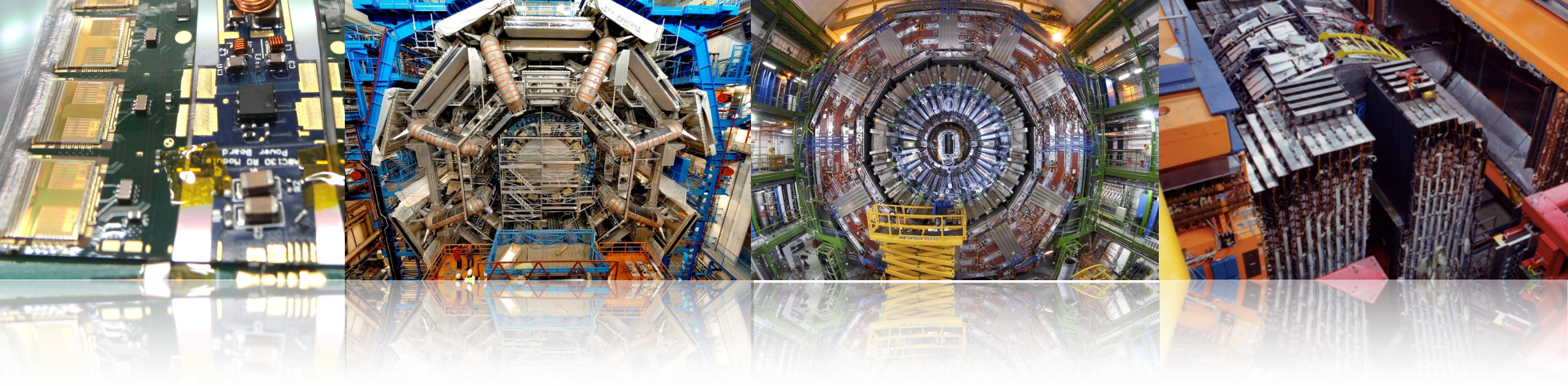


Instrumentation and Detectors

Part 4

Ingrid-Maria Gregor
DESY/Universität Bonn

BND School

Overview

I. **Detectors for Particle Physics**

II. **Interaction with Matter** } *Monday*

III. **Calorimeter** } *Tuesday*

IV. **Tracking Detectors Overview** } *Wednesday I*

- Gas detectors
- Muon Detectors
- Semiconductor trackers

V. **Current Pixel and Strip Detector Projects** } *Wednesday II*

VI. **Examples of what can go wrong**

Real Life Examples

Building an Experiment (Example LHC)

How to do a particle Physics Experiment

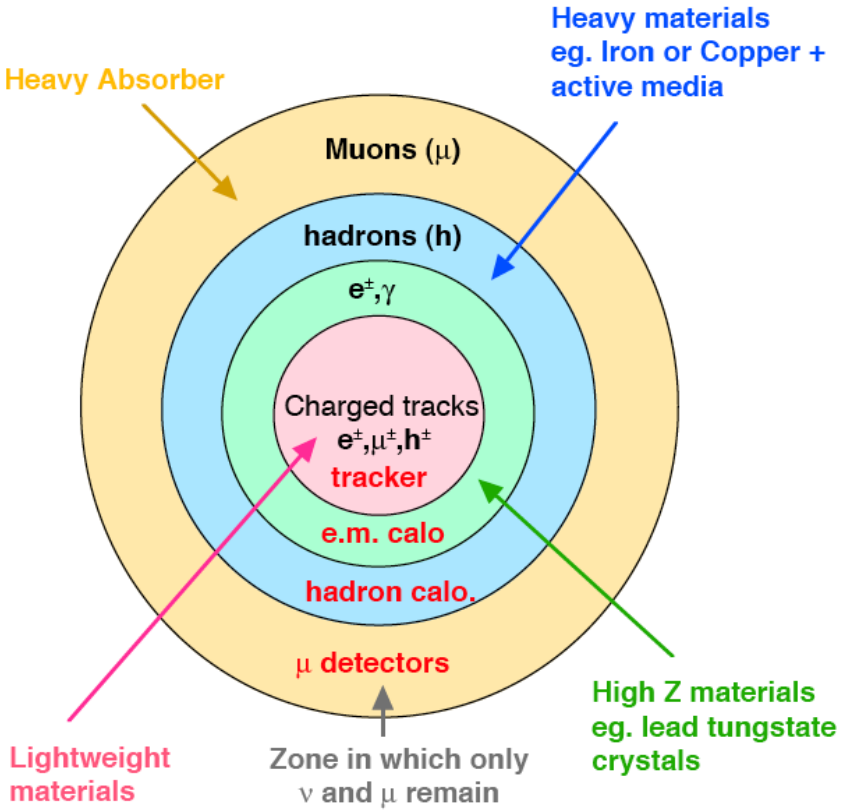
- Ingredients needed:
  - particle source
  - accelerator and aiming device
  - detector
  - trigger
  - recording devices
- Recipe:
  - get particles (e.g. protons, antiprotons, electrons, …)
  - accelerate them
  - collide them
  - observe and record the events
  - analyse and interpret the data
  - many people to:
    - design, build, test, operate accelerate
    - design, build, test, calibrate, operate, understand the detector
    - analyse data
  - lots of money to pay all this ….

typical HERA collaboration: ~400 people
LHC collaborations: >2000 people

Pic: DESY

Conceptual Design of HEP Dete

- Need detailed understanding of
  - processes you want to measure ("physics case")
  - signatures, particle energies and rates to be expected
  - background conditions
- Decide on magnetic field
  - only around tracker?
  - extending further ?
- Calorimeter choice
  - define geometry (nuclear reaction length, X0)
  - type of calorimeter (can be mixed)
  - choice of material depends also on funds



at a collider experiment

- Tracker
  - technology choice (gas and/or Si?)
  - number of layers, coverage, …
  - pitch, thickness, ….
  - also here money plays a role

Detailed Monte Carlo Simulations need to guide the design process all the time !!

A magnet for a LHC experiment

- **Wish list**
  - big: long lever arm for tracking
  - high magnetic field
  - low material budget or outside detector (radiation length, absorption)
  - serve as mechanical support
  - reliable operation
  - cheap
  - ….

www.positoons.de

Eierlegende Wollmilchsau

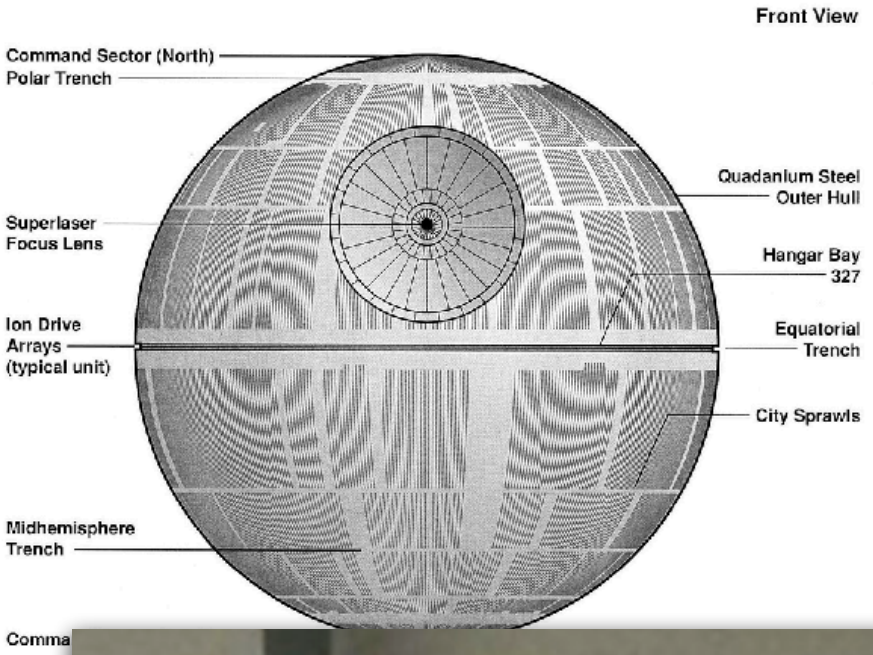
- **ATLAS decision**
  - achieve a high-precision stand-alone momentum measurement of muons
  - need magnetic field in muon region -> large radius magnet

- **CMS decision**
  - single magnet with the highest possible field in inner tracker (momentum resolution)
  - muon detector outside of magnet

And what can go wrong....

Disclaimer

- Designing a large (silicon) detector for particle tracking or identification is a very complex business
- Many very nice examples exist
- Also some examples of failures



- Some stuff you don't find in textbooks
- Collection of failures might give the impression of overall incompetence
  - Overwhelming majority of detectors run like a chime
  - Unbelievable effort to get large accelerators and experiments in a global effort to run so nicely
  - Even sociologists are interested in how we do this …

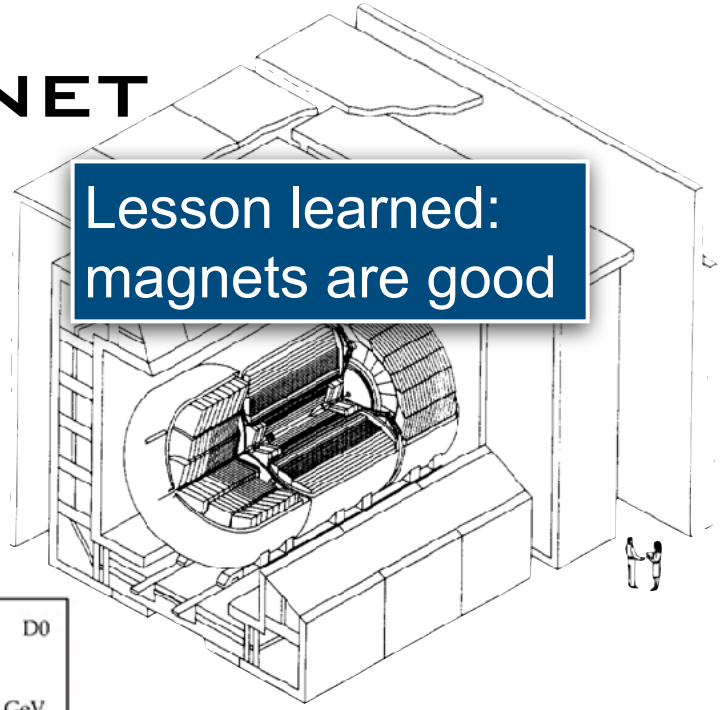
D0 without Inner Tracking Magnet

- D0 Experiment at Tevatron constructed to study proton-antiproton collisions
- **Top quark discovery** in 1995 together with CDF experiment

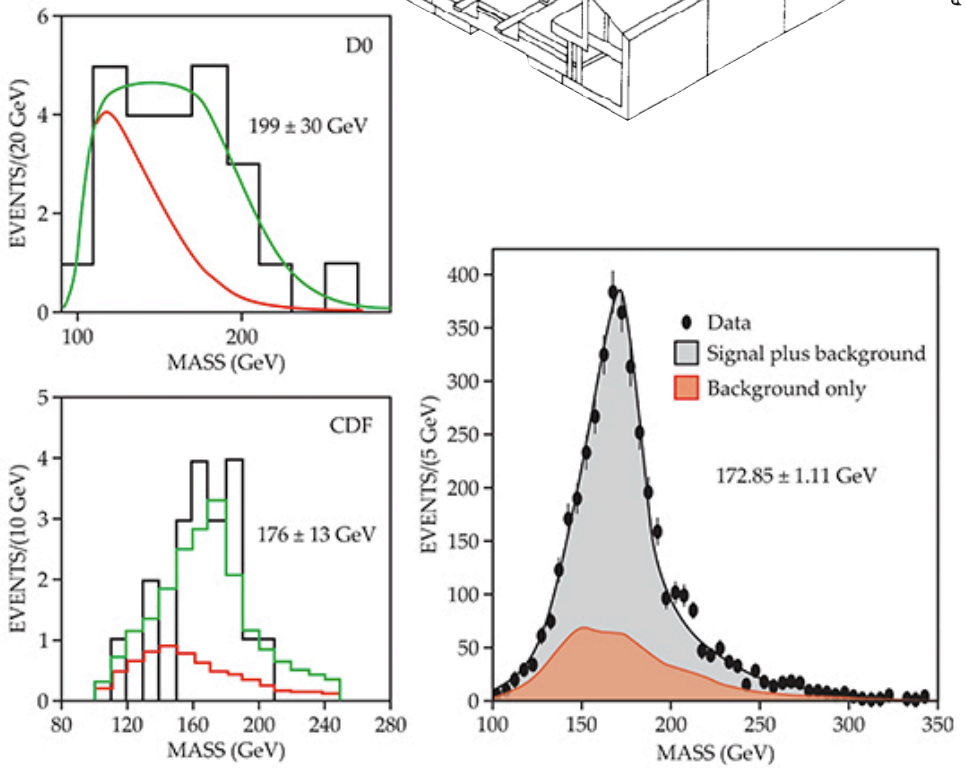
  - Original design for Run I: no magnet for tracking
    - "Focussing on parton jets for deciphering the underlying physics than emphasis on individual final particle after hadronisation"
    - Very compact tracking system
    - Uranium-liquid argon calorimeter for identification of electrons, photons, jets and muons

  - Effect of low momentum charged particles greatly underestimated resulting in analysis difficulties.

Run II system included a silicon microstrip tracker and a scintillating-fibre tracker located within a 2 T solenoidal magnet.



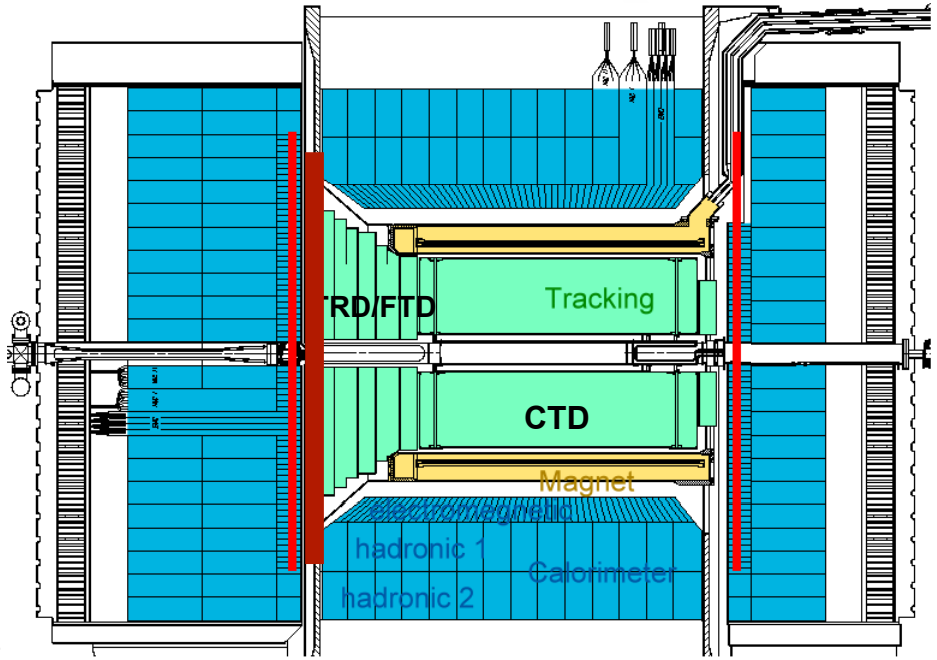
Lesson learned: magnets are good



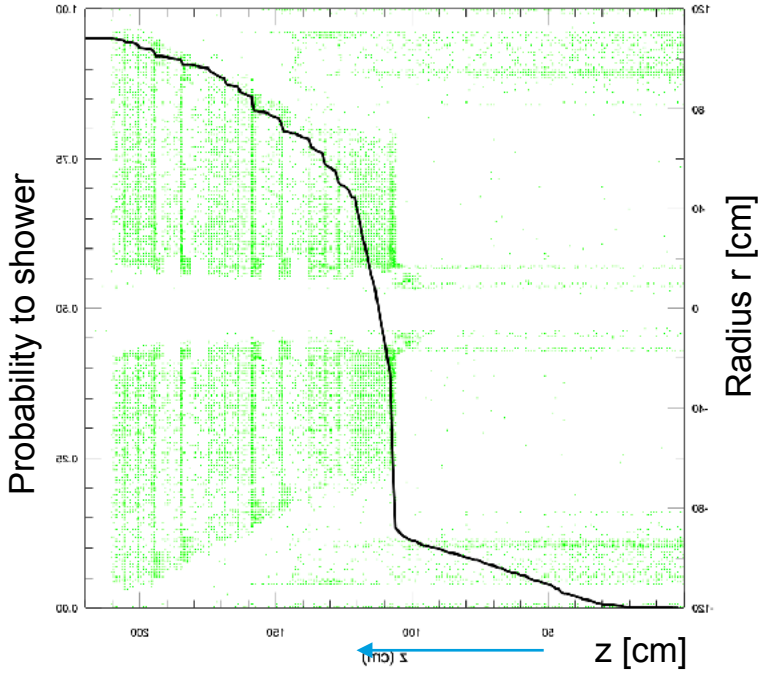
Top quark discovery

ZEUS TRD

- Zeus Transition Radiation detector for electron identification.
- Aim: h/e rejection ratio of about 10^{-2} for electron tracks embedded in jets (1 - 30 GeV/c).

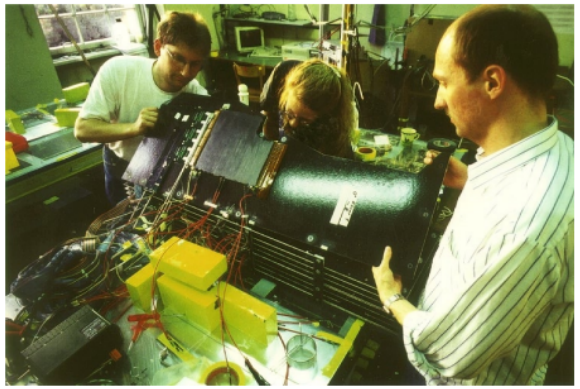


- However - central tracking detector (wire chamber) had 2cm end-plate for wire fixation
  - Electrons 100% probability to shower and thus were not present in showers anymore
- Reason for mishap: no proper Monte Carlo simulation tools available at time of detector design
  - TRD used for Here Run I Replaced by Straw Tube Tracker for Run II



Lesson learned:
Monte Carlos simulations should include everything

Challenges in Tracking System

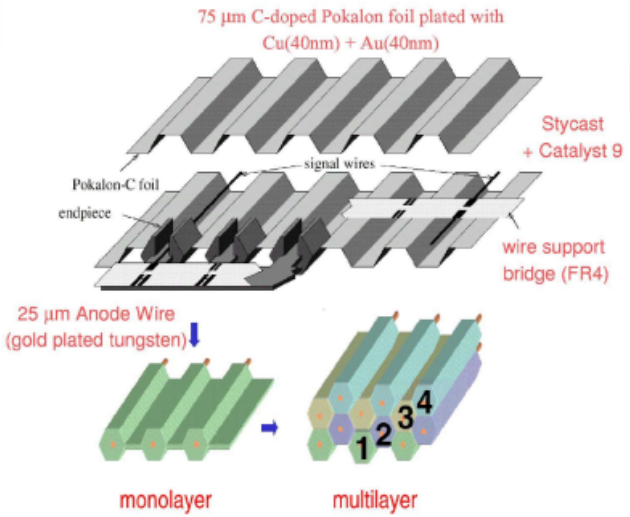


Inner tracker:

- Microstrip gas chamber based on new technology: micro-pattern gas detectors (GEMs)
  - particle flux too high for conventional wire chambers (pitch > mm) (too high occupancy)
  - area too large for Silicon Micro Strips (pitch 50 µm) (expensive, too many channels, large capacity…)
- Before production: Breakdowns occurred at the intolerable high rate of a few sparks per hour -> cured by changing field geometry
- During production: New massive ageing phenomena on production series chambers -> reduced HV stability due to radiation damage

Outer tracker:

- Honeycomb Drift Chamber with 5 mm and 10 mm drift cells
- Rapid ageing of chambers due to radiation environment
- Painful learning curve resulting in 1.5 years delay
- During running: started to lose channels due to faulty mounting of certain HV capacitors!



Reasons

- Very challenging particle physics experiment
  - Particle flux in detector
  - Radiation damage
  - Event rate
  - Data throughput

03/03/03 06:10
7

Comment from **SG, UH**
Arriving at Hall West at 6:00, we don't see anybody around. The control room is dark and locked, and the HERA display announces "SHUTDOWN" (sounds a bit like Genesis 1,1, but that was a beginning...)

03/03/03 07:16
8

Comment from **Bernhard Schmidt**
... in fact, at 6:45 the darkness was quite complete.
And nobody around to say goodbye...Sleep well, old lady ;-)

- Hera-B was a "flip/flop" experiment
  - Only one physics measurement:
    CP violation in B decays
  - No backup plan for reduced requirements

Not all bad ….

- More than 100 Phd theses
- Most technical challenges solved
- CMS changed tracking design

- Schedule from the start very tight in light of a challenging project
  - B-factories (e^+e^-) BarBar (SLAC) and BELLE (KEK) in construction
  - Competing with B-factories: HERA-B without a chance

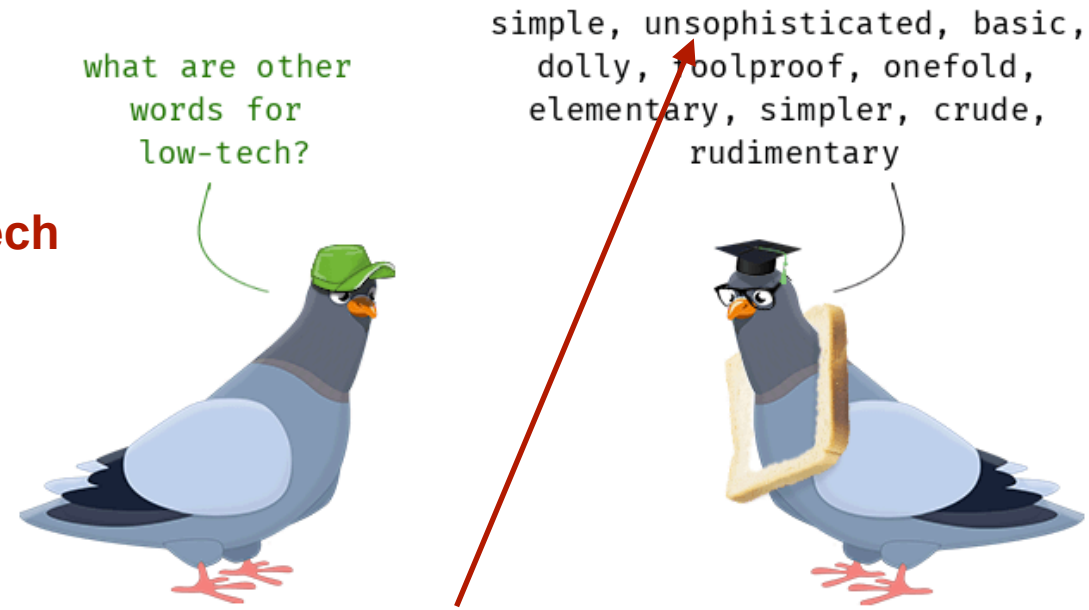
2002 : CP-Verletzung mit > 5σ gemessen

Hera-B: LHC detector prototype !

“Low Tech” Failures

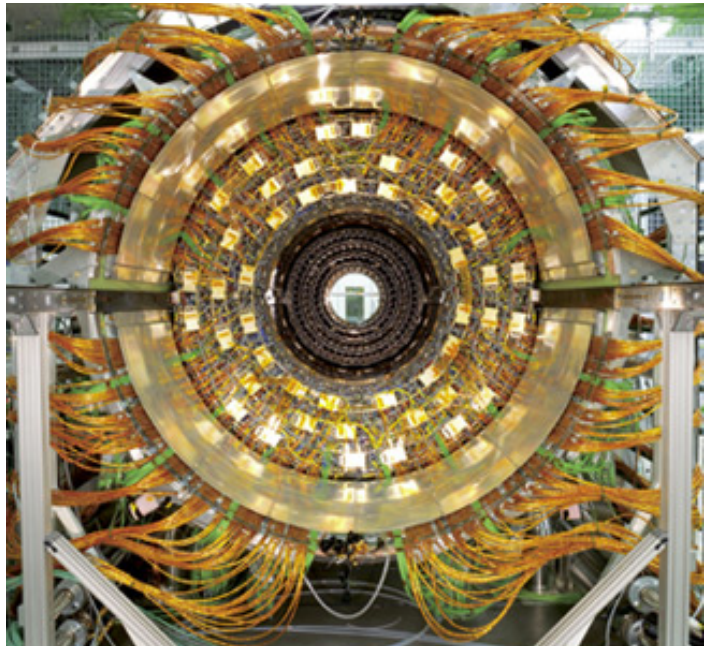
What is "Low" Tech ?

- In particle physics experiments almost everything is **high tech**
  - Need extreme reliability
  - Radiation tolerance
  - Precision
  - Mostly running longer than originally planned



- However - some areas considered as "low tech" and people (and funding agencies) don't like to invest research money into those areas
  - Cables for powering
  - Power plants
  - Cooling
  - Data transfer (optical and electrical)
  - Non sensitive materials (mechanics)
  - Glues
  - .....

For particle physics experiments this is not true !

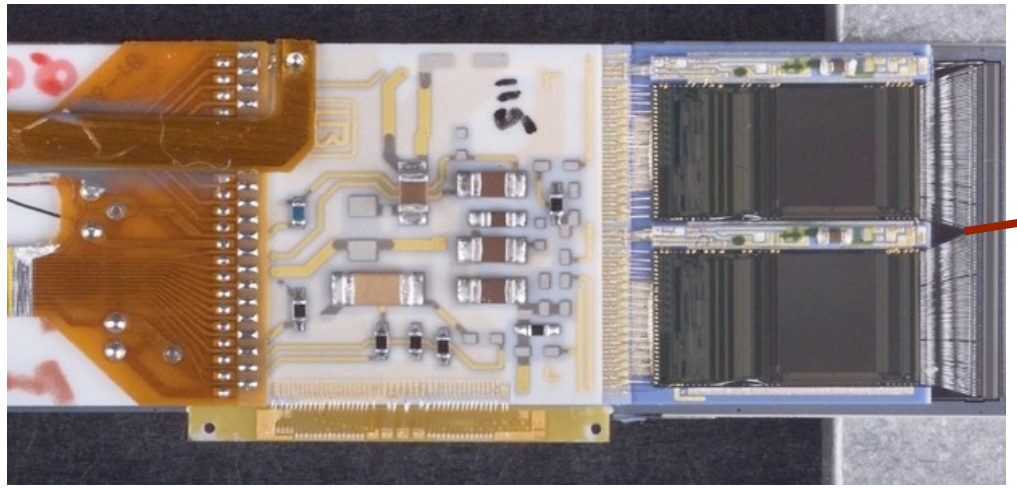


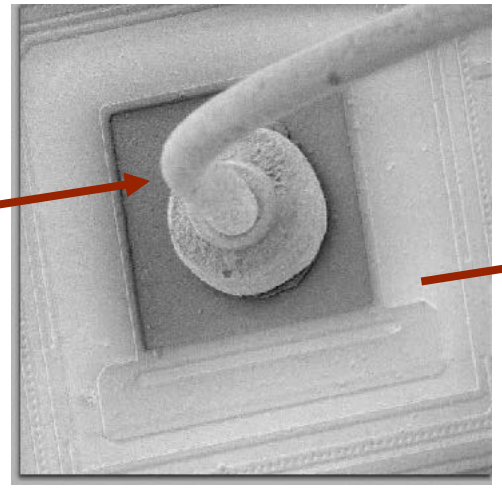
Wire-Bonds and Wire Breakage

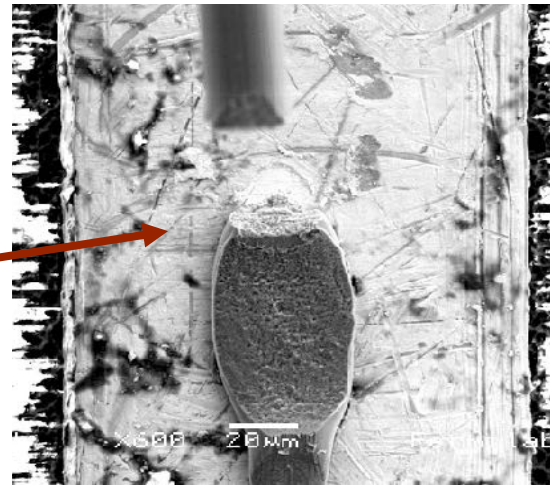
Problems with Wire Bonds (CDF, D0)

during running

- Very important connection technology for tracking detectors: wire bonds:
  - 17-20 um small wire connection -> terrible sensitive ….
- Observation: During synchronous readout conditions, loss of modules (no data, Drop in current)



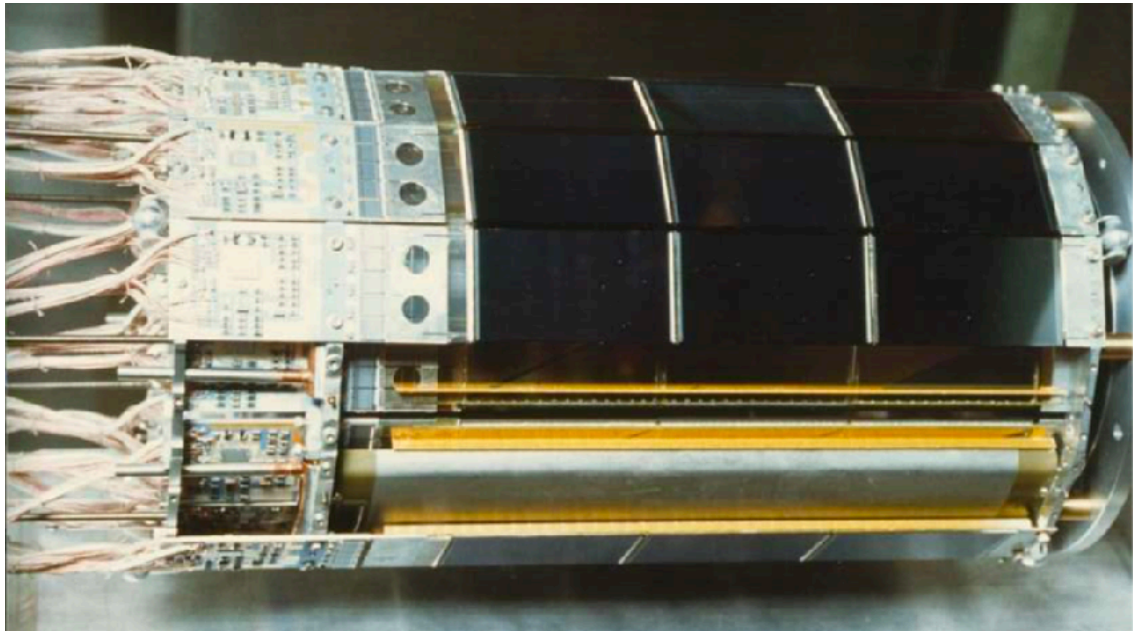




- Tests revealed:
  - Bonds start moving due to Lorentz Force in magnetic field
  - Wire resonance in the 20 kHz range
  - Current is highest during data readout
  - Already a few kicks are enough to get the bond excited

Implemented “Ghostbuster” system which avoids long phases with same readout frequency

OPAL MVD 1994



- OPAL MVD ran for a short while without cooling water flow.
- Temperature of the detector rose to **over 100°C.**
  - Most of the modules to fail or to be partially damaged.

- Chain of problem causing damage:
  - MVD expert modified the control/monitoring software between consecutive data taking runs.
  - Inserted bug which stopped software in a state with cooling water off but with the low voltage power on.
  - Stopped software also prevented the monitoring of the temperature from functioning
  - Should have been prevented by additional interlock but that was also disabled….

Lucky outcome:

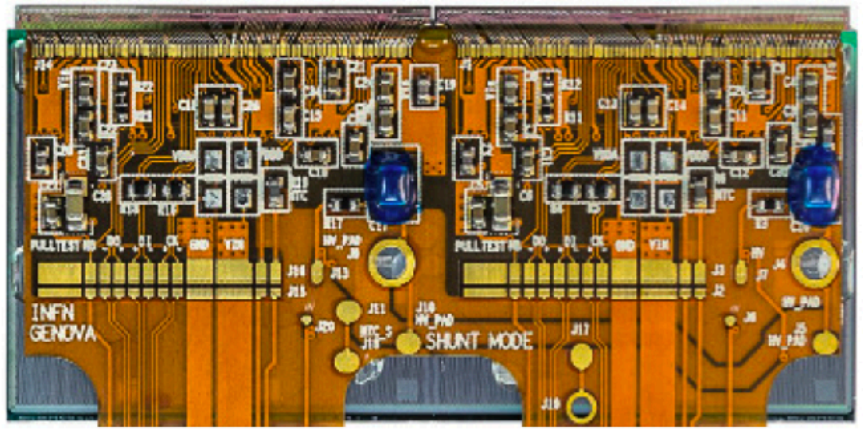
- Damage was mostly melted wire bonds
- Detector could be fixed in winter shutdown

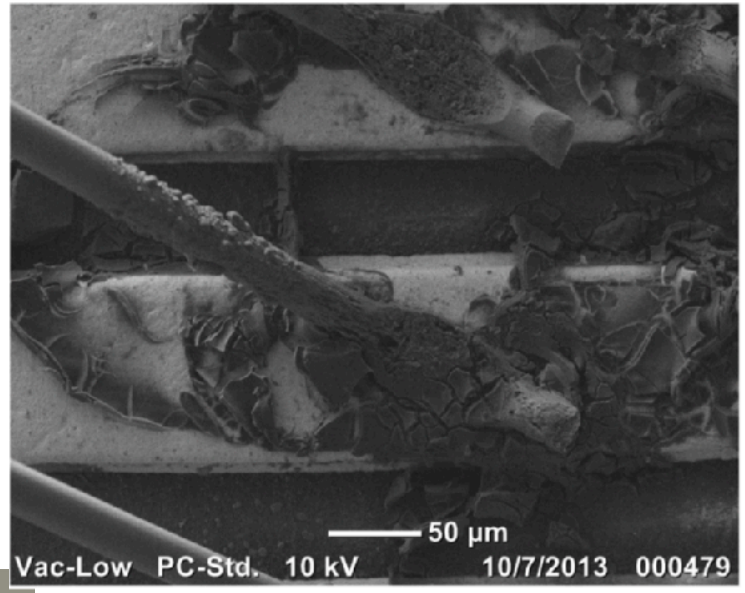
Mitigation plan:

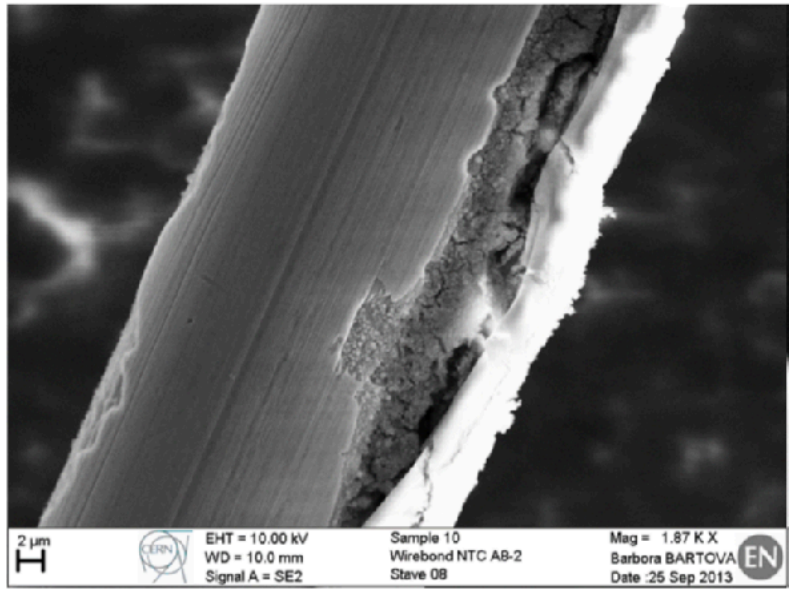
- new and more rigorous interlock system that could not be in a disabled state during data taking conditions.
- rule was implemented that prohibited software modifications between consecutive data taking runs.

ATLAS IBL - Wire Bond Corrosion

- Additional pixel layer for ATLAS installed in 2015
- Five months **before** installation: corrosion residues observed at wire-bonds after cold tests (-25 C)
  - Severe damage of many wire-bonds
- Residue showed traces of chlorine: catalyst of a reaction between Aluminium (wire-bonds) and H_2O (in air)
- Origin of chlorine in system never fully understood







- Emergency repair and additional staves from spare parts

during production

https://indico.cern.ch/event/435798/contributions/1074098/attachments/1134177/1622192/encapsulation_study_-_Oxford.pdf

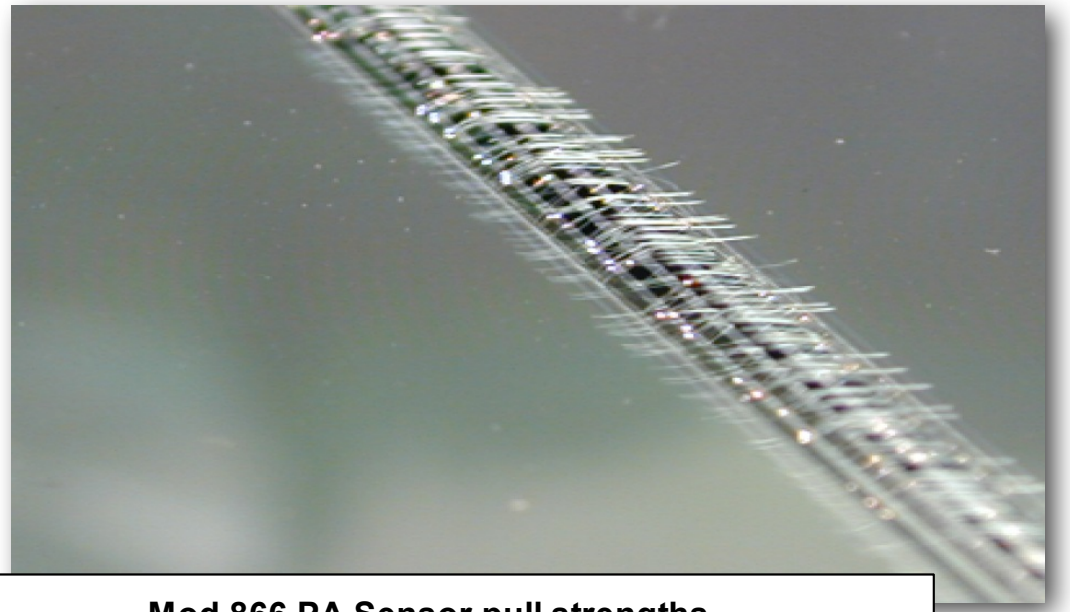
More Wire Bond Wreckage

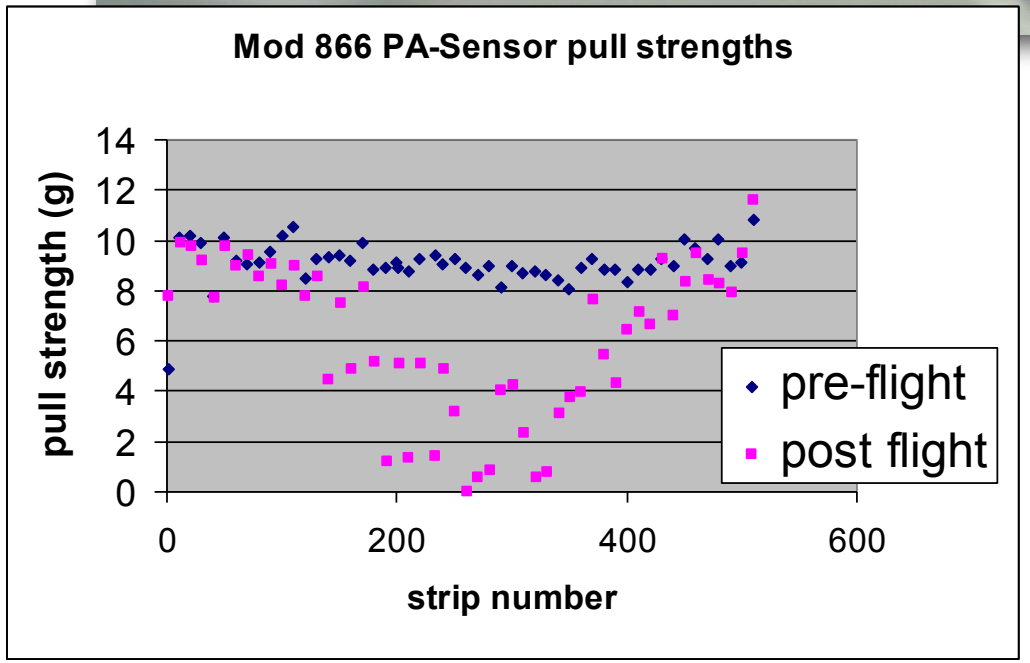
- During CMS strip tracker production quality assurance applied before and after transport
  - Quality of wires is tested by pull tests (measured in g)

- Wire bonds were weaker after transport with plane
- Random 3.4 g NASA vibration test could reproduce same problem

- Problem observed during production -> improved by adding a glue layer
- No further problems during production

during production

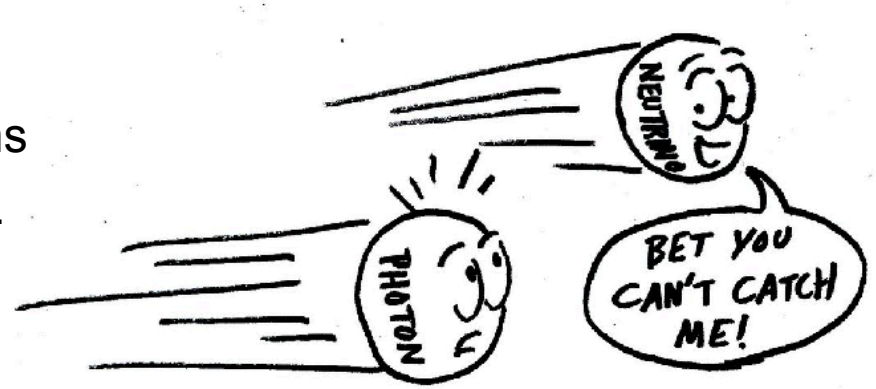




Other Problems and Famous Problems

Cable Problem with Press Coverage

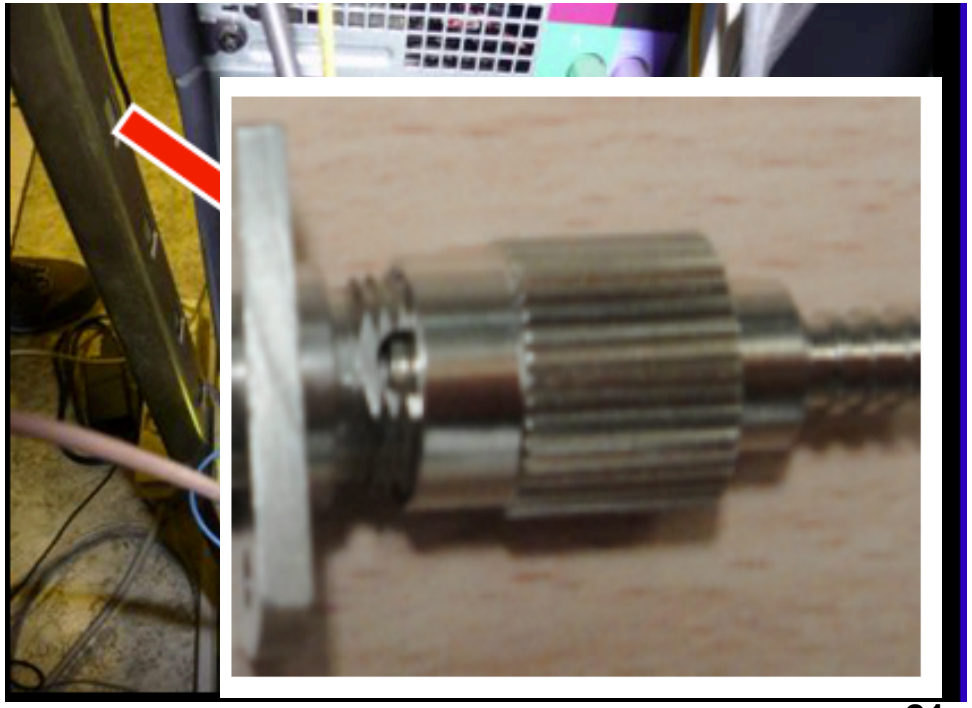
- Oscillation Project with Emulsion-tRacking Apparatus — **OPERA:** instrument for detecting tau neutrinos from muon neutrino oscillations
- In 2011 they observed neutrinos appearing to travel faster than light.
  - Very controversial paper also within collaboration



The top 10 biggest science stories of the decade

- Kink from a GPS receiver to OPERA master clock was loose
  - Increased the delay through the fibre resulting in decreasing the reported flight time of the neutrinos by 73 ns,
  - making them seem faster than light.

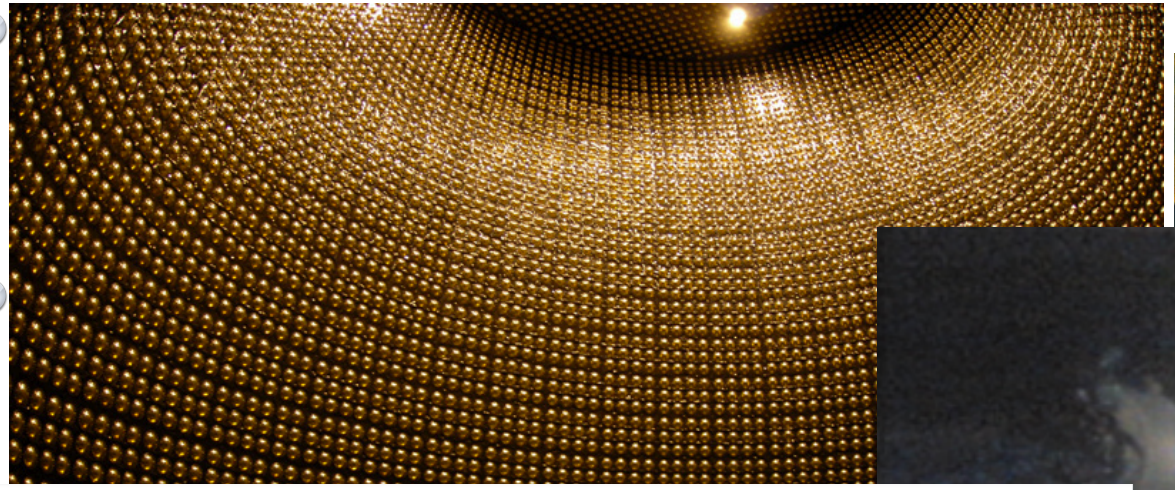
After finding the problem, the difference between the measured and expected arrival time of neutrinos was approximately 6.5 ± 15 ns.

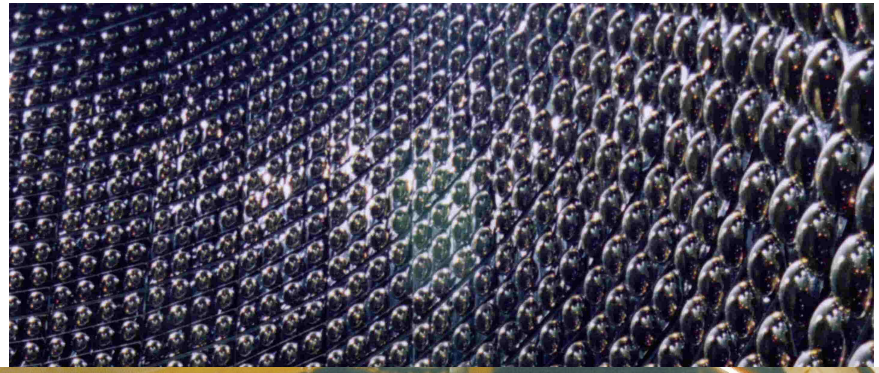


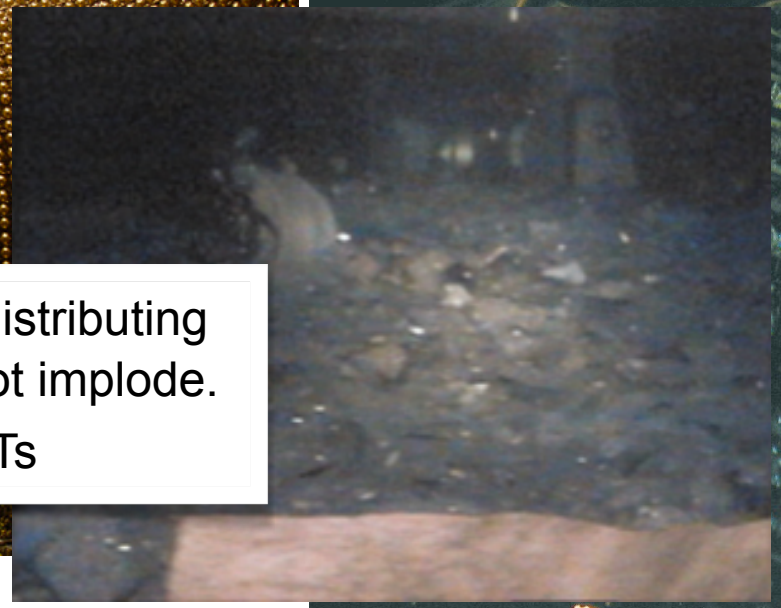
Maybe Most Famous Damage ....

during commissioning

- Underground water Cherenkov detector with 50,000 tons of ultrapure water as target material
- Nov 2001: One PMT imploded creating shock wave destroying about 7700 of PMTs



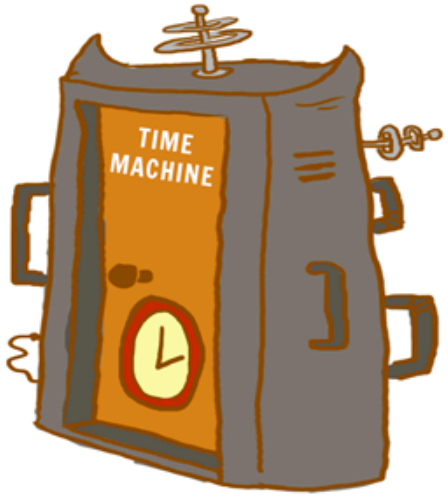




- Detector was partially restored by redistributing the photomultiplier tubes which did not implode.
- Eventually added new reinforced PMTs

Pic: unknown source....

Lessons Learned ?



- Spend enough time on simulating all aspects of your detector with ALL materials implemented
- Don't underestimate the "low tech"
  - Cables
  - Cooling
  - Mechanics including FEA
  - Radiation damage of non-sensitive materials
  - …..
- Make sure the overall timeline is not completely crazy (tough job)
- When mixing materials — ask a chemist once in a while
- …..

Solving and preventing theses kind of problems is also part of the fascination of detector physics!!

Summary

- I could only give a **glimpse** at the wealth of particle detectors. More detectors are around: medical application, synchrotron radiation experiments, astro particle physics, ...
- All detectors base on similar principles
  - Particle detection is indirectly by (electromagnetic) interactions with the detector material
- Large detectors are typically build up in layers (onion concept):
  - Inner tracking: momentum measurement using a B-field
  - Outside calorimeter: energy measurement by total absorption
- Many different technologies:
  - Gas- and semiconductors (light material) for tracking
  - Sampling and Homogeneous calorimeters for energy measurement
- Similar methods are used in astro particle physics
- **Always looking for new ideas and technologies!**

Detector Literature

Text books:

- **N. Wermes, H. Kolanoski: Particle Detectors: Fundamentals and Applications,** Oxford University Press (30. August 2020)
- Frank Hartmann, Evolution of Silicon Sensor Technology in Particle Physics, Springer Verlag 2018
- C.Grupen: Particle Detectors, Cambridge UP 22008, 680p
- D.Green: The physics of particle Detectors, Cambridge UP 2000
- K.Kleinknecht: Detectors for particle radiation, Cambridge UP, 21998
- W.R. Leo: Techniques for Nuclear and Particle Physics Experiments, Springer 1994
- G.F.Knoll: Radiation Detection and Measurement, Wiley, 32000
- Helmuth Spieler, Semiconductor Detector Systems, Oxford University Press 2005
- W.Blum, L.Rolandi: Particle Detection with Drift chambers, Springer, 1994
- F. Sauli, Principles of Operation of Multiwire Proportional and Drift Chambers
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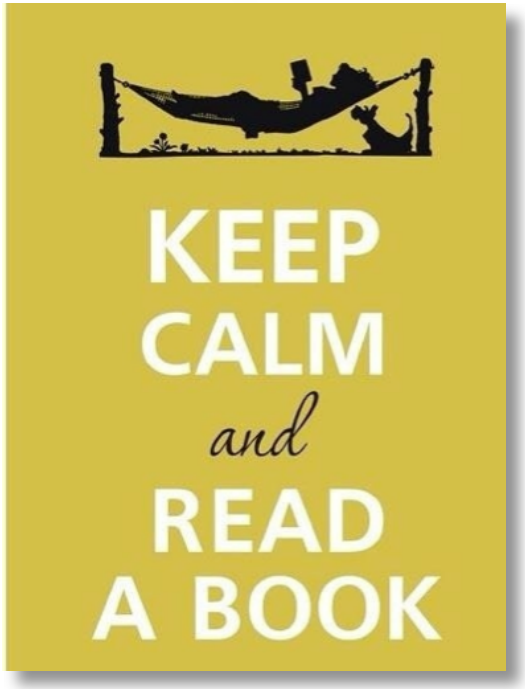
- R. Wigmans: Calorimetry, Oxford Science Publications, 2000



web:
Particle Data Group: *Review of Particle Properties: pdg.lbl.gov*
further reading:
The Large Hadron Collider - The Harvest of Run 1; Springer 2015