TRIGGER & DATA ACQUISITION

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Lecture 1
LEVEL OF LECTURES

• Students at this School come from various backgrounds
  – Phenomenology
  – Analysis of physics data from experiments (or Monte Carlo studies)
  – Preparing for future experiments
  – Some working on Trigger and DAQ systems
• I have tried to strike a balance between making the lectures accessible to all, and going into details for those already more familiar with T/DAQ systems
  – Will go quite fast today, covering the basics
    • Refer to notes from my lectures at a previous school, and I am happy to answer questions in the Discussion Session or privately
  – More on topical (LHC-specific) aspects tomorrow
INTRODUCTION

• I will concentrate on experiments at high-energy particle colliders, especially the general-purpose experiments at LHC
  – Very challenging case
    • Illustrates well the problems that have to be addressed in state-of-the-art HEP Trigger/DAQ systems
  – Where I am working myself (ATLAS experiment at LHC)
    • I will include in the second lecture some material from the experience of commissioning triggers in single-beam running last September

• However, I will start with a more general discussion, building up to some examples from the $e^+e^-$ collider LEP
  – LEP has complementary challenges to LHC and is a good starting point to see how HEP T/DAQ systems have evolved in the last few years as we moved towards LHC
DEFINITION AND SCOPE OF TRIGGER/DAQ

• What is T/DAQ? Basically:
  – System that selects particle interactions that are potentially of interest for physics analysis (trigger), and which takes care of collecting the corresponding data from the detector system, putting them into a suitable format and recording them to permanent storage (DAQ)

• Many other aspects
  – Associated systems, e.g. run control, data monitoring, clock distribution, book-keeping, etc
    • all of which are essential for efficient collection of the data and for their subsequent offline analysis
Basic Trigger requirements

• Need high **efficiency** for selecting processes for physics analysis
  – Efficiency should be precisely known (preferably measured)
  – Selection should not have biases that affect physics results

• Need **large reduction of rate** from unwanted high-rate processes (capabilities of DAQ and also offline!)
  – Instrumental background
  – High-rate physics processes that are not relevant for analysis

• **System must be affordable**
  – e.g algorithms executed at high rate must be fast

• **Not easy to achieve above simultaneously!**
Trigger menus

• Typically, trigger systems select events according to a “trigger menu”, i.e. a list of selection criteria
  – An event is selected by the trigger if one or more of the criteria are met
  – Different criteria may correspond to different signatures for the same physics process
    • Redundant selections lead to high selection efficiency and allow the efficiency of the trigger to be measured from the data
  – Different criteria may reflect the wish to concurrently select events for a wide range of physics studies
    • HEP “experiments” — especially those with large general-purpose “detectors” (detector systems) — are really experimental facilities
  – The menu has to cover the physics channels to be studied, plus additional event samples required to complete the analysis:
    • Measure backgrounds, check the detector calibration and alignment, etc.
Basic DAQ requirements

• **Collection** of data from detector digitisation systems
• **Buffering** of data pending final trigger decision
• **Recording** of data for selected events in suitable format
  – Event size depends on use of data compression, etc.
• Providing numerous Online services (e.g. Run Control system)
• Keeping record of conditions (book-keeping)
• Avoiding data corruption or data loss
  – And being robust against imperfection in the detector and associated electronic systems
• Minimising dead-time (see later)
• System must be **affordable**
In the following I will use a very simple example to illustrate issues for designing a T/DAQ system.

Here, I will try to omit all the detail and concentrate on the essentials.

Will look at examples from real experiments later.

Before going on, I introduce the concept of dead-time which will be an important element in what follows.

What does \textit{dead-time} mean?

Dead-time is generally defined as the fraction or percentage of total time where valid interactions could not be recorded for various reasons.

\begin{itemize}
\item e.g. typically there is a minimum period between triggers — after each trigger the experiment is dead for a short time.
\end{itemize}
Sources of dead time

• Dead-time can arise from a number of sources, with a typical total of up to $O(10\%)$
  – Readout and trigger dead-time (see next slides)
  – Operational dead-time (e.g. time to start/stop runs)
  – T/DAQ down-time (e.g. following computer failure)
  – Detector down-time (e.g. following high-voltage trip)

• Given the investment in the accelerators and the detectors for a modern HEP experiment, it is clearly very important to keep dead-time to a minimum!
Let’s see what can be learned from a very simple example

- Consider Time-of-Flight (ToF) measurement using a scintillation-counter telescope read out with Time-to-Digital Converters (TDCs)
  - Figure on next slide omits details (discriminators, dead-time logic)
- Start with “traditional” approach (as one might implement using e.g. off-the-shelf electronic modules + a DAQ computer)
  - This case is still common, e.g. in small test set-ups
- Discuss limitations of this model
  - Then see how we can improve on it
- Of course, a big HEP experiment has an enormous number of sensor channels (up to $O(10^8)$ at LHC), c.f. 3 in the example!
  - However, the principles are the same as we will see later
Simple example

Beam

Measure ToF

Scintillation counters

Trigger

TDC

Start TDC

Initiate readout

Delay may be cable

Trigger has to get to TDC before signals A, B, C
Limitations

• **Need very fast trigger decision**
  - The TDCs require a “start” signal that arrives before the signals that we wish to digitise — a TDC is like a multi-channel stop watch
  - The situation is similar with traditional Analogue-to-Digital Converters (ADCs) that require a “gate” during which the signal to be digitised must arrive

• **Readout from TDCs to the computer is quite slow — implies significant dead time if the trigger rate is high**
  - This becomes much more important in larger systems where many channels have to be read out for each event
    • *e.g.* 1000 channels @ 1 μs each = 1 ms per event
      - Excludes event rates above 1 kHz
Traditional readout

1. Trigger
2. Signals
3. Read out

(Digitizer) Register

“Start TDC”
“Gate ADC”

Readout dead-time: trigger rate $\times$ readout time
Fast local readout

Measure ToF

Beam

Scintillation counters

Trigger has to get to TDC before signals A, B, C

Delay may be cable

Trigger

TDC

Start TDC
Local memory buffer

1. Trigger

   “Start TDC”
   “Gate ADC”

   (Digitizer)
   Register

2. Signals

3. Fast read out

4. Final (slower) read out

Buffer

Readout dead-time:
trigger rate × *local readout time*
Comments

• **Addition of a local buffer with fast readout reduces dead-time**
  – In a large system, transfer of data from digitizers to local buffers can proceed in parallel, e.g. one buffer per crate
    • Local readout can remain fast in a large system

• **Issue of fast trigger still remains**
  – Signals have to be delayed until trigger decision is available at digitizers
    • Even with very simple trigger logic, this is not easy to achieve — need to rely on using:
      – Fast (air-core) cables for trigger signals with shortest possible routing
        » Not always convenient (e.g. UA1 experience)
      – Restricted to very simple logic to form trigger decision
    • Cannot apply complex selection criteria on this time-scale
Multi-level triggers

- It is often not possible to simultaneously meet the physics requirements (high efficiency, high background rejection) and an extremely short trigger “latency” (i.e. time to form trigger decision and distribute it to digitisers)
  - Need to introduce the concept of multi-level triggers, where the first level has a short latency, maintains high efficiency, but only has a modest rejection power
    - Further background rejection comes from the higher trigger levels which can be slower
  - Sometimes the very fast first stage of the trigger is called the “pre-trigger” — it may be sufficient to signal the presence of minimal activity in the detectors at this stage
Pre-trigger and fast clear

1. Pre-trigger
   “Start TDC”
   “Gate ADC”

2. Signals
   (Digitizer) Register

3. Trigger (or fast clear)

4. Read out

Readout dead-time: $\text{trigger rate} \times \text{readout time}$
PLUS trigger dead-time:
pre-trigger rate $\times$ trigger latency

Trigger can now come later
(allows more refined selection – lower rate)
Combine pre-trigger & local buffer

1. Pre-trigger

“Start TDC”
“Gate ADC”

2. Signals

(Digitizer)
Register

3. Trigger (or fast clear)

4. Fast read out

5. Final read out

Buffer

Readout dead-time:
trigger rate × *local readout time*
PLUS trigger dead-time:
pre-trigger rate × trigger latency
Summary

• Introduction of pre-trigger, allows complex trigger algorithms to be implemented
  – Pre-trigger decision (very fast & very simple criteria) still has to arrive before signals to be digitised
  – Main trigger decision can come later
    • More refined selection; lower rate ⇒ less readout dead-time

• However, latency (i.e. decision-making time) of main trigger introduces trigger dead-time
  – trigger dead-time = pre-trigger rate × trigger latency

• Introduction of local buffers with fast readout further reduces the readout dead-time
  – readout dead-time = trigger rate × local readout time
Further improvements (1)

• Idea of multi-level triggers can be extended beyond having two levels (pre-trigger and main trigger)
  – Can have a series of trigger levels that progressively reduce the rate
    • The efficiency for the desired physics must be kept high at all levels
      – Rejected events are lost forever
    • The initial levels can have modest rejection power, but they must be fast since they see high rate
      – Selected events can still be rejected later
    • The final levels must have strong rejection power, but they can be slower because they see much lower rate (thanks to the rejection from earlier levels)

• Total dead-time is now the sum of
  – trigger dead-time summed over trigger levels:
    • $\sum_{\text{levels}} (\text{trigger rate out of previous level} \times \text{trigger latency for this level})$
  – Readout dead-time:
    • final trigger rate $\times$ local readout time
Further improvements (2)

• There are some implicit assumptions in the above:
  – All trigger levels are completed before readout starts
    • This results in a very long dead period for some events
      (those that make it past the first, fast trigger levels)
    • This long dead-time can be avoided by reading out to intermediate storage all
      events passing the initial stages of trigger selection
      – after that, further triggers can be accepted (in parallel with the execution
        of the later stages of trigger selection on the first event)
  – Need for a pre-trigger — i.e. initial level of triggering — that is available
    by the time the signals from the detector arrive at the digitizers
    • This too can be avoided, e.g. in collider experiments with bunched beams as
      we will see shortly
In high-energy particle colliders (Tevatron, HERA, LEP, LHC), the particles in the counter-rotating beams are bunched
- Bunches cross at regular intervals
  - Interactions only occur during the bunch-crossings
- The trigger has the job of selecting the bunch-crossings of interest for physics analysis, i.e. those containing interactions of interest

I will use the term “event” to refer to the record of all the products of a given bunch-crossing (plus any activity from other bunch-crossings that gets recorded along with this)
- Be aware (beware!): the term “event” is not uniquely defined!
  - Some people use the term “event” for the products of a single interaction between the incident particles
    - People sometimes unwittingly use “event” interchangeably to mean different things!
LHC in tunnel formerly used by LEP

CERN

Airport

Circumference of ring ~ 27 km
LEP and LHC

• LEP
  – Electron-positron collider
    • Energy per beam up to \( \sim 100 \text{ GeV} \)
    • Luminosity \( 10^{32} \text{ cm}^{-2}\text{s}^{-1} \)
    • Bunch-crossing period 22 \( \mu\text{s} \)

• LHC (design parameters)
  – Proton-proton collider
    • Energy per beam 7 TeV
    • Luminosity \( 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
    • Bunch-crossing period 25 ns
LHC Detectors
(see lectures of Jordan Nash next week)
“Pile-up”

• In $e^+e^-$ colliders, the interaction rate is very small compared to the bunch-crossing rate (because of the low $e^+e^-$ cross-section)
  – Generally, selected events contain just one interaction
    • i.e. event is generally a single interaction
    • This was the case at LEP (and also at the e-p collider HERA)

• In contrast, at the LHC with its design parameters, each bunch-crossing will on average contain about 25 interactions
  – Interaction of interest, e.g. the one that produced $H \rightarrow ZZ \rightarrow e^+e^-e^+e^-$, will be recorded together with $\sim25$ other proton–proton interactions
    • The interactions that contribute to the “underlying event” are often called “minimum-bias” interactions, i.e. the ones that would be selected by a trigger than selects interactions in an unbiased way
“Exposure time”

• A further complication is that particle detectors do not have an infinitely fast response time
  – This is analogous to the exposure time of a camera
  – If the “exposure time” is shorter than the bunch-crossing period, the event will contain only information from the selected bunch crossing
    • Otherwise, the event will contain activity (if any) from neighbouring bunches in addition
      – In e^+e^- colliders, e.g. LEP, such activity was very unlikely — this allowed the use of slow detectors such as the Time-Projection Chamber
        » The same is true in ALICE due to the low luminosity for heavy-ion running at LHC
  – At LHC, despite a short (25 ns) bunch-crossing period (i.e. 40 MHz rate), there will be activity in essentially all bunch crossings (BCs)
    • Some detectors, e.g. ATLAS silicon tracker, achieve an exposure time of less than 25 ns, but many do not
      – For example, signals from the ATLAS liquid-argon calorimeter extend over many BCs (so need to read out several BC, “readout frame”)

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Using the bunch-crossing signal as a “pre-trigger”

- If the time between bunch crossings is reasonably long, one can use the clock that signals when bunches cross as the pre-trigger
  - The first-level trigger can then use the time between bunch-crossings to make a decision
    - For most crossings, the trigger will reject the event by issuing a fast clear
      - In such cases, no dead-time is introduced
    - Following an accept signal, dead-time will be introduced until the data have been read out (or until the event has been rejected by a higher-level trigger)

- This model was used at LEP
  - Bunch crossing interval 22 µs (11 µs in 8-bunch mode) allowed comparatively complicated trigger processing (latency ~few µs)
BC clock and fast clear

1. BC clock
   "Start TDC"
   "Gate ADC"

2. Signals

3. Trigger (or fast clear)

4. Fast readout

5. Final readout

Readout dead-time:
trigger rate \times \text{local readout time}

No trigger dead-time!
Note trigger rate \ll \text{BC rate}

(Digitizer)
Register

Buffer
LEP model (e.g. ALEPH)

1. BC clock (every 22 µs)
   - “Start TDC”
   - “Gate ADC”

2. Signals
   (TPC signals up to 45 µs)

3. LVL1
   (< 5 µs)

4. LVL2
   (50 µs)

5. Fast readout
   (~few ms)

6. ROC

7. Global buffer

8. LVL3

9. Recording

Readout dead-time:
$LVL2$ rate $\times$ local readout time
PLUS trigger dead-time:
$LVL1$ rate $\times$ $LVL2$ latency

# lost BCs $\times$ BC period
LEP numbers (e.g. DELPHI)

Illustrative numbers for LEP-II:
LVL1 rate ~ 500 – 1000 Hz (instrumental)
LVL2 rate = 6 – 8 Hz
LVL3 rate = 4 – 6 Hz
LVL2 latency = 38 µs (22 µs effective)
Local readout time ~ 2.5 ms

Only lose 1 BC
(BC period = 22 µs)!

Readout dead-time:
LVL2 rate × local readout time
PLUS trigger dead-time:
LVL1 rate × LVL2 latency

# lost BCs × BC period

7 Hz × 2.5×10⁻³ s = 1.8%
PLUS trigger dead-time:
750 Hz × 38×10⁻⁶ s = 2.9%
750 Hz × 22×10⁻⁶ s = 1.7%
DAQ at LEP (e.g. ALEPH)

• Event building was bus-based
  – Each ROC collected data over a bus from the digitizing electronics
  – Each sub-detector Event Builder (EB) collected data from several ROCs over a bus
  – The main EB collected data from the sub-detector EBs over a bus

• The main EB and the main readout computer saw the full data rate prior to the final LVL3 selection
  – At LEP this was fine
    • Event rate after LVL2 ~few Hz
    • Event size ~100 kByte
    • Data rate ~ few hundred kByte/s
      – c.f. ~ 40 MByte/s maximum on the bus (for VME)
TOWARDS LHC

• In some experiments, it is not practical to make a trigger decision in the time between bunch crossings because of the short BC period
  – In such cases, we have to introduce the concept of “pipelined” readout (and also pipelined LVL1 trigger processing)

• In experiments at high-luminosity hadron colliders, the data rates after the LVL1 trigger selection are still very high
  – We have to introduce new ideas also for the High-Level Triggers and DAQ
    • e.g. event building based on data networks rather than data buses

<table>
<thead>
<tr>
<th>Machine</th>
<th>BC period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron-II</td>
<td>132 ns</td>
</tr>
<tr>
<td>HERA</td>
<td>96 ns</td>
</tr>
<tr>
<td>LHC</td>
<td>25 ns</td>
</tr>
</tbody>
</table>
Pipelined readout

- In pipelined readout systems, the information from each bunch-crossing, for each detector element, is retained during the latency of the LVL1 trigger (several µs).
- The information retained may be in several forms:
  - Analogue level (held on capacitor)
  - Digital value (e.g. ADC result)
  - Binary value (i.e. hit / no hit)
Pipelined readout (e.g. LHC)

1. BC clock (every 25 ns)

2. Signals (every 25 ns)

3. Trigger y/n (every 25 ns)

Latency of LVL1 trigger matches length of the pipeline

Small dead-time here (few BC to avoid overlap of readout frames)

Introduce dead-time here to avoid overflow of derandomizers
Example: ATLAS

Dead-time (1):
Depends on readout frame size
75 kHz LVL1 rate
4 BC dead = 100 ns
Dead-time =
\[ 7.5 \times 10^4 \times 10^{-7} = 0.75\% \]

Dead-time (2):
Depends on size of derandomizer and speed with which it is emptied
Require dead-time
\(< 1\% \text{ @ } 75 \text{ kHz} \)
\(< 6\% \text{ @ } 100 \text{ kHz} \)
LHC model (e.g. CMS)

Signals (every 25 ns) → (Digitizer) Pipeline → Derandomizers → FED

BC clock (every 25 ns) → LVL1 (fixed latency) → Multiplex → Large Buffer

On Detector
No access
Radiation environment
Etc.

Off Detector

Data Network → LVL2/3
Digitisation options

Signals (every 25 ns)

(Digitizer) Pipeline

BC clock (every 25 ns)

e.g. CMS calorimeter

e.g. ATLAS EM calorimeter

e.g. CMS tracker

FED
Pipelined LVL1 trigger

- The LVL1 trigger has to deliver a new decision every BC, but the trigger latency is much longer than the BC period
  - The LVL1 trigger must concurrently process many events
  - This can be achieved by “pipelining” the processing in custom trigger processors built using modern digital electronics
    - Break processing down into a series of steps, each of which can be performed within a single BC period
    - Many operations can be performed in parallel by having separate processing logic for each one
  - Note that the latency of the trigger is fixed
    - Determined by the number of steps in the calculation plus the time taken to move signals and data to and from the components of the trigger system
Pipelined LVL1 trigger

EM Calorimeter
(~3500 trigger towers)

Output = (A+B)>T OR (A+C)>T
LVL1 data flow

Many input data

Energies in calorimeter towers
(e.g. ~7000 trigger towers in ATLAS)

Pattern of hits in muon detectors
(e.g. $O(10^6)$ channels in ATLAS)

Fan-out
(e.g. each tower participates in many calculations)

Tree

(Data for monitoring)

1-bit output
(YES or NO)

(Information to guide next selection level)
High-Level Triggers and DAQ at LHC

• In the LHC experiments, data are transferred to large buffer memories after a LVL1 accept
  – In normal operation, the subsequent stages should not introduce further dead-time
• The data rates at the HLT/DAQ input are still massive
  – ~1 MByte event size (after data compression) @ ~100 kHz event rate ⇒ ~100 GByte/s data rate (i.e. ~800 Gbit/s)
• This is far beyond the capacity of the bus-based event building of LEP
  – Use network-based event building to avoid bandwidth bottlenecks

Data are stored in Readout Systems until they have been transferred to the Filter Systems (associated with HLT processing), or until the event is rejected

No node in the system sees the full data rate — each Readout System covers only a part of the detector — each Filter System deals with only a fraction of the events
HLT and DAQ: Concepts

- The massive data rate after LVL1 poses problems even for network-based event building — different solutions have been adopted to address this, for example:
  - In CMS, the event building is factorized into a number of slices each of which sees only a fraction of the rate
    - Requires large total network bandwidth (⇒ cost), but avoids the need for a very large single network switch
  - In ATLAS, the Region-of-Interest (RoI) mechanism is used to access the data selectively – only move data needed for LVL2 processing
    - Reduces by a substantial factor the amount of data that needs to be moved from the Readout Systems to the Processors
    - Implies relatively complicated mechanisms to serve the data selectively to the LVL2 trigger processors ⇒ more complex software
CMS: The Slicing concept

Eight slices:
Each slice sees only 1/8\textsuperscript{th} of the events

Additional advantage:
Don’t have to implement all slices initially (funding limitations)
ATLAS: The Region-of-Interest and sequential-selection concepts

- **Muon identification**
  - LVL1 identifies RoIs
  - Validate in muon spectrometer
    - Reject?
  - Validate in inner tracker
    - Reject?
  - Isolation in calorimeter
    - Reject?

- Two concepts are used to avoid moving all the data from the Readout Systems
  - **The Region-of-Interest (RoI) concept**
    - LVL1 indicates the geographical location of candidate objects
      - E.g. two muon candidates
    - LVL2 only accesses data from RoIs
      - Small fraction of total data
  - **The sequential-selection concept**
    - Data are accessed by LVL2 initially only from a subset of detectors (e.g. muon spectrometer only)
    - Many events rejected without accessing the other detectors
      - Further reduction in total data transfer
HLT/DAQ at LHC: Implementation

• There are many commonalities in the way the different experiments have implemented their HLT/DAQ systems
  – The computer industry provides the technologies that have been used to build much of the HLT/DAQ systems at LHC
    • Computer networks & switches: high performance at affordable cost
    • PCs: exceptional value for money in processing power
    • High-speed network interfaces: standard items (e.g. Ethernet at 1 Gbit/s)
  – Some custom hardware is needed in the parts of the system that see the full LVL1 output event rate ($O(100)$ kHz in ATLAS/CMS)
    • Readout Systems that receive the detector data following a positive LVL1 decision
    • In ATLAS, the interface to the LVL1 trigger that receives RoI information
    • Of course, this is in addition to the specialized front-end electronics of the detector
Lecture 2
Questions from last lecture?
Plan for today’s lecture

• Requirements and constraints for triggering at the LHC
  – Driven by the physics objectives of the experiments
    • ATLAS and CMS (general-purpose, proton-proton, discovery physics)
    • LHCb (B physics, proton-proton)
    • ALICE (specialized for heavy-ion collisions)

• Case study from LHC illustrating how the T/DAQ implementation follows the ideas presented yesterday
  – Example of electron/photon trigger in ATLAS

• Commissioning of the T/DAQ systems for LHC in 2008
  – With single bunch, single beam at the injection energy of 450 GeV
    • No collisions or acceleration yet, unfortunately!
  – And using cosmic rays (won’t have time to cover this)
Requirements – ATLAS and CMS

• Triggers in the general-purpose proton–proton experiments, ATLAS and CMS, will have to:
  – Retain as many as possible of the events of interest for the diverse physics programmes of these experiments
    • Higgs searches (Standard Model and beyond)
      – e.g. $H \rightarrow ZZ \rightarrow$ leptons, $H \rightarrow gg$; also $H \rightarrow tt$, $H \rightarrow bb$
    • SUSY searches
      – With and without R-parity conservation
    • Searches for other new physics
      – Using inclusive triggers that one hopes will be sensitive to any unpredicted new physics
    • Precision physics studies
      – e.g. measurement of W mass
    • B-physics studies (especially in the early phases of these experiments)
      – N.b. selections often need to be made at analysis level to suppress backgrounds, so focus especially on events that will be retained
Constraints – ATLAS and CMS

• However, they also need to reduce the event rate to a manageable level for data recording and offline analysis
  – $L = 10^{34}$ cm$^{-2}$s$^{-1}$, and $\sigma \sim 100$ mb $\Rightarrow 10^9$ Hz interaction rate
    • Even rate of events containing leptonic W and Z decays is $O(100$ Hz$)$
  – The size of the events is very large, $O(1)$ MByte
    • Huge number of detector channels, high particle multiplicity per event
  – Recording and subsequently processing offline, $O(100)$ Hz event rate per exp$^t$ with $O(1)$ MByte event size implies major computing resources!
  – Hence, only a tiny fraction of proton–proton collisions can be selected
    • Maximum fraction of interactions triggering at full luminosity $O(10^{-7})$

• Have to balance needs of maximising physics coverage and reaching acceptable (i.e. affordable) recording rates
The LHCb experiment, which is dedicated to studying B-physics, faces similar challenges to ATLAS and CMS.

- It will operate at a comparatively low luminosity ($\sim 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$), giving an overall proton–proton interaction rate of $\sim 20$ MHz.
  - Chosen to maximise the rate of single-interaction bunch-crossings.
- The event size is comparatively small ($\sim 100$ kByte).
  - Fewer detector channels.
  - Less occupancy due to lower luminosity.
- However, there is a very high rate of beauty production.
  - Given $\sigma \sim 500$ µb, bb production rate $\sim 100$ kHz.
- The trigger must therefore search for specific B decay modes that are of interest for the physics analysis.
  - Aim to record event rate of only $\sim 200$ Hz.

LHCb
ALICE

- The heavy-ion experiment ALICE is also very demanding, particularly from the DAQ point of view
  - The total interaction rate will be much smaller than in the pp experiments
    - \( L \sim 10^{27} \text{ cm}^{-2}\text{s}^{-1} \Rightarrow R \sim 8000 \text{ Hz for Pb–Pb collisions} \)
  - The trigger will select “minimum-bias” and “central” events (rates scaled down to total \( \sim 40 \text{ Hz} \)), and events with dileptons (\( \sim 1 \text{ kHz with only part of the detector read out} \))
  - However, the event size will be huge due to the high particle multiplicity in Pb–Pb collisions at LHC energy
    - Up to \( O(10,000) \) charged particles in the central region
    - Event size up to \( \sim 40 \text{ MByte} \) when the full detector is read out
  - Even more than in the other experiments, the volume of data to be stored and subsequently processed offline will be massive
    - Data rate to storage \( \sim 1 \text{ GByte/s} \) (limited by what is possible/affordable)
Signatures used for triggers

- IDET
- ECAL
- HCAL
- MuDET

- e
- γ
- jet
- μ
- ν
LVL1 selection criteria

- Features that distinguish new physics from the bulk of the cross-section for Standard Model processes at hadron colliders are
  - In general, the presence of high-\(p_T\) particles (or jets)
    - e.g. these may be the products of the decays of new heavy particles
      - In contrast, most of the particles produced in minimum-bias interactions are soft (\(p_T \sim 1\) GeV or less)
  - More specifically, the presence of high-\(p_T\) leptons (e, \(\mu\), \(\tau\)), photons and/or neutrinos
    - e.g. the products (directly or indirectly) of new heavy particles
      - These give a clean signature c.f. low-\(p_T\) hadrons in minimum-bias case, especially if they are “isolated” (i.e. not inside jets)
  - The presence of known heavy particles
    - e.g. W and Z bosons may be produced in Higgs particle decays
      - Leptonic W and Z decays give a very clean signature
        » Also interesting for physics analysis and detector studies
LVL1 signatures at hadron colliders

• LVL1 triggers therefore search for
  – High-\(p_T\) muons
    • Identified beyond calorimeters; need \(p_T\) cut to control rate from \(\pi^+ \rightarrow \mu\nu\), \(K^+ \rightarrow \mu\nu\), as well as semi-leptonic beauty and charm decays
  – High-\(p_T\) photons
    • Identified as narrow EM calorimeter clusters; need cut on \(E_T\); cuts on isolation and hadronic-energy veto reduce strongly rates from high-\(p_T\) jets
  – High-\(p_T\) electrons
    • Same as photon (some experiments require matching track already at LVL1)
  – High-\(p_T\) taus (decaying to hadrons)
    • Identified as narrow cluster in EM+hadronic calorimeters
  – High-\(p_T\) jets
    • Identified as cluster in EM+hadronic calorimeter — need to cut at very high \(p_T\) to control rate (jets are dominant high-\(p_T\) process)
  – Large missing \(E_T\) or total scalar \(E_T\)
LVL1 trigger menu

• An illustrative trigger menu for LHC at high luminosity includes:
  – One or more muons with $p_T > 20$ GeV (rate ~ 11 kHz)
  – Two or more muons each with $p_T > 6$ GeV (rate ~ 1 kHz)
  – One or more e/$\gamma$ with $E_T > 30$ GeV (rate ~ 22 kHz)
  – Two or more e/$\gamma$ each with $E_T > 20$ GeV (rate ~ 5 kHz)
  – One or more jets with $E_T > 290$ GeV (rate ~ 200 Hz)
  – One or more jets with $E_T > 100$ GeV & $E_T^{miss} > 100$ GeV (rate ~ 500 Hz)
  – Three or more jets with $E_T > 130$ GeV (rate ~ 200 Hz)
  – Four or more jets with $E_T > 90$ GeV (rate ~ 200 Hz)

• Full menu will include many items in addition (>100 items total)
  – Items with $\tau$ (or isolated single-hadron) candidates
  – Items with combinations of objects (e.g. muon & electron)
  – Pre-scaled triggers with lower thresholds
  – Triggers for technical studies and to aid understanding of data
    • e.g. trigger on bunch-crossings at random to collect unbiased sample
HLT menu

• Illustrative menu for LHC at $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ luminosity (CMS):
  - $p_T^e > 29 \text{ GeV}$ or 2 electrons $p_T^e > 17 \text{ GeV}$
    • Rate $\sim 34 \text{ Hz}$
  - $p_T^\gamma > 80 \text{ GeV}$ or 2 photons $p_T^\gamma > 40, 25 \text{ GeV}$
    • Rate $\sim 9 \text{ Hz}$
  - $p_T^\mu > 19 \text{ GeV}$ or 2 muons $p_T^\mu > 7 \text{ GeV}$
    • Rate $\sim 29 \text{ Hz}$
  - $p_T^\tau > 86 \text{ GeV}$ or 2 taus $p_T^\tau > 59 \text{ GeV}$
    • Rate $\sim 4 \text{ Hz}$
  - $p_T^{\text{jet}} > 180 \text{ GeV}$ and missing $E_T > 123 \text{ GeV}$
    • Rate $\sim 5 \text{ Hz}$
  - $p_T^{\text{jet}} > 657 \text{ GeV}$ or 3 jets $p_T^{\text{jet}} > 247 \text{ GeV}$ or 4 jets $p_T^{\text{jet}} > 113 \text{ GeV}$
    • Rate $\sim 9 \text{ Hz}$
  - Others (electron•jet; b-jets, etc.)
    • Rate $\sim 7 \text{ Hz}$
  - Total $\sim 100 \text{ Hz}$ of which a large fraction is “physics” – large uncertainty on rates!
    • Need to balance physics coverage against offline computing cost
Case study (e/γ trigger in ATLAS)

• Some general LVL1 trigger issues
  – The ATLAS LVL1 trigger system

• LVL1 e/γ algorithm and implementation
  – Example of pipe-lined trigger processing

• High-level electron trigger
  – Example where sophisticated event-selection algorithms need to be used online to get the required separation, with good signal efficiency and with high background rejection
    • Background primarily comes from high-\(p_T\) jets that are misidentified as electrons
      – There are lots of jets!
General LVL1-trigger design goals

• Need large reduction in physics rate already at the first level (otherwise readout system becomes unaffordable)
  – $O(10^9)$ interaction rate $\rightarrow$ less than 100 kHz in ATLAS and CMS
    • Require complex algorithms to reject background while keeping signal

• An important constraint is to achieve a short latency
  – Information from all detector channels ($O(10^8)$ channels!) has to be held in local memory on detector pending the LVL1 decision
    • The pipeline memories are typically implemented in ASICs (Application Specific Integrated Circuits), and memory size contributes to the cost
      – Typical values are a few $\mu$s (e.g. less than 2.5 $\mu$s ATLAS, 3.2 $\mu$s CMS)

• Require flexibility to react to changing conditions (e.g. wide luminosity range) and — hopefully — new physics
  – Algorithms must be programmable (adjustable parameters at least)
Overview of ATLAS LVL1 trigger

~7000 calorimeter trigger towers

Calorimeter trigger
- Pre-Processor (analogue → $E_T$)
- Jet / Energy-sum Processor
- Cluster Processor ($e/\gamma, \tau/h$)

Muon trigger
- Muon Barrel Trigger
- Muon End-cap Trigger
- Muon central trigger processor

Central Trigger Processor (CTP)
Local Trigger Processors (LTP)
Timing, Trigger, Control (TTC)

Radiation tolerance, cooling, grounding, magnetic field, no access

Latency limit 2.5 µs

Design all digital, except input stage of calorimeter trigger Pre-Processor

$O(1M)$ RPC/TGC channels
ATLAS LVL1 e/γ trigger

- ATLAS e/γ trigger is based on 4×4 “overlapping, sliding windows” of trigger towers
  - Each trigger tower 0.1×0.1 in η×φ
    - η pseudo-rapidity, φ azimuth
  - ~3500 such towers in each of the EM and hadronic calorimeters
- There are ~3500 such windows
  - Each tower participates in calculations for 16 windows
    - This is a driving factor in the trigger design
ATLAS LVL1 calorimeter trigger

- Analogue electronics on detector sums signals to form trigger towers
- Signals received and digitised
  - Digital data processed to measure $E_T$ per tower for each BC
    - $E_T$ matrix for ECAL and HCAL
- Tower data transmitted to Cluster Processor (only 4 crates in total)
  - Fan out values needed in more than one crate
    - Motivation for very compact design of processor
- Within CP crate, values need to be fanned out between electronic modules, and between processing elements on the modules
- Connectivity and data-movement issues drive the design
Bunch-crossing identification

- Calorimeter signals extend over many bunch-crossings
  - Need to combine information from a sequence of measurements to estimate the energy and identify the bunch-crossing where energy was deposited
- Apply Finite Impulse Response filter
  - Result $\rightarrow$ LUT to convert value to $E_T$
  - Result $\rightarrow$ peak finder to determine BC where energy was deposited
- Need to take care of signal distortion for very large pulses
  - Don’t lose most interesting physics!
- An ASIC incorporates the above
Data transmission and Cluster Processor  
(numbers for ATLAS)

- The array of $E_T$ values computed in the previous stage has to be transmitted to the CP
  - Use digital electrical links to Cluster Processor modules
    - ~5000 links @ 400 Mbps
  - Fan-out data to neighbouring modules over very high-density custom back-plane
    - ~800 pins per slot in 9U crate
    - 160 Mbps point-to-point
  - Fan out data to 8 large FPGAs † per module
    - On-board fan out is comparatively straightforward

- The e/$\gamma$ (together with the $\tau/h$) algorithm is implemented in FPGAs
  - This has only become feasible with recent advances in FPGA technology
    - Require very large and very fast devices
  - Each FPGA handles $4\times2$ windows
    - Needs data from $7\times5\times2$ towers ($\eta\times\phi\times\{E/H\}$)
  - Algorithm is described in a programming language that can be converted into FPGA configuration file
    - Flexibility to adapt algorithms in the light of experience
  - Parameters of the algorithms can be changed easily
    - e.g. cluster-$E_T$ thresholds are held in registers that can be programmed

† FPGA = Field Programmable Gate Array  
i.e. reprogrammable logic
HLT electron trigger

• LVL1 $e/\gamma$ trigger is already very selective
  – Need to use complex algorithms and full-granularity detector data in HLT
• Calorimeter selection
  – Sharpen $E_T$ cut
  – Use shower-shape variables
    • Laterally and in depth
• Associated track in inner detector
  – Matching calorimeter cluster
    • Energy – momentum consistent
• Much work to develop algorithms and tune their many parameters to optimize signal efficiency and background rejection
  – Efficiency depends on signal definition

• HLT is implemented in software, running on farms of PCs
  – Almost full flexibility within the constraints of the available computing resources
  – Available time per event is 10s of milliseconds to a few seconds (second and third
Commissioning of the T/DAQ systems during start-up of LHC in 2008

• Some history
  – 10 September 2008, first beam in the LHC (1 bunch at a time, 450 GeV)
    • Beam on collimators – “beam splash” events
    • Beam circulating for a few turns
    • Beam circulating for tens of minutes
    • No collisions (just single beam), no acceleration (injection energy)
    • Lots of media attention!
  – 19 September 2008, serious incident required shut-down of LHC
    • Will restart commissioning the T/DAQ systems with beam this autumn
      – After repairs and improvements to the LHC machine
    • In meantime, much experience gained running experiments with cosmic rays
Commissioning of the T/DAQ systems

• First objectives (plans)
  – Establish a stable time reference
    • Trigger on incoming beam (beam pick-ups, see later)
  – Time-in the experiment
    • Adjust programmable delays to read out the correct BC over the full detector
      – Note that Time-of-Flight corrections are different for outgoing collision products, downward-going cosmic-ray muons, and beam-halo (see later)
    • Adjust programmable delays to align all other LVL1 triggers to the reference
      – Minimum-bias trigger
      – Calorimeter triggers (including e/γ)
      – Muon triggers
  – Provide minimum-bias trigger (for single beam / collisions)
    • Trigger on activity in detector as well as (in time coincidence with) beam
  – Provide more selective LVL1 triggers, then progressively add HLT
Some examples from ATLAS and CMS

• Splash event and associated distribution
  – These events had a huge amount of activity in the detectors and fired many triggers

• Beam pick-up signals
  – See beam signals correlated with timing signals provided by machine

• Beam-halo event and associated distribution
  – Small number of beam-halo muons in each event, see correlations between different detector subsystems

• Illustration of progress in tuning trigger timing
  – Example of work done in all experiments

• Muon time of flight (consistent with speed of light)
Beam-splash event in ATLAS
Study $E_T$ and time versus $\eta$, $\phi$

- Beam-splash events very useful
  - Identify (very few) problem channels, e.g. bad time calibration

- Note that ToF and 8-fold symmetry of ATLAS detector in $\phi$ can be seen in this plot of LVL1 calorimeter trigger $E_T$ versus $\eta$, $\phi$
Use beam pick-ups as time reference

Plot from CMS
A beam-halo event in CMS
(muon seen in CSCs and in HCAL)
CMS – beam halo and cosmic muons

beam halo data 12-Sep-2008

orange: beam ON data
black: beam OFF data
blue: beam halo simulation

angle w.r.t. normal (radians)
Tuning the timing of ATLAS trigger (progress between 10 and 12 Sep 2008)

- Note change in horizontal scale
- Note logarithmic vertical scale
See Time-of-Flight of beam-halo muons (~100 ns to traverse ATLAS)

Distance between muon TGC detectors at opposite ends of ATLAS is 28 m (92 ns) at speed of light
Final Remarks

- I hope I have succeeded to give you some insight into the challenges of building T/DAQ systems for HEP experiments
  - Challenges in physics (inventing algorithms that are fast, efficient for the physics that we want to do and give good rate reduction), and challenges in electronics and computing
- Also how the subject has evolved to meet the increasing demands, e.g. LHC compared to LEP
  - New ideas exploiting new technologies
- Finally, I hope that more of you will participate actively in this exciting field in the years to come!
Spares
Triggers at LEP

- The triggers at LEP aimed to select any $e^+e^-$ annihilation event giving a visible final state
  - Including events with little visible energy
  - Plus some fraction of two-photon events
  - Plus Bhabha scattering events

- Furthermore, they aimed to select most events by multiple, independent signatures
  - Maximize efficiency
    - Probability to pass trigger A OR trigger B $\sim 1 - \delta_A \delta_B$
      - $\delta_X = \text{inefficiency of trigger } X$, assuming losses uncorrelated
    - Allow measurement of the trigger efficiency from the data
      - Use events selected by trigger A to measure the efficiency for trigger B, and vice versa
PHYSICS REQUIREMENTS — TWO COMPLEMENTARY EXAMPLES

- **LEP**
  - Precision physics was main emphasis
  - Absolute cross-section determination was critical
    - E.g. determination of the number of neutrino species

- **LHC**
  - Discovery physics will be main emphasis
    - Vast range of predicted processes with diverse signatures
      - Very low signal rates expected in some cases
    - Should also be sensitive to new physics that has not been predicted!
  - Huge rate of Standard Model physics backgrounds
    - Rate of proton–proton collisions $\sim 10^9$ Hz ($\sigma = 100$ mb, $L = 10^{34}$ cm$^{-2}$s$^{-1}$)
LEP requirements (1)

- Trigger had to:
  - Identify all events coming from $e^+e^-$ annihilations with visible final states
    - Including at LEP-I: $Z \rightarrow $ hadrons, $Z \rightarrow e^+e^-$, $Z \rightarrow \mu^+\mu^-$, $Z \rightarrow \tau^+\tau^-$
    - Including at LEP-II: WW, ZZ, single-boson
    - Including cases where there is little visible energy
      - e.g. in Standard Model: $e^+e^- \rightarrow Z\gamma \rightarrow \nu\nu\gamma$
      - e.g. in new particle searches such as $e^+e^- \rightarrow \chi^+\chi^-$ (with small $\chi^+ - \chi^0$ mass difference), giving only low energy visible particles ($\chi^0$ LSP)
  - Retain some fraction of two-photon collision events
    - Used for QCD studies
  - Identify Bhabha scatters
    - Needed for precise luminosity determination
LEP requirements (2)

• Could retain events with any significant activity in the detector
  – Even when running at Z peak, rate of Z decays was only $O(1 \text{ Hz})$
    • Physics rate was not an issue

• Challenge was in maximising efficiency/acceptance of trigger
  – And also, making sure that the efficiency and acceptance could be determined with very high precision
    • Absolute cross-section determination depends on knowing:
      – Integrated luminosity (efficiency to trigger on Bhabha events)
      – Experimental efficiency and acceptance for process in question (efficiency to trigger on physics process)
        » Events selected by many redundant triggers
          (high efficiency; cross-checks)
    • A major achievement at LEP was to reach per-mil precision

• The trigger rates and also the DAQ data rates were modest
Selection criteria at LEP

• Details depend on the experiment, e.g. ALEPH “menu” was as follows:
  – Triggers implemented within segments (60 regions in $\theta$, $\phi$)
    • Single muon trigger
      – Track seen penetrating the hadron calorimeter & seen in the Inner Tracker
    • Single charged EM energy trigger
      – EM calorimeter cluster and track in Inner Tracker
    • Single neutral EM energy trigger
      – EM calorimeter cluster
        » Higher threshold than above to keep the rate down
  – Total-energy triggers
    • Threshold on energies summed over large regions (barrel or a full endcap)
  – Back-to-back tracks trigger
  – Bhabha luminosity-monitor triggers
Trigger implementation at LEP

- In general, LVL1 triggers were implemented using a combination of analogue and digital electronics.
- Details depend on the experiment, e.g. ALEPH was as follows:
  - Calorimeter triggers were implemented using analogue electronics to sum signals, applying thresholds on the sums.
  - LVL1 tracking trigger looked for patterns of hits in the Inner Tracking Chamber (ITC) consistent with a track with $p_T > 1$ GeV/c.
    - At LVL2, information from the TPC was used instead.
  - Final decision was made by combining digital information from the calorimeter and tracking triggers.
    - Local combinations within segments of the detector.
    - Global combination (logical OR of conditions).
HLT/DAQ Software

- A major challenge lies in the HLT/DAQ software
  - Algorithms
    - HLT can be subdivided into LVL2 and LVL3
    - Separate processor systems (e.g. ATLAS) or two distinct processing steps in the same processor system (e.g. CMS)
  - Framework that manages the flow of data and supports the algorithms
    - Supervising an event from when it arrives at the HLT/DAQ system until it is rejected or accepted and recorded to permanent storage
    - Transporting data to the algorithms as required
  - Large amount of associated online software
    - Run control
    - Databases (description of hardware & software, calibration constants, etc.)
    - Book-keeping (run conditions, log of errors, etc)
    - Etc
DAQ at LEP (e.g. ALEPH)
Minimum-Bias Trigger Scintillators
Following a LVL2 trigger, events were read out as follows:

- Data were transferred within each crate to the readout controller (ROC)
  - After this, further LVL1 and LVL2 triggers could be accepted
  - Events were “built” in two stages
    - Event
      - Sub-event $\times n$
        » ROC data block $\times m$

Once events were in the main readout computer, the LVL3 trigger made a final selection before data were recorded
The ALEPH DAQ used a hierarchy of computers

- Local readout controllers (ROCs) in each crate
  - In addition to reading out the data from ADCs, TDCs, etc., these performed processing (e.g., applying calibration to convert raw ADC values to energies)
    - Zero suppression was already performed at the level of the digitizers where appropriate
  - Event builders (EBs) for sub-events
    - These combined data read out from the ROCs of a given sub-detector into a sub-event
  - Main event builder
    - Combined data from the EBs for the different detectors
  - Main readout computer
    - Received full events from main EB; performed LVL3 trigger selection; recorded selected events for subsequent offline analysis
Size of detectors and the speed of light

$\mathbf{p_T} \equiv \text{transverse momentum } \perp \text{ beams}$

Trigger finds high-$\mathbf{p_T}$ muon here $\Rightarrow$ select event

ATLAS, the biggest of the LHC detectors, is 22 m in diameter and 46 m in length

Need to read out also here

The other LHC detectors are smaller, but similar considerations apply

22 m $\times$ 3.3 ns/m = 73 ns

c.f. 25 ns BC period

It is impossible to form and distribute a trigger decision within 25 ns given that the readout pipelines are mounted on the detector