

Triggering And Data Acquisition in High Energy Physics

for the Heidelberg GK BSM
Lecture 1/3

15th November 2017

by
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• Lecture 1 (today):

- The definition of data acquisition and triggering, and little bits of history.

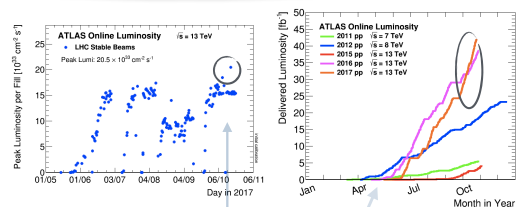
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During the first lecture in this series I will give a formal definition of data acquisition and triggering, and introduce basic ideas in historical context: the experimental establishment of electroweak interactions.

As a preamble, I however first give a broad overview of how data is handled at the collider and its experiments that is at the forefront of high energy physics: the Large Hadron Collider (LHC).

Being part of the ATLAS collaboration at CERN, a strong bias towards this experiment could not be avoided.

2017: the Large Hadron Collider @ CERN



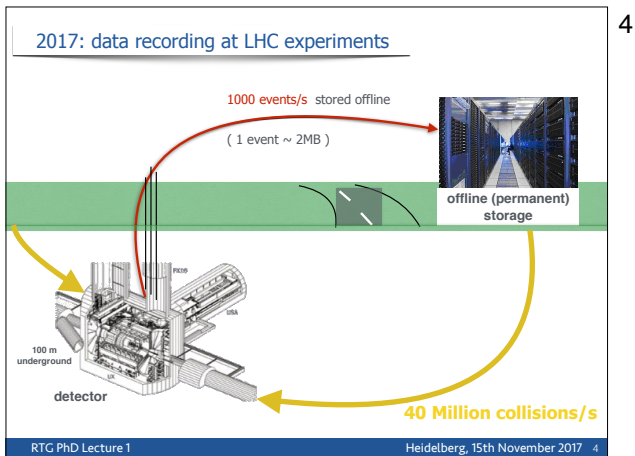
• Records (repeatedly) broken at the LHC:

- highest accelerated beam energy: 6.5 TeV (Tevatron: 1 TeV), at a rate of 40 Million Hz (LHC Run 1: 20 Million Hz, Tevatron: 2 Million Hz)
- highest stored beam energy: 30 MJ - 2556 stored proton bunches (Tevatron: 1MJ, 36 stored bunches)
- highest instantaneous luminosity (above design): $2.05 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with peak of 78 average number of interactions per bunch. (Tevatron: $4 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ 10 interactions per bunch)
- highest total integrated luminosity: 0.5 fb⁻¹/day towards 45 fb⁻¹ goal for 2017 (LHC Run 1 total: 28 fb⁻¹, Tevatron: ~ 0.01 fb⁻¹/day)

Experiments at the LHC are being challenged in unprecedented ways as the LHC repeatedly breaks hadron collider records.

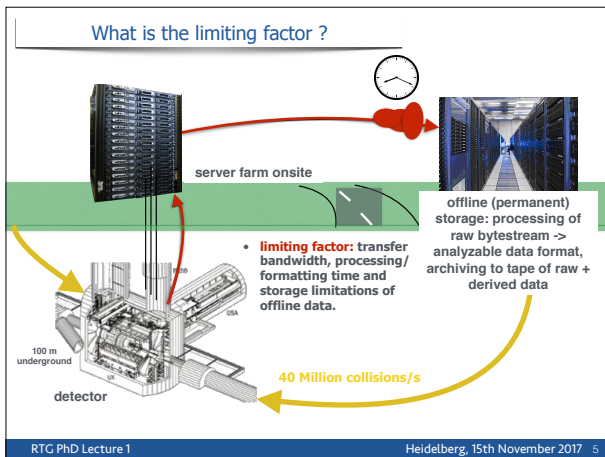
These records translate to one challenge in particular: recording data fast, efficiently whilst not missing a discovery.

Record log on ATLAS web page: <https://atlas.web.cern.ch/Atlas/GROUPS/DATAPREPARATION/DataSummary/2017/records.py>



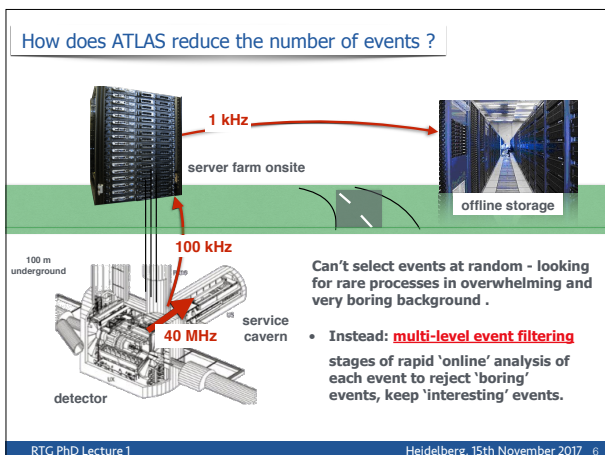
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An average general-purpose detector at the LHC, such as ATLAS, analyses every collision, however records just a tiny fraction of it: 1 out of every 40 000 events per second (ATLAS). Recording every collision is clearly not feasible: at 2 MB per event and 12 hour fills, this would amount to ~ 3000 PB a day. ATLAS reduces this to ~80 TB per day. But one can still consider: What is currently the factor limiting us in recording more events ? And which events do we record ?



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The back-pressure originates from the transfer, processing and storing of data from the experiment site to permanent storage offsite.



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Selecting events at random would be a waste of time as most events are all the same: QCD multijet background. The better strategy is to be selective in order to enhance the number of possible signal events ('interesting events') over the overwhelming background ('boring events'). ATLAS selects its events using a multi-level trigger system (stages of event filtering).

What is data acquisition ?

collision particles -> bytestream

- **Data acquisition** is the process of sampling signals that are a **measurement of the physical world**, and **converting** these samples into a **digital numeric format** that can be **manipulated** by a computer.
- Signals can be of various forms. One can think of
 - scintillation light, ionized charge, magnet currents, voltage, temperature, ...
- The more signal channels, and the more the type of signal, that need to be **integrated**, the more complex the role of the DAQ system.

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Development of data acquisition and triggering through history

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The techniques of triggering and data acquisition, along with detector and accelerator design, develop hand-in-hand with the physics that was being discovered or predicted at the time.

This is nicely illustrated by considering the history of discoveries establishing the electroweak theory of our Standard Model.

Development of DAQ

Where does the Trigger enter ?
The Trigger activates DAQ

1911: cloud chamber is invented

1952: bubble chamber is invented

end 1950s-60s: spark chamber is developed

1968: multi-wire proportional chamber is invented

Development of Trigger

external trigger system

self-triggering

coincident counts (fast)

pre-processing and selective triggering (fast + high event rate)

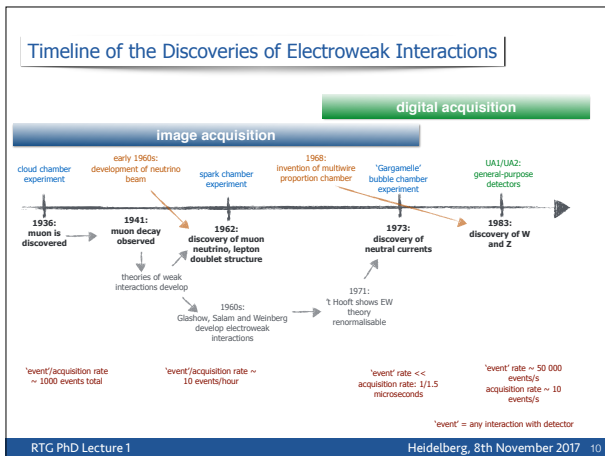
fast + high event rate

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The study of particle interactions in detectors kicked off with the invention of the cloud chamber, with subsequent discoveries such as the positron in the early 30s.

It led to the long-standing method of 'image acquisition': a photo was taken of the inside of the detector in which particle tracks are made visible. The developments around spark chambers throughout the 50s and 60s, although experimental use was similar to cloud and bubble chamber experiments, were stepping towards direct digitization of a signal since there the signal was essentially an electrical current. True data acquisition began with the breakthrough of the multiwire proportional chamber invention. The direct capturing of signal onto computer processors soon led to detectors that consisted of different components (drift chambers to calorimeters) as different types of signal could be digitized and formatted the same, making it possible to integrate the system.

From the start, it was important for experiments to use triggering systems to know when to 'shoot a photo'. These triggering systems and the signals they received usually lay or originated external to the detector itself. Their logic was based on simple coincident and anti-coincident counts. With the digitization of signal off detector components, triggering became more complex as it worked with different signals straight from the event. Digital data could be temporarily stored whilst the trigger performed a more complex decision. With access to the full (albeit coarse) reconstructed signature of the event, triggering could be made more selective.



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At the start of the 1930s, it had not yet been realized that lepton generations and their doublet structure existed. Lepton number conservation had not yet been formulated and weak interactions were awaiting discovery. The muon was discovered in a cloud chamber in 1936, and was the first evidence of weak interactions.

Discovery of the muon

Fig. 3. Track B. June 19, 1936

cloud chamber experiment (1936)

trigger on cosmic rays image acquisition

World map showing the location of the experiment in the USA.

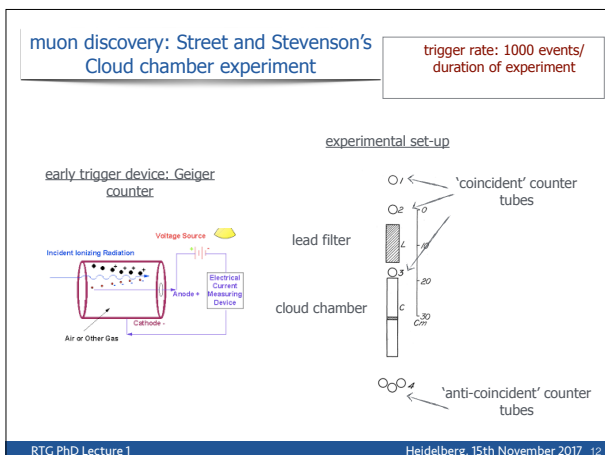
- first observation by Anderson and Neddermeyer, 1936: "Note on the nature of cosmic-ray particles"
- verified by Street and Stevenson

"a new particle of mass intermediate between a proton and an electron"

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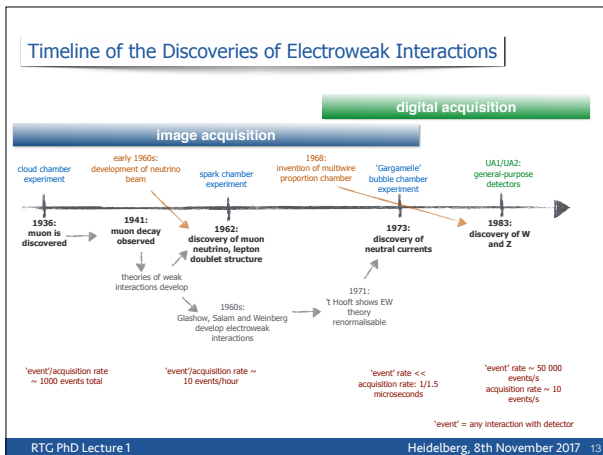
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Discovery of the Muon: A new particle was identified in the detection of cosmic rays in a spark chamber in 1936 by Anderson and Neddermeyer. A second spark chamber experiment by Street and Stevenson verified this: out of a 1000 photos they identified one containing a track with an ionization width and curvature that indicated a negatively charged particle with a mass intermediate between an electron and a proton.



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Street's and Stevenson's cloud chamber experiment was a simple set-up immersed in a magnetic field. They used an early triggering device - the geiger counter. These were used to select cosmic rays travelling from the top through the chamber, and coming towards a stand-still, so that the magnetic deflection is easily measured. Paper: <https://doi.org/10.1103/PhysRev.52.1003>



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The muon decay to an electron and 2 neutrinos was measured. Theories postulating a weak force carrier mediating the decay began to emerge. Puzzling was the non-observance of the muon (seen merely as a 'heavier' electron) conversion to an electron with the emission of a photon. It was pointed out (Feinberg, Pontecorvo) that if the 2 neutrinos in the decay were a different type (flavour) of particle, it was not so simple to 'do away' with them, and the electromagnetic process is suppressed.

In order to test the flavour of the neutrinos, one needed to test whether a muon neutrino interacting with matter would give rise to muons only. The trickiness was getting neutrinos to interact with your detector. It had to wait for the invention of the neutrino beam.

Discovery of the muon neutrino

- neutrino beam !
- cosmic rays have become background
- 1988 Nobel Prize to Schwartz, Steinberger and Lederman for the neutrino beam method and evidence of the doublet structure of leptons.

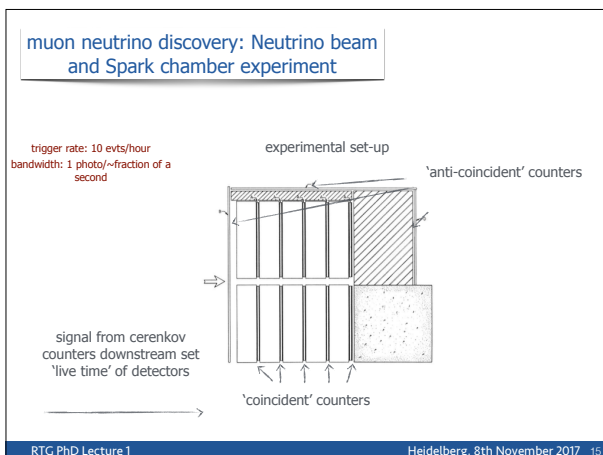
trigger 'live time' in sync with beam image acquisition

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The discovery of the muon neutrino: was made possible with the creation of a neutrino beam using 15 GeV protons accelerated by the Brookhaven AGS. The protons were targeted at a Beryllium target, creating a subsequent beam of (mostly) pions, and kaons. These decayed mid-flight to muons and (muon) neutrinos. Meters of shielding in front of the detector, a spark chamber, helped filter out all but the neutrinos.

Although the spark chamber (here an array of 10 1-ton aluminum modules) was used as an imaging detector, since it produced electric signals, its development was in the direction of computerizing signals directly.

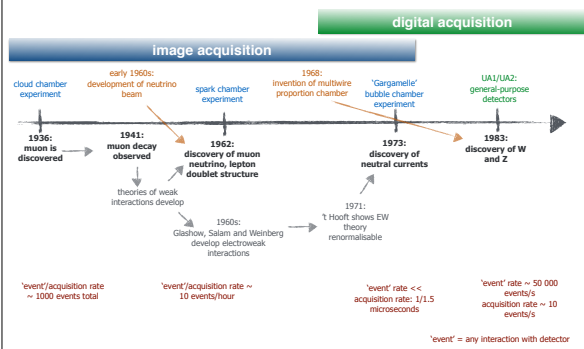


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In order to reduce cosmic ray background the detector 'live-time' was limited to 30 ns after a signal from cerenkov sensors downstream sensing the passage of the pion beam was received. Coincident counters within the chamber were used in conjunction with anti-coincident counters around the chamber in order to trigger on particles originating inside the chamber and travelling along the beam axis (vetoing particles traveling in from the sides of the chamber). 34 muon events were observed; in contrast to 6 'showering' events (indications of 'not very convincing' electrons). This not only provided evidence of the muon neutrino but also that leptons come in pairs.

Paper: <https://doi.org/10.1103/PhysRevLett.9.36>.

Timeline of the Discoveries of Electroweak Interactions



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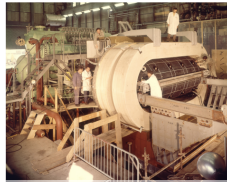
In the 1960s, Glashow, Salam and Weinberg began formulating their theory unifying electromagnetic and weak interactions. Within their formulation, a second, neutral, weak boson was predicted - the Z boson. The theory could however not be shown to be renormalisable.

Meanwhile, with the undiscovered weak force carrier, the W boson, neutrino physics, the window to weak interactions, was a hot topic. Neutrinos furthermore offered a probe of the proton structure via inelastic scattering - a way of verifying the quark model. Europe to not be outdone in this field, devised a great big bubble chamber experiment at CERN: Gargamelle.

observation of neutral weak current



- a (more intense) neutrino beam
- -> 'triggered' on every event!
Doable, as CERN had the computing power to read out loads of film (2000 m/ hour ..)
- Long process of event filtering after ...
- an early international collaboration: 7 institutes provided scanning tables and scanners.



Gargamelle, a 12 ton bubble chamber experiment, CERN, 1970-1979

recorded everything
image acquisition

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Gargamelle made use of a neutrino beam from the PS 25 GeV proton beam (and later the SPS) at CERN.

A snapshot of the chamber was taken with every beam pulse, leading to the productions of hundreds of thousands of photos. The incredible feat of Gargamelle was the great human effort in analyzing every event of activity. It lead to one of the earliest collaborations (7 institutes contributed to the event analysis).

neutral weak currents discovery: bubble chamber experiment

'trigger' rate: ~ 1 event/1.5 seconds
film: 2000 m / hour
during 1st experiment: 500 000 photos taken

The great Human-Level Event Filter

- step 1: scanning by eye for interesting events
- step 2: manual precise measurements of coordinates of interest
- step 3: particle identification on computer.
- step 4: final eye-scan by expert physicists.

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Bubble chamber analysis: scanning

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“Scanning girls” or “gap-year students” identified interesting events by looking at projections on scanning tables. Snapshots from 8 different cameras allowed one to inspect the events from several angles.

Bubble chamber analysis: tracing

<http://cds.cern.ch/record/43141/>

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The coordinates of tracks and vertices in all selected (interesting) events were measured and logged into a computer.

Bubble chamber analysis: computer processing for particle identification

bubble density - $1/v^2$

low bubble density - relativistic

proton track $R - p/q$

electron track

spiralling - energy loss through bremsstrahlung

\otimes
B field out of page.

18 DV= 6113
07 DZ= 17169
RROR= 19277
XX XX XX XX XX

measurement of trace down to 1/10th of mm.

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Computers processed the measurements for particle identifications. One can already identify particles by eye considering that proton (or in general, hadron) tracks curve with a greater radius and result in track widths growing in width as they slow down and suffer increasing ionization energy loss; electron tracks appear wispy, spiral in sharply, opposite to a positively charged proton, as they rapidly lose energy to bremsstrahlung, creating secondary positron-electron tracks from photon emissions. Computers will measure the curvature as well as the width of the tracks to infer the mass-to-charge ratio of particles - and hence their mass assuming a charge of e.

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Bubble chamber analysis: final analysis by physicist

3 leptonic NC events found. (lucky find!) → spurred search for hadronic NC → 163 events found.

leptonic: CC, NC

hadronic: NC, CC

two new particles to be discovered!

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An interesting event caught the attention of a graduate student: an electron was ‘bumped’ and made to move along the beam axis by an invisible particle. This was the first evidence of neutral weak currents. Only a further 2 such events were found. Around the same time Gerard ‘t Hooft showed the electroweak theory to be renormalisable. The Gargamelle collaboration quickly changed their search strategy: they searched for events with one vertex from which only hadrons and no leptons emerged, evidence of hadronic weak current. They found 163 such events in total.

Papers: leptonic NC [https://doi.org/10.1016/0370-2693\(73\)90494-2](https://doi.org/10.1016/0370-2693(73)90494-2), hadronic NC [https://doi.org/10.1016/0370-2693\(73\)90499-1](https://doi.org/10.1016/0370-2693(73)90499-1)

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In parallel: The filmless era

CERN 64 - 30
Data Handling Division
16 June, 1964

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PROCEEDINGS OF THE INFORMAL MEETING
ON FILM-LESS SPARK CHAMBER TECHNIQUES
AND ASSOCIATED COMPUTER USE

1968:

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In the meantime, experimentalists starting dreaming of being able to capture particle signals straight from the detector onto computer. It was clear that the very time-consuming intermediate step of recording and analyzing film had to be done away with. It is interesting to note that one of the concerns that was raised is that the role of the experimentalist will become obsolete with filmless detectors. We know today, that similar to how Gargamelle gave rise to a collaboration in a combined effort to analyze streams of photos manually, modern experiments give rise to large international collaborations connected by a computer grid, working together for years on one search, calibrating, cutting, plotting and understanding offline data.

The invention of the multiwire proportion chamber by Georges Charpak, which relied on the direct capture of an electric signal, was a great breakthrough into the era of digital data acquisition.

Proceedings: <https://cds.cern.ch/record/223865>.

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discovery of W and Z bosons

- used proton-antiproton colliding beams -> for the energy boost.
- UA1 collaboration of 19 institutions.
- Got what they were looking for: Discoveries of the W and Z bosons announced in 1983.
- 1984 Nobel Prize to Rubbia and van der Meer for work towards these discoveries.

4pi digital acquisition.
DAQ and trigger prototypes of modern detectors.

General-purpose, 4pi solid angle, 'filmless' detectors, UA1 and UA2, 1981-1990, CERN

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The race was on to find the W and Z boson.

The SPS at CERN was quickly converted to a proton-antiproton collider, colliding beams of 315 GeV. Two ‘Underground Area’ detectors were built dedicated to the discovery of the W and Z boson (and with success): the UA1 and UA2 experiments. Both detectors were hermetic general-purpose detectors (meaning maximum, almost 4 pi solid angle coverage and consisting of several different detector components dedicated to measuring different types of particles), with complete digital read-out.

W and Z discovery

collision rate: ~ 3.8 microseconds
read out to tape: 120kb/s

experimental set-up: general-purpose 'onion' detector

UA1

4π solid angle detector coverage

magnets

muon drift chambers

hadronic (HAD) calorimeter

electromagnetic (EM) calorimeter

inner tracking: drift chambers

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The UA1 detector was like a prototype of a general-purpose detector at the LHC today, constructed in 'layers': inner tracking detector (drift chambers - direct consequence of the multiwire proportional chamber invention.), electromagnetic calorimeter, hadronic calorimeter, drift chambers for muon detection and magnets. The solid-angle coverage was important in the measurement of total missing energy. UA2 was similarly hermetic but more purpose-built: it had a finer granularity calorimeter, and didn't make use of a magnetic field nor muon detection.

UA experiments: Multi-Level Trigger

bunch crossing at ~ 280 kHz

interaction rate ~ 50 kHz

50 kHz

100 Hz

10 Hz

tape

hardware-based first level trigger:
use of calorimeter signals for rapid 'trigger object' reconstruction

second level trigger on multiprocessors:
use of more accurate event information

detector

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Both experiments made use of a multi-level trigger. First-stage trigger decisions were based on calorimeter signals due to the fast response from calorimeters. The drift times, which were on the order of a beam crossing, as well as large number of channels for the tracking system meant processing tracks was 'computationally expensive'. Tracking information from the inner tracker was therefore only written out (for triggered events) and reconstructed offline.

Trigger Object Reconstruction

hadrons: wide showers across EM + HAD calorimeter

electron, positron and photons: narrow showers in EM calorimeter

UA1 Level-1 Trigger based decision on calorimeter energy deposits

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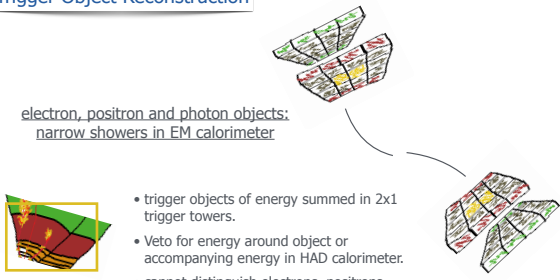
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Electrons, positrons and photons were identified by narrow showers of energy depositions in the electromagnetic (EM) calorimeter only. Hadrons were identified by their wide showers across both the electromagnetic and hadronic (HAD) calorimeters.

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Trigger Object Reconstruction

electron, positron and photon objects:
narrow showers in EM calorimeter



- trigger objects of energy summed in 2x1 trigger towers.
- Veto for energy around object or accompanying energy in HAD calorimeter.
- cannot distinguish electrons, positrons, photons without tracking information, but tracking processing unfeasible at trigger level: signals too slow (drift time), large amount of data (channels) to process.

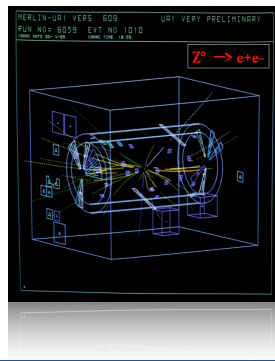
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At the first trigger stage, 'trigger object' were reconstructed. To reconstruct 'narrow shower' EM trigger objects, energies in 2 cells are summed and it is required for there to be no energy in surrounding cells and in the HAD calorimeter. Trigger objects above pre-programmed energy thresholds are counted. In that way one can for example have a trigger based on the requirement of 2 EM trigger objects with energy > 15 GeV to trigger on a $Z \rightarrow ee$ event.

Paper on UA1 $Z \rightarrow ee$ measurement: [https://doi.org/10.1016/0370-2693\(83\)90188-0](https://doi.org/10.1016/0370-2693(83)90188-0)

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UA1 Event Display: $Z \rightarrow ee$



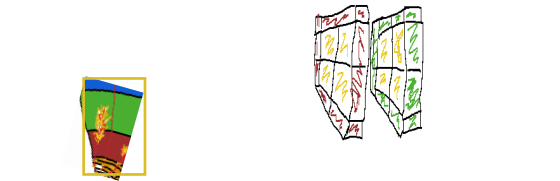
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To reconstruct 'wide shower' HAD trigger objects, energies in groups of 4 cells across both the EM and HAD calorimeter layers are summed. Requiring one energetic HAD trigger object in the event, would for example record mono-jet events.

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Trigger Object Reconstruction

hadrons (jets): wide showers across EM and HAD calorimeters



trigger objects of energy summed in 2x2 (EM) + 2x2 (HAD) trigger towers.

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UA1 Event Display: mono-jet event

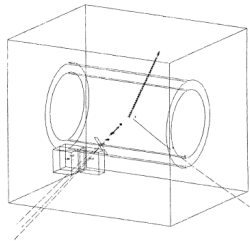


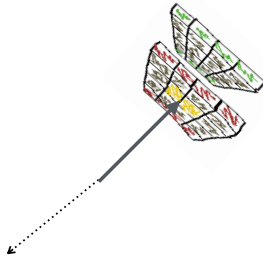
Figure 10. Event display showing tracks with p_T greater than 7 GeV/c and calorimeter hits with E_T greater than 5 GeV. The arrow indicates the direction of the missing E_T (59 GeV).

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video on UA1 experiment: <https://cds.cern.ch/record/1054445?ln=en> (with excitement around evidence believed to be SUSY).

Trigger Object Reconstruction

missing_transverse_energy

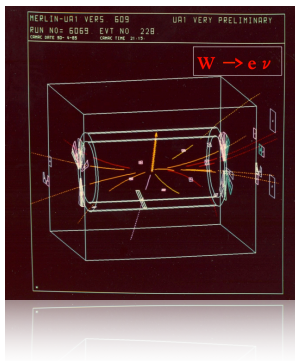


missing energy vector: negative of all trigger object energy vectors summed

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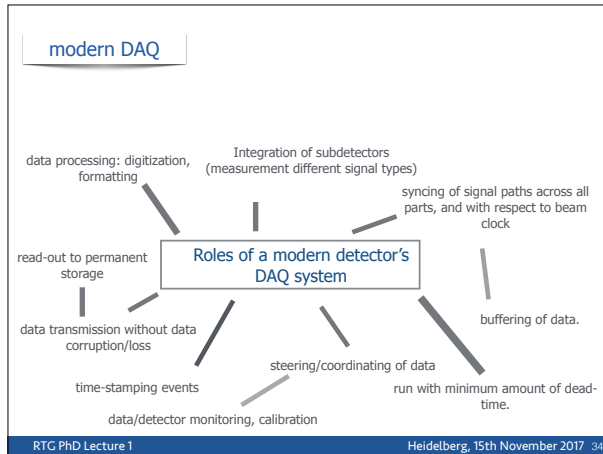
A missing energy (MET) vector was computed after all trigger objects in an event were reconstructed. The MET vector was the negative of the sum of all trigger object vectors. This would trigger on events with an energy imbalance, as is caused by for example $W \rightarrow$ electron + electron anti-neutrino processes.

UA1 Event Display: $W \rightarrow e \nu$



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The new era of hermetic detector design* consisting of several subdetectors quickly lead to the necessity of involved data acquisition systems in order to obtain the data. With the use of multi-level triggers, the trigger system has become an integral part of the DAQ system. There is so much to the role of a DAQ system that one does not immediately think of.

* the first 'onion' detector was Mark I (1973-1977) at the SPEAR collider at SLAC. The experiment discovered the tau lepton and the J/Psi particle.

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... and today experimental set-ups are not much different ...


general-purpose detector design today not much different except increasingly bigger, higher recording rate, more signal channels, higher number of interactions per crossing, **exploiting power of statistics**.


And the data acquisition system grows in complexity.

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... though some things we will probably never see again ;) ...

In the 80s, 'express stream' data transfer to data center at CERN in looked like:  the so-called B-O-L ('bicycle-on-line'). Very poor bandwidth.

Physicist's artistic expressions through eh lovely line printed pictures on 'histogramming' paper. 

(Video on Gargamelle. I missed the first time)

<http://cds.cern.ch/record/43141/>

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