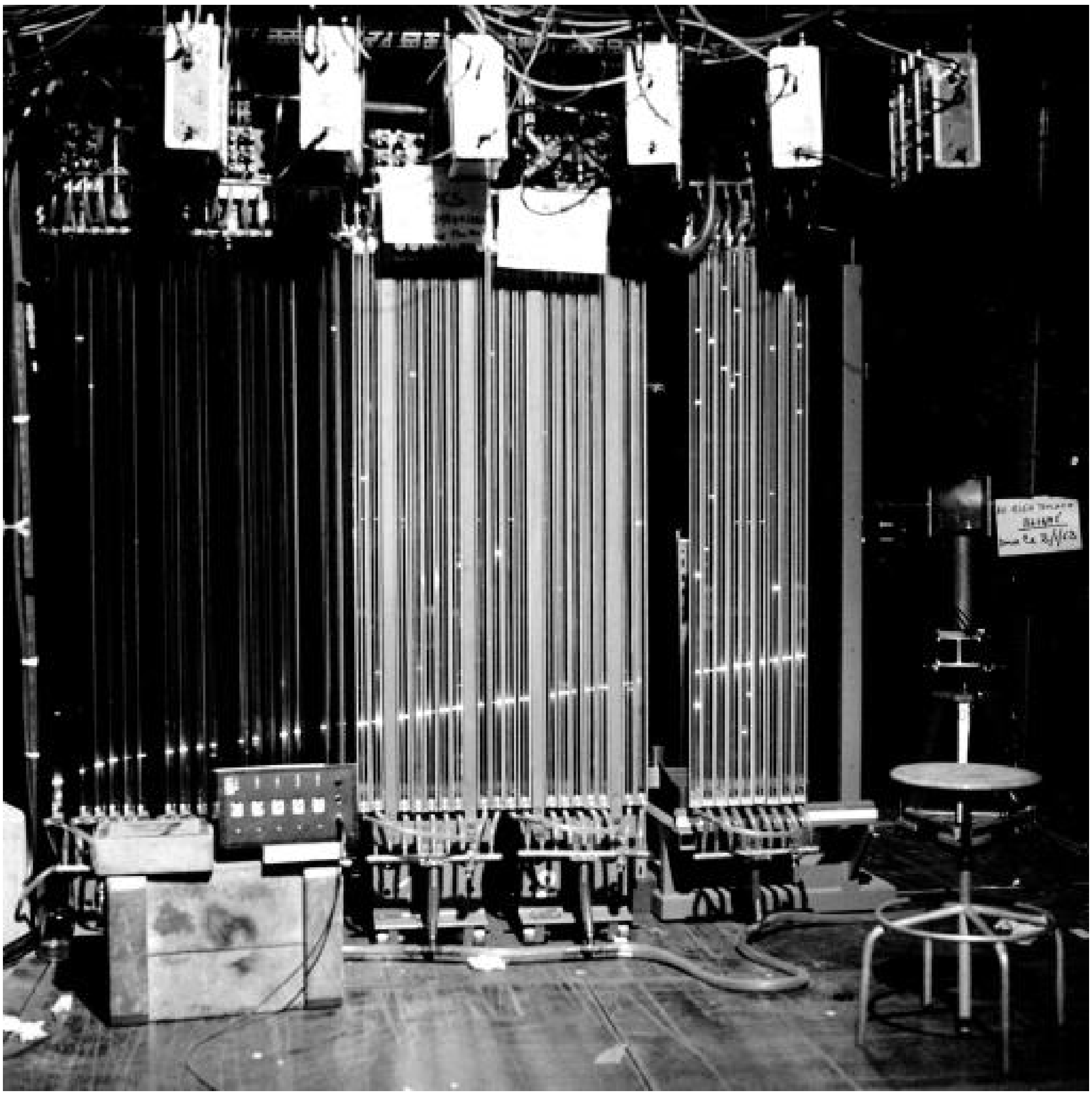
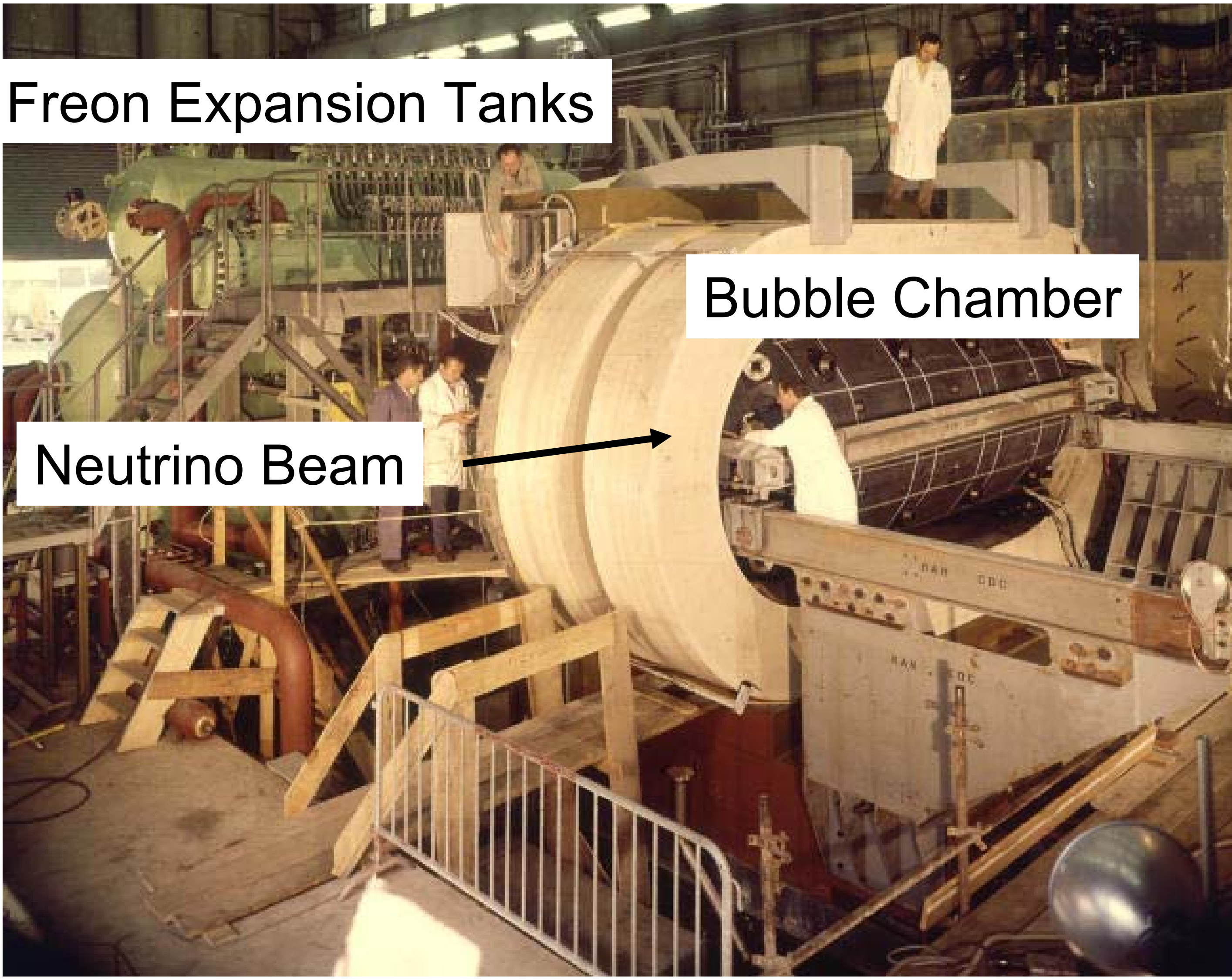
Muon Neutrino Interaction in Spark Chamber



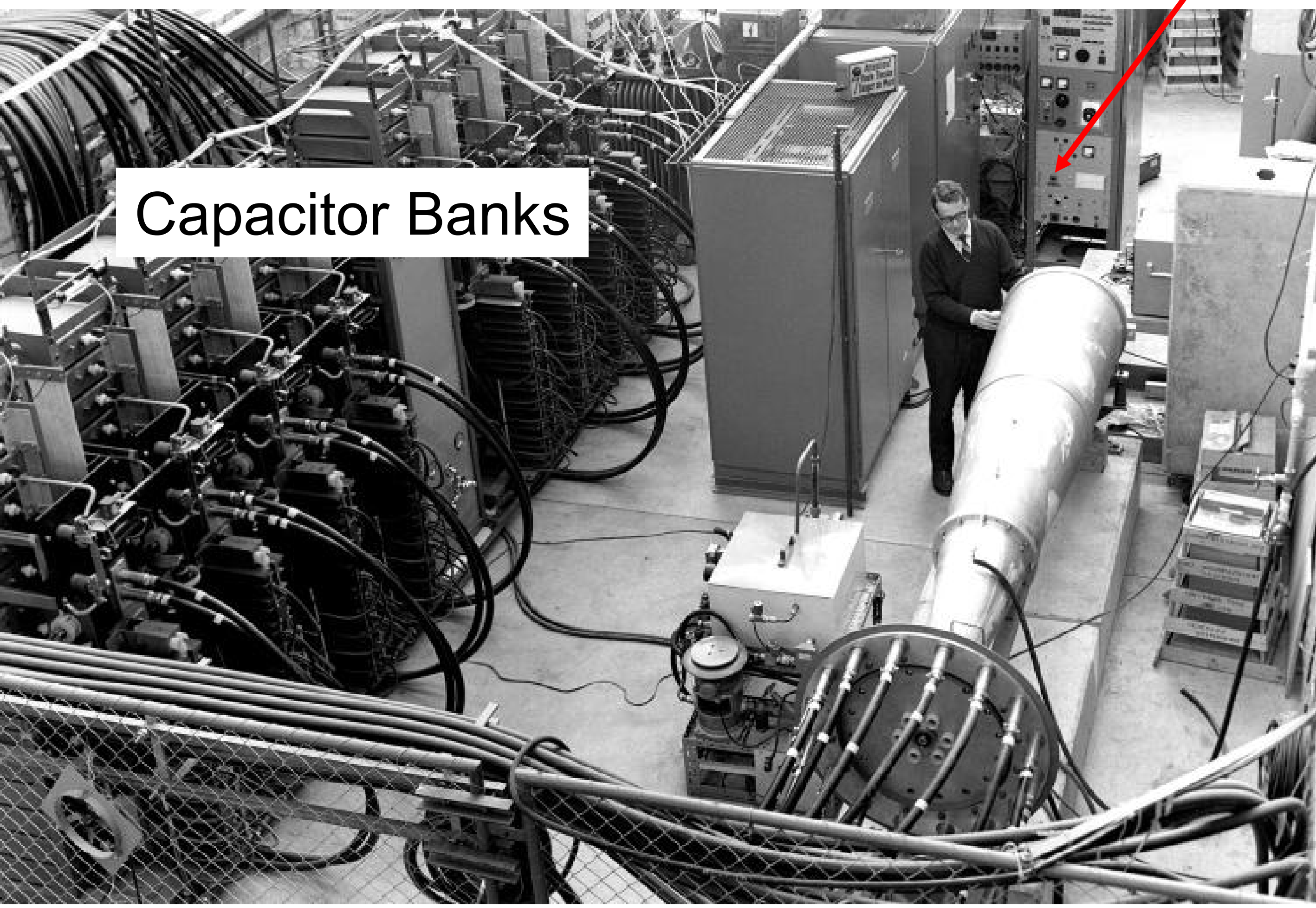
Gargamelle at CERN



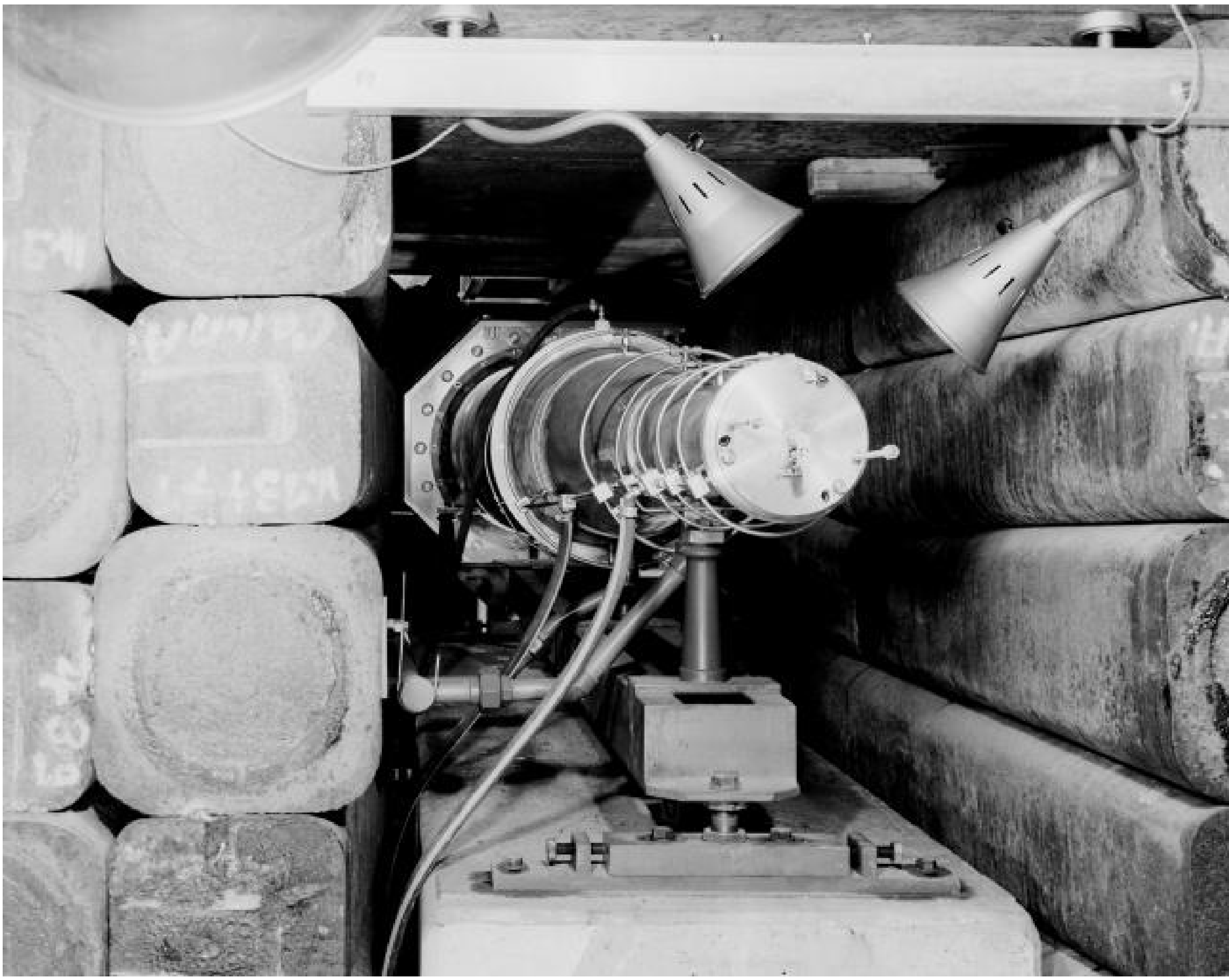
Neutrino Horn

Neutrino Horn

Is the Power Off?

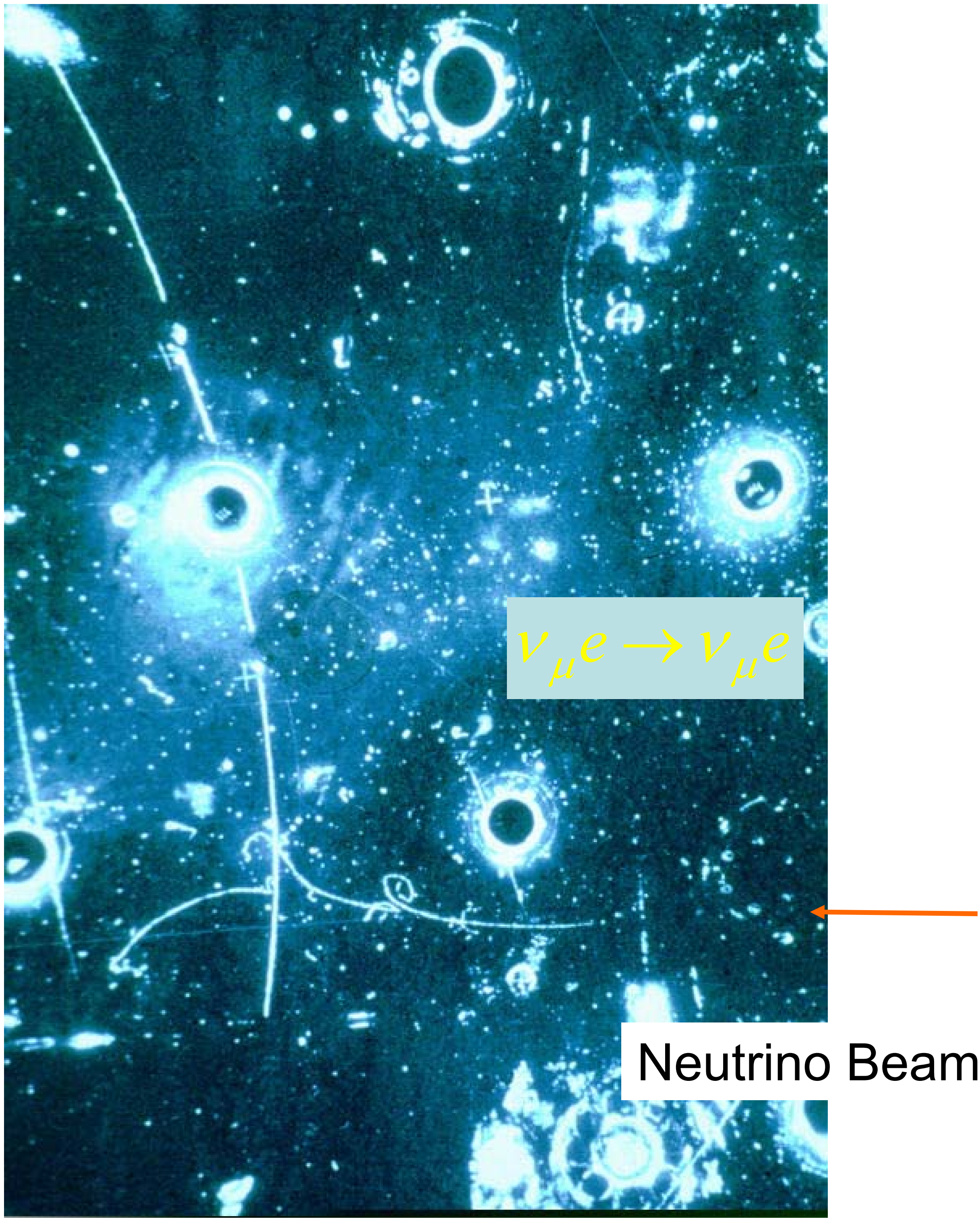


Neutrino Horn Inside Shielding Cavern



Looking for NC Events on GGM Film

First Observed Neutral Current Event



$\bar{\nu}_\mu \rightarrow$

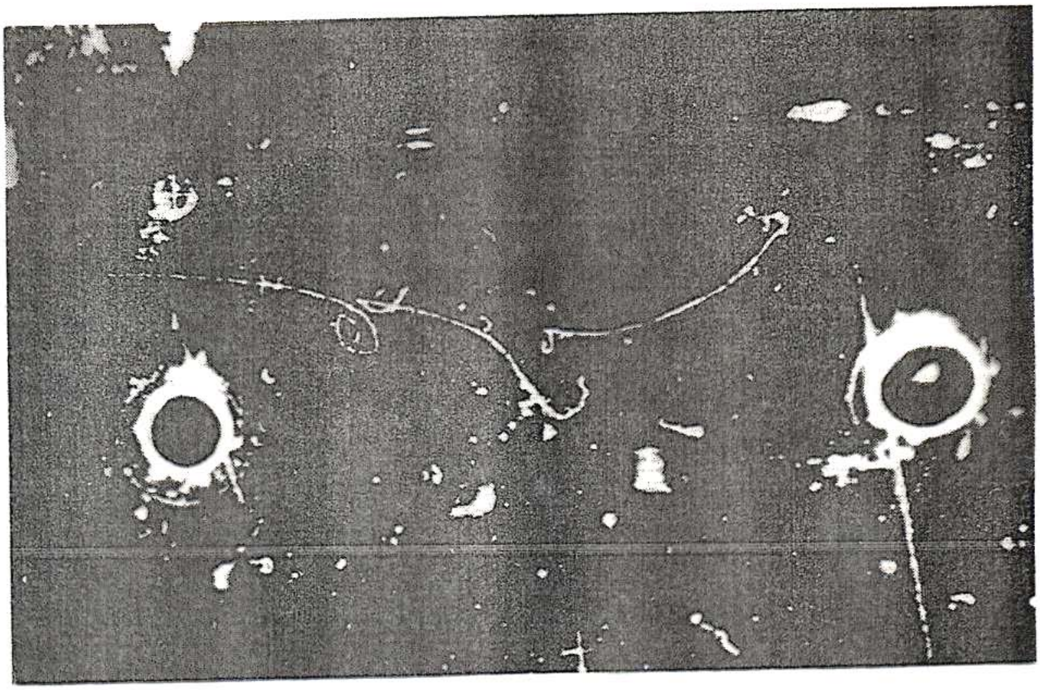
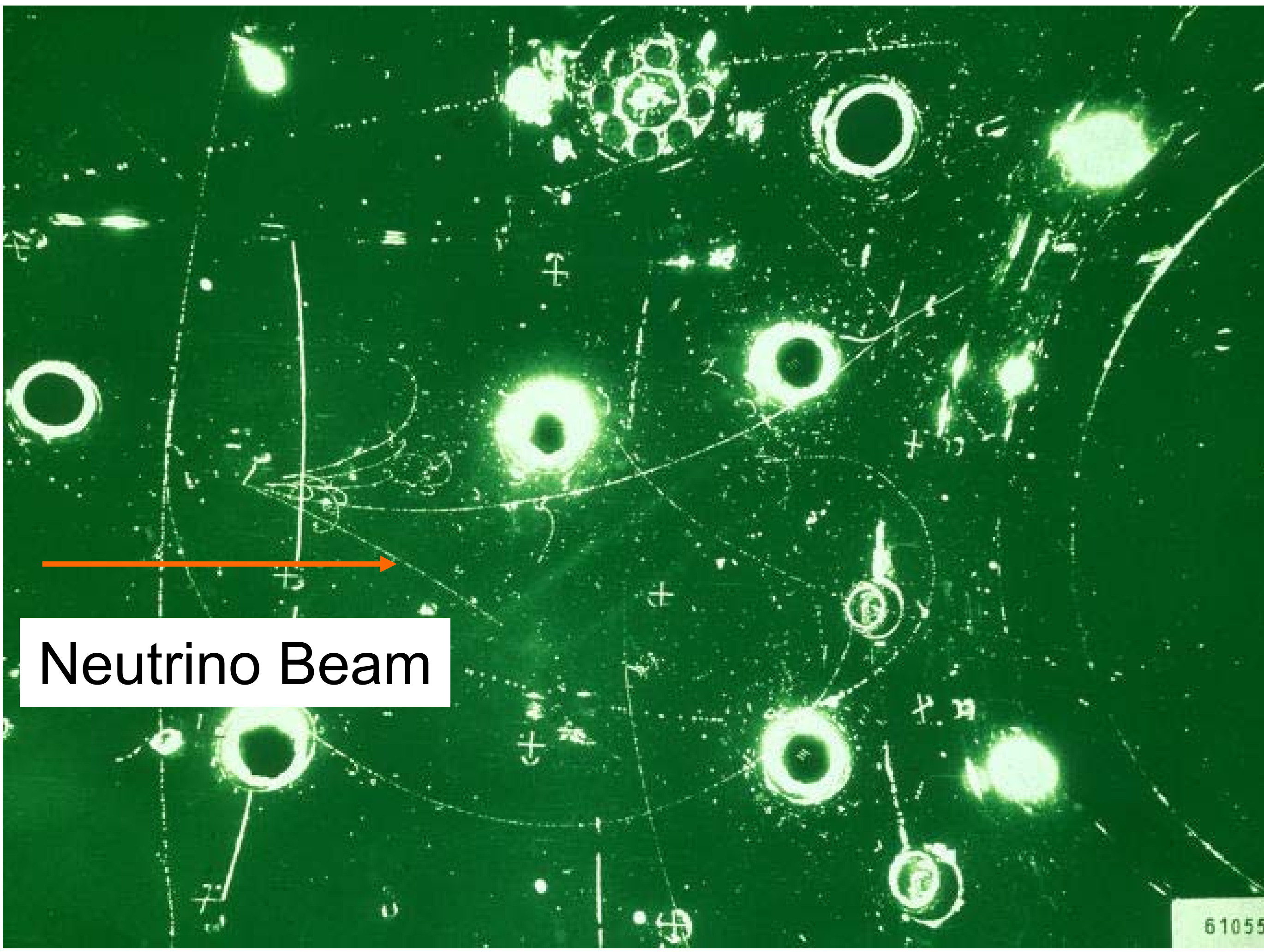
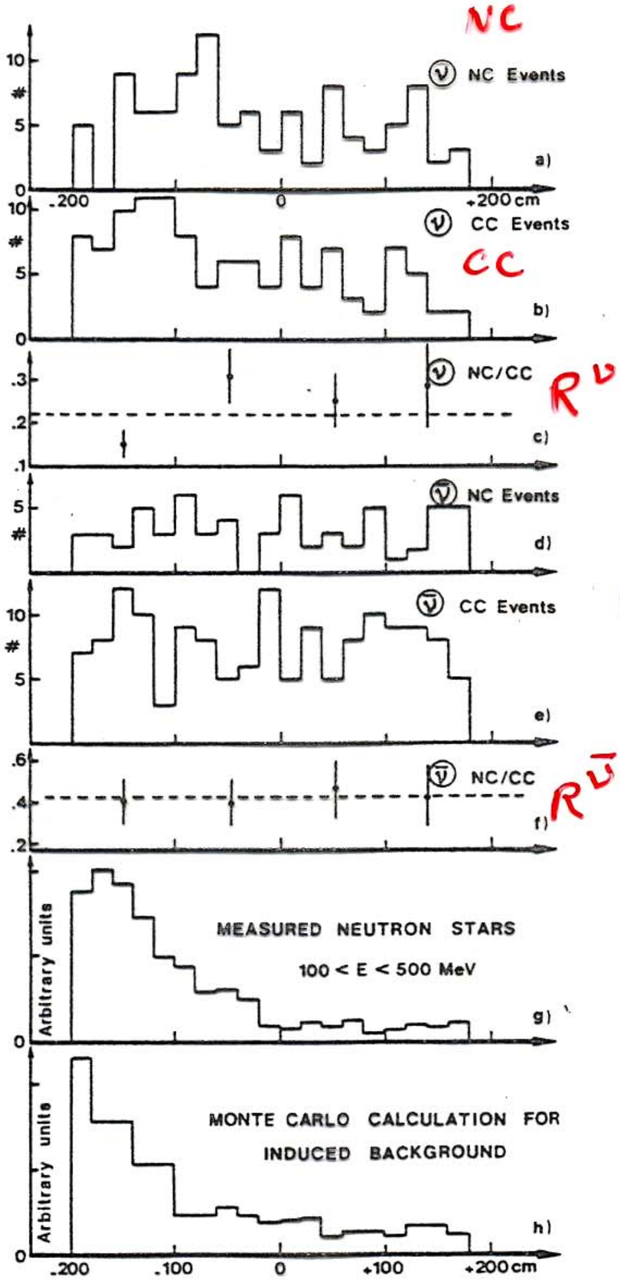


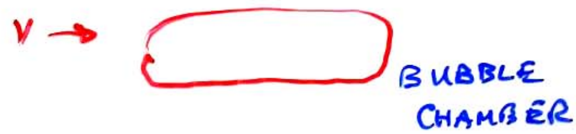
Figure 1.6 First example of weak neutral-current process $\bar{\nu}_\mu + e \rightarrow \bar{\nu}_\mu + e$ observed in heavy-liquid bubble chamber Gargamelle at CERN irradiated with a $\bar{\nu}_\mu$ beam (Hasert *et al.*, 1973). A single electron of energy 400 MeV is projected at a small angle $(1.5 \pm 1.5°)$ to the beam, and is identified by bremsstrahlung and pair production along the track (see Chapter 2). About 10^9 $\bar{\nu}_\mu$'s traverse the chamber in each pulse and three such events were observed in 1.4 million pictures. (Courtesy CERN.)

Neutral Current in Gargamelle



- GARGAMELLE HEAVY LIQUID BUBBLE CHAMBER
- BOILING FREON





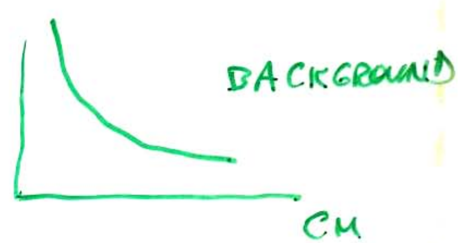


Fig. 1. Distributions along the ν-beam axis. a) NC events in ν. b) CC events in ν (this distribution is based on a reference sample of ~ 1/4 of the total ν film). c) Ratio NC/CC in ν (normalized). d) NC in $\bar{\nu}$. e) CC events in $\bar{\nu}$. f) Ratio NC/CC in $\bar{\nu}$. g) Measured neutron stars with $100 < E < 500$ MeV having protons only. h) Computed distribution of the background events from the Monte-Carlo.

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$E_\nu \sim 4$ GeV

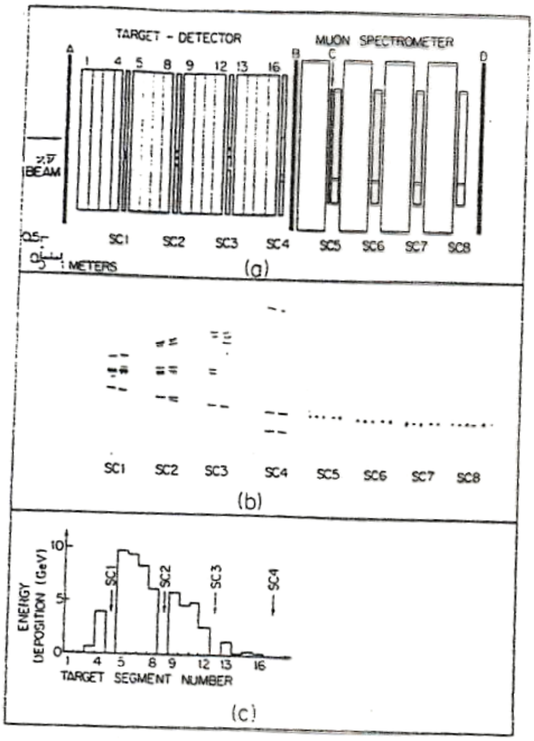

FIG. 1. (a) Plan view of experimental apparatus. The target-detector consists of liquid-scintillator segments (1–16) with wide-gap spark chambers (*SC*1–*SC*4) interspersed, each with two gaps. The muon spectrometer consists of four magnetized iron toroids whose axes coincide with the beam line. After each toroid are narrow-gap spark chambers (*SC*5–*SC*8) each with six gaps. Auxiliary scintillation counters are labeled *A*, *B*, *C*, and *D*. A typical inelastic neutrino event with an associated muon is sketched into the spark chambers. Its enlarged photograph appears in (b) and the energy deposition in each segment is shown in (c).

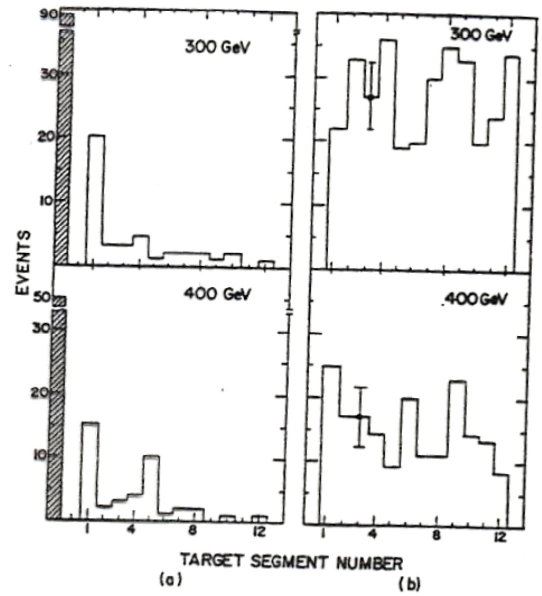

FIG. 2. (a) Distributions of event vertices along the neutrino beam path for events in which counter *A* fired. The crosshatched bins contain all events with a vertex upstream of the detector. (b) Events that did not fire *A*.

INITIAL CONFUSION
HPW @ FNAL
$E_\nu \sim 100$ GeV

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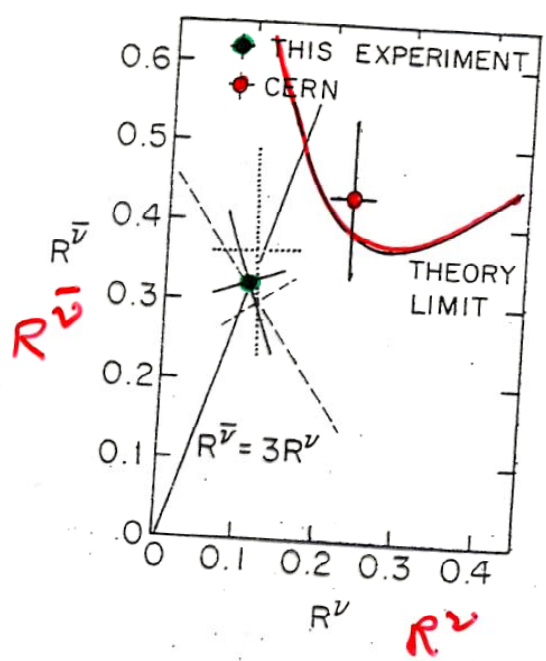


$\sin^2 \theta = 0.220 \pm 0.014$.

1984

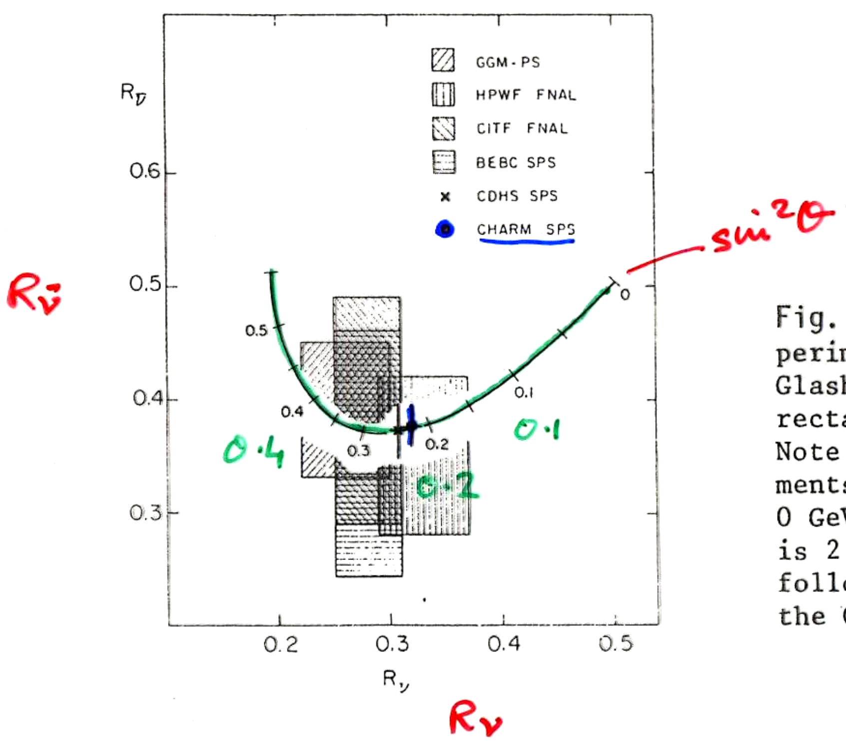
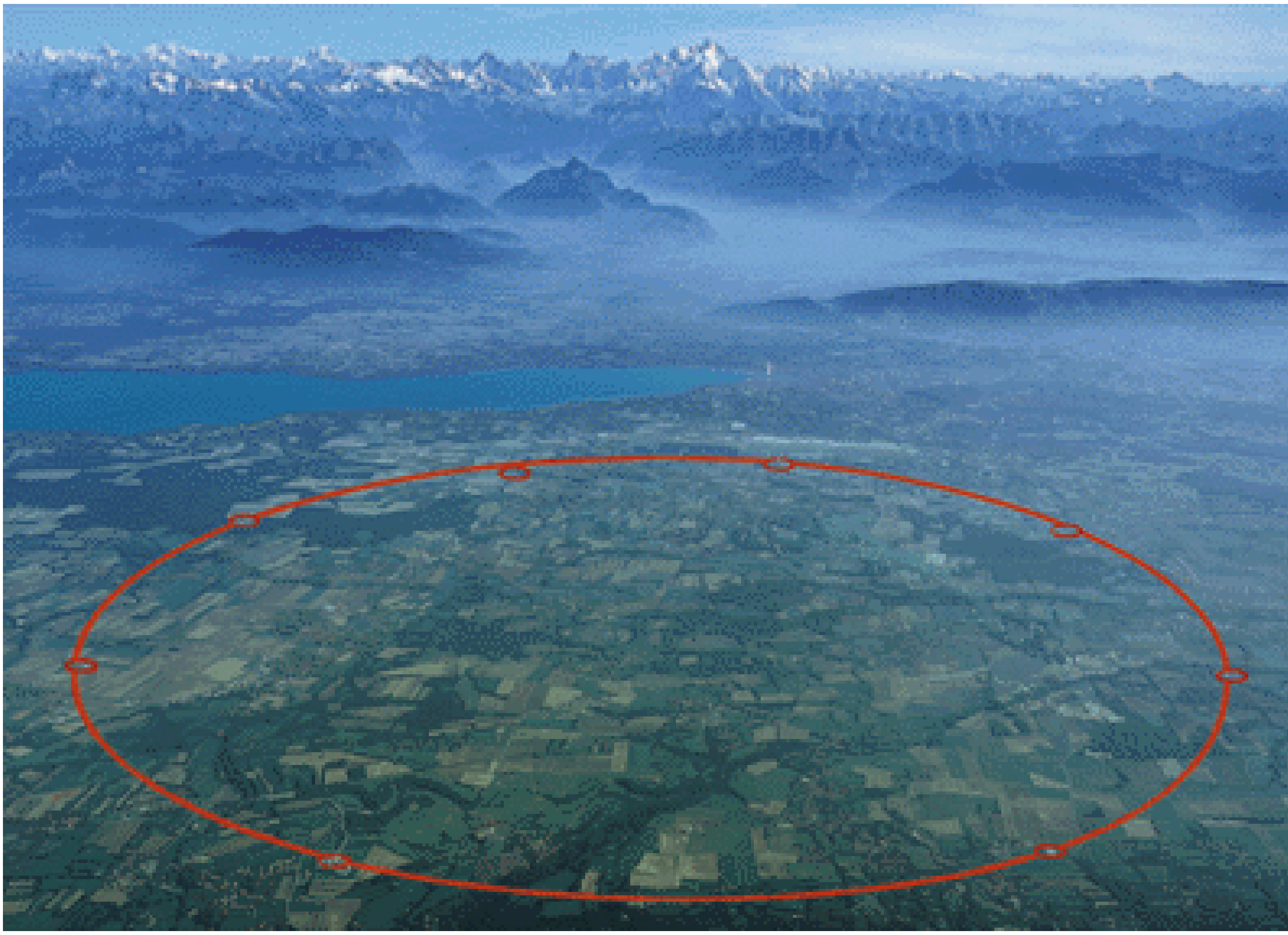


Fig. 3 Comparison of various experiments on R^{ν} and $R^{\bar{\nu}}$ with the Glashow-Salam-Weinberg model; the rectangles correspond to $\pm 1\sigma$. Note that the different experiments have E_h cuts varying from 0 GeV to 15 GeV, the cut for CHARM is 2 GeV; the curve is calculated following Ref. 7, incorporating the CHARM experimental conditions.

CERN Seen from the Air



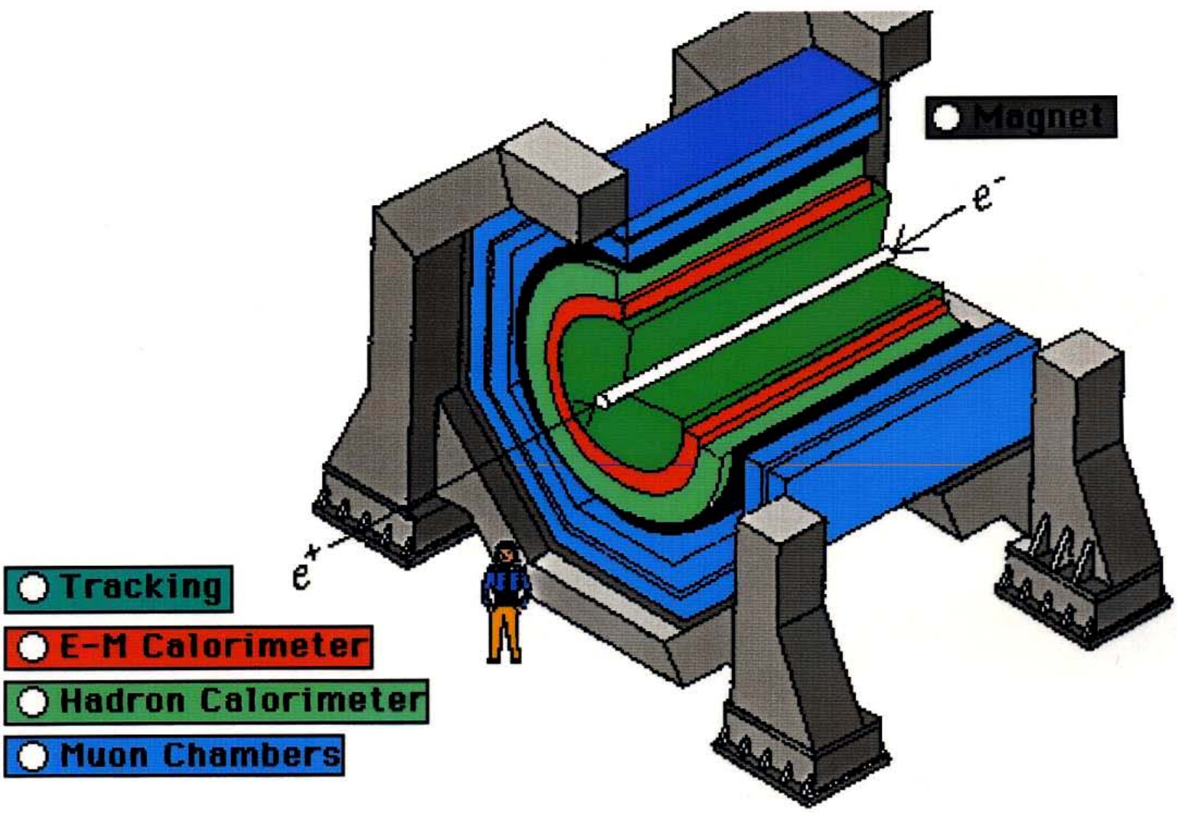
- Tunnels of CERN accelerator complex superimposed on a map of Geneva.

- Accelerator is 50 m underground

LHC Tunnel

This is an arc of the circular tunnel
Circumference 26.7 Km

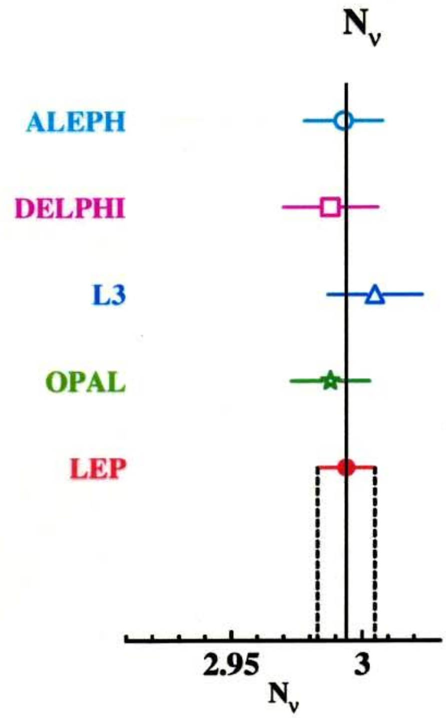
Generic Experiment



Layers of detector systems around collision point

The invisible width

$$\Gamma_Z = \Gamma_{hadronic} + \Gamma_{leptonic} + \Gamma_{invisible}$$



- **The number of light neutrino families (N_ν) is obtained from $\Gamma_{inv} / \Gamma_{lept.}$:**

$$\frac{\Gamma_{inv.}}{\Gamma_{lept.}} = \frac{\Gamma_Z}{\Gamma_{lept.}} - R_{lept.} - 3 = N_\nu \cdot \frac{\Gamma_\nu}{\Gamma_{lept.}}$$

- **The ratio $\Gamma_\nu / \Gamma_{lept}$ is taken from MSM:**

$$\Gamma_\nu / \Gamma_{lept.} = 1.991 \pm 0.001$$

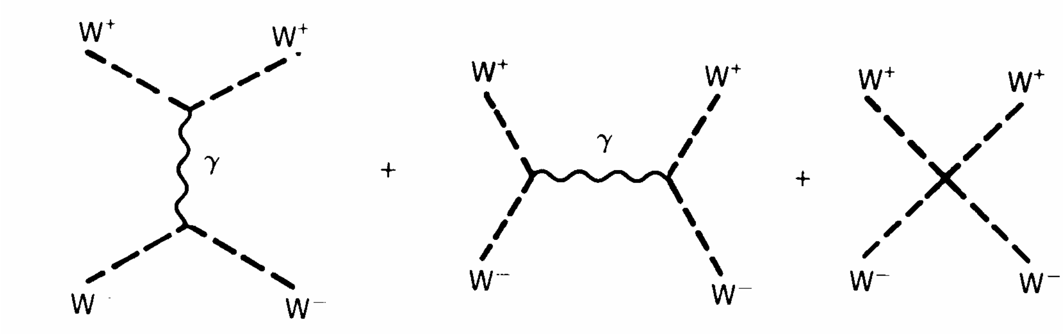
- **Forcing N_ν=3 gives :**

$$\Gamma_\nu / \Gamma_{lept.} = 1.9867 \pm 0.073$$

Higgs Boson

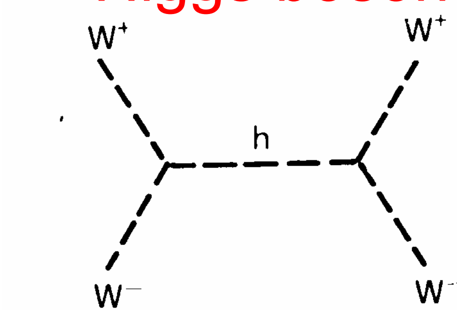
• Electromagnetism on its own can be made to give finite results for all calculations.

• Unified Electroweak theory gives infinite results for process like:



• Become finite if include new particle

Higgs boson



• Higgs makes $W^{\pm}$ Z^{0} massive, and actually generates masses of fundamental particles. It is a quantum field permeating the universe.

How Does Higgs Generate Mass?

- In vacuum, a photon:

  has velocity c and has zero mass

- In glass a photon

  has velocity < c , same as an effective mass

- This is due to photon interacting with

  electromagnetic field in condensed matter

- By analogy can understand masses of particles

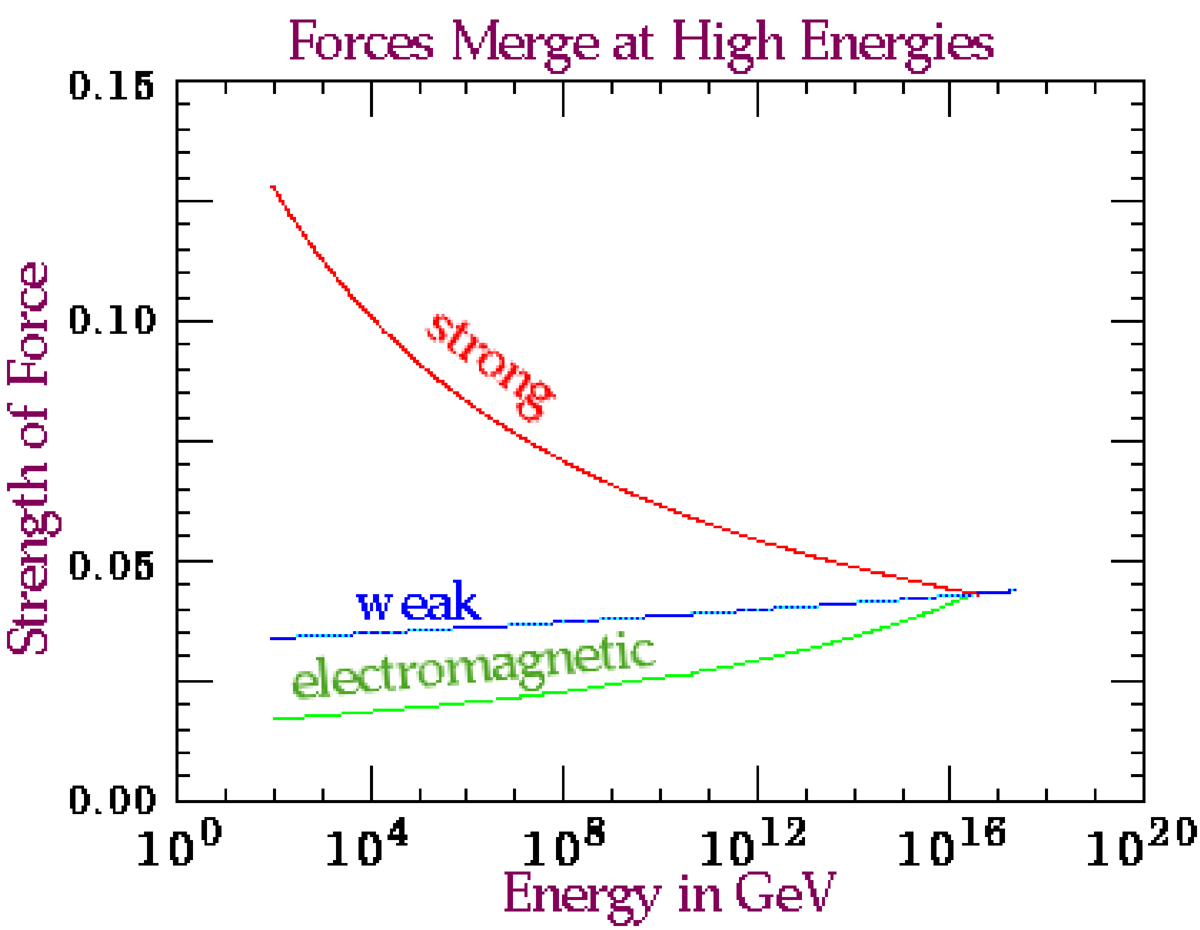
  generated by Higgs Field in vacuum

Grand Unification.

- At a high enough energy

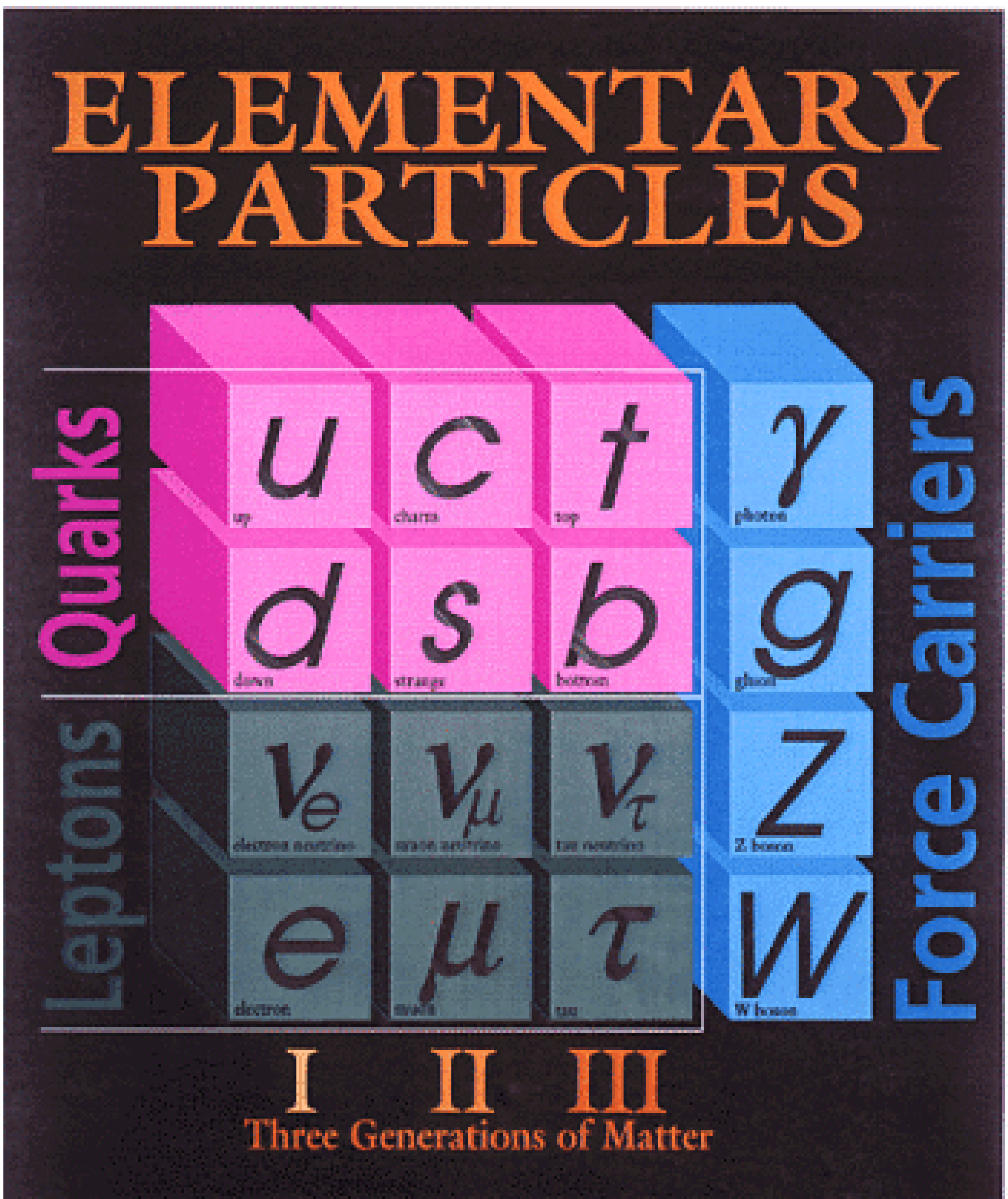
electromagnetism
weak force
strong (colour) force

become aspects of Grand Unified Force



Understand History of Universe?

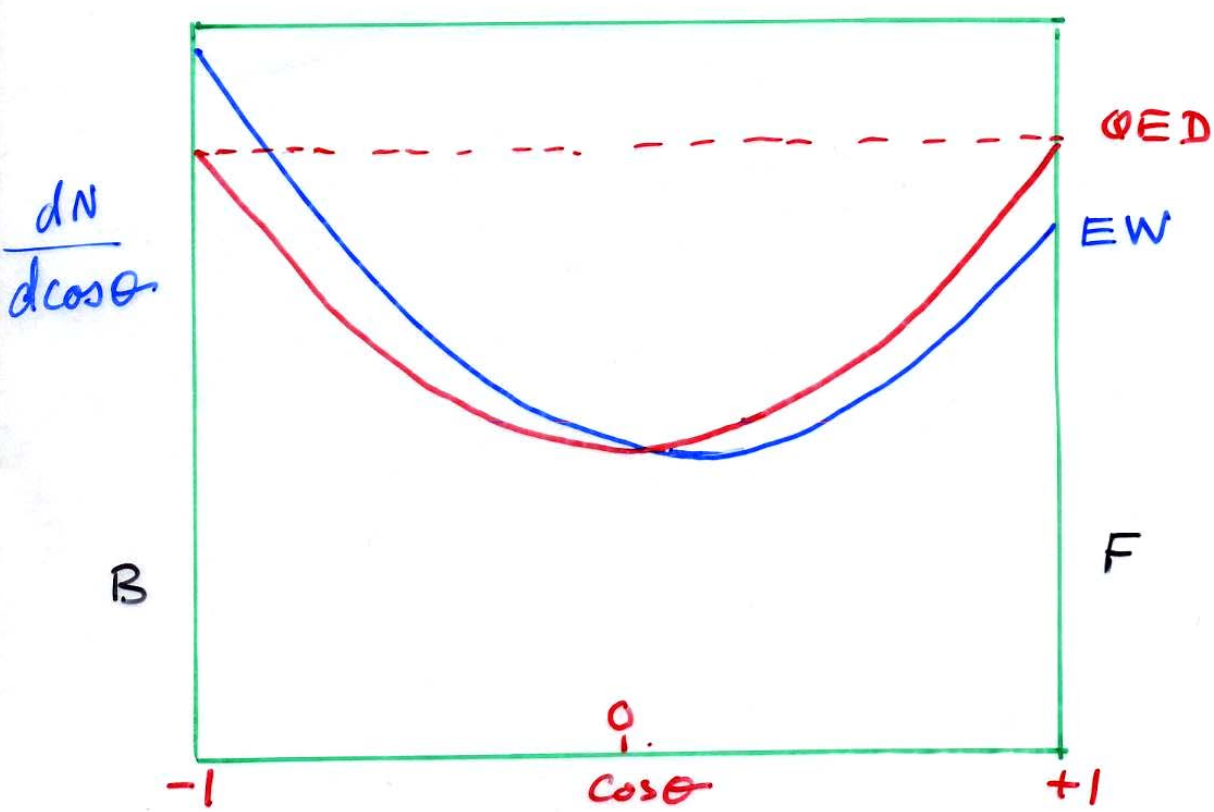
- What we think (thought?) visible matter is made of.



PRECISE VALUES OF $\sin^2\theta$

$$e^+e^- \rightarrow \begin{matrix}\gamma^* \\ Z^*\end{matrix} \rightarrow \ell^+\ell^-$$

↑ INTERFERENCE   V
V–A



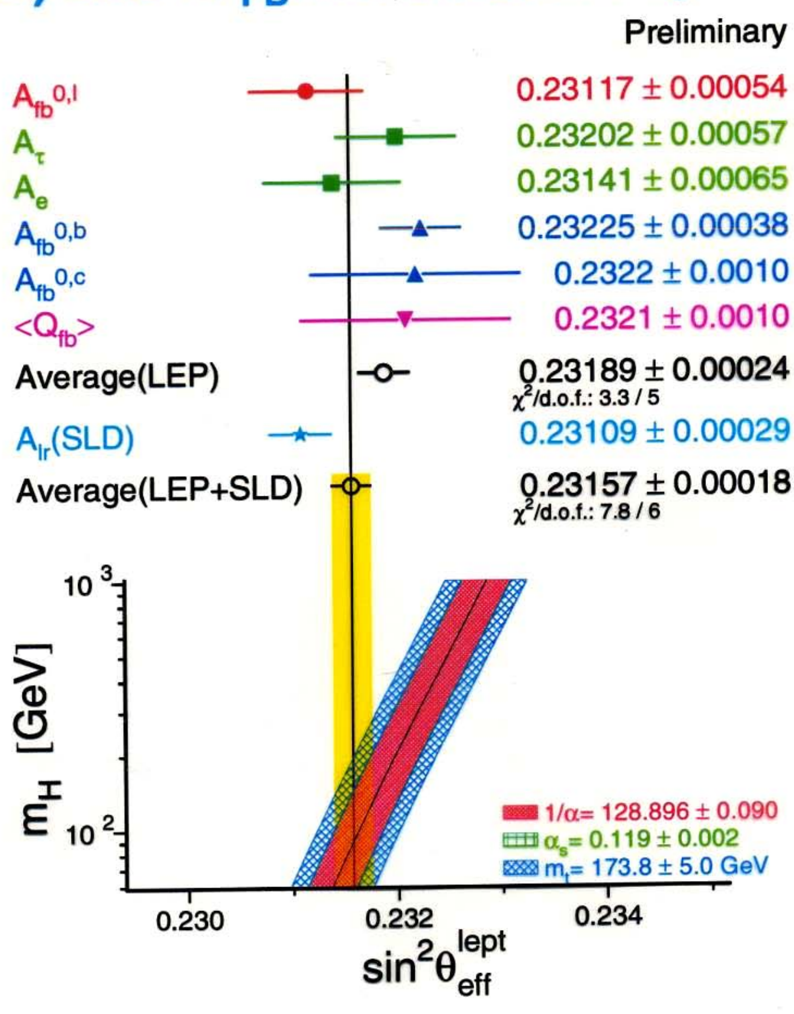
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

Asymmetries & the effective EW mixing angle

- The various asymmetry measurements can be expressed as a determination of:

$$\sin^2\theta^{l}_{eff} \equiv \frac{1}{4}\left(1-\frac{g^{l}_{V}}{g^{l}_{A}}\right)$$

- The 2 most precise measurements: A_{LR} (SLD) and A^{b}_{FB} are different by ~2.4σ



Motivation:

W mass and top mass are fundamental parameters of the Standard Model:

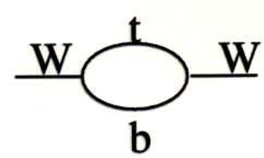
Electromagnetic constant
measured in atomic transitions,
e+e- machines, etc.

$$m_W = \left(\frac{\pi \, \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

Fermi constant
measured in muon decay

Weinberg angle
measured at LEP/SLC

f (m_{top}^2, log m_H)
radiative corrections



→ since G_F, α_{EM}, $\sin\theta_W$ are known with high precision, precise measurements of m_{top} and m_W allow constraining Higgs mass (weakly because of logarithmic dependence)

Measurement of m_{top}

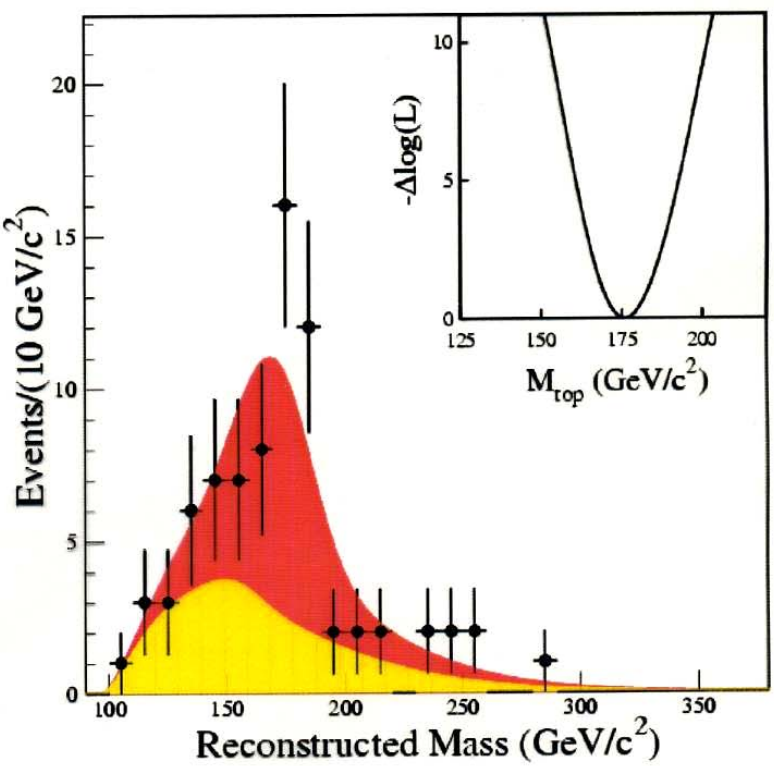
- Top is most intriguing fermion:

-- $m_{top} \approx 174$ GeV $\rightarrow$ very heavy

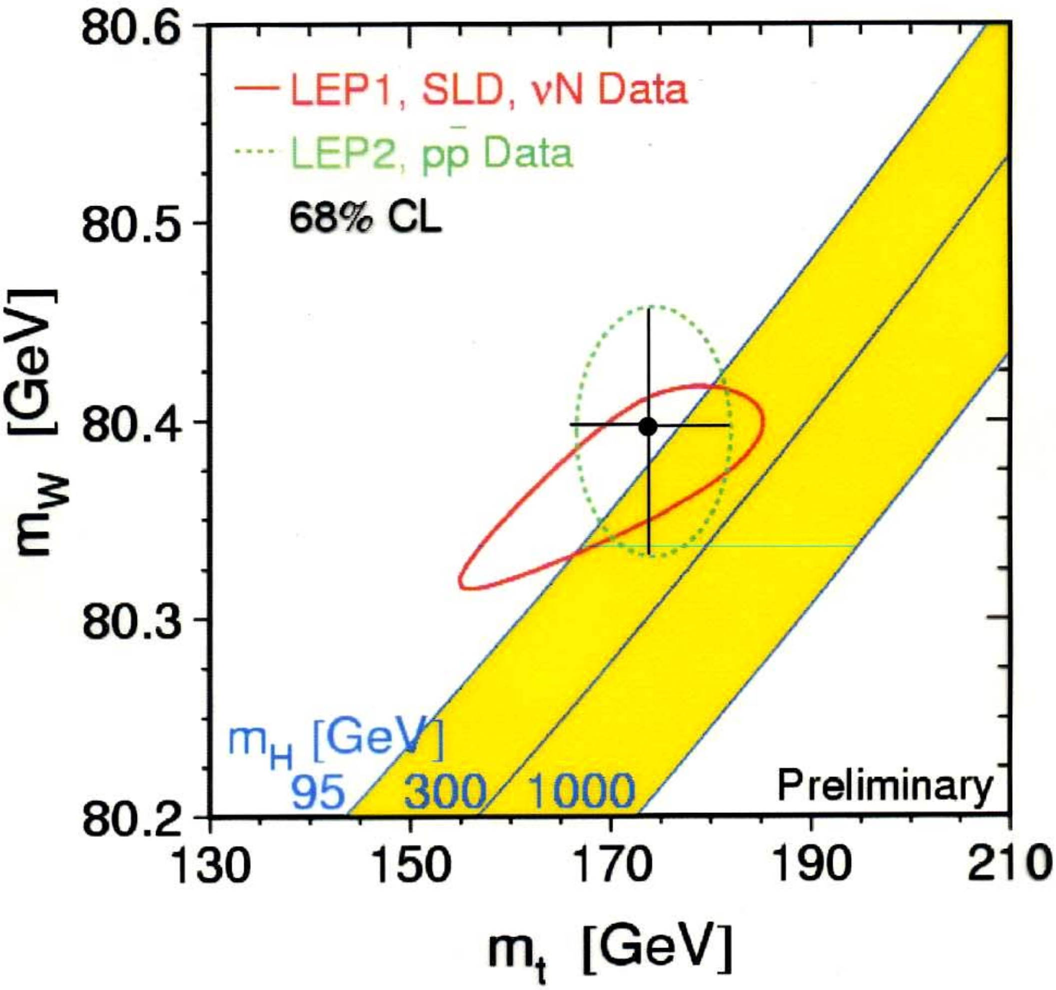
-- $\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$ $\leftarrow$ Δm (t-b) $\approx$ 170 GeV

- Discovered in '94 at Tevatron $\rightarrow$ precise measurements of mass, couplings, etc. just started

Top mass spectrum from CDF



$$m_W = \left(\frac{\pi \, \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$



m_W (from LEP2 + Tevatron) = 80.394 ± 0.042 GeV

m_{top} (from Tevatron) = 174.3 ± 5.1 GeV

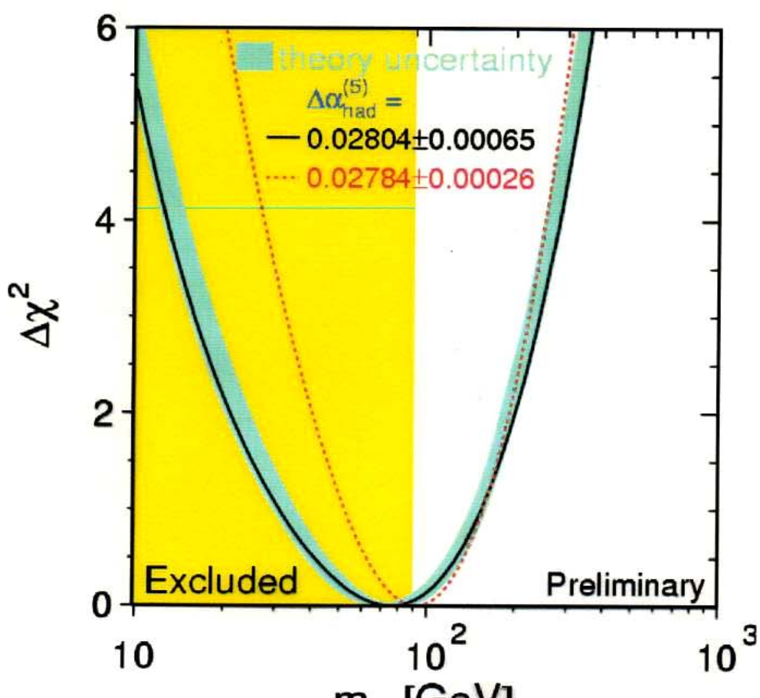
3/27/00

What do we know today about m_H ?

Not predicted by theory (but production and decays versus m_H predicted).

Experimental limits /indications:

- $m_H > 95$ GeV from searches at LEP
- indirect limits from fit of SM to:
  - -- LEP1/SLD precise measurements at $\sqrt{s} = m_Z$
  - -- m_W measurement LEP2/Tevatron
  - -- m_{top} measurement at Tevatron



Best fit of SM to data (minimum χ^2) found for $m_H = 92^{+78}_{-45}$ GeV

$m_H < 245$ GeV 95% C.L.

Year 2005 : if Higgs not found at LEP/Tevatron then $m_H > 110\text{-}120$ GeV from direct searches