Trigger di primo livello per gli esperimenti ATLAS & CMS ad LHC

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INFN Sezione di Roma

II Workshop sulla fisica di ATLAS e CMS
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Outline

- LHC Physics Program
- Requirements for trigger systems for experiments at the LHC
- ATLAS & CMS Level-1 Trigger systems
- Conclusions
The Large Hadron Collider

On a proton-proton beam

- CM Energy = 14 TeV
- \( L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) (2x10^{33} cm^{-2} s^{-1} initial luminosity for 1.5 years)
- Bunch Spacing: 25 ns
  - Beam current = 0.56 A
  - Protons per bunch = 10^{11}
  - p-p interactions per bunch = \( \simeq \) 23
- Event size 1-2 Mbytes

=> Average of 600 Million Proton Interactions per second!!

We need highly efficient selection process.

For example, signal rate for SM H->\( \gamma \gamma \) with a Higgs mass of 120GeV is about 10^{-13}
Proton-proton interactions

- **High event rate: 1 Ghz**
  the rate of these “minimum-bias” events is such that can have an impact on the Trigger system.
  Ex: the muon Trigger of ATLAS and CMS;

- **LHC is a heavy-flavor factory:**
  - $b\bar{b}$ cross-section 500 $\text{b}$
  - $t\bar{t}$ cross-section 1 $\text{nb}$

- **LHC is a vector-bosons factory**

- **The event rate is huge**
  big implications in the trigger/daq System
The LHC Physics Programme

SM cannot be the ultimate theory:
- no gravity
- hierarchy problem

Origin of the particle masses: search for the Higgs boson(s)
- The LHC will search for a SM-like Higgs, covering whole range $m_H < 1$ TeV
- SuSy prediction for light Higgs ($m_H < 135$ GeV)

SuSy particles search
- Jets and missing transverse energy ($E_T$)

Standard Model Physics
- Precision measurements with 10-30 fb$^{-1}$

Origin of the Matter Anti-matter imbalance in the universe
- SM CP-violation not sufficient; least tested aspect of the SM

New Physics beyond the SM
- Using inclusive triggers sensitive to unpredicted new physics
Electroweak symmetry breaking

- **Standard Model Higgs**
  - Cover the full mass range with at least two decay modes
  - Relevant final states: $\gamma \gamma - ttbb - 4l - l\nu l\nu - lllj$ (l=e,\mu)

- **MSSM Higgs bosons**
  - Additional final states relevant for H/A and H±: $\tau\tau - \mu\mu - \tau\nu - tb$

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Selection signatures

<table>
<thead>
<tr>
<th>Particles</th>
<th>Example of physics coverage</th>
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<tbody>
<tr>
<td>Electrons</td>
<td>Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W, top</td>
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<tr>
<td>Photons</td>
<td>Higgs (SM, MSSM), extra dimensions, SUSY</td>
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<td>Muons</td>
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<tr>
<td>Jets</td>
<td>SUSY, compositeness, resonances</td>
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<tr>
<td>Jet + missing ET</td>
<td>SUSY, leptoquarks</td>
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<tr>
<td>Tau + missing ET</td>
<td>Extended Higgs models (e.g. MSSM), SUSY</td>
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</tbody>
</table>

Standard Model processes are mandatory to

- Understand background processes for discoveries and measurements (production of Wbb, ttbb, vector boson pairs, …)
- Understand detector performance (esp. during the first year(s))
  - Calibration / energy scale: \( Z \rightarrow \text{ee}/\text{\mu\mu} \), \( W \rightarrow jj, W \rightarrow \text{ev}, W \rightarrow \tau\nu \), \( Z+\text{jet}, J/\psi \text{\mu\mu} \)

SUSY events over all have high multiplicity jets, or leptons, and big missing transverse energy (\( E_T^{\text{miss}} \)).

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General trigger requirements

The role of the **trigger** is to make the online selection of particle collisions potentially containing interesting physics

- **Need high efficiency** for selecting processes of interest for physics analysis
  - Efficiency should be precisely known
  - should not have biases affecting physics results

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

- **System must be affordable**
  - Limits complexity of algorithms that can be used

“During one second of CMS running, a data volume equivalent to 10,000 Encyclopaedia Britannica is recorded”
**p-p collisions at LHC**

- Event rate: \(~10^9\) Hz
- Event size: \(~1\) MB
- Level-1 Output: 100 kHz
- Mass storage: \(10^2\) Hz
- Event Selection: \(~1/10^{13}\)

**ATLAS / CMS**

**Event Rates:** \(~10^9\) Hz  
**Event size:** \(~1\) MB  
**Level-1 Output:** 100 kHz  
**Mass storage:** \(10^2\) Hz  
**Event Selection:** \(~1/10^{13}\)
Why need *multi-level* triggers?

Multi-level triggers provide:

- Rapid rejection of high-rate backgrounds without incurring (much) dead-time \(\Rightarrow\)

  **Fast first-level trigger (custom electronics)**
  - Needs high efficiency, but rejection power can be *comparatively* modest
  - Short latency is essential since information from all (up to \(O(10^8)\)) detector channels needs to be buffered (often on detector) pending result

- High overall rejection power to reduce output to mass storage to affordable rate \(\Rightarrow\)

  **one or more “High” Trigger Levels:**
  - Progressive reduction in rate after each stage of selection allows use of more and more complex algorithms at affordable cost
  - Final stages of selection, running on computer farms, can use comparatively very complex (and hence slow) algorithms to achieve the required overall rejection power

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<table>
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<th>Exp.</th>
<th>No of Levels</th>
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<tr>
<td>ATLAS</td>
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Trigger Rate reduction

Inclusive trigger

Confirm L1, inclusive and semi-incl., simple topology, vertex rec.

Confirm L2, more refined topology selection, near offline

<table>
<thead>
<tr>
<th>N.of Levels</th>
<th>First Level Rate (Hz)</th>
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<th>FilterOut MB/s</th>
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**Trigger baselines and remarks**

**CMS**

- Build full events at output of Level-1: 100 kHz, 1MB events

  Risk: there is a lot of data to handle

  ⇒ Able to fall back to a partial-readout Level 2 model

**ATLAS**

- L2 trigger operates on “ROIs”, nominally 2% of event data, at output of Level-1 (75 kHz, 1MB events, 20 kB ROI data)

- Full event build at L2 rate of ~1 kHz, sent to Event Filter (EF) farm

  Risk: not yet completely clear that small ROIs provide enough information

  ⇒ Able to shift boundary between L2, EF somewhat
First Level Trigger Requirements

- Rate reduction of a factor of $10^4$-$10^5$
- Each single Bunch Crossing must be processed, so data are held in pipeline
  - Also electronics must be structured in pipelines, each component repeating its specific actions every 25 ns. Pipelines allow a fixed latency of up to 2.5 μs for a trigger decision, then events are sent to ROD
  - Fast detector responses and data movement are required
  - Logic decisions are taken by custom hardware systems (FPGAs and ASICs)
- BC identification is crucial in order to select the event among hundreds filling the detector each moment
- Redondance of selection criteria ("trigger menus") leads to high trigger efficiency and the possibility to measure it from the data
  - Concurrently select events of a wide range of physics studies
- Must be sufficiently flexible to face possible variations of LHC luminosity, one order of magnitude at least
  - Event characteristics vary with luminosity, due to changings in pile-up, so it's not a simple events rescaling but events with different number of muons, clusters,... must be managed
First Level Trigger Overview

Muon detector signals

Search for high-$p_T$:
- muons
- electrons/photons
- taus/hadrons
- jets

Calorimeter signals

Introduce deadtime to avoid data loss or buffer overflow in front-end electronics

First-level Trigger

Calculate $E_T$, missing $E_T$

Distribute first-level trigger decision to front-end electronics

Form trigger decision for each BC based on combinations of above

Decision every 25 ns
Latency ~few μs

Yes/No

Less than 3 μs for trigger decision, while data are held in pipelines
Level-1 Trigger $p_T$ cut

- In contrast to particles produced in typical pp collisions (typical hadron $p_T \sim 1$ GeV), products of new physics are expected to have large $p_T$
  - E.g. if $m_h \sim 100$ GeV $\Rightarrow p_T \sim 50$ GeV
- At low $p_T$, muons from K and $\pi$ decays, and from b- and c-quarks are the large background: precise measurement of $p_T$ is needed. Since they are produced in jets, isolation criteria based on energy deposited around the muon in the calorimeter or trackers are used
- Typical first-level trigger thresholds for LHC design luminosity
  - Single muon $p_T > 20$ GeV (rate $\sim 10$ kHz)
    - Pair of muons each with $p_T > 6$ GeV (rate $\sim 1$ kHz)
  - Single e/$\gamma$ $p_T > 30$ GeV (rate $\sim 10$-20 kHz)
    - Pair of e/$\gamma$ each with $p_T > 20$ GeV (rate $\sim 5$ kHz)
  - Single jet $p_T > 300$ GeV (rate $\sim 200$ Hz)
    - Jet $p_T > 100$ GeV and missing-$p_T > 100$ GeV (rate $\sim 500$ Hz)
    - Four or more jets $p_T > 100$ GeV (rate $\sim 200$ Hz)
- Very inclusive triggers keep the thresholds sufficiently low to be sensitive to decay products of new particles and to leptons from Z and W decays. (LHC is a discovery machine!)
  - Also important to understand the background and low energy spectrums.
  - Ensure safe overlap with potential RunII at the Tevatron
Effect of $p_T$ cut in minimum-bias events

Simulated $H \rightarrow 4\mu$ event + 17 minimum-bias events
**ATLAS Level-1 Trigger Structure**

CTP makes the final decision based on multiplicities of identified trigger objects, using $p_T$ thresholds and global energy variables.

Decisions are sent via the TTC system to the Front End electronics.

For accepted events the LVL1 trigger sends readout information to the RoI Builder which assembles the list of RoIs for the event, to be used by LVL2.
The Level-1 selection is dominated by local signatures

- Based on coarse granularity (calo, mu trig chamb), w/out access to inner tracking
- Important further rejection can be gained with local analysis of full detector data

The geographical addresses of interesting signatures identified by the LVL1 (Regions of Interest)

- Allow access to local data of each relevant detector
- Sequentially

Typically, there are less than 2 RoIs per event accepted by LVL1 (~1.6)

The resulting total amount of RoI data is minimal: a few % of the Level-1 throughput
ATLAS LVL1 Muon Trigger

Algorithm requires coincidence of hits within a road, which is related to the $p_T$ threshold applied.

Two algorithms are applied: Low and High $p_T$.

Programmable coincidence logic allows multiple thresholds to be used at the same time, 3 for each Low and High algorithm.

Fast and high redundancy system
1. Wide $p_T$-threshold range
2. Safe Bunch Crossing Identification
3. Strong rejection of fake muons (induced by noise and physics background)
• Requirement for cosmic-ray and beam-halo triggers included in design
  • e.g. trigger ASICs include programmable delays to compensate for TOF of down-going cosmic-ray muons in barrel
  • Projectivity constraints mainly from cabling between planes of trigger chambers. However system is flexible, e.g. can change coincidence requirements

The total expected rate in ATLAS at $L=10^{34}$ is about 40 kHz (whith a safety factor of 2).

Rate is dominated by the single EM trigger which has a rate of more than 20kHz.
ATLAS: RPC trigger BC capability, 25 ns run

Readout system time resolution

$$\sigma = 1.9 \text{ ns}$$

CM ASIC uses 1BC/8 LSB time interpolator to measure time of arrival of RPC hits and trigger output.

2004 CERN-H8 testbeam

Low-Pt trigger Bunch counter
Identification efficiency vs pipeline delay
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CMS (Compact Muon Solenoid)

MUON BARREL
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)

CALORIMETERS
ECAL Scintillating PbWO₄ Crystals
HCAL Scintillating brass sandwich

IRON YOKE

SUPERCONDUCTING COIL

TRACKERS
Pixels
Silicon Microstrips

Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)

Total weight : 12,500 t
Overall length : 21.6 m
Overall diameter : 15 m
Magnetic field : 4 Tesla

Oct. 2004
CMS Level-1 Trigger

- Trigger decision is held in 3.2 $\mu$s, but only 1 $\mu$s is needed, rest is due to cable length.

- The Global Muon Trigger receives 4 muons candidate of maximum $p_T$, selects the best quality candidates (n.of hits, matched track segments, responses by the 3 detectors) $\Delta \eta \times \Delta \phi = 0.35 \times 0.35$ rad.

- The Global Calorimeter Trigger selects the best 4 $e, \gamma$ (separately single and not), $\tau$ and jets. It calculates the total $E_T$ and the $E_T$ missing vector.

- The Global Trigger applies the thresholds and performs the trigger algorithms.

- Up to 128 algorithms can run in parallel: arbitrary combinations of trigger objects passing thresholds and topological correlations.

ECAL: lead-Tungstate Crystals
HCAL: sc+cupper absorber plates
HCAL Forward: sc+steel absorber plates

Barrel: Drift Tubes
EndCaps: Cathod Strip Chambers
Barrel + EndCaps: RPC (for BC identification)
On-detector electronics digitizes analog signals at 40MHz with the full detector granularity.

Off-detector the trigger towers are formed by digital summation.

The signal is processed in order to associate the measured energy to the correct BC. This is done with a Finite Impulse Response filter, that sends its results to a look-up table to convert to $E_T$ and to a peak finder which determines the BC.

**Segmentation**
- **Barrel**: Energy Tower=25 ECAL crystals ($5\eta\times5\phi$)
- **EndCap**: 10 to 25 crystals per Tower, no $\eta\times\phi$ geometry
- **HCAL**: follows the ECAL geometry
- **HF**: used for seamless jets and missing $E_T$, coarser segmentation in $\phi$
CMS Calo Trigger Algorithms

Electron (Hit Tower + Max)
- 2-tower $\Sigma E_T$ + Hit tower H/E
- Hit tower 2x5-crystal strips $>90\% E_T$ in 5x5 (Fine Grain)

Isolated Electron (3x3 Tower)
- Quiet neighbors: all towers pass Fine Grain & H/E
- One group of 5 EM $E_T < \text{Thr.}$

Jet or $\tau E_T$
- 12x12 trig. tower $\Sigma E_T$ sliding in 4x4 steps w/central 4x4 $E_T > \text{others}$

$\tau$: isolated narrow energy deposits
- Energy spread outside $\tau$ veto pattern sets veto
- Jet = $\tau$ if all 9 4x4 region $\tau$ vetoes off
First-level triggers for both ATLAS and CMS represent a huge challenge. They have a direct impact on the exploitation of the physics program.

Multi-Level selection can handle the high p-p collision rate and rejects events with no physics interest.

- 100 kHz is only $10^{-4}$ of the interaction rate!

The implementation is based on new technologies for data taking and transport.

System scalability is essential to face staging/deferral scenarios of the LHC detectors.

Trigger systems flexibility important for event selection of unknown physics.
ATLAS Commissioning

- Full system of prototype level-1 trigger now being evaluated at the test-beam
  - First time for calorimeter trigger and CTP
  - Builds on previous test-beam experience for muon trigger

- Full set of algorithmic slices
  - Calorimeters - Receivers - Pre-Processor - Cluster Processor - CTP
  - Calorimeters - Receivers - Pre-Processor - Jet/energy Processor - CTP
  - RPCs - Splitters/Pads - Sector Logic - MUCTPI - CTP
  - TGCs - PS packs - IHT - Sector Logic - MUCTPI - CTP

- Readout and control paths functional
  - But not yet final RODs at test-beam
<table>
<thead>
<tr>
<th>Module</th>
<th>Trigger</th>
<th>First prototype(s)</th>
<th>Final prototype</th>
<th>Final system</th>
<th>Comments</th>
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<tbody>
<tr>
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