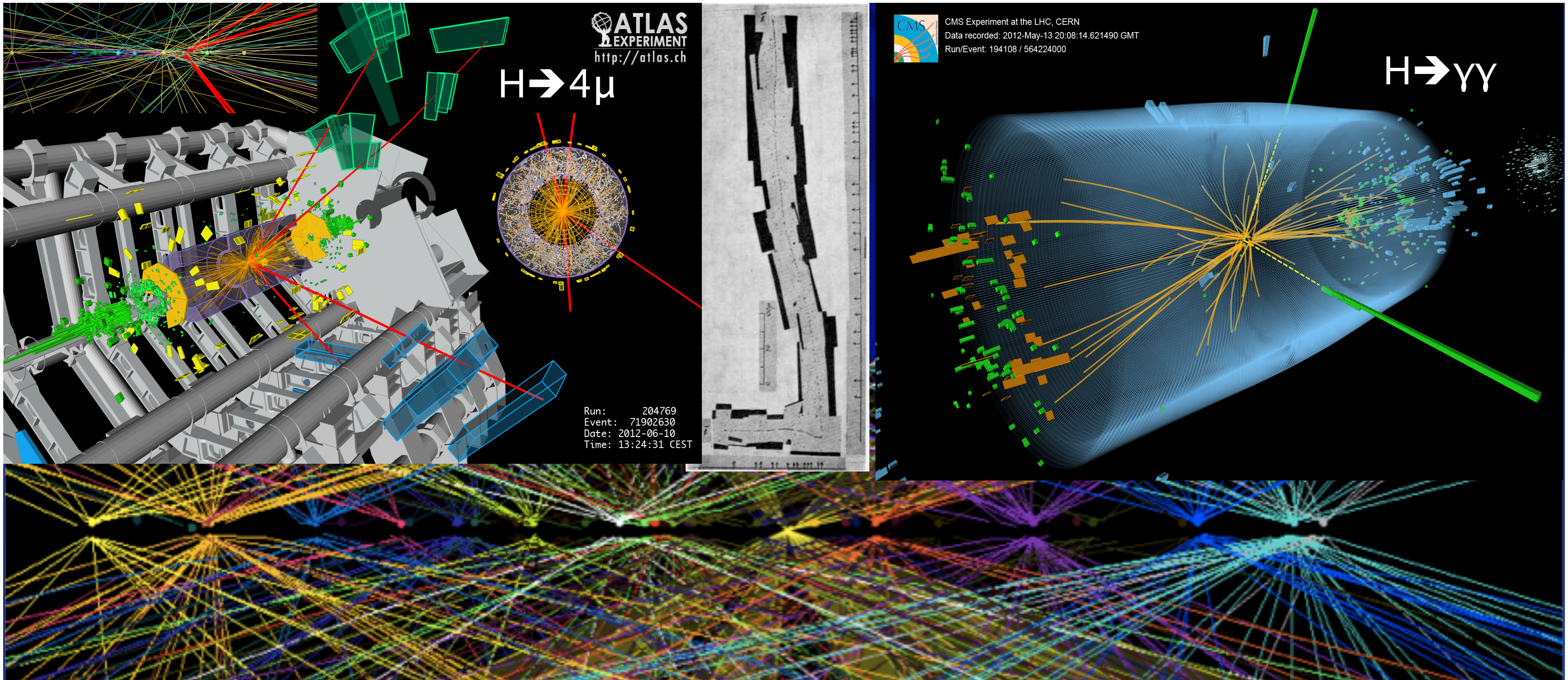


Detectors for Particle Physics

An Introduction

D. Bortoletto
Purdue University

INSTRUMENTATION

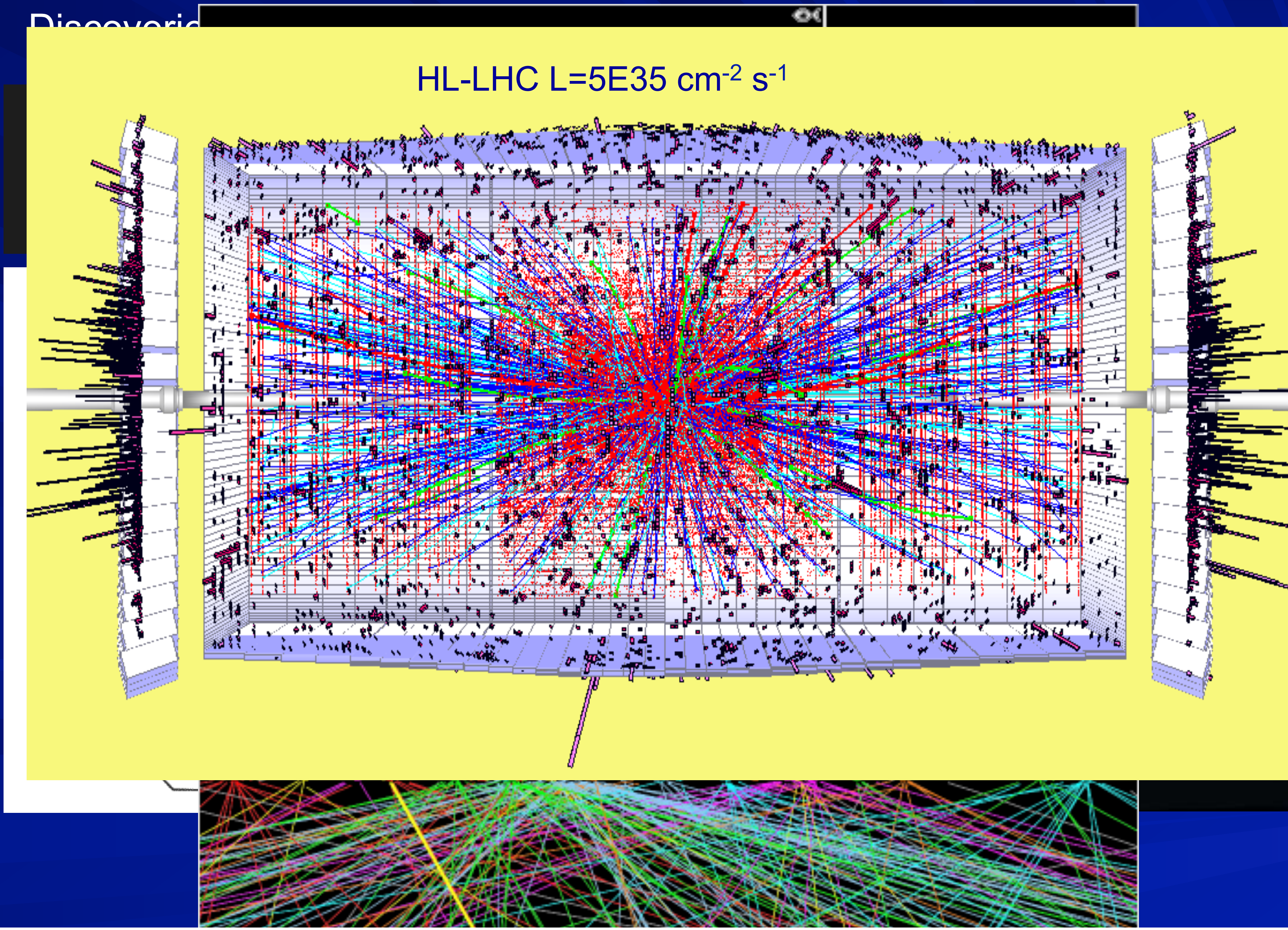
- "New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained"

  Freeman Dyson

- "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 ?



PARTICLE DETECTION

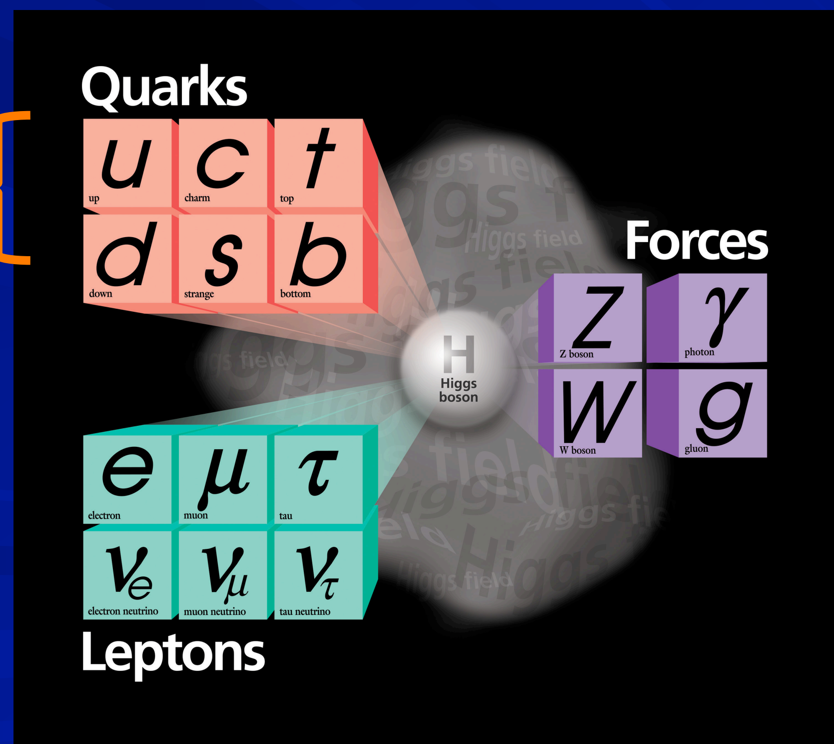
- What is a particle
  - Irreducible representation of the Poincaré group (Wigner)
- What is a detector
  - an instrument to measure the all properties (E, p, m, lifetime, quantum numbers,…) of a particle and identifying it

Elementary particles

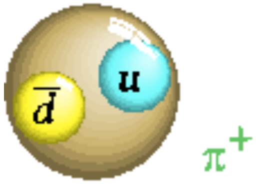
Weak Interaction

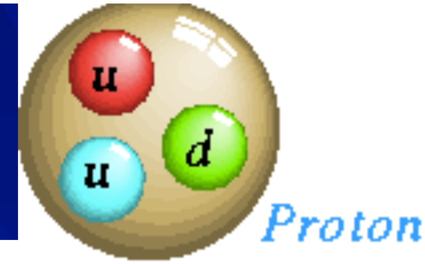
Electro-magnetic Interaction

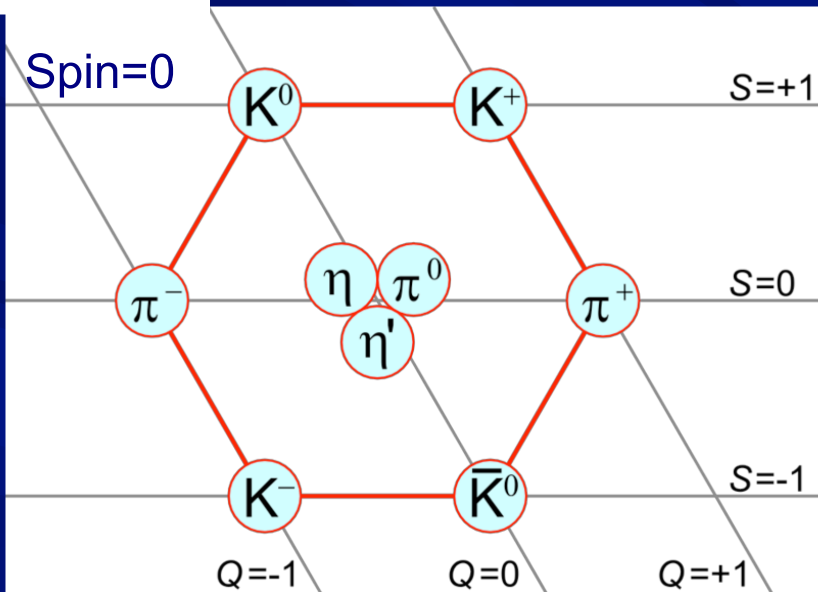
Strong interaction

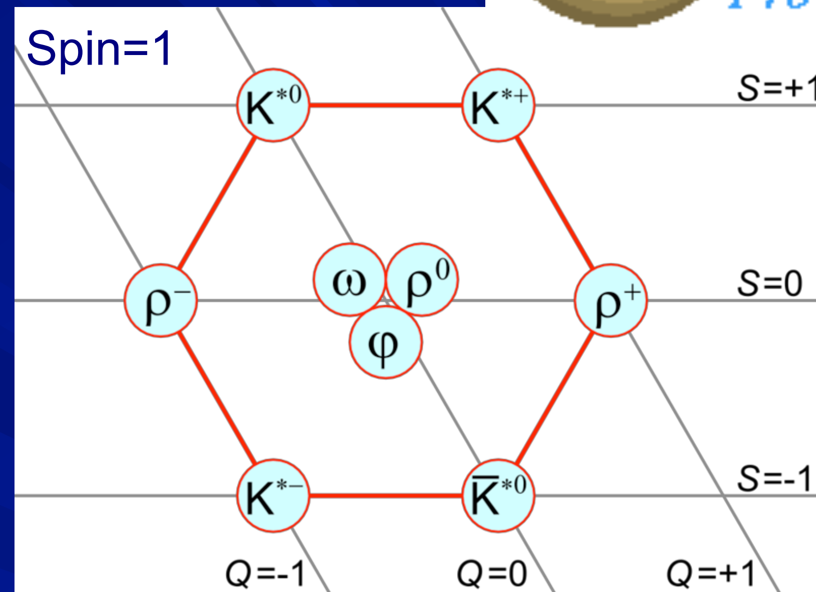


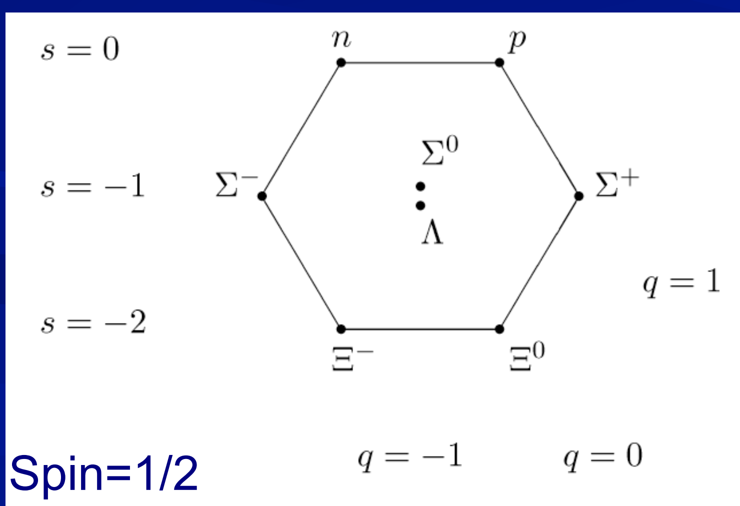
Mesons and Baryons

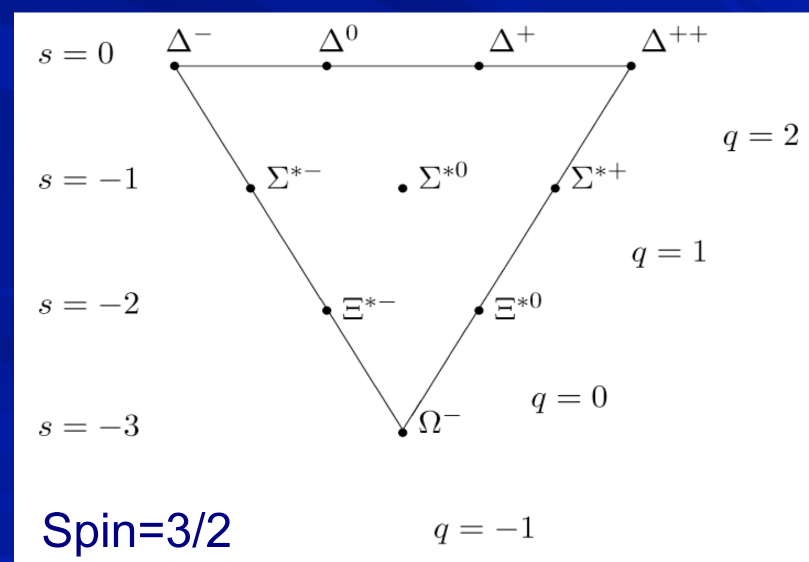




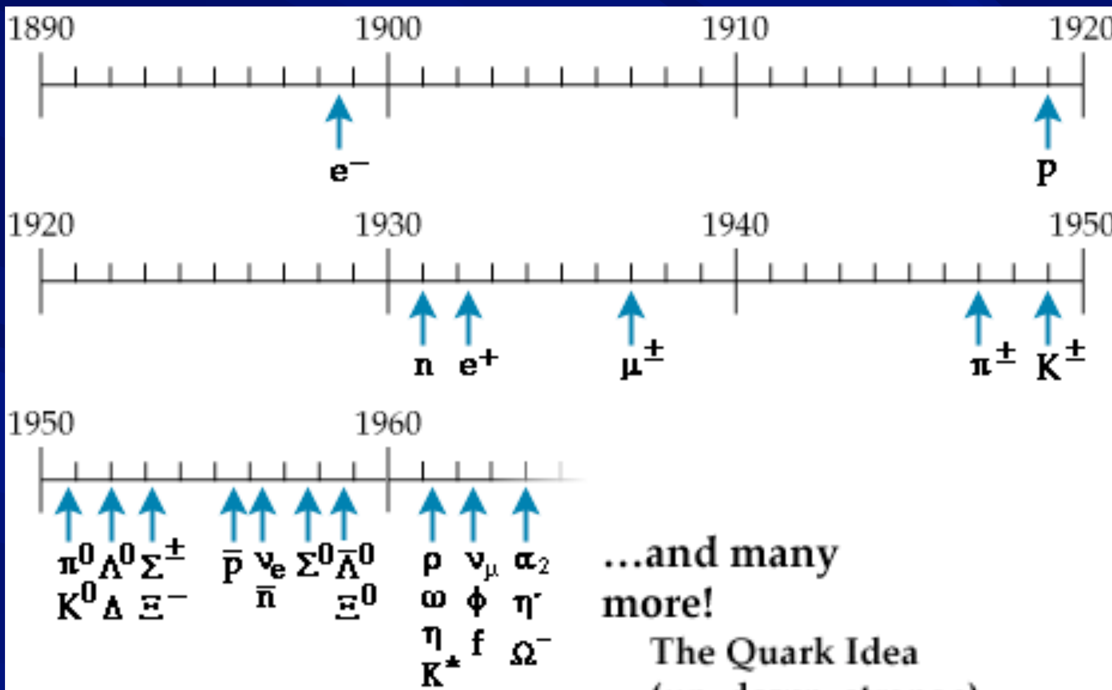




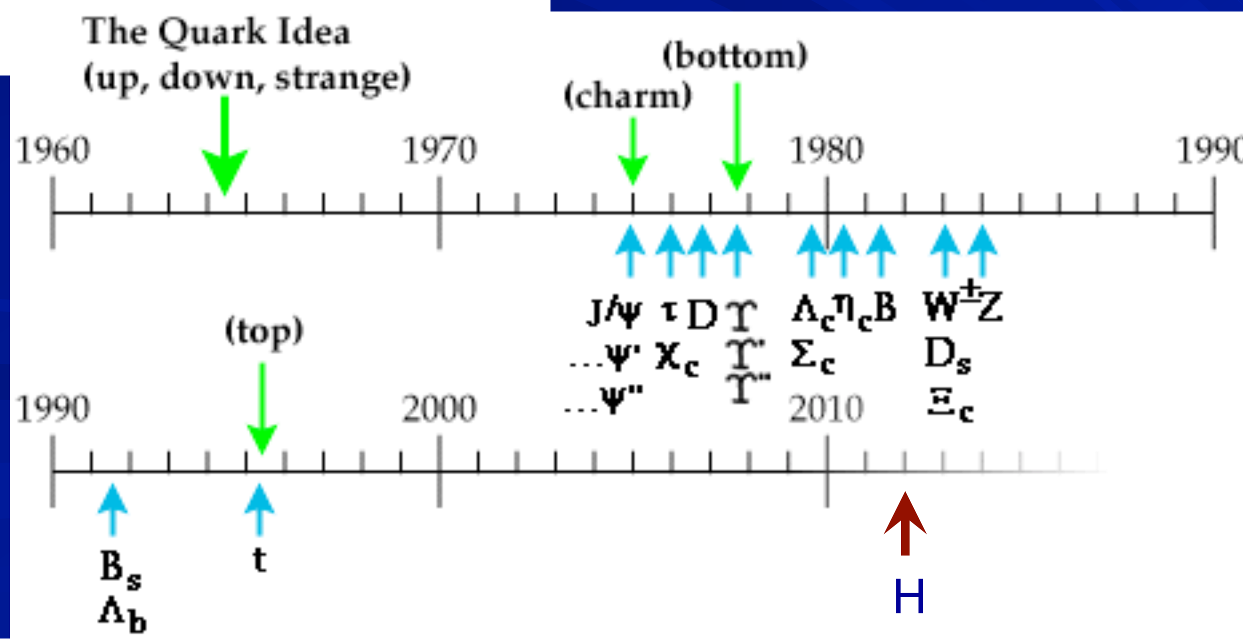




Particle Physics Timeline

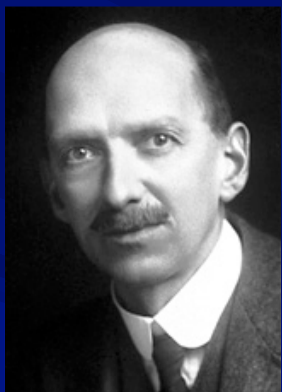


- Today > 200 particles listed in PDG:
  - 27 have $c\tau$ > 1 μm
    - Yield tracks in a detectors
  - 13 have $c\tau$ < 500 μm
    - Yield displaced vertices



NOBEL PRIZES FOR INSTRUMENTATION

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

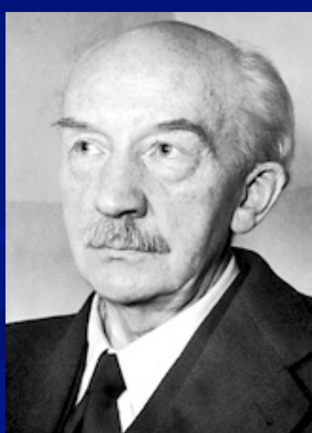


1927: C.T.R. Wilson, Cloud Chamber

1939: E. O. Lawrence, Cyclotron

1948: P.M.S. Blacket, Cloud Chamber

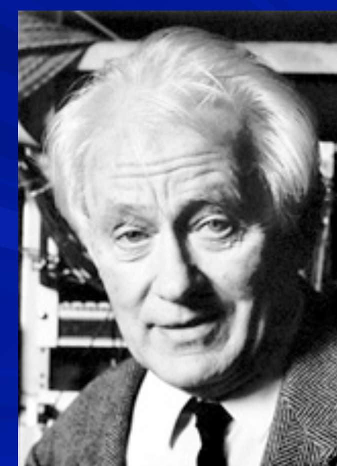
1950: C. Powell, Photographic Method



1954: Walter Bothe, Coincidence method

1960: Donald Glaser, Bubble Chamber

1968: L. Alvarez, Hydrogen Bubble Chamber



1992: Georges Charpak, Multi Wire Proportional Chamber

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:

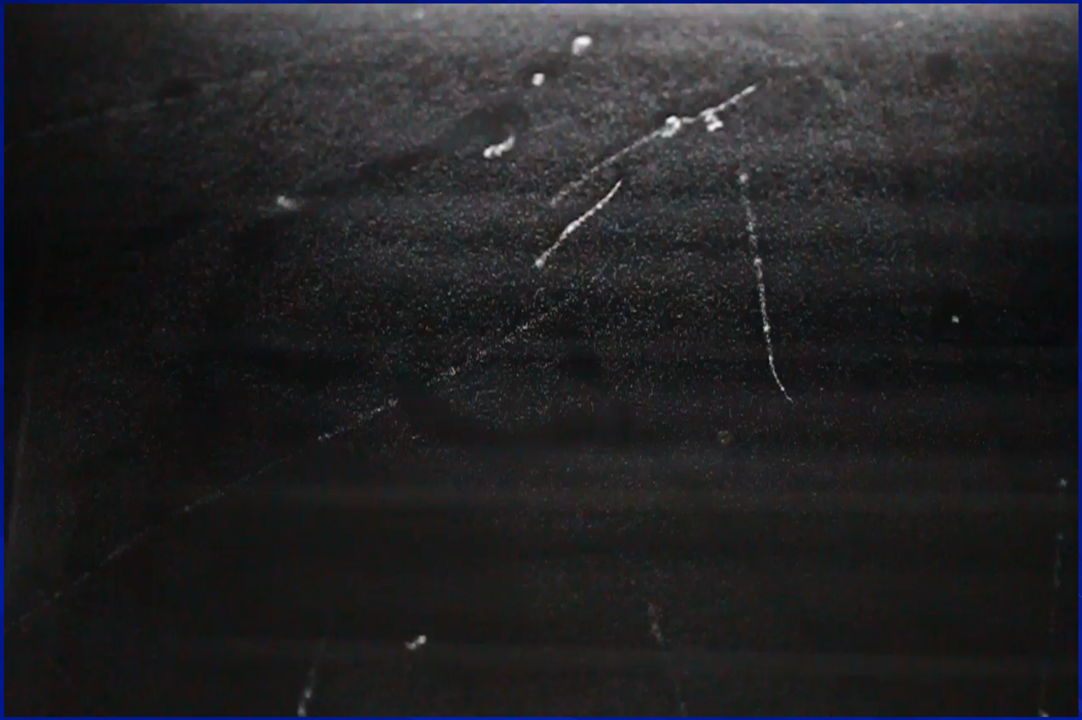
- Ξ^0
- Σ^0

3 with Electronic techniques:

- anti-n
- anti-p
- π^0

Imaging Detectors: Cloud Chamber

- The **cloud chamber** contains a supersaturated vapor of water or alcohol.
  - A charged particle interacting with the mixture, creates ions.
  - Ions act as condensation nuclei around which a mist will form
- If a magnetic field is applied positively and negatively charged particles curve in opposite directions.

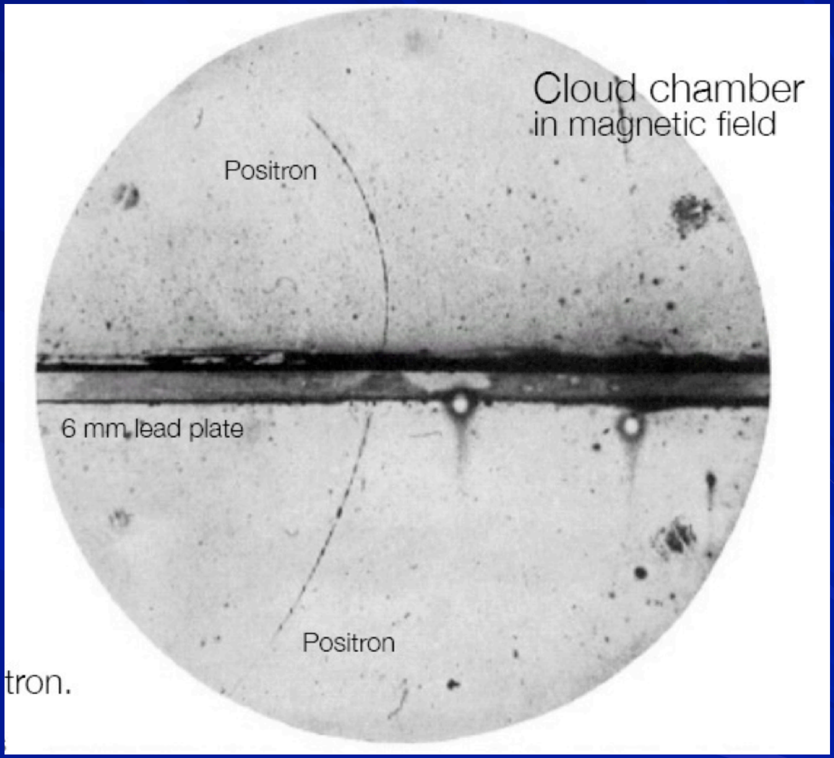


- High energy α and β particles leave a track due to the ions they produce along their path

The positron

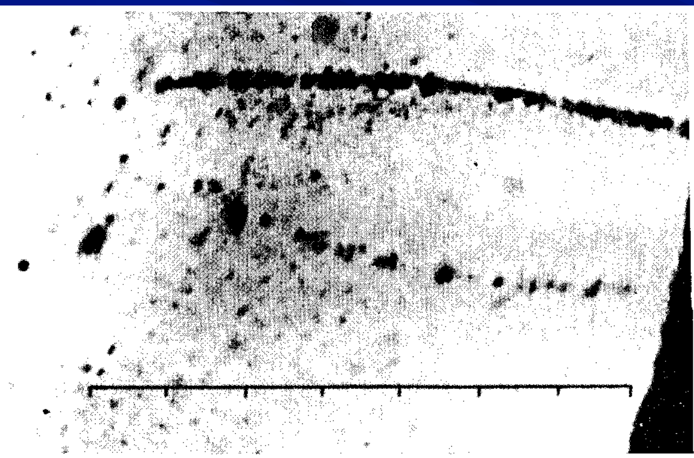
- Positron discovery, Carl Andersen 1933 [Nobel price 1936]

- 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



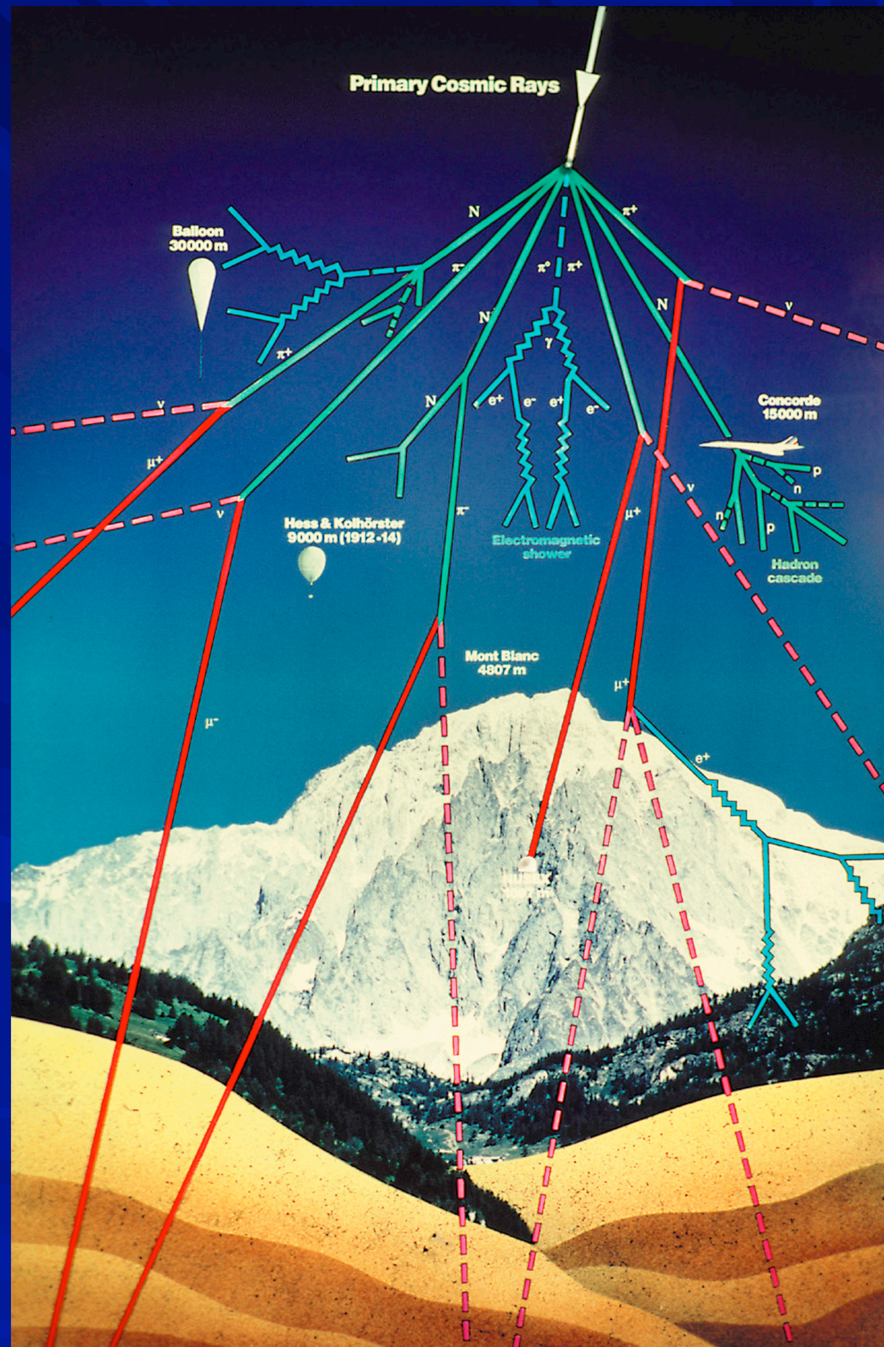
The muon

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

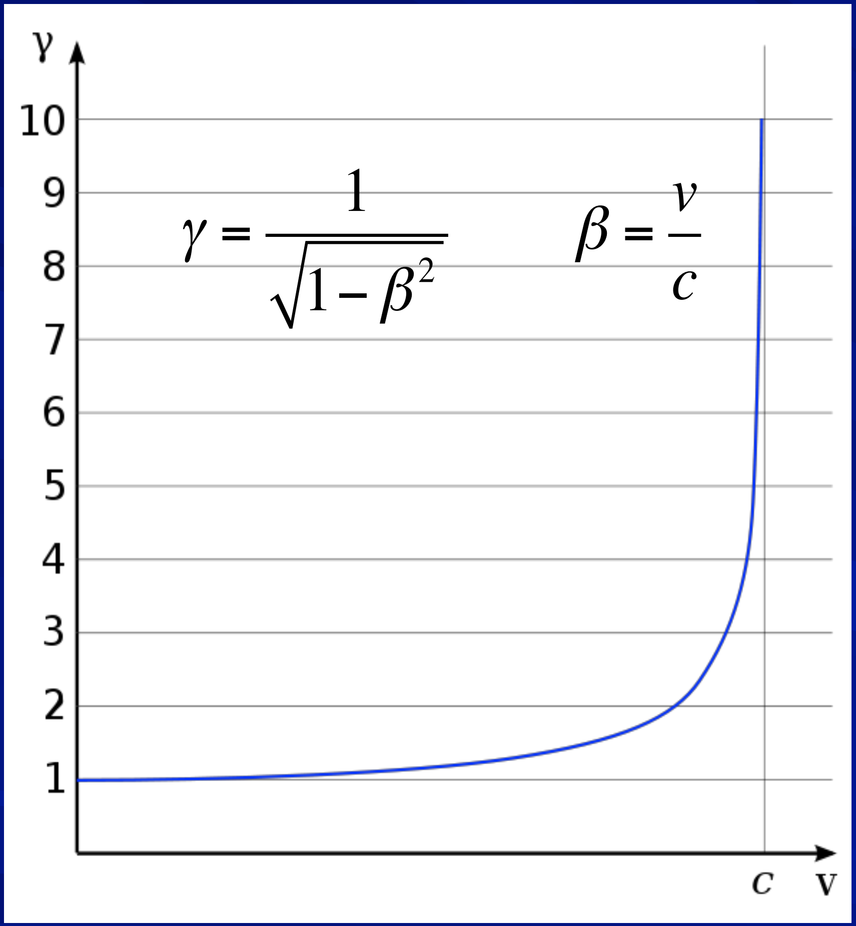


"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive 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

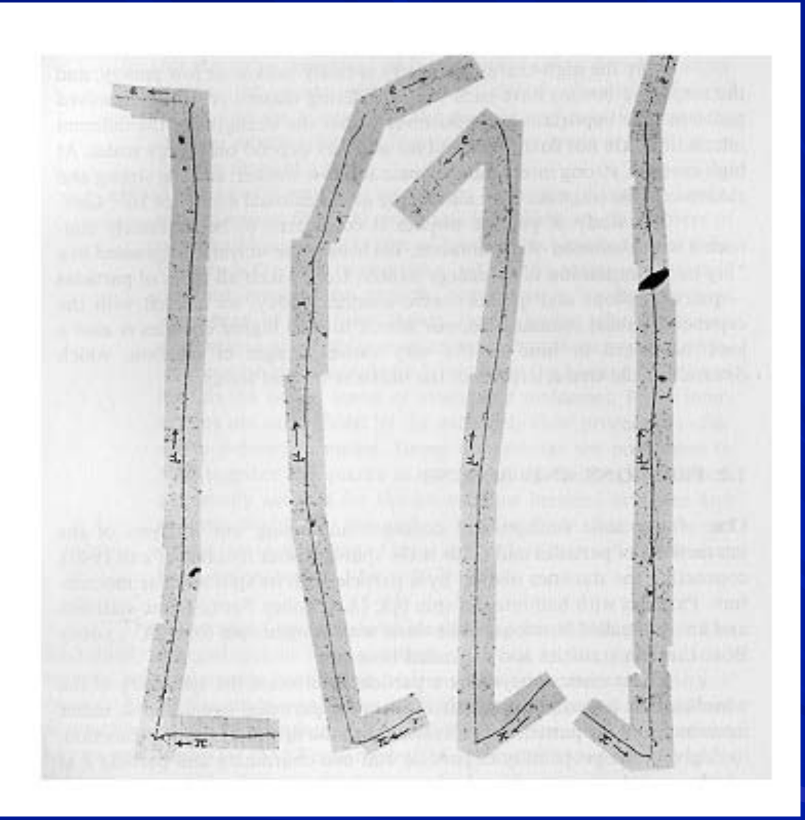


- Muons produced in the upper atmosphere ≈10 km
- Lifetime τ_μ=2.2 x 10^{-6} s
  - s = vτ ≈ 600 m
  - Therefore no muon should reach Hearth!
- But we see them
  - Relativity $\gamma=E/m_\mu c^2$
  - s = vγτ = 12.5 km
- Pions: τ_π= 2.6X10^{-8} s,
  - s = vγτ = 115 m

The Pion

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

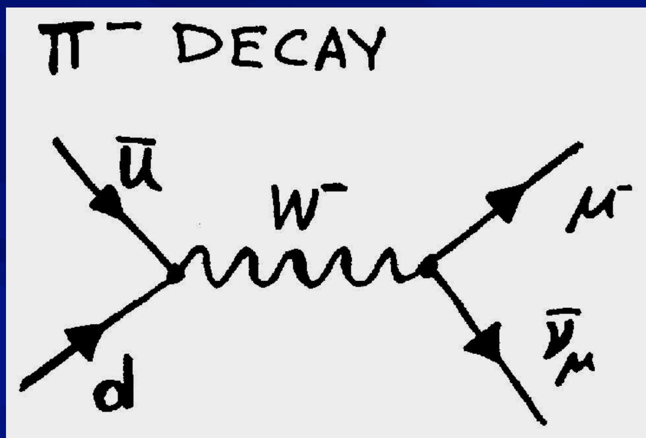
- Discovered in 1947 in nuclear emulsions exposed to cosmic rays, and they showed that it decay to a muon and an unseen partner.
- The constant range of the decay muon from the pion decay indicate that this is a two body decay

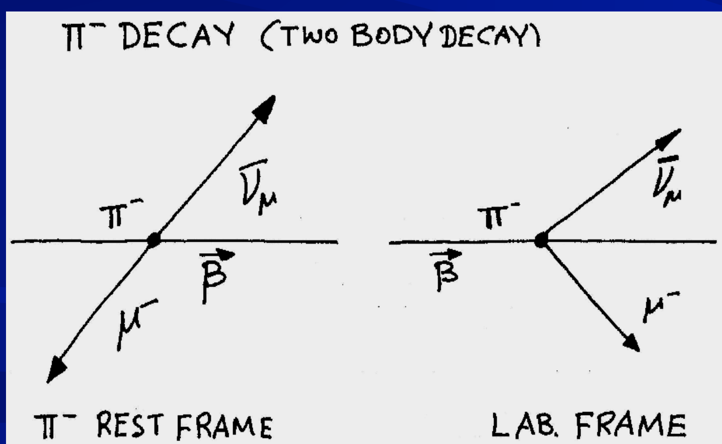


$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

The kinematics of two body decays





- Relativistic Kinematics

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

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

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

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

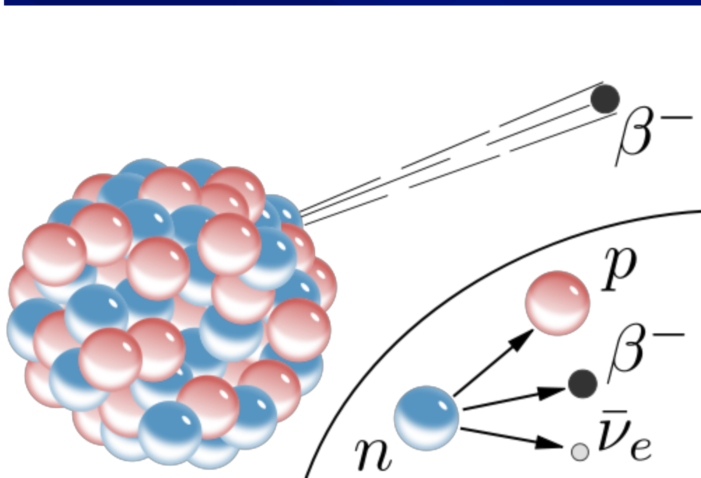
$$m_\pi^2 + 0 - 2m_\pi \cdot E_\nu = m_\mu^2 \qquad m_\mu \approx 106 MeV$$

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

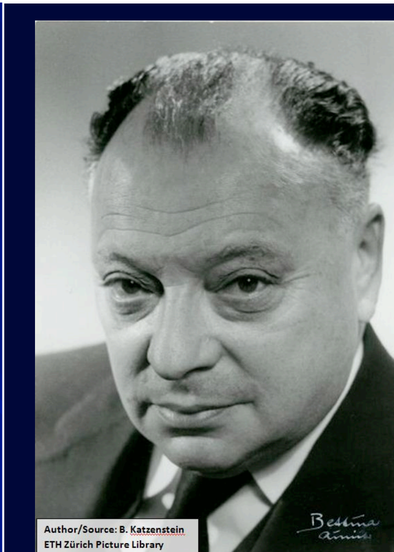
$$|\vec{p}_\mu| \approx 30 MeV \qquad E = \sqrt{\vec{p}_\mu^{\,2} + m_\mu^2} = 110 MeV$$

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

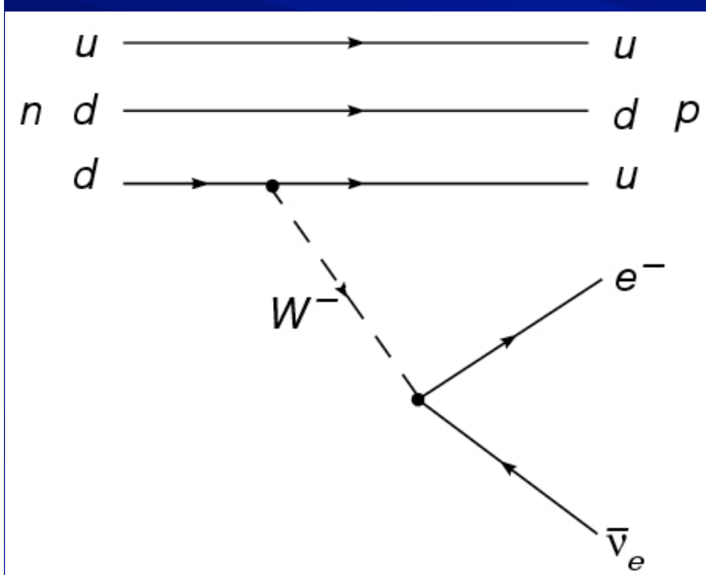
3-body kinematics: the neutrino

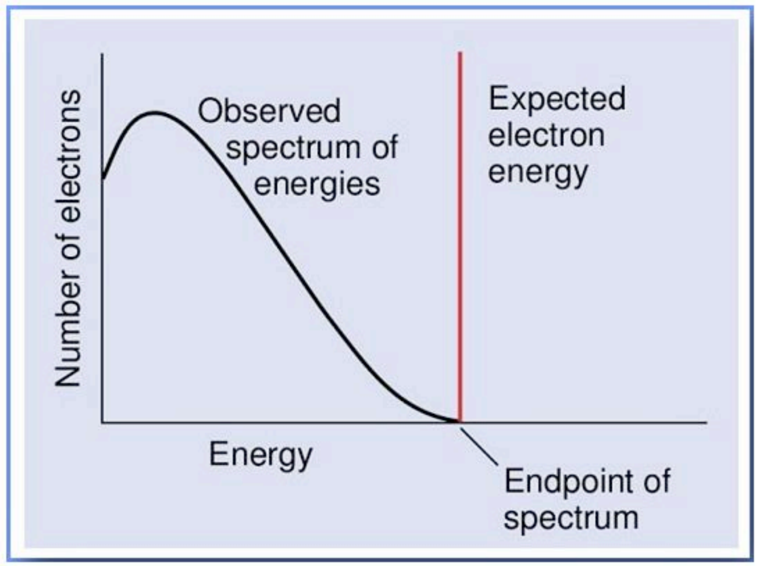


- Neutrinos do not carry any charge ➔ take part in the electroweak and gravitational interaction ➔ neutrinos hardly interact with matter
- Existence of neutrinos was inferred from studies of the lepton spectrum in beta decays.



"I have done a terrible thing.



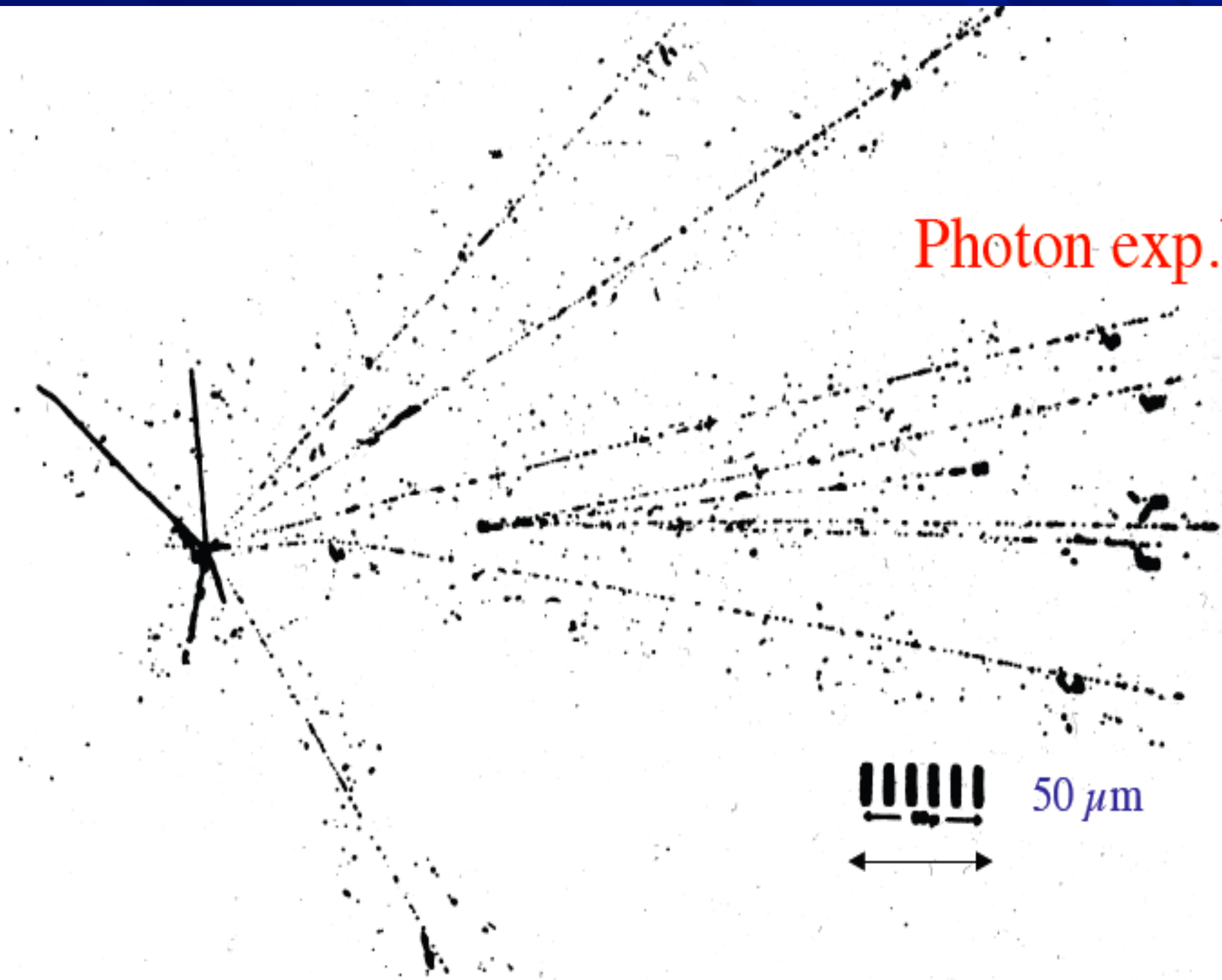


Single beta decay energy spectrum. The observed spectrum is continuous and not at a constant energy as was initially expected. [D. Stewart]

ermi's idea to easure the eutrino mass

heory of beta decay, showing
um varies with neutrino mass

Imaging techniques: Nuclear Emulsions



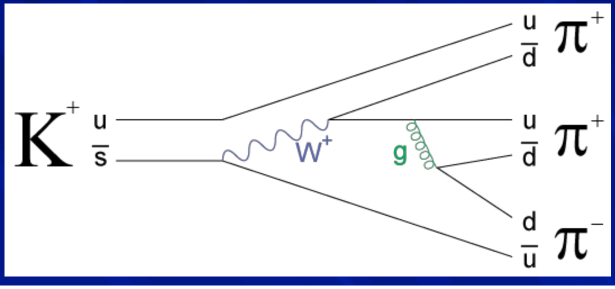
CHARM DECAY

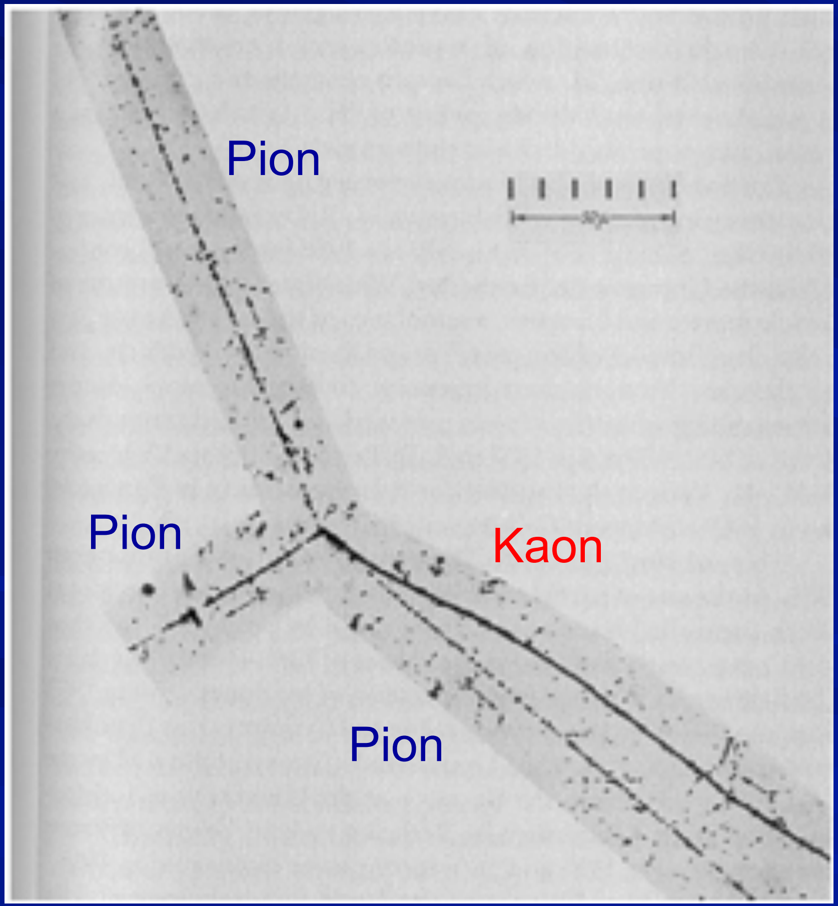
Photon exp.WA59 ~ 1985

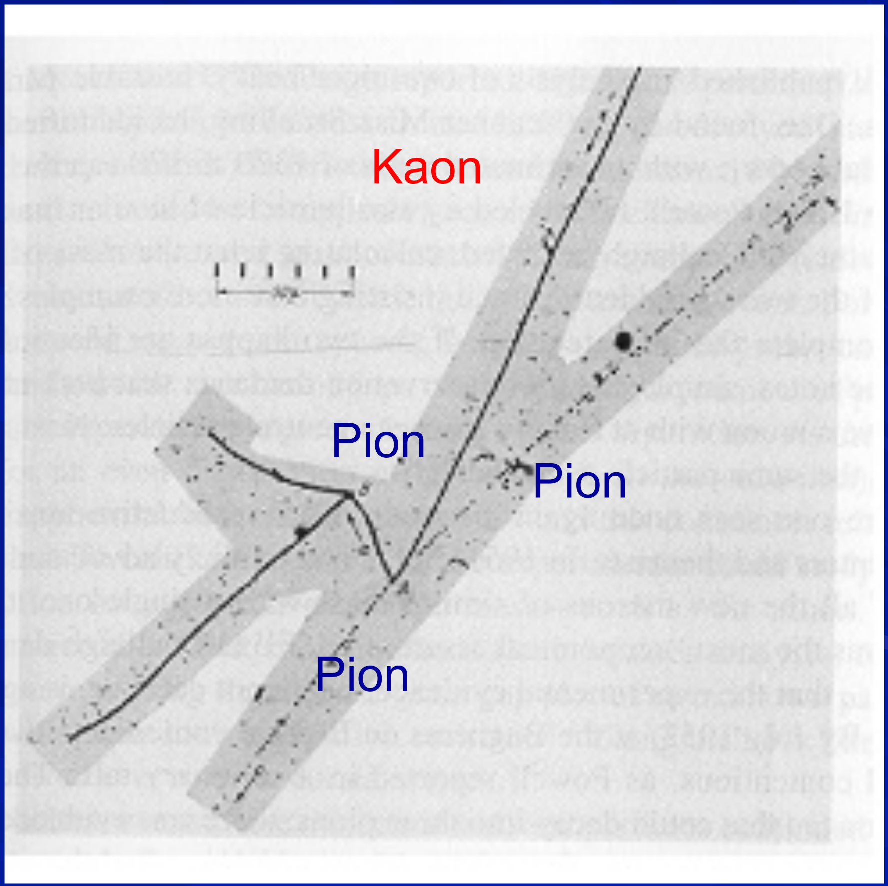
Thick film AgBr reached submicron resolution

The discovery of the Kaon

- First evidence of the decay of the Kaon into 3 pions was found in 1949 in Nuclear emulsion

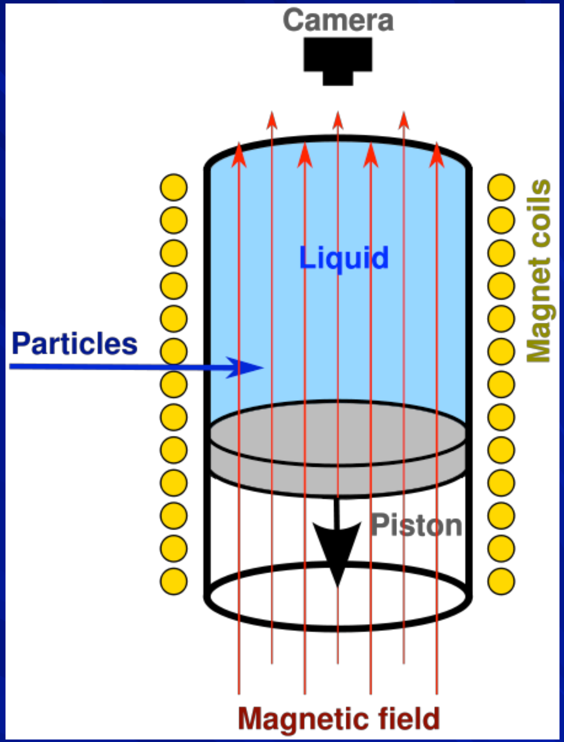






Imaging Detectors: the Bubble chamber

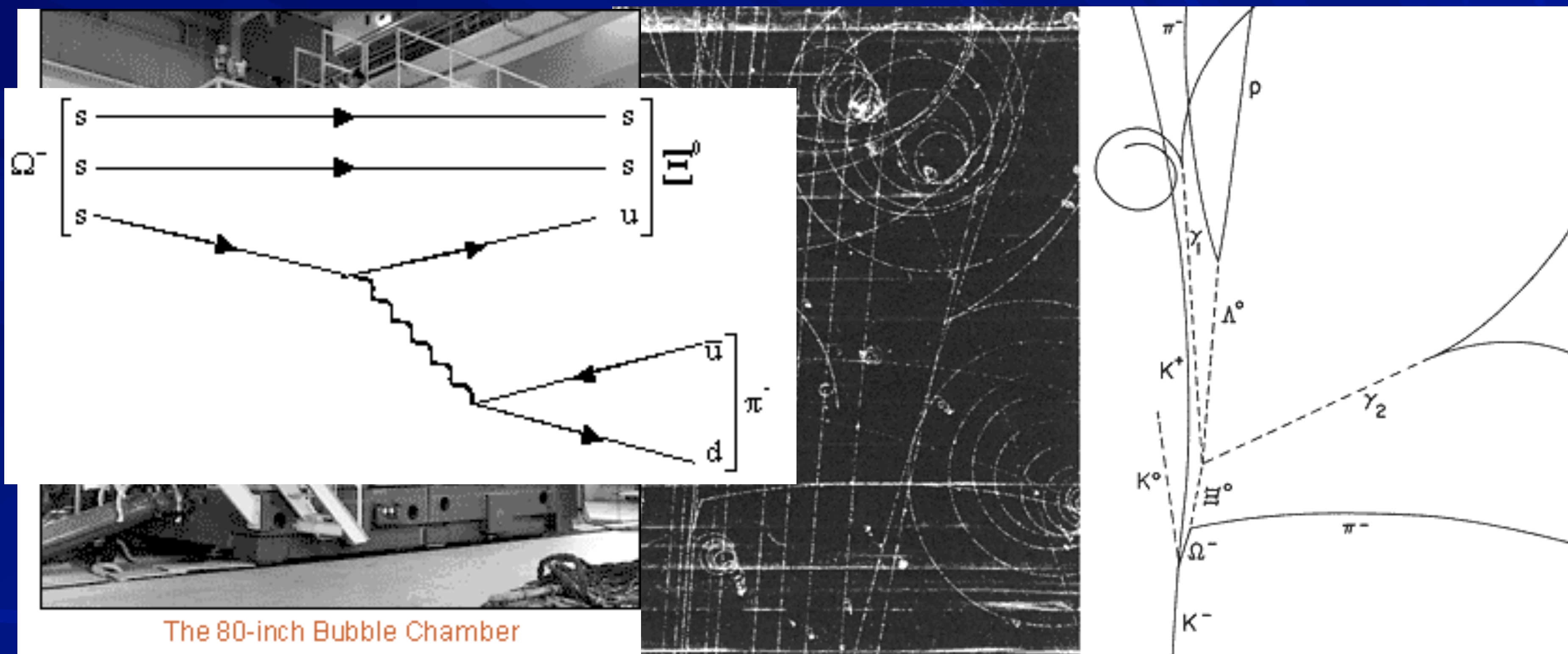
Invented in 1952 by Glaser (1960 Nobel Prize in Physics)



- A **bubble chamber** is a vessel filled with a superheated transparent liquid (for ex. Hydrogen at T=30K). A charge particle initiate boiling.
- The size of chambers grew quickly:
  - 1954: 2.5'' (6.4 cm)
  - 1954: 4'' (10 cm)
  - 1956: 10'' (25 cm)
  - 1959: 72'' (183 cm)
  - 1963: 80'' (203 cm)
  - 1973: 370 cm
- 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 said that he did experiments using beer to fill early prototypes.

Discovery of the Omega



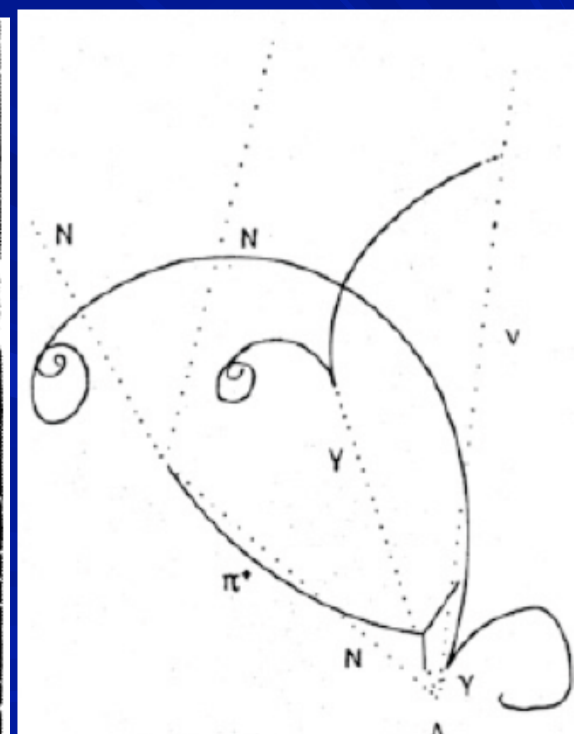
The 80-inch Bubble Chamber

BNL, First Pictures 1963, 0.03s cycle

Ω^- = sss   Confirmation of the quark model

The discovery of neutral currents

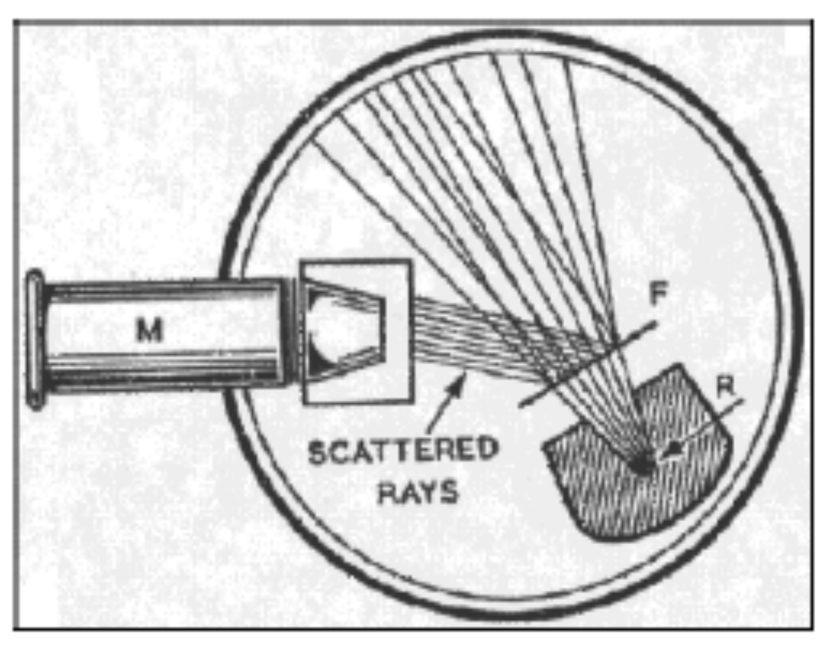
- Gargamelle, a very large heavy-liquid (freon) chamber constructed at Ecole Polytechnique in Paris, came to CERN in 1970.
- 2 m in diameter, 4 m long and filled with Freon at 20 atm, in 2 T B field
- Gargamelle in 1973 was the tool that permitted the discovery of neutral currents.



$$\nu N \rightarrow \nu N \pi^0$$

Electronics detectors

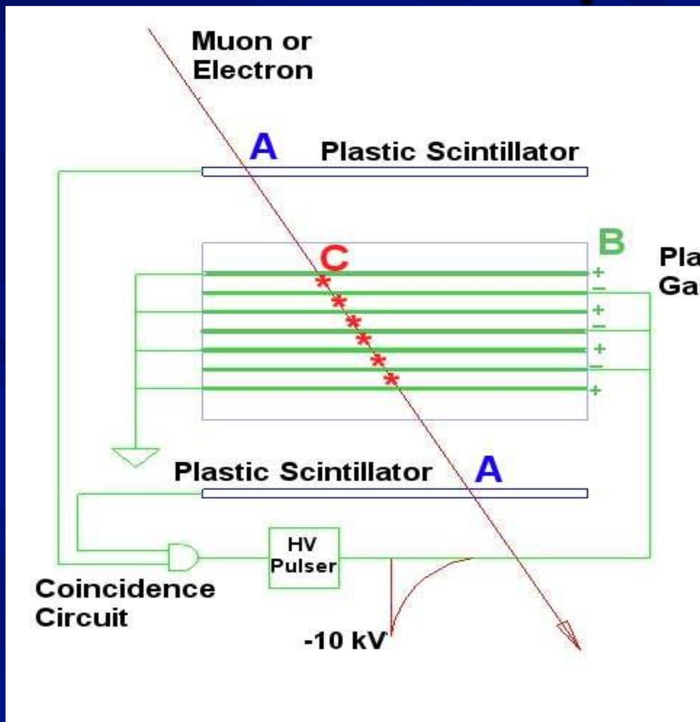
- In the 70ies the logic (electronic) detectors took over
  - Geiger counters
  - Scintillator + photomultipliers
  - Spark counters
- The particle is not “seen” but its nature and existence “deduced” via a logic experiment (coincidences, triggers, detection of decay products …)



Scintillating Screen:

- Rutherford Experiment 1911:
  - Zinc Sulfide screen used as detector.
  - If an alpha particle hits the screen, a flash could be detected

Spark Chamber

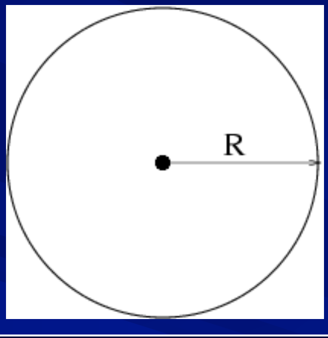


- The Spark Chamber was developed in the early 60ies.
- Schwartz, Steinberger and Lederman used it in the discovery of the muon neutrino

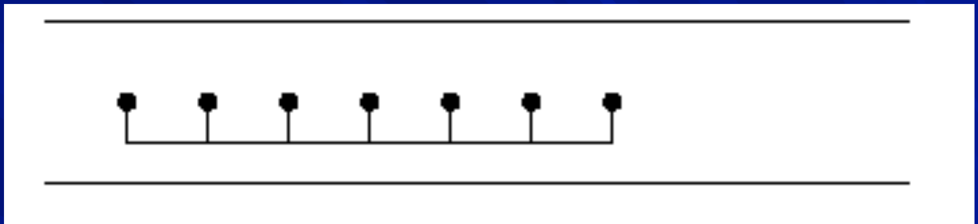
- A charged particle traverses the detector and leaves an ionization trail.
- The scintillators trigger an HV pulse between the metal plates and sparks form in the place where the ionization took place.

Multi-wire proportional chambers

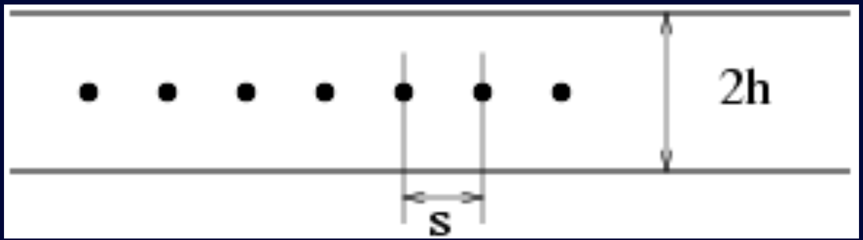
Tube, Geiger- Müller, 1928



Multi Wire Geometry, in H. Friedmann 1949

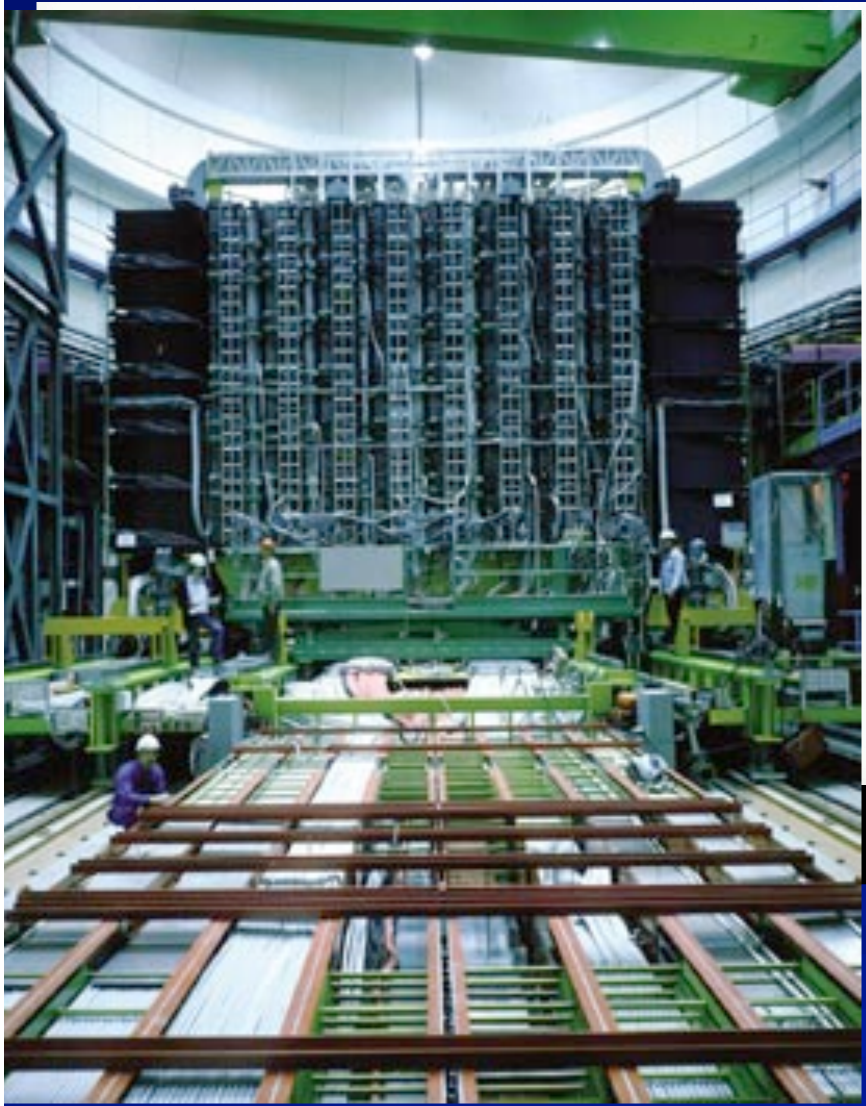


G. Charpak 1968, Multi Wire Proportional Chamber,
readout of individual wires and proportional mode working point.

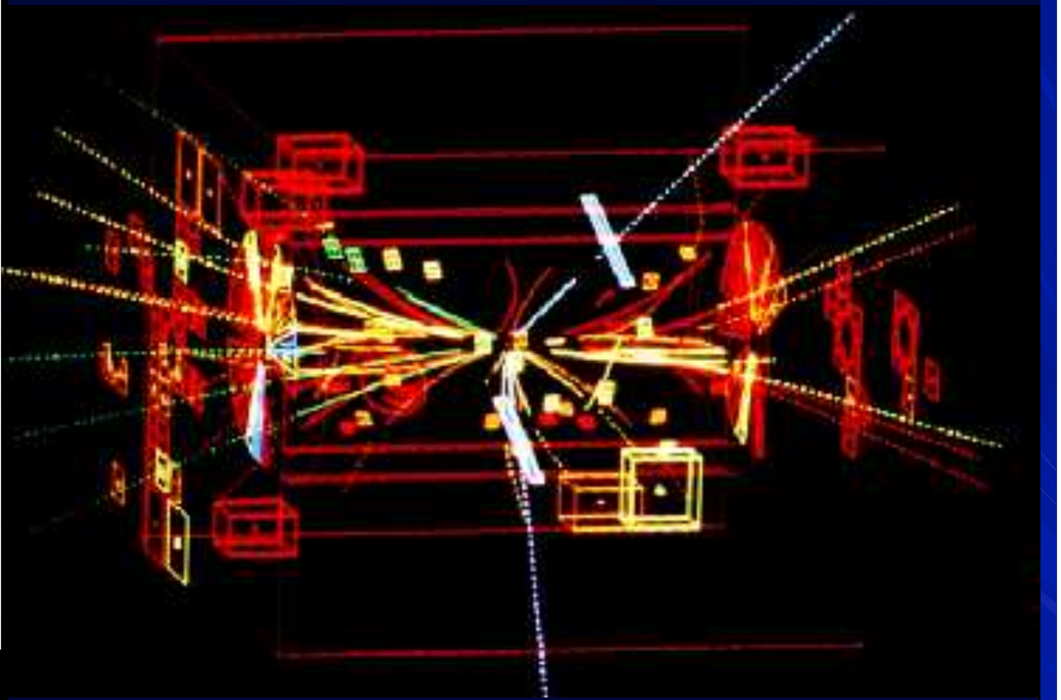


- A charged particle traversing the detector leaves a trail of electrons and ions.
- Wires are kept at positive HV.
- Electrons drift to the wires in the E field and form an avalanche close to the wire.
- This induces a signal on the wire which can be read out by an amplifier.

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 e^- and e^+.

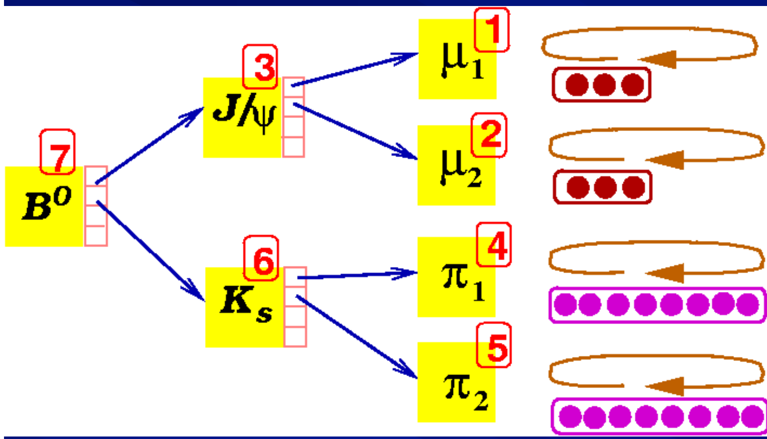
Particle Detection and stable particles

- **The most frequent** "stable" particles ($c\tau$ > 500 μm) 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: pion (m_π=139.6 MeV), Charged kaons (m_{K^+}=493.7 MeV), protons (m_p=938.3 MeV)
- Strong interaction: Neutral K (m_{K^0} = 497.7 MeV) and n (m_n=939.6 MeV)

The difference in Mass, Charge, Interaction are keys to particle identification

Unstable Particles

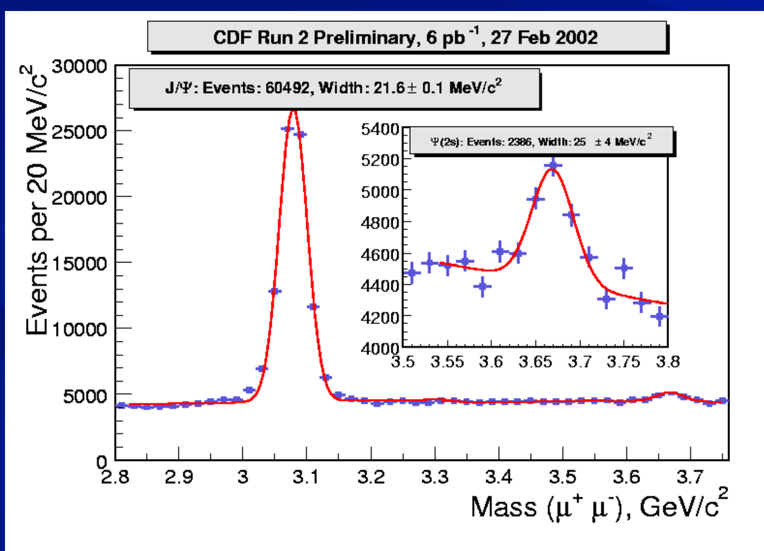


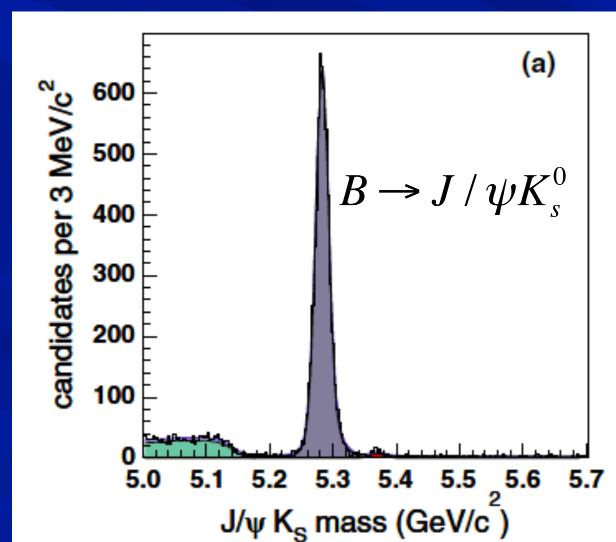
$$m_{inv,x}^2 = (E_1 + E_2)^2 - (p_1 + p_2)^2$$

$$E_x = E_1 + E_2$$

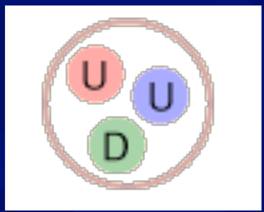
$$\vec{p}_x = \vec{p}_1 + \vec{p}_2$$

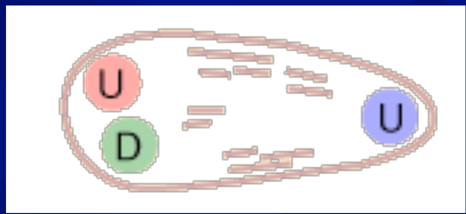
$$J/\psi \rightarrow \mu^+\mu^-$$

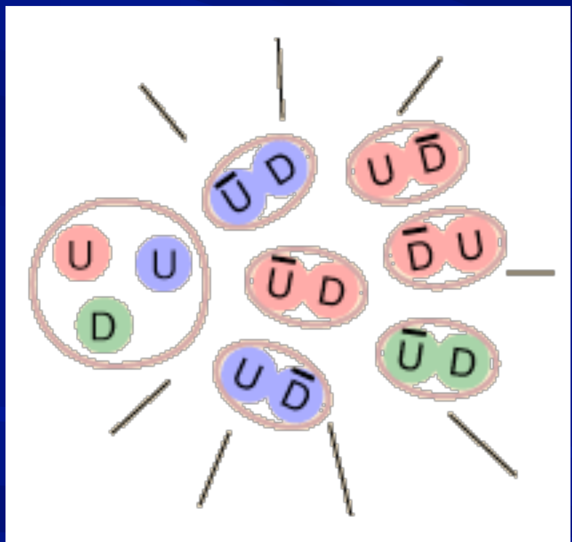


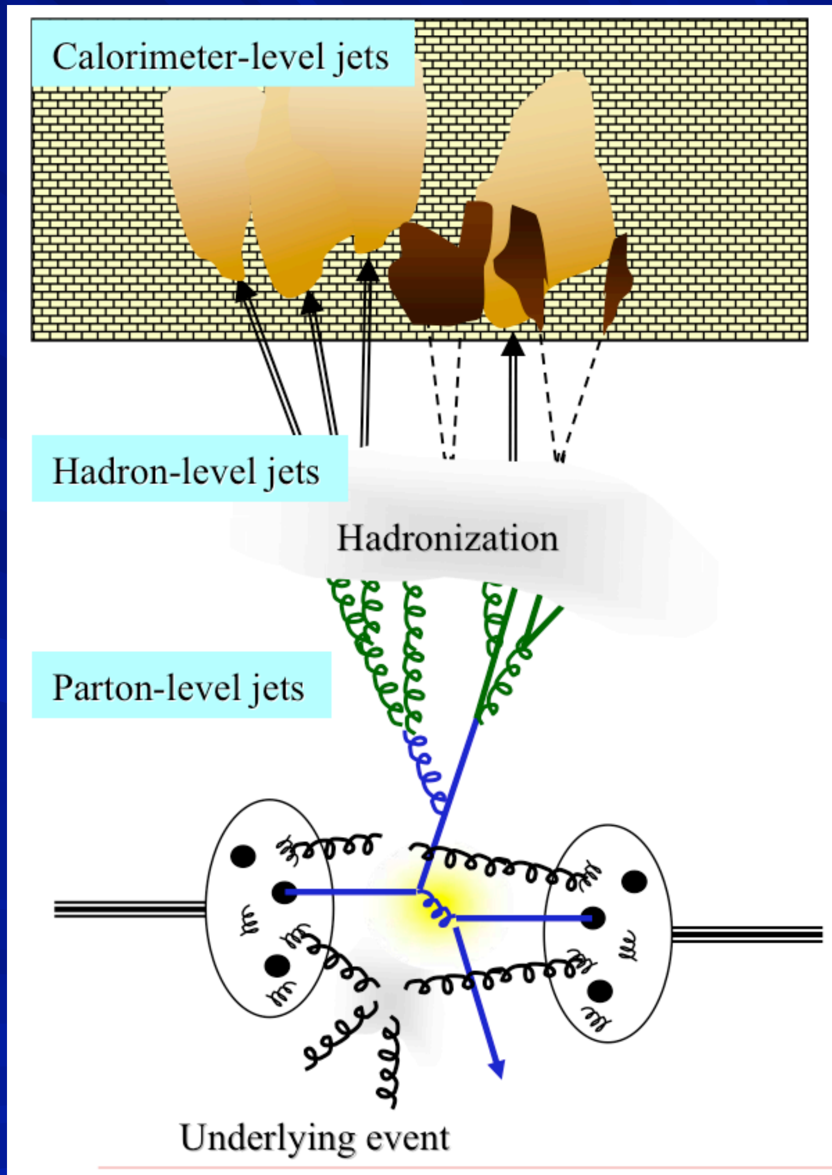


Quark confinement and Jets

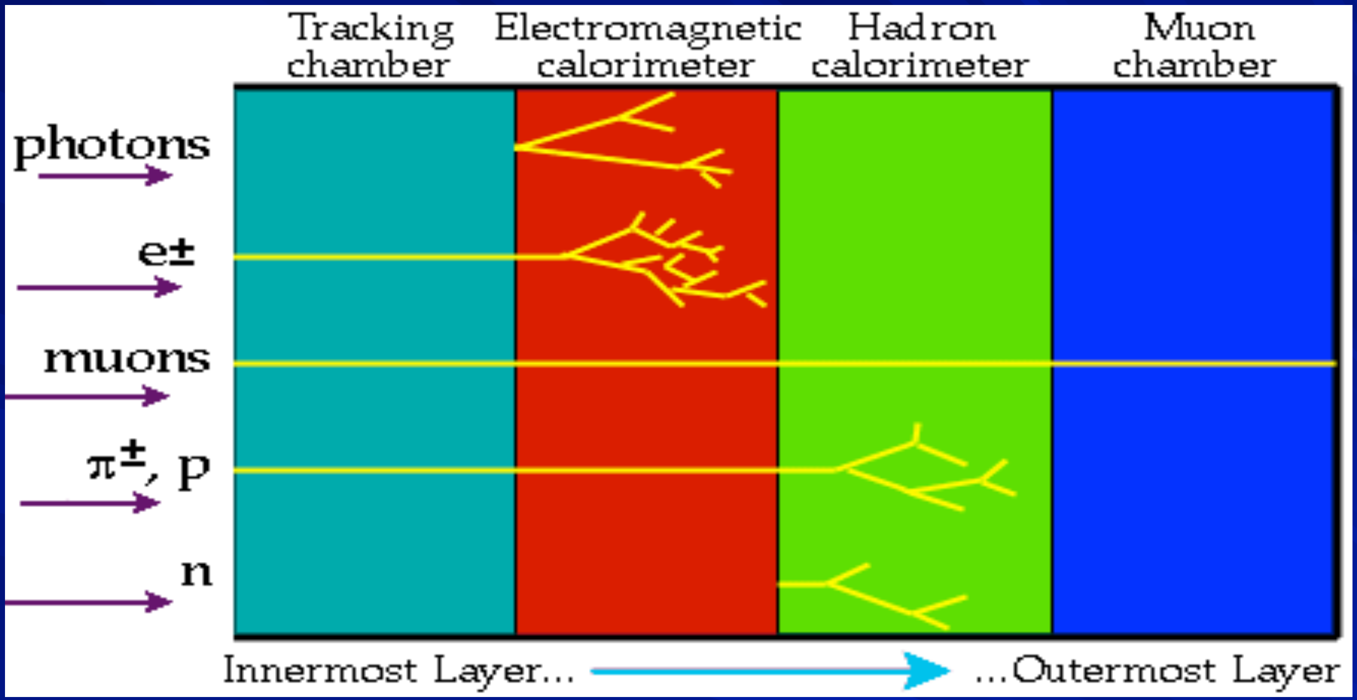








Particle Identification



B field
Low ρ

High ρ

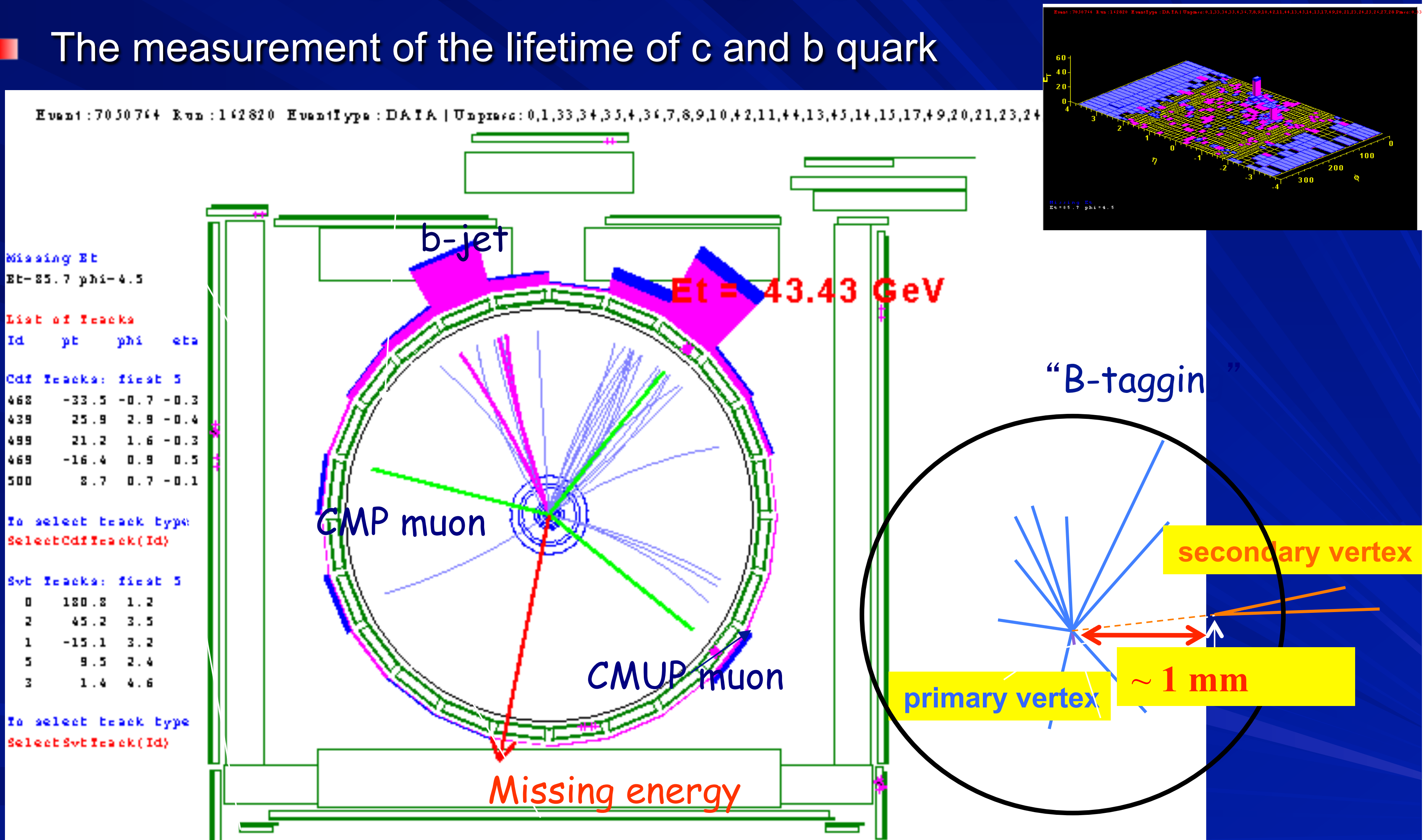
High ρ

Tracking

- Electrons ionize and bremsstrahlung due to their 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

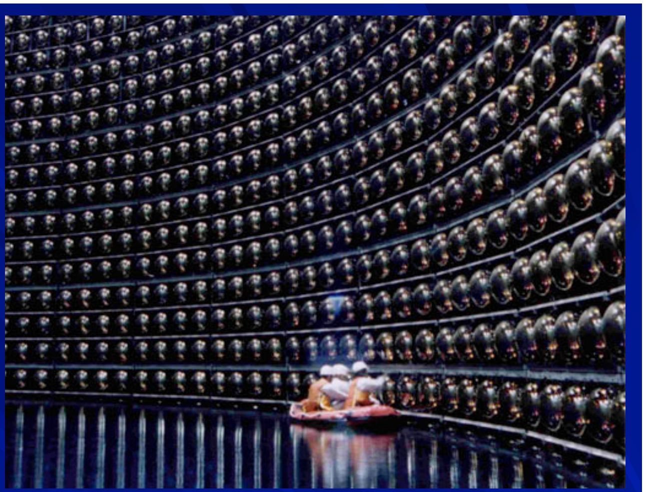


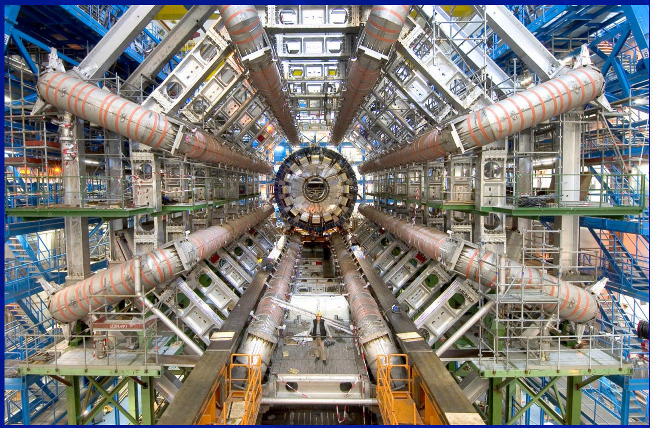
Tracking and vertex detectors were crucial to the discovery of top

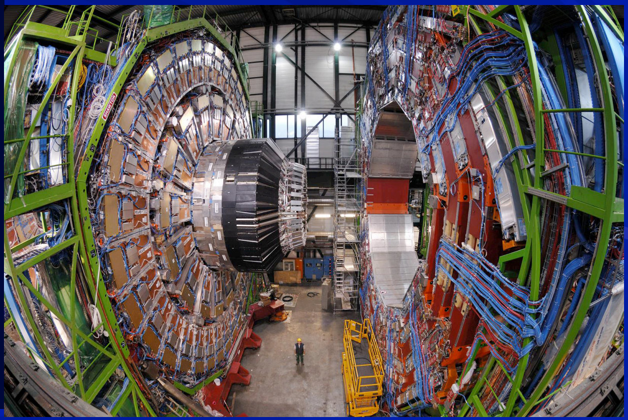
$$p\bar{p} \rightarrow t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow b\ell^+\nu\bar{b}\ell^-\bar{\nu}$$

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?



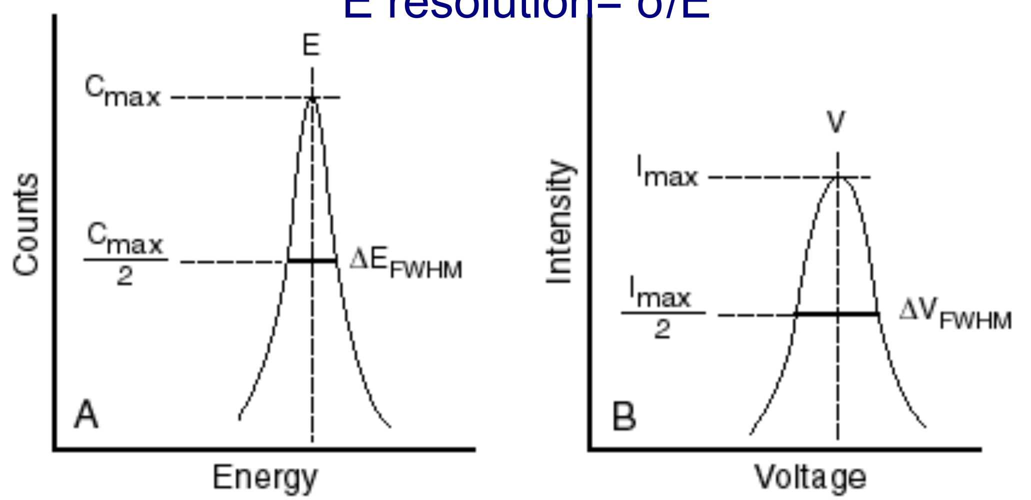




Measurement Resolution

- Resolution generally defined as 1 standard deviation (1**σ**) for a Gaussian distribution, or the FWHM (**Δ**z)
  - For a Gaussian **σ=FWHM/2.36**
- If the measurement is dominated by Poisson fluctuations

E resolution= σ/E



$$\frac{\sigma_z}{\langle z \rangle} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

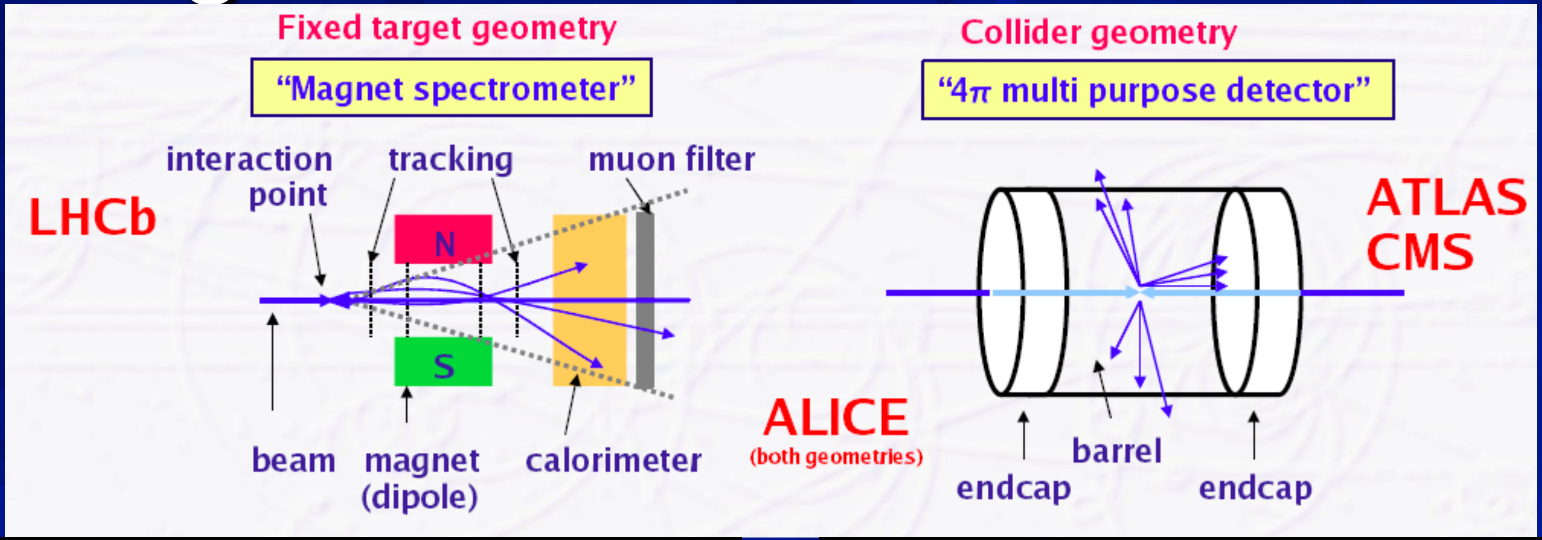
- What if the distribution is not Gaussian ?
  - Box distribution: σ_z= pitch/ √12
  - Other distributions: RMS

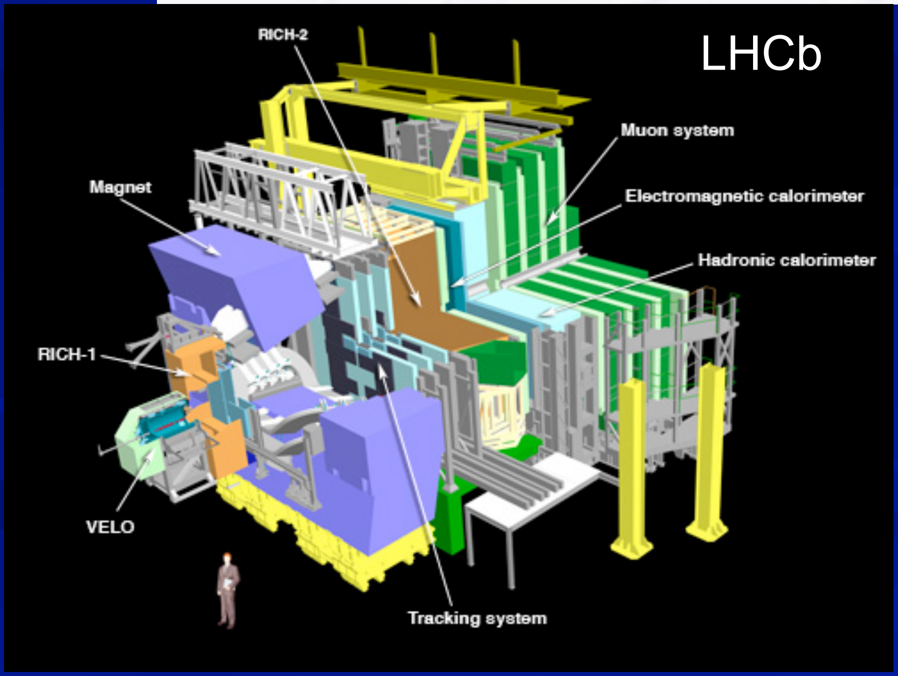
$$\sigma^2 = \frac{\int_{-\frac{p}{2}}^{\frac{p}{2}} (x_r - x_m)^2 D(x_r)\, dx_r}{\int_{-\frac{p}{2}}^{\frac{p}{2}} D(x_r)\, dx_r} = \frac{p^2}{12}$$

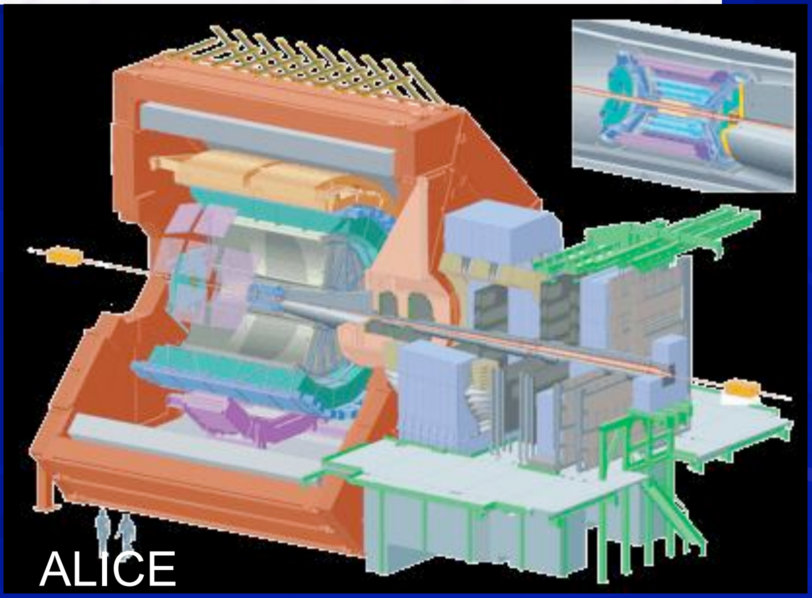
D(x) =1 uniform distribution of tracks

X_m=0 pixel centre

Configuration of HEP Detectors

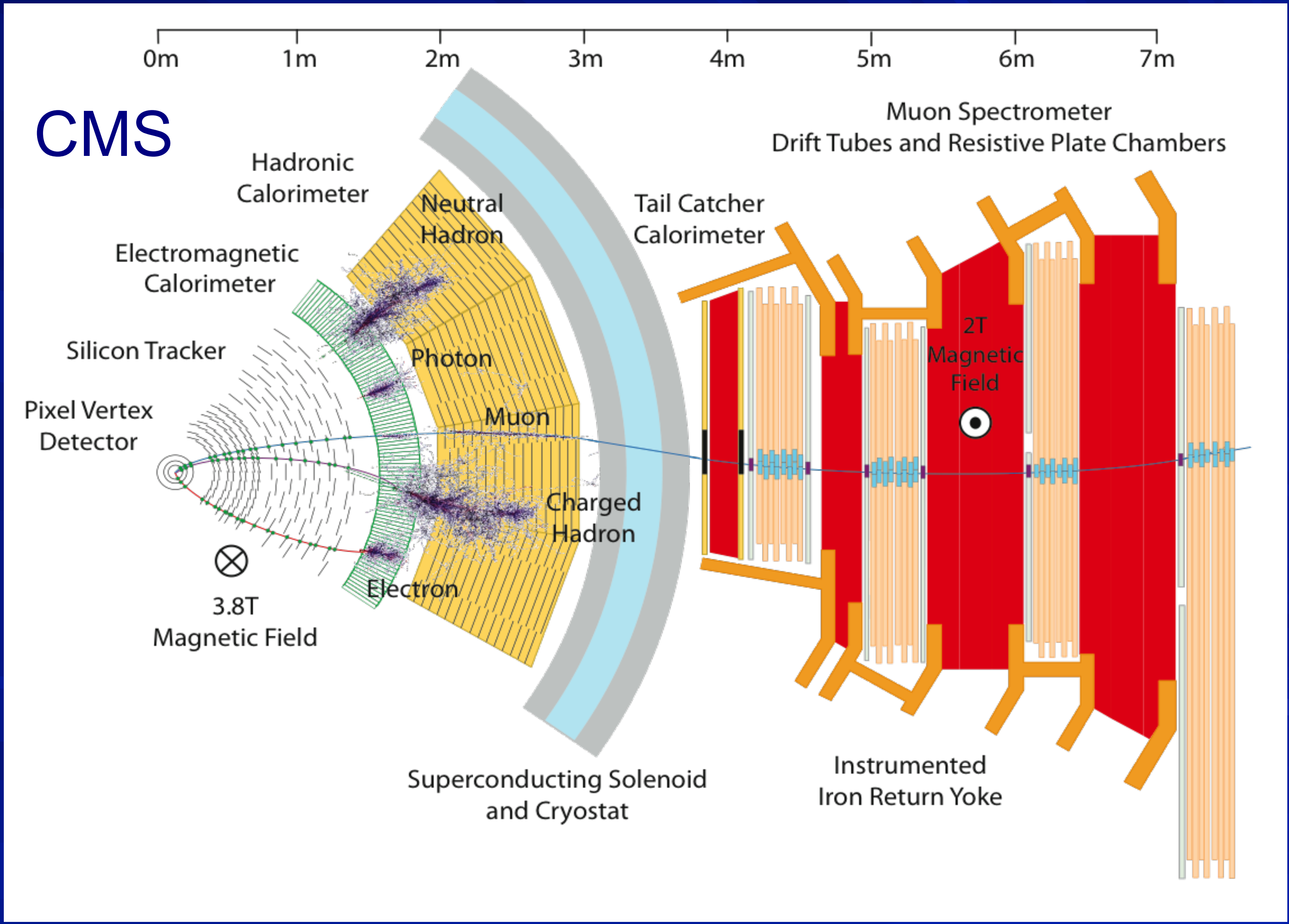




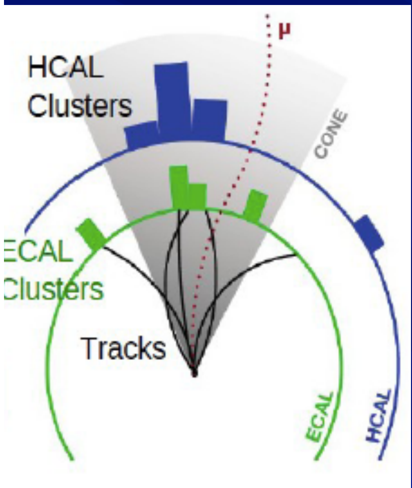


Multipurpose Detectors

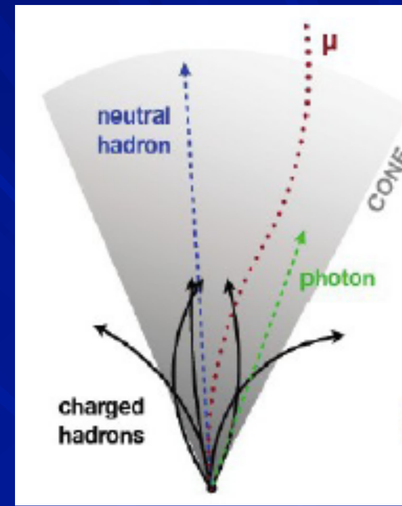
Particle flow reconstruction



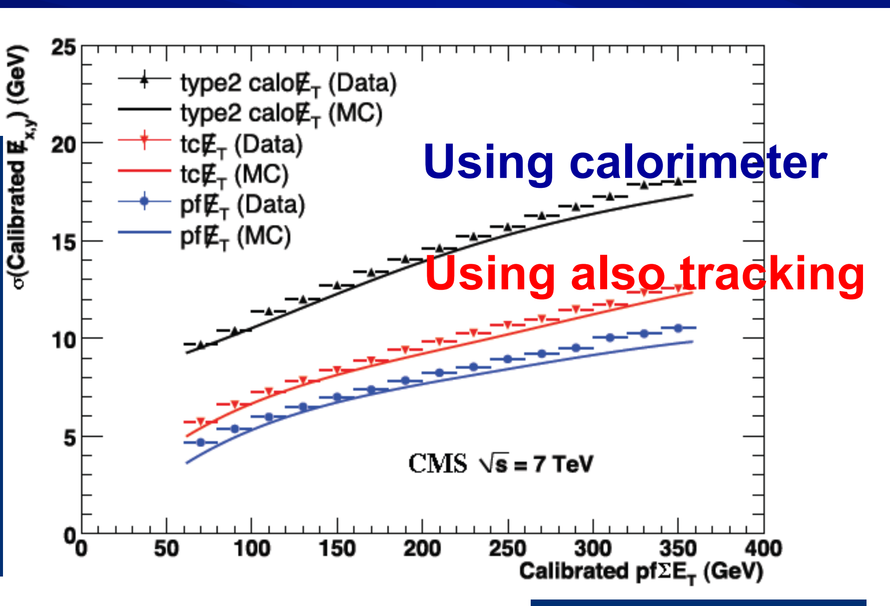
Particle Flow and Missing E_T



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



MET Resolution

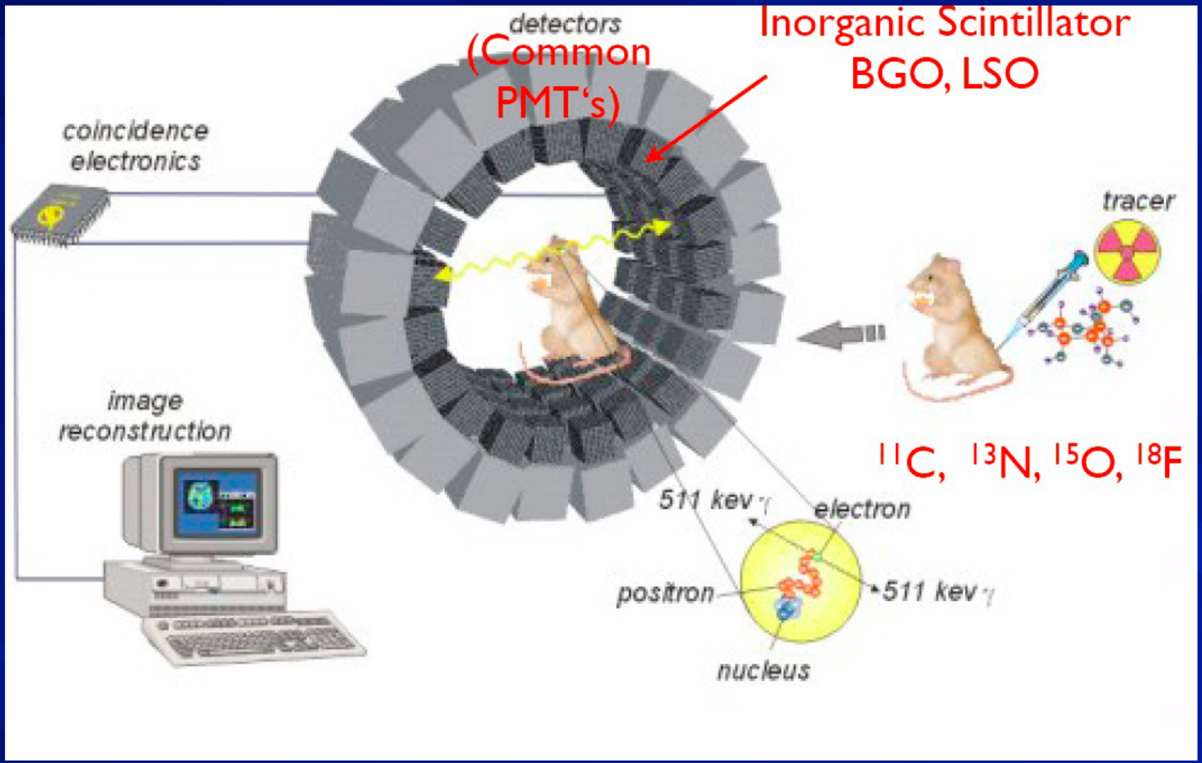


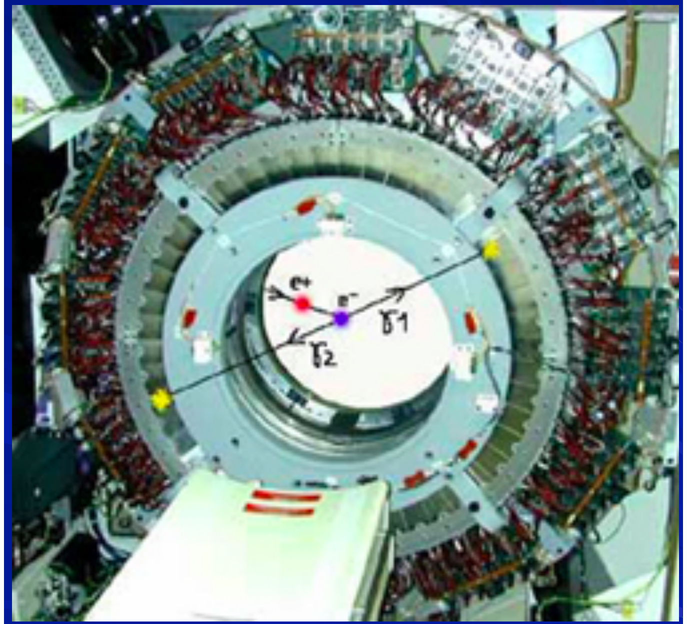
PF ΣE_T

- 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

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

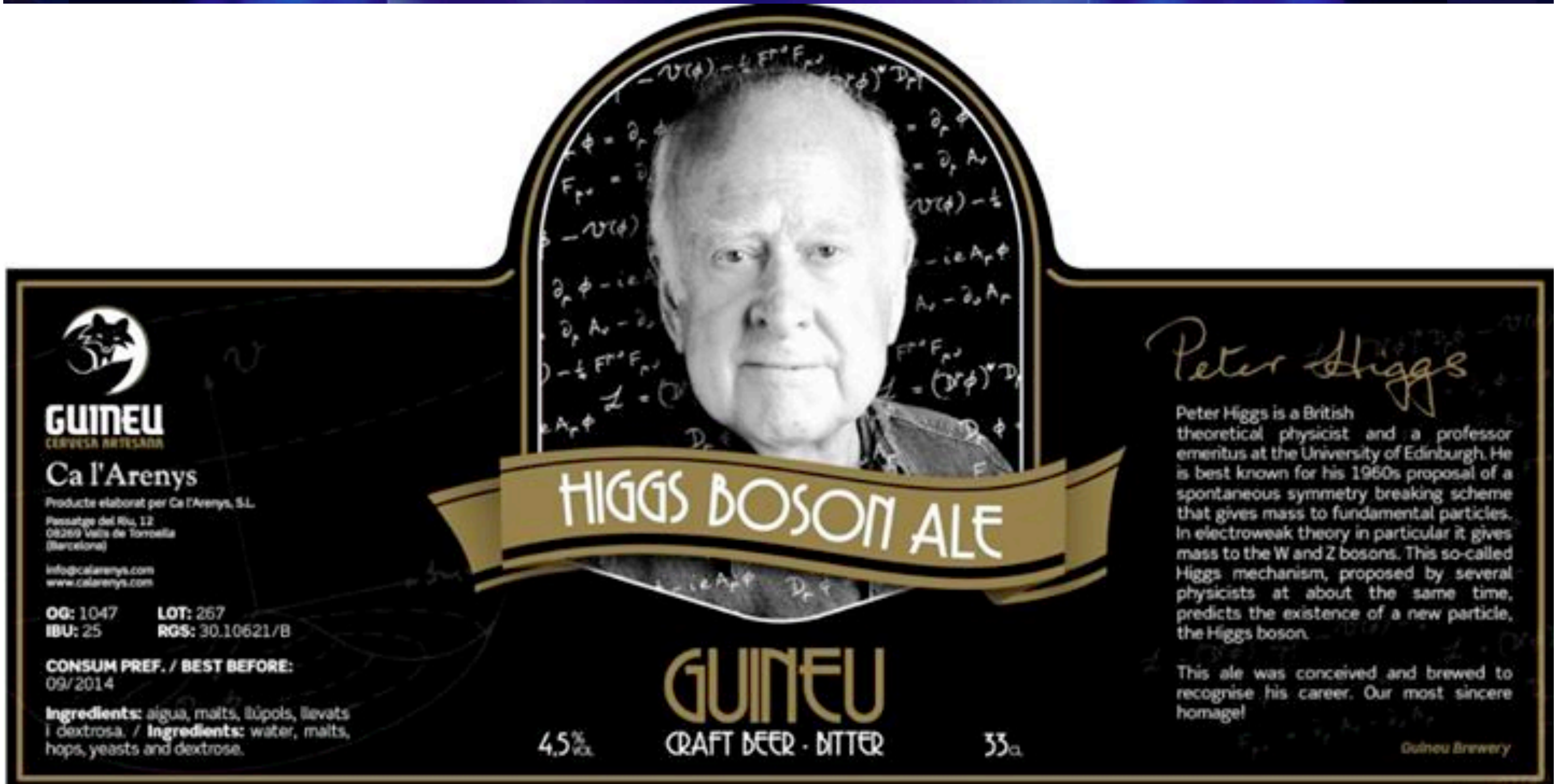
Application of HEP Detectors: PET





Understand these brilliant events

FUNDAMENTAL PHYSIC PRIZE
March 2013



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

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

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