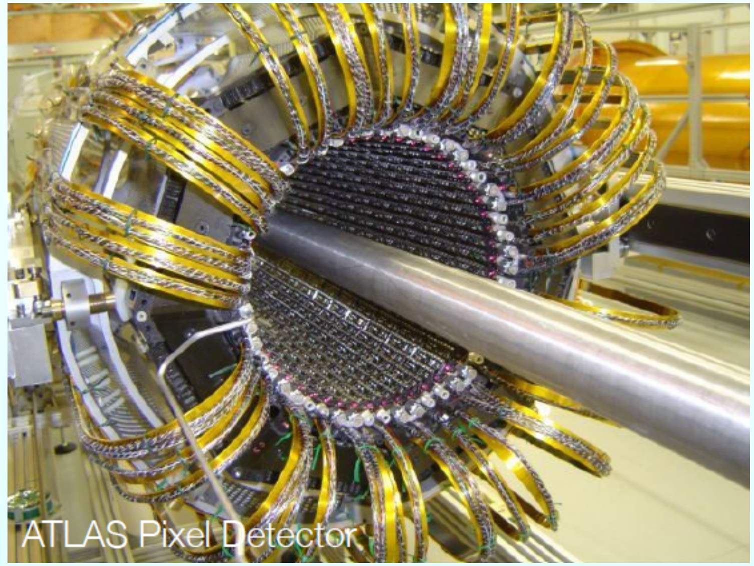
Particles and Detectors

Fulvio Tessarotto (I.N.F.N. – Trieste)



Introduction

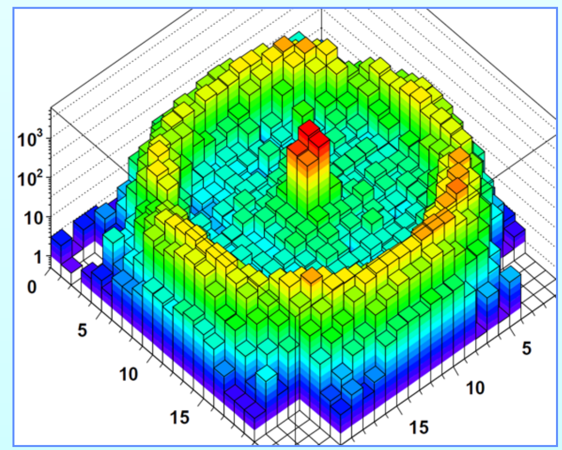
particle detectors history

CERN

Detection technologies

Gaseous Detectors

Particle Identification



Radioactivity is everywhere

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

$$\beta^- : {}^{40}_{19}K \rightarrow {}^{40}_{20}Ca + e^- + \overline{\nu}_e$$

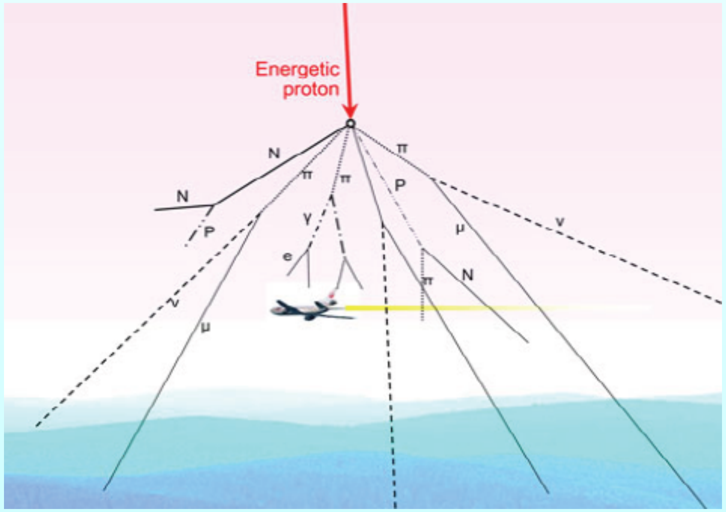
$$EC : {}^{40}_{19}K + e^- \rightarrow {}^{40}_{18}Ar^* + \nu_e \rightarrow {}^{40}_{18}Ar^* + \nu_e \rightarrow {}^{40}_{18}Ar + \gamma + \nu_e$$

$$\beta^+ : {}^{40}_{19}K \rightarrow {}^{40}_{18}Ca + e^+ + \nu_e$$

My activity is ~ 5000 disintegrations per second

An average banana has 14 Bq

The average annual human exposure to natural background radiation is 2.4 mSv (from 0.4 to 4 mSv/y depending on the location)

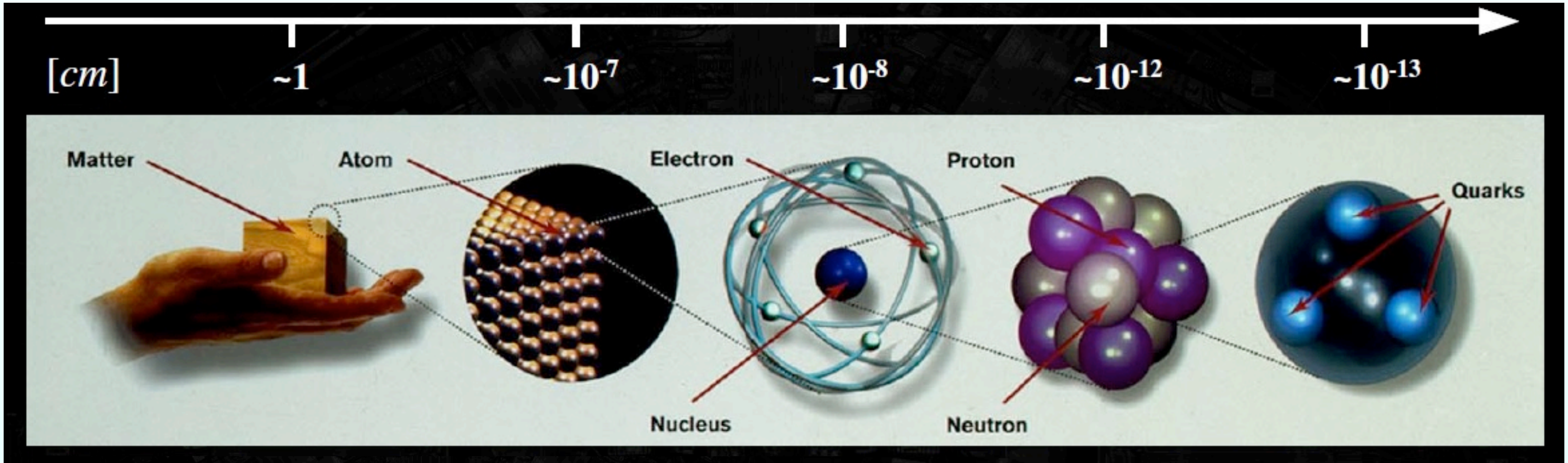


During a flight the background dose rate increases by a factor between 10 and 30

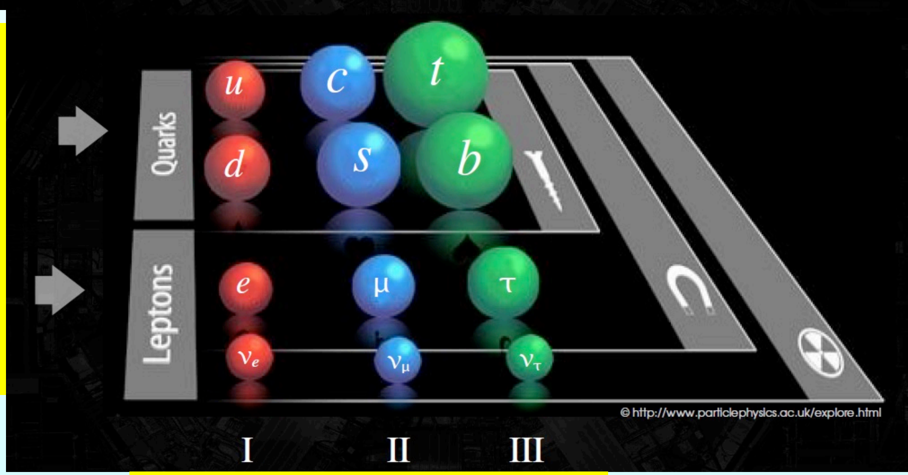
Charged particles:
- ***heavy (μ, π, p, α, …)***
- ***light (electrons and positrons)***

Neutral particles:
- ***photons***
- ***neutrons***
- ***neutrinos***

The constituents of matter

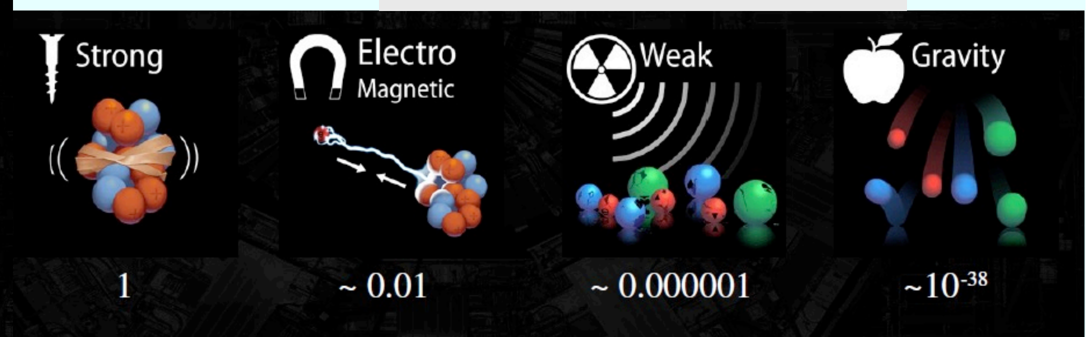


Two families



Three generations

Four interactions



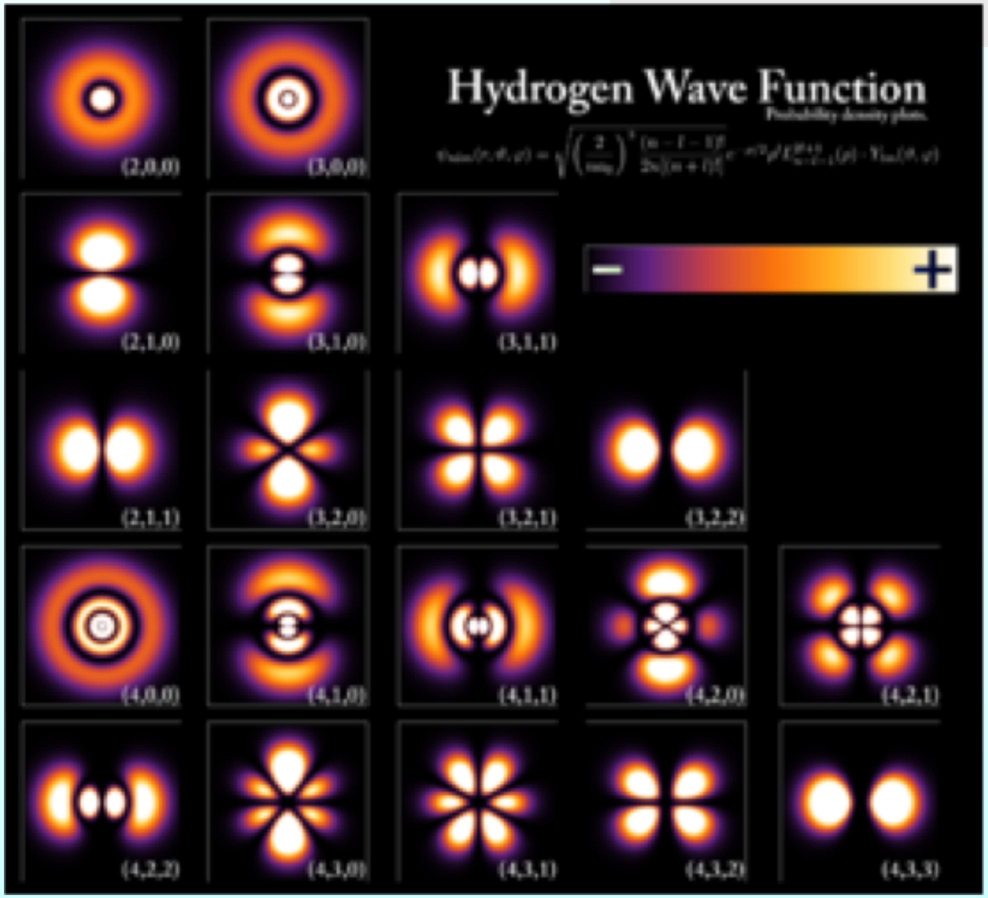
gluon *photon* *W-Z* *graviton*

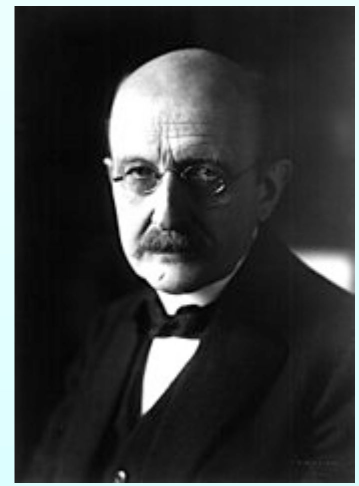
Particles do what we cannot

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

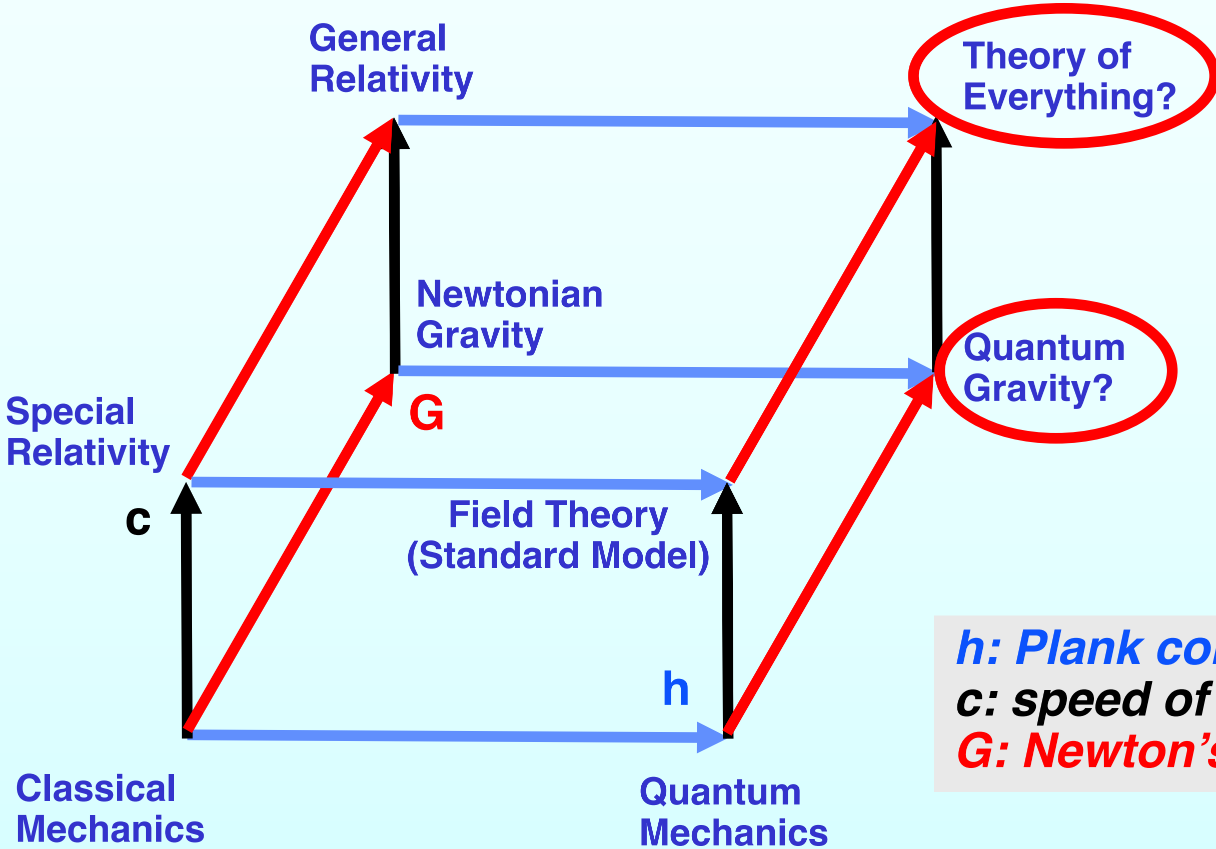


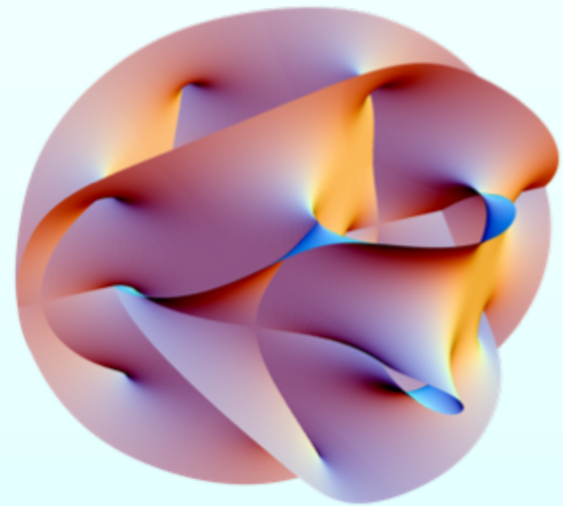


Max Plank is the father of the quantum theory

Theoretical panorama

The fundamental constants of nature and unified theories





h: Plank constant
c: speed of light
G: Newton's constant

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 included 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/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	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

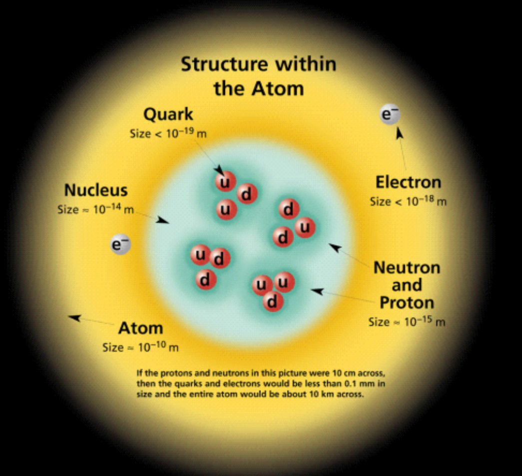
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	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

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} 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 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 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/c²	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/c²	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 electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** 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.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	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
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

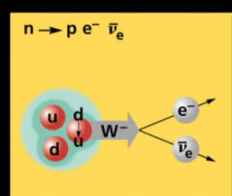
Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

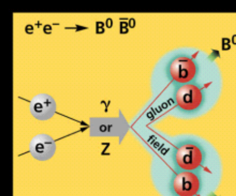
Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). 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.

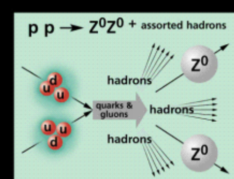
Figures
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



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 (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons 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:
U.S. Department of Energy
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American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

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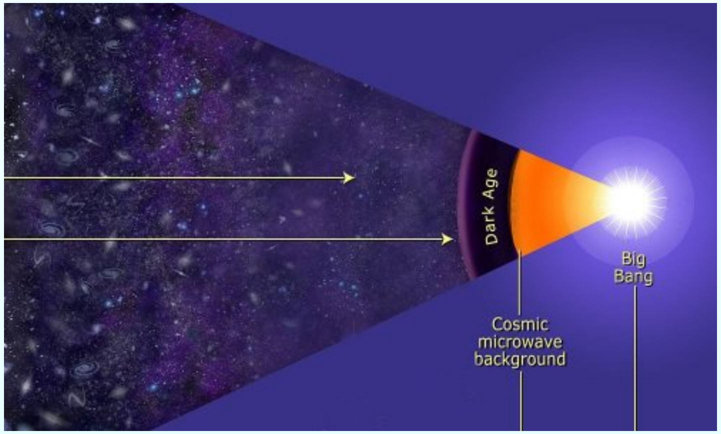
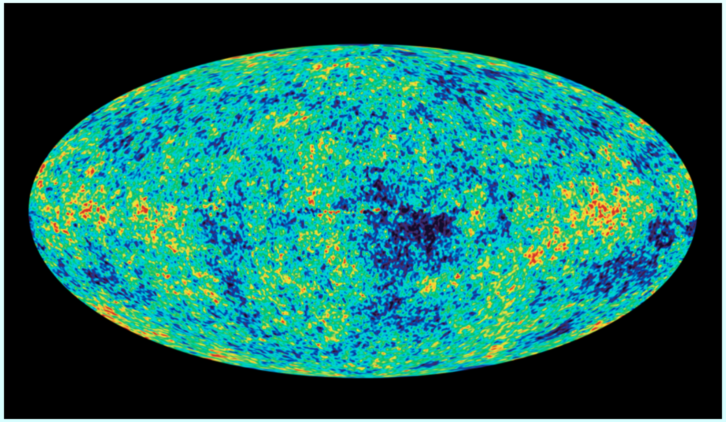
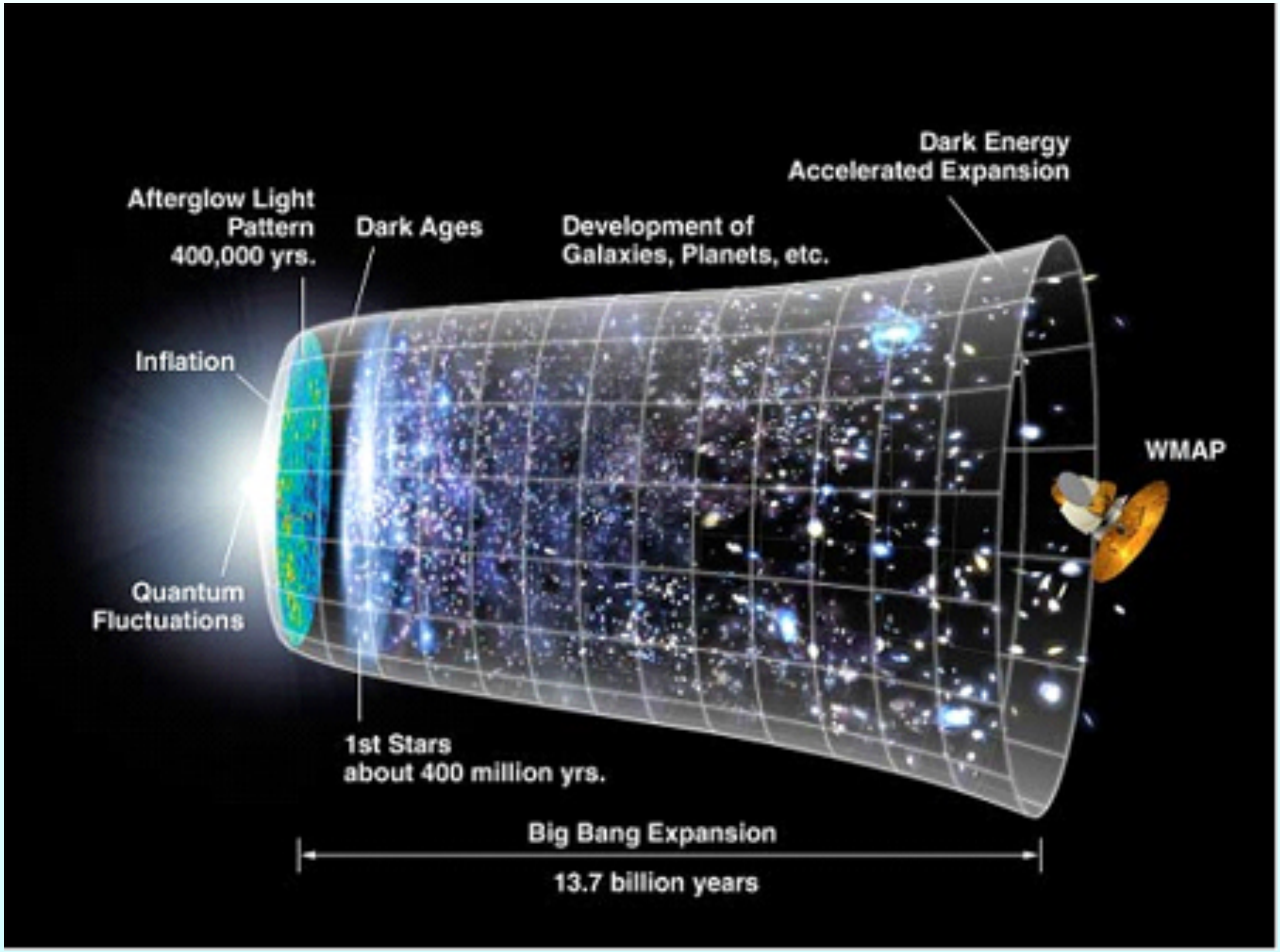
History of the Universe

From Cosmic Microwave Background Radiation and other measurements







We know a lot about our world

Thanks to theoreticians and experimentalists

There is an ancient Chinese saying:

"He who labors with his mind rules over he who labors with his hand".

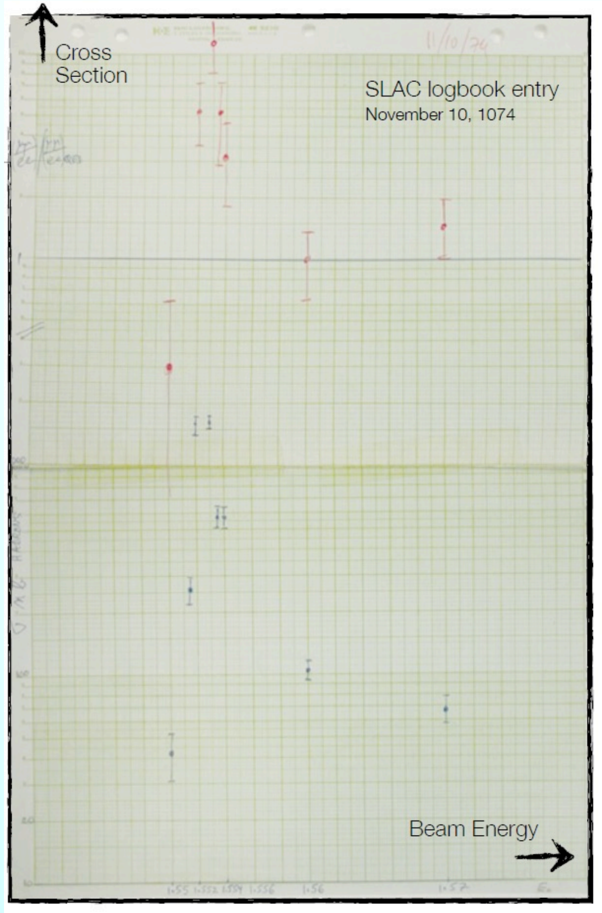
This kind of backward idea is very harmful to youngsters from developing countries.

Partly because of this type of concept, many students from these countries are inclined towards theoretical studies and avoid experimental work.

In reality, a theory in natural science can not be without experimental foundations; physics, in particular, comes from experimental work ...

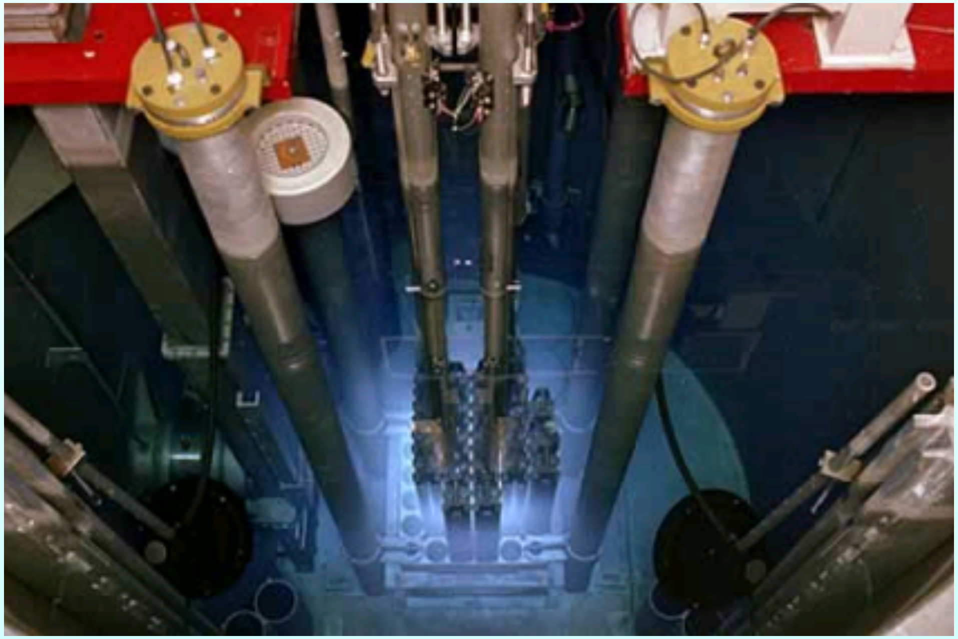
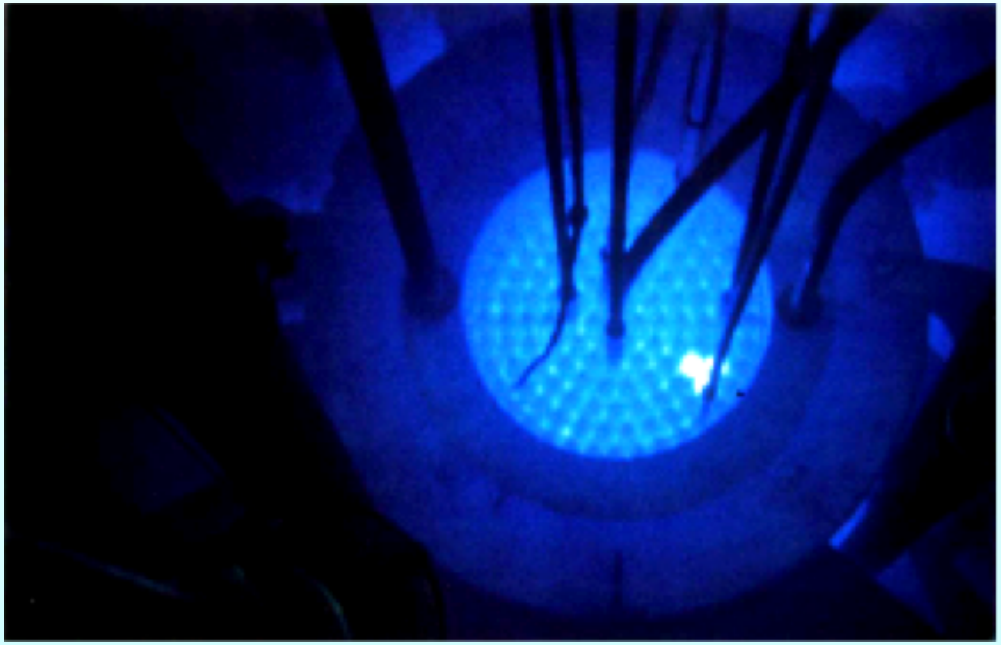
Samuel Ting
December 10, 1976

Nobel Prizes 1974 for the J/ψ discovery

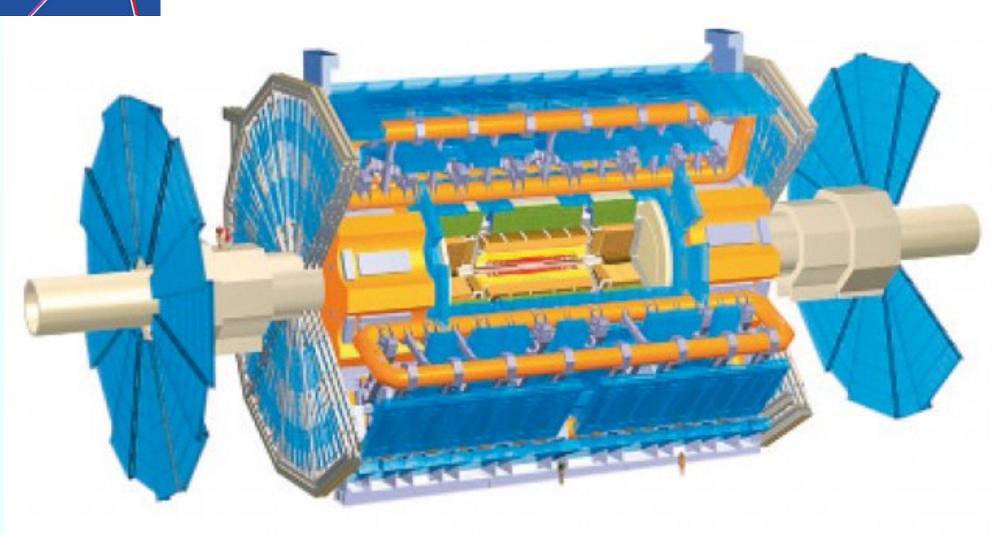


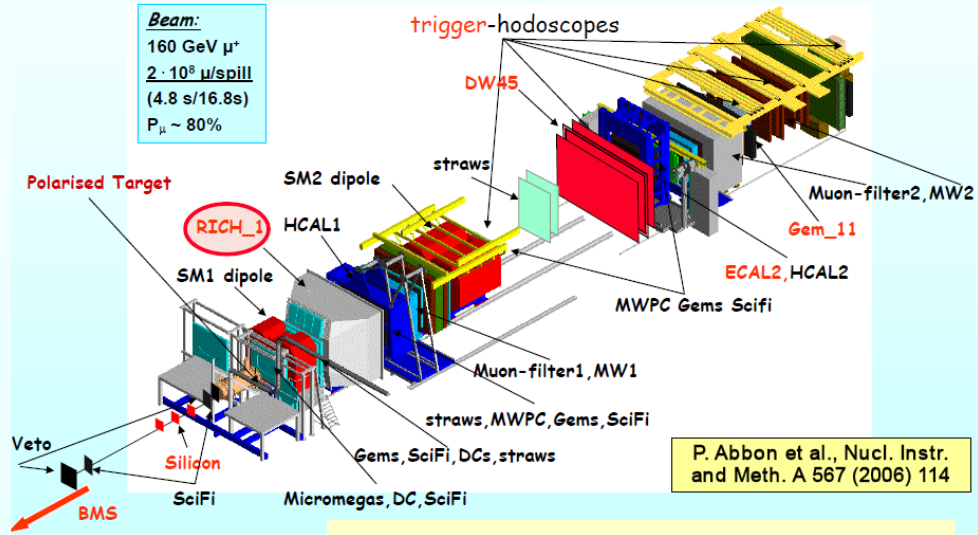
Auroras and nuclear reactors



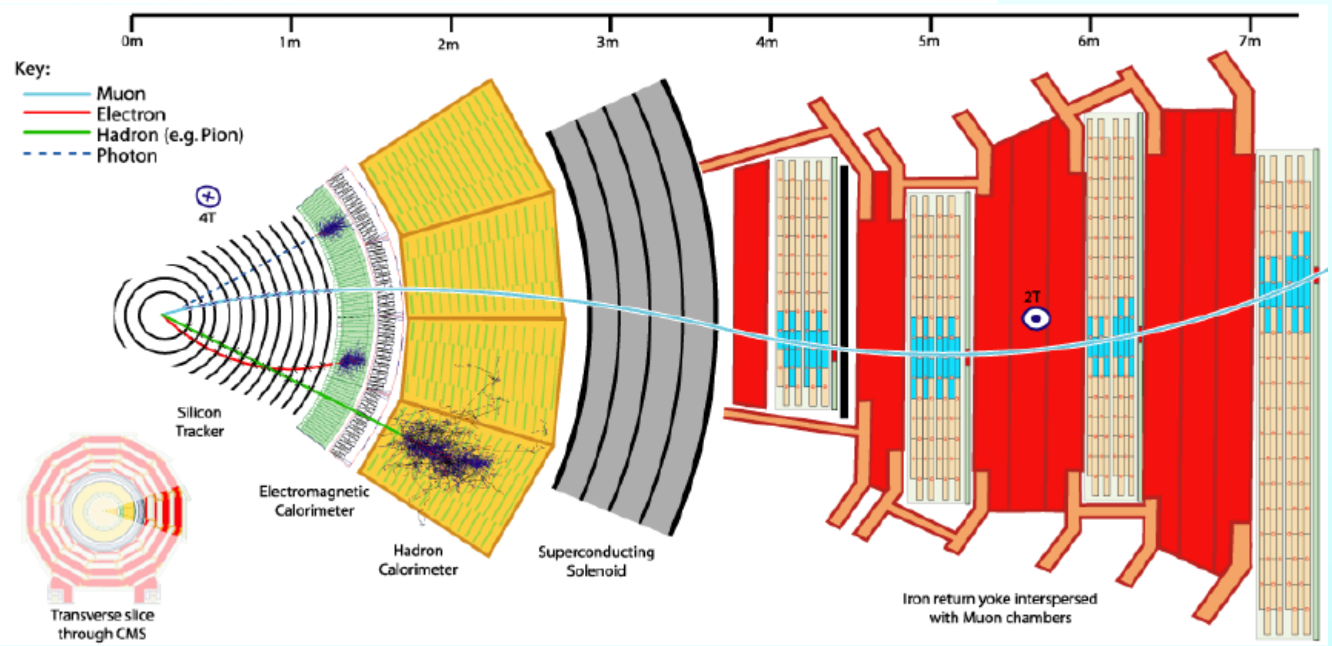




A modern experiment



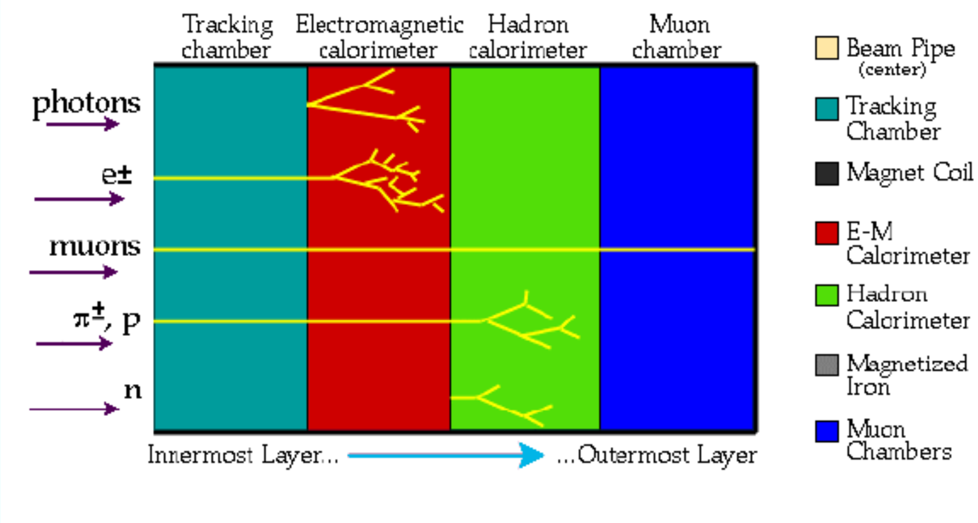


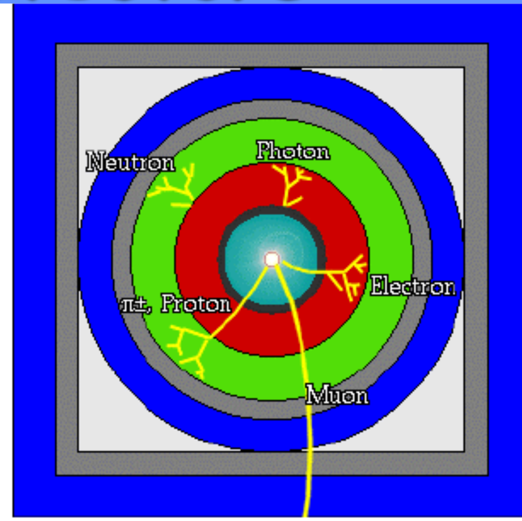
P. Abbon et al., Nucl. Instr. and Meth. A 567 (2006) 114

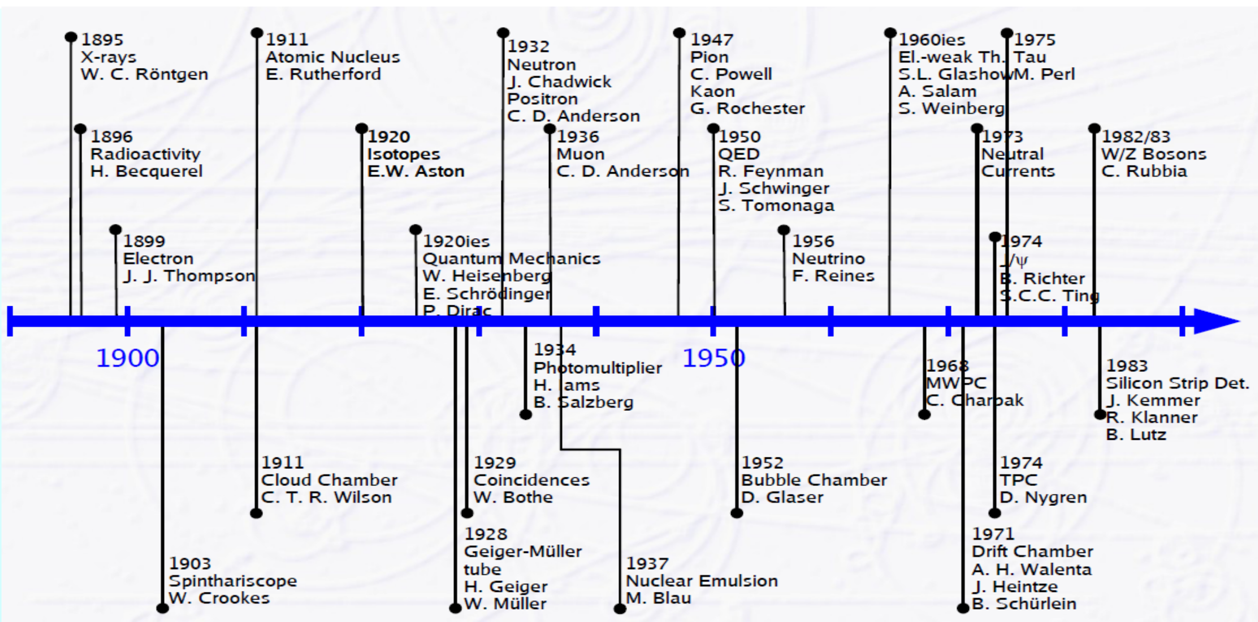


uses a combination of different detectors, combines the information from all of them and fully reconstructs the characteristics of the interesting event which took place

Different particles are seen by different detectors







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

The discovery of radiation

First

Detection of

α-, β- and γ-rays

1896

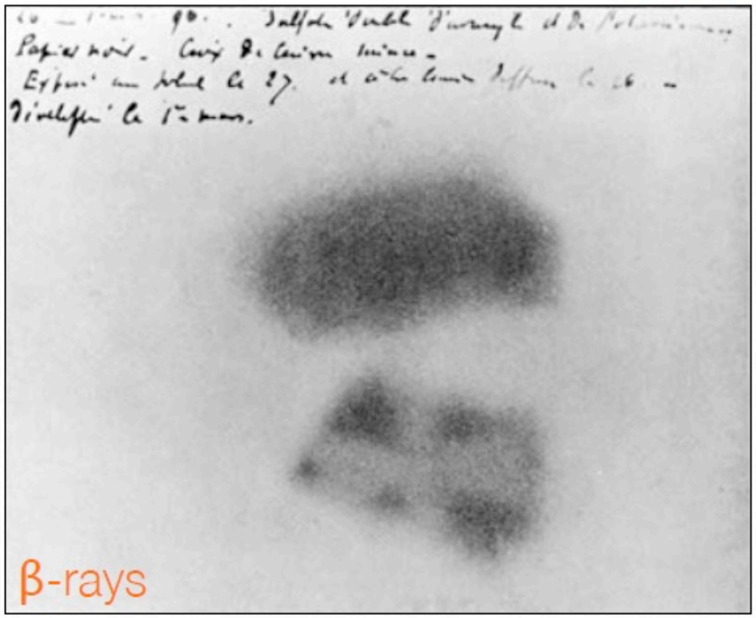
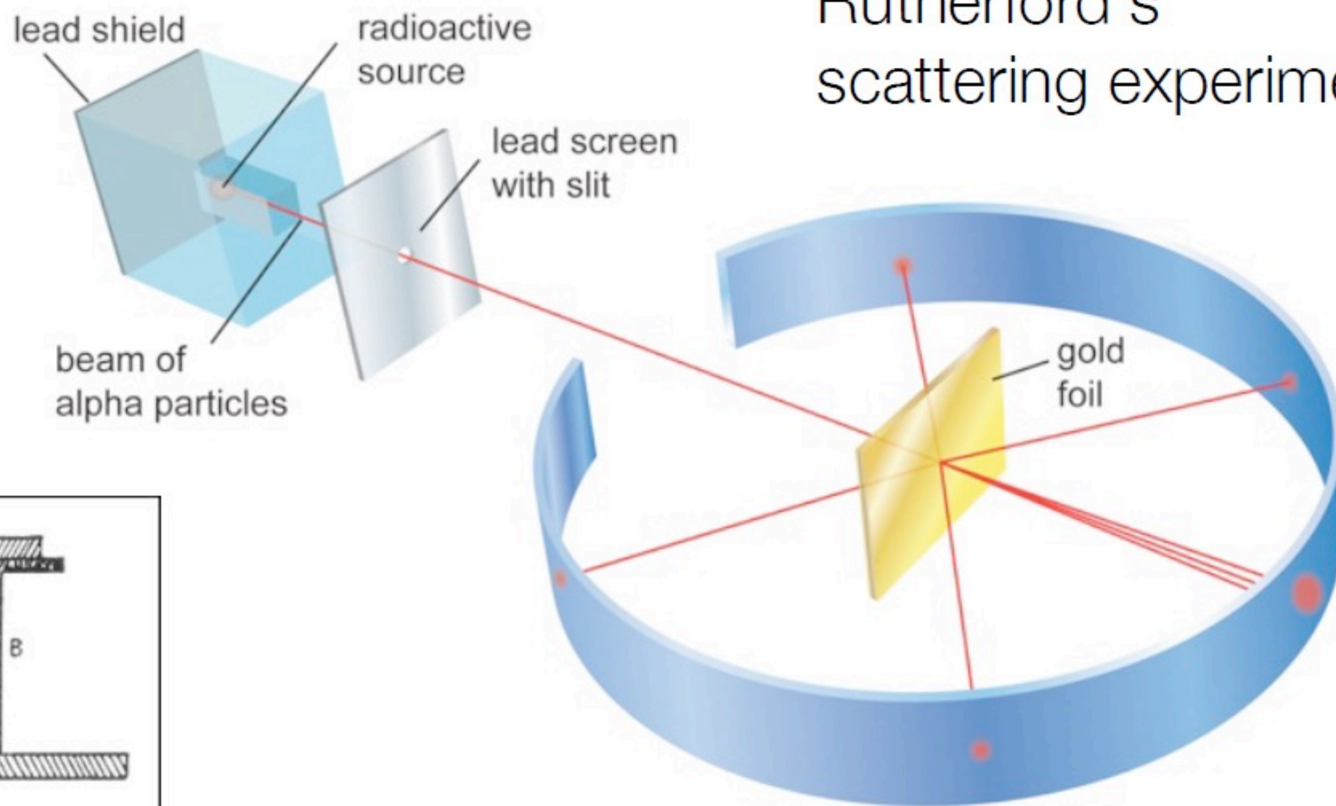


Image of Becquerel's photographic plate which has been fogged by exposure to radiation from a uranium salt.

1896

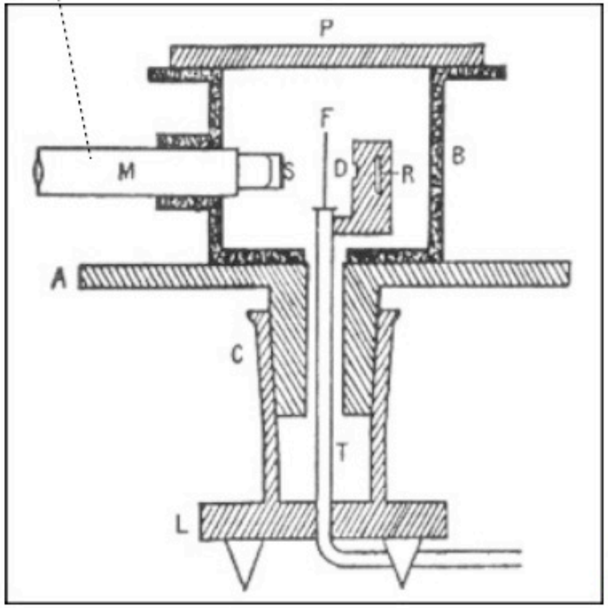
An x-ray picture taken by Wilhelm Röntgen of Albert von Kölliker's hand at a public lecture on 23 January 1896.

The discovery of the atomic nucleus



Rutherford's scattering experiment

Microscope +
Scintillating ZnS screen



Rutherford's original experimental setup

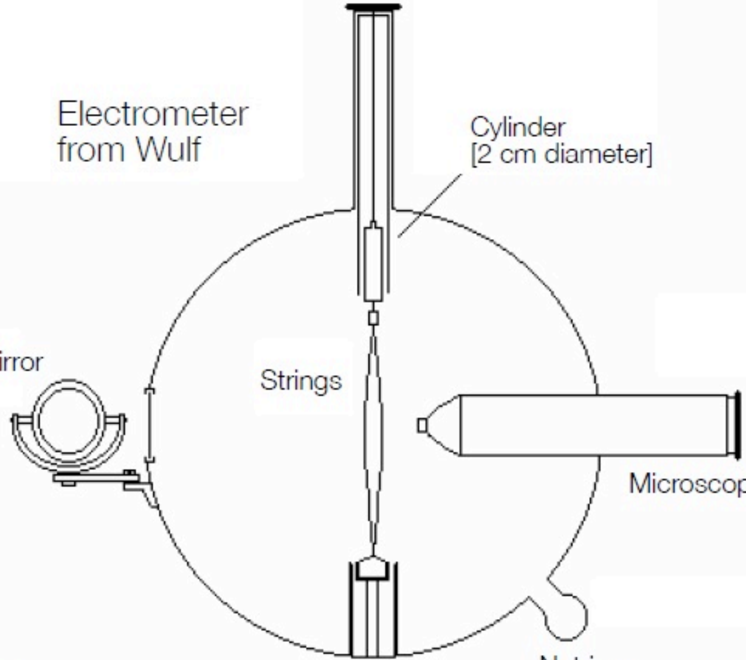
Schematic view of Rutherford experiment

1911

1912: cosmic rays

Detection of cosmic rays

[Hess 1912; Nobel prize 1936]



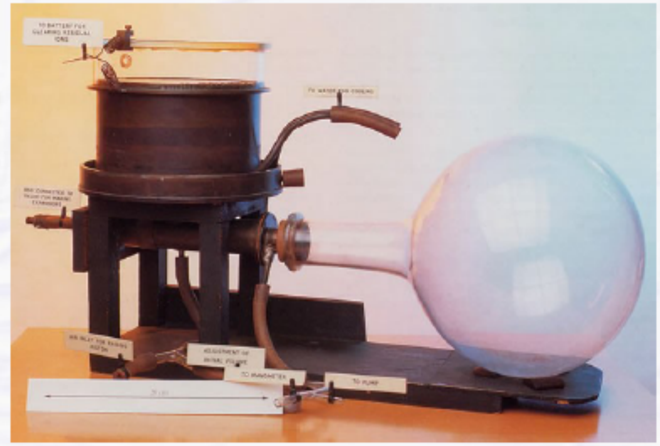
1912

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)

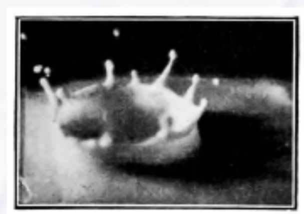
- chamber with saturated water vapour
- charged particles leave trails of ions
  - water is condensing aound ions
- visible track as line of small water droplets



UK Science Museum

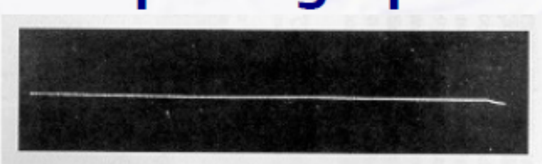
Also required

- 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

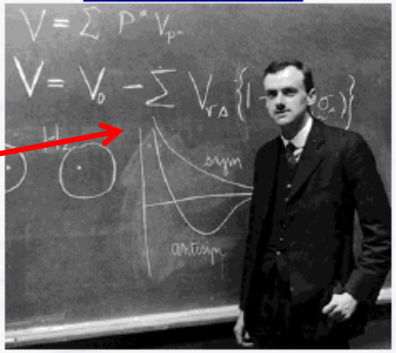
First photographs of α–ray particles 1912



1932: antimatter, 1936: muon

Was also used for the discovery of the positron

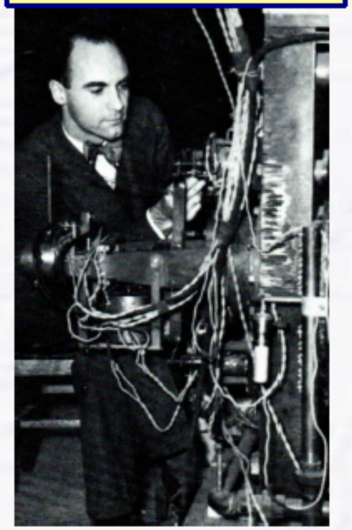
- predicted by Paul Dirac 1928 (Nobel Prize 1933)
- found in cosmic rays by Carl D. Anderson 1932 (Nobel Prize 1936)



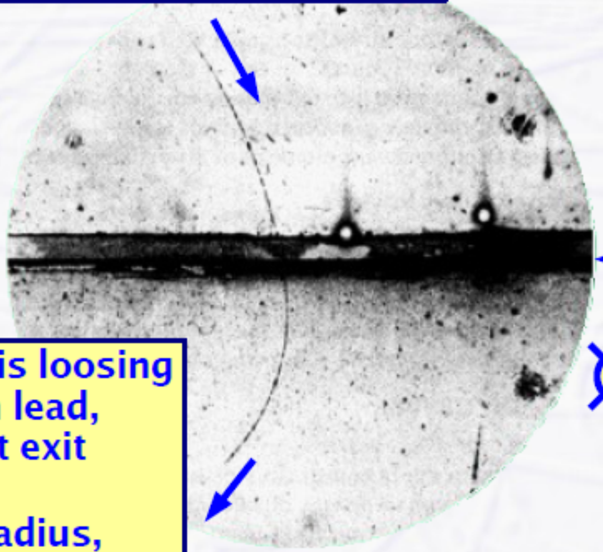
Anderson also found the muon in 1936, the first 2nd generation particle in the Standard Model

Isidor Isaac Rabi said:
"Who ordered that?"

Carl D. Anderson



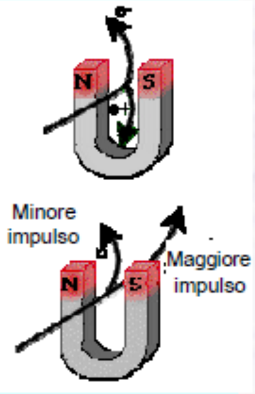
downward going positron, 63 MeV



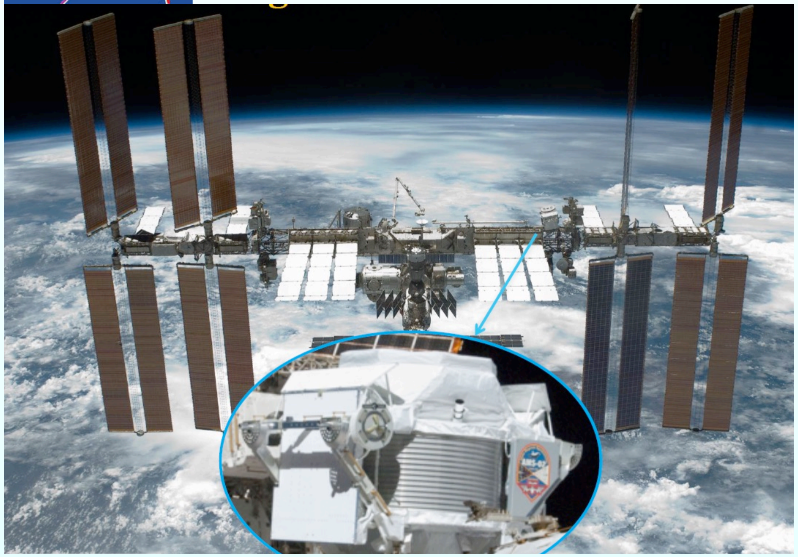
6 mm lead plate

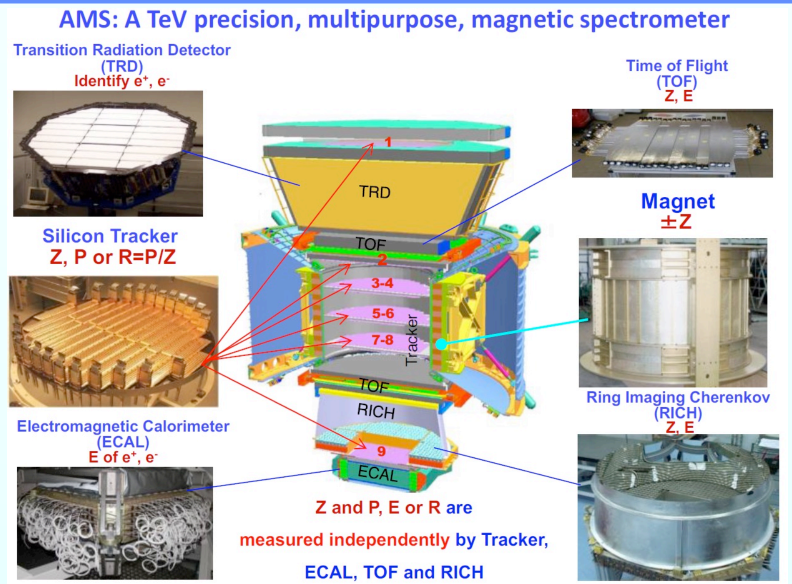
1.5 T magnetic field

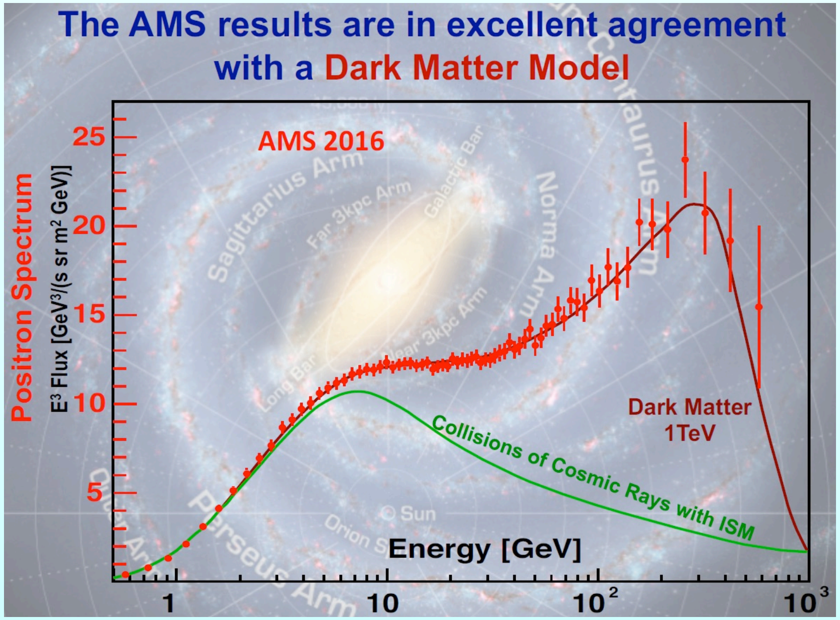
positron is loosing energy in lead, 23 MeV at exit
→
smaller radius, this defines the track direction!

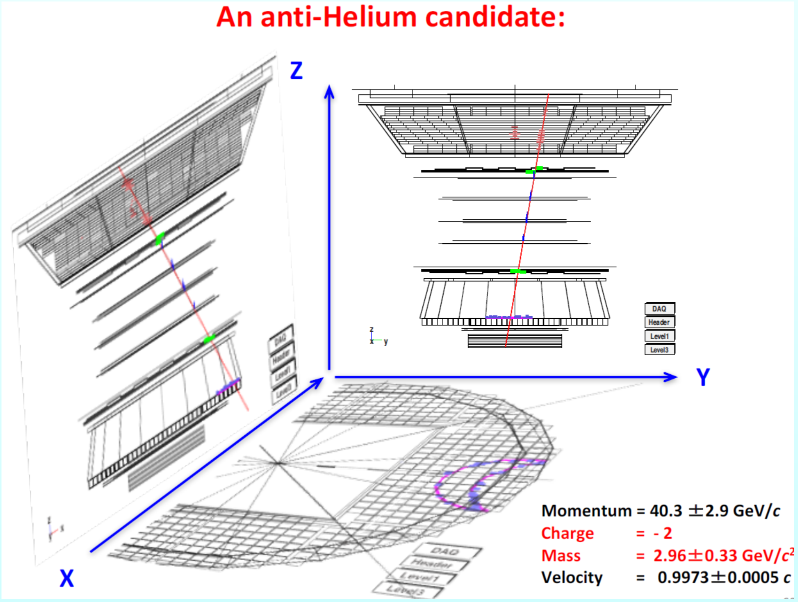


AMS 2017: cosmic antihelium?





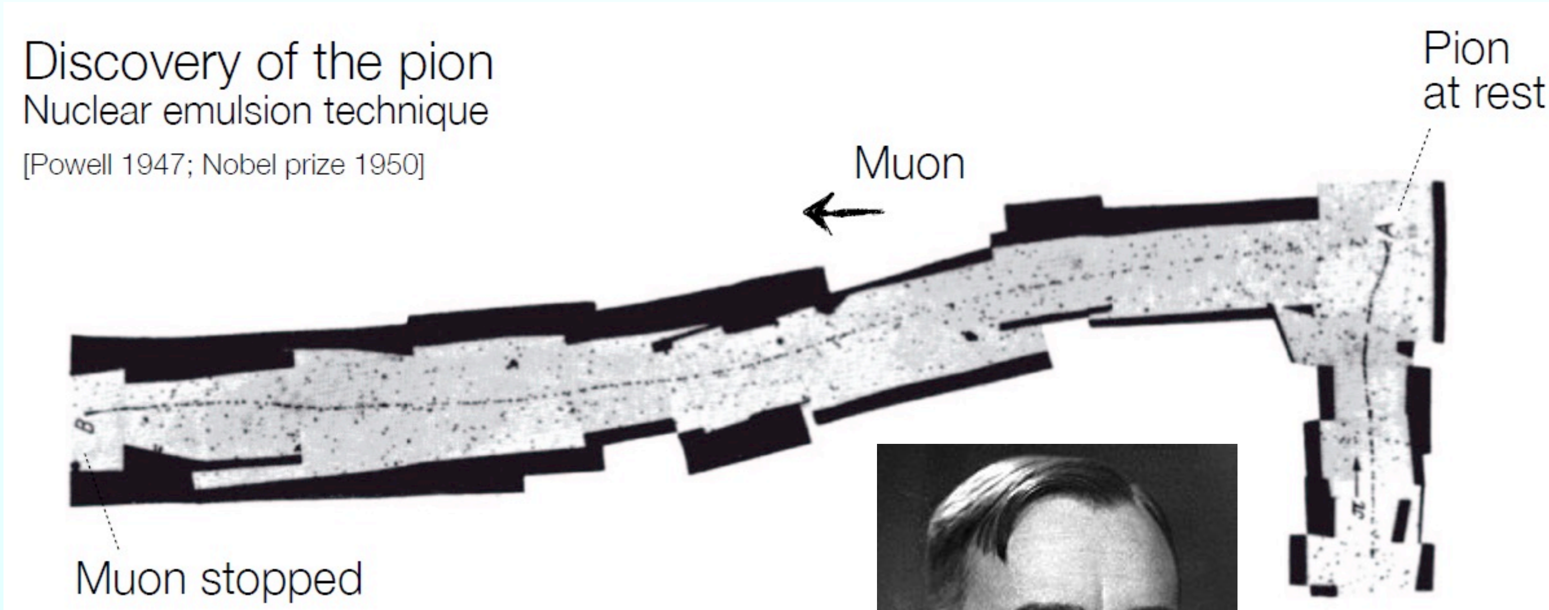


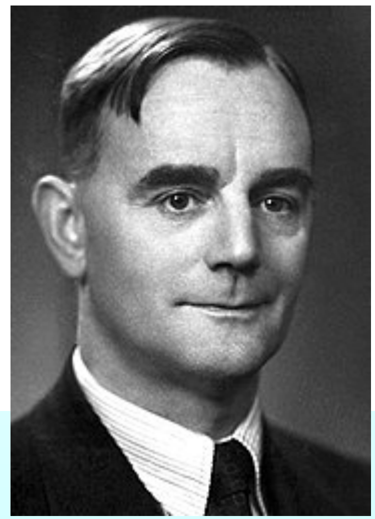


Nuclear emulsions

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





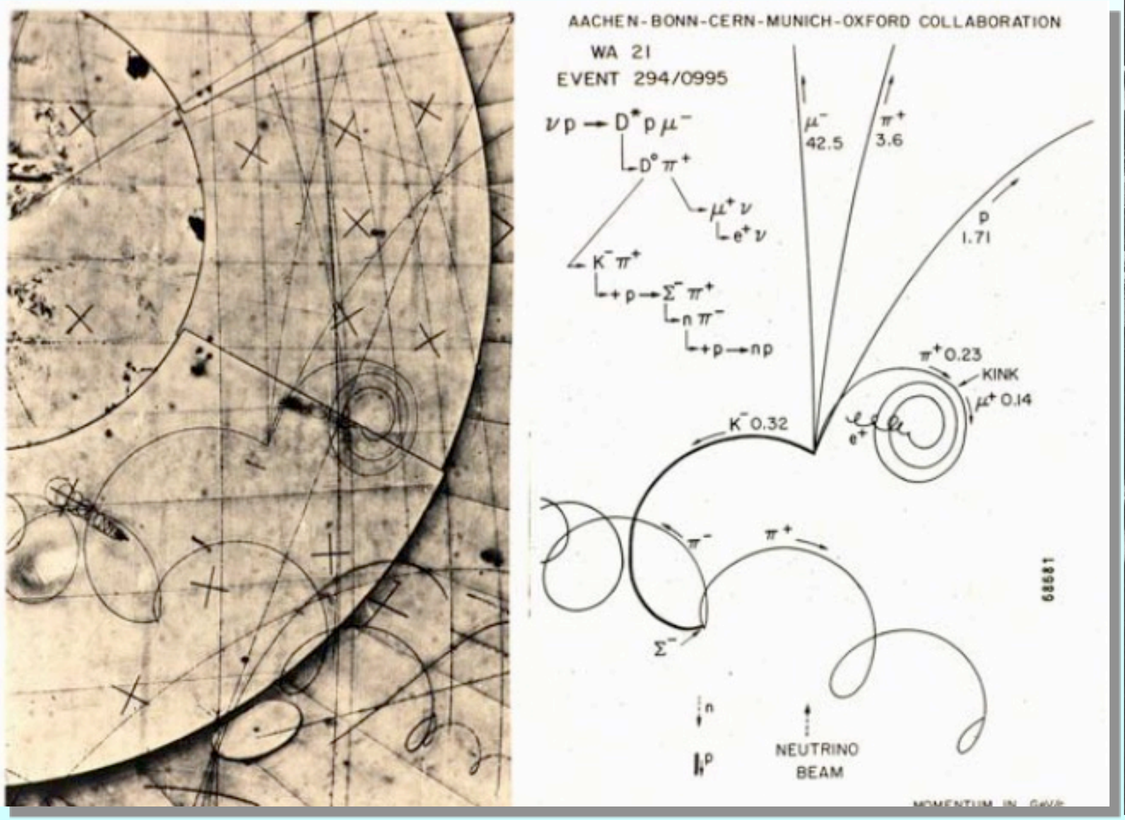
Cecil Frank Powell
Nobel Prizes 1950

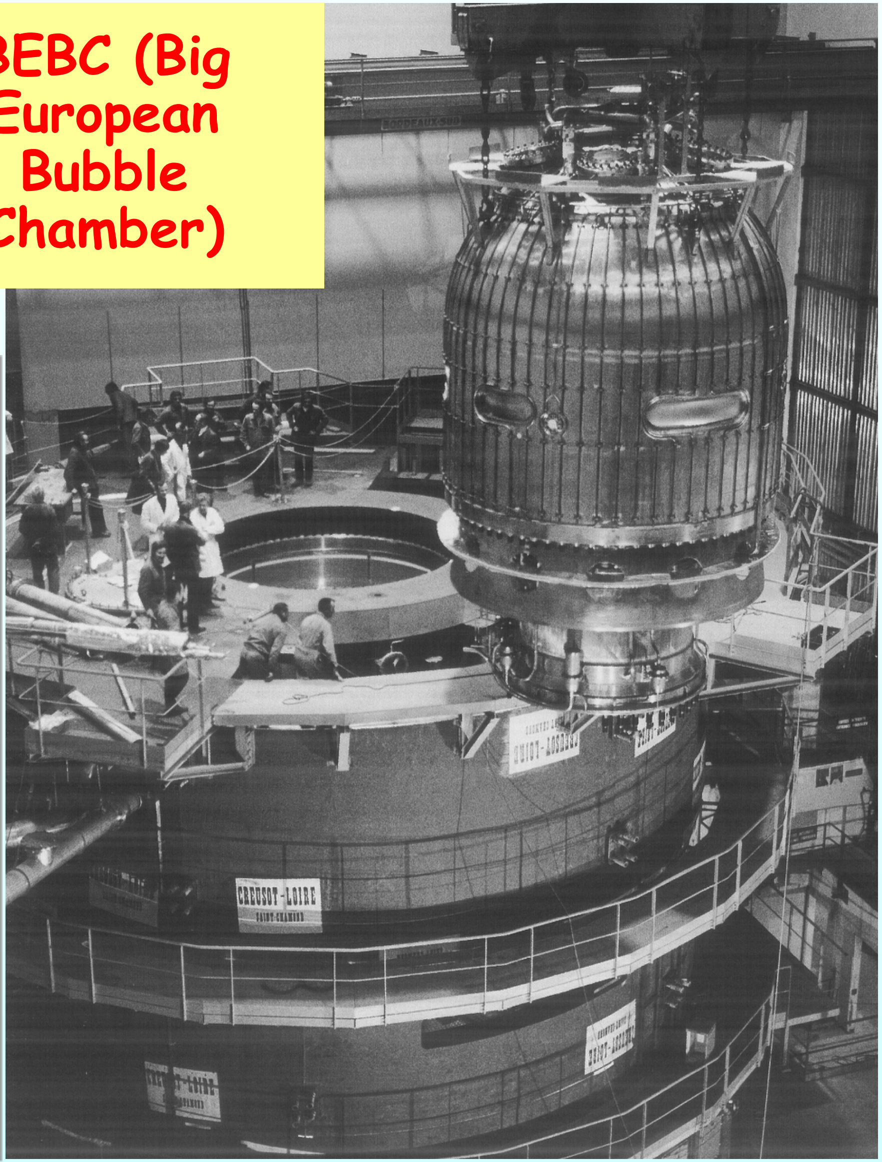
emulsions are still the detectors with the highest intrinsic space resolution: < 1 μm

1952: bubble chamber

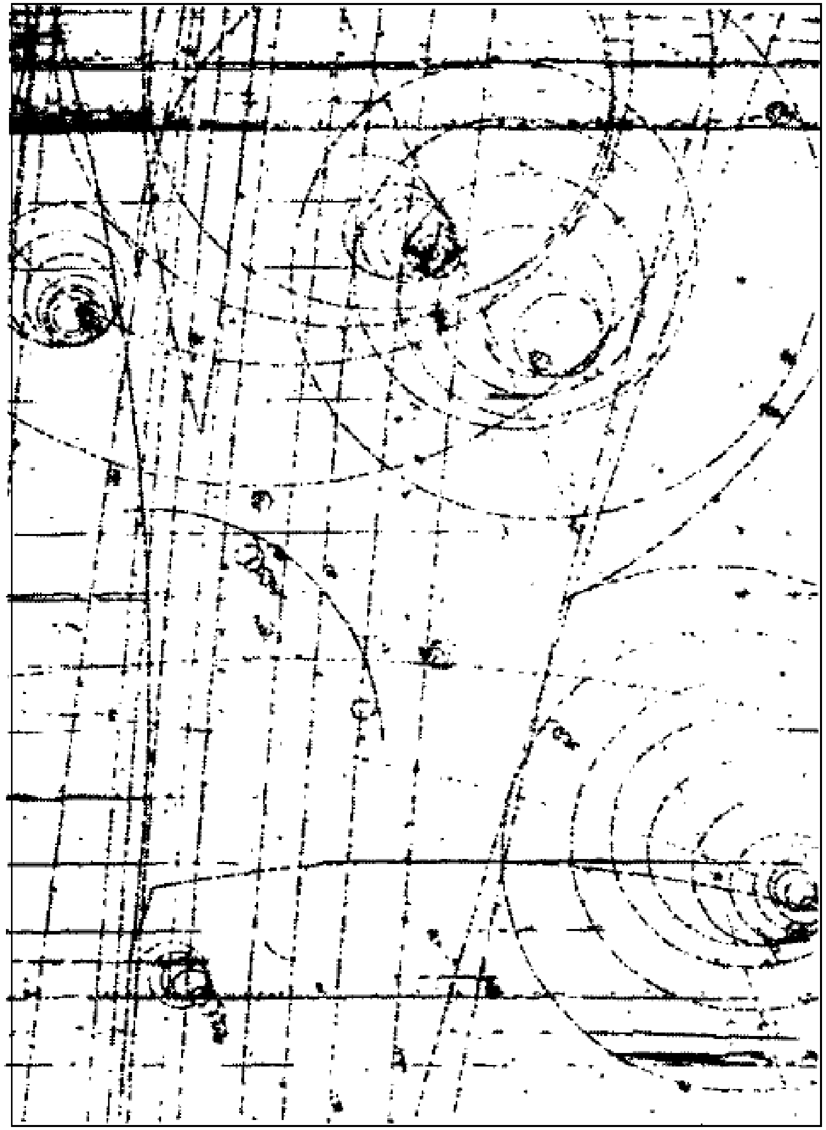
The bubble chamber, invented by Donald Arthur Glaser in 1952, has been for many years the most powerful instrument of ionizing particles investigation.

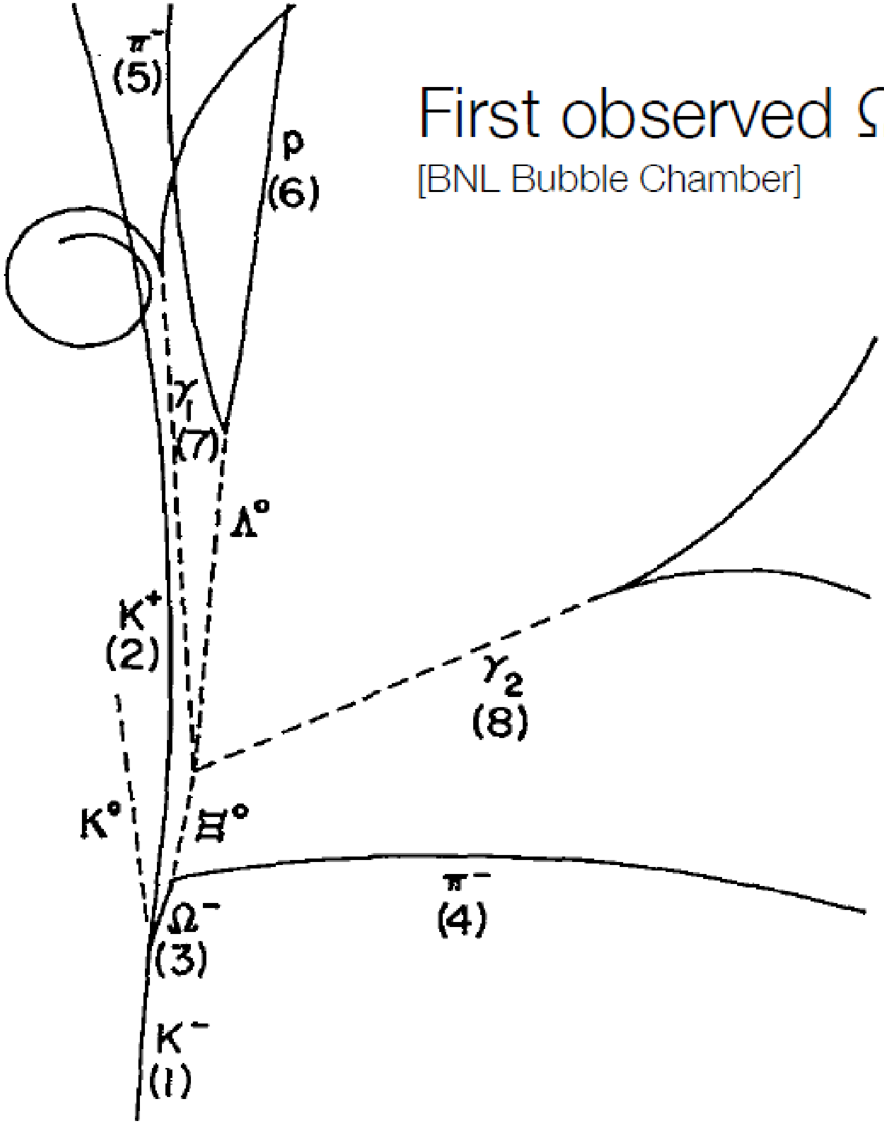
BEBC (Big European Bubble Chamber)





1964: the first predicted particle





First observed Ω^- event

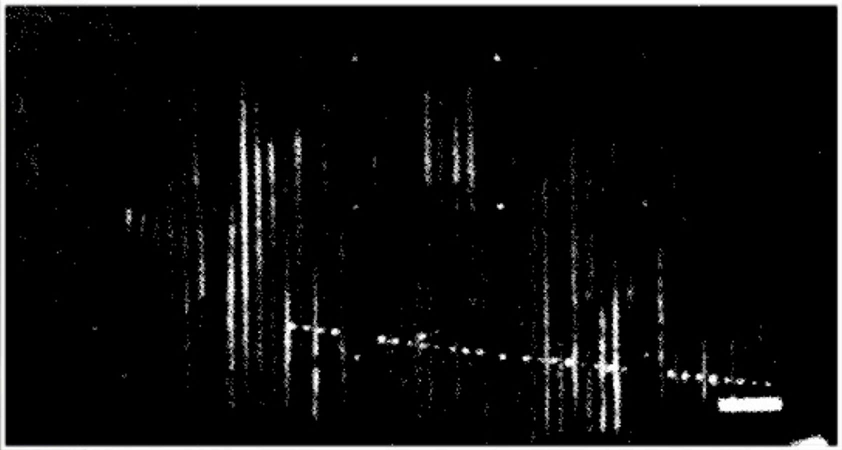
[BNL Bubble Chamber]

1962: the neutrino

Discovery of the muon neutrino (1962)

Leon M. Lederman
Melvin Schwartz
Jack Steinberger

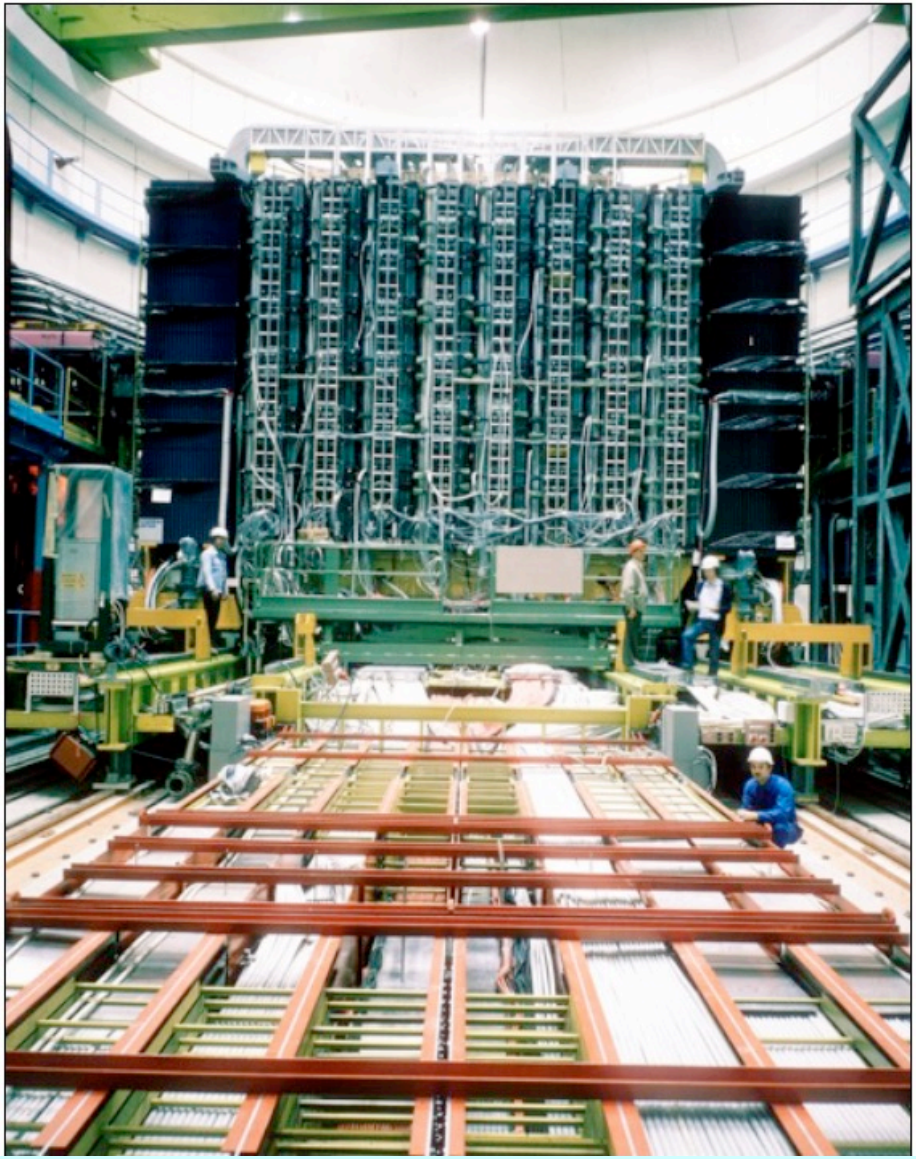
[Nobel prize 1988]



Single muon event from original publication

Melvin Schwartz in front of the spark chamber used to discover the muon neutrino

1983: the weak bosons



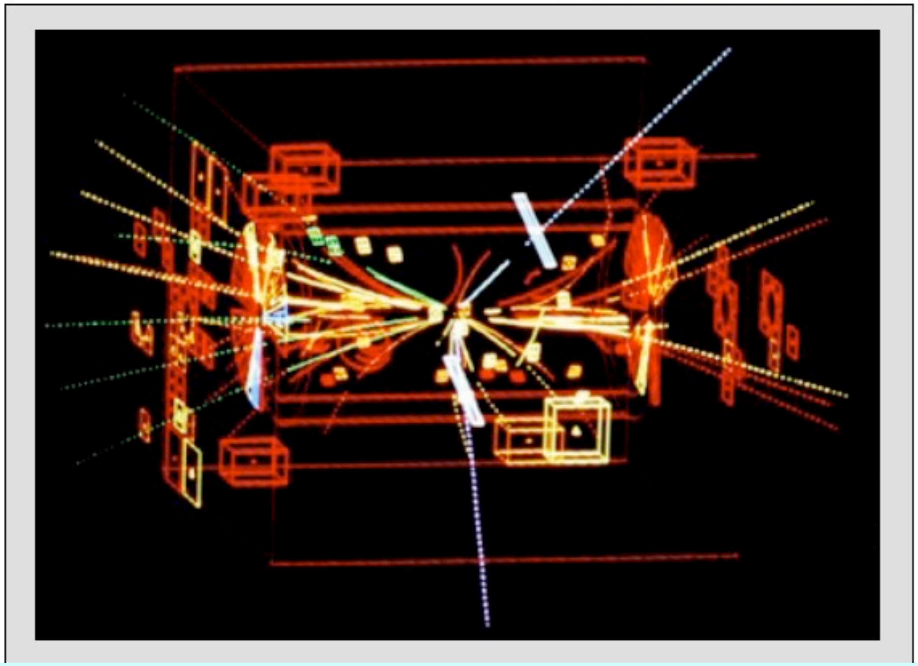
UA1
Detector

Discovery of the W/Z boson (1983)

Carlo Rubbia
Simon Van der Meer

[Nobel prize 1984]

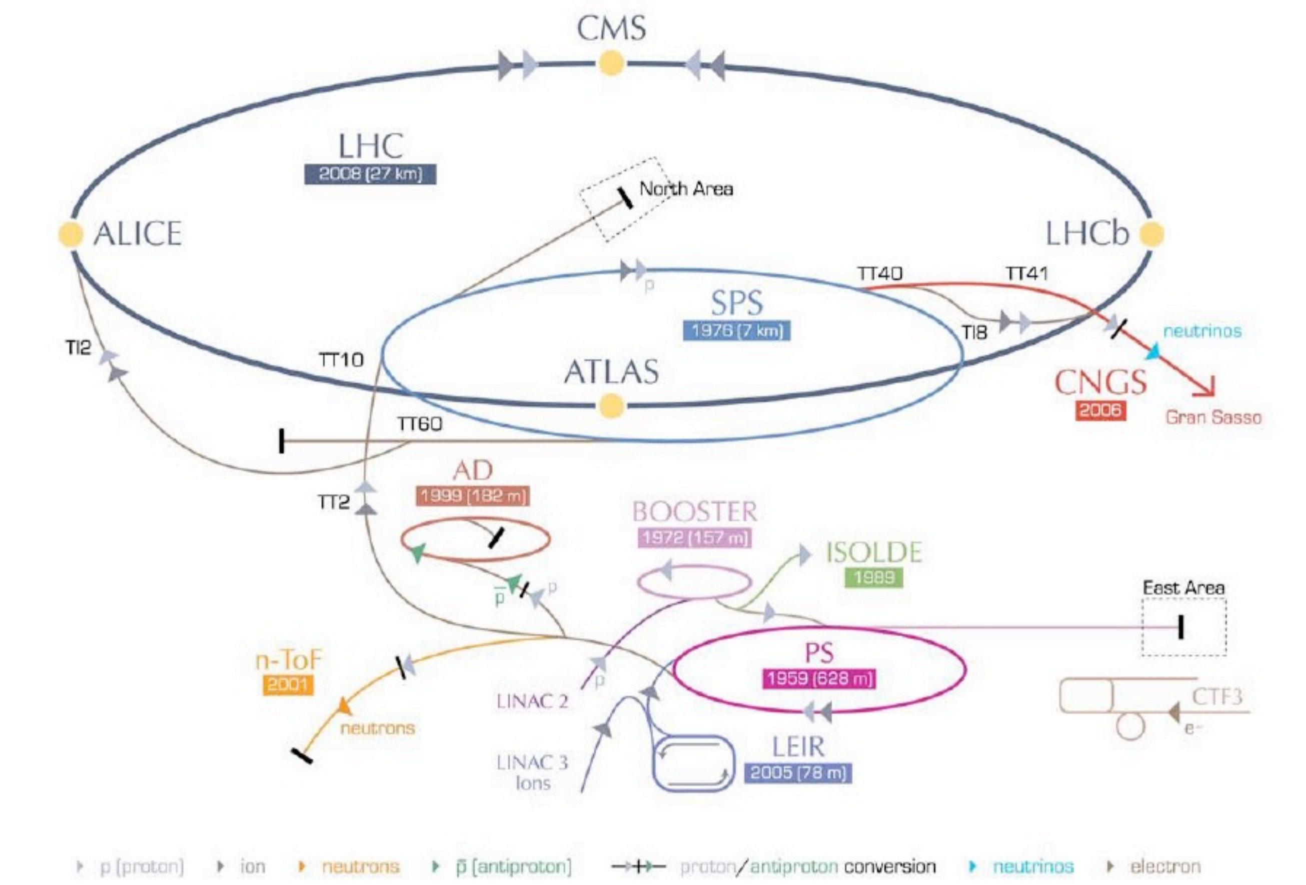
First Z^0 particle seen by UA1



CERN:
European Organization for Nuclear Research

CERN:
European Organization for Nuclear Research

CERN's accelerator complex



LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

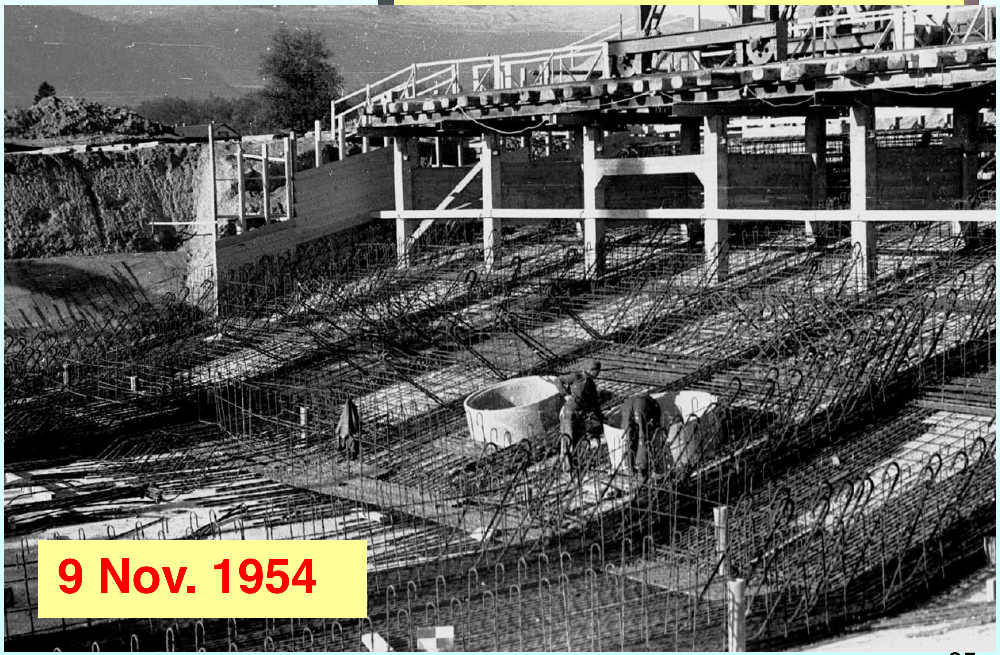
AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

CERN

- Is the largest particle physics laboratory in the world
- It hosts ~2500 staff members and ~12000 users
- Provides particle accelerators and infrastructures for particle physics research.
- Founded in 1954 as a European common project
- All results are published and universally accessible

P. Auger, E. Amaldi, L. Kowalski

15 May 1954



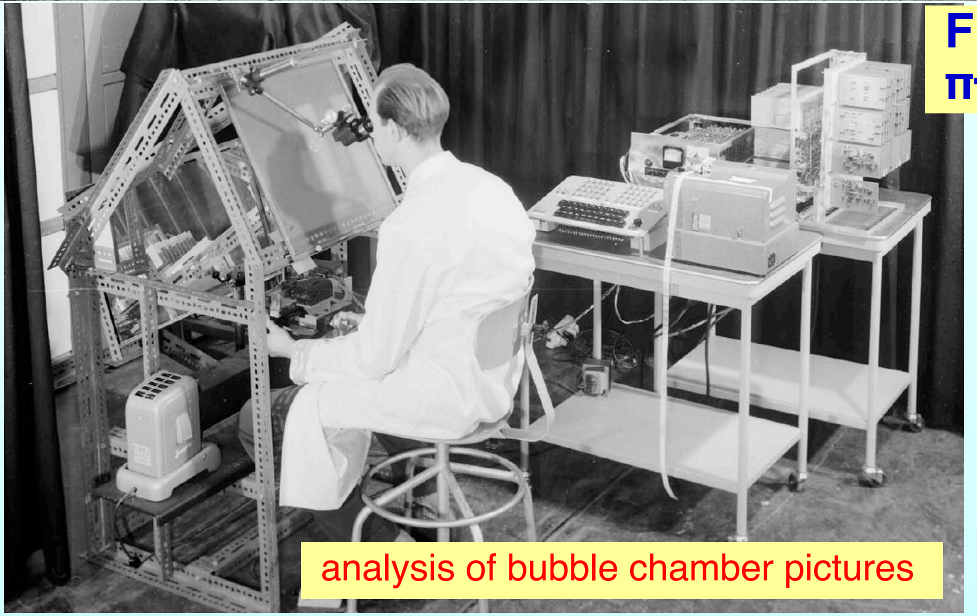
9 Nov. 1954

The 600 MeV Syncro-Cyclotron

1 Jan. 1956

1957

First physics result in 1958:
$\pi \rightarrow e\,\nu$ BR = 10^{-4}



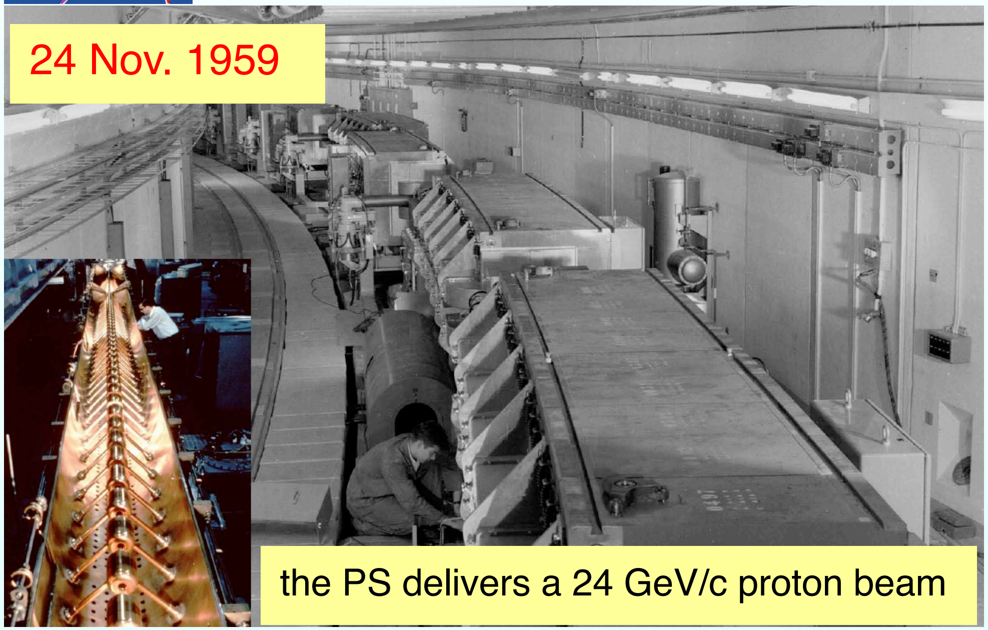
analysis of bubble chamber pictures

G. Fidecaro,
(is the first INFN Trieste director)

Giuseppe and Maria Fidecaro

The Proton-Syncrotron and the ISR

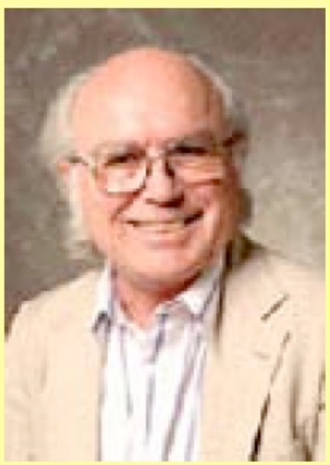
24 Nov. 1959



the PS delivers a 24 GeV/c proton beam

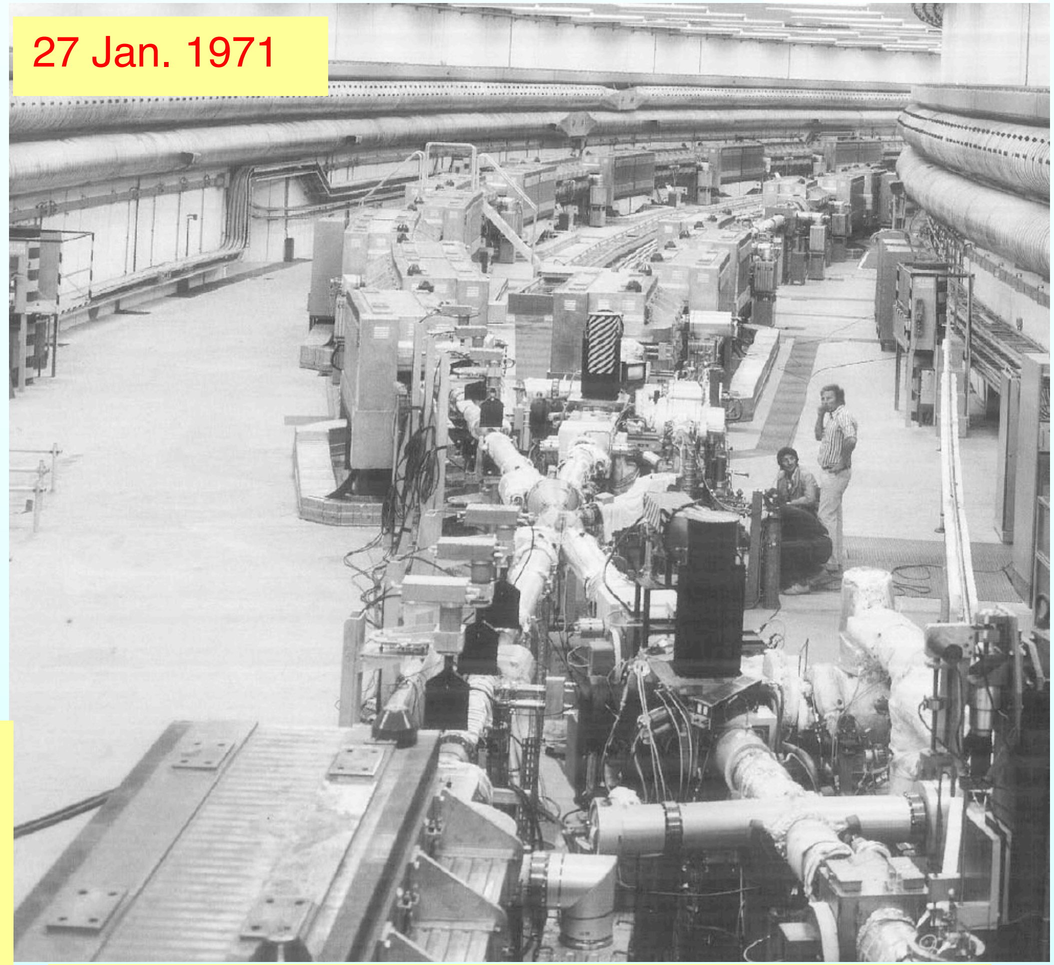
Julius Wess

Bruno Zumino



1974: Super-symmetry theory

27 Jan. 1971

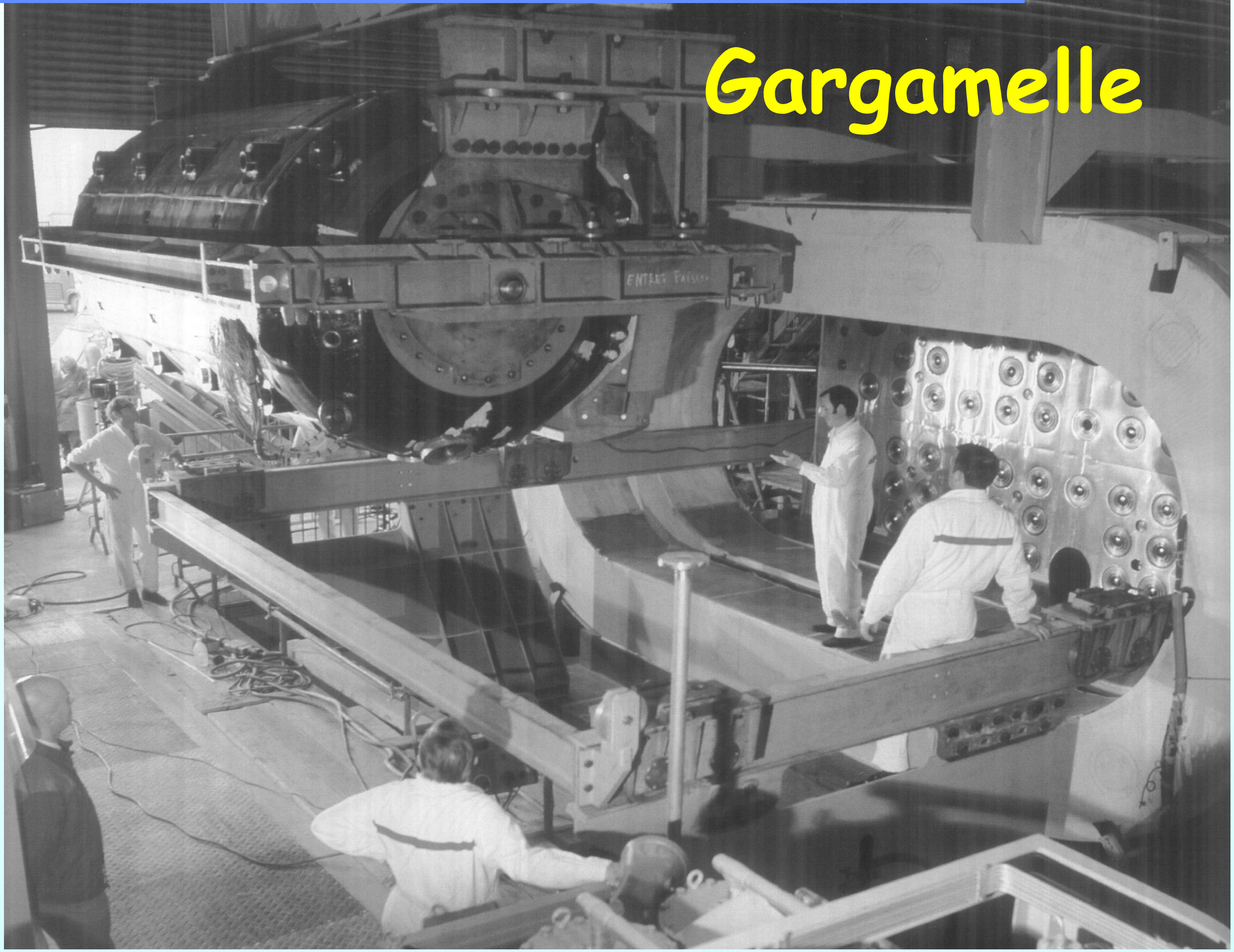


Two proton beams collide for the first time in the world.

The ISR reached a luminosity 1000 times larger than the project design one.

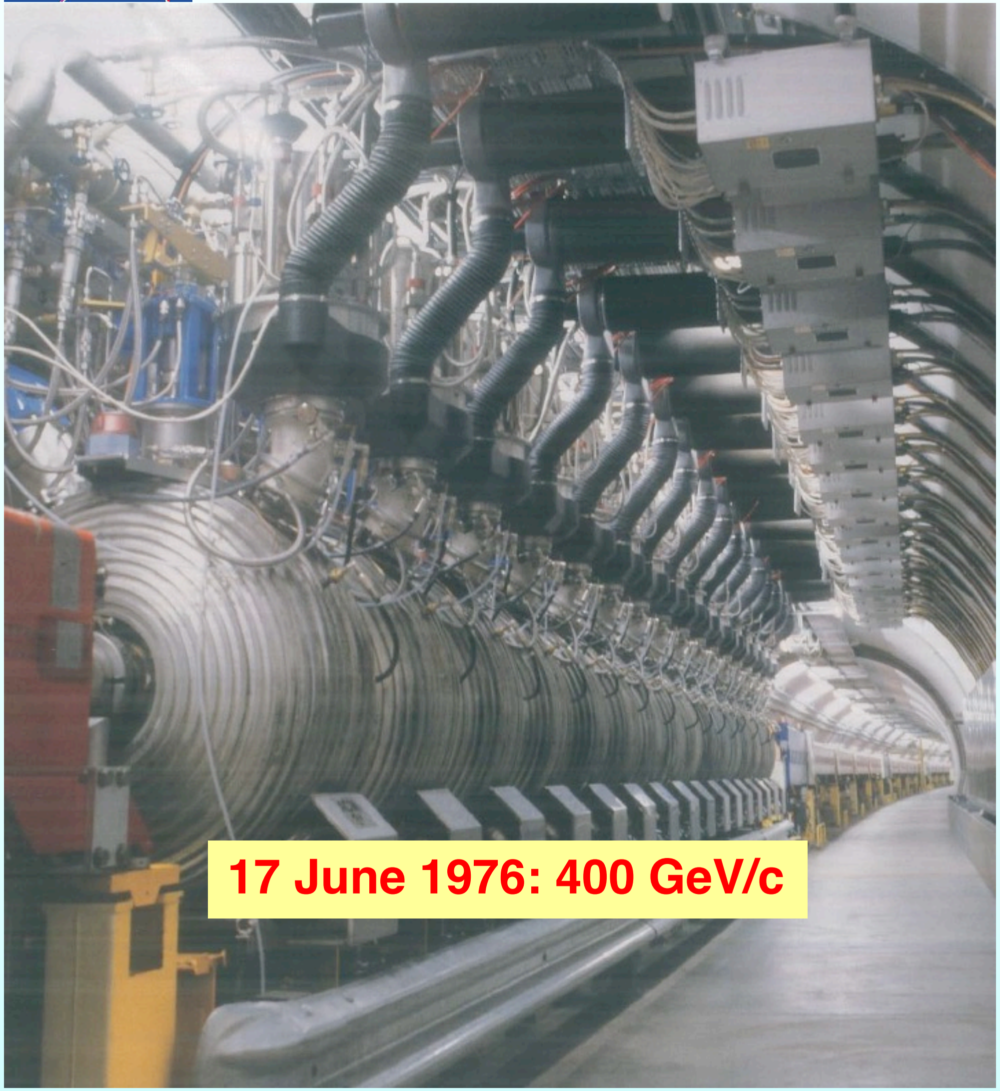
1973: the e.w. theory is confirmed

1973: the first big discovery in Europe.
Gargamelle detects weak neutral currents
The electroweak theory is confirmed



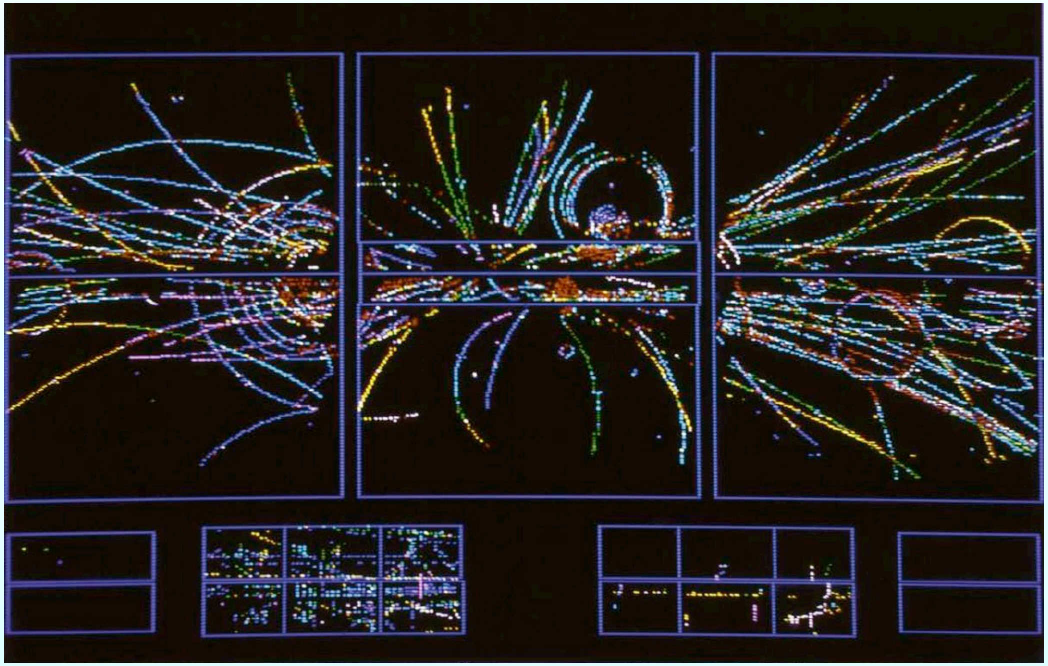
Salam receives the Nobel prize in 1979 together with Weinberg and Glashow

The Super-Proton-Syncrotron



17 June 1976: 400 GeV/c

1981: The SPS is the first proton-antiproton collider



1983: an event in the UA1 detector

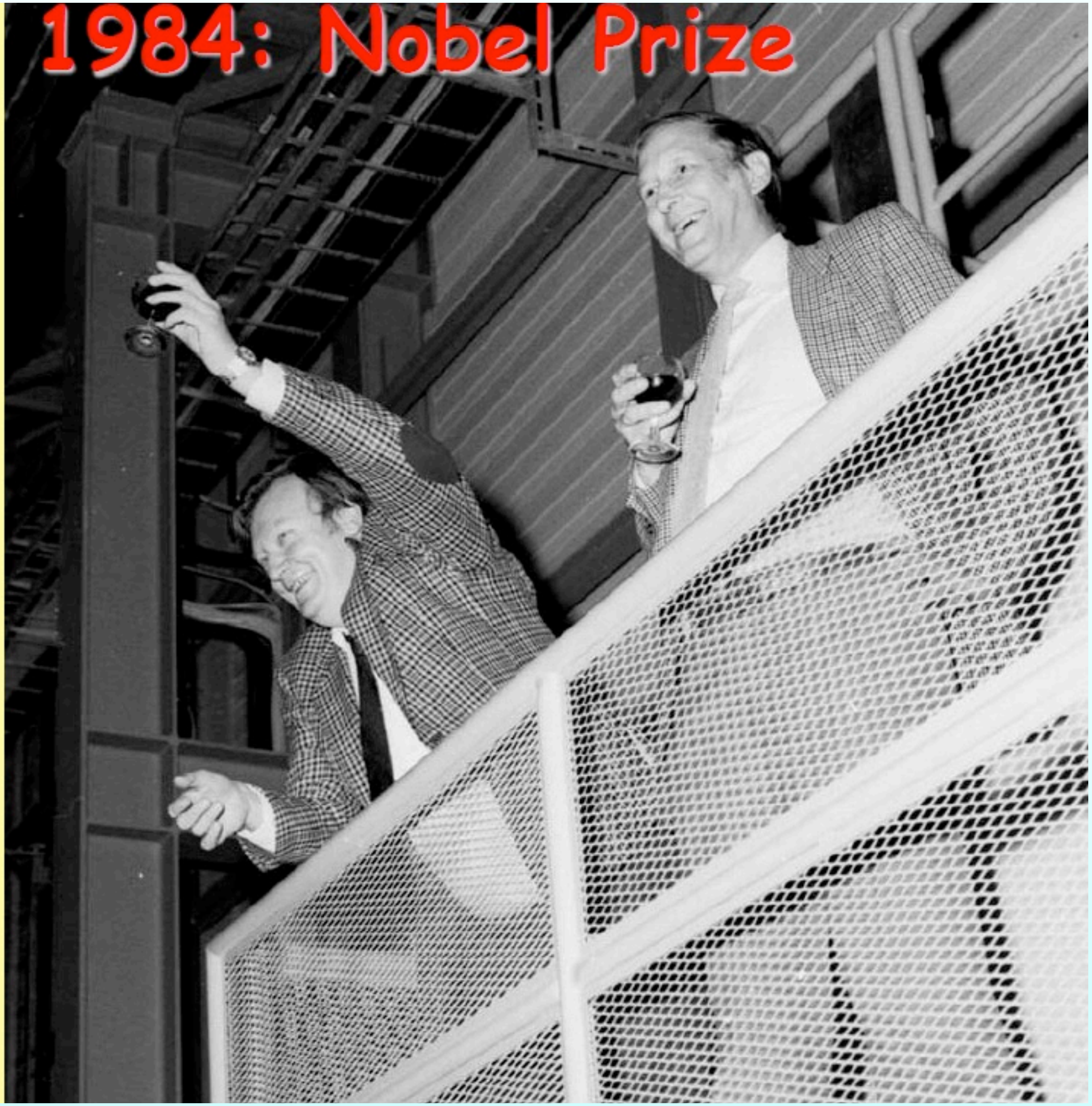
The discovery of W and Z bosons

Nobel Prize in Physics 1984

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

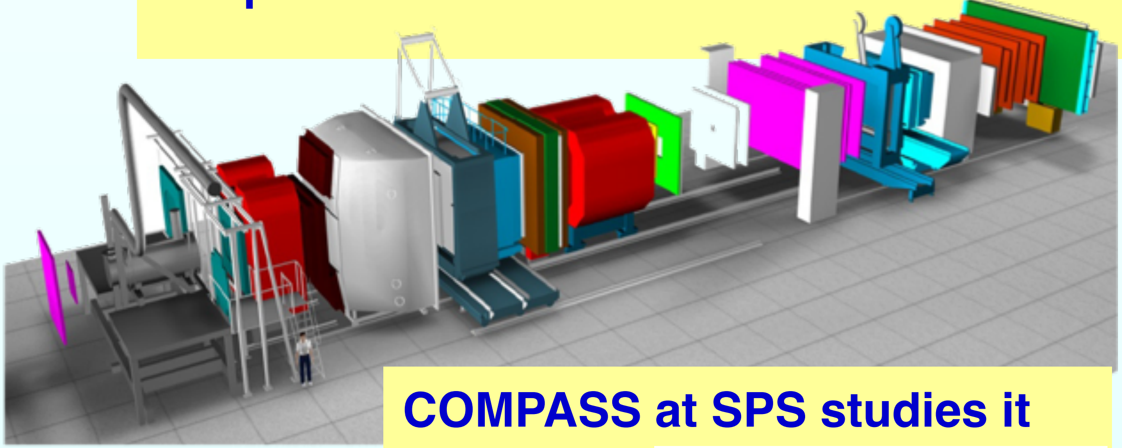
Carlo Rubbia and

Simon Van der Meer

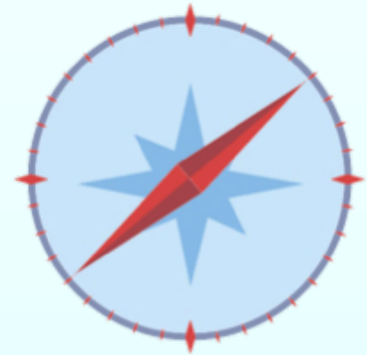


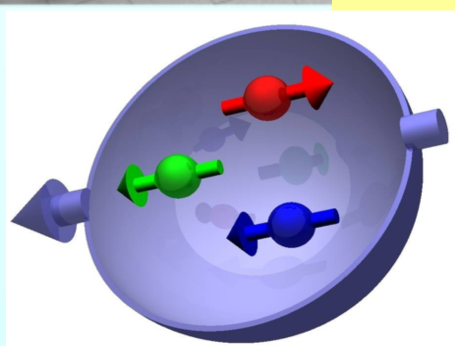
The mistery of the proton spin

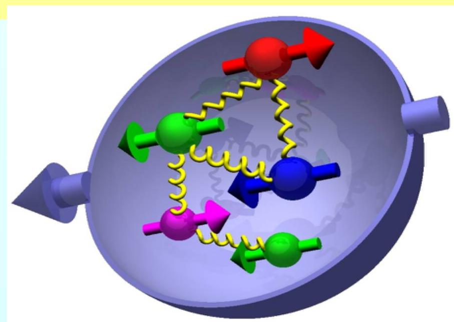
1989: The EMC at SPS measures the proton spin decomposition
→ spin crisis

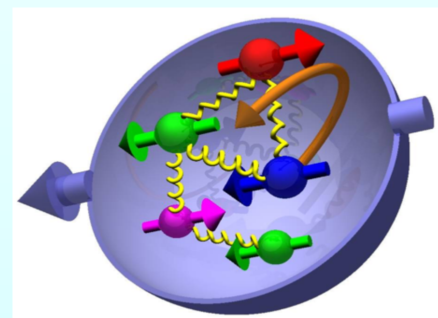


COMPASS at SPS studies it









Partonmodel

1989 EMC measured
$\Sigma = 0.120 \pm 0.091 \pm 0.138$

Gluons are important !

⇒ Δg
⇒ Sea quarks Δq_s

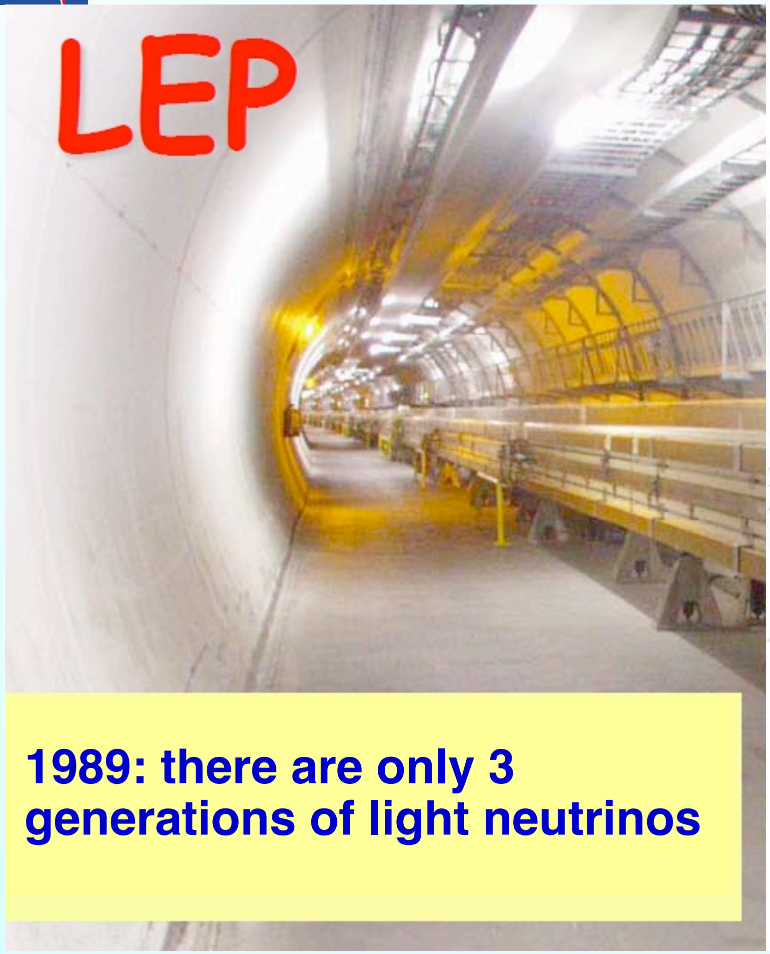
Full description
needs
orbital angular momentum

The Large Electron-Positron Collider

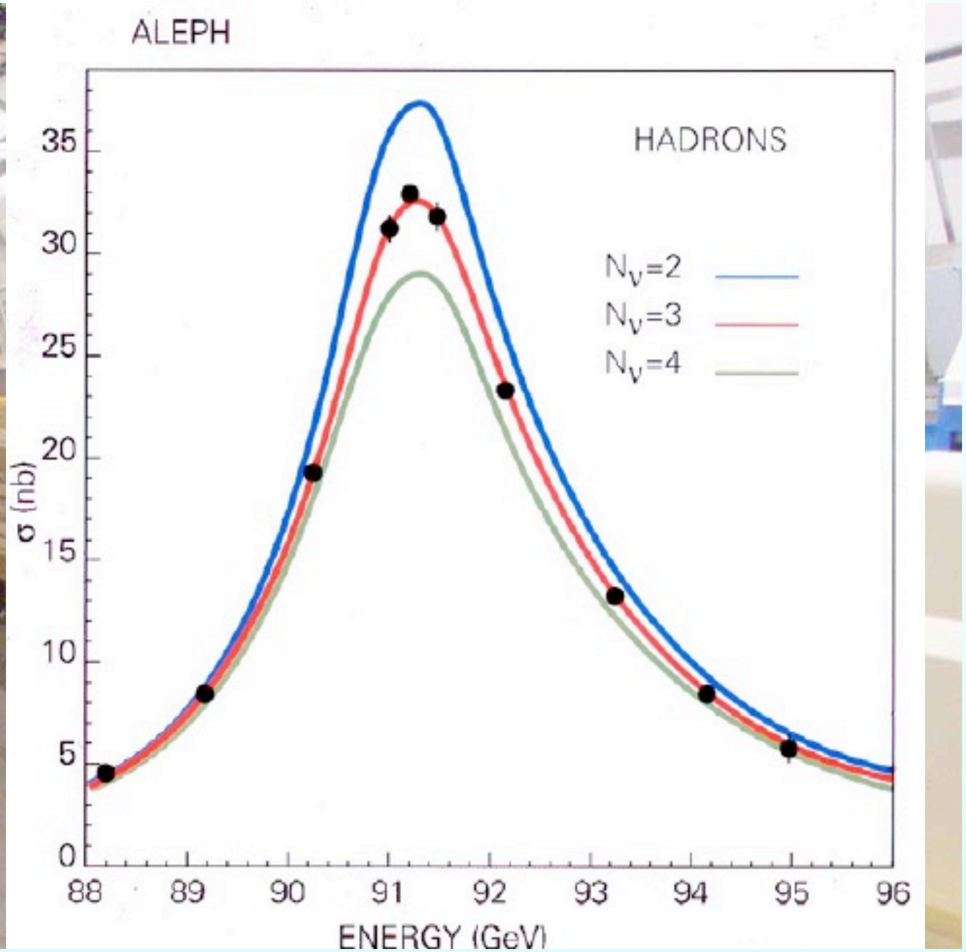
High precision W and Z measurement

Between 1985 and 1988 1.4 M m^3 were escavated at a depth of 100 m for a length of 27 km: the largest European civil engineering work of that period

Counting particle generations

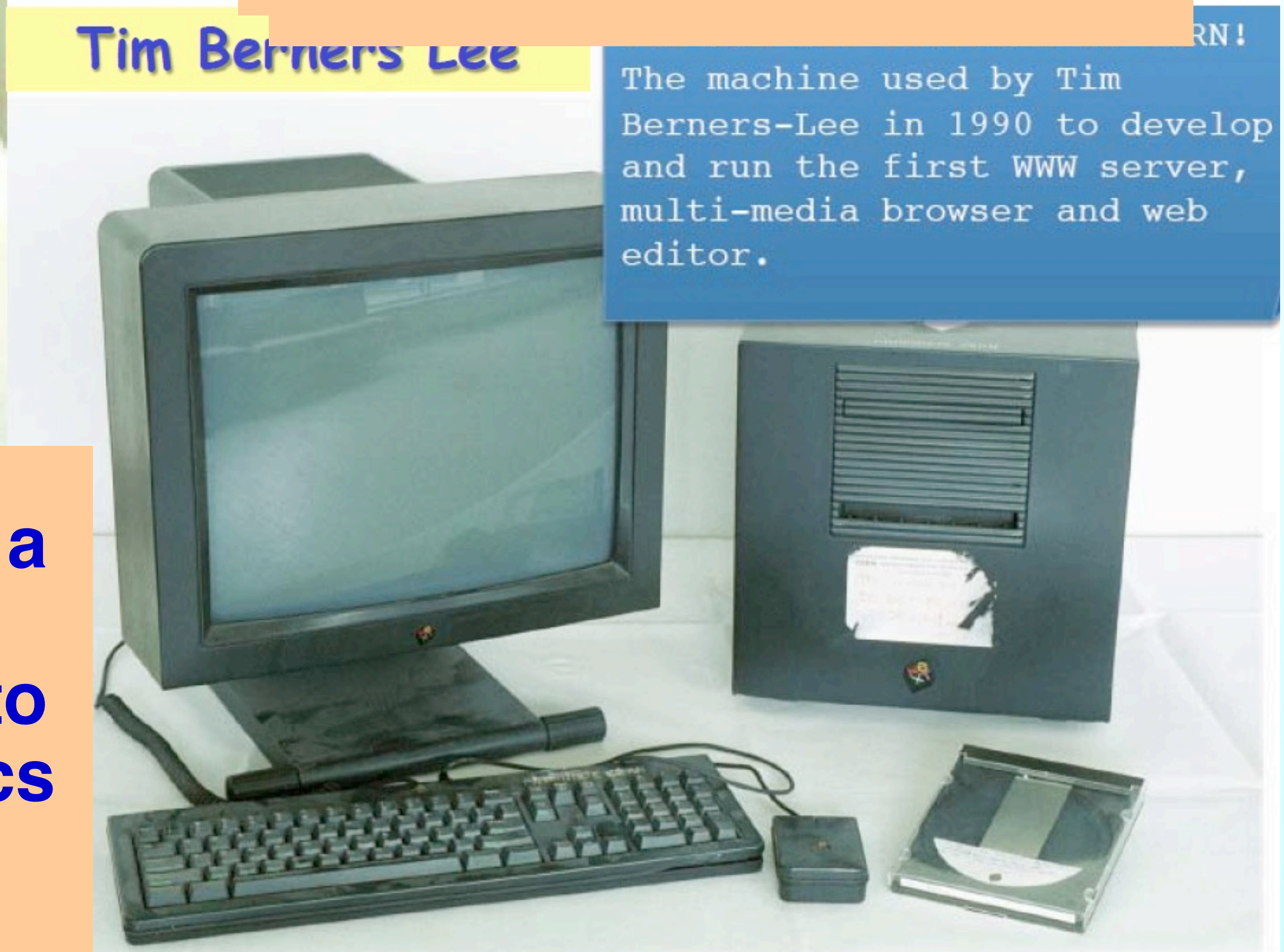


1989: there are only 3 generations of light neutrinos



Tim Bernes-Lee invents the www

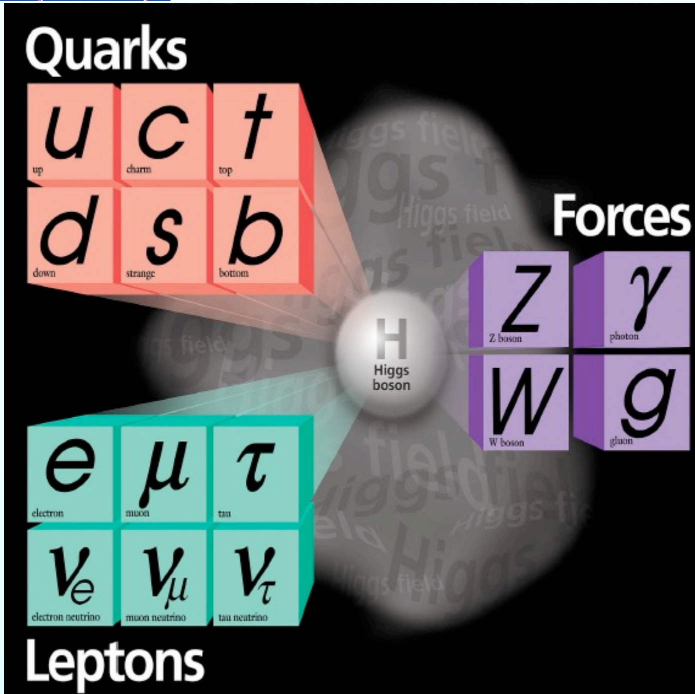
1990: the web is born!

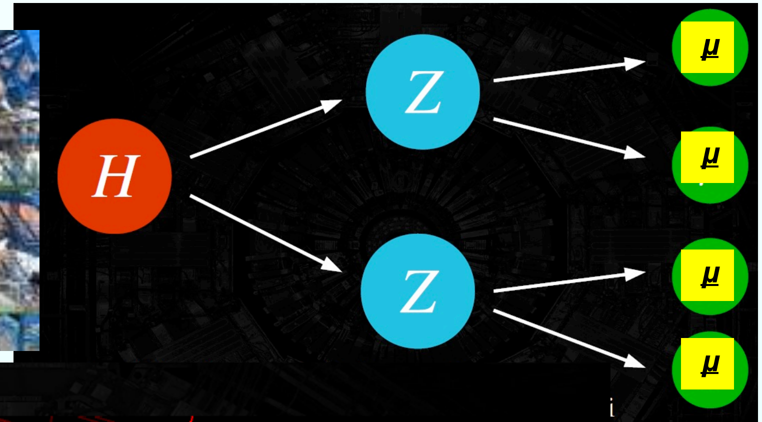


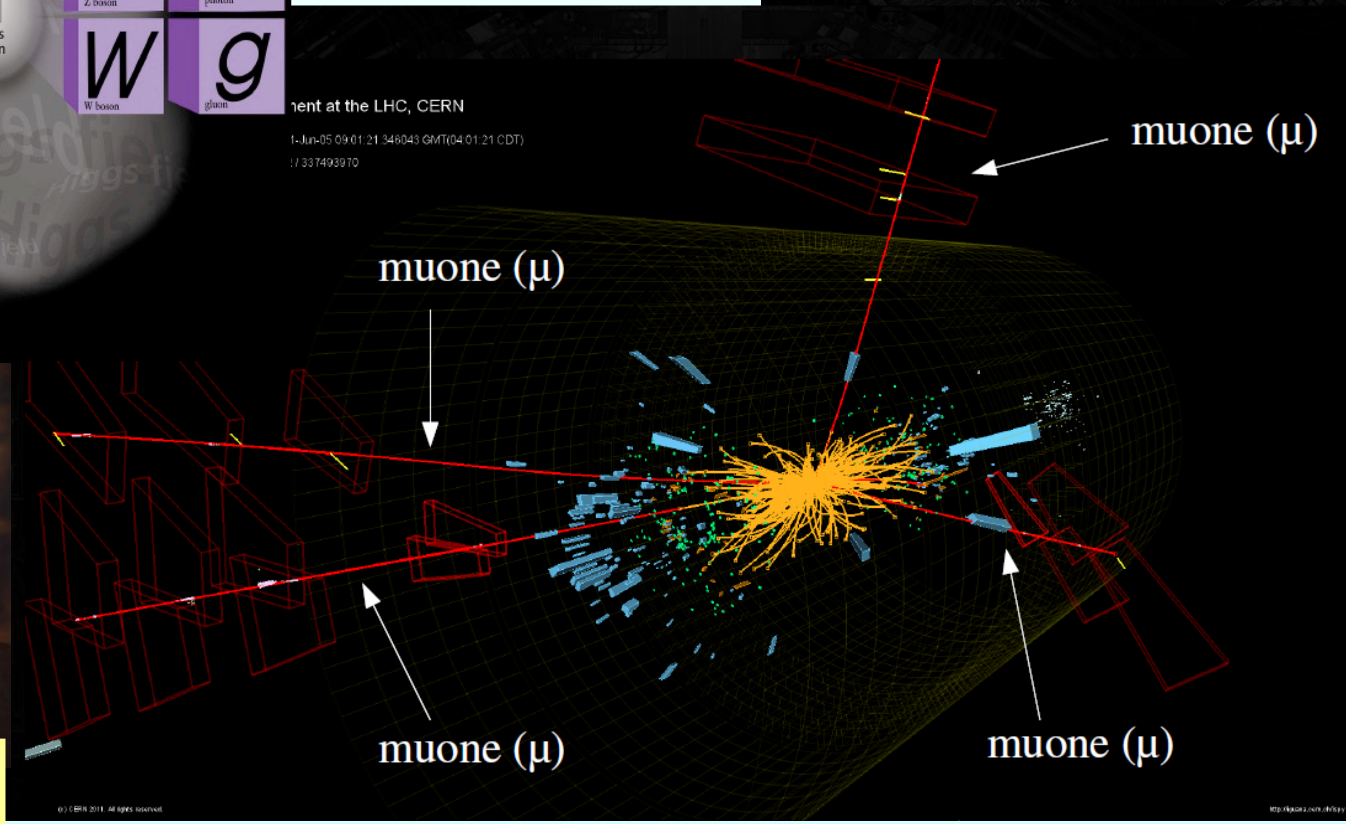
CERN gives a fundamental contribution to the informatics revolution

The largest accelerator in the world

2012: discovery of the Higgs boson



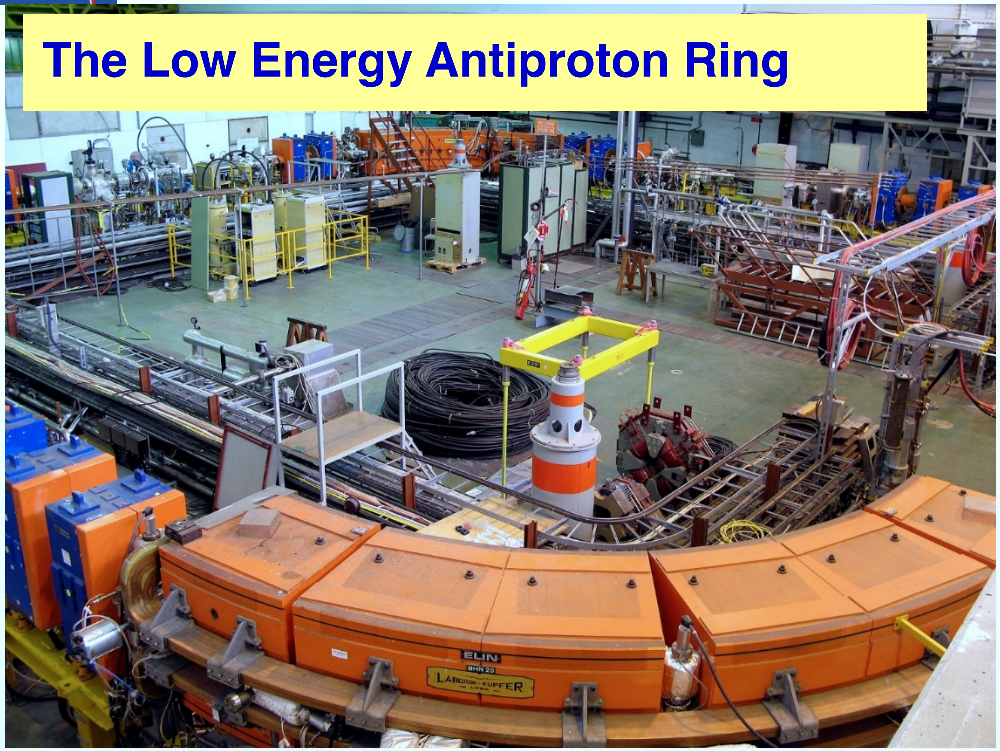




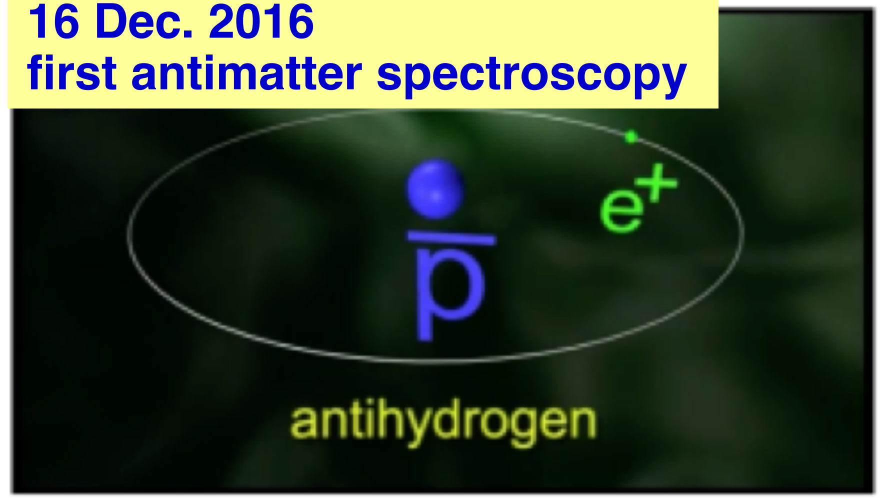
Peter Higgs,
Nobel Prize 2013

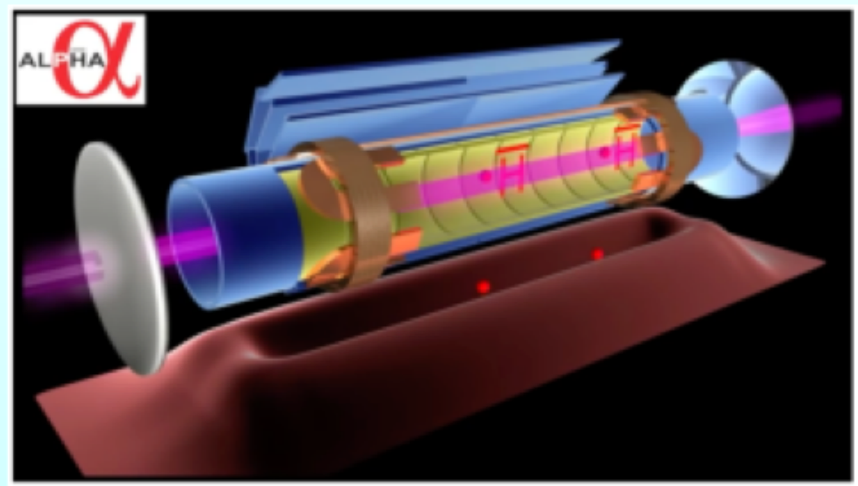
The antihydrogen

The Low Energy Antiproton Ring



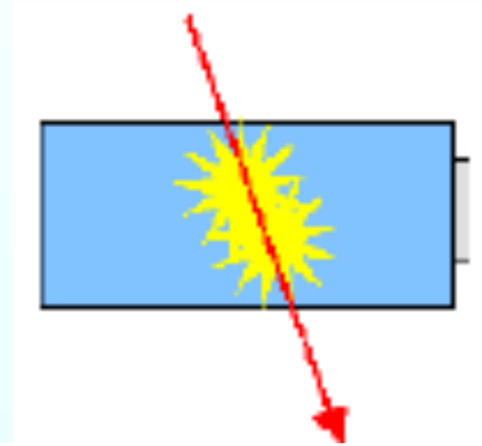
16 Dec. 2016
first antimatter spectroscopy





Scintillation detectors

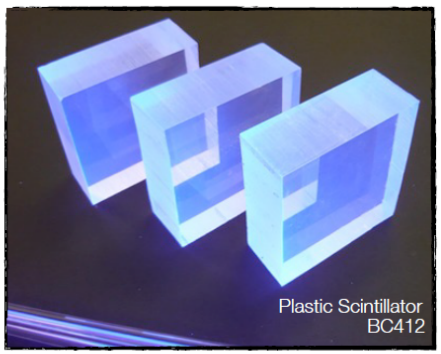
Particle Detection via Luminescence



Scintillators – General Characteristics

Principle:

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



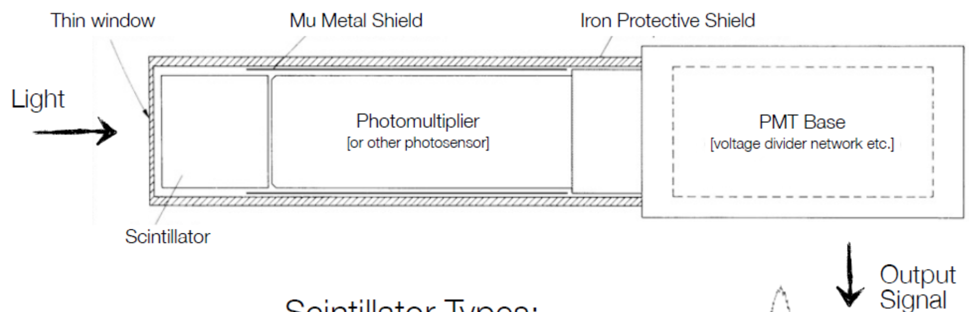
Main Features:

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

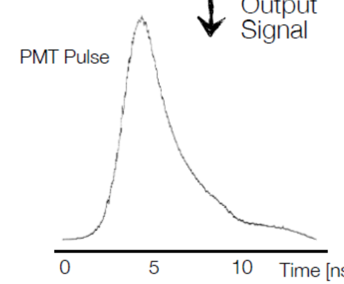


Scintillator Types:

Organic Scintillators
Inorganic Crystals
Gases

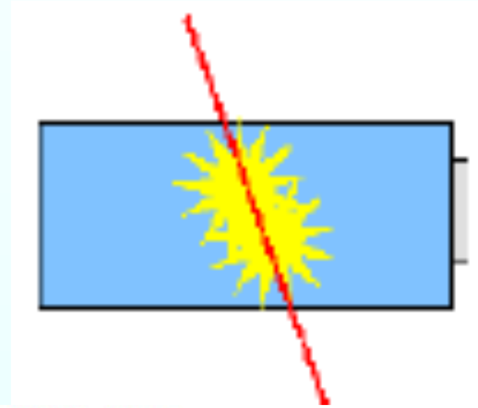
Photosensors

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



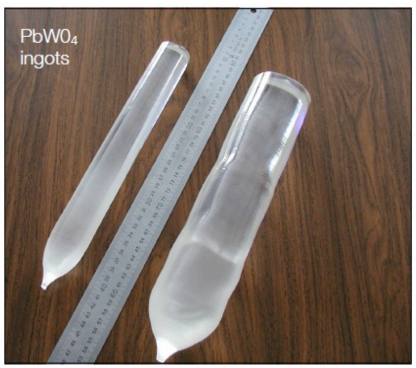
Scintillation detectors

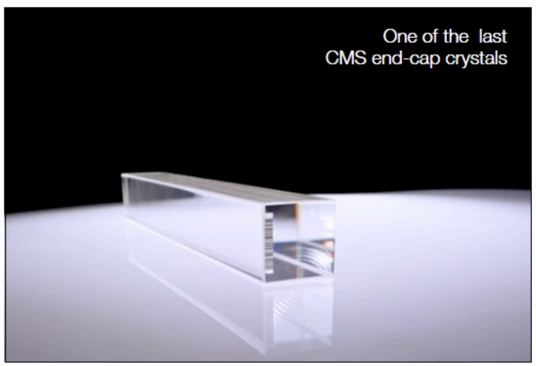
Particle Detection via Luminescence



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]

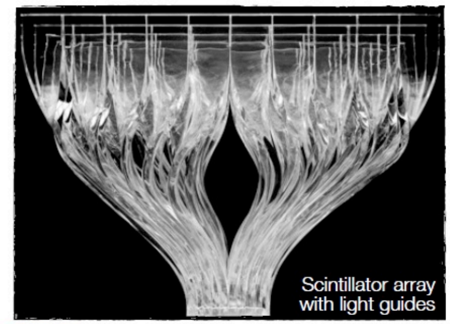
+ large concentration of primary 'fluor'
+ smaller concentration of secondary 'fluor'
+ ...

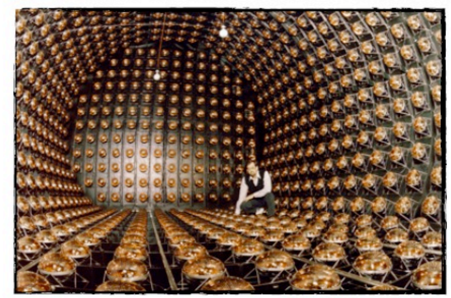
Scintillator requirements:

Solvable in base material

High fluorescence yield

Absorption spectrum must overlap with emission spectrum of base material





LSND experiment

Fast and cheaper

Photomultipliers

Photomultipliers

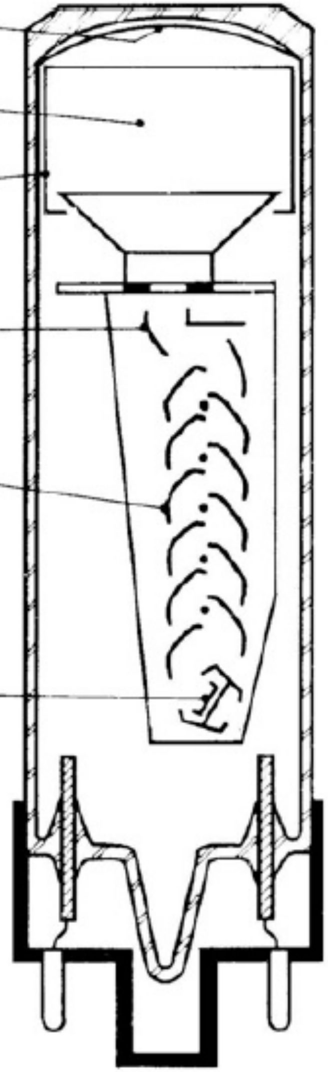
Principle:

Electron emission
from photo cathode

Secondary emission
from dynodes; dynode gain: 3-50 [f(E)]

Typical PMT Gain: > 10^6
[PMT can see single photons ...]

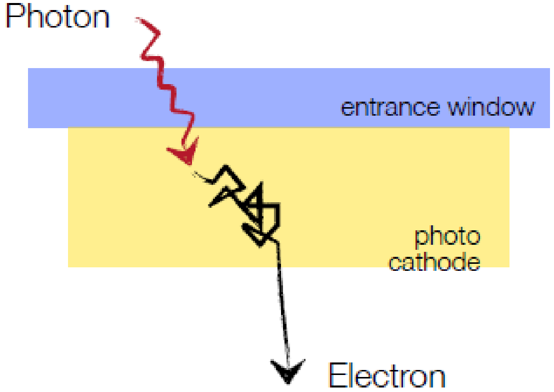
PMT
Collection



Photocathodes

Bialkali: SbRbCs; SbK_2Cs

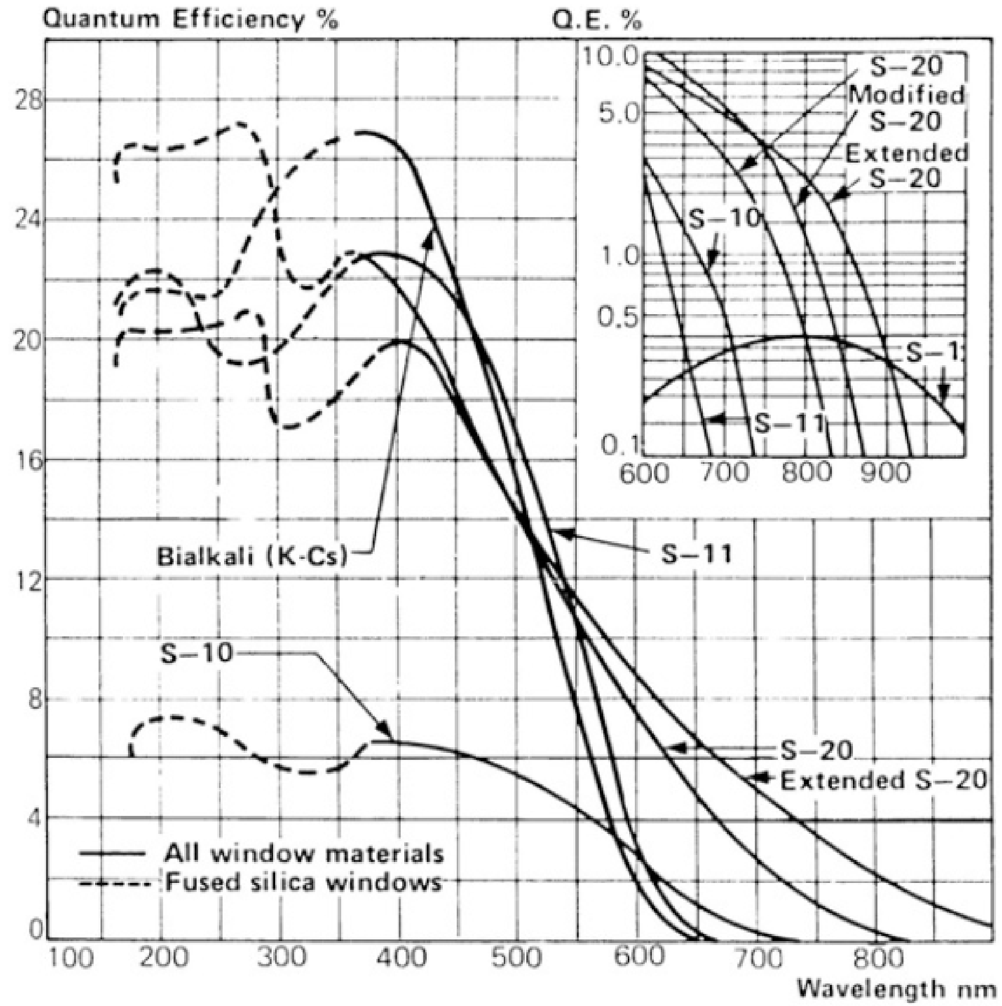
γ-conversion
via photo effect ...



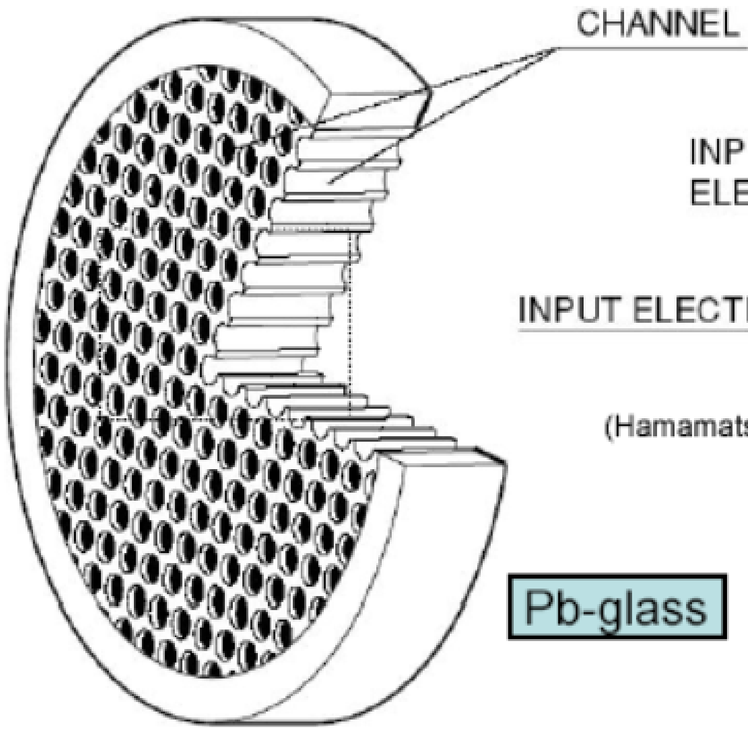
3-step process:

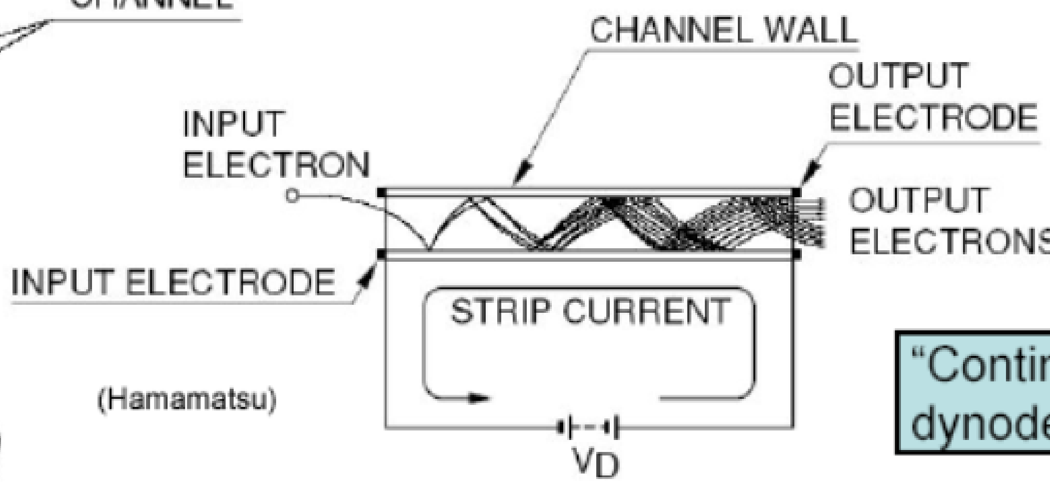
- Electron generation via ionization
- Propagation through cathode
- Escape of electron into vacuum

Q.E. ≈ 10-30%
[need specifically developed alloys]



Micro-Channel Plates

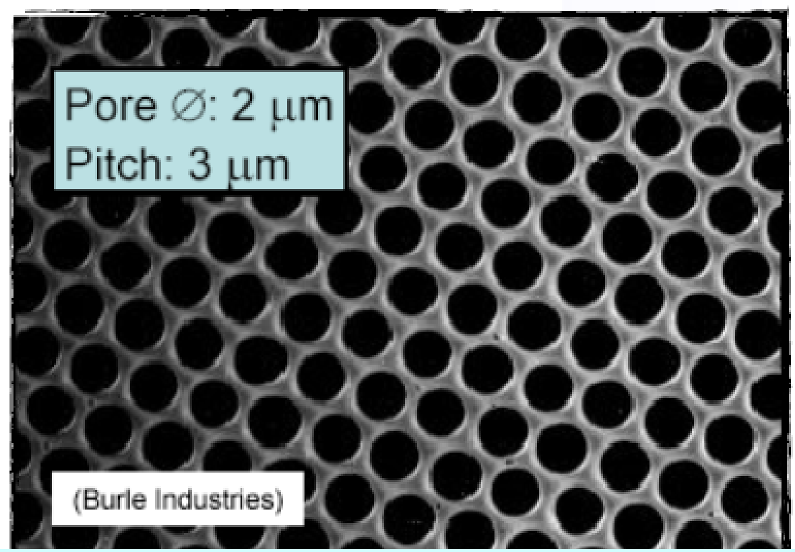




(Hamamatsu)

"Continuous" dynode chain

Pb-glass



"2D Photomultiplier"

Gain: $5 \cdot 10^4$

Fast signal [time spread ~ 50 ps]

B-Field tolerant [up to 0.1T]

Si PMs

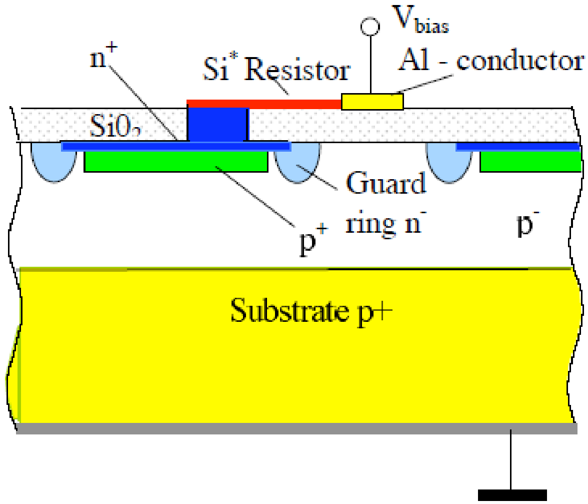
Silicon Photomultipliers

Principle:

Pixelized photo diodes
operated in Geiger Mode

Single pixel works as a binary device

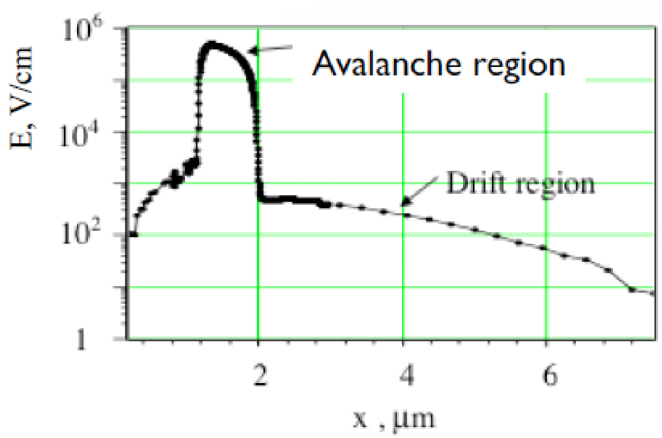
Energy = #photons seen by
summing over all pixels



Features:

Granularity	:	10^3 pixels/mm^2
Gain	:	10^6
Bias Voltage	:	< 100 V
Efficiency	:	ca. 30 %

Insensitive to magnetic fields!
Works at room temperature ...



Scintillating Fibers hodoscopes

Scintillating Fibers Hodoscopes

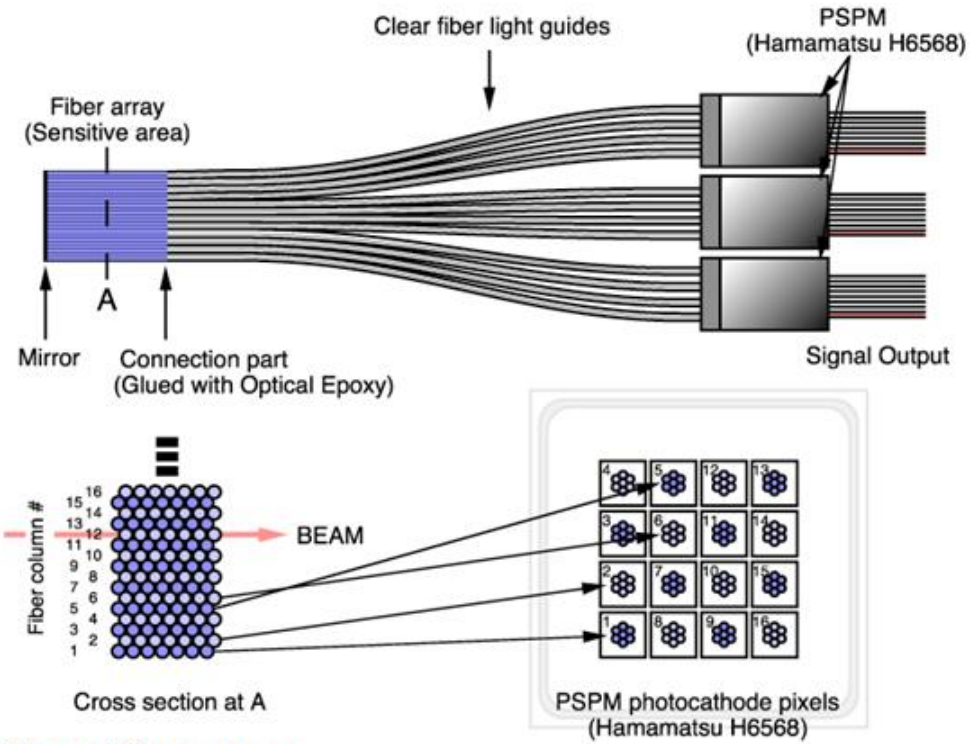
9 stations: 21 coordinates

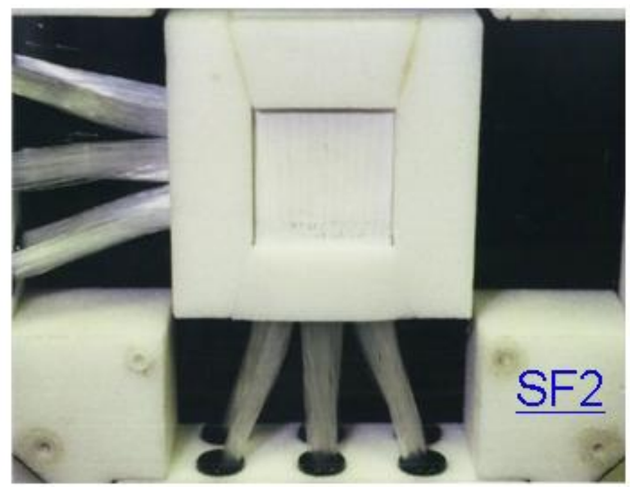
Rate capability > 5 MHz per channel

Efficiency: 99%

Space resol. 130 – 250 μm

Time resol. < 400 ps

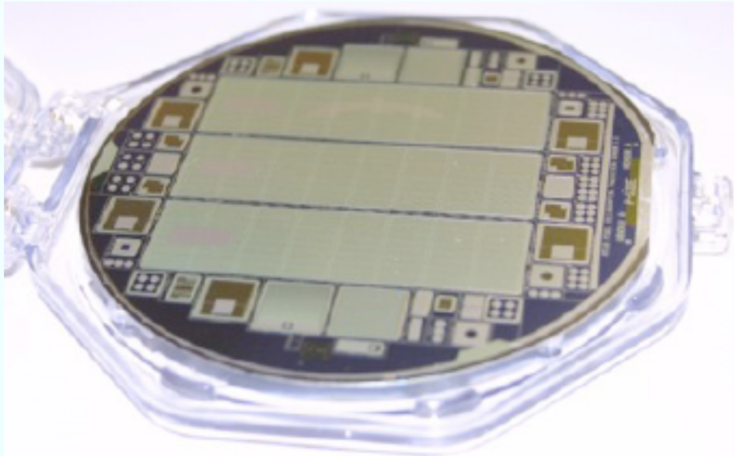


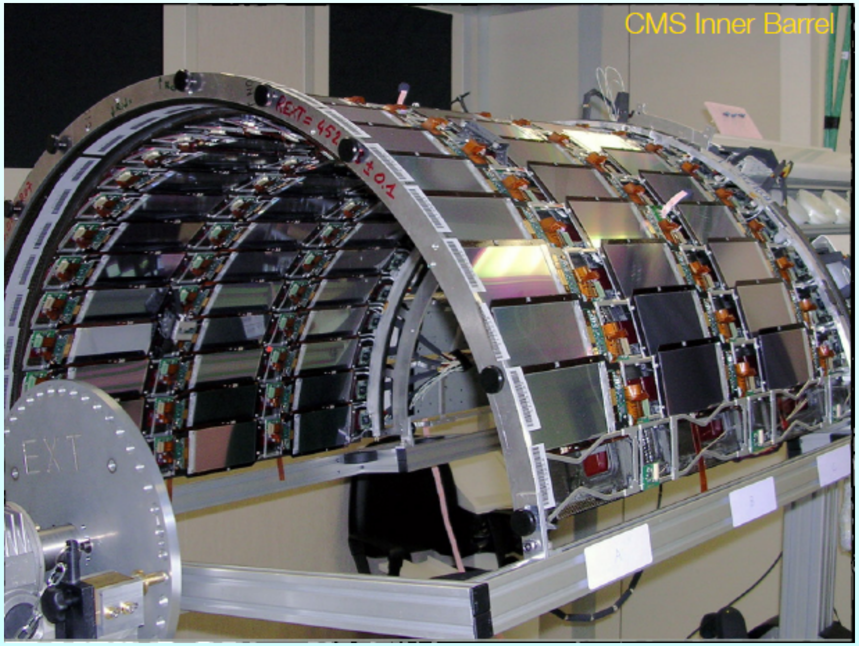


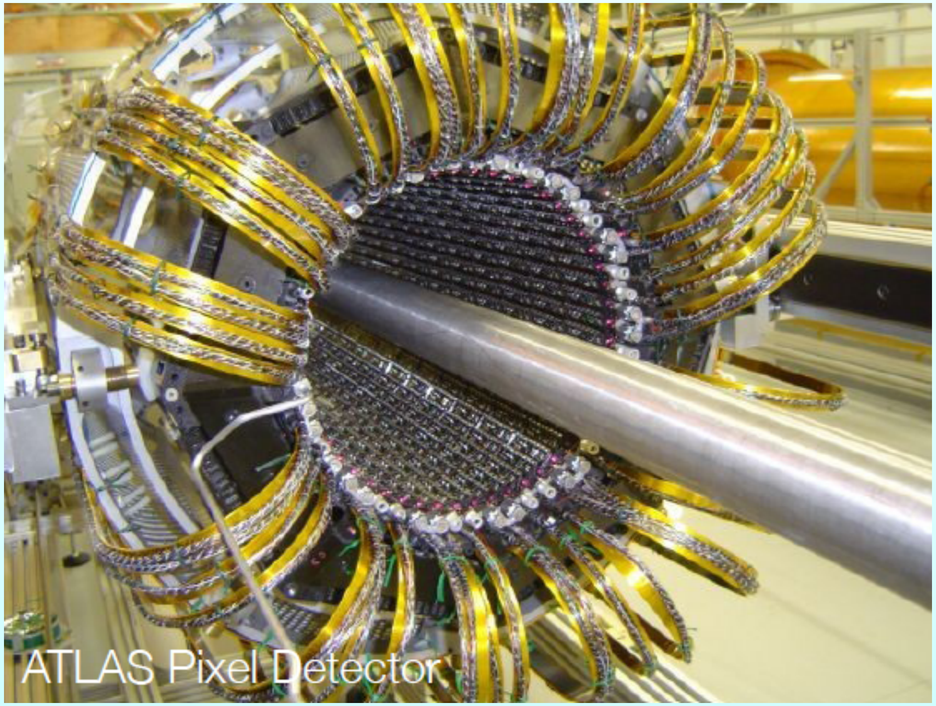
Sensitive area:

7-layers of Kuraray SCSF-78MJ 0.5 mm Ø

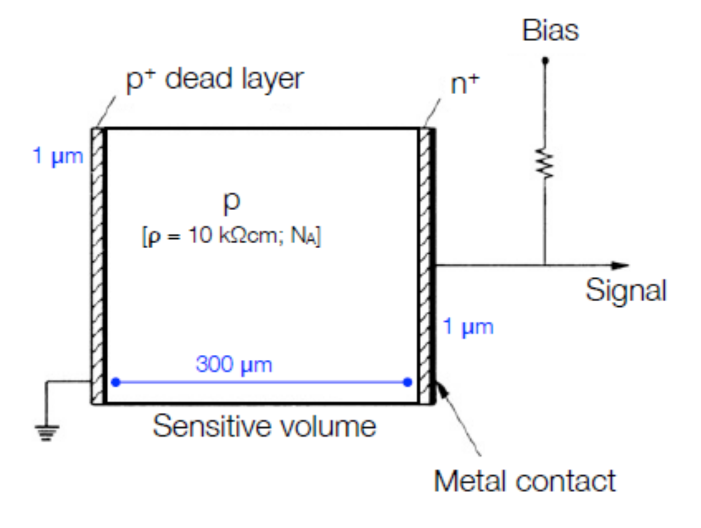
Si detectors

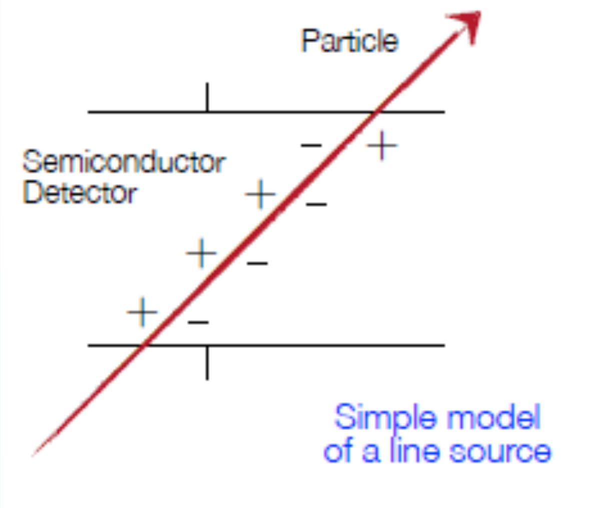




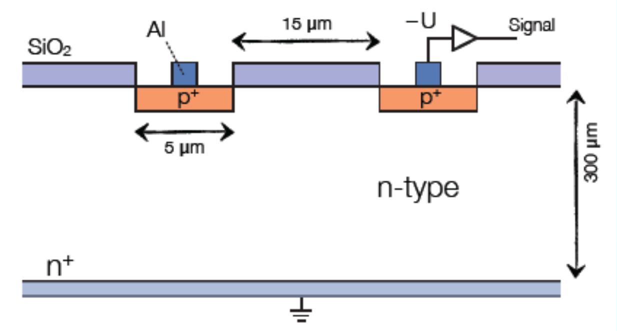


Si microstrips





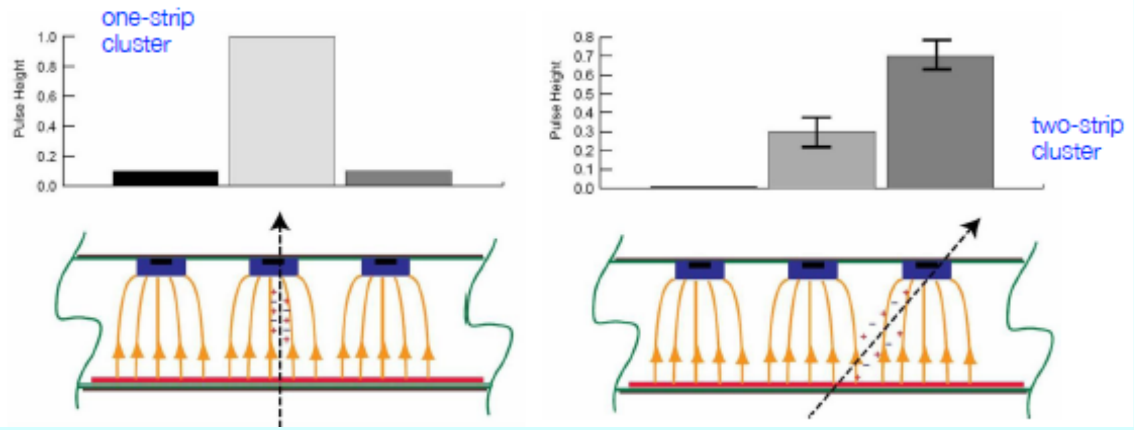
Simple model of a line source

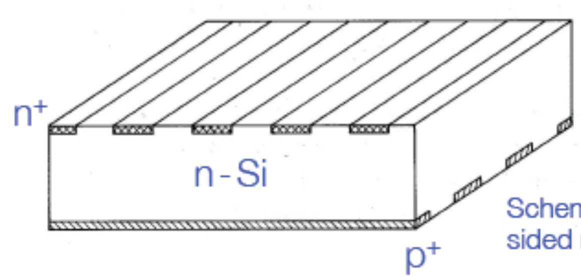


Schematics of Silicon Strip Detector

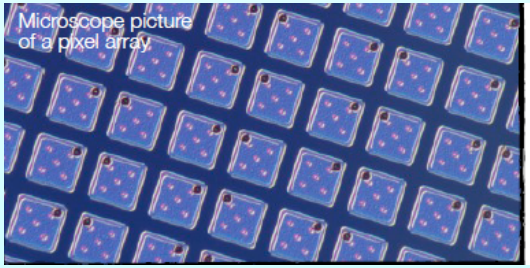
[from 1983]

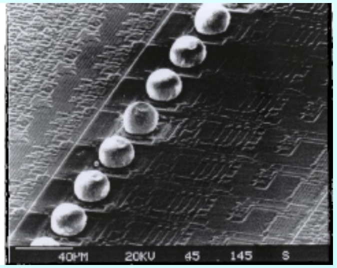
High resistive n-type silicon onto which p+ diode strips with aluminum contacts are implanted



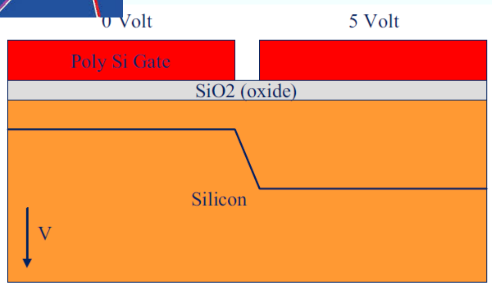


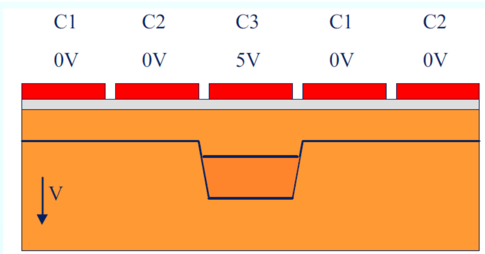
Schematics of a double sided micro-strip detector

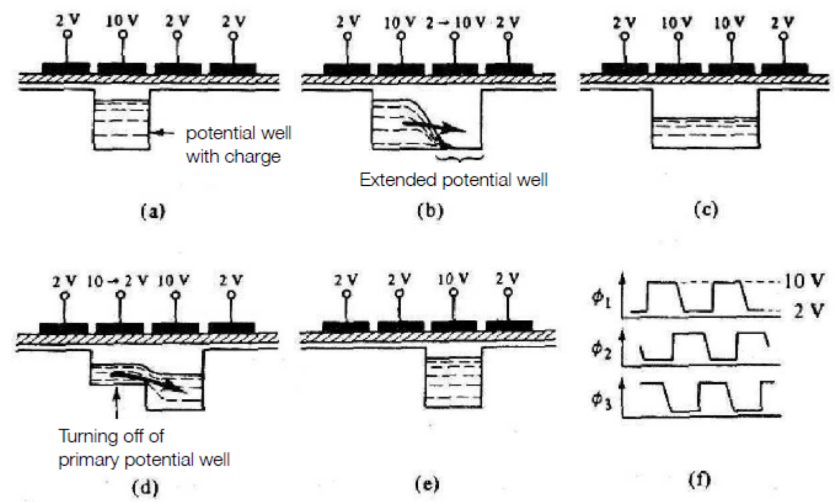




CCD





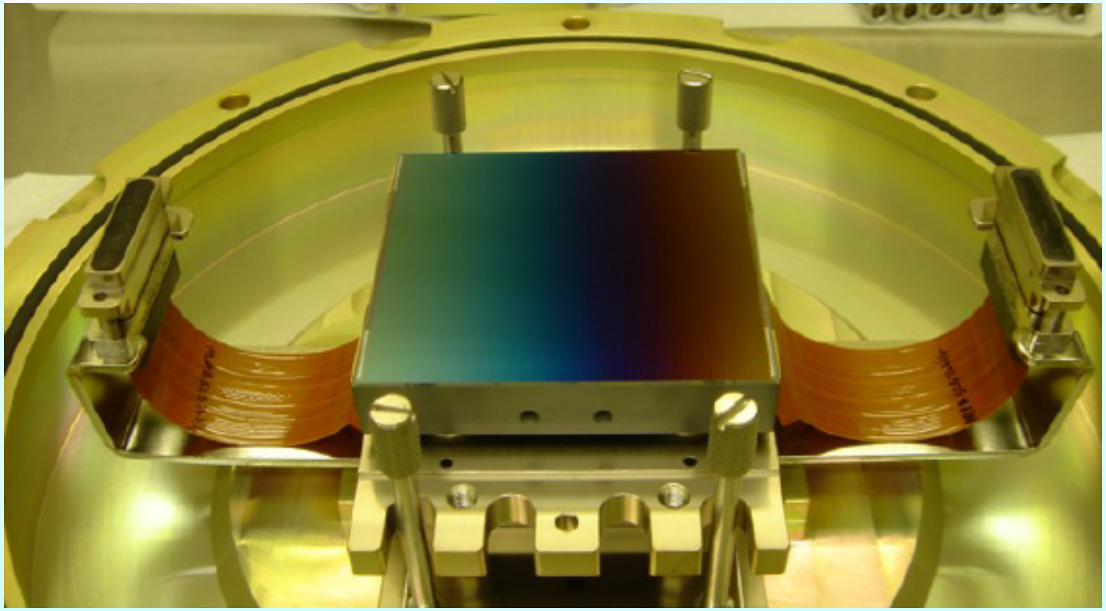


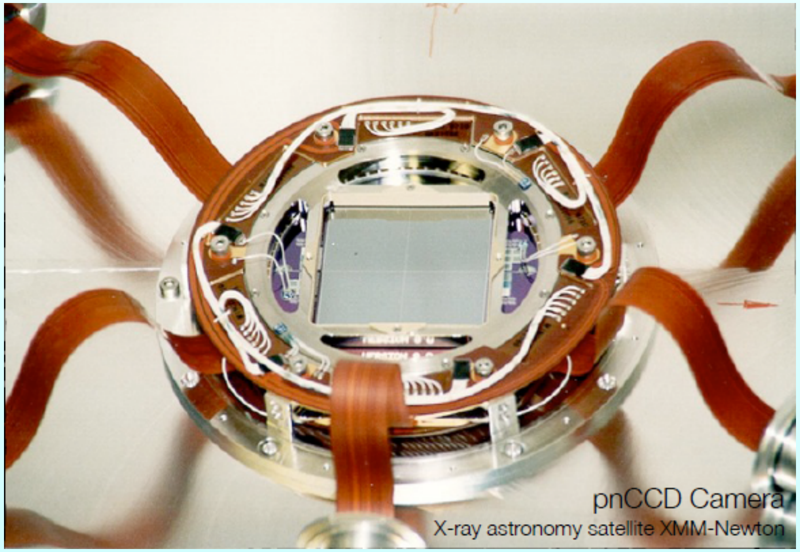
The Nobel Prize in Physics 2009

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

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

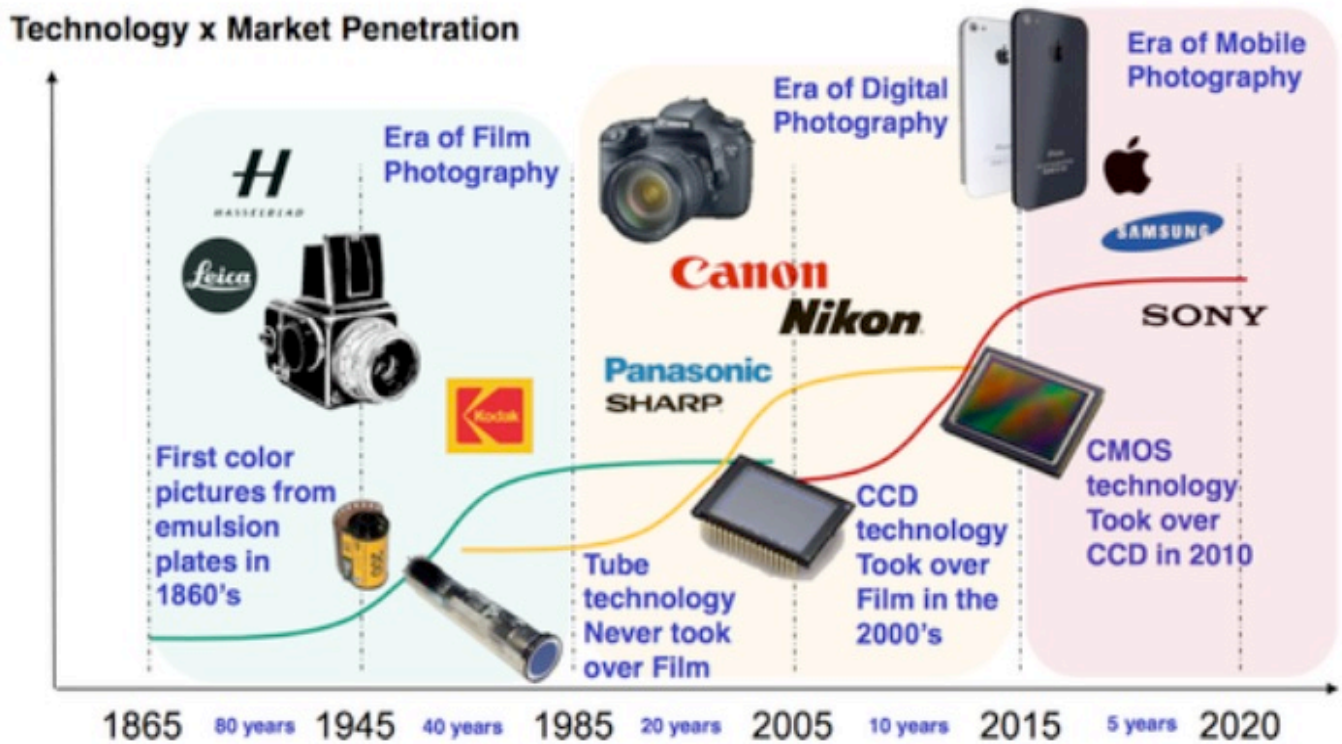
Charles K. Kao **Willard S. Boyle** **George E. Smith**





CMOS Image Pixel Sensors

- While 1980s were dominated by CCDs (camcorder market)
- The 1990s/2000s have shown an increasing demand for CMOS imaging sensors due to the camera phone market

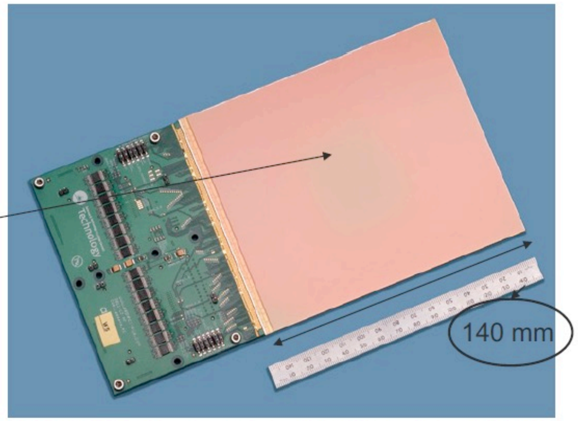


ALICE inner tracker upgrade

MAPS (Monolithic Active Pixel Sensors) for Imaging and More

Many developments in the field of CMOS imaging sensors and MAPS in general within the community!

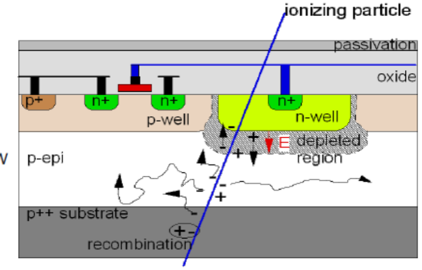
Example:
Wafers scale (8") imaging sensor developed by the RAL team (stitched)

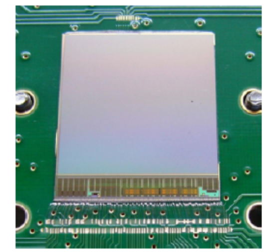


N. Guerrini, RAL, 5th school on detectors, Legnaro, April 2013

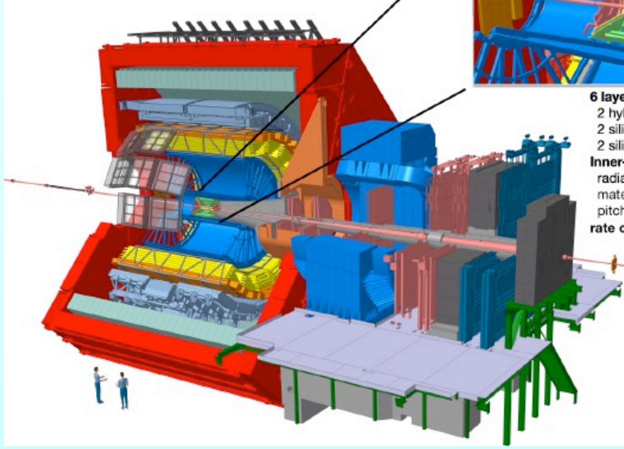
Developments lead by IPHC created a number of monolithic pixel sensors of the MIMOSA family:

- Epitaxial wafers with collection diode and few transistors per cell (size ~ 20 x 20 μm²)
- 0.35 μm CMOS technology with only one type of transistor (NMOS)
- Rolling shutter architecture (readout time O(100 μs))
- **Charge collection mostly by diffusion**
- Limited radiation tolerance (< 10^{13} n_{eq} cm^{-2})





ULTIMATE chip for STAR HFT (IPHC Strasbourg)

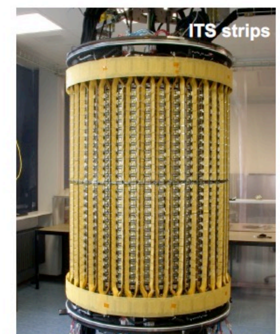


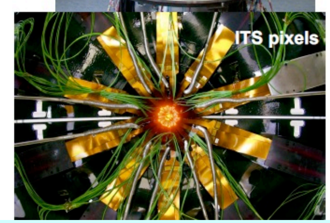
6 layers:
2 hybrid silicon pixel
2 silicon drift
2 silicon strip
Inner-most layer:
radial distance: 39 mm
material: X/X_0 = 1.14%
pitch: 50 × 425 μm²
rate capability: 1 kHz

7 layers:
all Monolithic Active Pixel Sensors
Inner-most layer:
radial distance: 23 mm
material: X/X_0 = 0.3%
pitch: O(30 × 30 μm²)
rate capability: 100 kHz (Pb-Pb)

ALICE ITS upgrade

- Complete removal of the **present inner tracking system and installation of a new tracker based on monolithic silicon pixel** sensors (~ 10m²)
- **Change of technology** compared to the present system: hybrid pixels silicon drift, silicon strips → **monolithic CMOS sensors**
- **First use of monolithic pixel detectors in an LHC experiment.**

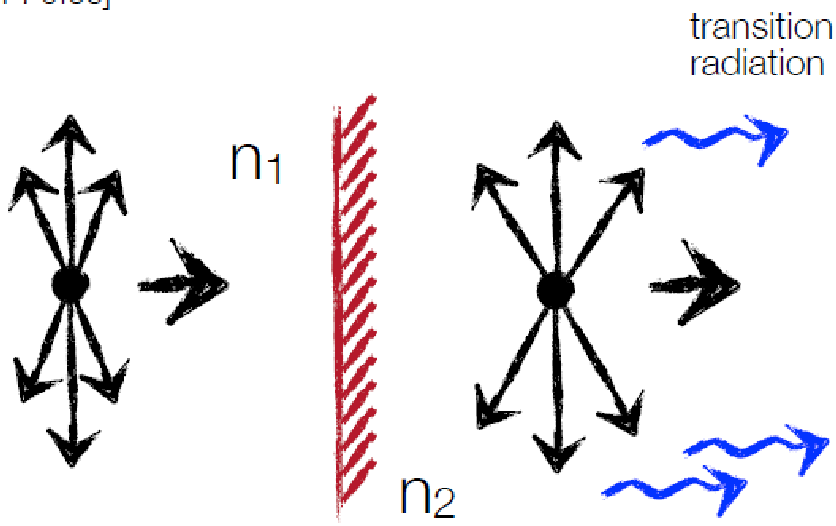




Transition radiation detectors

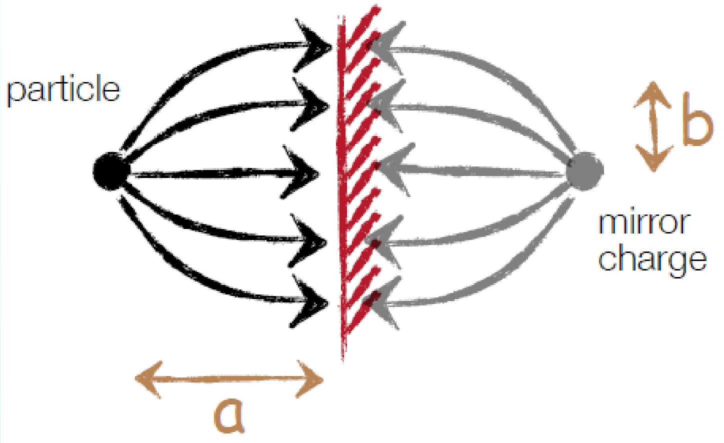
Transition radiation occurs if a relativist particle (large γ) passes the boundary between two media with different refraction indices ...

[predicted by Ginzburg and Frank 1946; experimental confirmation 70ies]



Effect can be explained by re-arrangement of electric field ...

Simple model: Electron moves towards conducting plate ...



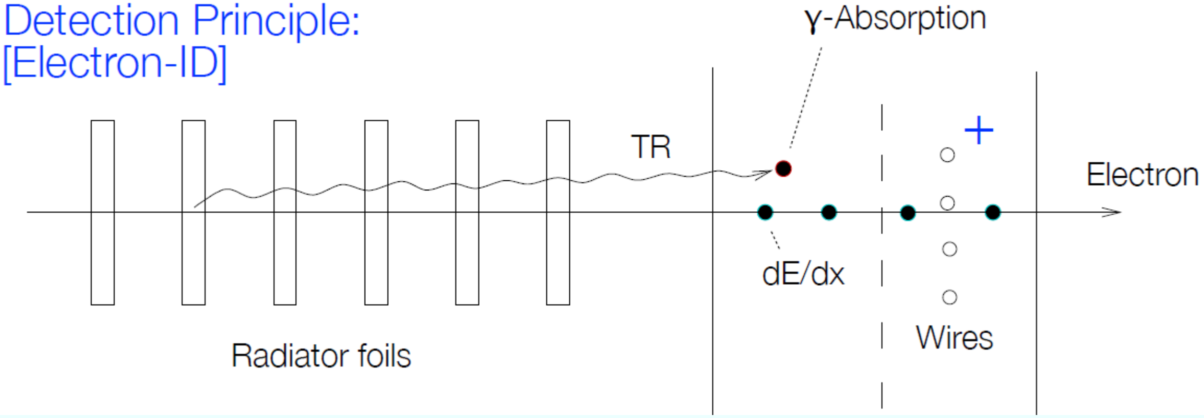
with dipole moment:

$$\vec{p} = 2e\vec{a}$$

$$\left[\text{and electric field at surface} \quad |\vec{E}_n| \propto \frac{\vec{p}}{(a^2+\rho^2)^{\frac{3}{2}}} \right]$$

ATLAS TRD

Detection Principle:
[Electron-ID]



CH$_2$: $\hbar\omega_p = 20$ eV; $\gamma = 10^3$

[Air: $\hbar\omega_p = 0.7$ eV]

D = 10 μm

[d > D: absorption dominates]

Straw Tube Tracker
with interspace filled with foam

➛ Tracking & transition radiation