Triggering (at the LHC)

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CERN/PH and Univ. of Athens
SLAC Summer Institute 2006
July 2006

- Introduction
  - LHC: The machine and the physics
  - Trigger/DAQ architectures and tradeoffs

- Level-1 Trigger
  - Architectures, elements, performance

- DAQ
  - Readout, Event-Building, Control & monitor

- High-Level trigger
  - Farms, algorithms
LHC: physics goals and machine parameters
Collisions at the LHC: summary

- **Proton - Proton**: 2804 bunch/beam
- **Protons/bunch**: $10^{11}$
- **Beam energy**: 7 TeV ($7 \times 10^{12}$ eV)
- **Luminosity**: $10^{34}$ cm$^{-2}$ s$^{-1}$
- **Crossing rate**: 40 MHz
- **Collision rate**: $\approx 10^7$-$10^9$
- **New physics rate**: $\approx 0.00001$ Hz
- **Event selection**: 1 in $10,000,000,000,000$
Higgs boson production at LHC

- Primary physics goal: explore the physics of Electroweak symmetry breaking.
  - In the SM: the Higgs
  - Energy of the collider: dictated by machine radius and magnets
  - Luminosity: determine from requirements

- Higgs mass: unknown; could be up to \( \sim 1\) TeV/c\(^2\).
  - Wish: \( \sim 20-30 \) events/year at highest masses

- Luminosity needed: \( 10^{34} \) cm\(^{-2}\) s\(^{-1}\)
  - At \( 10^{11} \) protons/bunch, 27 km (i.e. 90 \( \mu \)s), need \( \sim 3000 \) bunches
LHC will have ~3600 bunches
  - And same length as LEP (27 km)
  - Distance between bunches: 27km/3600=7.5m
  - Distance between bunches in time: 7.5m/c=25ns

- LEP: e⁺e⁻ Crossing rate 30 kHz
  - 22µs

- Tevatron Run I
  - 3.5µs

- Tevatron Run II
  - 396ns

- LHC: pp Crossing rate 40 MHz
  - 25ns

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**pp cross section and min. bias**

- **# of interactions/crossing:**
  - **Interactions/s:**
    - $\text{Lum} = 10^{34} \text{ cm}^{-2}\text{s}^{-1} = 10^7 \text{mb}^{-1}\text{Hz}$
    - $\sigma(pp) = 70 \text{ mb}$
    - Interaction Rate, $R = 7 \times 10^8 \text{ Hz}$
  - **Events/beam crossing:**
    - $\Delta t = 25 \text{ ns} = 2.5 \times 10^{-8} \text{ s}$
    - Interactions/crossing = 17.5
  - **Not all p bunches are full**
    - 2835 out of 3564 only
    - Interactions/”active” crossing = $17.5 \times 3564/2835 = 23$

**Operating conditions (summary):**
1) A "good" event containing a Higgs decay +
2) $\approx 20$ extra "bad" (minimum bias) interactions
**pp collisions at 14 TeV at 10^{34} cm^{-2}s^{-1}**

- 20 min bias events overlap
- \( H \rightarrow ZZ \)
- \( Z \rightarrow \mu \mu \)
- \( H \rightarrow 4 \) muons: the cleanest ("golden") signature

Reconstructed tracks with \( p_T > 25 \) GeV

And this (not the H though…) repeats every 25 ns…
Impact on detector design

- LHC detectors must have fast response
  - Avoid integrating over many bunch crossings (“pile-up”)
  - Typical response time: 20-50 ns
    → integrate over 1-2 bunch crossings → pile-up of 25-50 minimum-bias events → very challenging readout electronics

- LHC detectors must be highly granular
  - Minimize probability that pile-up particles be in the same detector element as interesting object (e.g. γ from H → γγ decays)
    → large number of electronic channels

- LHC detectors must be radiation resistant:
  - high flux of particles from pp collisions → high radiation environment e.g. in forward calorimeters:
    - up to $10^{17}$ n/cm² in 10 years of LHC operation
    - up to $10^7$ Gy (1 Gy = unit of absorbed energy = 1 Joule/Kg)
Pile-up

- “In-time” pile-up: particles from the same crossing but from a different pp interaction

- Long detector response/pulse shapes:
  - “Out-of-time” pile-up: left-over signals from interactions in previous crossings
  - Need “bunch-crossing identification”

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In-time pulse

super-
impose

Out-of-time pulses

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Time of Flight

c=30cm/ns; in 25ns, s=7.5m
Selectivity: the physics

- Cross sections of physics processes vary over many orders of magnitude
  - Inelastic: $10^9$ Hz
  - $W \rightarrow \ell \nu$: $10^2$ Hz
  - $t\bar{t}$ production: 10 Hz
  - Higgs (100 GeV/c$^2$): 0.1 Hz
  - Higgs (600 GeV/c$^2$): $10^{-2}$ Hz

- QCD background
  - Jet $E_T \sim 250$ GeV: rate = 1 kHz
  - Jet fluctuations $\rightarrow$ electron bkg
  - Decays of $K, \pi, b \rightarrow$ muon bkg

- Selection needed: $1:10^{10-11}$
  - Before branching fractions...
Physics selection at the LHC

LEVEL-1 Trigger
Hardwired processors (ASIC, FPGA)
Pipelined massive parallel

HIGH LEVEL Triggers
Farms of processors

Reconstruction & Analysis
Tier 0/1/2 Centers

ON-line
OFF-line
Trigger/DAQ requirements/challenges

- $N$ (channels) $\sim O(10^7)$; $\approx 20$ interactions every 25 ns
  - need huge number of connections
  - need information super-highway
- Calorimeter information should correspond to tracker info
  - need to synchronize detector elements to (better than) 25 ns
- In some cases: detector signal/time of flight $> 25$ ns
  - integrate more than one bunch crossing's worth of information
  - need to identify bunch crossing...
- Can store data at $\approx 10^2$ Hz
  - need to reject most interactions
- It's On-Line (cannot go back and recover events)
  - need to monitor selection
Trigger/DAQ: architectures
Online Selection Flow in pp

- Level-1 trigger: reduce 40 MHz to $10^5$ Hz
  - This step is always there
  - Upstream: still need to get to $10^2$ Hz; in 1 or 2 extra steps

```
Front end pipelines
Readout buffers
Switching network
Processor farms
```

"Traditional": 3 physical levels

```
Front end pipelines
Readout buffers
Switching network
Processor farms
```

CMS: 2 physical levels
Three physical entities

- Additional processing in LV-2: reduce network bandwidth requirements

![Diagram showing the flow of data through different levels of processing and the timeline of various processes.]

- **Level-1 Trigger**: 40 MHz, 10^5 Hz, 10^3 Hz, 10 Gb/s
- **Level-2**: 10^2 Hz
- **Level-3**: 25 ns, 1 µs, 1 ms, 1 sec

**QED**
- W, Z
- Top
- Z*
- Higgs

**Available processing time**
- High Level Triggers 1 kHz
- Specialized processors (feature extraction and global logic)
- Massively Parallel Pipelined Logic Systems
- LEVEL-1 Trigger 40 MHz
- Hardwired processors (ASIC, FPGA)

**Event Manager**
- Level-1
- Level-2
- Level-3

**Detector Frontend**
- Readout
- Builder Network
- Computing services

**Farms**
- Switch

**Switches**
- Level-1 to Level-2
- Level-2 to Level-3

**Switches**
- Event Manager

**Processing Rates**
- 10^8 Hz
- 10^6 Hz
- 10^4 Hz
- 10^2 Hz
- 10^1 Hz
- 10^0 Hz
Two physical entities

- Reduce number of building blocks
- Rely on commercial components (especially processing and communications)
Comparison of 2 vs 3 physical levels

- **Three Physical Levels**
  - **Investment in:**
    - Control Logic
    - Specialized processors

- **Two Physical Levels**
  - **Investment in:**
    - Bandwidth
    - Commercial Processors
### Trigger/DAQ parameters: summary

<table>
<thead>
<tr>
<th>Experiment</th>
<th>No. Levels</th>
<th>Level-1 Trigger Rate (Hz)</th>
<th>Event Size (Byte)</th>
<th>Readout Bandw.(GB/s)</th>
<th>Filter Out MB/s (Event/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>3</td>
<td>10^5</td>
<td>10^6</td>
<td>10</td>
<td>100 (10^2)</td>
</tr>
<tr>
<td></td>
<td>LV-2</td>
<td>10^3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMS</td>
<td>2</td>
<td>10^5</td>
<td>10^6</td>
<td>100</td>
<td>100 (10^2)</td>
</tr>
<tr>
<td>LHCb</td>
<td>3</td>
<td>LV-0 10^6</td>
<td>2x10^5</td>
<td>4</td>
<td>40 (2x10^2)</td>
</tr>
<tr>
<td></td>
<td>LV-1</td>
<td>4 10^4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALICE</td>
<td>4</td>
<td>Pp-Pp 500</td>
<td>5x10^7</td>
<td>5</td>
<td>1250 (10^2)</td>
</tr>
<tr>
<td></td>
<td>p-p</td>
<td>10^3</td>
<td>2x10^6</td>
<td></td>
<td>200 (10^2)</td>
</tr>
</tbody>
</table>

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## Trigger/DAQ systems: grand view

### ATLAS

- Levels: 3
- LV-1 rate: 100 kHz
- Readout: 10 GB/s
- Storage: 100 MB/s

### ALICE

- Levels: 4
- LV-1 rate: 500 kHz
- Readout: 5 GB/s
- Storage: 1250 MB/s

### CMS

- Levels: 2
- LV-1 rate: 100 kHz
- Readout: 100 GB/s
- Storage: 100 MB/s

### LHCb

- Levels: 3
- LV-1 rate: 1 MHz
- Readout: 4 GB/s
- Storage: 40 MB/s

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Level-1 Trigger
Physics selection at the LHC

- **LEVEL-1 Trigger**
  - Hardwired processors (ASIC, FPGA)
  - Pipelined massive parallel

- **HIGH LEVEL Triggers**
  - Farms of processors

- **Reconstruction & Analysis**
  - Tier 0/1/2 Centers

- ON-line vs OFF-line

- Time scales:
  - 25 ns
  - 3 µs
  - ms
  - sec
  - hour
  - year

- Data sizes:
  - 10^9 Giga
  - 10^12 Tera
  - 10^15 Petabit

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Physics facts:
- pp collisions produce mainly hadrons with $P_T \sim 1$ GeV
- Interesting physics (old and new) has particles (leptons and hadrons) with large transverse momenta:
  - $W \rightarrow e\nu$: $M(W)=80$ GeV/c$^2$; $P_T(e) \sim 30-40$ GeV
  - $H(120$ GeV$) \rightarrow \gamma\gamma$: $P_T(\gamma) \sim 50-60$ GeV

Basic requirements:
- Impose high thresholds on particles
  - Implies distinguishing particle types; possible for electrons, muons and “jets”; beyond that, need complex algorithms
- Typical thresholds:
  - Single muon with $P_T > 20$ GeV (rate $\sim 10$ kHz)
  - Dimuons with $P_T > 6$ (rate $\sim 1$ kHz)
  - Single $e/\gamma$ with $P_T > 30$ GeV (rate $\sim 10-20$ kHz)
  - Dielectrons with $P_T > 20$ GeV (rate $\sim 5$ kHz)
  - Single jet with $P_T > 300$ GeV (rate $\sim 0.2-0.4$ kHz)
Particle signatures in the detector(s)

Use prompt data (calorimetry and muons) to identify:
High $p_t$ electron, muon, jets, missing $E_T$

CALORIMETERS
Cluster finding and energy deposition evaluation

New data every 25 ns
Decision latency ~ $\mu$s

MUON System
Segment and track finding

φ η

γ e

ν μ

n p
At Level-1: only calo and muon info

- Pattern recognition much faster/easier

- Compare to tracker info
  - Complex algorithms
  - Huge amounts of data
  - Need to link sub-detectors

- Simple algorithms
- Small amounts of data
- Local decisions
Level-1 Trigger: decision loop

- Synchronous 40 MHz digital system
  - Typical: 160 MHz internal pipeline
  - Latencies:
    - Readout + processing: < 1μs
    - Signal collection & distribution: ≈ 2μs
- At Lvl-1: process only calo+μ info

### Diagram

- Global Trigger 1
- Local level-1 trigger
  - Primitive e, γ, jets, μ
  - Pipeline delay (≈ 3 μs)
  - ≈ 2-3 μs latency loop

- Front-End Digitizer
- Trigger Primitive Generator
- Accept/Reject LV-1
Signaling and pipelining

Detector front end

Front end pipelines

Readout buffers

Light cone

Lvl-1

Control Room

Experiment

TIME

SPACE
Detector Readout: front-end types

ANALOG pipeline
- Shaper
- ASP
- Pipeline
- MUX
- ASP
- ADC
- DSP

DIGITAL Asynchronous
- LVL 1
- Bunch#
- Discr.
- Bunch#
- Pipeline
- DSP
- ADC
- Shaper

DIGITAL Synchronous
- 40 MHz
- Readout
- Pipeline
- DSP
- ADC
- Shaper
Clock distribution & synchronization

- Trigger, Timing & Control (TTC); from RD12

Global Trigger 1, Local level-1
Primitive e, g, jets, µ

Clock distribution & synchronization

Total latency - 128 BX

LHC Bunch Crossing number (from TTC)

Anode LCT Bunch Crossing number (data)

Clock phase adjustment

Programmable delays (in BX units)

Layout delays

t_{DET} + ALCT decision time
Lvl-1 trigger architecture: ATLAS

CMS ~ similar

~7000 calorimeter trigger towers
(analogue sum on detectors)

Calorimeter trigger

Pre-Processor
(analogue → E_T)

Jet / Energy-sum Processor

Cluster Processor
(e/γ, τ/h)

Muon trigger

Muon Barrel Trigger

Muon End-cap Trigger

Muon central trigger processor

Central Trigger Processor (CTP)

Timing, Trigger, Control (TTC)

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

O(1M) RPC/TGC channels

Latency limit 2.5 μs
Lvl-1 trigger data flow: ATLAS

- **On-detector:**
  - analog sums to form trigger towers

- **Off-detector:**
  - Receive data, digitize, identify bunch crossing, compute $E_T$
  - Send data to Cluster Processor and Jet Energy Processor crates

- **Local processor crates:**
  - Form sums/comparisons as per algorithm, decide on objects found

- **Global Trigger: decision**
Lvl-1 Calo Trigger: $e/\gamma$ algorithm (CMS)

\[ E_T(\text{Hit}) + \max E_T(\text{EM towers}) > E_T^{\min} \]

\[ E_T(\text{EM tower}) / E_T(\text{Hadron tower}) < H_o E^{\max} \]

At least 1 \[ E_T(\text{EM tower}) < E_{iso}^{\max} \]

Fine-grain: \[ \geq 1(\text{hits}) > R \ E_T^{\min} \]
Lvl-1 Calo e/γ trigger: performance

- Efficiencies and Trigger Rates

![Graphs showing efficiency and trigger rates for Lvl-1 Calo e/γ trigger.](image-url)
Lvl-1 jet and $\tau$ triggers

- Issues are jet energy resolution and tau identification
  - Single, double, triple and quad thresholds possible
  - Possible also to cut on jet multiplicities
  - Also ETmiss, SET and SET(jets) triggers

Sliding window:
- granularity is 4x4 towers = trigger region
- jet $E_T$ summed in 3x3 regions  \( \Delta \eta, \Delta \phi = 1.04 \)
Lvl-1 muon trigger

- The goal: measure momentum online
  - Steeplly falling spectrum; resolution costs!

- The issue: speed
  - ATLAS: dedicated muon chambers (RPC and TGC)
  - CMS: RPC added to DT and CSC (which provide standalone trigger)

![Diagram of Lvl-1 muon trigger]

- Threshold \( \mu T_p \)
- Rate [Hz]
- \( \times 10^{33} \) cm\(^{-2}\)s\(^{-1}\)
- 4 kHz
- 30 Hz
**Lvl-1 muon trigger (CMS)**

**Drift Tubes**
- Meantimers recognize tracks and form vector / quartet.
- Correlator combines them into one vector / station.
- Hit strips of 6 layers form a vector.

**CSC**
- Comparators give 1/2-strip resol.

**Hardware implementation:**
- ASICs for Trigger Primitive Generators
- FPGAs for Track Finder processors

- Extrapolation: using look-up tables
- Track Assembler: link track segment-pairs to tracks, cancel fakes
- Assignment: $P_T$ (5 bits), charge, $\eta$ (6 bits), $\phi$ (8 bits), quality (3 bits)
Lvl-1 muon trigger (CMS)

Pattern of strips hit: Compared to predefined patterns corresponding to various $p_T$

Implemented in FPGAs
Global muon trigger (CMS)

- Combine results from RPC, CSC and DT triggers
- Match muon candidates from different trigger systems; use complementarity of detectors
- Improve efficiency and rate
- Assign muon isolation
- Deliver the 4 best (highest $P_T$, highest-quality) muons to Global Trigger
- Pt resolution:
  - 18% barrel
  - 35% endcaps
- Efficiency: ~ 97%
Technologies in Level-1 systems

- **ASICS (Application-Specific Integrated Circuits) used in some cases**
  - Highest-performance option, better radiation tolerance and lower power consumption (a plus for on-detector electronics)

- **FPGAs (Field-Programmable Gate Arrays) used throughout all systems**
  - Impressive evolution with time. Large gate counts and operating at 40 MHz (and beyond)
  - Biggest advantage: flexibility
    - Can modify algorithms (and their parameters) in situ

- **Communication technologies**
  - High-speed serial links (copper or fiber)
    - LVDS up to 10 m and 400 Mb/s; HP G-link, Vitesse for longer distances and Gb/s transmission
  - Backplanes
    - Very large number of connections, multiplexing data
      - operating at ~160 Mb/s
Lvl-1 Calo Trigger: prototypes

Trigger Crate
(160 MHz backplane)

Receiver Card

Links

Electron (isolation) Card
Bunch-crossing identification

- Need to extract quantities of the bunch-crossing in question (and identify the xing)
- FIR (finite impulse response filter)
  - Feed LUT to get $E_T$
  - Feeds peak-finder to identify bunch-xing
  - Special handling of very large pulses (most interesting physics…)
- Can be done in an ASIC (e.g. ATLAS)
Global Trigger

- A very large OR-AND network that allows for the specification of complex conditions:
  - 1 electron with $P_T > 20$ GeV OR 2 electrons with $P_T > 14$ GeV OR 1 electron with $P_T > 16$ and one jet with $P_T > 40$ GeV...
  - The top-level logic requirements (e.g. 2 electrons) constitute the “trigger-table” of the experiment
    - Allocating this rate is a complex process that involves the optimization of physics efficiencies vs backgrounds, rates and machine conditions
      → More on this in the HLT part
Lvl-1 trigger: summary

- Some challenges of unprecedented scale
  - Interaction rate and selectivity
  - Number of channels and synchronization
  - Pile-up and bunch-crossing identification
  - Deciding on the fate of an event given \( \sim 3 \, \mu s \)
    - Of which most is spent in transportation

- Trigger levels: the set of successive approximations (at the ultimate save-or-kill decision)
  - Number of physical levels varies with architecture/experiment

- Level-1 is always there, reduces 40 MHz to 40-100 kHz
  - Level-0 may be used to (a) reduce initial rate to \( \sim 1 \)MHz allow for slightly more complex processing (e.g. simple tracking)
DAQ system
Physics selection at the LHC

LEVEL-1 Trigger
Hardwired processors (ASIC, FPGA)
Pipelined massive parallel

HIGH LEVEL Triggers
Farms of processors

DAQ

Reconstruction&ANALYSIS
TIER0/1/2 Centers

ON-line
OFF-line

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Online Selection Flow in pp

- **LEVEL-1 TRIGGER**
  - 40 MHz COLLISION RATE
  - 75 kHz

- **DETECTOR CHANNELS**
  - Charge
  - Time
  - Pattern

- **16 Million channels**
- **3 Gigacell buffers**
- **1 Megabyte EVENT DATA**

- **1 Terabit/s READOUT**
  - 50,000 data channels

- **500 Gigabit/s**
  - SWITCH NETWORK

- **200 Gigabyte BUFFERS**
  - ~ 400 Readout memories

- **500 Gigabit/s**
  - 100 Hz FILTERED EVENT
  - 5 TeraIPS 400 CPU farms
  - EVENT FILTER

- **100 Hz**
  - FILTERED EVENT
  - Gigabit/s
  - SERVICE LAN

- **Computing Services**

- **Energy Tracks**

- **PETabyte ARCHIVES**

**EVENT FILTER**
A set of high performance commercial processors organized into many farms convenient for on-line and off-line applications.

**EVENT BUILDER**
A large switching network (400+400 ports) with total throughput ~ 400 Gbit/s forms the interconnection between the sources (deep buffers) and the destinations (buffers before farm CPUs). The Event Manager distributes event building commands (assigns events to destinations).
Trigger/DAQ systems: grand view

### ATLAS
- **Levels**: 3
- **LV-1 rate**: 100 kHz
- **Readout**: 10 GB/s
- **Storage**: 100 MB/s

### ALICE
- **Levels**: 4
- **LV-1 rate**: 500 Hz
- **Readout**: 5 GB/s
- **Storage**: 1250 MB/s

### CMS
- **Levels**: 2
- **LV-1 rate**: 100 kHz
- **Readout**: 100 GB/s
- **Storage**: 100 MB/s

### LHCb
- **Levels**: 3
- **LV-1 rate**: 1 MHz
- **Readout**: 4 GB/s
- **Storage**: 40 MB/s

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Readout types

- **Analog MUX**
  - 40 MHz
  - Level-1
  - 1
  - Analog fibers: ~60000
  - Digital fibers: ~1000

- **MUX/ADC**
  - 40 MHz
  - Level-1
  - Rx
  - Analog fibers: ~60000
  - Digital fibers: ~1000

- **Hit Finder**
  - 40 MHz
  - Level-1
  - N buffers
  - Analog fibers: ~80000
  - Digital fibers: ~1000

- **Tracker**
  - 40 MHz
  - Tag
  - SP
  - High occupancy

- **Preshower**
  - 40 MHz
  - T1 T2
  - High occupancy

- **Calorimeters**
  - 40 MHz
  - 1
  - Level-1
  - Digital fibers: ~1000
  - Low occupancy

- **PIXELs**
  - 40 MHz
  - Tag
  - SP
  - Low occupancy

- **CSC**
  - 40 MHz
  - Tag
  - SP
  - Low occupancy

- **DT**
  - 40 MHz
  - Tag
  - SP
  - Low occupancy
Need standard interface to front-ends

- Large number of independent modules

DAQ
Event Building

- Form full-event-data buffers from fragments in the readout. Must interconnect data sources/destinations.

**Event fragments**:
Event data fragments are stored in separated physical memory systems

**Full events**: Full event data are stored into one physical memory system associated to a processing unit

**Hardware**:
- Fabric of switches for builder networks
- PC motherboards for data Source/Destination nodes
Barrel-shifting with variable-size events

- **Demonstrator**
  - Fixed-block-size with barrel-shifter
  - Basic idea taken from ATM (and time-division-muxing)
  - As seen in composite-switch analysis, this should work for large N as well
  - Currently testing on 64x64... (originally: used simulation for \(N \approx 500\); now ~obsolete)
Detector readout & 3D-EVB

FrontEnd Readout Link (512 x 5 Gb/s)

Fed Builder: Random traffic

8 x 8 FED Builder (64 units)

Readout Builder: Barrel shifter

Readout Units

Builder Units

64x64 DAQ slice

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Challenges:

- Large N (on everything)
- Disparity in time scales ($\mu$s–s; from readout to filtering)
- Need to use standards for
  - Communication (Corba? Dead! “now”: SOAP!)
  - User Interface (is it the Web? Yes…)
- Physics monitoring complicated by factor 500 (number of sub-farms);
  - Need merging of information; identification of technical, one-time problems vs detector problems

Current work:

- Create toolkits from commercial software (SOAP, XML, HTTP etc); integrate into packages, build “Run Control” on top of it;

Detector Control System: DCS. All of this for the ~10^7 channels… SCADA (commercial, standard) solutions
High-Level Trigger
Physics selection at the LHC

**LEVEL-1 Trigger**
Hardwired processors (ASIC, FPGA)
Pipelined massive parallel

**HIGH LEVEL Triggers**
Farms of processors

**Reconstruction & Analysis**
Tier 0/1/2 Centers

**25 ns 3 µs ms sec hour year**

**ON-line**

**OFF-line**

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Branches

1. Throughput of ~32 Gb/s is enough (ALICE)
   - ALICE needs 2.5 GB/s of “final EVB”
   - Then proceed no further; software, control and monitor, and all issues of very large events (storage very important)

2. Need more bandwidth, but not much more (e.g. LHCb; event size ~100 kB @ 40 kHz = 4 GB/s = 32 Gb/s)
   - Implement additional capacity

3. Need much more than this; CMS+ATLAS need 100 GB/s = 800Gb/s
   - Two solutions:
     - Decrease rate by using a Level-2 farm (ATLAS)
       - Thus, two farms: a Level-2 and Level-3 farm
     - Build a system that can do 800 Gb/s (CMS)
       - Thus, a single farm
Level-2 (ATLAS):
- Region of Interest (ROI) data are ~1% of total
- Smaller switching network is needed (not in # of ports but in throughput)
- But adds:
  - Level-2 farm
  - “ROB” units (have to “build” the ROIs)
  - Lots of control and synchronization
- Problem of large network → problem of Level-2

Combined HLT (CMS):
- Needs very high throughput
- Needs large switching network
- But it is also:
  - Simpler (in data flow and in operations)
  - More flexible (the entire event is available to the HLT – not just a piece of it)
- Problem of selection → problem of technology
**ATLAS: from demonstrator to full EVB**

- **With Regions of Interest:**
  - If the Level-2 delivers a factor 100 rejection, then input to Level-3 is 1-2 kHz.
  - At an event size of 1-2 MB, this needs 1-4 GB/s
    - An ALICE-like case in terms of throughput
    - Dividing this into ~100 receivers implies 10-40 MB/s sustained – certainly doable
  - Elements needed: ROIBuilder, L2PU (processing unit),
3D-EVB: DAQ staging and scaling

DAQ unit (1/8th full system):
- Lv-1 max. trigger rate: 12.5 kHz
- RU Builder (64x64): 0.125 Tbit/s
- Event fragment size: 16 kB
- RU/BU systems: 64
- Event filter power: ≈ 0.5 TFlop

Data to surface:
- Average event size: 1 Mbyte
- No. FED s-link64 ports: > 512
- DAQ links (2.5 Gb/s): 512+512
- Event fragment size: 2 kB
- FED builders (8x8): ≈ 64+64
Event Filter (a processor farm)

- Explosion of number of farms installed
  - Very cost-effective
    - Linux is free but also very stable, production-quality
    - Interconnect: Ethernet, Myrinet (if more demanding I/O); both technologies inexpensive and performant
  - Large number of message-passing packages, various API’s on the market
    - Use of a standard (VIA?) could be the last remaining tool to be used on this front
  - Despite recent growth, it’s a mature process: basic elements (PC, Linux, Network) are all mature technologies. Problem solved. What’s left: Control & Monitor.
    - Lots of prototypes and ideas. Need real-life experience.
      ➔ Problem is human interaction
**Strategy/design guidelines**
- Use offline software as much as possible
  - Ease of maintenance, but also understanding of the detector

**Boundary conditions:**
- Code runs in a single processor, which analyzes one event at a time
- HLT (or Level-3) has access to full event data (full granularity and resolution)
- Only limitations:
  - CPU time
  - Output selection rate (~10^2 Hz)
  - Precision of calibration constants

**Main requirements:**
- Satisfy physics program (see later): high efficiency
- Selection must be inclusive (to discover the unpredicted as well)
- Must not require precise knowledge of calibration/run conditions
- Efficiency must be measurable from data alone
- All algorithms/processors must be monitored closely
HLT (regional) reconstruction (I)

**Global**
- process (e.g. DIGI to RHITs) each detector fully
  - then link detectors
  - then make physics objects

**Regional**
- process (e.g. DIGI to RHITs) each detector on a "need" basis
  - link detectors as one goes along
  - physics objects: same
For this to work:

- Need to know where to start reconstruction (seed)

For this to be useful:

- Slices must be narrow
- Slices must be few

Seeds from Lvl-1:

- $e/\gamma$ triggers: ECAL
- $\mu$ triggers: $\mu$ sys
- Jet triggers: E/H-CAL

Seeds $\approx$ absent:

- Other side of lepton
- Global tracking
- Global objects (Sum $E_T$, Missing $E_T$)
Example: electron selection (I)

- **“Level-2” electron:**
  - 1-tower margin around 4x4 area found by Lvl-1 trigger
  - Apply “clustering”
  - Accept clusters if H/EM < 0.05
  - Select highest $E_T$ cluster

- **Brem recovery:**
  - Seed cluster with $E_T > E_T^{\text{min}}$
  - Road in $\phi$ around seed
  - Collect all clusters in road
  - “supercluster” and add all energy in road:

![Diagram of electron selection process]
**Example: electron selection (II)**

- "Level-2.5" selection: add pixel information
  - Very fast, high rejection (e.g. factor 14), high efficiency ($\varepsilon=95\%$)
  - Pre-bremsstrahlung
  - If # of potential hits is 3, then demanding $\geq 2$ hits quite efficient

![Diagram of electron selection process](image)

1. Predict a track
2. Cluster position
3. Nominal vertex (0,0,0)
4. Cluster E
5. If a hit is found, estimate z vertex
6. Propagate to the pixel layers and look for compatible hits
7. Pixel hit
8. Predict a new track and propagate
9. Estimated vertex (0,0,z)

**Graph:**
- No staging: $3$ cylinders + $2$ disks
- Staged: $2$ cylinders + $1$ disk

**Legend:**
- No staging: $2 \times 10^{33}$/cm$^2$/s
- Staged + Si strips
- Barrel
- Alt.

**Additional Text:**

- Pre-bremsstrahlung
- If # of potential hits is 3, then demanding $\geq 2$ hits quite efficient

**Notes:**
- Very fast, high rejection (e.g. factor 14), high efficiency ($\varepsilon=95\%$)
Example: electron selection (III)

- “Level-3” selection
  - Full tracking, loose track-finding (to maintain high efficiency):
  - Cut on E/p everywhere, plus
    - Matching in $\eta$ (barrel)
    - H/E (endcap)
  - Optional handle (used for photons): isolation

<table>
<thead>
<tr>
<th>Signal</th>
<th>Background</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single e</td>
<td>$W \rightarrow e\nu$: 10 Hz</td>
<td>33 Hz</td>
</tr>
<tr>
<td></td>
<td>$\pi^+/\pi^0$ overlap: 5 Hz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\pi^0$ conversions: 10 Hz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$b/c \rightarrow e$: 8 Hz</td>
<td></td>
</tr>
<tr>
<td>Double e</td>
<td>$Z \rightarrow ee$: 1 Hz</td>
<td>~0</td>
</tr>
<tr>
<td>Single $\gamma$</td>
<td>2 Hz</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Double $\gamma$</td>
<td>~0</td>
<td>5 Hz</td>
</tr>
</tbody>
</table>

Electrons $p_T$, 10-50 GeV
Barrel

Weighted jet bkg
30% overflow
Online Physics Selection: summary

- Level-1 max trigger rate: 100 kHz
- Average event size: 1 Mbyte
- Builder network: 1 Tb/s
- Online computing power: \( \approx 5 \times 10^6 \) MIPS
- Event flow control: \( \approx 10^6 \) Mssg/s
- No. Readout systems: \( \approx 512 \)
- No. Filter systems: \( \approx 512 \times n \)
- System dead time: \( \approx \% \)

What we covered
After the Trigger and the DAQ/HLT

Networks, farms and data flows

- Raw Data: 1000 Gbit/s
- Events: 10 Gbit/s
- Controls: 1 Gbit/s
- 5 TeraIPS
- 10 TeraIPS
- To regional centers: 622 Mbit/s
- Remote control rooms

P. Sphicas
Triggering

SSI 2006
July 2006
(Grand) Summary

- The Level-1 trigger takes the LHC experiments from the 25 ns timescale to the 10-25 $\mu$s timescale
  - Custom hardware, huge fanin/out problem, fast algorithms on coarse-grained, low-resolution data

- Depending on the experiment, the next filter is carried out in one or two (or three) steps
  - Commercial hardware, large networks, Gb/s links.
  - If Level-2 present: low throughput needed (but need Level-2)
  - If no Level-2: three-dimensional composite system

- High-Level trigger: to run software/algorithms that are as close to the offline world as possible
  - Solution is straightforward: large processor farm of PCs
  - Monitoring this is a different issue

- All of this must be understood, for it’s done online.
With respect to offline analysis:

**Same** hardware (Filter Subfarms)

**Same** software ()

**But different** situations