Detectors for Particle Physics
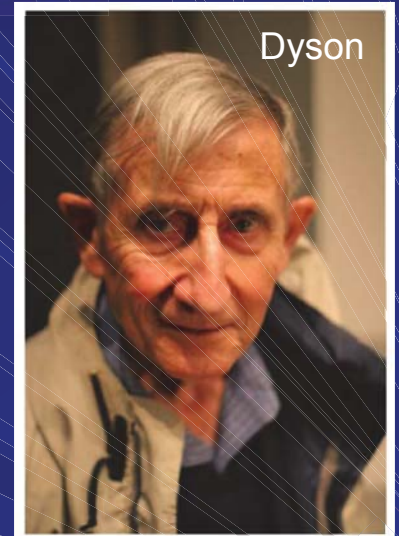
An Introduction

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INSTRUMENTATION

- **"New directions in science are launched by new tools much more often than by new concepts.**

  The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained"

  Freeman Dyson

Dyson

Turner

- **"Instrumentation for the 21st century. No one does it better than physicists when it come to innovation for instrumentation, and thus the future of all scientific fields rests on our hands."**
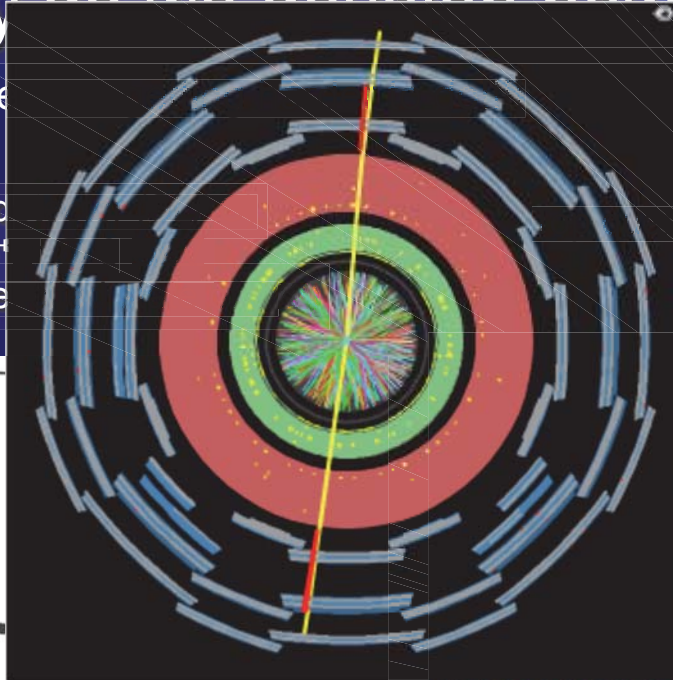
  Michael S. Turner

Why do we develop new instruments
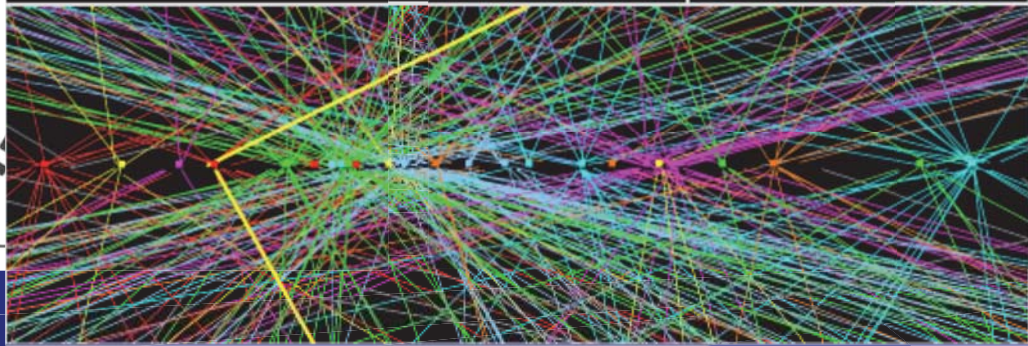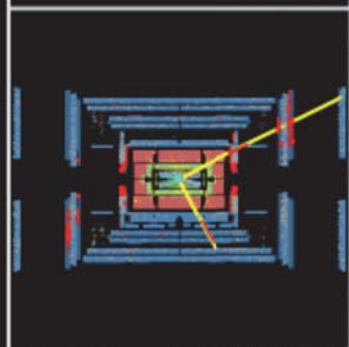
Discoverie

MARK-I d   nd D0
           e⁺
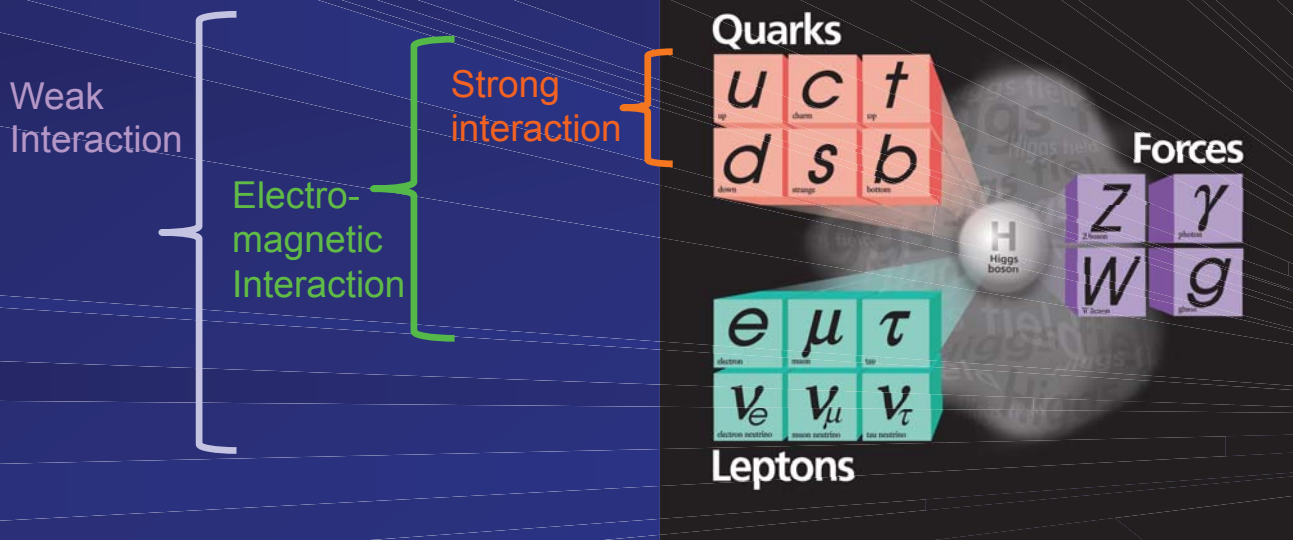   Ψ′ (e

PARTICLE DETECTION
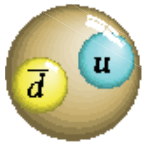
- ■ What is a particle
  - – Irreducible representation of the Poincaré group (Wigner)

- ■ What is a detector
  - – an instrument to measure the all properties (E, p, m, lifetime, quantum numbers,…) of a particle and identifying it
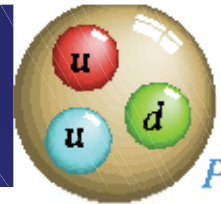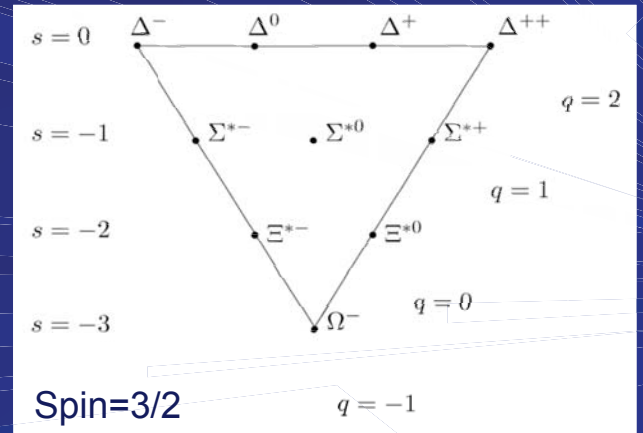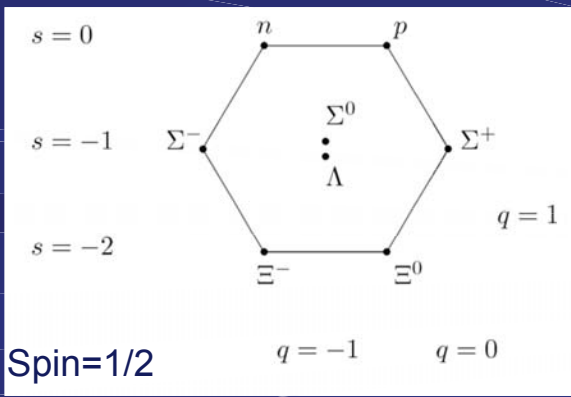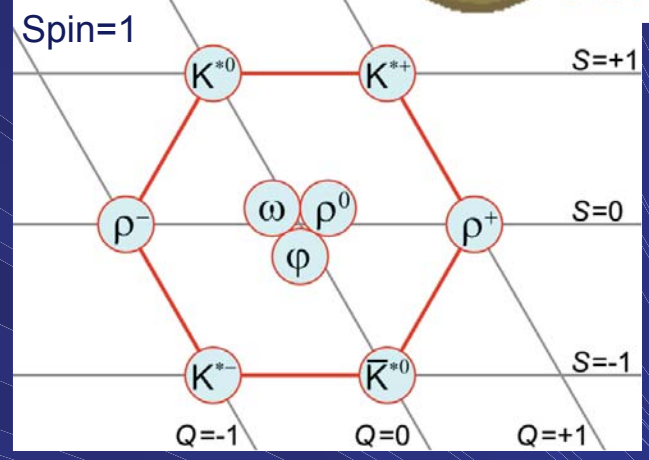
Elementary particles

Weak Interaction

Strong interaction

Electro-magnetic Interaction

Quarks
u c t
d s b

Forces
Z γ
W g

H Higgs boson

e μ τ
ν_e ν_μ ν_τ

Leptons

Mesons and Baryons

π⁺

Proton

Spin=0

K^0 K^+ $S=+1$

π^- η π^0 π^+ $S=0$

η'

K^- $\overline{K}^0$ $S=-1$

$Q=-1$ $Q=0$ $Q=+1$

Spin=1

K^{*0} K^{*+} $S=+1$

ρ^- ω ρ^0 ρ^+ $S=0$

φ

K^{*-} $\overline{K}^{*0}$ $S=-1$

$Q=-1$ $Q=0$ $Q=+1$

$s=0$ n p

$s=-1$ Σ^- Σ^0 Σ^+

Λ

$s=-2$ Ξ^- Ξ^0 $q=1$

$q=-1$ $q=0$

Spin=1/2

$s=0$ Δ^- Δ^0 Δ^+ Δ^{++}

$q=2$

$s=-1$ Σ^{*-} Σ^{*0} Σ^{*+}

$q=1$

$s=-2$ Ξ^{*-} Ξ^{*0}

$q=0$

$s=-3$ Ω^-

Spin=3/2

$q=-1$
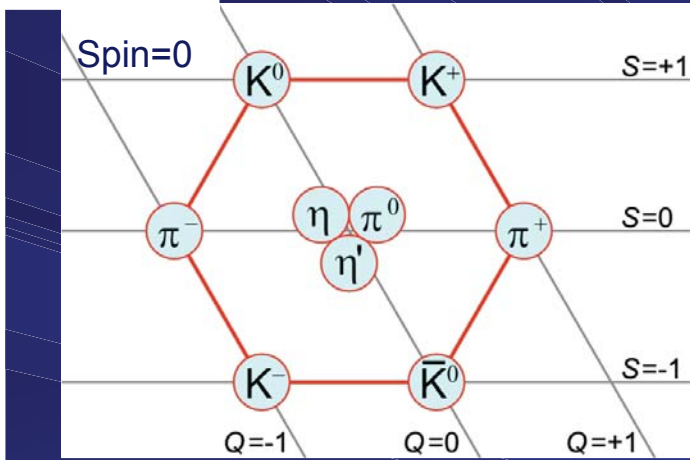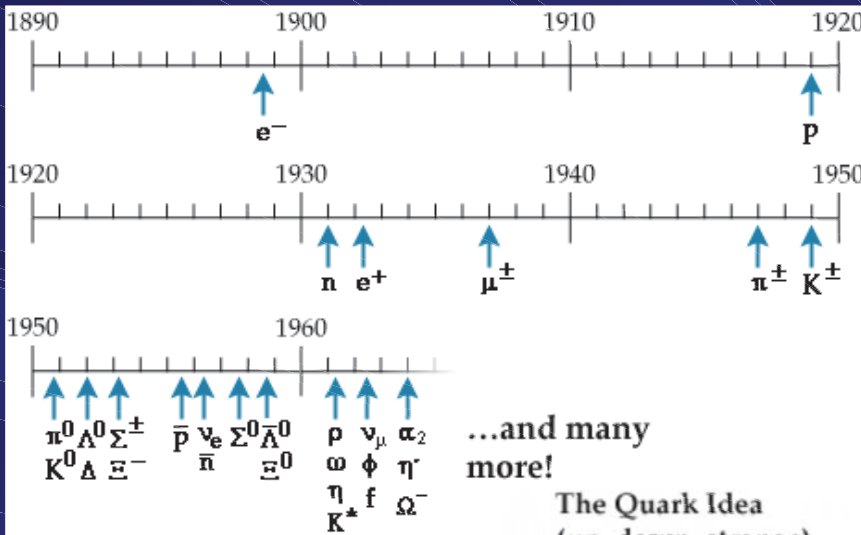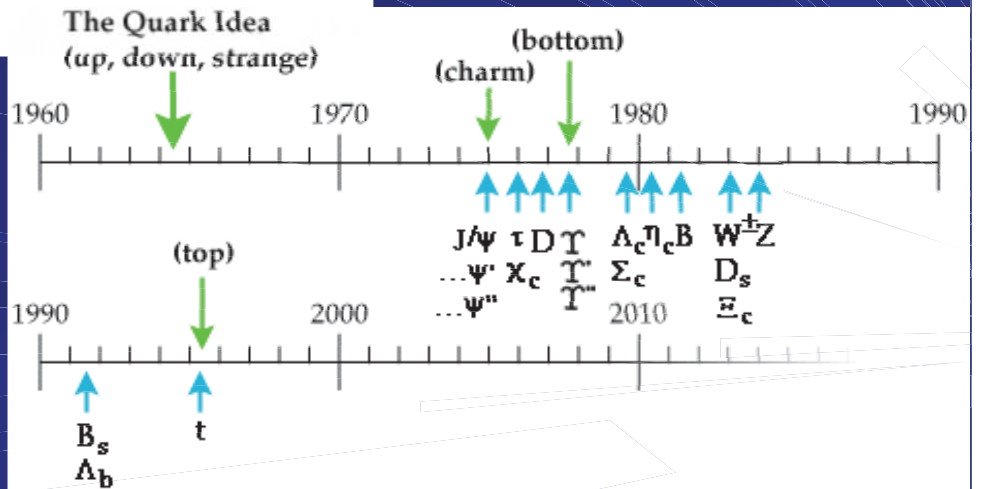
Particle Physics Timeline

Today > 200 particles listed in PDG:
- 27 have $c\tau > 1$ μm
  - they can be seen as tracks in a detectors
- 13 have $c\tau < 500$ μm
  - displaced vertices

NOBEL PRIZES FOR INSTRUMENTATION

http://www.lhc-closer.es/php/index.php?i=1&s=9&p=2&e=0

1927: C.T.R. Wilson, Cloud Chamber

1939: E. O. Lawrence, Cyclotron

1948: P.M.S. Blacket, Cloud Chamber
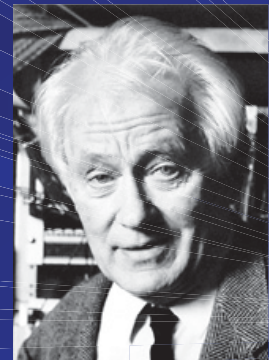
1950: C. Powell, Photographic Method

1954: Walter Bothe, Coincidence method

1960: Donald Glaser, Bubble Chamber

1968: L. Alvarez, Hydrogen Bubble Chamber

1992: Georges Charpak, Multi Wire Proportional Chamber

7

Particle discoveries

By 1959: 20 particles

e^- : fluorescent screen

n : ionization chamber

7 Cloud Chamber:

e^+

μ^+, μ^-

K^0

Λ^0

Ξ^-

Σ^-

6 Nuclear Emulsion:

π^+, π^-

anti-Λ^0

Σ^+

K^+, K^-

2 Bubble Chamber:

Ξ^0

Σ^0

3 with Electronic techniques:

anti-n

anti-p

π^0

Imaging Detectors: The Cloud Chamber

- The **cloud chamber** contains a supersaturated vapor of water or alcohol.
  - A charged particle interacting with the mixture, creates ions.
  - The ions act as condensation nuclei around which a mist will form
- High energy alpha and beta particles leave a track due to the ions they produce along their path
- If a magnetic field is applied positively and negatively charged particles will curve in opposite directions.

The positron

- Positron discovery, Carl Andersen 1933 [Nobel price 1936]

- Magnetic field 15000 Gauss, chamber diameter 15cm.
- A 63 MeV positron passes through a 6mm lead leaving the plate with energy 23MeV.
- The ionization of this particle, and its behavior in passing through the foil was the same as those of an electron but with positive charge

Cloud chamber in magnetic field

Positron

6 mm lead plate

Positron

tron.
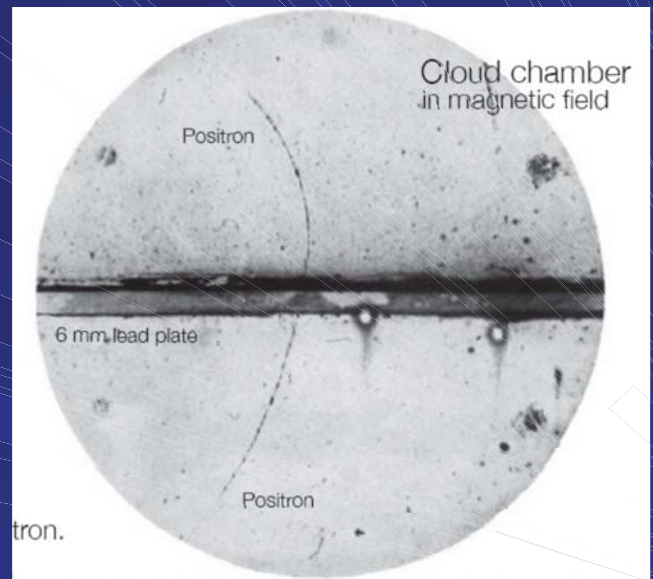
The muon

- Muons were discovered by Carl D. Anderson and Seth Neddermeyer at Caltech in 1936 with a cloud chamber while studying cosmic radiation
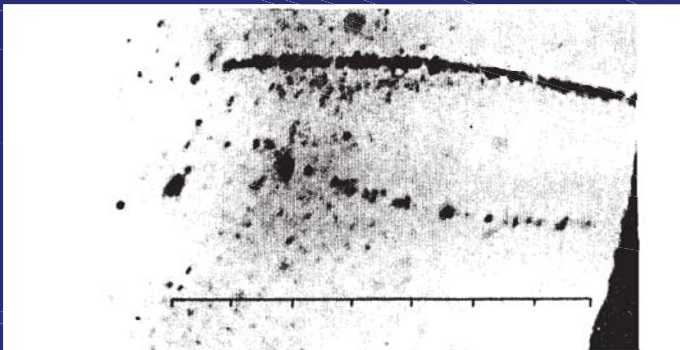

"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

Kunze, P., Z. Phys. 83, (1933) 1
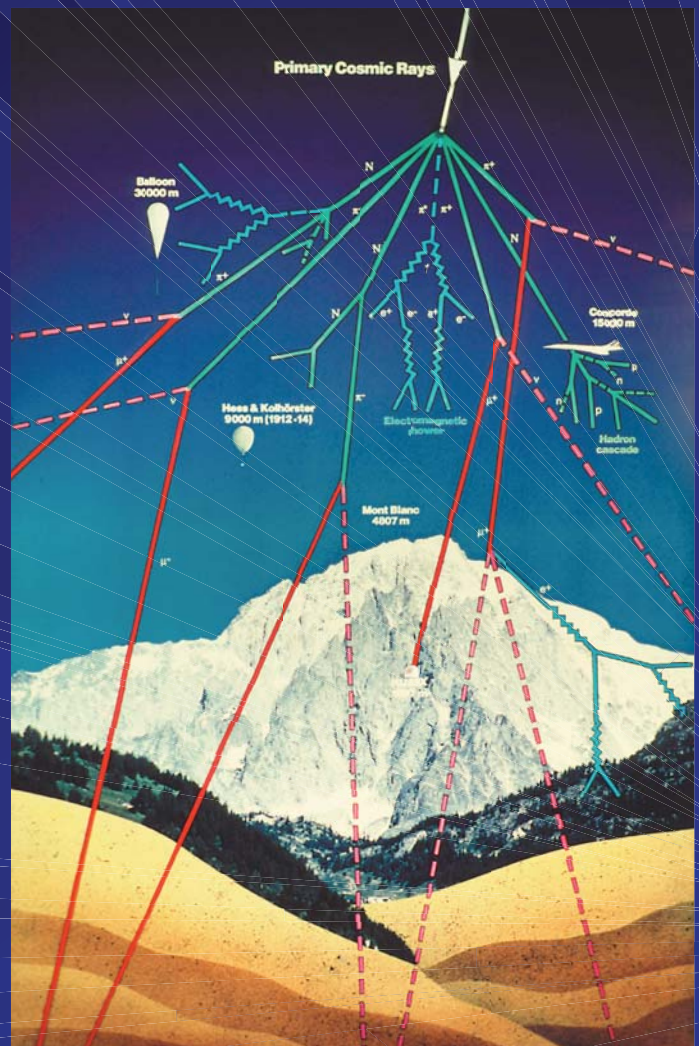
The muon and relativity

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = \frac{v}{c}$$
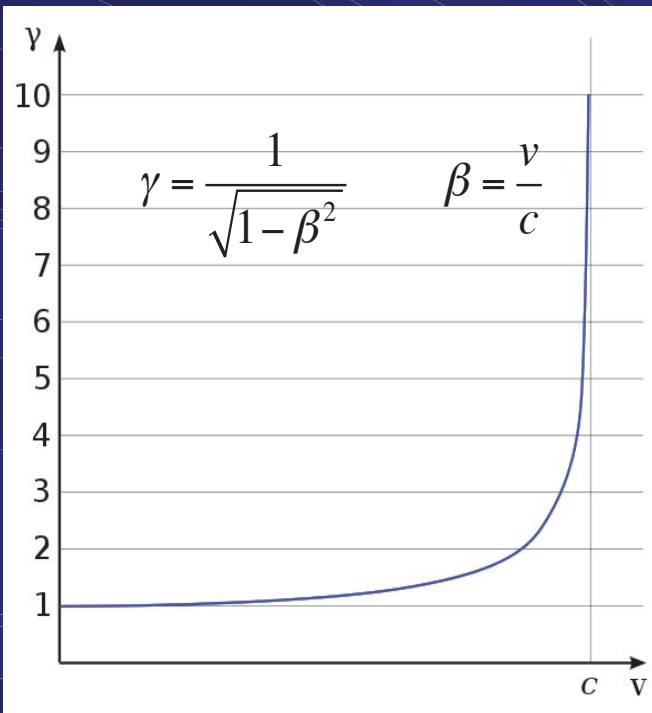
- Muons produced in the upper atmosphere ≈10 km
- Lifetime τ_μ=2.2 x 10^{-6} s
  - s = $v\tau$ ≈ 600 m
  - Therefore no muon should reach Hearth!
- But we see them
  - Relativity γ=E/$m_\mu c^2$
  - s = $v\gamma\tau$ = 12.5 km
- Pions: τ_π= 2.6X10^{-8} s,
  - s = $v\gamma\tau$ = 115 m

The Pion

- The pion was discovered in Nuclear emulsion techniques, Powell 1947; Nobel Prize 1950

- Discovered in 1947 in nuclear emulsions exposed to cosmic rays, and they showed that it decay to a muon and an unseen partner.
- The constant range of the decay muon from the pion decay indicate that this is a two body decay
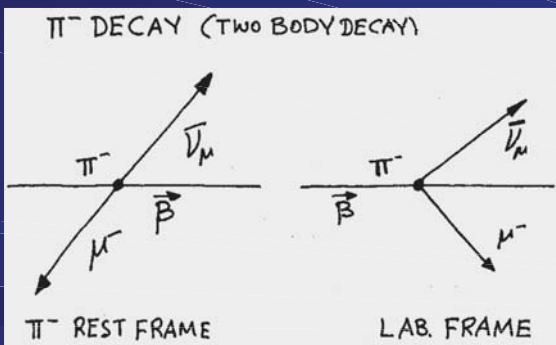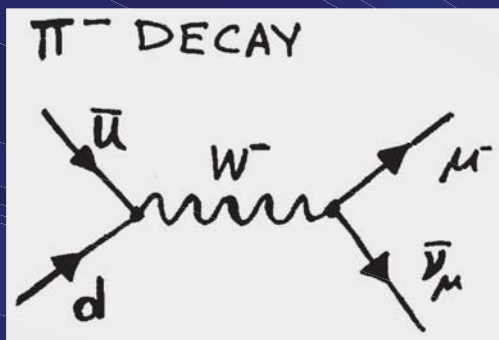
$$\pi^- \rightarrow \mu^- \overline{\nu}_\mu$$
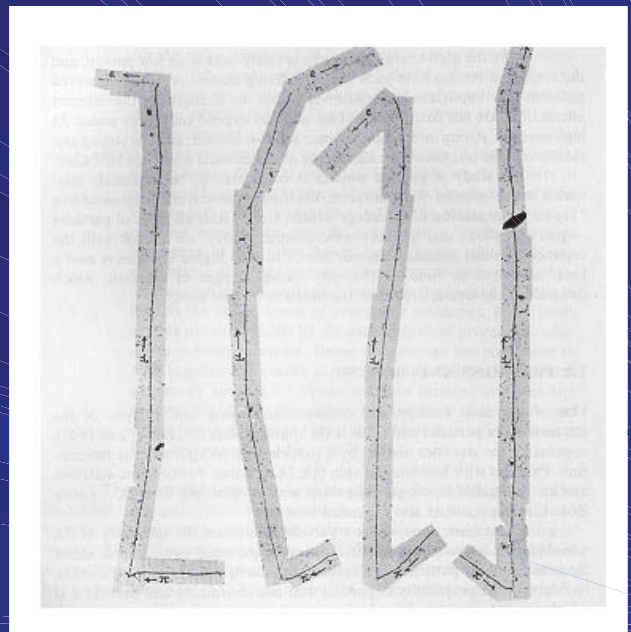
$$\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$$

The kinematics of two body decays

π⁻ DECAY

π⁻ DECAY (TWO BODY DECAY)

π⁻ REST FRAME   LAB. FRAME

- Relativistic Kinematics

$$P_\pi = \left(m_\pi, 0\right)^2 \qquad P_\mu = \left(E_\mu, \vec{p}_\mu\right) \qquad P_\nu = \left(E_\nu, \vec{p}_\nu\right)$$

$$P_\pi = P_\mu + P_\nu$$

$$\left(P_\pi - P_\nu\right)^2 = \left(P_\mu\right)^2 \qquad\qquad m_\nu \approx 0$$

$$P_\pi^2 + P_\nu^2 - P_\pi \cdot P_\nu = m_\mu^2 \qquad\qquad m_\pi \approx 140\, MeV$$
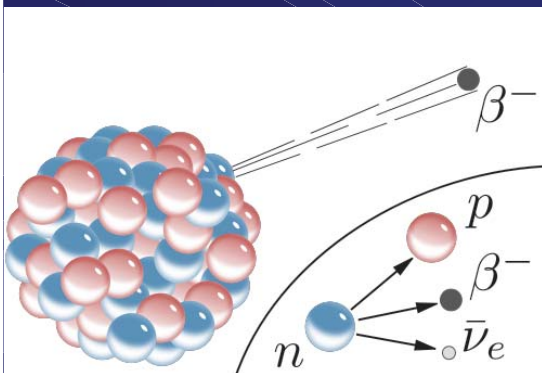
$$m_\pi^2 + 0 - 2m_\pi \cdot E_\nu = m_\mu^2 \qquad\qquad m_\mu \approx 106\, MeV$$

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} \approx 30\, MeV$$

$$\left|\vec{p}_\mu\right| \approx 30\, MeV \qquad\qquad E = \sqrt{\vec{p}_\mu^2 + m_\mu^2} = 110\, MeV$$

In the pion rest frame, the muon has
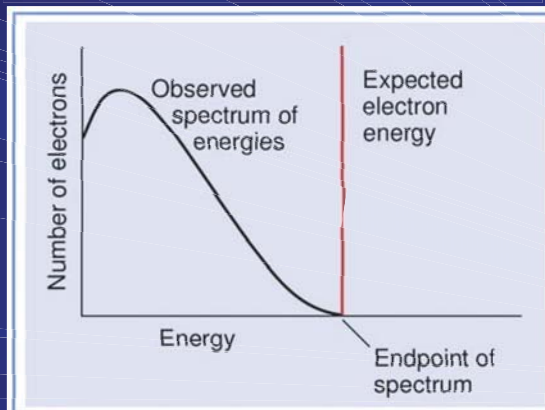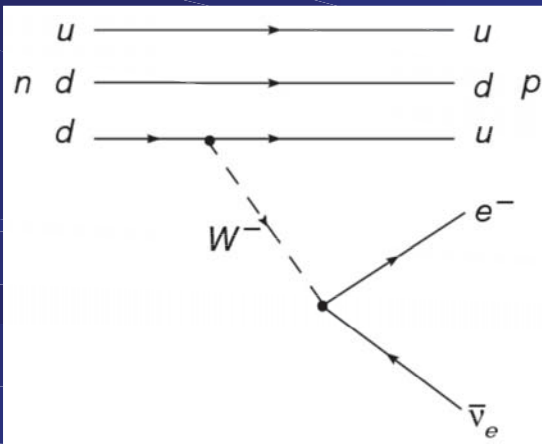KE = 110 MeV−106 MeV = 4 MeV

3-body kinematics: the neutrino

- Neutrinos do not carry any charge → take part in the electroweak and gravitational interaction → neutrinos hardly interact with matter
- Existence of neutrinos was inferred form studies of the lepton spectrum in beta decays.


"I have done a terrible thing. I invented a particle that cannot be detected."

W. Pauli

Single beta decay energy spectrum. The observed spectrum is continuous and not at a constant energy as was initially expected. [D. Stewart]

Imaging techniques: Nuclear Emulsions

- A nuclear emulsion plate is a photographic plate with a thick emulsion layer and uniform grain size.
  - It records the tracks of charged particles passing through
  - It produce a cumulative record
  - The plates must be developed before the tracks can be observed.
- In 1937, Marietta Blau and Hertha Wambacher discovered nuclear *disintegration stars* due to spallation in nuclear emulsions exposed to cosmic radiation at a height of 2,300 meters above sea level.

'EXPLOSIVE' DISINTEGRATION OF A NUCLEUS
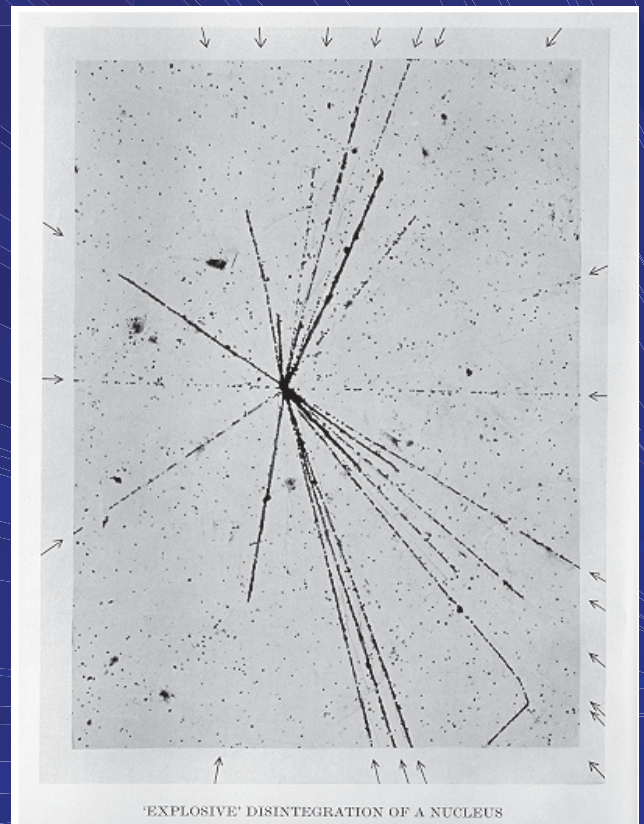
The discovery of the Kaon

- First evidence of the decay of the Kaon into 3 Pions was found in 1949 in Nuclear emulsion
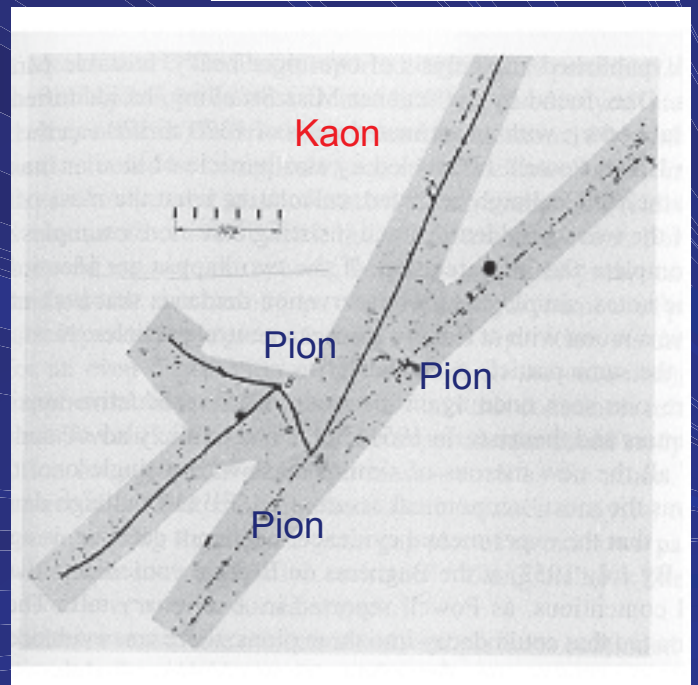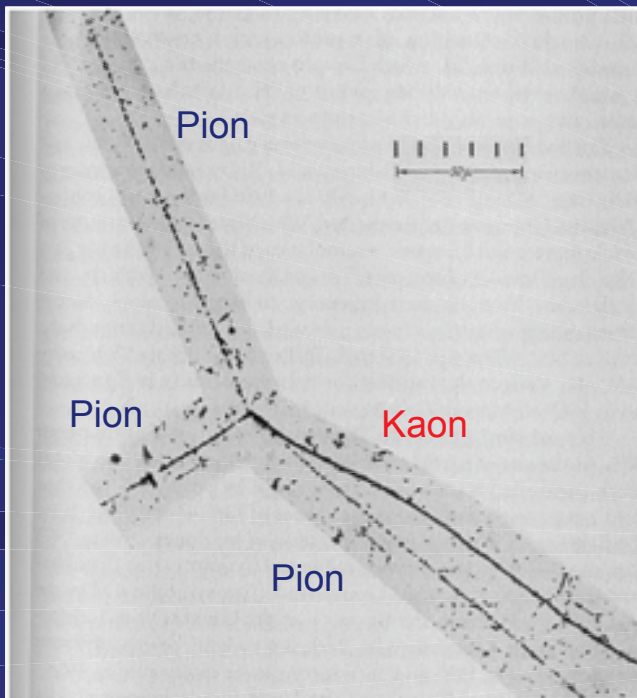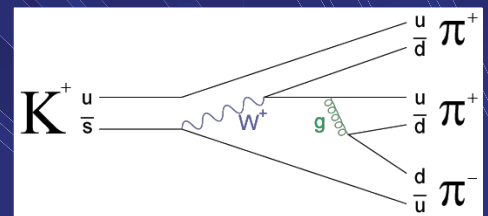
Imaging Detectors: the Bubble chamber

- A **bubble chamber** is a vessel filled with a superheated transparent liquid (Hydrogen at T=30K). A charge particle initiate boiling.

- The size of the chambers grew quickly:
    - 1954:   2.5'' (6.4cm)
    - 1954:   4''   (10cm)
    - 1956:   10'' (25cm)
    - 1959:   72'' (183cm)
    - 1963:   80'' (203cm)
    - 1973:   370cm

- Some disadvantages:
    - It cannot be triggered
    - Low rate capability
    - The photographic readout: for data analysis one had to look through millions of photos
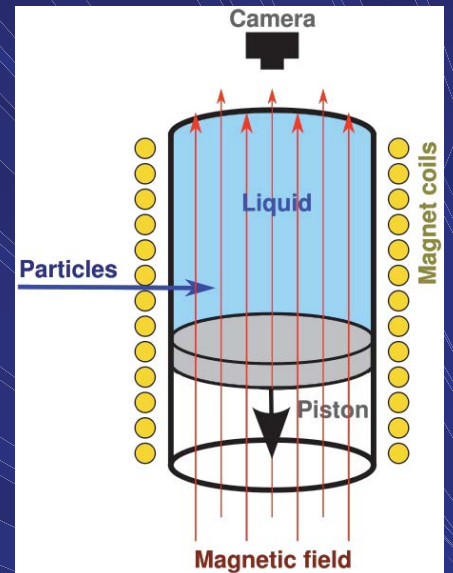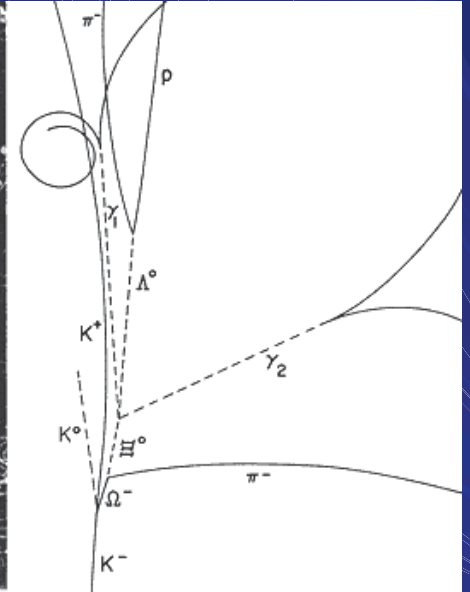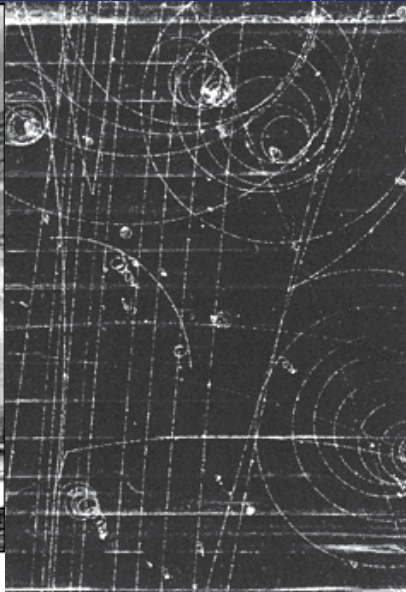
- Urban history: Glaser was inspired by the bubbles in a glass of beer

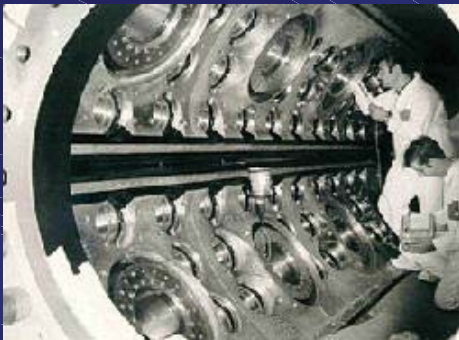- In a 2006 talk he did experiments using beer to fill early prototypes.

Discovery of Omega
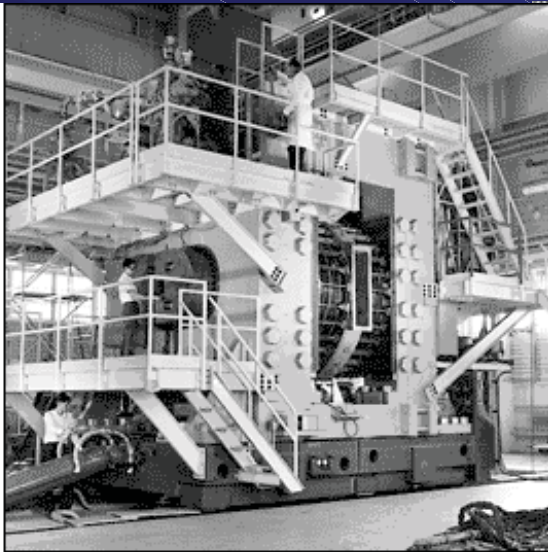
The 80-inch Bubble Chamber
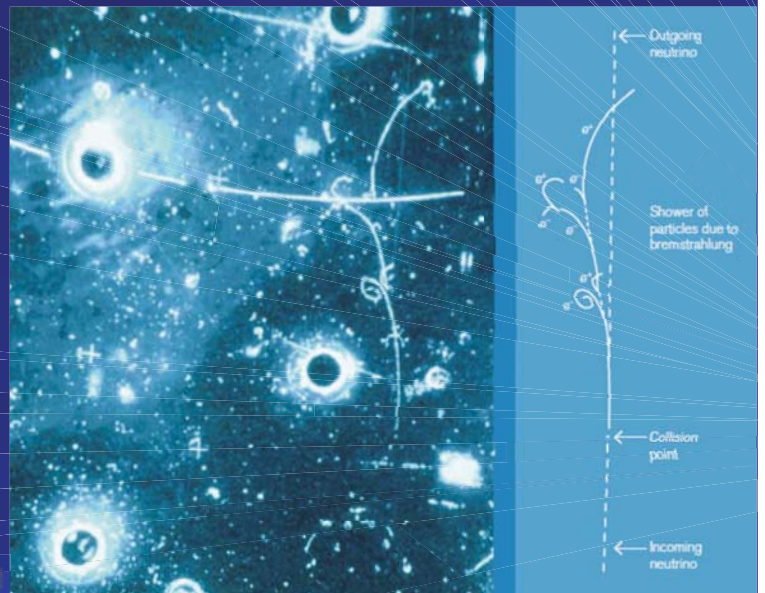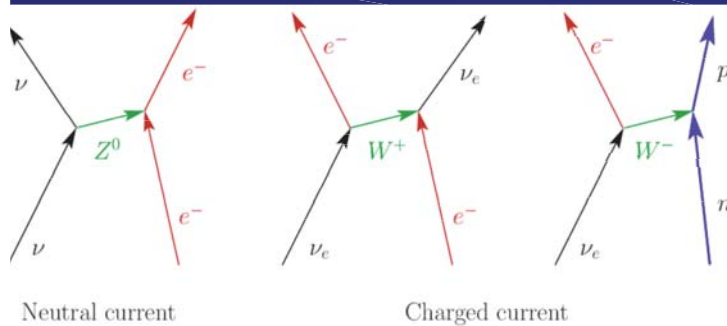
BNL, First Pictures 1963, 0.03s cycle

$\Omega^- = sss$ Confirmation of the quark model

The discovery of neutral currents

- Gargamelle, a very large heavy-liquid (freon) chamber constructed at Ecole Polytechnique in Paris, came to CERN in 1970.
- 2 m in diameter, 4 m long and filled with Freon at 20 atm, in 2 T B field
- Gargamelle in 1973 was the tool that permitted the discovery of neutral currents.

Can be seen outside the Microcosm Exhibition

Neutral current

Charged current

D. Bortoletto   Lecture 1

Outgoing neutrino

Shower of particles due to bremsstrahlung

Collision point

Incoming neutrino

Electronics detectors

■ In the 70ies the logic (electronic) detectors took over
  – Geiger counters
  – Scintillator + photomultipliers
  – Spark counters

■ The particle is not "seen" but its nature and existence "deduced" via a logic experiment (coincidences, triggers, detection of decay products …)
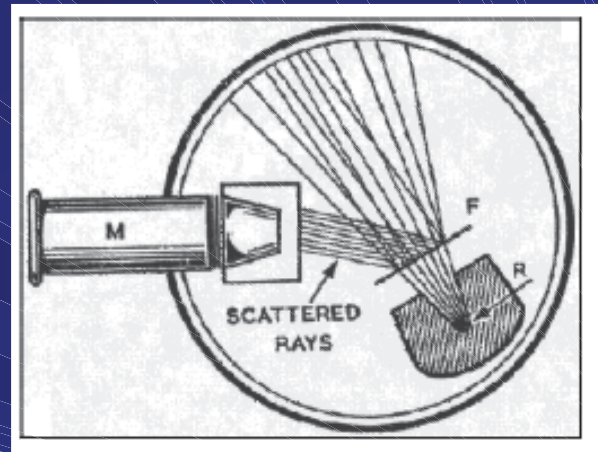

Scintillating Screen:
Rutherford Experiment 1911, Zinc Sulfide screen was used as detector. If an alpha particle hits the screen, a flash can be seen through the microscope.

Spark Chamber

Muon or Electron

A Plastic Scintillator

C

B Pla... Gas...

Plastic Scintillator **A**

HV Pulser

Coincidence Circuit

-10 kV

The Spark Chamber was developed in the early 60ies.
Schwartz, Steinberger and Lederman used it in discovery of the muon neutrino
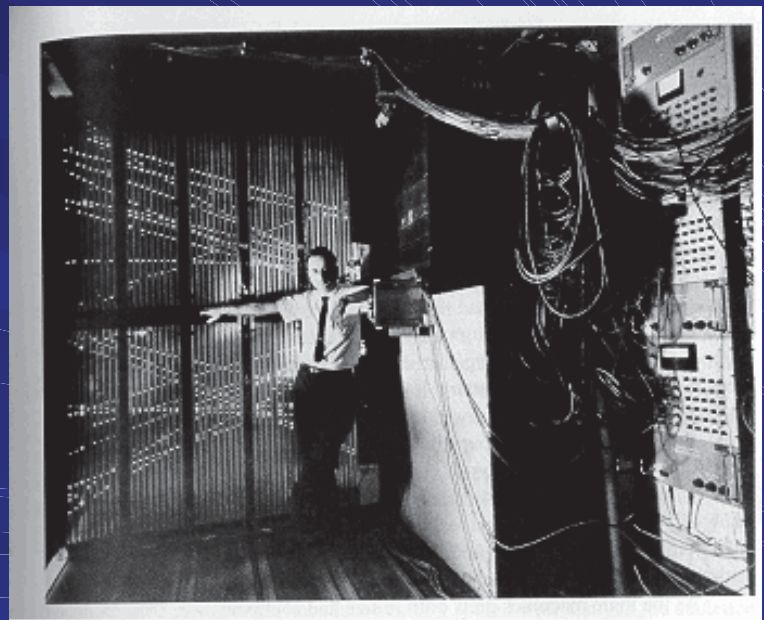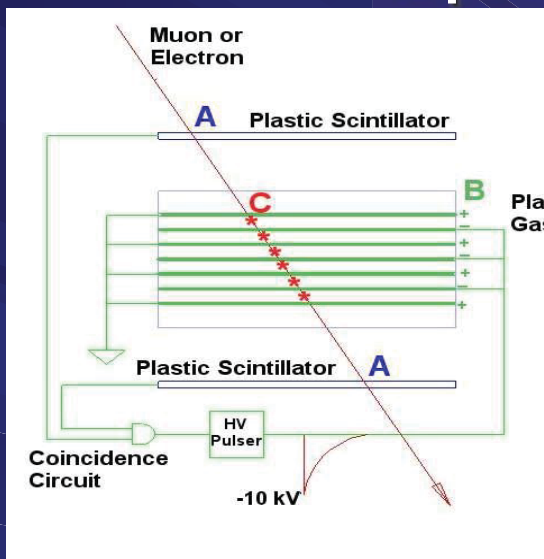
- A charged particle traverses the detector and leaves an ionization trail.
- The scintillators trigger an HV pulse between the metal plates and sparks form in the place where the ionization took place.
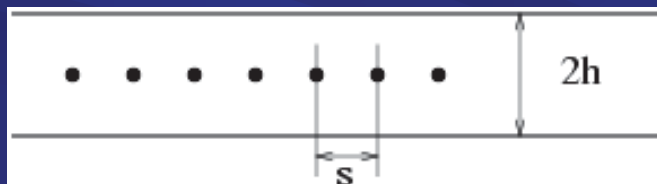
Multi-wire proportional chambers

Tube, Geiger- Müller, 1928
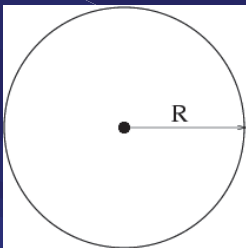
Multi Wire Geometry, in H. Friedmann 1949
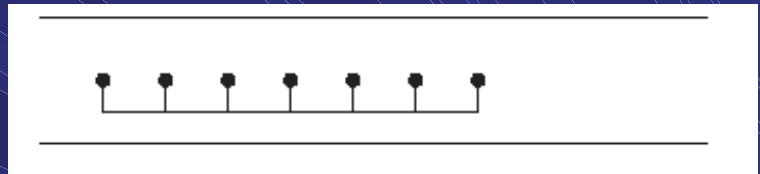
*G. Charpak 1968, Multi Wire Proportional Chamber,
readout of individual wires and proportional mode working point.*

A charged particle traversing the detector l eaves a trail of electrons and ions. The wires are on positive HV. The electrons drift to the wires in the electric field and start to form an avalanche in the high electric field close to the wire. This induces a signal on the wire which can be read out by an amplifier.

The merge of electronic Images

Discover of the W and Z (1983)
Rubbia & Van der Meer, Nobel Prize 1984
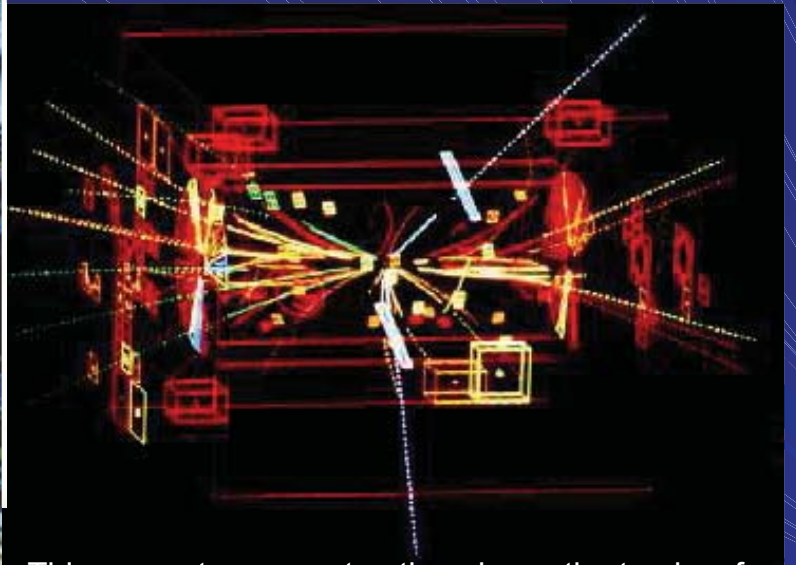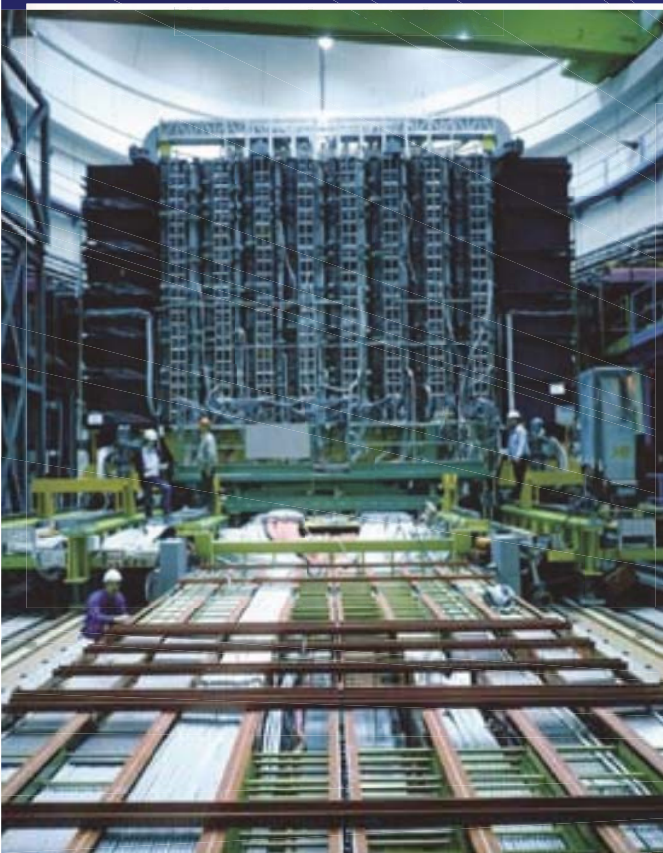
This computer reconstruction shows the tracks of charged particles from the proton-antiproton collision. The two white tracks reveal the Z's decay. They are the tracks of a high-energy electron and positron.

Particle Detection and stable particles

- **The most frequent** "stable" particles ($c\tau > 500$ **μ**m) are: Electrons (e), muons (μ), photons (γ), pions (π), kaons (K), protons (p) and neutrons (n)

- A particle detector must be able to identify and measure at least the energy & momentum of these 8 particles.
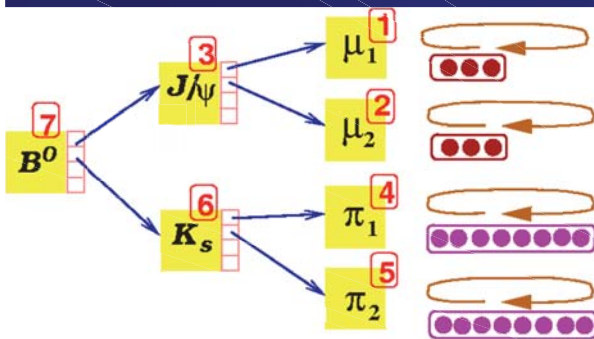
EM Interactions: Electrons (m_e=0.5 MeV), muons (m_μ=105.7 MeV), photons (m_γ=0)

EM & Strong interaction: pions (m_π=139.6 MeV), Charged kaons (m_K+=493.7 MeV), protons m(p=938.3 MeV)

Strong interaction: Neutral K^0 (m_K = 497.7 MeV) and n (m_n=939.6 MeV)

The difference in Mass, Charge, Interaction is the key to particle identification

Unstable Particles

$$m^2_{inv,x} = \left(E_1 + E_2\right)^2 - \left(p_1 + p_2\right)^2$$

$$E_x = E_1 + E_2$$

$$\vec{p}_x = \vec{p}_1 + \vec{p}_2$$

$$J/\psi \rightarrow \mu^+ \mu^-$$

CDF Run 2 Preliminary, 6 pb^{-1}, 27 Feb 2002

J/Ψ: Events: 60492, Width: 21.6± 0.1 MeV/c^2

Ψ(2s): Events: 2386, Width: 25 ±4 MeV/c^2

Mass ($\mu^+\mu^-$), GeV/c^2

(a)

$B \rightarrow J/\psi K^0_s$

J/ψ K$_S$ mass (GeV/c^2)

26
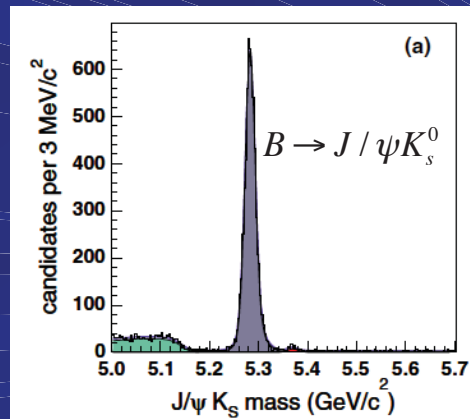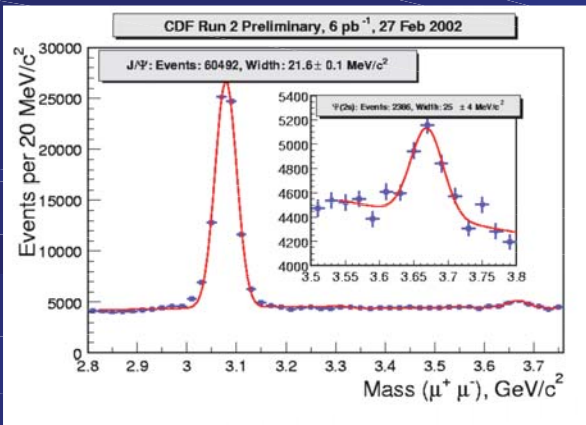
Quark confinement and Jets

Particle Identification

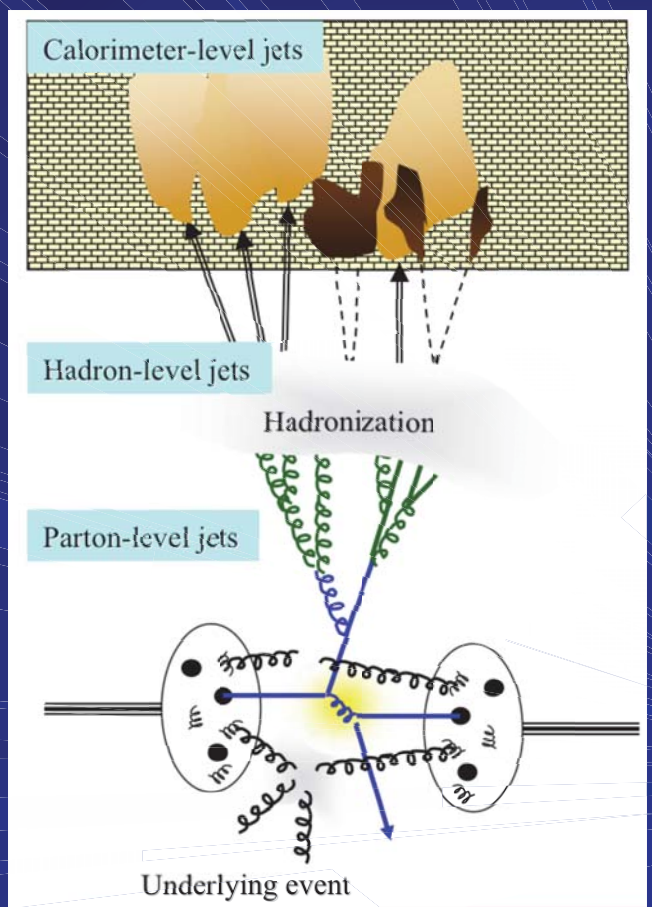| Tracking chamber	Electromagnetic calorimeter	Hadron calorimeter	Muon chamber
photons			
e±			
muons			
π±, p			
n			

Innermost Layer... →→→ ...Outermost Layer

B field
Low ρ · High ρ · High ρ · Tracking
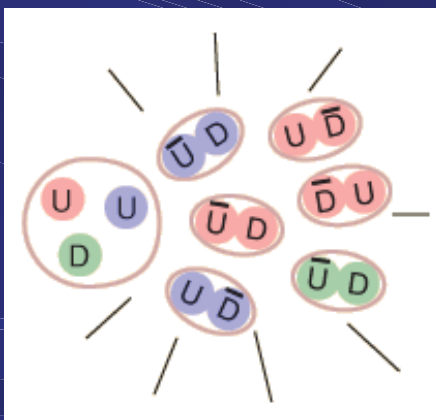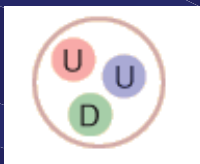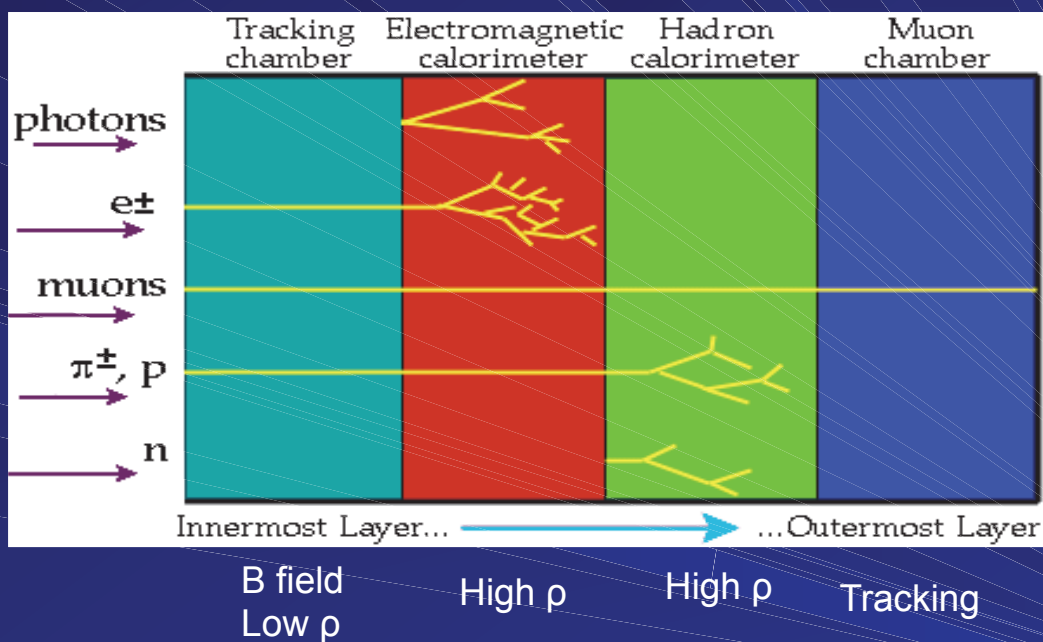
- Electrons ionize and show bremsstrahlung due to the small mass
- Photons do no ionize but undergo pair production in high Z material
- Charge hadrons ionize and produce hadron shower in dense material
- Neutral hadron do not ionize but produce hadron shower in dense material

The advent of silicon

- The measurement of the lifetime of c and b quark

Event:7050764 Run:162820 EventType:DATA | Unpress:0,1,33,34,35,4,36,7,8,9,10,42,11,44,13,45,14,15,17,49,20,21,23,24

b-jet

Et = 43.43 GeV

Missing Et
Et=85.7 phi=4.5

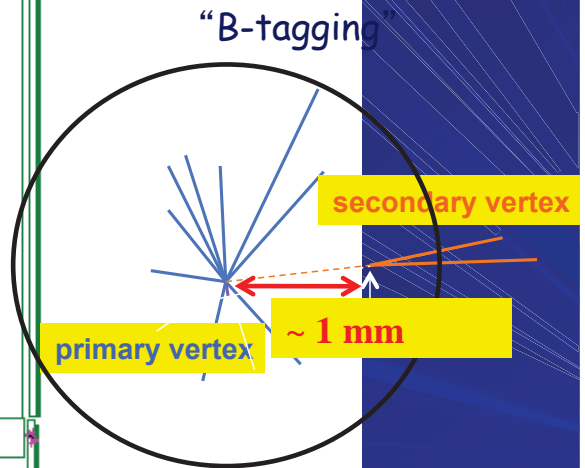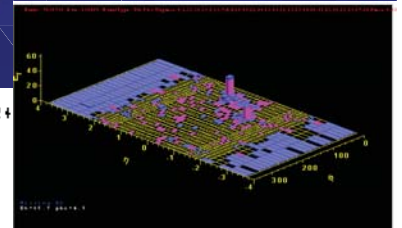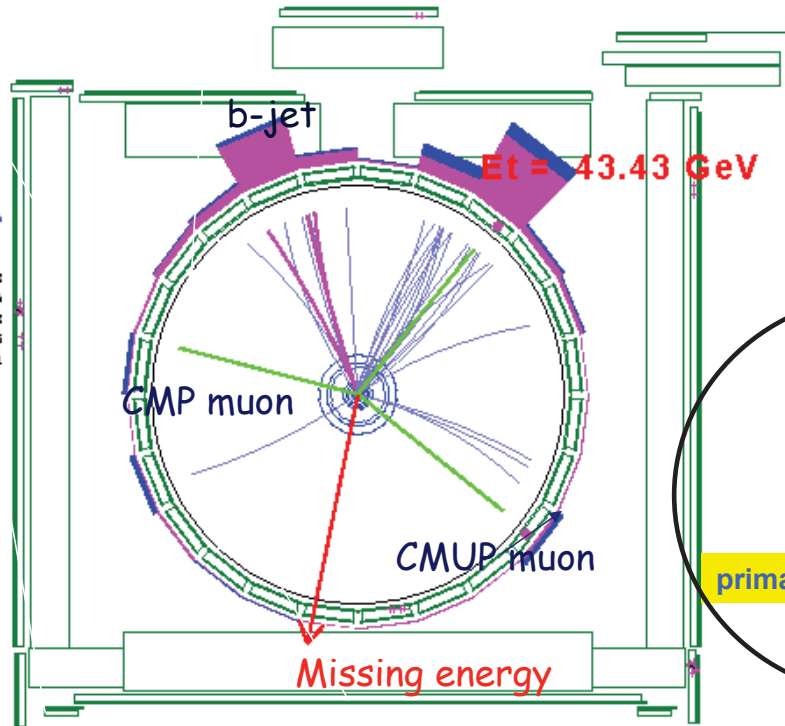List of tracks
Id   pt   phi   eta

Cdf tracks: first 5
468   -33.5   -0.7   -0.3
439   25.9   2.9   -0.4
499   21.2   1.6   -0.3
469   -16.4   0.9   0.5
500   8.7   0.7   -0.1

To select track type:
SelectCdftrack(Id)

Svt tracks: first 5
  0   180.8   1.2
  2   45.2   3.5
  1   -15.1   3.2
  5   9.5   2.4
  3   1.4   4.6

To select track type
SelectSvttrack(Id)

CMP muon

CMUP muon

Missing energy

"B-tagging"

secondary vertex

~ 1 mm

primary vertex

Tracking and vertex detectors were crucial to the discovery of top

$$p\bar{p} \rightarrow t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow \ell^+ \nu \ell^- \bar{\nu}$$

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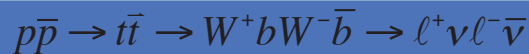
Detector Optimization

- Which kind of "particle" we have to detect?
- What is the required dimension of the detector?
- Which "property" of the particle we have to know?
  - Position
  - Lifetime
  - Quantum numbers
  - Energy
  - Charge
- What is the maximum count rate?
- What is the "time distribution" of the events?
- What is the required resolution ?
- What is the dead time?

Measurement Resolution

- Resolution generally defined as 1 standard deviation (1σ) for a Gaussian distribution, or the FWHM (Δz)
  - For a Gaussian $\sigma = \text{FWHM}/2.36$
- If the measurement is dominated by Poisson fluctuations

E resolution= σ/E
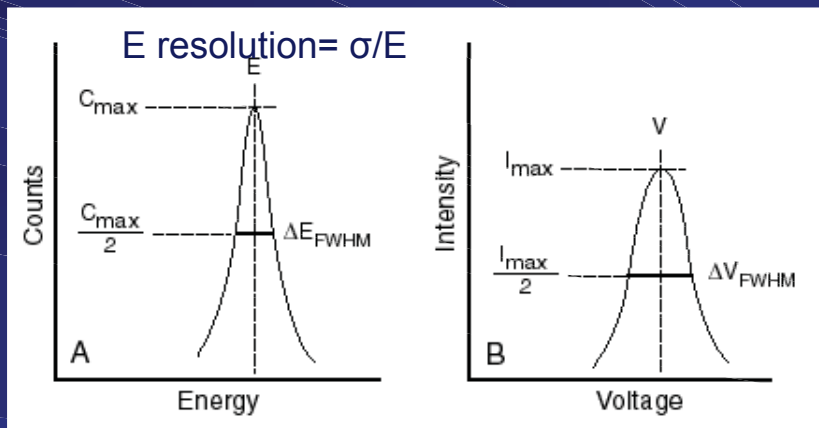
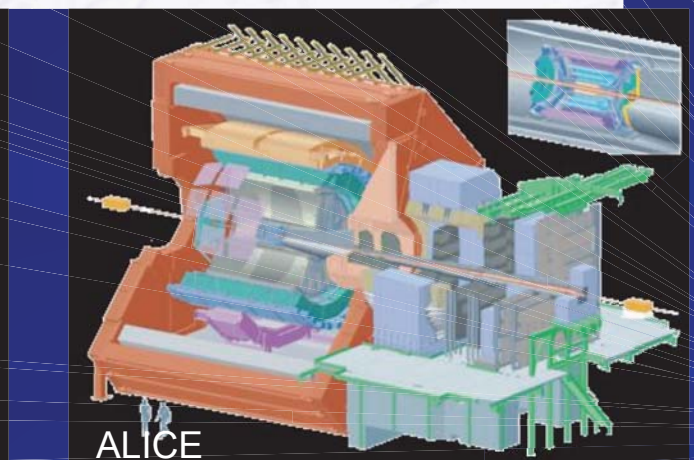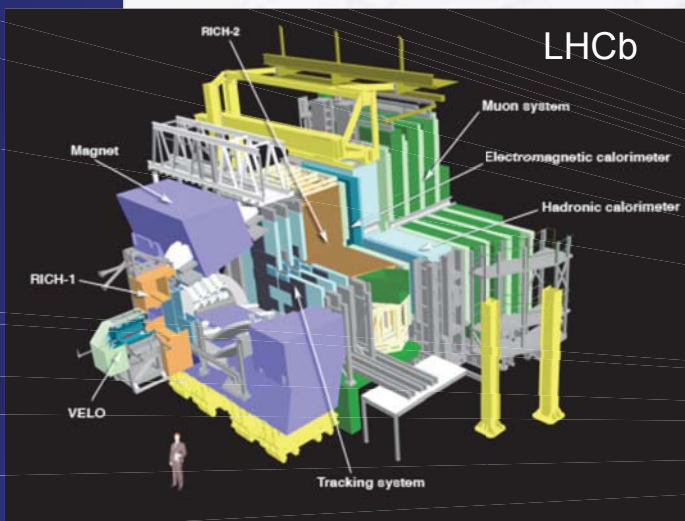$$\frac{\sigma_z}{\langle z \rangle} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$
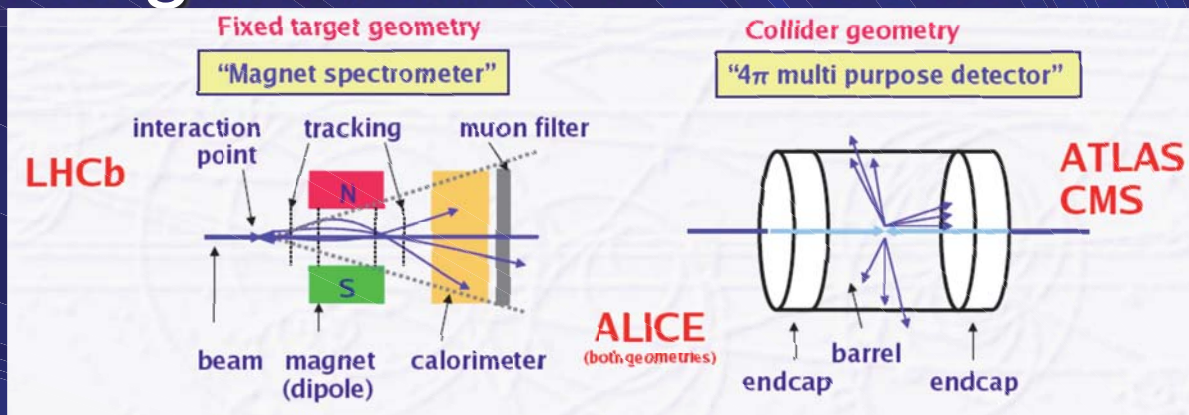
What if the distribution is not Gaussian ?
- Box distribution: $\sigma_z = \Delta z / \sqrt{12}$
- Other distributions: RMS

$$\sigma^2 = \frac{\int_{-\frac{p}{2}}^{\frac{p}{2}} (x_r - x_m)^2 D(x_r)\, dx_r}{\int_{-\frac{p}{2}}^{\frac{p}{2}} D(x_r)\, dx_r} = \frac{p^2}{12}$$
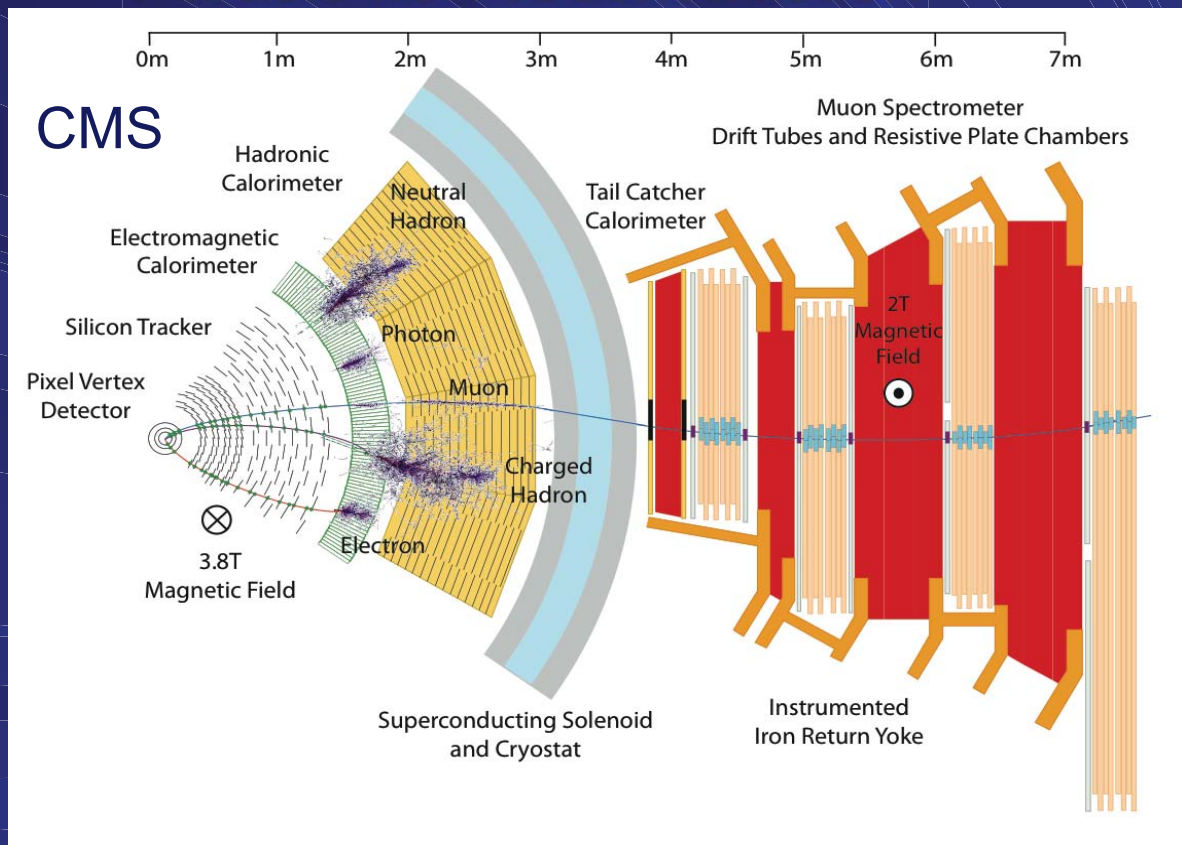
D(x) =1 uniform distribution of tracks
X_m =0 pixel centre

D. Bortoletto   Lecture 1

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Configuration of HEP Detectors

Fixed target geometry
"Magnet spectrometer"

LHCb

interaction point — tracking — muon filter

N

S

beam — magnet (dipole) — calorimeter

Collider geometry
"4π multi purpose detector"

ATLAS CMS

ALICE (both geometries)

endcap — barrel — endcap

LHCb

RICH-2

Muon system

Electromagnetic calorimeter

Hadronic calorimeter

Magnet
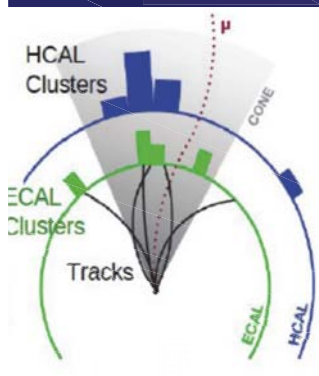
RICH-1

VELO

Tracking system

ALICE

Multipurpose Detectors
Particle flow reconstruction

Particle Flow and Missing E$_T$

Particle Flow: reconstruct stable particles in the event (e, μ, γ & charged and neutral hadrons) from the information from all sub-detectors, to optimize the determination of particle types, directions and energies

Using calorimeter

Using also tracking

CMS √s = 7 TeV

MET Resolution

PF ΣE$_T$
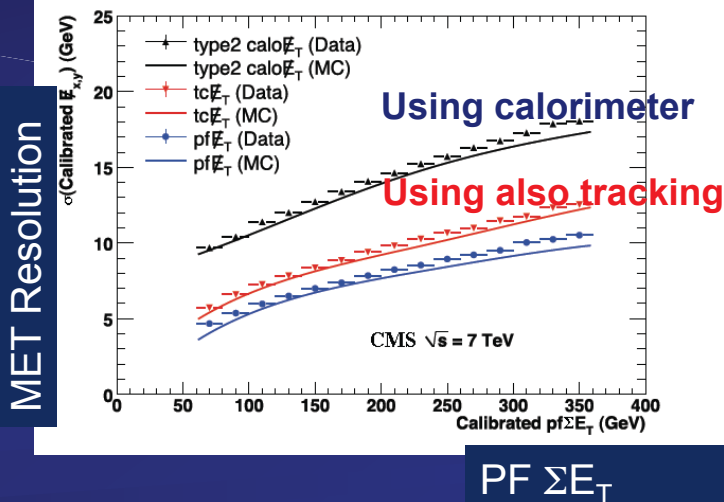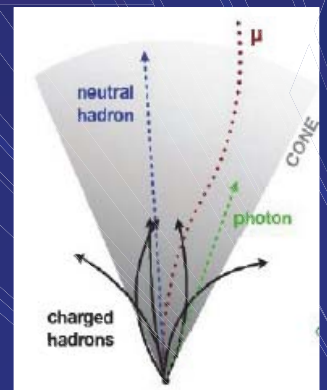
- At the LHC an unknown proportion of the energy of the colliding protons escapes down the beam-pipe.
- If invisible particles (neutrinos, neutralinos ?) are created their momentum can be constrained in the plane transverse to the beam direction

$$E_T^{\mathrm{miss}} = -\sum_i p_T(i)$$

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Application of HEP Detectors: PET
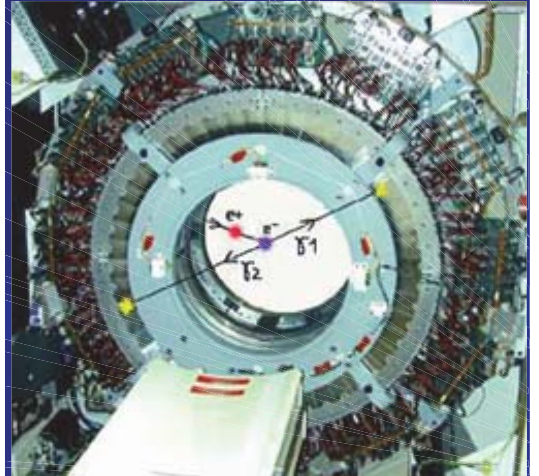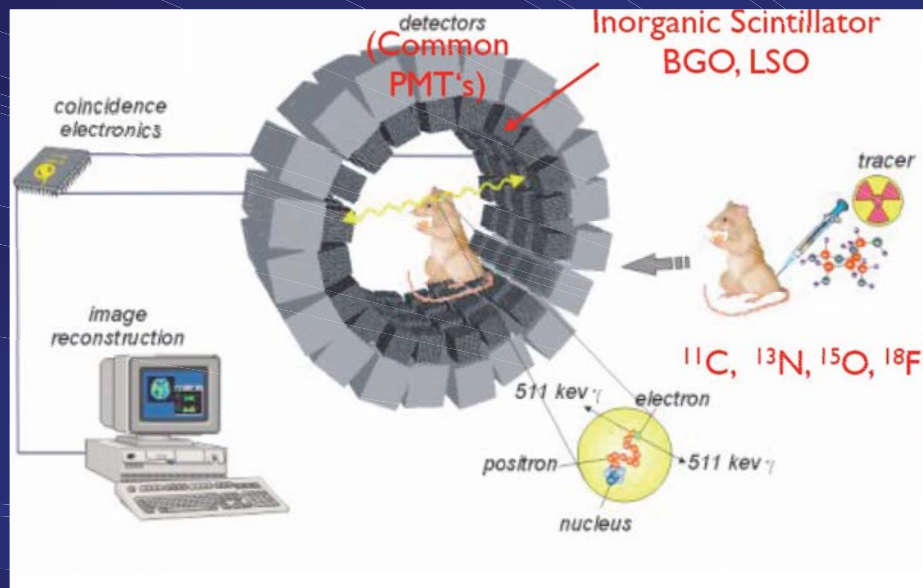
Useful material & acknowledgments

- I have taken part of the content of these lecture from Werner Riegler's summer student lectures in 2011 and Erika Garutti's DESY lecture notes
- Useful books
  - Detector for particle radiation, Konrad Kleinknecht
  - Techniques for Nuclear and Particle Physics Experiments, W. R. Leo
  - Particle Detectors, Claus Grupen
  - Introduction to Experimental Particle Physics, R. Fernow
  - The Physics of Particle Detectors, D. Green
  - Review in data particle book on Passage of particles through matter
  - Review in data particle book on Particle Detectors at accelerators

Historical legacies

- CDF pioneered the silicon vertex detector in the hadron collider environment and pioneered the silicon vertex trigger separating *b*-hadrons
- CDF and D0 developed multi-level triggering with fast microprocessor farms to select interesting events.
- Tracker information at L2 triggering with associative memories

Photo courtesy of Brenna Flaugher

CDF's first Silicon Vertex Detector at the Smithsonian Museum, Washington

Many of these advances have been adopted and improved for the LHC experiments