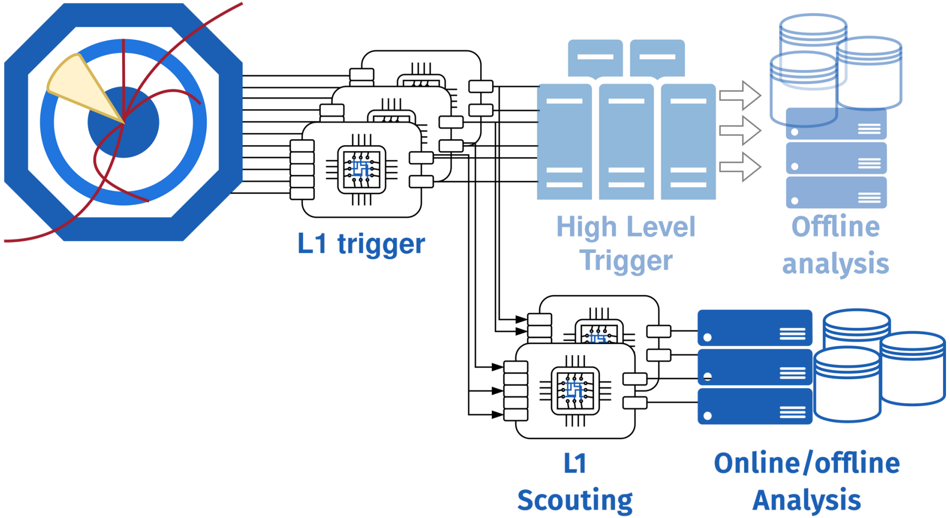
The CMS Level-1 Trigger Data Scouting system for the HL-LHC upgrade



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Outline

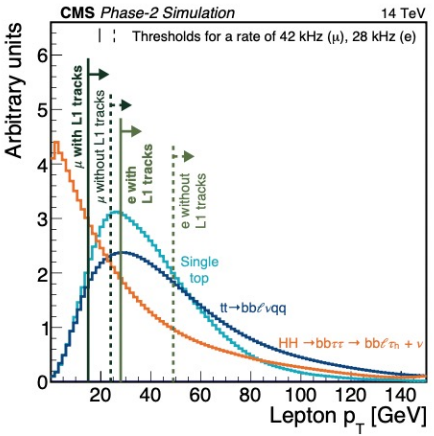
- The Phase-2 (HL-LHC) CMS trigger upgrade
- L1 Scouting: concept and motivation
- Baseline design
- Physics case
- The Run 3 demonstrator
- Summary

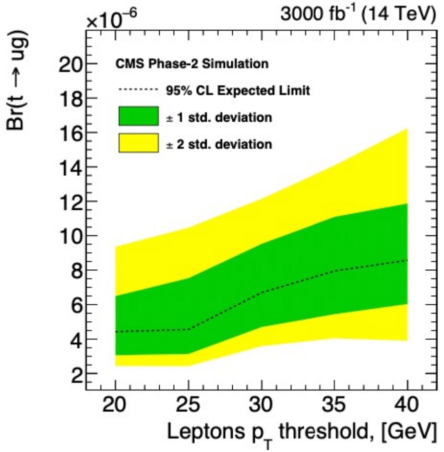
CMS L1 Trigger Phase-2 Upgrade

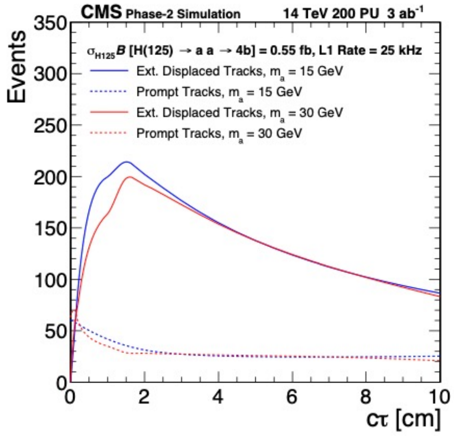
At HL-LHC: peak instantaneous **luminosity** up to **7.5x10^{34} cm^{-2}s^{-1}**, up to **200 Pile-Up** per crossing –entails a major detector upgrade, including both trigger stages

Goals of the L1 upgrade:

- Optimally **exploit HL-LHC data** and extend sensitivity to new physics
- **Maintain Run-3 thresholds** for all basic trigger objects in the presence of high pileup
- Improve capability to efficiently **select specific signatures**
- **Extend reach** for new physics searches

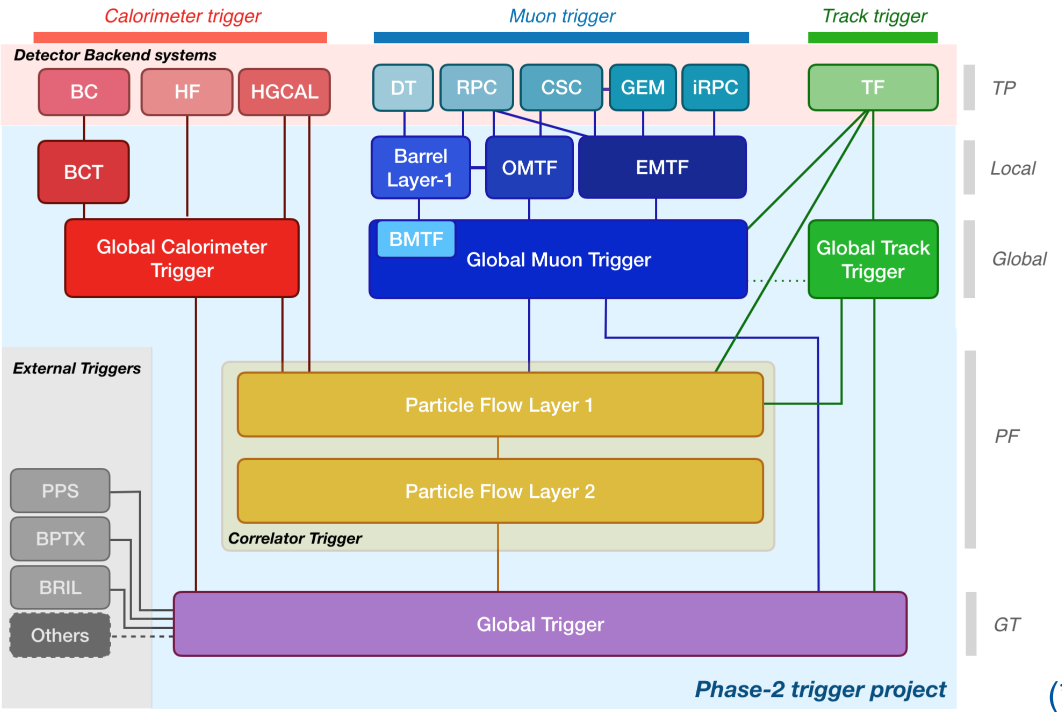






CMS L1 Trigger Phase-2 Upgrade

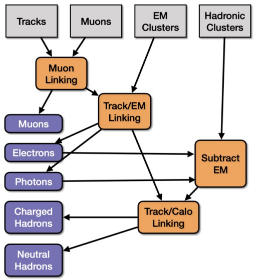
At HL-LHC: peak instantaneous luminosity 7.5x10^{34} $cm^{-2}s^{-1}$, up to 200 Pile-Up per crossing
L1 upgrade: exploit tracks at L1, finer granularity calorimeter and refined muon primitives

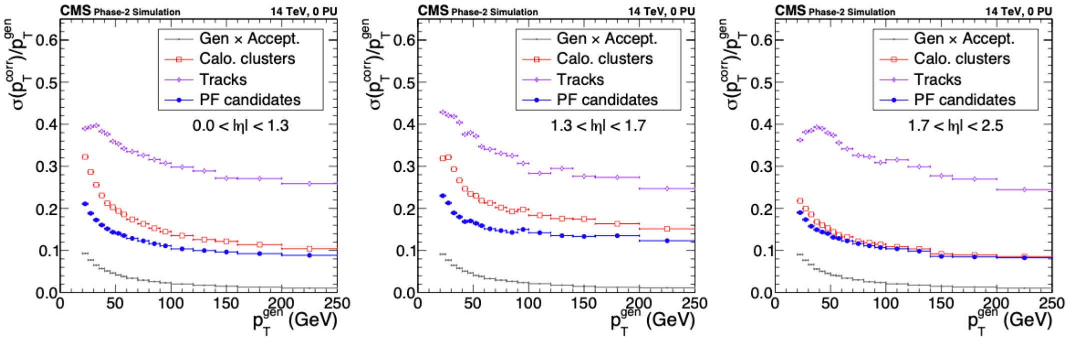


Extended muon **coverage** and granularity, displaced muons
High(er) **granularity** calorimeter primitives
Tracking at L1 for pt>2 GeV, up to |η|<2.4 – improves resolution of all objects
Particle Flow reconstruction
Pileup subtraction using **PUPPI***
State-of-the-art FPGAs enabling **ML-based approach**
Sophisticated **multi-object, multi-BX selection** and **NNs** in the Global Trigger

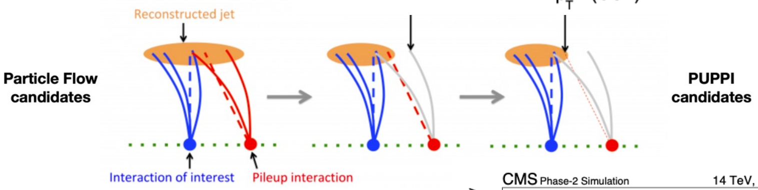
(*) PUPPI: PileUp Per Particle Identification

Phase-2 L1: performance

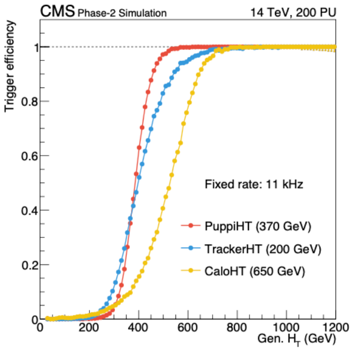


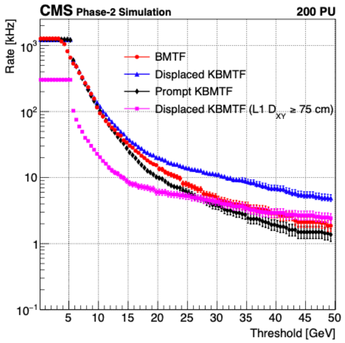


Particle flow objects combine tracker and calorimeter information to attain best resolution



Pileup subtraction ensures sharp turn on of energy sum triggers





Kalman filter based standalone barrel muon trigger provides sustainable rate for displaced muons

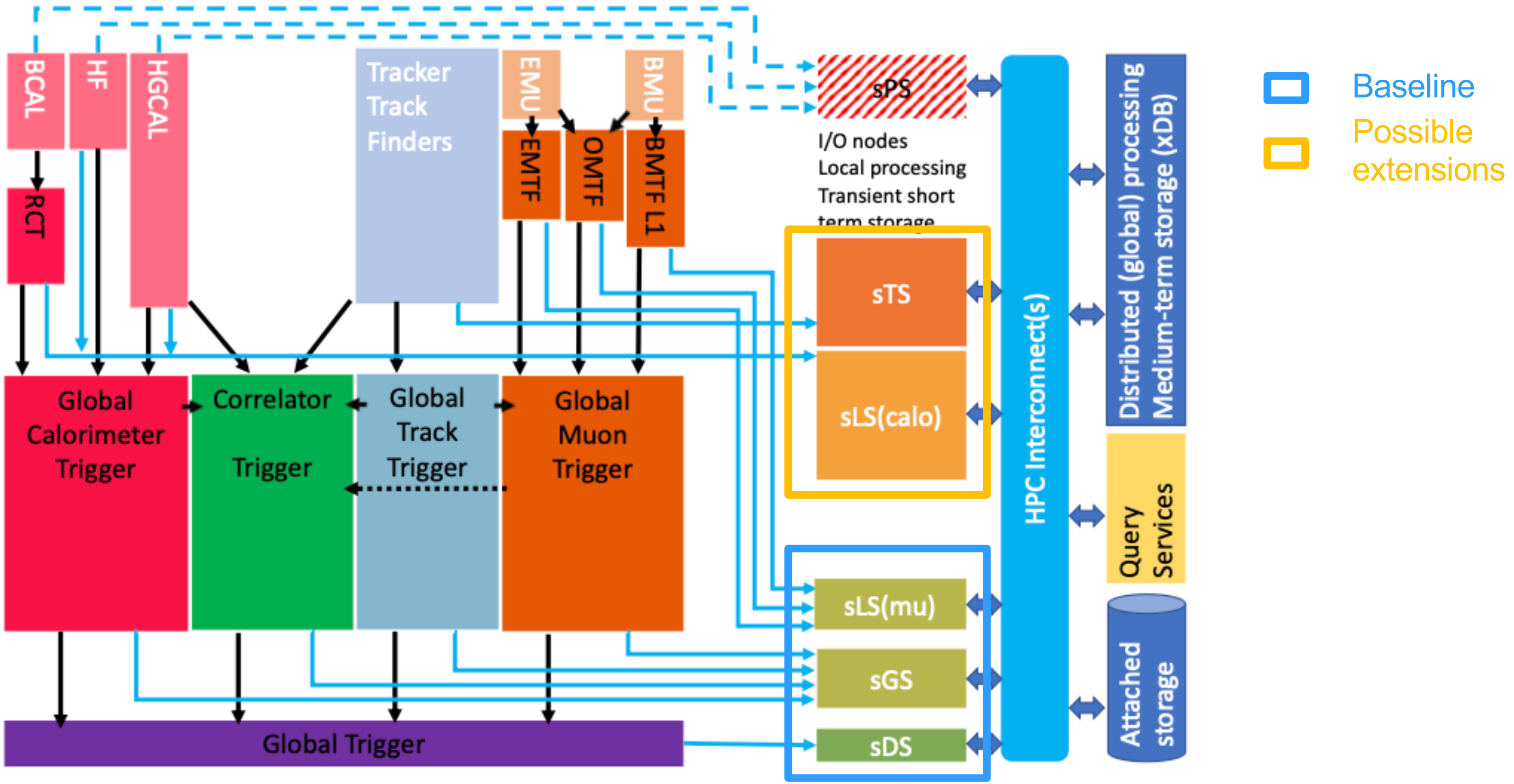
What may be missed

- The Phase-2 L1 trigger will be a very capable system
  - **Tracking** at L1 enables reconstruction of **exclusive signatures**
  - In many cases **close-to-offline** resolution thanks to the inclusion of tracking and particle flow
  - Control over pileup
  - Access to **displaced** objects
- Possible additional ground to cover ?
  - Physics that does not fit into the **total accept rate** (dictated by the readout b/w of some detectors and offline storage and processing capacity)
  - Channels whose combinatorics or complexity exceed **latency** constraint, or **“computing” capacity** - (latency is dictated by length of readout pipelines, complexity limited by the [albeit very large] amount of logic available in FPGAs)
  - Exotic signatures with **orthogonal requirements** to “mainstream” physics.

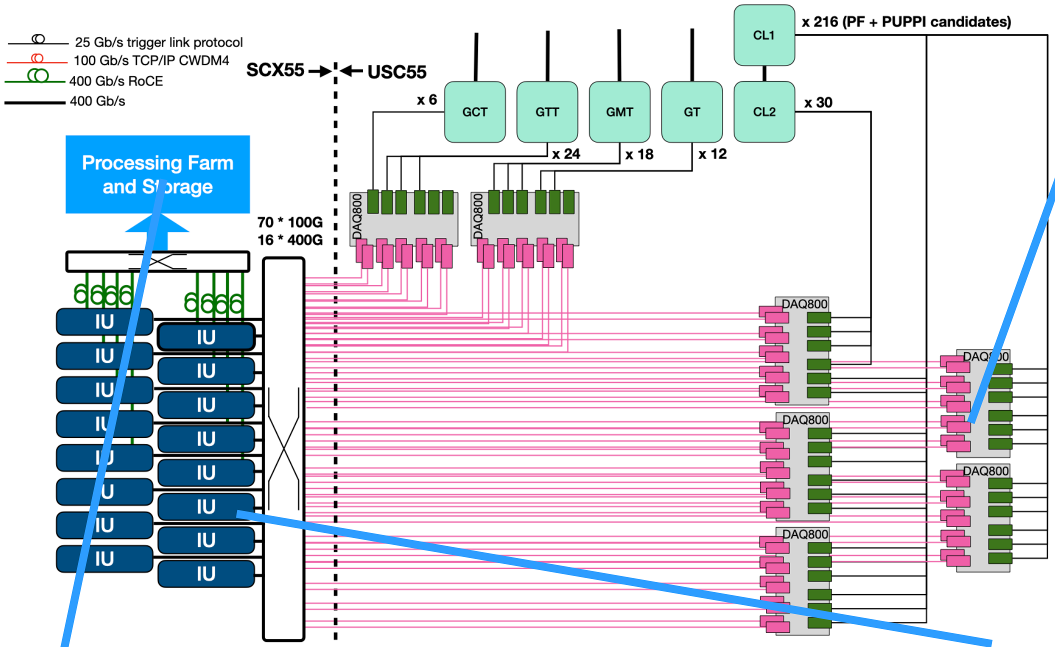
L1 Data Scouting

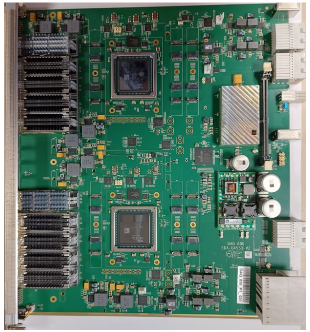
- A **Level-1 Trigger Data Scouting** system collecting and analysing L1 objects produced for every bunch crossing:
  - Has **full access to physics** otherwise constrained by the L1 latency and maximum accept rate…
  - Potentially enables the exploration of additional **exotic signatures**
  - **A powerful tool** to study correlations over several bunch-crossings, for diagnostics and physics
- **Acquire and process** the trigger objects produced by the L1 processors **at the accelerator bunch-crossing rate of 40 MHz**
- Caution! trigger primitives
  - Trigger primitives are designed to provide **best and well-understood efficiency** for physics objects and to **control the accept rate**
  - This does not necessarily translate into objects that are **easy to use for physics**
    - For example: sharp turn-on at threshold != (always) best accuracy
    - **Features** could be introduced by limitations of the processing hardware / transport protocols and their bandwidth
    - Objects **calibration** may not be optimal for physics
  - **Detailed simulation studies needed** to explore the capabilities of a scouting system

Phase-2 L1DS: Principle



Phase-2 L1DS Baseline: how





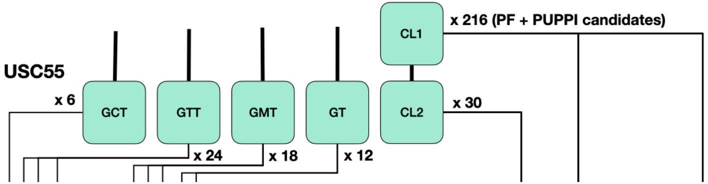
Up to 48 input links @25 Gb/s
Up to 10 output links (TCP/IP) @100 Gb/s

Capture primitives from trigger boards using high-speed optical links fed into data acquisition boards (DAQ800)

Distributed online processing creates reduced data streams for analysis

Aggregate data into orbits (orbit builder) and buffer for processing

Phase-2 L1DS Baseline: what



1. All candidate objects feeding the final GT algorithms
   - Calorimeter and muon objects from standalone processors
   - Tracker objects (PV, multi-track objects) from GTT
   - PUPPI objects (electrons, jets, etc.) from Correlator Layer 2 – and the final GT decision itself
2. Pileup-subtracted candidates and Particle-flow candidates (optionally) – prior to L2 processing

Extensive diagnostic and monitoring capabilities
Physics with PUPPI objects without rate limitations

Do own jets, electrons, etc. – without latency limitations
Full combinatorics with PUPPI candidates (for exclusives, etc.)
Alternative pileup subtraction approaches

Source	Links (baseline)	Links (upstream ZS)
GT	12	12
GTT	24	24 + 48 (Tracks ZS)
GCT	6	6
GMT	18	18
CL2	30	30 + 24 (PUPPI ZS)
CL1	216 (PUPPI)	84[*] (PF $\|\eta\|\leq 3$ ZS)
Total	306	246

Physics Case I

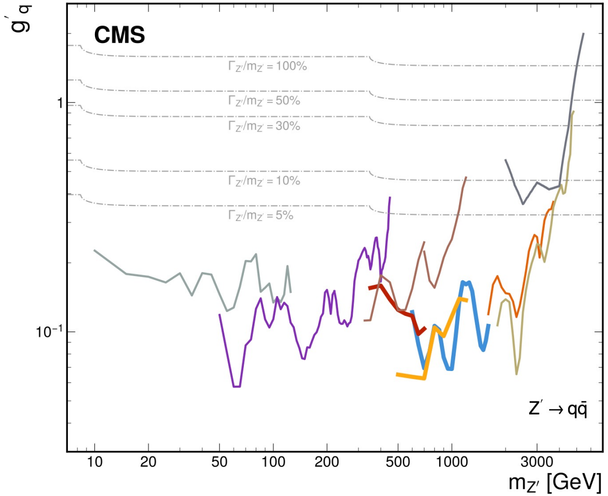
Bold = ongoing studies with L1 scouting

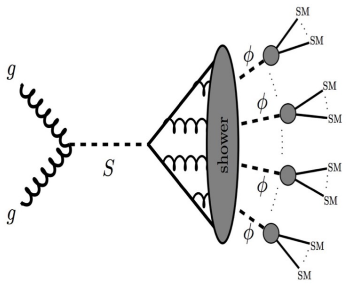
- Soft hadronic final states
  1. **Classic dijet resonance searches** in regions of phase-space inaccessible to standard L1 (no rate limitation, PF-jet resolution)

  Current low-mass searches use boosted jets and jet substructure

  2. **Multiple jet** final states in general, that can benefit from a cut-and-count approach less sensitive to L1 jet features
  3. High multiplicity unclustered hadronic final states (from different models, including or not a "dark" sector)

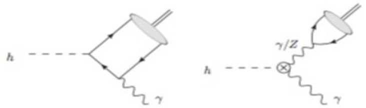
  More on 1. later





Physics Case II

Bold = ongoing studies with L1 scouting

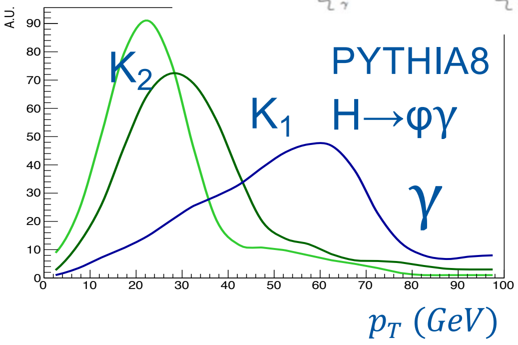


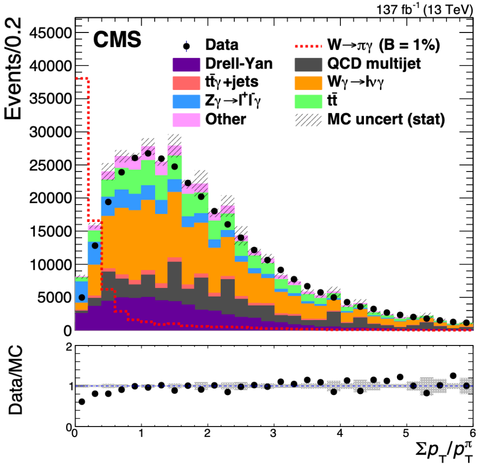
- Standard Model rare decays
  1. Exclusive **rare Higgs decay** channels
     $H \to J/\psi\gamma, H \to \phi\gamma, H \to \rho\gamma, \ldots$

     Tiny BRs, can all be selected with single photon triggers, but mind efficiency
  2. **Radiative W decays**
     (such as $W \to \pi\gamma, D_s\gamma$)

     Currently (Run 3) using W from $\bar{t}t$
  3. **All-hadronic SM boson decays**
     $H \to \phi\phi, W \to \pi\,\pi\,\pi,$

     potentially challenging computationally and latency-wise due to large combinatorics





Physics Case III

Bold = ongoing studies with L1 scouting

- Flavor anomalies, τ physics
  1. Single and multiple τ final states

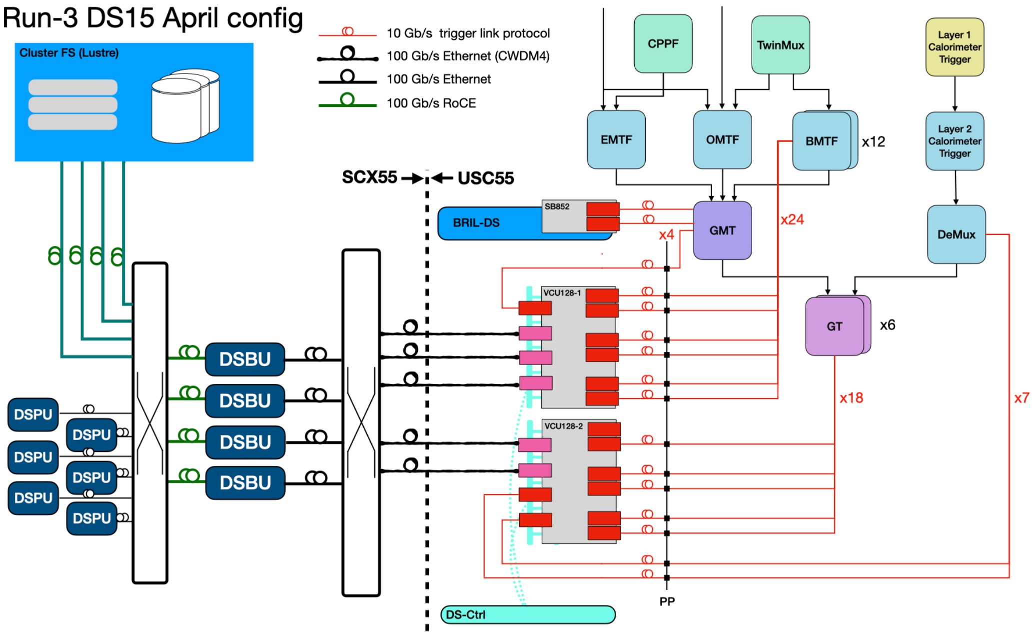
  can benefit from scouting because of notorious difficulties in controlling trigger rate

  2. The $\boldsymbol{B_s \rightarrow \tau\,\tau}$ decay (requiring high efficiency τ selection at low-p_t) – e.g. $\tau \rightarrow 3\,\pi + X$
  3. The decay $\tau \rightarrow 3\,\mu$, where acceptance for low-pt muons (not necessarily fully reconstructed) is key
- Dark sector
- LLP and vLLP, displaced muons and jets
  1. Bridge the gap between small displacement (tracks) and large displacement (standalone objects), for example by **relaxing muon-track matching**
  2. Look for **multi-BX correlation** as a signature of slow charged particles
- **Anomaly Detection** using all available L1 information at the BX rate

A L1DS demonstrator for Run 3

Collect global muon candidates, calorimetric candidates (Jets,e/γ,τ,energy sums), barrel muon stubs, GT bits

Demonstrate the complete chain
L1 → DAQ → online processing → storage
"Orbit" building
Online processing using standard CMS reco/analysis software
Produce standard datasets **for offline analysis**



Uses two VCU128 board
≈ one **DAQ800 board**

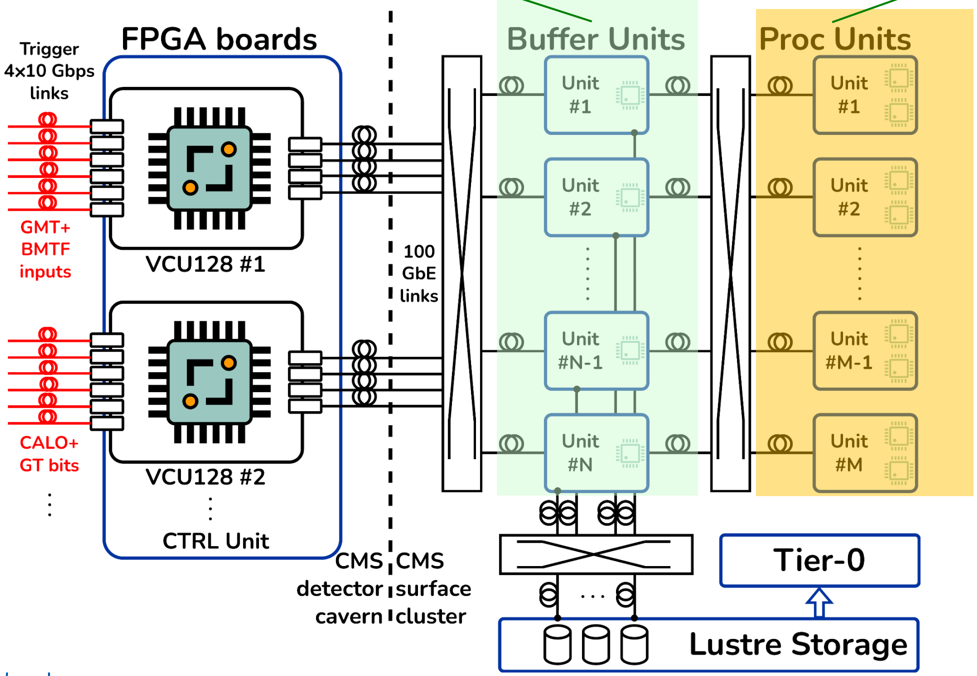
TCP/IP from board into standard network switch @100 Gb/s

Processing+Characterization

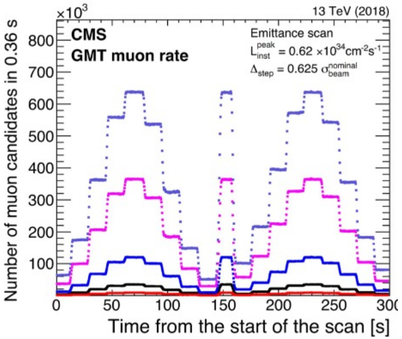
See poster by S. Giorgetti for more details

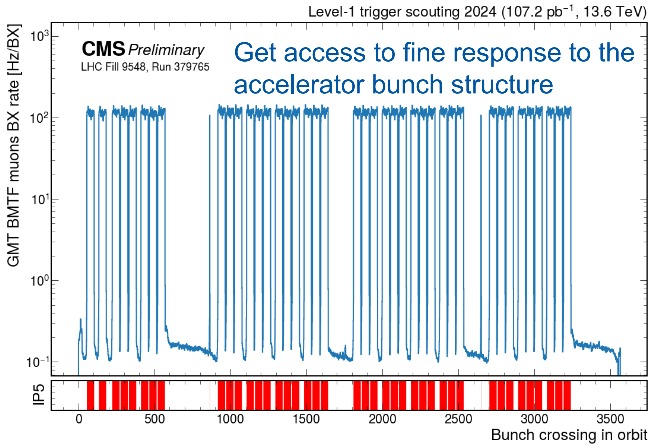
Receive and buffer **streams from multiple links**

Combine buffered streams from same orbit range (orbit building). Run online processing **using CMS** reconstruction and analysis sw



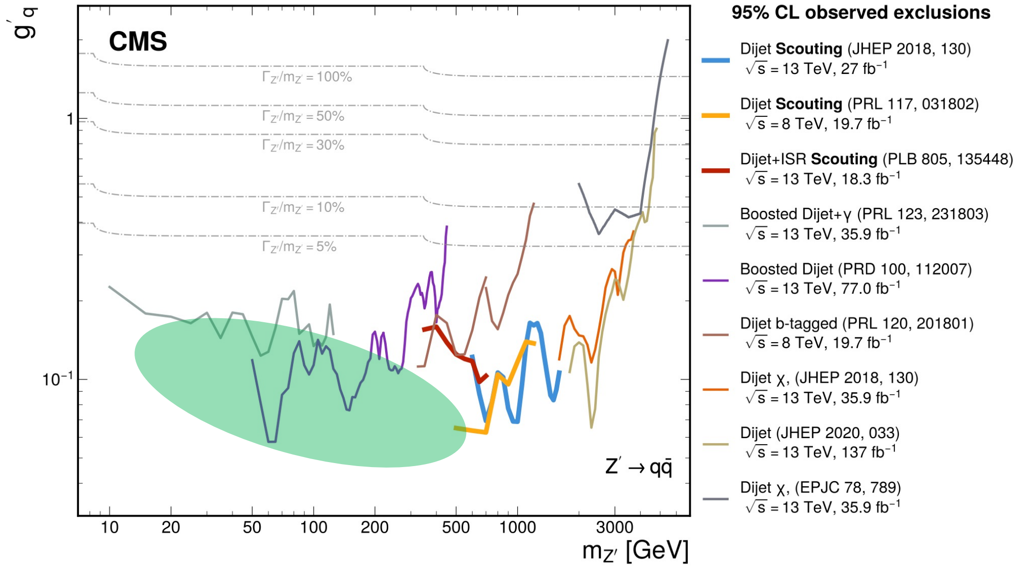
Collect data from every bunch crossing with close to 100% efficiency

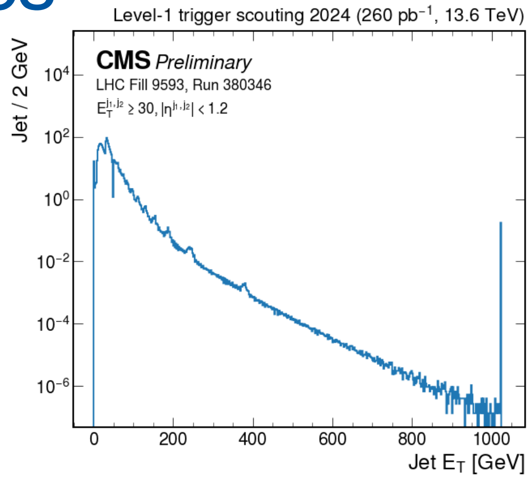


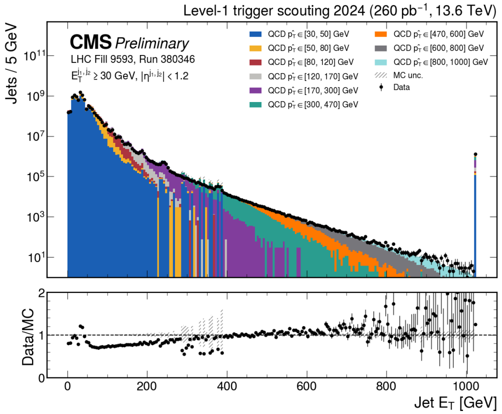


Get access to fine response to the accelerator bunch structure

Run 3 example: soft jet physics







Summary

- L1 Trigger Data Scouting promises to complement the “standard” CMS HL-LHC physics program
- A well-established baseline design – using technology and approach mediated in part from Phase-2 DAQ upgrade
- A wealth of physics cases to study in detail
- Run-3 demonstrator successfully operating since 2023 – an important testing ground
  - Stay tuned for physics results

See also

176. New CMS trigger strategies for the Run 3 of the LHC (earlier in this parallel session)

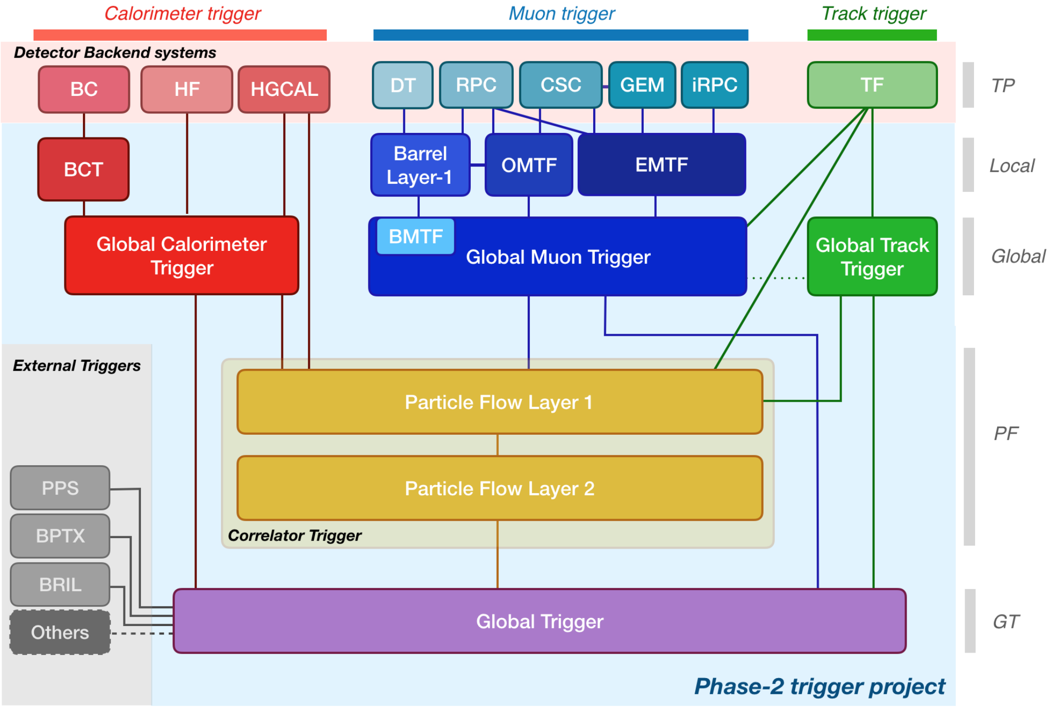
175. Overview of the HL-LHC Upgrade for the CMS Level-1 Trigger (in parallel session 14…now)

754. Performance of CMS Level-1 Trigger Data Scouting during LHC Run 3 (poster session)

Backup

CMS L1 Trigger Phase-2 Upgrade

At HL-LHC: peak instantaneous luminosity 7.5x10^{34} $cm^{-2}s^{-1}$, up to 200 Pile-Up per crossing
Goal of the L1 upgrade: To optimally exploit HL-LHC data and extend sensitivity to new physics



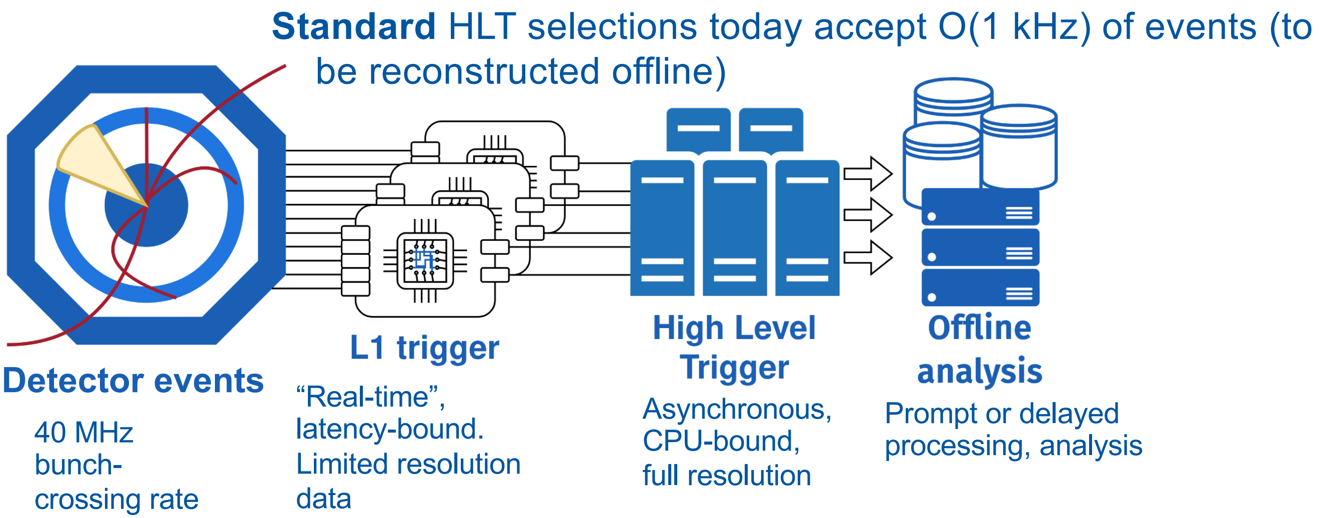
Maintain Run-3 thresholds for all trigger objects in the presence of high pileup
- Use particle-flow approach

Improve capability to efficiently select specific signature e.g.:
- VBF, rare b-meson decays
- exclusive decays
- displaced objects

Expand reach for NP searches e.g.
- low-mass jet resonances
- Anomaly detection

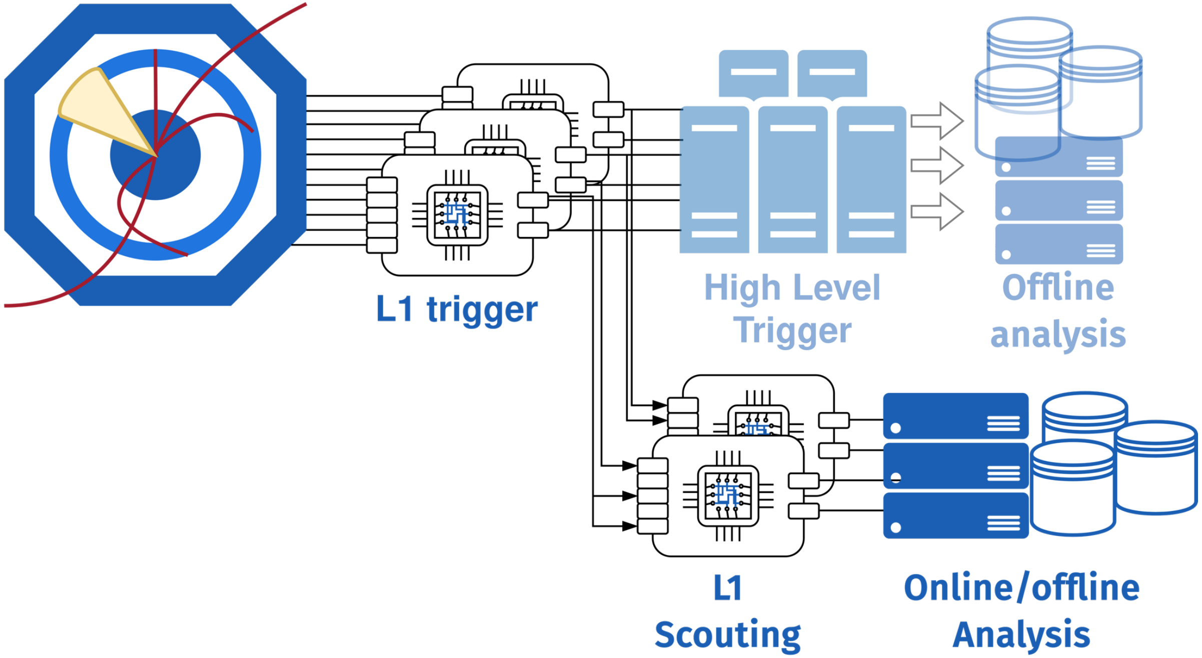
Be ready to trigger the unexpected, e.g.:
- Appearing/disappearing tracks
- Soft unclustered energy
- Slow charged particles

CMS already pioneered alternative data handling strategies



- Data-**parking** exploits additional DAQ b/w and offline storage to collect samples with delayed processing [O(5 kHz) today]
- HLT **scouting** exploits the availability of full-resolution data at HLT to perform online reconstruction, storing only high-level event information ready for analysis, at rates O(30 kHz) today, enabling specific physics studies requiring high rates but compatible with less-than-perfect calibration and reconstruction

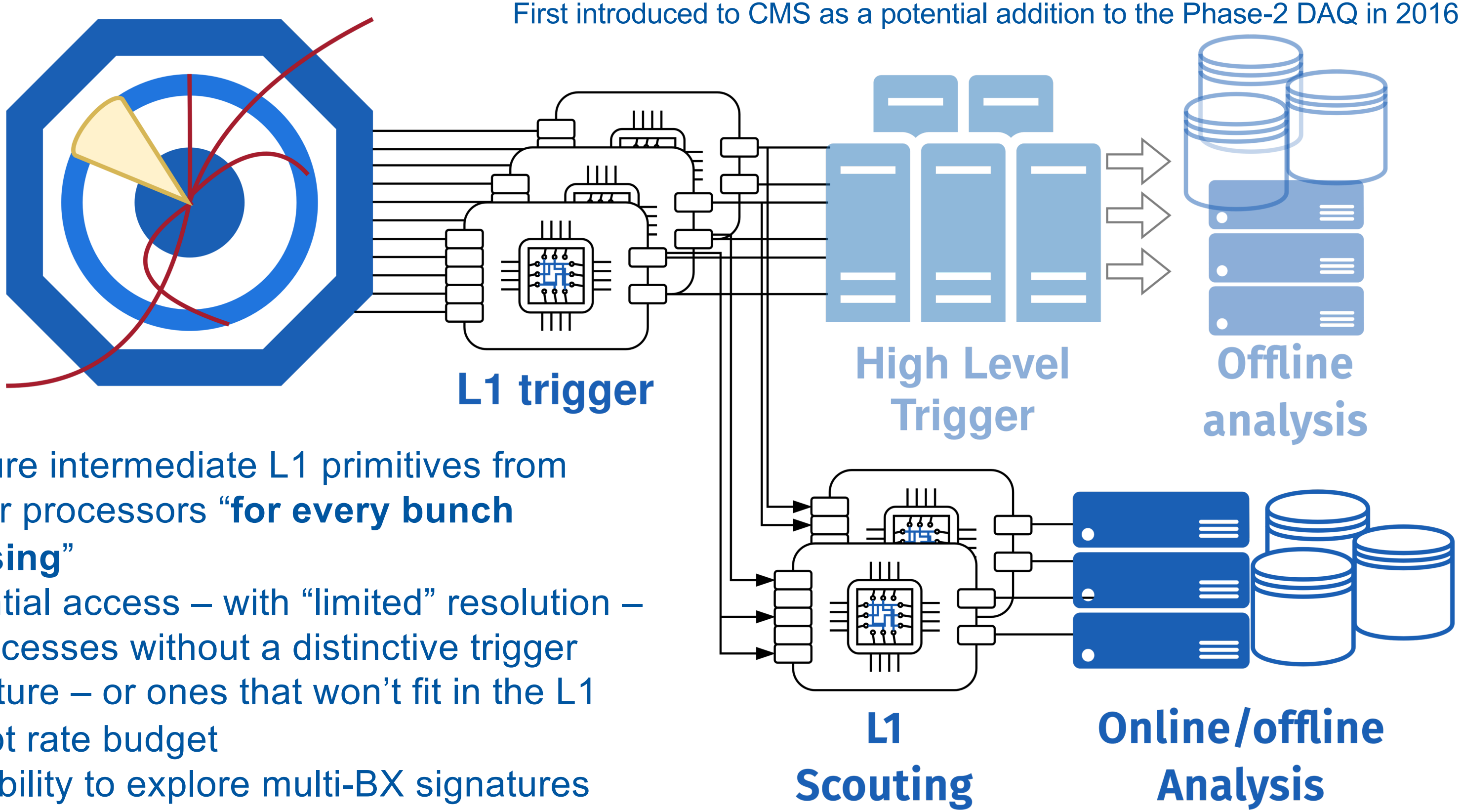
CMS already pioneered alternative data handling strategies



- What with physics that is hampered or severely limited by the **L1 accept budget** or the bias the L1 selection introduces ?
- Level-1 Scouting aims at **removing the last limitation** by giving access to the L1 primitives at the **full bunch-crossing rate**

"40 MHz Scouting" concept

First introduced to CMS as a potential addition to the Phase-2 DAQ in 2016

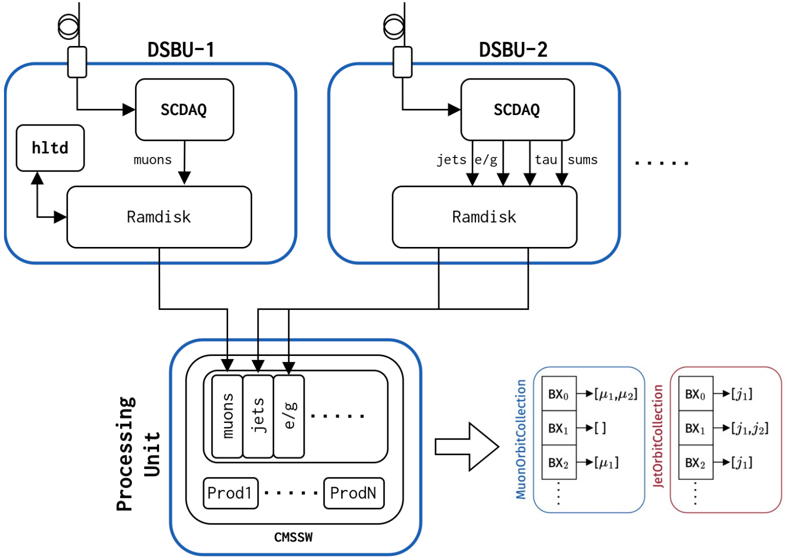


Capture intermediate L1 primitives from trigger processors "**for every bunch crossing**"

Potential access – with "limited" resolution – to processes without a distinctive trigger signature – or ones that won't fit in the L1 accept rate budget

Possibility to explore multi-BX signatures

Formats and datasets



OrbitCollections repacked and stored as “standard” CMS data
(one orbit = one CMSSW event)

GMT x8

Parameter		Range	Step	Bits
Transverse momentum	p_T	[0, 256] GeV	0.5	9
Unconstrained transverse momentum	$p_T^{uncon.}$	[0, 256] GeV	1.0	8
Azimuthal angle	ϕ	2π	$2\pi/576$~0.011	10
Azimuthal angle extrapolated at vertex	ϕ_{ext}	2π	$2\pi/576$~0.011	10
Pseudorapidity	η	[2.45, 2.45]	$0.0870/8 = 0.010875$	9
Pseudorapidity extrapolated at vertex	η_{ext}	[2.45, 2.45]	$0.0870/8 = 0.010875$	9
Charge sign (+ valid)	q	-1, 1		1 (+1)
Quality	Q	[0, 12]	4	4
Impact parameter	d_{XY}	0, 1, 2, 3		2
Isolation bit	iso			2
Track finder index	index	[0, 107]	1	7
Bunch crossing number	BX			32
Orbit counter	OC			32

CALO

object	coll. × inst.	parameter	range	step
jet	1 × 12	E_t η φ DISP quality flags	0..1024 GeV -5..5 2π	0.5 0.0435 ~0.044
e/γ	1 × 12	E_t η φ iso	0..256 GeV -5..5 2π	0.5 0.0435 ~0.044
tau	1 × 12	E_t η φ iso	0..256 GeV -5..5 2π	0.5 0.0435 ~0.044
ET	1 × 1	E_t [ET] E_t [ETTEM]	0..2048 GeV 0..2048 GeV	0.5 0.5
ET$_{miss}$	1 × 1	E_t φ	0..2048 GeV 2π	0.5 ~0.044
HT	1 × 1	E_t [ET]	0..2048 GeV	0.5
HT$_{miss}$	1 × 1	E_t φ	0..2048 GeV 2π	0.5 ~0.044

Phase-2 L1DS Baseline: what

Link count based based on current design of different L1 processors – estimates on

- Links from GT boards
- Links from all sub-systems feeding GT (same number of links go to scouting as to GT): GTT, GCT, GMT, and Correlator Layer 2
- Enough links to collect all PUPPI candidates from Correlator Layer 1 (non zero-suppressed)
- Total of 296 links at 25 Gb/s (nominal input throughput of 7.4 Tb/s)
- Link count is (should be) based on maximum multiplicity (i.e. most fixed-size frames will not be full)
- With some zero suppression in the upstream systems, can capture more: PF, tracks

Source	Links (baseline)	Links (upstream ZS)
GT	12	12
GTT	24	24 + 48 (Tracks ZS)
GCT	6	6
GMT	18	18
CL2	30	30 + 24 (PUPPI ZS)
CL1	216 (PUPPI)	84[*] (PF $\lvert\eta\rvert \leq 3$ ZS)
Total	306	246

Available links with seven DAQ800: 224 full links (no ZS possible) 336 maximum (30% compression required)

[*] rough estimate, more study needed. PF $\lvert\eta\rvert > 3$ would need to come from GCT

Run 3: DT stubs from BMTF

Collect input stubs for barrel muon Drift Tubes (DT) from Barrel Muon Track Finder (BMTF)

Extract **muon parameters** from stubs **using regression**

Use to sharpen unconstrained p_T, impact parameter resolution

E.g. “soft” displaced muon pairs

http://arxiv.org/pdf/1603.08926v1.pdf

Multi-BX

Combine DT stubs **across subsequent BXs**

look into reconstructing “**slow charged objects**” traversing the muon chambers