Next Generation Triggers for CMS

Work Package leaders and Task leaders: WP3

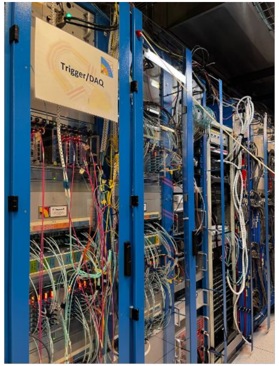
Andrea Bocci (CERN), Cristina Botta (CERN), Silvio Donato (INFN-Pisa), Emilio Meschi (CERN)
Jennifer Ngadiuba (Fermilab), Felice Pantaleo (CERN), Giovanni Petrucciani (CERN),
Marco Rovere (CERN), Sioni Summers (CERN), Thiago Tomei (SPRACE)

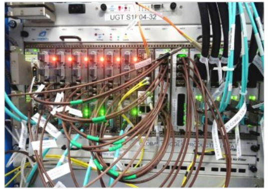
Task leaders and contacts from CMS in WP1, WP4

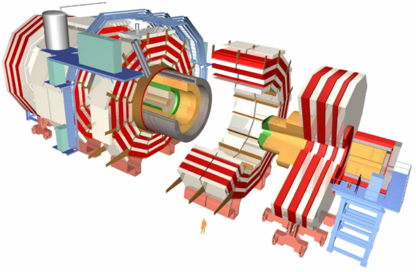
Andrea Bocci (CERN), Maurizio Pierini (CERN), Felice Pantaleo (CERN)

The CMS Trigger system (design)

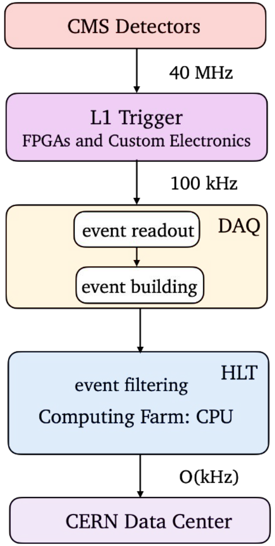
CMS L1 Trigger







CMS High Level Trigger



CMS Detectors

40 MHz

L1 Trigger
FPGAs and Custom Electronics

100 kHz

DAQ
event readout
event building

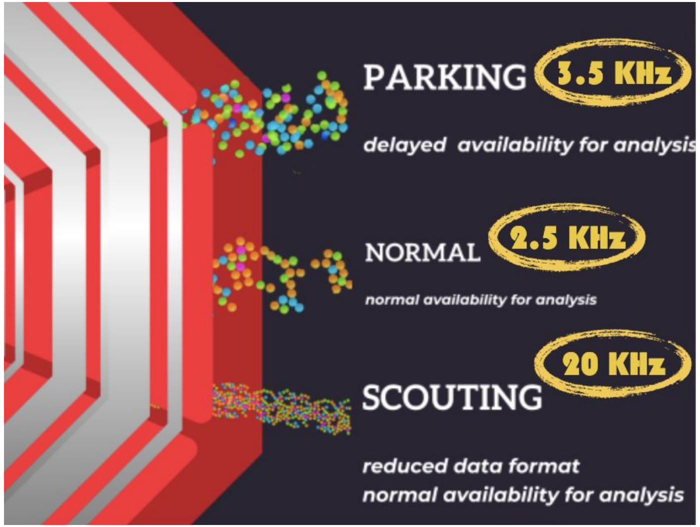
HLT
event filtering
Computing Farm: CPU

O(kHz)

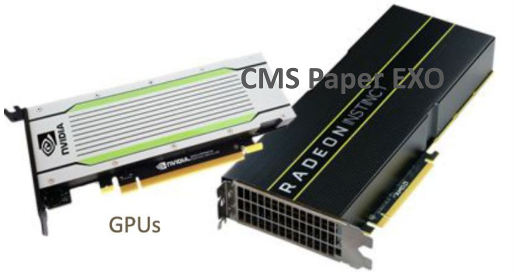
CERN Data Center

- **Perfect compromise between technological limitations and theory motivated New Physics at O(100-1000)GeV scale with ewk-like cross sections**:
  - 99.75% events rejected at L1T, 98% rejected at HLT

The CMS Trigger system (now)

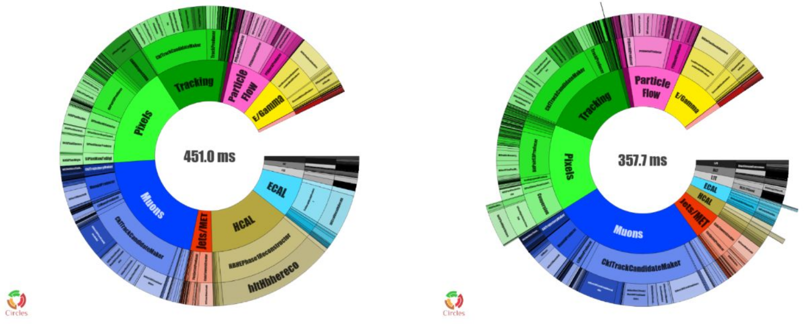

PARKING
3.5 KHz
delayed availability for analysis
NORMAL
2.5 KHz
normal availability for analysis
20 KHz
SCOUTING
reduced data format
normal availability for analysis

- **After Higgs boson discovery and null results of NP searches in Run 1 and 2:**
  - In Run-3 pushed much further the potentialities of the CMS Data Acquisition system with: **Parking**, **HLT Scouting** and **L1T Scouting demonstrator**
  - Enlarged acceptance for **B-physics, VBF, Long-Lived particles, HH production**
  - Thanks to these new ideas & heterogeneous computing at HLT



CMS Paper EXO

GPUs

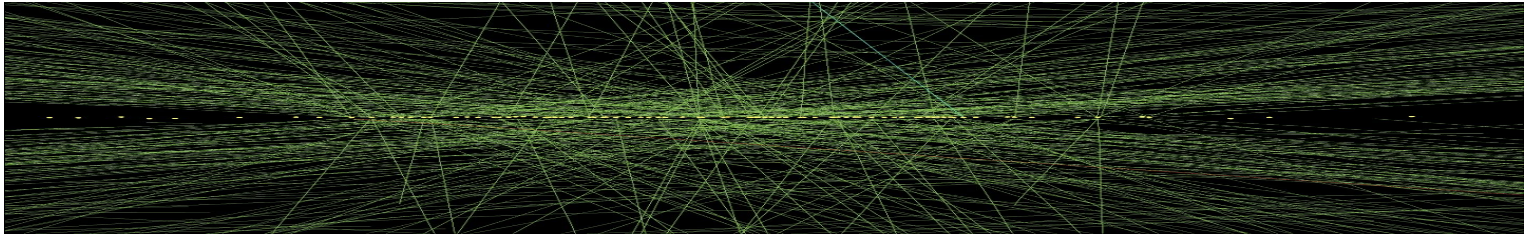


(a) CPU-only

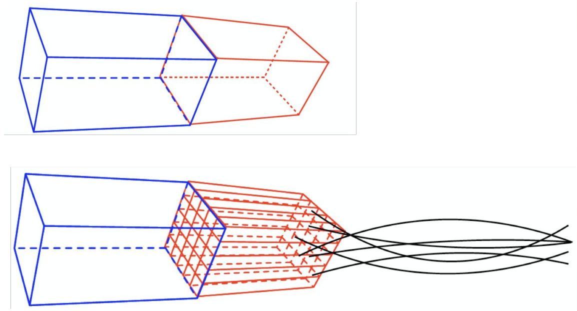
(b) CPU and GPU

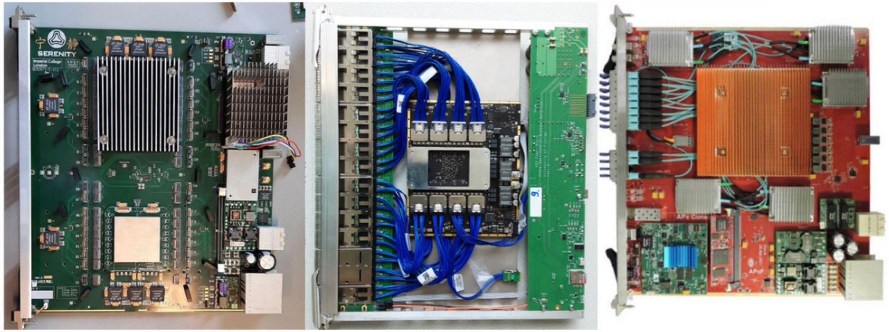
The CMS Trigger for HL-LHC

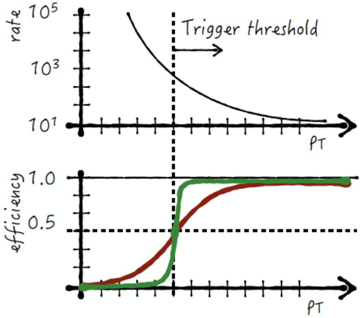
- At HL-LHC, up to 200 pile-up interactions: **CMS is upgrading the L1T and HLT to enable the same physics program we are doing now (at @60 PU)**



New CMS L1 Trigger: input data from 2 Tb/s to 63 Tb/s (~1/10 of the internet traffic), 12.5µs to take decision







Rethinking the CMS Real-Time data processing (with NGT @ HL-LHC)

- **But what if New Physics doesn't look as expected, and it's instead buried under the bulk of the background events we are throwing away due to the trigger selections?**

NexTGen Redesign the data collection and scouting strategy to **reduce the need to reject events in the Level-1 and High-Level CMS triggers** aiming at complementing the current workflows

NexTGen **Replace the trigger filtering task** with an event processing task **similar to what happens with offline** events stored on disk.

NexTGen Leverage traditional physics-based algorithms and **advanced AI solutions**, remove the bottleneck currently implied by the real-time event selection and **extend CMS discovery and precision measurement reach**.

NGT Implementation in CMS

WP leaders, L1T/HLT/O&C/ML coordination, Spokesperson and CERN Team leader oversee the implementation in CMS (CMS Steering committee)

WP3 Tasks and Task Leaders

1.1 R^3 Faster Reconstruction for HLT
M. Rovere (CERN)

1.2 Optimized data structures for HLT
F. Pantaleo (CERN)

2. Towards a distributed HLT architecture
A. Bocci (CERN)

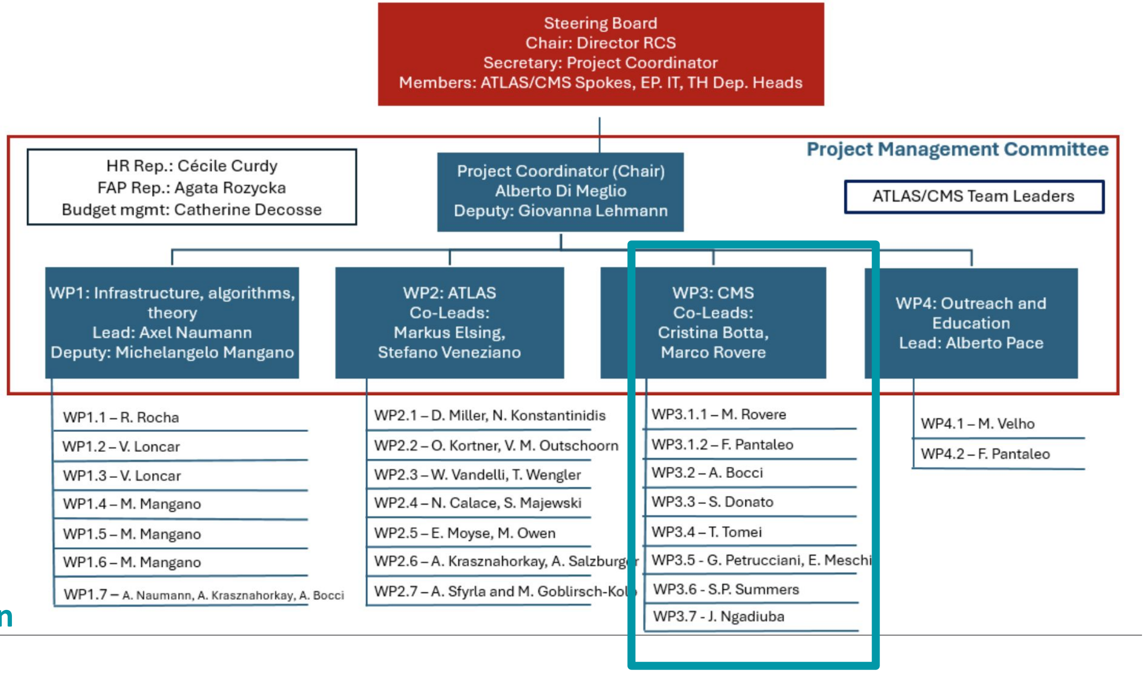
3. Reduction of the RAW data size for HLT
S. Donato (INFN-Pisa)

4. Optimal calibrations for HLT
T. Tomei (SPRACE)

5. Enhancing L1T Scouting for HL-LHC
G. Petrucciani (CERN), E. Meschi (CERN)

6. Practical real-time AI for L1T
S.P. Summers (CERN)

7. L1T anomaly detection & data compression
J. Ngadiuba (FERMILAB)



Steering Board
Chair: Director RCS
Secretary: Project Coordinator
Members: ATLAS/CMS Spokes, EP. IT, TH Dep. Heads

Project Management Committee

HR Rep.: Cécile Curdy
FAP Rep.: Agata Rozycka
Budget mgmt: Catherine Decosse

Project Coordinator (Chair)
Alberto Di Meglio
Deputy: Giovanna Lehmann

ATLAS/CMS Team Leaders

WP1: Infrastructure, algorithms, theory
Lead: Axel Naumann
Deputy: Michelangelo Mangano

WP2: ATLAS
Co-Leads:
Markus Elsing,
Stefano Veneziano

WP3: CMS
Co-Leads:
Cristina Botta,
Marco Rovere

WP4: Outreach and Education
Lead: Alberto Pace

WP1.1 – R. Rocha
WP1.2 – V. Loncar
WP1.3 – V. Loncar
WP1.4 – M. Mangano
WP1.5 – M. Mangano
WP1.6 – M. Mangano
WP1.7 – A. Naumann, A. Krasznahorkay, A. Bocci

WP2.1 – D. Miller, N. Konstantinidis
WP2.2 – O. Kortner, V. M. Outschoorn
WP2.3 – W. Vandelli, T. Wengler
WP2.4 – N. Calace, S. Majewski
WP2.5 – E. Moyse, M. Owen
WP2.6 – A. Krasznahorkay, A. Salzburger
WP2.7 – A. Sfyrla and M. Goblirsch-Kol

WP3.1.1 – M. Rovere
WP3.1.2 – F. Pantaleo
WP3.2 – A. Bocci
WP3.3 – S. Donato
WP3.4 – T. Tomei
WP3.5 - G. Petrucciani, E. Meschi
WP3.6 - S.P. Summers
WP3.7 - J. Ngadiuba

WP4.1 – M. Velho
WP4.2 – F. Pantaleo

Participation of CMS also in WP1 and WP4 with M. Pierini (CERN) as CMS contact, A. Bocci (CERN), F. Pantaleo (CERN

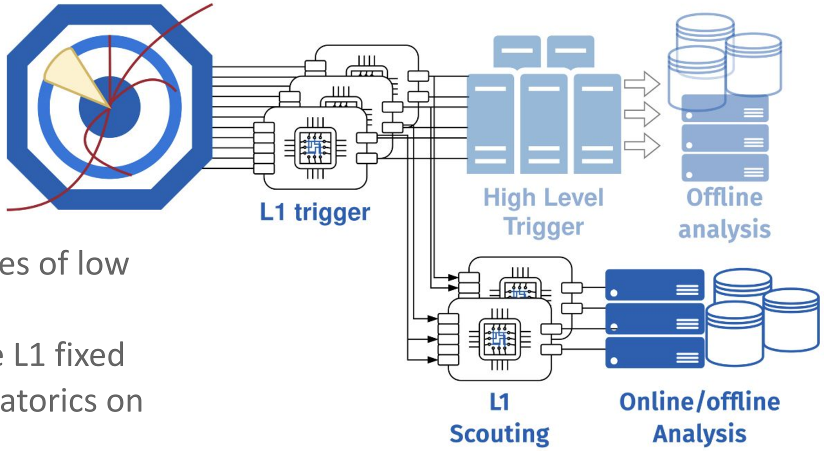
NexTGen
Next Generation Triggers

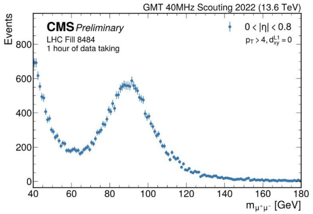
NGT @ L1T

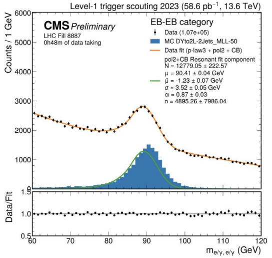
Cristina Botta (CERN), Emilio Meschi (CERN)
Jennifer Ngadiuba (Fermilab), Giovanni Petrucciani (CERN),
Sioni Summers (CERN)

3.5: Enhancing L1T Scouting for HL-LHC

- L1T Data Scouting: **acquire and analyse the L1 Trigger information for all events (at 40 MHz)**
- Look for physics signatures identifiable with **just L1 information** but that would evade the L1T → HLT → Offline chain, e.g.:
  - Too large “irreducible” backgrounds, e.g. narrow resonances of low and unknown mass
  - Signal identification requires an algorithm that can’t fit the L1 fixed latency and resource budget, e.g. has too complex combinatorics on some events
- FPGA-equipped boards that receive L1 data via optical links and transfer it to PCs and the software world via TCP/IP or PCI express
- at HL-LHC: can profit from much improved L1T object reconstruction quality
  - L1 Tracker Tracks, Particle-flow linking, Pile-up per particle identification..
  - Demonstrated already in 2018 (muons), Run 3 (muons + calo)





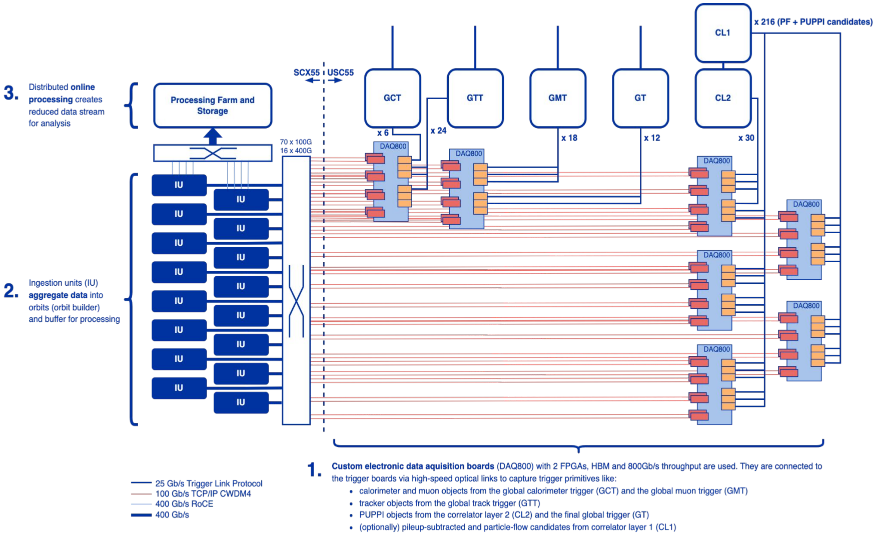


ICHEP's talk by Emilio

Run3 L1T Scouting demonstrator

3.5: Enhancing L1T Scouting for HL-LHC

- **Goal of this project:** explore the physics opportunities and technical feasibility using **different L1 inputs with respect to TDR baseline and R&D to investigate different implementations**



3. Distributed **online processing** creates reduced data stream for analysis

2. Ingestion units (IU) **aggregate data** into orbits (orbit builder) and buffer for processing

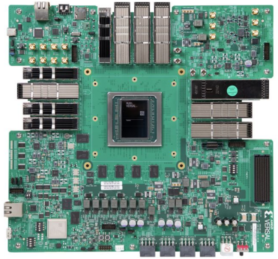
1. **Custom electronic data aquisition boards** (DAQ800) with 2 FPGAs, HBM and 800Gb/s throughput are used. They are connected to the trigger boards via high-speed optical links to capture trigger primitives like:
   - calorimeter and muon objects from the global calorimeter trigger (GCT) and the global muon trigger (GMT)
   - tracker objects from the global track trigger (GTT)
   - PUPPI objects from the correlator layer 2 (CL2) and the final global trigger (GT)
   - (optionally) pileup-subtracted and particle-flow candidates from correlator layer 1 (CL1)

ICHEP's talk by Emilio
L1T Scouting
baseline for HL-LHC

- How: investigate **different prototype analyses of increasing complexity** in terms of data processing and bandwidth:
  - from dilepton resonances to soft hadronic final states with NN, GNN taggers, multi-BX signatures
  - ML algorithms for soft objects (e/ɣ/jet) reconstruction & tagging
- How: incrementally build a **test system of increasing bandwidth & processing power** to run the benchmark analyses
  - investigate running algorithms on CPU / GPU / FPGA / AI engines
  - investigate different approaches for data acquisition from DAQ board: protocols (e.g. TCP/IP vs RoCE vs direct fpga-fpga links), networking (e.g. NICs vs accelerator cards or converged NIC+GPU), workflows (HLT-like, analysis-like, kafka,..)
  - prototype a Scouting DAQ board with newer technology (Large Versal HBM chips?) to have more links on the same FPGA and more on-board resources to allow more data aggregation and pre-processing for Scouting

3.5: Enhancing L1T Scouting for HL-LHC

- **On going:** some analyses defined and exploration started for some
  - Exclusive rare decays: $\mathbf{W \to 3\pi}$, $\mathbf{W \to D_s\,\gamma \to KK\pi\,\gamma}$, $\mathbf{W \to \pi\,\gamma}$, $\mathbf{H \to \phi\phi \to 4K}$, $\mathbf{B_s \to \tau\tau}$. **Multiple soft objects** inspired from arXiv:1902.05535 (new scalars with long decay chains). **Resonances in** $\boldsymbol{\mu\mu}$ (in progress), $\mathbf{ee}$, $\boldsymbol{\gamma\gamma}$, $\boldsymbol{\tau\tau}$ (students identified)
- **On going:** procurement of hardware in good shape and work on firmware & software for demonstrator system in in B40 DAQ Lab started
  - Representative algorithms are being tested on different architectured and benchmarked on the available hardware



Versal Premium Series VPK180 Evaluation Kit

Versal HBM Series VHK158 Evaluation Kit

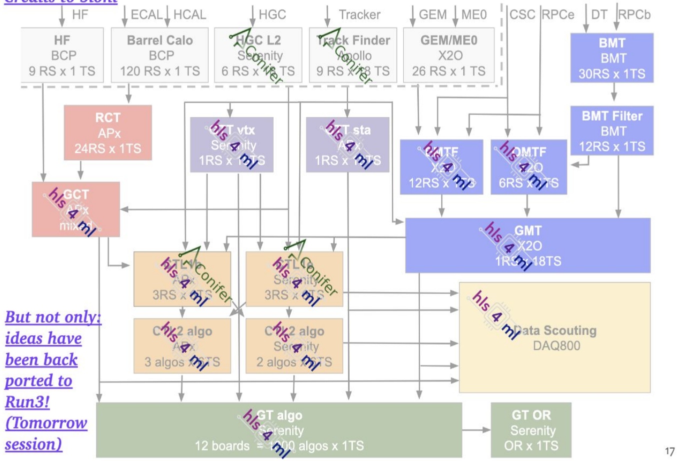
- **NGT team so far: Cristina Botta, Valentina Camagni, Gianluca Cerminara, Emilio Meschi, Łukasz Michalski, Matteo Migliorini, Giovanni Petrucciani, Leah-Louisa Sieder**

3.6: Practical real-time AI for L1T/Scouting

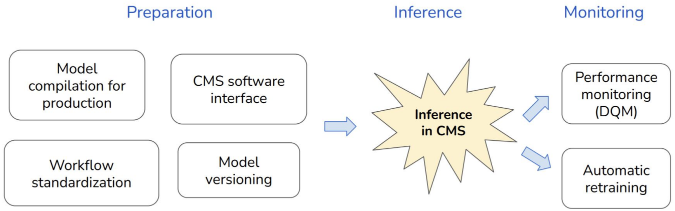
- Develop and operate advanced and fast **ML algorithms for improving the L1T reconstruction (used by standard triggers, and L1 Scouting)**
  - Into FPGAs of **Global Trigger, Correlator and Global Track Trigger subsystems**
  - This is already happening, but the project will **boost it** profiting from experience on advanced ML methods
- Develop practices for training & deployment of ML algorithms in L1T **(MLOps)**
  - updating & redeploying algorithms for changes in detector conditions
  - tracking, archiving & retrieving ML models (e.g. for consistent emulation)
  - gain experience from Run3 Global Trigger and develop for HL-LHC
- Develop **setup for complex trainings of multiple algorithms**
  - e.g. simultaneously optimize algorithms for particle ID, object reconstruction, and event selection (implemented in different subsystems, only limited amount of information is propagated between subsystems)

From CMS ML@L1T workshop

Credits to Sioni



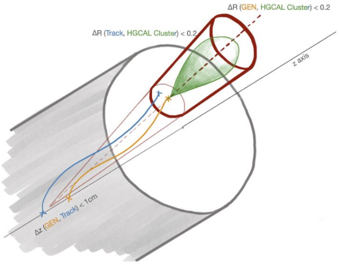
But not only: ideas have been back ported to Run3! (Tomorrow session)

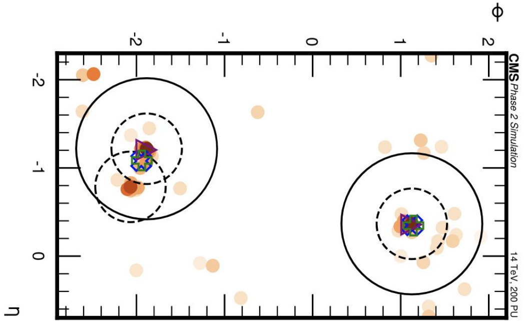


Nice talk from Dylan on Edge ML at on-going SMARTHEP School

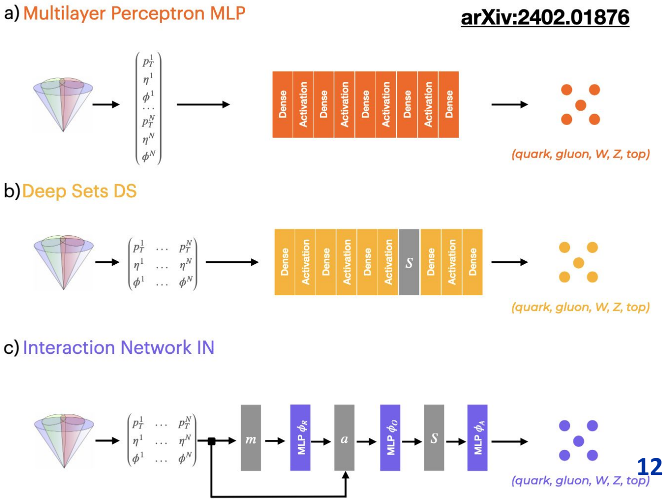
3.6: Practical real-time AI for L1T/Scouting

- **On going:** improving baseline algorithms to expand baseline acceptance
    - Multiclass discriminator to improve and harmonize IDs for e/γ, pions, pile-up separation for PF reconstruction: **goal increase efficiency at low pT for e/γ and missing energy reconstruction**
    - Multi-class jet taggers **to improve current b and tau tagging**
- **On going:** develop prototype MLOps training and model tracking for correlator ML algorithms
    - Gaining experience with Run-3 (Anomaly Detection models recently deployed)
- **NGT team so far:** **Cristina Botta, Chris Brown, Gianluca Cerminara, Duc Hoang, Leon Joel Kerner, Kyungmin Park, Stella Scheafer, Sioni Summers**


ΔR (GEN, HGCAL Cluster) < 0.2
ΔR (Track, HGCAL Cluster) < 0.2
z axis
Δz (GEN, Track) < 1cm

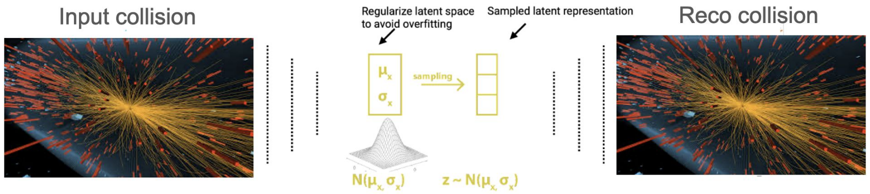


arXiv:2402.01876

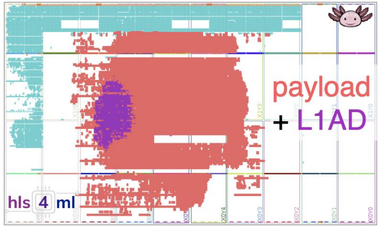

a) Multilayer Perceptron MLP
Dense
Activation
(quark, gluon, W, Z, top)
b) Deep Sets DS
S
c) Interaction Network IN
m
MLP ϕR
a
MLP ϕO
MLP ϕA

3.7: L1T Anomaly Detection and Data Compression

- **Another way:** trigger on “anomalous” events using ML unsupervised models (sub-µs autoencoders!)
  - CMS recently established a **new trigger paradigm with sub-µs autoencoders** for anomaly detection (**[Abhijith’s talk at ICHEP](#)): AXOL1TL deployed in L1T Global Trigger**


Input collision
Regularize latent space to avoid overfitting
Sampled latent representation
Reco collision
μ_x
σ_x
sampling
$N(\mu_x, \sigma_x)$
$z \sim N(\mu_x, \sigma_x)$

$$\text{loss} = ||x - \hat{x}||^2 + \text{KL}[\,N(\mu_x, \sigma_x), N(0, I)\,]$$

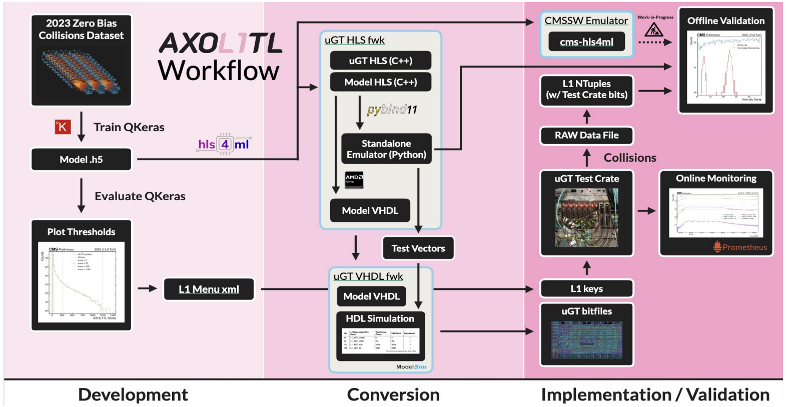


CMS-DP-2023-079

- **Next: Commissioning and validation of the Run 3 unsupervised AD algorithms**
  - Learn end-to-end algo integration and system operations
  - Optimize the model to be more robust against conditions (e.g. pileup)
- **Next: Demonstrate end-to-end physics analysis using unsupervised anomaly detection on Run 3 data**
  - Develop innovative methods for the analysis of anomalous data: a) seed/enhance supervised searches with the new AD algo and b) use new methods (e.g. active learning or clustering) to inform what to search next
- **Next: Develop new AD model suited for HL-LHC L1 trigger system using TPs/particle-based info**
  - Design an innovative GNN-based autoencoder for low latency and resources which will serve as baseline AD at HL-LHC
- **Next: Develop intelligent data compression and/or reduction for L1 Scouting system (to allow long-term storage of more scouting data)**

3.7: L1T Anomaly Detection and Data Compression

- **On going:** full training-to-deployment workflow has large number of steps
  - Model versioning, rate stability monitoring …
  - **CMSSW-hls4ml emulator workflow established to be followed by every future NN!**
- **On going:** improving baseline: more robust against PU and other system changes to make it usable for physics searches


AXOL1TL Workflow

2023 Zero Bias Collisions Dataset

Train QKeras

Model .h5

Evaluate QKeras

Plot Thresholds

L1 Menu xml

hls4ml

uGT HLS fwk

uGT HLS (C++)

Model HLS (C++)

pybind11

Standalone Emulator (Python)

Model VHDL

Test Vectors

uGT VHDL fwk

Model VHDL

HDL Simulation

ModelSim

CMSSW Emulator

cms-hls4ml

Work-in-Progress

Offline Validation

L1 NTuples (w/ Test Crate bits)

RAW Data File

Collisions

uGT Test Crate

Online Monitoring

Prometheus

L1 keys

uGT bitfiles

Development

Conversion

Implementation / Validation

- **NGT team so far:** Diptarko Choudhury, Sabrina Giorgetti, Maciej Glowacki, Eric Moreno, Jennifer Ngadiuba, Sioni Summers

NexTGen
Next Generation Triggers

CMS

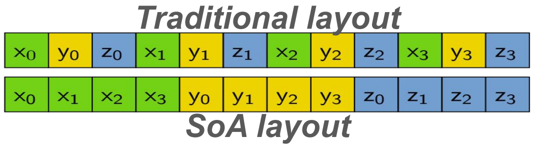
CERN

NGT @ HLT

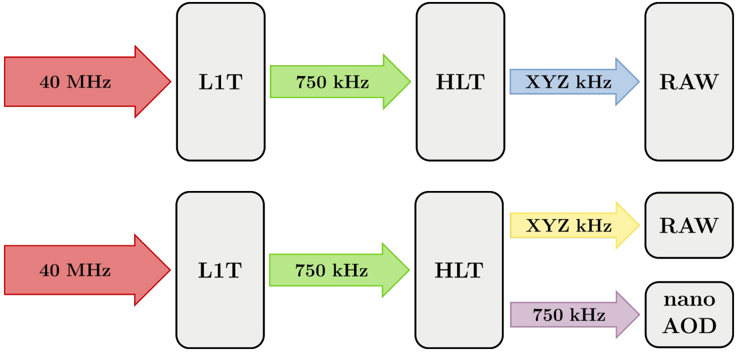
Andrea Bocci (CERN), Silvio Donato (INFN-Pisa), Felice Pantaleo (CERN),
Marco Rovere (CERN), Thiago Tomei (SPRACE)

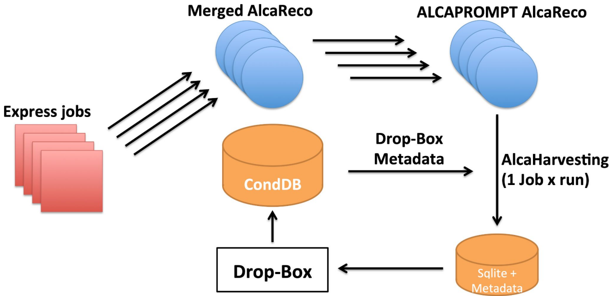
R^3 Has ambitious goals

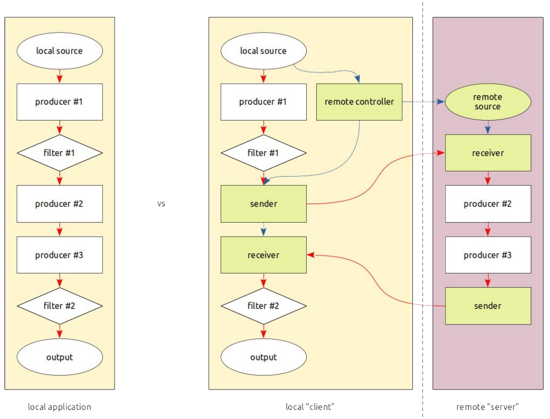
- R^3 aims to transform the HLT event reconstruction by developing a suite of algorithms that rethink the process entirely, rather than just speeding up existing ones. Depending on the level of speed-up required, innovative approaches will be applied as needed to meet live physics analysis requirements. Key efforts include optimizing data structures for accelerators like GPUs, redesigning CMSSW as a distributed application with minimal code impact, and leveraging high-speed interconnects to reduce latency.
- R^3 will also reduce disk usage by compressing or simplifying data, and compute necessary conditions at HLT to match offline reconstruction quality, ensuring high physics performance with minimal disk space.



Traditional layout
x0 y0 z0 x1 y1 z1 x2 y2 z2 x3 y3 z3
x0 x1 x2 x3 y0 y1 y2 y3 z0 z1 z2 z3
SoA layout

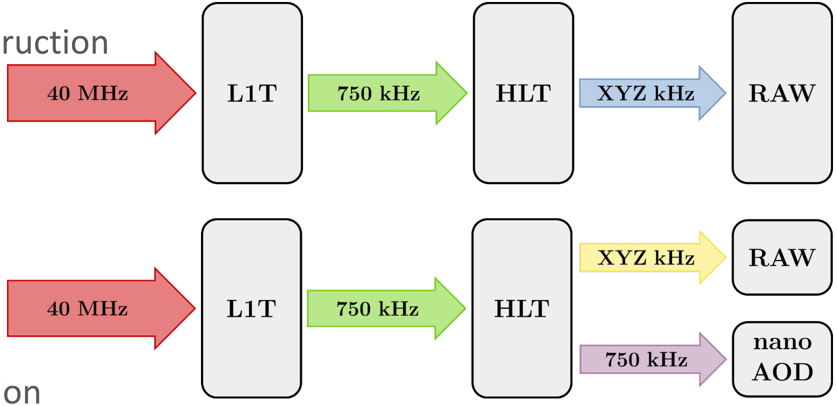






Task 3.1.1: R³ Faster Reconstruction (*task leader M. Rovere*)

- The successful **Patatrack experience** in CMS has shown that it is possible to **improve the physics quality and reconstruction throughput of selected physics objects (pixel tracks) by leveraging heterogeneous architectures**
- This required ~4 years of development to:
  - Study the performance of the current algorithm and identify bottlenecks
  - **Rethink the algorithms** and **data structures** targeting heterogeneous architectures
  - Develop, integrate and validate the results in CMSSW
  - Propagate the new objects to the rest of the reconstruction
- The R³ project will use a similar approach to **redesign the most important physics objects**:
  - Muons
  - Electrons and photons
  - Taus
  - Jets, MET and Particle Flow Global Event interpretation
- **Perform offline-like full event reconstruction, in addition to the traditional event selection**



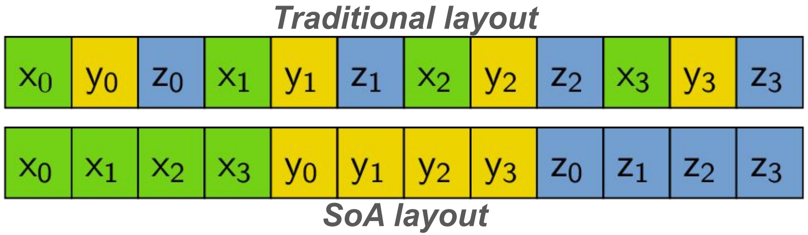
Task 3.1.1: R^3 Faster Reconstruction (*task leader M. Rovere*)

- **Ongoing**:
  - Start a systematic investigation of the reconstruction performance in different scenarios:
    1. HLT Phase2 reconstruction
    2. Offline Phase2 reconstruction
    3. Run3 Offline reconstruction
  - Critically compare the 3 scenarios, understand the differences between them, highlight the bottlenecks
  - The outcomes of this study will be the backbone of the EOY report
  - All measurements and considerations are available at this link
  - Start investigating the current status of the Monte Carlo truth information at large in CMS
    1. This is in view of the work scheduled for next year, 2025.

- **Team so far**: Marco Rovere, Jan Gerrit Schulz, Luca Ferragina, Marco Musich, Davide Valsecchi

Task 3.1.2: Optimized data structures (*task leader F. Pantaleo*)

- The development of **data-oriented structures** (“Structure of Arrays”, SoA for short) **will be fundamental for R³ to reach its goal**.
  - achieve better memory bandwidth and vectorization performance
  - provide a seamless interface to AI algorithms



Traditional layout

x_0	y_0	z_0	x_1	y_1	z_1	x_2	y_2	z_2	x_3	y_3	z_3
x_0	x_1	x_2	x_3	y_0	y_1	y_2	y_3	z_0	z_1	z_2	z_3

SoA layout

- Their adoption in the HEP software stack requires the development of a user-friendly, **generic SoA implementation**.
- To achieve the best performance running real-time reconstruction, the I/O subsystem of the CMS framework should be extended to leverage **direct data transfers** between the **network and storage** subsystems on one side, and the **accelerators** on the other, bypassing the host CPU.

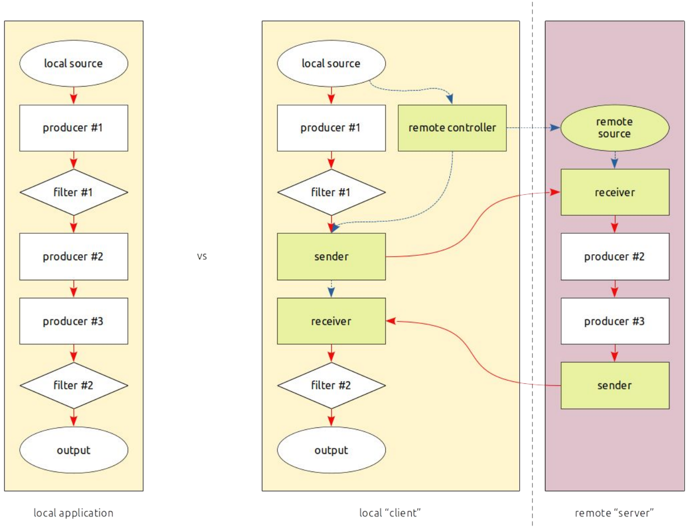
- **Ongoing**:
  - Discussion with CMSSW FW Core team ongoing
  - More details discussed during a dedicated meeting
  - Establishing a small test bench for demonstrating different prototypes

- **Team so far**: Felice Pantaleo, Leonardo Beltrame

Task 3.2: Evolving the CMSSW into a distributed application (*task leader A. Bocci*)

- The main goal is to **achieve more flexibility in the design of the HLT farm for Phase-2**:
  - independently *scale the amount of CPU and GPU processing power*;
  - support *different kind of accelerators*, like GPUs and FPGAs.

- The plan is to ***extend CMSSW to a fully distributed application***, based on a loose set of requirements:
  - to support *arbitrary CMSSW configurations*
  - to *minimise the impact* and maintenance on the framework and reconstruction code:
    - → leverage the portability libraries and microarchitecture features
    - → do not rewrite the reconstruction code, or move it out of CMSSW
  - to *minimise inter-process traffic*:
    - → schedule entire sequences and tasks on a remote node
  - to *minimise latency* and overhead:
    - → leverage high speed, efficient interconnects
    - → RDMA protocols like InfiniBand and RoCE for direct network-to-memory and network-to-GPU copies

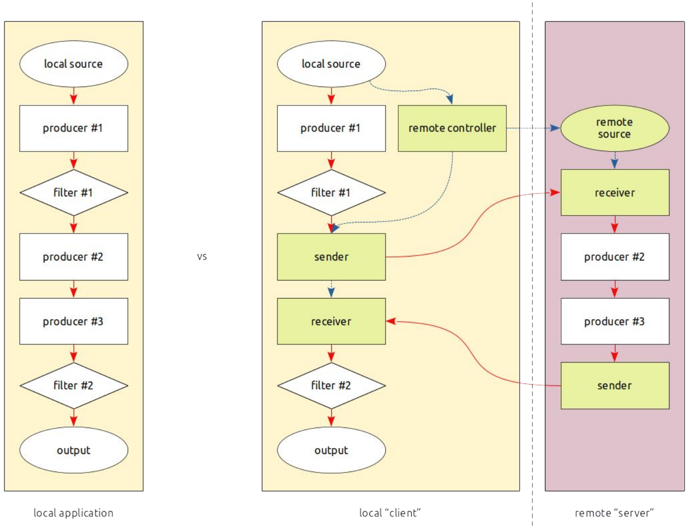


Task 3.2: Evolving the CMSSW into a distributed application (*task leader A. Bocci*)

- The approach being considered to minimise the impact and maintenance burden is to leverage the Event-based interface of CMSSW:
  - wrap all communications in a small number of modules (a controller, a source, a sender, a receiver);
  - use the rest of CMSSW unchanged;
  - automatically support all kind of modules (legacy, alpaka-based, ML-based, …) that can run in CMSSW.
- The implementation of a client-server prototype is **in progress**.

- **Personpower**:
  - hiring of a doctoral student is in progress
  - continue the collaboration with non-CERN experts

- **Team so far**: Andrea Bocci, Fawaz Alazemi



Task 3.3: Reduction of the RAW data size for HLT (*task leader S. Donato*)

- A **limiting factor** in the amount of data that the HLT can select for offline storage and further processing is the **size of the RAW events**.

- Characterize multiple approaches to the **compression of RAW data**, with different trade-offs between the compression factor, latency, available hardware and impact on the final physics result.
  - lossless compression on accelerators
  - lossy compression algorithms
  - physics-driven compression, replacing basic information with higher-level quantities
    - build upon the work done by the Heavy Ions group
    - leverage prompt-reconstruction-level calibrations to reduce the physics impact

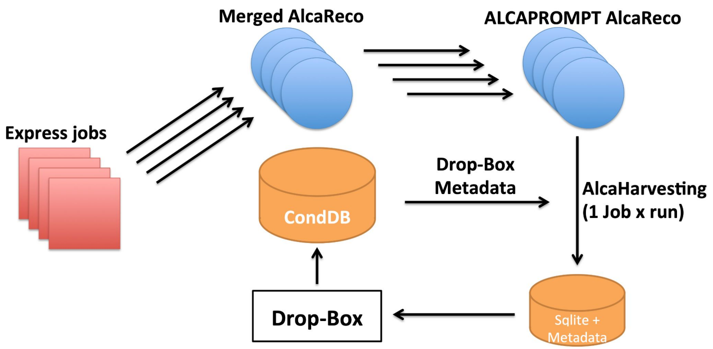
- reducing the RAW size:
  - increase the rate of full RAW data collected by the HLT
  - leave more space for the scouting data
  - reuse offline the high-level quantities reconstructed online

- **Ongoing**: evaluate the impact of RAW data compression and of their replacement with low-level reconstructed quantities (RAW') in view of the EOY report
- **Team so far**: Silvio Donato, Simone Rossi Tisbeni

Task 3.4: Optimal Calibration at HLT (*task leader T. Tomei*)

- Current status in Run 3:
  - Prompt offline reconstruction done with **Prompt Calibration Loop** (PCL) calibrations
  - Calibrations for HLT reconstructions run on different schedules instead (weekly, per-fill, …)
- Reminder of **Prompt Calibration Loop** (PCL):
  - Express stream (100 Hz) ⟶ calibration ⟶ prompt RECO of the run
  - Time window: 48h
  - Workflows:
    - Beamspot
    - SiPixel: bad components, alignment, Lorentz Angle
    - SiStrip: bad components, efficiency, gains
    - ECAL: pedestals
    - PPS: alignment, offset, timing

Run 3 PCL



- **Small-scale prototype at the HLT**, explore tradeoffs:
  - Buffer RAW data for *N* hours ⟶ Latency vs. how much data to hold
  - Derive improved calibrations ⟶ Express rate vs. latency vs. accuracy
  - Inject and use them for online reconstruction of HLT scouting

Task 3.4: Optimal Calibration at HLT (*task leader T. Tomei*)

- **Ongoing**:
  - documenting all the alignment and calibration workflows in CMS and trying to ascertain the more important ones, to focus on them.
    - ECAL and Tracker already addressed/ongoing
    - HCAL, Muons, and all Physics Objects will follow

- **Team so far**: Thiago Tomei, Mateuzs Zaruki, Jessica Prendi, Marco Musich

NexTGen
Next Generation Triggers

CMS

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Welcome to the CMS NGT team!

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