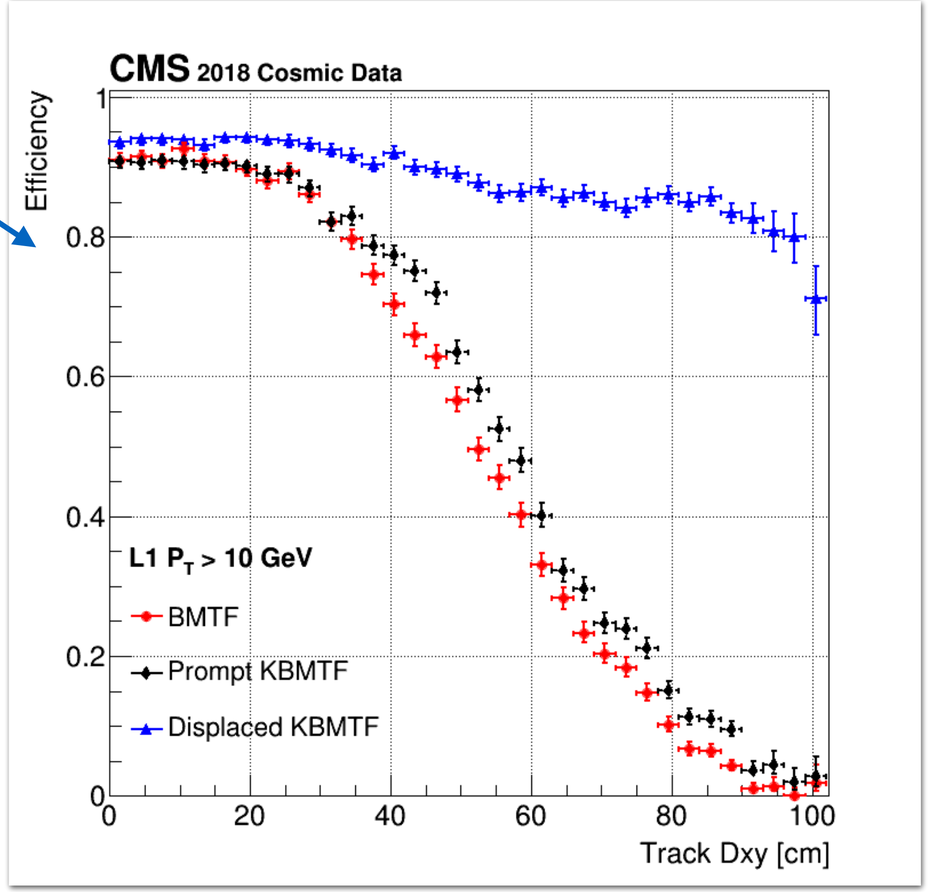
L1 Muon Triggers

- 3 Track Finders which:
  - Reconstruct muon track from hits or primitives
  - Assign η, ϕ, pT and quality to each candidate
- BMTF: The Barrel Muon Track Finder
  - Uses DT+RPC "super primitives" created in previous layer for track finding
  - Using Kalman BMTF for Run 3
- OMTF: The Overlap Muon Track Finder
  - Treats hits from CSCs, DTs, and RPCs on an equal footing using a Golden Pattern approach
- EMTF: The Endcap Muon Track Finder
  - Exploits look-up tables generated from BDTs to create tracks from CSC, RPC and GEM hits
- μGMT: The Global Muon Trigger
  - Receives up to 108 muon tracks from all track finders, sorts and removes duplicates



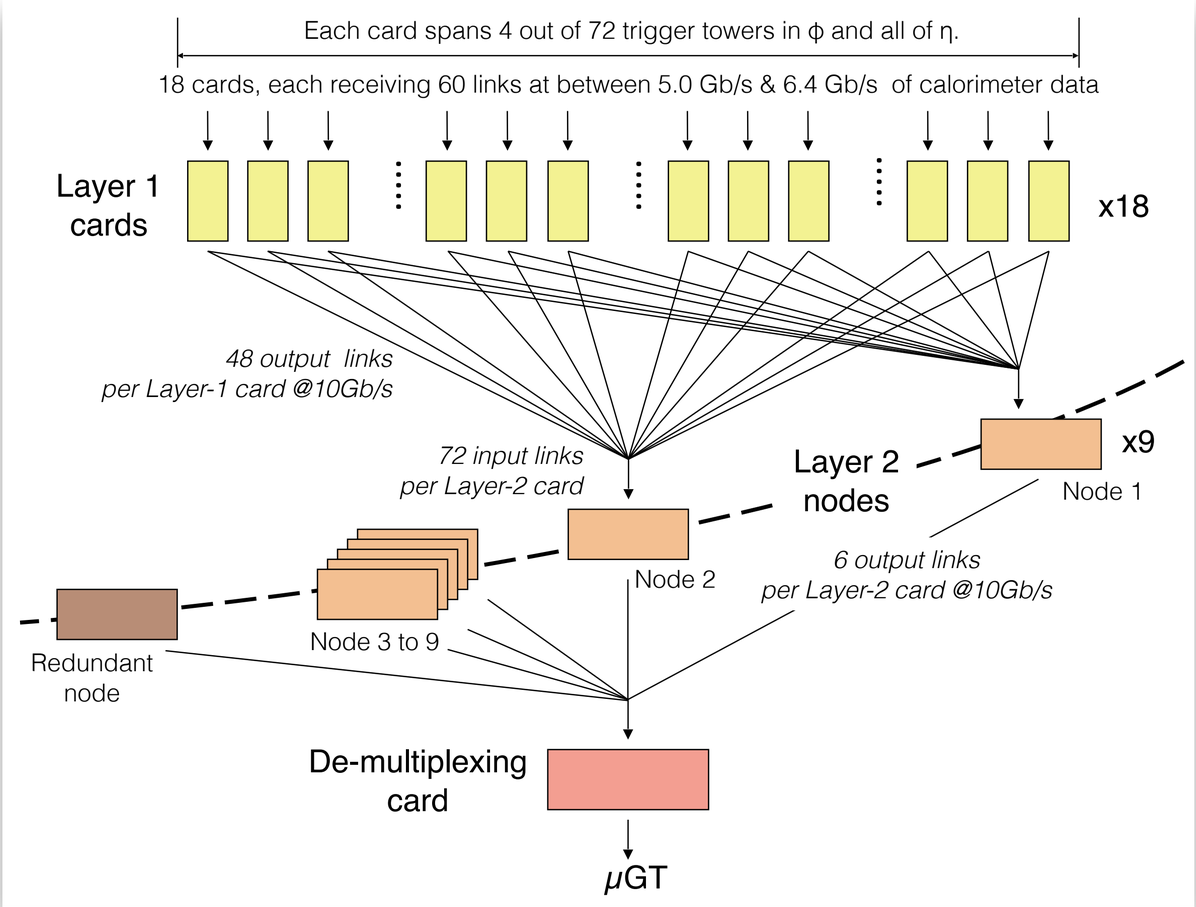
L1 Displaced Muons

- All 3 Track Finders are working on triggering displaced muons
  - BMTF: Kalman BMTF allows for displaced muons
  - OMTF: Is working on proposals to trigger on displaced tracks
  - EMTF: Is working on using a NN to work with the displaced patterns
- μGMT: The Global Muon Trigger
  - Is being updated in order to cope with the new displaced information



L1 Calorimeter Triggers

- Layer-1
  - Combines inputs from electromagnetic and hadronic calorimeters into "trigger towers"
  - Applies position- and energy-dependent calibrations
- Layer-2
  - Finds Jets, e/gamma and Tau candidates
  - For each object, applies pileup subtraction, computes isolation, applies object-based calibrations
  - Computes global quantities: transverse energy, missing energy, etc.
  - Time-multiplexed architecture
    - Array of processors that each receive the full event information for subset of events

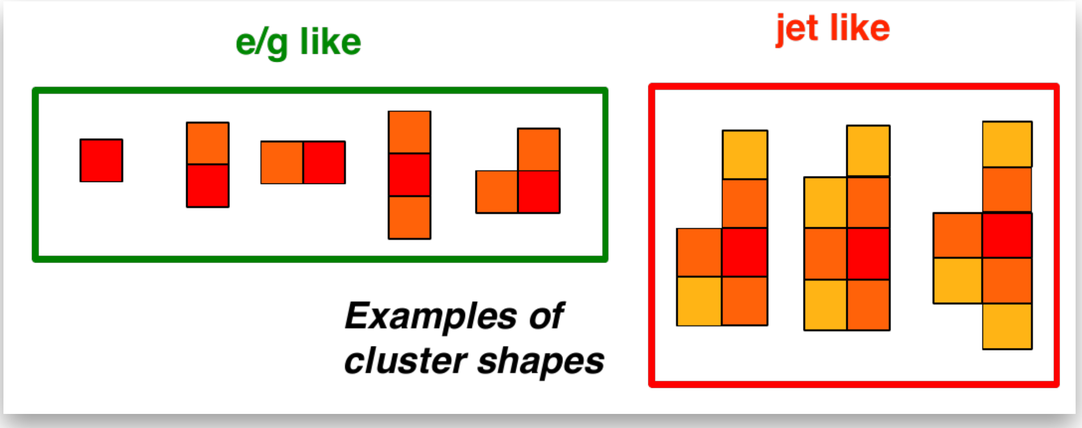


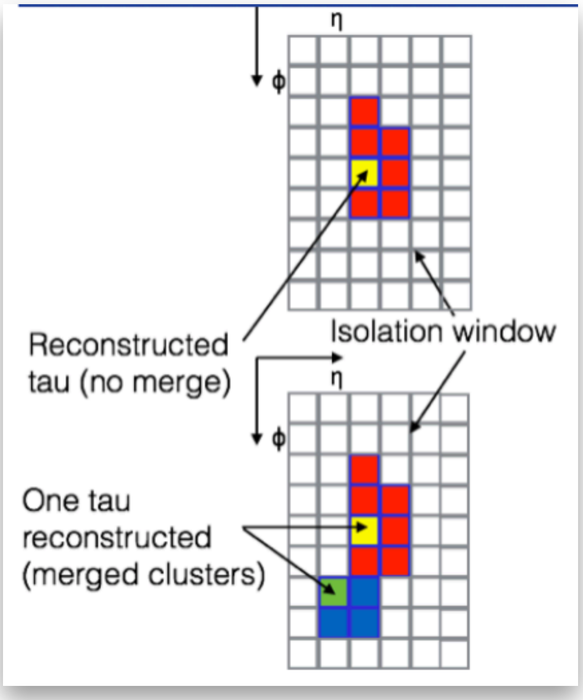
L1 Global Trigger

- Receives candidates from the Global Muon Trigger and Layer-2 Calo Trigger:
  - 8 muon candidates
  - 12 e/gamma candidates (isolated and non-isolated)
  - 12 jets
  - 8 tau candidates (isolated and non-isolated)
  - Energy sums (ET/MET, HT/MHT, …)
  - External conditions (e.g. beam coincidence or anti-coincidence, …)
- Combines the candidates in up to 512 algorithms

L1 Triggers

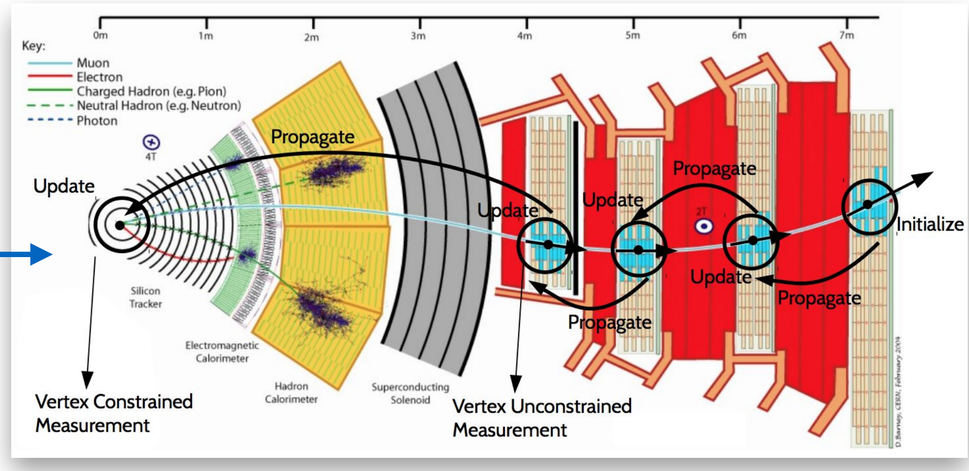
- E/γ:
  - Clustering algorithm uses dynamic clustering around a local maximum (seed)
  - Corrections due to brem/losses in material, PU, improving energy resolution
  - Calibrations depending on E_T, η and shape
  - ID: veto jet-like shapes, small H component, small isolation energies
- Tau:
  - Uses EG-cluster type, possible to merge with neighbouring clusters to capture multi-prong hadronic taus
  - Calibrations depending on E_T, η and E/H fraction
  - ID: Isolation energy depending on η_{TT}, E_T and η





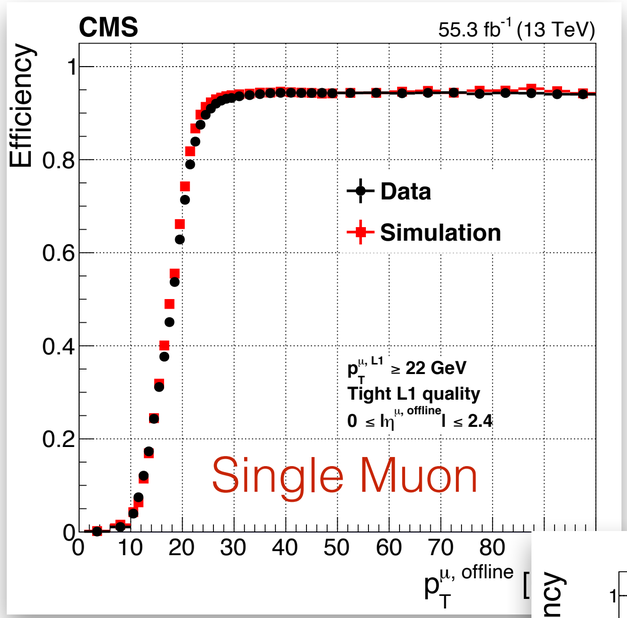
L1 Triggers

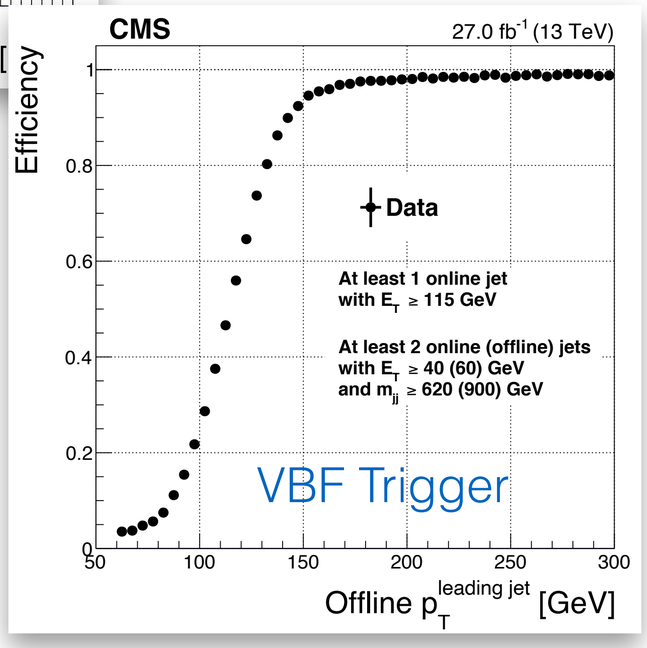
- Jet/MET:
  - Sliding window jet algorithm: search for TT above threshold and maximum in 9x9 window (~AK4 jet size)
  - "Chunky donut" PU subtraction: energy in 3 lowest 3x9 E_T regions used to determine PU energy density which is then scaled and subtracted from individual jet E_T
  - Calibration: corrected energies as a function of η and E_T
- Sums:
  - E_T: Scalar sum of p_T of calorimeter deposits
  - H_T: Scalar sum of p_T of jets
- Muons:
  - KBMTF: Use dedicated Kalman filter to find tracks
  - OMTF & EMTF: Use pattern-based track finding with Look-Up-Tables



L1 Trigger Algorithms

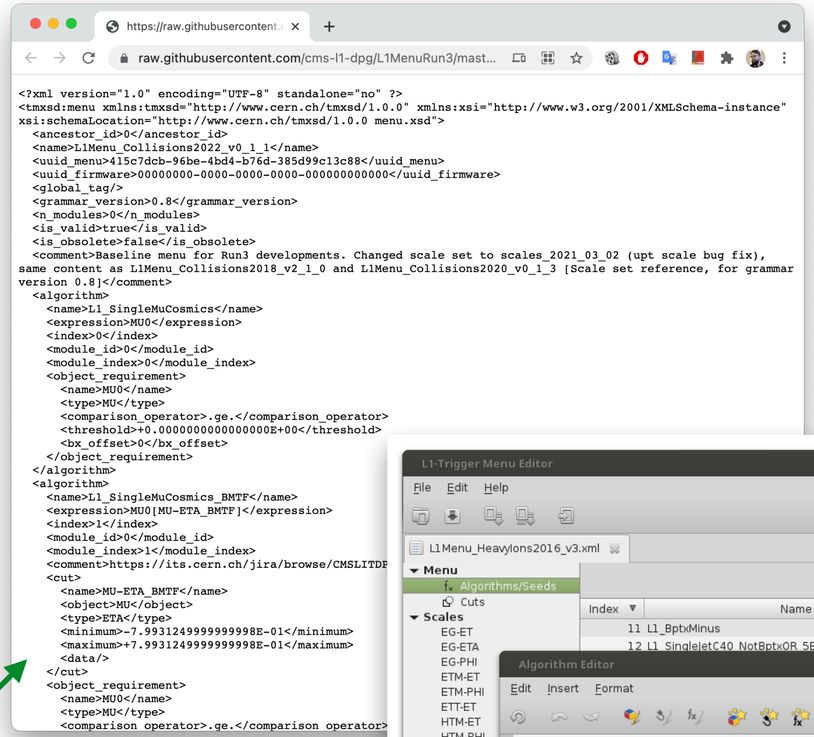
- Transverse momentum (p_T) thresholds
  - e.g. “single muon, p_T>22 GeV”
- Charge correlations
  - Opposite sign/same sign
- Spatial correlations
  - e.g. “2 electrons with Δη/Δϕ in given range”
  - Can be used to e.g. explicitly trigger on back-to-back objects
- Two-body invariant mass
  - e.g. “two muons with M(μμ) > 30 GeV”
  - Introduced for 2017 data taking year
- Prescales
  - e.g. “Every n_{th} triggered event by this algorithm”
  - Used to trigger interesting, but very common events
- Combine these algorithms with each other
  - “Trigger menu”

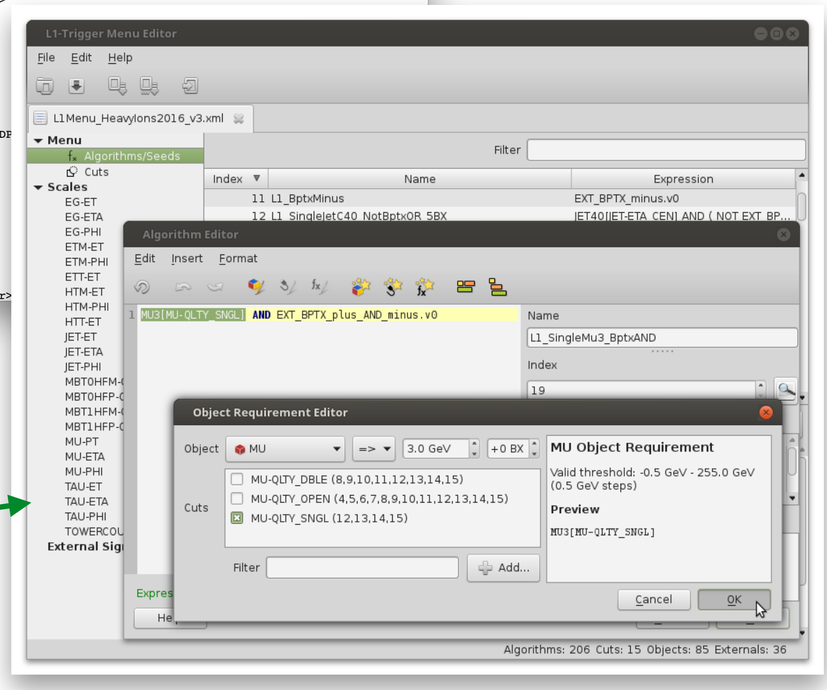




L1 Trigger Menu

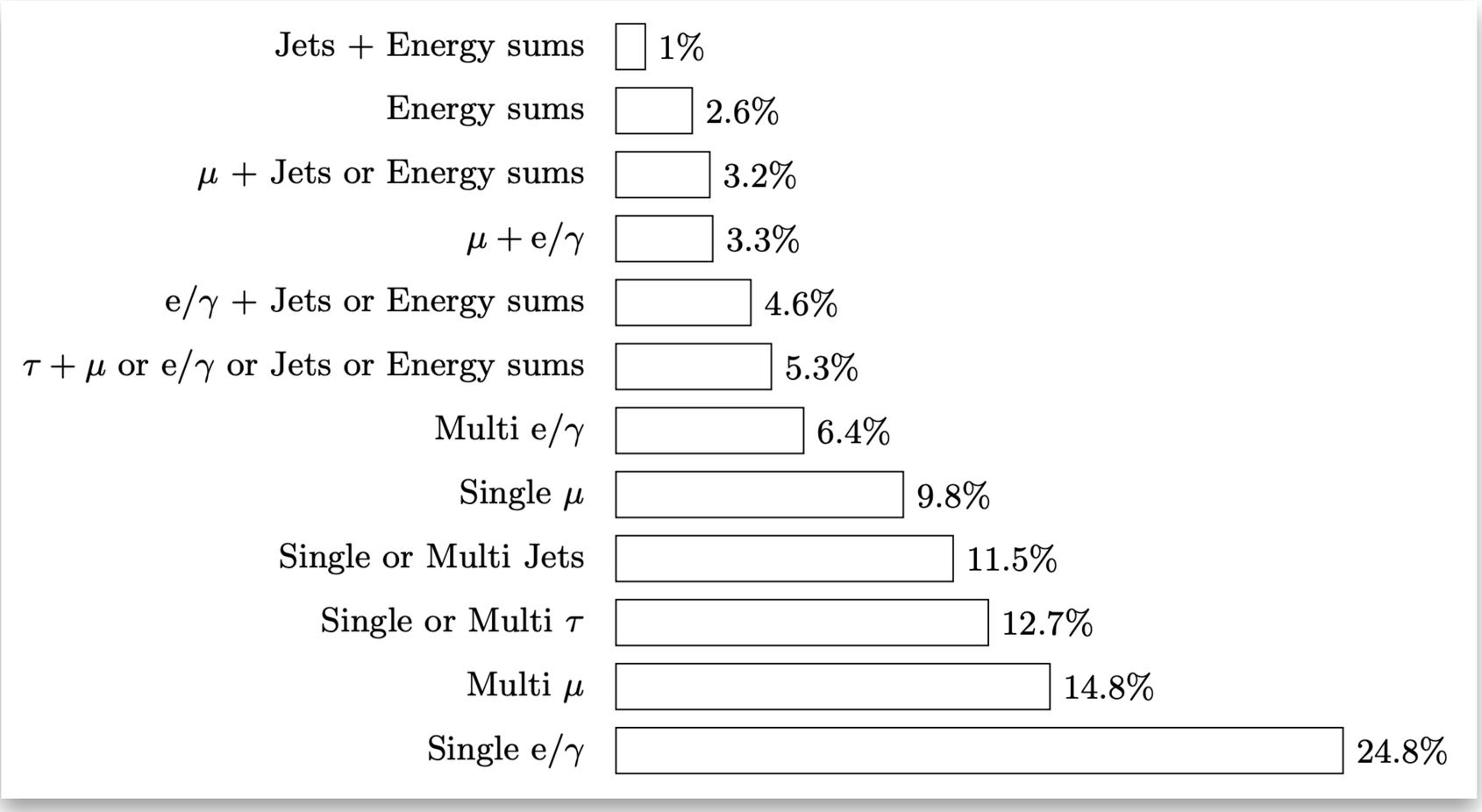
- The menu is the collection of algorithms
  - Physics seeds (mostly unprescaled)
  - Backup seeds (mostly shadowed)
  - Monitoring seeds (often prescaled)
- Prescale columns used to adapt to LHC running conditions
  - Each column implements slightly different seed collection
- The Menu is stored as an XML document
  - You can edit this directly
  - Or preferably: use the Trigger Menu Editor





L1 Rate Fraction in Run 2

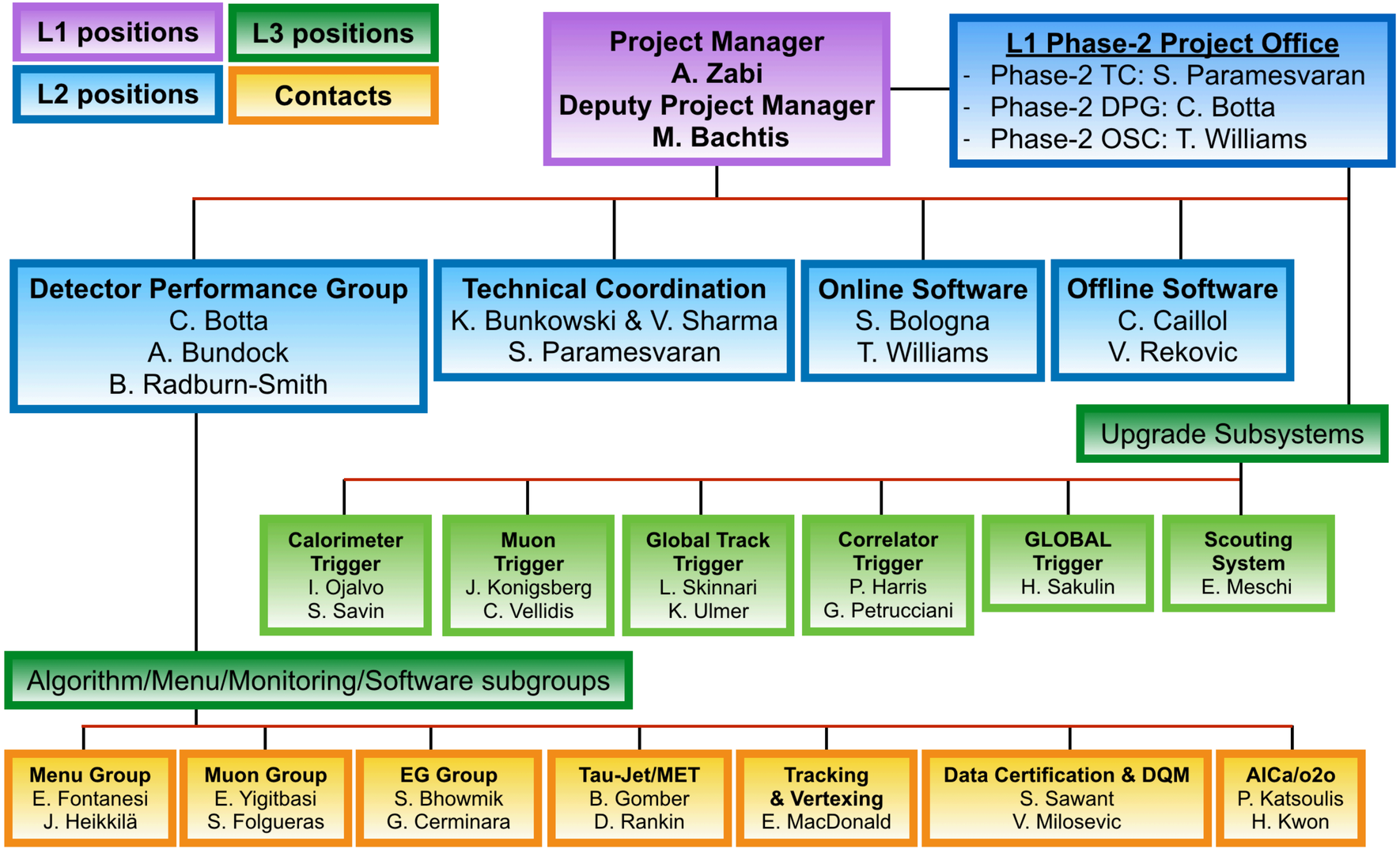
- What do we trigger on at L1?



- From our 2020 paper

L1T Organisation

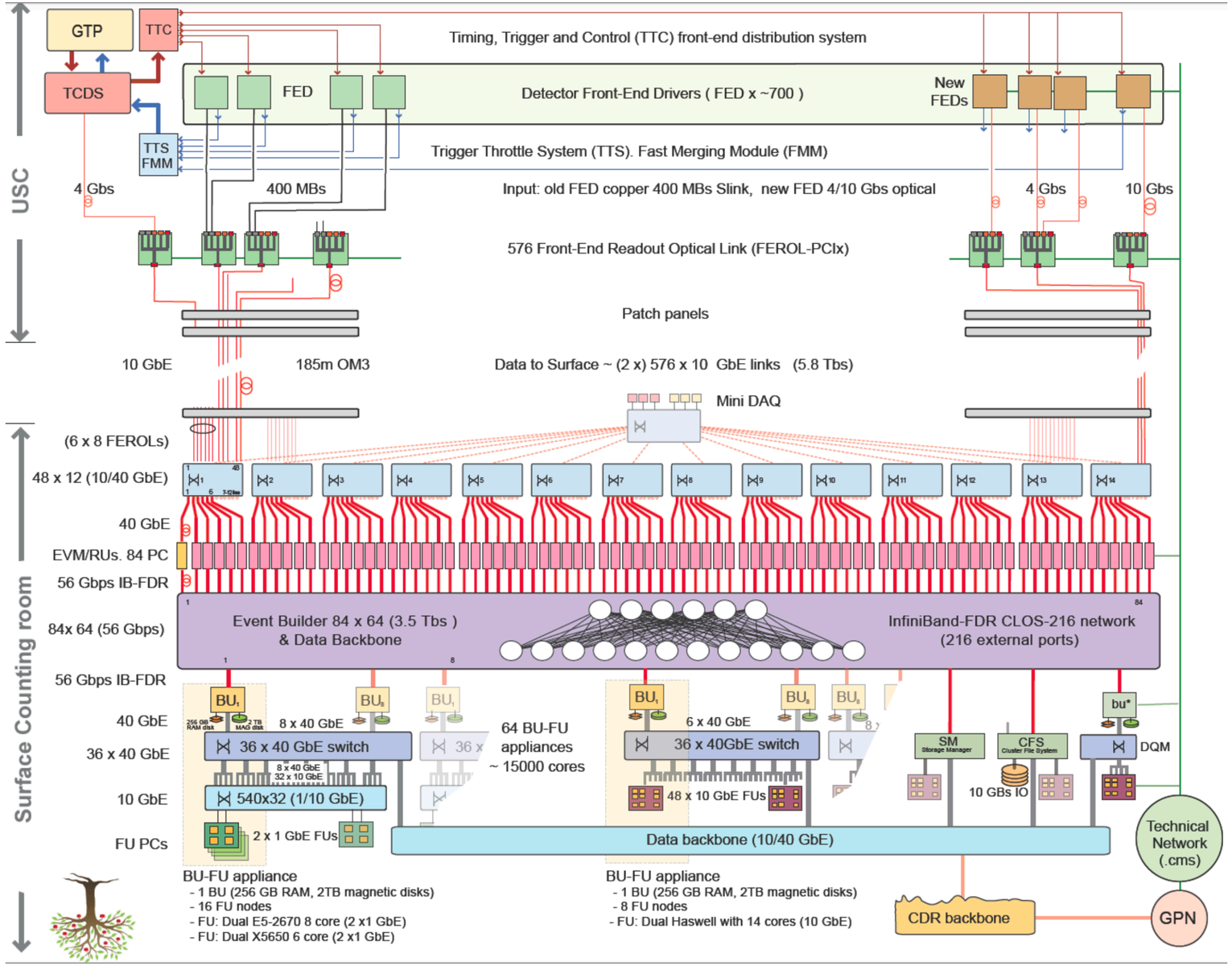
L1 TRIGGER TEAM ORGANISATION



L1T Resources

- L1T meetings are listed on indico:
  - https://indico.cern.ch/category/2091/
  - Weekly L1T meeting on Tuesdays at 4pm
- Twiki links:
  - https://twiki.cern.ch/twiki/bin/view/CMS/L1Trigger
- Hypernews:
  - https://hypernews.cern.ch/HyperNews/CMS/get/L1Trigger.html
- Recent Documentation:
  - Run 2 paper: https://arxiv.org/abs/2006.10165
  - Phase 2 TDR: https://cms-docdb.cern.ch/cgi-bin/DocDB/ShowDocument?docid=13929

Data Acquisition (DAQ)



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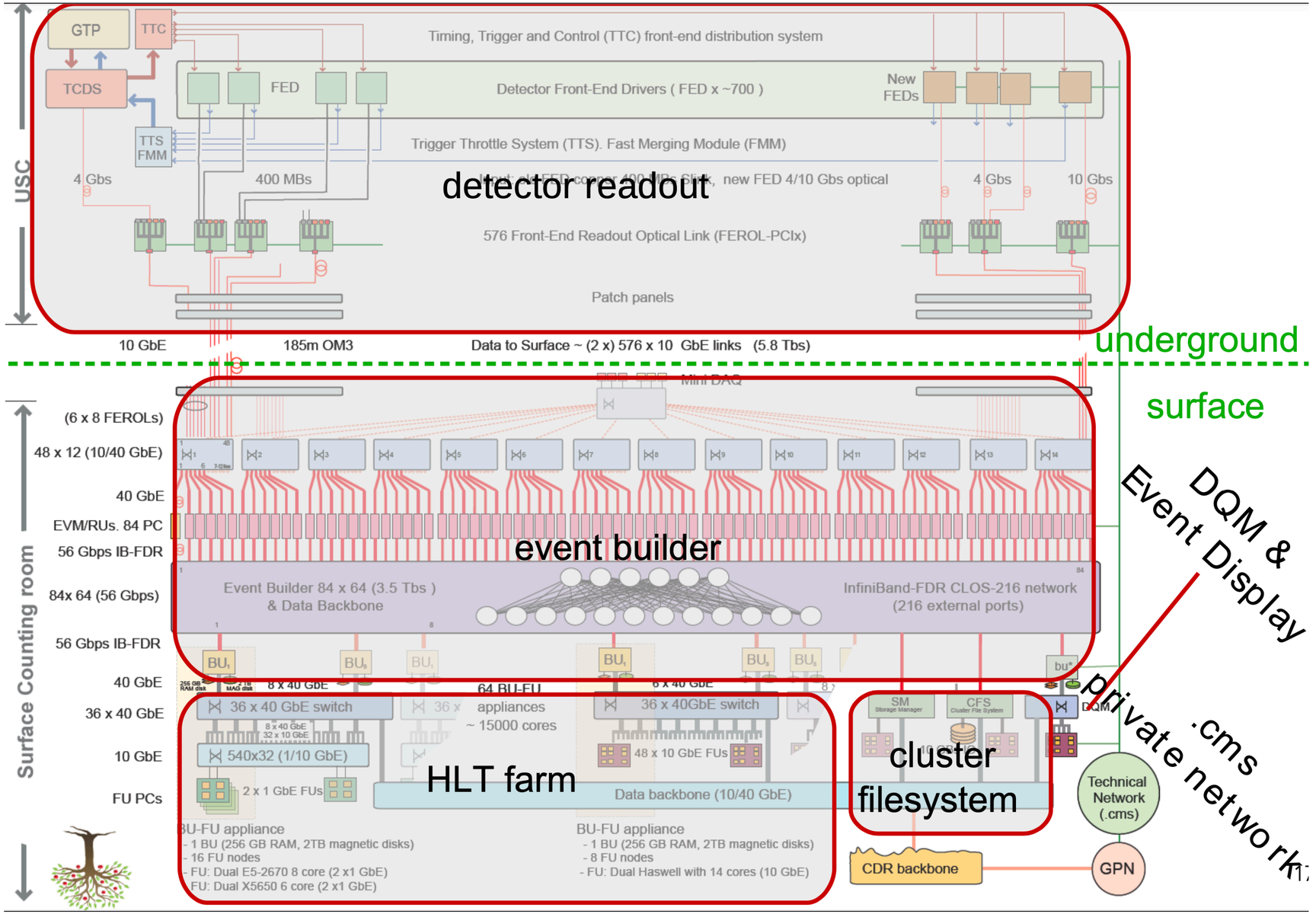
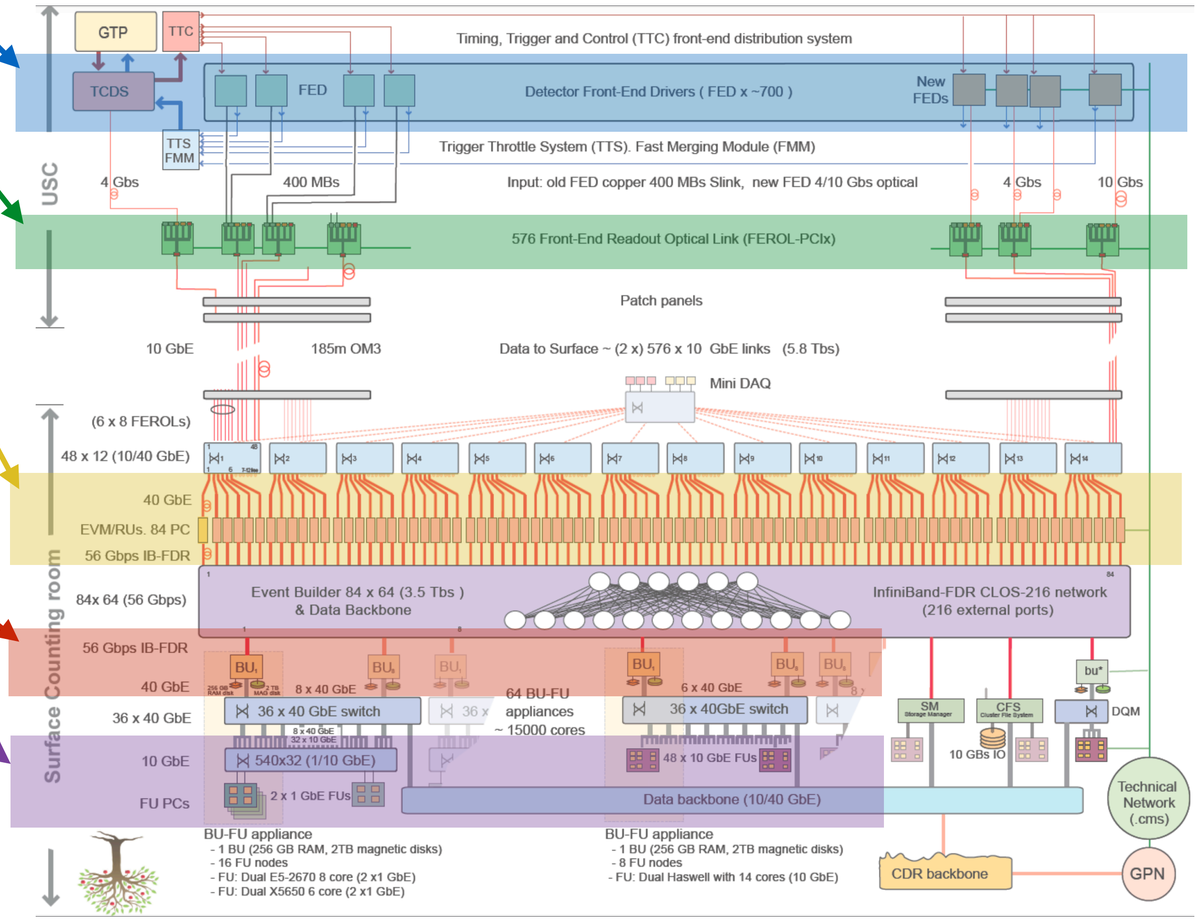


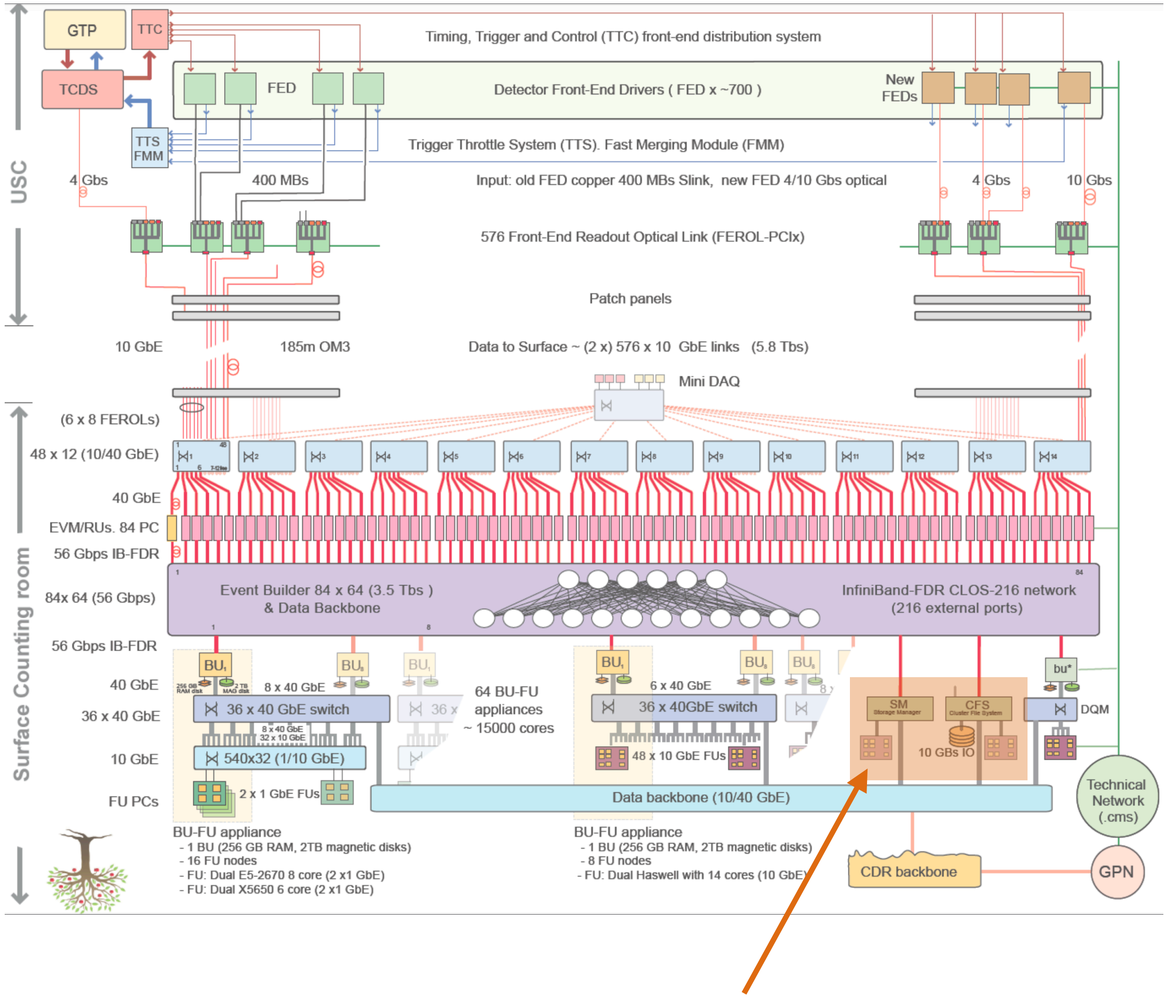
DAQ Data Flow

- After Level-1 trigger accept detector frontends send data fragments to front-end readout optical link (FEROL) cards
  - Custom hardware placed in underground cavern
- FEROL cards are connected to readout units (RUs) via Ethernet-based fat tree network
- RUs are connected to builder units (BUs) which assemble full events
  - Large Infiniband network
- Each BU is connected to a set of filter units (FUs) which run the High Level trigger algorithms
  - Filter farm is comprised of ~25 000 "Haswell-equivalent" cores
- RUs, BUs, and FUs are implemented in commercial server hardware



Storage Manager and Transfer System

- Storage Manager
  - Collect the output “streams” from the filter farm
    - One file per stream per “luminosity section” per HLT job
  - Low-latency, hierarchical merge of data into smaller number of files
    - Micro-merger: merge files on each HLT node
    - Mini-merger: merge files at the “builder unit” level
    - Macro-merger: merge files for the whole farm
    - Additional metadata files insure the integrity of the data through the chain
  - Based on a distributed Lustre FS
    - Copy-less merge (aggregate fragments without reading/ writing them back)
- Transfer System
  - Transfer the fully merged files to the Tier-0 for offline processing and reconstruction



DAQ Organisation

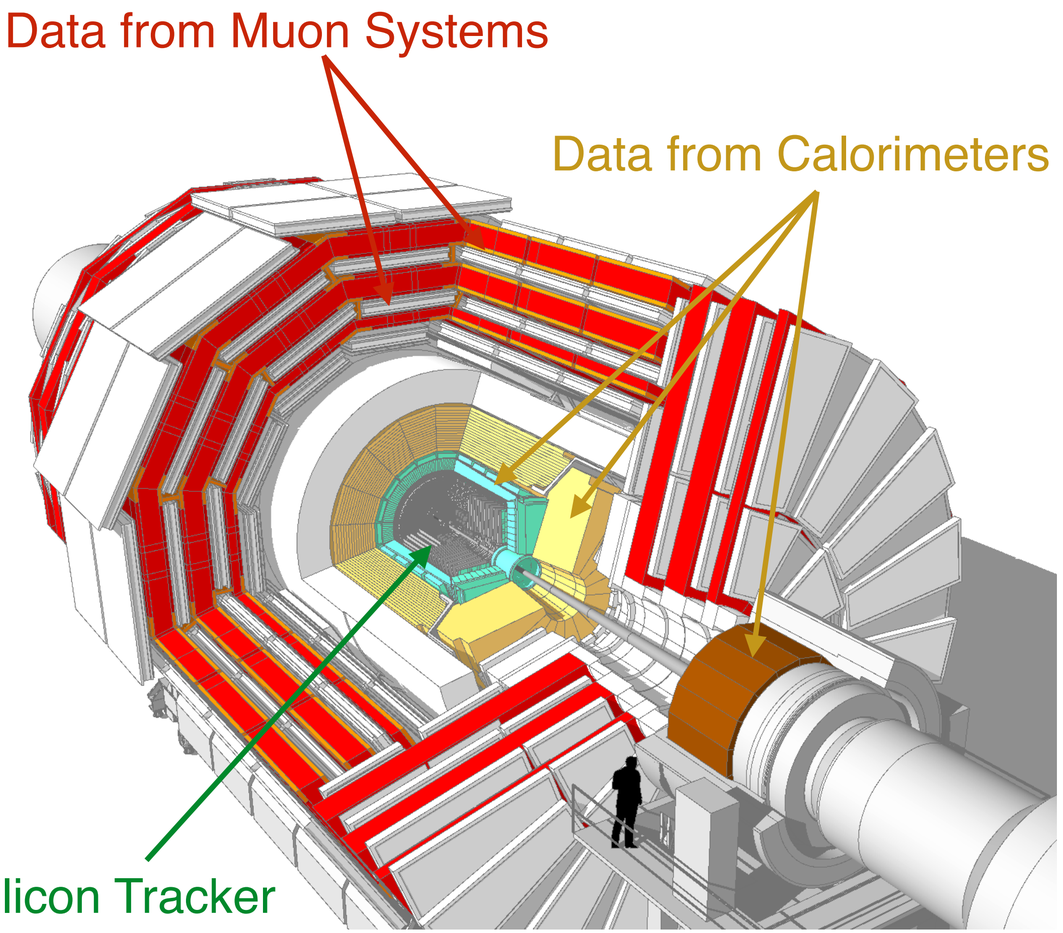
Out of Date

DAQ Project Manager: ~~F. Meijers~~ → **E. Meschi**

- Sub-projects
  - DAQ event flow: F. Meijers
  - Detector Control System (DCS): F. Glege
  - IT Support and Sysadmins: M. Dobson
  - OMS monitor acquisition: U. Behrens
- DAQ Office and representation
  - Resource planning: F. Meijers
  - DAQ Technical Coordinator: A. Racz
  - DAQ Upgrade Steering Group: E. Meschi
  - Electronics and Online Systems Working Group: J. Hegeman

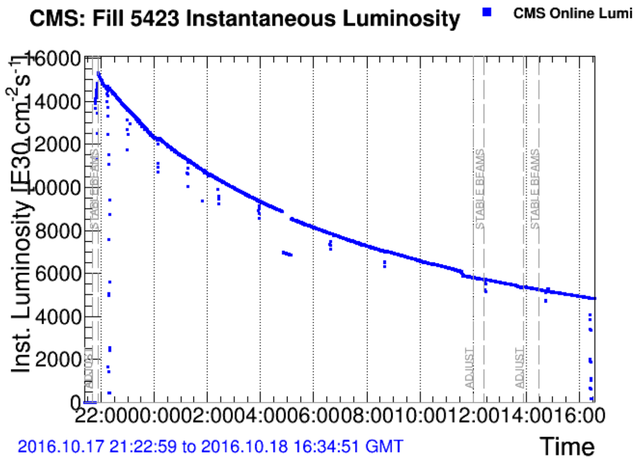
High Level Trigger (HLT)

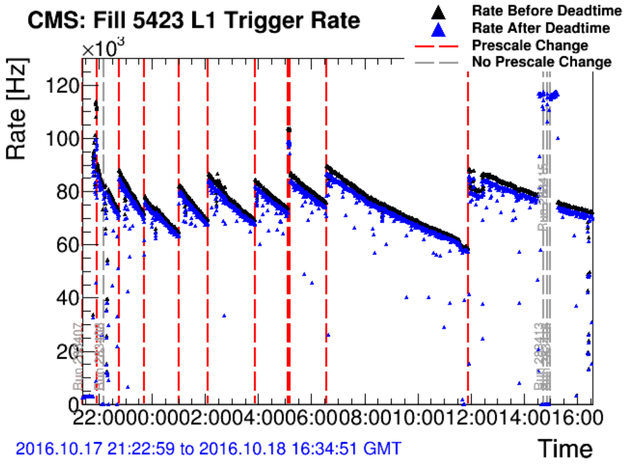
- Full detector readout, full granularity
  - ~100 kHz input rate
- Implementation
  - C++ software: CMSSW
    - Same as used for simulation and offline analyses
  - Running on a cluster of commercial PCs (filter farm)
  - Now utilising GPUs as well (see dedicated talk)
  - Quasi-online, input buffer 1-2 minutes
- Constraints
  - ~350 ms average processing time to take a decision
  - Peak throughput of ~ 6 GB/s aggregated over all streams
  - ~1 kHz average output rate (limited by offline resources)

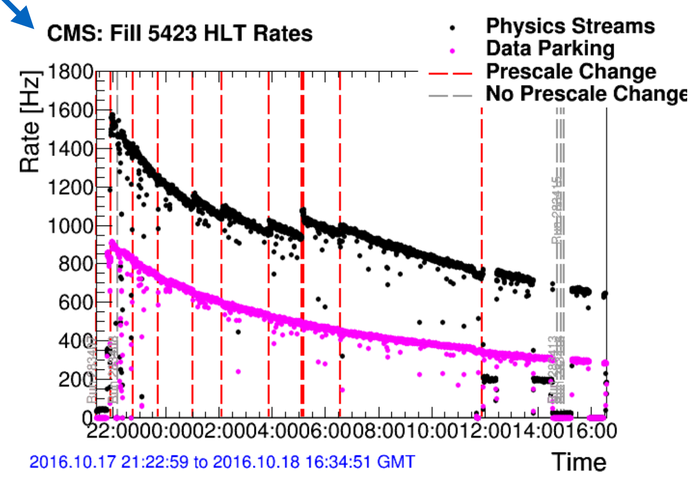


L1T vs HLT Rates

- Luminosity and pileup (usually) decrease during each fill
- L1T is limited to a peak rate value
  - Thresholds and prescales are relaxed during the fill to make better use of the bandwidth
- HLT is limited to an average value
  - Take high rate at higher luminosity
  - Let the rate decrease during the fill to get a lower average
  - Keep trigger thresholds constant

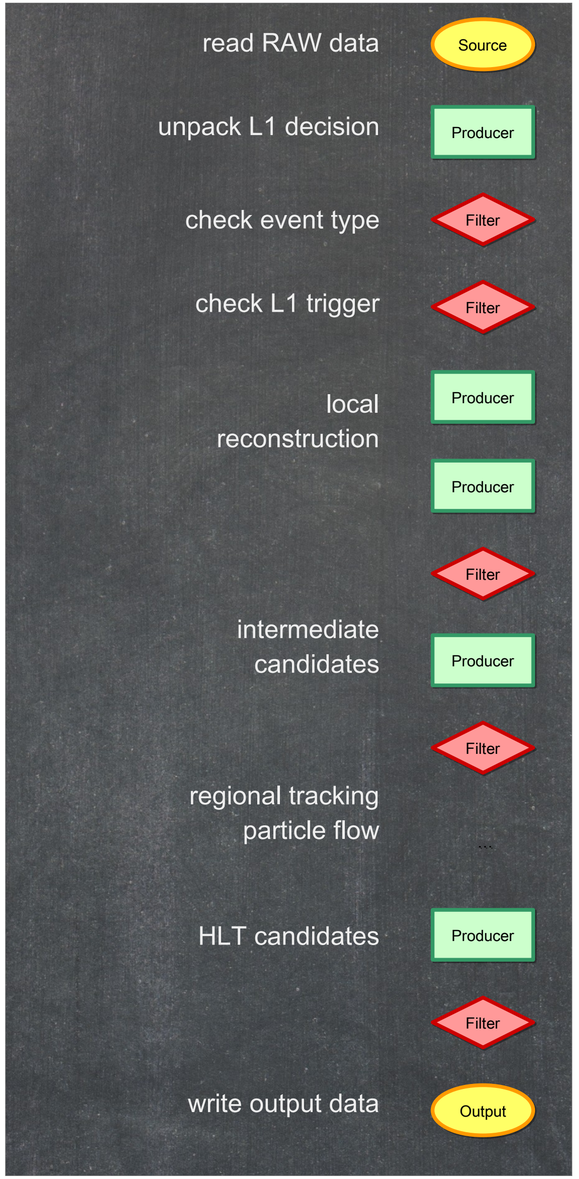






HLT Workings

- Trigger Paths
  - Succession of Producers, Analyzers, and Filters
  - Filters can stop the execution along a Path
    - Other Paths are not affected
    - Logically parallel execution
  - Stop each Path as early as possible
    - Reject events not meeting the selection criteria
- What methods can we use to speed up the HLT?
  - Regional reconstruction
    - Around L1 candidates, existing candidates, etc.
  - Reject often, reject early
    - Intermediate reconstruction steps
    - Reject events as soon as possible
  - Modularity and reuse of the reconstructed quantities
  - Good enough reconstruction
    - Trade large speed gains for small accuracy losses



HLT Workings

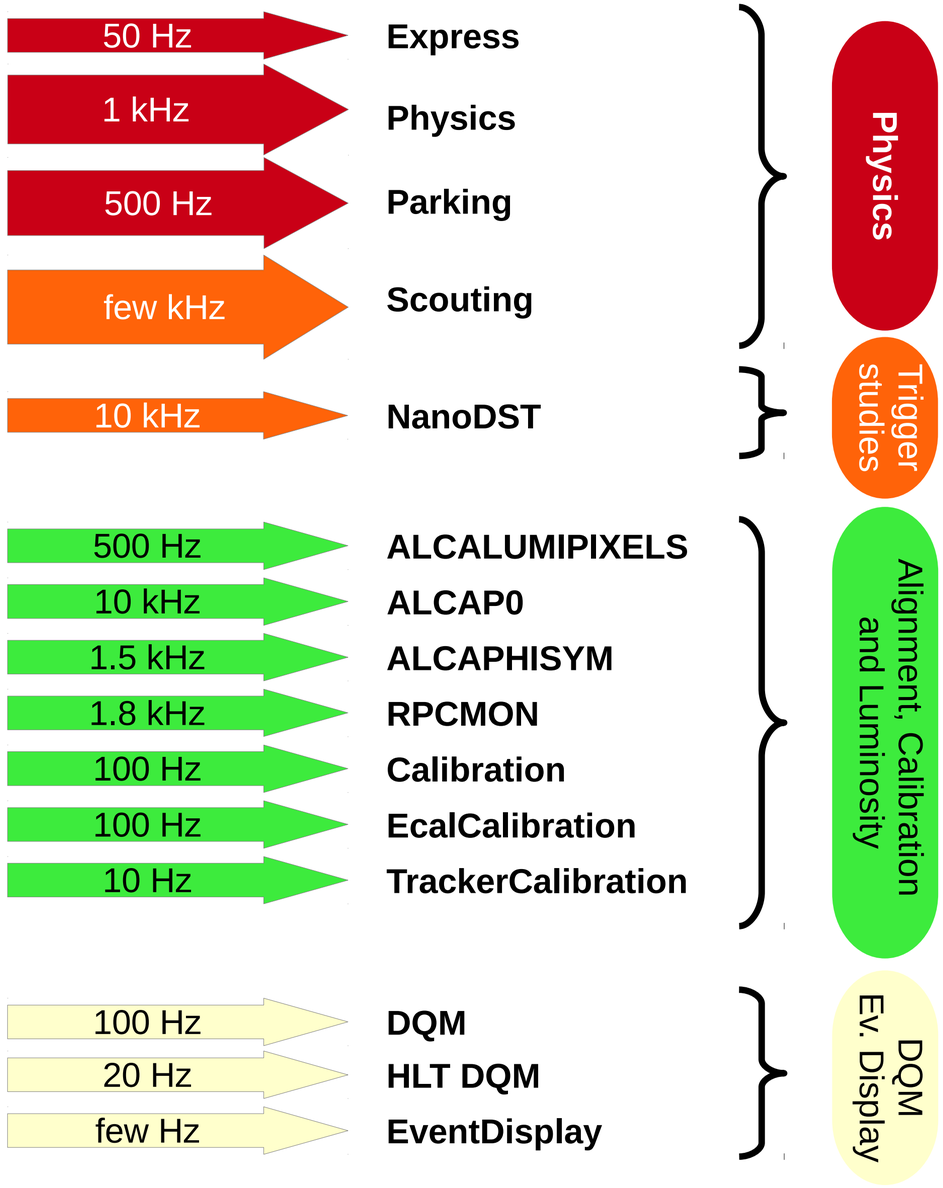
- HLT is a specific configuration of CMSSW
  - Python config used to drive C++
- RECO vs HLT
  - RECO has full calibrations and reconstructs the full event
  - HLT has preliminary calibrations and reconstructs what is necessary to make the decision
  - Code is shared as much as possible → optimisations are used where needed
- Further reading here

HLT Objects

- Muons
  - “L2” stand alone muons
  - “L3” global and tracker muons
- Photons
  - Based on ECAL superclusters
  - Calorimeter-based id
- Electrons
  - Based on ECAL superclusters,
  - Pixel- and GSF tracking
  - Calorimeter and track-based id
- In general
  - Iterative tracking
  - Particle-flow based isolation
  - Pileup correction for isolation and jet energy
- Taus
  - Based on particle flow reconstruction
- Jets, MET, HT
  - Calo- and PF-based jets, MET and HT/MHT
  - AK4 and AK8 jets with pileup corrections
  - Jet-based pileup correction for MET
- b-tagging
  - Secondary vertex reconstruction
  - Soft-lepton based b-tagging
  - “Deep learning” CSV being commissioned
- But also
  - Razor, αT, dE/dx, …
  - Jet substructure, …
  - Displaced decays for non-prompt searches

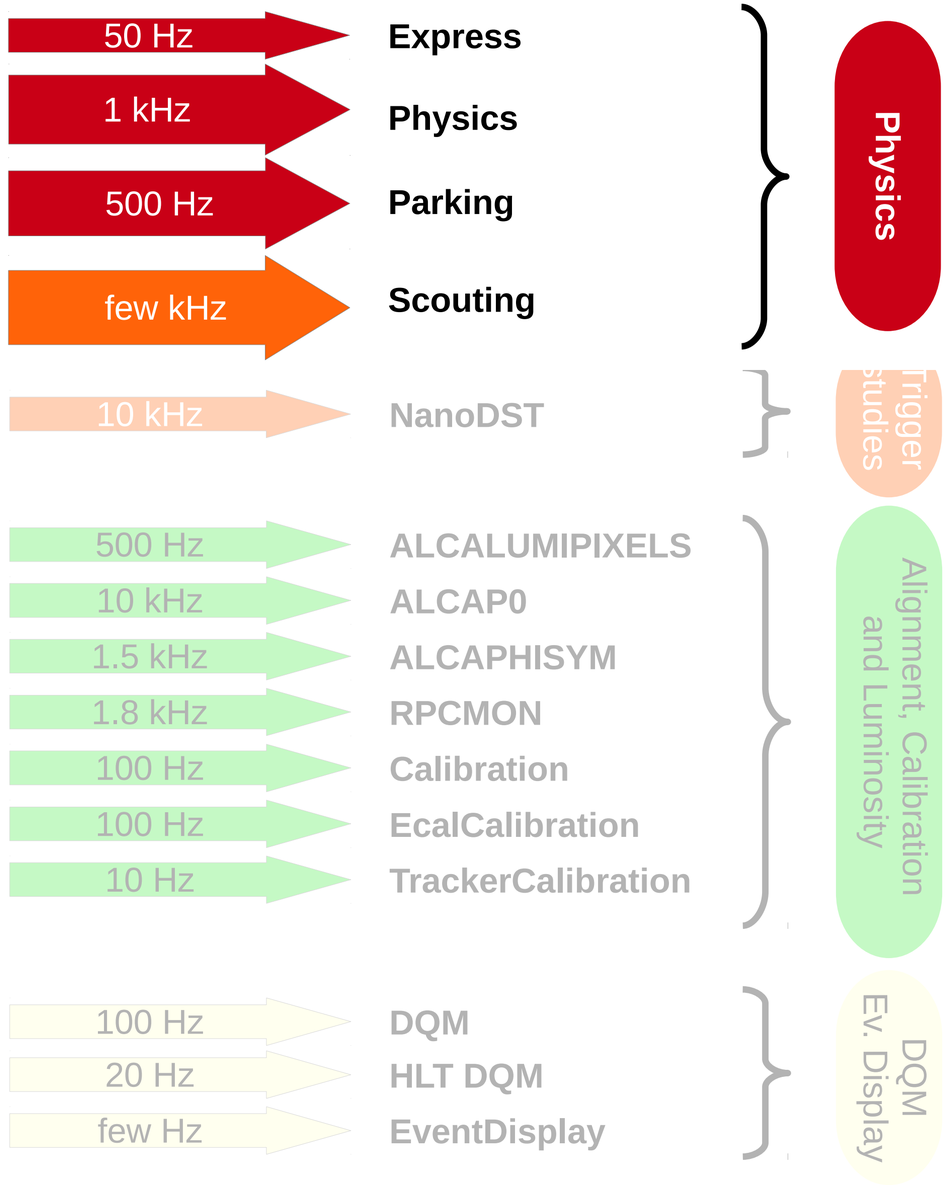
Streams

- The HLT is responsible also for splitting the data in different streams
  - Different purposes
  - Different event content
  - Different rates
- Physics, calibrations, monitoring, etc.
- Each streams then goes into its own dataset
  - Stream is ~collection of root files outputted from HLT



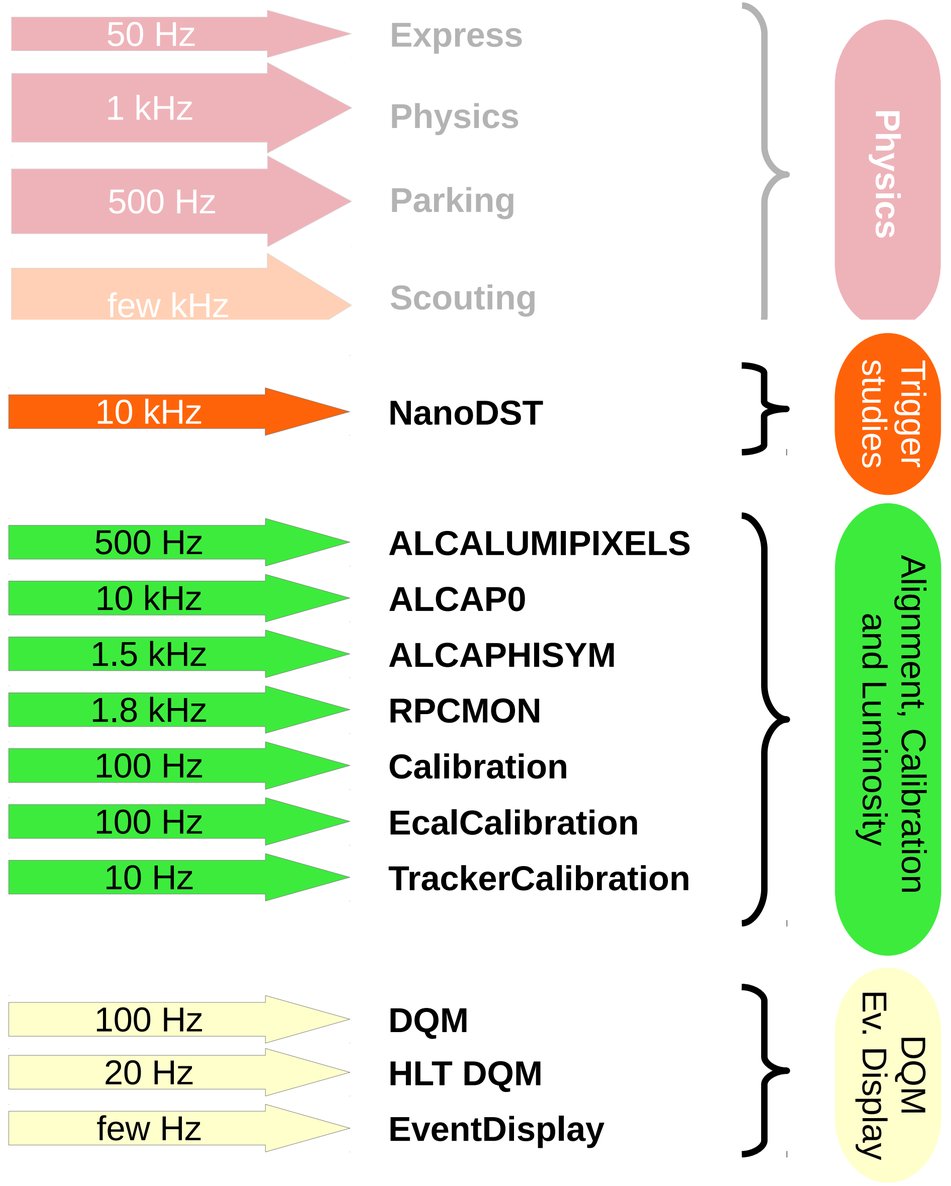
Streams

- The Physics stream collects all the events for physics analysis
  - Average: ~ 1 kHz
- Parking …
  - Additional events stored Offline
  - To be reconstructed or analysed at later date
  - Rate: ~ 500 Hz
- … and Scouting
  - No offline reconstruction
  - Analysis is performed directly on HLT objects
  - Possibility to reconstruct the parked data for a thorough analysis



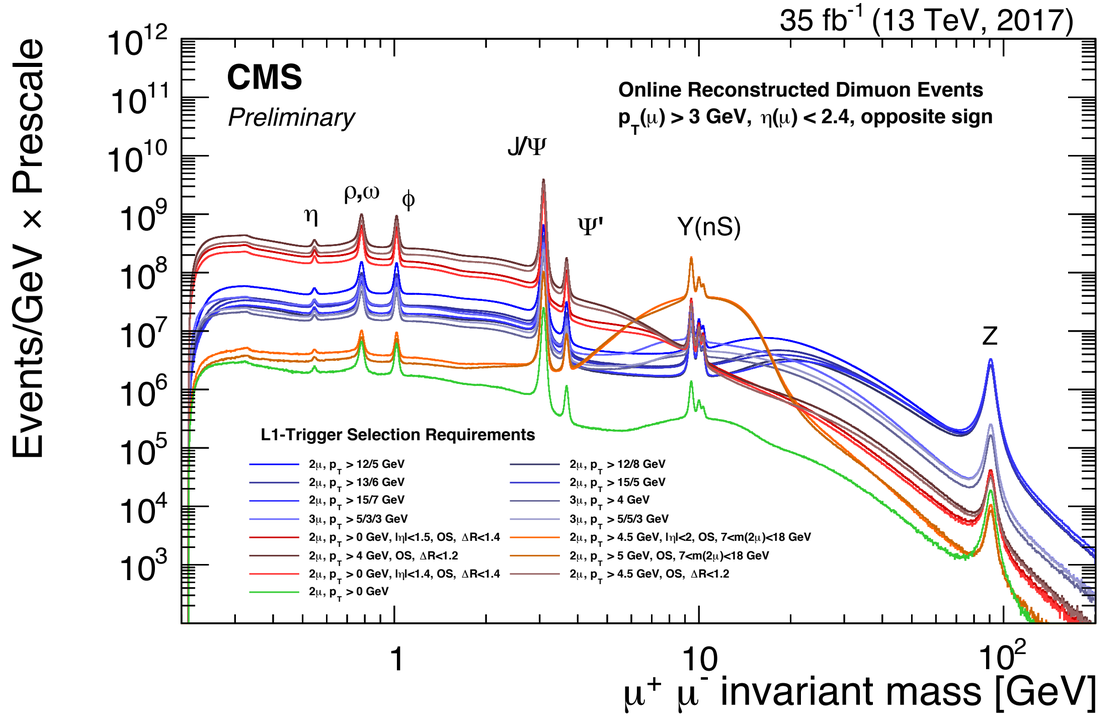
Streams

- NanoDST stream
  - Saves trigger information for 10% of all L1-accepted events
  - Useful for trigger studies
- AlCa streams collect events for dedicated calibration workflows
  - Only a fraction of the detector is read: small event size, high rate
- DQM and Event Display streams
  - Monitor different aspects of data taking (online, offline)
  - Select events for online display

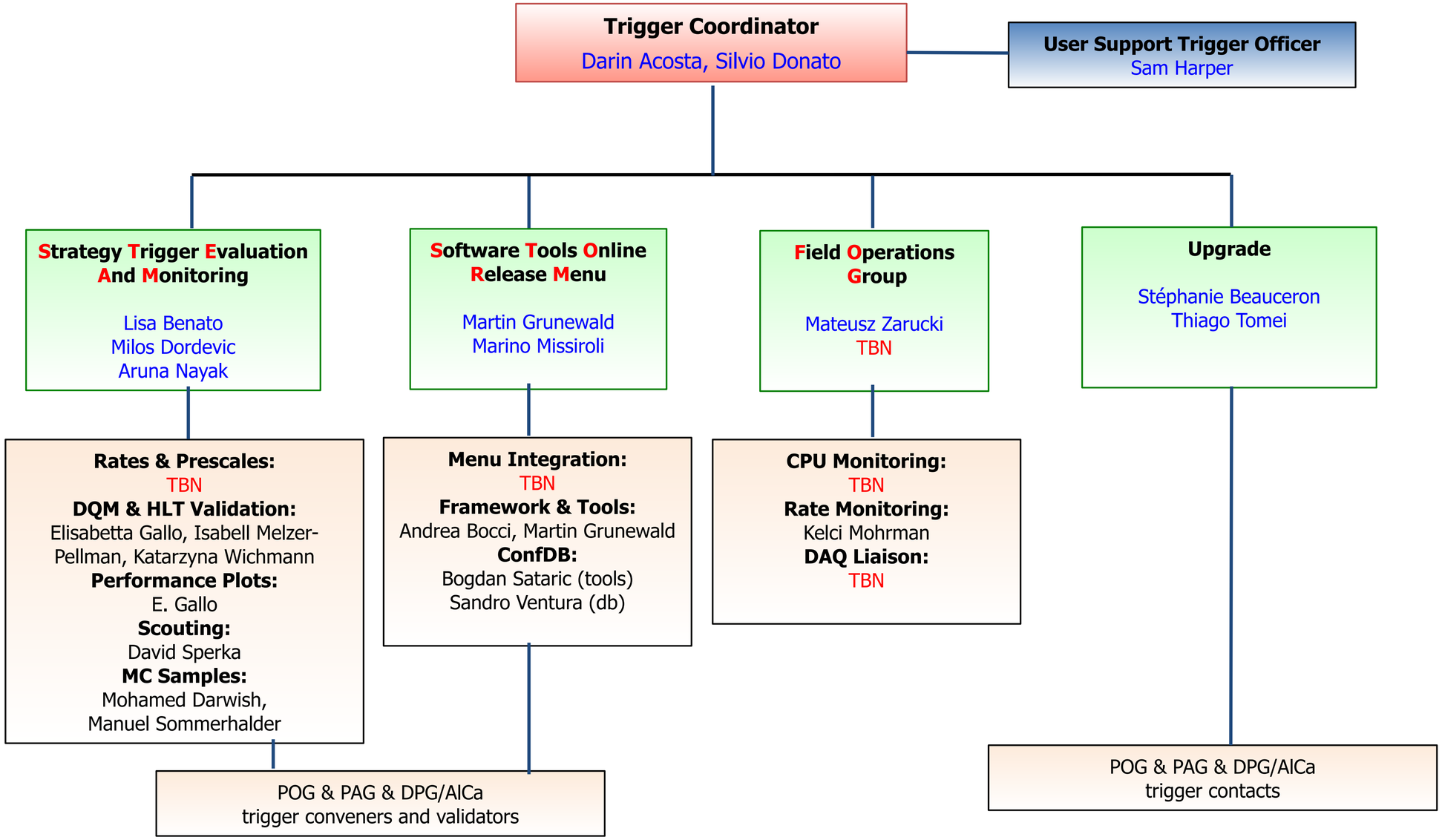


Scouting

- The scouting program will be expanded for Run 3
- Dedicated subgroup in TSG:
  - https://twiki.cern.ch/twiki/bin/view/CMS/CMSScouting
- Example of online only reconstruction dimuons probing from MeV to 100s of GeV



Trigger Studies Group Organisation

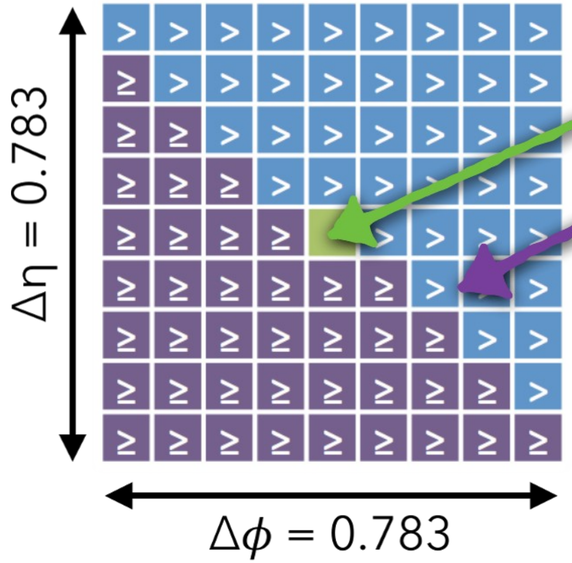


HLT Resources

- TSG meetings are listed on indico:
  - https://indico.cern.ch/category/1576/
  - Weekly TSG meeting on Wednesdays at 2pm
- Twiki links:
  - https://twiki.cern.ch/twiki/bin/view/CMS/TriggerStudies
- egroup:
  - cms-hlt@cern.ch
- Mattermost:
  - https://mattermost.web.cern.ch/signup_user_complete/?id=txypsaoi53ytzkbodsdignpmew
- L1 + HLT Tutorial:
  - https://indico.cern.ch/event/850482/

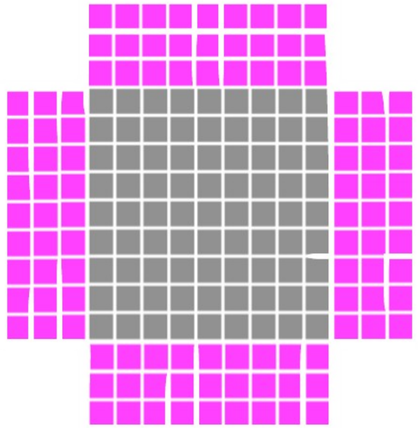
Extra

L1 Jets



1. Look for local maximum above jet seed threshold
2. Apply mask to surrounding tower (antisymmetric to avoid double-counting of overlapping jets)
3. Jet E_T = ∑ TT in 9 × 9, jet centre = highest energy TT

Local correction to jet using energy in TT strips surrounding jet area:



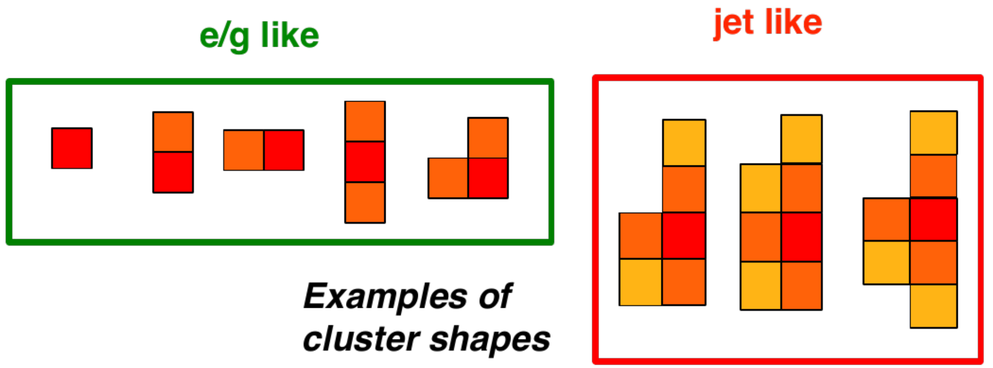
Subtract total energy in **lowest** 3 sides - avoids overcorrection from overlapping jets

Use 3 strips to mitigate fluctuations, but keeping correction local and robust

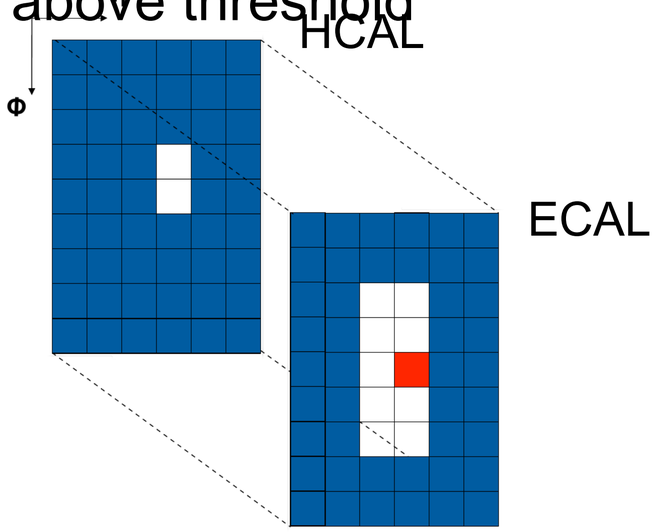
Correct jet energy as a function of E_T and η

L1 e/gamma

- discrimination between jets and e/gamma candidates based on
  - H/E (ratio HCAL / ECAL energy)
  - cluster shape

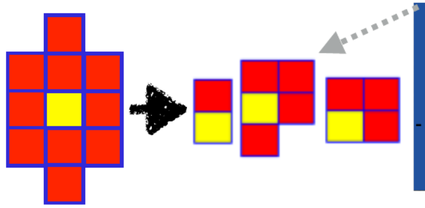


- estimate pileup from the number of trigger towers above threshold



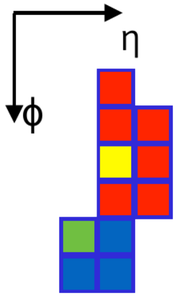
- compute isolation
  - energy in a 6×9 region
  - $E+H_{6x9} - E_{2x5} - H_{1x2}$ < isolation cut
  - function of position and pileup

L1 Taus



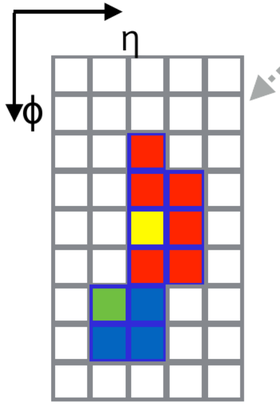
Clustering

- TT are regrouped into clusters
- Basic object to form L1 tau candidates



Merging

- Search for neighbors in a defined path (tau decay products can be spread out)
- ~**15%** merged, **85%** non merged



Isolation

- Compute isolation as E(6x9) - E (tau)
- **PU subtraction at hardware level**

Calibration

- Improves energy resolution

Shape veto

- Cluster with certain shapes are rejected
- Additional background rejection

L1 Objects in Data/MC

- L1 objects from the unpacker are available in Data and MC
  - They are available at the AOD and MiniAOD level
- The objects are of the type DataFormats/L1Trigger/interface/L1Candidate.h
- Here you can access:
  - The hardware pT, η, Φ, quality and isolation flags
  - The physics properties of the object: pT, η, Φ