Online reconstruction and Trigger

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Introduction

- The reconstruction of raw detector data and its processing in real time represents a **major challenge in HEP**

- **Demands for higher throughputs in upcoming years**

  - Two demands for Trigger:
    - Decrease throughput to backend DAQ
    - Keep trigger efficiency high
  
  - Two trends:
    - Triggerless/continuous readout (ALICE-LHCb)
    - Higher-level reconstruction in hardware trigger (ATLAS-CMS)

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**Disclaimer**

This presentation is in no way an exhaustive view of all LHC experiments trigger systems, rather a selection of some topic biased from my view
The ATLAS Run 3 trigger

Trigger system consists of Level-1 (hardware) and High Level Trigger (software):
- reduce data rate from \(\sim 40\) MHz to \(O(1\) kHz\)
- **L1 improvements**: data from calorimeters and muon detectors processed by dedicated trigger systems with expected improved efficiency
  - L0Calo and L0Muon
- Highly selective triggering with strong channel dependence (\(~50\%\) central Z → ee, \(~50\%\) central HH→4b)
- High trigger thresholds for hadronic jets → focus on new physics at high masses
- Online reconstructs partial or full event to offline-like quality
- CPU and readout limited at high beam intensities
- HLT software framework fully redesigned to be **multi-threaded compliant**
- No accelerated computing for Run 3, but lots of R&D for HL-LHC.

Courtesy of M. Amerl
The ATLAS HLT improvements

- **Inner Detector Trigger MinBias tracking** in 900GeV collisions
  - The 4(6)GeV track-triggers have an unbiased tracking spectra below 4(6)GeV & very high efficiency

- Improvements to the **offline large radius tracking (LRT)** allow it to be used online in the trigger to target signatures with long lived particles
  - LRT outperforms standard tracking decision

- **Improved jet and b-jet performance**
  - b-jet efficiency of the new DIPS and DL1d algorithms outperforms the benchmark DL1r algorithm
  - Improved GN1 tagger [see poster by M. Chen]
The CMS Run 3 trigger

Two level triggering system to reduce the rate to a manageable level
• L1 (< 100 kHz): large effort to develop new seed features, algorithms, and triggers to target LLP signatures and rare signals
• HLT (~ 1 kHz)
  • **New tracking** based on the optimized pixel track (= Patatrack) reconstruction
    • it allows to reduce the HLT tracking to a single-iteration approach
  • **Improved tagging** capabilities of low-level calorimeter objects + new L2 τ reconstruction using pixel tracks
  • **New muon reconstruction** and ML-based inside-out and outside-in seeding
  • **Improved performance of jets** reconstructed with Patatrack pixel tracks as inputs to the Particle Flow (PF) algorithm

All performance available at CMS HLT Tracking Results

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**CMS Simulation Preliminary** $\sqrt{s} = 14$ TeV

1.3 < $|\eta| < 2.4$

- HLT Run2 Tracking
- HLT Patatrack pixel tracks (tight criteria)
- HLT Patatrack pixel tracks (loose criteria)

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**CMS-DP-2022-030**

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**CMS-DP-2022-014**

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**CMS-DP-2021-005**
CMS HLT: a new CPU + GPU farm

Software based trigger with full event information available running on CPU + GPU based farm

- Run 3 HLT farm composed of **200 nodes (25600 CPU cores and 400 GPUs)**
  - Each node equipped with two AMD Milan 64-core CPUs and two NVIDIA Tesla T4 GPUs
- Increasing usage of GPUs at Run 3
  - Offloading **30% of the HLT reconstruction to GPU**
- GPU reconstruction implemented and fully commissioned
  - calorimeter and pixel local reconstruction + pixel tracking + vertex reconstruction
  - The **execution time per event** of was **reduced by ~40%**
- HLT throughput requirement ~500Hz:
  - Throughput increases by a factor of ~1.80
  - Power Consumption (per throughput) reduced by ~30%

![CMS Preliminary 13.6 TeV](image)

**Execution time CPU only**

![Execution time CPU+GPU](image)

**Link**

**Link**

**Link**
The ALICE Run 3

Challenges for Run 3:

- **Completely new detector readout** and substantial detector upgrades: new ITS, MFT, FIT. New GEM for TPC readout
- ~100 x more data than Run 2
- Many important physics signals have very small signal-to-noise ratio
- Triggering (selection) techniques very inefficient if not impossible
- Needs large statistics
  - **Read the data resulting from all interactions** (LHC will deliver min bias Pb-Pb collisions at 50 kHz)

Courtesy of G. Eulisse
Reconstruction using GPUs in ALICE

- Trigger-less acquisition: **continuous detector read-out**
  - $L_{\text{int}}>10 \text{ nb}^{-1}$ of PbPb data at 50kHz: 50x more than Run 2
- Reconstruction is two-stepped
  - **Synchronous phase** (beam circulating): for calibration and data compression
  - **Asynchronous phase** (no beam): full processing of data staged on a temporary buffer. One common online-offline system ($O^2$)

- ALICE uses **GPUs** to accelerate the process
  - TPC track reconstruction is the most time consuming during synchronous reconstruction and is therefore performed on GPUs (the most cost effective solution)
  - During the asynchronous reconstruction, the fraction of available GPU increases
  - Use those resources efficiently by offloading also ITS reconstruction there

Courtesy of V. Barroso
The LHCb experiment

- Major upgrade of all subsectors:
  \[ \mathcal{L} = 2 \times 10^{33} \, cm^{-2} \, s^{-1} \]
- 100% of the readout electronics replaced
- New data acquisition system and data center

- Cannot effectively trigger on heavy flavour using hardware signatures
- Trigger for many hadronic channels saturated already at Run 1-2 luminosity
- **Solution:** fully software trigger

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CERN-LHCC-2012-007
The LHCb data flow

- Detector data @30 MHz received by O(500) FPGAs
- 2-stage software trigger, HLT1 & HLT2
- Real-time alignment & calibration
- After HLT2, 10 GB/s of data for offline processing
LHCb HLT1 trigger

The goal of HLT1

- Be able to intake the entirety of the LHCb raw data (5 TB/s) at 30 MHz
- Perform partial event reconstruction & coarse selection of broad LHCb physics cases
- Reduce the input rate by a factor of 30 (~1 MHz)
- 30 MHz benchmark can be achieved with $O(200)$ GPUs (max number EB can host is 500)
- ~350 GPUs now installed -> Additional functionalities are being explored
- Throughput scales well with theoretical TFLOPs of GPU card

Allen: a GPU HLT1 trigger platform

[Comput Softw Big Sci 4, 7 (2020)]

First complete high-throughput GPU trigger for a HEP experiment!
LHCb real-time alignment & calibration

- Store data selected in HLT1 in intermediate buffer for real-time alignment and calibration
- Fully aligned and calibrated data needed before running HLT2
- Online alignment and calibration pioneered in Run 2, crucial in Run 3
- Buffer capacity of $O(10 \text{ PB})$ situated between HLT1 and HLT2
- Two types of processes
  - Alignment: VELO, RICH mirrors, UT, SciFi, Muon
  - Calibration: RICH, ECAL, HCAL
LHCb HLT2 trigger

• Given the hard limit on bandwidth and expected signal rate, event size is the only free parameter

• Instead of saving full event, only information needed for a physics analysis can be stored (Turbo paradigm)

• Successful hybrid strategy for Run 2 [J. Phys.: Conf. Ser. 664 082004]

• Significant reduction of data size ⇒ more events at same bandwidth

• Preliminary signals from 2022 are very encouraging!

<table>
<thead>
<tr>
<th>Persistence method</th>
<th>Average event size [kB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbo</td>
<td>O(10)</td>
</tr>
<tr>
<td>Turbo+/SP</td>
<td>O(10-100)</td>
</tr>
<tr>
<td>Raw event</td>
<td>O(100)</td>
</tr>
</tbody>
</table>
Towards the future

Trigger & data acquisition challenge for HL-LHC
• Luminosity: ATLAS/CMS  \( (2 \rightarrow 7.5) \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)
  LHCb  \( (2 \times 10^{33} \rightarrow 1.5 \times 10^{34}) \text{ cm}^{-2} \text{ s}^{-1} \)
• Pileup: ATLAS/CMS  60 \( \rightarrow 200 \)
  LHCb  \( 5 \rightarrow 40 \)

**ATLAS** L0 trigger for HL-LHC
• HLT-like object-level and event-level reconstruction and analysis at 40 MHz
• Collect all trigger data from a single event onto one FPGA

**LHCb** planning Upgrade II for LS4
• FTDR approved in March 22 [LHCB-TDR-023]
• Exciting challenges in trigger and DAQ
• 4D reconstruction: timing added to tracking to better isolate signals
• Actively considering which processors will work best

**CMS** phase II upgrade of Level 1 trigger
• The Particle Flow used for offline will be brought to L1 trigger
• Include tracking trigger in L1 trigger system
• Displaced vertex trigger for exotic events

![CMS Phase-2 Simulation](image)
Thanks for your attention!
Backup
The ATLAS Trigger Level analysis

- Trigger bandwidth limitations:
  \[ \text{bandwidth} = \text{trigger rate} \times \text{event size} \]

- Trigger-Level Analysis (TLA): save only the HLT reconstructed objects (e.g. CMS Data Scouting (i), LHCb Turbo Stream (ii))

- Substantial event size reductions
  - (1.5MB (standard) vs. \(\sim\)5kB (TLA))
  - Higher rate triggers
  - Small bandwidth footprint (right, (b))

Trigger-Level Analyses require excellent performance of trigger physics objects
The CMS Run 3 trigger

- Two level triggering system to reduce the rate to a manageable level
  - L1 (< 100 kHz): large effort to develop new seed features, algorithms, and triggers to target LLP signatures and rare signals
Upgraded LHCb online system

- Event builder farm equipped with 173 servers

- Each server has 3 free PCIe slots
  - can host GPUs
  - sufficient cooling and power
  - advantageous to have GPUs as self-contained processors
  - sending data to GPUs is like sending data to network card

- GPUs map well into LHCb DAQ architecture
- HLT1 tasks inherently parallelizable
- Smaller network between EB & CPU HLT
- Cheaper & more scalable than CPU alternative
- Implemented with 326 Nvidia RTX A5000 GPUs
LHCb HLT1 sequence

**Tracking** relies on

- **VELO**: clustering, tracking, vertex reconstruction
- **UT**: tracking, momentum estimate, fake rejection
- **SciFi**: tracking, momentum measurement

+ **PID** from **MUON** and **CALO** systems

- Raw data
- Global Event Cut
  - Velo decoding & clustering
  - Velo tracking
  - Straight line fit
  - Find primary vertices

  - UT decoding
  - UT tracking
  - SciFi decoding
  - SciFi tracking

  - Muon decoding
  - Muon ID
  - Calo decoding & clustering
  - Electron ID

- Find secondary vertices
- Select events
- Selected events

- Trigger lines
  - Event selection

- Upstream track
- Long track
- Downstream track
- T track

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LHCb Track reconstruction

**Velo tracking**
- 26 silicon pixel modules with $\sigma_{x,y} \sim 5 \, \mu m$
- Local paralleled clustering algorithm (Search by Triplet)
- Tracks fitted with simple Kalman filter assuming straight line model

**UT tracking**
- 4 layers of silicon strips
- Velo tracks extrapolated to UT taking into account B field
- Parallelized trackless finding inside search window requiring at least 3 hits

**SciFi tracking**
- 3 stations with 4 layers of Scintillating Fibres
- Velo-UT tracks extrapolated using parametrisation
- Parallelized Forward algorithm to reconstruct long tracks
  - Search windows from Velo-UT momentum estimate
  - From triplets and extend to remaining layers
LHCb Tracking performance

- Run 2 performance maintained at x5 instantaneous luminosity
  - Excellent track reconstruction efficiency (> 99% for VELO, 95% for high-p forward tracks)
  - Good momentum resolution and fake rejection
LHCb Tracking without the UT

1. Forward without UT

- Extrapolate VELO track as a straight line, make two windows — assuming positive/negative charge
- Assume \( p > 5 \text{ GeV}, p_T > 1 \text{ GeV} \) (low-p tracks get bent out of the SciFi acceptance anyway)

In 2022, the UT detector is unfortunately not be available for data-taking

Tracking performance and throughput maintained, at the cost of larger fake rate

Commissioning two options, which **both maintain the current throughput**
LHCb Tracking without the UT

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- Tracking performance and throughput maintained, at the cost of larger fake rate
- Commissioning two options, which **both maintain the current throughput**

**2. Seeding+matching**

- Standalone SciFi reconstruction & matching to VELO seeds
- Highly efficient for low momenta
- Opens the door to additional physics cases in HLT1 (downstream and SciFi tracks)
LHCb Tracking without the UT

- In 2022, the UT detector will unfortunately not be available for data-taking
- Tracking performance and throughput maintained, at the cost of larger fake rate
- Opportunity to commission 2 options, which **both maintain the current throughput**
LHCb Vertex reconstruction

- Primary vertices found from clusters in the closest approach of tracks to the beamline
- 1-1 mapping between tracks and vertices requires serialization
  - Instead, every track assigned to every vertex based on weight
- Efficiency > 90% for vertices with number tracks > 10

*Comput. Softw. Big Sci. 6 (2022) no.1, 1*
LHCb Calorimeter and muon PID

• **CALO reconstruction**

  • Loop over calorimeter cells and look for energetic clusters
  
  • Originally not foreseen within the baseline TDR, but outcome of ambition and good design (and lots of optimisation)
  
  • The very first algorithm that was tested with real Run 3 data!
**LHCb Calorimeter reconstruction**

- **CALO reconstruction**
  - Loop over calorimeter cells and look for energetic clusters
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  - The very first algorithm that was tested with real Run 3 data!

- Calo digits attached to long tracks for electrons
- Momentum is corrected if clusters are found in the Bremsstrahlung recovery area
LHCb Muon PID

- Muon particle identification
  - Extrapolate tracks from SciFi to Muon stations
  - Match hits to tracks in a field of interest
  - Excellent muon identification and misID background rejection

LHCB-FIGURE-2020-014
LHCb HLT1 selection performance

- Inclusive rate for the main HLT1 lines ~ 1 MHz
- O(30) lines implemented so far:
  - Cover majority of LHCb physics programme (B, D decays, semileptonic, EW physics)
  - Special lines for monitoring, alignment and calibration
Allen: a GPU HLT1 LHCb trigger platform

- Public software project: [gitlab repo](#)

- Supports three modes:
  - Standalone
  - Compiling within the LHCb framework for data acquisition
  - Compiling within the LHCb framework for simulation and offline studies

- Runs on CPU, Nvidia GPU (CUDA, CUDACLANG), AMD GPUs (HIP)

- GPU code written in CUDA

- Cross-architecture compatibility (HIP, CPU) via macros

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**Allen**

**pipeline** passed

Welcome to Allen, a project providing a full HLT1 realization on GPU.

Documentation can be found [here](#).

**Mattermost discussion channels**

- Allen developers - Channel for any Allen algorithm development discussion.
- Allen core - Discussion of Allen core features.
- AllenPR throughput - Throughput reports from nightlies and MRs.

**Performance monitoring**

- Allen throughput evolution over time in grafana
- Allen dashboard with physics performance over time
LHCb HLT1 CPU/GPU comparison

Compatible performance between CPU and GPU!
LHCb HLT1 CPU/GPU comparison

- Compatible performance between CPU and GPU

*Comput. Softw. Big Sci. 6 (2022) no.1, 1*