Detectors for High energy Physics

Part 4

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Overview

I. **Detectors for Particle Physics**

II. **Interaction with Matter**

III. **Calorimeters**

IV. **Tracking Detectors**
- Gas detectors
- Semiconductor trackers
- Muon detectors

V. **Examples from the real life**

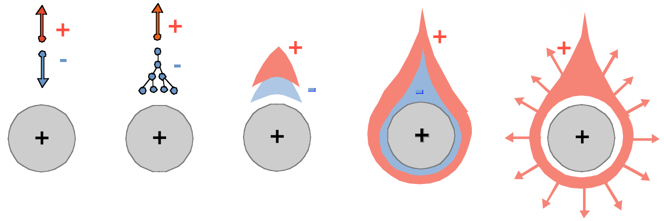
} *Tuesday*

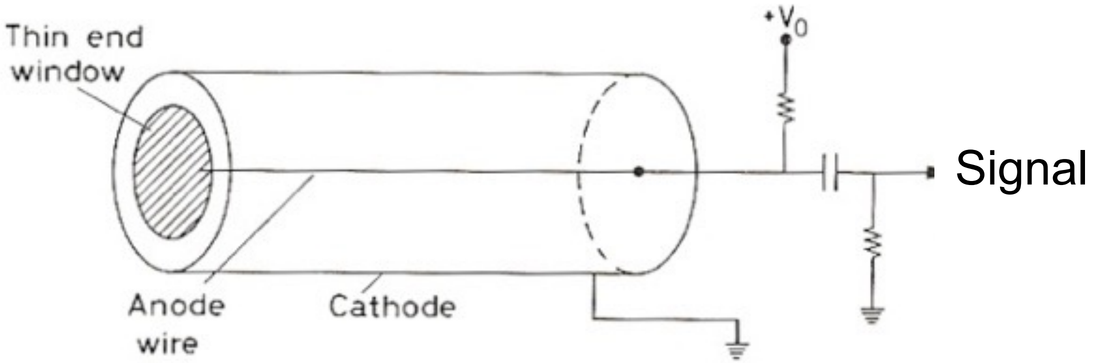
} *Wednesday*

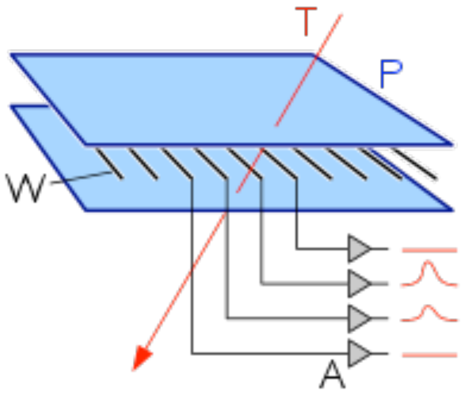
IV.B Gas-Detectors

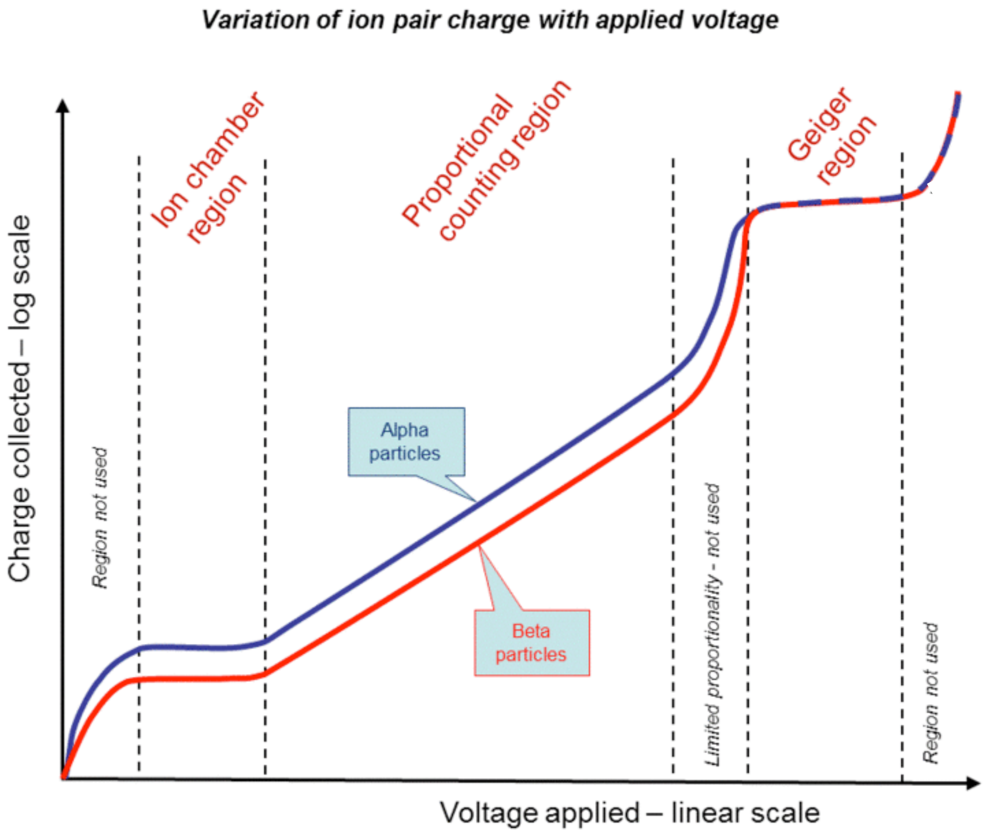
Another Classic: Ionisation Chamber

- Passage of particles creates within the gas volume electron-ion pair (ionisation)
- Electrons are accelerated in a strong electric field -> amplification
- The signal is proportional to the original deposited charge or is saturated (depending on the voltage)



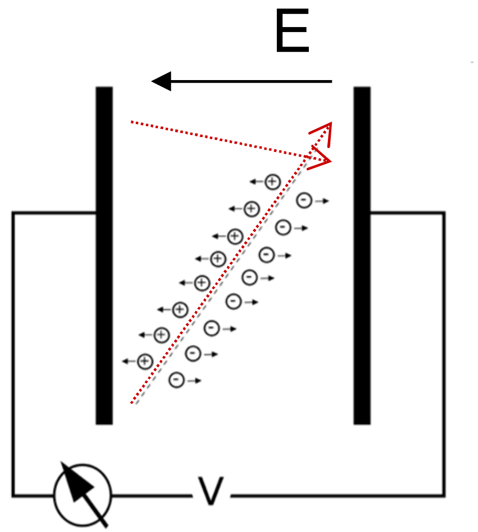






By Doug Sim - https://commons.wikimedia.org/w/index.php?curid=19789442

Proportional Chamber

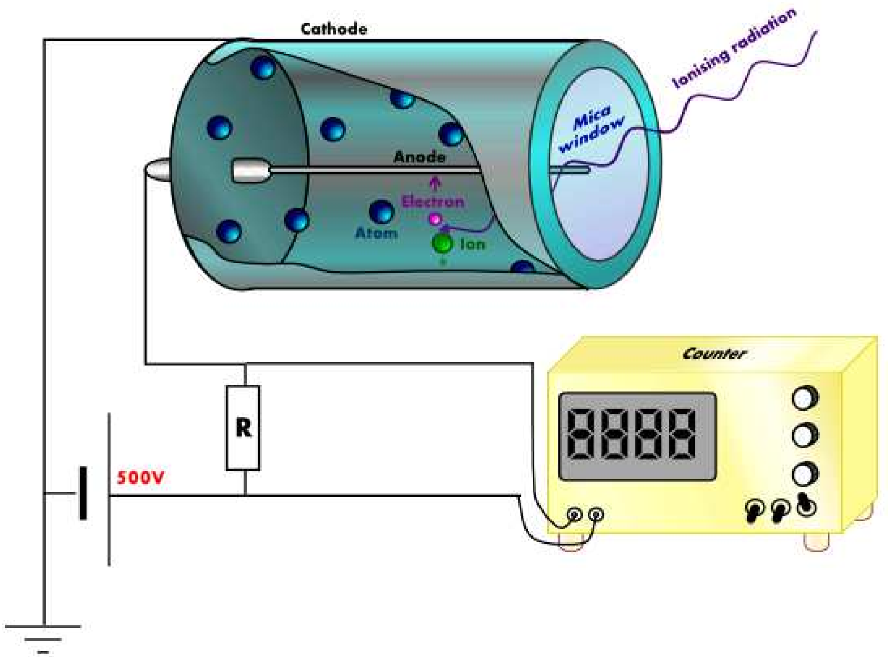


Disadvantage of planar design:

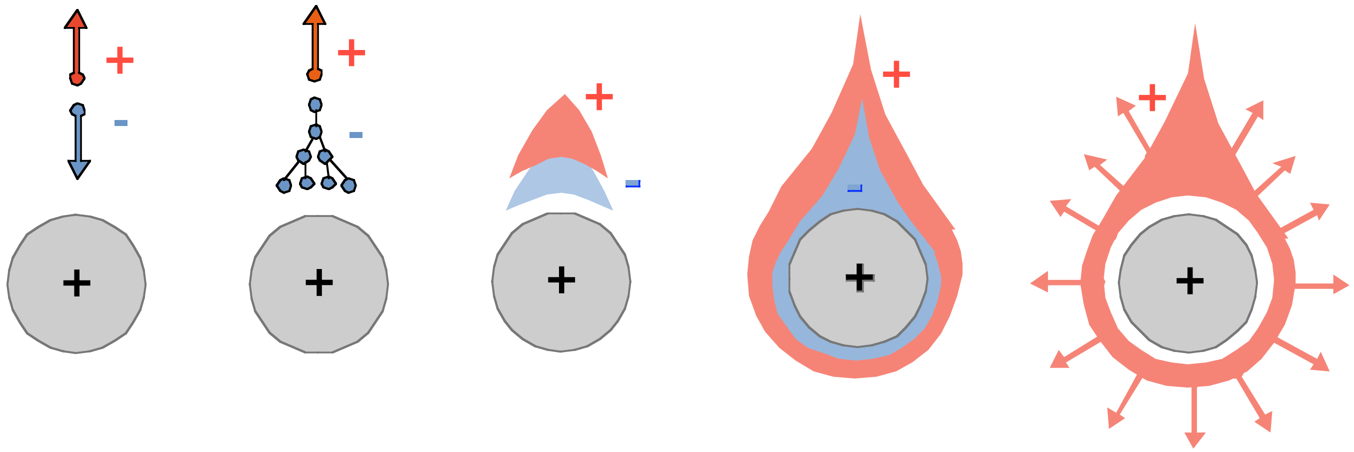
- E uniform and ⊥ to the electrodes:
- amount of ionisation produced proportional to path length and to position where the ionisation occurs
  -> not proportional to energy

Problem solved using **Cylindrical proportional counter:**

- Single anode wire in a cylindrical cathode
- E~1/r: weak field far from the wire electrons/ions drift in the volume multiplication occurs only near the anode



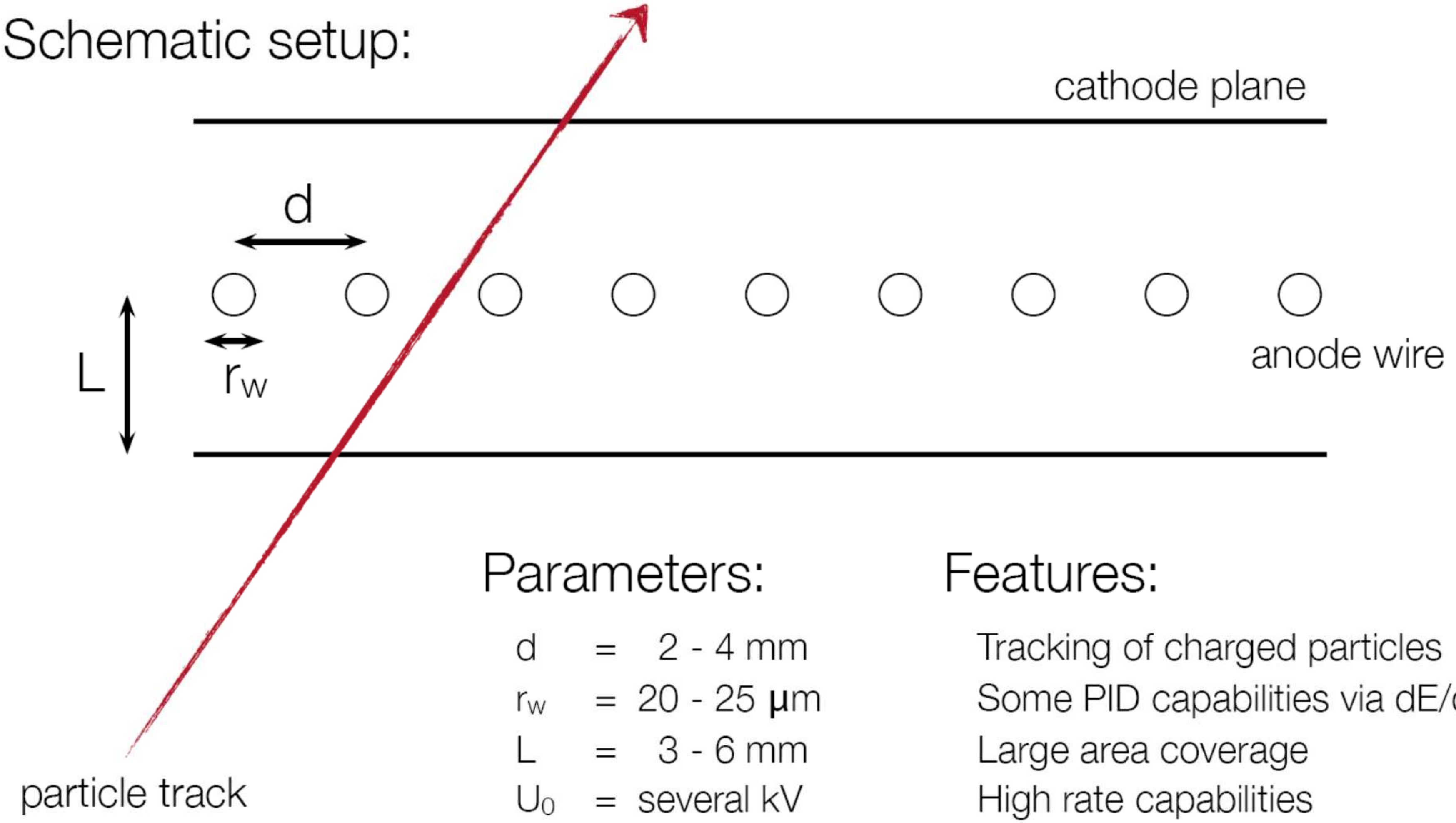
Time Development of the Signal



- The signal on the electrodes is **induced by the movement of ions and electrons as they drift towards the cathode and anode** respectively rather than by collection of charge a the electrodes
- The electrons are collected very fast (in ~1ns) while drifting over the few mm drift distance, while the positive ions drift slowly towards the cathode.
- It is the **ion drift** which determines the time development and the size of the induced signal. The electrons induce very little signal.

Multi-Wire-Proportional Chamber

Schematic setup:



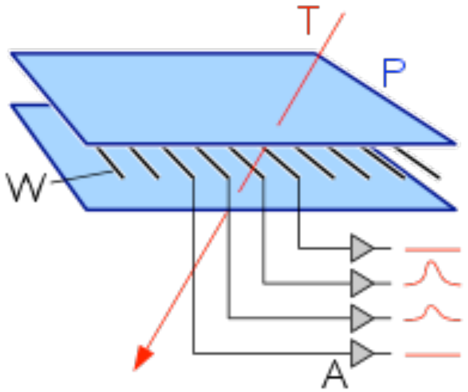
Parameters:

- d = 2 - 4 mm
- r_w = 20 - 25 μm
- L = 3 - 6 mm
- U_0 = several kV
- Total area: $O(m^2)$

Features:

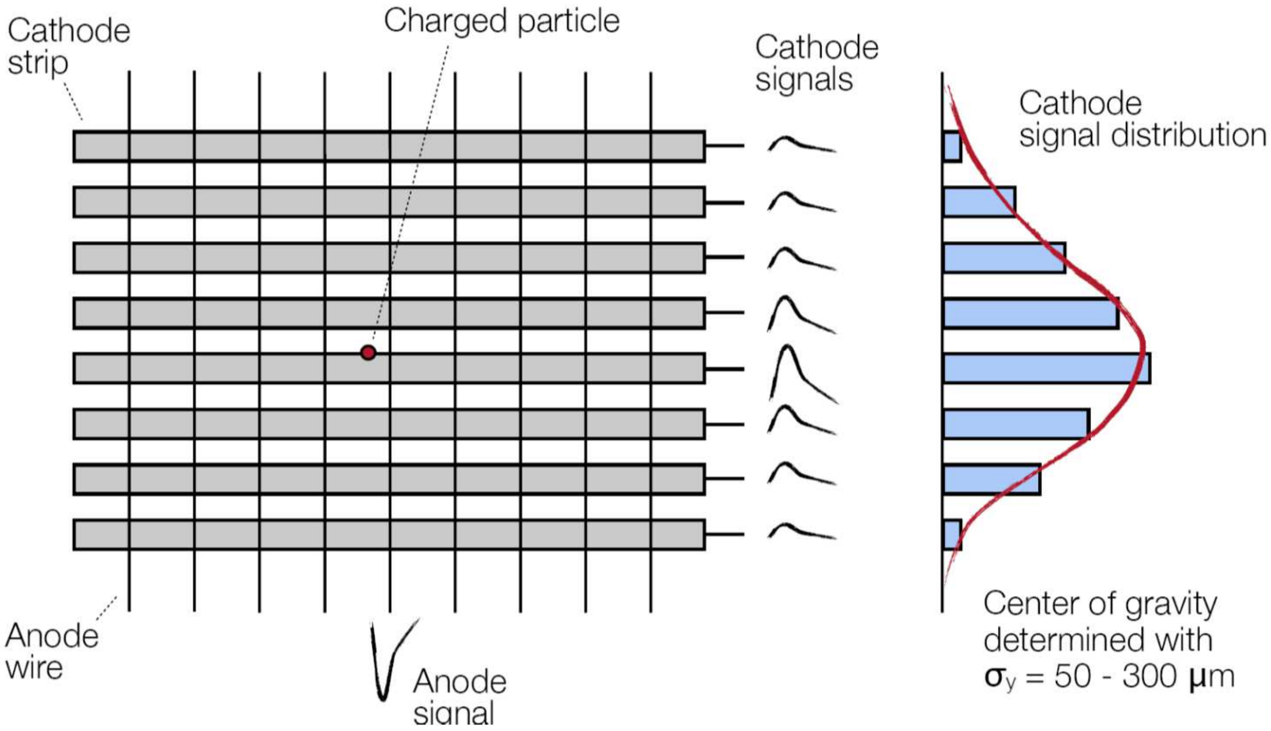
- Tracking of charged particles
- Some PID capabilities via dE/dx
- Large area coverage
- High rate capabilities

Signal in MWPC



Signal generation:

- Electrons drift to closest wire
- Gas amplification near wire ➛ avalanche Signal generation due to electrons and mainly slow ions

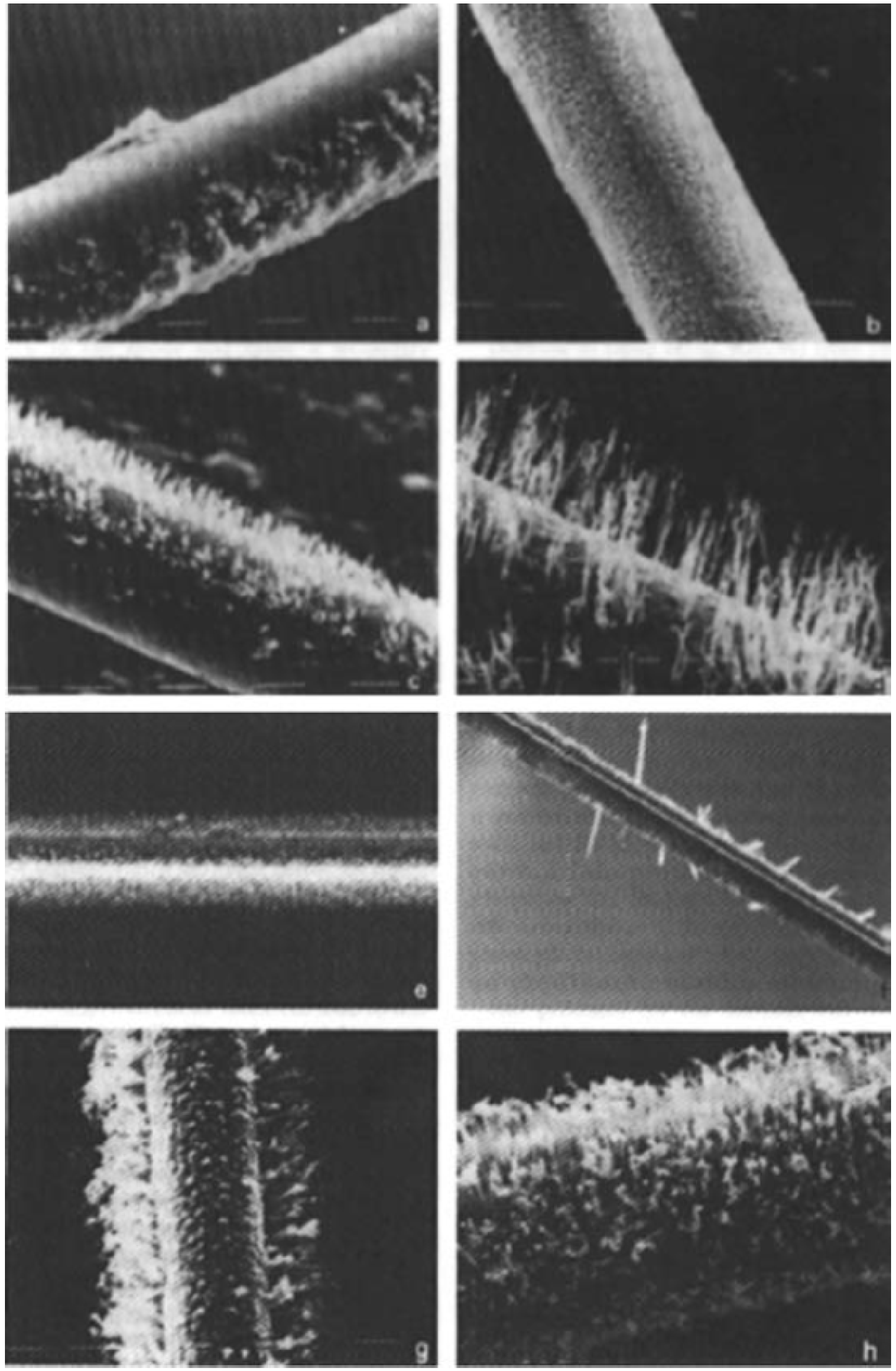


- Only information about closest wire ➛ $\sigma_x = d/\sqrt{12}$
  [Only one dimension information]
- **Possible improvements:** - segmented cathode
  - 2-dim.: use 2 MWPCs with different orientation
  - 3-dim.: several layers of such X-Y-MWPC combinations [tracking]

Ageing in wire chambers

- Avalanche formation can be considered as micro plasma discharge.
- Consequence:
  - Formation of radical i.e. molecular fragments
  - Polymerisation yield long chains of molecules
  - Polymers may be attached to the electrodes
  - Reduction of gas amplification

- Important: Avoid unnecessary contamination such as
  - Halogens or halogen compounds
  - Silicon compounds
  - Carbonates, halocarbons
  - Polymers
  - Oil, fat ….



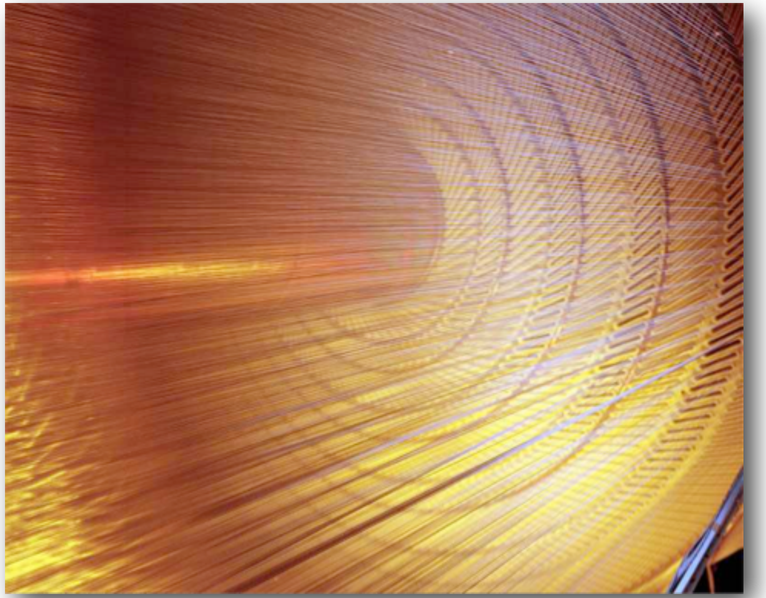
Adding Time: Drift Chamber

- Alternative way to obtain spatial information: measure the electrons drift time:
  - time measurement started by an external (fast) detector, i.e. scintillator counter
  - electrons drift to the anode (sense wire), in the field created by the cathodes with constant velocity
  - the electron arrival at the anode stops the time measurement
  - one-coordinate measurement:

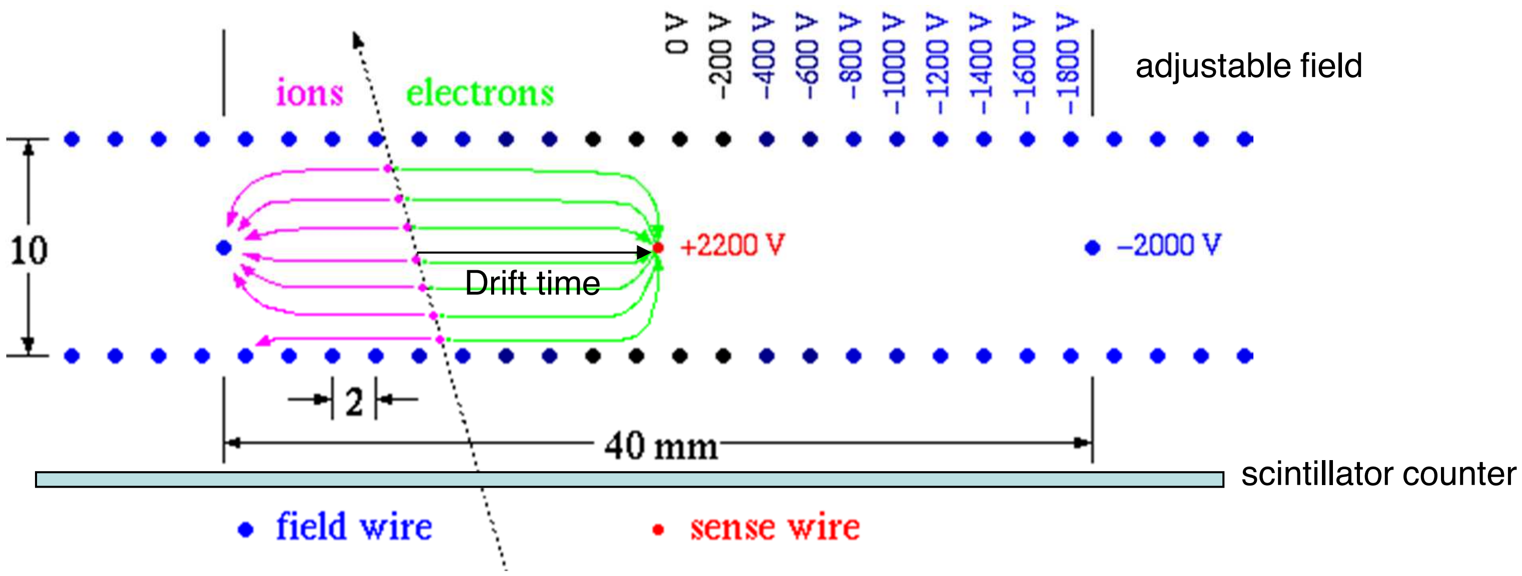
$$x = \int_0^{t_D} v_D \, dt$$

velocity $\vec{v}_D = \mu_{\pm} |\vec{E}|$

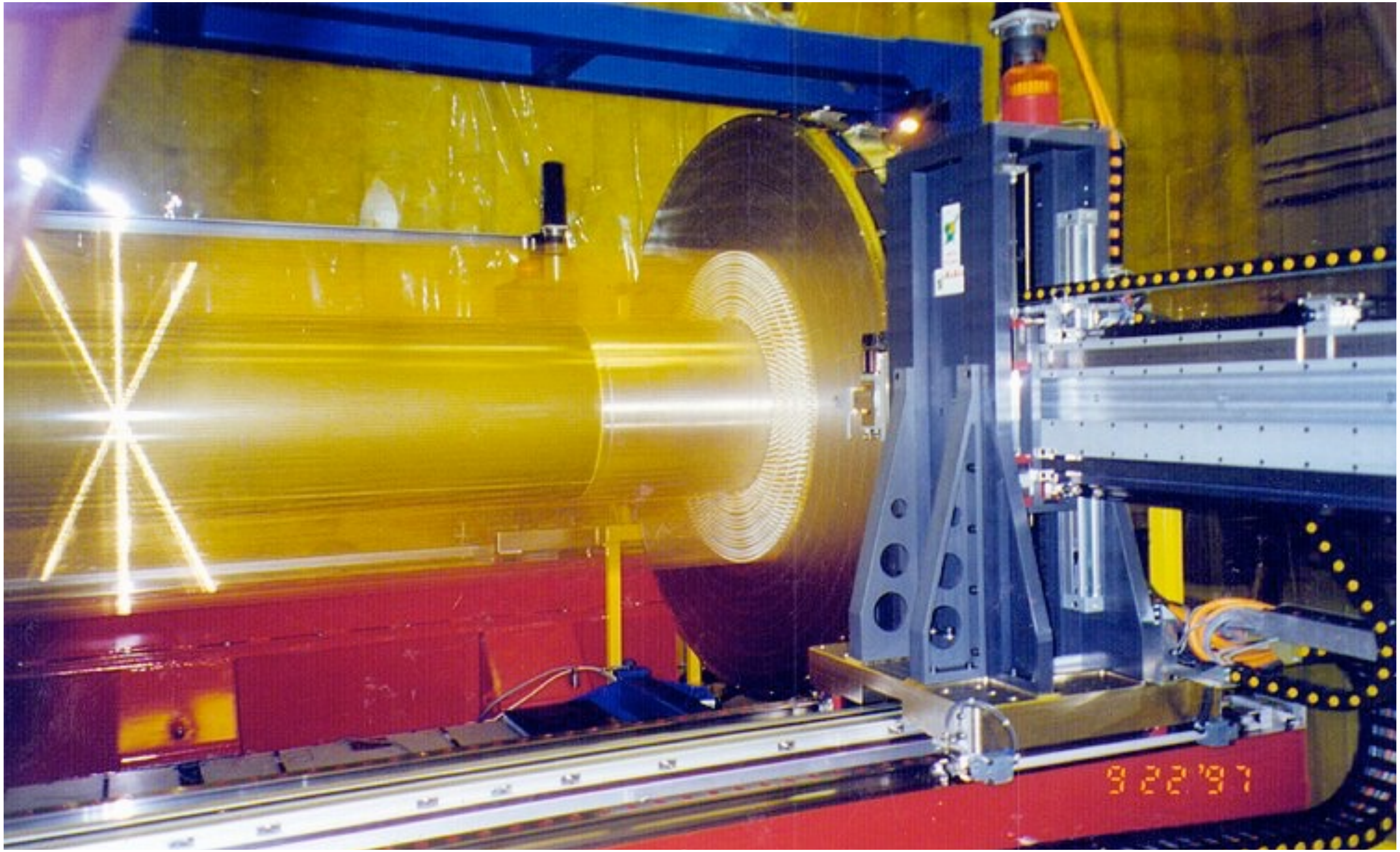
μ_{+} mobility



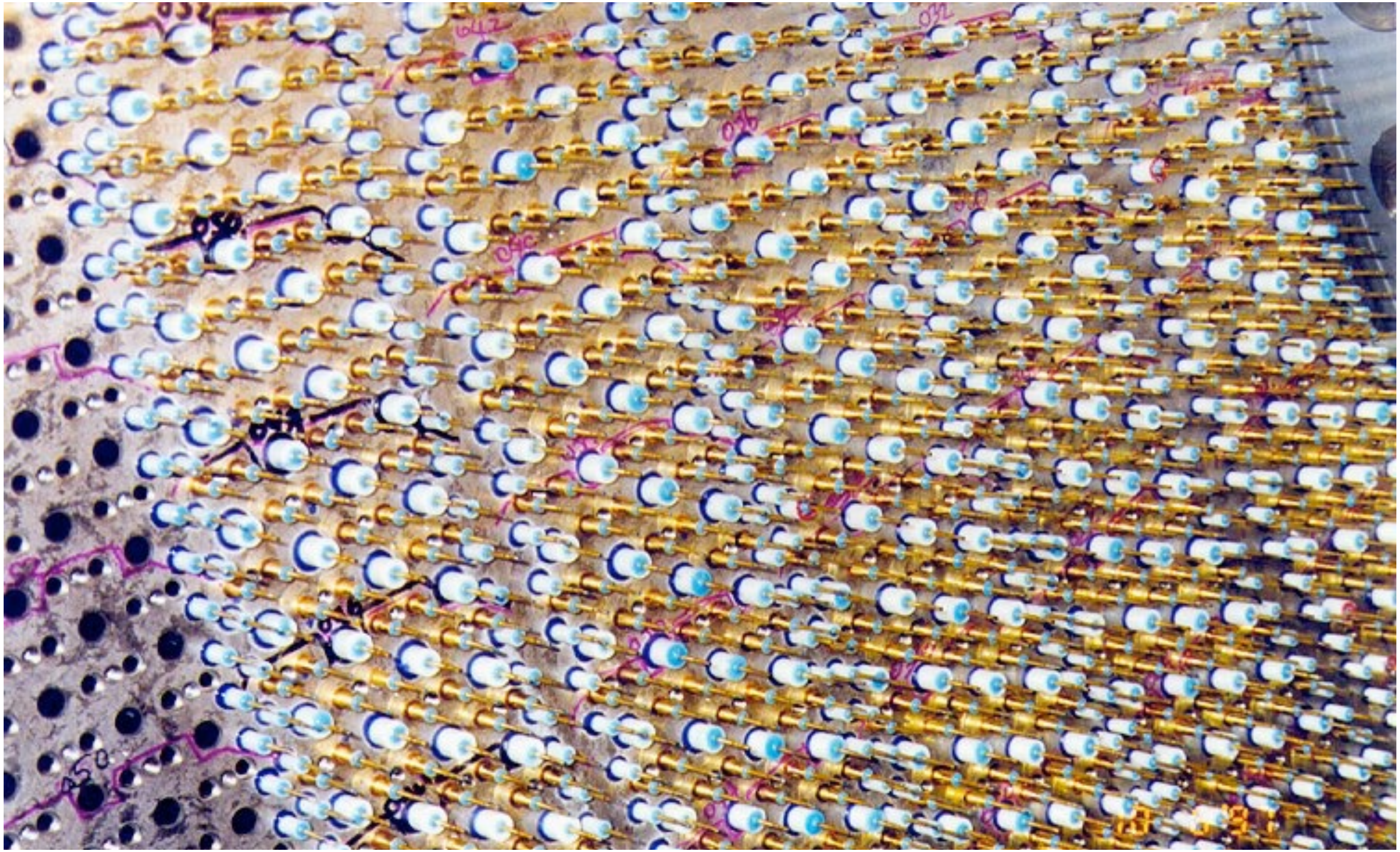
Wire chamber CDF (@Tevatron)



Wire Stringing In Progress



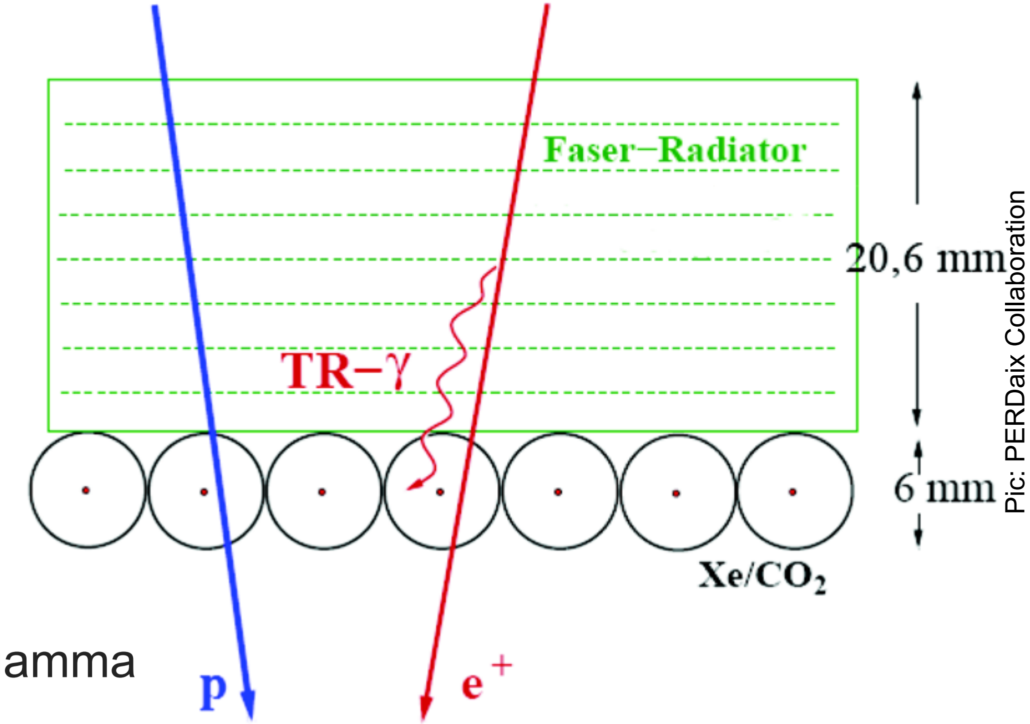
End Plate Close Up



Transition Radiation

Transition Radiation

- Produced by relativistic charged particles when they cross the interface of two media of different refraction indices
- Can be explained by re-arrangement of electric field



Pic: PERDaix Collaboration

- Energy loss at a boundary is proportional to the relativistic gamma factor.
- A significant amount of transition radiation is produced for a gamma greater then 1000.
- Gamma factor of protons is, up to a momentum of 5GeV, still in the order of 10.
- Positron's gamma is greater than 1000 starting at 0.5GeV momentum.

$$I \propto m\gamma = \frac{1}{\sqrt{(1-\beta^2)}}$$

=> particle identification

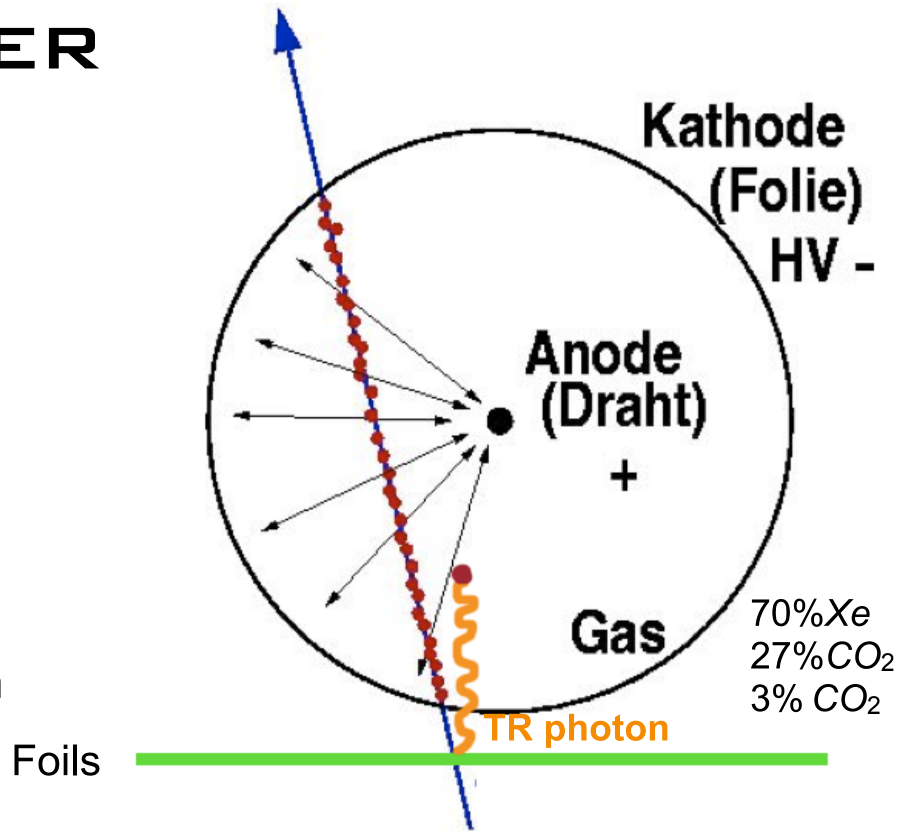
Transition radiation tracker

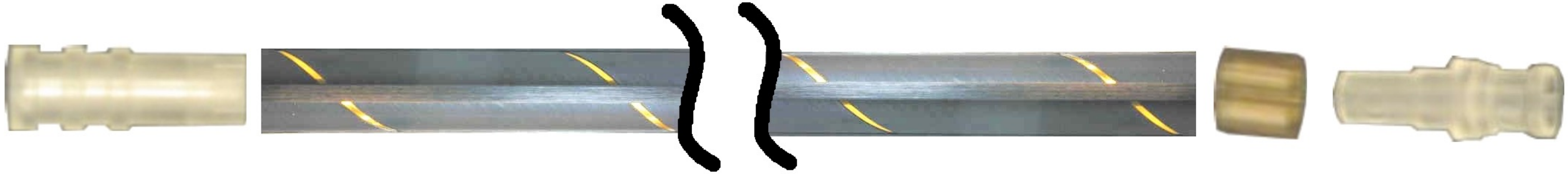
Signal formation

- charged particles ionize the gas
- electrons drift towards the wire
- gas amplification avalanche
- first arrival determines drift time

Signal readout

- signal gets amplified
- sampled in 24 time bins of 3.12 ns
- each time bin compared against threshold (≈ 300 eV): 24-bit pattern
- buffered in 6-μs readout pipeline
- passed on to central ATLAS DAQ

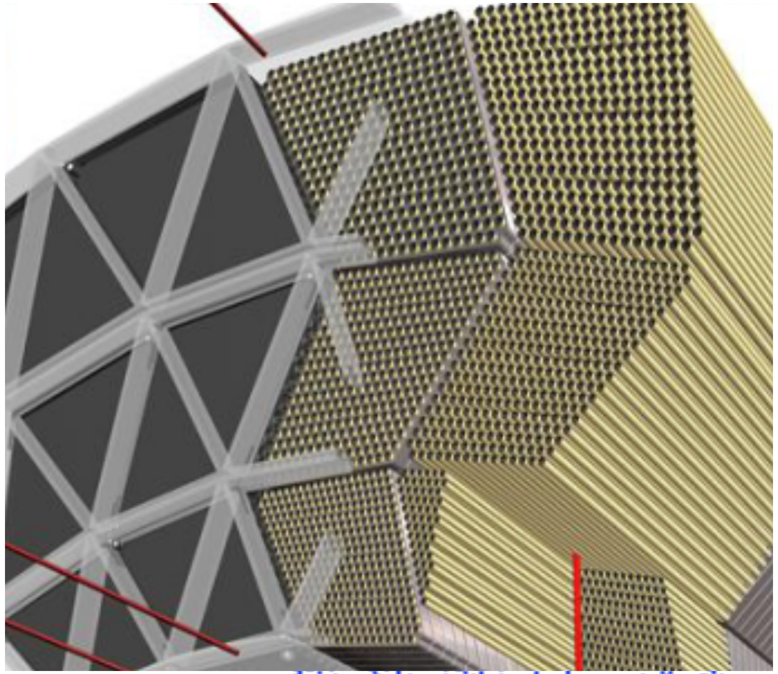


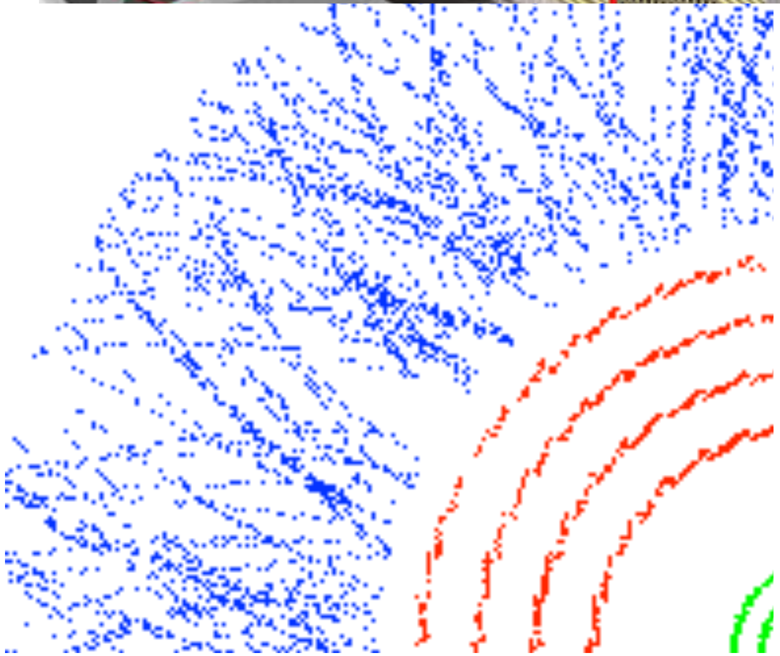


allows self supporting structures

ATLAS TRT

- Many thin radiator fibres/foils increase emission probability
- Xenon gas acts as X-ray absorber
- Ternary readout electronics register high-threshold hits (6 keV) sampled in 25-ns time bins





TRT Barrel

- longitudinal straws of 1.5 m length
- three layers of 32 modules each, 52 544 straws
- wires electrically split, read out on both sides
- ranging from r = 0.5 m to r = 1.1 m, covering $|\eta| < 1$

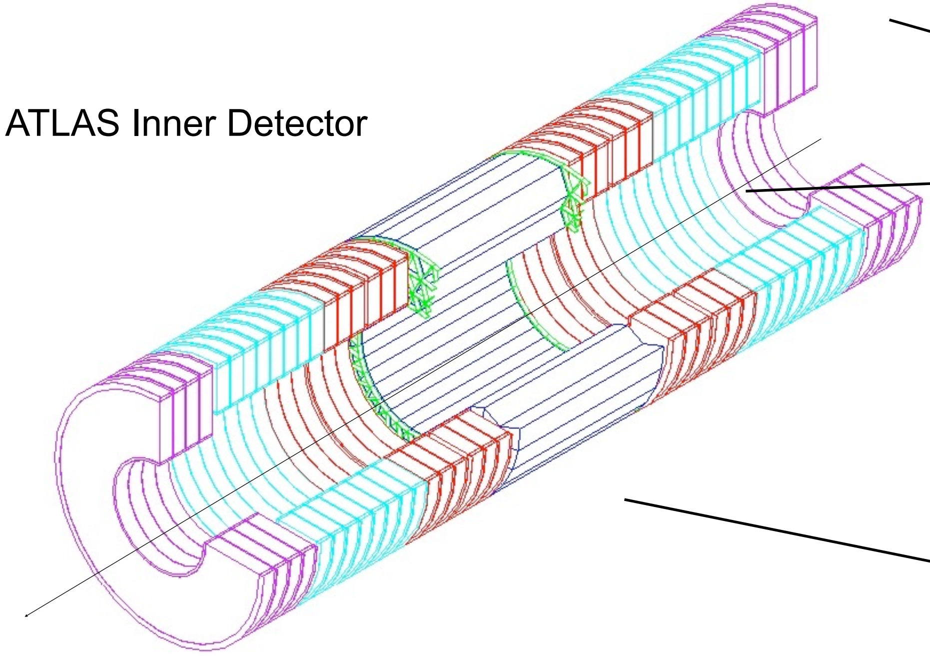
TRT Endcap A and C

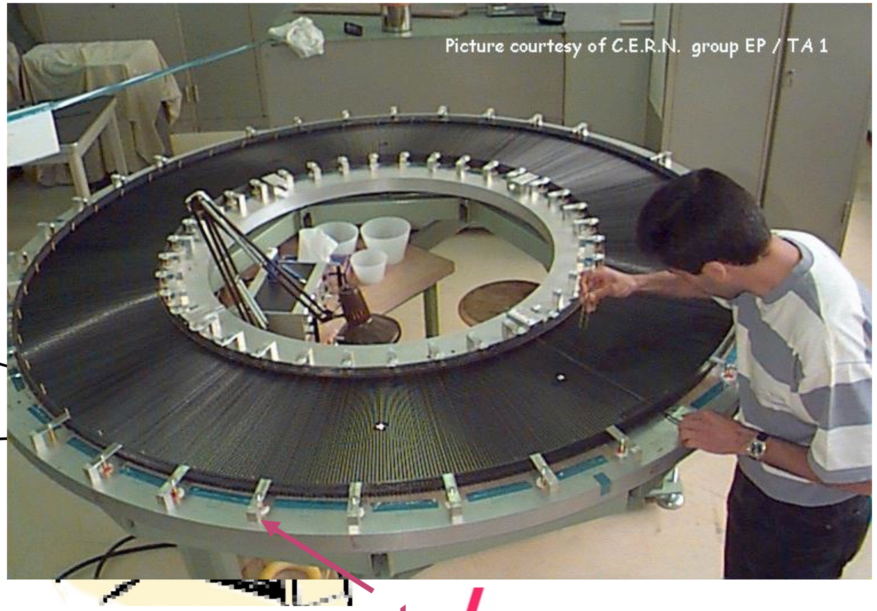
- radial straws of 0.4 m length
- 8 inner wheels, 12 outer wheels per side, 122 880 straws
- wires read out at their outer end
- ranging from $|z| = 0.8$ m to $|z| = 2.7$ m, covering $1 < |\eta| < 2$

A Stack of Straws

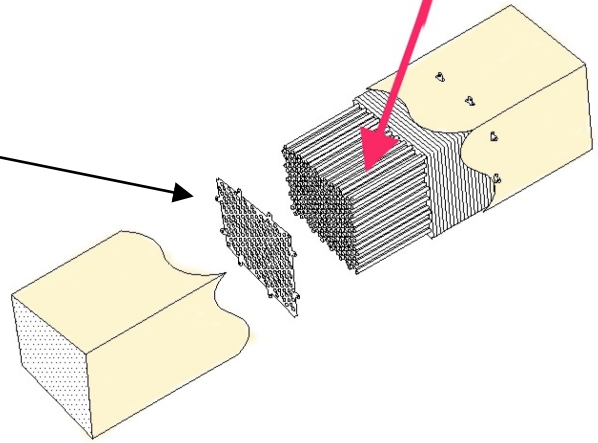
Endcap (~32000 straws)
radial from beam axis

ATLAS Inner Detector



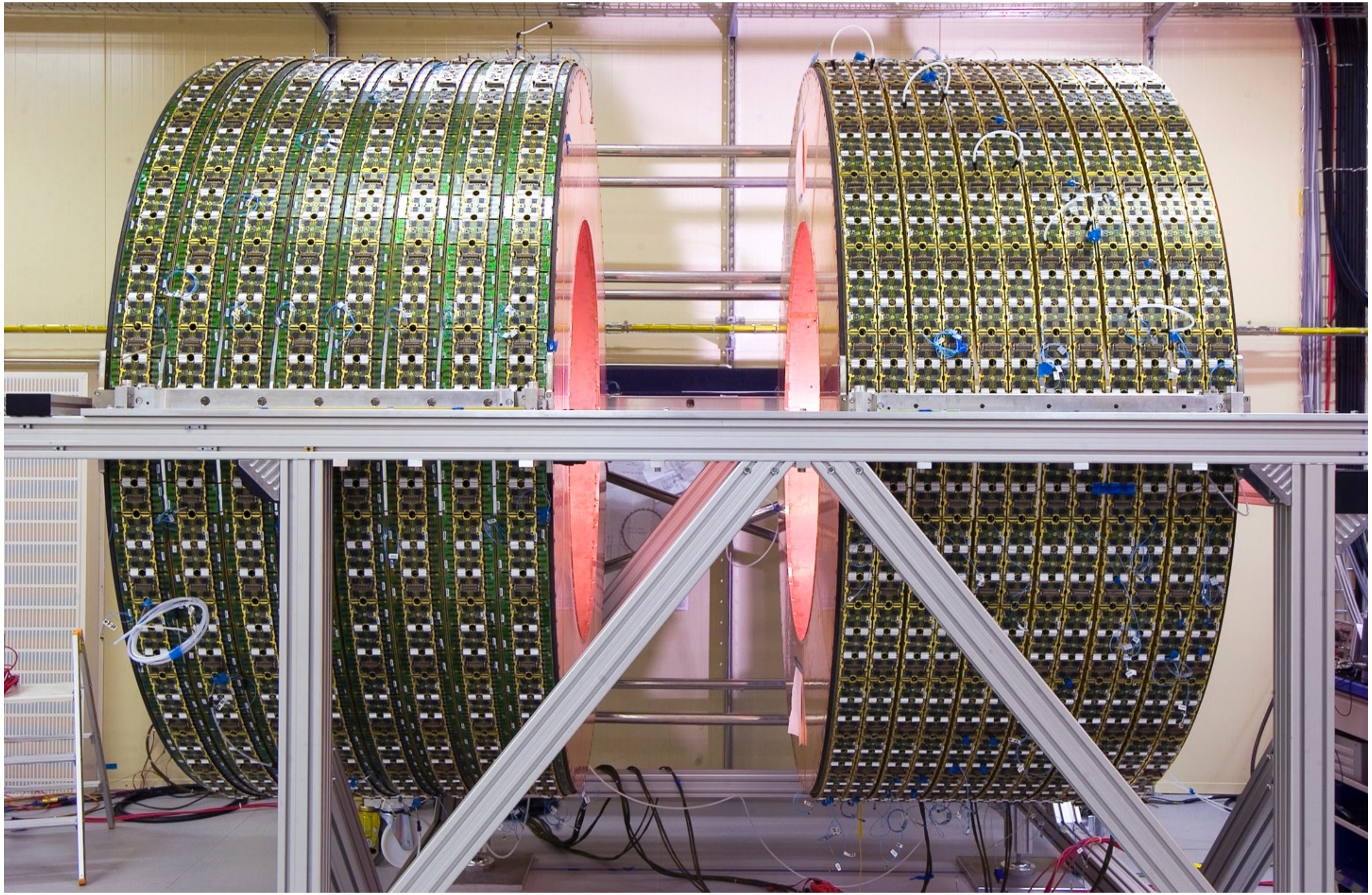


straws



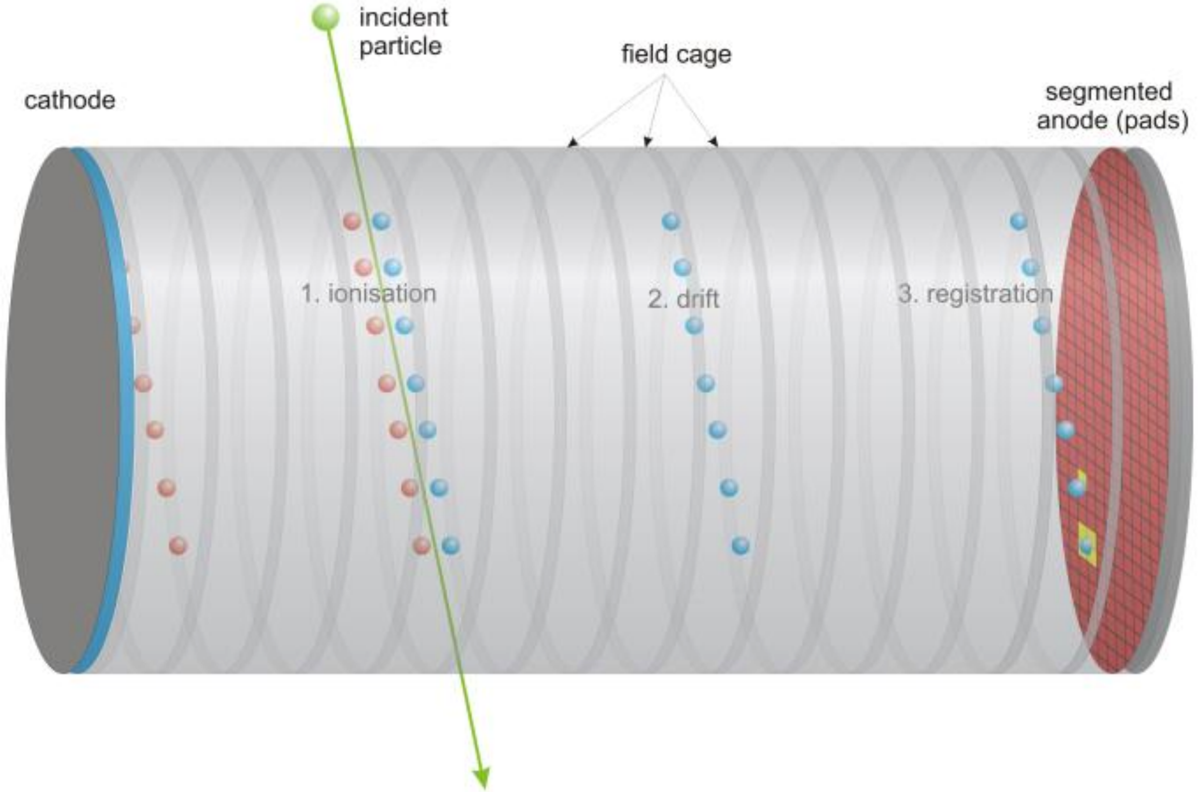
Barrel (~10000 straws)
parallel to beam axis

The First ATLAS TRT End-Cap (3 Aug 2005)

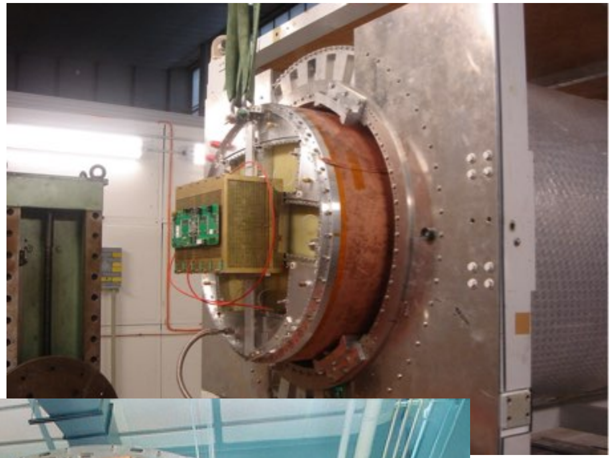


TPC- Time Projection Chamber: 3D

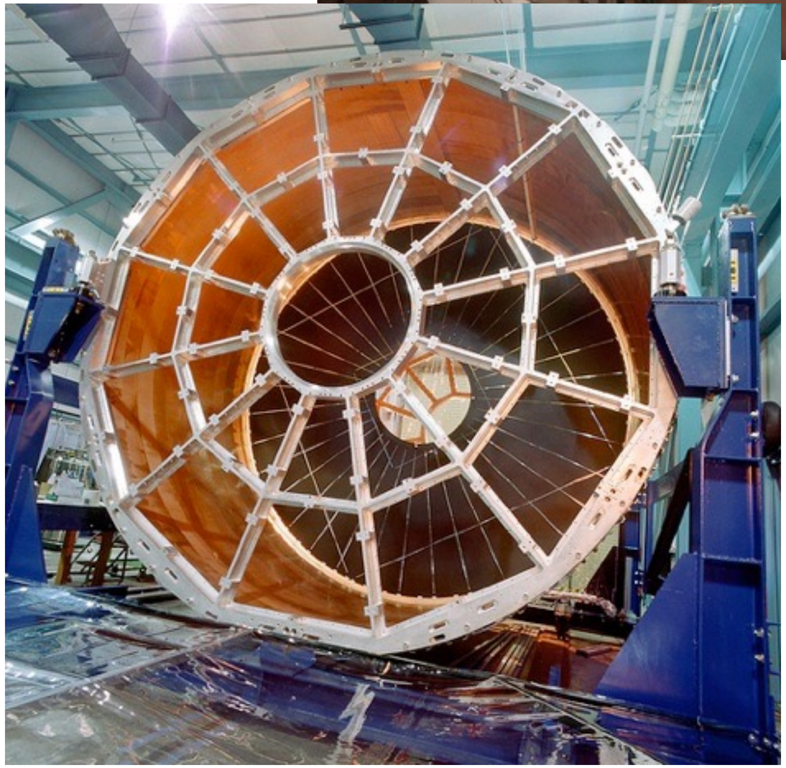
- Combination of the the 2D track information and the time results in a real 3D point



Pic: O. Schäfer



Pic: DESY



Pic: ALICE Collaboration

- Readout of the anode usually with multi wire projection chambers
- Nowadays new developments under way.

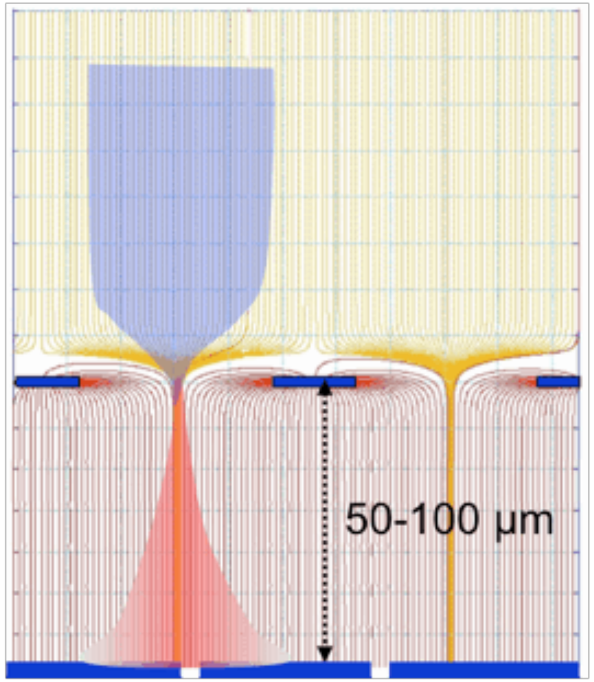
New Developments

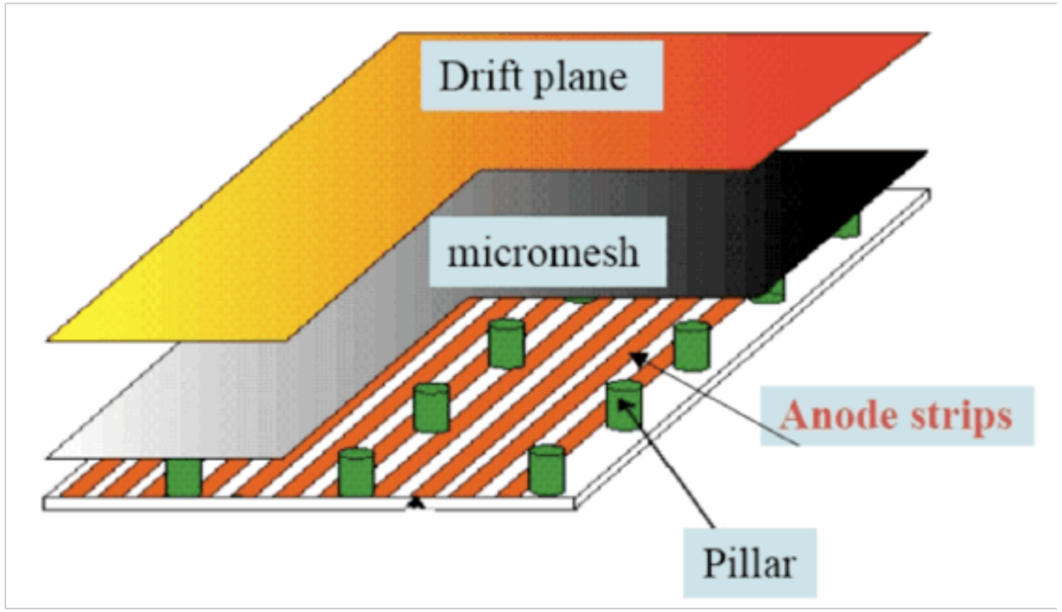
- Largely improved spacial resolution and higher particle rates:

Micro-Pattern Gas Detectors

  - a number of developments were started, some with a lot of problems
  - two technologies are currently the most successful: GEMs and MicroMegas

  - MicroMegas: Avalanche amplification in a small gap

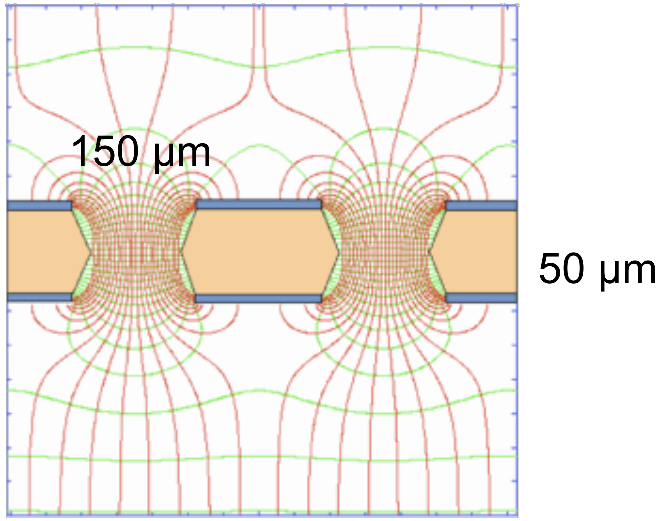


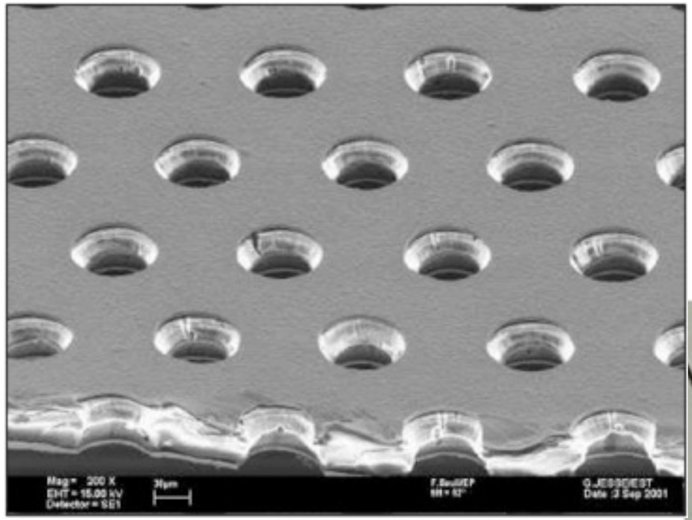


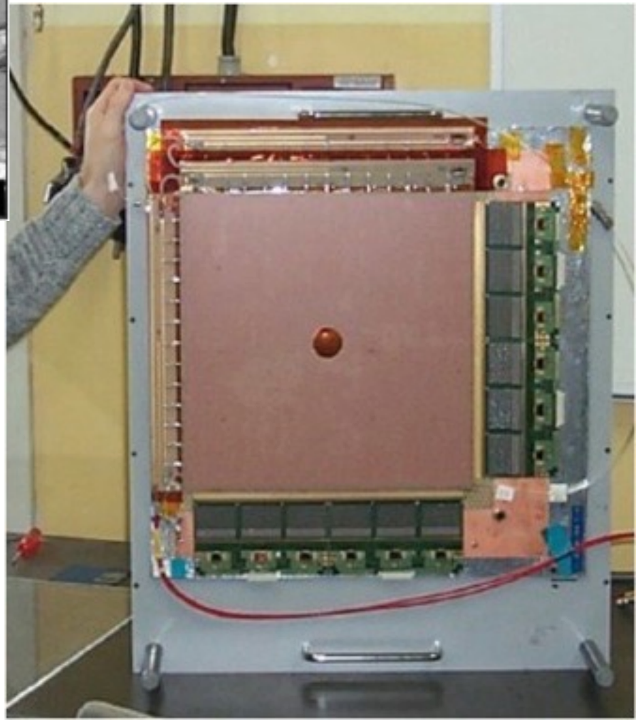
Y. Giomataris et al, NIM A376, 29(1996)

New Developments

- GEM: Gas Electron Multiplier: Gas amplification in small holes in a special foil







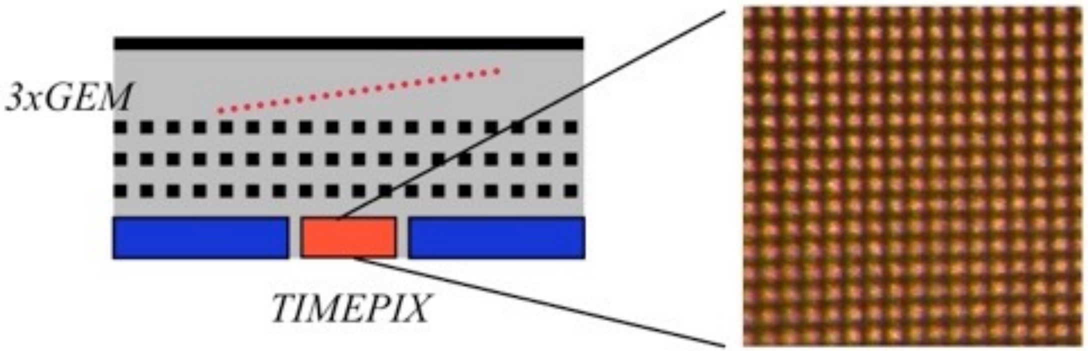
Charge collection on two separate levels: 2D structure possible: separation of amplification and read out

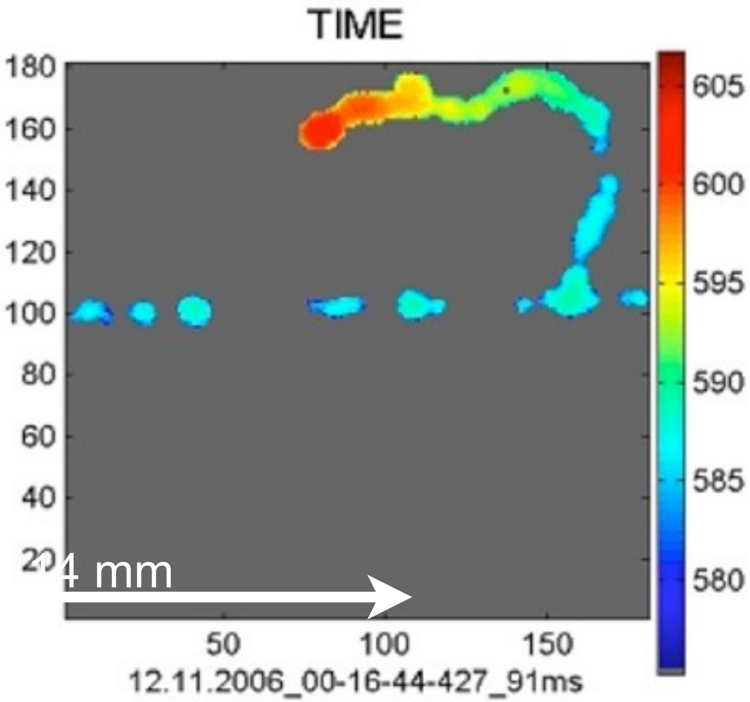
Both technologies, MicroMegas and GEMs are used in experiments. Typical spacial resolution: ~70 um

F. Sauli, NIM A386, 531(1997)

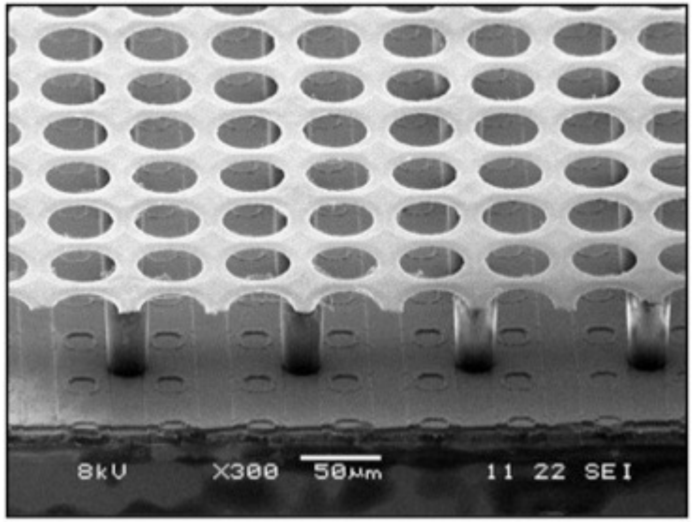
MPGDs as next generation detector

- Combination of gas detectors and Silicon
  - Integration of MPGDs with pixel read out chips





- Amplification and read out made of silicon



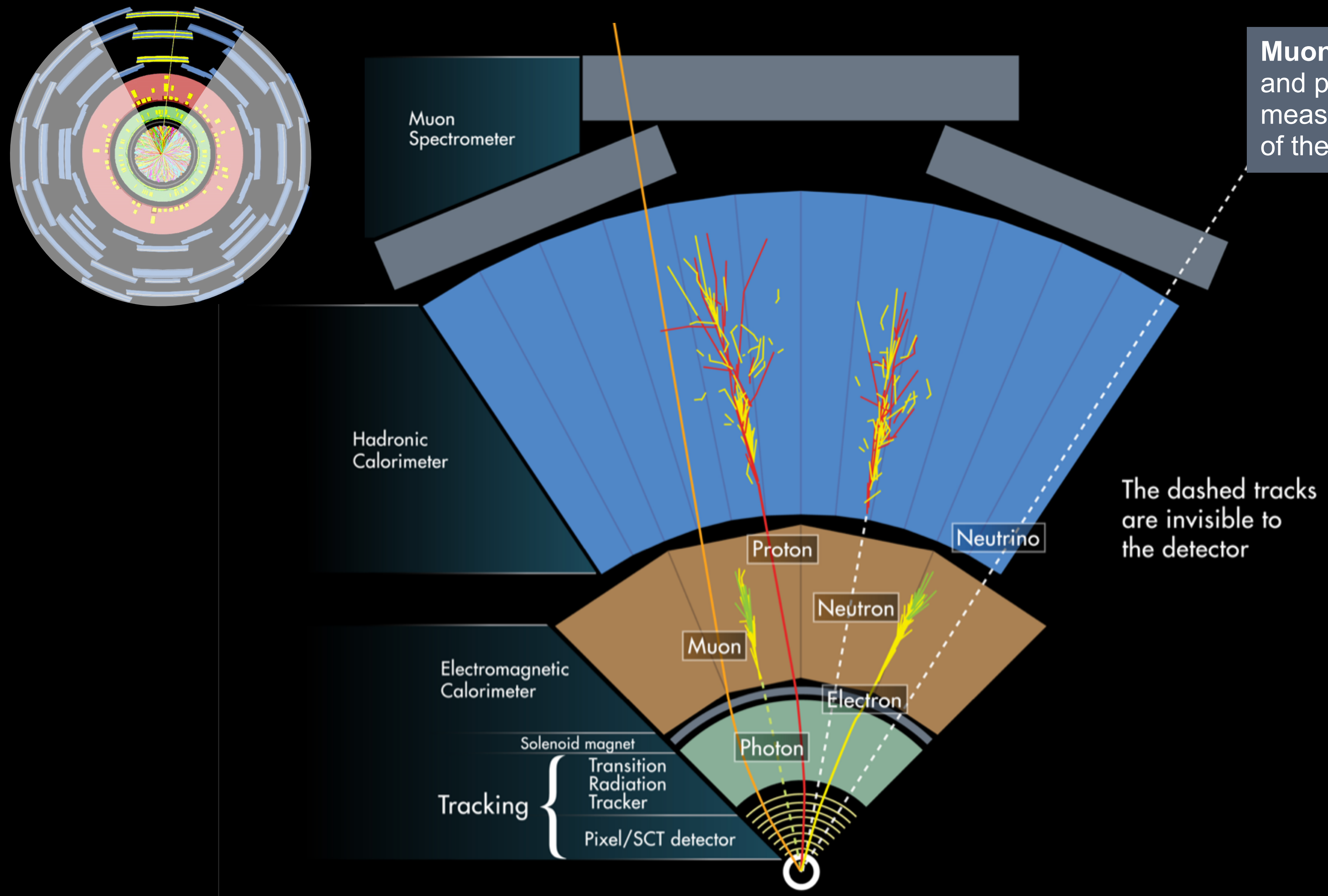
Advantages of gas detectors:
- Low radiation length
- Gas can be replaced regularly: Reduction of radiation damages!

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

Muon Spectrometer



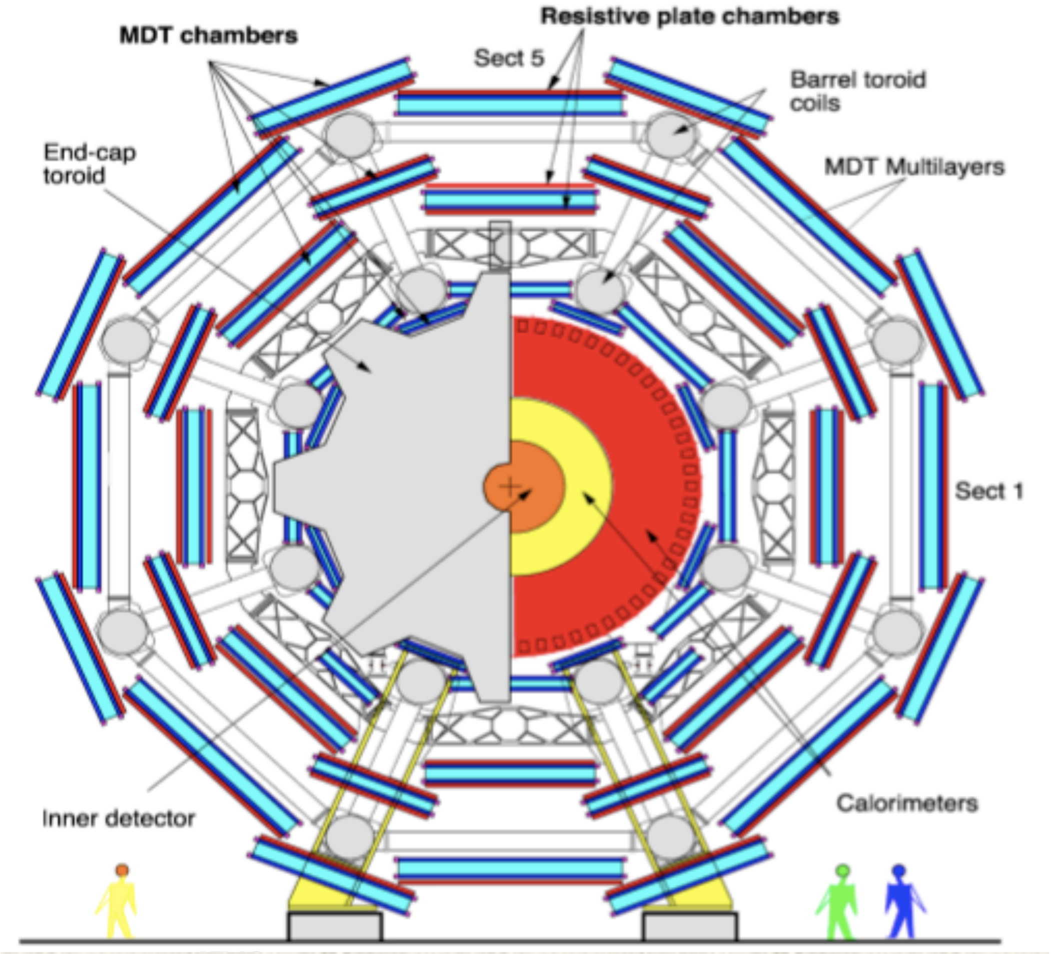
Muon-Detectors: Identification and precise momentum measurement of muons outside of the magnet

Muon Detectors

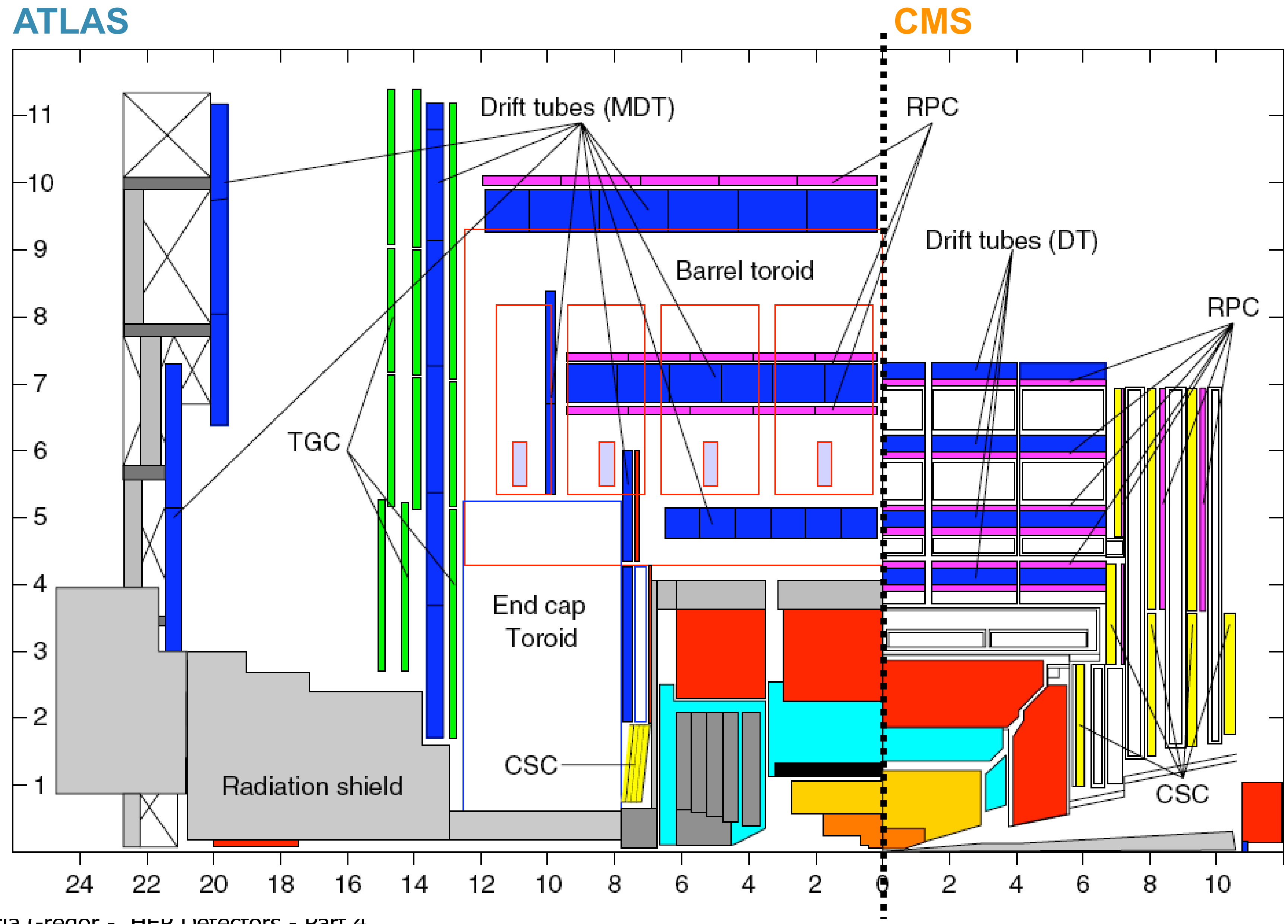
- Identification and precise momentum measurement of muons outside of the magnet
- Benchmark design for muon detectors:
  momentum measurement better than 10% up to 1 TeV.
  - $\Delta pT/pT \approx 1/BL^2$

- Typical track in Muon System has ≈ 20 hits
- A muon tracks can be:
  - “standalone” purely based on MS
  - “combined” btw MS and ID

- The standalone capability can be crucial at high luminosity when ID is “very crowded”
- The momentum measurement is dominated by
  - ID @ low p_T
  - MS @ high p_T

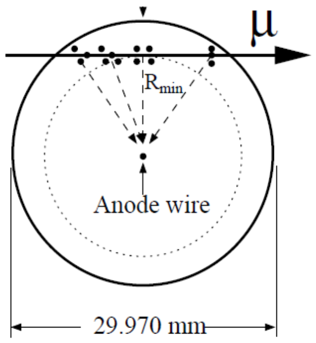


Muon Systems

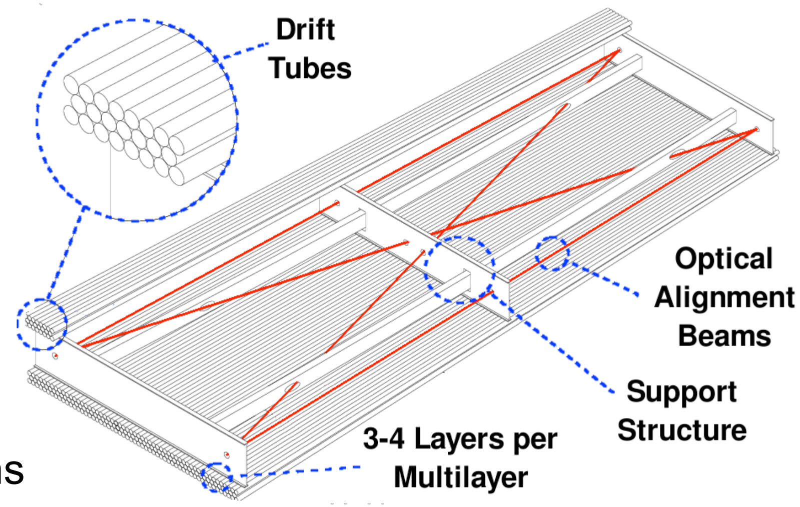


Precision Chambers

1) Monitored Drift Tubes (MDT)



Drift Tube

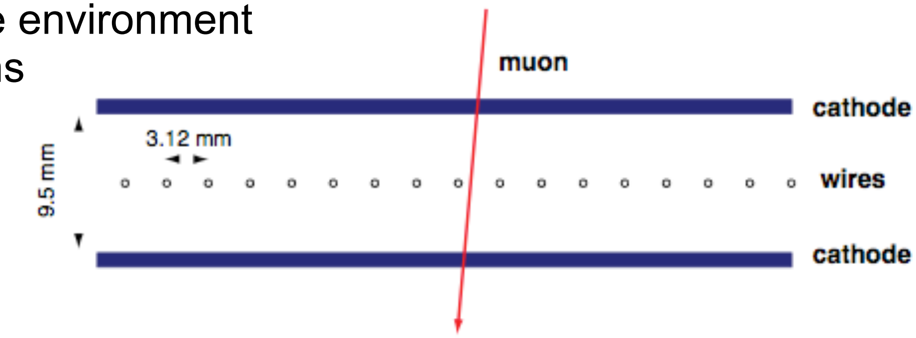


High-pressure drift tubes
$\sigma(R) \approx 100 \mu m$, $T_{drift} \approx 700ns$

- Gas-filled drift tubes with central wire
- Signal read out on both ends
- Spatial resolution increased by recording drift time.
- Three concentric barrel layers plus end-cap (eta=2.7).
- Total of 355000 tubes.

2) Cathode Strip Chambers

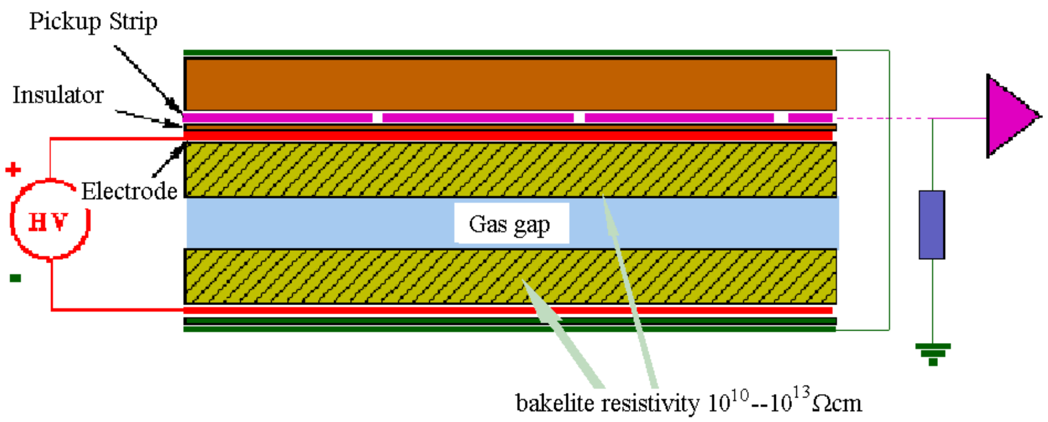
Operation in high rate environment
$\sigma(R) \approx 60 \mu m T_{drift} \approx 20ns$



- Array of anode wires crossed with copper cathode strips within gas volume.
- Short drift distances.
- Suited for high eta

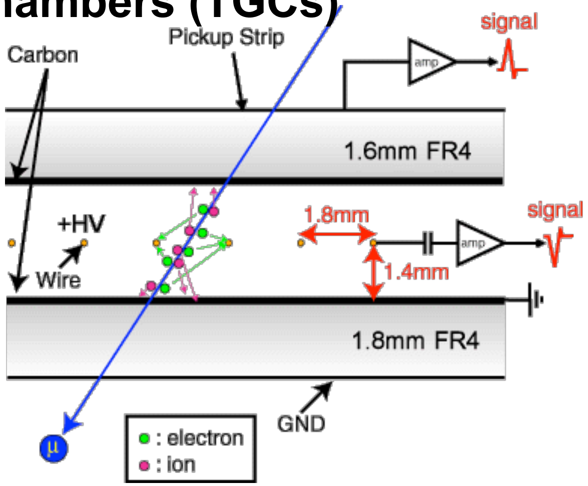
Trigger Chambers

1) Resistive Plate Chambers (RPCs)



- Robust detector with up to 5ns time resolution
- Charge carriers drift towards anode and get multiplied by electric field (avalanche).
- Applied high voltage at parallel plate electrodes leads to uniform electric field in the gas gap.
- The propagation of the growing number of charges induces a signal on a read out electrode.
- In ATLAS the Barrel is equipped with RPCs.

2) Thin Gap Chambers (TGCs)



- Derivative of MWPCs
- Operation in saturated mode. Signal amplitude limited by by the resistivity of the graphite layer
- In ATLAS the End-cap is equipped with TGCs.

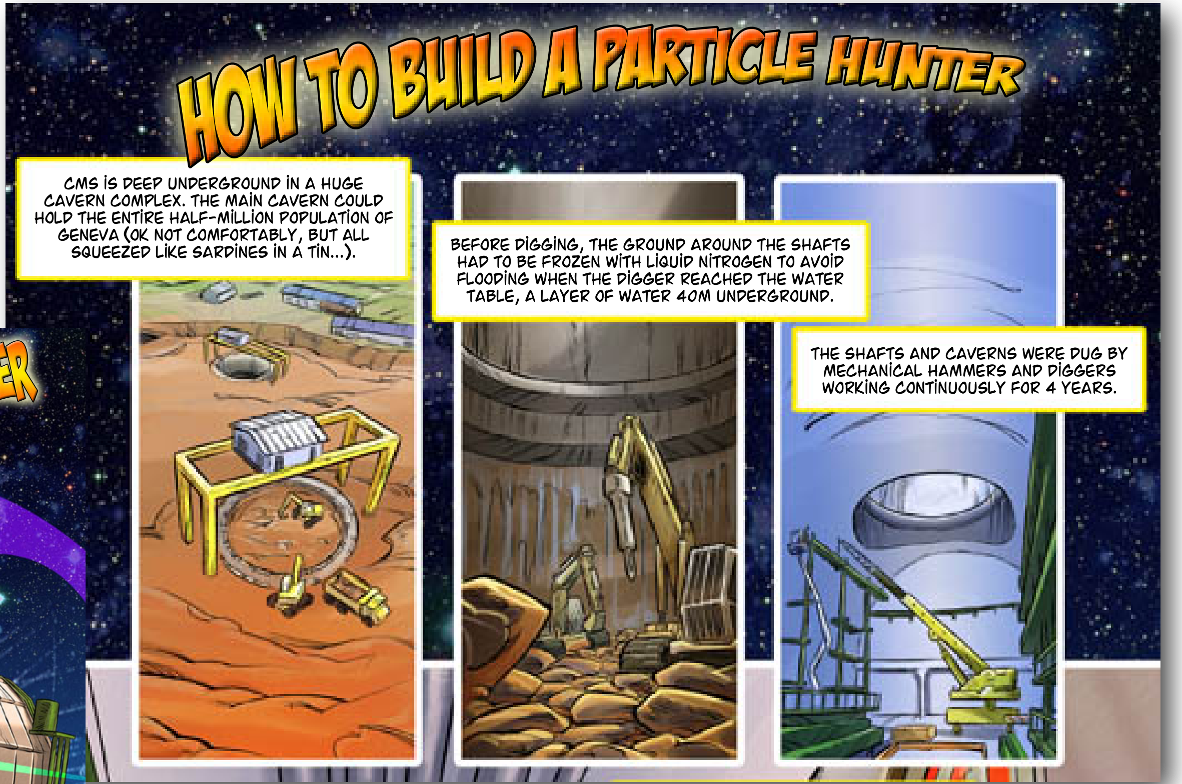
V. Real Life Examples

Building an Experiment (Example 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 ongoing)
  - PANDA and CBM @Fair
  - …..



source: “CMS Particle Hunter”

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

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

Pic: DESY

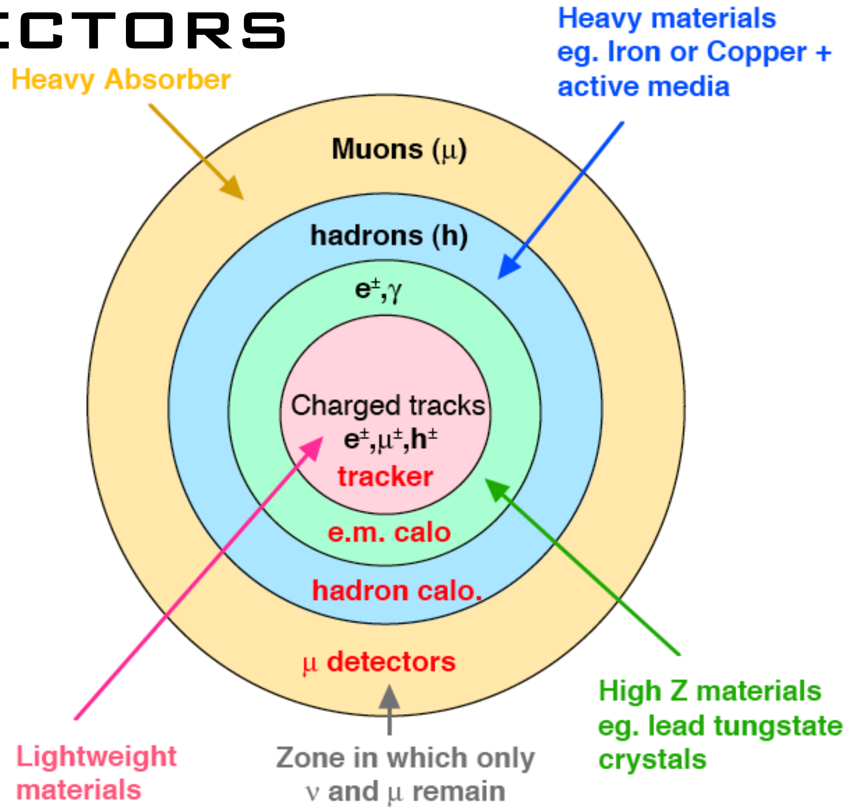
- lots of money to pay all this ….

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 ?

- 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

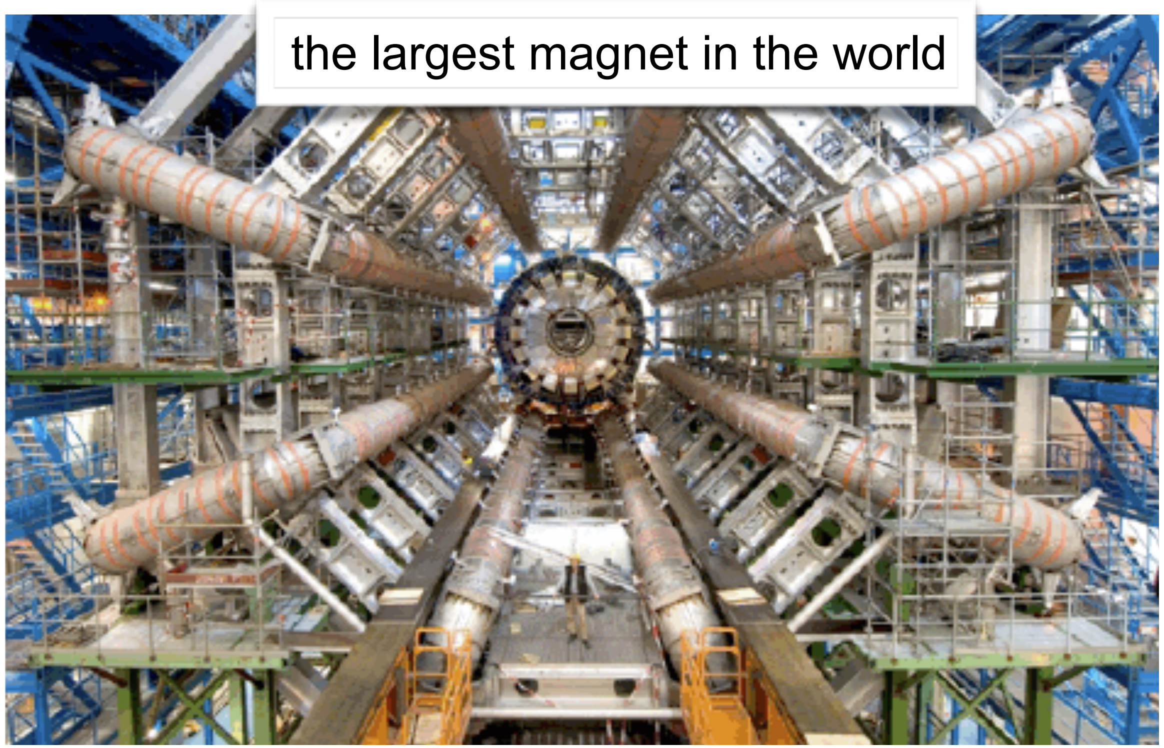
- **Wish list**
  - big: long lever arm for tracking
  - high magnetic field
  - low material budget or outside detector (radiation length, absorption)
  - serve as mechanical support
  - reliable operation
  - cheap
  - ….

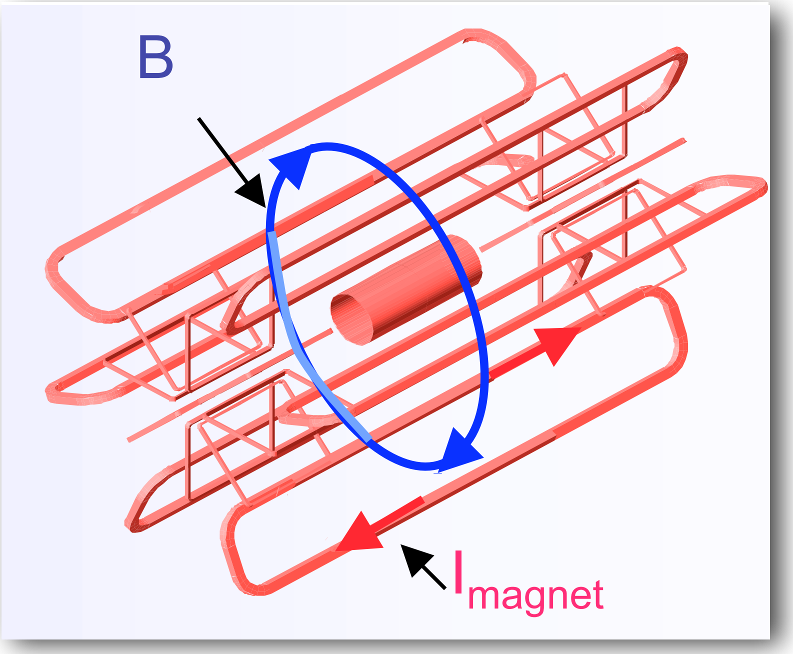
Eierlegende Wollmilchsau

- **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

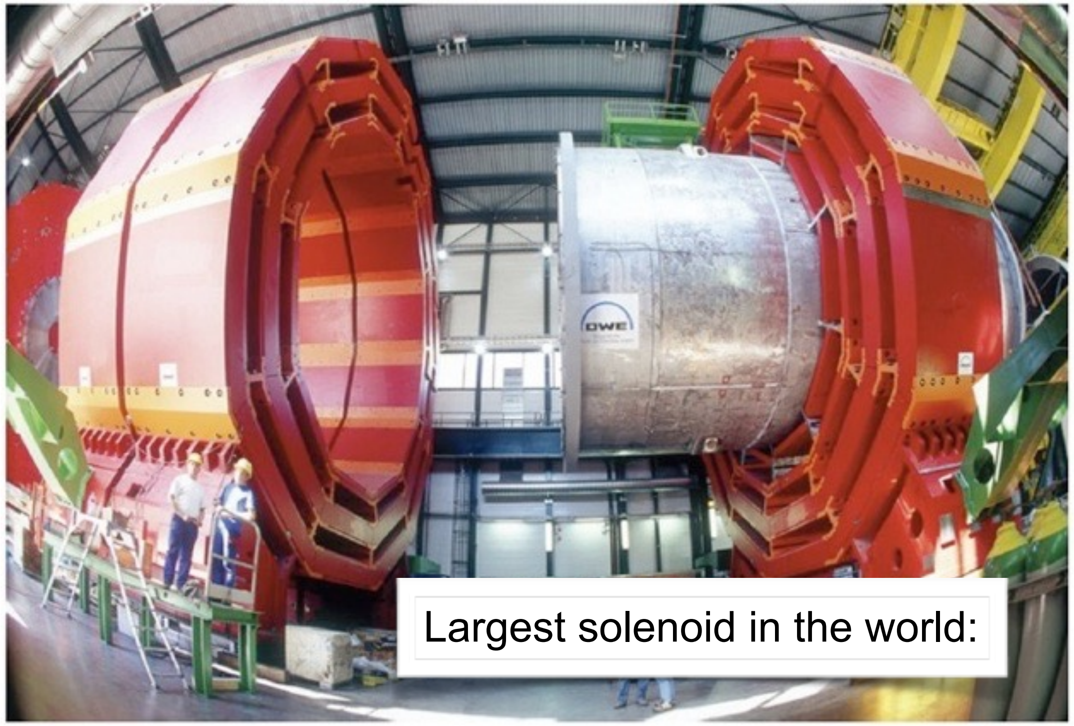


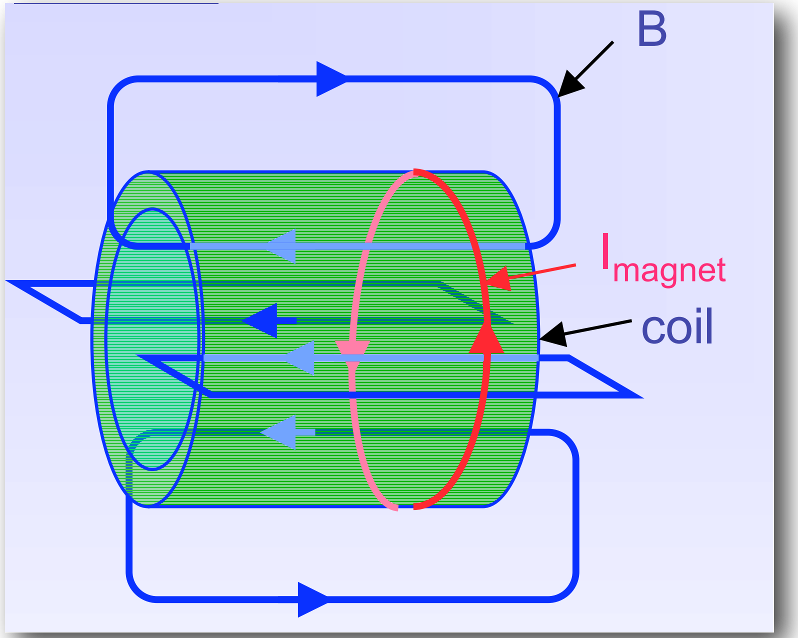


- Central toroid field outside the calorimeter within muon-system: <4 T
  - Closed field, no yoke
  - Complex field
- Thin-walled 2 T Solenoid-field for trackers integrated into the cryostat of the ECAL barrel

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

Magnet-Concepts: CMS -> Solenoid





- 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

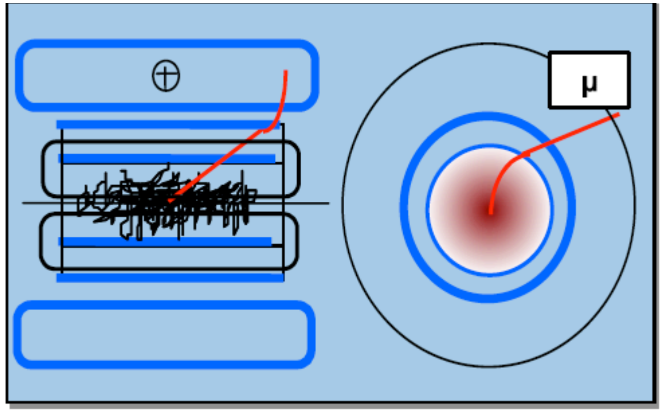
+ large homogeneous field inside coil
+ weak opposite field in return yoke
- size limited (cost)
- relative high material budget

Muon Detectors

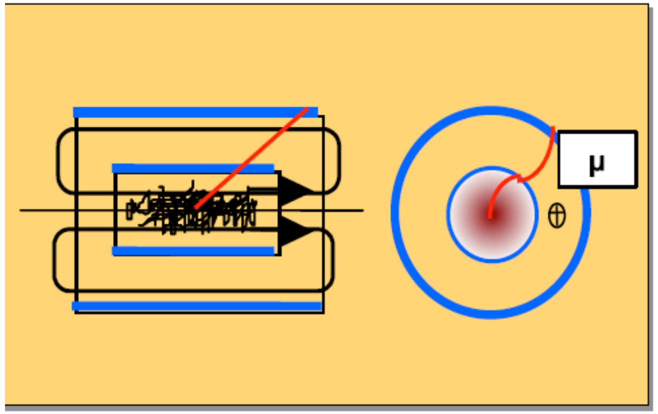
another tracker outside of the magnet

- 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

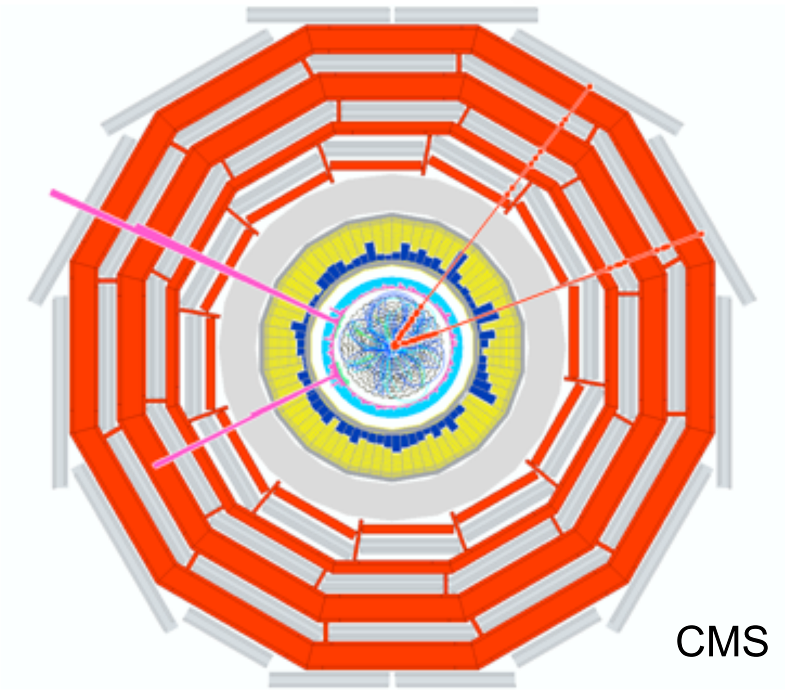


CMS



What is a Trigger ?

- Collisions every 25 ns with many simultaneous interactions
- A lot of information stored in the detectors - we need all information
- Electronics too slow to read out all information for **every** collision
- But: a lot of the interactions are very well known - we only want rare events
- “Trigger” is a system that uses simple criteria to rapidly decide which events to keep when only a small fraction of the total can be recorded.



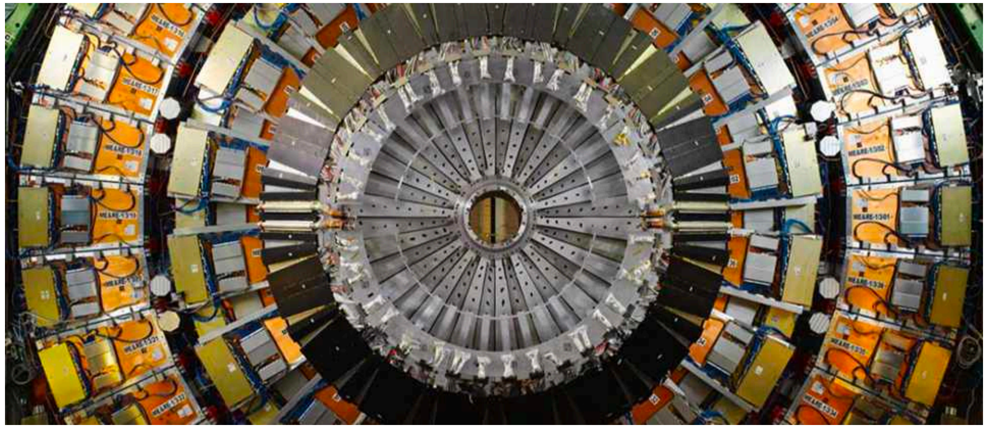
CMS

- 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

Experimental Constraints

Different experiments have very different trigger requirements due to operating environments

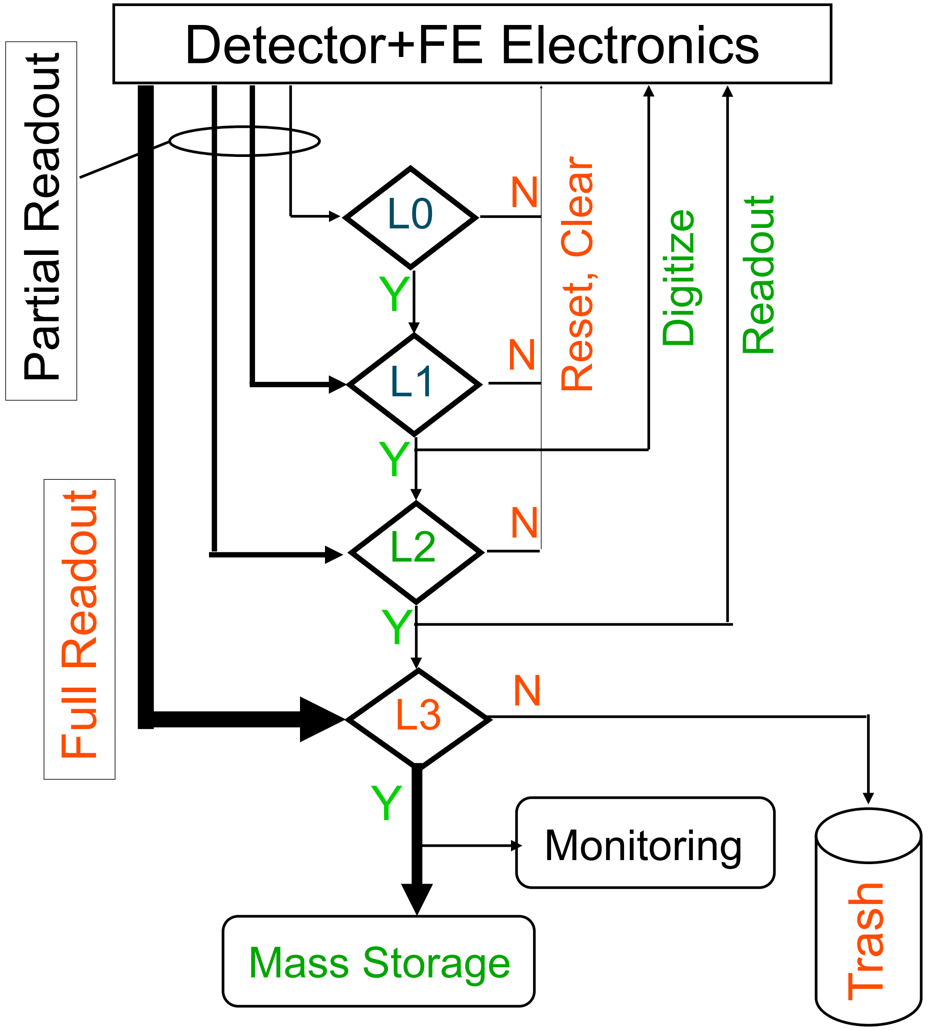
- Timing structure of beam
- Rate of producing physics signals of interest and rate of producing backgrounds
- **Cosmic Ray Experiments**
  - no periodic timing structure, background/calibration source for many other experiments
- **Fixed Target Experiments**
  - close spacing between bunches in train which comes at low rep rate (~Hz)
    - backgrounds from un-desirable spray from target
    - cosmics are particularly a background for neutrino beams
- **e+e- colliders**
  - very close bunch spacing (few nsec), beam gas and beam wall collisions
- **ep collider**
  - short bunch spacing (96ns), beam gas backgrounds
- **pp/ppbar collider**
  - modest bunch spacing (25-400ns), low produced soft QCD



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)

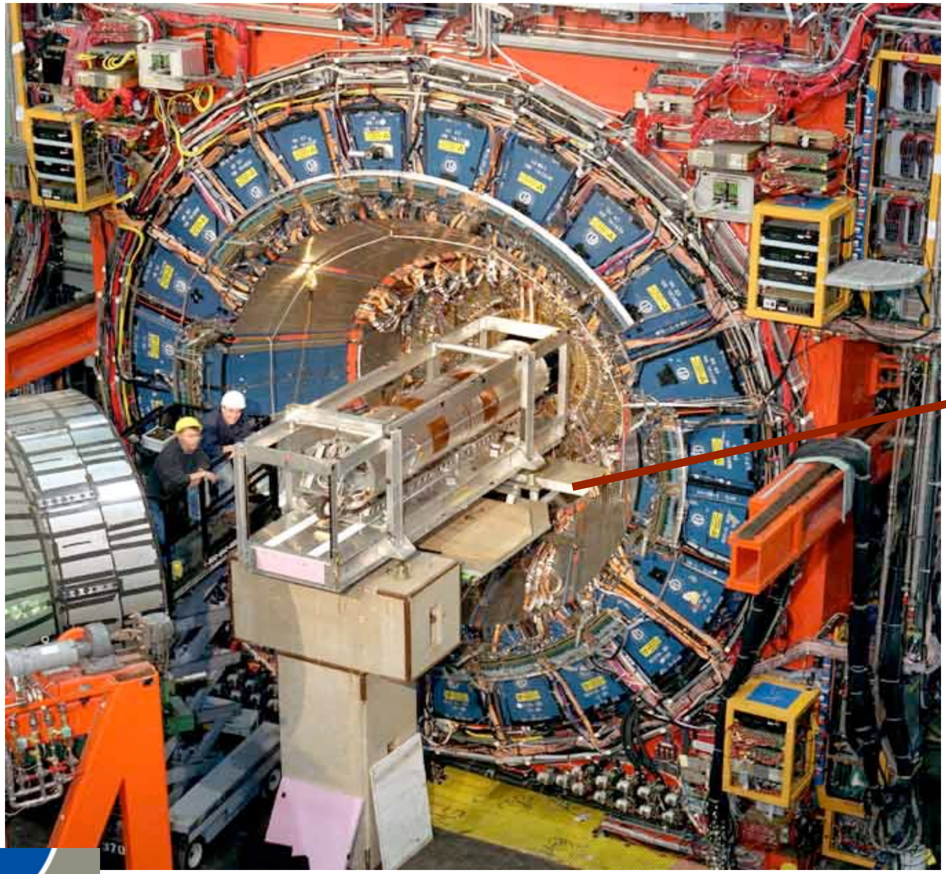


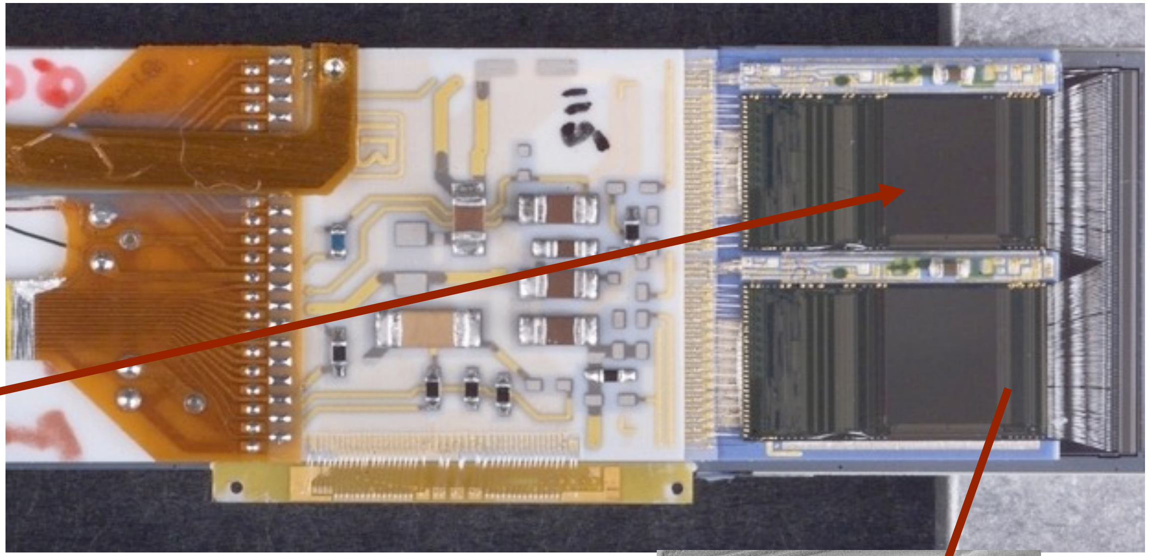
- **Next generation:** implement triggering stage already in tracking detector to handle very high multiplicities (example: HL-LHC)
- Other extreme: trigger-less operation -> read out at 40MHz and do the work offline (LHCb)

V. Real Life Examples
And What Can Go Wrong …

Problems with Wire Bonds (CDF, D0)

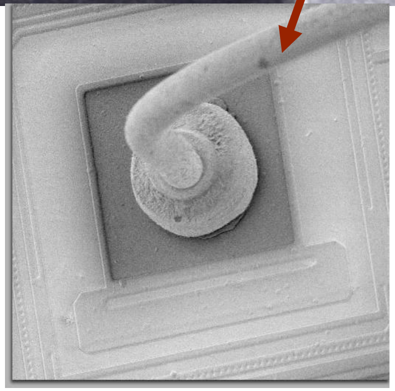
- Very important connection technology for tracking detectors: wire bonds:
  - 17-20 um small wire connection -> terrible sensitive ….
- During test pulse operation, Lorentz force on bonding wires (perpendicular to magnetic field) caused resonances …





…breaks wire bonds between detector and read out.

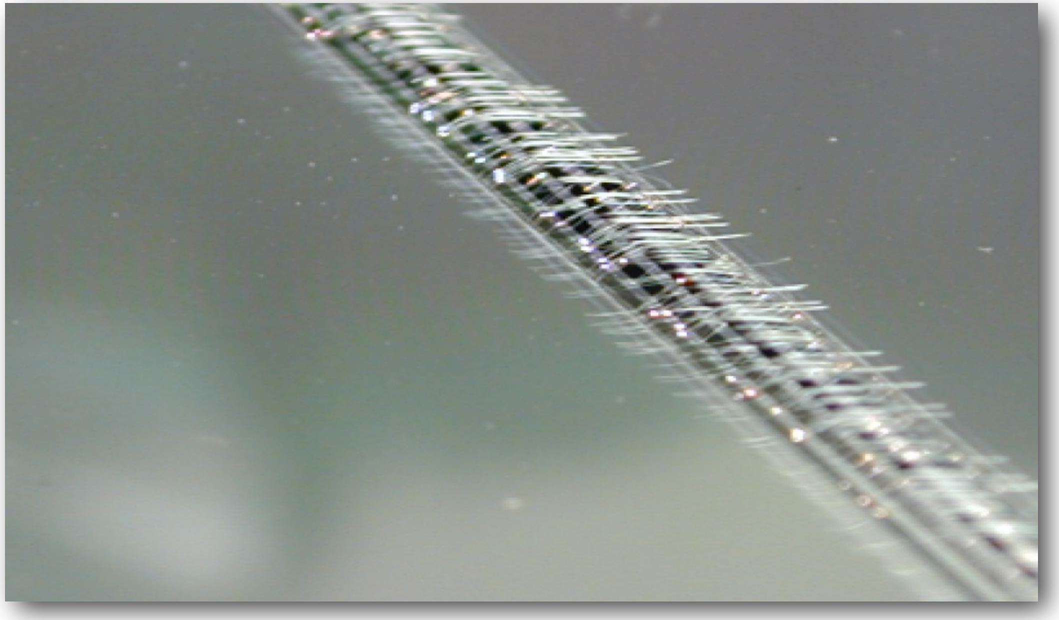
during running



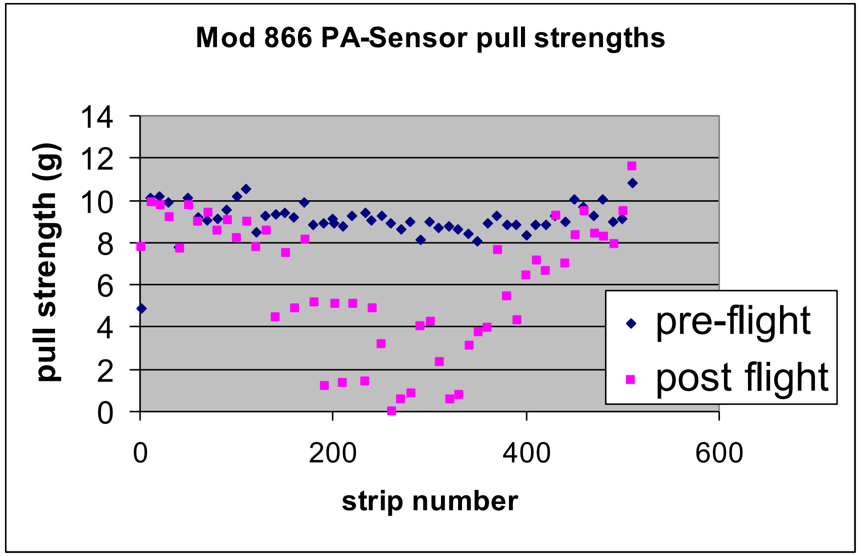
More Wire Bond Wreckage

- 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 vibration test causes similar damage

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

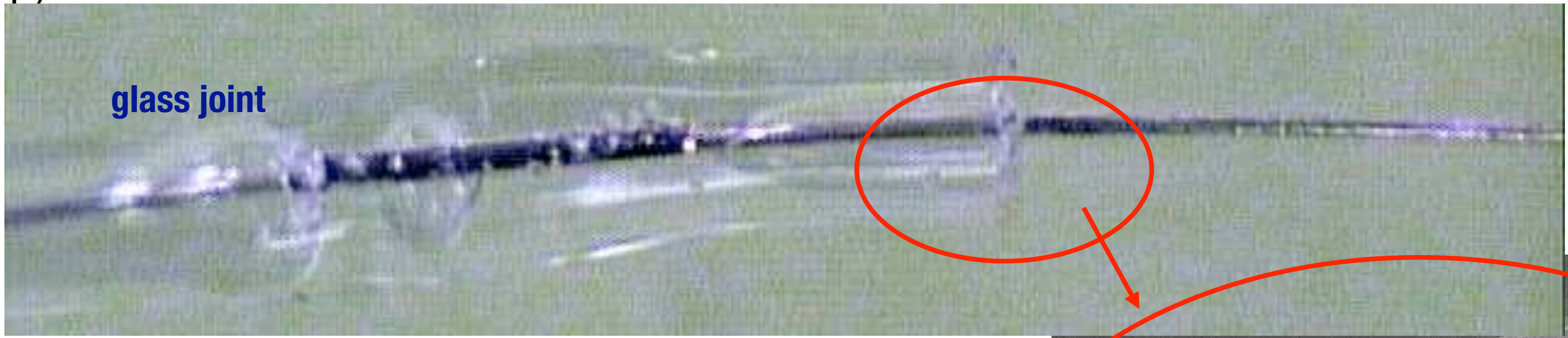


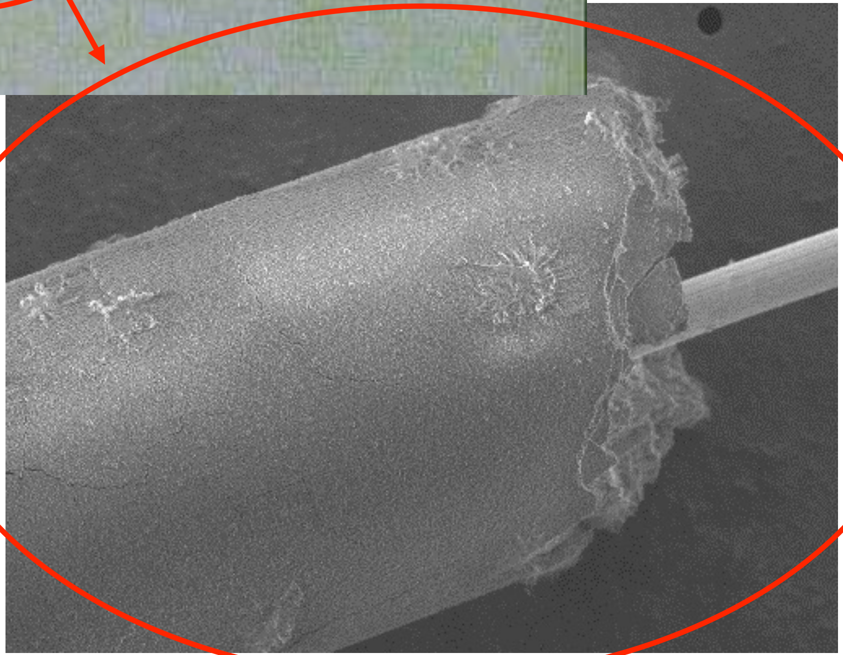
during production



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

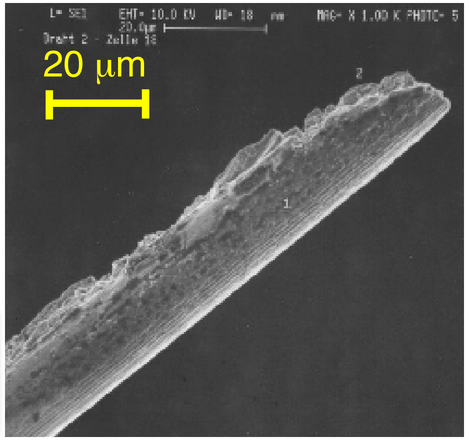
- Changed gas mixture, after ~10 years of R&D with old mixture

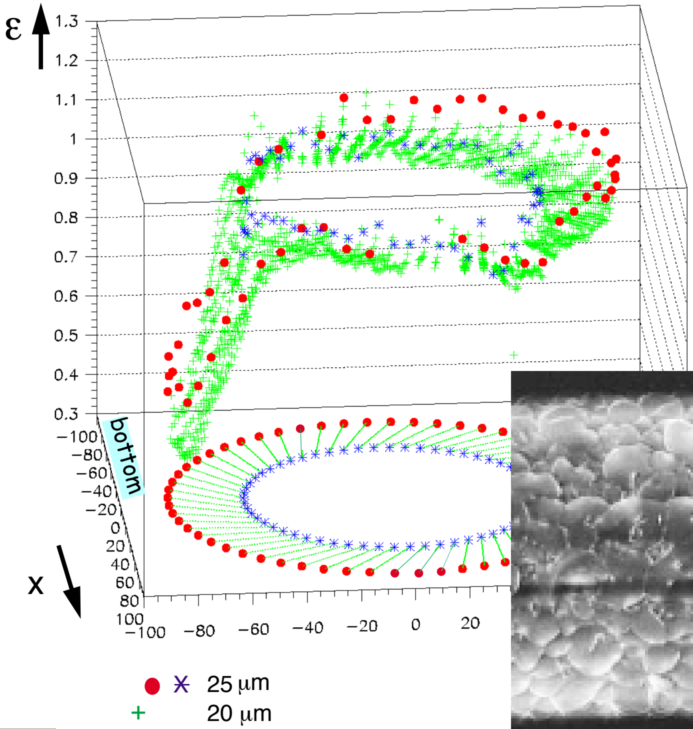
during production

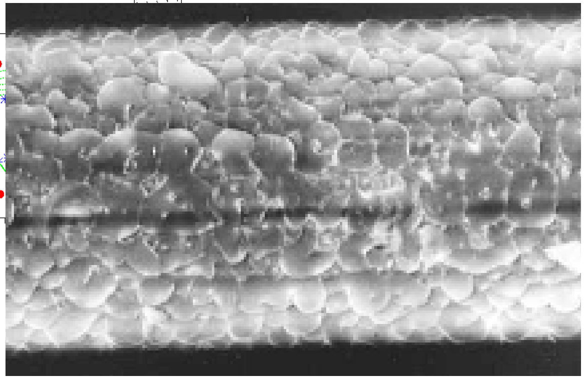
Wires H1 Central Jet Chamber

- 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

during production







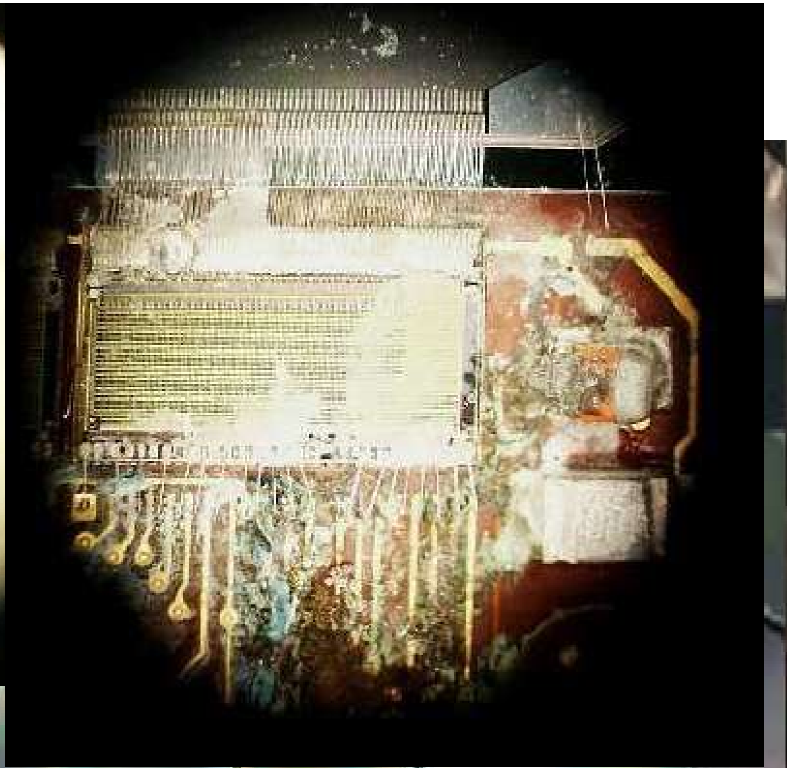
- Sense Wire Deposits in CJC2
- Observation / possible reason:
  - y dependence implies most likely gas impurity
- Consequences:
  - sense wires replaced
  - changes in gas distribution
  - increased gas flow

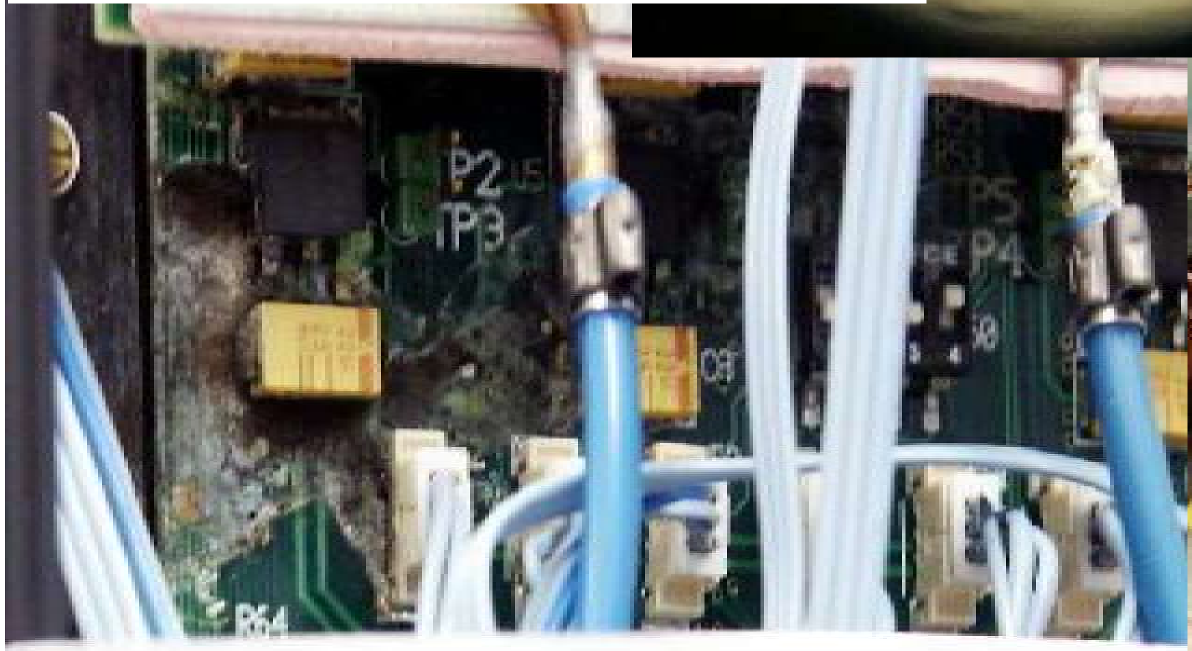
during running

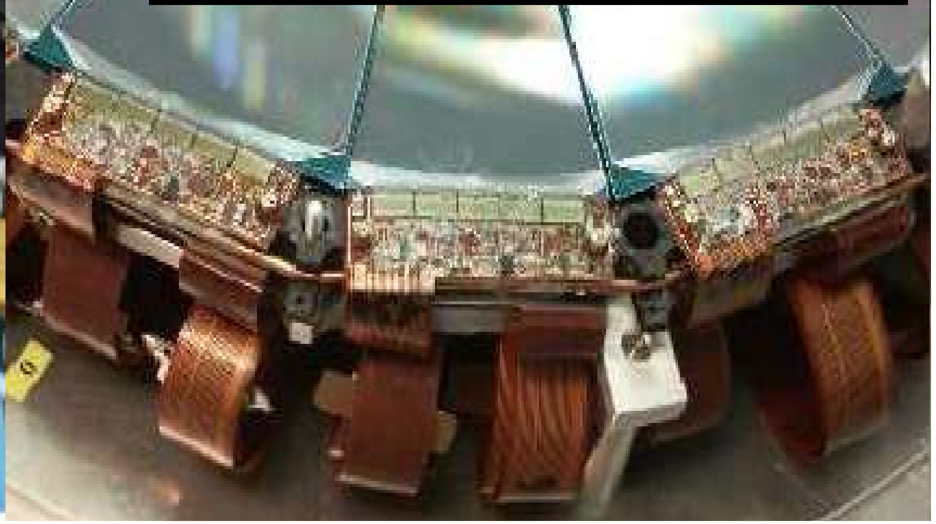
Water Damage in Tracker ...

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

during running





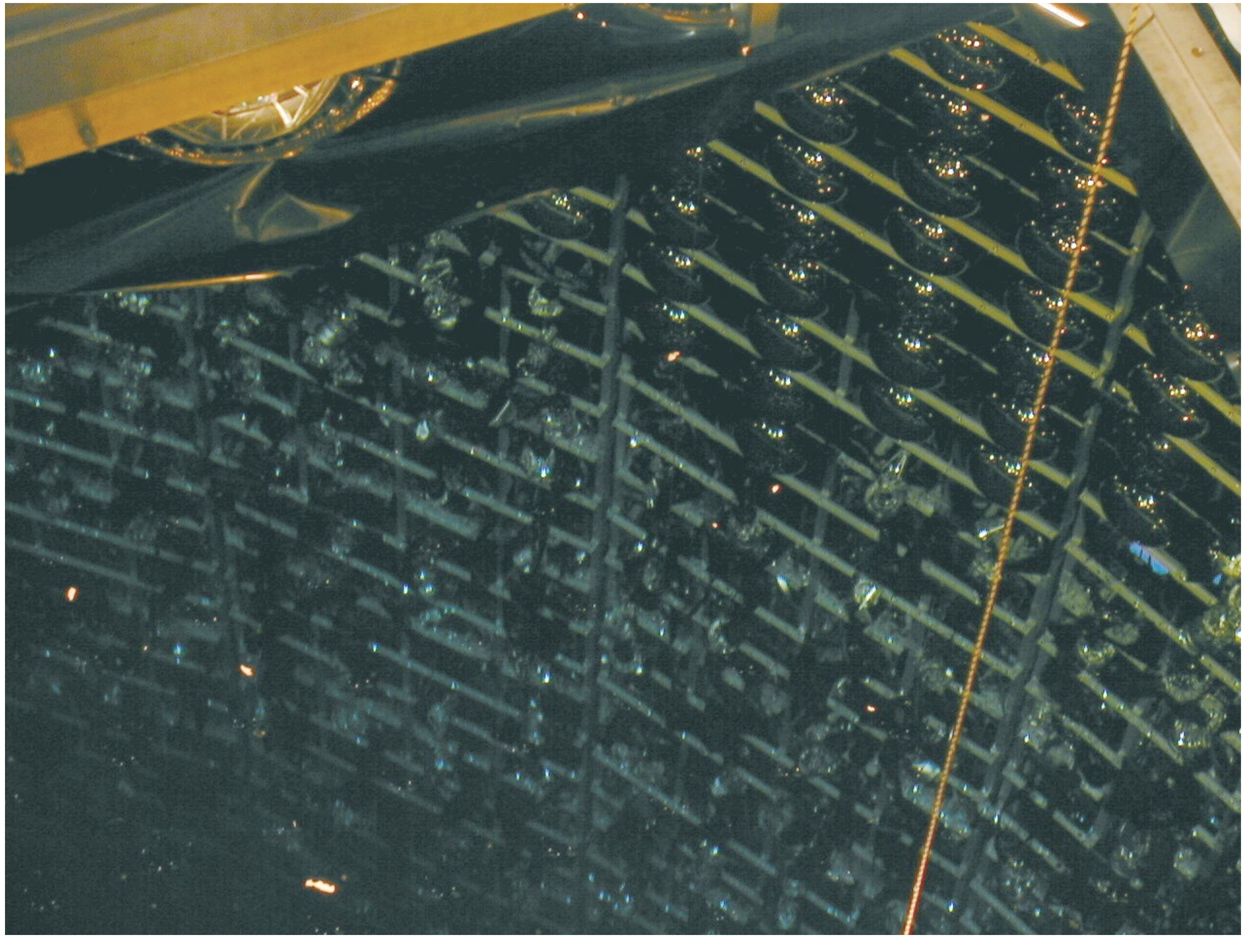


Imploded PMTs @ Superkamiokande

- On November 2001 a PMT imploded creating a shock wave destroying about 7700 of other PMTs (costing about $3000 each)

- Chain reaction: a 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.

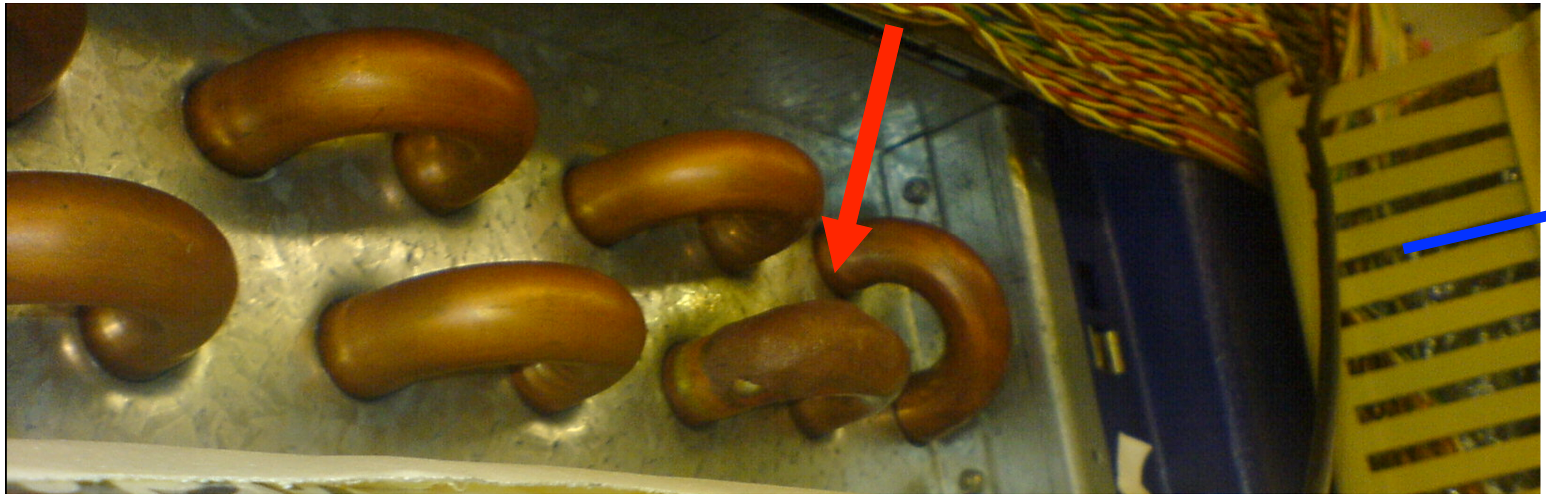
during commissioning

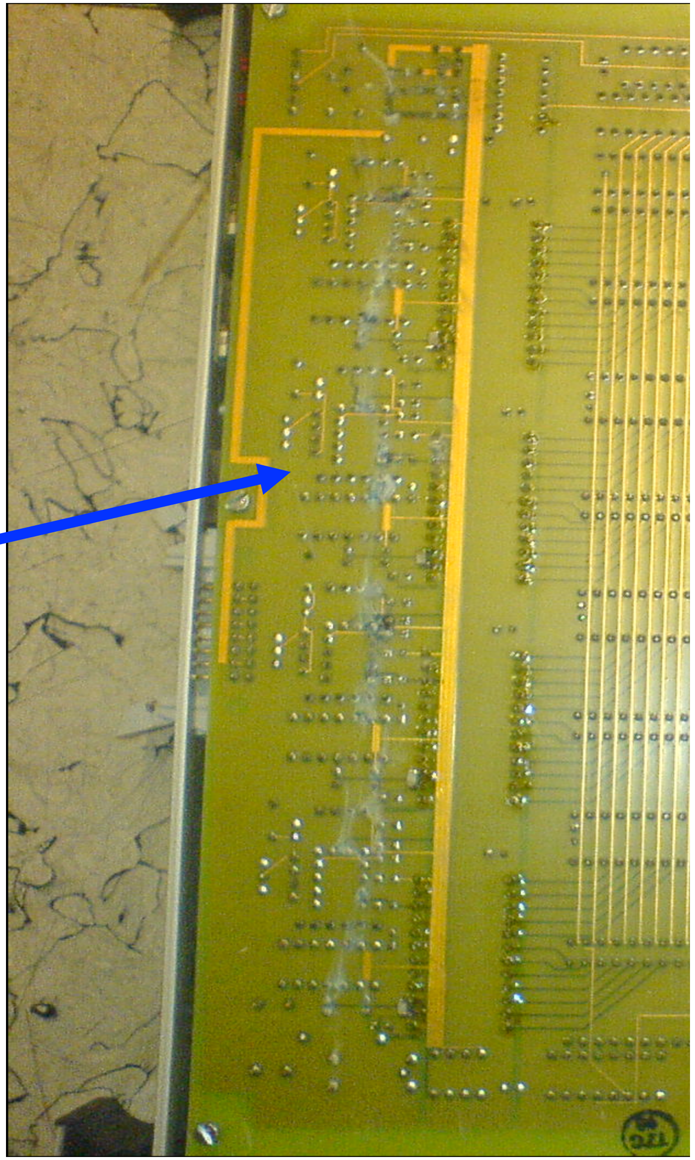


Pic: unknown source….

ZEUS - one of many Water Leaks

- 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 ….



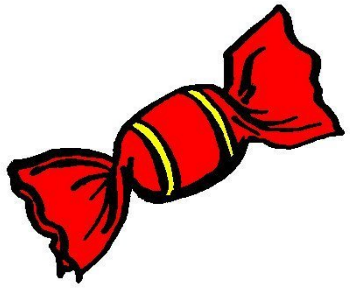


- Where ever you chose to cool with a liquid - it will leak one day !

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!**

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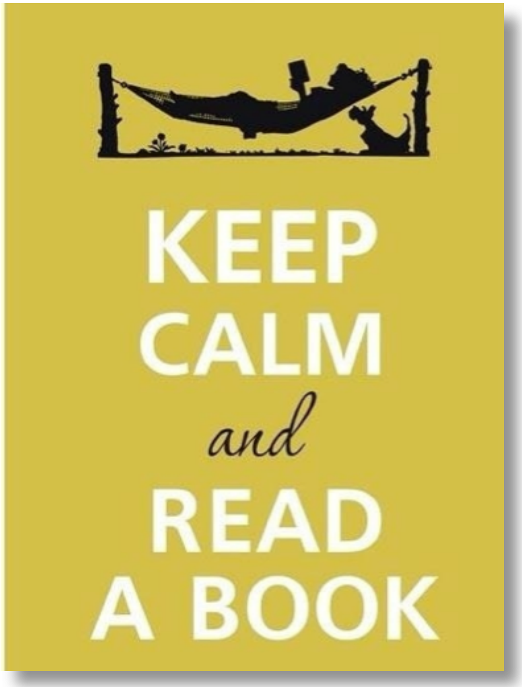
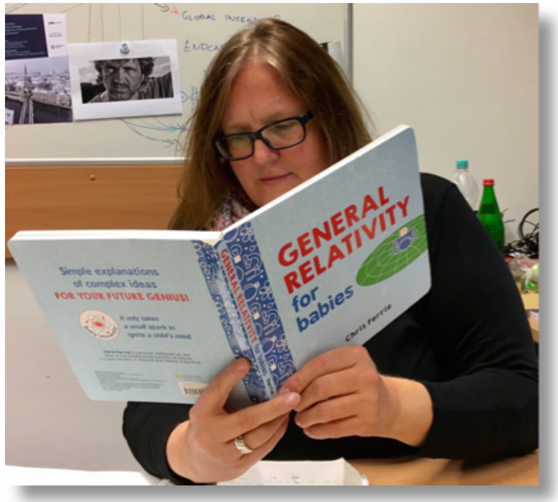
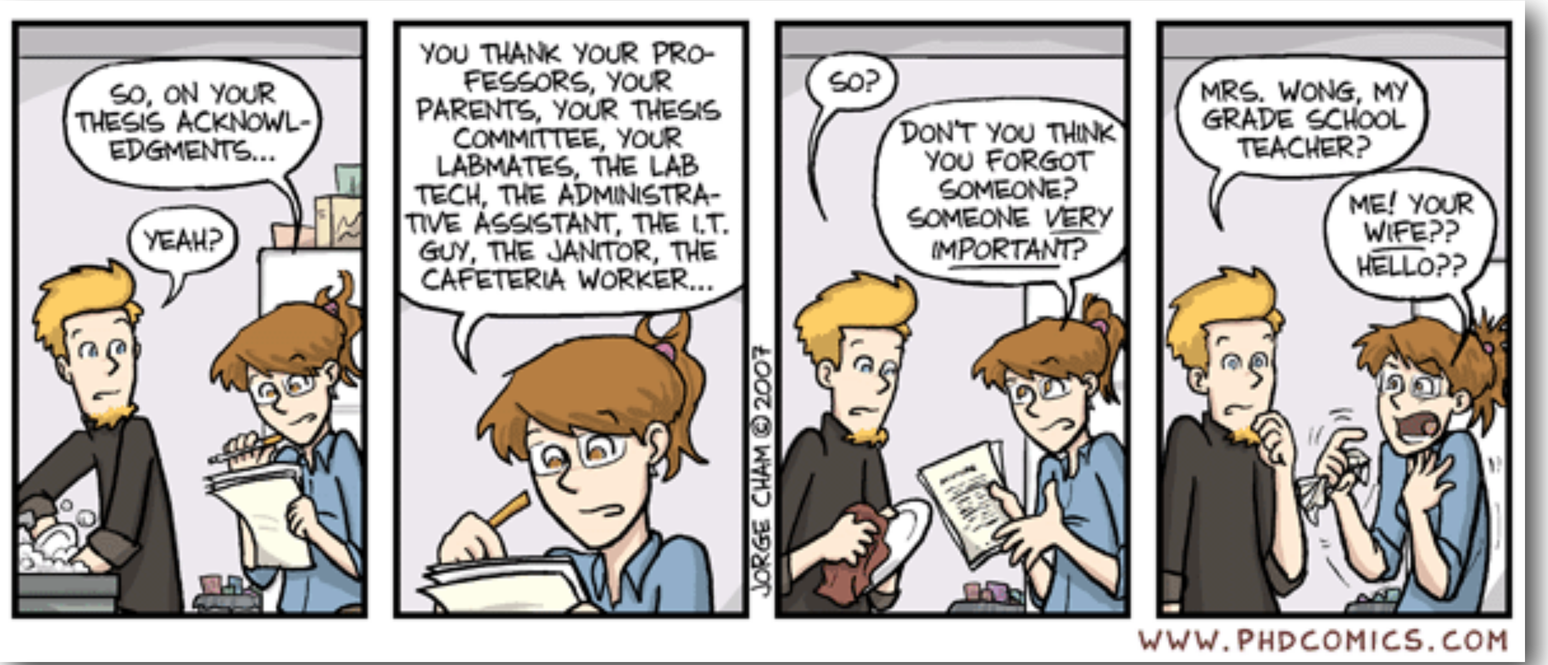




Important ....



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Steinar Stapnes

Erika Garutti

...freaky husband ;-)

Symphony of Science

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