



Fundamentals of Particle Detectors



Fulvio Tessarotto (CERN and INFN – Trieste)

Introduction

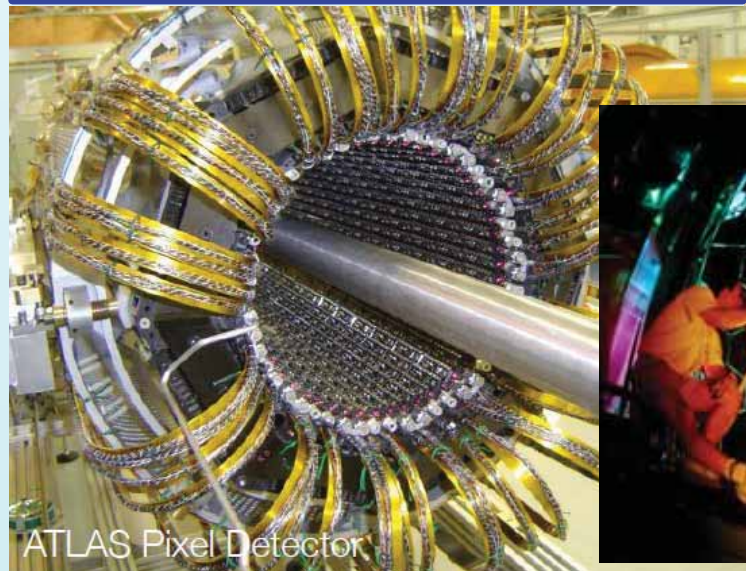
discoveries and detectors

gas detectors

silicon detectors

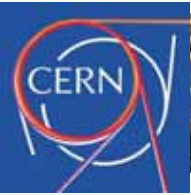
photon detectors

calorimeters



ATLAS Pixel Detector





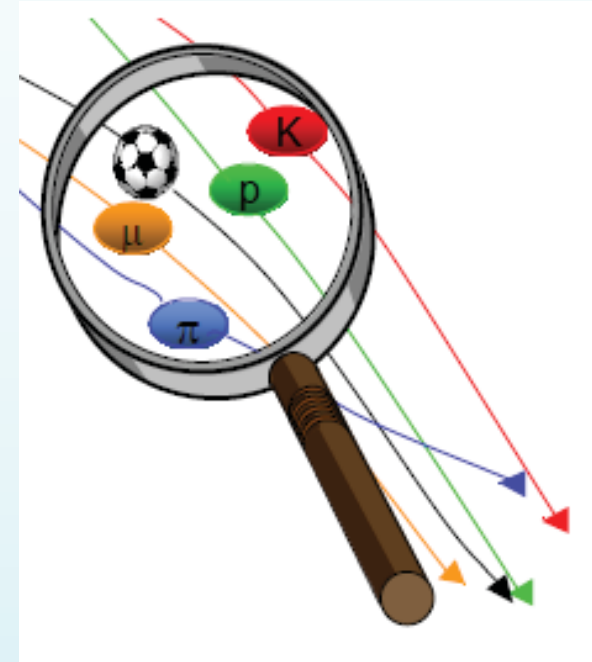
Particle detectors to see the invisible



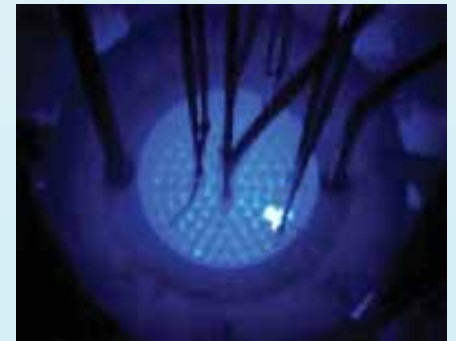
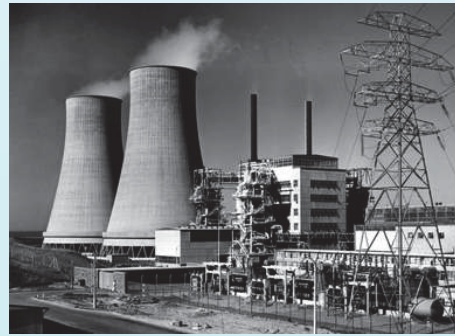
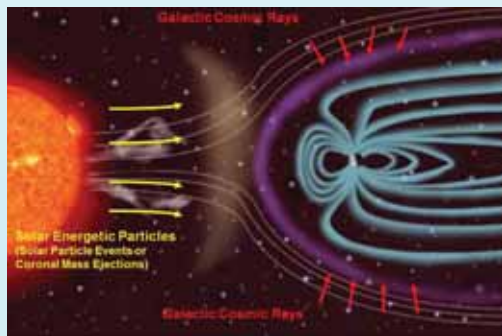
Particle detectors are instruments invented to measure the feeble signals produced by subatomic particles

Thanks to particle detectors subatomic particles can be “seen” and their characteristics can be measured

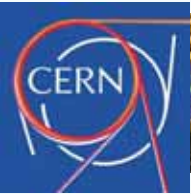
A single particle is “invisible” but many particles at the same time can produce an effect visible to naked eye:



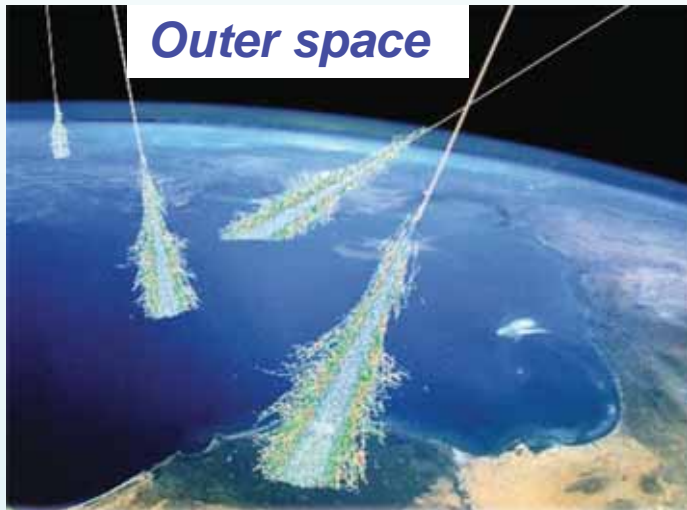
← **Polar aurora images**



Nuclear reactor cores

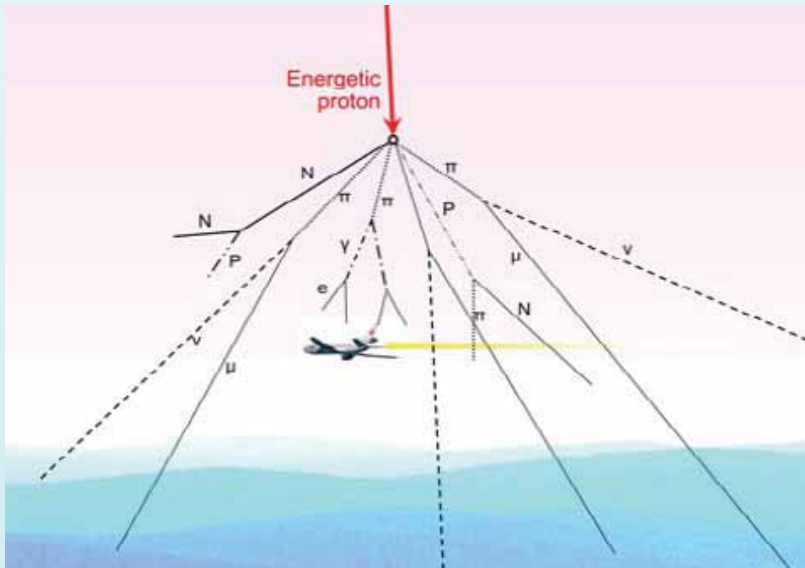
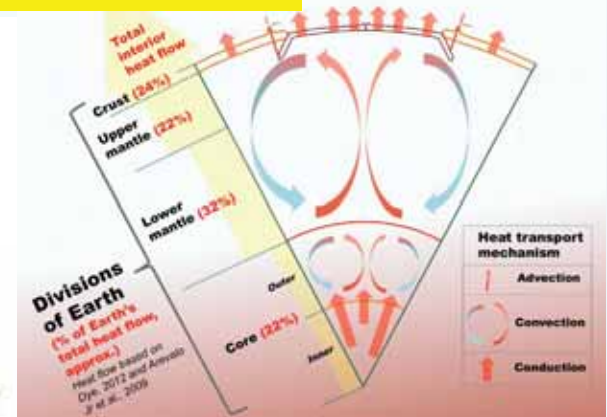
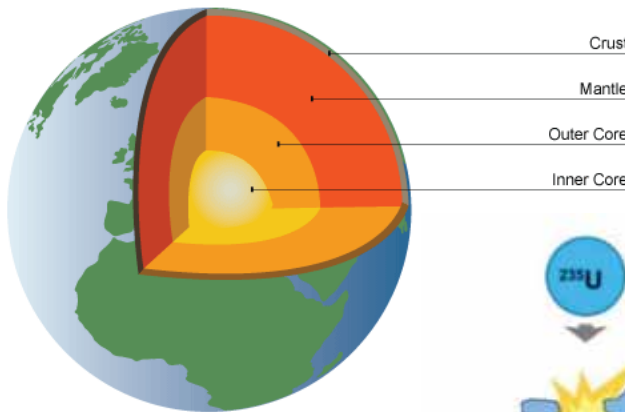


particles come from everywhere



Outer space

Radioactive decays inside the Earth



Almost every material on the Earth surface too, including our own bodies

On average a human body has ~30 mg of Potassium 40, corresponding to ~ 4 kBq





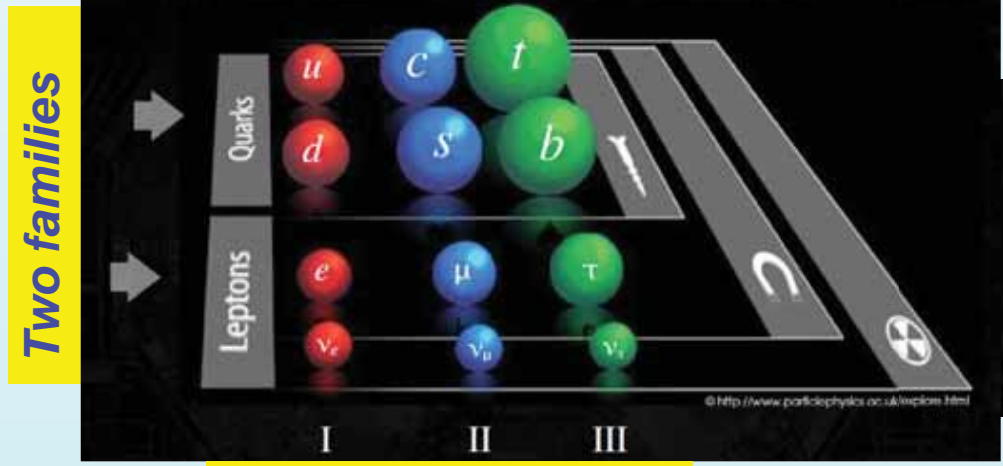
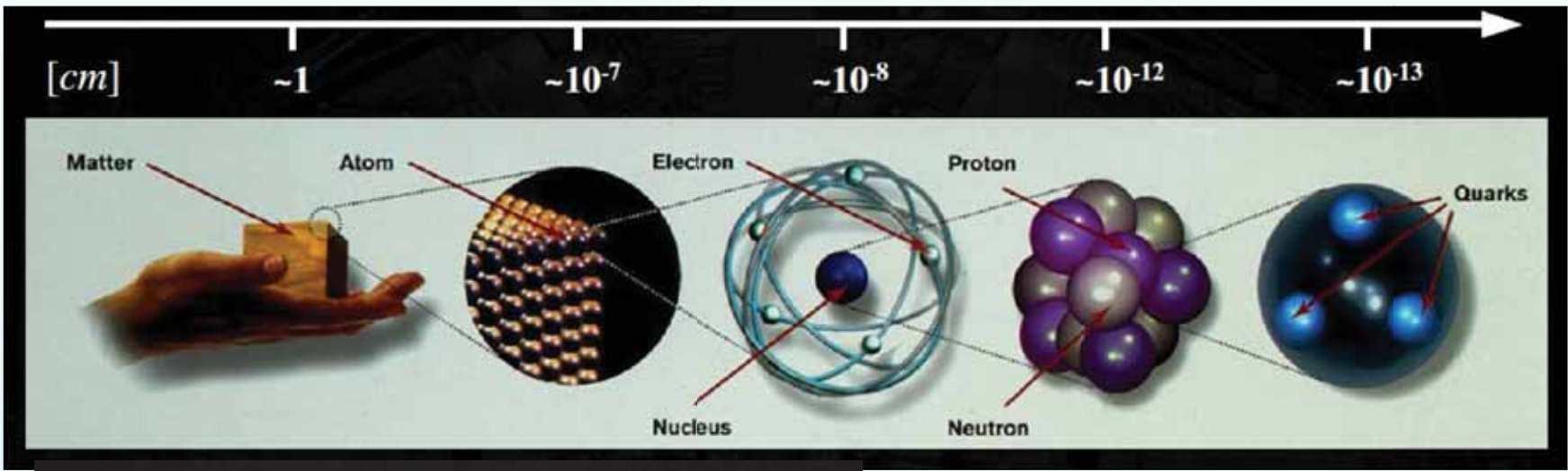
and can be produced in a laboratory



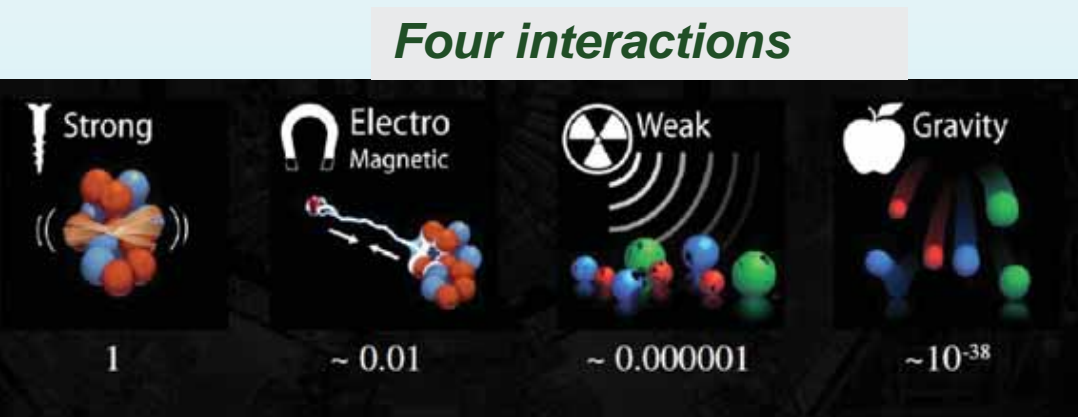
In a high-energy event all kind of particles are produced: many of them immediately decay, others survive long enough to interact with the materials they traverse.

The complete reconstruction of an event requires the detection of the produced particles and the identification of their characteristics: a complex set of particle detectors has to be used to accomplish this task.

The constituents of matter

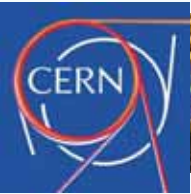


Three generations



gluon photon W-Z graviton

and the Higgs boson



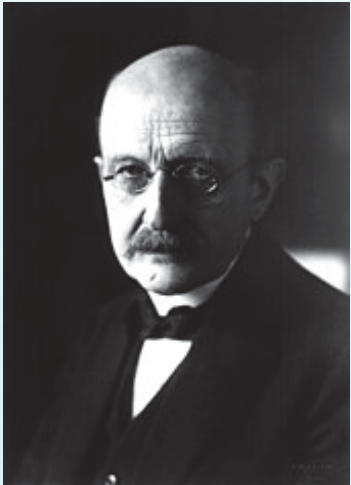
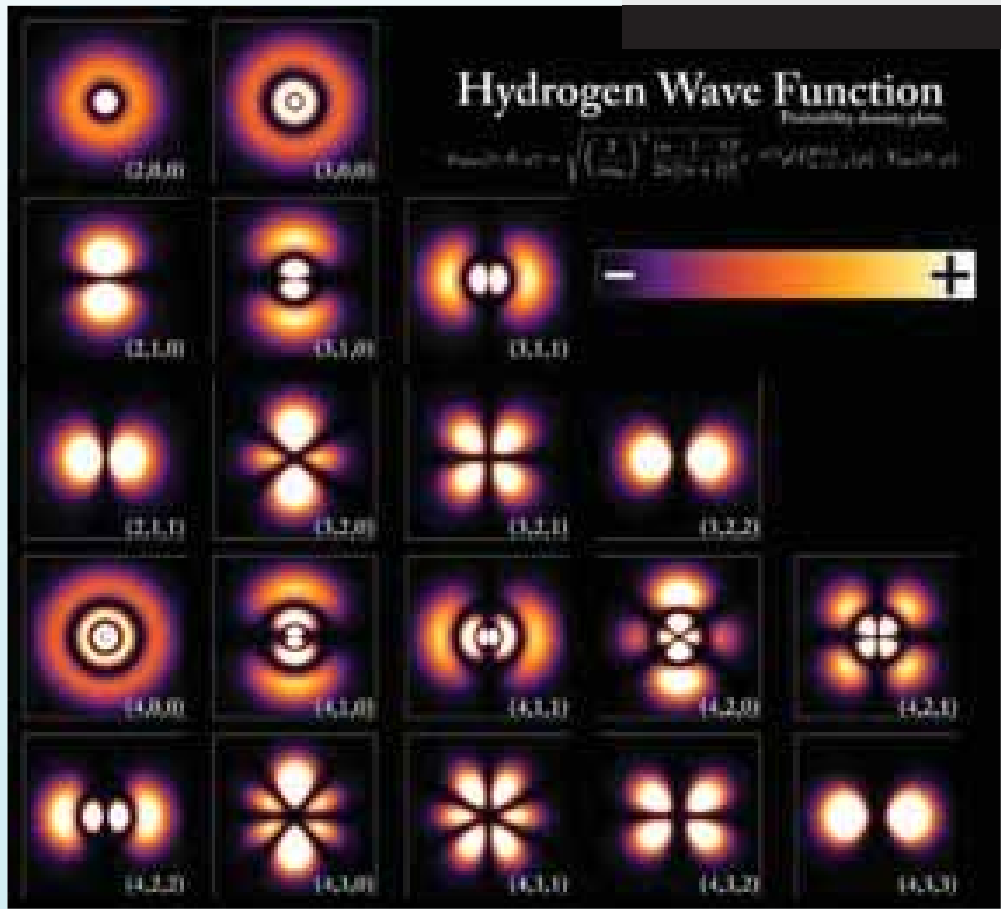
Particles do what we cannot



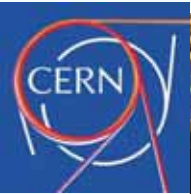
The laws which hold at the microscopic level are different from ours

A particle or an atom can stay at the same time in two or more different places

A particle can move from a point to another in space without passing anywhere in between the two points



Max Plank is the father of the quantum theory



The Standard Model



Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

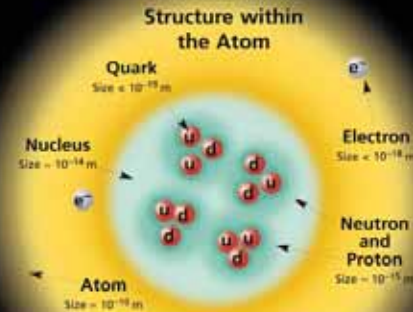
The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is excluded on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c ²	Electric charge
ν_e electron neutrino	$<1 \times 10^{-6}$	0
e^- electron	0.000511	-1
ν_μ muon neutrino	<0.0002	0
μ^- muon	0.106	-1
ν_τ tau neutrino	<0.02	0
τ^- tau	1.7771	-1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c ²	Electric charge
u up	0.003	2/3
d down	0.006	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	175	2/3
b bottom	4.3	-1/3



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c ²	Electric charge
γ photon	0	0
W^-	80.4	-1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electric charges interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W^+ and Z^0 bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq .

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

Spin is the intrinsic angular momentum of particles. Spin is given in units of \hbar , which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 4.58 \times 10^{-35} \text{ GeV} \cdot \text{s} = 1.05 \times 10^{-34} \text{ J} \cdot \text{s}$.

Electric charges are given in units of the proton's charge. In 'e' units the electric charge of the proton is $1.60 \times 10^{-19} \text{ coulombs}$.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10} \text{ joule}$. The mass of the proton is $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27} \text{ kg}$.

PROPERTIES OF THE INTERACTIONS

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$				
Baryons are fermions; hadrons. There are about 120 types of baryons.				
Symbol	Name	Quark content	Electric charge	Spin
p	proton	uud	1	1/2
\bar{p}	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	1/2
n	neutron	udd	0	1/2
Λ	lambda	uds	0	1/2
Ω^-	omega	sss	-1	1/2

Property	Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong	
		Mass - Energy	Flavor	Electric Charge	Fundamental	Residual
Acts on:		All	Quarks, Leptons	Electrically charged	Color Charge	See Residual Strong Interaction Note
Particles experiencing:		All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:		Graviton (not yet observed)	$W^+ W^- Z^0$	γ	Gluons	Mesons
Strengths relative to the binding of two u quarks at:		10^{-41}	0.8	1	25	Not applicable to quarks
10^{-16} m		10^{-41}	10^{-6}	1	60	Not applicable to hadrons
$3 \cdot 10^{-17} \text{ m}$		10^{-36}	10^{-7}	1	20	Not applicable to hadrons

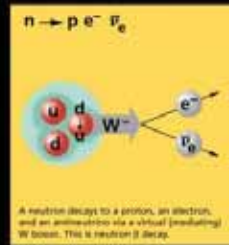
Mesons $q\bar{q}$					
Mesons are bosons; hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0
p^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B meson	$d\bar{b}$	0	5.270	0
η_c	eta-c	$c\bar{c}$	0	2.380	0

Matter and Antimatter

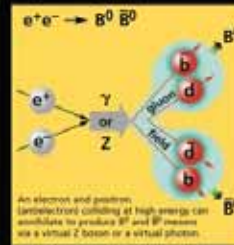
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (antiparticle). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0 , γ , and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

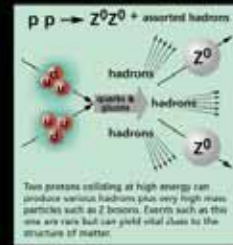
These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antiparticle) colliding at high energy can annihilate to produce Z^0 and γ bosons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

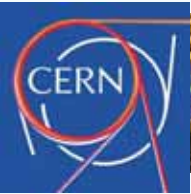
The Particle Adventure

Visit the award-winning web feature The Particle Adventure at <http://ParticleAdventure.org>

This chart has been made possible by the generous support of:

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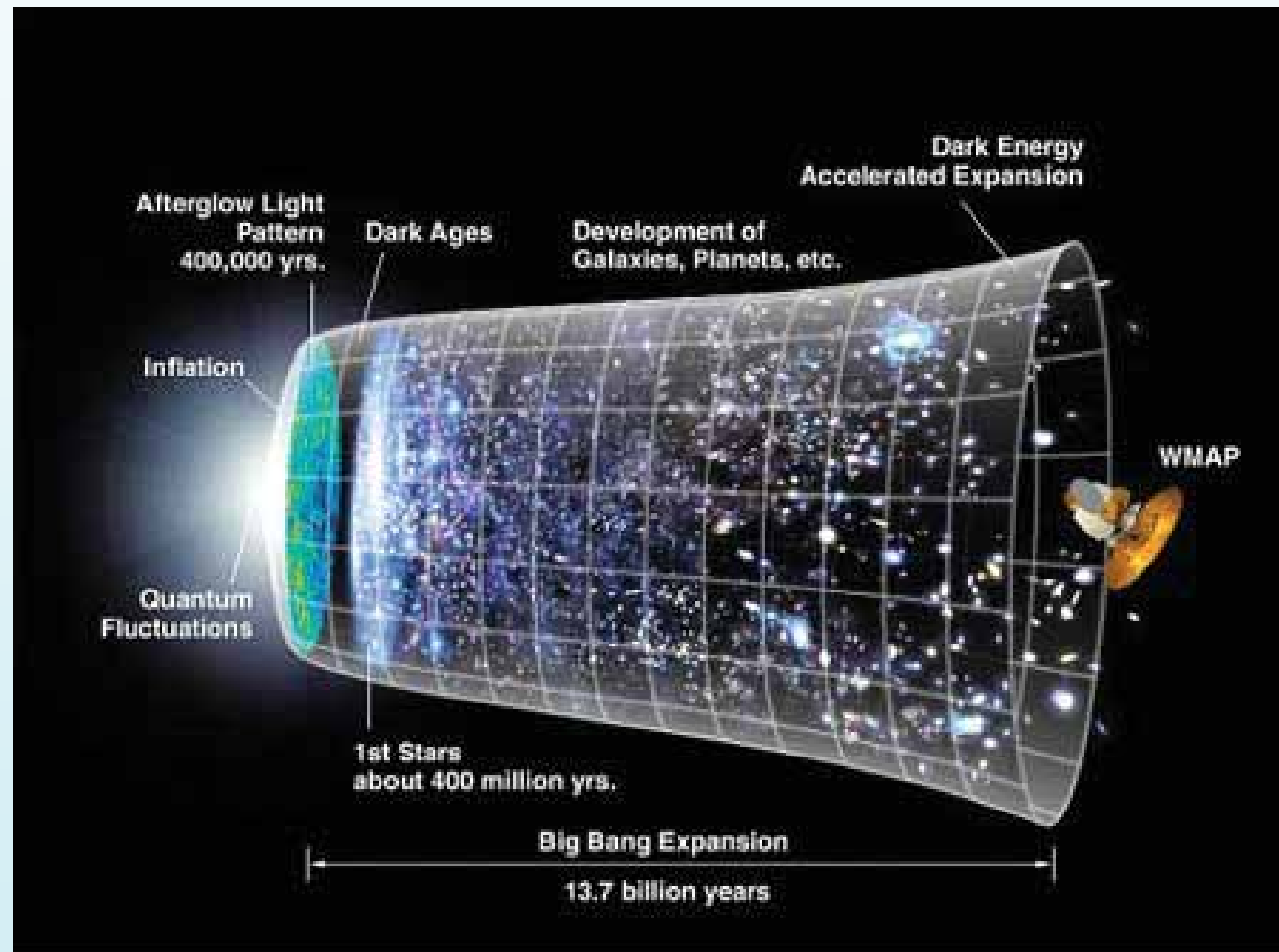
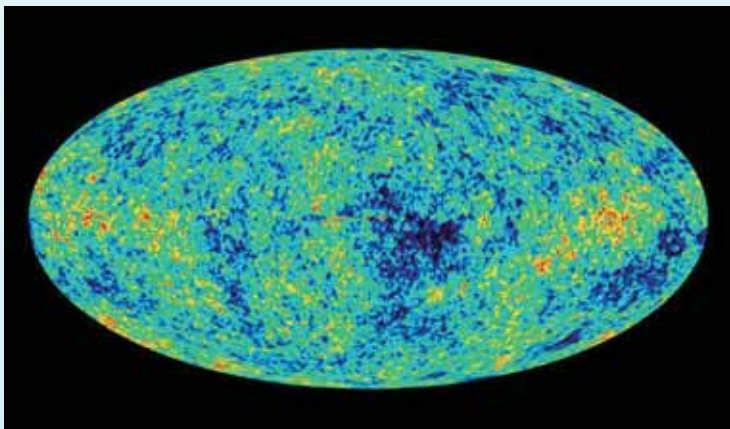
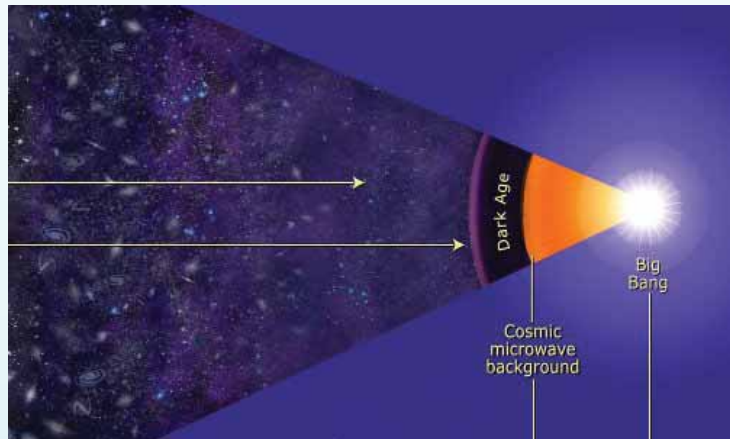
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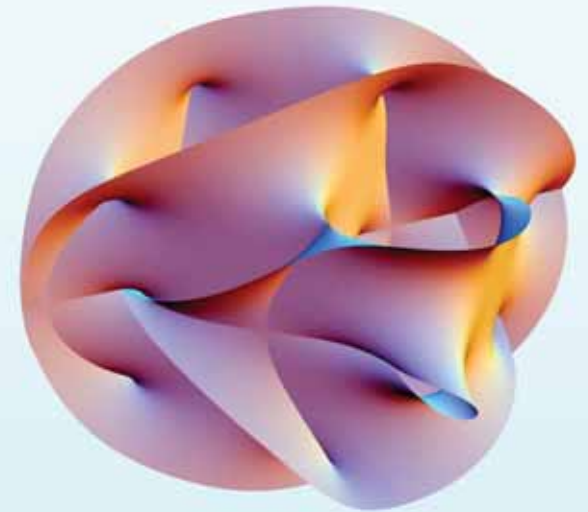
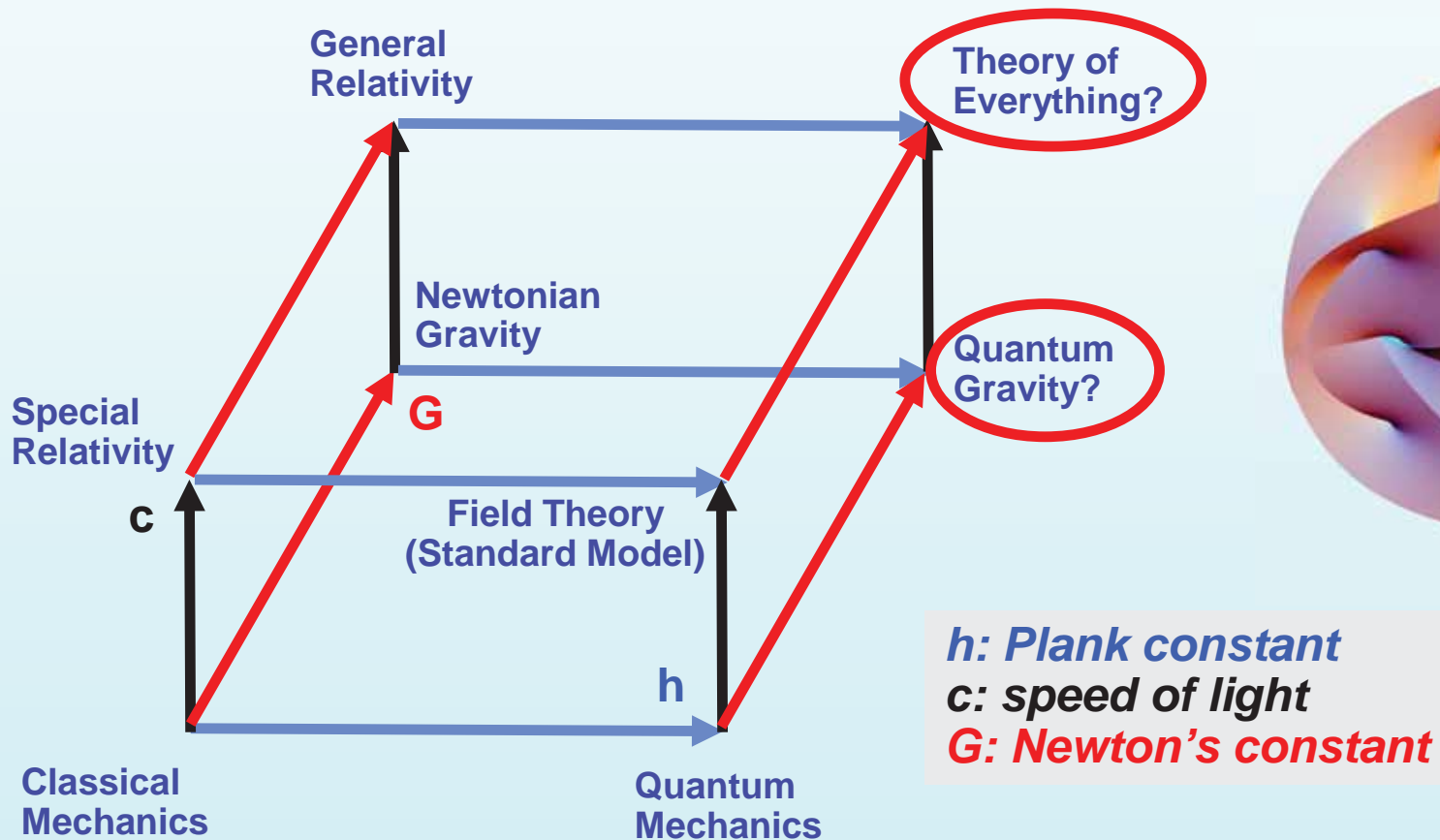
History of the Universe



From Cosmic Microwave Background Radiation and other measurements

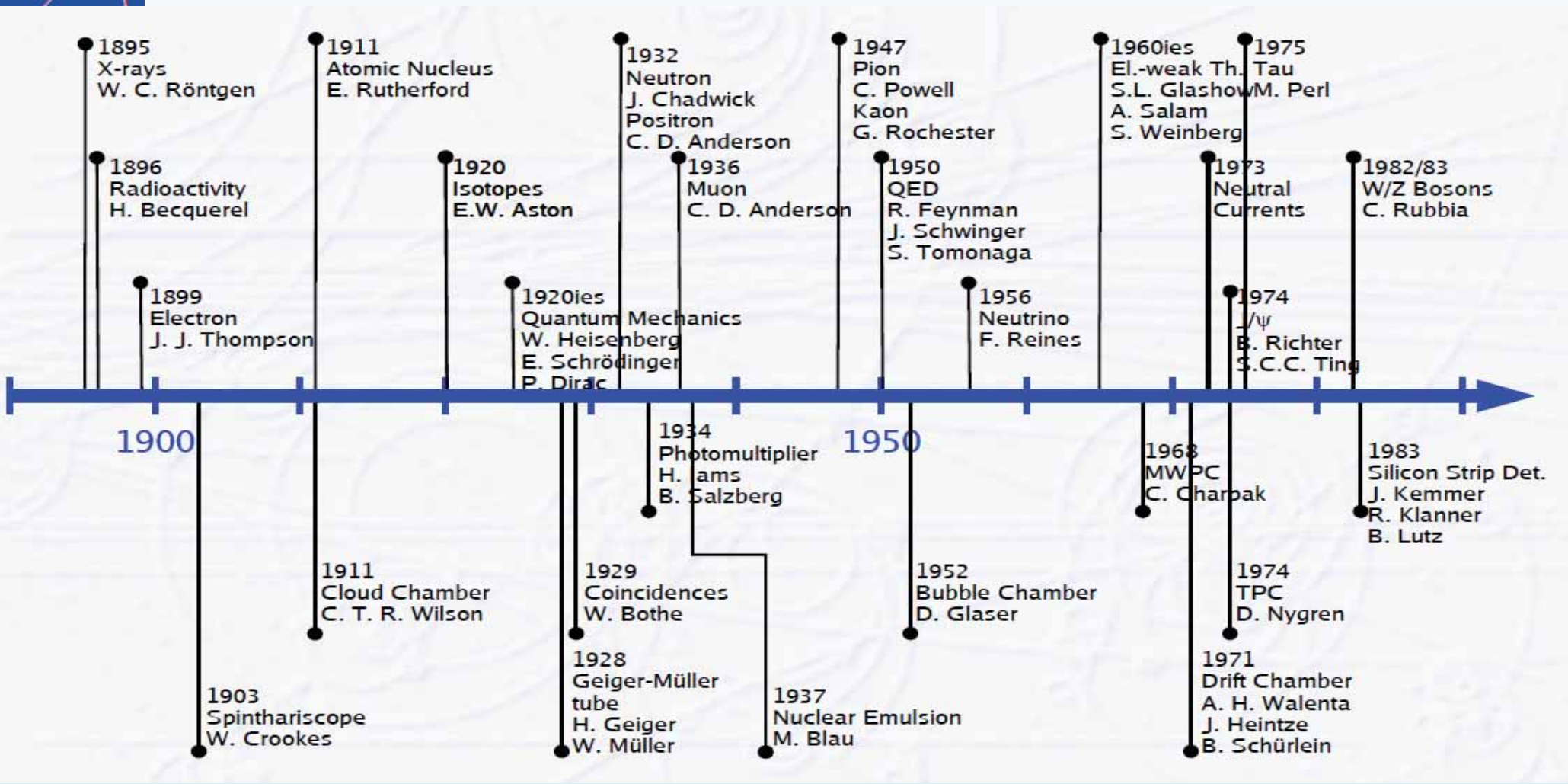


The fundamental constants of nature and unified theories





Discoveries and detector technologies



The history of discoveries and that of particle detectors are intimately interconnected

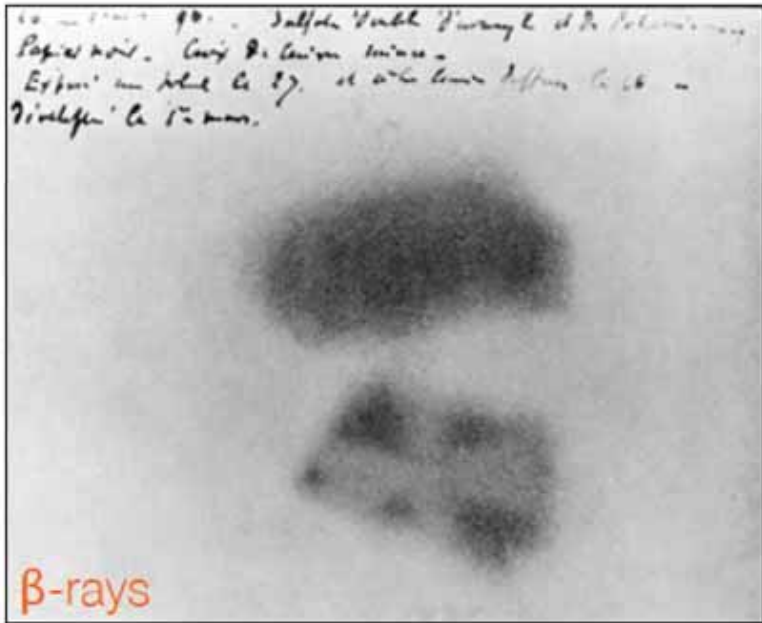
The discovery of radiation

Photographic plates

First

Detection of α -, β - and γ -rays

1896



β -rays

Image of Becquerel's photographic plate which has been fogged by exposure to radiation from a uranium salt.

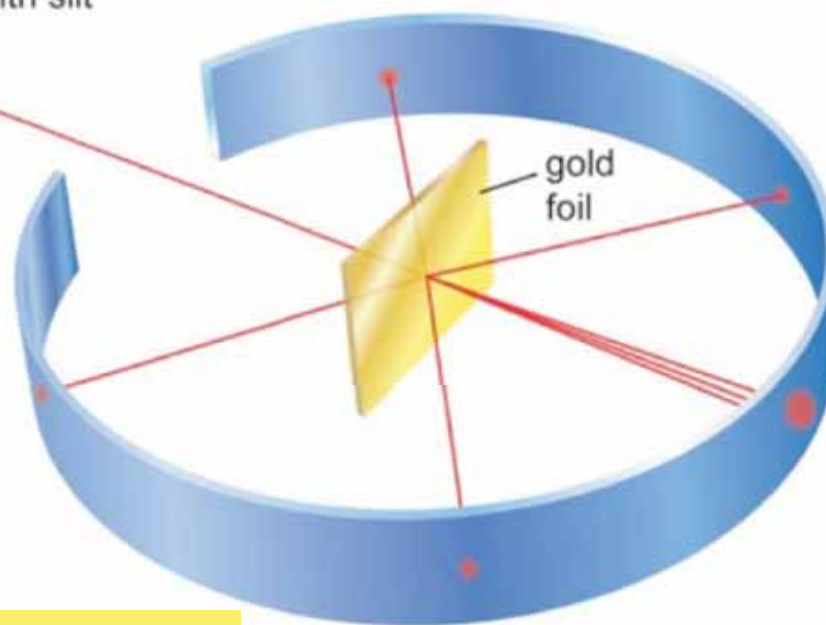
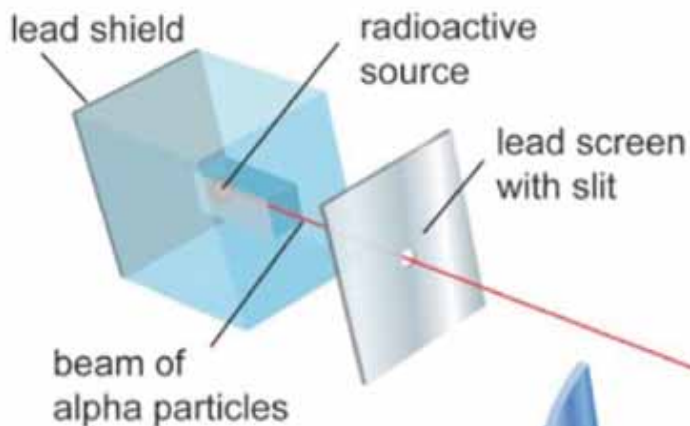


1896

An x-ray picture taken by Wilhelm Röntgen of Albert von Kölliker's hand at a public lecture on 23 January 1896.

The discovery of the atomic nucleus

Rutherford's scattering experiment

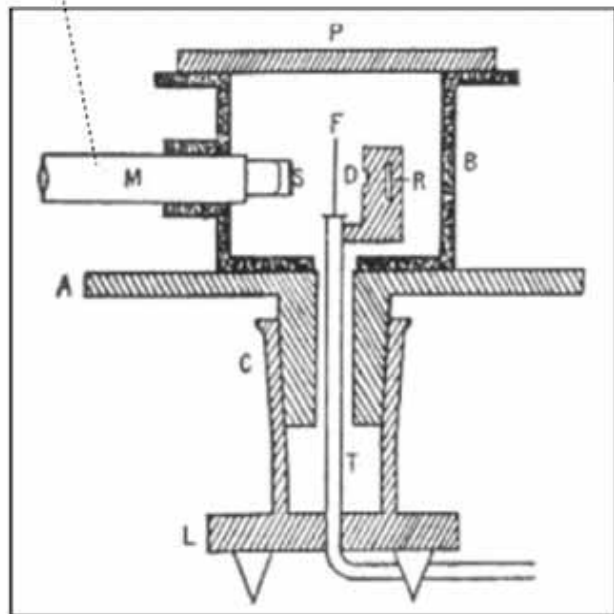


Schematic view of Rutherford experiment

1911

**Scintillating screens:
William Crooks, 1903**

Microscope +
Scintillating ZnS screen

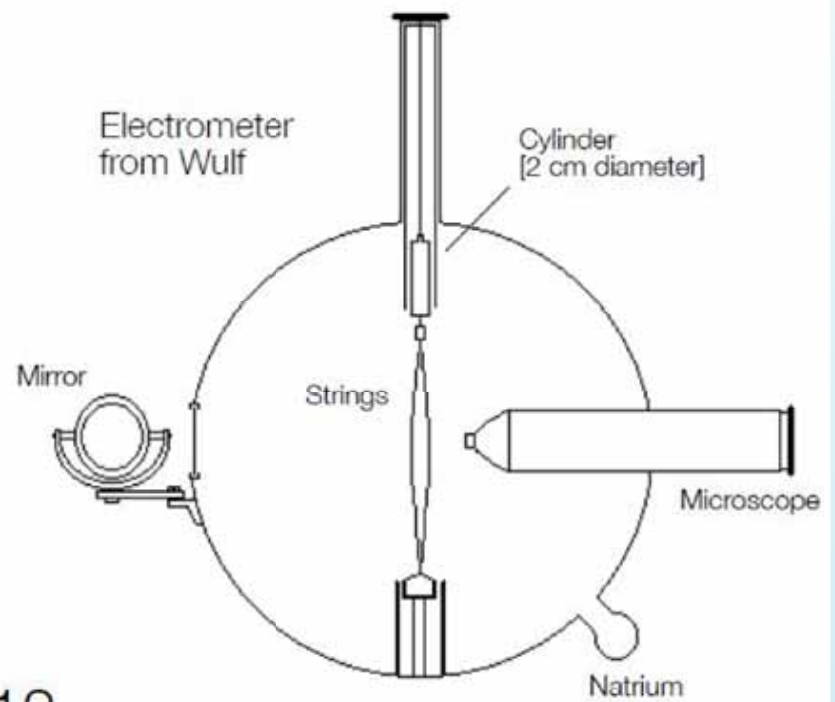


Rutherford's original experimental setup

1912: cosmic rays

Wulf electroscope invented in 1909

Detection of cosmic rays
[Hess 1912; Nobel prize 1936]



1912

Victor F. Hess before his 1912 balloon flight in Austria during which he discovered cosmic rays.

1911: the cloud chamber

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 around ions
- ➔ visible track as line of small water droplets



UK Science Museum



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



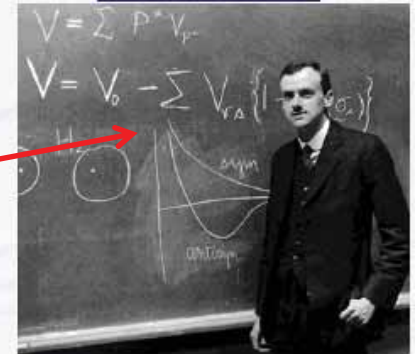
First photographs of α -ray particles 1912



1932: antimatter, 1936: muon

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)



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

Isidor Isaac Rabi said: "Who ordered that?"

downward going positron, 63 MeV

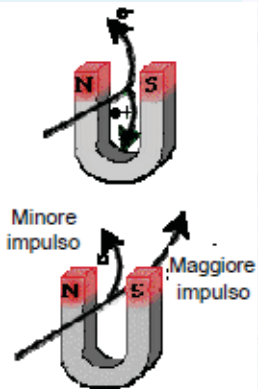
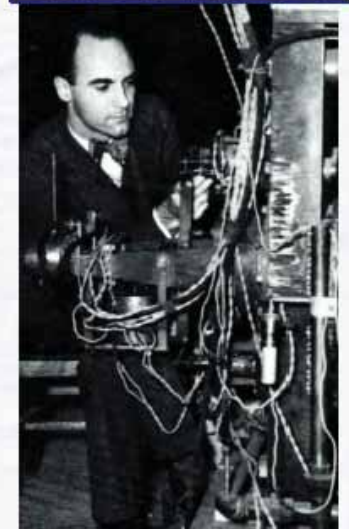


6 mm lead plate

1.5 T magnetic field

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

Carl D. Anderson



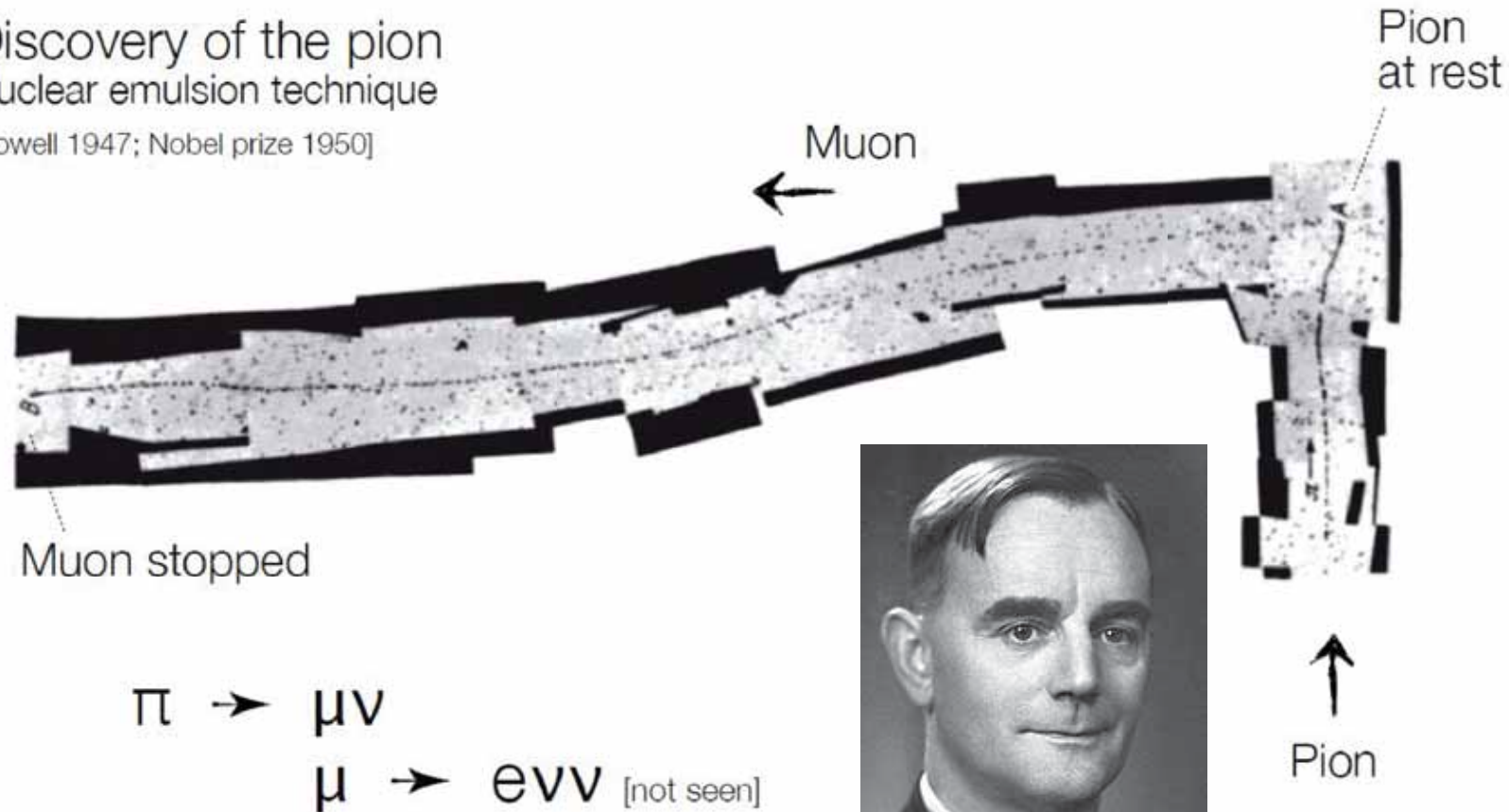


Marietta Blau:

she developed in Vienna the photographic nuclear emulsion technology for very accurate measurement of high energy nuclei and discovered the "disintegration stars" of spallation events

Discovery of the pion
Nuclear emulsion technique

[Powell 1947; Nobel prize 1950]



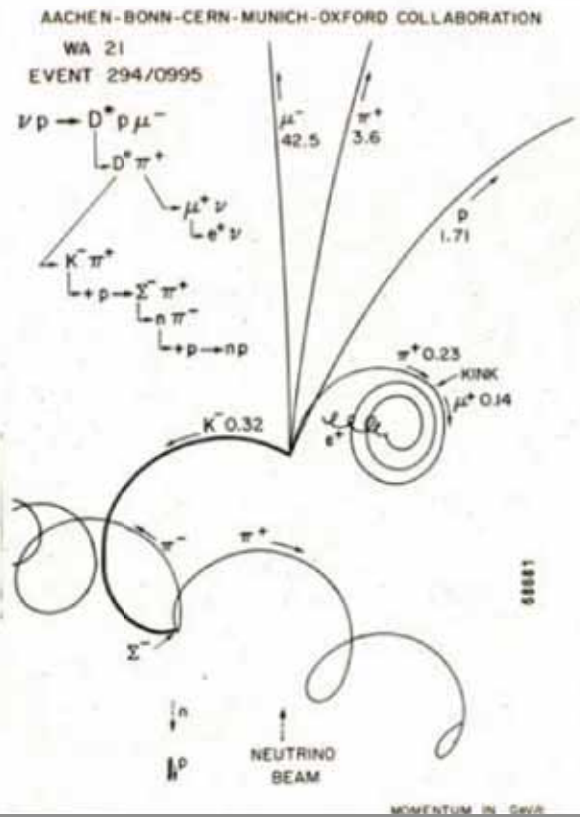
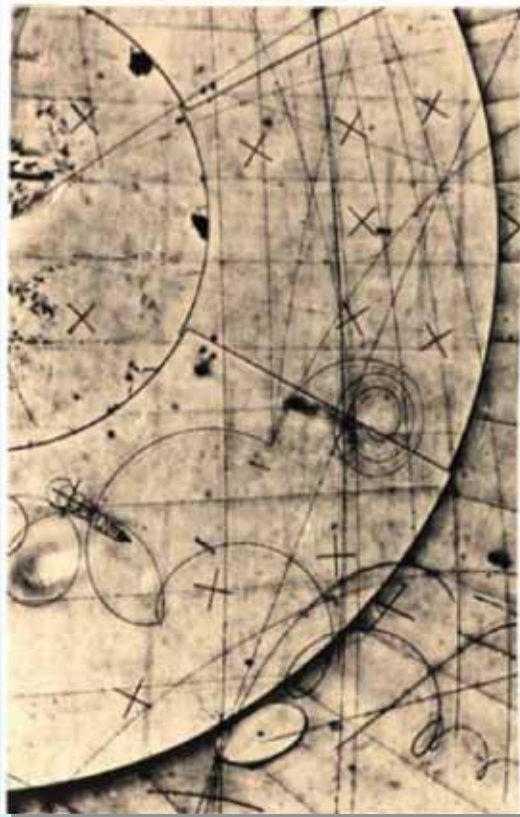
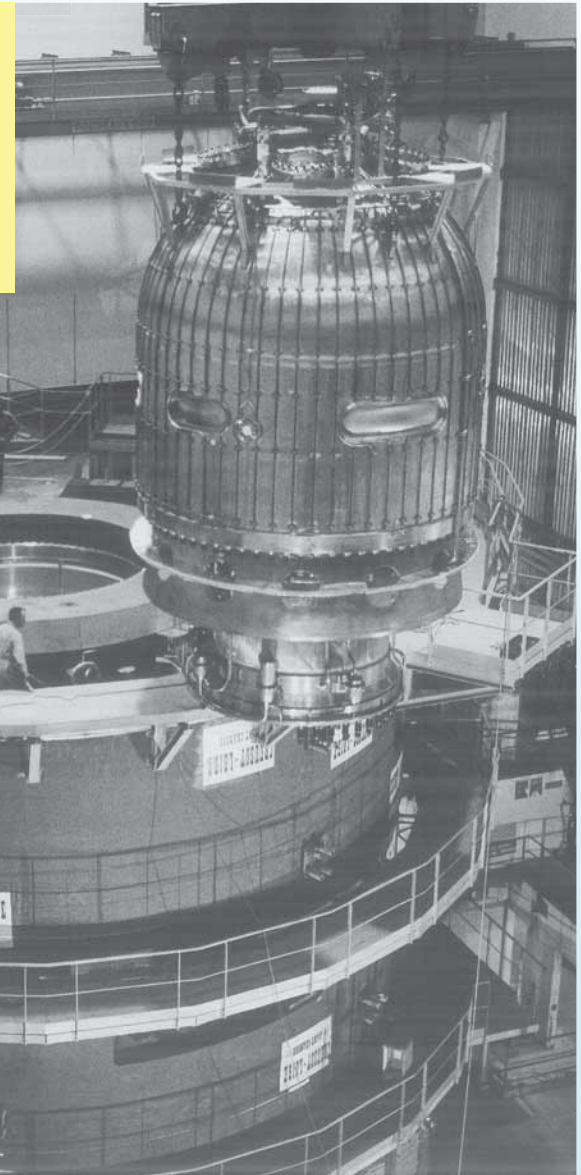
Cecil Frank Powell
Nobel Prizes 1950

emulsions are still the detectors with the highest intrinsic space resolution: < 1 μm

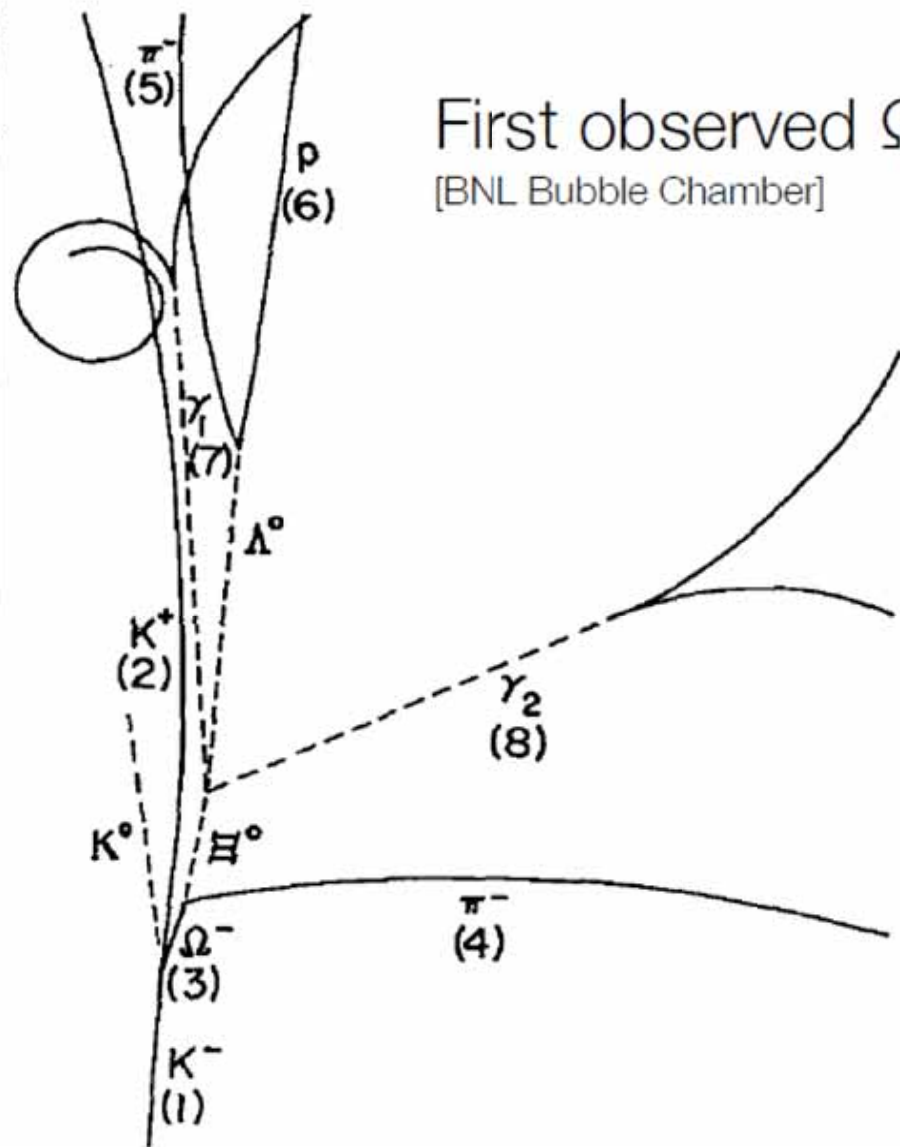
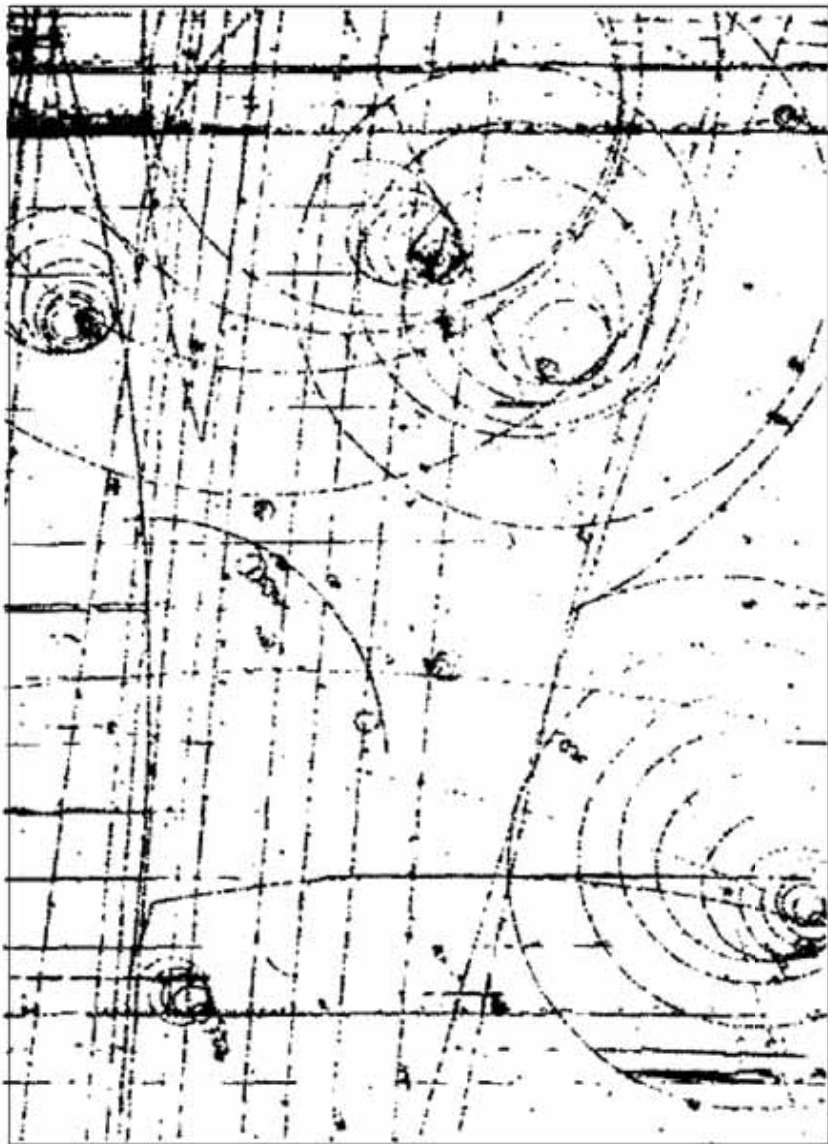
1952: bubble chamber

The bubble chamber, invented by Donald Arthur Glaser in 1952, has been for many years the most powerful instrument of ionizing particles investigation.

BEBC (Big European Bubble Chamber)



1964: the first predicted particle



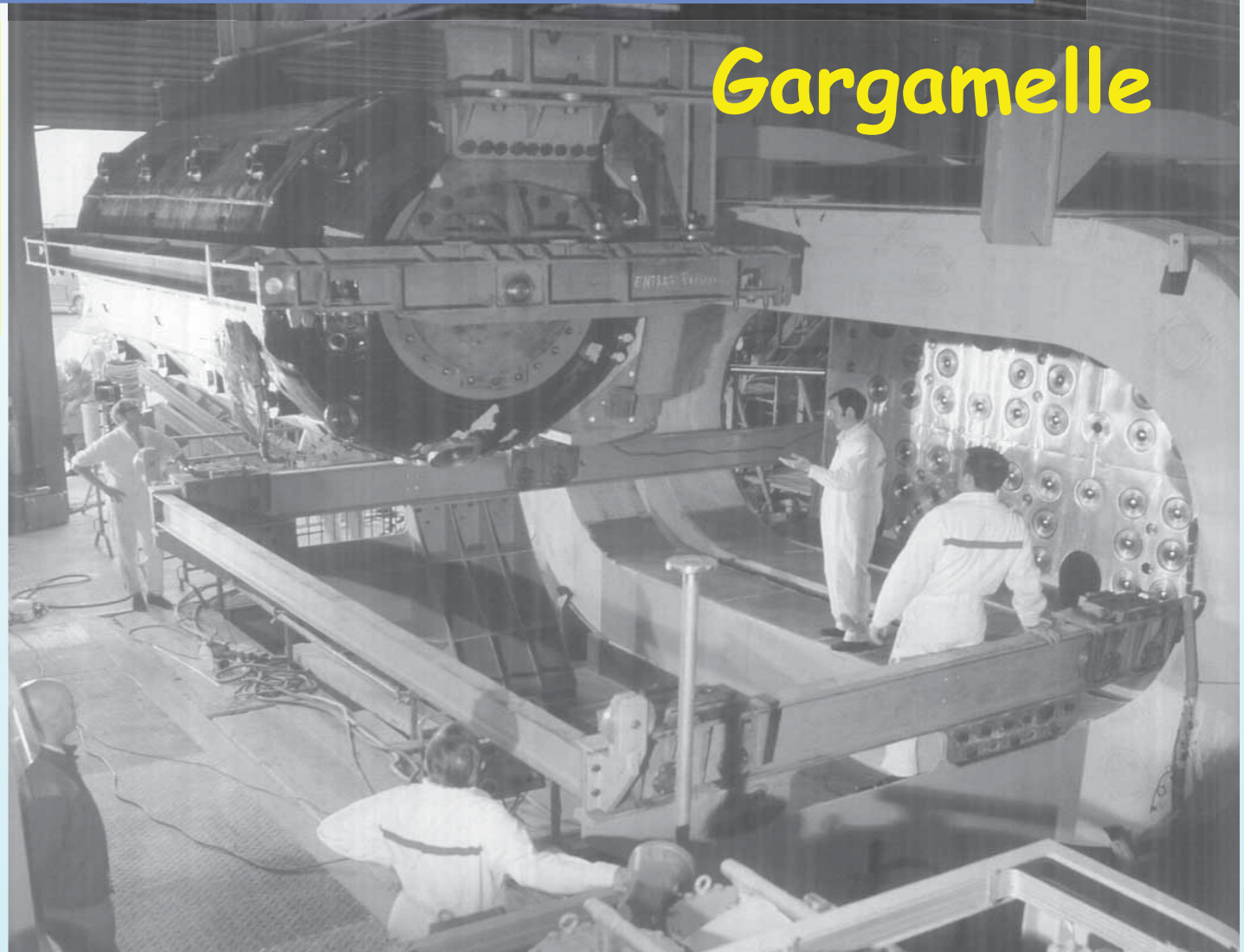
First observed Ω^- event
[BNL Bubble Chamber]



1973: the e.w. theory is confirmed



1973: a big discovery in Europe, at CERN. **Gargamelle detects weak neutral currents**
The electroweak theory is confirmed

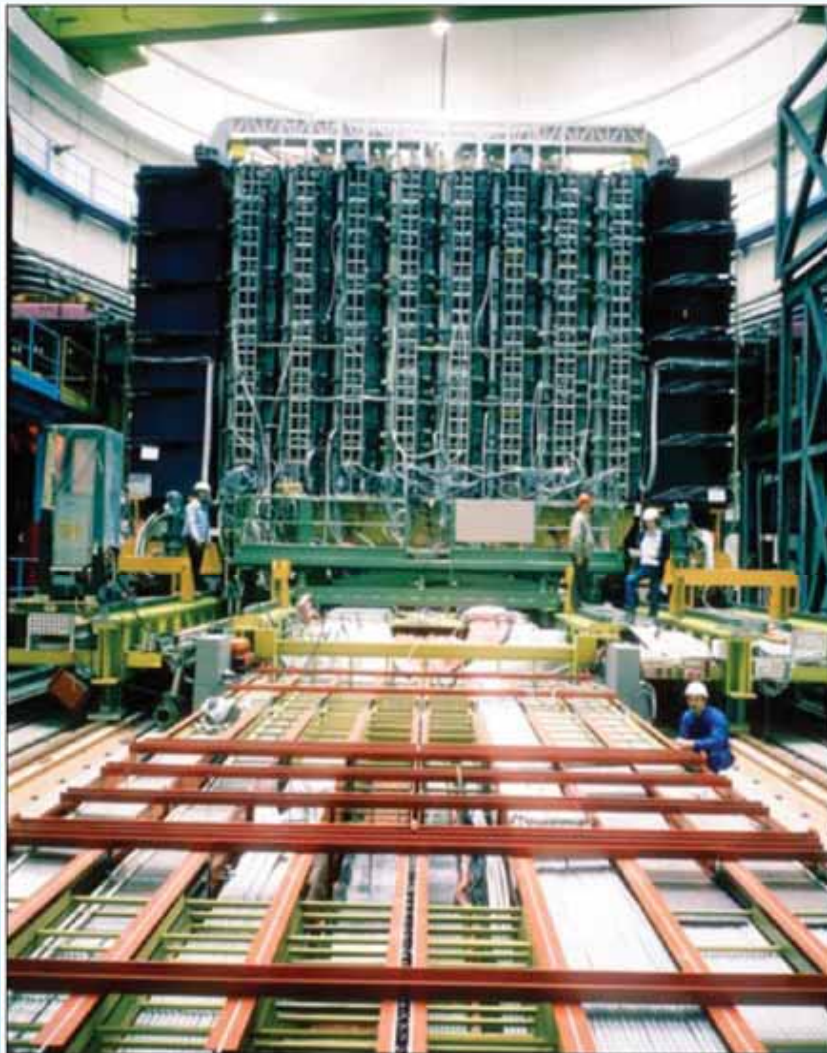


Gargamelle

Salam receives the Nobel prize in 1979 together with Weinberg and Glashow

1983: the weak bosons discovery

Was achieved thanks to complex accelerator and detector systems

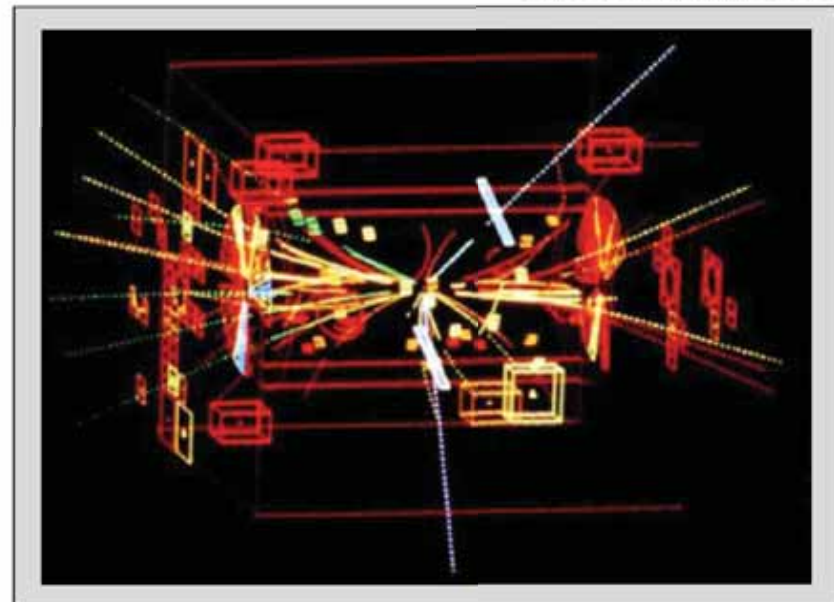


UA1
Detector

Discovery of the W/Z boson (1983)

Carlo Rubbia
Simon Van der Meer
[Nobel prize 1984]

First Z^0 particle seen by UA1





Tim Bernes-Lee invented the www



in 1990 at CERN, to allow full exploitation of the data from these particle detectors



Tim Berners Lee

The web was invented at CERN! The machine used by Tim Berners-Lee in 1990 to develop and run the first WWW server, multi-media browser and web editor.



fundamental contribution to the informatics revolution

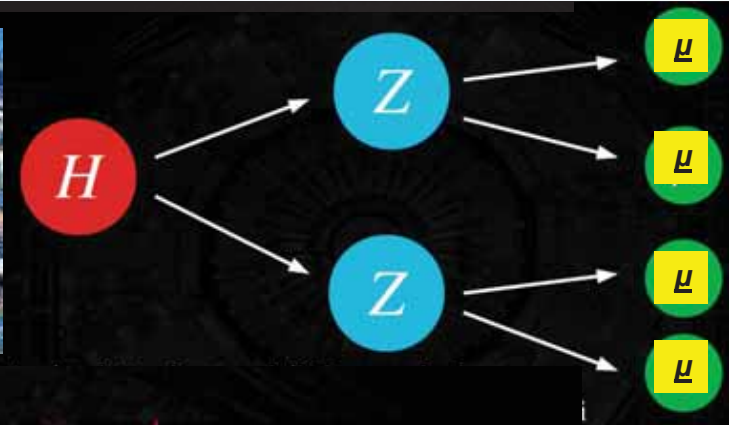
Quarks



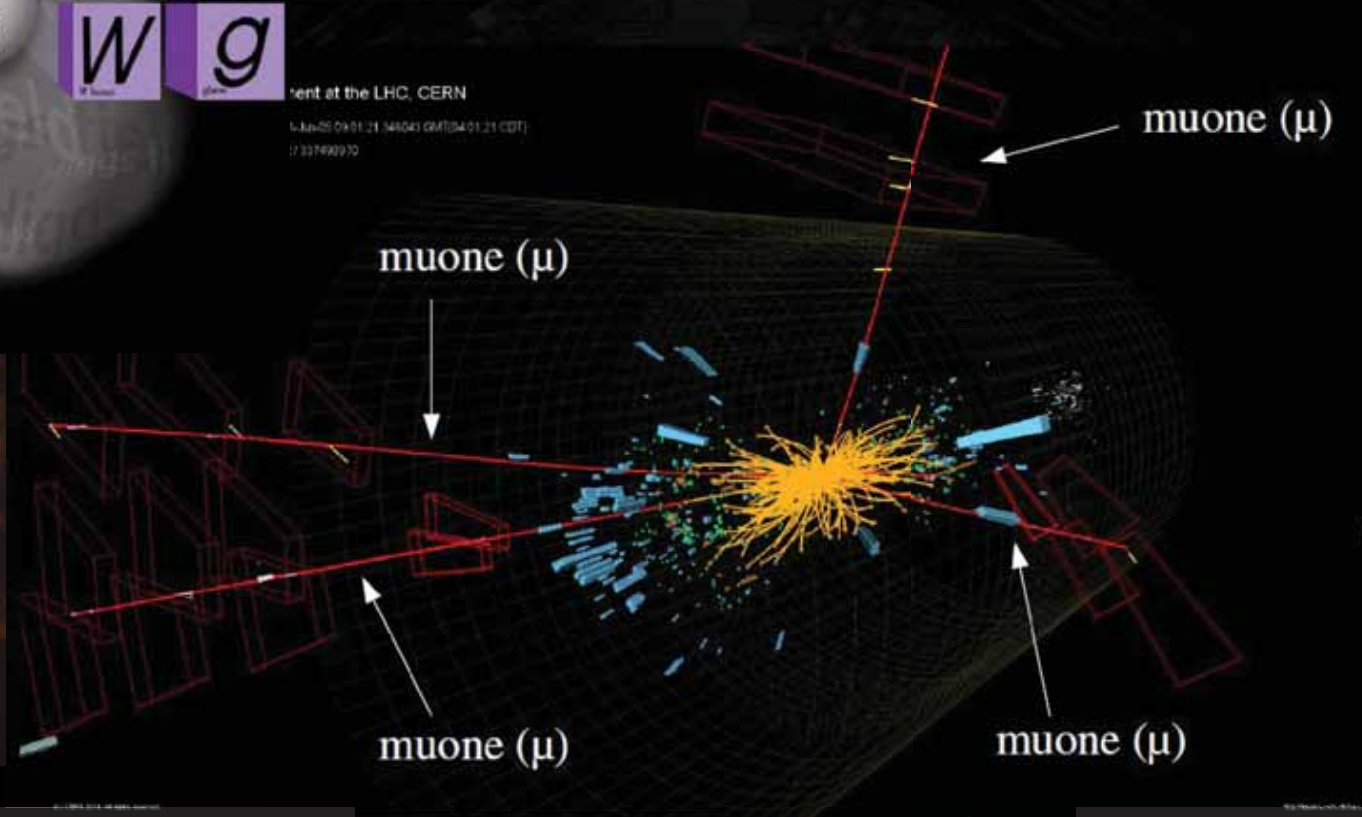
Forces



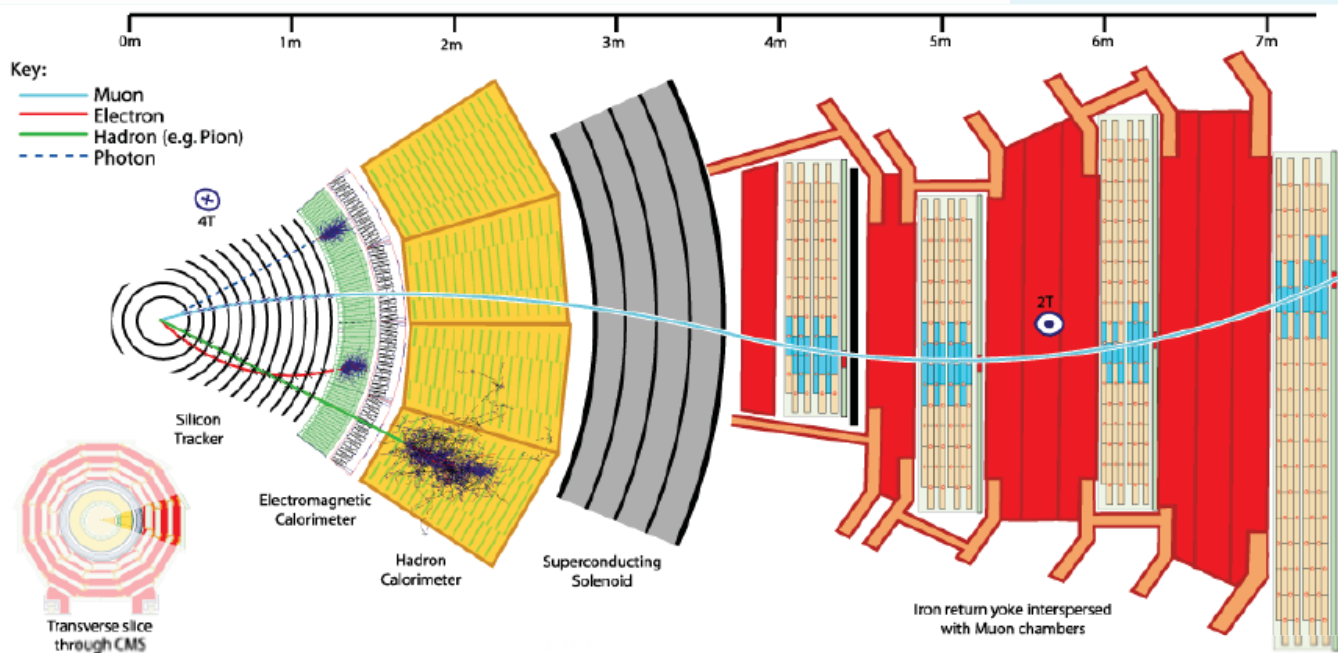
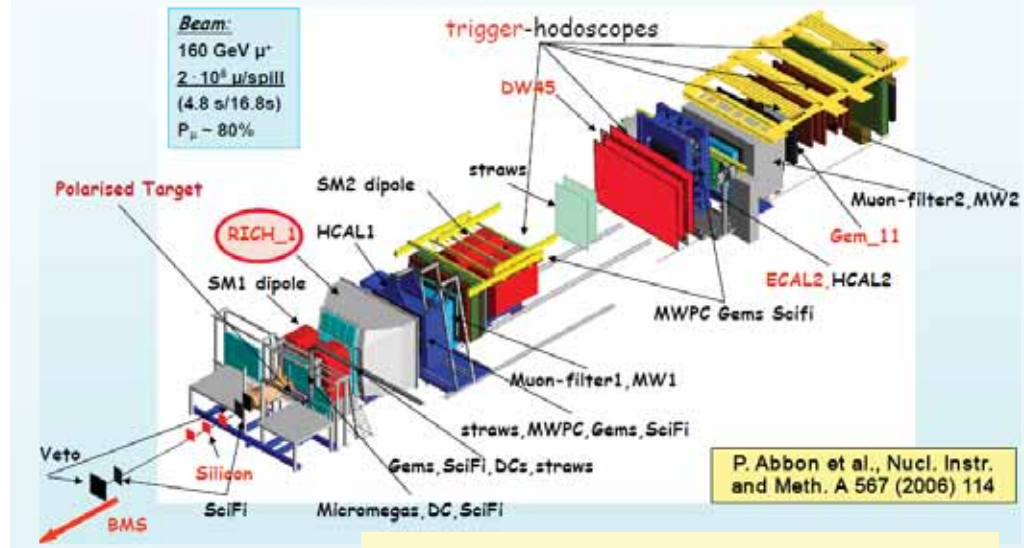
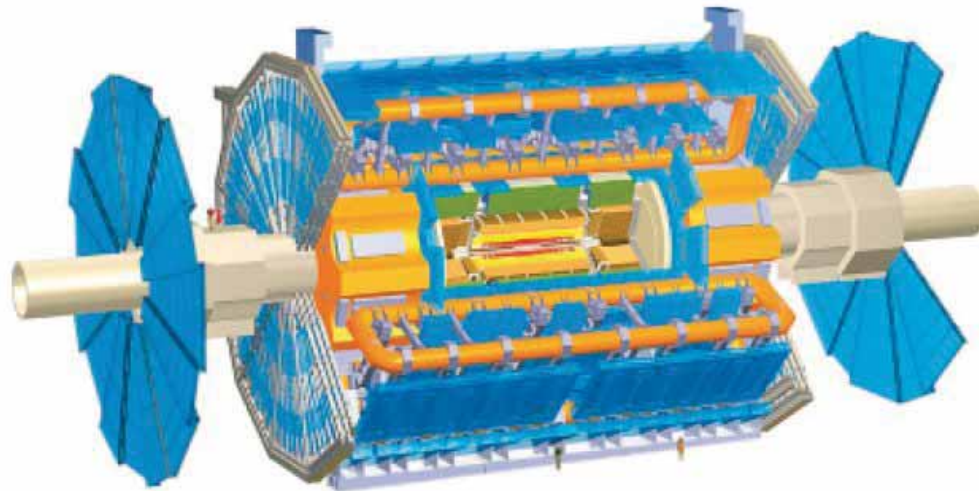
Leptons



Peter Higgs,
Nobel Prize 2013

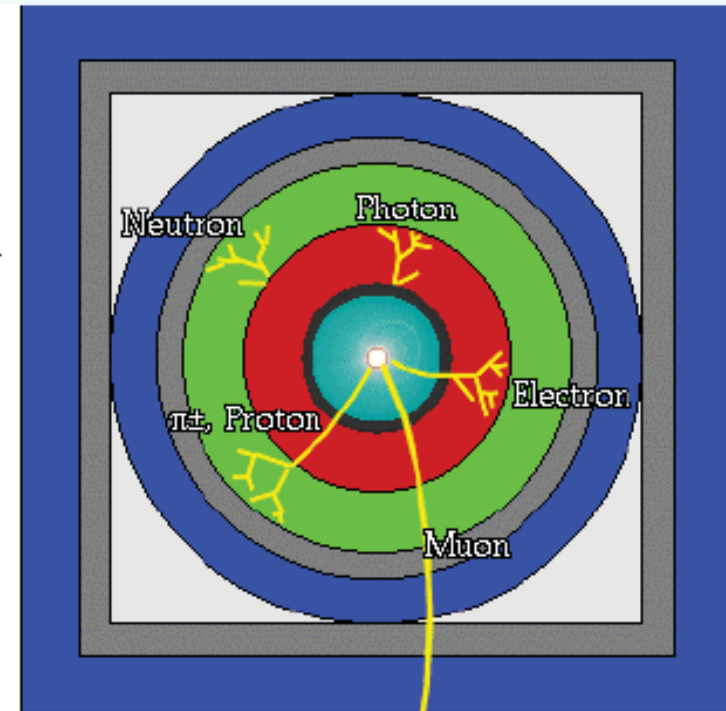
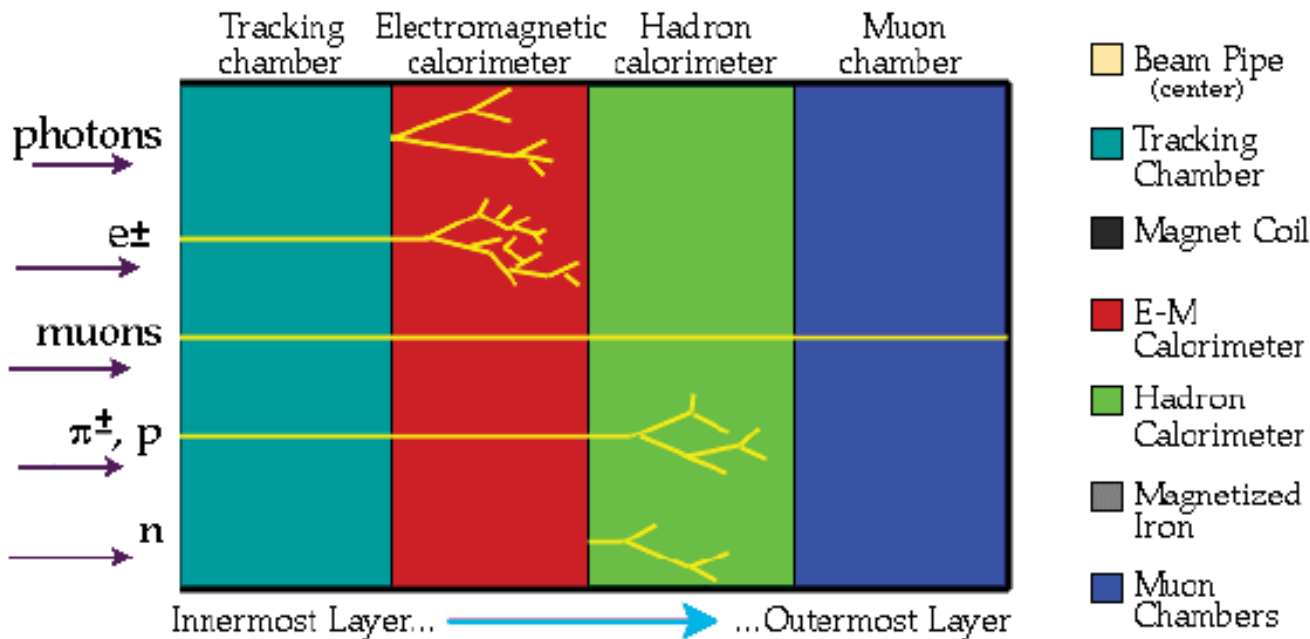


A modern experiment



uses a combination of different detectors, combines the information from all of them and fully reconstructs the characteristics of the interesting event which took place

Different particles are seen by different detectors



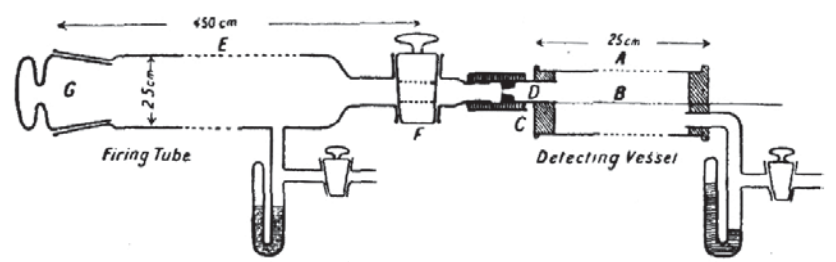
- Particles are detected via their interaction with matter.
- Many different physical principles are involved (mainly of electromagnetic nature). Finally we will always observe ionization and excitation of matter.



100 years of gaseous detectors: gallery 1



1908: FIRST WIRE COUNTER
USED BY RUTHERFORD IN THE STUDY OF NATURAL RADIOACTIVITY

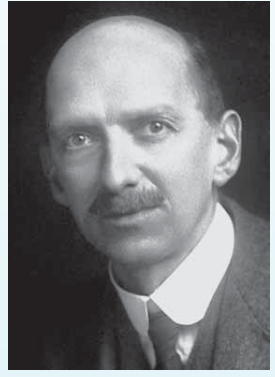


E. Rutherford and H. Geiger,
Proc. Royal Soc. A81 (1908) 141



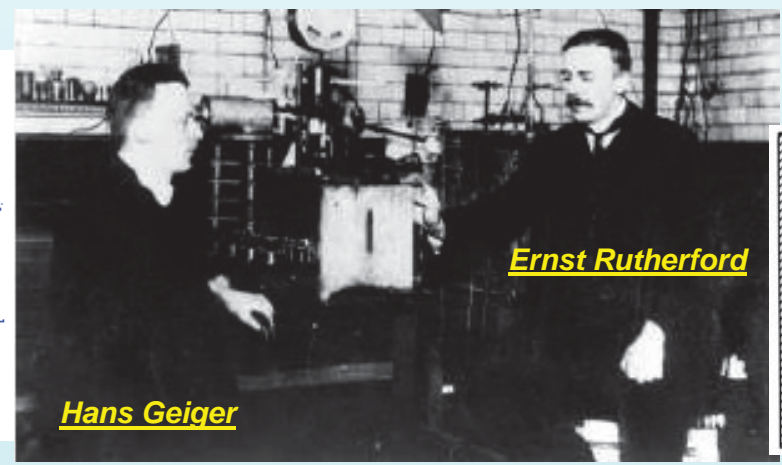
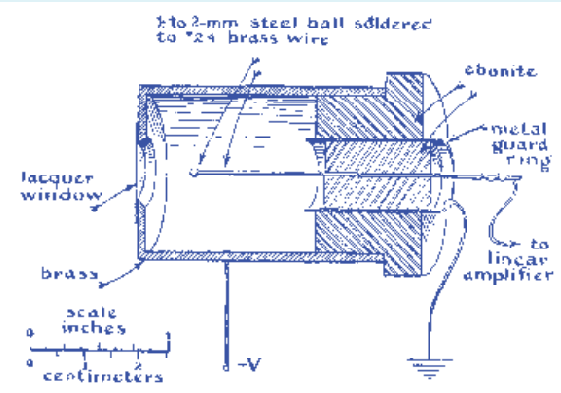
Nobel Prize in Chemistry in 1908

1911: CLOUD CHAMBER



Charles T.R. Wilson
Nobel Prize in 1927

1928: GEIGER COUNTER
SINGLE ELECTRON SENSITIVITY

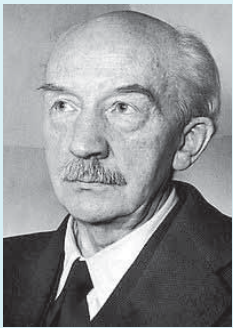
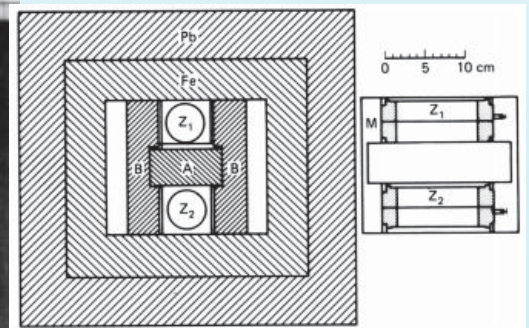


Hans Geiger

Ernst Rutherford

H. Geiger and W. Müller,
Phys. Zeits. 29 (1928) 839

COINCIDENCE METHOD



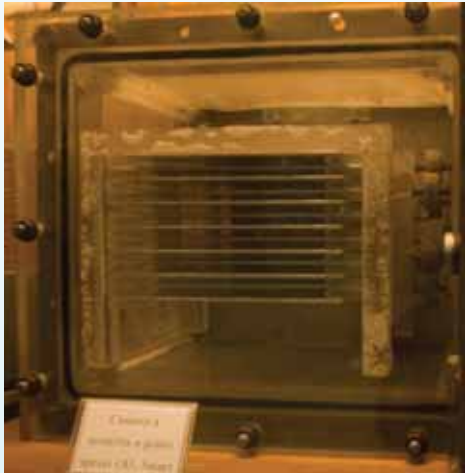
Walther Bothe
Nobel Prize in 1954



100 years of gaseous detectors: gallery 2



SPARK CHAMBER

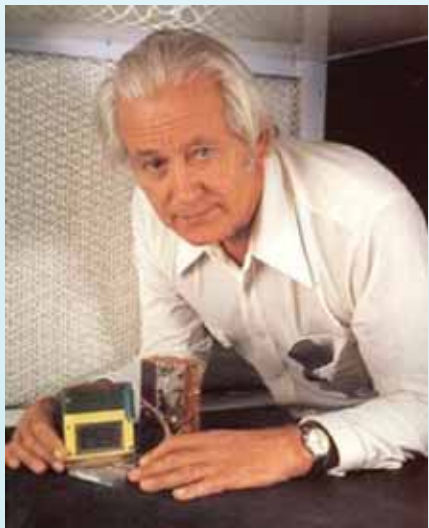
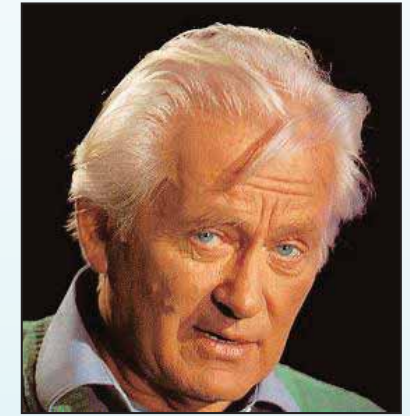
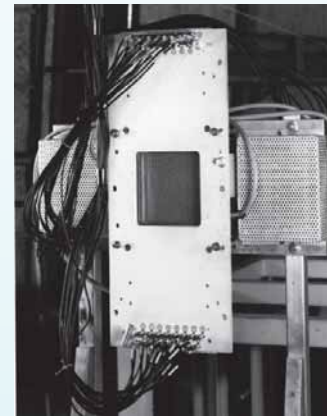


1952: BUBBLE CHAMBER

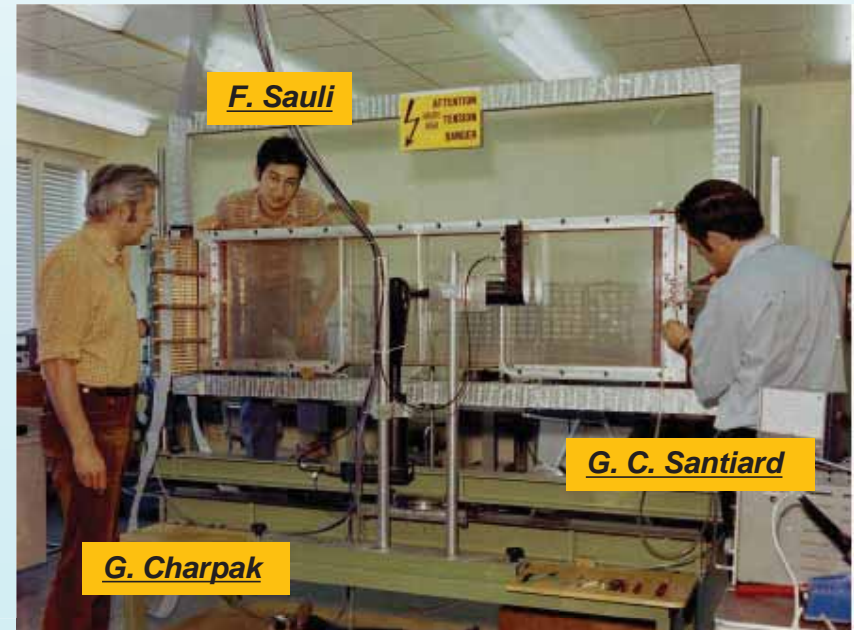
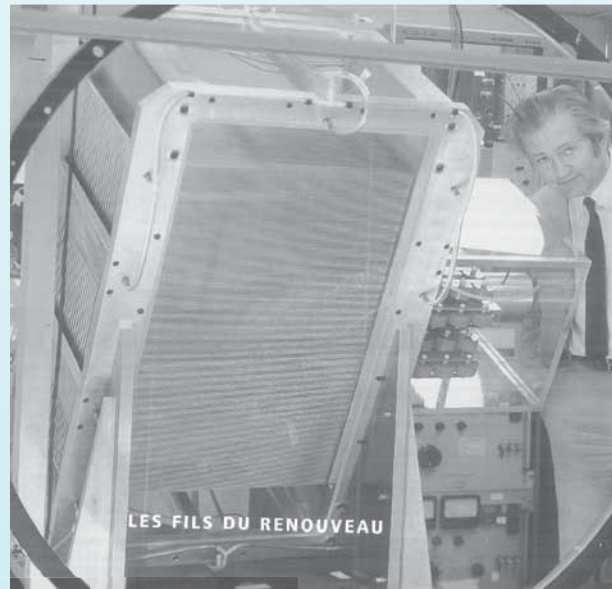


Donald A. Glaser
Nobel Prize in 1992

1968: MULTIWIRE PROPORTIONAL CHAMBER



George Charpak
Nobel Prize in 1992



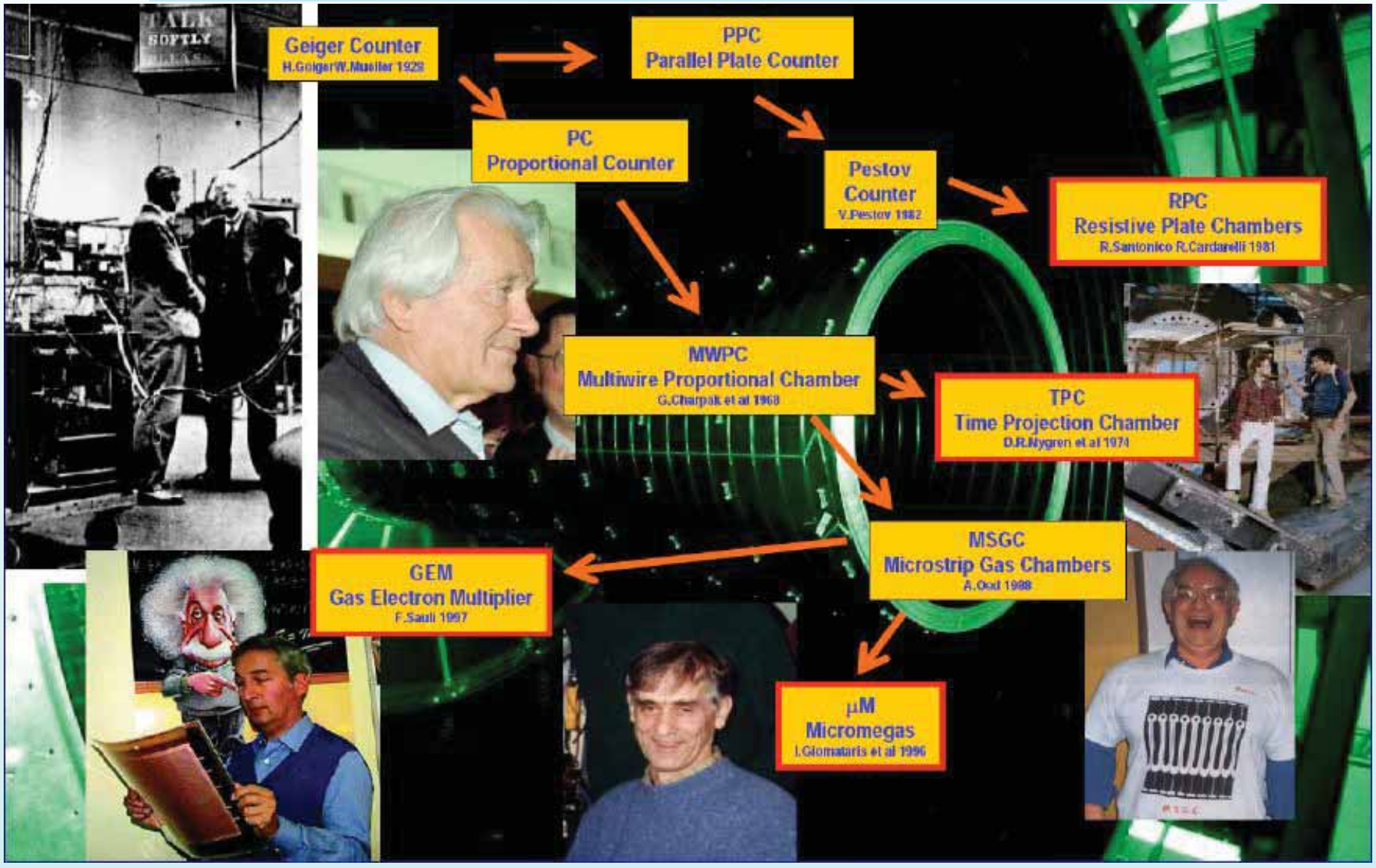
F. Sauli

G. C. Santiard

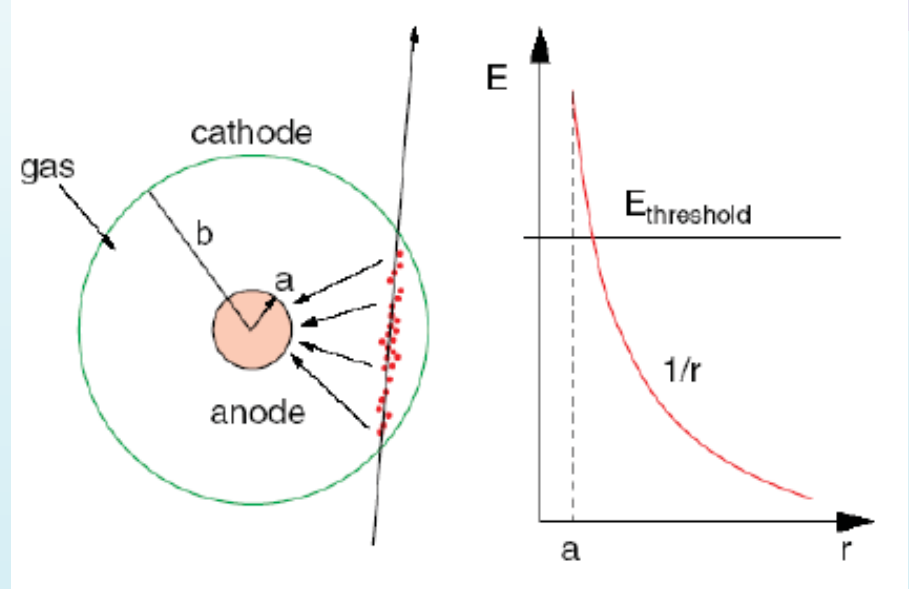
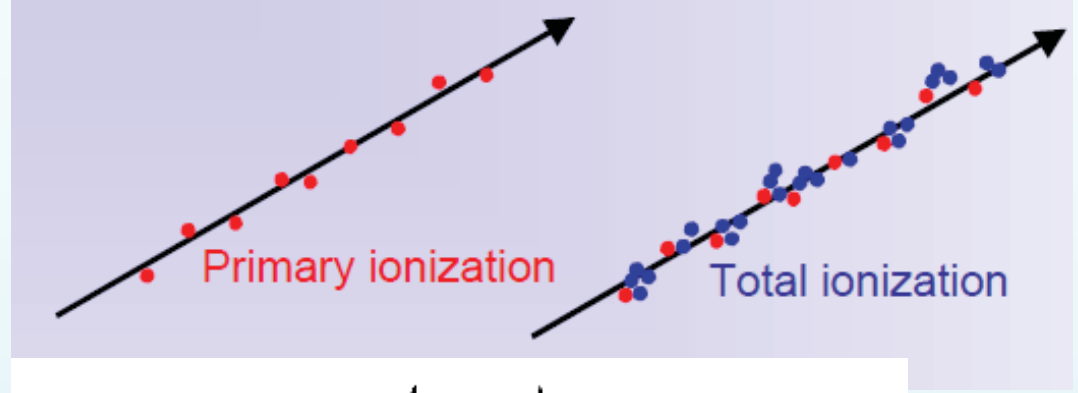
G. Charpak



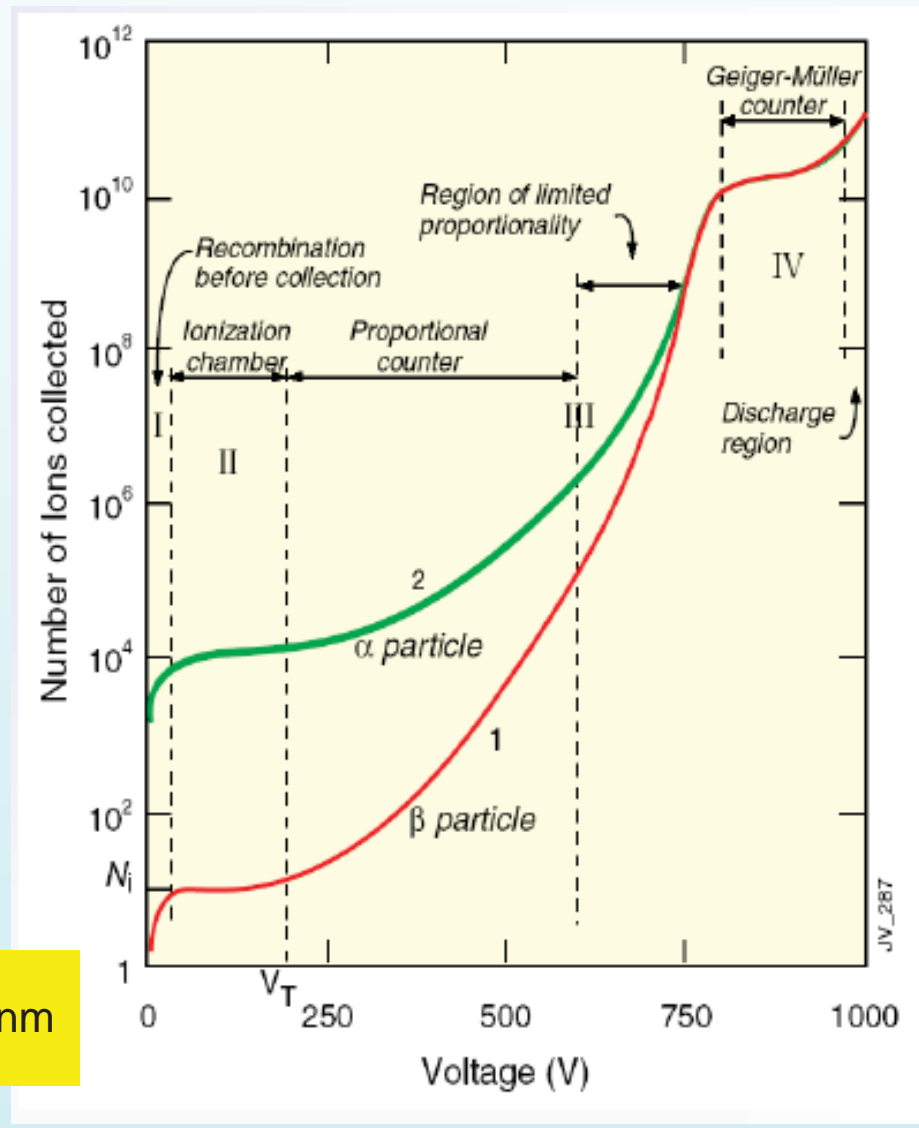
100 years of gaseous detectors: gallery 3



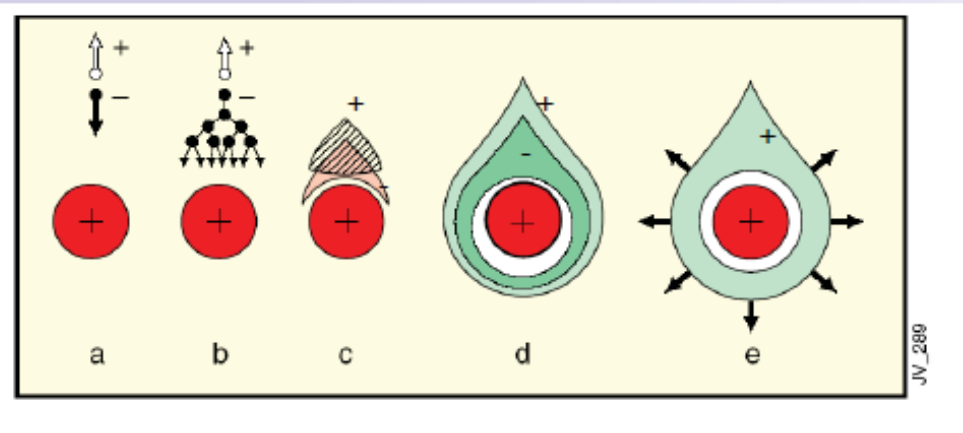
Gas ionization & single wire detector



Ar atom radius: ~ 70 pm
 distance between Ar atoms: ~ 4 nm
 mean free path: ~ 2 μm



Signal formation



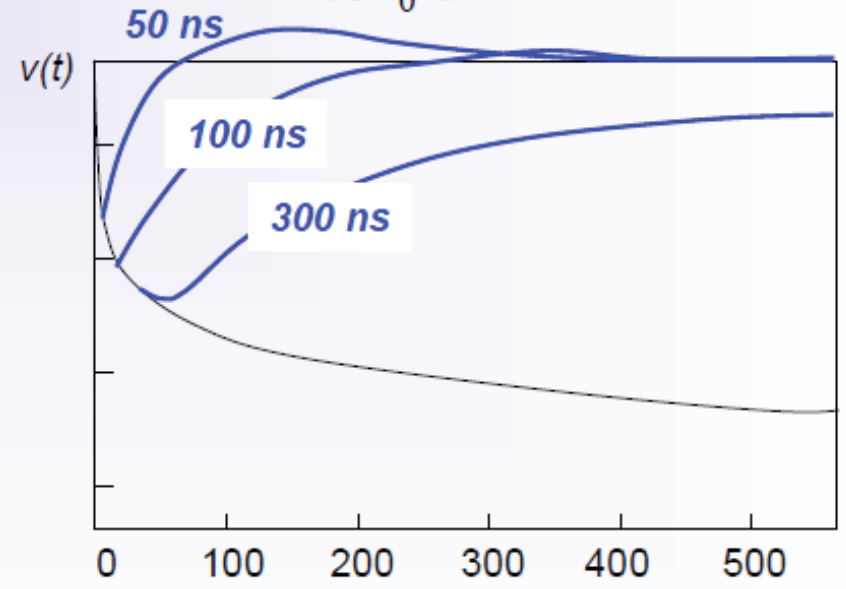
Electrons collected by the anode wire i.e. dr is very small (few μm). Electrons contribute only very little to detected signal (few %).

Ions have to drift back to cathode i.e. dr is large (few mm). Signal duration limited by total ion drift time.

Need electronic signal differentiation to limit dead time.

Avalanche formation within a few wire radii and within $t < 1$ ns. Signal induction both on anode and cathode due to moving charges (both electrons and ions).

$$dv = \frac{Q}{lCV_0} \frac{dV}{dr} dr$$





Ernest Rutherford
(1871-1937)



EN
Istituto Nazionale
di Fisica Nucleare

Geiger counter

- ▶ Detects radiation by discharge;
- ▶ can count α , β and γ particles (at low rates ...);
- ▶ no tracking capability.
- ▶ 1908: Ernest Rutherford and Hans Geiger
- ▶ 1928: Hans Geiger and Walther Müller



Hans Geiger
(1882-1945)



Walther Müller
(1905-1979)

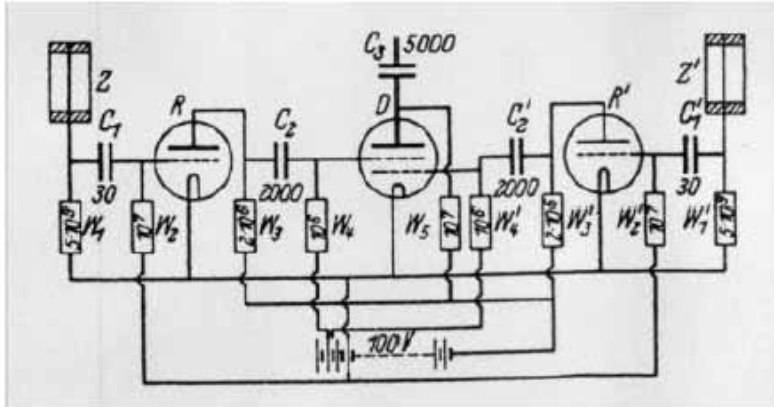


A Geiger-Müller counter built in 1939 and used in the 1947-1950 for cosmic ray studies in balloons and on board B29 aircraft by Robert Millikan et al.

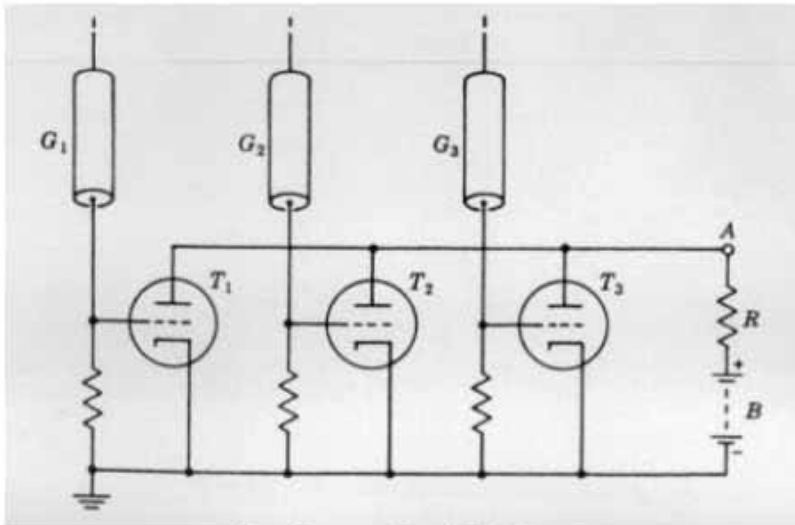
Made of copper, 30 cm long

Electric Registration of Geiger Müller Tube Signals

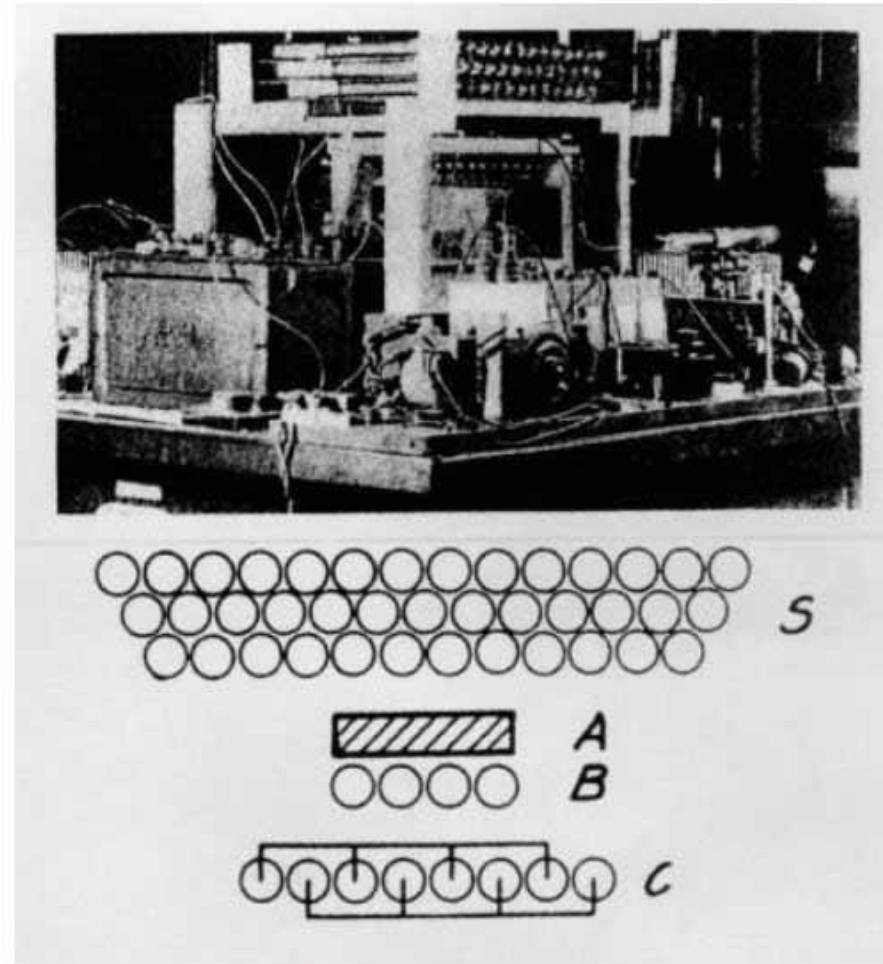
Charges create a discharge in a cylinder with a thin wire set to HV. The charge is measured with a electronics circuit consisting of tubes → electronic signal.



W. Bothe, 1928



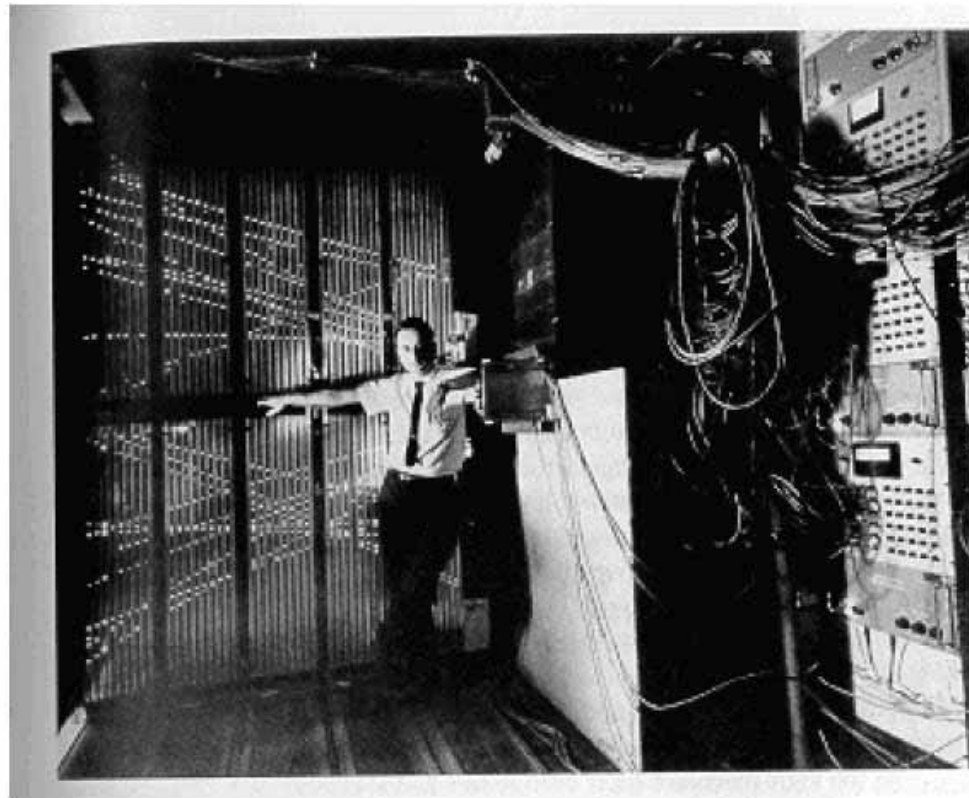
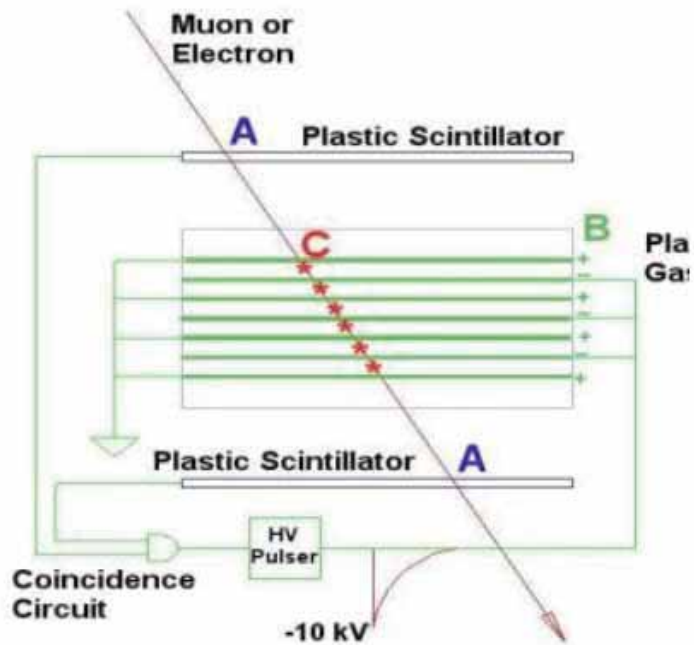
B. Rossi, 1932



Cosmic Ray Telescope 1930ies

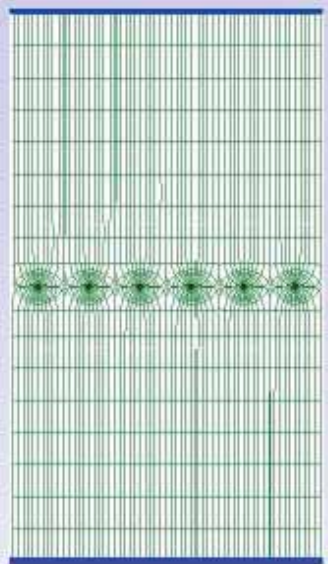
Spark Chamber, 1960ies

Charges create 'conductive channel' which initiates a spark in case HV is applied.



Discovery of the Muon Neutrino 1960ies

Multi Wire Proportional Chamber



Simple idea to multiply SWPC cell : Nobel Prize 1992



First electronic device allowing high statistics experiments !!

Typical geometry
5mm, 1mm, 20 μm

Normally digital readout :
spatial resolution limited to

$$\sigma_x \approx \frac{d}{\sqrt{12}}$$

for d = 1 mm $\sigma_x = 300 \mu\text{m}$



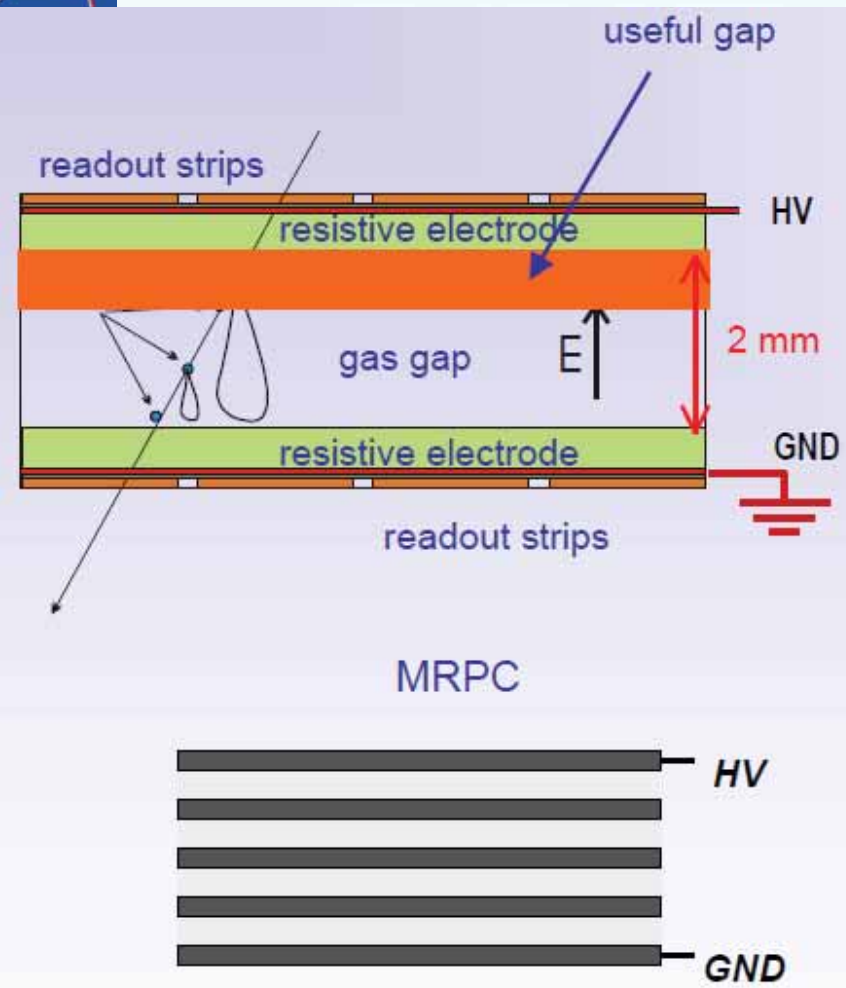
G. Charpak, F. Sauli and J.C. Santiard



Old ALICE TPC



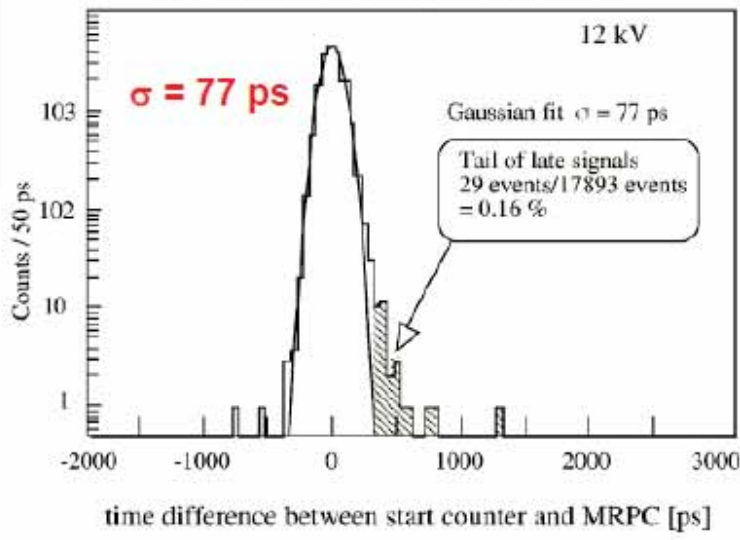
Resistive plate chambers



Rate capability strong function of the resistivity of electrodes in streamer mode.

A. Akindinov et al., NIM A456(2000)16

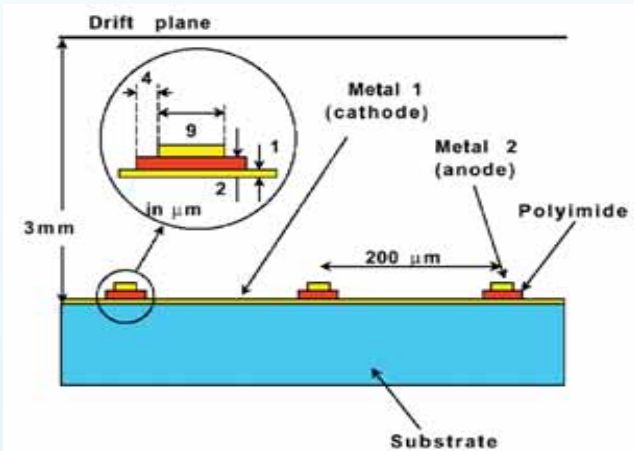
Typical time spectrum from 5 gap MRPC



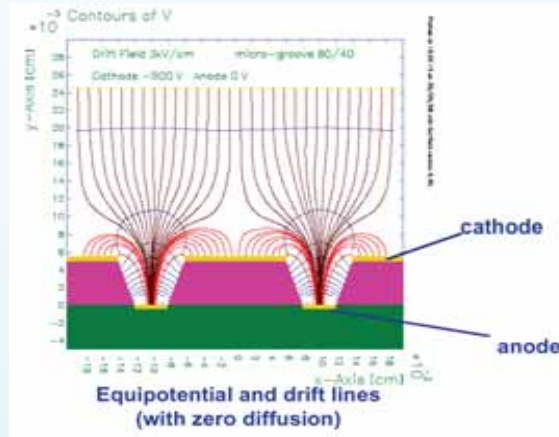
Time resolution

Multigap RPC - exceptional time resolution suited for the trigger applications

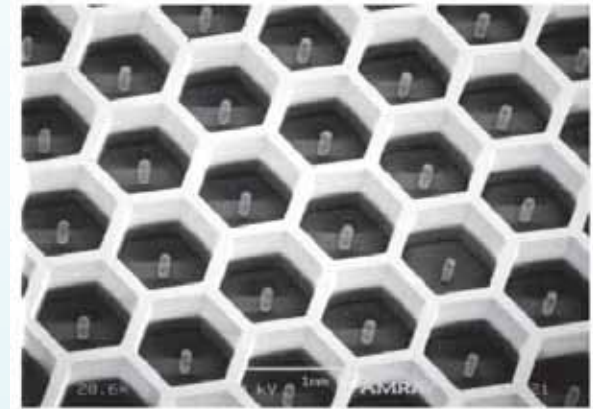
MICRO-GAP CHAMBER



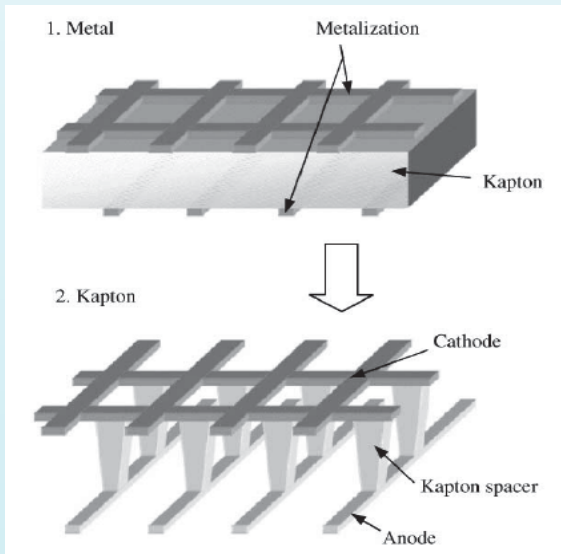
MICRO-GROOVE CHAMBER



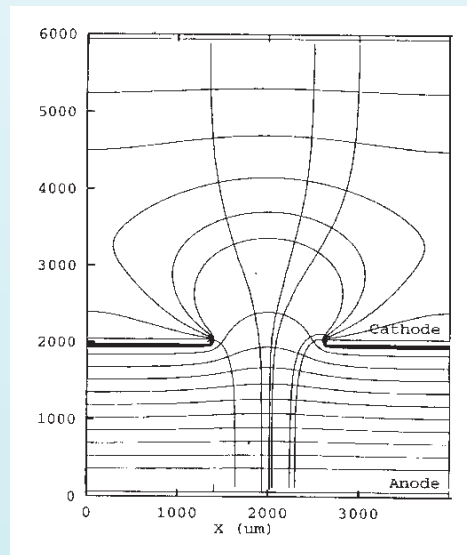
MICRO-PIN ARRAY



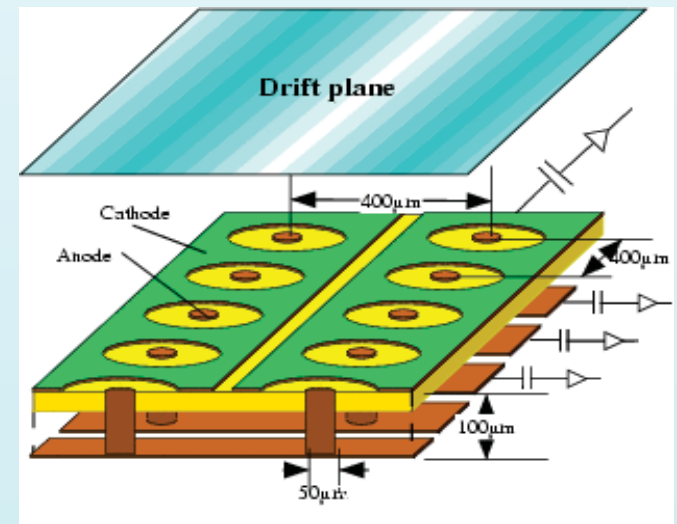
MICRO-WIRE CHAMBER

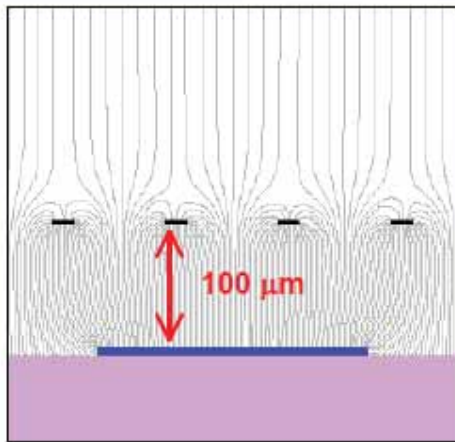


COMPTEUR A TROUS



MICRO-PIXEL CHAMBER



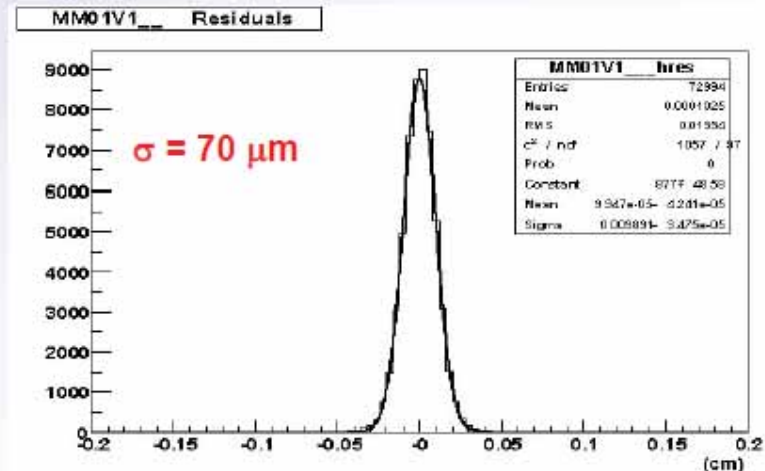
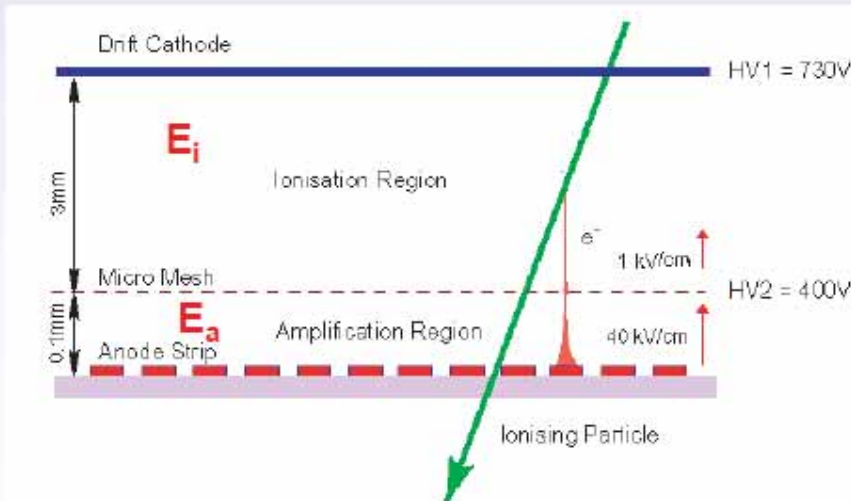


micromesh

Micromesh mounted above readout structure (typically strips).

E field similar to parallel plate detector.

$E_a/E_i \sim 50$ to secure electron transparency and positive ion flowback suppression.



Space resolution



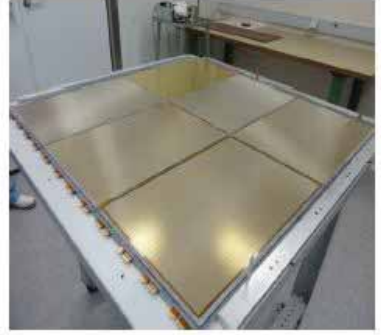
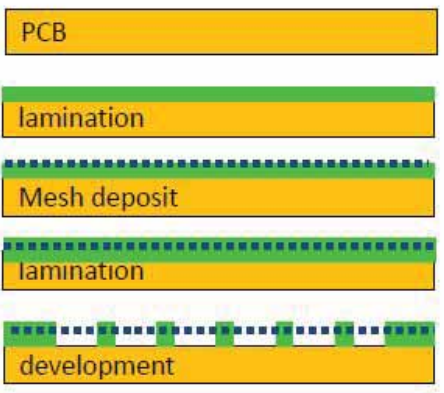
Bulk Micromegas technology



Y. Giomataris
R. de Oliveira

M. Chefdeville

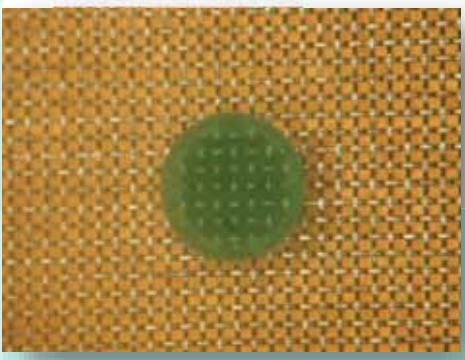
T2K TPC, A. Delbart, M. Zito



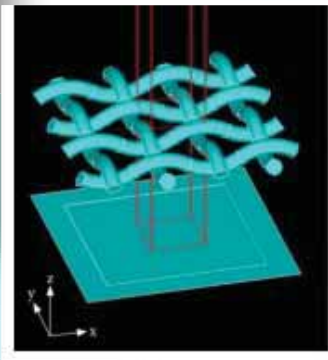
- Fine segmentation 1cm², thickness 8mm for ILC Hadronic calorimetry
- Tested in the RD51 1 kHz beam



Bulk Micromegas ILC DHCAL first m²
LAPP Annecy



woven mesh



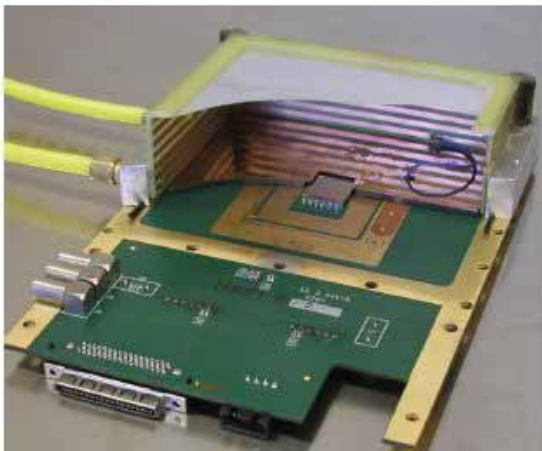
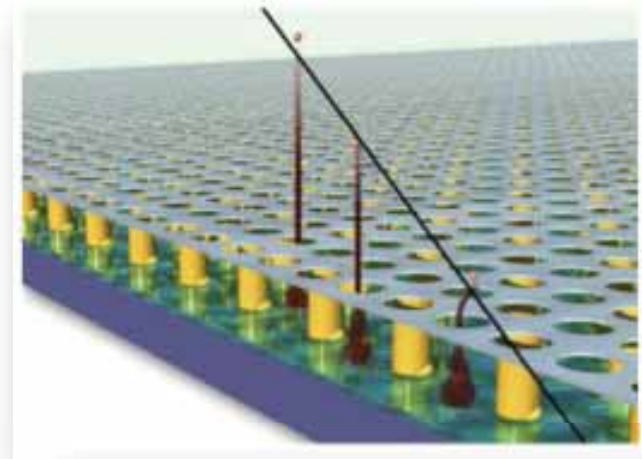
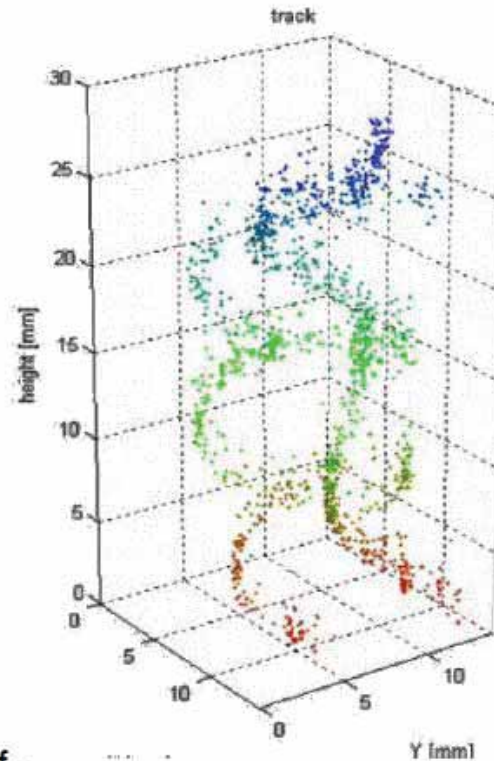
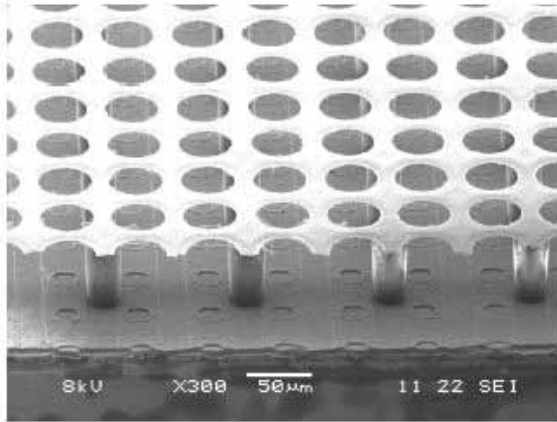


INGRID

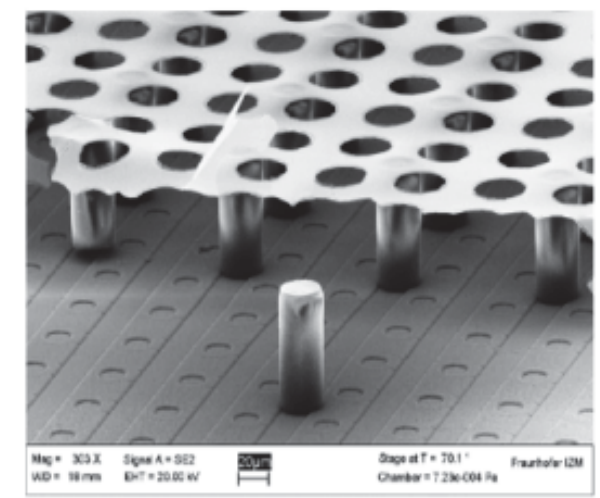


Integrated Micromegas and Pixel Sensor
Postprocessing of the TIMEPIX chip to build a metal mesh on insulating pillars

Electron tracks from ^{90}Sr in magnetic field (0.2 T):



H. Van der Graaf,
IEEE Nucl. Sci. Symp. Conf. Rec. (Dresden, October 2008)

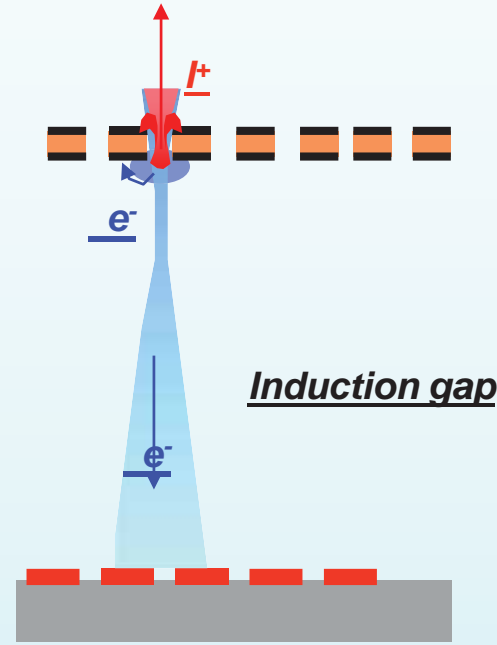
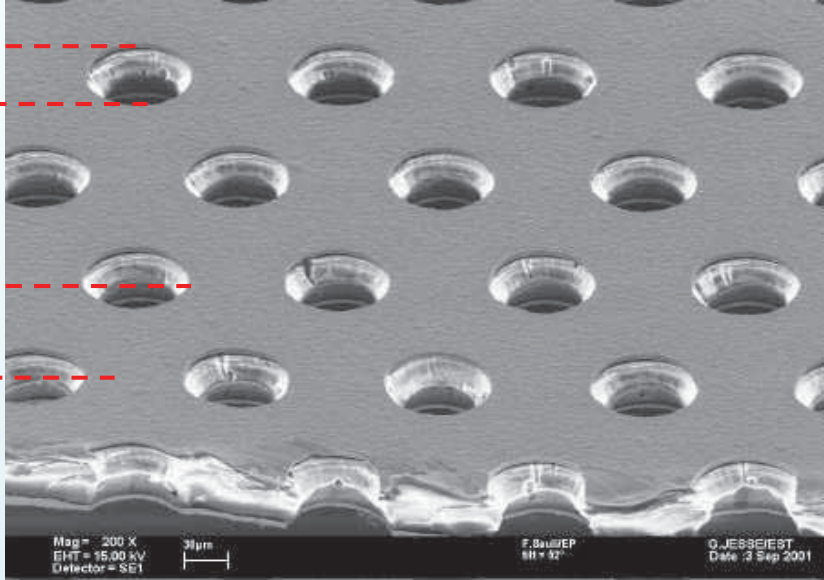




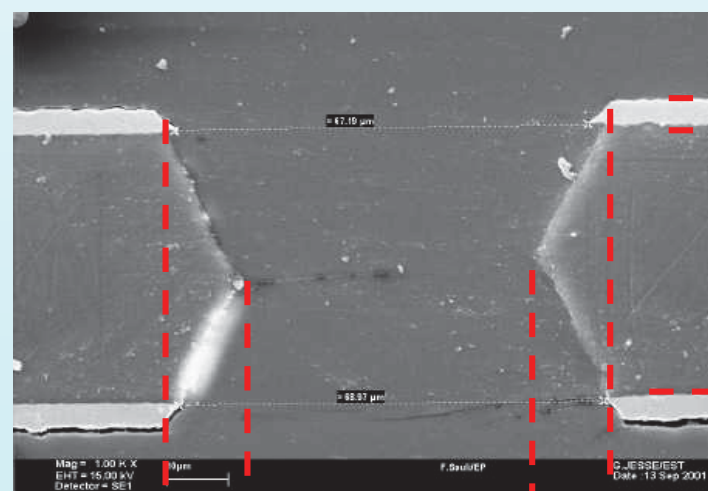
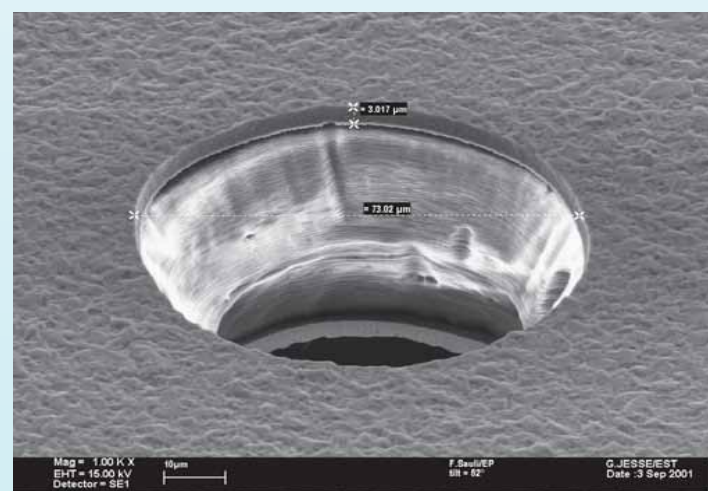
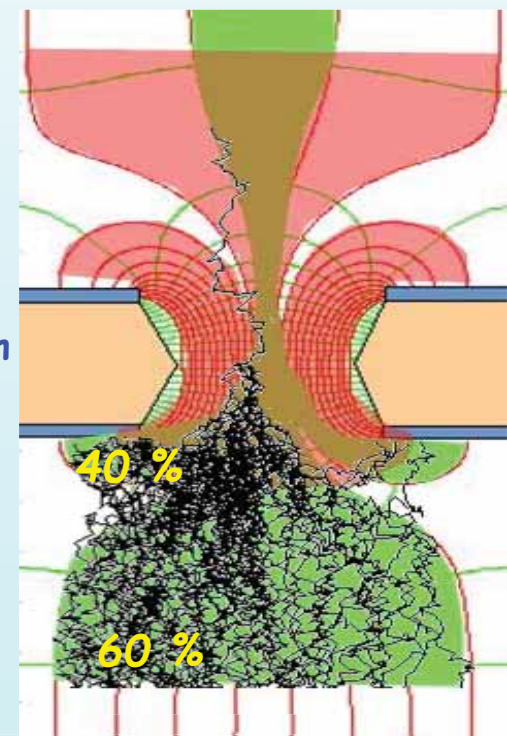
GEM

Thin metal-coated polymer foil pierced by a high density of holes (50-100/mm²)
Typical geometry: 5 μm Cu on 50 μm Kapton, 70 μm holes at 140 μm pitch

70 μm
140 μm



Ions



5 μm
50 μm

55 μm
70 μm



GEM Manufacturing

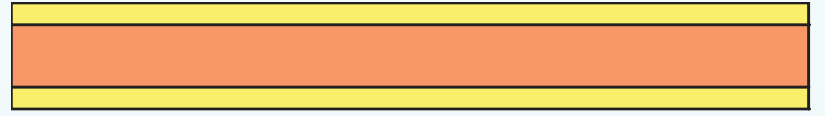


GEM foils are produced at CERN using proprietary process.

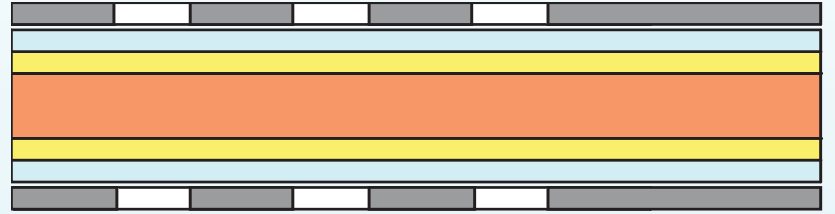
Rui De Oliveira
CERN-EST-DEM



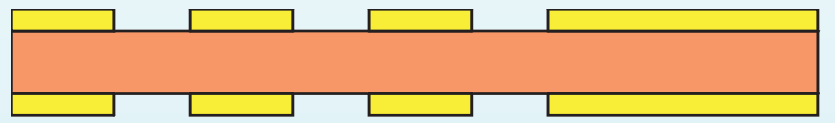
50 μm Kapton
5 μm Cu both sides



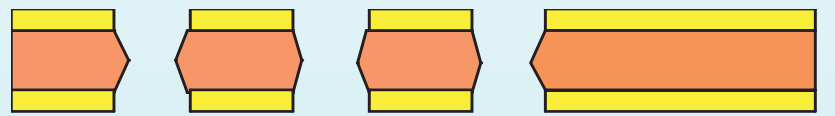
Photoresist coating, masking
and exposure
to UV light



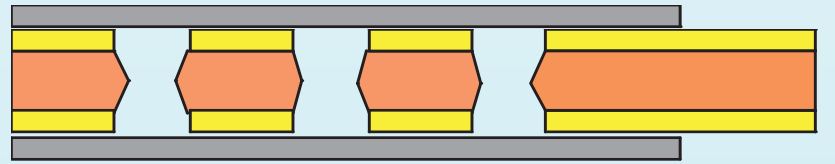
Metal etching



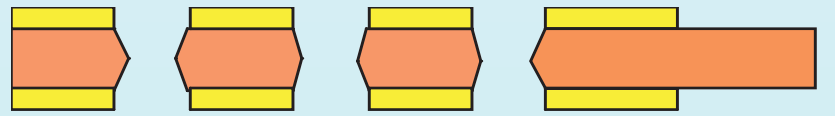
Kapton etching



Second masking

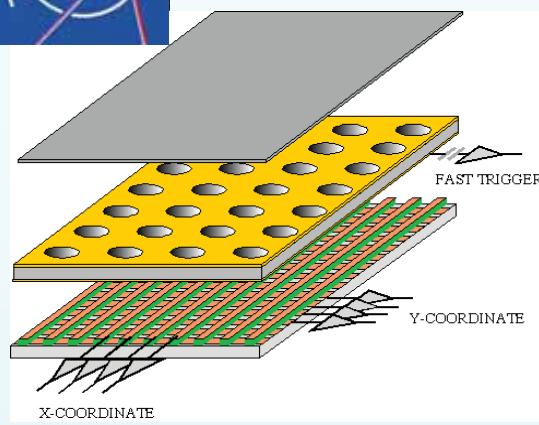


Metal etching
and cleaning





GEM – Gas Electron Multiplier

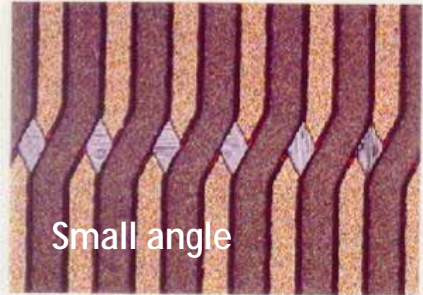


Full decoupling of the charge amplification structure from the charge collection and readout structure.
Both structures can be optimized independently !

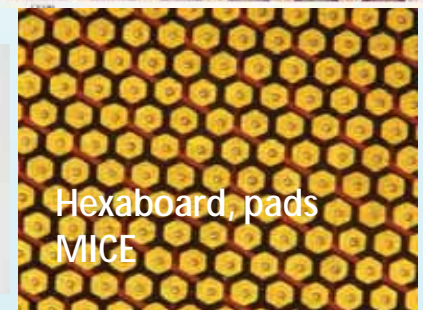
A. Bressan et al, Nucl. Instr. and Meth. A425(1999)254



Cartesian
Compass, LHCb



Small angle



Hexaboard, pads
MICE



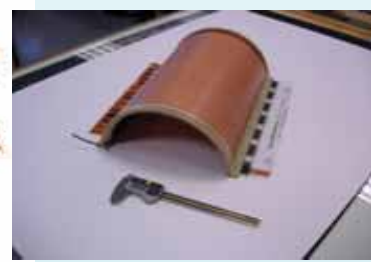
Mixed
Totem



Different flat shapes



cylindrical



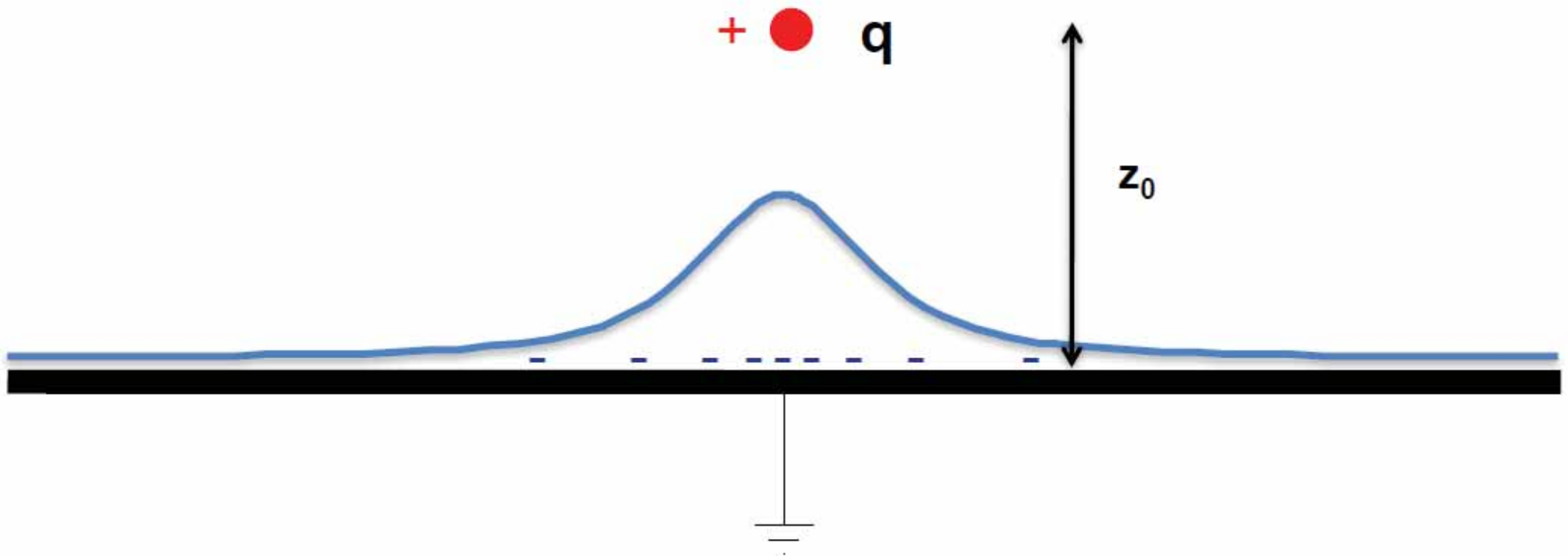
spherical

Most of the detectors use three GEM foils in cascade for amplification to reduce discharge probability by reducing field strength.



Induced charges

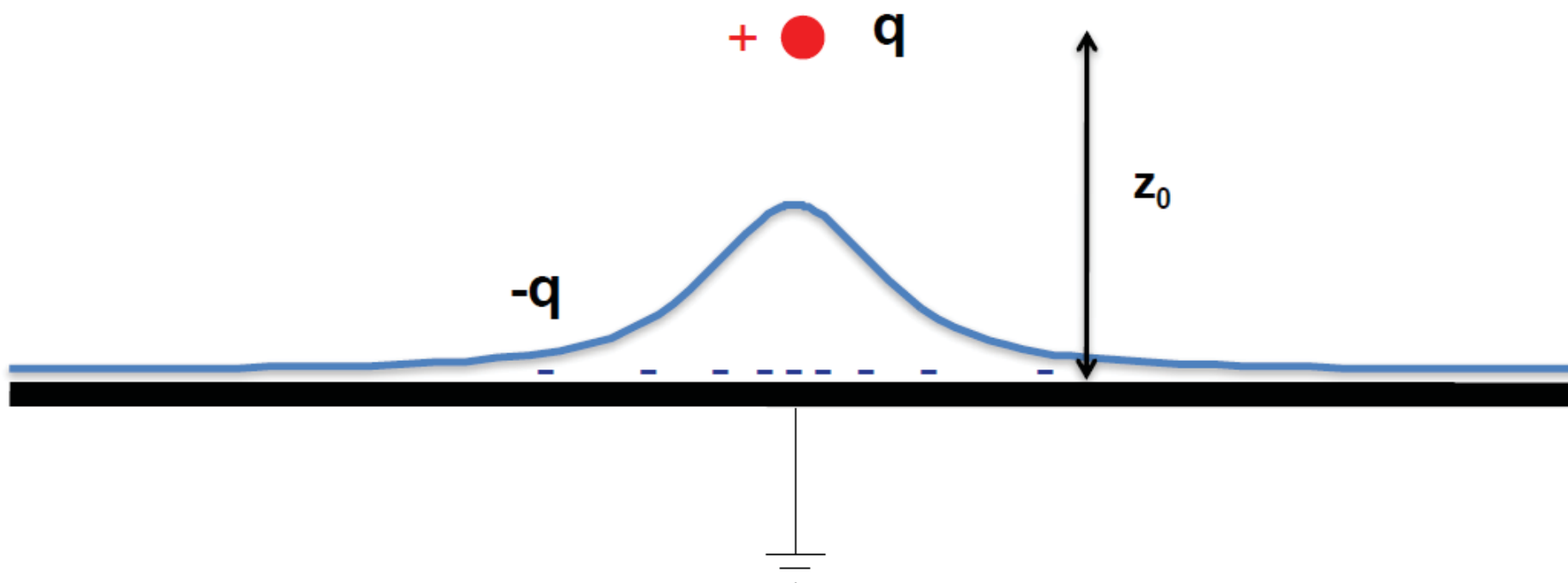
A point charge q at a distance z_0 above a grounded metal plate 'induces' a surface charge.



Induced charges

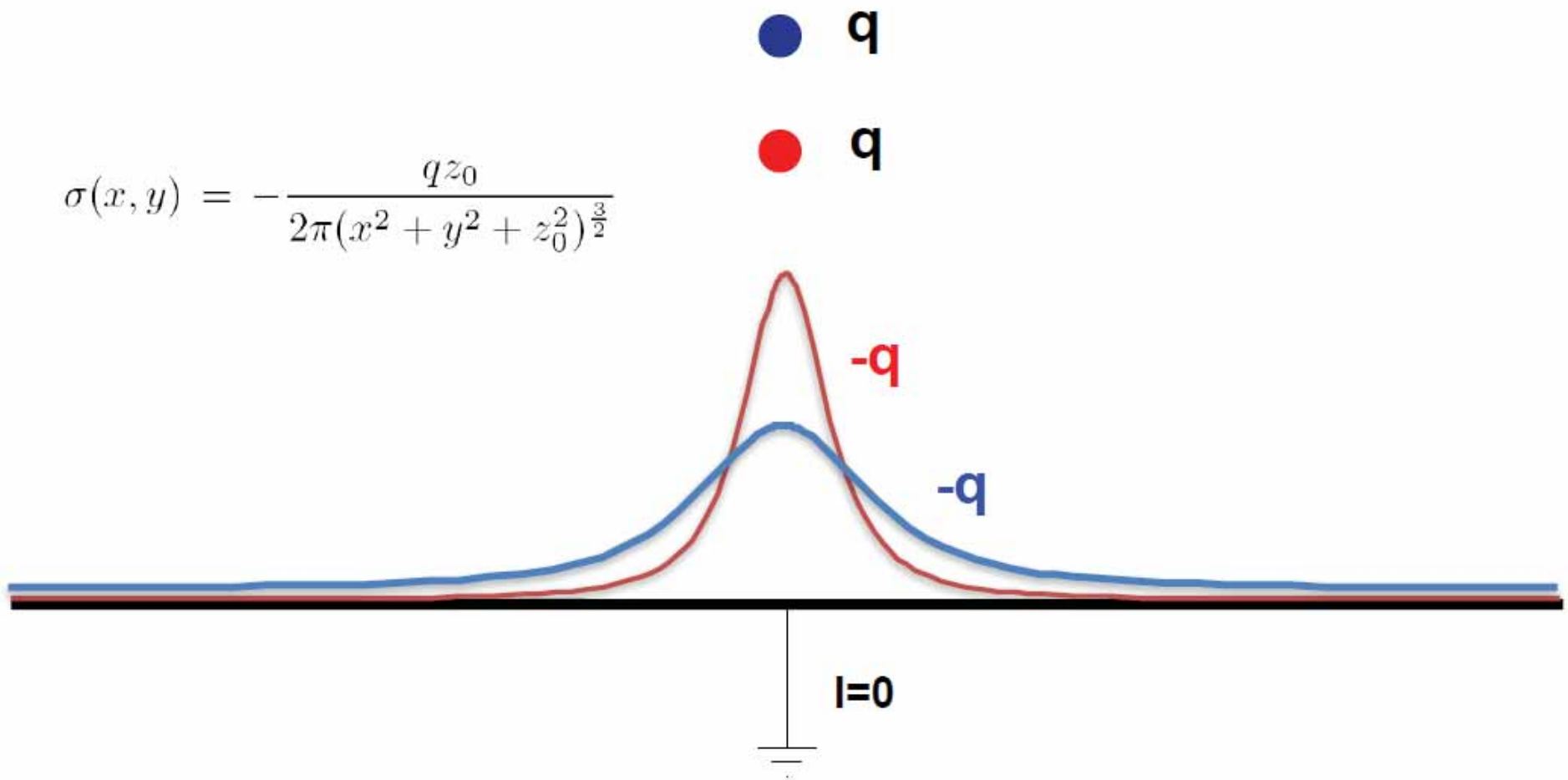
The total charge induced by a point charge q on an infinitely large grounded metal plate is equal to $-q$, independent of the distance of the charge from the plate.

The surface charge distribution is however depending on the distance z_0 of the charge q .



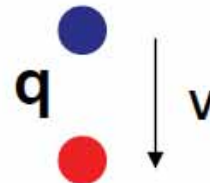
Induced charges

Moving the point charge closer to the metal plate, the surface charge distribution becomes more peaked, the total induced charge is however always equal to $-q$.



Induced charges

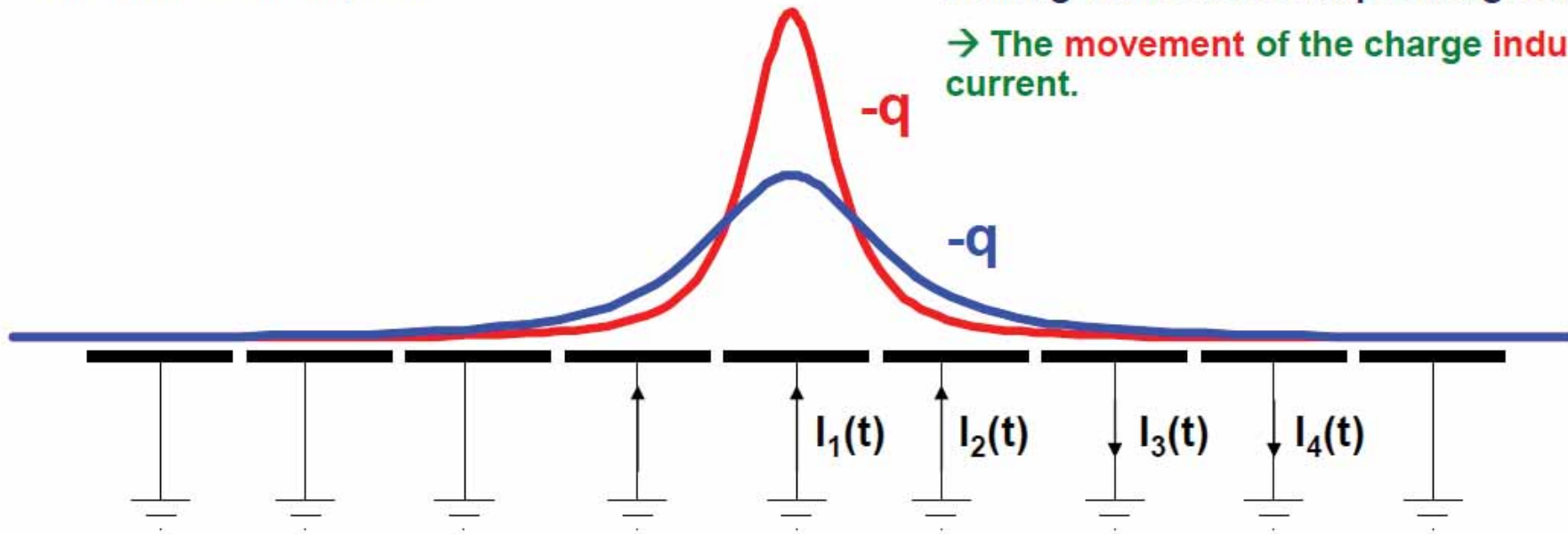
If we segment the grounded metal plate and if we ground the individual strips, the surface charge density doesn't change with respect to the continuous metal plate.



The charge induced on the individual strips is now depending on the position z_0 of the charge.

If the charge is moving there are currents flowing between the strips and ground.

→ The movement of the charge induces a current.



$$Q_1(z_0) = \int_{-\infty}^{\infty} \int_{-w/2}^{w/2} \sigma(x, y) dx dy = -\frac{2q}{\pi} \arctan\left(\frac{w}{2z_0}\right) \quad z_0(t) = z_0 - vt$$

$$I_1^{ind}(t) = -\frac{d}{dt} Q_1[z_0(t)] = -\frac{\partial Q_1[z_0(t)]}{\partial z_0} \frac{dz_0(t)}{dt} = \frac{4qw}{\pi[4z_0(t)^2 + w^2]} v$$

■ Some characteristics of Silicon crystals

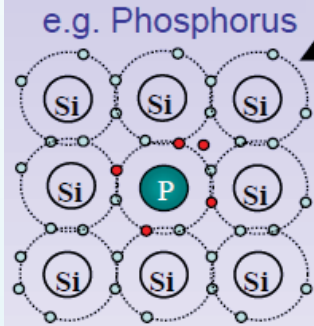
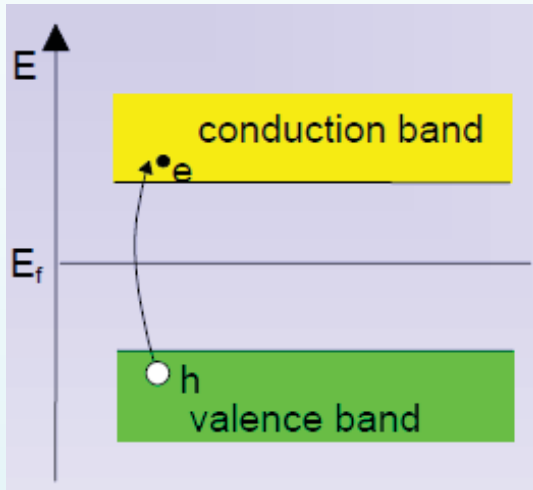
- **Small band gap** $E_g = 1.12 \text{ eV} \Rightarrow E(\text{e-h pair}) = 3.6 \text{ eV} (\approx 30 \text{ eV for gas detectors})$
- **High specific density** 2.33 g/cm^3 ; $dE/dx \text{ (M.I.P.)} \approx 3.8 \text{ MeV/cm} \approx 106 \text{ e-h}/\mu\text{m}$ (average)
- **High carrier mobility** $\mu_e = 1450 \text{ cm}^2/\text{Vs}$, $\mu_h = 450 \text{ cm}^2/\text{Vs} \Rightarrow$ fast charge collection ($< 10 \text{ ns}$)
- **Very pure** $< 1 \text{ ppm}$ impurities and $< 0.1 \text{ ppb}$ electrical active impurities
- **Rigidity** of silicon allows thin self supporting structures
- **Detector production by microelectronic techniques**
 \Rightarrow well known industrial technology, relatively low price, small structures easily possible

■ Alternative semiconductors

- Diamond
- GaAs
- Silicon Carbide
- Germanium

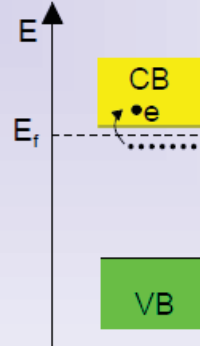
	Diamond	SiC (4H)	GaAs	Si	Ge
Atomic number Z	6	14/6	31/33	14	32
Bandgap E_g [eV]	5.5	3.3	1.42	1.12	0.66
$E(\text{e-h pair})$ [eV]	13	7.6-8.4	4.3	3.6	2.9
density [g/cm^3]	3.515	3.22	5.32	2.33	5.32
e-mobility μ_e [cm^2/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm^2/Vs]	1200	115	400	450	1900

Doping and p-n junction



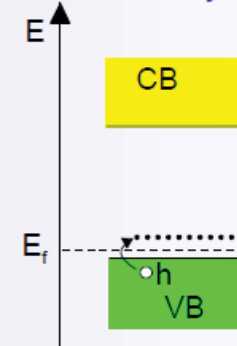
Doping: n-type Silicon

- add elements from Vth group
- ⇒ **donors** (P, As,...)
- electrons are majority carriers



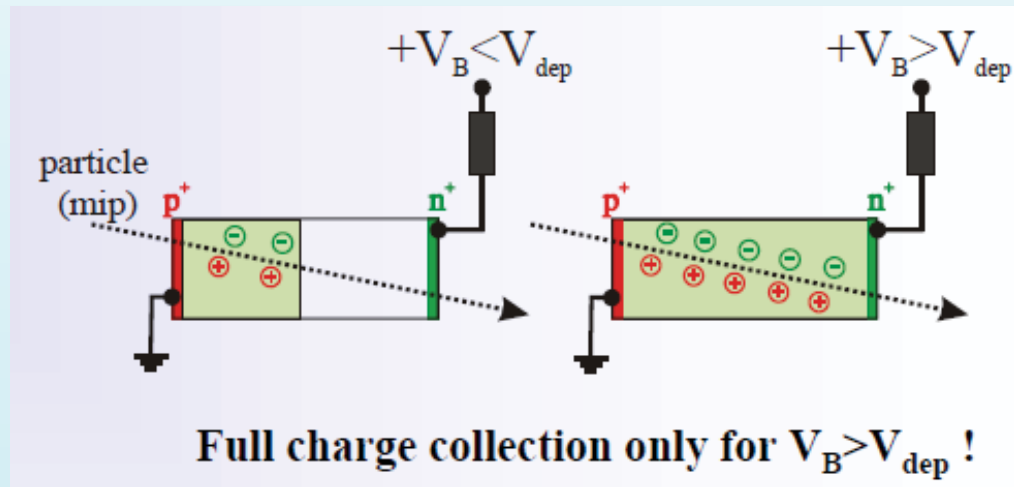
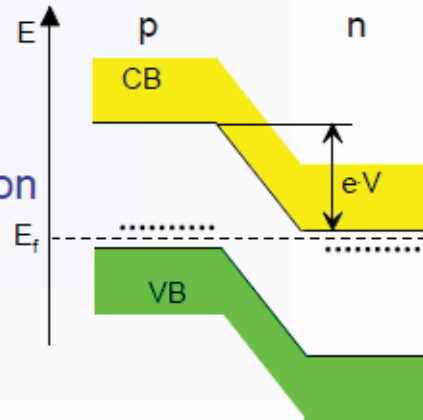
Doping: p-type Silicon

- add elements from IIIrd group
- ⇒ **acceptors** (B,...)
- holes are the majority carriers



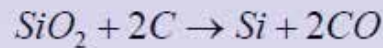
p-n junction

- There must be a single Fermi level !
- ⇒ band structure deformation
- ⇒ potential difference
- ⇒ depleted zone

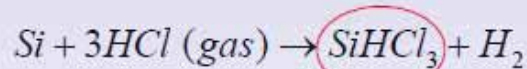


■ Produce a polysilicon rod

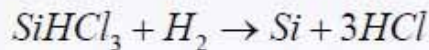
- Melt very **pure sand** (SiO_2) together with coke ($\sim 1800^\circ\text{C}$)



- Grind the "metallurgical grade silicon" (98% Si) and expose it to hydrochloric gas



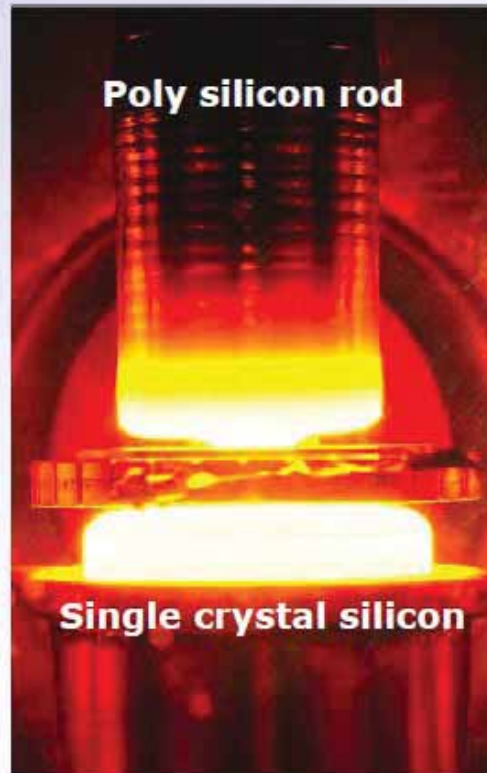
- **Trichlorsilane** boils at 31.7°C and can thus be distilled and purified
- Deposit silicon in a Chemical Vapour Deposition process



- Cast silicon into a **polycrystalline silicon rod**

■ Float Zone process

- Using a single Si crystal seed, melt the vertically oriented rod onto the seed using RF power and "pull" the **monocrystalline ingot**



■ Monocrystalline Ingot

- grind into round shape
- make the flat or a notch



■ Wafer production

- Slice the ingot into wafers of $300\text{-}500\ \mu\text{m}$ (diamond saw)
- lapping of wafers
- etching of wafers
- polishing of wafers



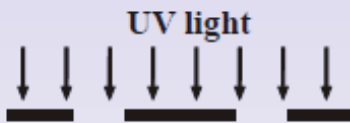
Silicon sensor production

n-type silicon

- Polished n-type silicon wafer (typical $\rho \sim 1-10 \text{ K}\Omega\text{cm}$)



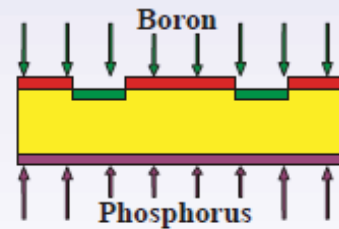
- Oxidation (800-1200°C)



- Photolithography (coat with photo resist; align mask, expose to UV light, develop photoresist);

Etching of oxide

etch



- Doping with boron and phosphorus by implantation (or by diffusion)
 Annealing to cure radiation damage and activate dopants
 - p⁺ n junction on front side
 - n n⁺ ohmic contact on back side

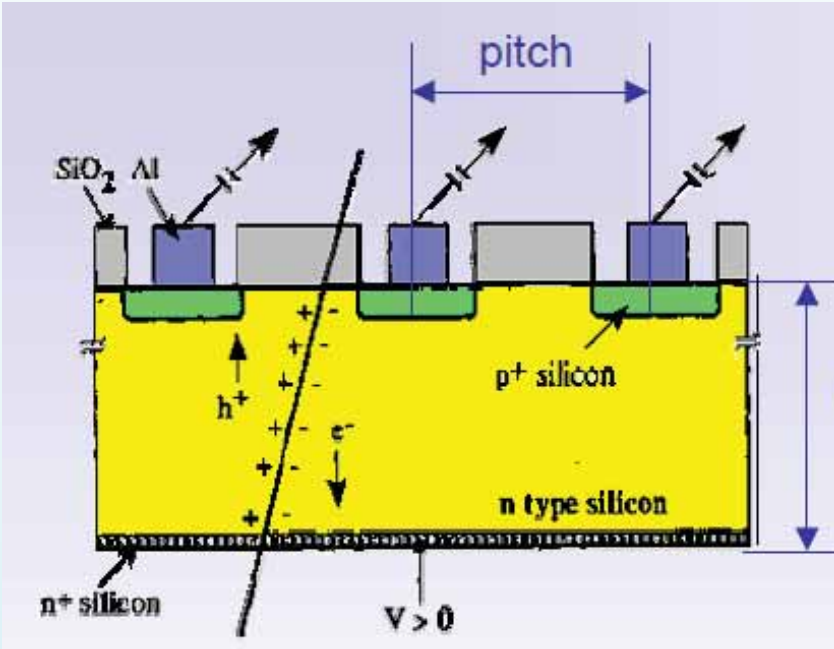


- Aluminize surface (e.g. by evaporation)



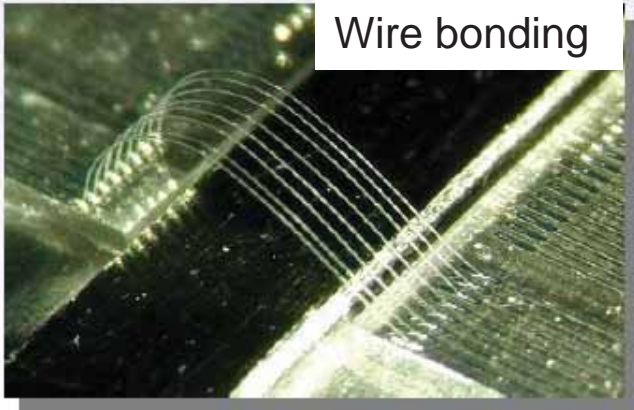
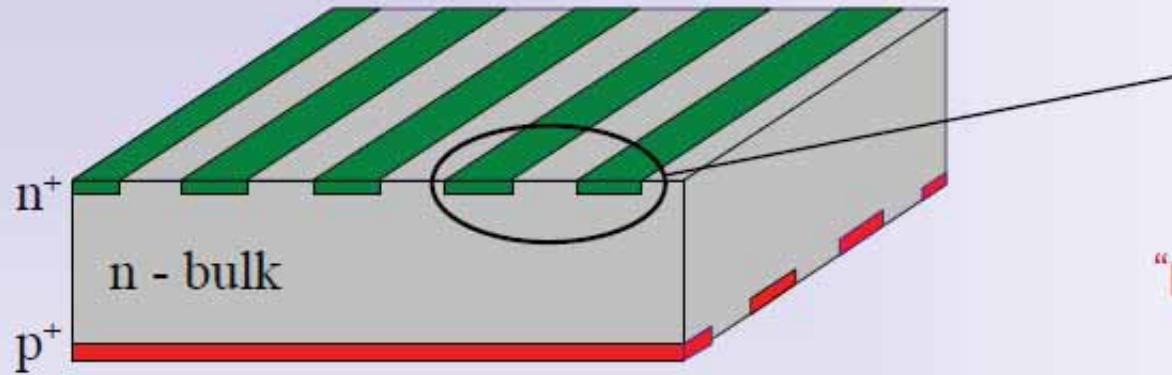
- Pattern metal for diode contacts

Silicon sensor production



Get a 2nd coordinate

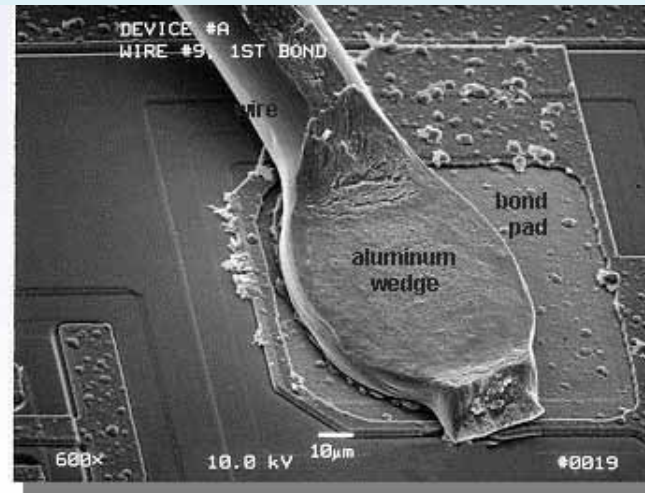
Put n⁺ and p⁺ strips on opposite sides and read them both



Wire bonding

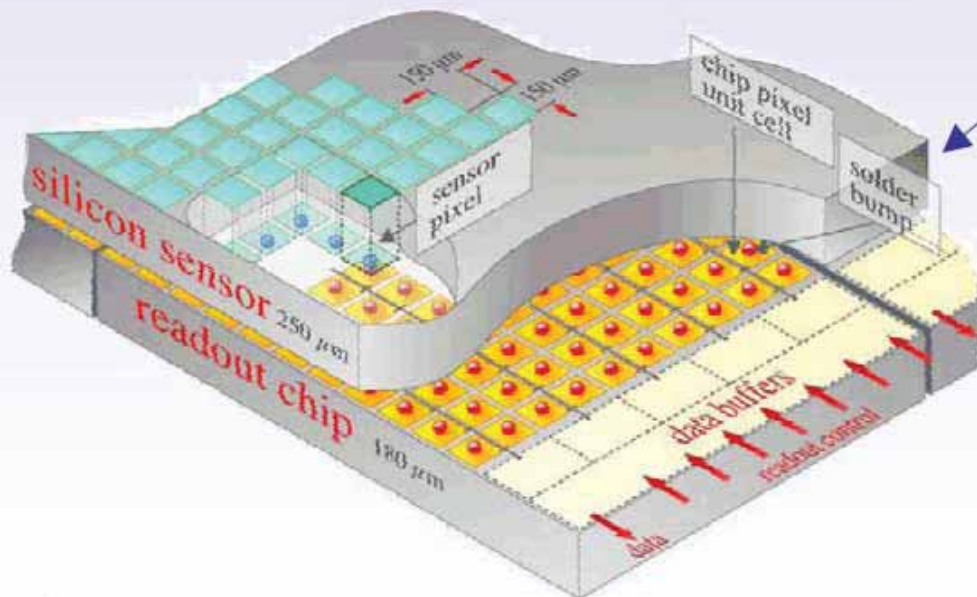
Microscope:
connect sensor to
fan-out circuit

Electron microscope:
bond "foot"

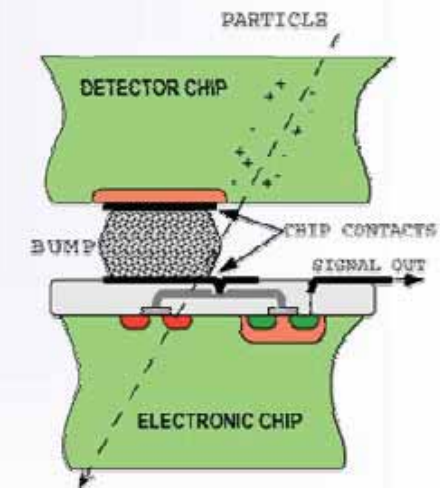
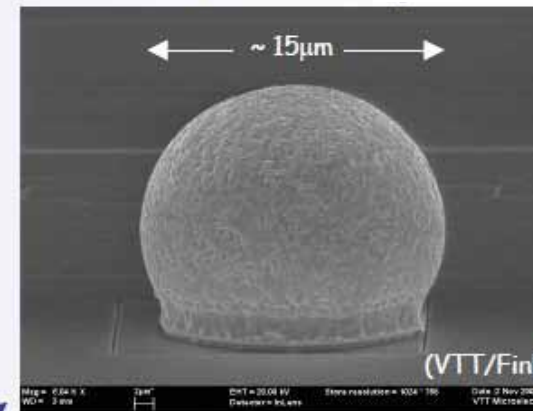


HAPS – Hybrid Active Pixel Sensors

- segment silicon to diode matrix with high granularity (⇒ true 2D, no reconstruction ambiguity)
- readout electronic with same geometry (every cell connected to its own processing electronics)
- connection by “bump bonding”
- requires sophisticated readout architecture
- Hybrid pixel detectors will be used in LHC experiments: ATLAS, ALICE, CMS and LHCb



Solder Bump: Pb-Sn



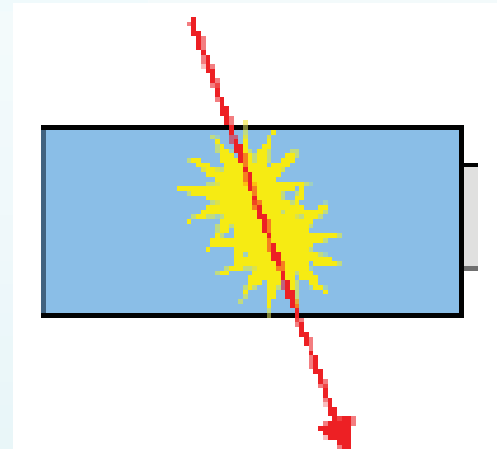
Flip-chip technique



Scintillation detectors



Particle Detection via Luminescence



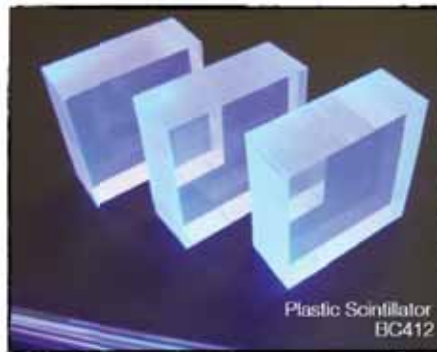
Scintillators – General Characteristics

Principle:

dE/dx converted into visible light
Detection via photosensor
[e.g. photomultiplier, human eye ...]

Main Features:

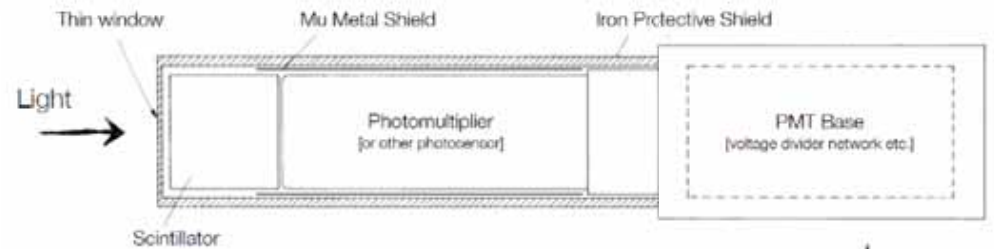
- Sensitivity to energy
- Fast time response
- Pulse shape discrimination



Requirements

- High efficiency** for conversion of excitation energy to fluorescent radiation
- Transparency** to its fluorescent radiation to allow transmission of light
- Emission of light** in a spectral range detectable for photosensors
- Short decay time** to allow fast response

Scintillators – Basic Counter Setup

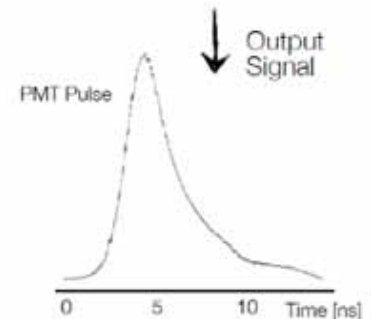


Scintillator Types:

Photosensors

- Photomultipliers
- Micro-Channel Plates
- Hybrid Photo Diodes
- Visible Light Photon Counter
- Silicon Photomultipliers

- Organic Scintillators
- Inorganic Crystals
- Gases

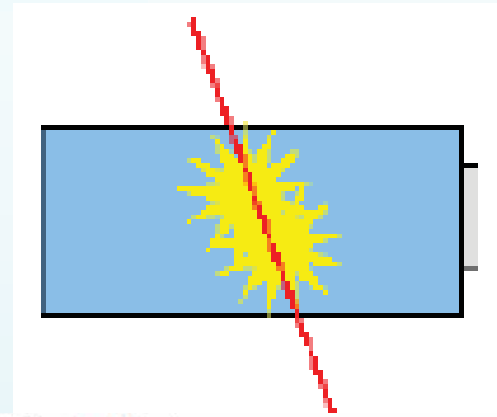




Scintillation detectors



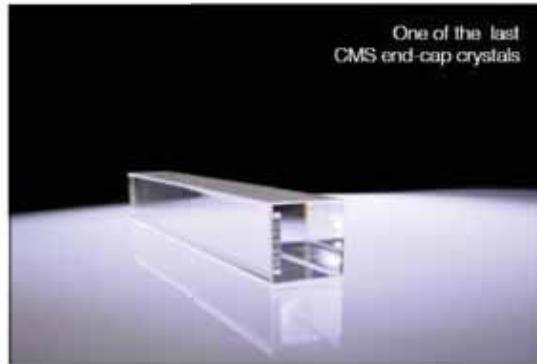
Particle Detection via Luminescence



Inorganic Crystals



Example CMS
Electromagnetic Calorimeter



Large light yield, good energy resolution

Plastic and Liquid Scintillators

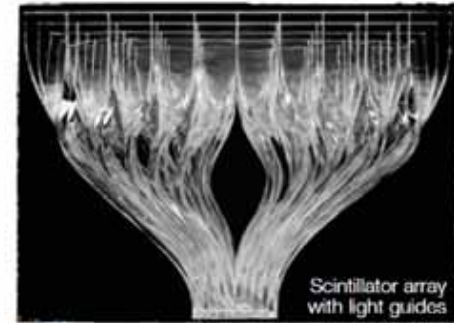
In practice use ...

- solution of organic scintillators
[solved in plastic or liquid]
- + large concentration of primary 'fluor'
- + smaller concentration of secondary 'fluor'
- + ...

Scintillator requirements:

- Solvable in base material
- High fluorescence yield
- Absorption spectrum must overlap with emission spectrum of base material

Fast and cheaper



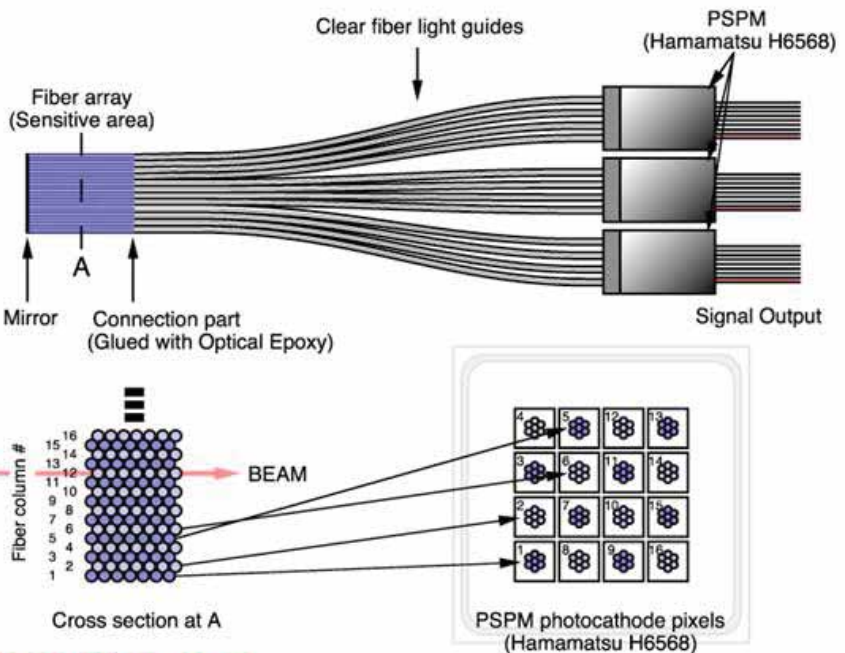


Scintillating Fibers hodoscopes



Scintillating Fibers Hodoscopes

9 stations: 21 coordinates



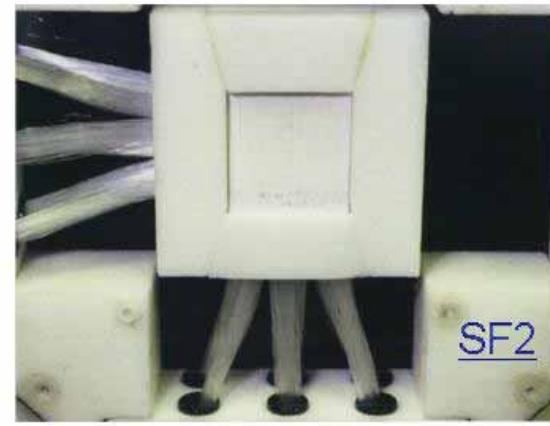
Sensitive area:
7-layers of Kuraray SCSF-78MJ 0.5 mm Ø

Rate capability > 5 MHz per channel

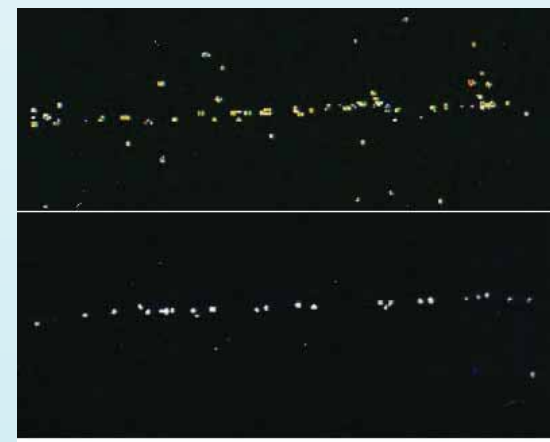
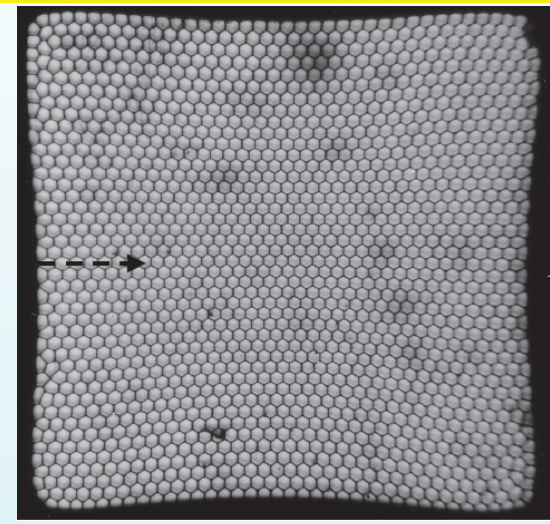
Efficiency: 99%

Space resol. 130 – 250 μm

Time resol. < 400 ps



RD7 60μm hexagonal fibers



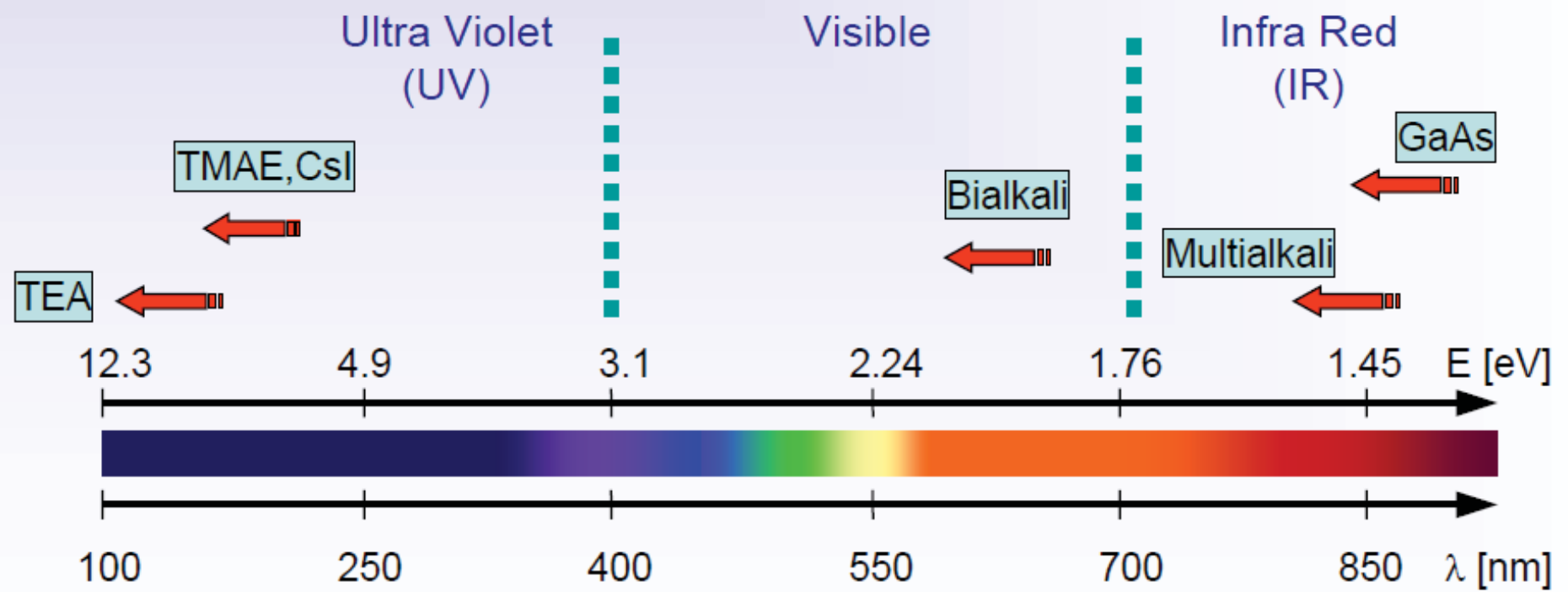
← 10 mm →



Photon detection



Photoemission threshold W_{ph} of various materials



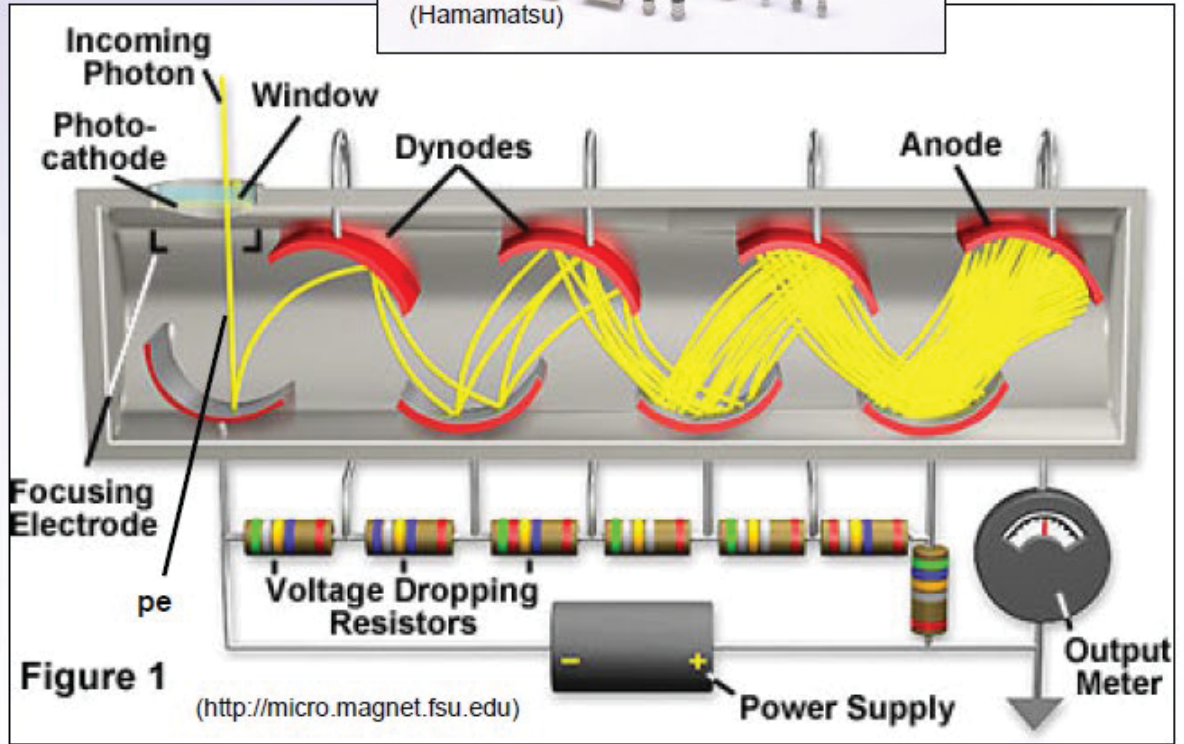
Photomultipliers

Basic principle:

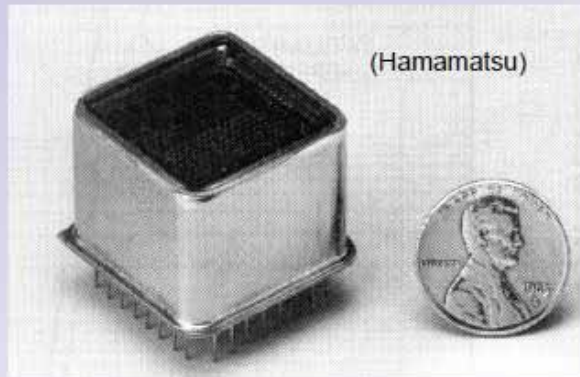
- Photo-emission from photo-cathode
- Secondary emission (SE) from N dynodes:
 - dynode gain $g \approx 3-50$ (function of incoming electron energy E);
 - total gain M :

$$M = \prod_{i=1}^N g_i$$

- Example:
 - 10 dynodes with $g=4$
 - $M = 4^{10} \approx 10^6$



Multianode and flat-panels

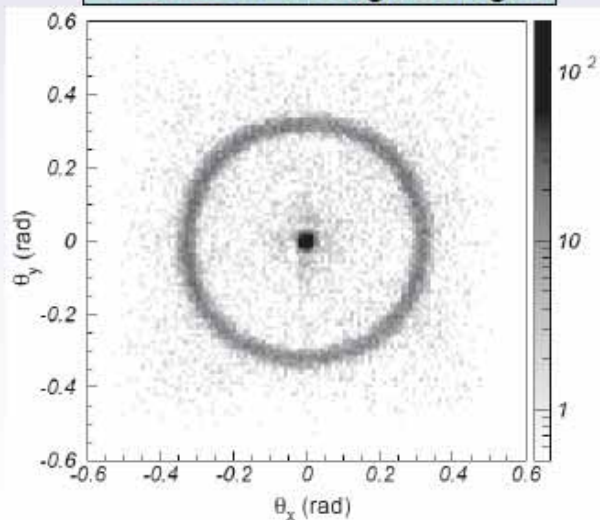


(Hamamatsu)

Multi-anode (Hamamatsu H7546)

- Up to 8×8 channels ($2 \times 2 \text{ mm}^2$ each);
- Size: $28 \times 28 \text{ mm}^2$;
- Active area $18.1 \times 18.1 \text{ mm}^2$ (41%);
- Bi-alkali PC: $\text{QE} \approx 20\%$ @ $\lambda_{\text{max}} = 400 \text{ nm}$;
- Gain $\approx 3 \times 10^5$;
- Gain uniformity typ. 1 : 2.5;
- Cross-talk typ. 2%

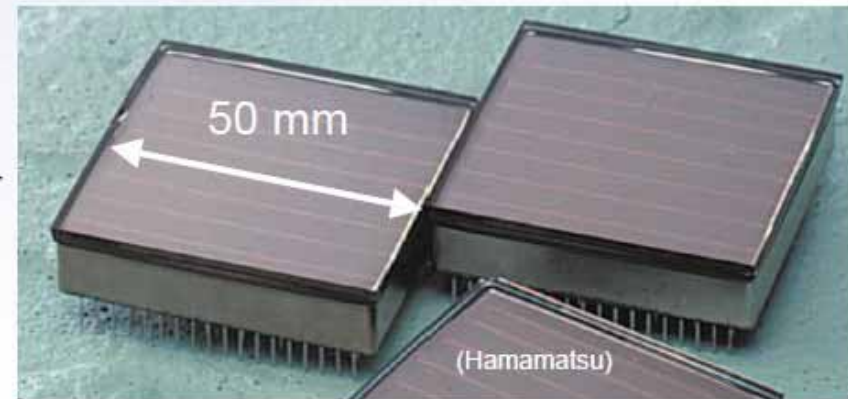
Cherenkov rings from
3 GeV/c π^- through aerogel



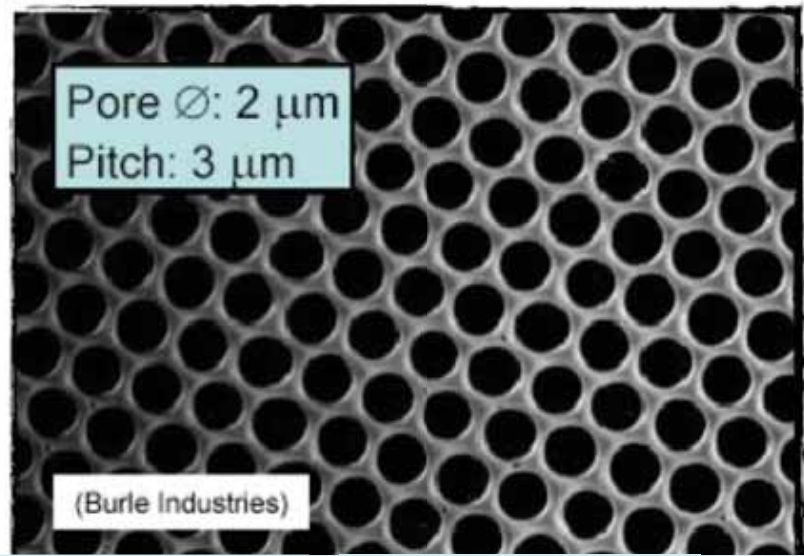
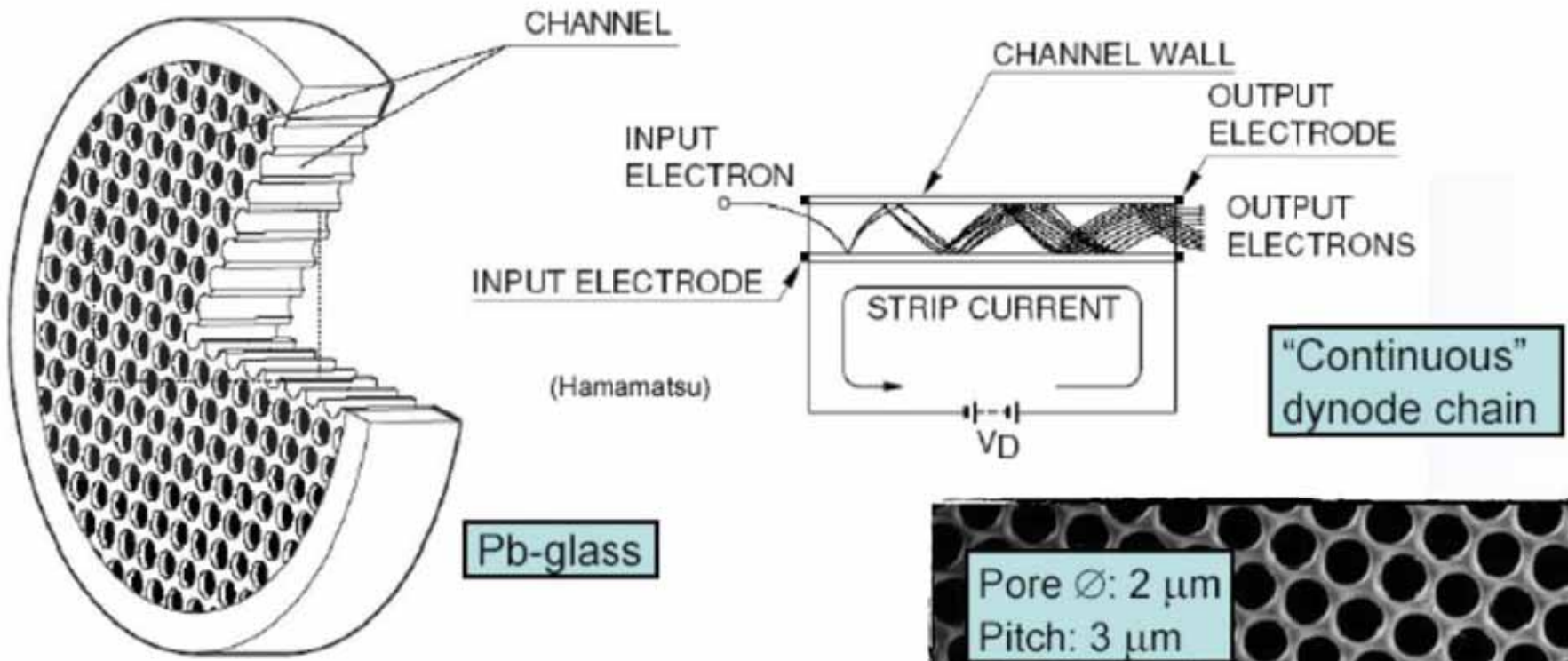
(T. Matsumoto et al., NIMA 521 (2004) 367)

Flat-panel (Hamamatsu H8500):

- 8×8 channels ($5.8 \times 5.8 \text{ mm}^2$ each);
- Excellent surface coverage (89%)



Micro-Channel Plates



"2D Photomultiplier"

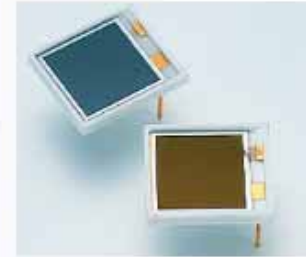
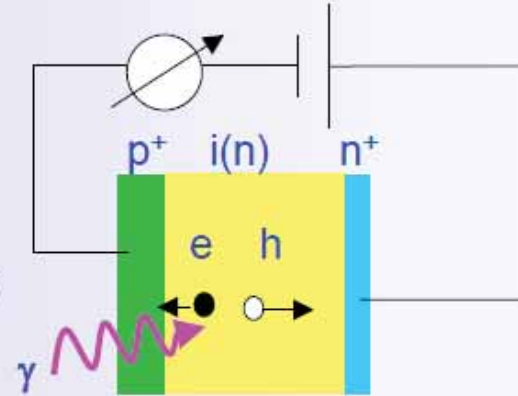
Gain: $5 \cdot 10^4$

Fast signal [time spread ~ 50 ps]

B-Field tolerant [up to 0.1T]

Photodiodes:

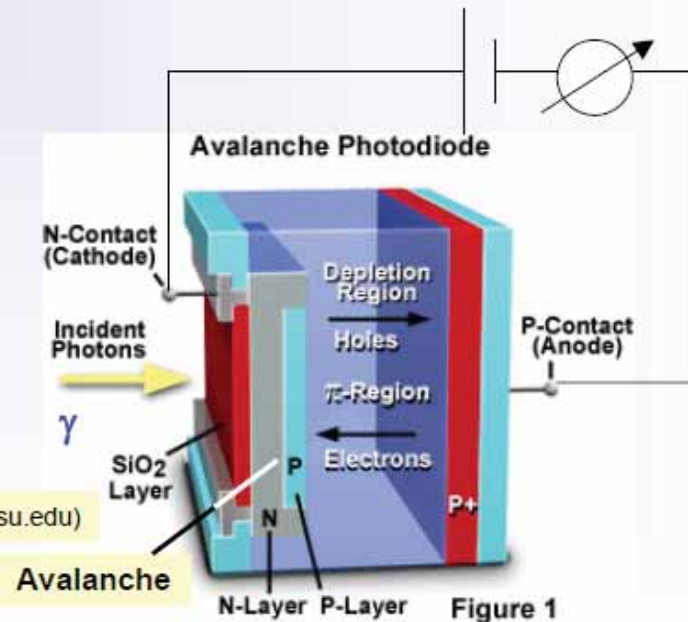
- P(I)N type
- p layer very thin ($<1 \mu\text{m}$), as visible light is rapidly absorbed by silicon (see next slide);
- High QE (80% @ $\lambda \approx 700\text{nm}$);
- No gain: cannot be used for single photon detection;



Avalanche photodiode:

- High reverse bias voltage: typ. 100-200 V
- ⇒ due to doping profile, high internal field and avalanche multiplication;
- High gain: typ. 100-1000;
 - Used in CMS ECAL;

(<http://micro.magnet.fsu.edu>)



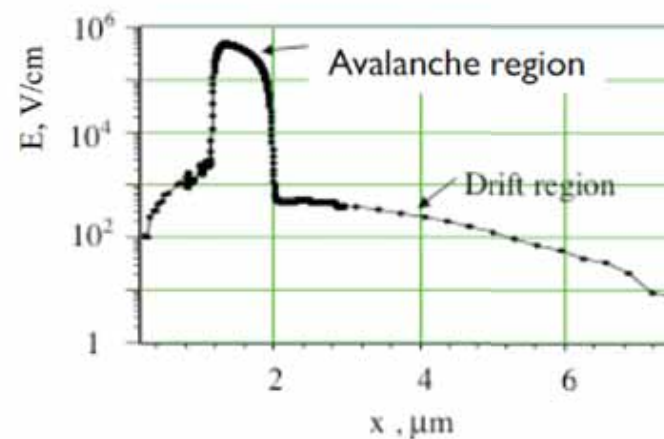
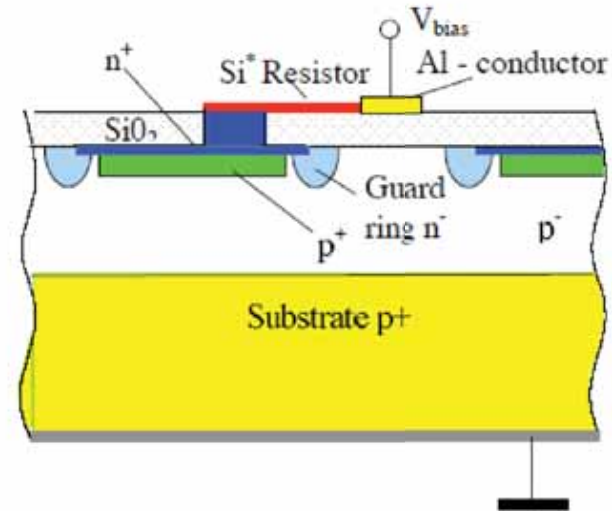
Silicon Photomultipliers

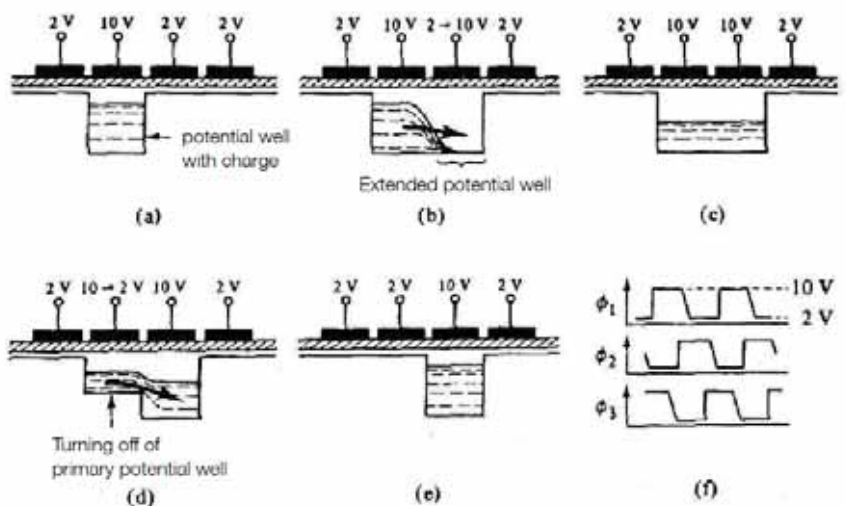
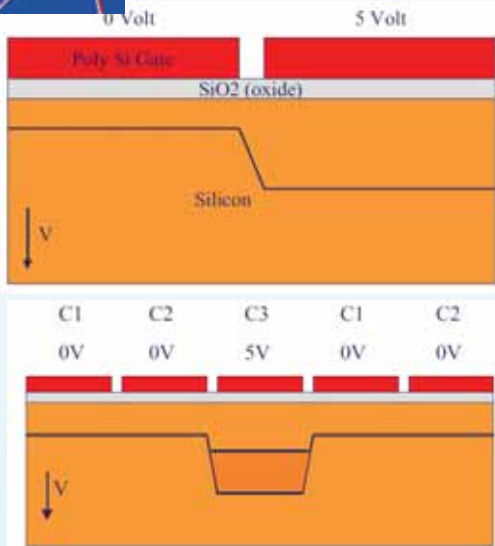
Principle:

- Pixelized photo diodes operated in Geiger Mode
- Single pixel works as a binary device
- Energy = #photons seen by summing over all pixels

Features:

- Granularity : 10^3 pixels/mm²
- Gain : 10^6
- Bias Voltage : < 100 V
- Efficiency : ca. 30 %
- Insensitive to magnetic fields!
- Works at room temperature ...





The Nobel Prize in Physics 2009

"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"

"for the invention of an imaging semiconductor circuit – the CCD sensor"



Photo: U. Montan

Charles K. Kao



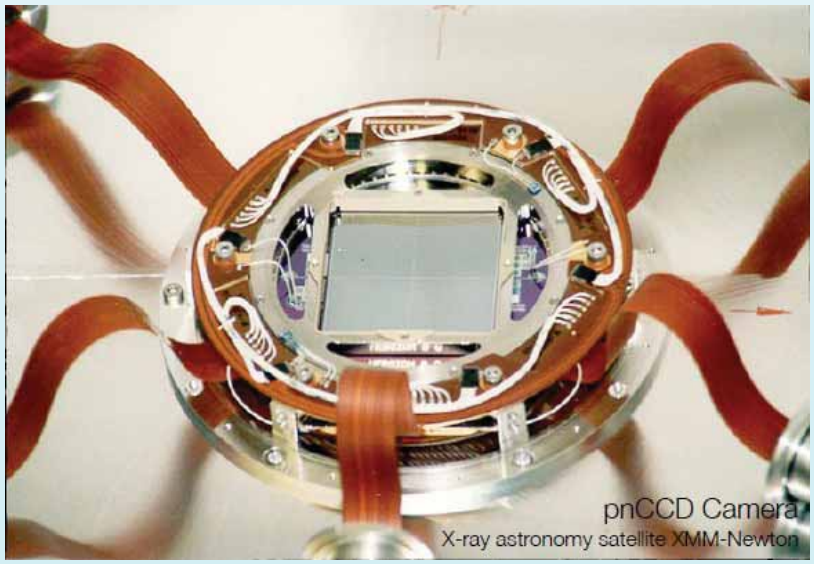
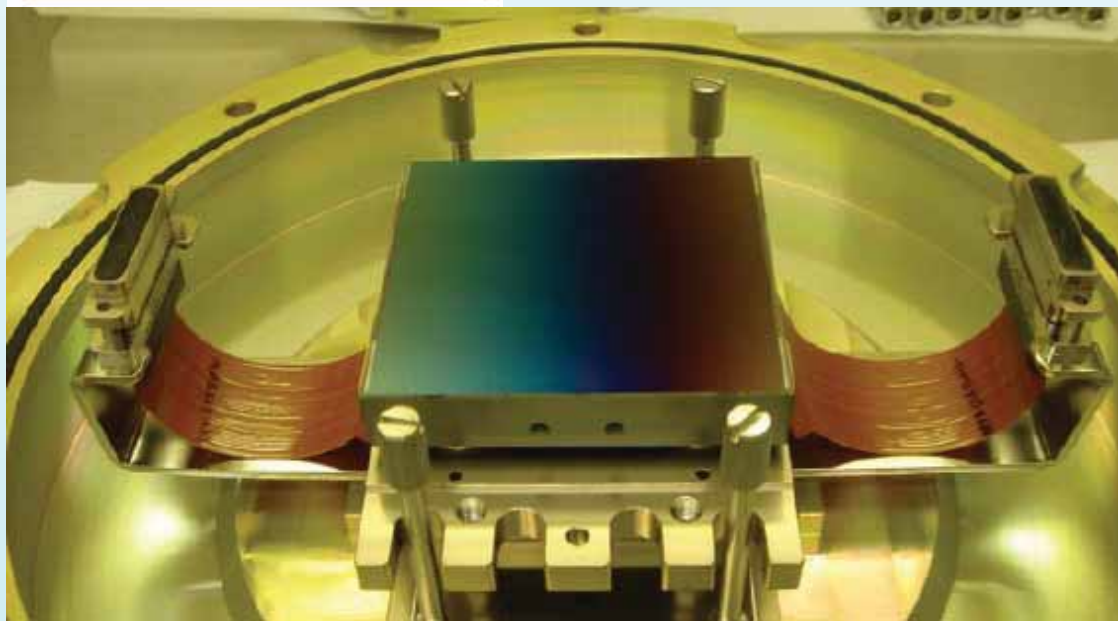
Photo: U. Montan

Willard S. Boyle



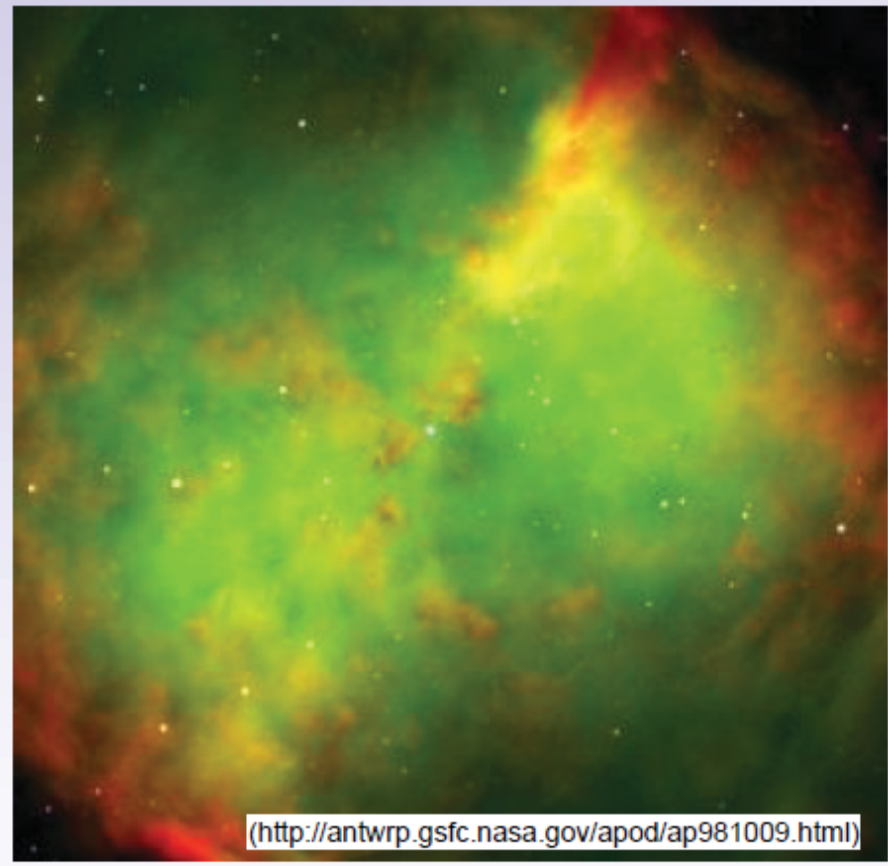
Photo: U. Montan

George E. Smith

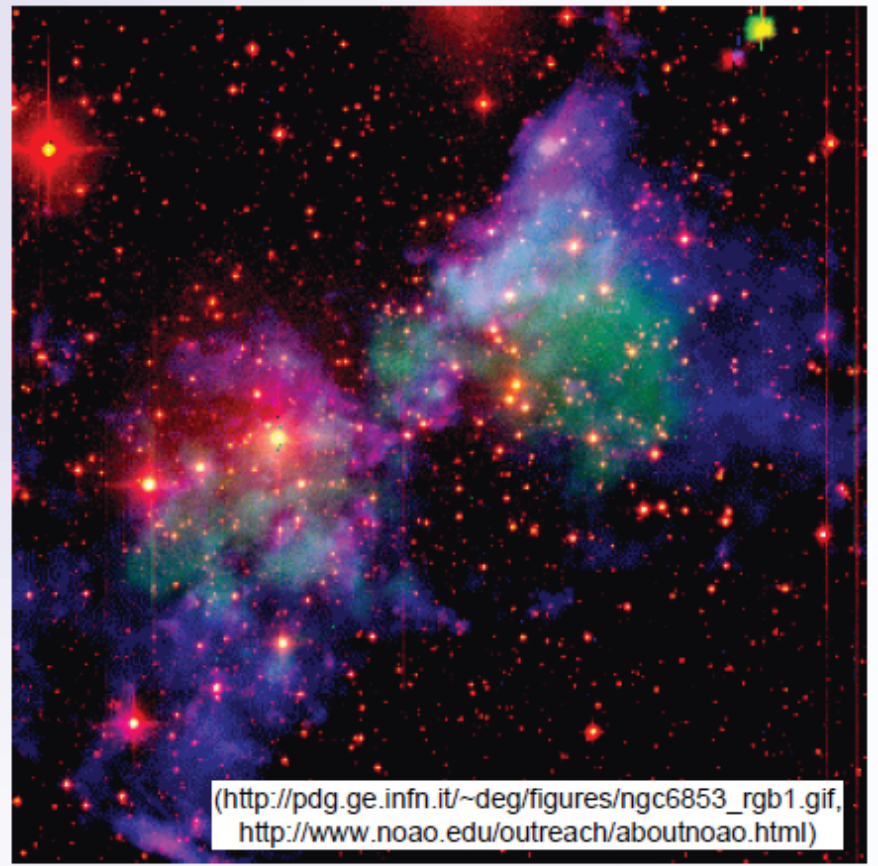


pnCCD Camera
X-ray astronomy satellite XMM-Newton

Dumbbell nebula in Vulpecula (M27, NGC 6853)

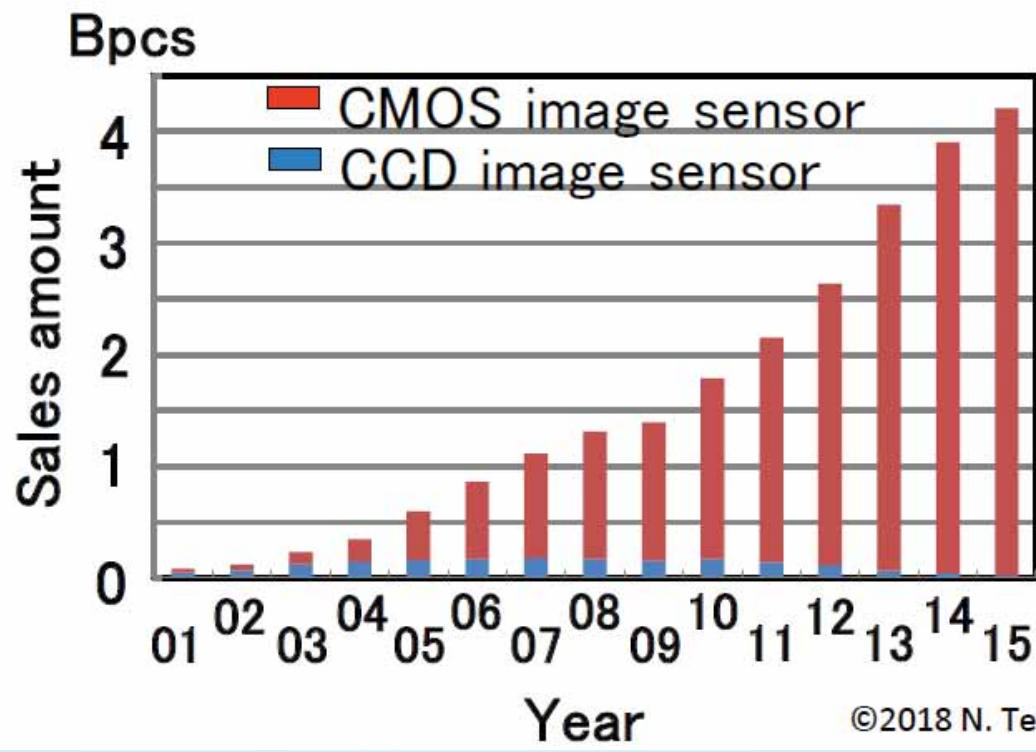


FORS false color image using a Tektronix back-illuminated 2k×2k CCD with 24μm pixels thinned and anti-reflection coated. This image was obtained on ESO 8.2-m VLT Unit Telescope (UT) 1 on September 28, 1998.

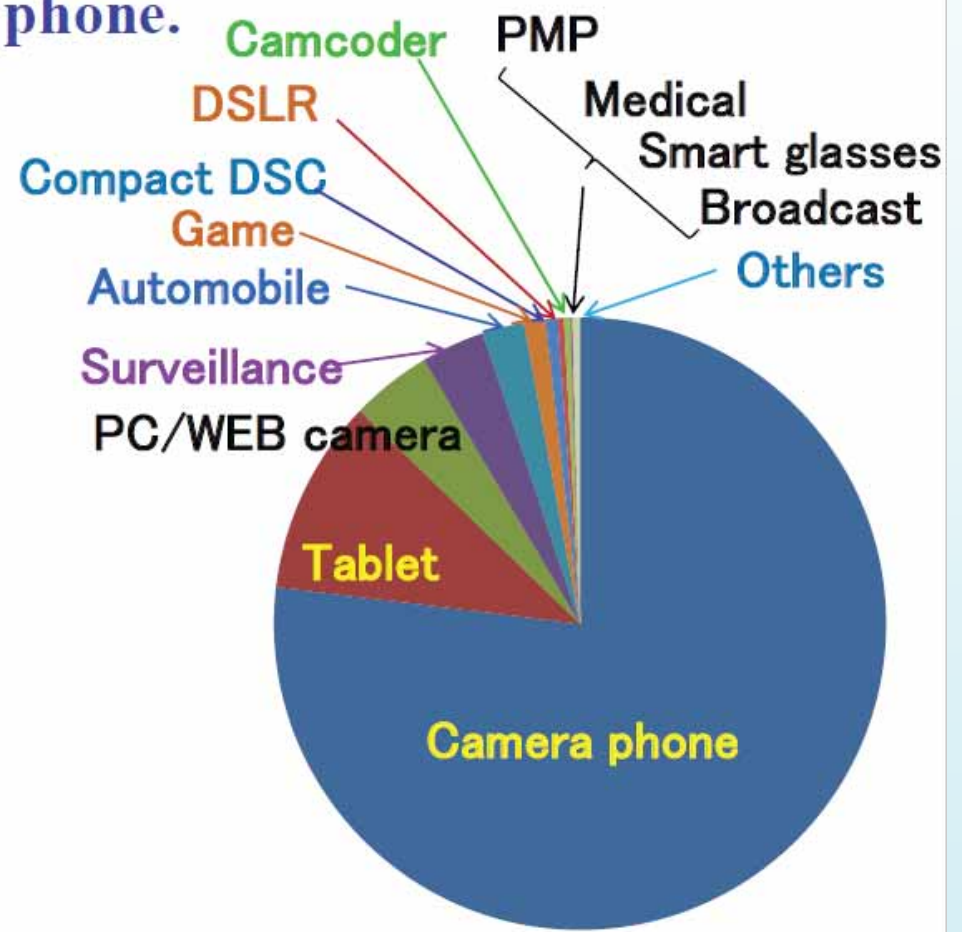


NOAO false color image using a back-illuminated fully depleted 2k×2k CCD with 15μm pixel. This image was obtained on WIYN 3.5-m Telescope on June 7, 2001.

- IS sales amount has grown by camera phone.
- IS spreads into various applications,
- “Others” includes scientific, industrial, ...



©2018 N. Teranishi



Application in amount (2015)

(Source: TSR)



Image Sensors



Examples of applications



Smart-phone

Movie

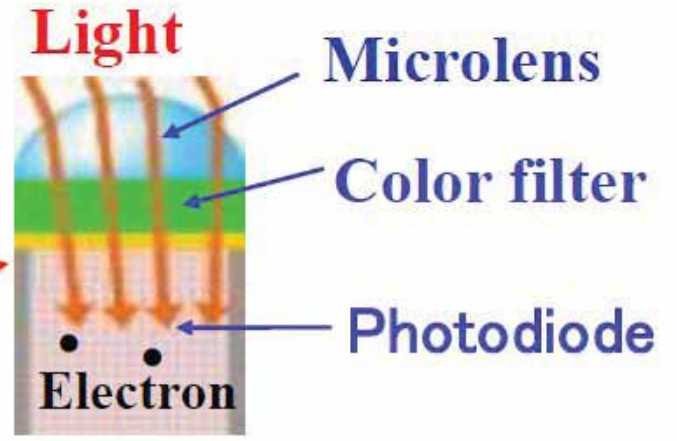
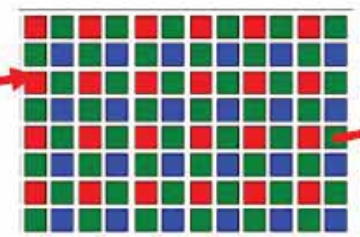
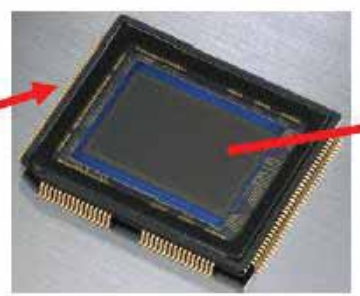
Automobile

Endoscope

Iris verification

Security

Image Sensor



DSC

Image sensor

Pixel array
©2018 N. Teranishi

Pixel cross-section

Calorimetry = Energy measurement by total absorption, usually combined with spatial reconstruction.

- LHC beam: Total stored beam energy
 $E = 10^{14} \text{ protons} \times 14 \cdot 10^{12} \text{ eV} \approx 1 \cdot 10^8 \text{ J}$

- Which mass of water M_{water} could one heat up ($\Delta T = 100 \text{ K}$) with this amount of energy ($c_{water} = 4.18 \text{ J g}^{-1} \text{ K}^{-1}$) ?

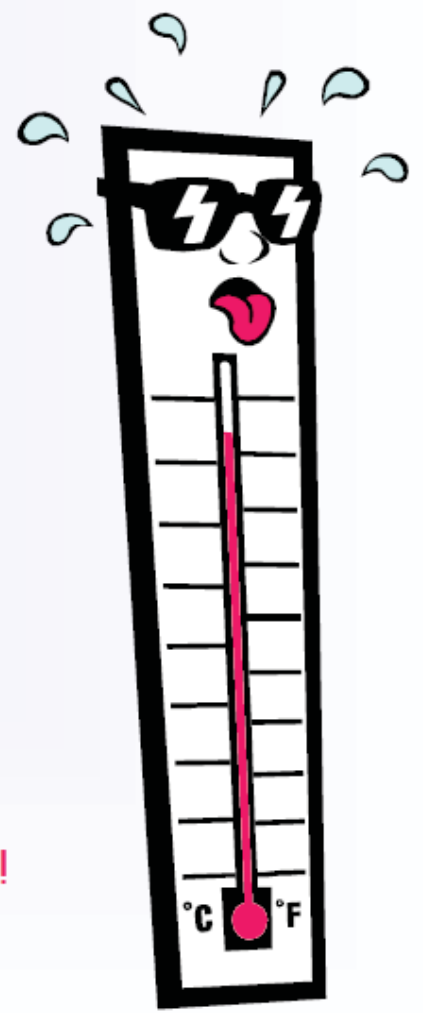
$$M_{water} = E / (c \Delta T) = 239 \text{ kg}$$

- What is the effect of a 1 GeV particle in 1 liter water (at 20° C)?

$$\Delta T = E / (c \cdot M_{water}) = 3.8 \cdot 10^{-14} \text{ K} !$$

There must be more sensitive methods than measuring ΔT !

latin: calor = heat





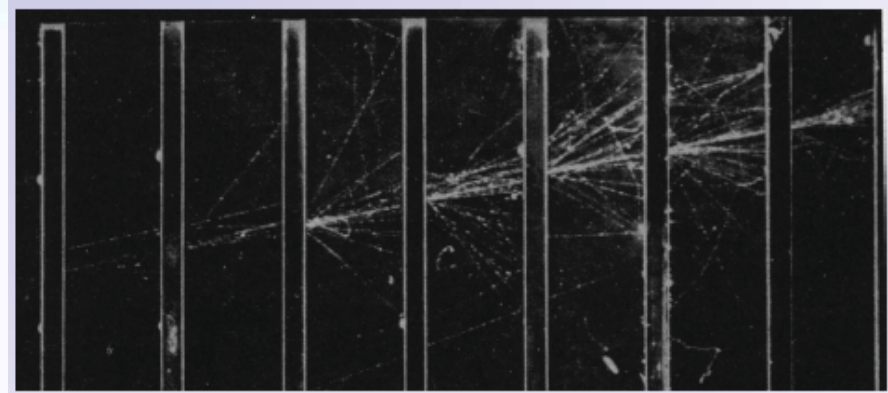
Electromagnetic Calorimeters



Basic mechanism for calorimetry in particle physics: formation of

- ⇒ electromagnetic
- ⇒ or hadronic showers.

Finally, the energy is converted into ionization or excitation of the matter.



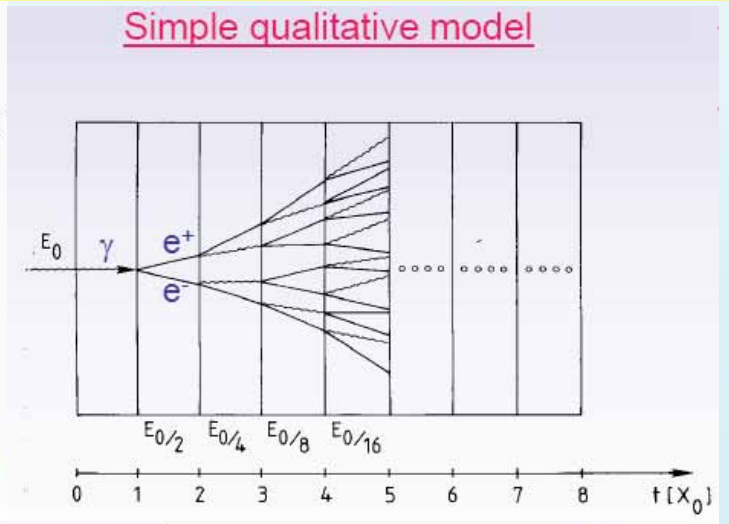
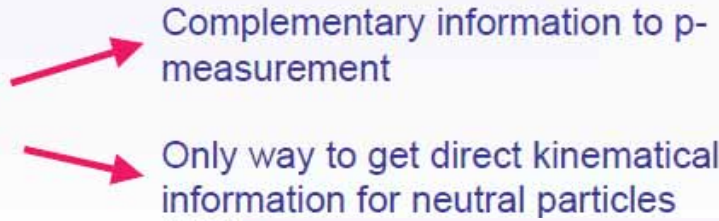
electron shower in a cloud chamber with Pb

Calorimetry is a “destructive” method. The energy and the particle get absorbed!

Detector response $\propto E$

Calorimetry works both for

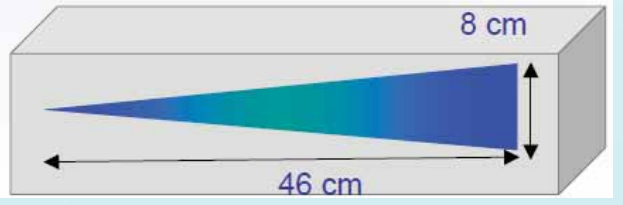
- ⇒ charged (e^\pm and hadrons)
- ⇒ and neutral particles (n, γ)



Example: $E_0 = 100 \text{ GeV}$ in lead glass

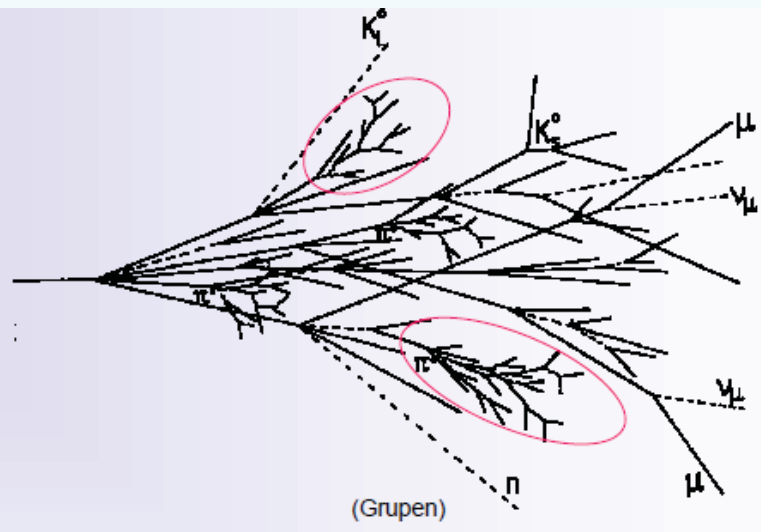
$E_c = 11.8 \text{ MeV} \rightarrow t_{max} \approx 13, t_{95\%} \approx 23$

$X_0 \approx 2 \text{ cm}, R_M = 1.8 \cdot X_0 \approx 3.6 \text{ cm}$



Hadronic Calorimetry

Various processes involved.
Much more complex than
electromagnetic cascades.



CMS Hadronic Calorimeter:
brass and plastic scintillators



A hadronic shower contains two components:

hadronic

+

electromagnetic

- charged hadrons p, π^\pm, K^\pm
- nuclear fragments
- breaking up of nuclei (binding energy)
- neutrons, neutrinos, soft γ 's, muons

neutral pions $\rightarrow 2\gamma$
 \rightarrow electromagnetic cascades

$$n(\pi^0) \approx \ln E(\text{GeV}) - 4.6$$

example $E = 100 \text{ GeV}$: $n(\pi^0) \approx 18$

invisible energy \rightarrow large energy fluctuations \rightarrow limited energy resolution