Lecture 2

Data acquisition and Trigger (with emphasis on LHC)

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- Introduction
  - Data handling requirements for LHC
- Design issues: Architectures
  - Front-end, event selection levels
- Trigger
- Future evolutions
- Conclusion
DAQ challenges at LHC

Challenge 1
- Physics – Rejection power
- Requirements for TDAQ driven by rejection power required for the search of rare events

Challenge 2
- Accelerator – Bunch crossing frequency
- Highest luminosity needed for the production of rare events in wide mass range

Challenge 3
- Detector – Size and data volume
  - Unprecedented data volumes from huge and complex detectors
Challenge 1: Physics

- Cross sections for most processes at the LHC span \(\sim 10\) orders of magnitude.
- LHC is a factory for almost everything: \(t, b, W, Z\)...
- But: some signatures have small branching ratios (e.g. \(H \rightarrow \gamma\gamma\), \(\text{BR} \sim 10^{-3}\))

<table>
<thead>
<tr>
<th>Process</th>
<th>Production Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>inelastic</td>
<td>(\sim 1) GHz</td>
</tr>
<tr>
<td>(b\bar{b})</td>
<td>5 MHz</td>
</tr>
<tr>
<td>(W \rightarrow l\nu)</td>
<td>150 Hz</td>
</tr>
<tr>
<td>(Z \rightarrow l\nu)</td>
<td>15 Hz</td>
</tr>
<tr>
<td>(t\bar{t})</td>
<td>10 Hz</td>
</tr>
<tr>
<td>(Z')</td>
<td>0.5 Hz</td>
</tr>
<tr>
<td>(H(125)) SM</td>
<td>0.4 Hz</td>
</tr>
</tbody>
</table>

- \(L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}\): Collision rate: \(\sim 10^9\) Hz.
  Event selection: \(\sim 1/10^{13}\) or \(10^{-4}\) Hz!
Challenge 1: Physics

- Requirements for TDAQ driven by the search for rare events within the overwhelming amount of “uninteresting” collisions

- Main physics aim
  - Measure Higgs properties
  - Searches for new particles beyond the Standard Model
    - Susy, extra-dimensions, new gauge bosons, black holes etc.
  - Plus many interesting Standard Model studies to be done

- All of this must fit in ~1 kHz of data written out to storage

- Not trivial, $W \rightarrow l\nu$: 150 Hz @ $10^{34}$ cm$^{-2}$s$^{-1}$

“Good” physics can become your enemy!
Challenge 2: Accelerator

- Unlike $e^+e^-$ colliders, proton colliders are more ‘messy’ due to proton remnants
- Multiple collisions per bunch crossing
  - Currently ~20-30 overlapping p-p interactions on top of each collision (pile-up) $\Rightarrow$ >1000 particles seen in the detector!

![Graph showing delivered luminosity vs mean number of interactions per crossing](image)

**ATLAS** Online 2016, $\sqrt{s}=13$ TeV $\int L dt=29.3$ fb$^{-1}$

$\langle \mu \rangle = 24.2$

DAQ and Trigger, Nov 2, 2016
Challenge 3: Detector

Besides being huge: number of channels are $O(10^6-10^8)$ at LHC, event sizes $\sim$1 MB for pp collisions, 50 MB for pb-pb collisions in Alice

- Need huge number of connections

- Some detectors need $> 25\text{ns}$ to readout their channels and integrate more than one bunch crossing's worth of information (e.g. ATLAS LArg readout takes $\sim 400\text{ns}$)

- It's On-Line (cannot go back and recover events)
  - Need to monitor selection - need very good control over all conditions
Let’s build a Trigger and DAQ for this

What do we need?
Let’s build a Trigger and DAQ for this

🌟 What do we need?

🌟 Electronic readout of the sensors of the detectors (“front-end electronics”)

🌟 A system to collect the selected data (“DAQ”)

![Diagram showing the process of data collection, triggering, and event building.](image-url)
Let’s build a Trigger and DAQ for this

- What else do we need?
  - A system to keep all those things in sync (“clock”)
  - Data belonging to the same bunch crossing must be processed together
  - Particle time of flight, cable delays, electronic delays all
Let’s build a Trigger and DAQ for this

What do we need?

- Electronic readout of the sensors of the detectors ("front-end electronics")
- A system to collect the selected data ("DAQ")
- A system to keep all those things in sync ("clock")
- A trigger – multi-level due to complexity
Let’s build a Trigger and DAQ for this

What do we need?

- Electronic readout of the sensors of the detectors ("front-end electronics")
- A system to collect the selected data ("DAQ")
- A system to keep all those things in sync ("clock")
- A trigger – multi-level due to complexity
- A Control System to configure, control and monitor the entire DAQ
Let’s look more at the trigger part…
Multi-level trigger system

Sometime impossible to take a proper decision in a single place
- too long decision time
- too far
- too many inputs

Distribute the decision burden in a hierarchical structure
- Usually $\tau_{N+1} \gg \tau_N, f_{N+1} \ll f_N$

At the DAQ level, proper buffering must be provided for every trigger level
- absorb latency
- De-randomize
LHC DAQ phase-space

- When LHC experiments were designed back in the 90’s
  - Raw data storage capped at ~ 1 PB / year per experiment
Hardware Trigger (L0, L1)

- Custom electronics designed to make very fast decisions
  - Application-Specified Integrated Circuits (ASICs)
  - Field Programmable Gate Arrays (FPGAs)
    - Possible to change algorithms after installation
- Must cope with input rate of 40 MHz
  - Reduce rate from 40 MHz to ~100 kHz
  - Otherwise cannot process all events
  - Event buffering is expensive, too
- Use pipeline for holding data during L1 processing
  - Digital/analog custom front-end pipelines
  - Parallel processing of different inputs as much as possible

DAQ and Trigger, Nov 2, 2016
Trigger Latency

This time determines the depth of the pipeline.
L1 Trigger in ATLAS

- Calorimeter and muons only
- Simple algorithms on reduced data granularity
- Selection based on particle type, multiplicities and thresholds
- Reject the bulk of uninteresting collisions
Example: ATLAS e/γ trigger

- Sum energy in calorimeter cells into EM and hadronic towers
- Loop over grid and search in 4x4 towers for a local maximum 1x2 (2x1): cluster

Can do something similar for other particles: jets, tau or sum the energy of all towers: missing $E_T$
Curved $p_T$-dependent muon path requires fast pattern recognition

Rough estimate of muon $p_T$ determined from bending in magnetic field

CMS L1 muon trigger

CMS, $\eta = 0$ (simulation)
Central/Global Trigger

.Now we have the information on the particle candidates found by L1 in the detector

- We know type, location and $E_T/p_T$ threshold passed
- Can also look at topological information
  - E.g. lepton opposite ETmiss, invariant mass of 2 leptons...

Need to decide if this event is of any interest to us

- This needs to be made quickly
L1 selected a large rate (up to 100 kHz) of events that “might be interesting”

These events are not kept yet (rate too high for storage), but sent to the HLT for additional filtering

Use network-based High Level Trigger computer farm(s)

commercially available HW organized in a farm
HLT Example: Muon

🎉 Muons in CMS:
- Reconstruct and fit tracks using only muon system
- Continue if sufficient $p_T$
- Combine tracker hits with muon system to improve $p_T$ measurement
- Keep the event if $p_T$ is large enough

🎉 Muons in ATLAS:
- At Level 2, using detector information from the region around the L1 muon candidate, assign muon $p_T$ based on fast look up tables
- Extrapolate to the collision point and find the associated track
- Is the muon isolated in the tracker, calorimeters?
- Refine selection at L3 using offline-based reconstruction, recompute $p_T$

🎉 More on HLT in next lecture

DAQ and Trigger, Nov 2, 2016
Higher Level Trigger

- Massive commercial computer farm
- Each CPU can process individual event or run multi-threaded
- Resources are still limited
  - Offline: Full reconstruction takes seconds (minutes)
  - Online latency: ms - s (input rate dependent)
- Need to reduce rate to $O(1 \text{ kHz})$
  - Note, output rate mainly driven by offline resources (CPU / disk space)
The ATLAS Trigger/DAQ System

- Overall Trigger & DAQ architecture: 3 trigger levels
- **Level-1:**
  - 2.5 µs latency
  - 100 kHz
- HLT: run L2 and EF in one farm
- Average output rate: ~1 kHz (physics), ~2 kHz (calib/monitoring)
- Processing time: 0.2s on average
- Average event size 1.5 - 2 MB

DAQ and Trigger, Nov 2, 2016
The ATLAS Special Features

- **On-demand event building seeded by Region of Interests**
  - No need to analyse the whole event in HLT, just look at regions flagged at L1 (e.g. regions with e/γ, μ, τ, jet candidates)
  - On average look only at ~5% of the data

- **L2 and EF run on same CPU within one farm** (new in 2015)
  - Provides efficient coupling between subsequent selection steps, reducing duplication of CPU usage and network transfer
  - Allows flexible combination of fast and detailed processing
The CMS Trigger/DAQ System

- Overall Trigger & DAQ architecture: 2 trigger levels
- DAQ & HLT decoupled via intermediate shared temp. storage
- Level-1:
  - 3.2 µs latency
  - 100 kHz output

- DAQ/HLT:
  - Event building at full L1 rate
  - Average output rate: ~1 kHz
  - Average event size 1.5 Mb
  - Max. average CPU time: ~160 ms/event
The CMS Special Features

- **2 stage event building!**
  - **1st stage:**
    - Combine fragments into super-fragment in RU (Readout Unit) builder
    - Event building in builder units which then write events to transient files on RAM disk
  - **2nd stage:**
    - Serve complete events to trigger farm.

- DAQ and HLT decoupled via intermediate shared temporary storage (new in 2015)
The LHCb Trigger/DAQ System

- Overall Trigger & DAQ architecture: 3 trigger levels
- Level-0:
  - 4 µs latency
  - 1 MHz output

- DAQ/HLT
  - L1: spot displaced high $p_T$ tracks, output 100-200 kHz
  - L2: full event reconstruction
  - ~34 (650) ms @ L1 (L2)
  - Average output rate: 12.5 kHz,
  - Average event size 50 kB

DAQ and Trigger, Nov 2, 2016
The LHCb Special Features

- HLT decoupled from data flow via local temporary storage!
  - Using periods without beam boost CPU usage by 200 %
- Full offline-quality reconstruction available online
  - Alignments done at beg of fill, calib done per run
- Turbo Stream + Tesla Application:
  - Store full information of trigger candidates, remove most of detector raw data
  - Save more than 90% space
  - Ideal for very high signal yield [millions]
  - Very quick turn around [24 h]
The ALICE Trigger/DAQ System

Alice has different constraints:
- Low rate: max 8 kHz pb+pb
- Very large events: > 40MB
- Slow detector (TPC ~ 100 µs)

Overall Trigger & DAQ architecture: 4 trigger levels
- 3 hardware-based trigger, 1 software-based:
  - L0 – L2: 1.2, 6.5, 100 µs latency
  - L3: further rejection and data compression
The Alice Special Features

- Deal with huge events
  - 3 hardware level triggers
  - Heavy utilisation of hardware acceleration: FPGA + GPU
  - Use of data compression in trigger
Towards the Future

- Experiments upgrade every time the conditions provided by the accelerator change
  - Preparations start well in advance
  - The 4 LHC TDAQ systems are already planning major upgrades
    - ALICE & LChb will upgrade for Run 3
    - CMS and ATLAS will mainly upgrade for Run 4

- Guiding Principles
  - Physics goals
  - Accelerator conditions
  - Technology reach
  - Cost

- Rapidly evolving area
Towards the Future

- **Alice**
  - Support for continuous read-out (TPC), as well as triggered read-out
  - Read out the data of all interactions at a maximum rate of 50kHz (upon min bias trigger)
  - One common online – offline computing system: O2

- **LHCb**
  - (Triggerless) Read-out @ 40 MHz + full software trigger
  - Data centre at the surface

- **CMS**
  - Hardware-based track trigger

- **ATLAS**
  - Hardware based track trigger after very first trigger level
Summary

- Challenge to design efficient trigger/DAQ for LHC
  - Very large collision rates (up to 40 MHz)
  - Very large data volumes (tens of MB per collision)
  - Very large rejection factors needed ($>10^5$)
- Showed data acquisition used in LHC experiments
- Introduction to basic functionality of trigger
- We’ll look in detail at the trigger aspects in the next lecture
  - That one will be less technical and more physics-oriented!
## Trigger/DAQ parameters

<table>
<thead>
<tr>
<th>No. Levels</th>
<th>Level-0,1,2</th>
<th>Event</th>
<th>Readout</th>
<th>HLT Out</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pb-Pb</strong></td>
<td>4</td>
<td>Rate (Hz)</td>
<td>Size (Byte)</td>
<td>Bandw.(GB/s)</td>
</tr>
<tr>
<td>p-p</td>
<td>500</td>
<td>5x10^7</td>
<td>25</td>
<td>1250 (10^2)</td>
</tr>
<tr>
<td>p-p</td>
<td>10^3</td>
<td>2x10^6</td>
<td></td>
<td>200 (10^2)</td>
</tr>
<tr>
<td>LV-1</td>
<td>10^5</td>
<td>1.5x10^6</td>
<td>4.5</td>
<td>300 (2x10^2)</td>
</tr>
<tr>
<td>LV-2</td>
<td>3x10^3</td>
<td>1.5x10^6</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>LV-0</td>
<td>10^5</td>
<td>10^6</td>
<td>100</td>
<td>~1000 (10^2)</td>
</tr>
<tr>
<td>LV-0</td>
<td>10^6</td>
<td>3.5x10^4</td>
<td>35</td>
<td>70 (2x10^3)</td>
</tr>
</tbody>
</table>
# TDAQ Comparison

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
<th>LHCb</th>
<th>ALICE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>“L1” Latency [μs]</strong></td>
<td>2.5</td>
<td>3.2</td>
<td>4</td>
<td>1.2/6/88</td>
</tr>
<tr>
<td><strong>Max “L1” output rate [kHz]</strong></td>
<td>75</td>
<td>100</td>
<td>1000</td>
<td>~2</td>
</tr>
<tr>
<td><strong>Frontend readout bandwidth [GBytes/s]</strong></td>
<td>120</td>
<td>100</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>L2: 40</td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>EF: 1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Max HLT avg. latency [ms]</strong></td>
<td></td>
<td></td>
<td>50 (in 2010)</td>
<td>20</td>
</tr>
<tr>
<td>(upgrade with luminosity)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Event building bandwidth [GBytes/s]</strong></td>
<td>4</td>
<td>100</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td><strong>Trigger output rate [Hz]</strong></td>
<td>~200</td>
<td>~300</td>
<td>~2000</td>
<td>~50</td>
</tr>
<tr>
<td><strong>Output bandwidth [MBytes/s]</strong></td>
<td>300</td>
<td>300</td>
<td>100</td>
<td>1200</td>
</tr>
<tr>
<td><strong>Event size [MBytes]</strong></td>
<td>1.5</td>
<td>1</td>
<td>0.035</td>
<td>Up to 20</td>
</tr>
</tbody>
</table>
Data handling requirements

- Every second: observe 40 million bunch crossings, each producing several (>20) p-p interactions resulting in events with 1000’s particles
- Identify and select single events out of 10 trillion collisions
- Locally digitize, read out, transport and process hundreds of TeraBits per sec

Collision rate: \( \sim 10^9 \) Hz
Detector granularity: \( \sim 10^8 \) cells
Event size: \( \sim 1 \) Mbyte
Selection power: \( \sim 1 \text{ in } 10^{13} \)
Readout bandwidth: \( \sim \text{Terabit/s} \)
Storage event rate: \( \sim \text{O}(100\text{Hz}) \)
Processing power: \( \sim \text{TeraFlops} \)

- Globally store, retrieve and analyze efficiently tens of PetaBytes of data per year