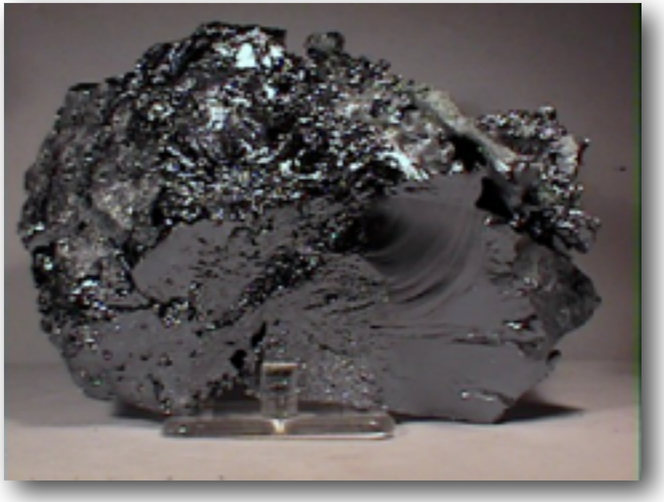
MATERIAL PROPERTIES

	Si	Ge	GaAs	CdTe	Diamond	SiC
band gap	1.12	0.67	1.42	1.56	5.48	2.99
energy for e-p pair [eV]	3.6	2.9	4.2	4.7	13.1	6.9
e- for MIP (300µm)	24000	50000	35000	35000	9300	19000
Z	14	32	31+33	48+52	6	14+6

Why is silicon used more often ?

- Silicon is the only material which can be produced in larger areas in high quality

- compare to kT = 0.026 eV at room temperature -> dark current under control
- high density compared to gases: $\rho=2.33 g/cm^3$
- good mechanical stability -> possible to produce mechanically stable layers
- large charge carrier mobility
- fast charge collection $\delta t \sim 10 ns$
- well understood -> radiation tolerant



PRINCIPLE OF SEMICONDUCTOR

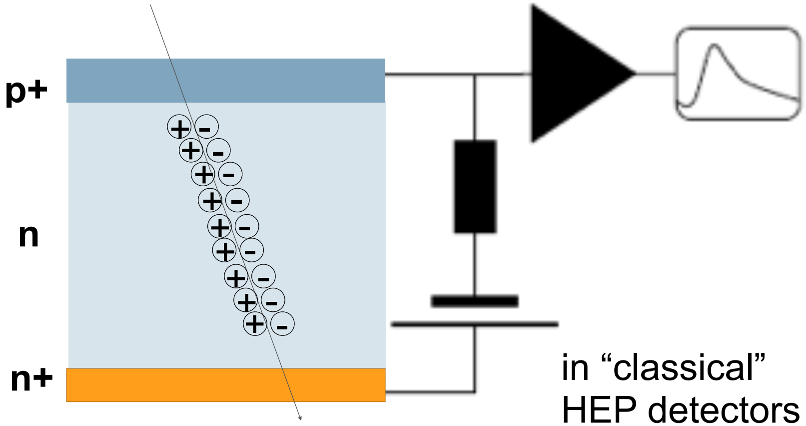
- Creation of electric field: voltage to deplete thickness d

with $n_A >> n_D$ $$d = \sqrt{\frac{2\epsilon\epsilon_0 V_{dep}}{e n_D}}$$

for $d = 300\mu m$ $V_{dep} \approx 160V$

- Passage of a charged particle: Electron-hole pairs formed in the depletion zone
  - Drift under the influence of the electric field
  - Signal depends on width of depletion zone

The signal is induced by the motion of charge after incident radiation (not when the charge reaches the electrodes).



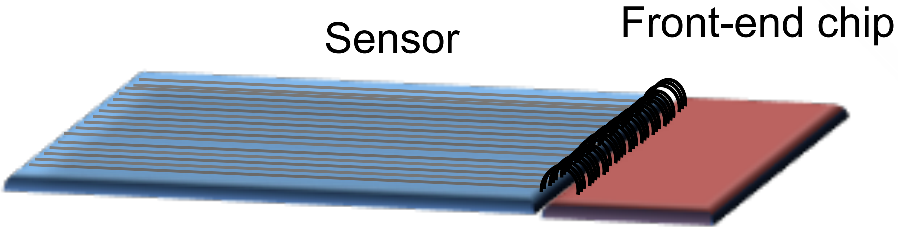
in “classical” HEP detectors

Typical numbers

Doping concentration

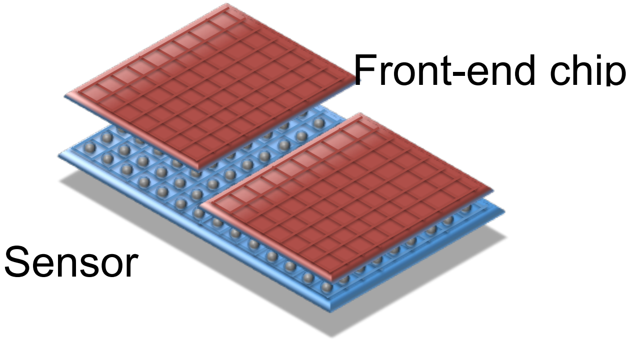
$n_A \approx 10^{19} cm^{-3}$	Acceptors
$n_D \approx 2 \cdot 10^{12} cm^{-3}$	Donators

STRIPS AND PIXELS



Microstrips detector

- **Strips detector:** charge sensed by long narrow strips 1D information (typically 20 - 100µm)
  - 2D information by double sided processing or adding back to back second layer slightly rotated (stereo angle)
- In regions with higher track density one dimensional measurements can lead to ambiguities.



Hybrid pixel detector

- **Pixel detector:** charge sensed by small pixels on one side of sensor
  - Hybrid pixels: sensors and readout joined via bump bonds
  - Monolithic pixels: sensor and readout on one substrate

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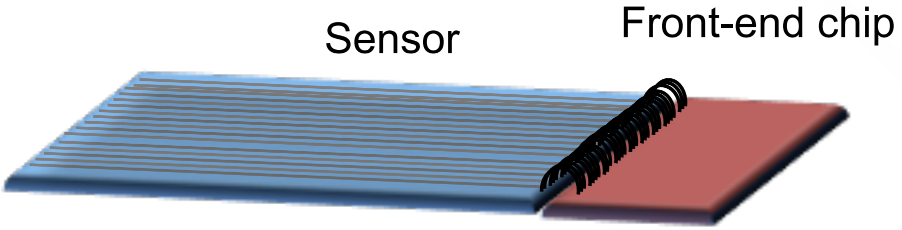

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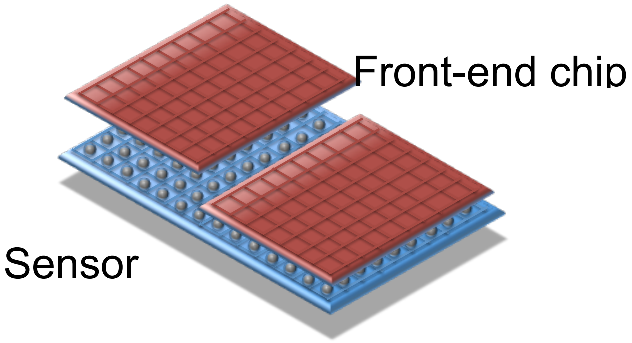
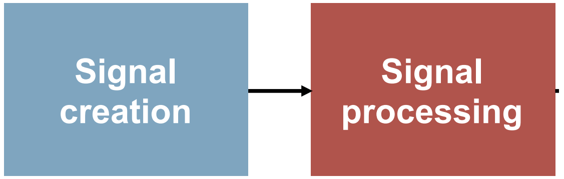


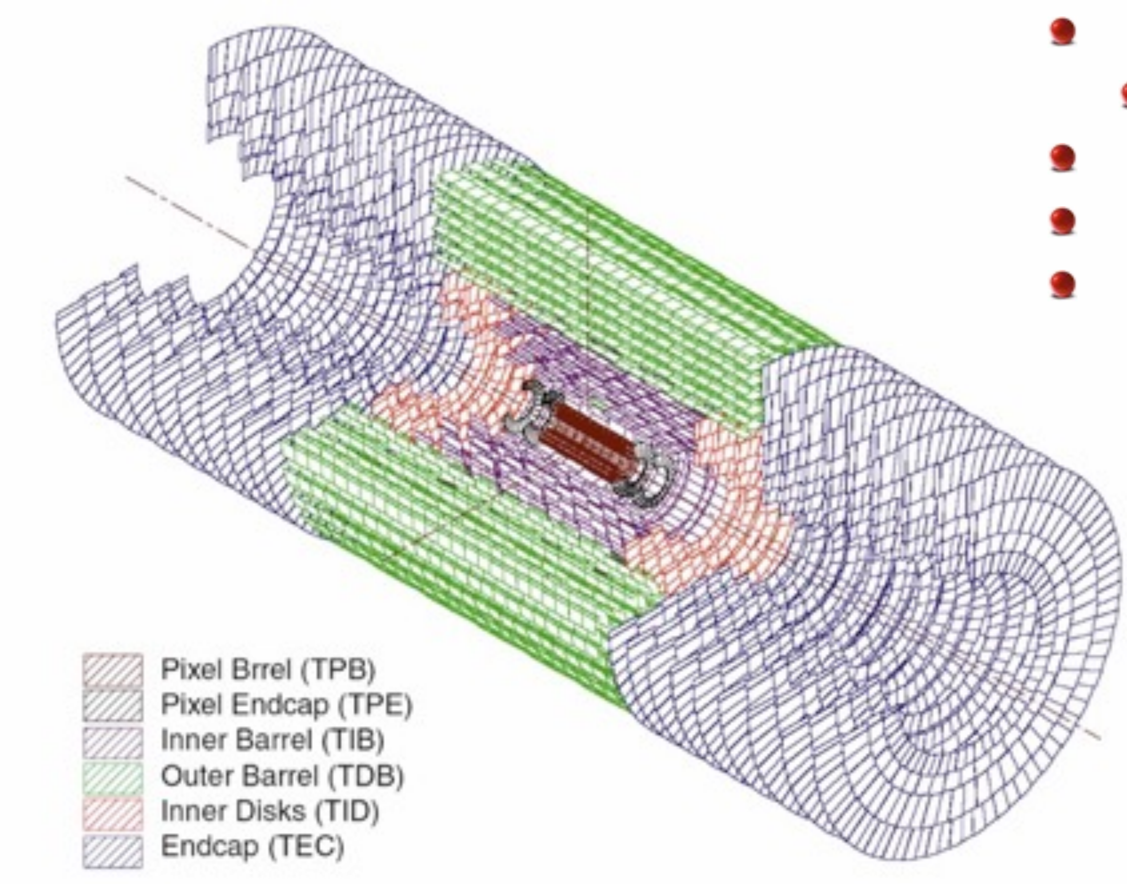
Hybrid pixel detector

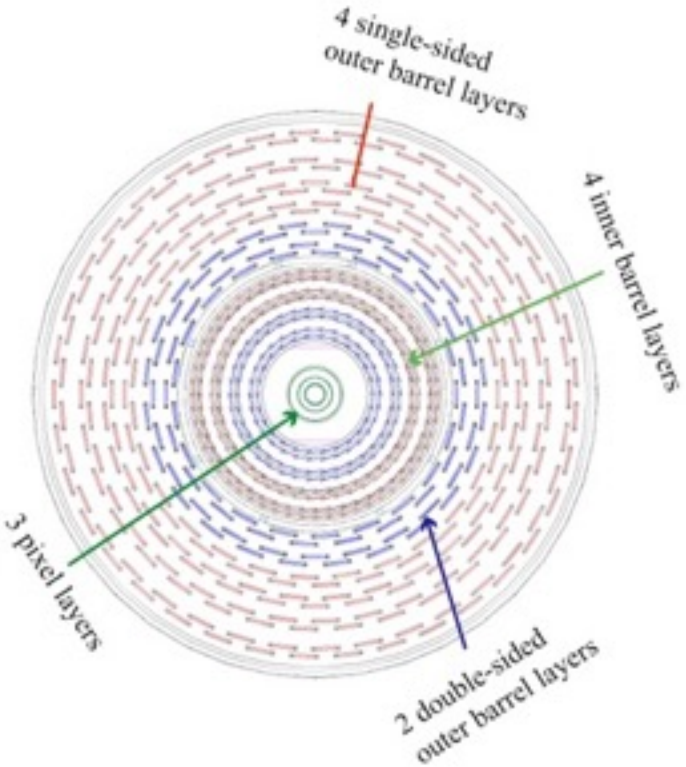


- Signals created in silicon by charged particle
  - Very small signals (fC): need amplification
  - Measurement of amplitude/hit and/or time
  - Several thousands to millions of channels

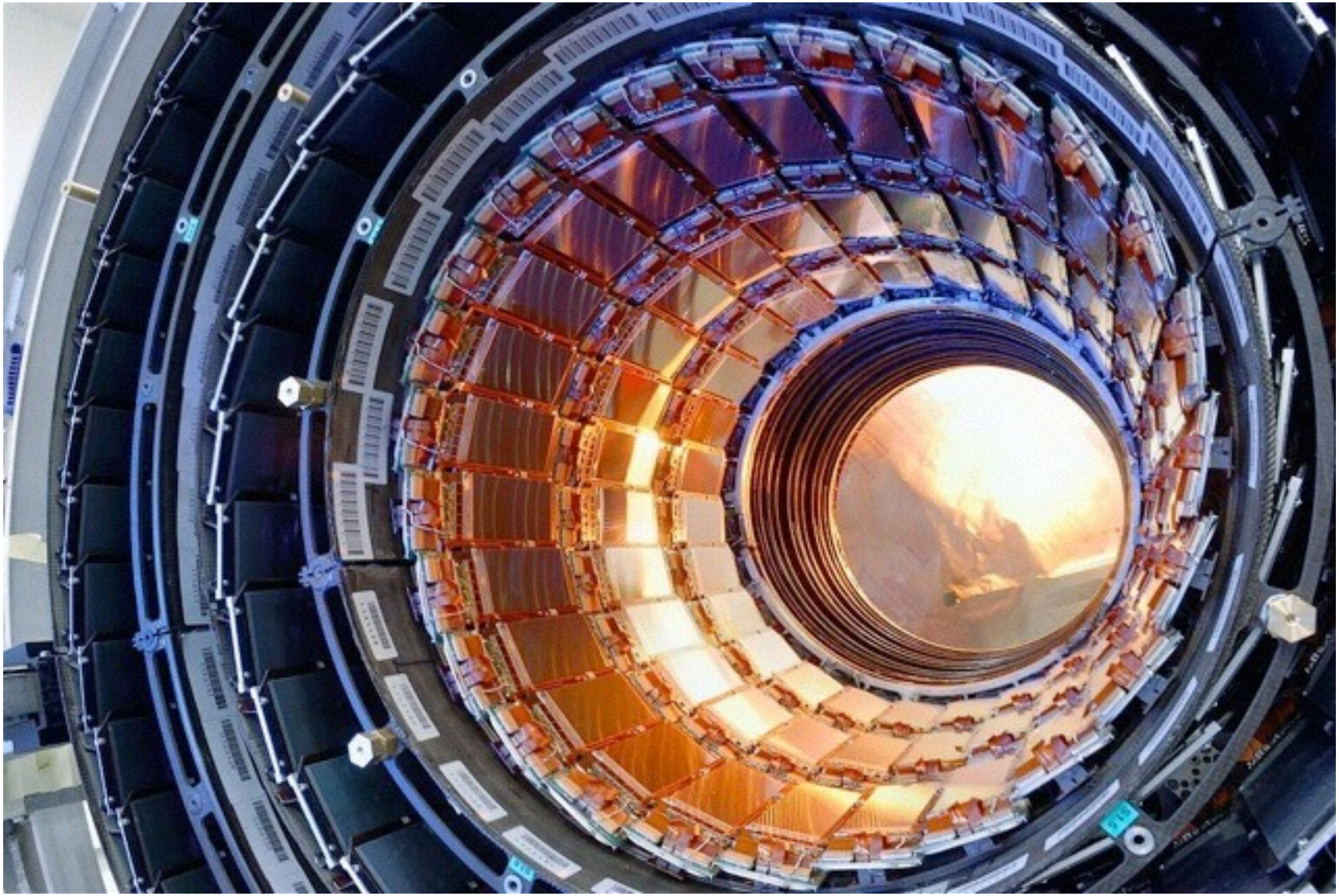
CMS SI-TRACKER

- 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



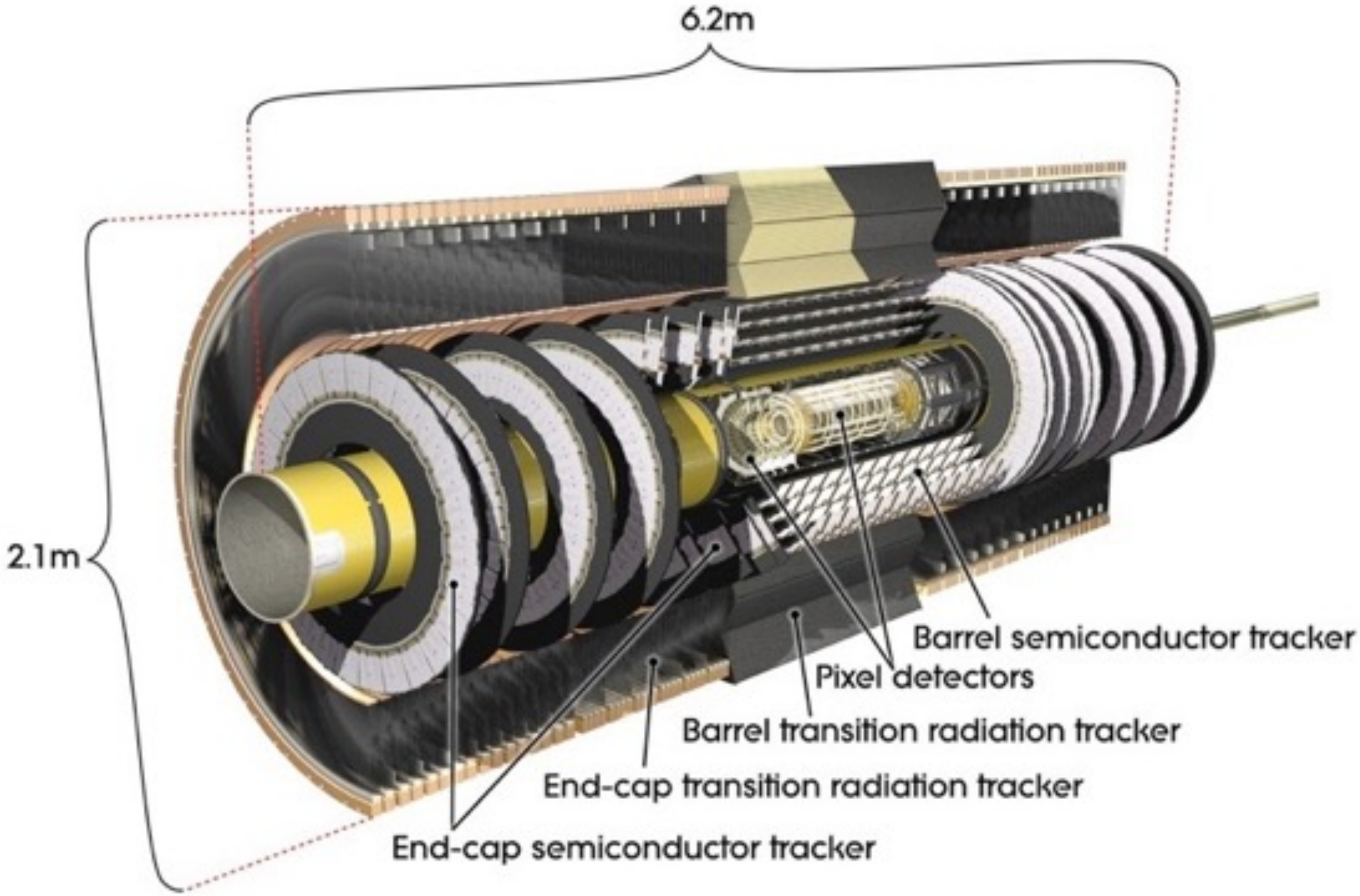


CMS TRACKER - BEAUTY SHOT



Pic: CERN

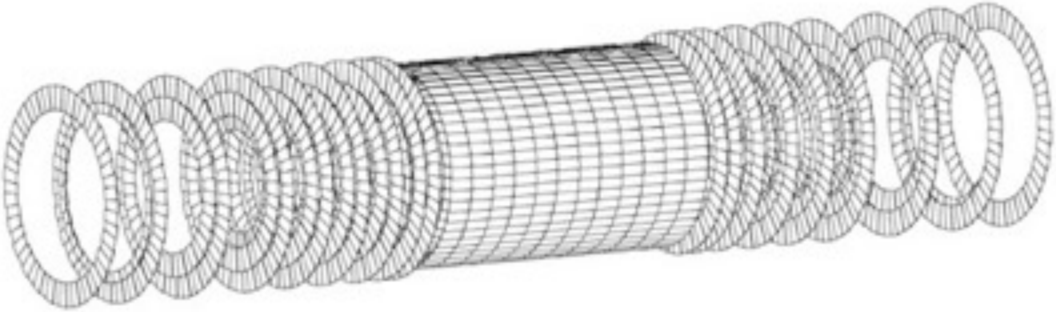
ATLAS SCT

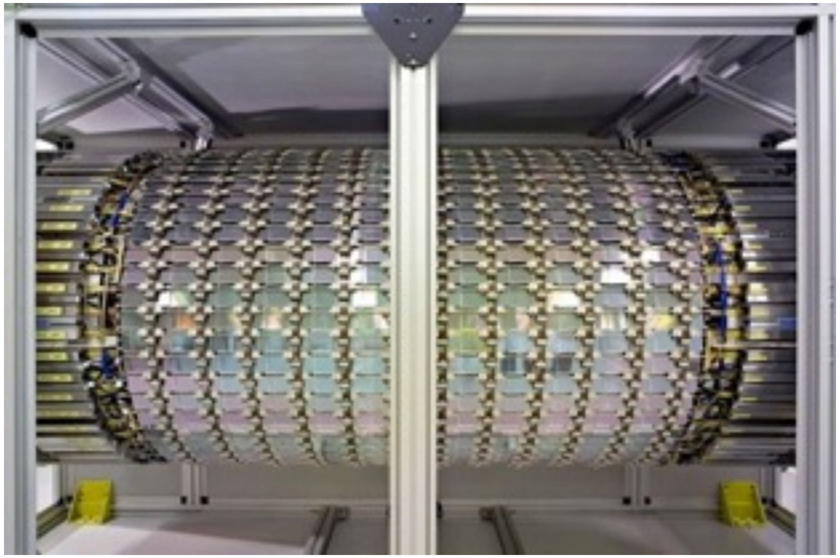


- ATLAS Si-Detector SCT:
  - Si- strips: 4 Barrel-layer, 2 x 9 discs

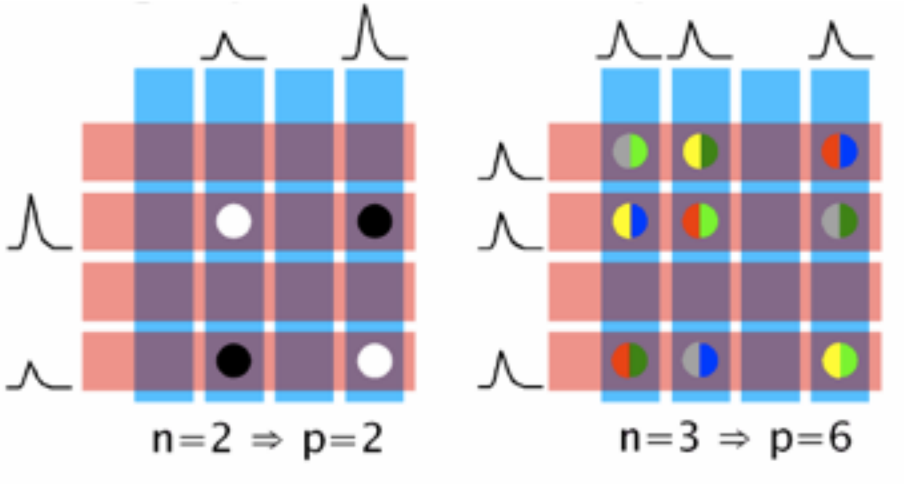
ATLAS SCT

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

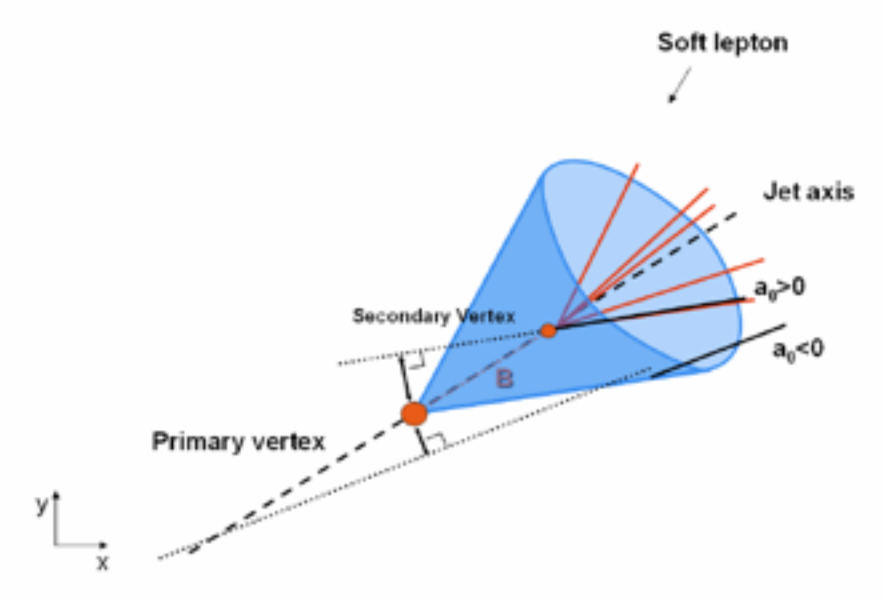




LIMITS OF STRIP DETECTORS



- 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

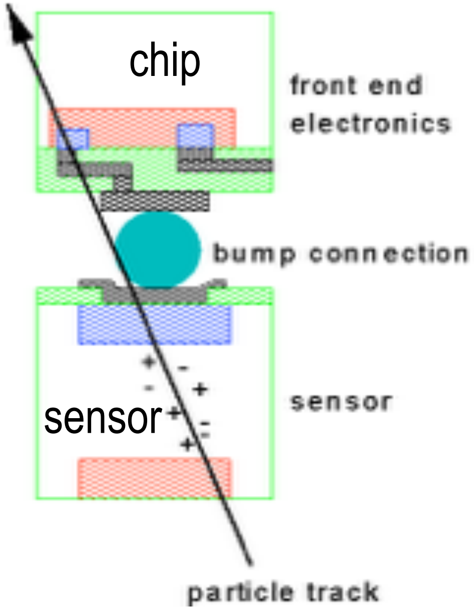
First pixels (CCDs)
in NA11/NA32: ~1983

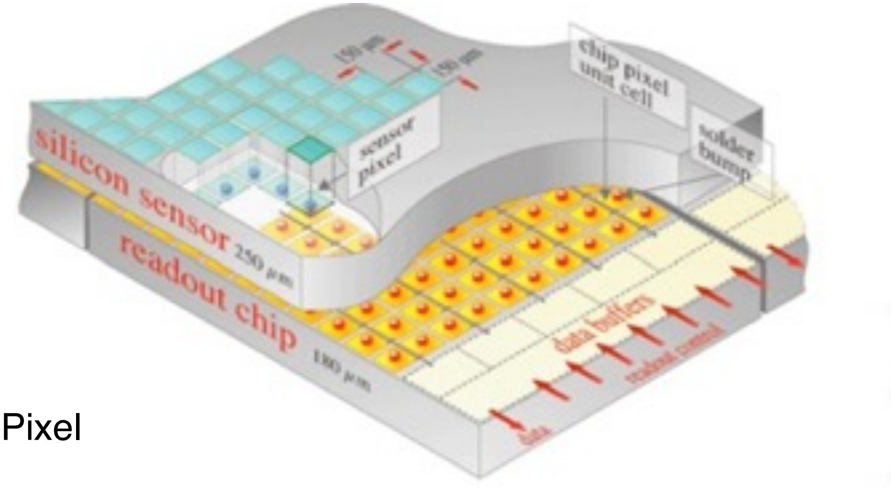
Hybrid Pixels – “classical” Choice HEP

- 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

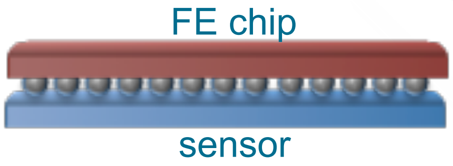




Hybrid Pixel (CMS)

- 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 . 10^{16} p/cm^2
- problem: HV might need to exceed 1000V

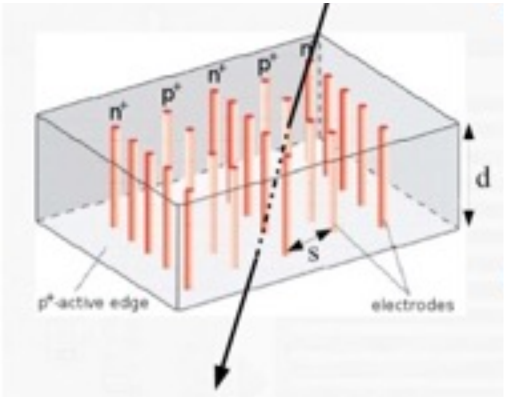
3D Silicon

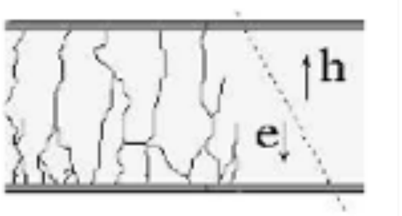
- Both electrode types are processed inside the detector bulk instead of being implanted on the wafer's surface.
- Max. drift and depletion distance set by electrode spacing
- Reduced collection time and depletion voltage
- Low charge sharing

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!

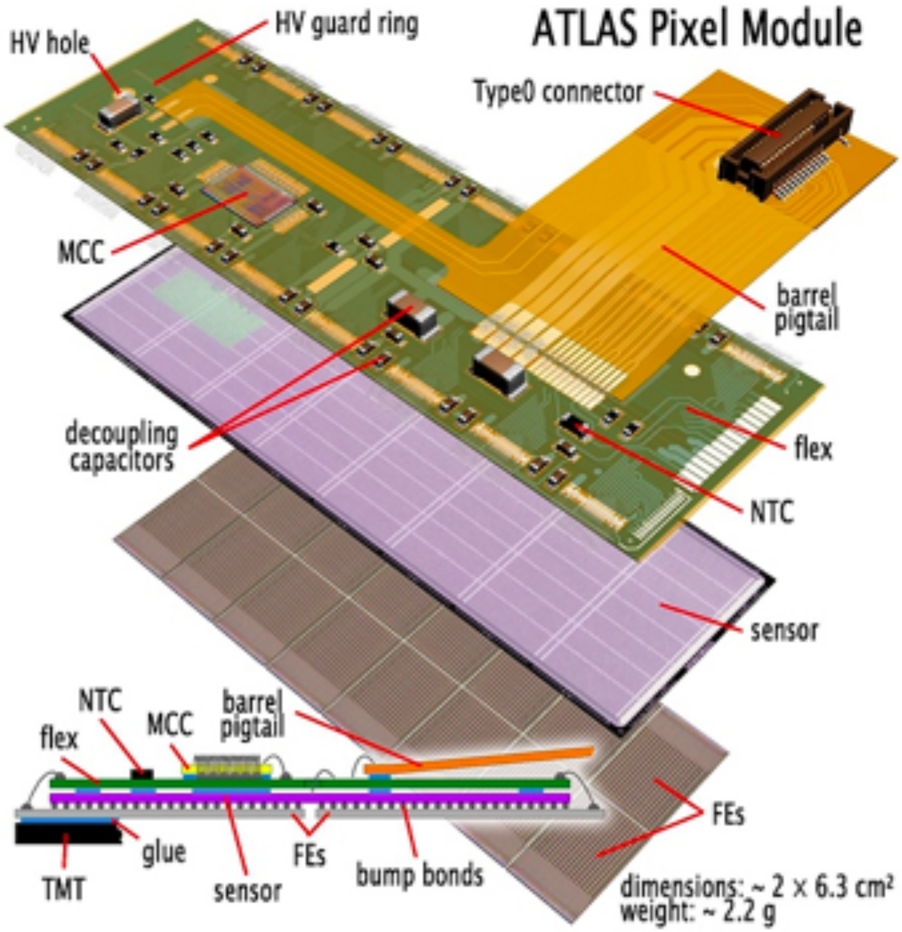


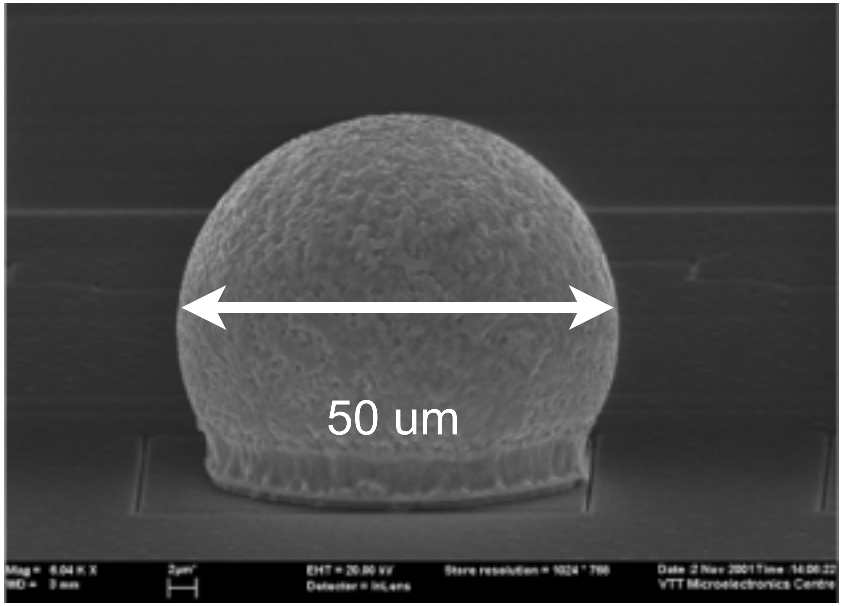


ATLAS-Pixels

A pixel module contains:

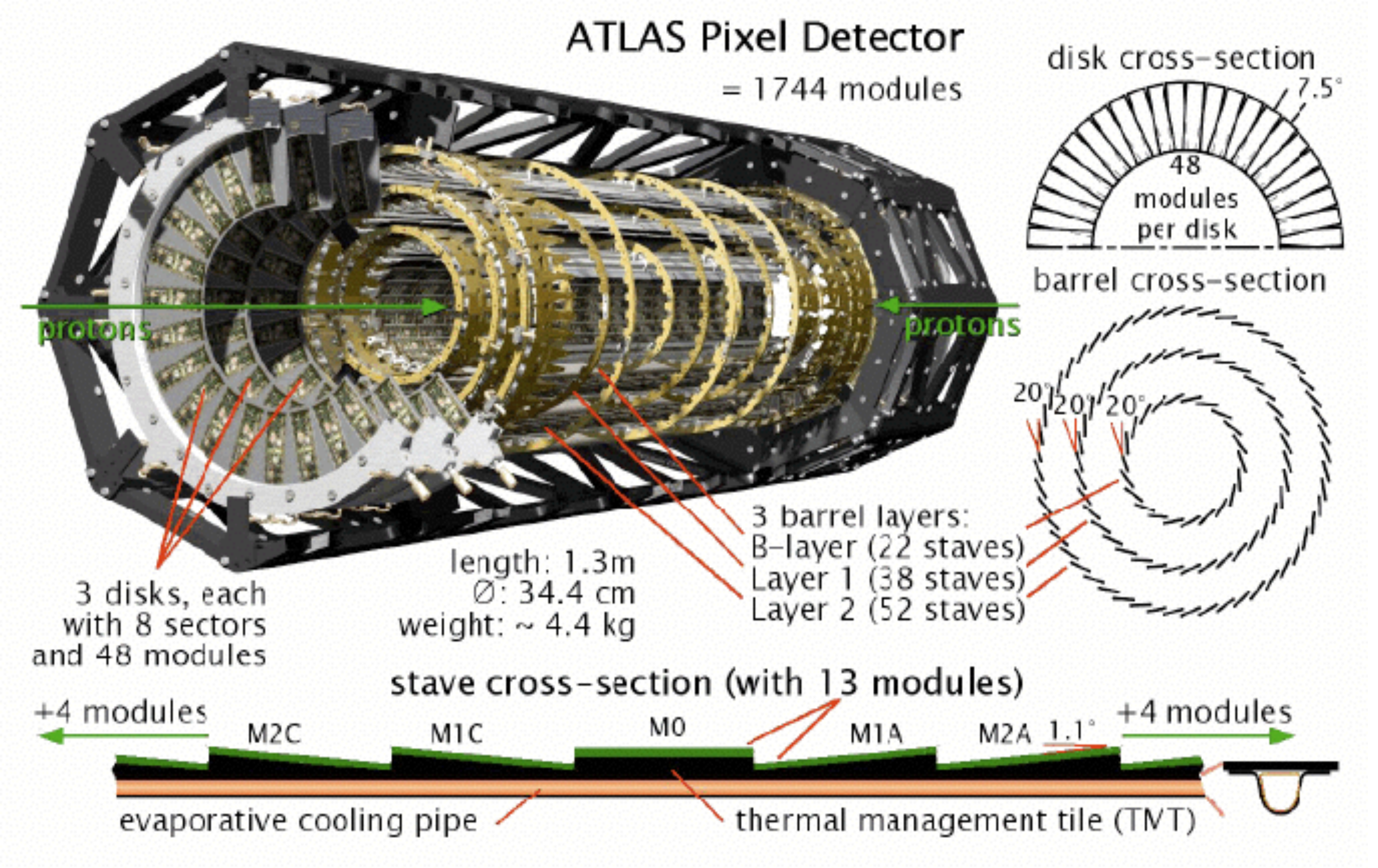
1 sensor (2x6cm)
  ~40000 pixels (50x500 mm)
16 front end (FE) chips
  2x8 array
  bump bonded to sensor
Flex-hybrid
1 module control chip (MCC)
There are ~1700 modules





Picture: VTT

ATLAS-PIXELS



ATLAS-PIXELS

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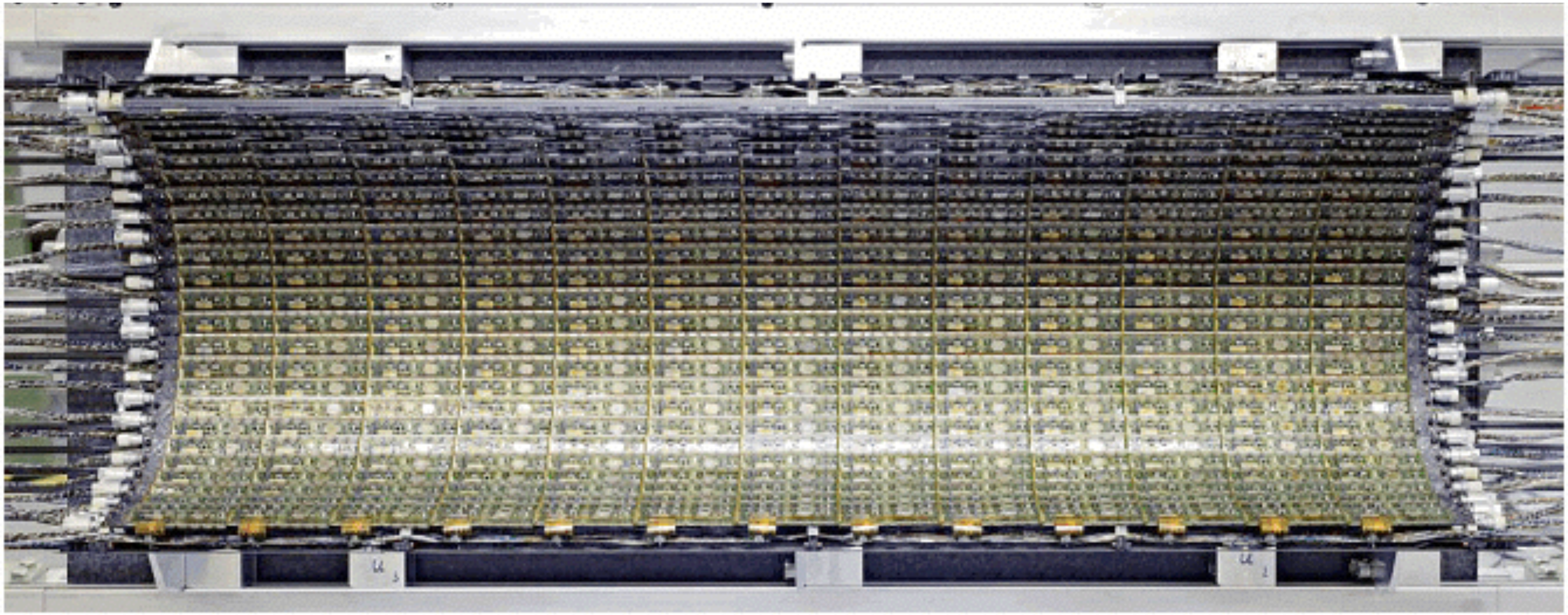
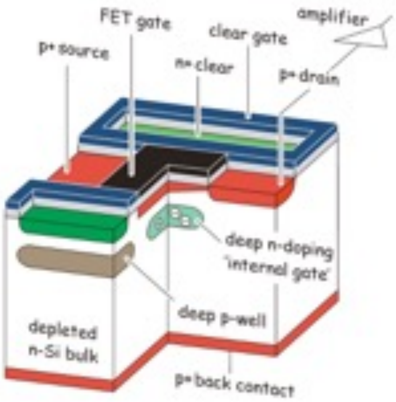


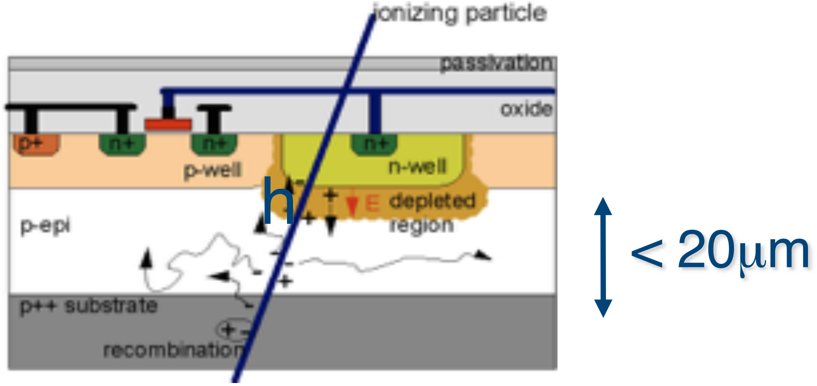
MONOLITHIC PIXEL SENSORS

- 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)



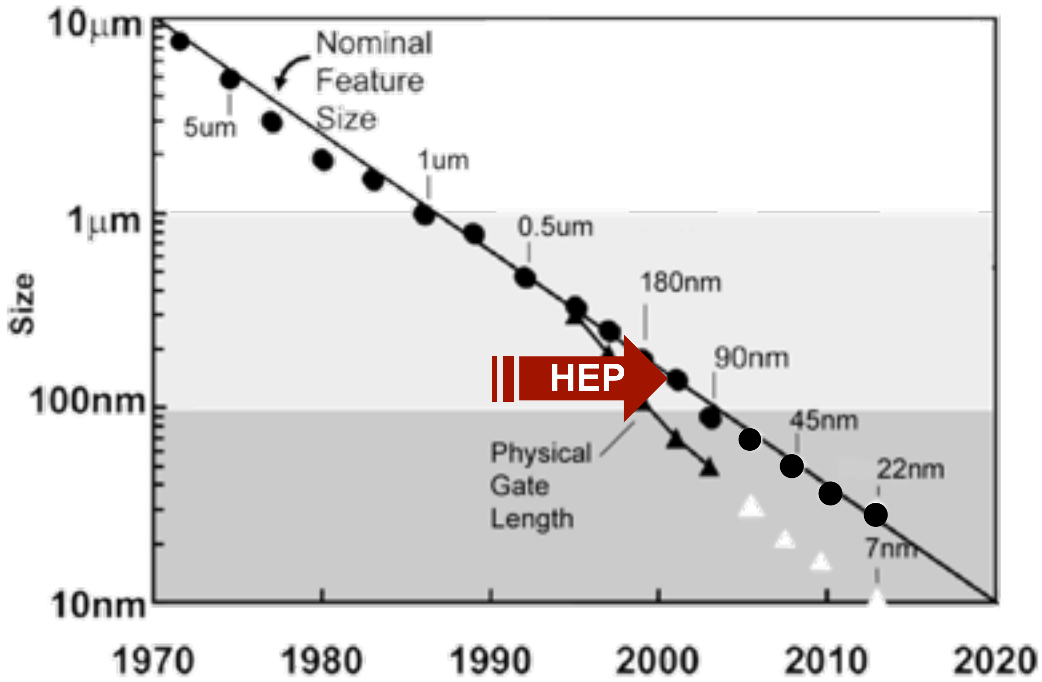
DEPFET



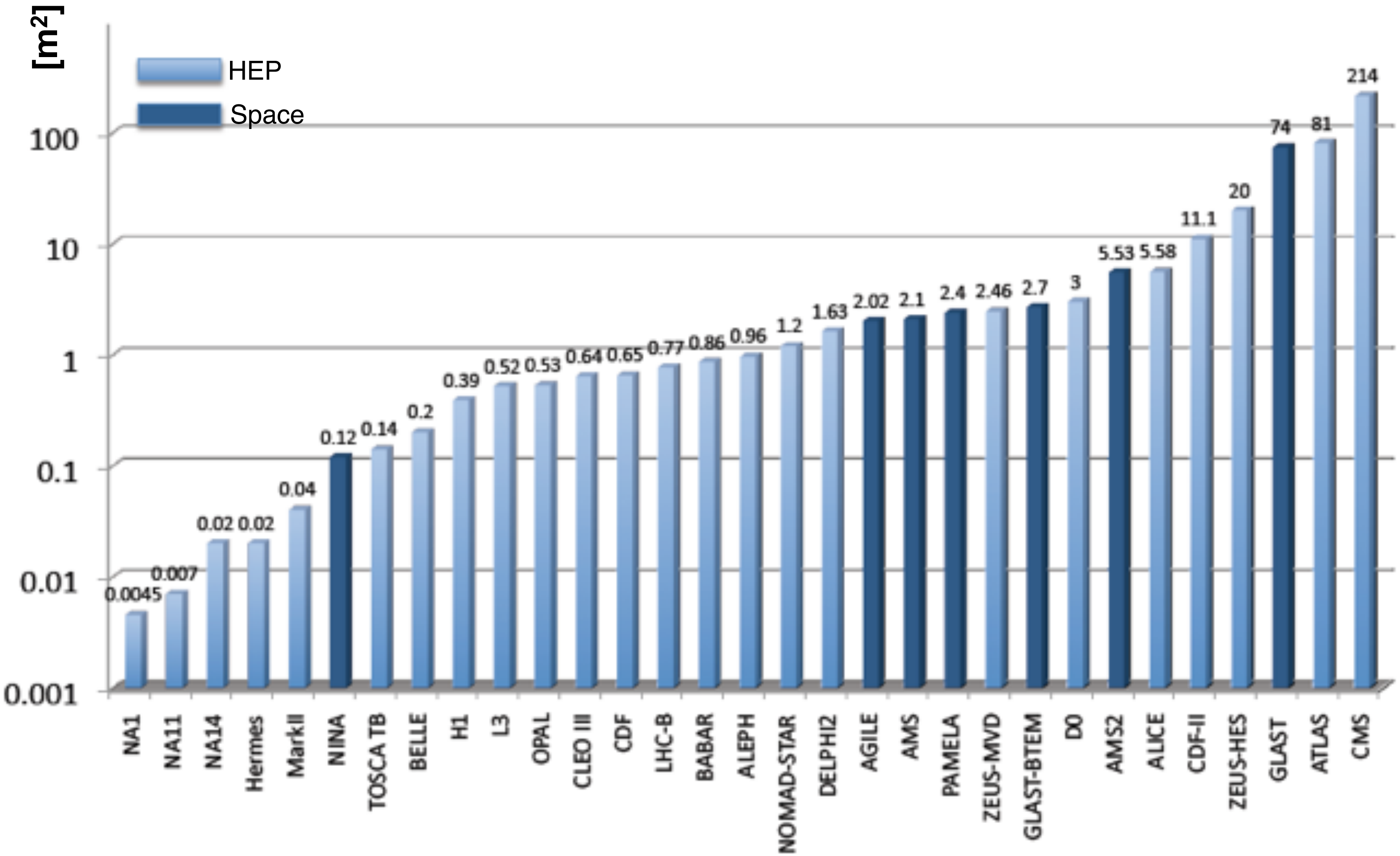
Mimosa MAPS

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

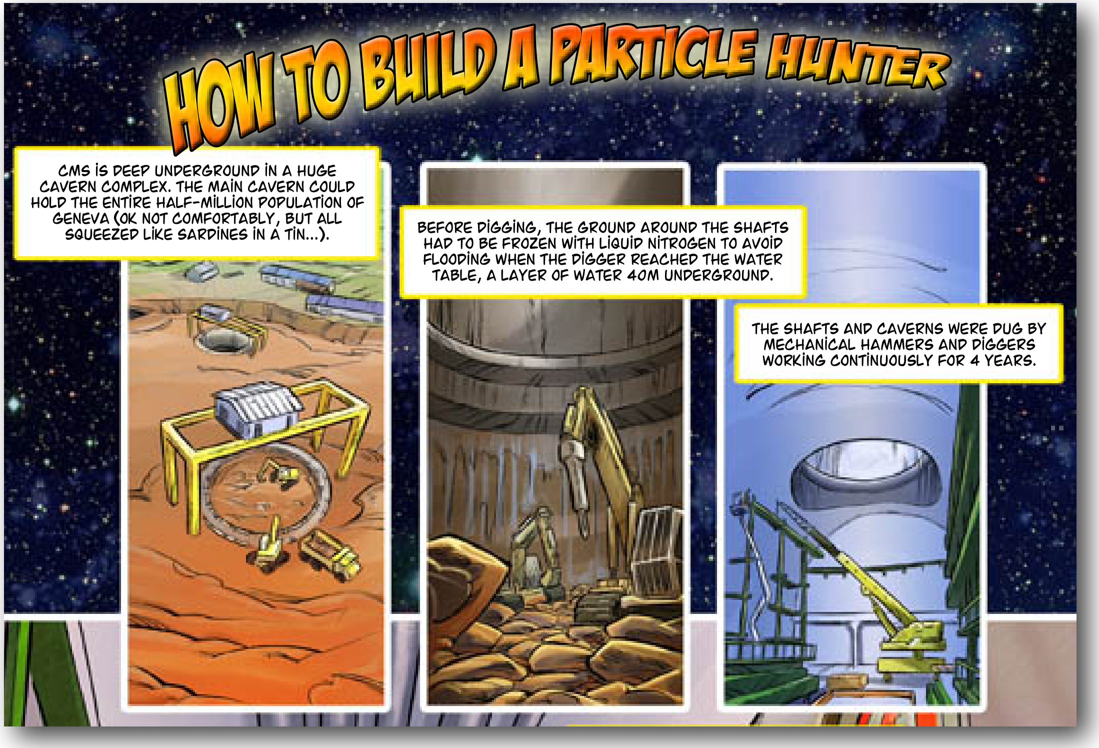
V. REAL LIFE EXAMPLES

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”

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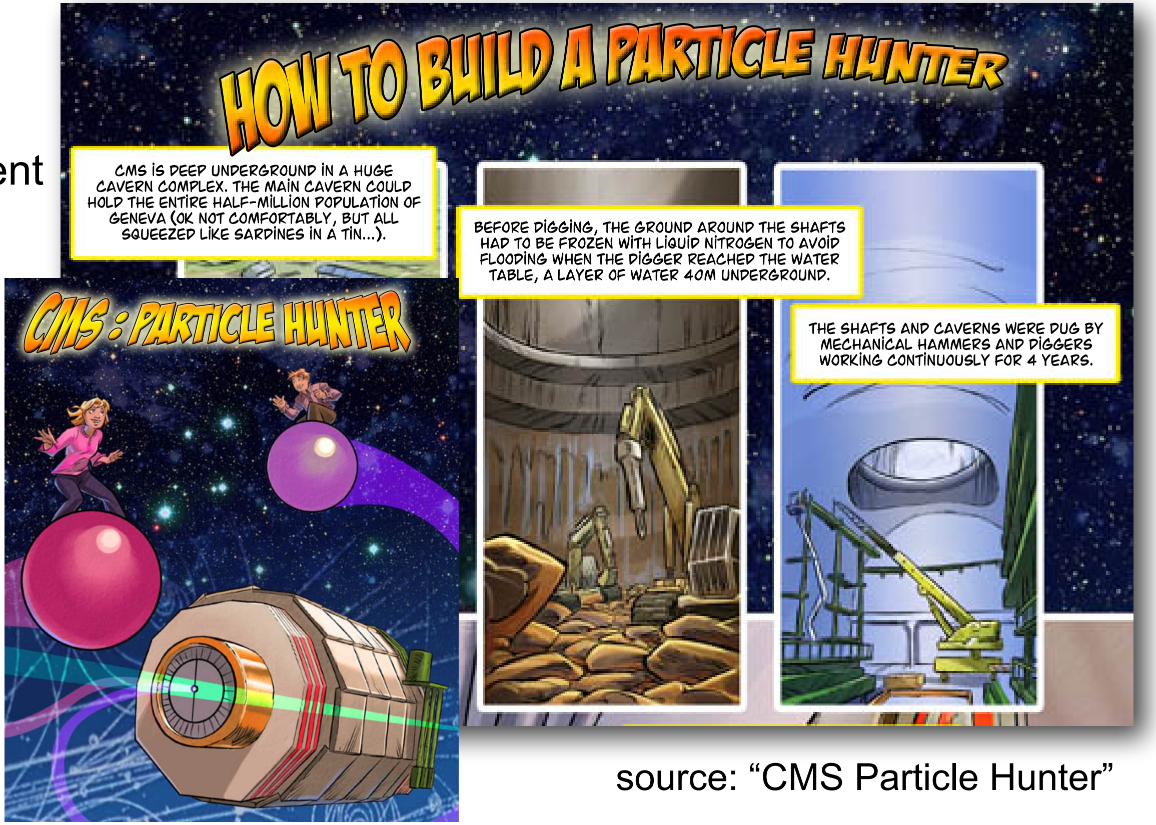

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How to do a particle Physics Experiment

- Recipe:
  - get particles (e.g. protons, antiprotons, electrons, …)
  - accelerate them
  - collide them
  - observe and record the events
  - analyse and interpret the data

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- Ingredients needed:
  - particle source
  - accelerator and aiming device
  - detector
  - trigger
  - recording devices

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- many people to:
  - design, build, test, operate accelerate
  - design, build, test, calibrate, operate, understand the detector
  - analyse data


Pic: DESY

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

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- many people to:
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  - design, build, test, calibrate, operate, understand the detector
  - analyse data
  - lots of money to pay all this ….

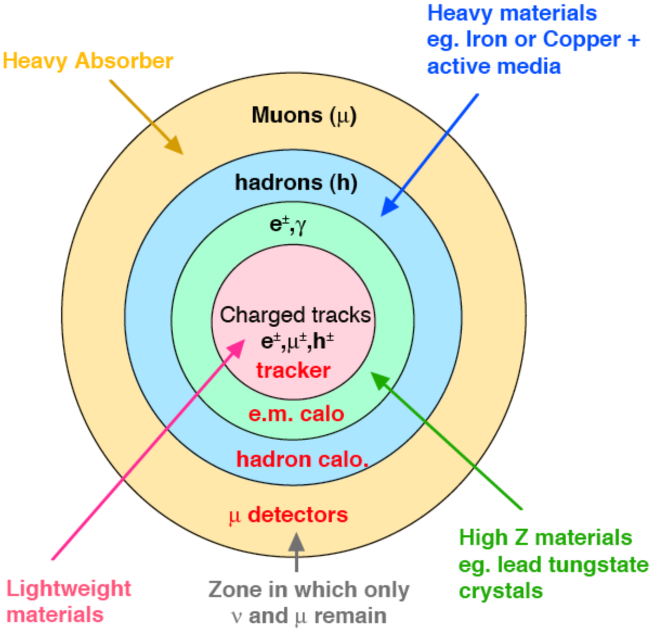
Pic: DESY

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 !!

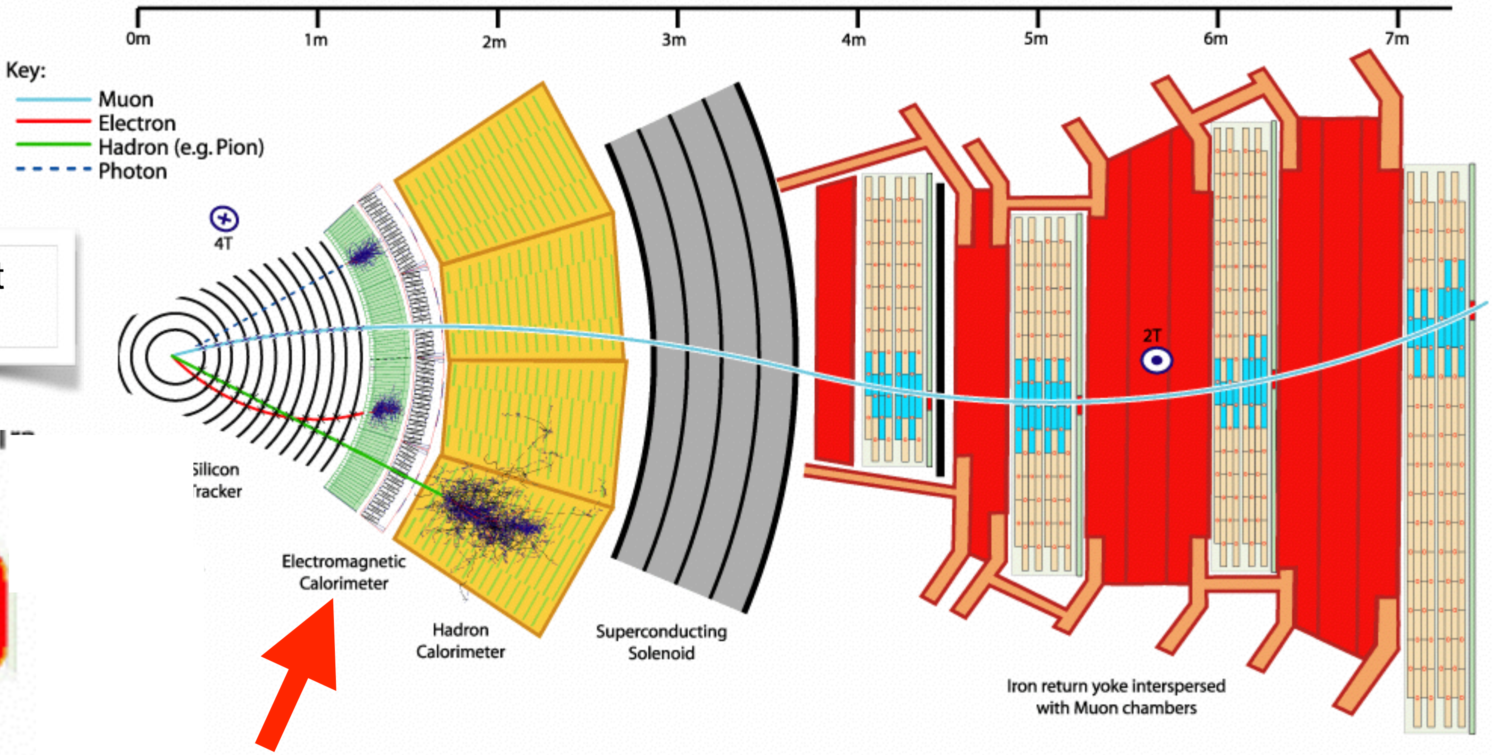
HEP DETECTOR OVERVIEW

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

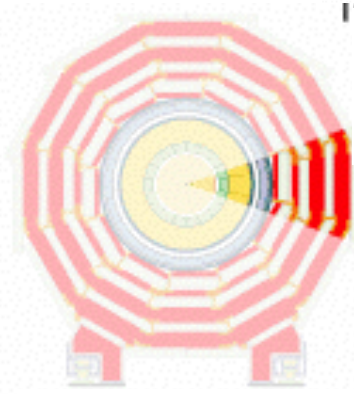
Calorimeter: Energy measurement of photons, electrons and hadrons through total absorption

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

Vertex: Innermost tracking detector



Good energy resolution up to highest energies



Transverse slice through CMS

picture: CMS@CERN

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
  - ….

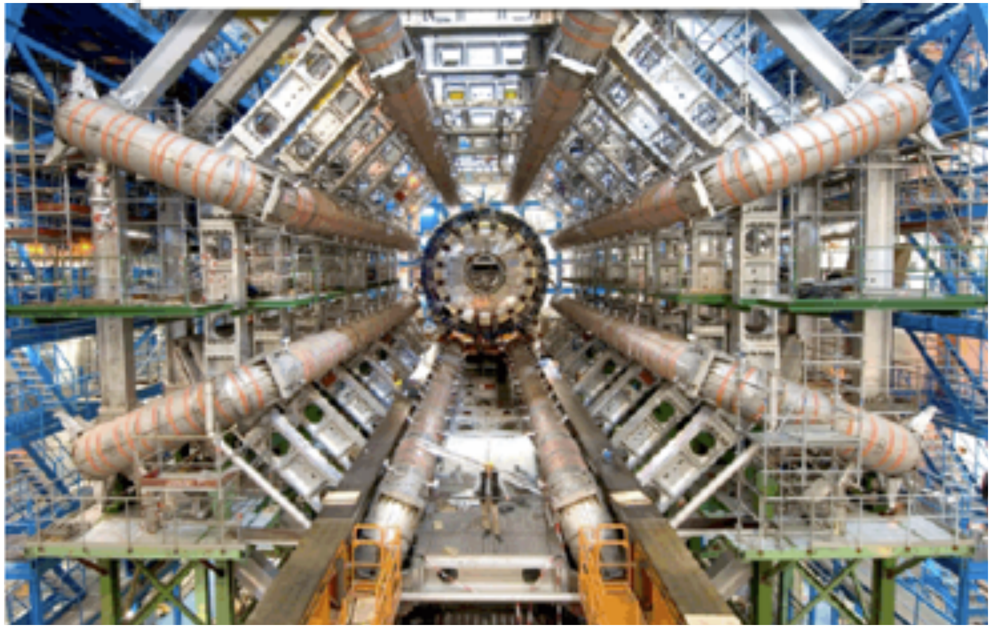
Eierlegende Wollmilchsau

www.positoons.de

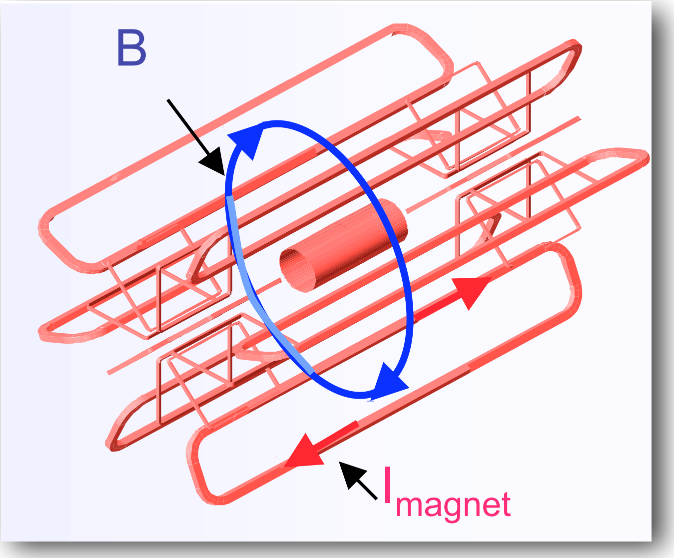
- **ATLAS decision**
  - achieve a high-precision stand-alone momentum measurement of muons
  - need magnetic field in muon region -> large radius magnet

- **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

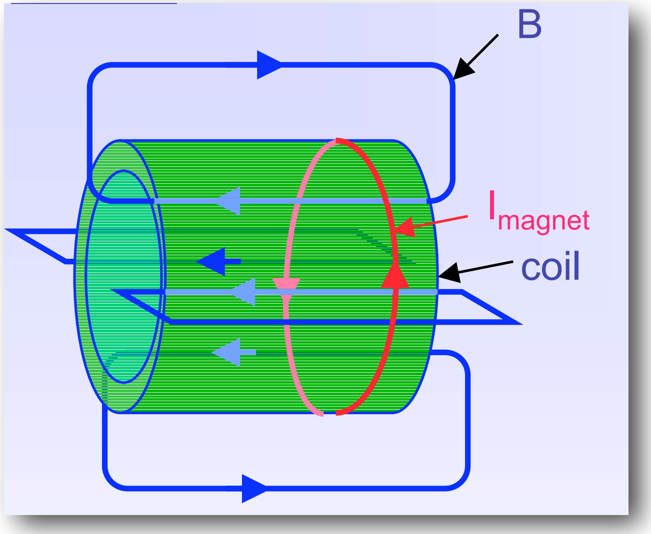


- Central toroid field outside the calorimeter within muon-system: <4 T
  - Closed field, no yoke
  - Complex field
- Thin-walled 2 T Solenoid-field for trackers integrated into the cryostat of the ECAL barrel

+ 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

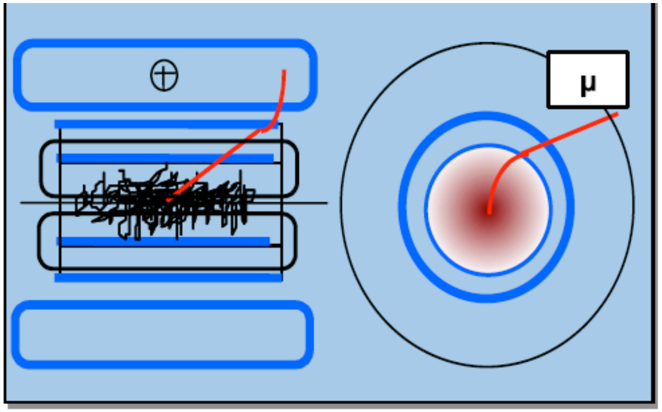
another tracker outside of the magnet

- 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.
    - $\Delta pT/pT \approx 1/BL^2$

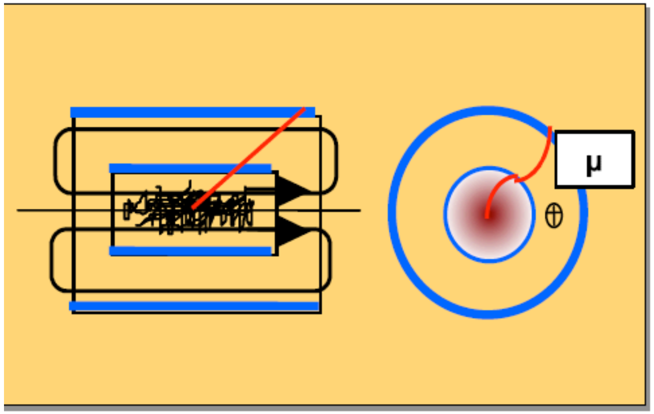
- ATLAS
    - independent muon system -> excellent stand capabilities
- CMS:
    - superior combined momentum resolution in the central region;
    - limited stand-alone resolution and trigger capabilities (multiple scattering in the iron)

- 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



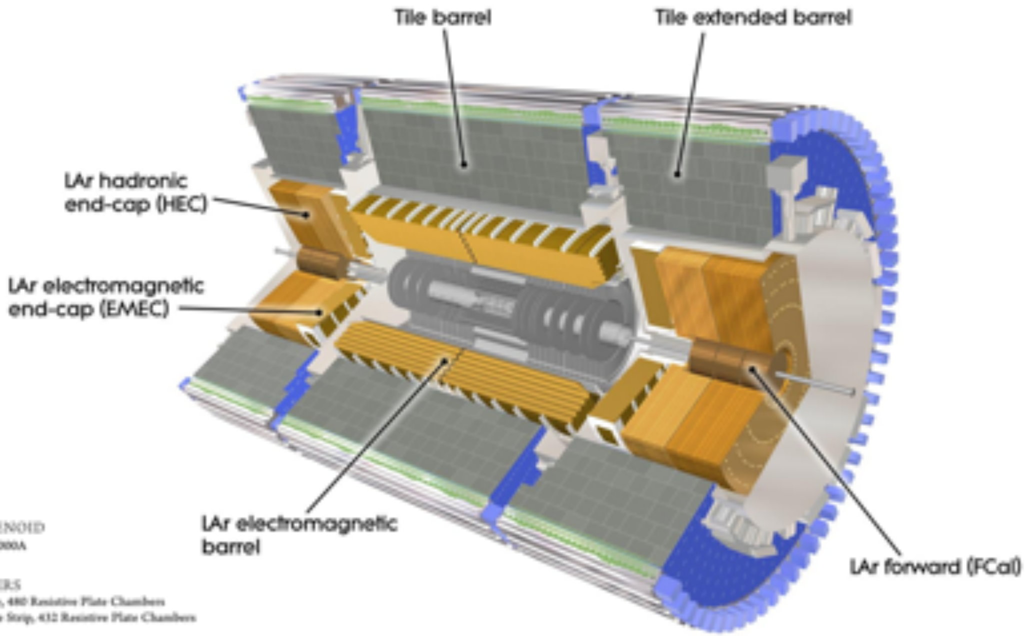
CMS



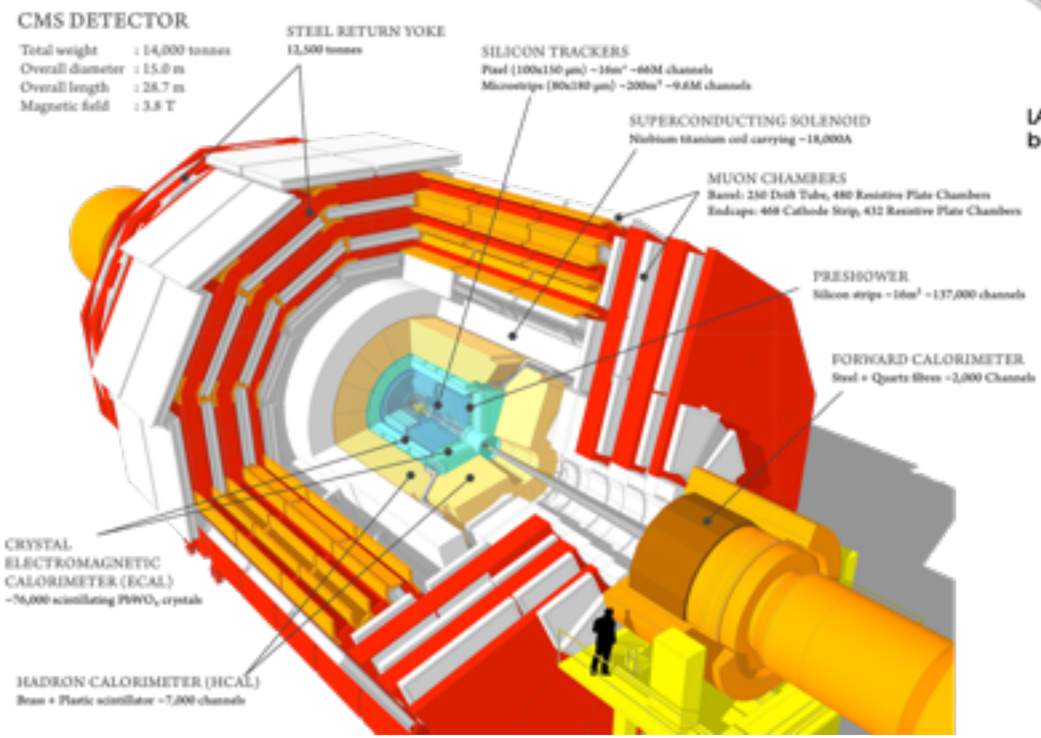
OVERVIEW OF CALORIMETERS

- 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



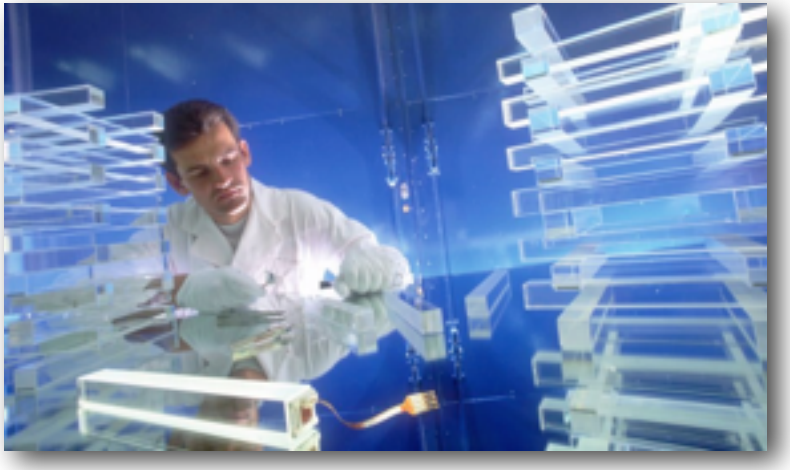
CMS



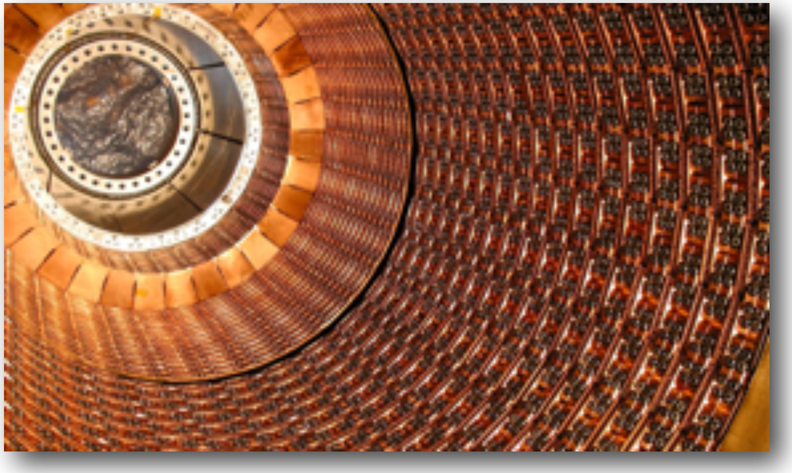
IMPORTANT DIFFERENCES: CALORIMETER

- **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



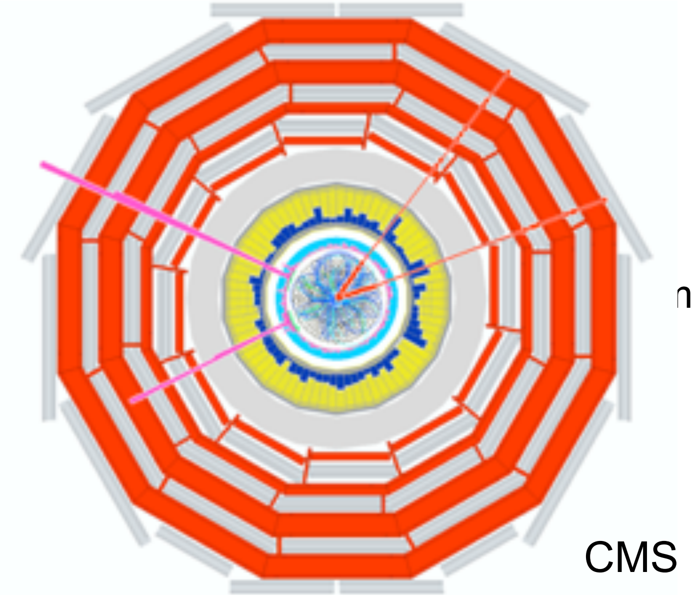
CMS Lead tungsten crystals (CERN)



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.



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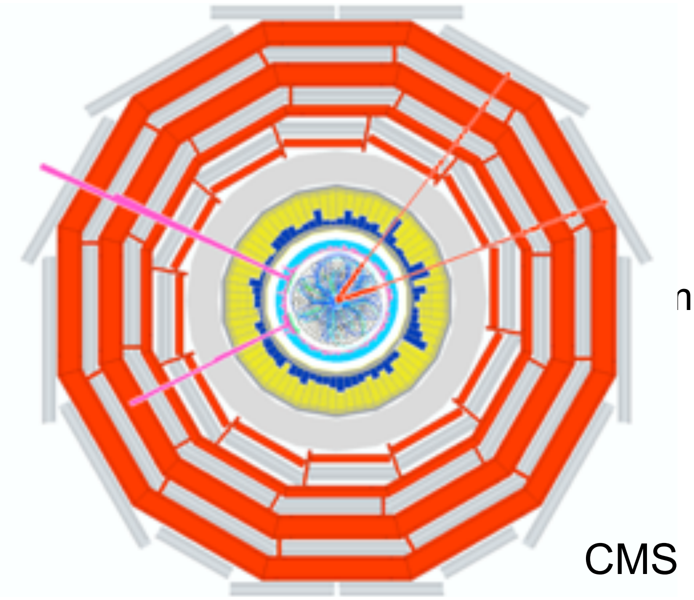
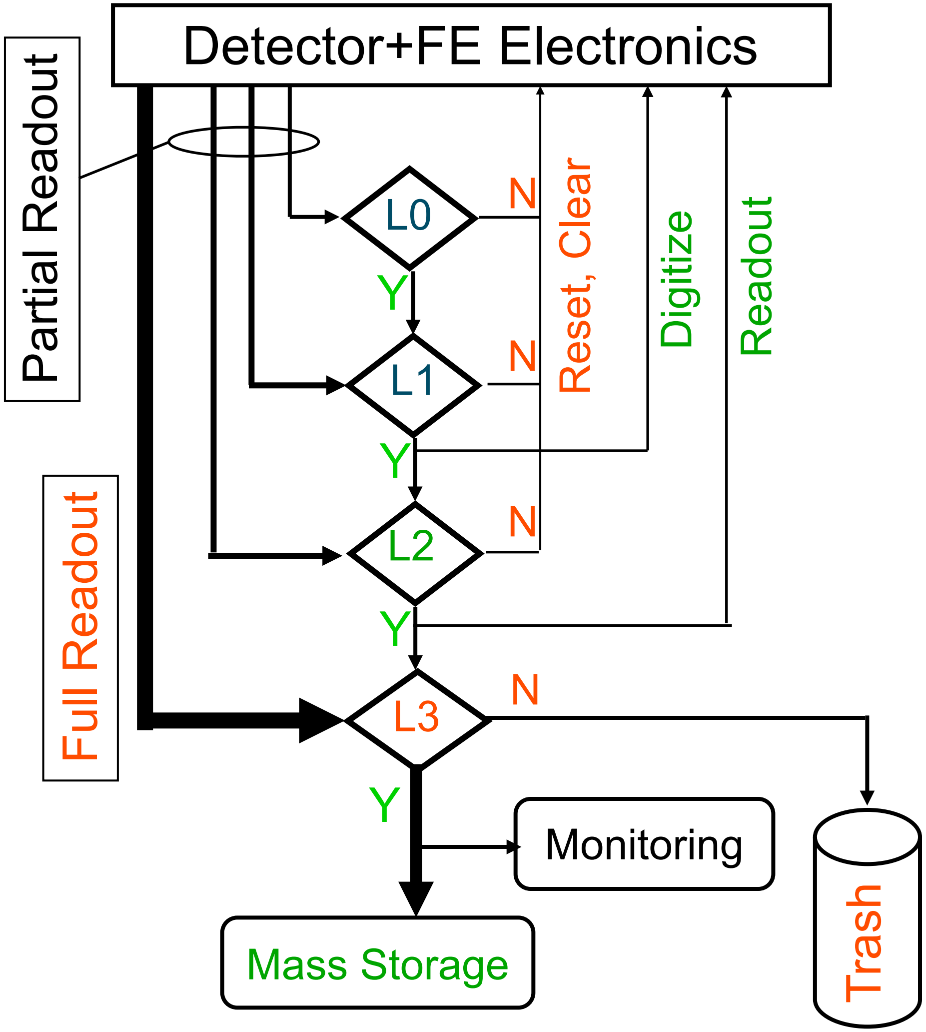

CMS

- 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**

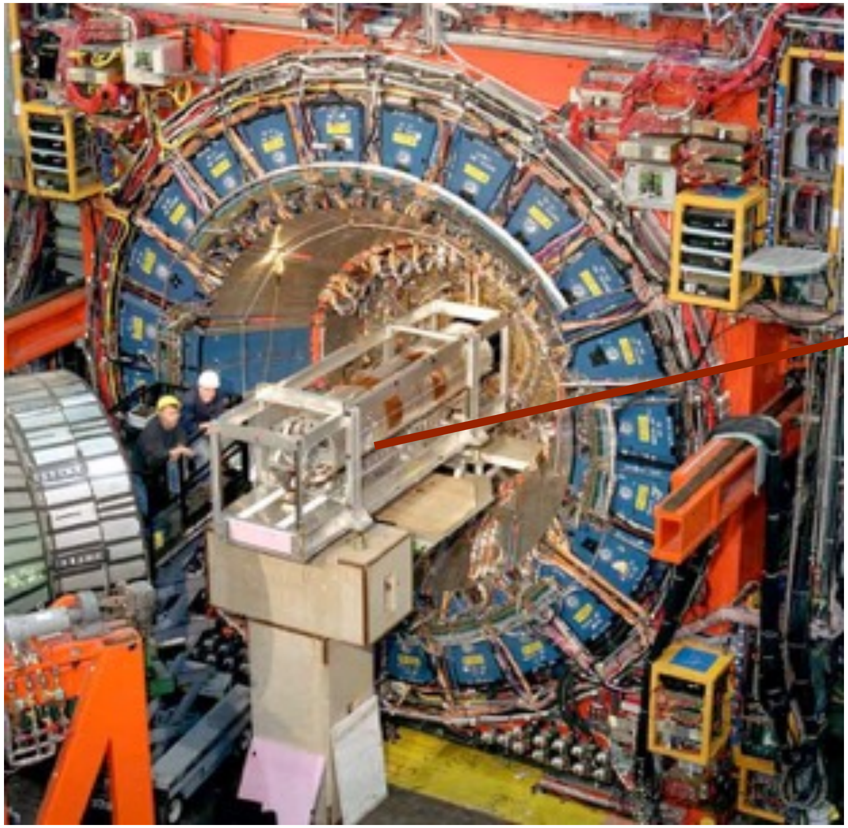
- Can’t achieve necessary rejection in a single triggering stage
- Reject in steps with successively more complete information
  - L0 – very fast (<~bunch x-ing), very simple, usually scint. (TOF or Lumi. Counters)
  - L1 – fast (~few μs) with limited information, hardware
  - L2 – moderately fast (~10s 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)

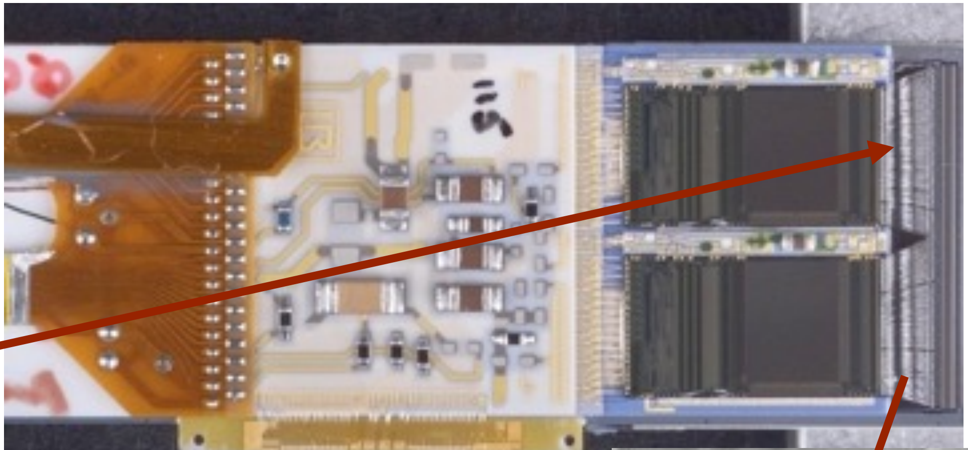


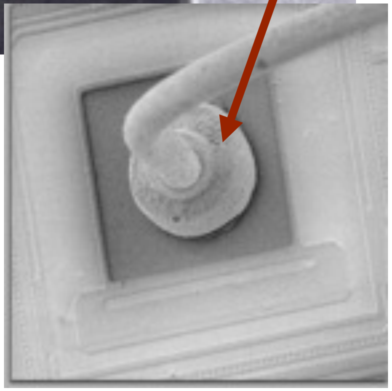
V. REAL LIFE EXAMPLES AND WHAT CAN GO WRONG ...

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) …





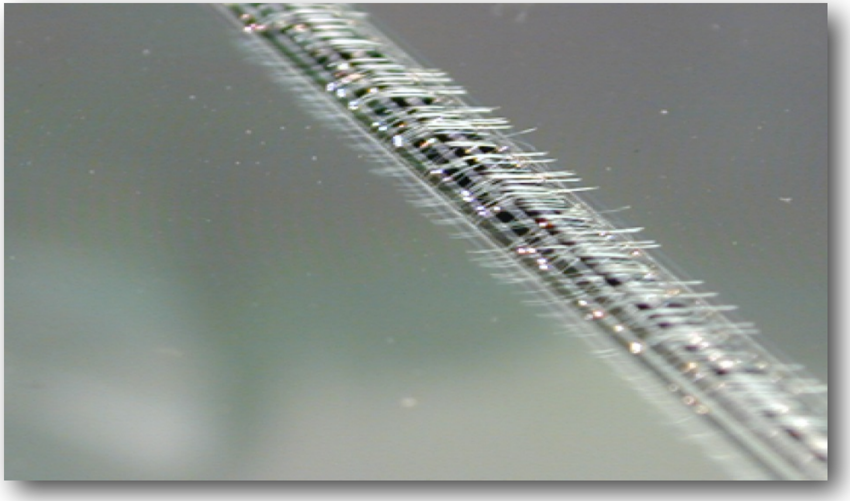


…breaks wire bonds between detector and read out.

during running

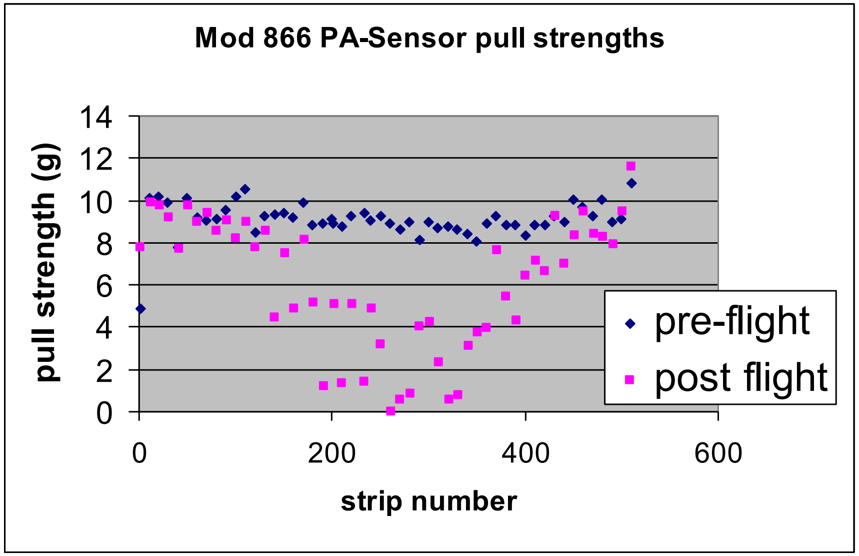
MORE WIRE BOND WRECKAGE

- 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



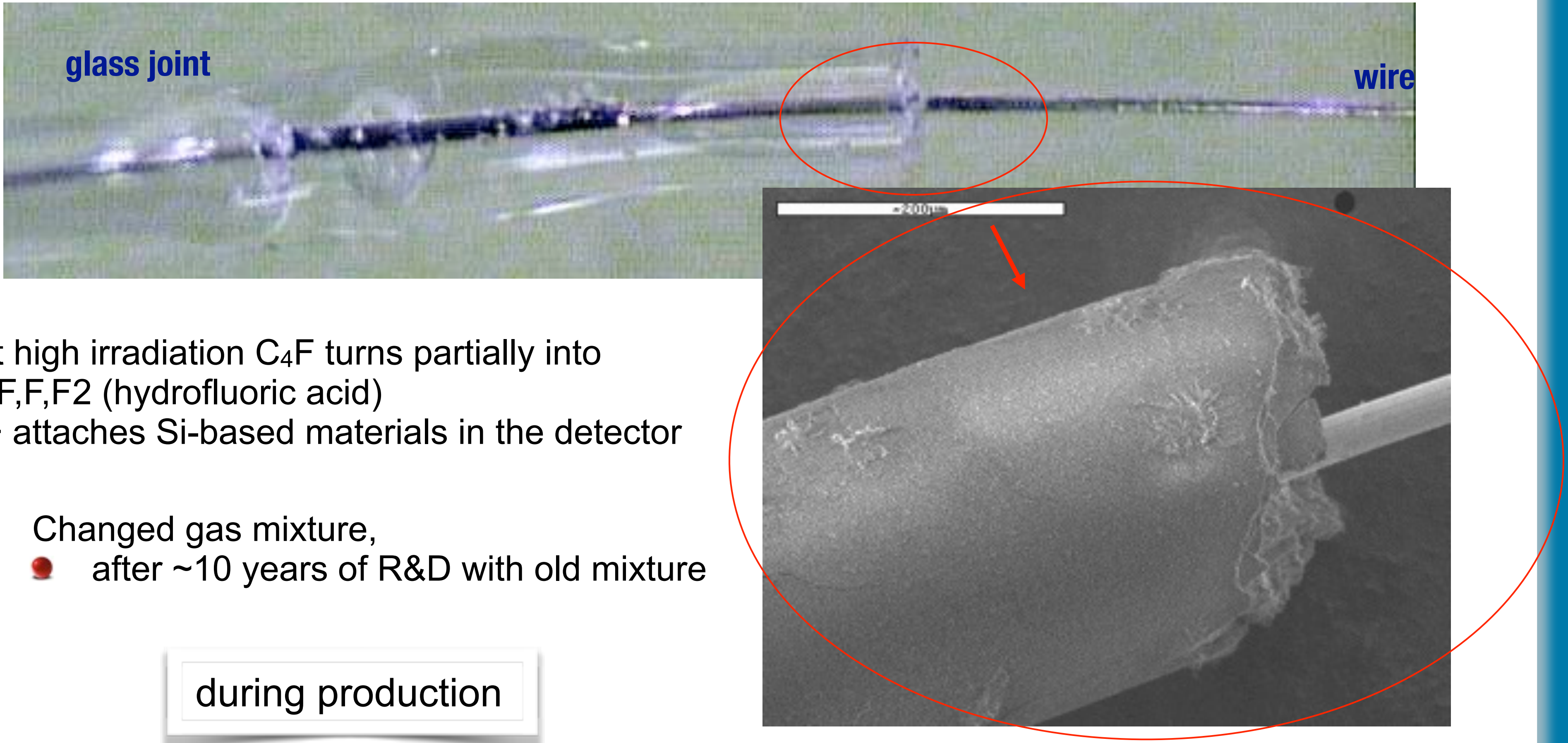
- Problem observed during production -> improved by adding a glue layer
- No further problems during production

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

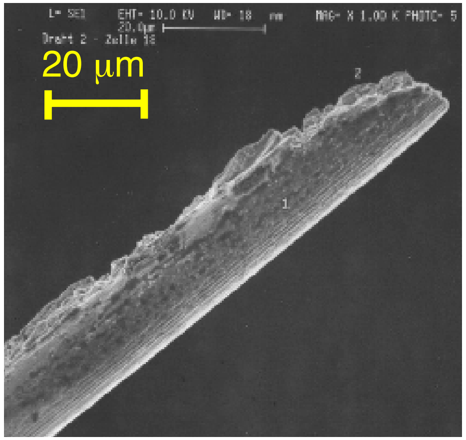
- Changed gas mixture,
  - after ~10 years of R&D with old mixture

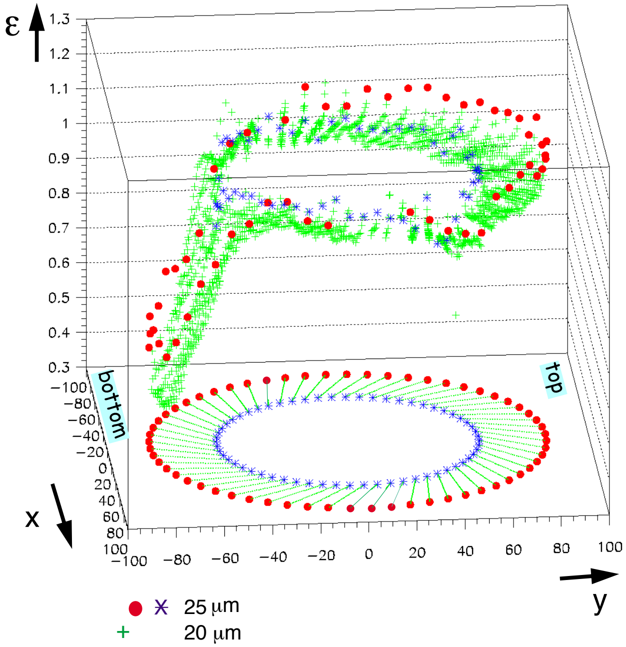
during production

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





- 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

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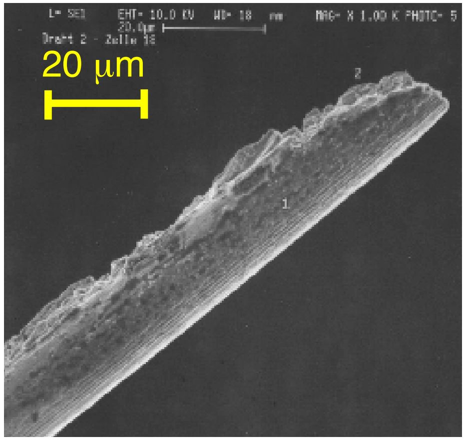

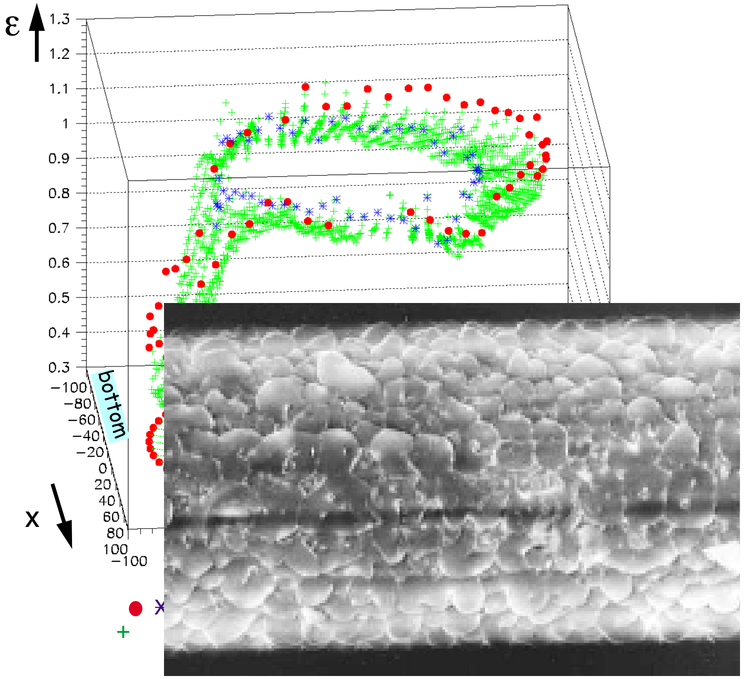

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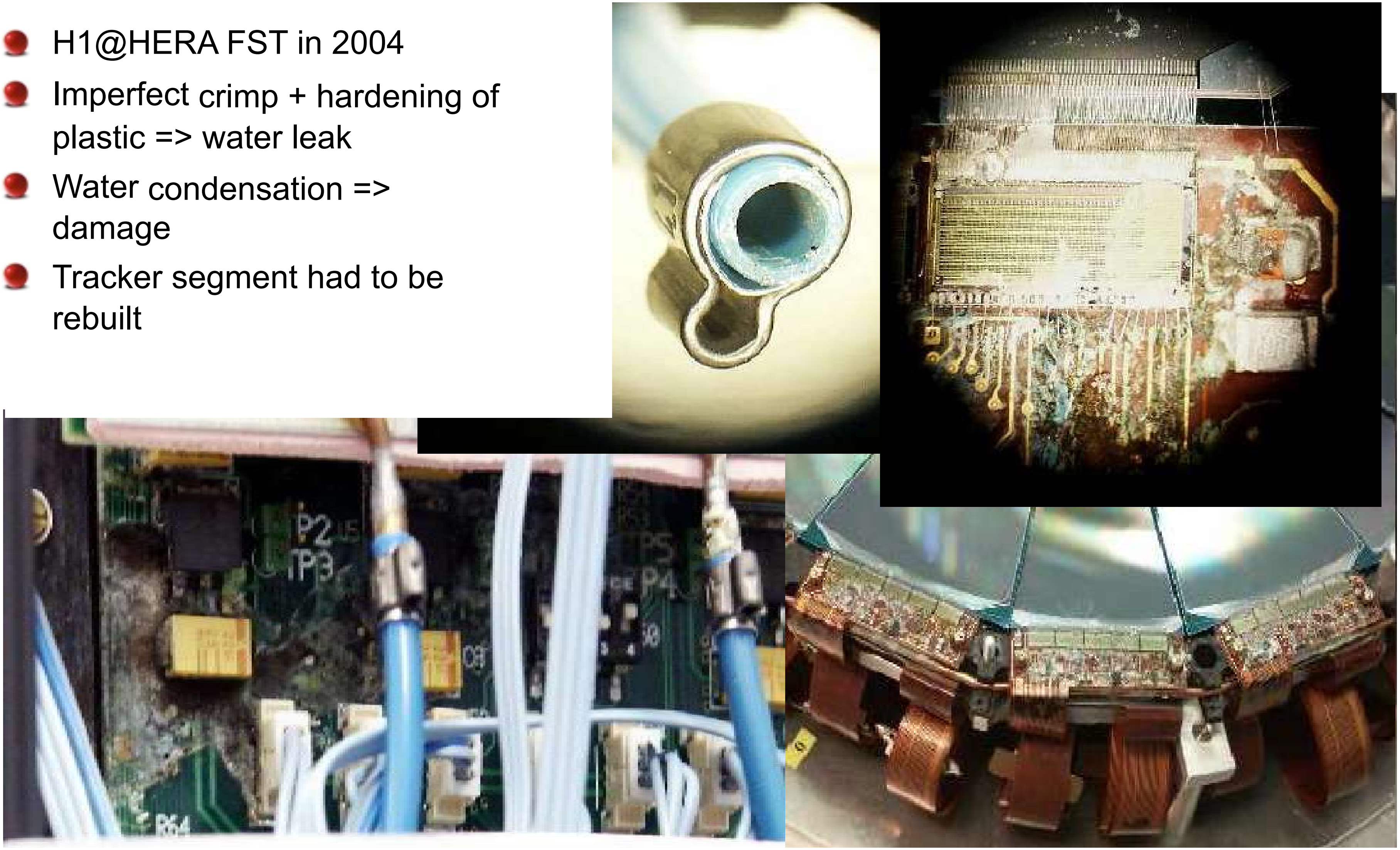
WATER DAMAGE IN TRACKER ...

during running

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

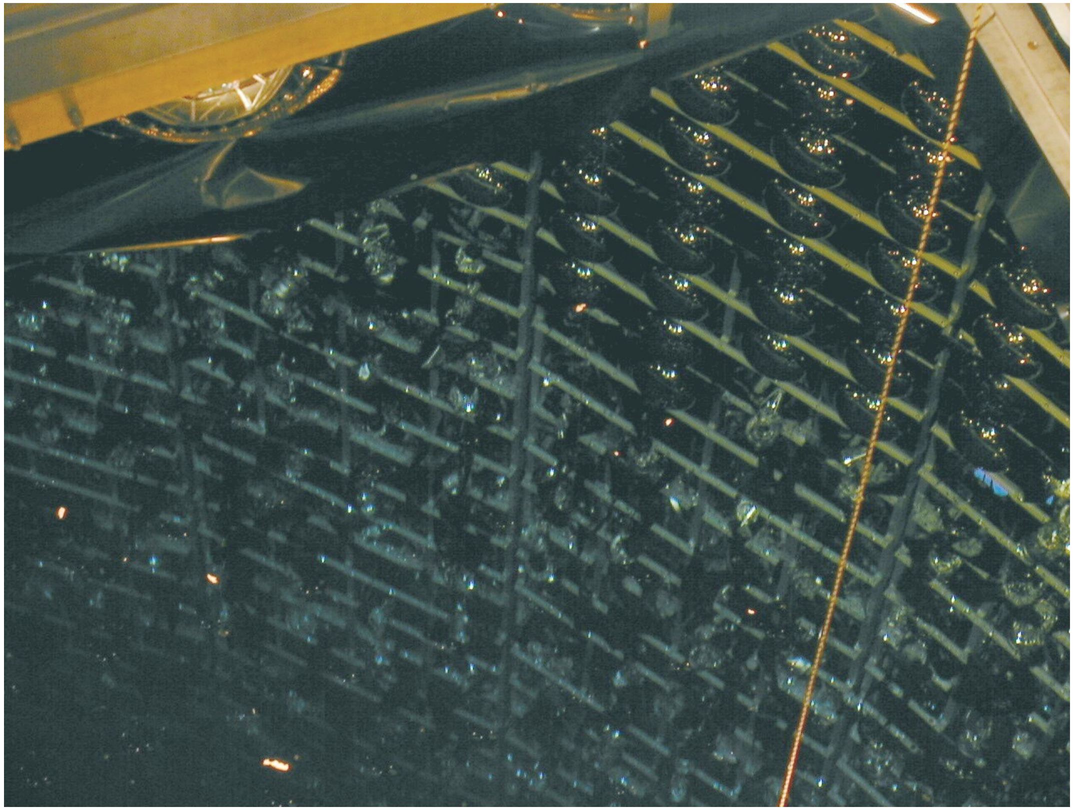


IMPLODED PMTS @ SUPERKAMIOKANDE

- 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.

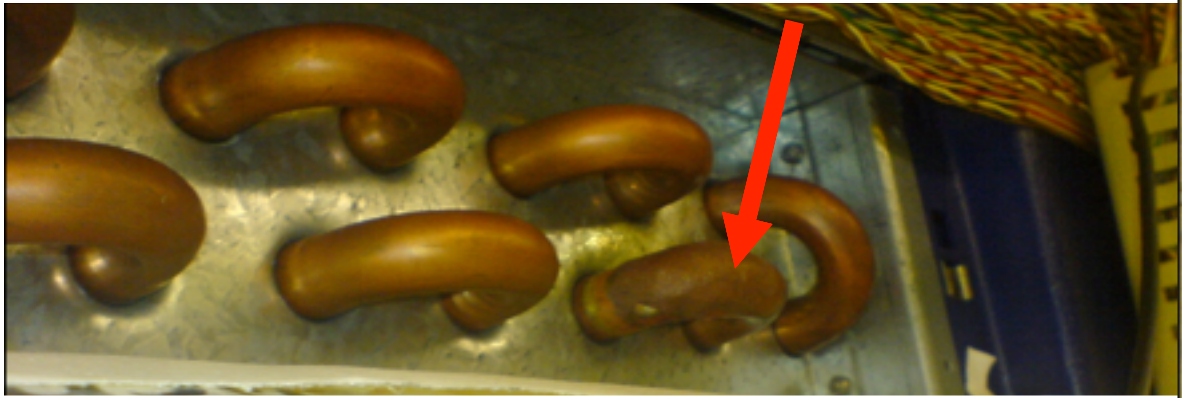
during running

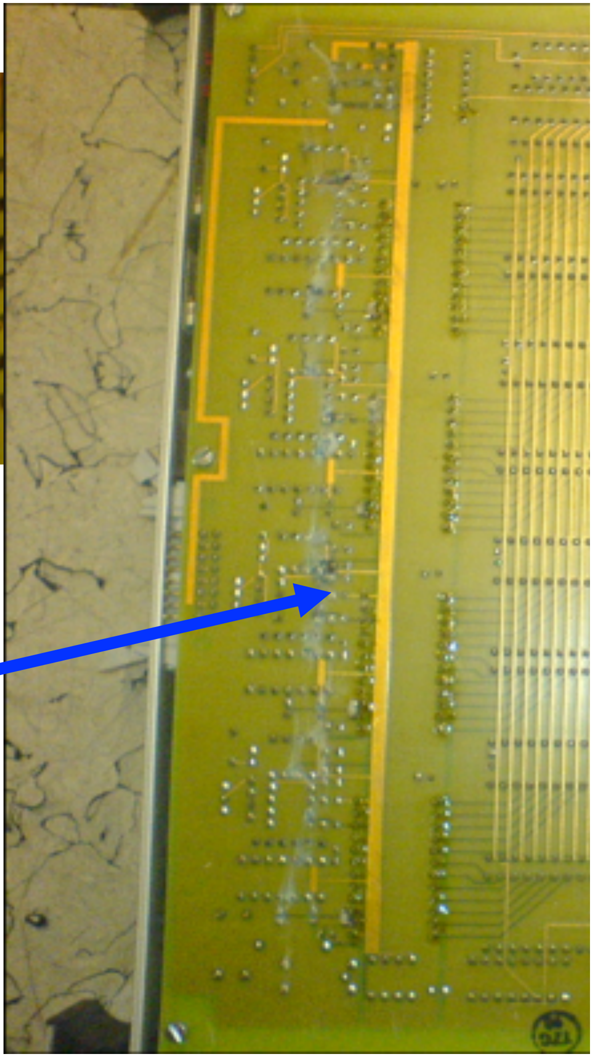


Pic: unknown source….

ZEUS - ONE OF MANY WATER LEAKS

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





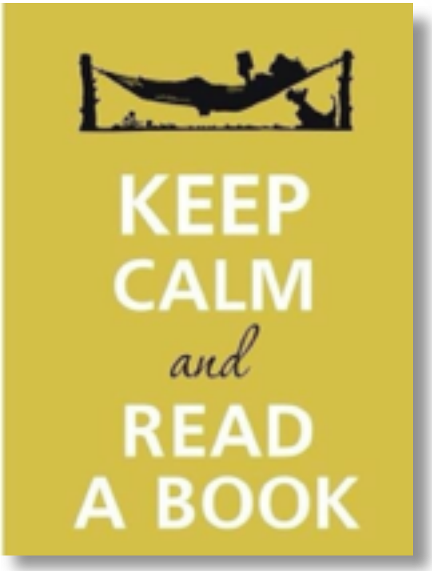
- Micro hole in copper hose led to water in the digital card crates
- Four crates were affected, but only seven cards were really showing traces of water
- Of course this all happened on a Saturday morning at 7am ….

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!**

LITERATURE



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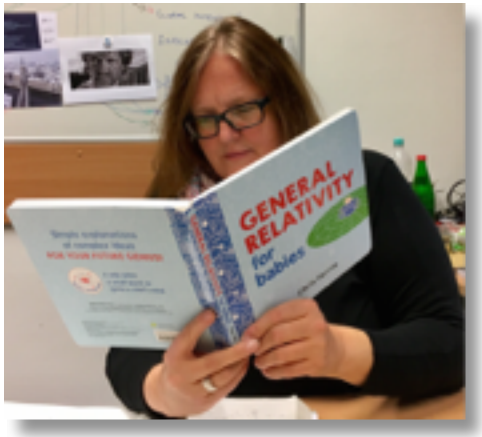
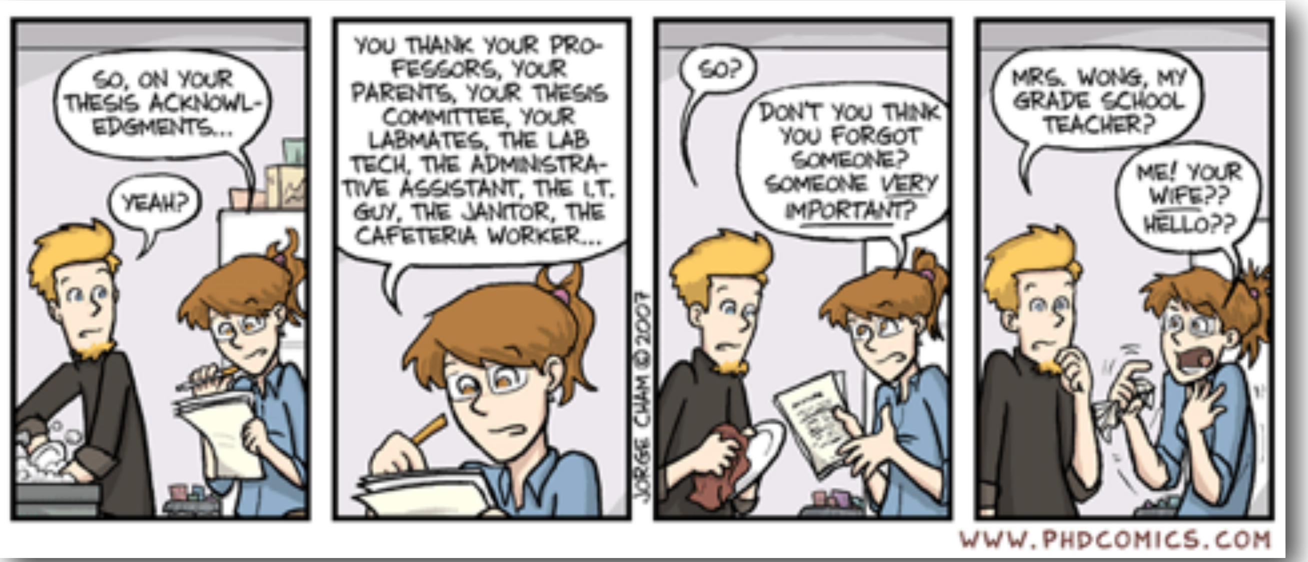


IMPORTANT ....



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Thanks to:

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Jim Virdee

Ulrich Koetz

Carsten Niehbuhr

Christoph Rembser

Marc Winter

Christian Joram

Steinar Stapnes

Doris Eckstein

…freaky husband ;-)

Symphony of Science

Symphony of Science Video
http://www.youtube.com/watch?v=DZGINaRUEkU

SYMPHONY OF SCIENCE

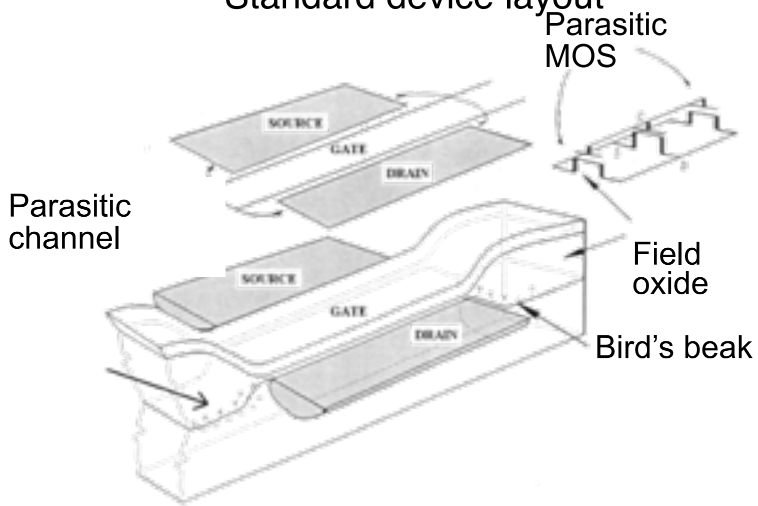
SYMPHONY OF SCIENCE

Radiation effects on CMOS: ionizing

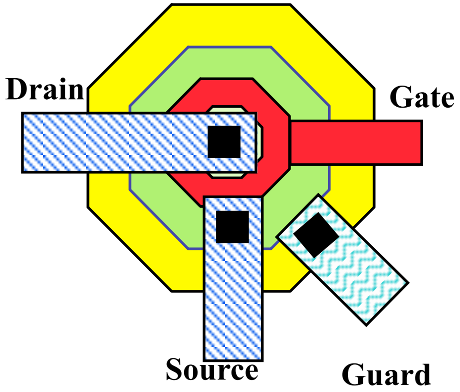
- Decrease of feature size: higher radiation tolerance:
  - Positive charge trapped in gate and field oxides
  - Trapped charge dissipates by tunnelling in thin-oxide transistors

- 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

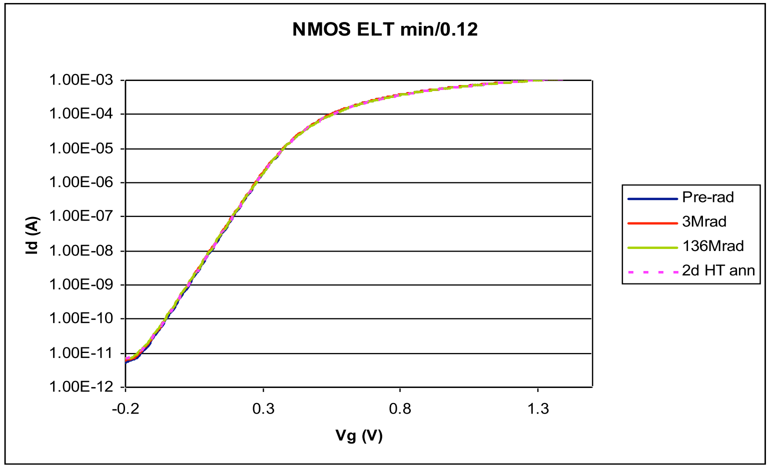
Standard device layout



Enclosed layout



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



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