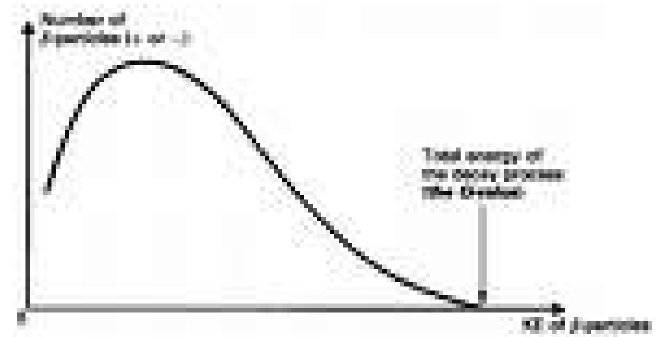
NEUTRINO PHYSICS

1. Historical milestones
2. Neutrinos at accelerators
3. Solar and atmospheric neutrinos
4. Neutrino oscillations
5. Neutrino astronomy
5. Future aims

When it all started…

Problem of energy conservation in β decays (also spin-statistics)



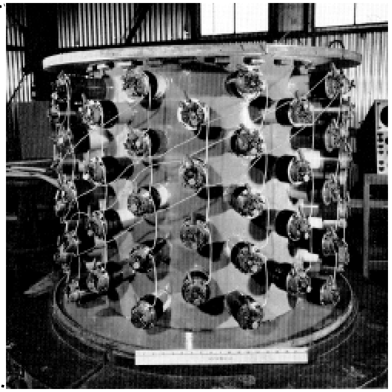
W. Pauli 1930, postulates a new invisible particle

E. Fermi 1933, the neutrino ν

$m(\nu) < 100$ keV

Reines and Cowan 1956, experimental proof

$$\bar{\nu}_e + p \rightarrow n + e^+$$



The second neutrino

New missing energy problems in π and μ decays, seen in cosmic rays

First neutrino beam built at the Brookhaven accelerator

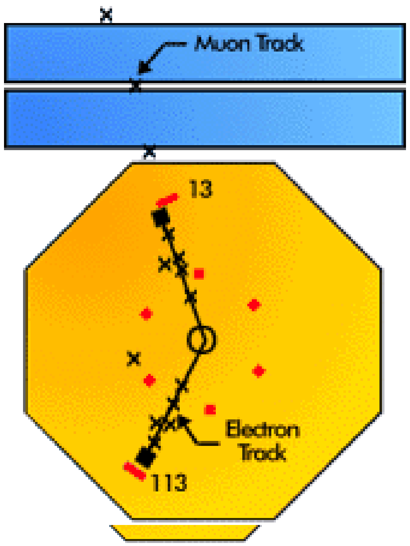
Lederman, Schwartz and Steinberger, 1964

29 interactions showing a muon, none with an electron

ν_μ *with* μ, ν_e *with* e

$\Rightarrow$ two different conserved leptonic numbers

The third neutrino



Mark 1 detector at SPEAR, 1975

~ 20 « anomalous events »

$e^+ + e^- \Rightarrow e + \mu + X$

Beginning of the 3rd family

$e^+ + e^- \Rightarrow \tau^+ + \tau^-$

Three conserved lepton numbers

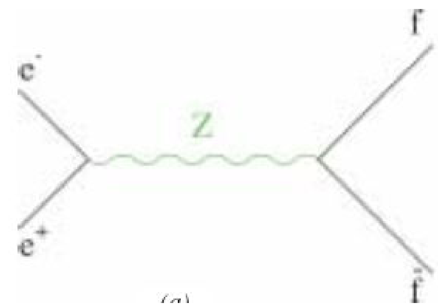
$\tau \Rightarrow e + \nu_\tau + \nu_e$

$\tau \Rightarrow \mu + \nu_\tau + \nu_\mu$

Direct proof: a few events obtained in the Donut exp,

Beam-dump at Fermilab 2000 , $D_s \Rightarrow \tau + \nu_\tau$

Three and only three neutrinos



LEP = Z factory

Z decays democratically to all pairs of constituants (m<45 GeV)

11 constituants: 2.7 GeV width

New ν flavor adds 167 MeV to the width

First LEP result (1989)

$N(\nu) = 3.00 \pm 0.01$

⇒ Three families of constituants

« Who ordered the other two? »

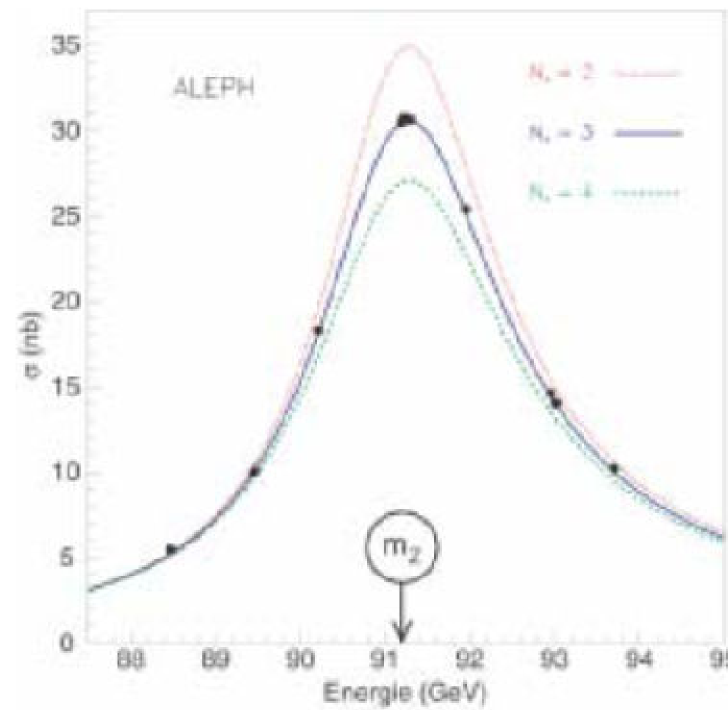
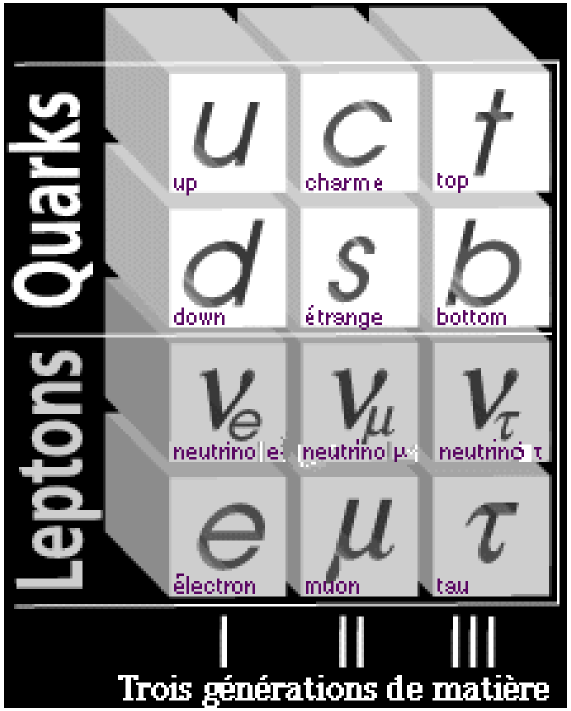
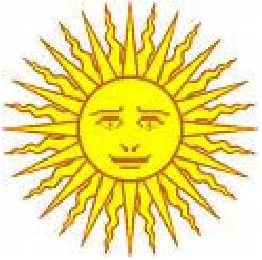
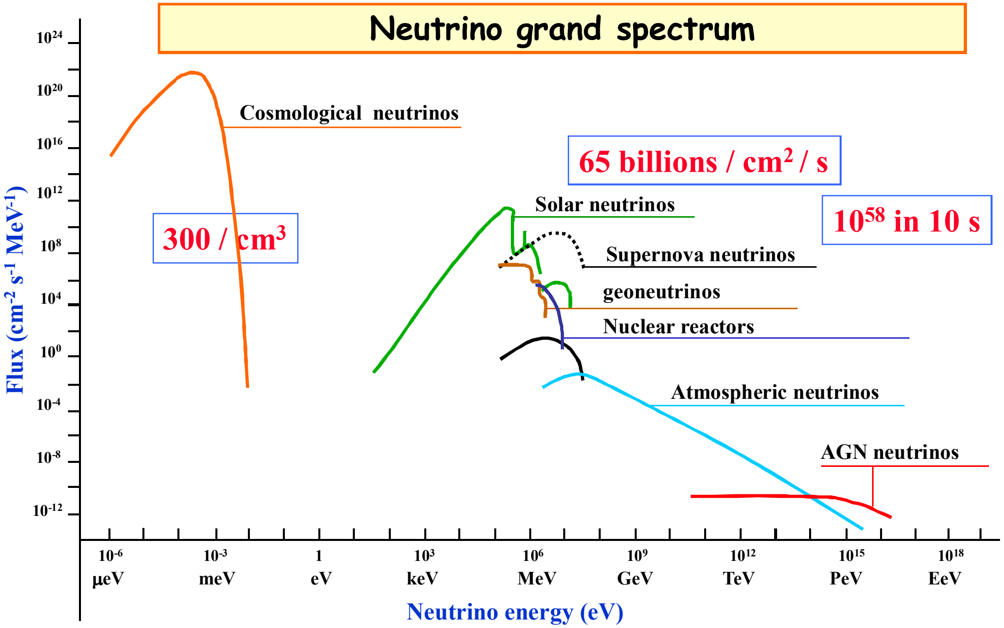


Table of elementary constituants



Neutrino sources



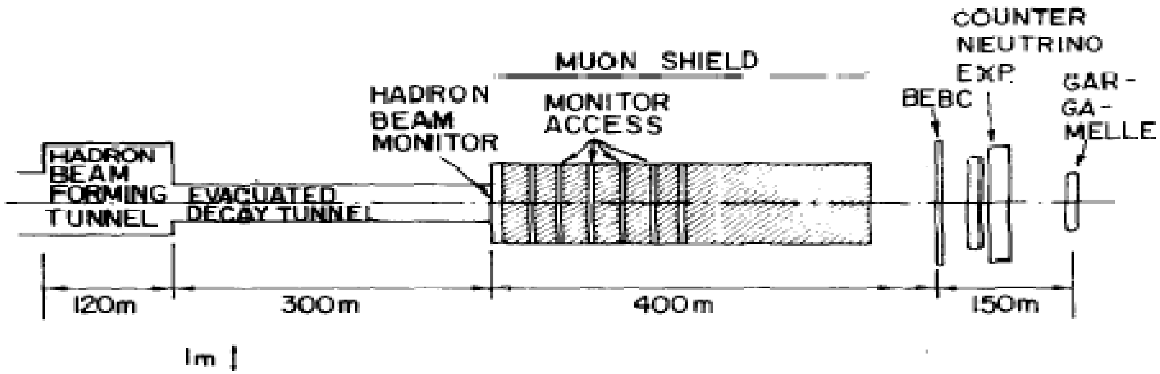


Accelerator neutrino beams

- Neutrino program exists at Cern since ~1965

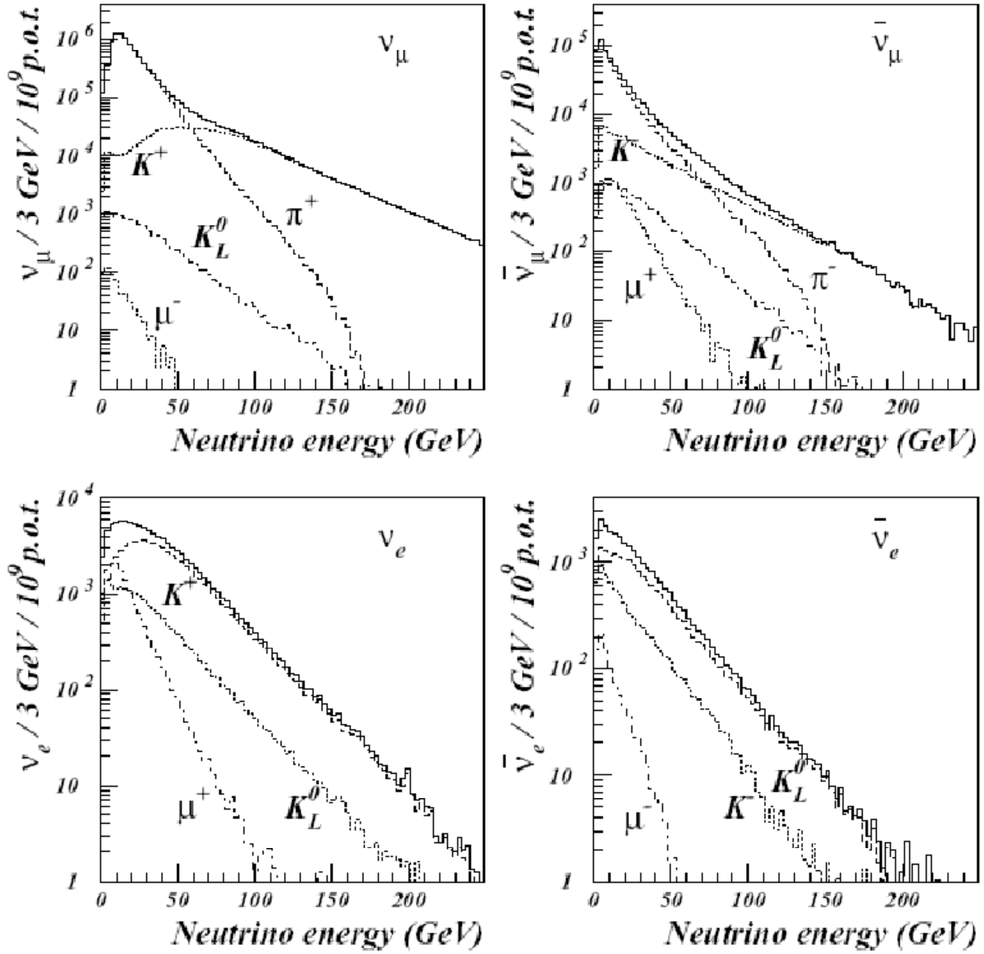
  - *Wide band beam: maximum intensity (99% ν_μ, 1% ν_e)*

  With a magnetic horn possibility to choose beams of ν_μ or anti-ν_μ



  - *Narrow band beam: Magnetically selected π and K; only 1% of the flux but energy information*

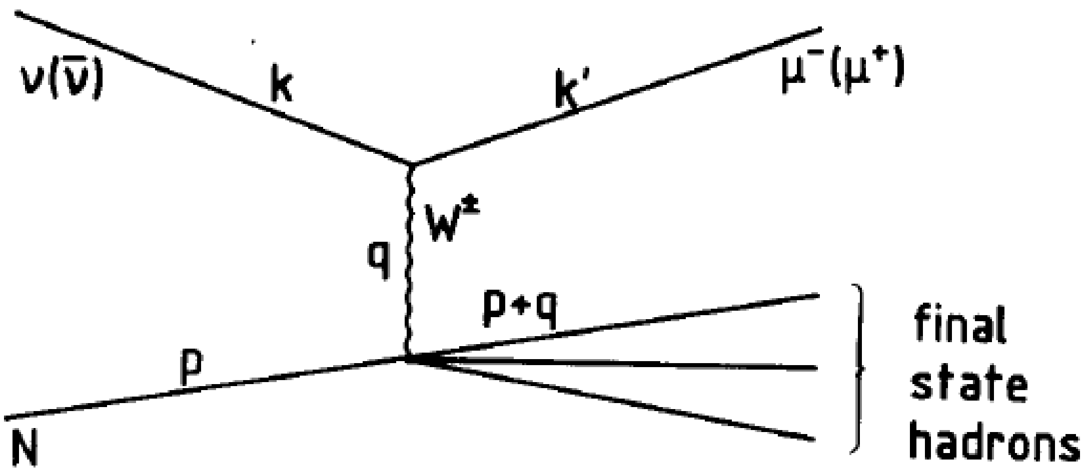
Neutrino energy spectrum (450 GeV protons)



Neutrino interactions

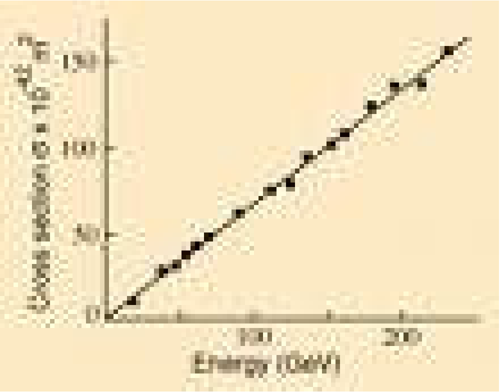
- *Weak interactions only*

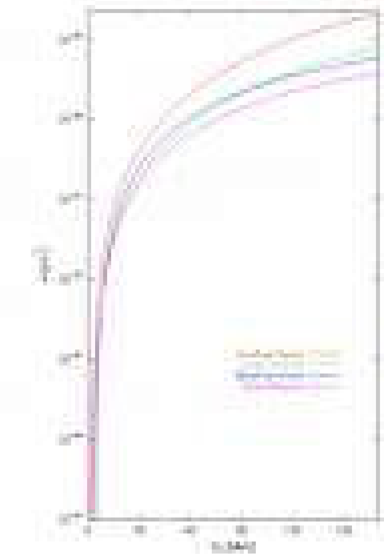
$$\nu_\mu + N \Rightarrow \mu + hadrons$$



Neutrino cross-section

$\sigma = 0{,}7\ 10^{-38} * E\ (\mathrm{GeV})\ \mathrm{cm}^2$





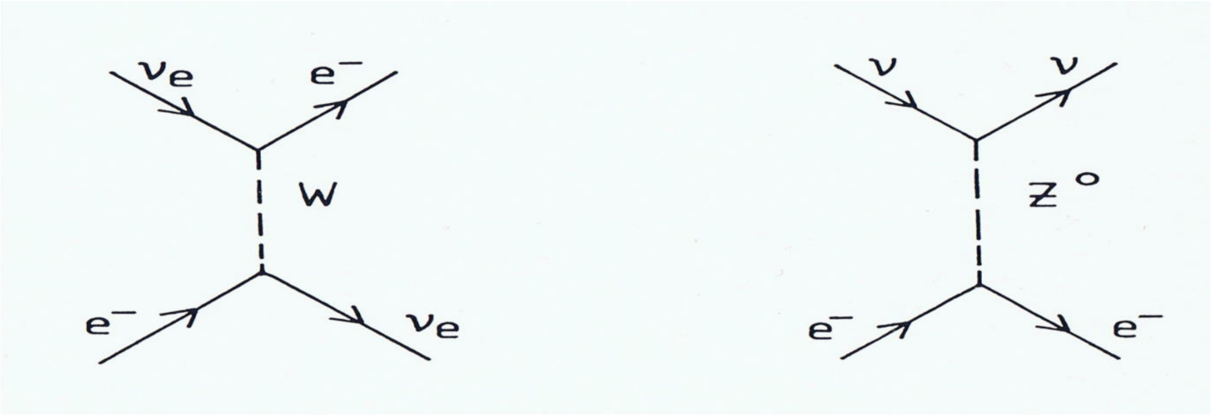
Solar ν: only 1/1 billion interacts in crossing the earth

But earth becomes opaque above 10^{15} eV

- ⇒ Neutrino physics: need of huge fluxes and gigantic detectors

Interactions on electrons

- *Purely leptonic process, simple in principle*



But experimentally difficult

$$\sigma(\nu+e)/\sigma(\nu+N) \sim m_e/m_N \sim 1/2000$$

Only 1 electron emitted in the beam direction

Evolution of neutrino detectors

Compromise between resolution measurement and statistics

Pioneer detectors: bubble chambers

They studied ν interactions in a non-biased way (<1985)

GGM, BEBC

Precise info but slow technique, limited statistics

Calorimeter type

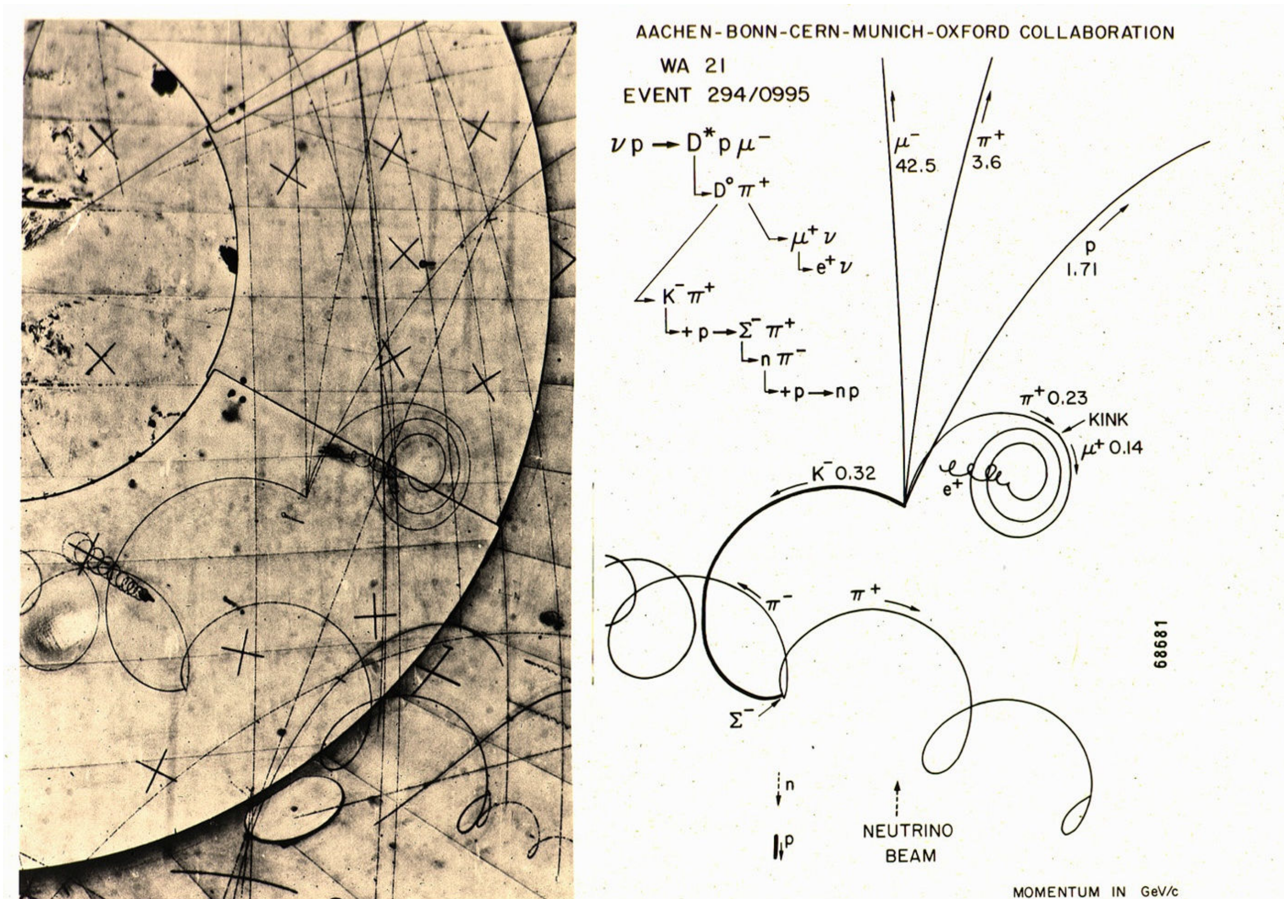
CDHS, Charm, HPW, CCFR

High statistics, limited resolution

More modern versions

NOMAD, Icarus

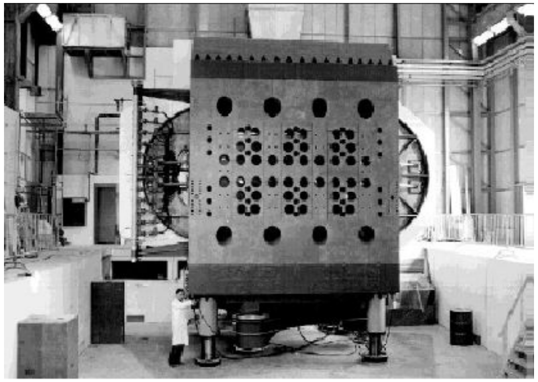
A textbook picture



Gargamelle

Discovery of neutral currents

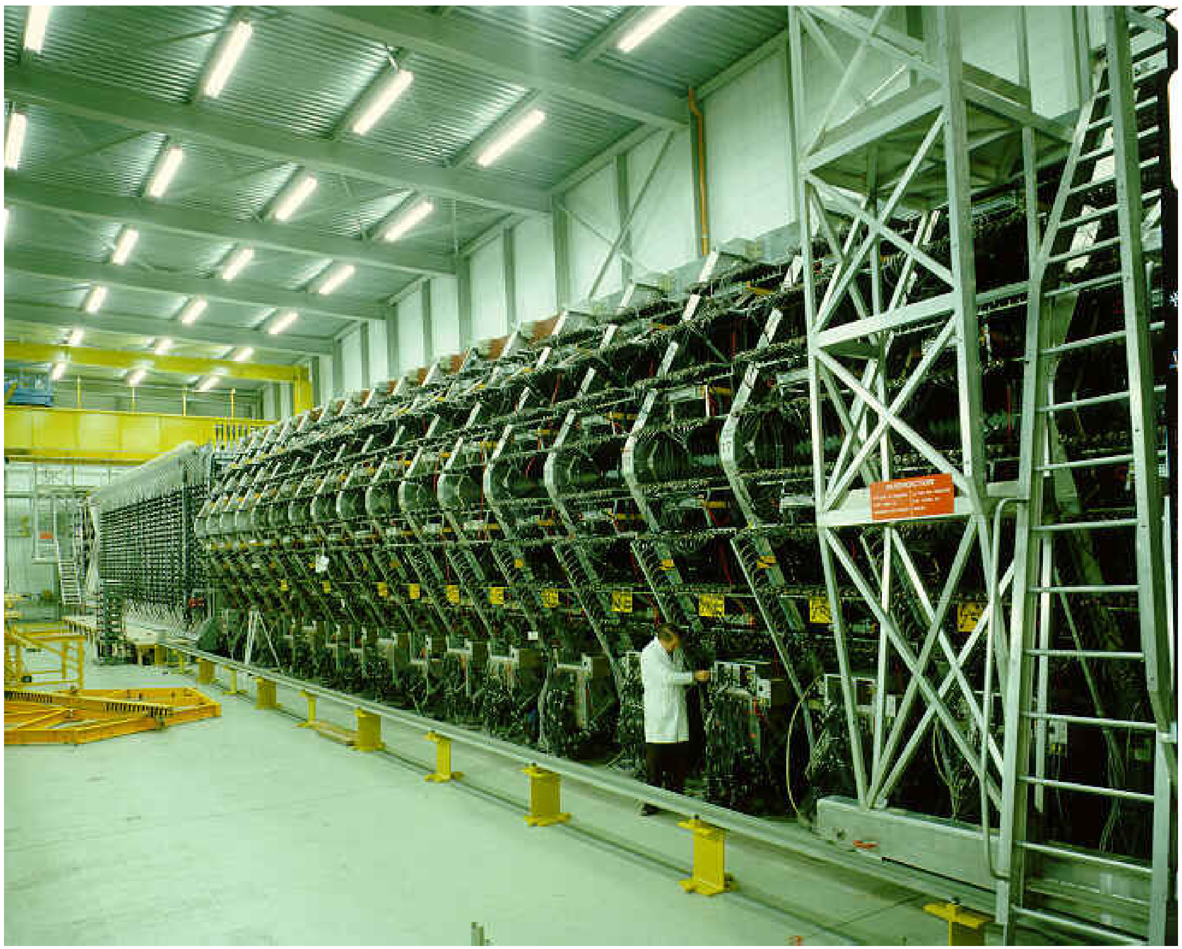
(1973)



$$\nu_\mu + N \to \nu_\mu + hadrons$$

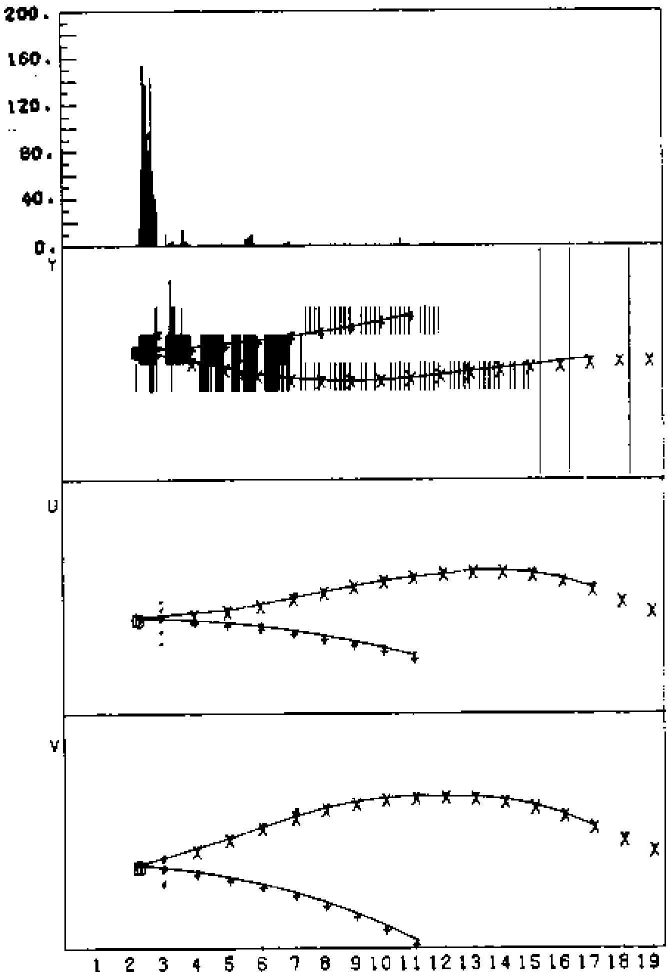
$$\nu_\mu + e^- \to \nu_\mu + e^-$$

The CDHS experiment (1977-1983)



1250 tons of magnetised iron sandwiched with planes of scintillators and wire chambers

« Typical event »



(b)

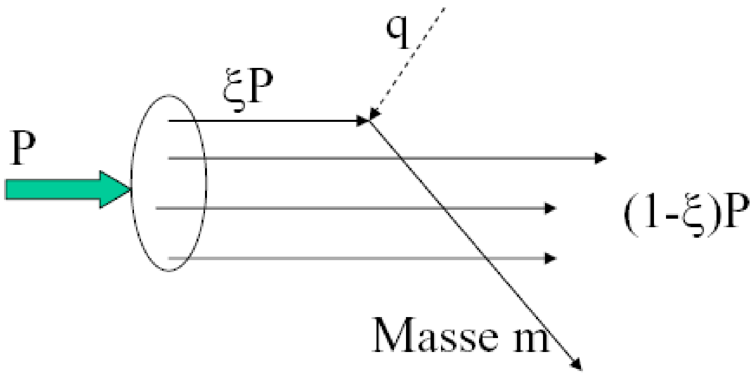
Good detection of muons

Sign and energy are measured

$\Delta p/p = 15\%$

Deep inelastic scattering

Neutrinoscopy of the nucleons



$$(\xi P+q)^2 = m^2 << Q^2$$

$$\xi^2 P^2 + q^2 + 2\,\xi Pq \sim 0$$

$$\xi^2 M^2 + 2\,\xi Pq \sim 2\,\xi Pq \sim Q^2$$

$$\xi = \frac{Q^2}{2Pq} = \frac{Q^2}{2M\nu} = x$$

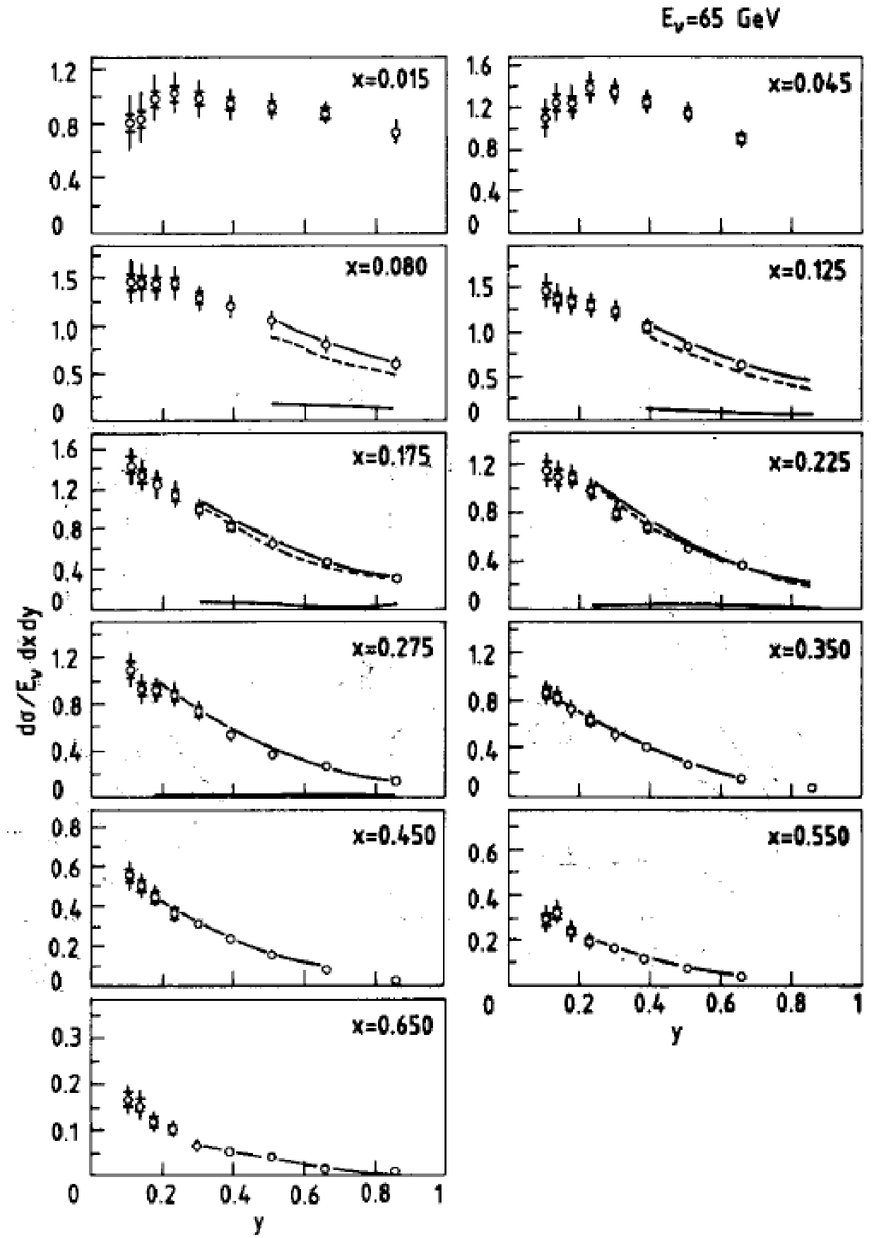
$$Q^2 = 4\,E\,E'\,\sin^2(\theta/2)$$

$$x = Q^2/2M\nu$$

Where $\nu = E_h - M$

x and Q^2 are measured event by event

$$y = \nu/E$$



E_ν=65 GeV
x=0.015
x=0.045
x=0.080
x=0.125
x=0.175
x=0.225
x=0.275
x=0.350
x=0.450
x=0.550
x=0.650
$d\sigma/E_\nu\,dx\,dy$
y

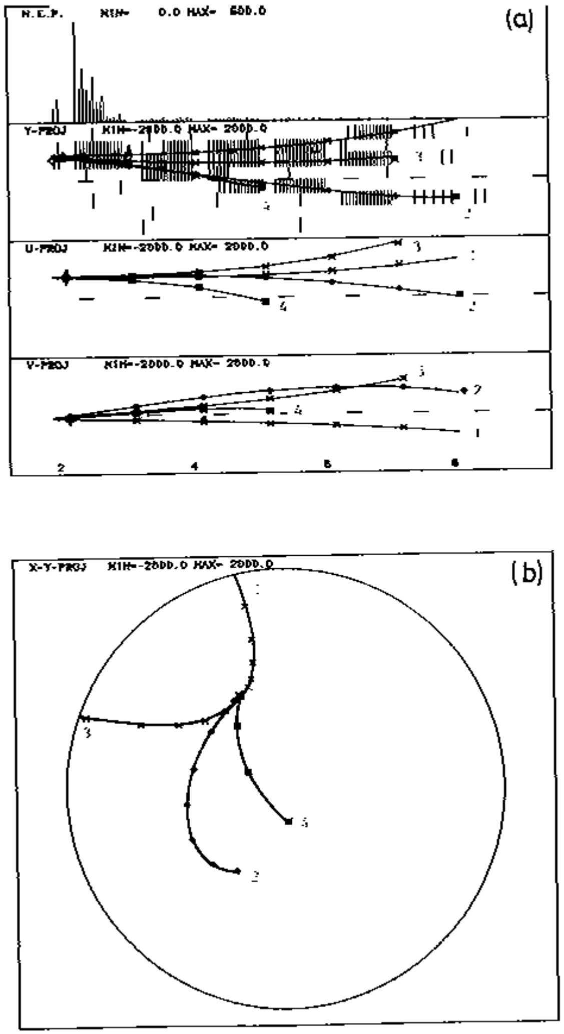
Internal structure of the nucleons

- Parton distribution functions:

  $\Rightarrow$ *One can extract u(x), d(x), s(x), c(x)*

- 3 valence quarks + sea of quarks, pairs of quark-antiquark
- *Gluons do not participate. They are extracted by missing momentum*
- *Confined at small x, they carry ~ 50% of the total momentum*

One, two, three and four muons



Opposite sign dimuons

Allow the study of D meson production

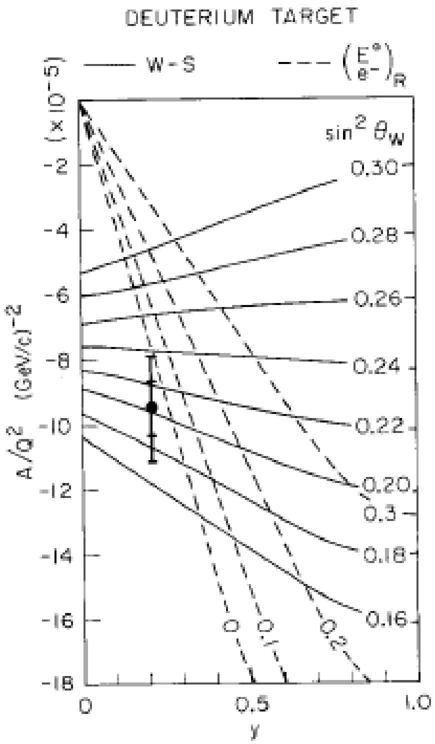
Gives the c quark distribution functions inside the nucleon

Neutrinos and the Standard Model

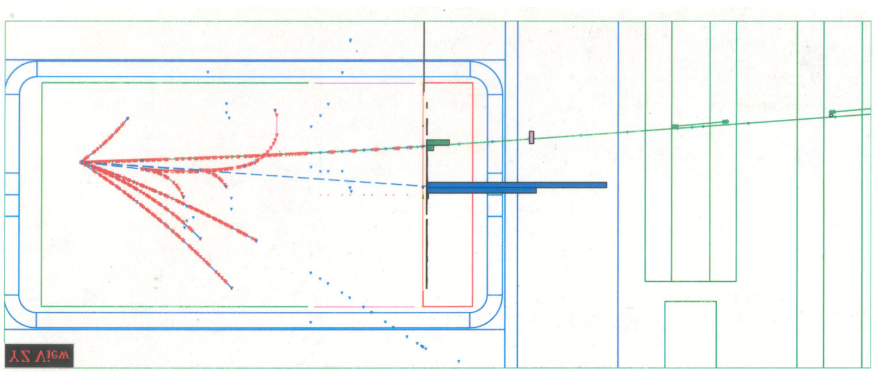
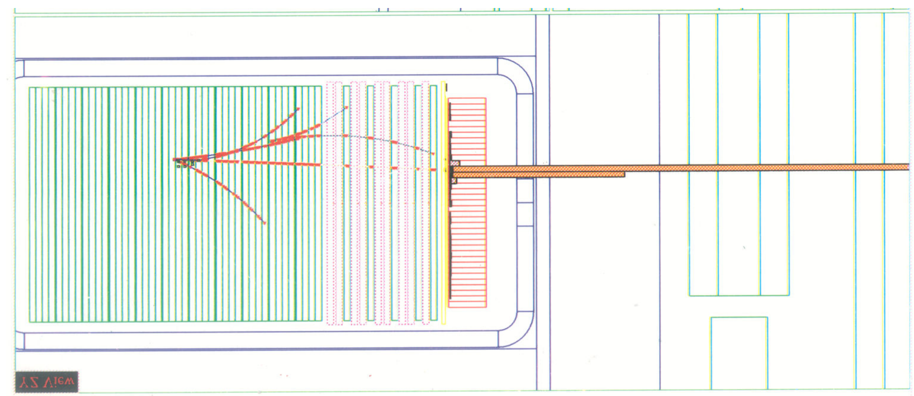
- *First measurement of Weinberg angle*

- $R = \sigma_{NC}/\sigma_{CC}$
  $= 1/2 - \sin^2\theta_W + \ldots$

GGM at SPS 1978
9 candidates for ν_μ e scattering
with 0.5 back, out of 64000 CC



The NOMAD experiment (1993-2000)

« Electronic bubble chamber »

Only 2-ton target, but very fine grain calorimeter

10^6 events obtained

Search for $\nu_\mu \rightarrow \nu_\tau$ (together with Chorus)

Partial summary

There exist 3 and only 3 « active » neutrinos, with their antineutrinos

$$\nu + N \Rightarrow l^- + hadrons$$

$$anti\text{-}\nu + N \Rightarrow l^+ + hadrons$$

They only feel weak interactions:

couplings to $W^\pm$ (CC) and Z^0 (NC)

In the MSM, SU(2)xU(1)

leptons appear as left-handed doublets + right-handed singlets

$$(l^- , \nu)_L \quad (l^-)_R$$

No right-handed ν (or left-handed anti-ν) ⇒ ν are massless