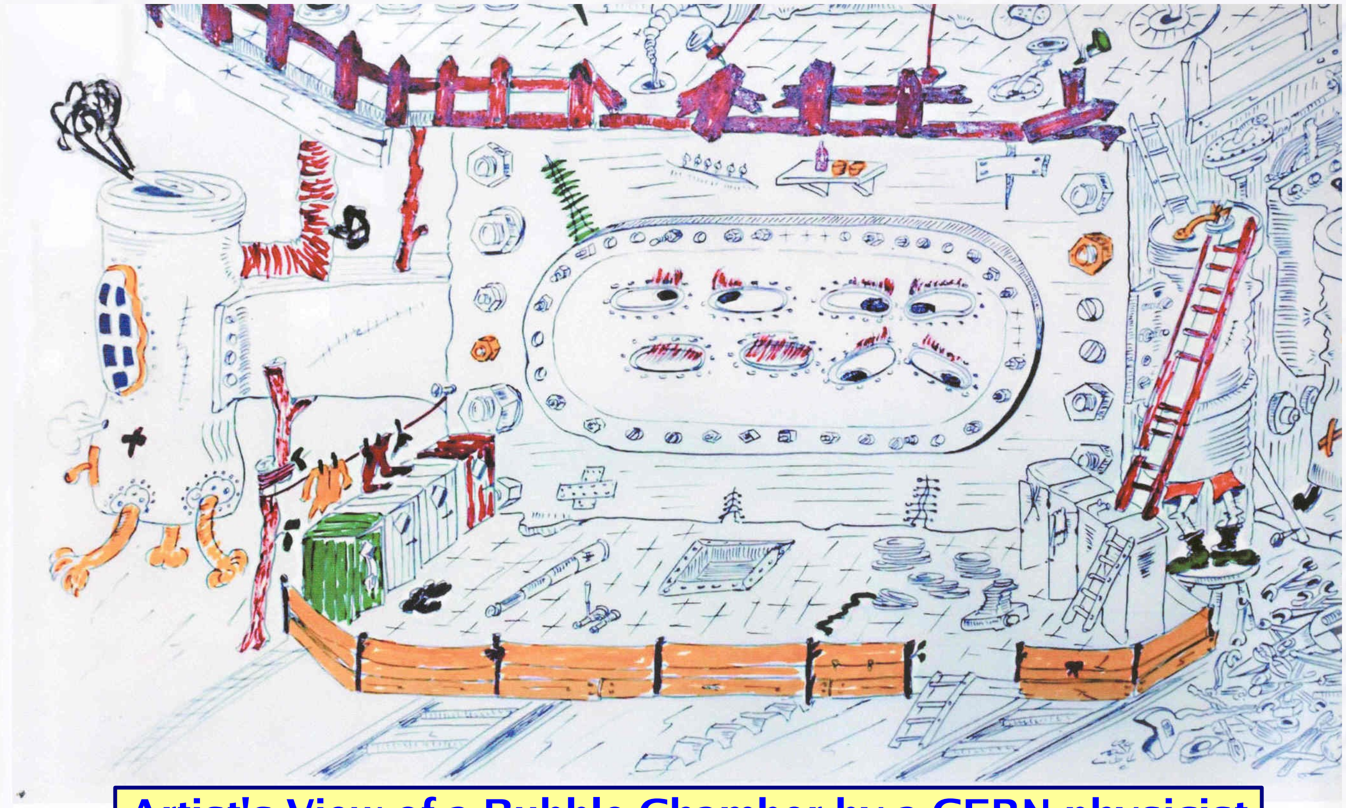
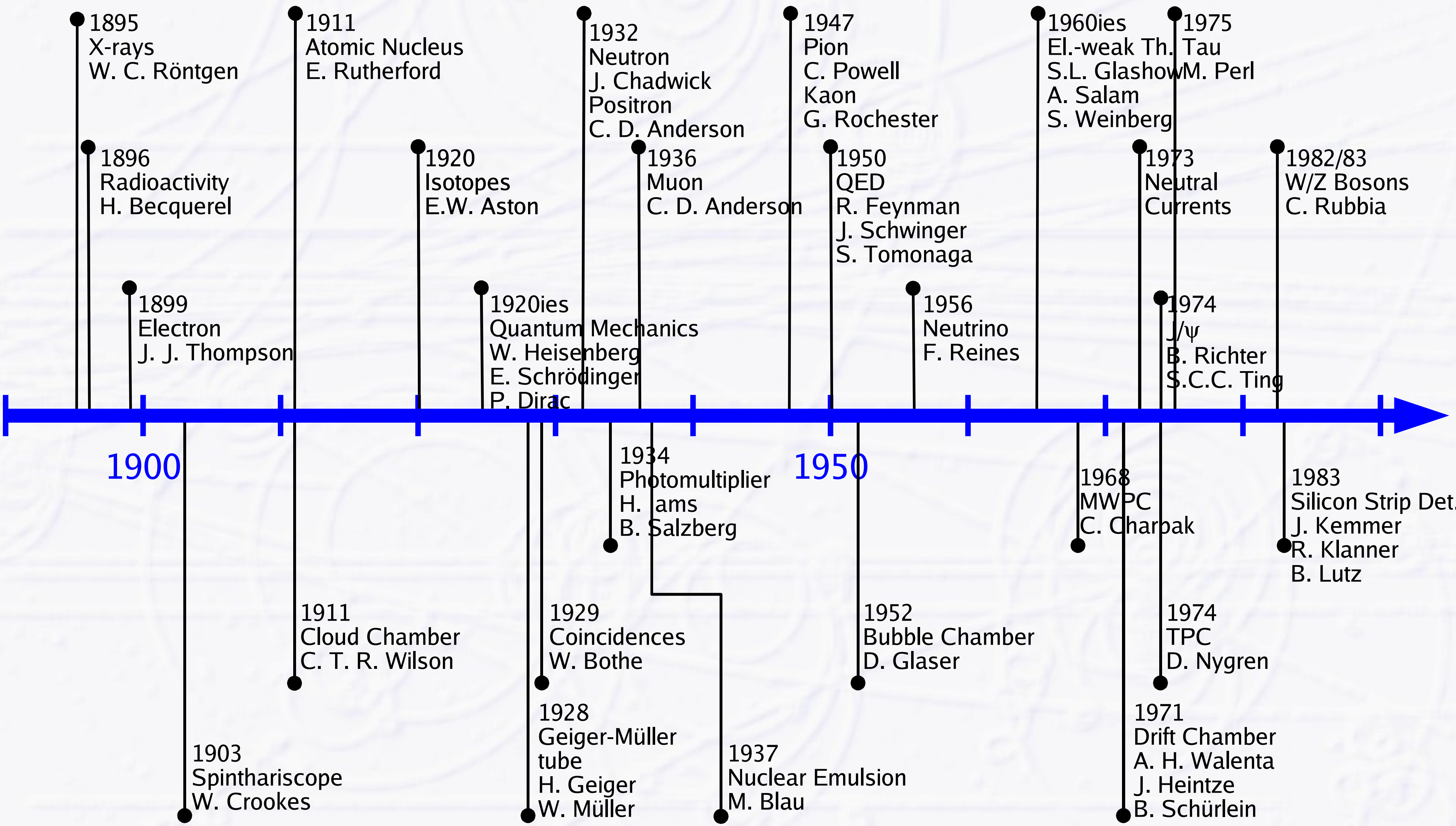
History of Particle Detectors



Artist's View of a Bubble Chamber by a CERN physicist

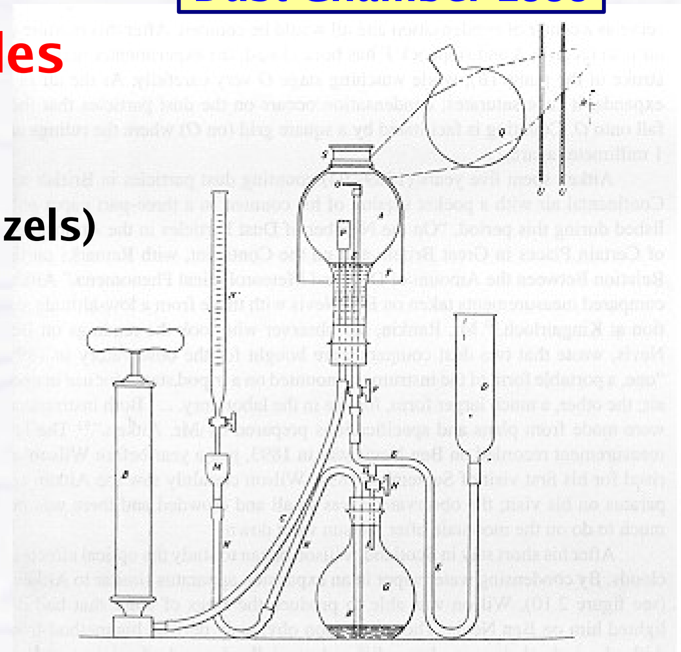
Timeline of Particle Physics and Instrumentation



Early Image Detectors

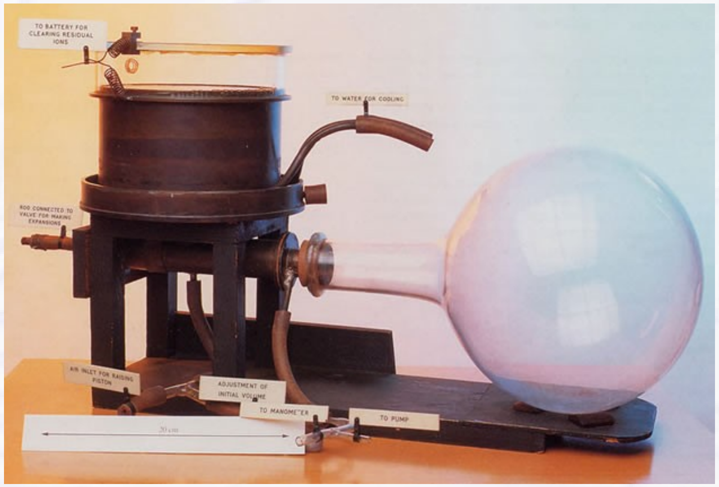
- Second half of 19th century
  - growing interest in meteorological questions
    - climate, weather phenomenon, cloud formation
  - people started to study condensation of water vapour in the lab
    - also motived by raising use of steam engines
- John Aitken built a “Dust Chamber” 1888
    - water vapour mixed with dust in a controlled way
  - result: droplets are formed around dust particles
  - further speculations
    - electricity plays a role (from observations of steam nozzels)
- Charles T. R. Wilson became interested
  - first ideas to build a cloud chamber 1895
    to study influence of electricity/ions
    - also to solve question why air shows
      natural slight conductivity

Dust Chamber 1888



Cloud Chamber I

- **Cloud chamber (1911 by Charles T. R. Wilson, Noble Prize 1927)**
  - chamber with saturated water vapour
  - charged particles leave trails of ions
    - water is condensing aound ions
  - visible track as line of small water droplets



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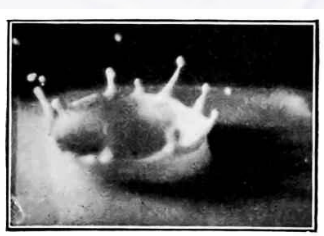
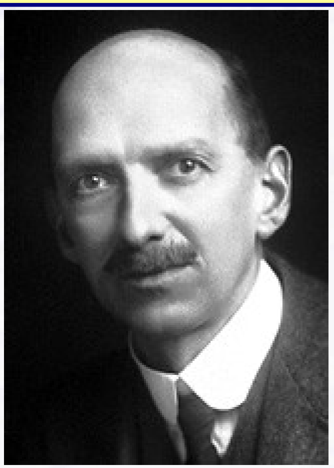
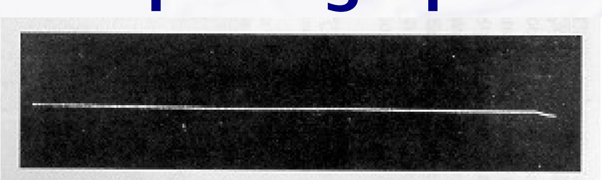
- **Also required**
  - high speed photographic methods
    - invented by Arthur M. Worthington 1908 to investigate the splash of a drop
    - ultra short flash light produced by sparks

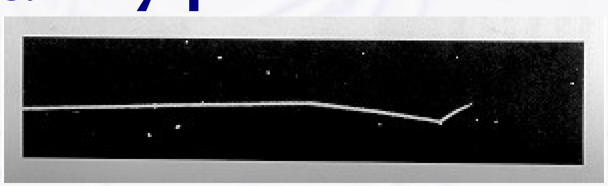


Charles T. R. Wilson



- **First photographs of α–ray particles 1912**



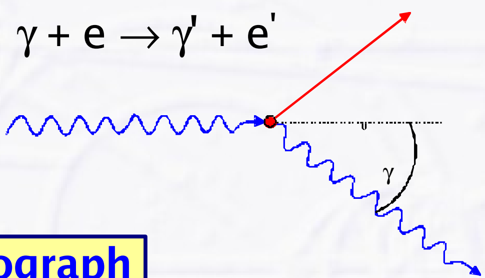


Cloud Chamber II

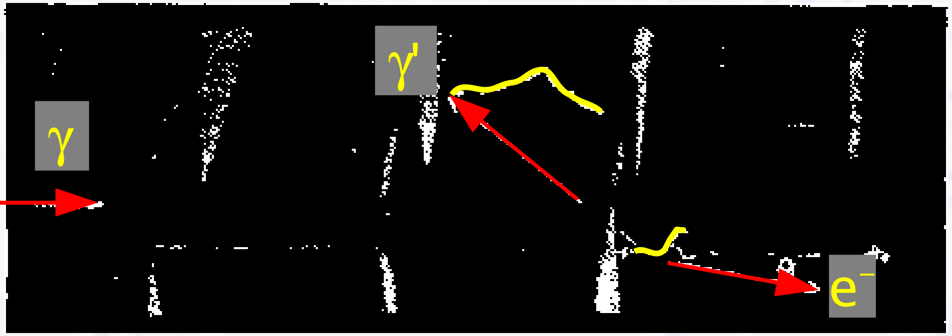
Arthur H. Compton

- **Arthur H. Compton used the cloud chamber in 1922 to discover scattering of photons on electrons (Compton effect)**
  (Nobel Prize 1927 together with Charles T. R. Wilson)
  - **X-rays emitted into cloud chamber**
    - **photon scattered on electrons (recoiling electron seen in cloud chamber)**
    - **photon with reduced energy under certain angle visible by photo effect or Compton effect again**

$$\gamma + e \rightarrow \gamma' + e'$$



original photograph



Nobel Lecture 1927

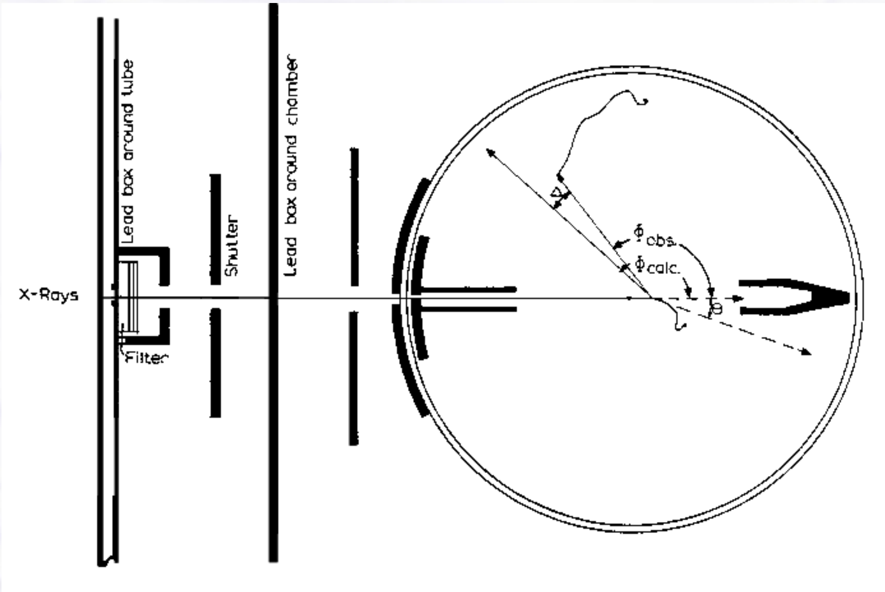


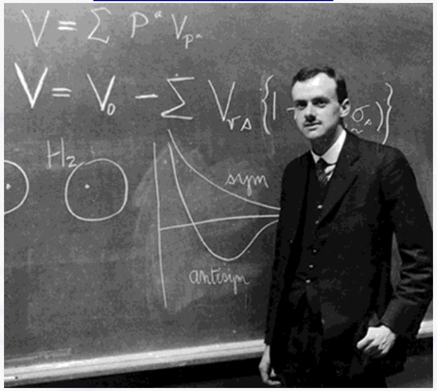
Fig. 10. An electron recoiling at an angle θ should be associated with a photon deflected through an angle φ.

Nobel Lecture 1927

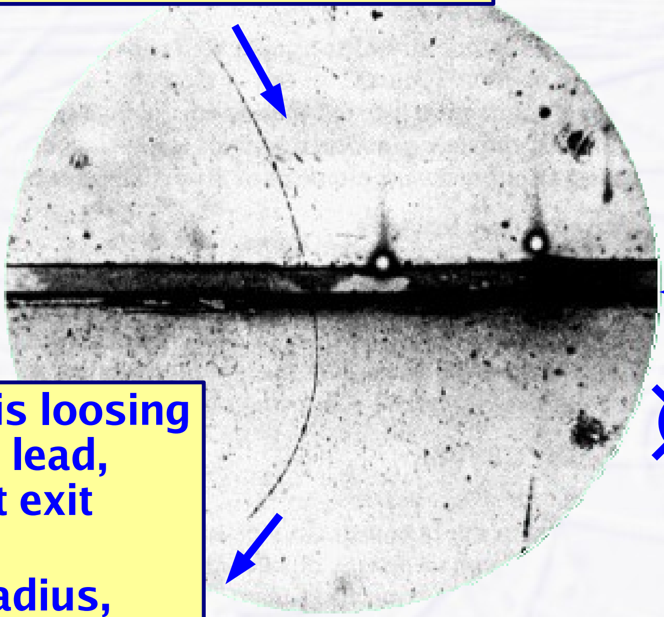
Cloud Chamber III

- Was also used for the discovery of the positron
  - predicted by Paul Dirac 1928 (Nobel Prize 1933)
  - found in cosmic rays by Carl D. Anderson 1932 (Nobel Prize 1936)

Paul Dirac



downward going positron, 63 MeV



6 mm lead plate

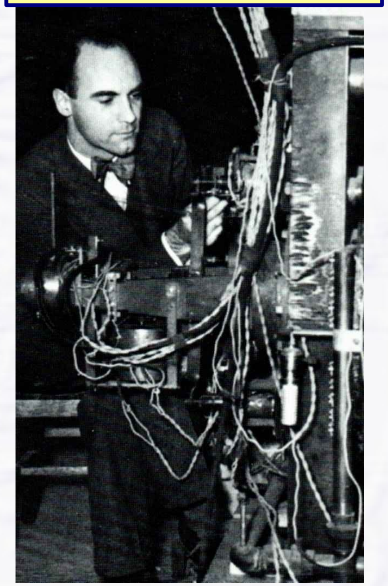
1.5 T magnetic field

positron is loosing energy in lead, 23 MeV at exit → smaller radius, this defines the track direction!

Anderson also found the muon in 1936, the first 2nd generation particle in the Standard Model

Isidor Isaac Rabi said: “Who ordered that?”

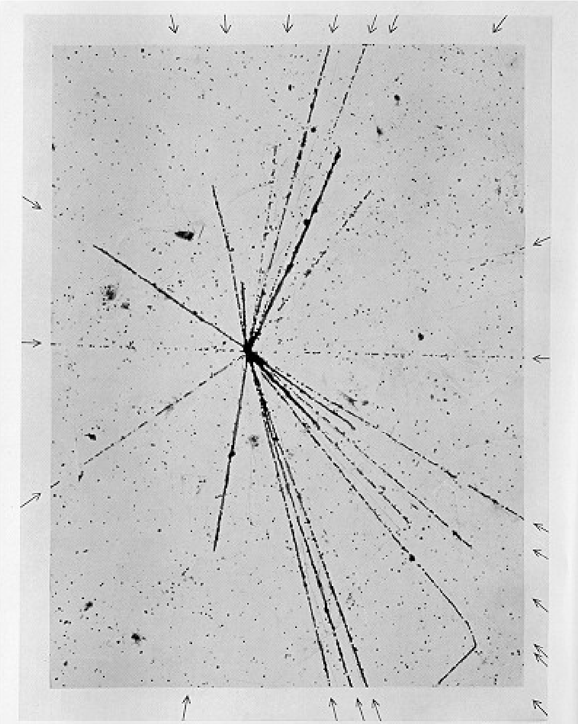
Carl D. Anderson



Nuclear Emulsion I

- **Pioneered by Marietta Blau between 1923 – 1938 (no Nobel Prize)**
  - photographic emulsion layer, 10 – 200 µm thick, uniform grains of 0.1 – 0.3 µm size
  - very high resolution for particle tracks
    - analysis of developed emulsion by microscope

Marietta Blau



'EXPLOSIVE' DISINTEGRATION OF A NUCLEUS

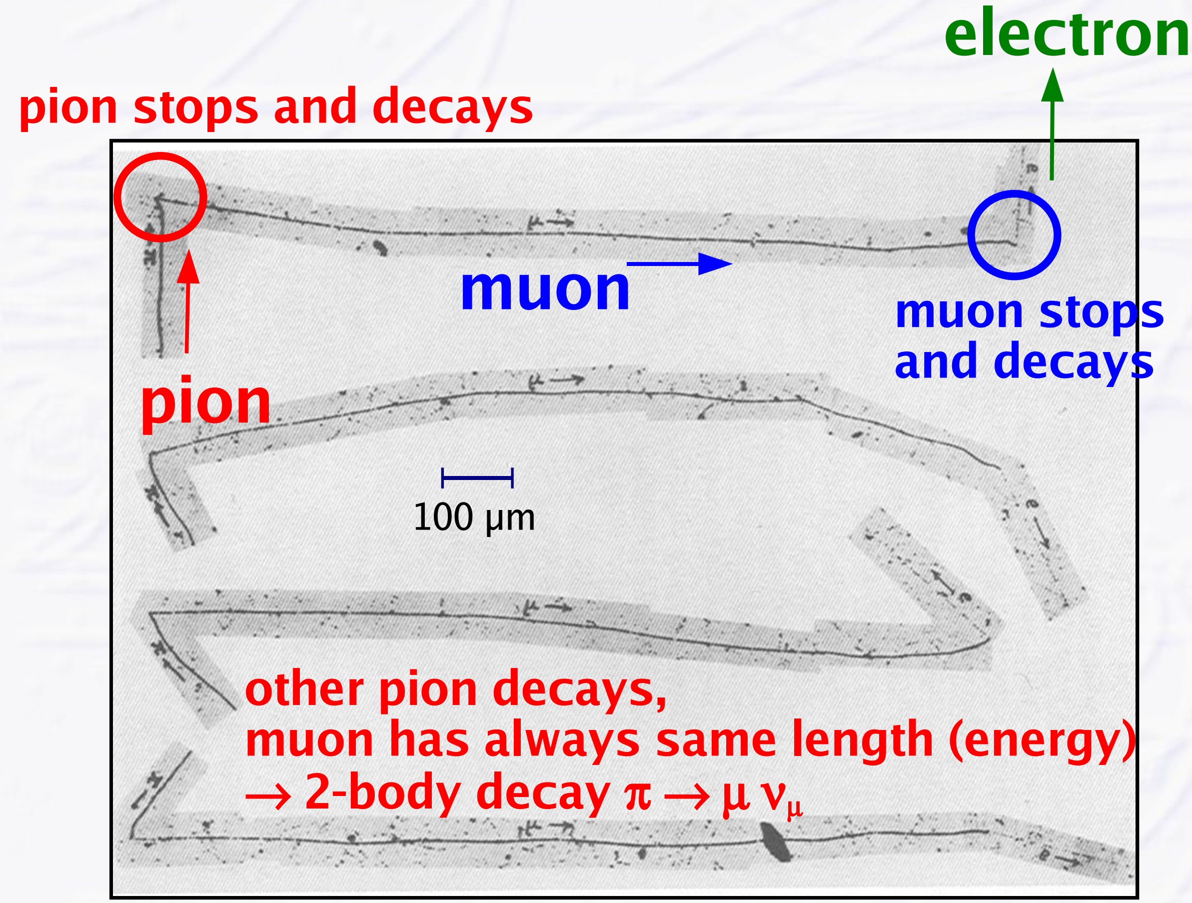
nuclear disintegration from cosmic rays, observed1937 for the first time

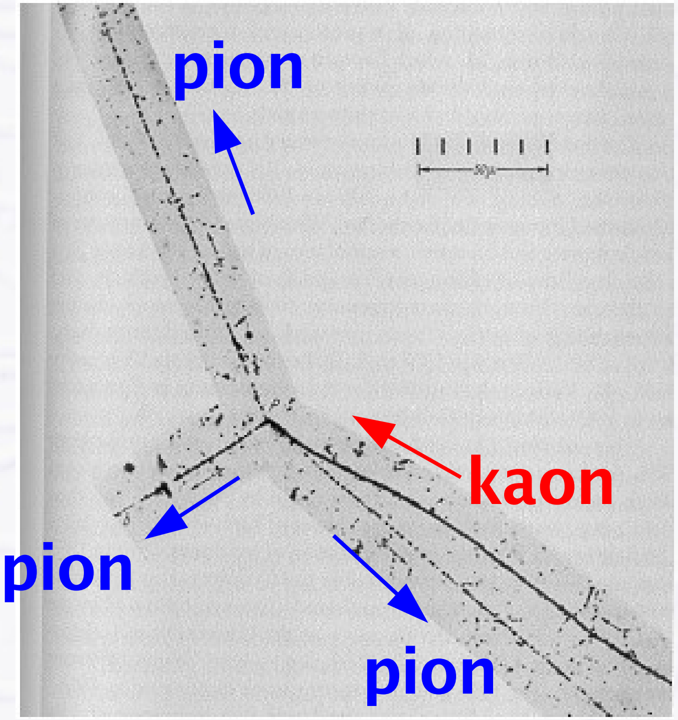
- **Since early 20th century**
  - important role of photography to study radioactivity
  - but capability to make individual tracks visible not seen until nuclear emulsion technique was developed

Nuclear Emulsion II

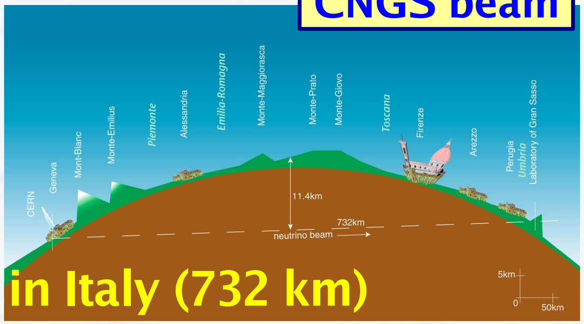
- Discovery of the pion in cosmic rays by Cecil Powell 1947 (Nobel Prize 1950)
- Discovery of the kaon 1949 (G. Rochester)

Cecil Powell



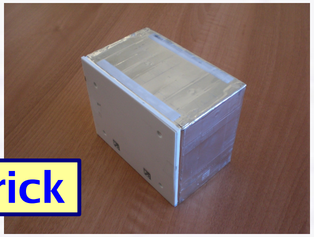


Nuclear Emulsion III

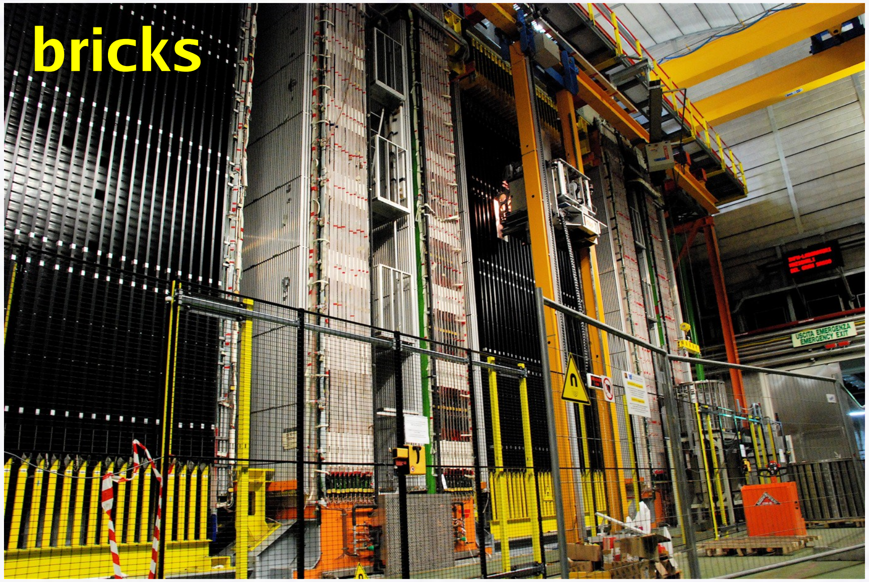


CNGS beam

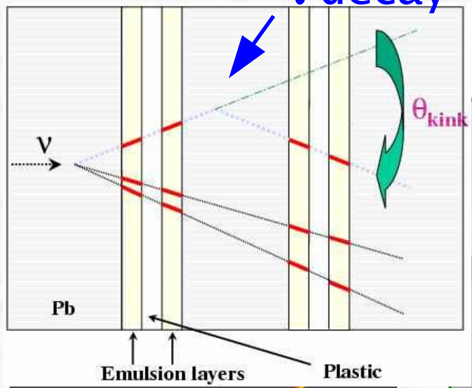
- **Still used in actual experiments with highest precision requirements over a large volume**
  - ν_μ beam sent from CERN to Gran Sasso Underground lab in Italy (732 km)
  - OPERA experiment is searching for ν_τ appearance after neutrino oscill. $\nu_\mu \rightarrow \nu_\tau$
    - need to reconstruct τ decays (ν_τ + N $\rightarrow \tau^-$ + X) (few ~100 µm track length)
    - 235'000 "bricks" (1.7 ktons) of lead + emulsion sheets

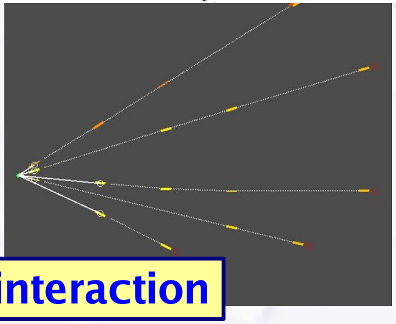


single brick

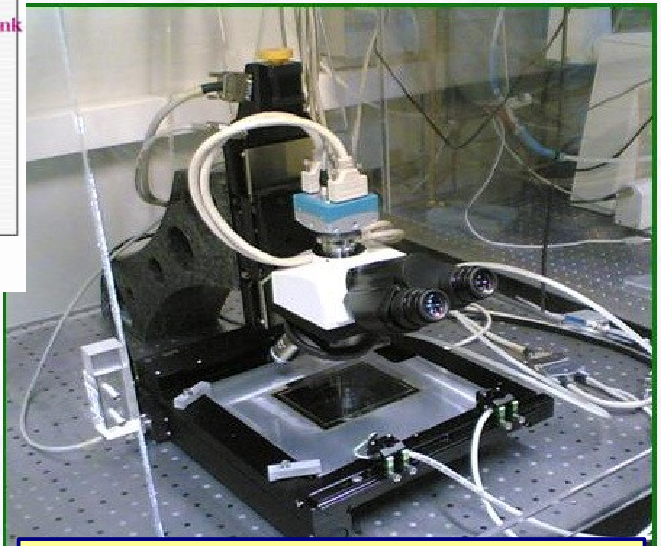


OPERA at Gran Sasso





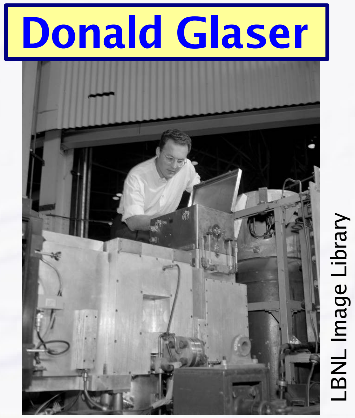
ν_μ interaction



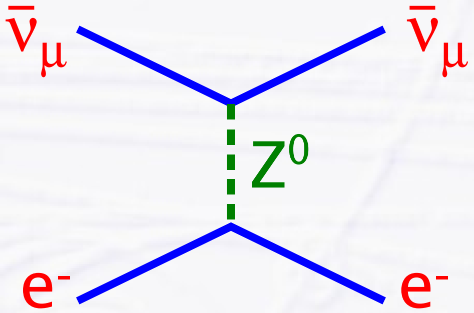
automatic emulsion scanning

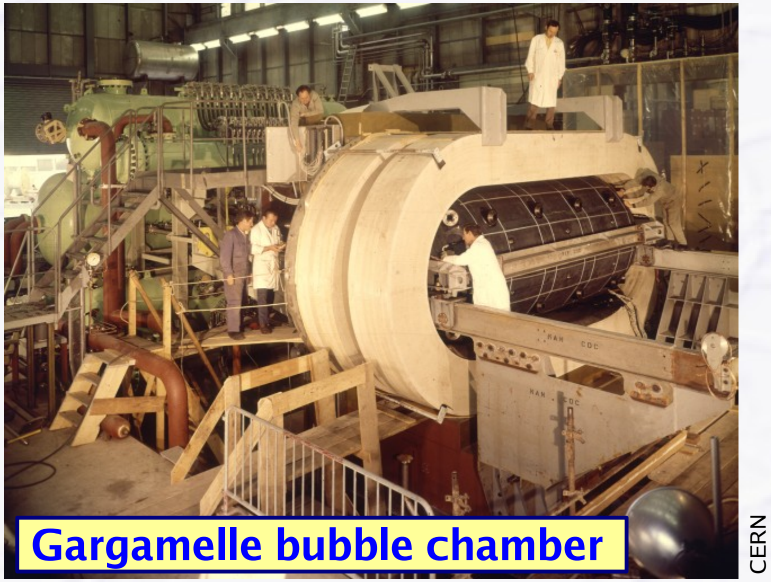
Bubble Chamber I

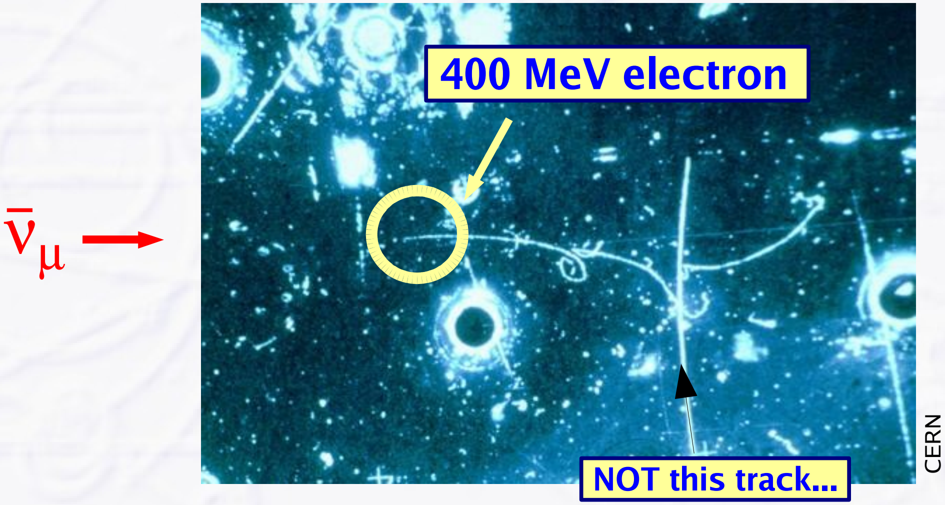
- Intented 1952 by Donald Glaser (Noble Prize 1960)
  - similar to could chamber
  - ➔ chamber with liquid (e.g. H_2) at boiling point ("superheated")
  - ➔ charged particles leave trails of ions
  - formation of small gas bubbles around ions



was used at discovery of the "neutral current"
(1973 by Gargamelle Collaboration, no Noble Prize yet)

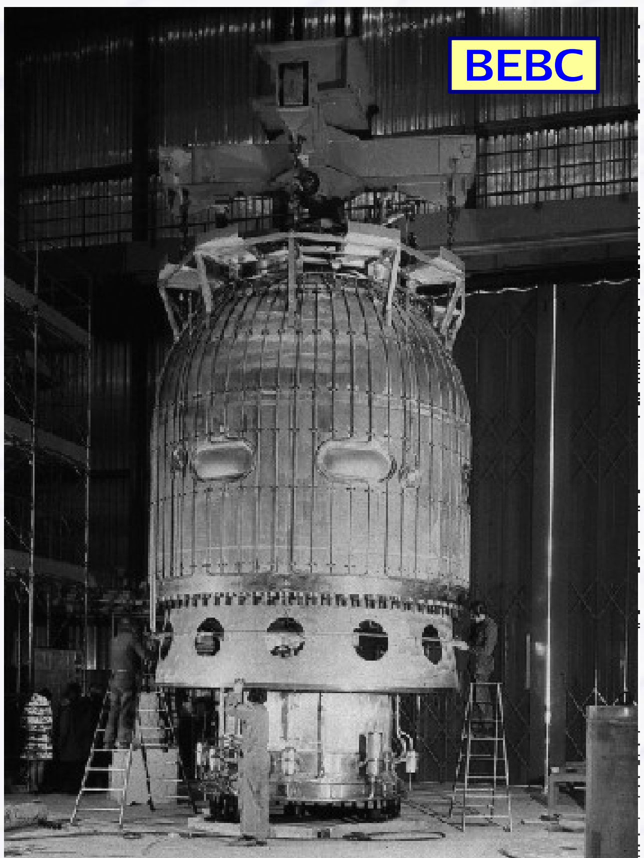


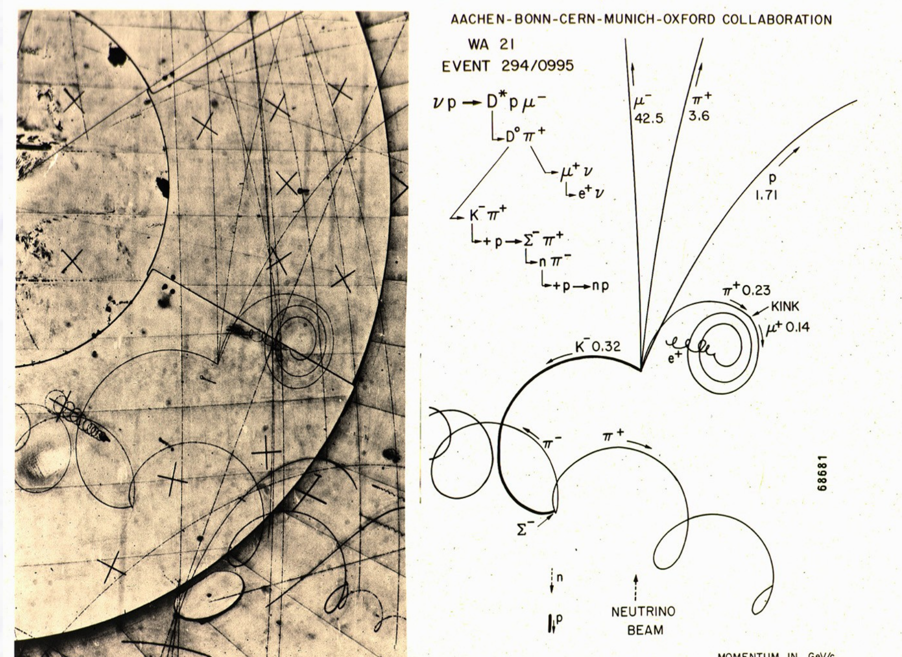




Bubble Chamber II

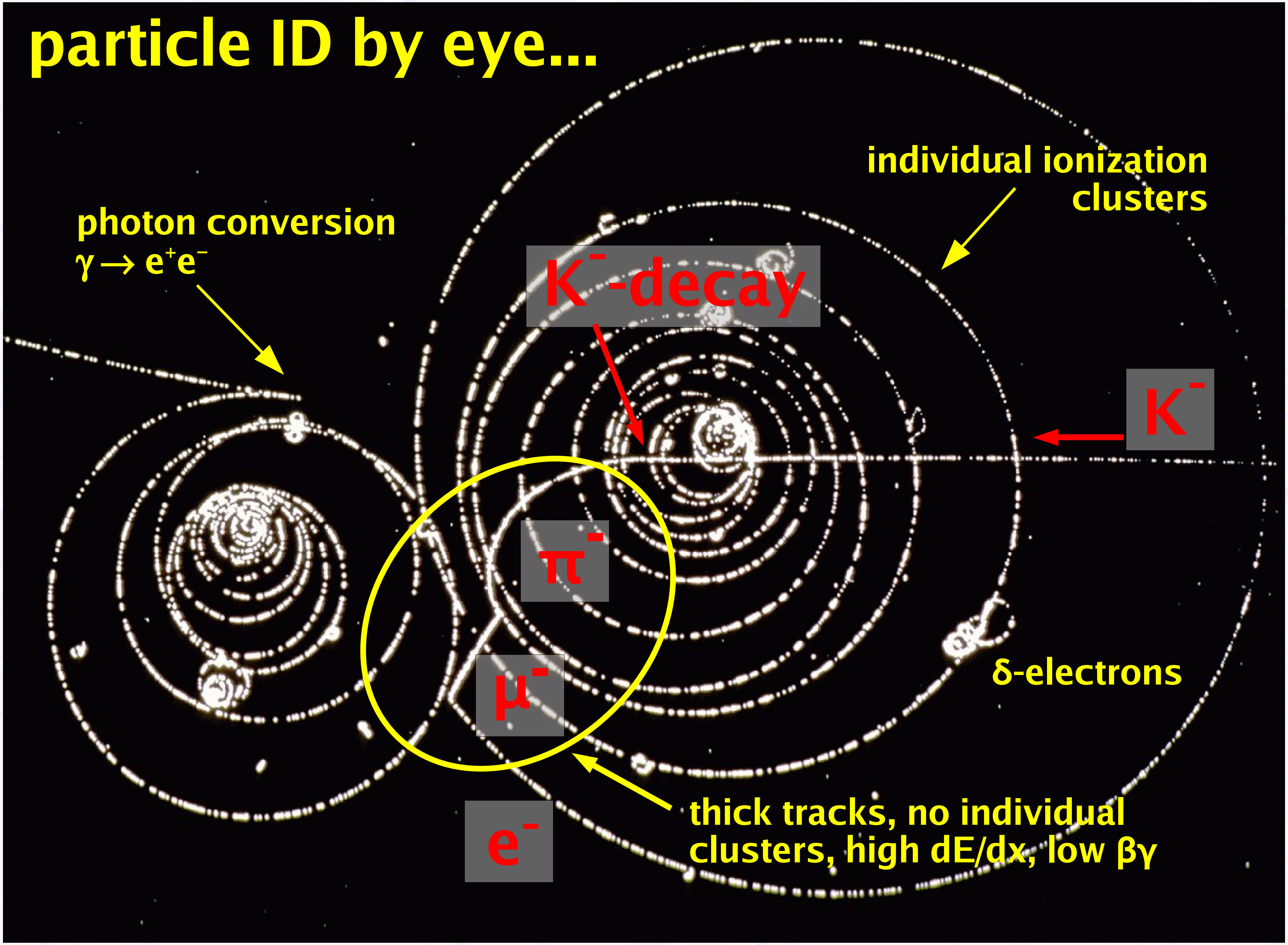
- **BEBC (Big European Bubble Chamber) at CERN, 1973 – 1984**
  - **largest bubble chamber ever built (and the last big one...), ∅ 3.7 m**
  - **6.3 million photographs taken, 3000 km of developed film**
  - **now displayed in permanent exhibition at CERN**





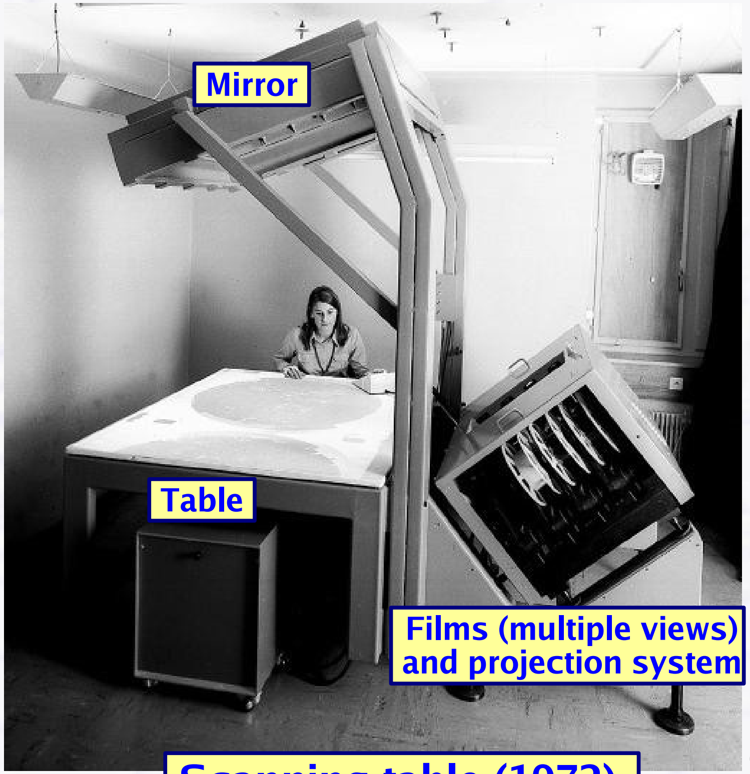
production of D* meson
with long decay chain

Bubble Chamber III



Bubble Chamber IV

- **Advantages of bubble chambers**
  - liquid is
    BOTH detector medium AND target
  - high precision
- **Disadvantages**
  - SLOW!!!
    - event pictures taken with cameras on film
    - film needs to be developed, shipped to institutes
    - and optically scanned for interesting events
  - Need FASTER detectors (electronic!)



Scanning table (1972)

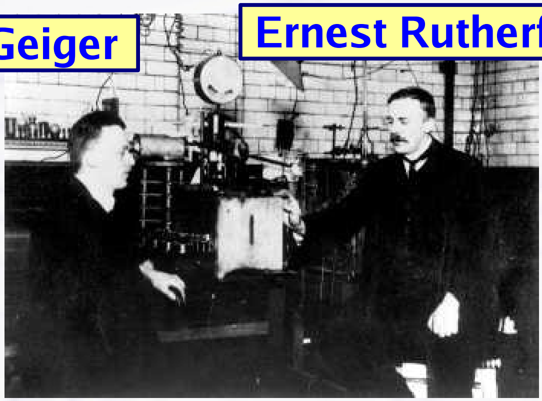
- **However:**
  Some important social side effects of bubble chamber era...
  - scanning was often done by young “scanning girls” (students)...
  - ...who later got married with the physicists...

Early "Electronic" Detectors - Spinthariscope

- **1911: Ernest Rutherford + studied (elastic) scattering of α particles on gold atoms** (famous Rutherford experiment)
  - ➾ discovery of atomic nucleus: small (heavy) positively charged nucleus orbited by electrons
- **Zinc sulfide screen with microscope (spinthariscope by William Crookes 1903) was used to detect scattered α particles**
  - ➾ light flash was observed by eye
    - to increase light sensitivity, "bella donna" (from the deadly night shade plant = Tollkirsche) was often used to open eye's pupil

Hans Geiger

Ernest Rutherford



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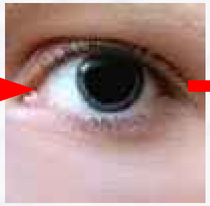
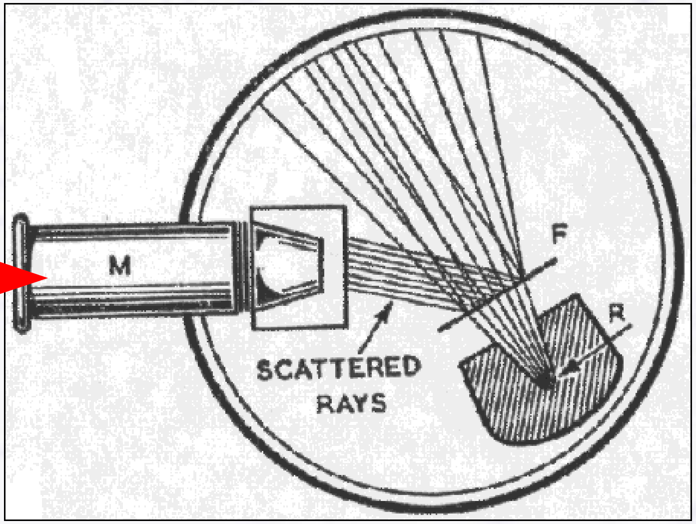
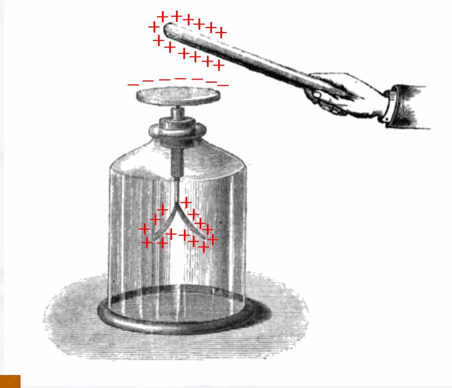
deadly night shade

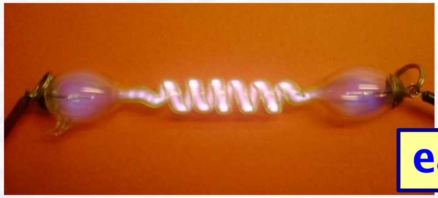




Early Electronic Detectors - Electroscope

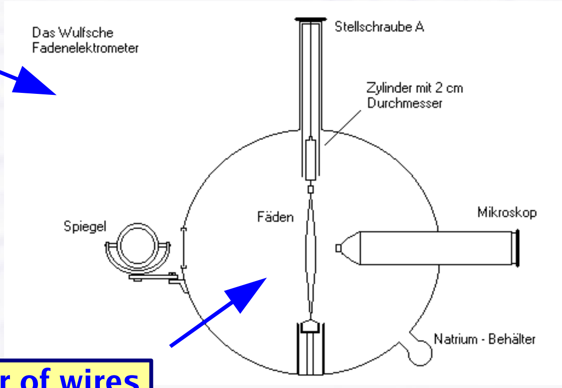


- Gold-leaf electroscope already invented 1787 by Abraham Bennet
- End of 19th century raising interest on electricity in gases
  - cathode ray tubes, glow discharges
  - observation:
    charged electroscope is loosing its charge in dry air after some time
    - source of conductivity? ionisation by recently discovered radioactivity?



early cathode ray tube

- Victor Hess discovered cosmic rays 1912 (Nobel Prize 1936)
  - used calibrated string electrometer by Theodor Wulf
  - found increasing ionisation at higher altitudes at a series of balloon ascents
    - not related to sun radiation!

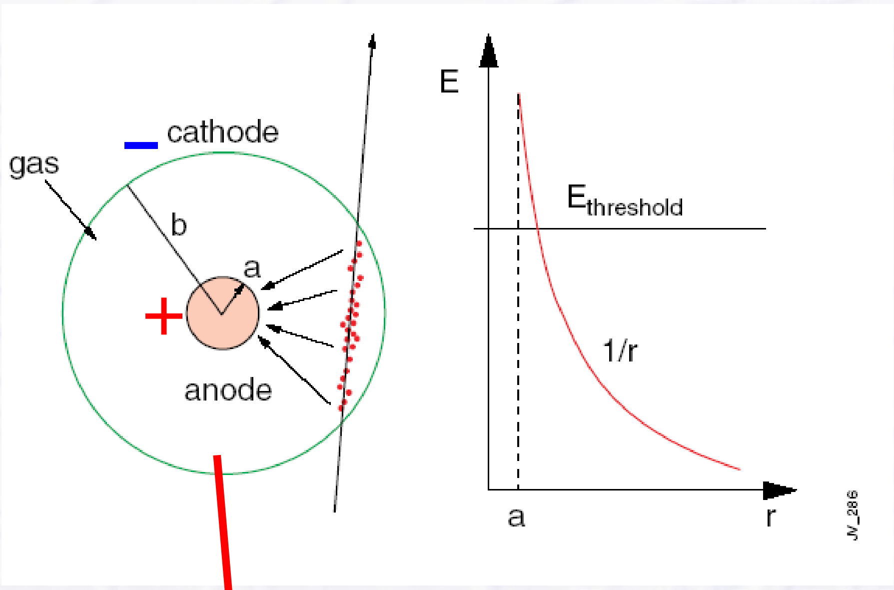


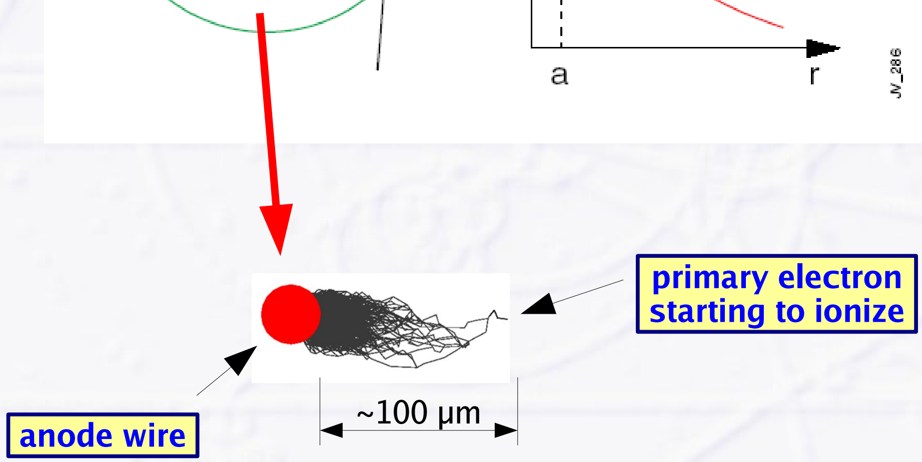
pair of wires

Victor Hess in balloon

Geiger-Müller Tube

- **The Geiger-Müller tube (1928 by Hans Geiger and Walther Müller)**
  - **Tube filled with inert gas (He, Ne, Ar) + organic vapour**
  - **Central thin wire (20 – 50 μm ∅) , high voltage (several 100 Volts) between wire and tube**

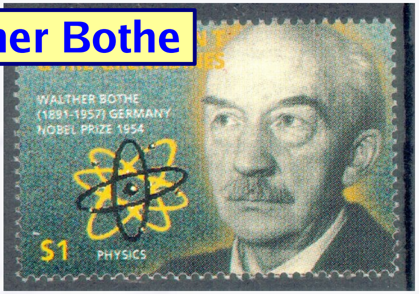




- **Strong increase of E-field close to the wire**
  - **electron gains more and more energy**
- **above some threshold (>10 kV/cm)**
  - **electron energy high enough to ionize other gas molecules**
  - **newly created electrons also start ionizing**
- **avalance effect: exponential increase of electrons (and ions)**
- **measurable signal on wire**
  - **organic substances responsible for "quenching" (stopping) the discharge**

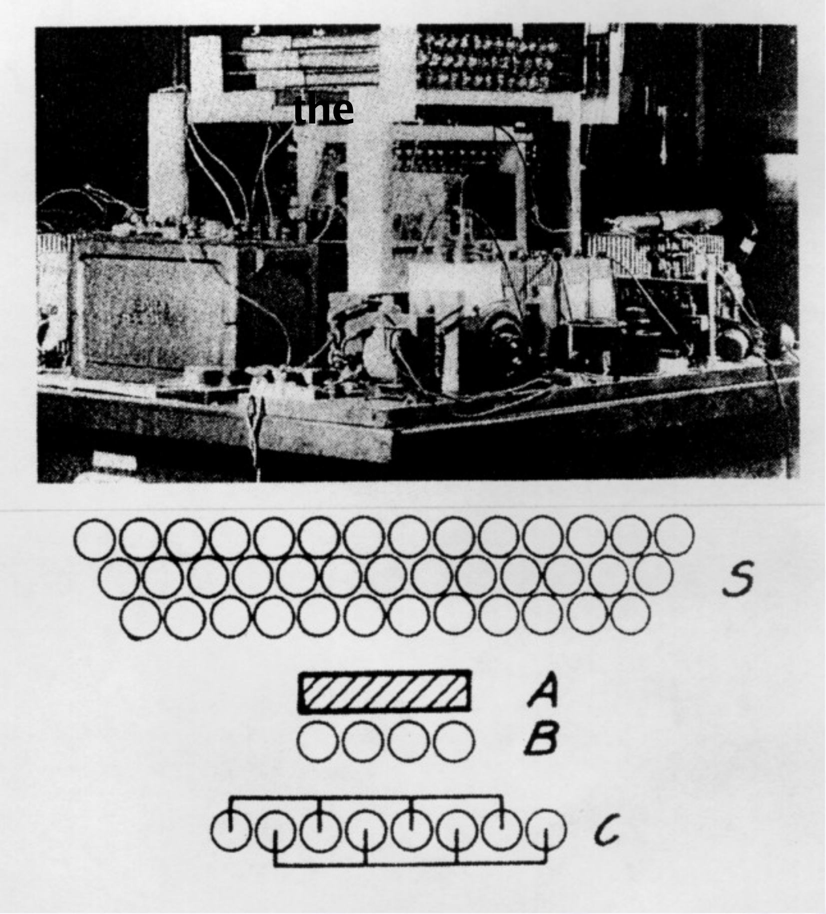
Coincidence Units

Walther Bothe



- **“Zur Vereinfachung von Koinzidenzzählungen”, Walther Bothe 1929 (Nobel Prize 1954)**
  - **single tube has no information on direction of incoming particle**
    - **two or more tubes giving signals within the same time window give direction**
    - **also information if two particles come from the same decay**

cosmic ray telescope 1934



coincidence unit with vacuum tubes for 2 Geiger-Müller tubes

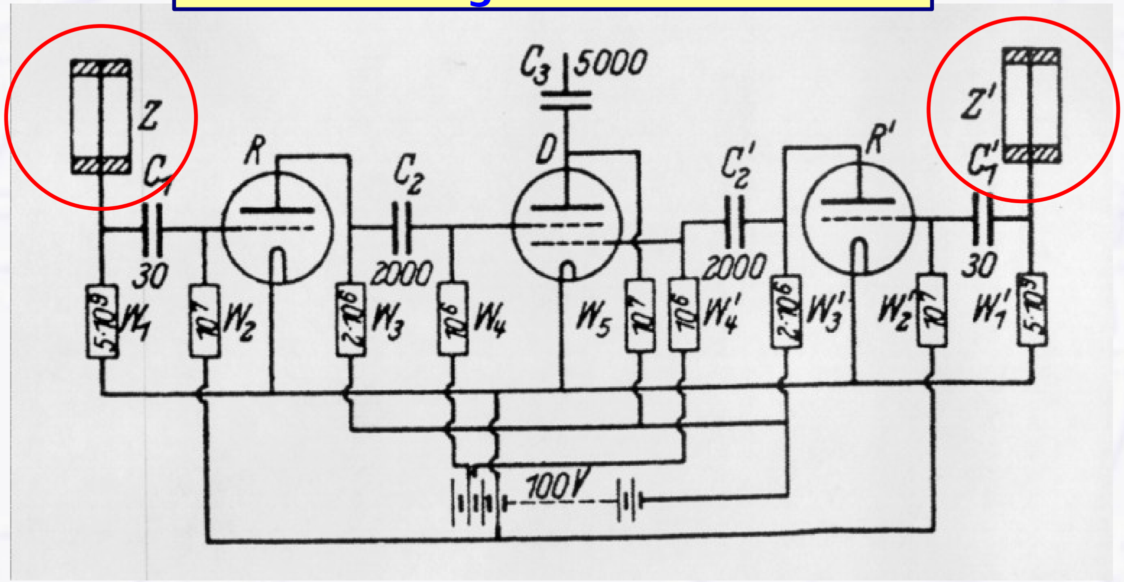


Photo Multiplier Tubes (PMT)

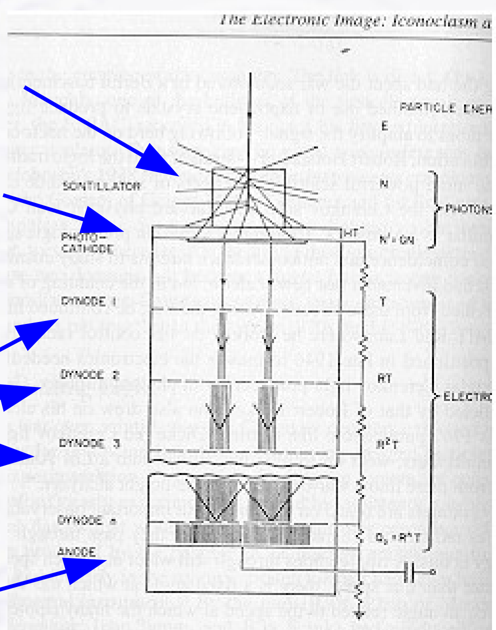
- **Invented 1934 by Harley Iams and Bernard Salzberg (RCA Coorperation)**
  - based on photo effect and secondary electron emission
  - sensitive to single photons, replaced human eye + belladonna at scintillator screen
  - ➔ **first device had gain ~8 only but already operated at >10 kHz (human eye: up to 150 counts/minute for a limited time)**
  - nowadays still in use everywhere, gain up to 10^8
  - recent developments: multi-anode (segmented) PMTs, hybrid and pure silicon PMs

plastic scintillator

photo cathode

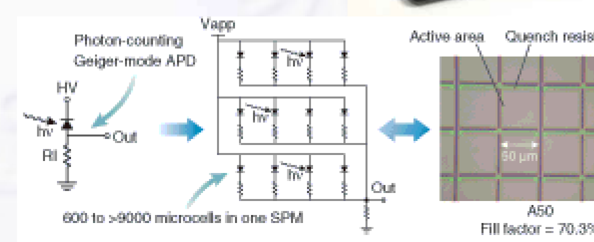
dynodes: secondary electron emission

anode



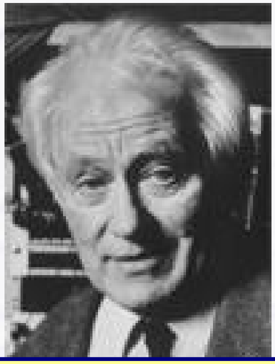
classic PMT

Silicon PM = array of avalance photo diodes

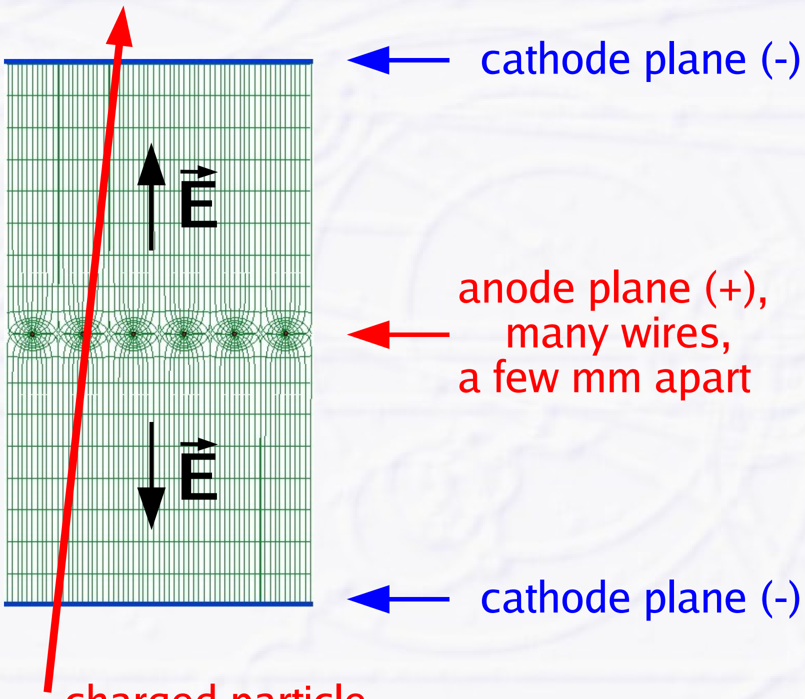


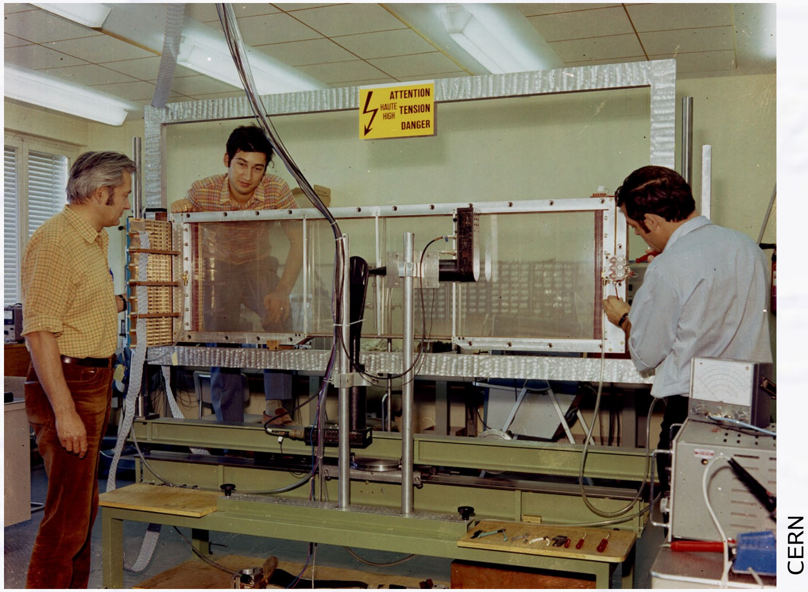
Multi Wire Proportional Chambers I

- **Geiger-Müller tube just good for single tracks with limited precision** (no position information inside tube)
  - ➔ **in case of more tracks more tubes are needed or...**
- **Multi Wire Proportional Chamber (MWPC)** (1968 by Georges Charpak, Nobel Prize 1992)
  - ➔ **put many wires with short distance between two parallel plates**



Georges Charpak



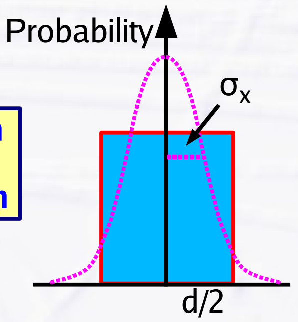


Georges Charpak, Fabio Sauli and Jean-Claude Santiard

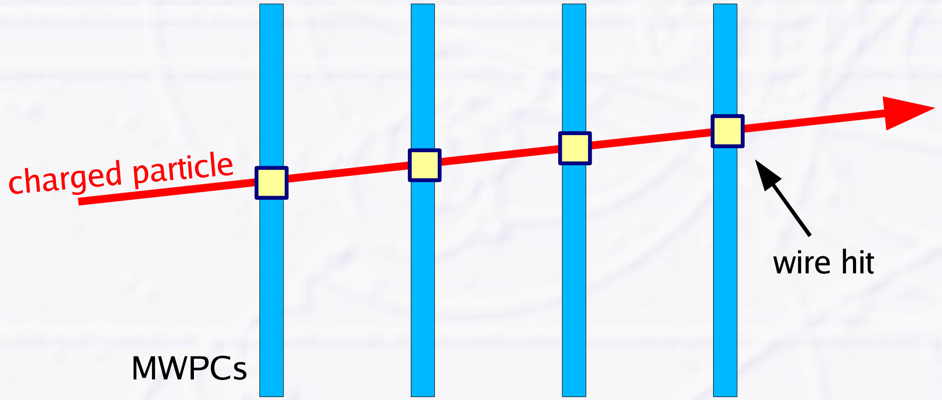
Multi Wire Proportional Chambers II

- Multi Wire Proportional Chamber (MWPC)
  - was first electronic device allowing high statistics experiments
  - with multiple channels and reasonable resolution
- Typically several 100 – 1000 wires, ~ 1 mm spacing
  - if charged particle is passing the MWPC → one wire gives signal
  - resolution: $\sigma_x \approx \frac{d}{\sqrt{12}}$ e.g. for d = 1 mm → ~300 µm

we don't know where the particle went through within the 1 mm spacing = "flat" probability distribution, this is the width of an equivalent Gaussian distribution



- If many MPWCs are put one after each other
  - each particle creates one point per MWPC (~300 µm resolution per point)

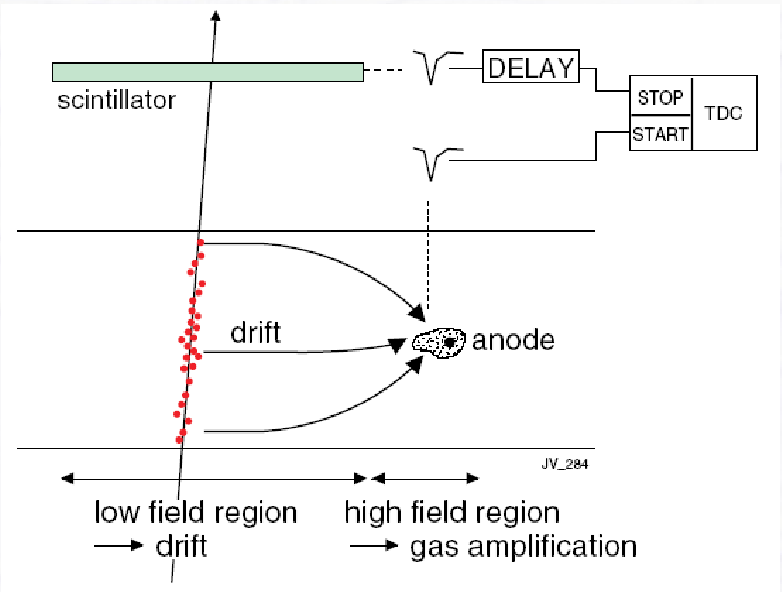


can reconstruct track with e.g. 4 points

one coordinate only, use additional MWPCs tilted by 90° to get other coordinate

Drift Chamber

- Resolution of MWPCs limited by wire spacing
  - better resolution → shorter wire spacing → more (and more) wires...
    - larger wire forces (heavy mechanical structures needed)
    - (too) strong electrostatic forces when wires too close to each other
- Solution by A. H. Walenta, J. Heintze, B. Schürlein 1971
  - obtain position information from drift time of electrons (fewer wires needed)
    - drift time = time between primary ionization and arrival on wire (signal formation)



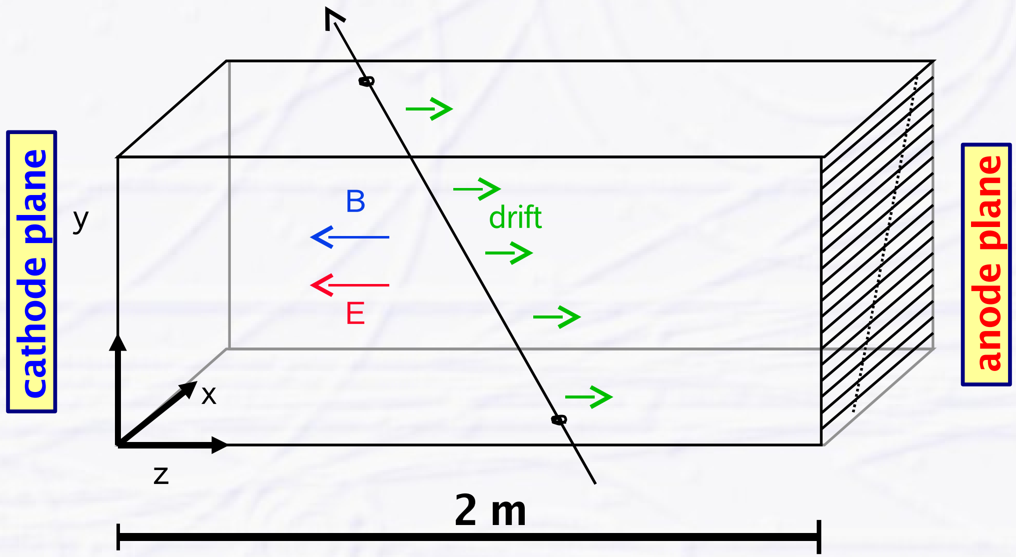
start signal (track is passing drift volume) has to come from external source: scintillator or beam crossing signal

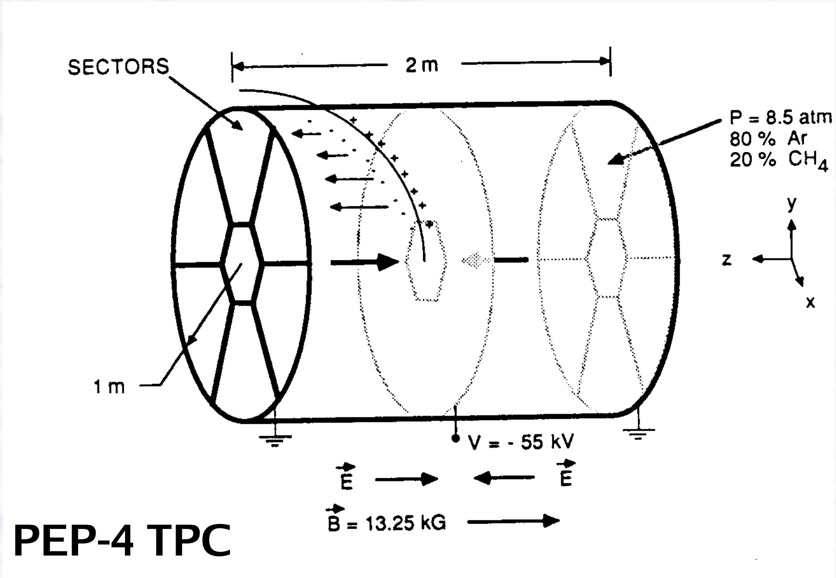
- Need to know drift velocity v_D to calculate distance s to wire (= track position within the detector)

$$s = \int_{t_{start}}^{t_{stop}} v_D \, dt$$

Time Projection Chamber (TPC)

- **A 3D-imaging chamber with rather long drift length**

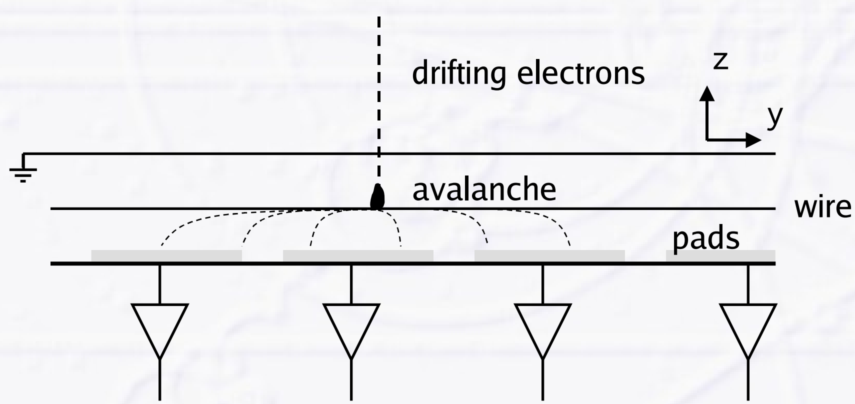


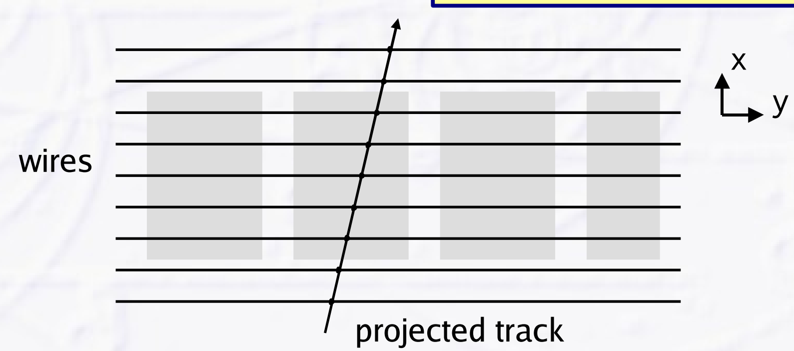


- **homogeneous B- and E-fields**
- **anode plane equipped with MWPC wire chambers**

Problem: pads have to be large (otherwise not enough induced charge)

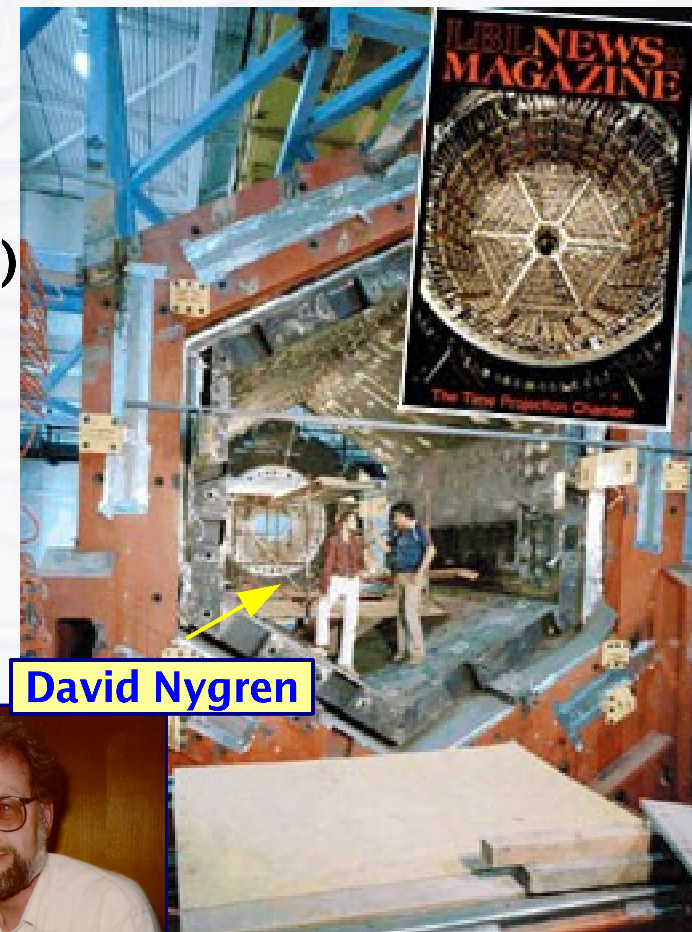
Limits number of points and double track resolution

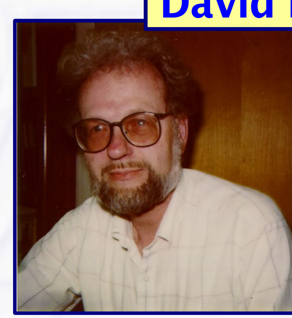




Time Projection Chamber (TPC)

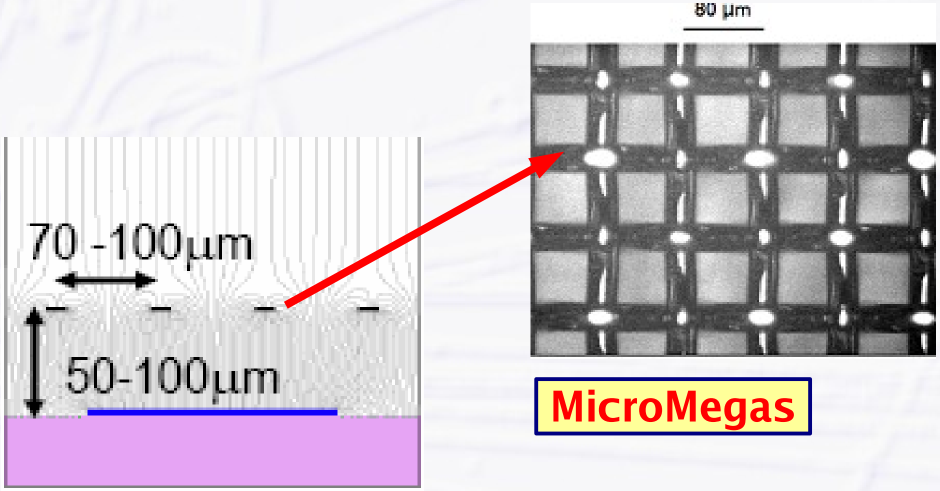
- Invented by David Nygren (Berkeley) in 1974
- Proposed as central tracking device for the PEP-4 detector at the PEP e^+e^- collider at SLAC 1976
- More (and even larger) TPCs were built or are planned at other colliders
  - TRISTAN (KEK, 2 x 32 GeV e^+e^-, 1986 – 1995)
    - TOPAZ
  - LEP (CERN, 2 x 104 GeV e^+e^-, 1989 – 2000)
    - ALEPH, DELPHI
  - RHIC (BNL, 2 x 100 GeV/nucleus, 2001 –)
    - STAR
  - LHC pp and Pb-Pb collider (CERN)
    - ALICE
  - ILC e^+e^- collider
    - ILD

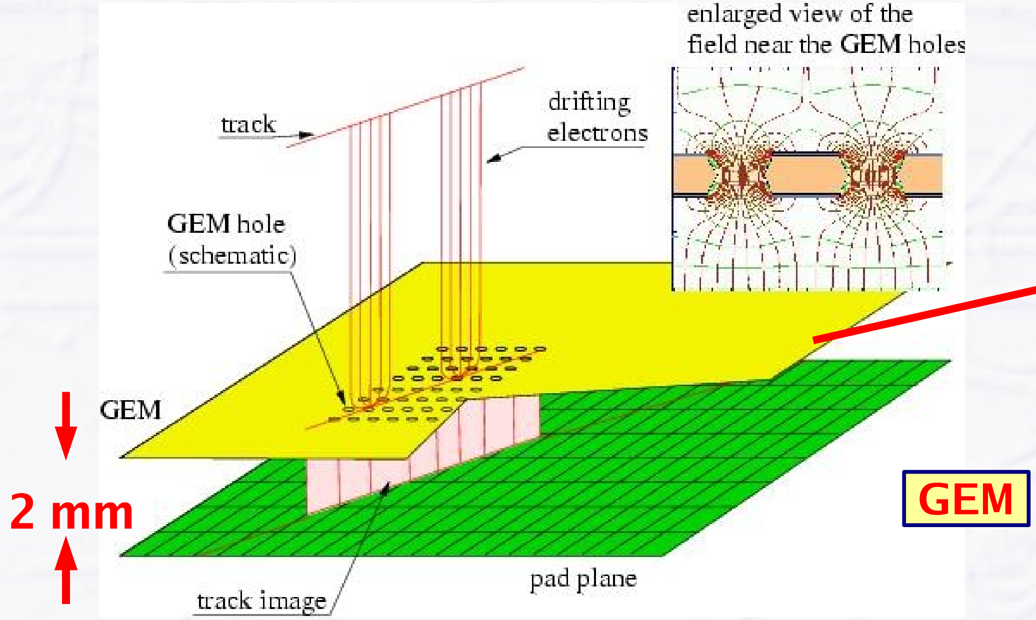


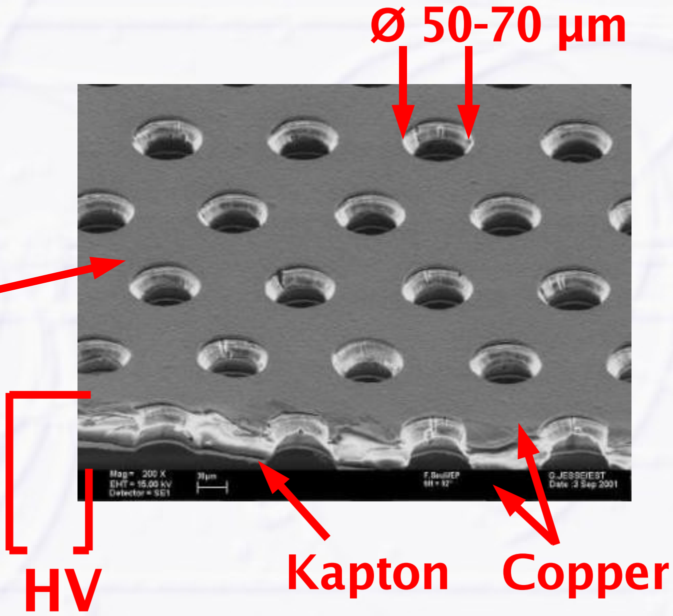


Recent Developments: Micro Pattern Gas Detectors (MPGD)

- **Replace wires at TPC with Micro Pattern Gas Detectors**
  - **MicroMegas (metallic micromesh)**
  - **GEM (Gas Electron Multiplier)**
- **Concept**
  - **2D structures**
    with holes + underlying pads
  - **Gas amplification inside holes,**
    collect electrons on small pads,
    few mm2





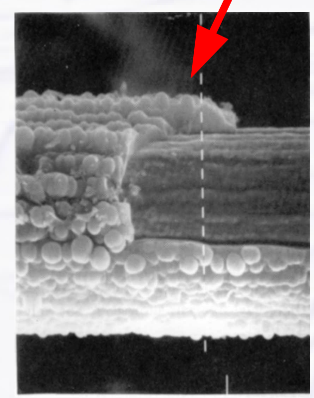


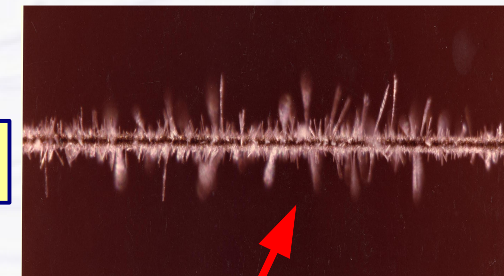
Wire Chambers – Ageing

black magic...

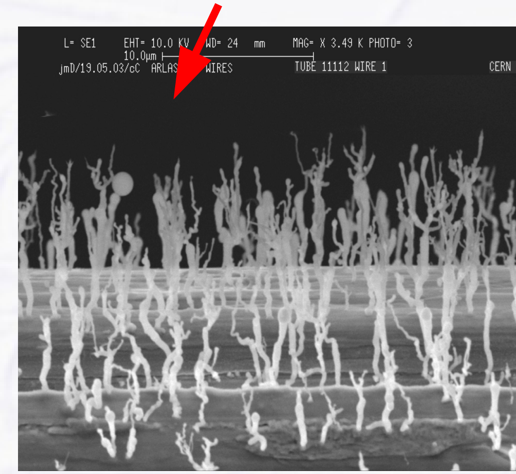
- **Wire Chambers don't work/live forever**
  - gas avalance region close to wire is region of plasma formation
    - ...and plasma chemistry not well understood in general
- **Avalance region**
  - dissociation of detector gas and pullutants
  - formation of highly active radicals
  - polymerization of organic quenchers
  - insulating deposits on anodes and cathodes

hard deposits, typically SiO_2 (quartz)

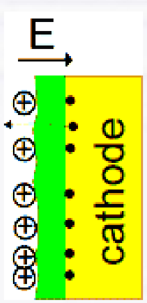




whiskers, typically carbon fibers



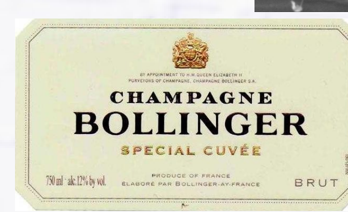
Anode: increase of wire diameter
reduced and variable E-field
variable gain and energy resolution



Cathode: ions on top of insulating layer cannot recombine
built-up of strong E-field across insulating layer
electron field emission and microdischarges

"Malter effect", first seen by L. Malter in 1936:
L. Malter; Phys. Rev. 50 (1936), 48

Conclusions of an ageing workshop many years ago:
CO_2 helps with water, and alcohol admixtures...

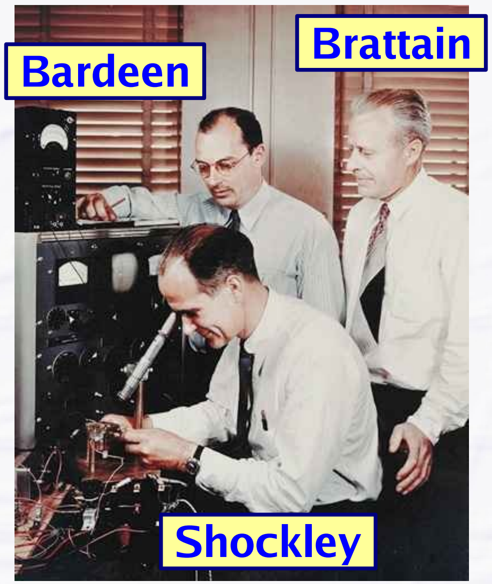


Gaseous Detectors in LHC Experiments

- Mainly used in Muon Systems (ALICE, ATLAS, CMS, LHCb)
  - precise muon tracking (drift tubes) and triggering (RPC plates)
- Also in Inner Tracking system (ALICE, ATLAS, LHCb, TOTEM)
  - mainly straw tubes = small, light weighted tubes
  - but not the innermost detector layer
    - domain of semi conductor (silicon) detectors
- Specific LHC challenges (for gaseous detector systems)
  - high track rate (25 ns) and density (~1000 tracks per bunch crossing)
    - need short drift times (avoid integrating over too many bunch crossings) + high granularity = fast gases, small sized detectors
    - need "ageing-free" gases/detectors
      - lots of effort spent over years in this field
      - extensive irradiations with Gamma irradiation source, lab studies with X-ray sources etc.

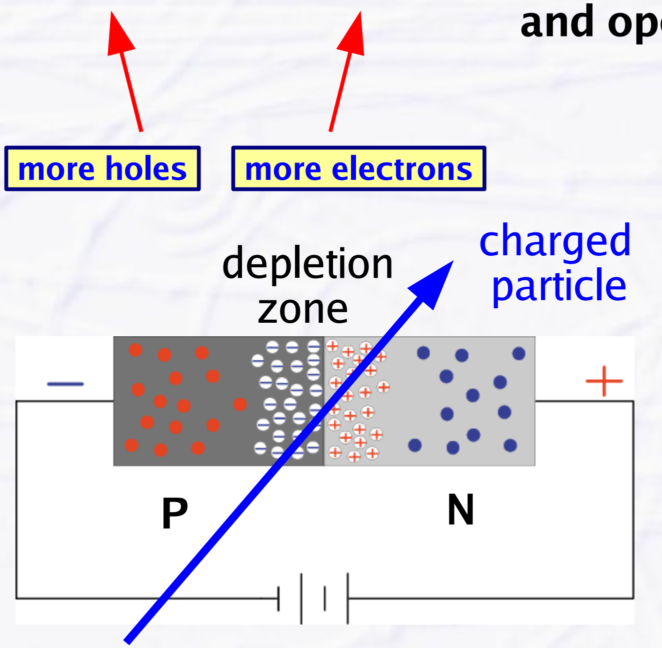
Solid State Detectors

- **First transistor was invented 1947 by William B. Shockley, John Bardeen and Walter Brattain (Nobel Prize 1956)**
  - transistors and diodes became common soon after



➔ **Germanium diodes were used for particle detection**

- p-type and n-type doped silicon material is put together and operated with reversed voltage



➔ **around junction of p- and n-type material depletion zone is created**

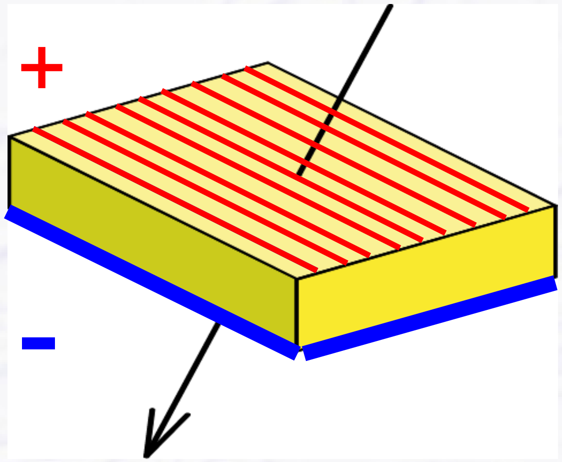
➔ **zone free of charge carriers**

- no holes, no electrons
- thickness of depletion zone depends on voltage, doping concentration

charged particle typically creates 20'000 – 30'000 electron/hole pairs in 300 μm thick material -> sufficient signal size

Silicon Strip Detectors

- Now take a large Si crystal, e.g. 10 x 10 cm², 300 µm thick

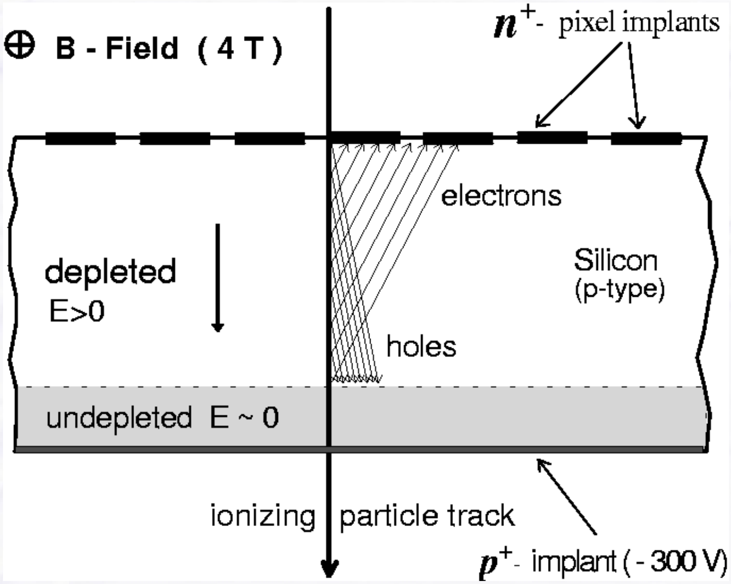


make bottom layer p-type

and subdivide the top n-type layer into many strips with small spacing

many diodes next to each other (like MWPC at wire chambers) with position information

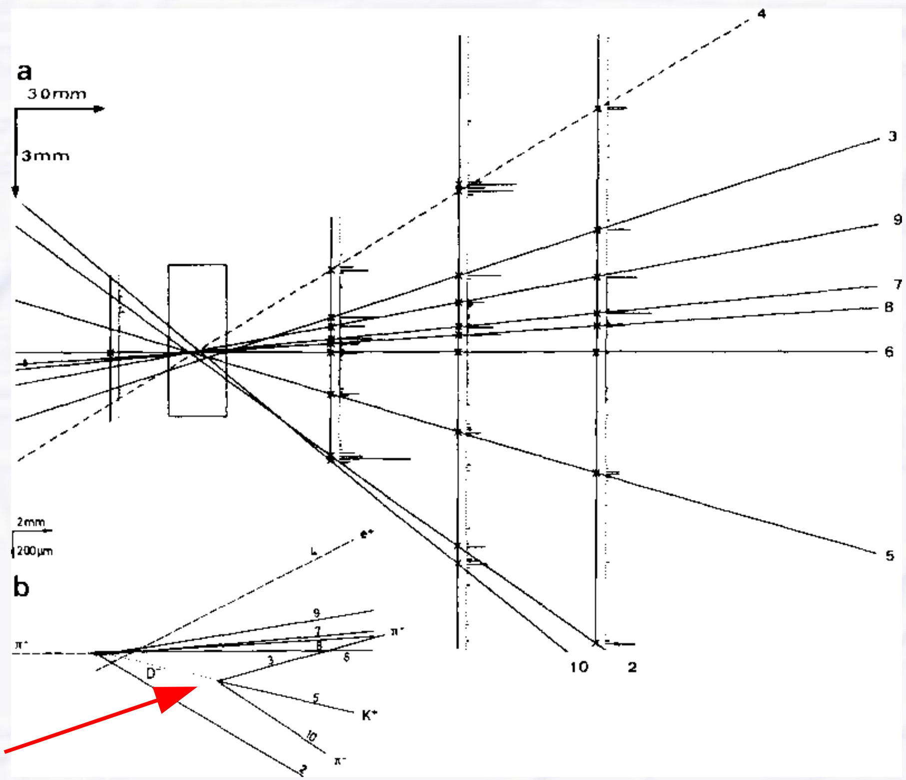
- Advantage compared to wire/gas detectors
  - strip density (pitch) can be rather high (e.g. ~20 µm)
    - high position accuracy
    - but also many electronics channels needed



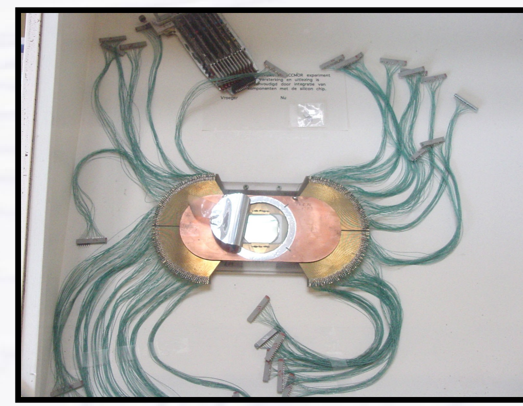
The first Silicon Strip Detector

- **First operational silicon strip detector used in an experiment (NA11 at CERN) by J. Kemmer, R. Klanner, B. Lutz et al. 1983**
  - **B. Lutz was founder of MPI Halbleiterlabor in Munich**
  - **NA11 aimed to search for new short lived particles**
    - **first observation of D_s**
      many branching ratio and lifetime measurements

Max-Planck-Institut
Halbleiterlabor



D⁻ decay



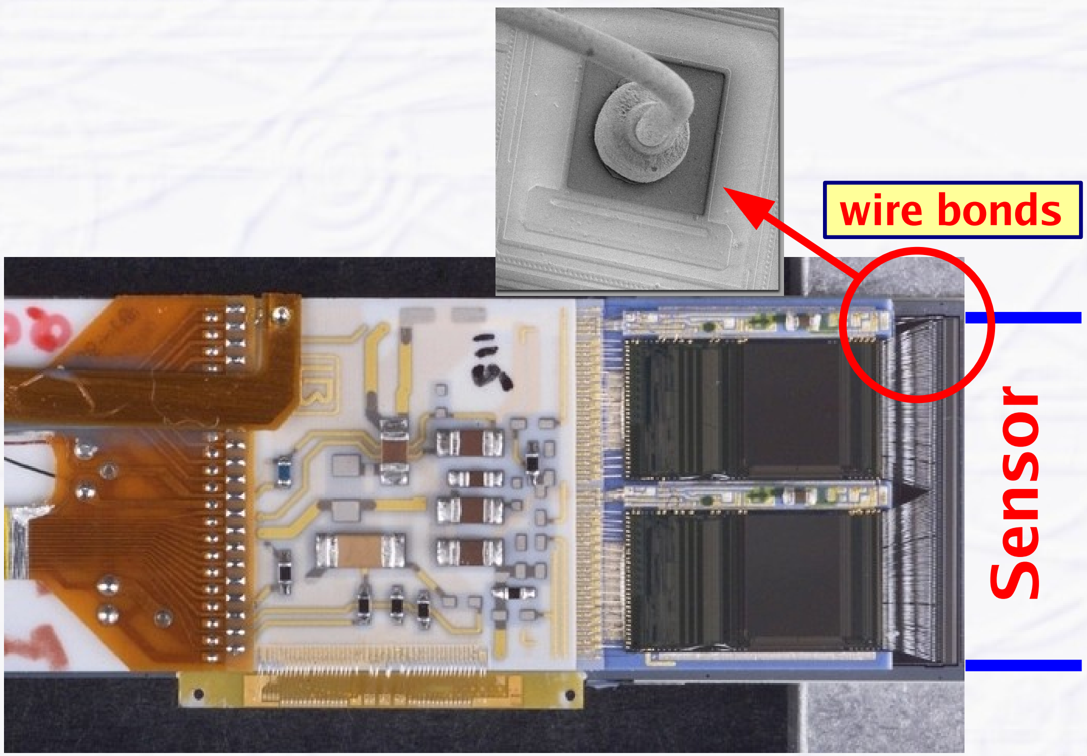
8 silicon strip planes
(4 groups of 2 planes each with tilted strips to measure xy coordinate)

24 x 36 mm² size per chip
1200 strips, 20 µm pitch
240 read-out strips
4.5 µm single hit resolution

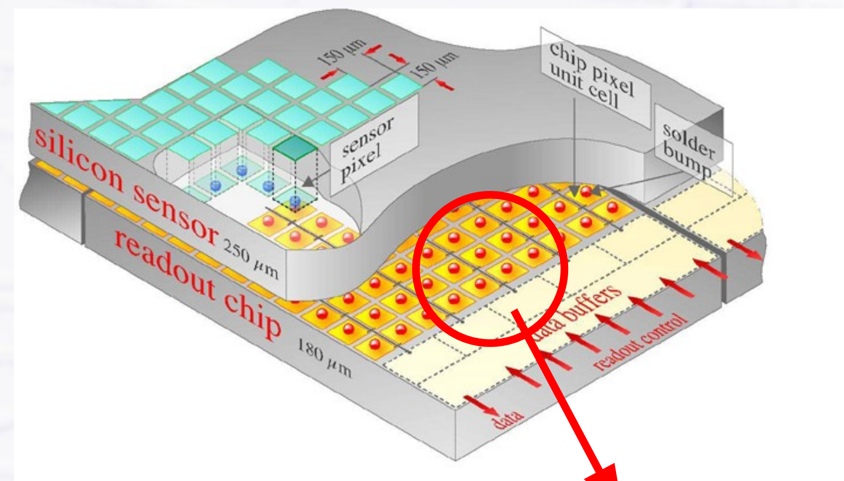
Si-Detector Electronics and Si-Pixels

- **Silicon strip detectors have a laaaarge number of electronics channels, ~10^7 each for ATLAS and CMS Si trackers**
  - requires highly integrated chips for amplification, shaping, zero suppression (only information of strips with signals is read-out) and multiplexing (put all strip signals on a few cables only)

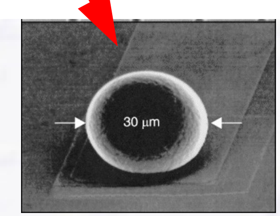
  → **electronics is directly connected to the sensor (the "multi-diode") via wire bonds**



Si-strip detectors provide only 1 coordinate,
Pixel detectors are 2D detectors

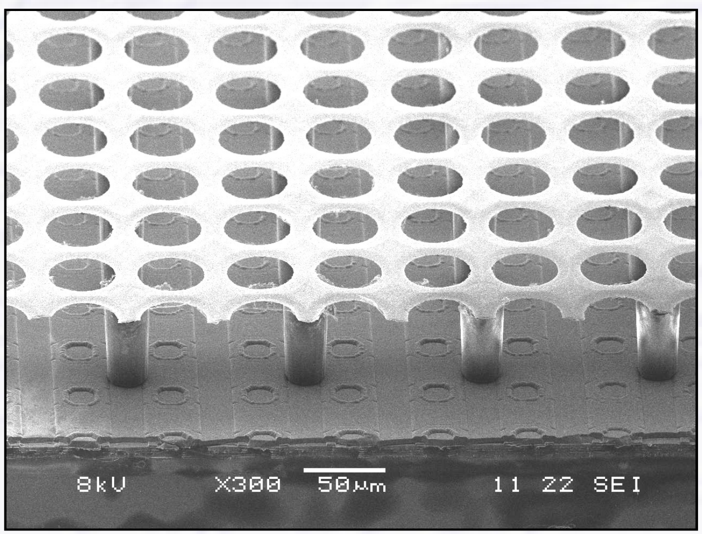


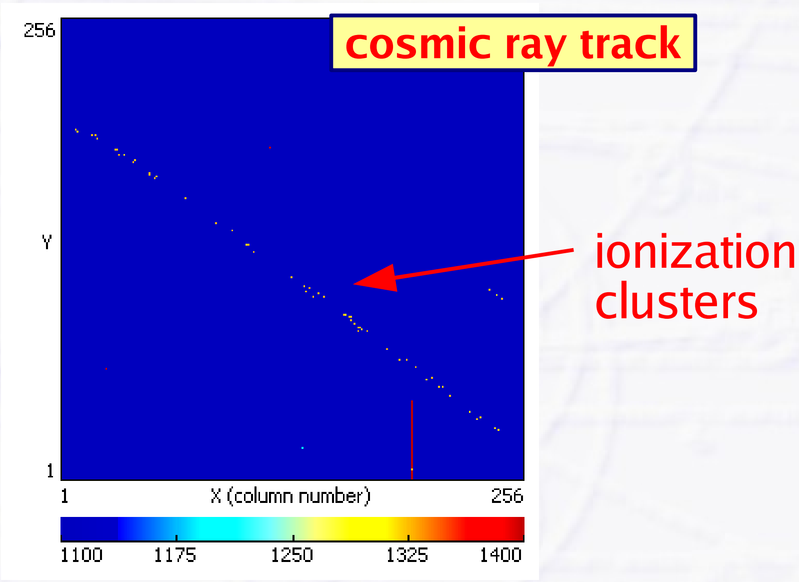
Pixel detector need "bump" bonding and have even more channels, ~10^8 - 10^9



Recent Developments: Hybrid Technologies

- Combine MPGD gaseous detector with silicon pixel detector
- Use MediPix2/TimePix chip as active TPC "padplane" for ILC detector
  - MediPix2 = 256x256 pixels with 55x55 μm^2 size for medical applications (X-ray film replacement)
  - MicroMegas mesh (provides gas amplification) integrated on top of pixel chip

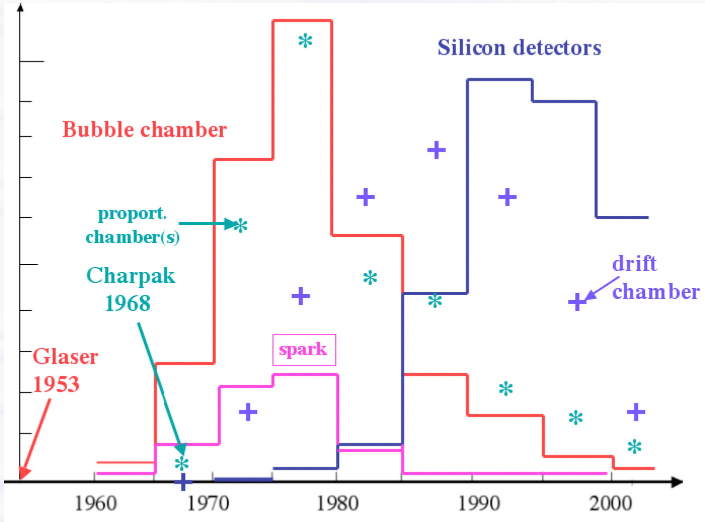




- Individual ionization visible:
  the **digital Bubble Chamber** is in reach

Detector History

- **Cloud Chambers, Nuclear Emulsions + Geiger-Müller tubes dominated until the early 1950s**
  - Cloud Chambers now very popular in public exhibitions related to particle physics
- **Bubble Chambers had their peak time between 1960 and 1985**
  - → last big bubble chamber was BEBC at CERN
- **Wire Chambers (MWPCs and drift chambers) started to dominate since 1970s**
- **Since late 1980s solid state detectors are in common use**
  - started as small sized vertex detectors (at LEP and SLC)
  - → now ~200 m^2 silicon surface in CMS tracker



- **Most recent trend: hybrid detectors**
  - → combining both gaseous and solid state technologies

A typical Today's Particle Detector

- **Cut-away view of CMS**