Muon Detection

Basics,

all you always wanted to know about muons

LECTURE 1

How everything started

esipap... European School of Instrumentation in Particle & Astroparticle Physics

esi... European Scientific Institute

The muon discovery

- Muons were discovered by Carl D. Anderson and Seth Neddermeyer in a cloud chamber experiment at CalTech in 1936.
  - Anderson had noticed particles in the cosmic radiation that curved differently from electrons and other known particles when they passed through a magnetic field.
  - The particles were positively and negatively charged and curved less sharply than electrons, but more sharply than protons for the same velocity. To account for the difference in curvature, it was supposed that their mass was greater than that of an electron but smaller than that of a proton.
- The existence of such a particle was confirmed in 1937 by J. C. Street and E. C. Stevenson in a cloud chamber experiment. “New Evidence for the Existence of a Particle Intermediate Between the Proton and Electron", Phys. Rev. 52, 1003 (1937).

Anderson & Neddermeyer I

Phys. Rev. 50 (1936) 263

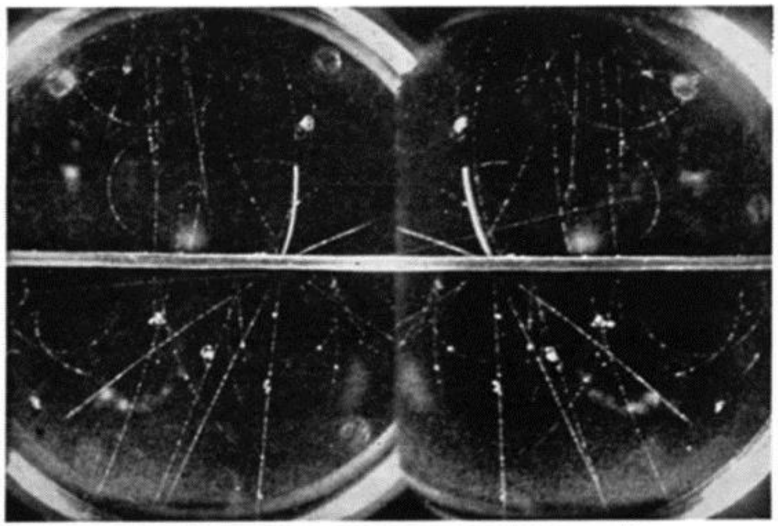

FIG. 12. Pike's Peak, 7900 gauss. A disintegration produced by a nonionizing ray occurs at a point in the 0.35 cm lead plate, from which six particles are ejected. One of the particles (strongly ionizing) ejected nearly vertically upward has the range of a 1.5 MEV proton. Its energy (given by its range) corresponds to an $H\rho = 1.7 \times 10^5$, or a radius of 20 cm, which is three times the observed value. If the observed curvature were produced entirely by magnetic deflection it would be necessary to conclude that this track represents a massive particle with an e/m much greater than that of a proton or any other known nucleus. As there are no experimental data available on the multiple scattering of low energy protons in argon it is difficult to

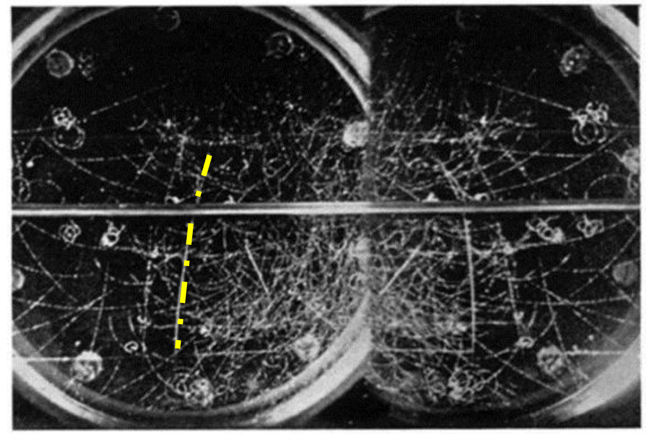

FIG. 13. Pasadena, 4500 gauss. A complex electron shower not clearly defined in direction, and three heavy particles with specific ionizations definitely greater than that of electrons. The sign of charge of two of these heavy particles represented by short tracks cannot be determined, but the assumption that they represent protons is consistent with the information supplied by the photograph. The third heavy track appears above the 0.35 cm lead plate where it has a specific ionization not noticeably different from that of an electron. It penetrates the lead plate and appears in the lower half of the chamber as a nearly vertical track near the middle. Below the plate it shows a greater ionization than an electron, and is deviated in the magnetic field to indicate a positively charged particle. Its $H\rho$ is apparently at most 1.4×10^5 gauss cm, which corresponds to a proton energy of 1 MEV and a range of only 2 cm in the chamber, whereas the observed range is greater than 5 cm. A difficulty of the same nature was discussed in the description of the previous photograph.

Anderson & Neddermeyer II

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Phys. Rev. 51 (1937) 884

(Acknowledgements …)

AND C. D. ANDERSON

and much smaller than that of a proton; this assumption would also account for the absence of numerous large radiative losses, as well as for the observed ionization. Inasmuch as charge and mass are the only parameters which characterize the electron in the quantum theory, assumption (*b*) seems to be the better working hypothesis. If the penetrating particles are to be distinguished from free electrons by a greater mass, and since no evidence for their existence in ordinary matter obtains, it seems likely that there must exist some very effective process for removing them.

The experimental fact that penetrating particles occur both with positive and negative charges suggests that they might be created in pairs by photons, and that they might be represented as higher mass states of ordinary electrons.

Independent evidence indicating the existence of particles of a new type has already been found,

AND C. D. ANDERSON

Street & Stevenson (cloud chamber)

NOVEMBER 1, 1937 PHYSICAL REVIEW VOLUME 52

LETTERS TO THE EDITOR

Prompt publication of brief reports of important discoveries in physics may be secured by addressing them to this department. Closing dates for this department are, for the first issue of the month, the eighteenth of the preceding month, for the second issue, the third of the month. Because of the late closing dates for the section no proof can be shown to authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents.

Communications should not in general exceed 600 words in length.

New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron

Anderson and Neddermyer[1] have shown that, for energies up to 300 and 400 Mev, the cosmic-ray shower particles have energy losses in lead plates corresponding to those predicted by theory for electrons. Recent studies of range[2] and energy loss[3] indicate that the singly occurring cosmic-ray corpuscles, even in the energy range below 400 Mev, are more penetrating than shower particles of corresponding magnetic deflection. Thus the natural assumptions have been expressed: the shower particles are electrons, the theory describing their energy losses is satisfactory, and the singly occurring particles are not electrons. The experiments cited above have shown from consideration of the specific ionization that the penetrating rays are not protons. The suggestion has been made that they are particles of electronic charge, and of mass intermediate between those of the proton and electron. If this is true, it should be possible to distinguish clearly such a particle from an electron or proton by observing its track density and magnetic deflection near the end of its range, although it is to be expected that the fraction of the total range in which the distinction can be made is very small. To examine this possibility experimentally we have used the arrangement of apparatus of Fig. 1. The three-counter telescope consisting of tubes 1, 2, and 3 and a lead filter *L* for removing shower particles, selects penetrating rays directed toward the cloud chamber *C* which is in a magnetic field of 3500 gauss. The type of track desired is one so near the end of its range as it enters the chamber that there is no chance of emergence below. In order to reduce the number of photographs of high energy particles, the tube group 4 was used as a cut-off counter with a circuit so arranged that the chamber would be set off only in those cases when a coincident discharge of counters 1, 2, and 3 was unaccompanied by a discharge of 4. The tripping of the cloud chamber valve was delayed about one sec. to facilitate determination of the drop count along a track. Because of geometrical imperfections of the arrangement and of counter inefficiency the cut-off circuit prevented

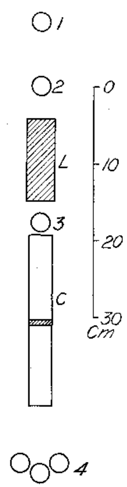


FIG. 1. Geometrical arrangement of apparatus.

FIG. 2. Track *A*.

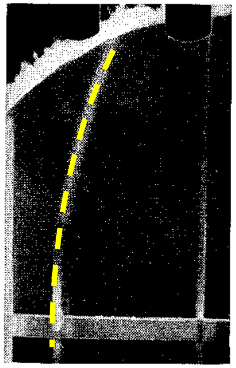


FIG. 3. Track *B*.

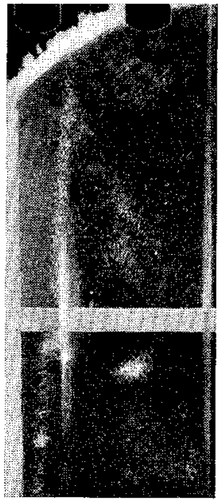


FIG. 4. Photograph of the track of a penetrating particle of high energy for comparison with *A* and *B*.

expansion for only $\frac{3}{4}$ of the discharges of the telescope. At the present time 1000 photos have been taken (equivalent to 4000 if the cut-off counter had not been used). Two tracks of interest, in that they have ionization densities definitely greater than usual, have been obtained: one *A* (see Fig. 2) is believed due to a proton and the other *B* (see Fig. 3) to a particle of mass approximately 130 times the rest mass of an electron. Track *A* which terminated in the lead strip at the center of the chamber exhibited an ionization density 2.4 times as great as the usual thin tracks and an $H\rho$ value approximately 2×10^6 gauss cm in a direction to indicate a positive particle. Track *B* which passed out of the lighted region above the lead plate had an ionization density about six times as great as normal thin tracks (the ion density was too great to permit an accurate ion count) and an $H\rho$ value of 9.6×10^4 gauss cm. If it is assumed, as seems reasonable, that the particle entered from above, the sign is negative. If it is taken that the ionization density varies inversely as the velocity squared, the rest mass of the particle in question is found to be approximately 130 times the rest mass of the electron. Because of uncertainty in the ion count this determination has a probable error of some 25 percent. In any case it does not seem possible to explain this track as due to a proton traveling up, for the observed $H\rho$ value would indicate a proton of 4.4×10^5 electron volts energy and therefore with a range of approximately one cm in the chamber. The track is clearly visible for 7 cm in the chamber.

The only possible objection to the conclusions reached above is that the bending of track *A* is largely due to distortion, but this is very unlikely, for the deflection is quite uniform and has a maximum value greater than ten times any distortions usually encountered in the thin tracks of high energy particles.

J. C. Street
E. C. Stevenson

Research Laboratory of Physics,
Harvard University,
Cambridge, Massachusetts,
October 6, 1937.

[1] Anderson and Neddermeyer, Phys. Rev. **50**, 263 (1936).
[2] Street and Stevenson, Phys. Rev. **51**, 1005 (1937).
[3] Neddermeyer and Anderson, Phys. Rev. **51**, 885 (1937).

Variation of Initial Permeability with Direction in Single Crystals of Silicon-Iron

Magnetic measurements at flux densities ranging from about 5 to 100 gauss have been made on single crystals of 3.85 percent silicon iron, in the crystallographic directions [100], [110] and [111]. Up to this time no data have been reported on the magnetic properties of single crystals at such low flux densities and it has generally been assumed that single crystals are magnetically isotropic at these flux densities.

Large crystals were produced in an atmosphere of pure hydrogen by melting silicon iron and permitting it to cool very slowly through the freezing point.[1] Three specimens were cut in the form of hollow parallelograms. Each

Anderson & Neddermeyer (III)

- Anderson initially called the new particle a *mesotron*, adopting the prefix *meso-* from the Greek word for "mid-". It later became mu-meson.
- In the Standard Model description, the mu-meson is different from the other “mesotrons” or “mesons”, it does not interact strongly and is not composed of quarks; it behaves rather like a heavy electron
- In fact, it is not a meson at all and, therefore, the name “muon” is much more appropriate.
- But this was not known at this time.

Note in passing …

- In these experiments of 1936/37 we see already two types of muon detectors
  - Cloud chamber (Precision tracking)
  - Geiger tubes (Trigger & veto)
- We have also introduced the use of a magnetic field and learned about one of the natural sources of muons: cosmic rays
- Things have not changed too much in the last 75 years … except
  - We now know how to make muons in a controlled way
  - We use somewhat more sophisticated detectors and …
  - the number of researchers (authors) involved in an experiment has slightly increased, from 2 to >2000 for, e.g., ATLAS or CMS

What are muons? Muon properties

http://pdg.lbl.gov/2013/listings/rpp2013-list-muon.pdf

- Muons are unstable charged particles with a mean life time of 2.2 μs (the second longest after the neutrons).
  - Negatively and positively charged
  - Decay to ≈100% into an electron and two neutrinos

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

$$\mu^+ \rightarrow e^+ \nu_e \, \bar{\nu}_\mu$$

- Their mass is 105.7 MeV, much heavier than electrons (0.511 MeV) and much lighter than taus (1777.8 MeV).
- Muons, electrons, and tau's, together with the neutrinos, form the family of leptons.
- Muons do not interact via the Strong Force and are much more penetrating than all other particles, except neutrinos.

Short excursion: Particle discoveries

- By the time of the muon discovery (1937) only protons, neutrons, electrons, and photons where known
- It took 10 years before the next particles were discovered, this time 'real' mesons
  - 1947: Pions (Cecil Powell (Nobel price 1950) in Bristol, using cosmic rays and photographic emulsions)
  - 1947: Kaons (Clifford Butler and George Rochester in Manchester, using a cloud chamber and cosmic rays at high altitude (Pyrenees)
- Another 10 years later the neutrinos were discovered
  - 1956: ν_e (Frederick Reines (Nobel Price 1995) and Clyde L. Cowan, using a Cd loaded water target at the Savannah River nuclear reactor)
  - 1962: ν_μ (Leon Ledermann, Melvin Schwarz, Jack Steinberger, at the new AGS at Brookhaven Nat. Lab.; Nobel Price 1988)
- 15 years later the tau lepton was discovered at SLAC by Martin Perl (Nobel Price 1995)

ν_μ discovery (1962)

Extract from Nobel price (1988) page of BNL

- The experiment used a beam of the AGS's*) energetic protons to produce a shower of pi mesons, which traveled 70 feet toward a 5,000-ton steel wall made of old battleship plates. On the way, they decayed into muons and neutrinos, but only the latter particles could pass through the wall into a neon-filled detector called a spark chamber. There, the impact of neutrinos on aluminum plates produced muon spark trails that could be detected and photographed -- proving the existence of muon-neutrinos.
- The experiment's use of the first-ever neutrino beam paved the way for scientists to use these particles in research at the AGS and around the world.

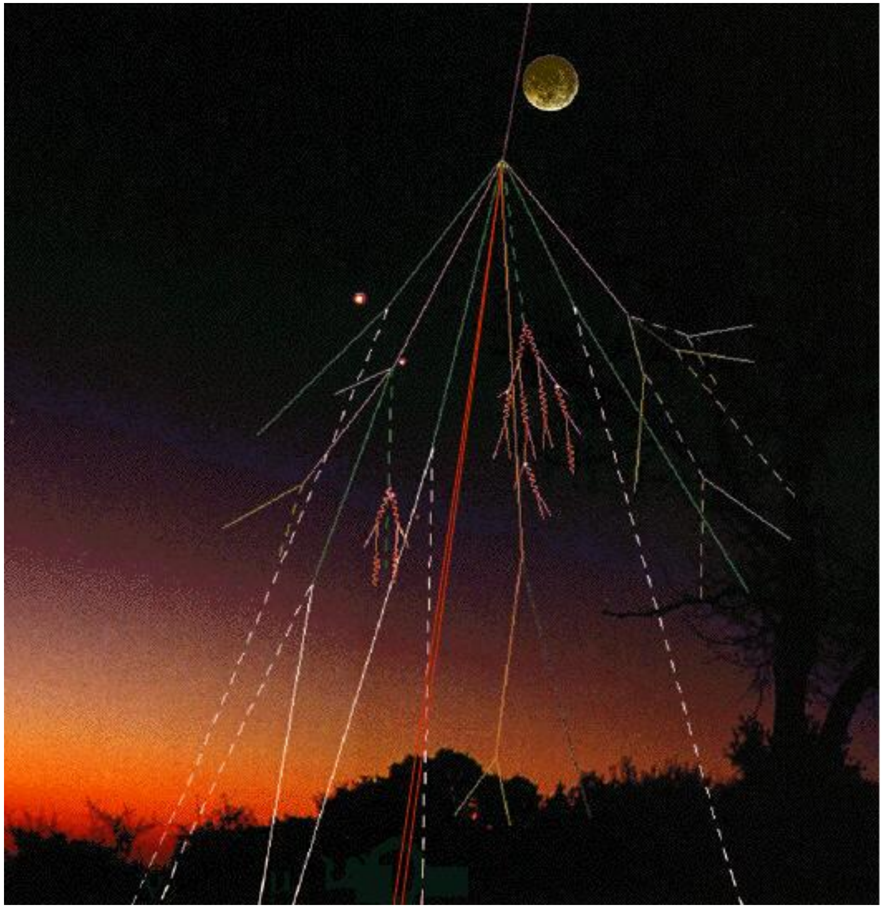
*) AGS = Alternating Gradient Synchrotron, a 33 GeV proton accelerator at the Brookhaven Nat. Lab.

Towards modern muon detectors

- The setup used at BNL in 1962 that lead to the ν_μ discovery brings us pretty close to modern muon detector systems. It exploited a number of features that we will find back all the time over the next two days.
  - The use of heavy shielding – absorption of unwanted particles (in this case of muons!)
  - A new type of detector (spark chamber)
  - The distinct event signature of muons to distinguish them from other particles

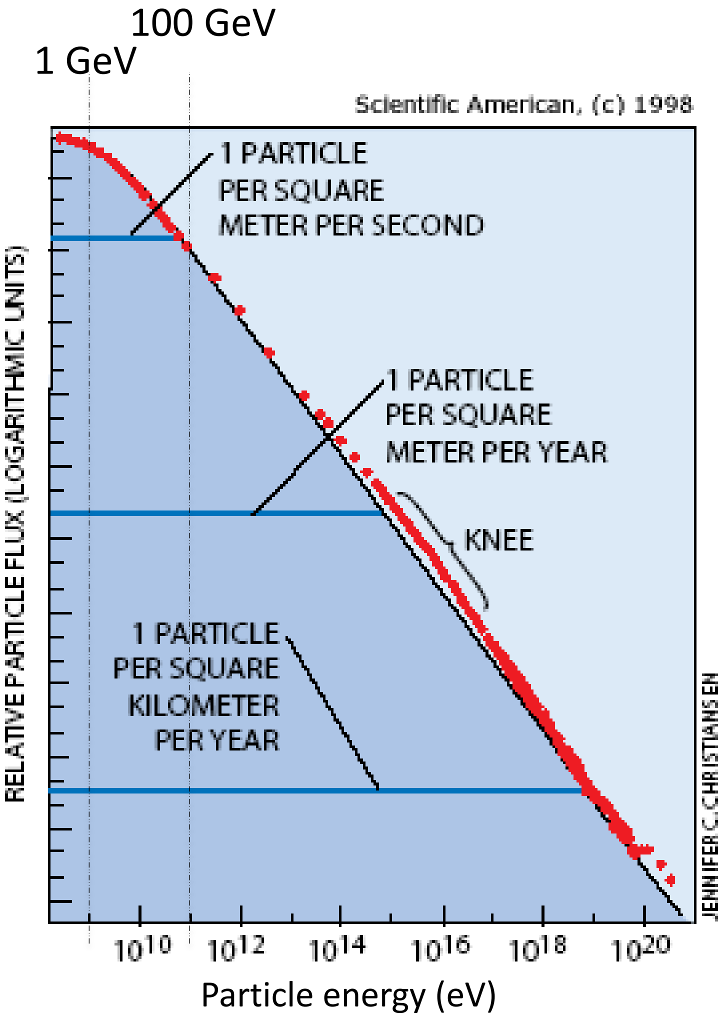
Muon sources

Muon production I



- Muons are mainly produced in the decay of charged pions
  - $\pi^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$ (anti ν_{μ})
- They represent about 80% of the cosmic ray flux at sea level
  - They are the result of hadronic interactions producing pions in the upper earth atmosphere, typically 15 km above sea level
  - Given their average life time (≈2.2 µs) they should not even make it to the earth if it was not for the time contraction owing to their high speed (relativistic, close to the speed of light)
  - Average energy loss of muons (2 GeV)
- Time dilatation experiment (Rossi, Hall, … in 1940) => Tutorial (?)

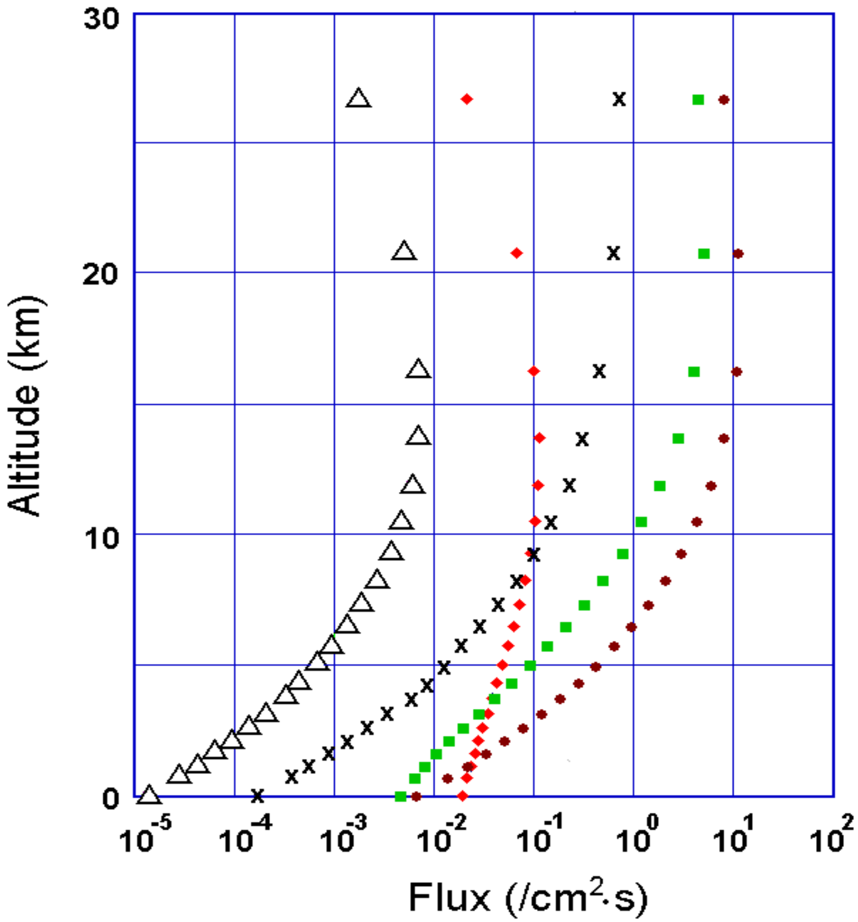
Cosmic ray flux



The composition of the cosmic ray flux is a strong function of the particle energy

- At sea level muons represent about 80% of the cosmic ray flux averaged over all energies
- Above E ≈ 1 GeV they contribute almost 100%
- Below 1 GeV/c the energy spectrum of muons is almost flat, above 1 GeV it falls, first gently then, above 100 GeV exponentially
- It extends to extremely high energies
- The average cosmic ray muon energy is 4 GeV

Composition of cosmic ray flux



NCRP Report No.94 (1987) "Exposure of the population in the United States and Canada from natural background radiation", National Council on Radiation Protection and Measurements, 7910 Woodmont Avenue/Bethesda MD 20814

The composition of the cosmic ray flux is also a strong function of the altitude

Muons dominate only below ≈3500 m, at higher altitudes electrons are the most abundant charged particle species

A typical muon rate for E_{μ}>1 GeV at sea level is

- 70 μ's $m^{-2}s^{-1}sr^{-1}$ or
- 1 $cm^{-2}min^{-1}$

A number to remember

Muon abundance in cosmic ray flux

- Going back to the muon discovery there are a number of interesting points to note by which we can understand why the muon was not discovered immediately in the cloud chambers
  - Anderson took data at sea level (Pasadena, L.A.) but also at 4300 m altitude on Pike's Peak (Colorado).
  - As we just saw, at high altitude electrons are more abundant than muons. This is one reason, the more important, however, is …
  - The cloud chambers were primarily seeing low-energy particles dominated by electrons since the very low energy muons do not make it to the sea level. They decay into electrons and neutrinos before they reach the ground.
- Anderson et al. did not know all this. If they had 'hardened' the energy spectrum by adding shielding above the setup and thus stopping all other low energy particles they would have seen muons immediately.
- Today, adding shielding in front of muon detection systems is common practice.

Composition of cosmic ray flux

- Another quantity to remember is the ratio

  $\mu^+/\mu^- > 1$

  in the cosmic ray flux
- This reflects the more abundant production of π^+ and K^+ in the forward direction in the primary interactions in the atmosphere (protons dominate over neutrons in the primary flux)

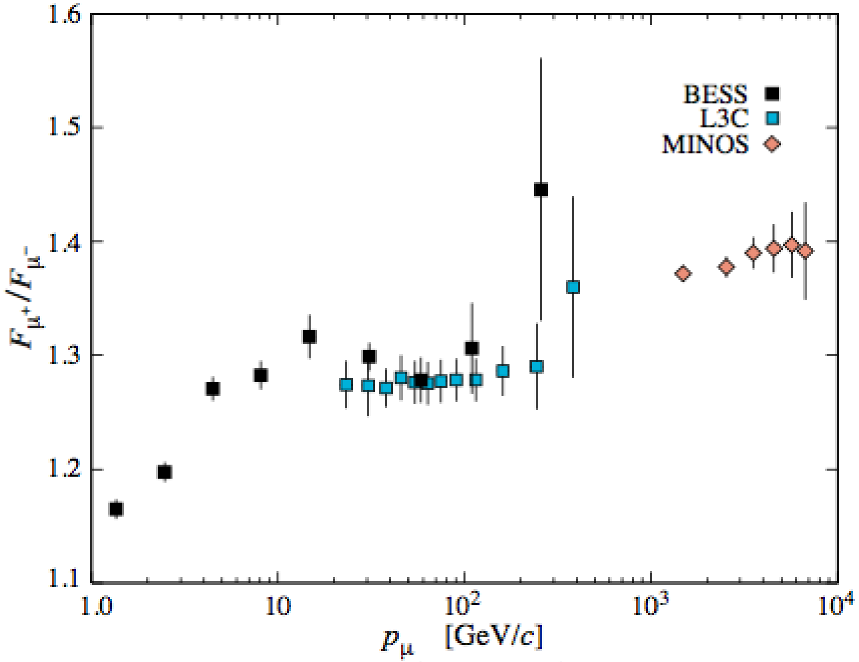


Figure 24.5: Muon charge ratio as a function of the muon momentum from Refs. [44,45,51].

Cosmic ray muon flux vs depth

- Given the cosmic muon energy spectrum and their typical energy loss muons can penetrate up to several kilometers water-equivalent (w.e.) of rock or ice or water
- The understanding of the muon energy loss is another important ingredient for designing a muon detector

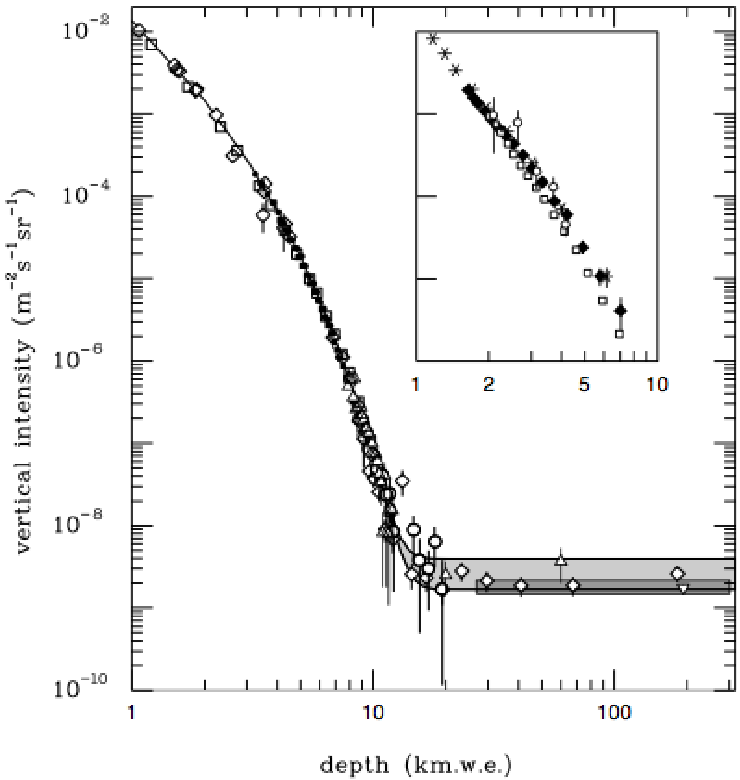


Figure 24.6: Vertical muon intensity vs depth (1 km.w.e. = 10^5 g cm^{-2} of standard rock). The experimental data are from: ◊: the compilations of Crouch [58], □: Baksan [63], ○: LVD [64], •: MACRO [65], ■: Frejus [66], and △: SNO [67]. The shaded area at large depths represents neutrino-induced muons of energy above 2 GeV. The upper line is for horizontal neutrino-induced muons, the lower one for vertically upward muons. Darker shading shows the muon flux measured by the SuperKamiokande experiment. The inset shows the vertical intensity curve for water and ice published in Refs. [59–62].

Muon energy loss

For muons with an energy above 1 GeV their energy loss (dE/dx) is governed by three processes

- Ionization dominates up to 100 GeV, very little dependent on energy, with a typical value of dE/dx for Fe of 2 MeV $g^{-1}cm^2$
- Above a few hundred GeV, Bremsstrahlung and Pair production become important and dominate
- Above 10 TeV also photonuclear interactions are no longer negligible; they result in rare (≈5%) but hard energy loss events

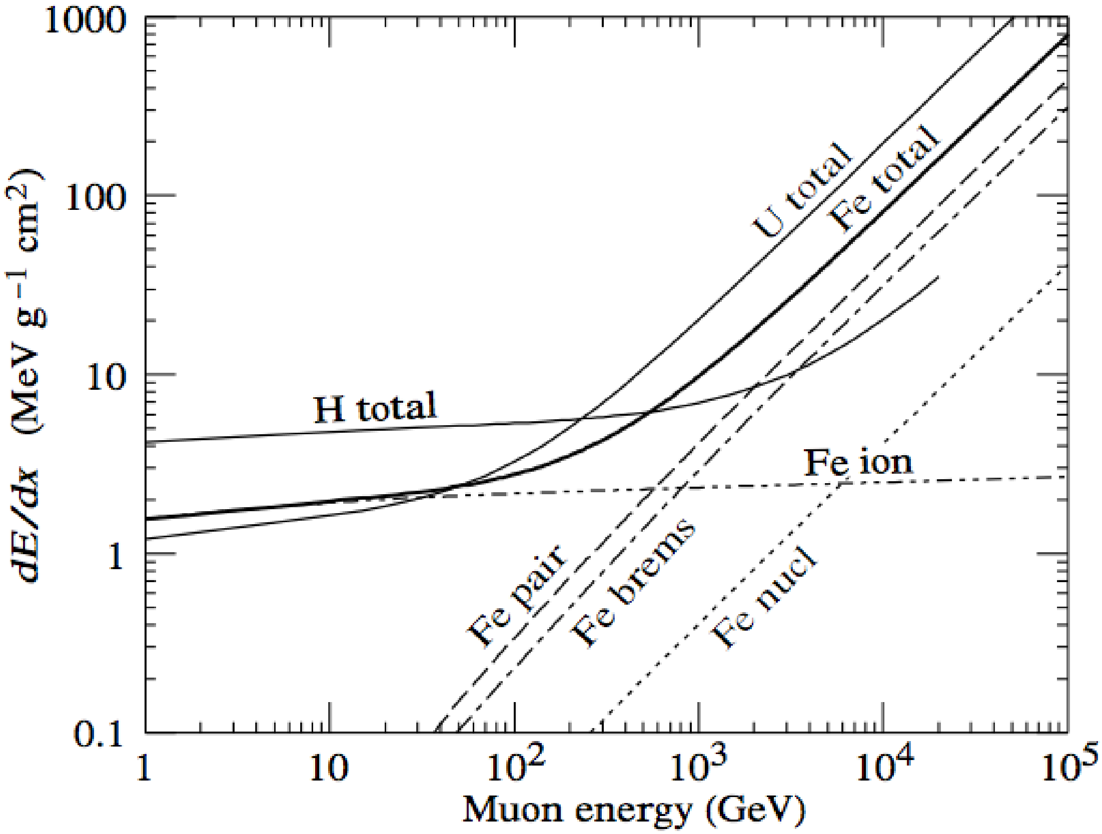
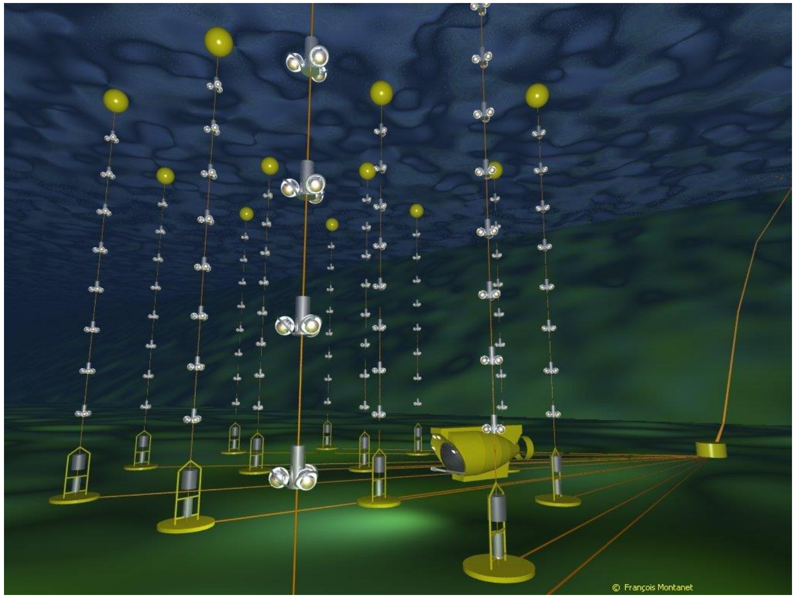
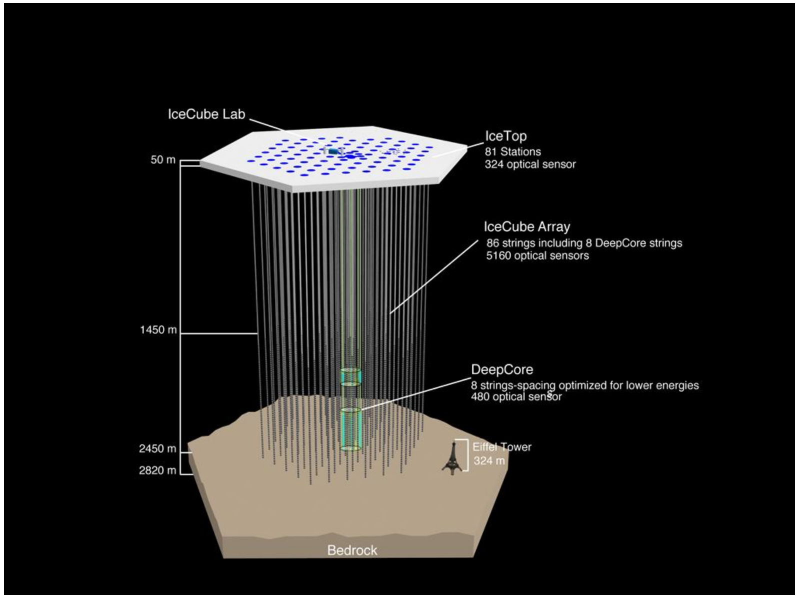


Figure 10.11: The average energy loss of a muon in hydrogen, iron, and uranium as a function of muon energy. Contributions to dE/dx in iron from ionization and the processes shown in Fig. 10.10 are also shown.

Underground 'muon' detectors





Antares, under-water Cherenkov detector in the Mediterranean sea close to Marseille.

The IceCube Neutrino Telescope (Antarctic) is made up of 86 strings with a total of 5,160 Digital Optical Modules that are used to sense and record neutrino events in ice.

Muons in underground detectors

In underground or under-water neutrino detectors muons play a dual role

- They are unwanted background; one tries to place the detectors are deep as possible at few thousand meters water equivalent
- They are signature. Muon neutrinos will most of the time interact via charge-current reactions

$$\nu N \rightarrow \mu + X$$

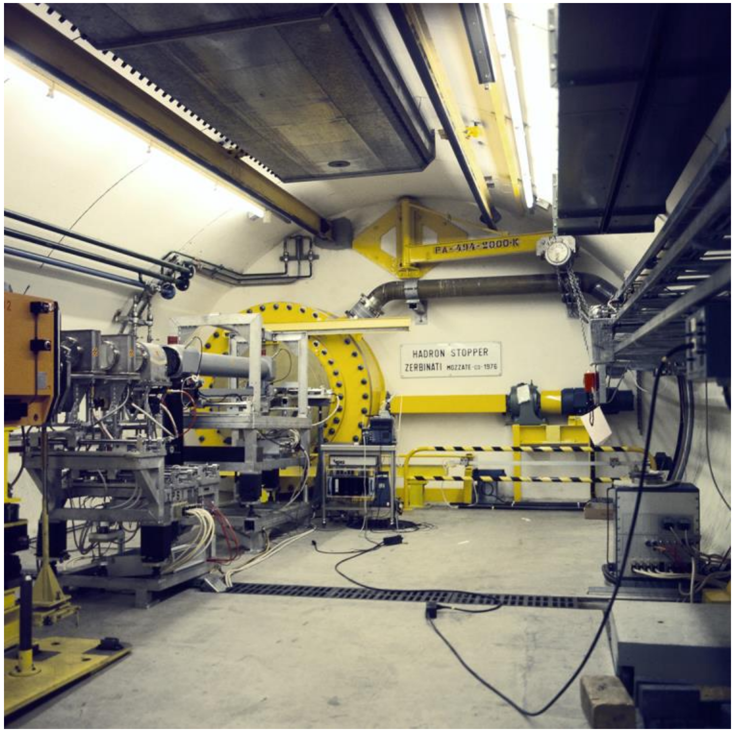
creating an energetic muon in the final state

- The muon is then detected via Cherenkov radiation by the phototubes employed in the water or ice

Muon production II (beams)

- In accelerators muons are abundantly produced in hadronic interactions through the chain

$$pp \rightarrow \pi + \ldots \quad \text{and} \quad \pi \rightarrow \mu\, \nu_\mu$$

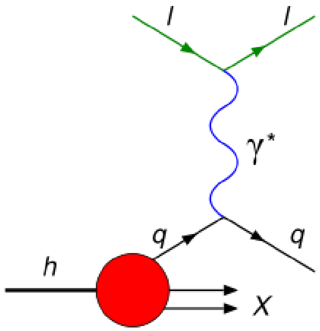


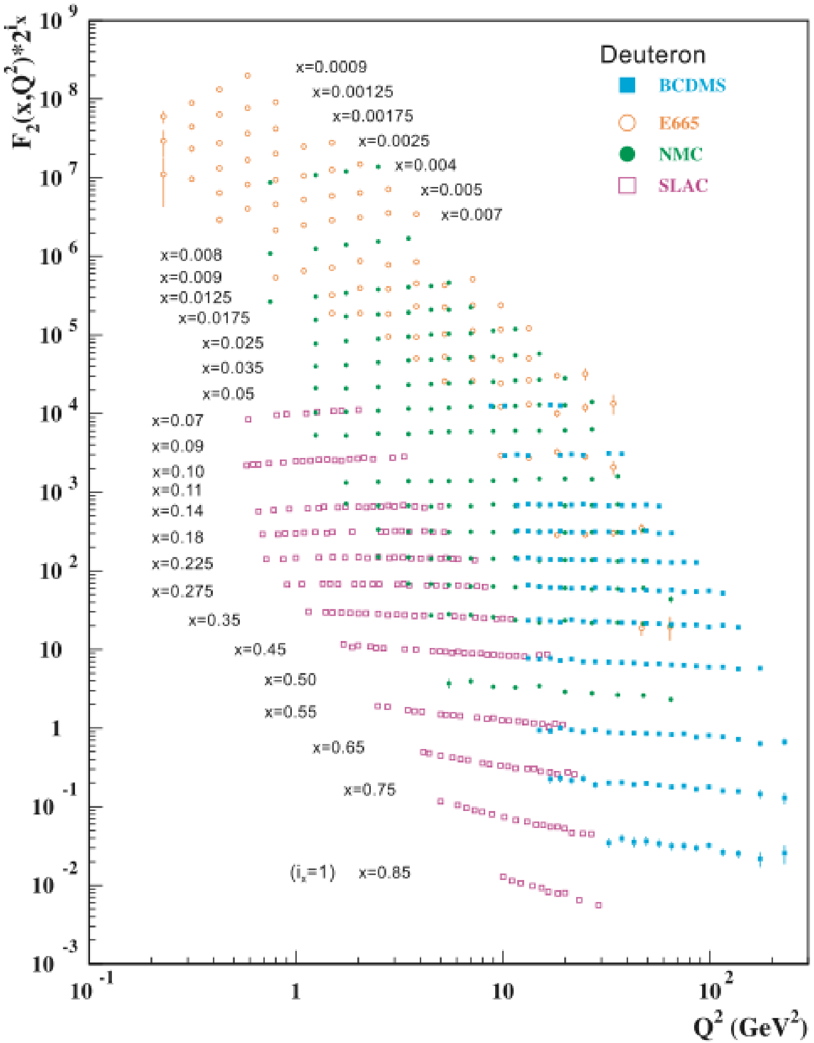
Muon beams

- Today muon beams are available at many places in Europe, Asia, and America.
    - High energy muon beams, e.g., at CERN SPS, FNAL
    - Low/medium energy: PSI, TRIUMF, Los Alamos, BNL, DUBNA, RAL, …
- Muons are also copiously produced in Collider experiments

Fixed-target experiments with muons

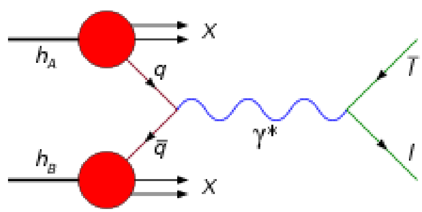
- The fact that muons (like electrons) can be considered as point-like objects they are ideal to probe the nuclear matter and have been intensively used as such in deep-inelastic scattering experiments.
- Dedicated muon experiments in the 1970's and 80's contributed, together with neutrino experiments, decisively to the understanding of the nuclear structure.

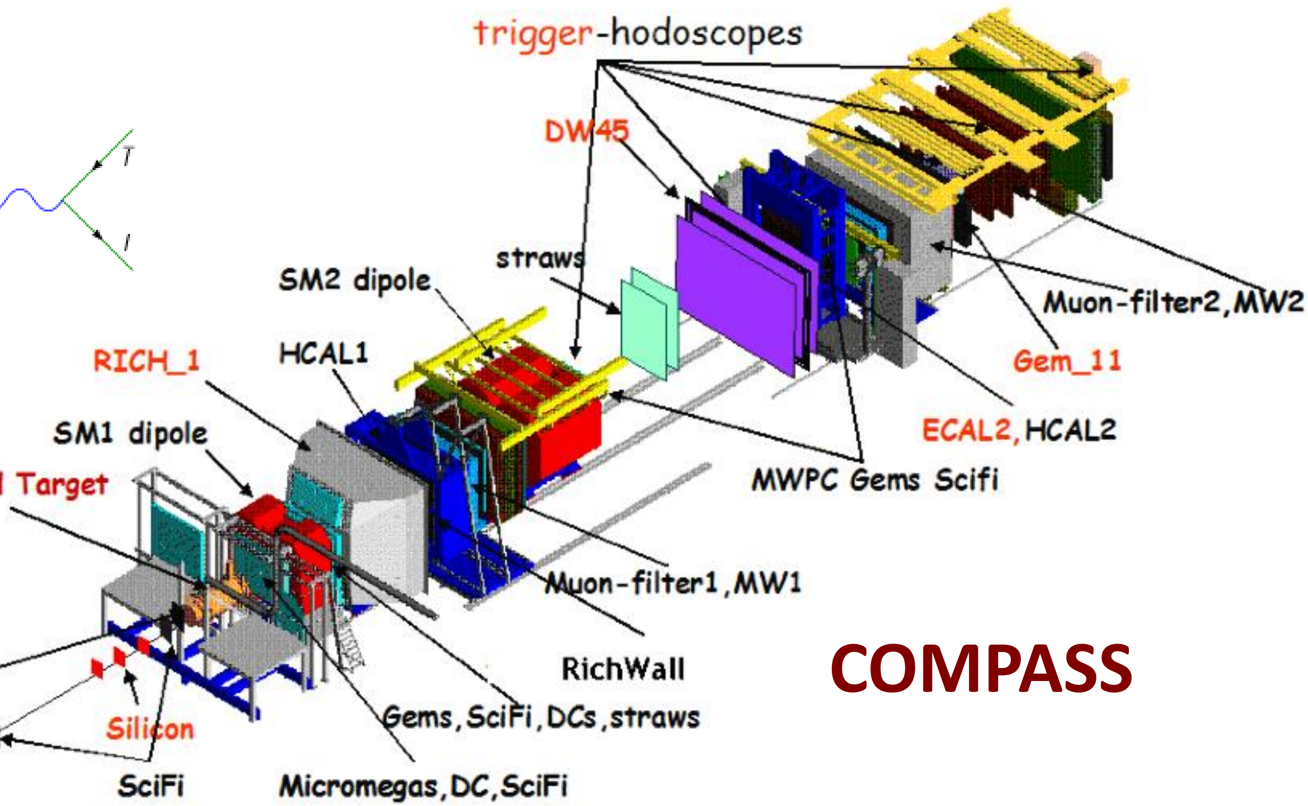




Fixed-target experiments with muons

- Muon detection played (and still plays) also an important role in hadron-production experiments, e.g., to identify and measure Drell-Yann processes

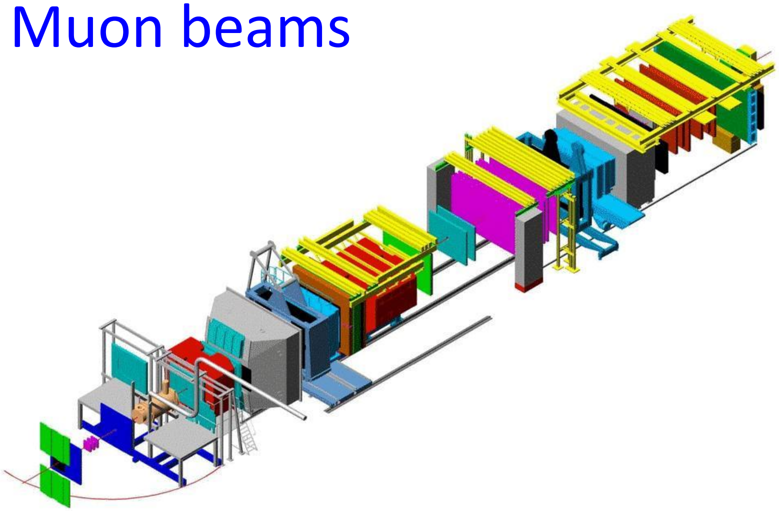




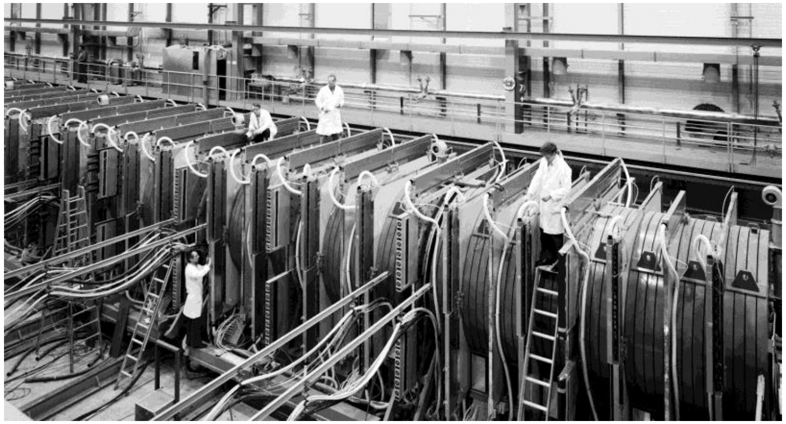
COMPASS

Fixed-target muon detectors

Muon beams



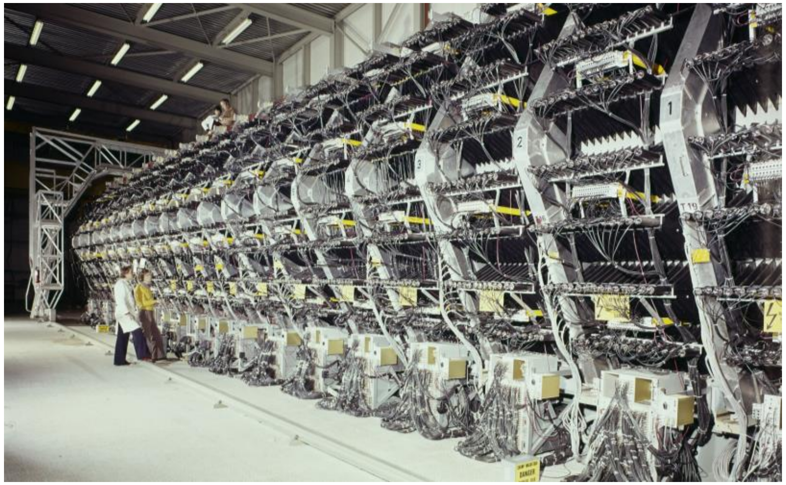
COMPASS muon scattering experiment at CERN (M2 beam line) - in operation



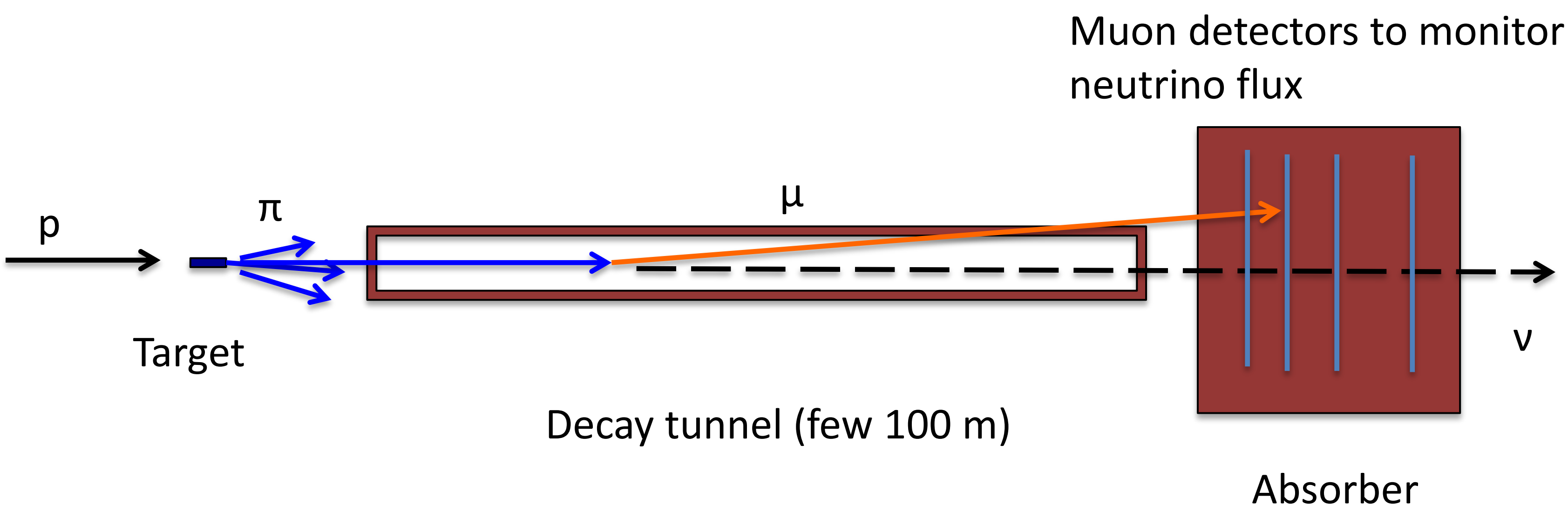
NA4 muon detector at CERN in 1978 deep-inelastic muon scattering experiment

Neutrino beams

CDHS (WA1) neutrino detector at CERN in 1977 (operational from 1976 to 1984)

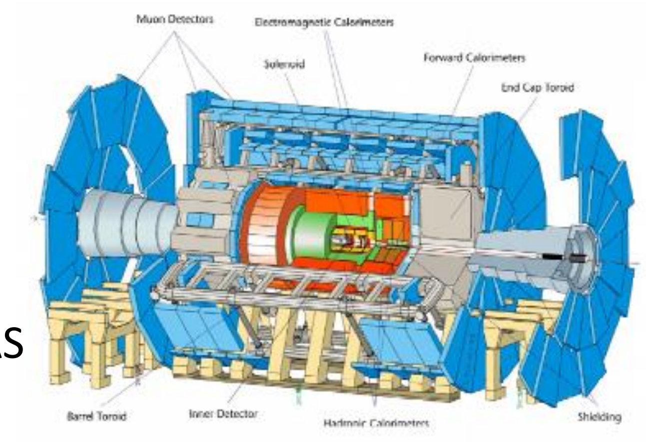


Neutrino beams

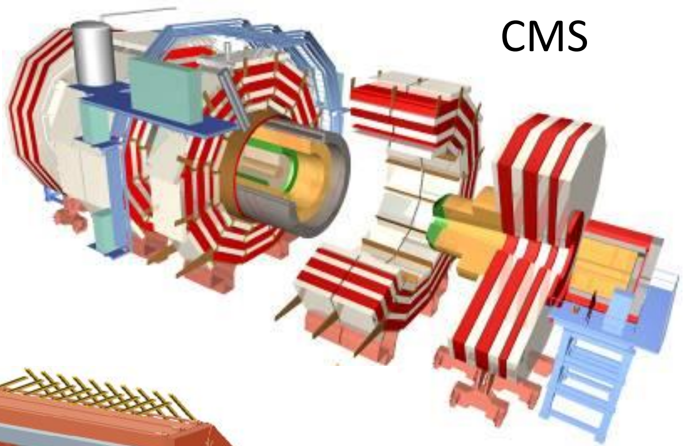


Collider experiments

- LEP detectors (ALEPH, DELPHI, L3, OPAL) had all muon systems (Z –> μμ, W –> μX, …)
- Hadron collider experiments make heavy use of muon systems

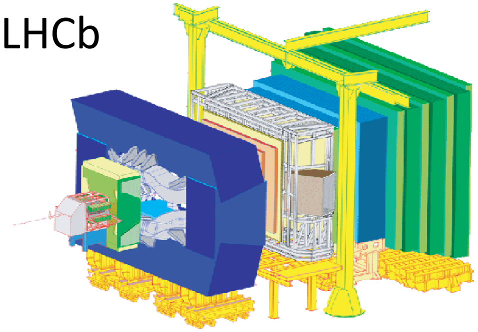


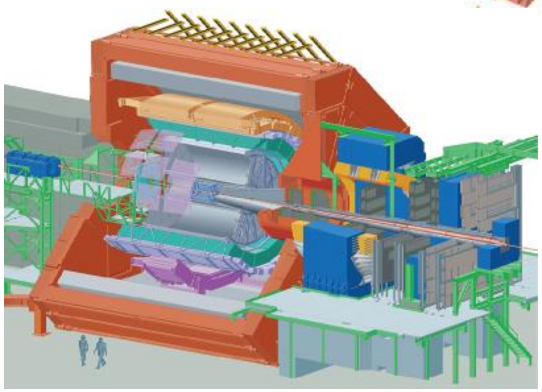
ATLAS



CMS

LHCb





Alice

European School of Instrumentation in Particle & Astroparticle Physics

What have we learned so far

European Scientific Institute

- Muons were discovered in 1937 in the cosmic ray flux where they are copiously present (but this was not known in 1937)
- Muons are charged(±) and unstable, but relatively long-lived particles (life-time 2.2 μs)
- They are point-like and not composed of quarks; they are like electrons, only about 200 times heavier
- Like electrons they do not interact via the strong interaction
- Differently from electrons, bremsstrahlung becomes only important above a few 100 GeV
- They are the most penetrating charged particles, in one meter of iron they lose only ≈1.5 GeV

We are ready

- We know now the basics to design ourselves a muon detector
- See you this afternoon …