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Triggering And Data Acquisition in High Energy Physics

for the Heidelberg GK BSM

Lecture 1/3

15th November 2017

by
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Table of Content

- **Lecture 1 (today):**
  - The definition of data acquisition and triggering, and little bits of history.

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.

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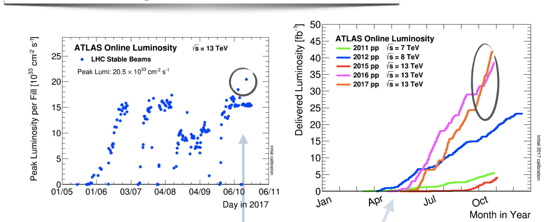
2017: the Large Hadron Collider @ CERN

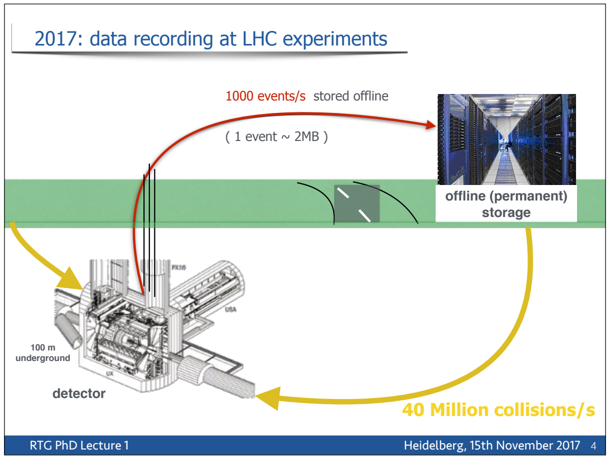


- **Records (repeatedly) broken at the LHC:**
  - highest accelerated beam energy: 6.5 TeV (Tevatron: 1 TeV), at a rate of 40 Million Hz (LHC Run 1: 20 Million Hz, Tevatron: 2 Million Hz)
  - highest stored beam energy: 30 MJ - 2556 stored proton bunches (Tevatron: 1MJ, 36 stored bunches)
  - highest instantaneous luminosity (above design): 2.05×10^{34} $cm^{-2}s^{-1}$, with peak of 78 average number of interactions per bunch. (Tevatron: 4×10^{34} $cm^{-2}s^{-1}$, 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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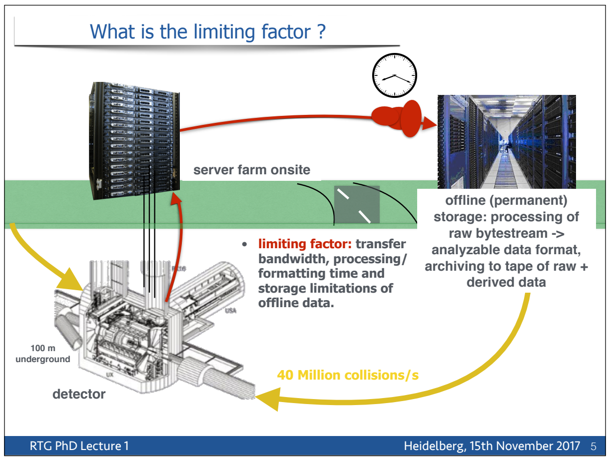
An average general-purpose detector at the LHC, such as ATLAS, analyses every collision, however records just a tiny fraction of it: 1 out of every 40 000 events per second (ATLAS). Recording every collision is clearly not feasible: at 2 MB per event and 12 hour fills, this would amount to ~ 3000 PB 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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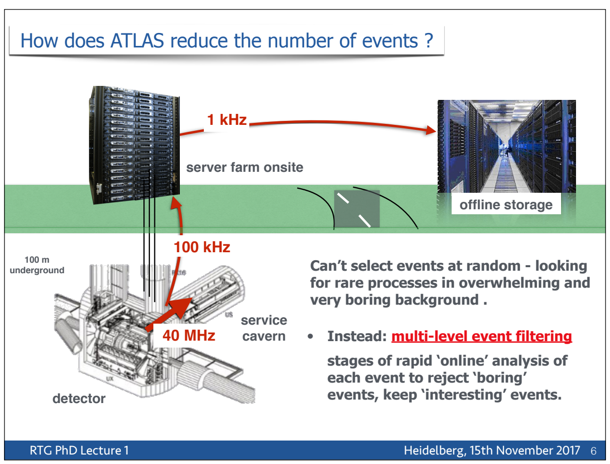
The back-pressure originates from the transfer, processing and storing of data from the experiment site to permanent storage offsite.



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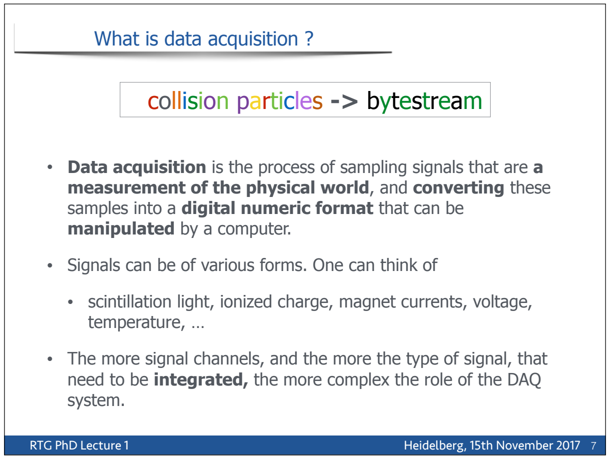
Selecting events at random would be a waste of time as most events are all the same: QCD multijet background. The better strategy is to be selective in order to enhance the number of possible signal events ('interesting events') over the overwhelming background ('boring events'). ATLAS selects its events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



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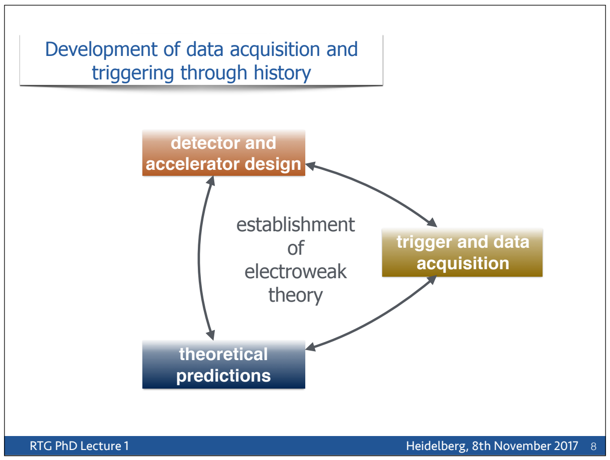

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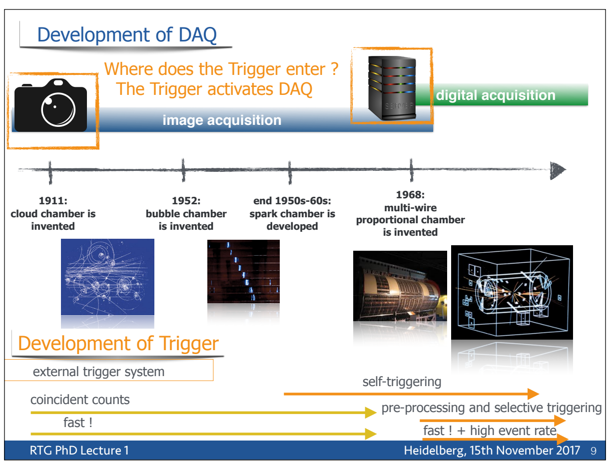
The techniques of triggering and data acquisition, along with detector and accelerator design, develop hand-in-hand with the physics that was being discovered or predicted at the time.

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



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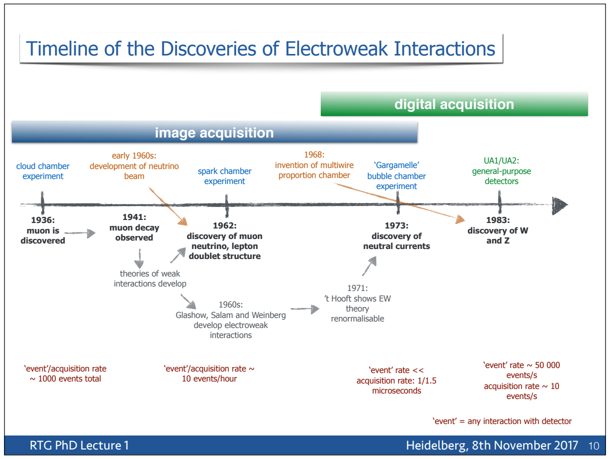
The study of particle interactions in detectors kicked off with the invention of the cloud chamber, with subsequent discoveries such as the positron in the early 30s.

It lead 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 lead 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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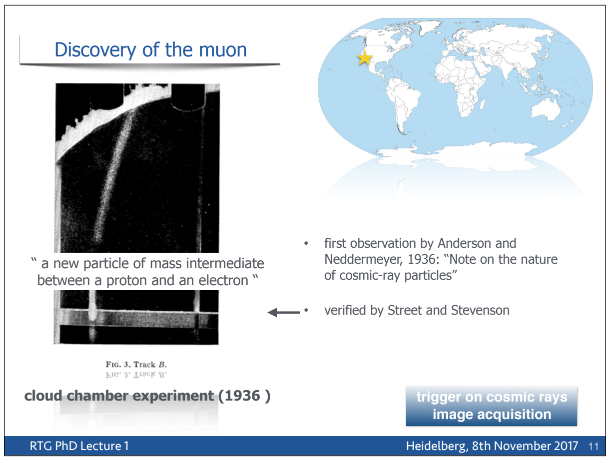
At the start of the 1930s, it had not yet been realized that lepton generations and their doublet structure existed. Lepton number conservation had not yet been formulated and weak interactions were awaiting discovery.

The muon was discovered in a cloud chamber in 1936, and was the first evidence of weak interactions.



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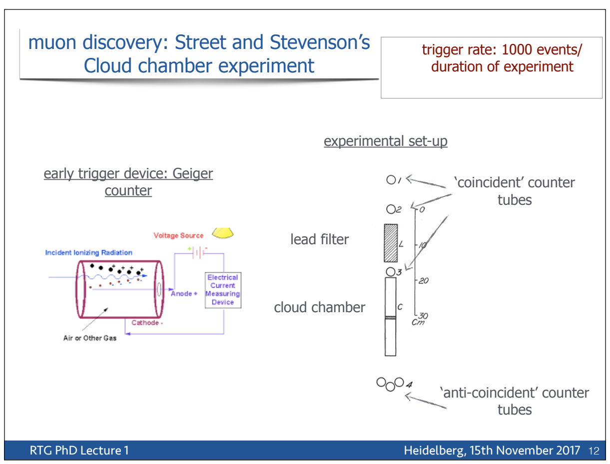
Discovery of the Muon: A new particle was identified in the detection of cosmic rays in a spark chamber in 1936 by Anderson and Neddermeyer. A second spark chamber experiment by Street and Stevenson verified this: out of a 1000 photos they identified one containing a track with an ionization width and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



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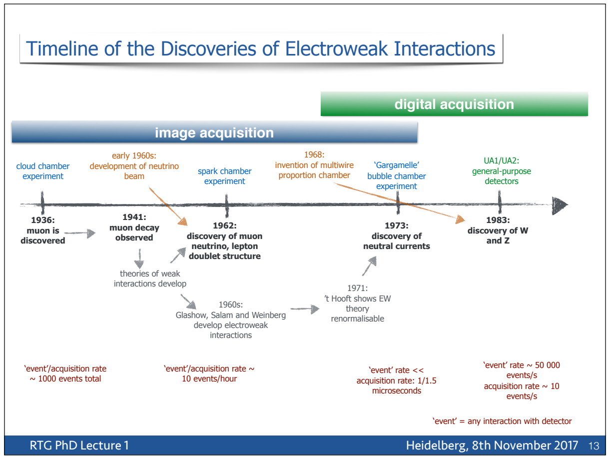
Street's and Stevenson's cloud chamber experiment was a simple set-up immersed in a magnetic field.

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.

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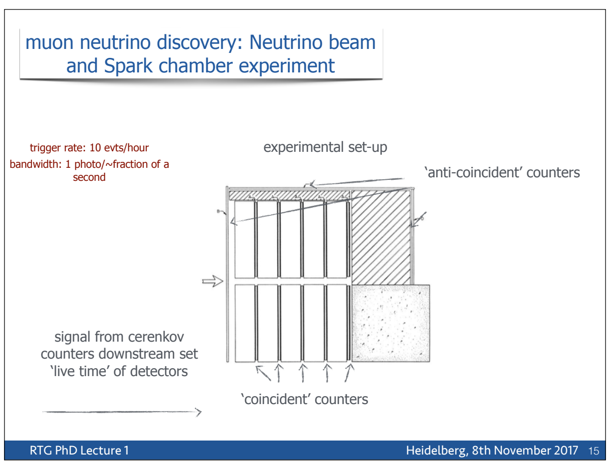
The discovery of the muon neutrino: was made possible with the creation of a neutrino beam using 15 GeV protons accelerated by the Brookhaven AGS. The protons were targeted at a Beryllium target, creating a subsequent beam of (mostly) pions, and kaons. These decayed mid-flight to muons and (muon) neutrinos. 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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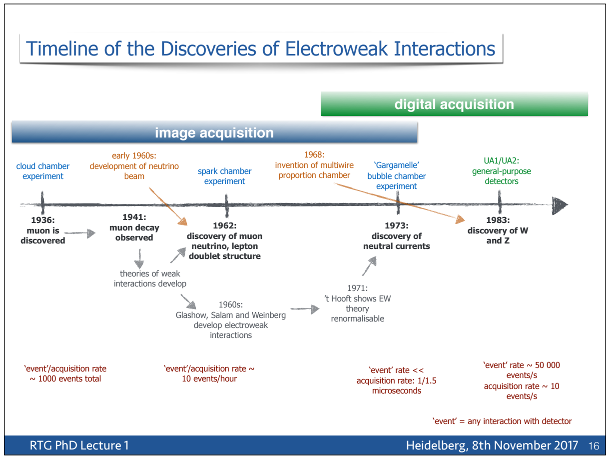
In order to reduce cosmic ray background the detector 'live-time' was limited to 30 ns after a signal from cerenkov sensors downstream sensing the passage of the pion beam was received. Coincident counters within the chamber were used in conjunction with anti-coincident counters around the chamber in 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.



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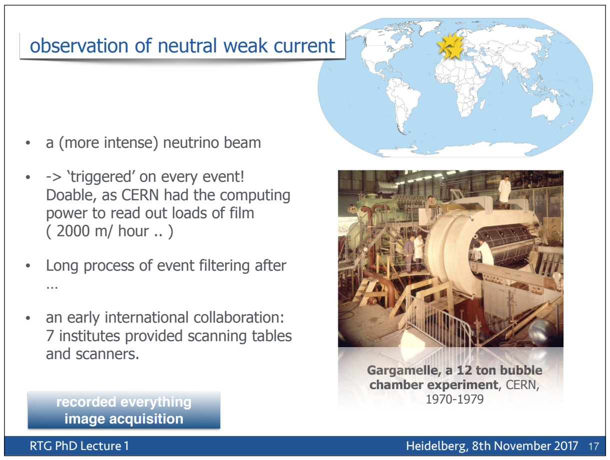
In the 1960s, Glashow, Salam and Weinberg began formulating their theory unifying electromagnetic and weak interactions. Within their formulation, a second, neutral, weak boson was predicted - the Z boson. The theory could however not be shown to be renormalisable.

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.



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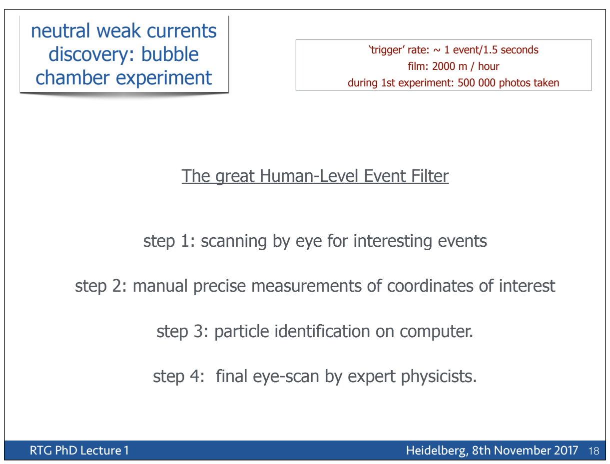
Gargamelle made use of a neutrino beam from the PS 25 GeV proton beam (and later the SPS) at CERN.

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).



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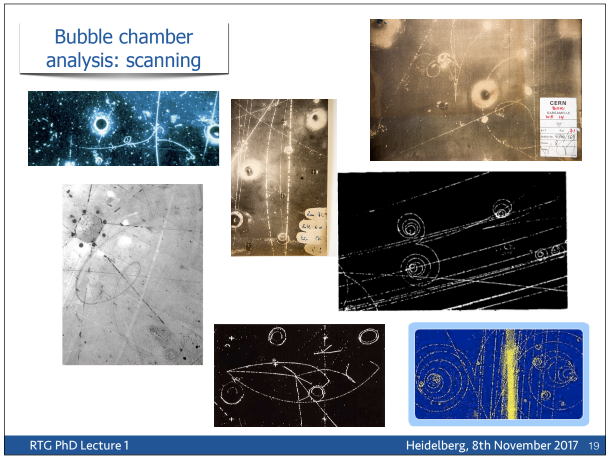
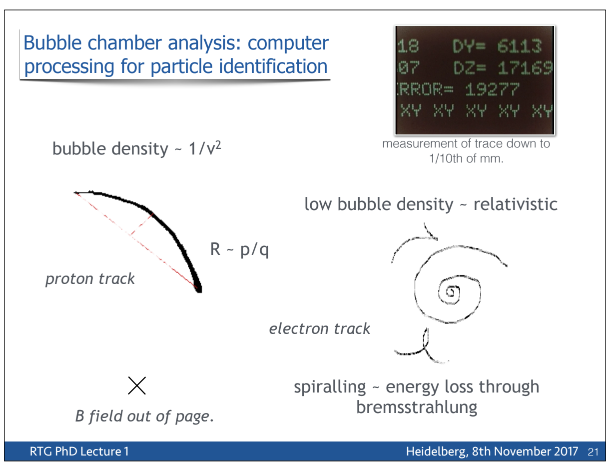


19 “Scanning girls” or “gap-year students” identified interesting events by looking at projections on scanning tables. Snapshots from 8 different cameras allowed one to inspect the events from several angles.

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



21 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 whispy, 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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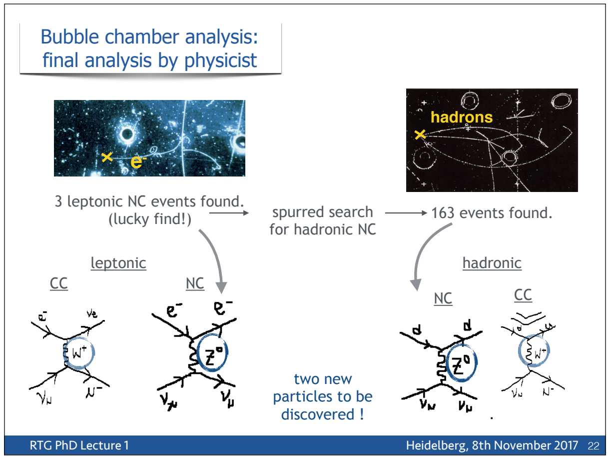

An interesting event caught the attention of a graduate student: an electron was 'bumped' and made to move along the beam axis by an invisible particle. This was the first evidence of neutral weak currents. Only a further 2 such events were found. Around the same time Gerard 't Hooft showed the electroweak 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, hadronic NC https://doi.org/10.1016/0370-2693(73)90499-1

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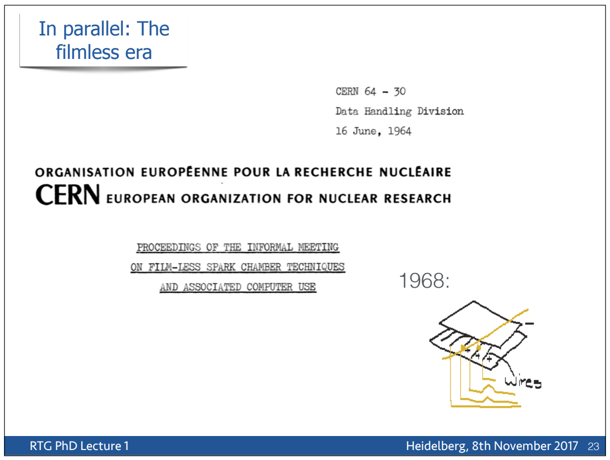

In the meantime, experimentalists starting dreaming of being able to capture particle signals straight from the detector onto computer. It was clear that the very time-consuming intermediate step of recording and analyzing film had to be done away with. It is interesting to note that one of the concerns 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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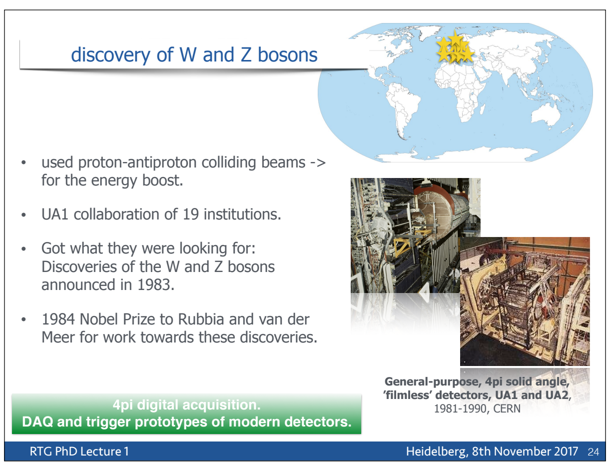
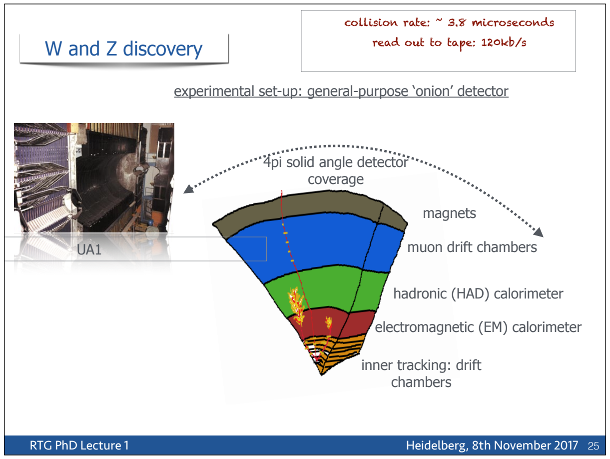


The race was on to find the W and Z boson.

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.



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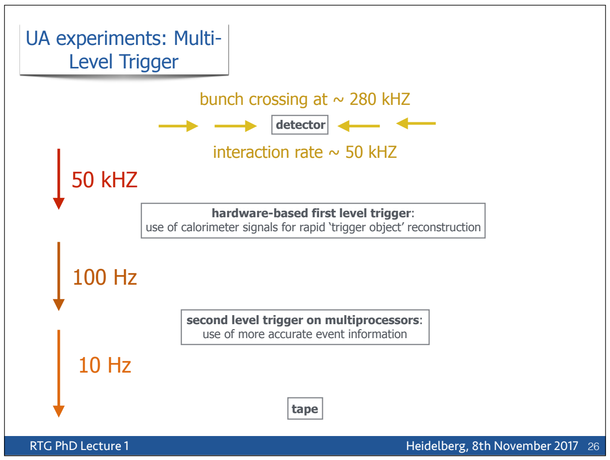
The UA1 detector was like a prototype of a general-purpose detector at the LHC today, constructed in 'layers': inner tracking detector (drift chambers - direct consequence of the multiwire proportional chamber invention.), electromagnetic calorimeter, hadronic calorimeter, drift chambers for muon detection 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.



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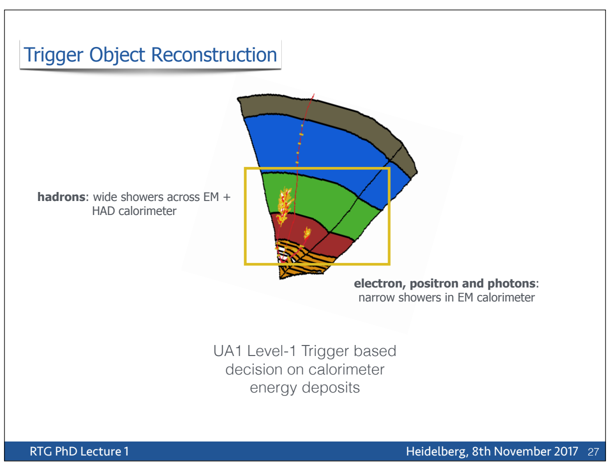
Both experiments made use of a multi-level trigger. First-stage trigger decisions were based on calorimeter signals due to the fast response from calorimeters. The drift times, which were on the order of a beam crossing, as well as large number of channels for the tracking system meant processing tracks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



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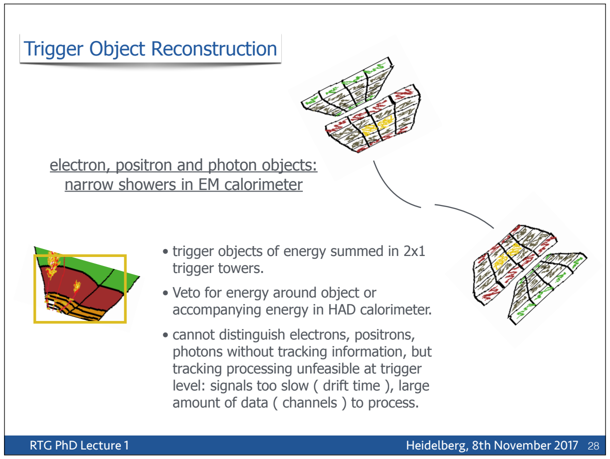
Electrons, positrons and photons were identified by narrow showers of energy depositions in the electromagnetic (EM) calorimeter only. Hadrons were identified by their wide showers across both the electromagnetic and hadronic (HAD) calorimeters.



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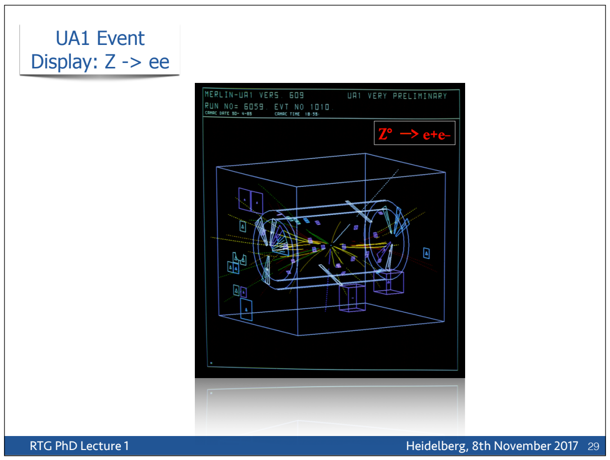
At the first trigger stage, 'trigger object' were reconstructed. To reconstruct 'narrow shower' EM trigger objects, energies in 2 cells are summed and it is required for there to be no energy in surrounding cells and in the HAD calorimeter. Trigger objects above pre-programmed energy thresholds are counted. 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 -> ee event.

Paper on UA1 Z->ee measurement: https://doi.org/10.1016/0370-2693(83)90188-0



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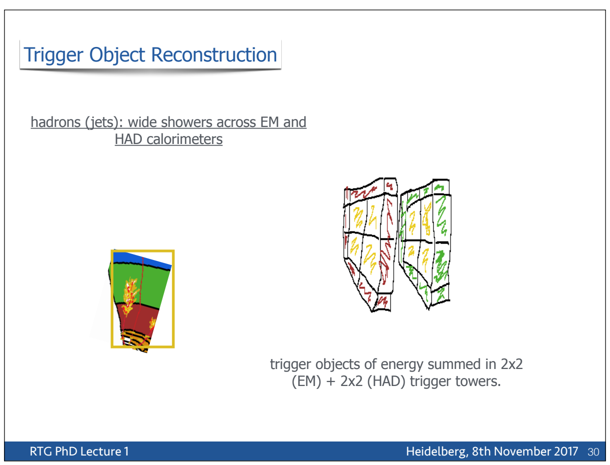

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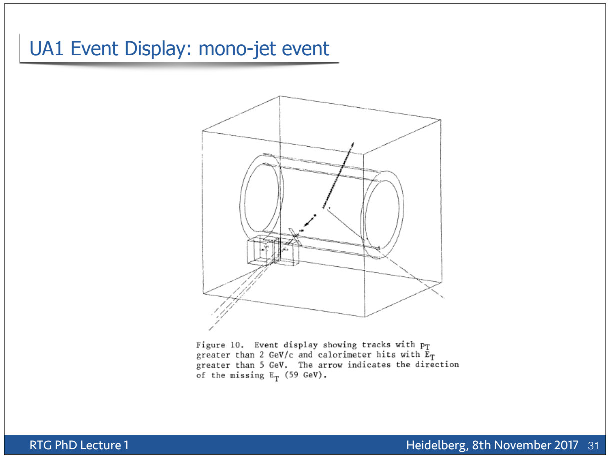
To reconstruct 'wide shower' HAD trigger objects, energies in groups of 4 cells across both the EM and HAD calorimeter layers are summed. Requiring one energetic HAD trigger object in the event, would for example record mono-jet events.



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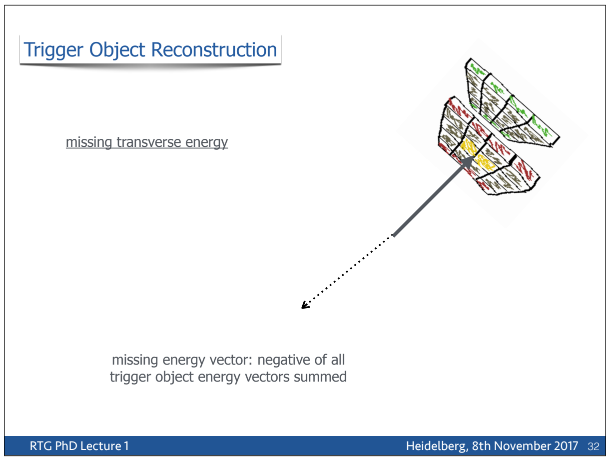
video on UA1 experiment: https://cds.cern.ch/record/1054445?ln=en
(with excitement around evidence believed to be SUSY).



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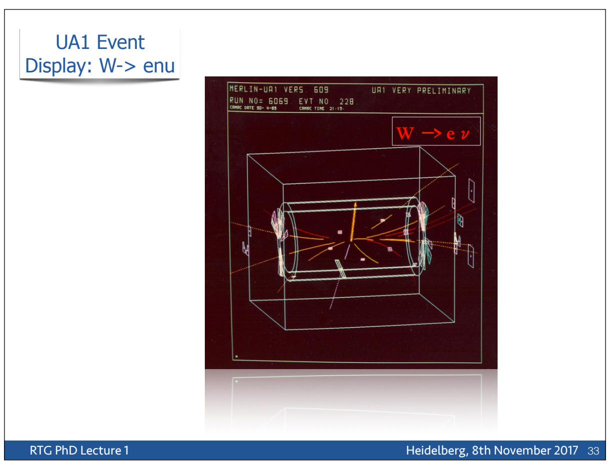
A missing energy (MET) vector was computed after all trigger objects in an event were reconstructed. The MET vector was the negative of the sum of all trigger object vectors. This would trigger on events with an energy imbalance, as is caused by for example W -> electron + electron anti-neutrino processes.



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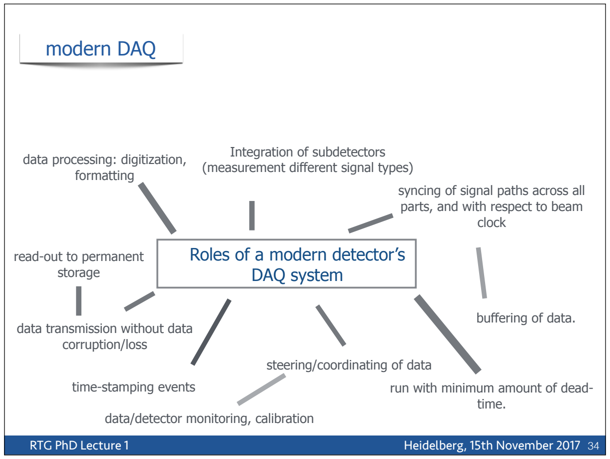

The new era of hermetic detector design* consisting of several subdetectors quickly lead to the necessity of involved data acquisition systems in order to obtain the data. With the use of multi-level triggers, the trigger system has become an integral part of the DAQ system. There is so much to the role 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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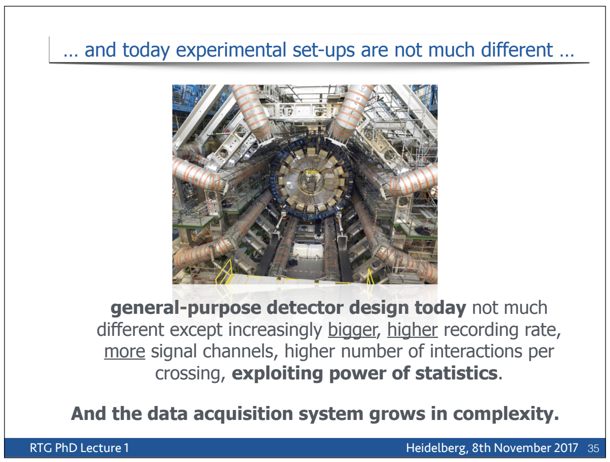

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