Principle of Semiconductor Detectors

1. Creation of electric field: voltage to deplete thickness d

$$V_{\rm dep} = d^2 N_{\rm eff} \frac{q}{2\epsilon\epsilon_0}$$

$N_{\rm eff}$: doping concentration

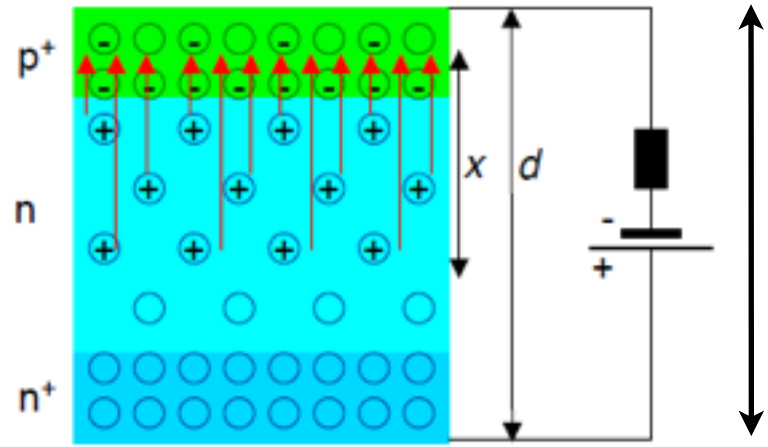
2. Keep leakage current low

$$I \propto \frac{1}{\tau_g} \cdot T^2 \cdot \exp^{-\frac{E_g}{2kT}} \times \text{volume}$$

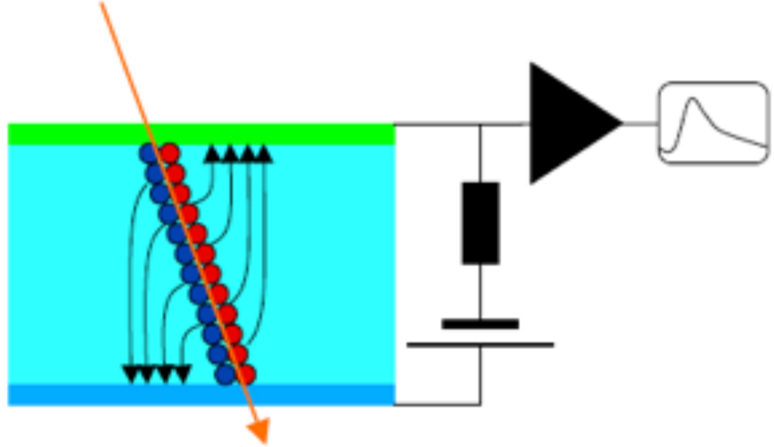
τ_g : charge carrier life time

3. Ionising particles create free charge carrier

4. Charge carrier drift to electrodes and induce signal

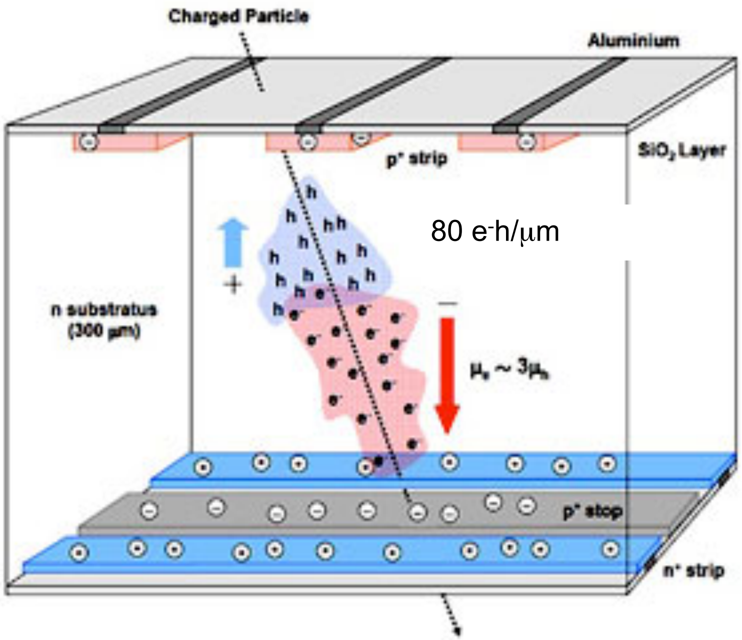


in “classical” HEP detectors 100-300 um



Strip Detectors

- First detector devices using the lithographic capabilities of microelectronics
- First Silicon detectors -> strip detectors

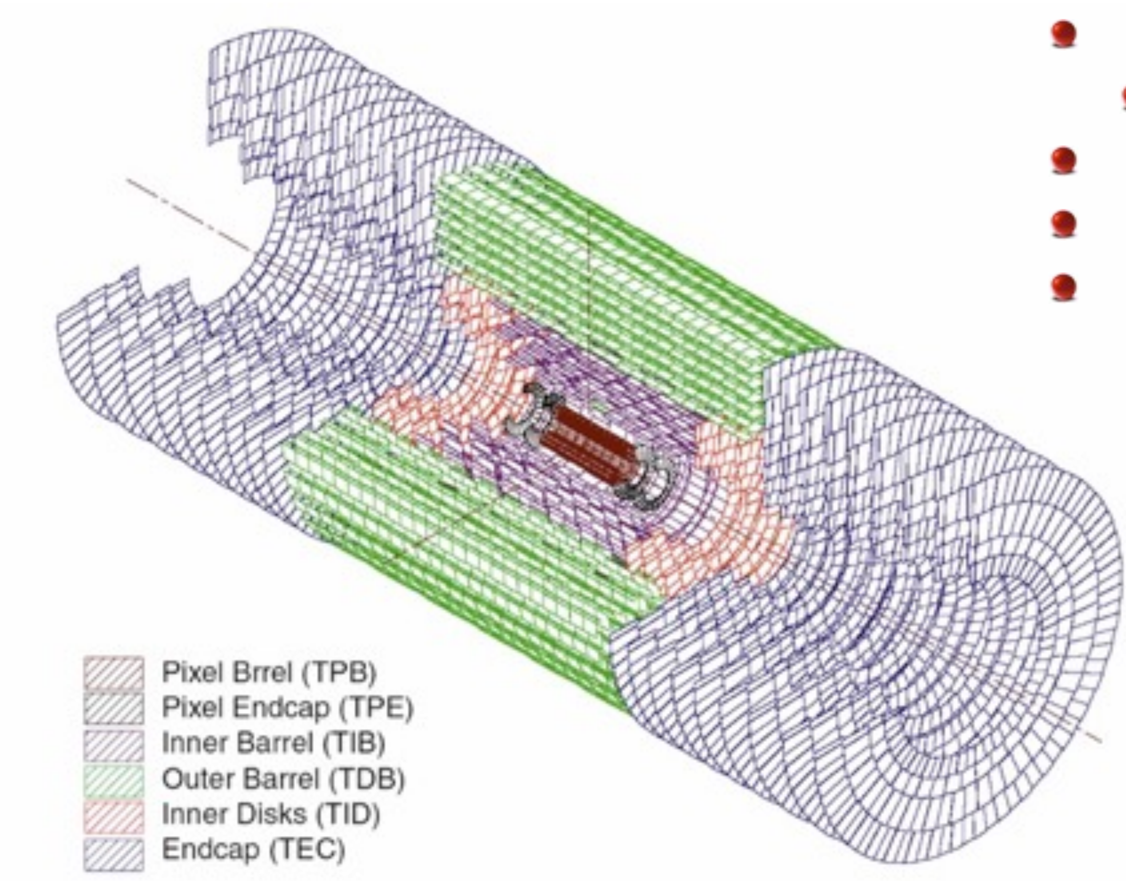


Pic: AMS Collaboration

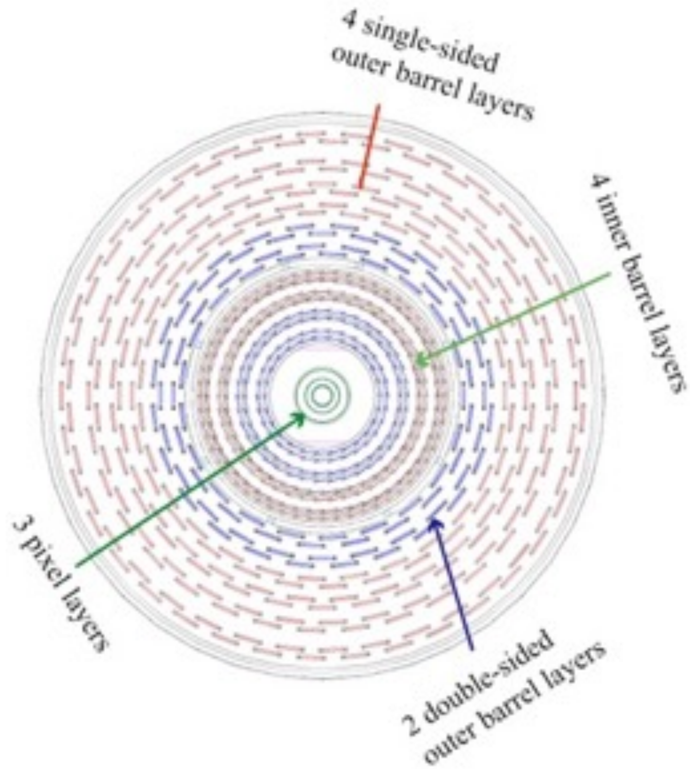
Principle: Silicon strip detector

- Arrangement of strip implants acting as charge collecting electrodes.
- Form a one-dimensional array of diodes (on a low doped fully depleted silicon wafer)
- By connecting each of the metallised strips to a charge sensitive amplifier a position sensitive detector is built.
- Two dimensional position measurements can be achieved by applying an additional strip like doping on the wafer backside (double sided technology)

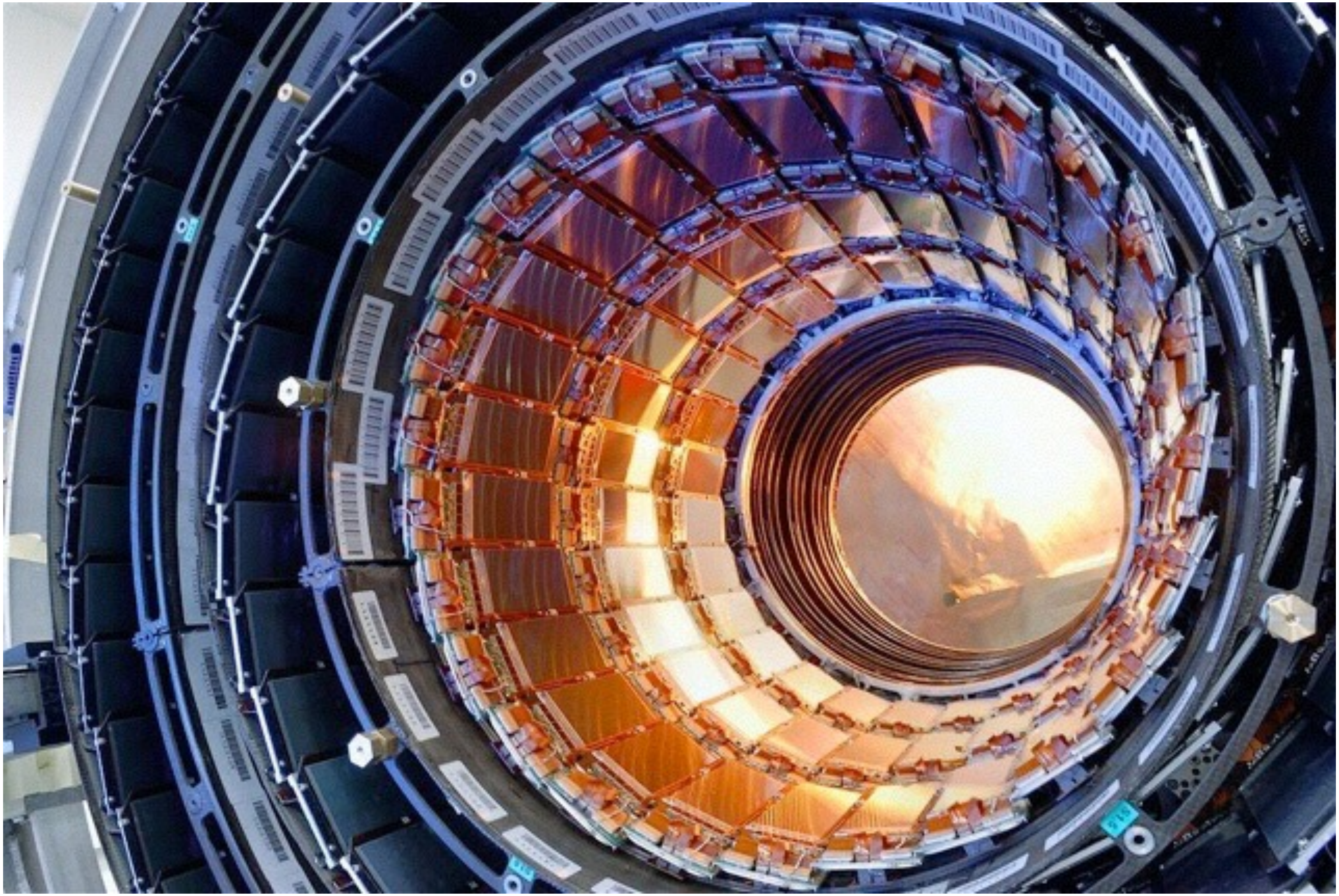
CMS Si-Tracker



- Si-Strip-Detector:
  - ~ 205 m^2 Silicon
- 25 000 Sensors, 9.6 M channels
- 10 barrel layers, 2x 9 discs
- The largest ever built silicon tracker

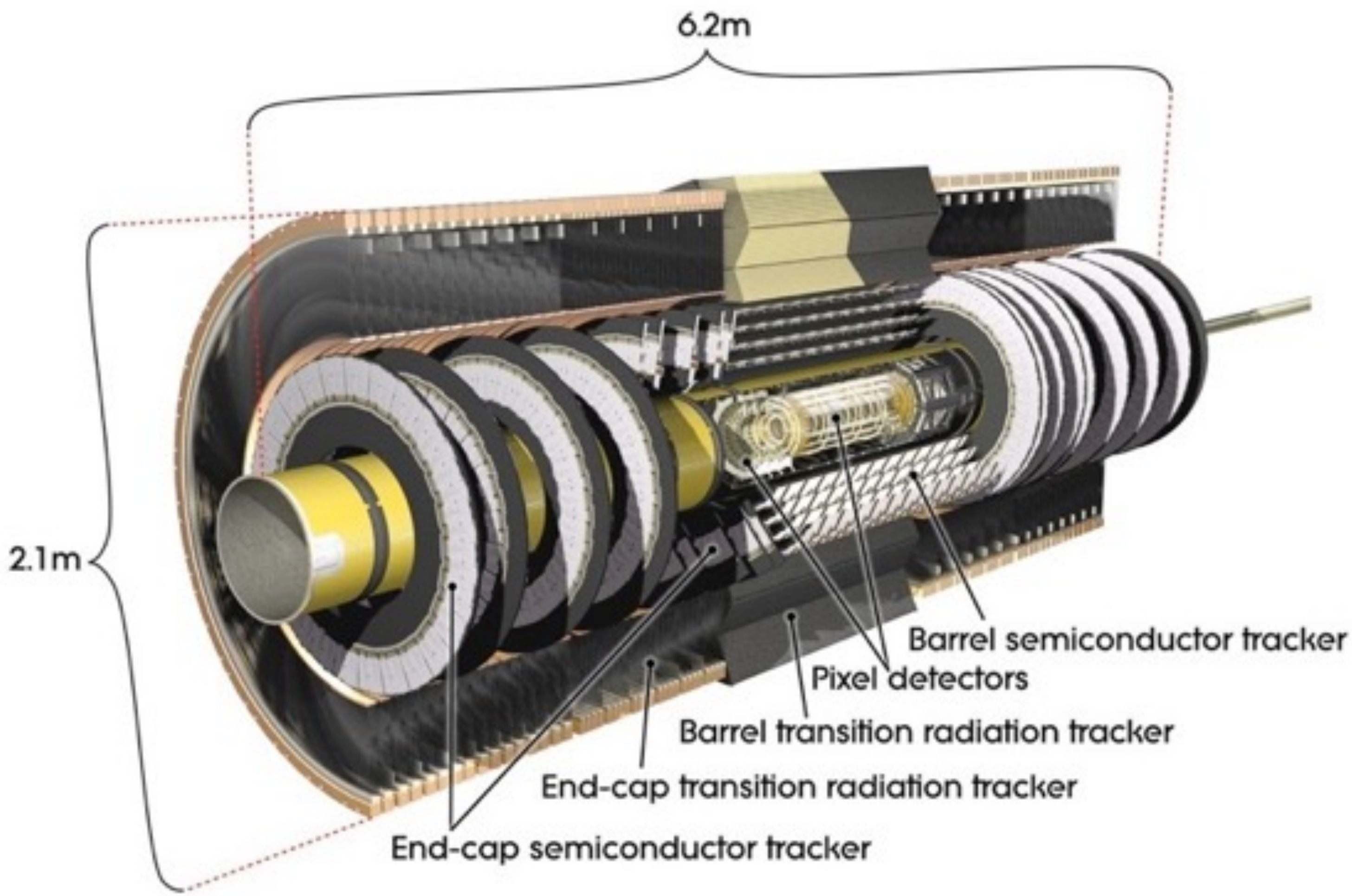


CMS Tracker - Beauty Shot



Pic: CERN

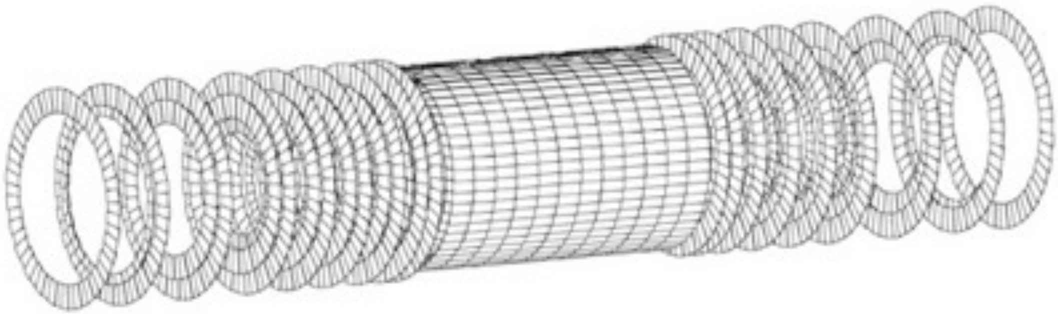
ATLAS SCT

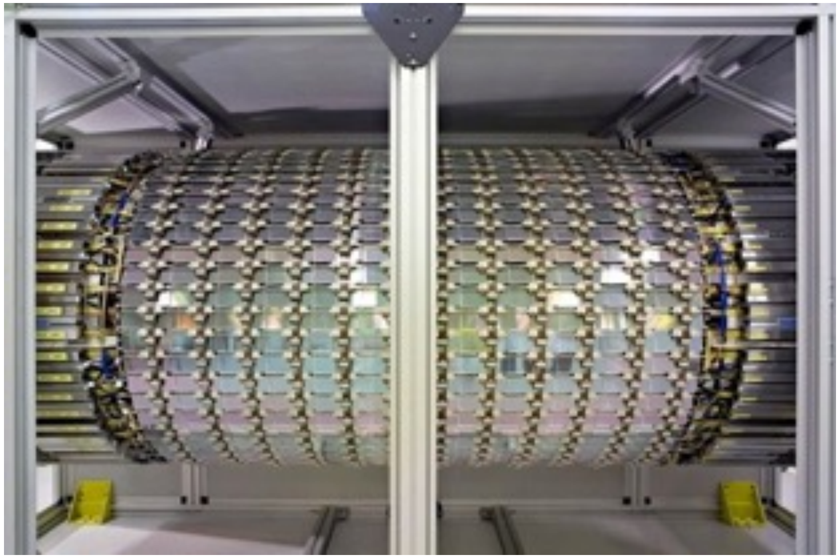


- ATLAS Si-Detector SCT:
  - Si- strips: 4 Barrel-layer, 2 x 9 discs

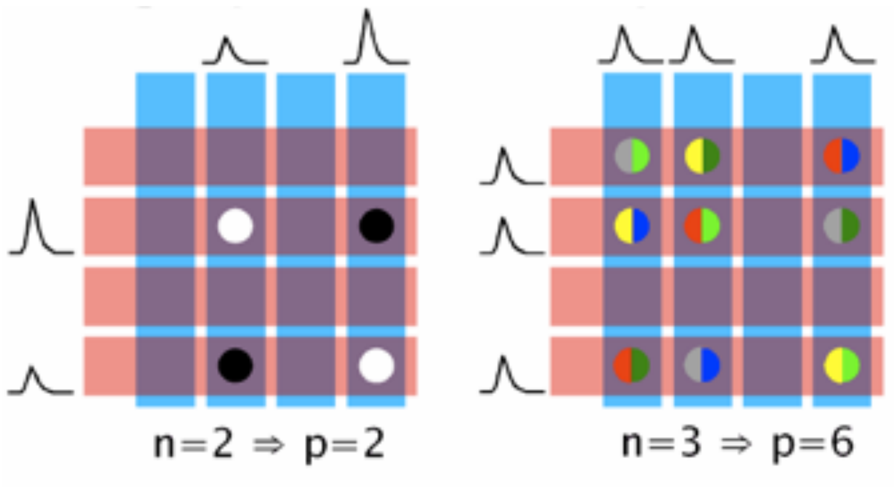
ATLAS SCT

- SCT strips:
  - 61 m^2 silicon, ~6.2 M channels
  - 4088 modules, 2112 barrel (1 type), 1976 in the discs (4 different types)

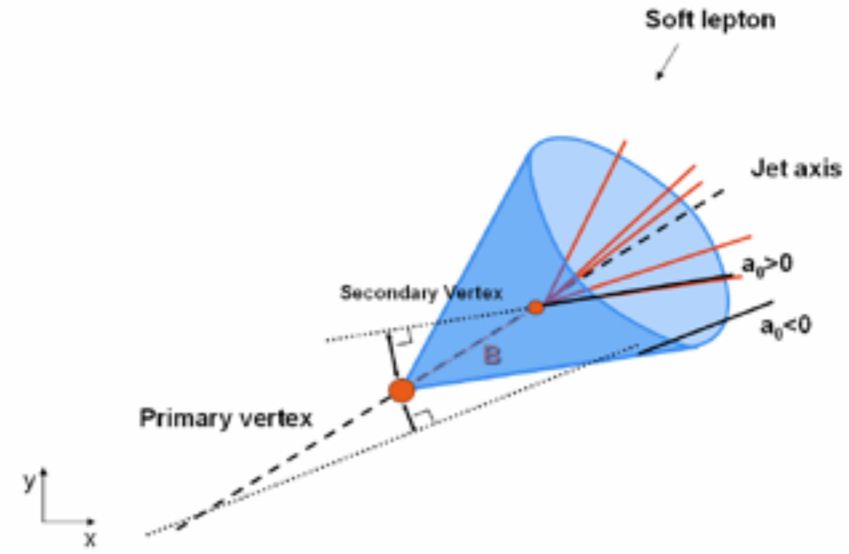




Limits of Strip Detectors



- In case of high hit density ambiguities give difficulties for the track reconstruction



- Deriving the point resolution from just one coordinate is not enough information to reconstruct a secondary vertex

- Pixel detectors allow track reconstruction at high particle rate without ambiguities
- Good resolution with two coordinates (depending on pixel size and charge sharing between pixels)
- Very high channel number: complex read-out
- Readout in active area a detector

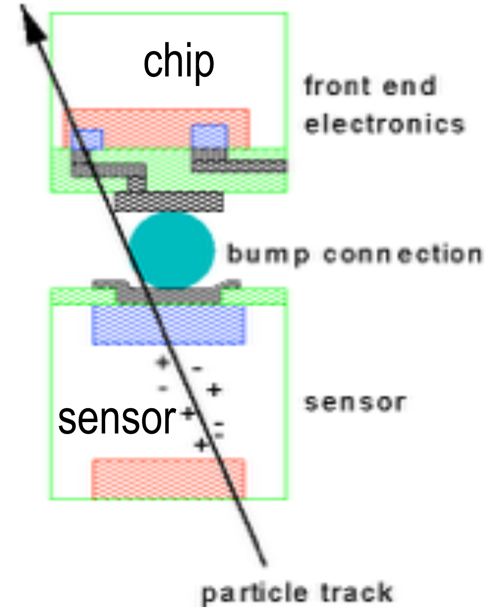
First pixels (CCDs) in NA11/NA32: ~1983

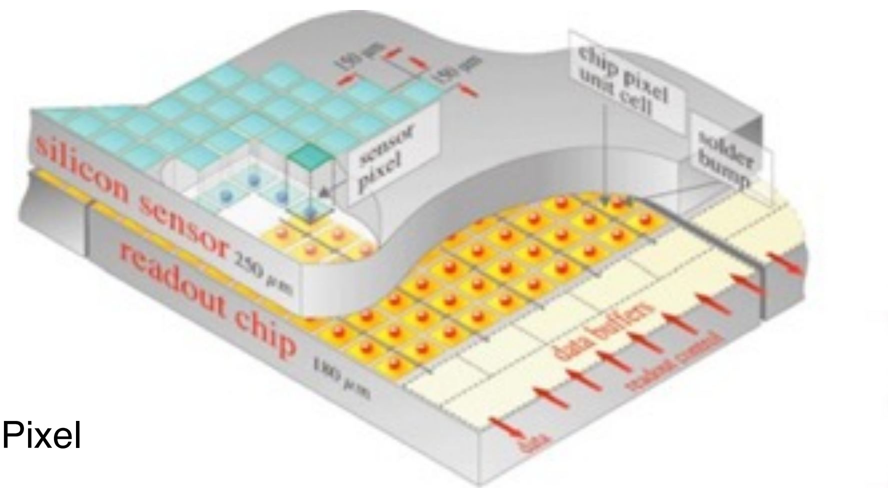
Hybrid Pixels – "classical" Choice HEP

- The read-out chip is mounted directly on top of the pixels (bump-bonding)
- Each pixel has its own read-out amplifier
- Can choose proper process for sensor and read-out separately
- Fast read-out and radiation-tolerant

… but:

- Pixel area defined by the size of the read-out chip
- High material budget and high power dissipation

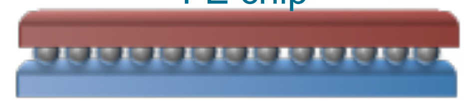




Hybrid Pixel
(CMS)

- CMS Pixels: ~65 M channels 150 μm x 150 μm
- ATLAS Pixels: ~80 M channels 50 μm x 400 μm (long in z or r)
- Alice: 50 μm x 425 μm
- LHCb
- Phenix@RHIC
- ….

Sensors for Hybrid Pixels



Planar Sensor

- current design is an n-in-n planar sensor
- silicon diode
- different designs under study (n-in-n; n-in-p ....)
- radiation hardness proven up to $2.4 \cdot 10^{16}$ p/cm^2
- problem: HV might need to exceed 1000V

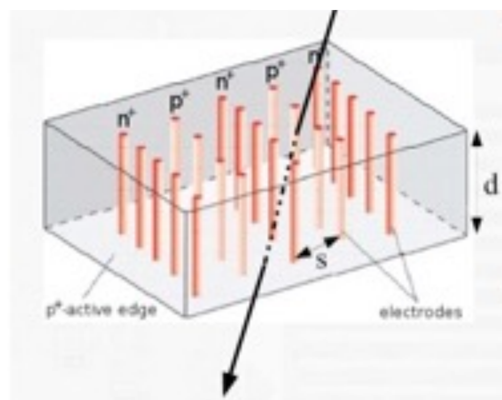
3D Silicon

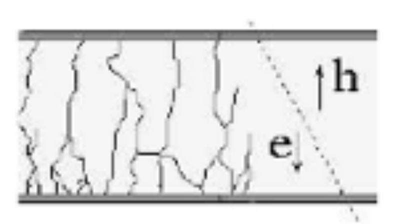
- Both electrode types are processed inside the detector bulk instead of being implanted on the wafer's surface.
- Max. drift and depletion distance set by electrode spacing
- Reduced collection time and depletion voltage
- Low charge sharing

CVD (Diamond)

- Poly crystalline and single crystal
- Low leakage current, low noise, low capacitance
- Radiation hard material
- Operation at room temperature possible
- Drawback: 50% signal compared to silicon for same X_0, but better S/N ratio (no dark current)

Very strong R&D efforts to develop sensors for future LHC applications!

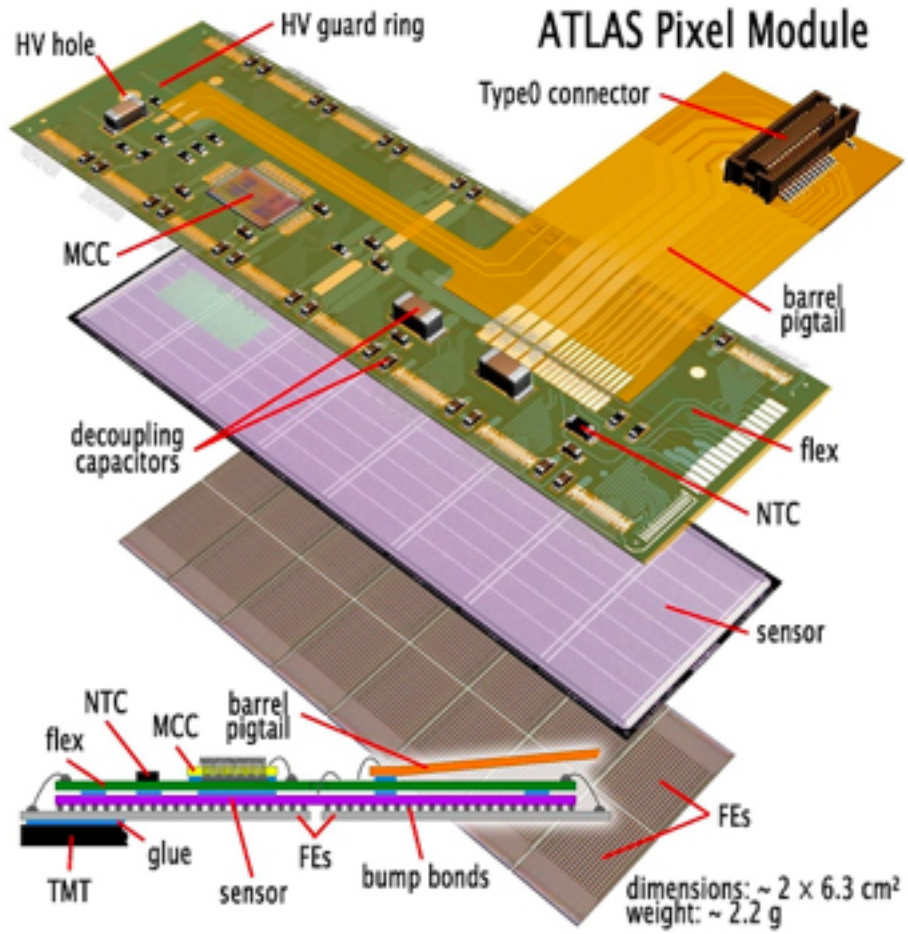


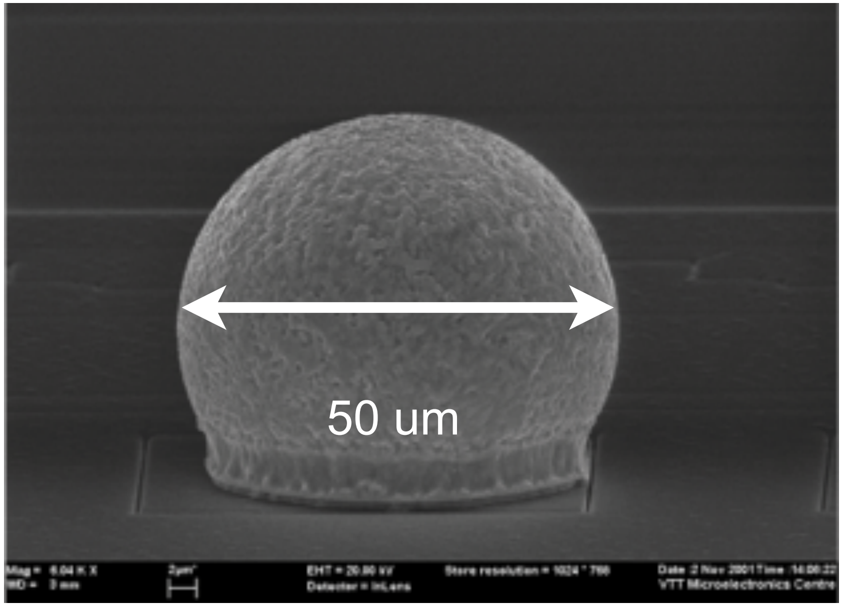


ATLAS-Pixels

A pixel module contains:

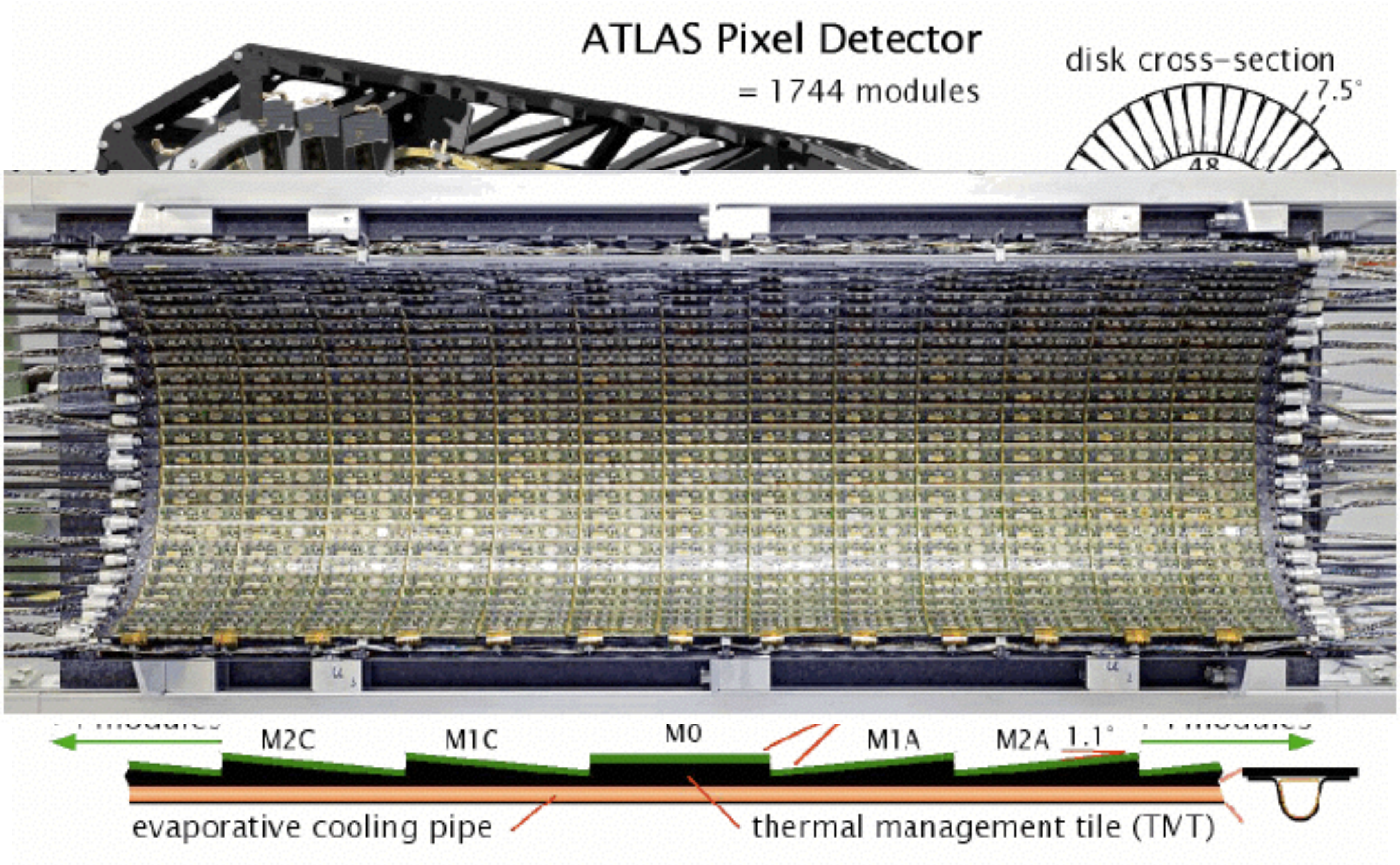
1 sensor (2x6cm)
  ~40000 pixels (50x500 mm)
16 front end (FE) chips
  2x8 array
  bump bonded to sensor
Flex-hybrid
1 module control chip (MCC)
There are ~1700 modules





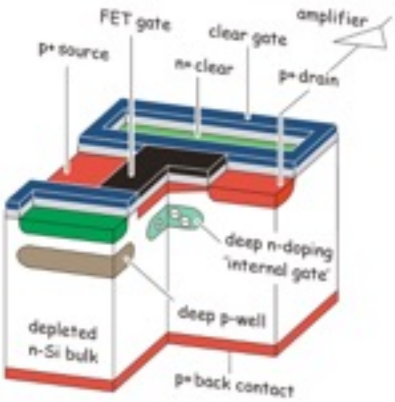
Picture: VTT

ATLAS-Pixels

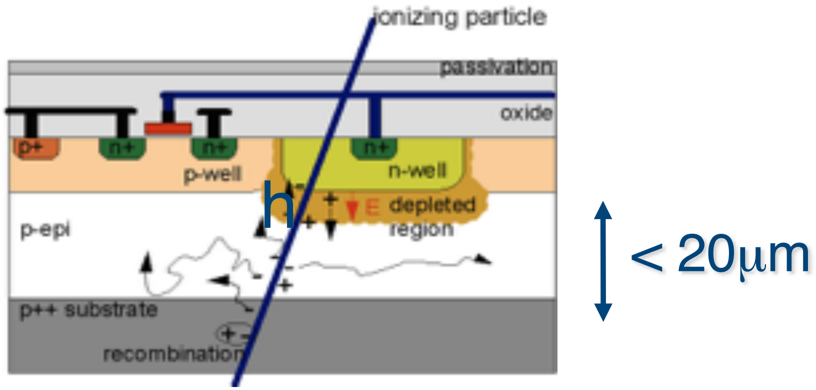


Monolithic Pixel Sensors

- Some HEP applications (Linear Collider etc.) require extremely good spatial resolution (factor 2-5 better than at LHC) and very low material in the tracker
- Hybrid pixel sensors are too thick for such applications
- Investigating technologies with sensor and readout electronics in one layers -> monolithic
- Four different technologies:
  - CCD, DEPFET, CMOS, and 3D
  - different variants of each technology approach under investigation
- Some of them where chosen as baseline technology for real experiments
  - DEPFET for Belle II @KEK (Japan)
  - Mimosa MAPS for Star @ RHIC (USA)



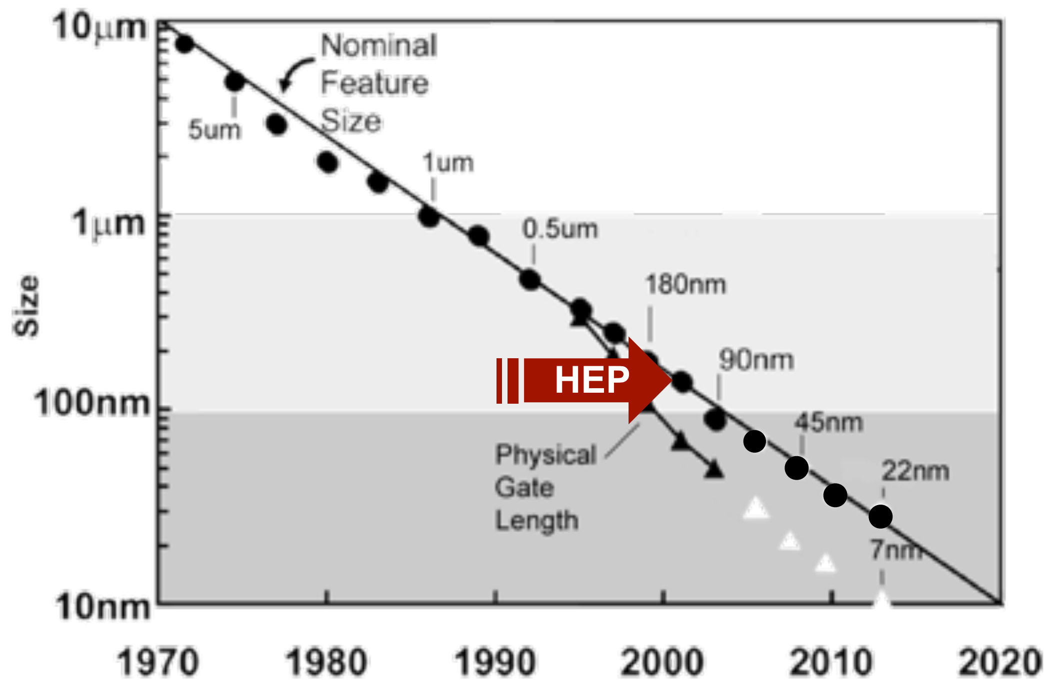
DEPFET



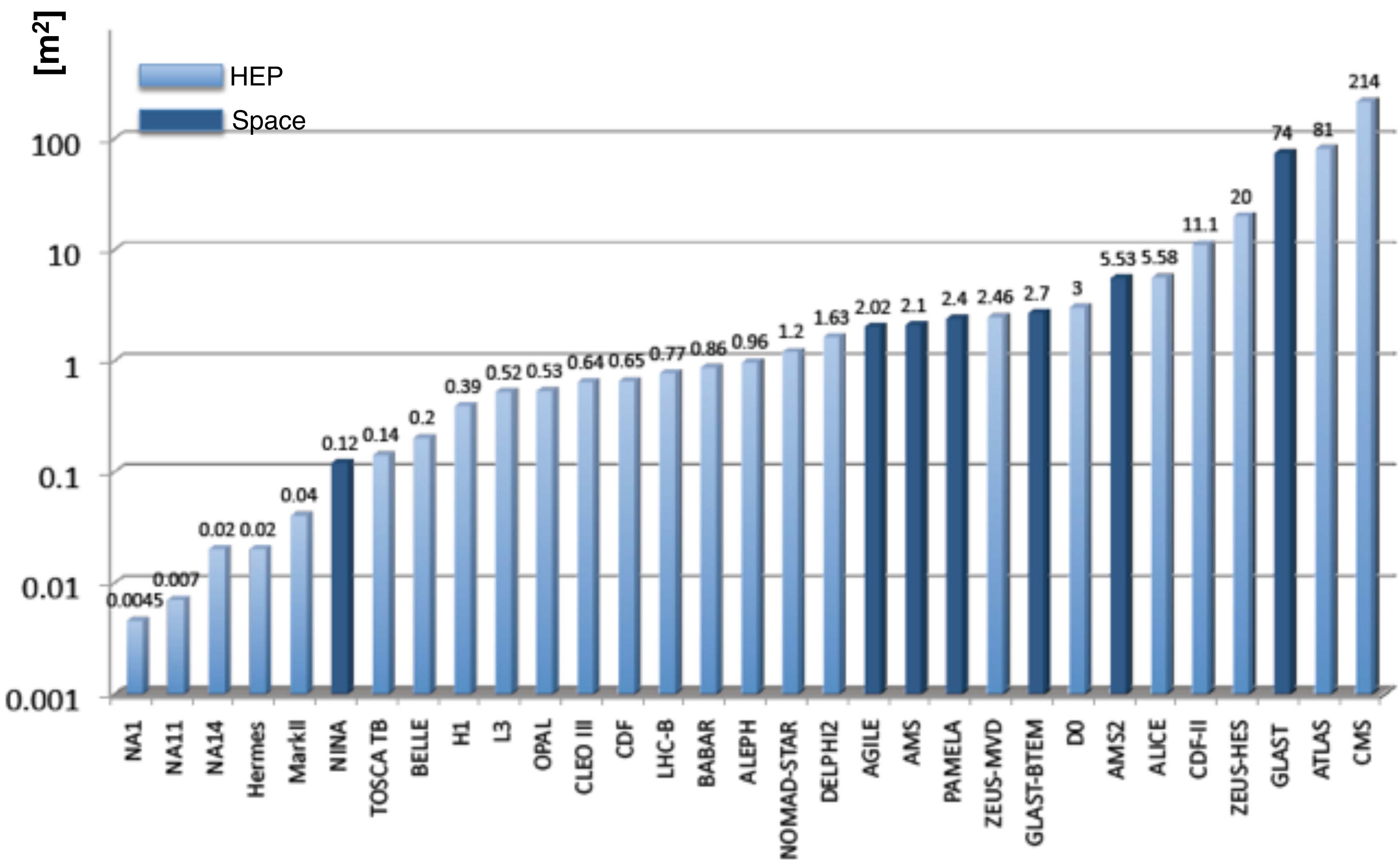
Mimosa MAPS

Industry Scaling Roadmap

- New generation every ~2 years with $\alpha = \sqrt{2}$
- from 1970 (8 μm) to 2013 (22 nm) (industrial application)
- End of the road ? Power dissipation sets limits
- HEP nowadays at 90nm and 130nm
- Problem: by the time a technology is ready for HEP -> “old” in industry standards



Silicon detector size 1981 - 2006



Summary Tracking Detectors

- Tracking detectors are playing an important role in HEP since the late 50ties
- Starting with bubble chamber the development of tracking detectors was rather rapidly
- Modern gas detectors and silicon trackers play an equal important role in HEP
- LHC silicon trackers are used for the inner systems while gas detector dominate the outer tracking systems (muon detectors)

- The technologies are rapidly evolving giving hope to have really fancy detectors for example for the future LC

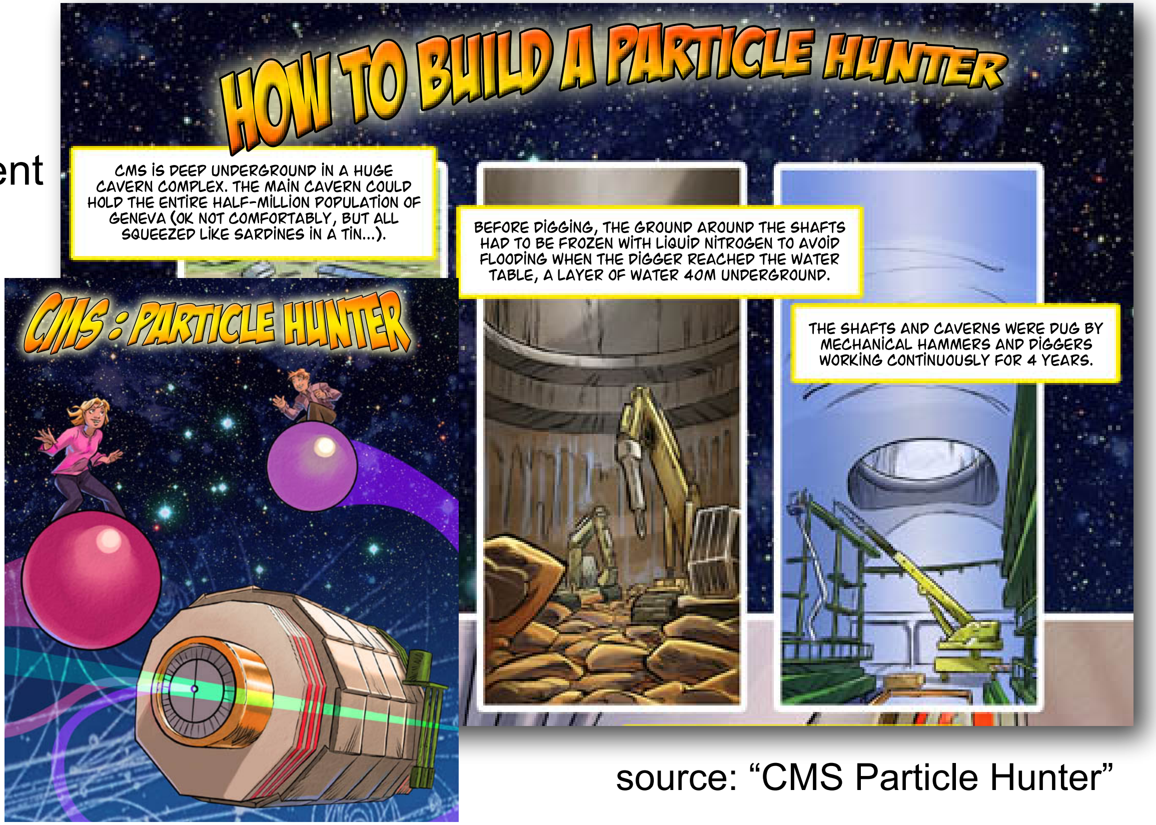
V. Real Life Examples

Building an Experiment (at LHC)

Current HEP Detector R&D

- Detector development is always an important topic in high energy physics
- Technical demands are constantly increasing due to new challenges in particle physics
  - higher occupancy, smaller feature size, larger trigger rates, radiation level, …..

- New HEP detector projects are planned for
  - Detector upgrades during different LHC phases up to HL-LHC (ATLAS, CMS, ALICE, LHCb)
  - Detector R&D for a future linear collider (ILC and CLIC)
  - Belle II (construction phase starting)
  - PANDA and CBM @Fair
  - …..



source: “CMS Particle Hunter”

How to do a particle Physics Experiment

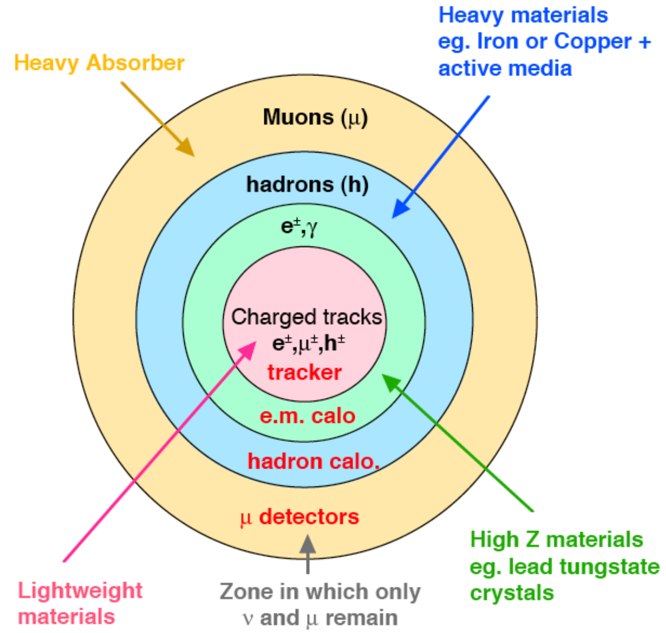
- Recipe:
  - get particles (e.g. protons, antiprotons, electrons, …)
  - accelerate them
  - collide them
  - observe and record the events
  - analyse and interpret the data
- Ingredients needed:
  - particle source
  - accelerator and aiming device
  - detector
  - trigger
  - recording devices
- 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 ….

Pic: DESY

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

Conceptual Design of HEP Detectors

- 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 ?



at a collider experiment

- Calorimeter choice
  - define geometry (nuclear reaction length, X0)
  - type of calorimeter (can be mixed)
  - choice of material depends also on funds
- 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 !!

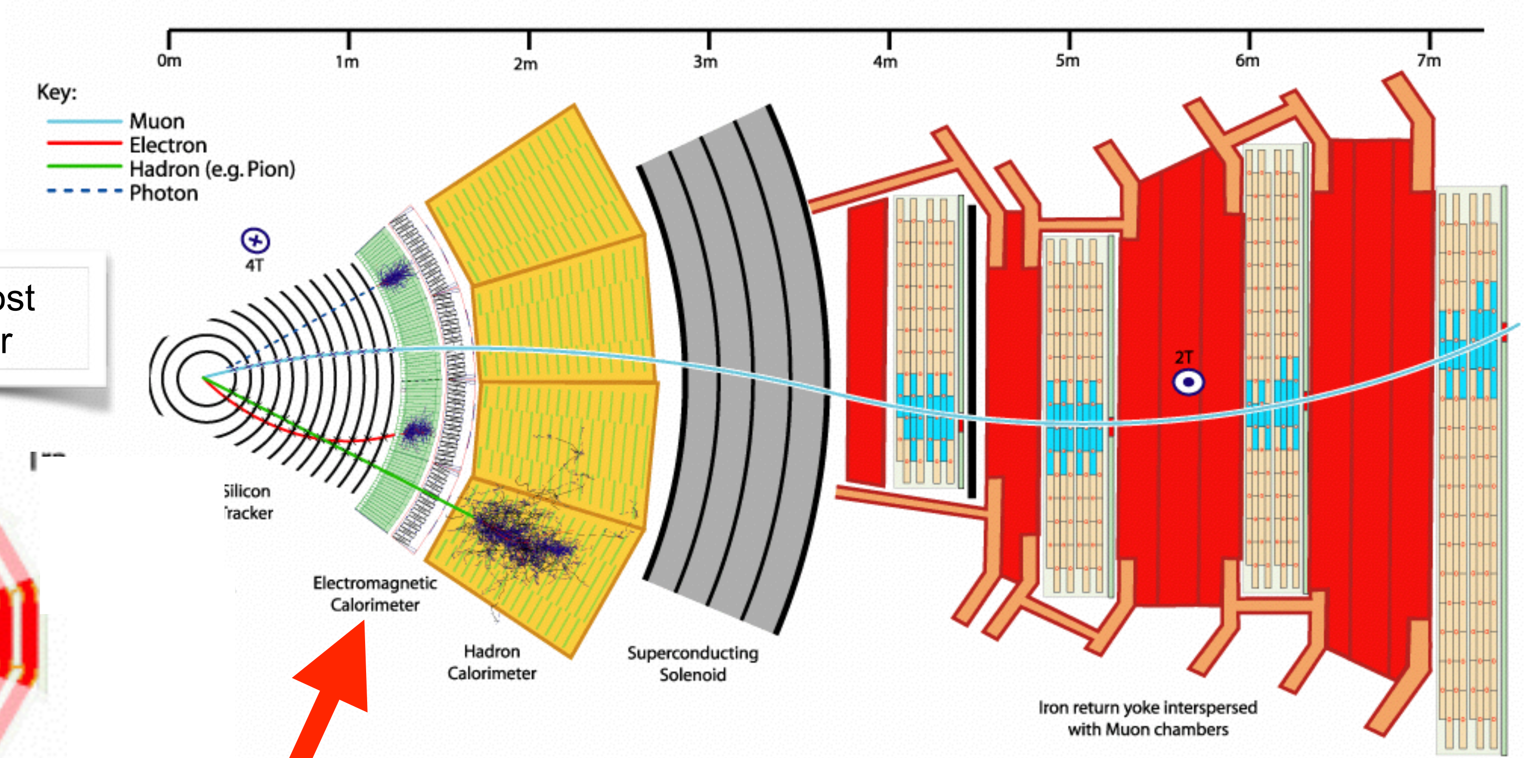
HEP Detector Overview

Tracker: Precise measurement of track and momentum of charged particles due to magnetic field.

Calorimeter: Energy measurement of photons, electrons and hadrons through total absorption

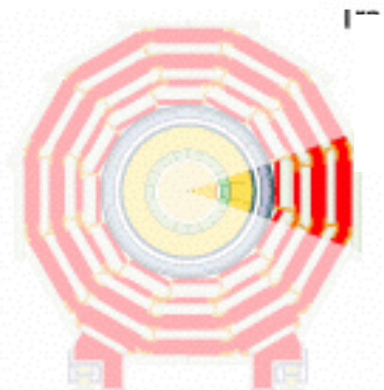
Muon-Detectors: Identification and precise momentum measurement of muons outside of the magnet

Vertex: Innermost tracking detector



Good energy resolution up to highest energies

picture: CMS@CERN



Transverse slice through CMS

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
  - ….

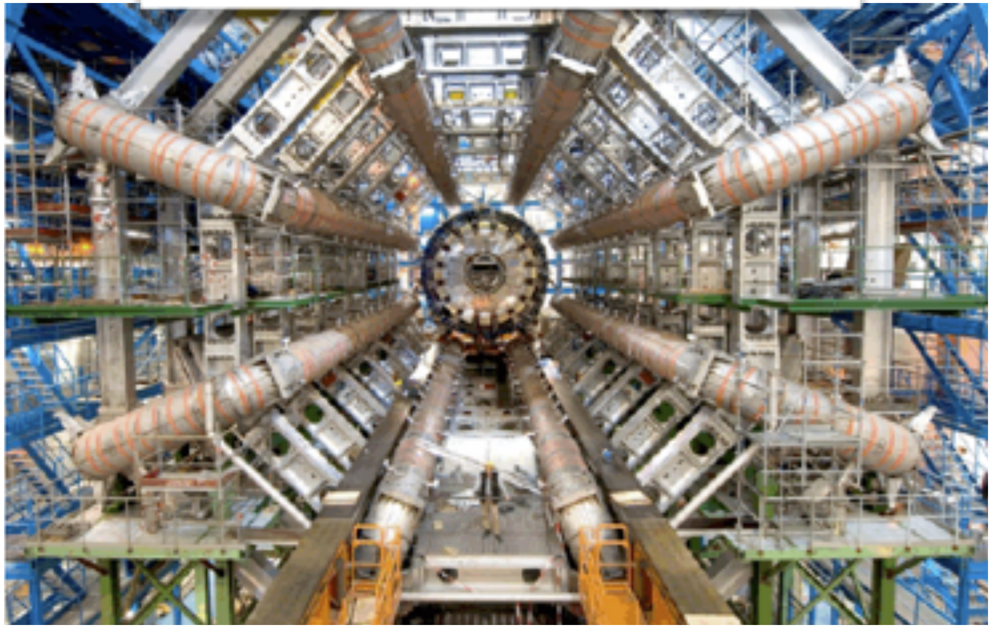
Eierlegende Wollmilchsau

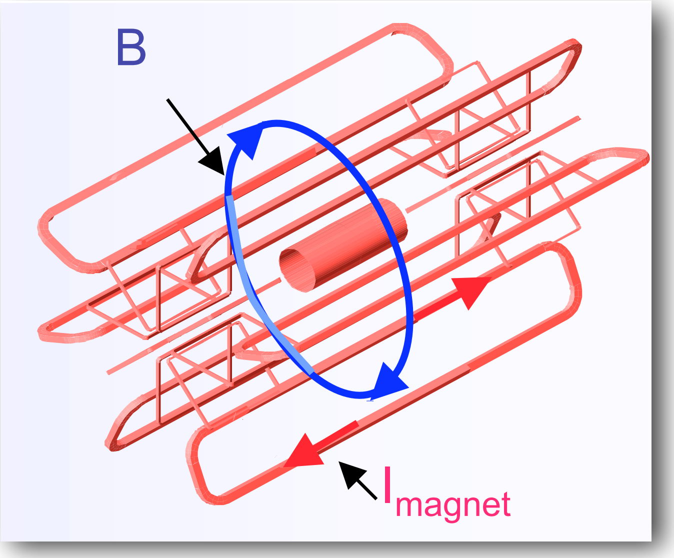
- **ATLAS decision**
  - achieve a high-precision stand-alone momentum measurement of muons
  - need magnetic field in muon region -> large radius magnet

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

Magnet-Concepts: ATLAS -> Toroid

the largest magnet in the world



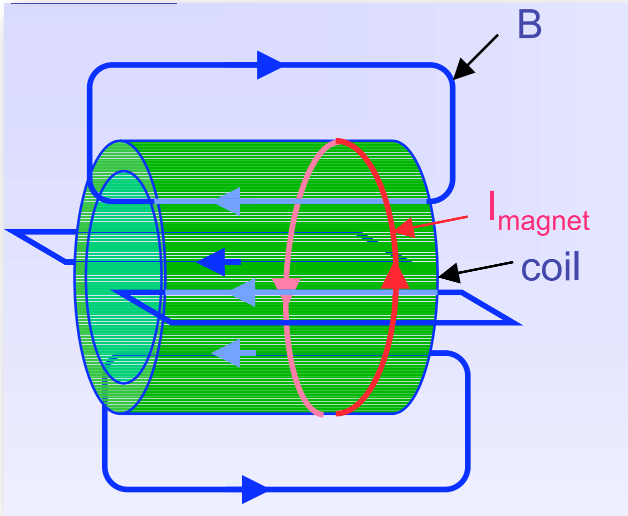


- Central toroid field outside the calorimeter within muon-system: <4 T
  - Closed field, no yoke
  - Complex field
- Thin-walled 2 T Solenoid-field for trackers integrated into the cryostat of the ECAL barrel

+ field always perpendicular to $\vec{p}$
+ relative large field over large volume
- non uniform field
- complex structure

Magnet-Concepts: CMS -> Solenoid

Largest solenoid in the world:



- super conducting, 3.8 T field inside coil
- weaker opposite field in return yoke (2T)
- encloses trackers and calorimeter
- 13 m long, inner radius 5.9 m, I = 20 kA, weight of coil: 220 t

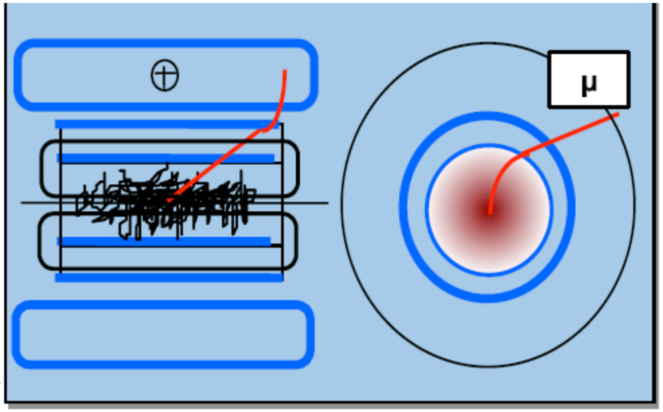
+ large homogeneous field inside coil
+ weak opposite field in return yoke
- size limited (cost)
- relative high material budget

Muon Detectors

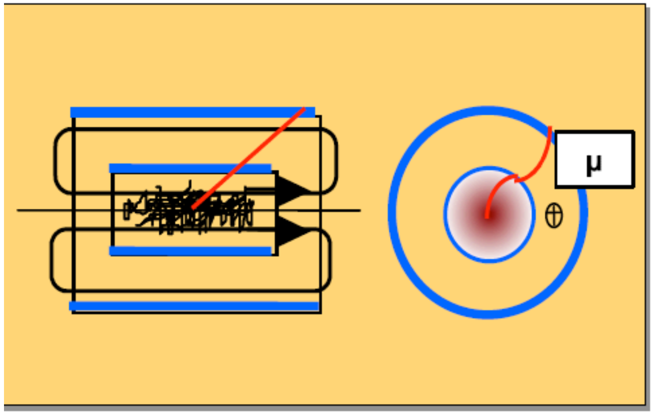
another tracker outside of the magnet

- Identification and precise momentum measurement of muons outside of the magnet
- Benchmark design for muon detectors:
  momentum measurement better than 10% up to 1 TeV.
  - $\Delta pT/pT \approx 1/BL^2$
- ATLAS
  - independent muon system -> excellent stand capabilities
- CMS:
  - superior combined momentum resolution in the central region;
  - limited stand-alone resolution and trigger capabilities (multiple scattering in the iron)
- ATLAS and CMS have both a combination of different gas detectors in the larger radius
  - Drift tubes
  - Resistive plate chambers
  - Multi-wire proportional chamber

ATLAS



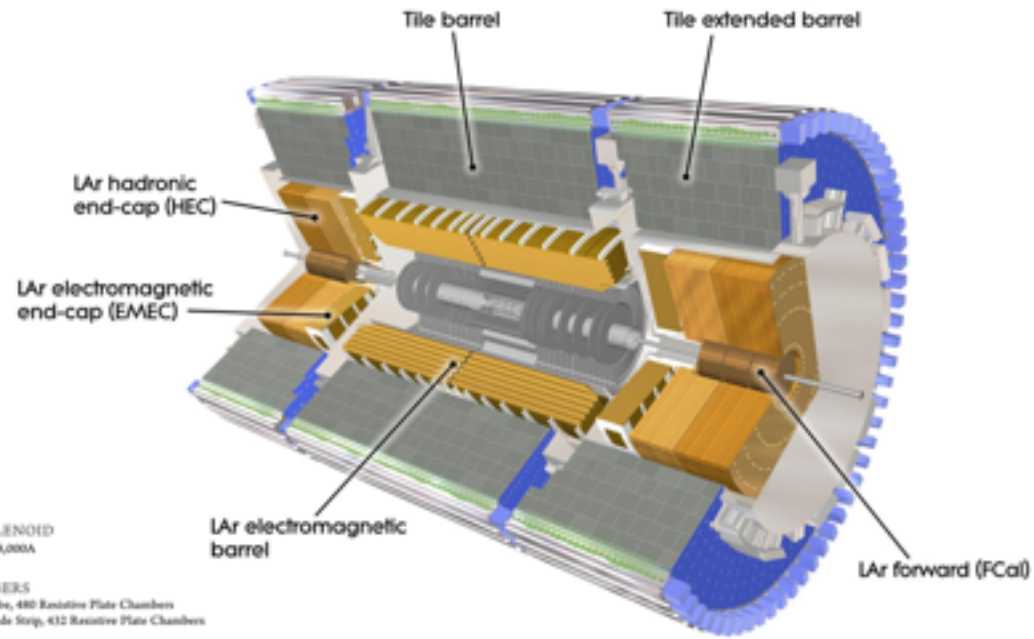
CMS



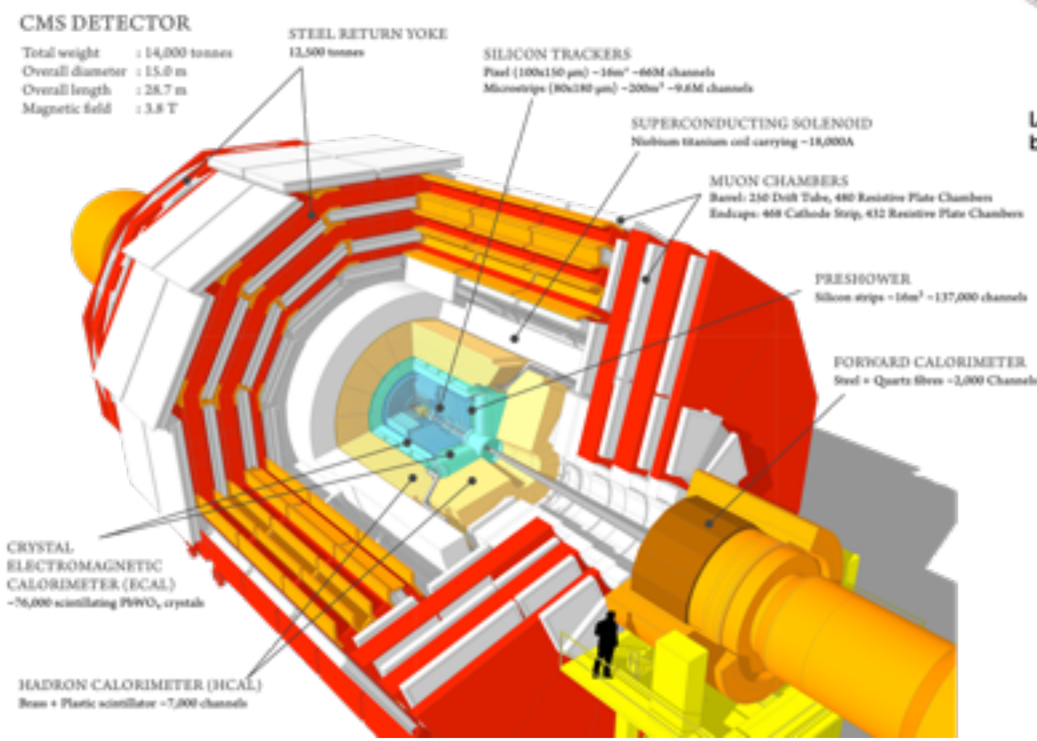
Overview of Calorimeters

- In order to maximize the sensitivity for $H \rightarrow \gamma\gamma$ decays, the experiments need to have an excellent e/γ identification and resolution

ATLAS



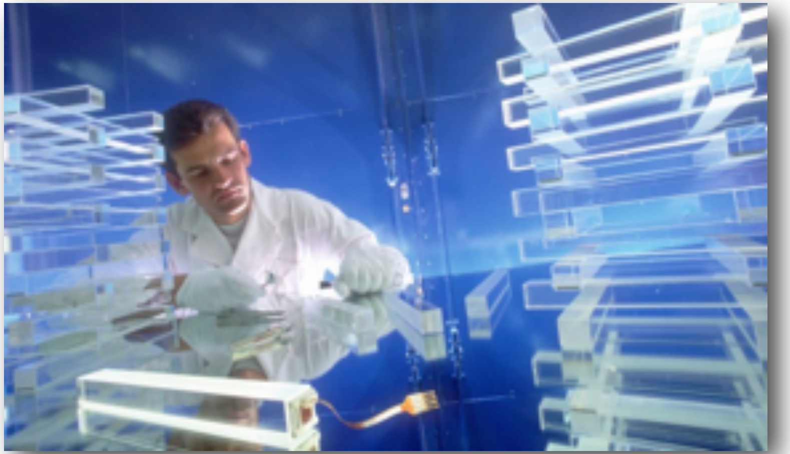
CMS



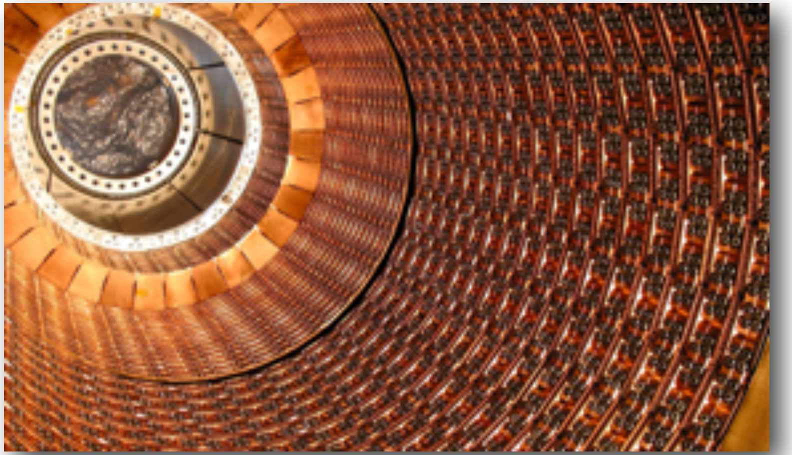
Important Differences: Calorimeter

- **CMS:** homogeneous calo
  - high resolution Lead Tungsten crystal calorimeter -> **higher intrinsic resolution**
  - constraints of magnet -> HCAL absorption length not sufficient
  - tail catcher added outside of yoke

- **ATLAS:** sampling calo (ECAL + HCAL)
  - liquid argon calorimeter -> high granularity and longitudinally segmentation (better e/ ID)
  - electrical signals, high stability in calibration & radiation resistant (gas can be replaced)
  - solenoid in front of ECAL -> a lot of material reducing energy resolution
  - accordion structure chosen to ensure azimuthal uniformity (no cracks)
  - liquid argon chosen for radiation hardness and speed



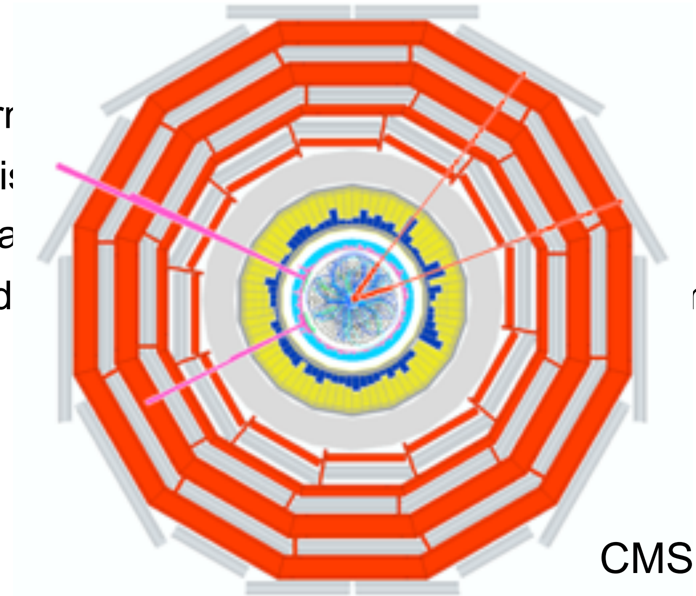
CMS Lead tungsten crystals (CERN)



ATLAS Hadronic endcap Liquid Argon Calorimeter. (CERN)

What is a Trigger ?

- Collisions every 25 ns with many simultaneous interactions
- A lot of information stored in the detectors - we need all infor
- Electronics too slow to read out all information for **every** colli
- But: a lot of the interactions are very well known - we only wa
- “Trigger” is a system that uses simple criteria to rapidly decid nall fraction of the total can be recorded.

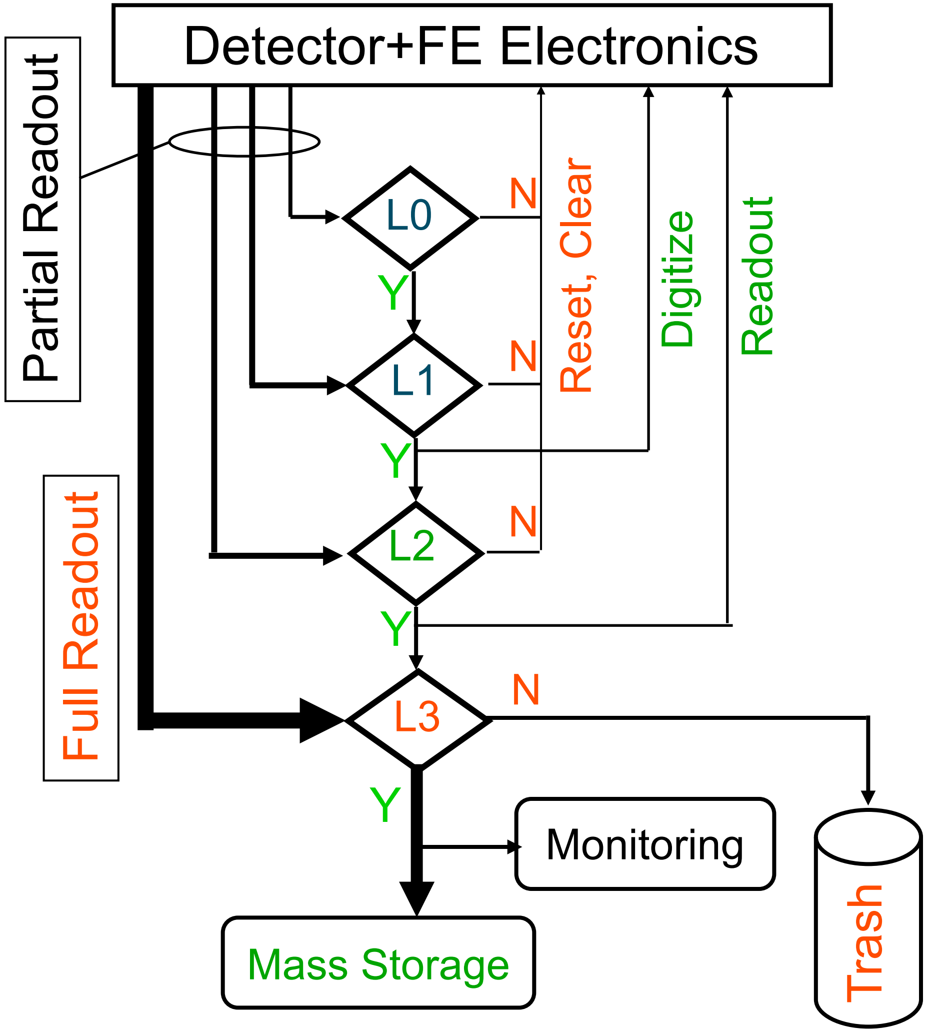


- Want to know the information of green cars
  - number of passengers
  - speed
  - weight
  - …..
- Trigger = system detecting the color and initiating the information transfer all information

Multi-Level Trigger Systems

High Efficiency ⟷ **Large Rejection**

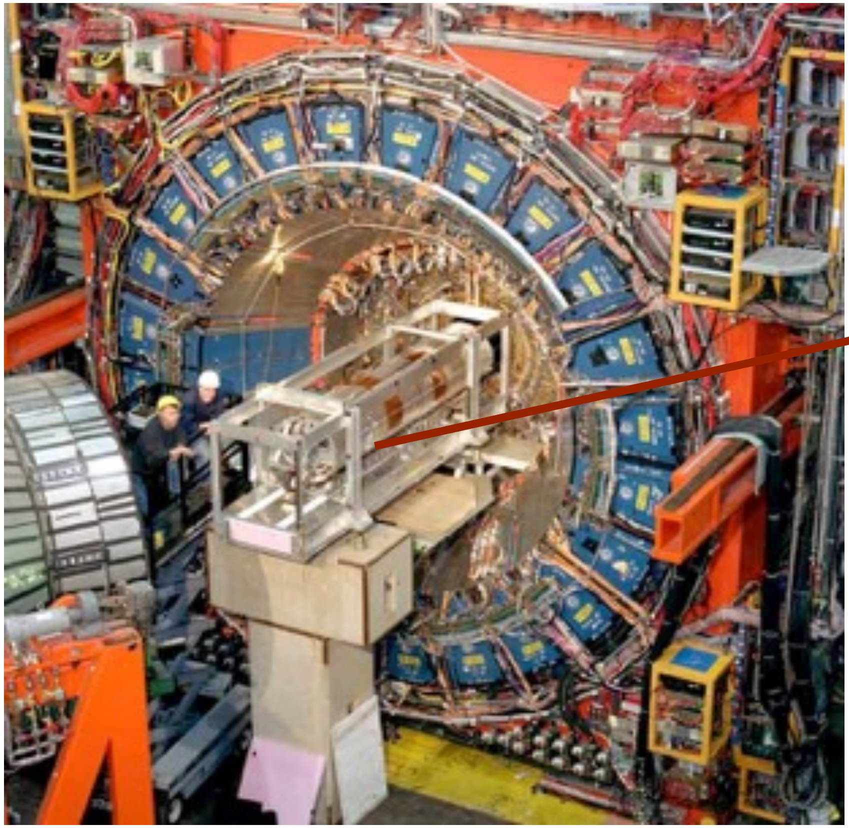
- Can't achieve necessary rejection in a single triggering stage
- Reject in steps with successively more complete information
  - L0 – very fast (<~bunch x-ing), very simple, usually scint. (TOF or Lumi. Counters)
  - L1 – fast (~few μs) with limited information, hardware
  - L2 – moderately fast (~10s of μs), hardware and sometimes software
  - L3 – Commercial processor(s)
- Next generation: implement triggering stage already in tracking detector to handle very high multiplicities (example: HL-LHC)
- Other extreme: trigger-less operation -> read out at 40MHz and do the work offline (LHCb)

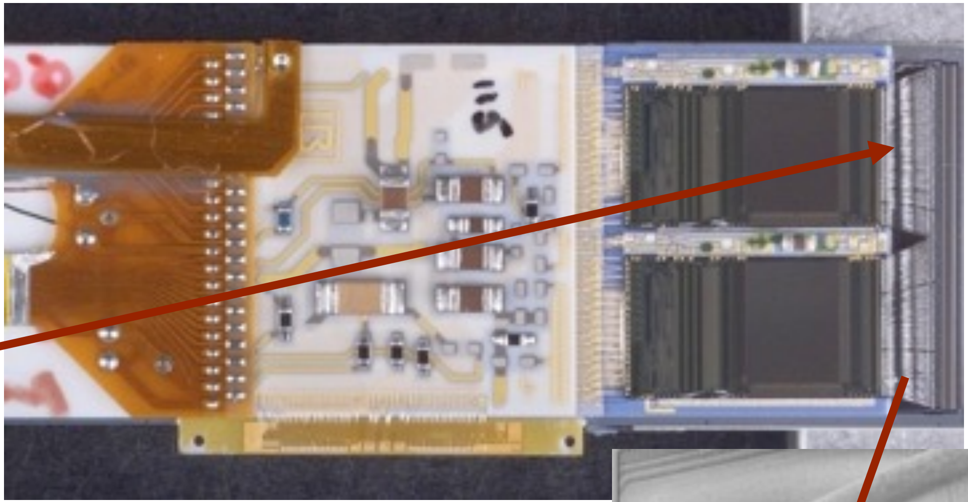


V. Real Life Examples And What Can Go Wrong ...

Problems with Wire Bonds (CDF, D0)

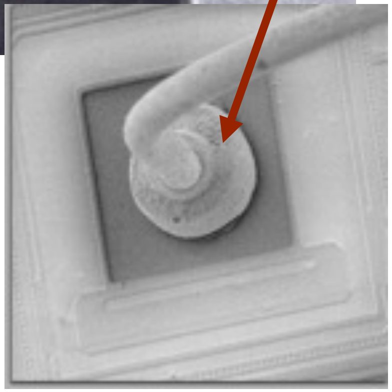
- Very important connection technology for tracking detectors: wire bonds:
  - 17-20 um small wire connection -> terrible sensitive ….
- During test pulse operation, Lorentz force on bonding wires (perpendicular to magnetic field) …





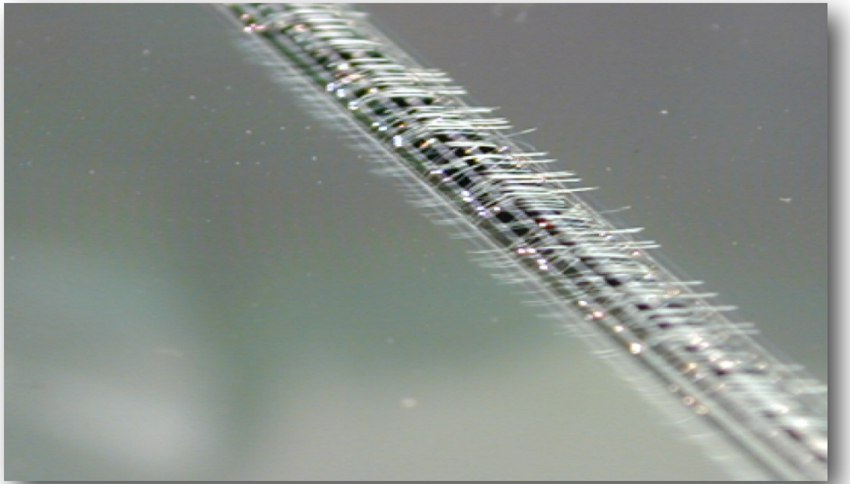
…breaks wire bonds between detector and read out.

during running



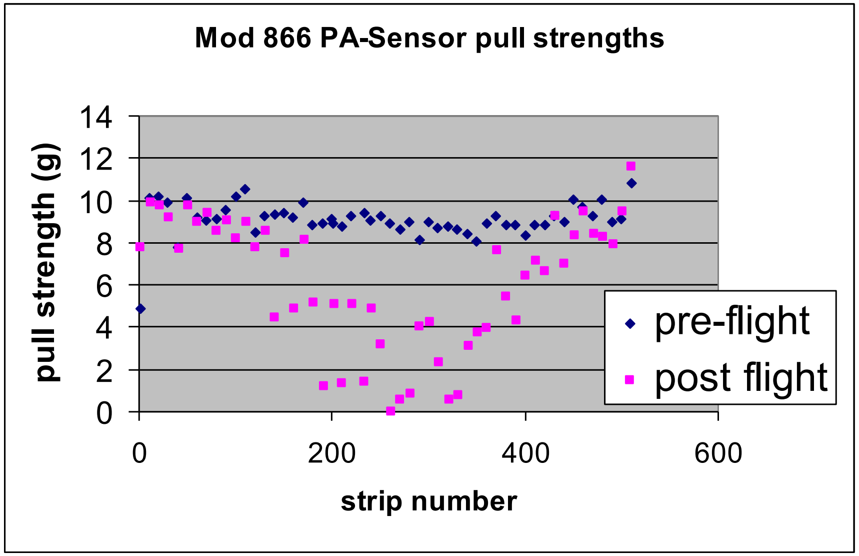
More Wire Bond Wreckage

- Quality of wires is tested by pull tests (measured in g)
- During CMS strip tracker production quality assurance applied before and after transport (via plane)
- Wire bonds were weaker after flight
- Random 3.4 g NASA random vibration test causes similar damage



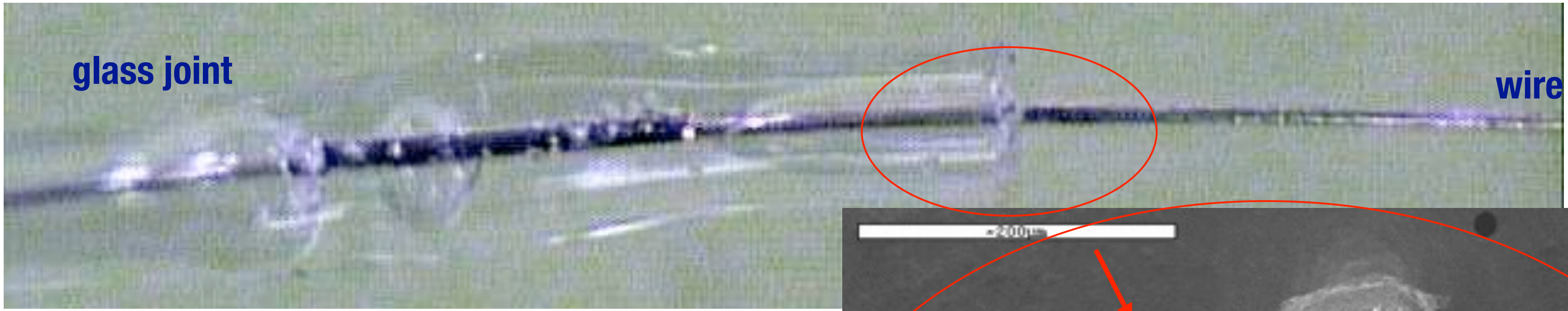
- Problem observed during production -> improved by adding a glue layer
- No further problems during production

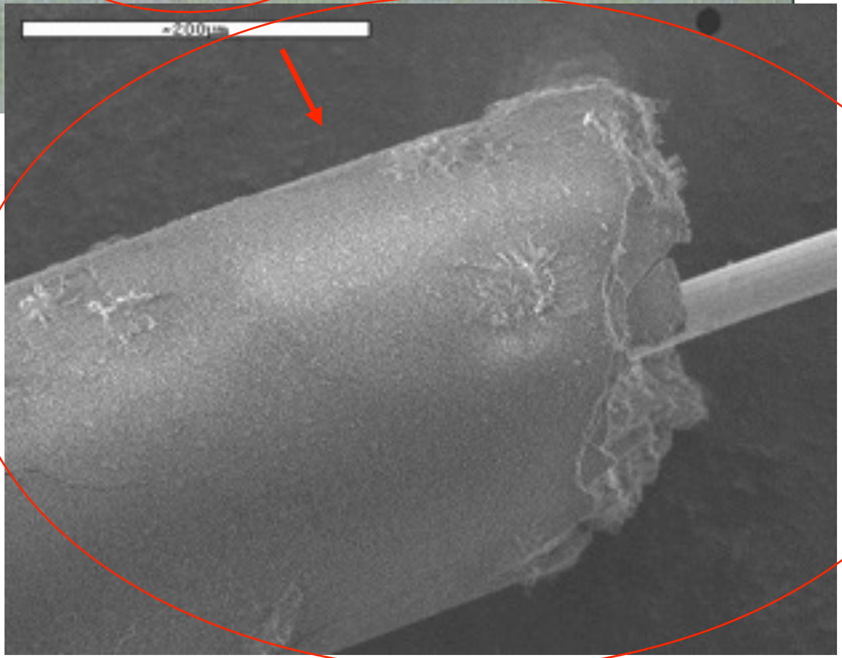
during production



Unexpected problems ATLAS barrel TRT

- Gas mixture: 70% Xe + 20 CF_4 + 10% CO_2
- Observed: destruction of glass joint between long wires after 0.3 - 0.4 integrated charge (very soon after start up)





At high irradiation C_4F turns partially into HF,F,F2 (hydrofluoric acid)
-> attaches Si-based materials in the detector

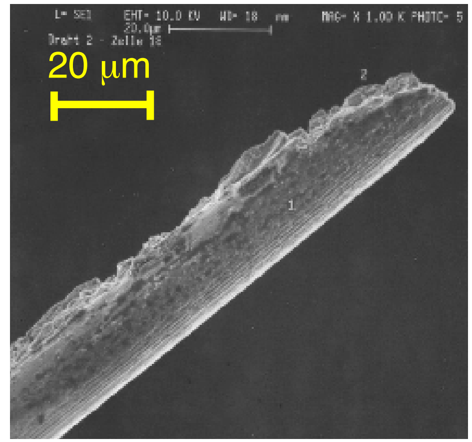
- Changed gas mixture,
  - after ~10 years of R&D with old mixture

during production

Wires H1 Central Jet Chamber

during running

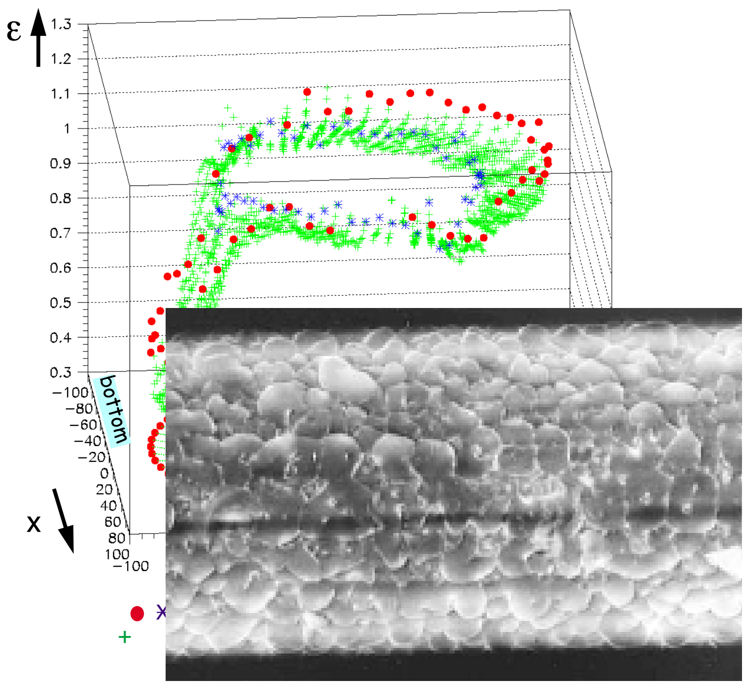
- Outer tracker of H1 ->
- Broken Wires in CJC1
- Observation / possible reason:
  - remnants from gold plating process lead to complex chemical reactions
- new design of crimp tube: jewels • better quality control



Cathode

Sense/Pot

Cathode

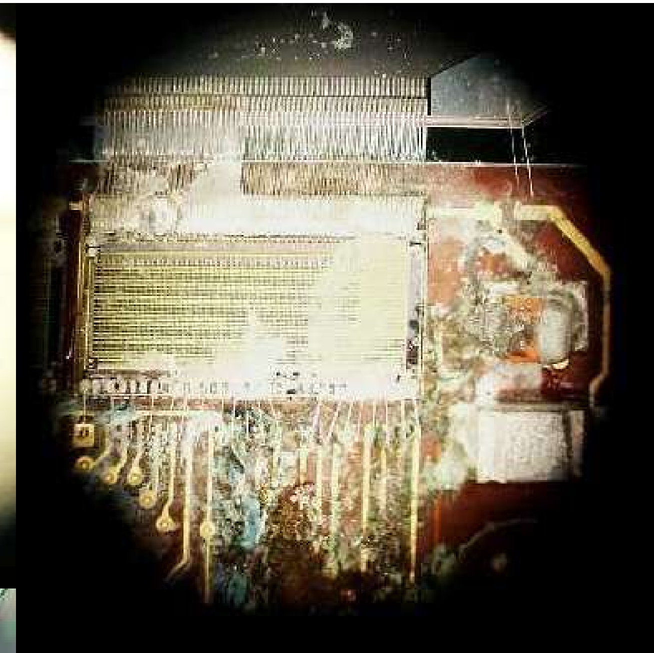


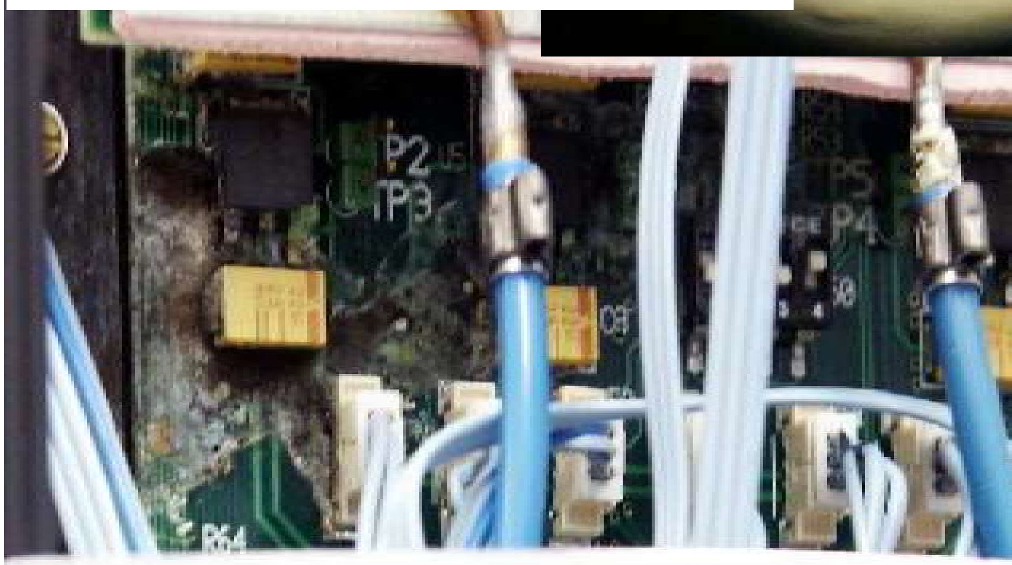
- Sense Wire Deposits in CJC2
- Observation / possible reason:
  - y dependence implies most likely gas impurity
- Consequences:
  - sense wires replaced
  - changes in gas distribution
  - increased gas flow

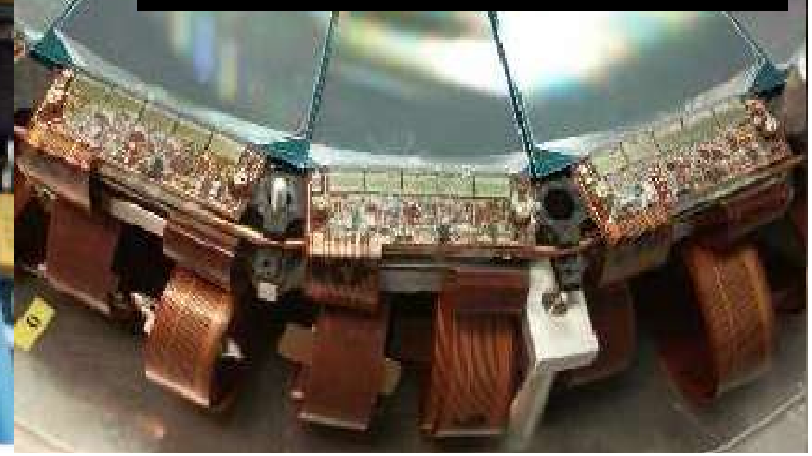
Water Damage in Tracker ...

during running

- H1@HERA FST in 2004
- Imperfect crimp + hardening of plastic => water leak
- Water condensation => damage
- Tracker segment had to be rebuilt





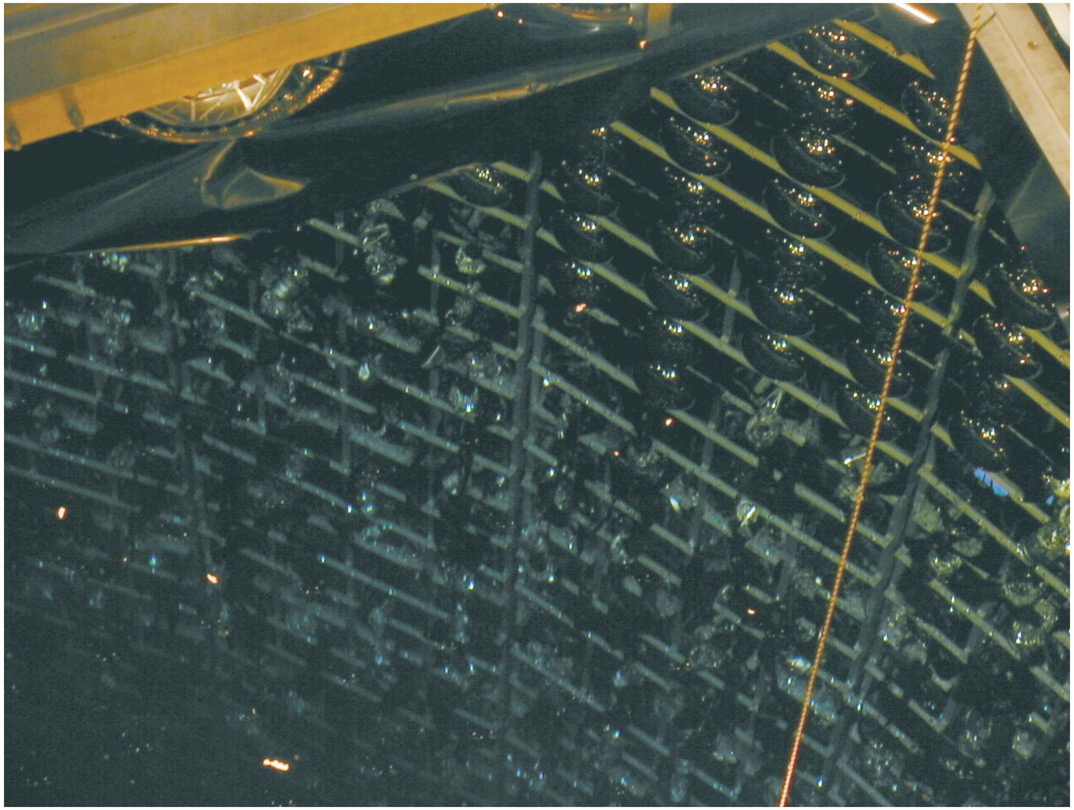


Imploded PMTs @ Superkamiokande

- On November 2001 a PMT imploded creating a shock wave destroying about 6600 of other PMTs (costing about $3000 each)

- Apparently in a chain reaction or cascade failure, as the shock wave from the concussion of each imploding tube cracked its neighbours.
- Detector was partially restored by redistributing the photomultiplier tubes which did not implode.

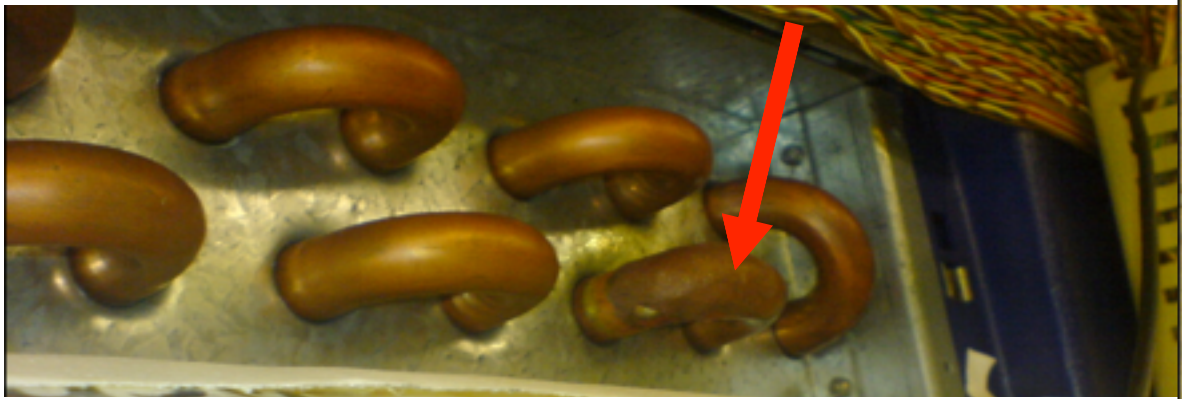
during running

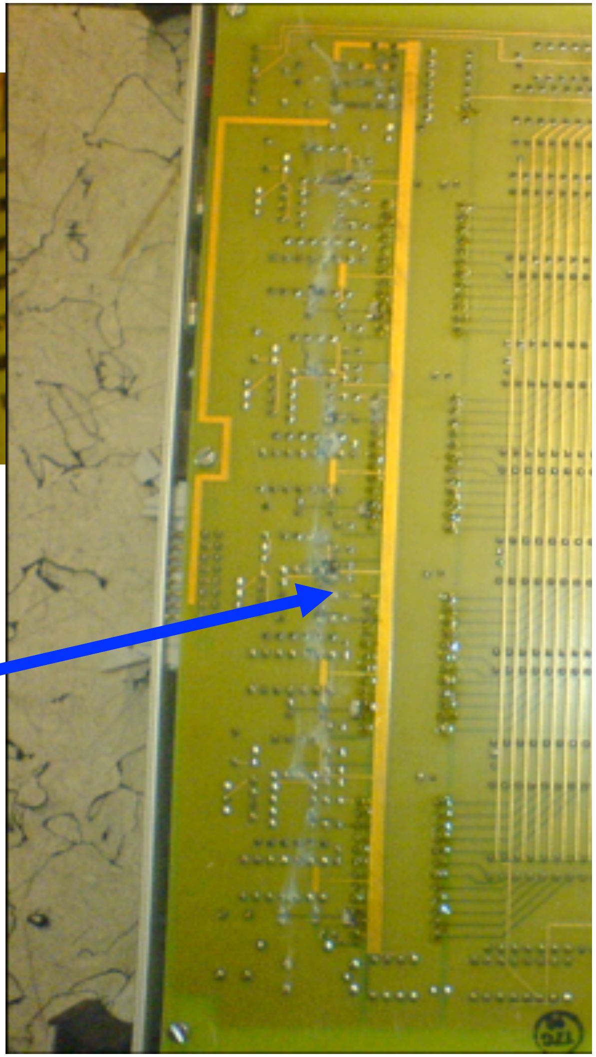


Pic: unknown source....

ZEUS - one of many Water Leaks

- Where ever you chose to cool with a liquid - it will leak one day !





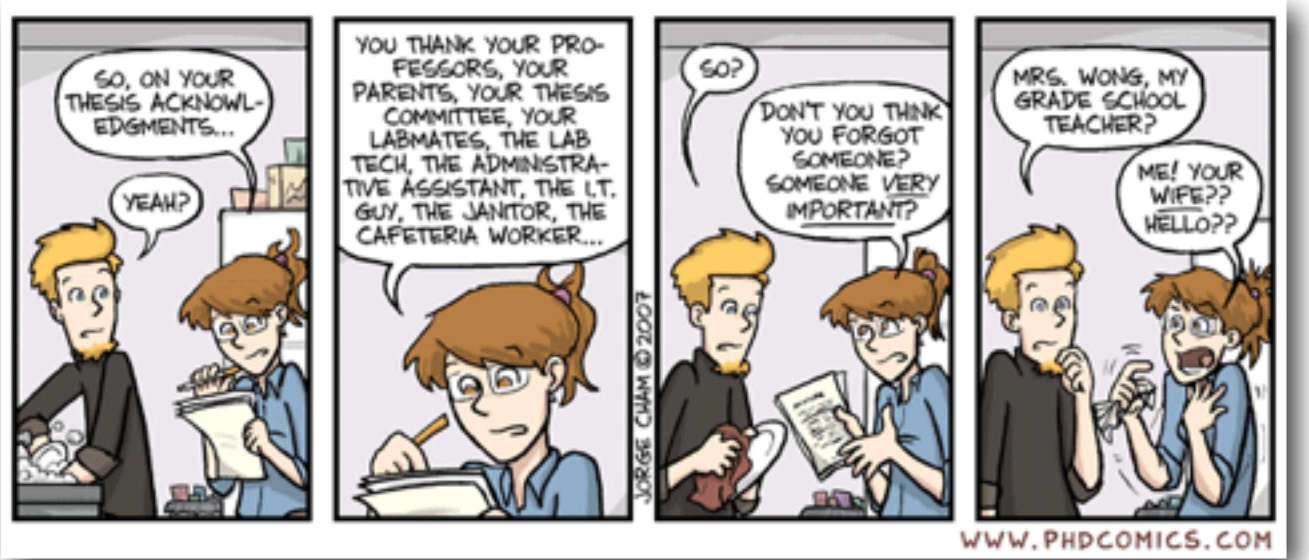
- Micro hole in copper hose led to water in the digital card crates
- Four crates were affected, but only seven cards were really showing traces of water
- Of course this all happened on a Saturday morning at 7am ….

during running

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!**

Important ....



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Carsten Niehbuhr

Christoph Rembser

Marc Winter

Doris Eckstein

Christian Joram

Steinar Stapnes

…freaky husband ;-)

LITERATURE

rather old books by now

Text books:

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
L. Rossi, P. Fischer, T. Rohde, N. Wermes, *Pixel Detectors – From Fundamentals to Applications*, Springer Verlag 2006
Frank Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics*, Springer Verlag 2009

W.Blum, L.Rolandi: *Particle Detection with Drift chambers,* Springer, 1994
F. Sauli, Principles of Operation of Multiwire Proportional and Drift Chambers, CERN 77-09
G.Lutz: *Semiconductor radiation detectors,* Springer, 1999
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

New Book ....

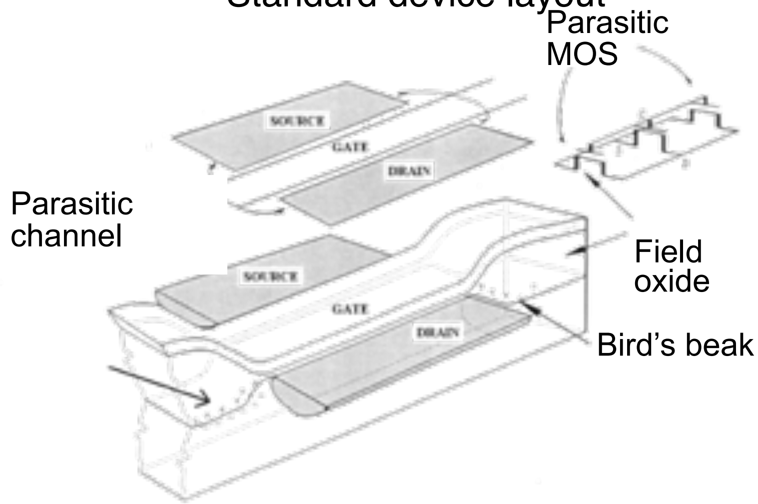
Teilchendetektoren
Grundlagen und Anwendungen
Taschenbuch – 19. Februar 2016

English translation in preparation

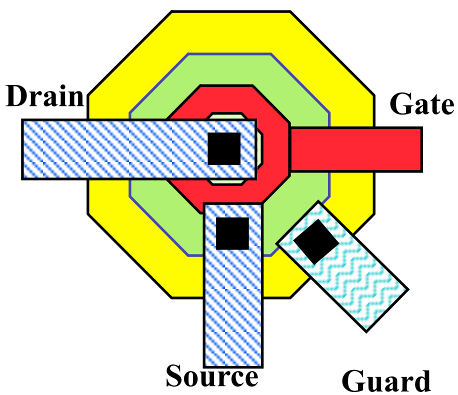
Radiation effects on CMOS: ionizing

- Decrease of feature size: higher radiation tolerance:
  - Positive charge trapped in gate and field oxides
  - Trapped charge dissipates by tunnelling in thin-oxide transistors
- Radiation tolerant layout techniques designed by CERN RD49 in 0.25µm to avoid parasitic transistor leakage
- New RD created for further work towards HL-HLC

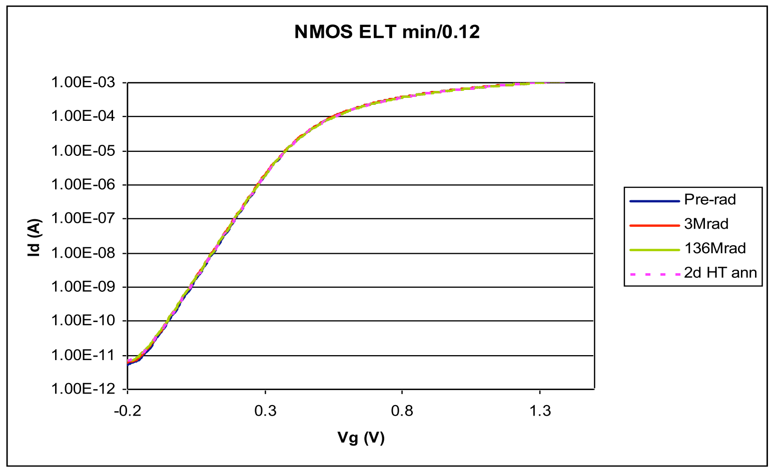
Standard device layout



Enclosed layout



gate encloses all n+ regions avoiding any thick transistor relevant oxide structures



TID on IBM 130nm NMOS [F. Faccio CERN]