Neutrino New Physics: *mass and oscillations*

Introduction to the

Intercollegiate Postgraduate Course

University of London

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Stefania Ricciardi,RAL

E-mail: stefania.ricciardi@stfc.ac.uk

Aims and outcomes of this course

- Provide basic knowledge on current research in the neutrino area
  - Phenomenology with massive neutrinos
  - Current experimental results
  - Future facilities
- Compare different experimental techniques for detection of neutrino oscillations and mass
  - Underlying principles
  - Examples from real life
  - Order of magnitude sensitivity calculations

Plan

- October 31
  - Minimal Introduction: overview on Neutrino Physics
  - Unit 1: Atmospheric and solar neutrinos
- November 15
  - Unit 2: Phenomenology of Neutrino Oscillations
    - Oscillation in matter – MSW effect
    - Oscillation among 3 neutrino species – PMNS matrix
  - Unit 3: Neutrino Oscillation Experiments with Terrestrial Sources
    - Conventional Neutrino Beams
    - Short and Long Baseline Experiments
- November 22
  - Unit 4: The intensity frontier:
    - Current and future neutrino beams, neutrino-factory, beta-beams.
  - Unit 5 Neutrino puzzles and anomalies
- November 29
  - Unit 6: Neutrino mass and nature
  - Unit 7: Problem class and Discussion

Material

- Slides can be downloaded from

  http://hepwww.rl.ac.uk/ricciardi/Neutrino%20Lectures.htm

  It may be useful to print and bring the copy to the class.
- Homework: past examination sheets on the web:

  http://www.hep.ucl.ac.uk/~mw/Post_Grads/2010-11/Exams/pg_2005_1.ps

  http://www.hep.ucl.ac.uk/~mw/Post_Grads/2010-11/Exams/pg_2006_1.ps

  http://www.hep.ucl.ac.uk/~mw/Post_Grads/2010-11/Exams/pg_2007_1.ps

  Neutrino questions can be found in Paper1

  Please solve the problems and bring solutions to the discussion class on November 29
- People interested in the subject can find more material in the suggested reading/attend specialized summer schools (e.g., NUFACT School)

References

Book:

- C. Giunti & C.W. Kim, "Fundamentals of Neutrino Physics & Astrophysics“, Oxford University Press 2007

  Comprehensive book on the subject. Recommended.

On the WEB:

Recent and pleasant readings for everybody:

- I. Gil-Botella, “Neutrino Physics”, http://arxiv.org/pdf/1504.03551 (50 pages)
- http://www.nu.to.infn.it/

Neutrino Unbound: A comprehensive collection of papers, lectures and news

- http://neutrinooscillation.org/

An index of experiments and related subjects having to do with neutrino mass and oscillations

Other recent Reviews:

Available on the PDG WWW pages

http://www-pdg.lbl.gov/2016/reviews/rpp2016-rev-neutrino-mixing.pdf

http://www-pdg.lbl.gov/2016/reviews/rpp2016-rev-neutrinoless-double-beta-decay.pdf

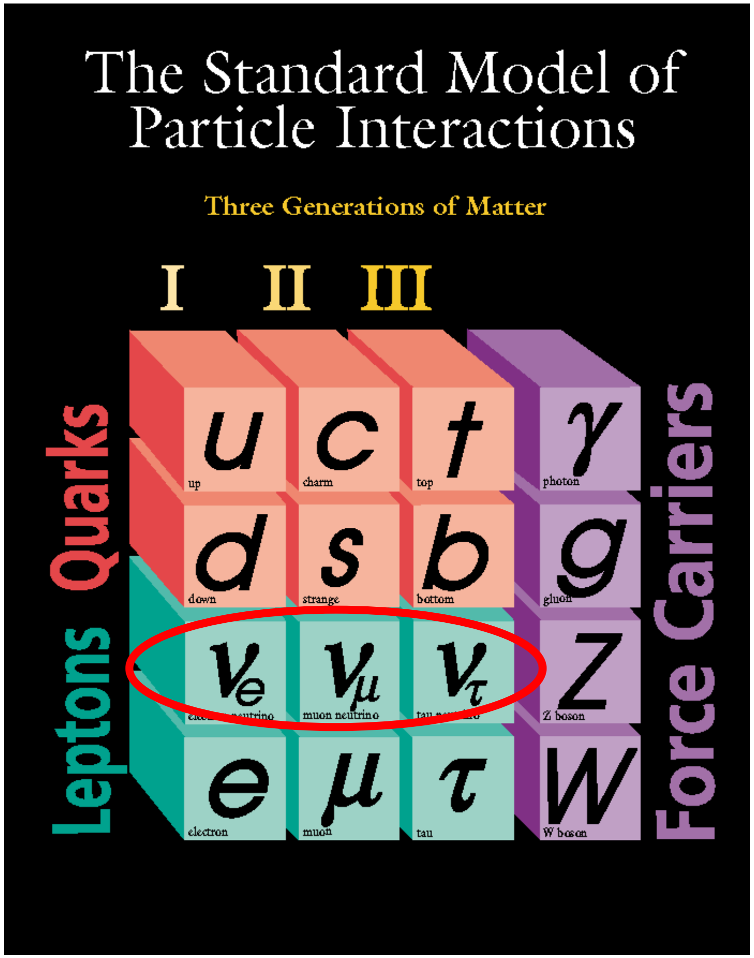
http://www-pdg.lbl.gov/2016/reviews/rpp2016-rev-3neutrino-mixing-intro.pdf

Minimal Introduction

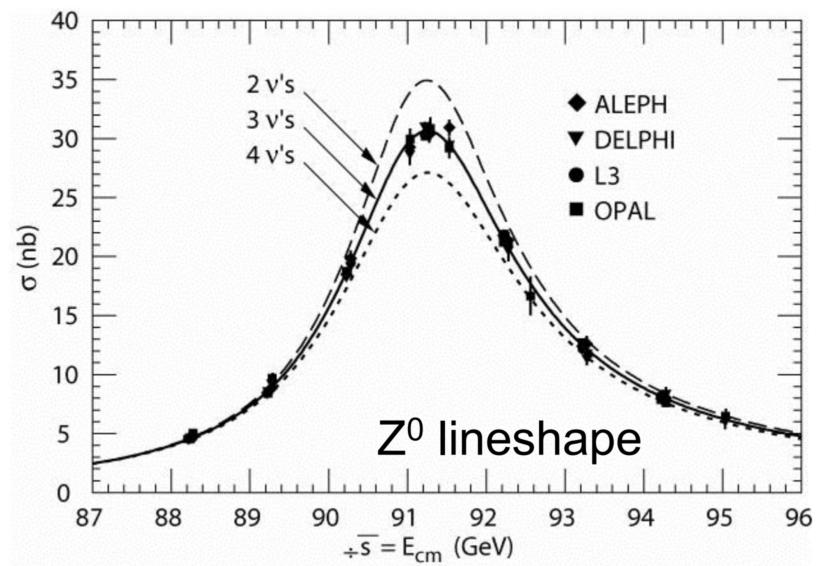
- Review of Basics
  - what are neutrino oscillations?
  - what do we need to measure?
  - How? Neutrino (weak) interactions
- Neutrino Who's Who
  - people and experiments who made a 80 years long history

Neutrinos in the Standard Model (SM)

Massless, chargeless leptons => only weak interactions



3 and only 3 ν generations: experimentally verified from Z^0 width measured at LEP (for ν masses <45 GeV/c^2)



The width of a resonance is related to the number of possible decays

Two-state neutrino oscillations

Neutrino oscillation are a consequences of:

1. Non-zero neutrino masses
2. Mixing: Weak eigenstates not coinciding with mass eigenstates

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$\alpha,\beta = e/\mu/\tau$
$\alpha \neq \beta$

Then a ν_α can evolve to ν_β with time,
i.e. in the propagation from source to detector
Probability of oscillation is:

$$\mathbf{P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 (1.27\, \Delta m^2\, L/E)}$$

With Δm^2 (eV^2) = $m_1^2 - m_2^2$
and L/E (Km/GeV) or (m/MeV)

A simple derivation of the neutrino oscillation probability

Use the fact that a weak-eigenstate is a superposition of mass-eigenstates according to the mixing matrix

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Then at t=0 (production): $|\nu_\beta(t=0)\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$

At a later time t (= L/c where detector is):

$$|\nu_\beta(t)\rangle = -\sin\theta\, e^{-iE_1 t}|\nu_1\rangle + \cos\theta\, e^{-iE_2 t}\,|\nu_2\rangle$$

$$= (\cos^2\theta\, e^{-iE_1 t} + \sin^2\theta\, e^{-iE_2 t})\,|\nu_\beta\rangle + \sin\theta\cos\theta(e^{-iE_2 t} - e^{-iE_1 t})\,|\nu_\alpha\rangle$$

$$P_{\alpha\beta} = |\langle\nu_\alpha|\nu_\beta(t)\rangle|^2 = ½ \sin^2 2\theta\,(1-\cos(E_2-E_1)t)$$

$$E_i = \sqrt{(p^2+m_i^2)} \cong p + m_i^2/2p$$

$$P_{\alpha\beta} = ½ \sin^2 2\theta\,\{1-\cos[(m_2^2-m_1^2)/2p]t\} =$$

$$= \sin^2 2\theta\,\sin^2[(\Delta m^2\, L)/(4E)]$$

where $t \cong L/c=L$, $p\cong E/c=E$, natural units $\hbar=c=1$

$$\Rightarrow P_{\alpha\beta} = \sin^2 2\theta\,\sin^2 (1.27\,\Delta m^2\,(eV^2)L(Km)/E(GeV))$$

What do we need to measure?

- The Basic Formula in vacuum for oscillation among two neutrino species

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E)$$

- Experimental Parameters:
  - Neutrino energy E
  - Source-Detector Distance L
- Physics Parameters:
  - Δm^2
  - θ

Appearance experiments:

measure P($\nu_\alpha \rightarrow \nu_\beta$) by detecting different species and identify the neutrino flavour (α,β). How?

Disappearance experiments:

measure P($\nu_\alpha \rightarrow \nu_\alpha$), *for example* by detecting one neutrino flavor at 2(or more) different sites. Other ways?

Neutrino Interactions

"all you have to do is imagine something that does practically nothing" (R.Feynman)

Neutrino weak interactions can be distinguished in:

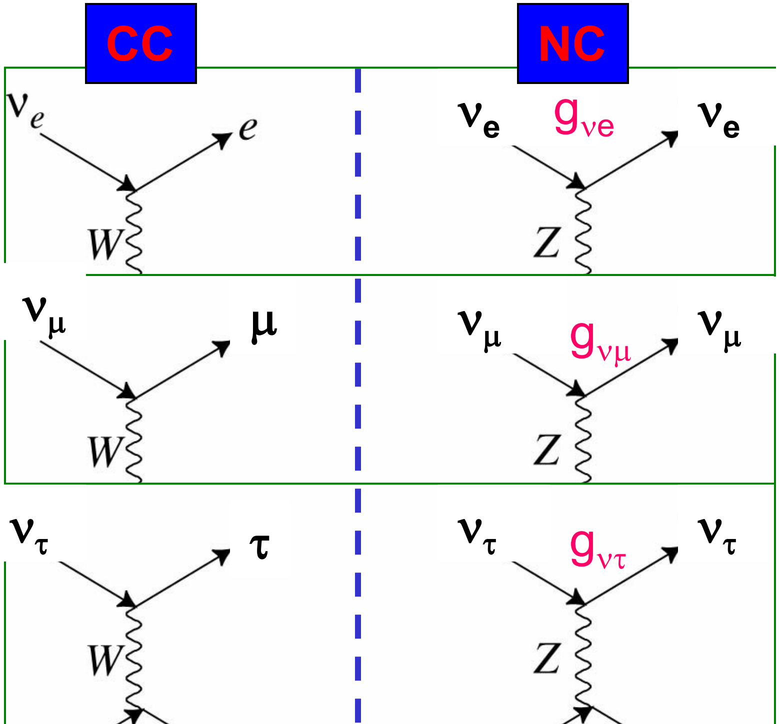
- **CC:** Charged Current interactions (via $W^{\pm}$ exchange)
  The charged lepton in the final state identifies neutrino flavour!
- **NC:** Neutral Current Interactions (via Z^0 exchange)
  No sensitivity to neutrino flavour

Universality: $g_{\nu e} = g_{\nu\mu} = g_{\nu\tau}$

CC only:

Flavor of lepton tags neutrino flavor

Charge of outgoing lepton (-/+) determines if ν or anti-ν

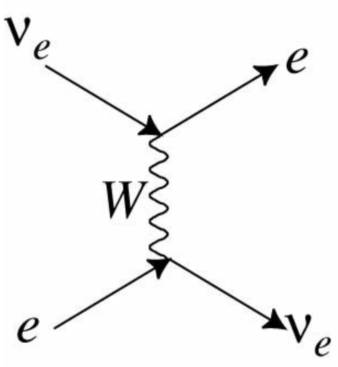


Interaction with matter/1

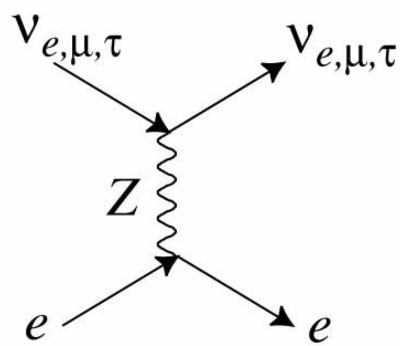
Most common targets for neutrino detection are nucleons (or quarks, increasing neutrino energy resolves smaller matter constituents) and electrons

$\nu\ e^- \rightarrow \nu\ e^-$ Elastic Scattering

Same particles in the initial and final state: ν in and ν out target left intact



Only ν_e



All ν flavours

$\sigma(\nu e) \sim G_F^2\ s \sim 10^{-41}\ cm^2 \times E_\nu\ (GeV)$ $\qquad s = E^2_{CM} = m_e^2 + 2 m_e E_\nu \sim 2 m_e E_\nu$

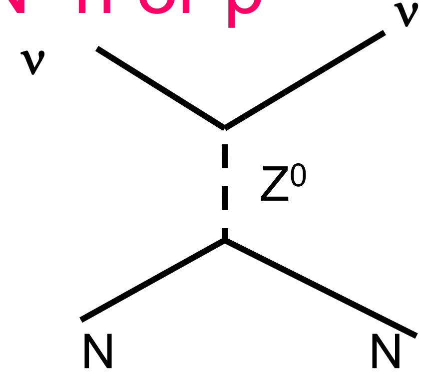
Increases linearly with energy! But really weak

Interactions with matter/2

Elastic interactions on nucleons N=n or p

$s = E^2_{CM} = m_N^2 + 2m_N E_\nu \sim 2m_N E_\nu$

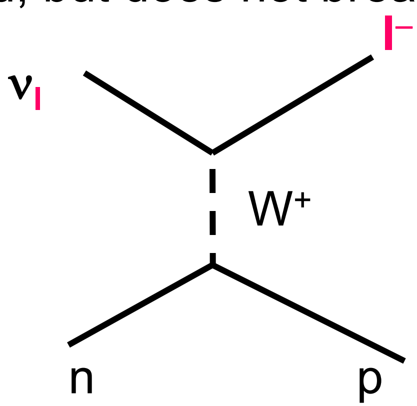
For the same neutrino energy the cross-section is much larger $m_N \sim 10^3\, m_e$

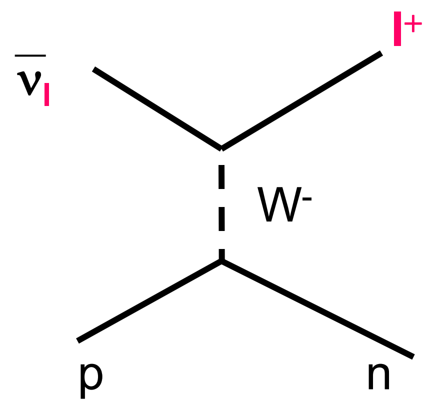


Quasi-Elastic interactions on nucleons

Target is modified, but does not break

This is very useful for ν detection. It is a CC ⇒ Allows identification of ν flavour through detection of charged lepton l=e,μ,τ



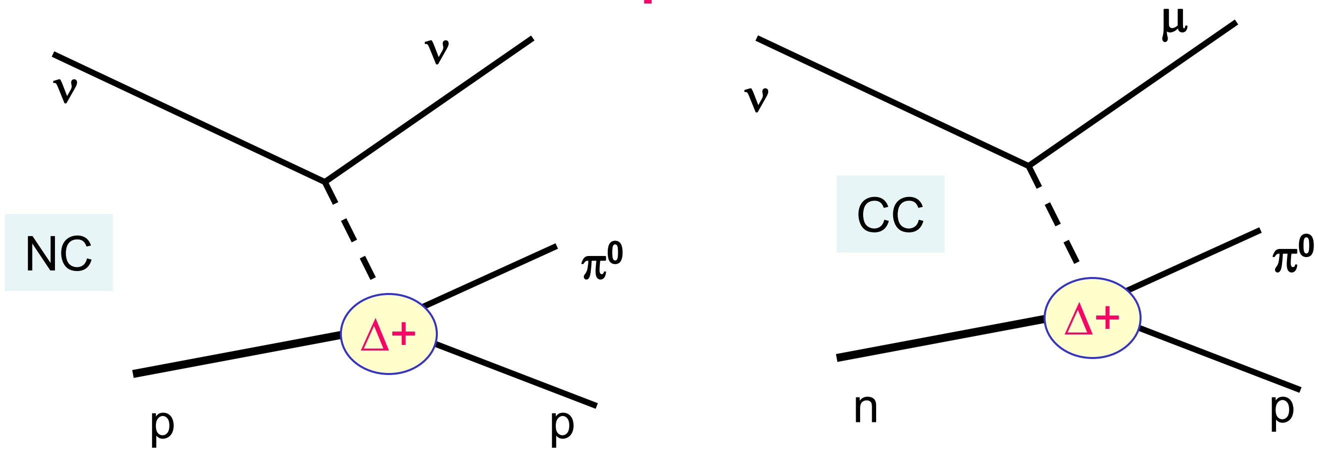


$\sigma(\nu N) \sim 10^{-38} cm^2$ Approximately independent of energy for $E\nu > 1$ GeV

Exercise: compute threshold energy for these reactions for different ν flavour!

Interactions with matter/3

Nucleon resonance production



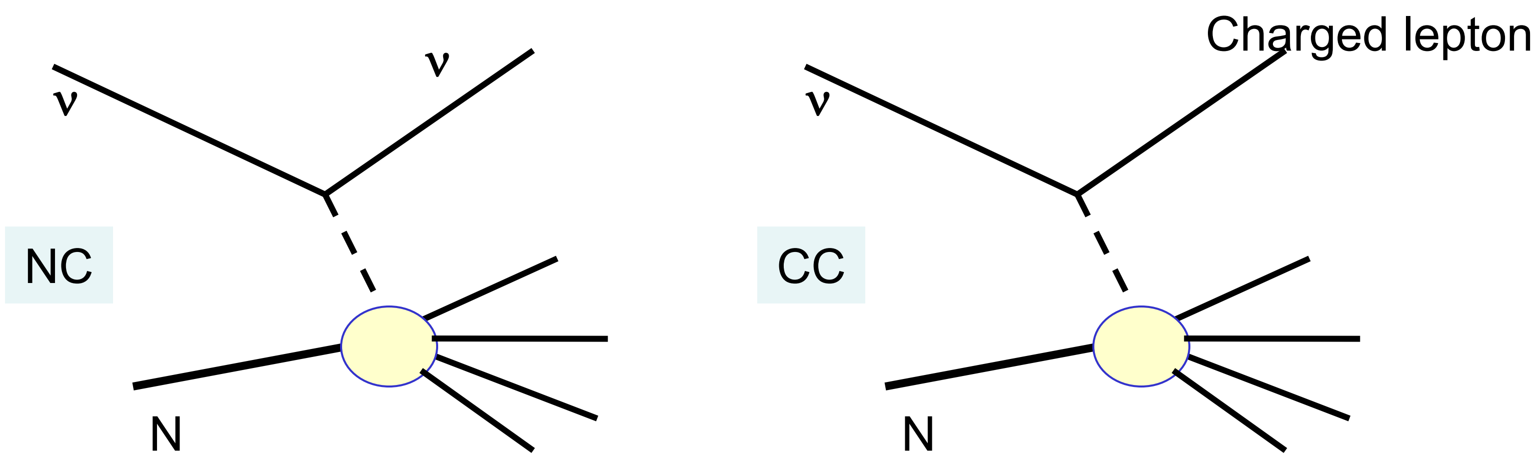
But also Δ^0, Δ^{++}, N'…several baryonic resonances can be produced
m_p < Resonances masses < few GeV
Cross-section same order of magnitude of quasi-elastic interactions

Interactions with matter/4

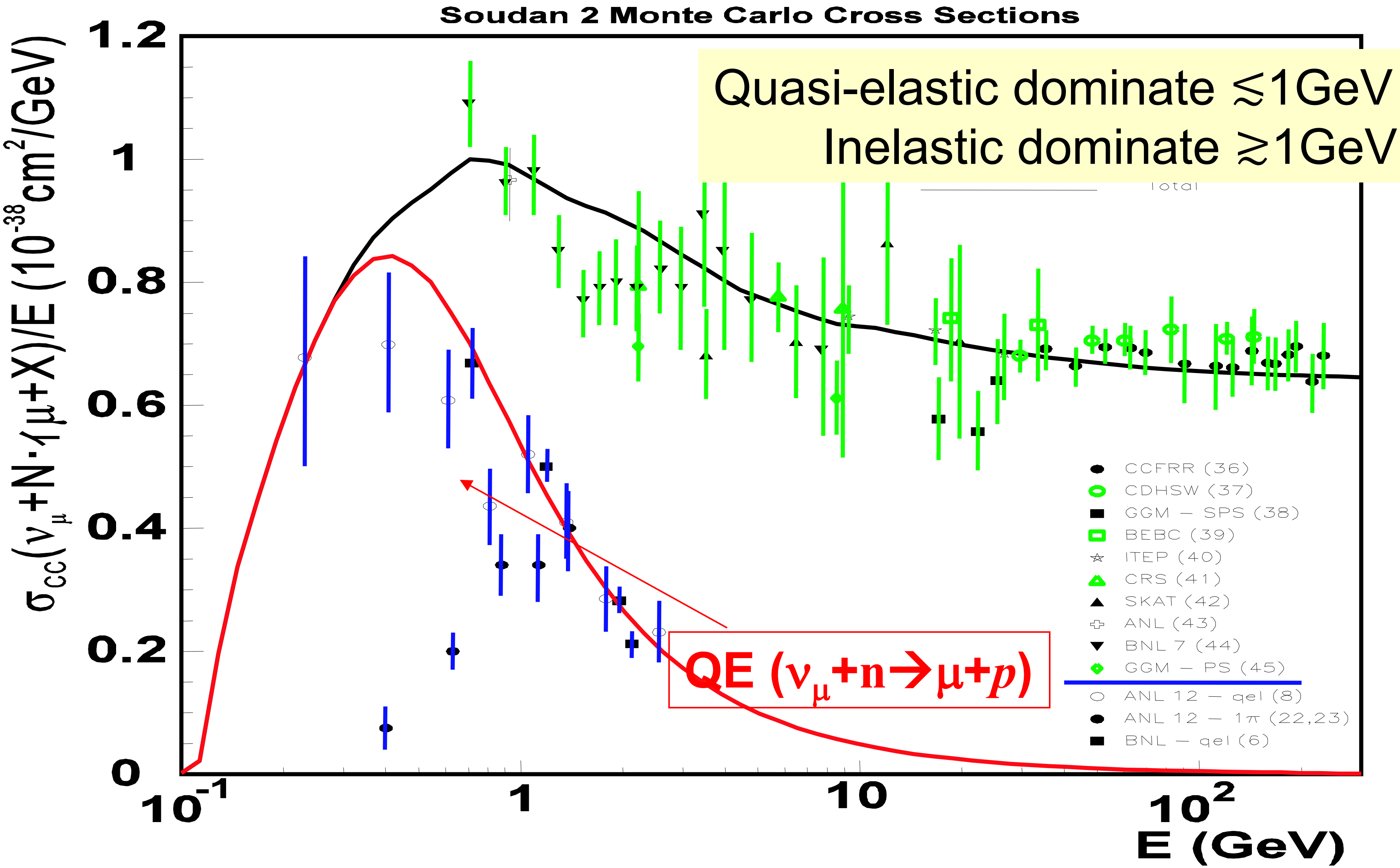
Deep Inelastic Scattering (DIS) on nucleons

Thoroughly studied with ν beams at accelerators (since 1970). Un-valuable in establishing SM physics: weak interaction structure and nucleon constituents.

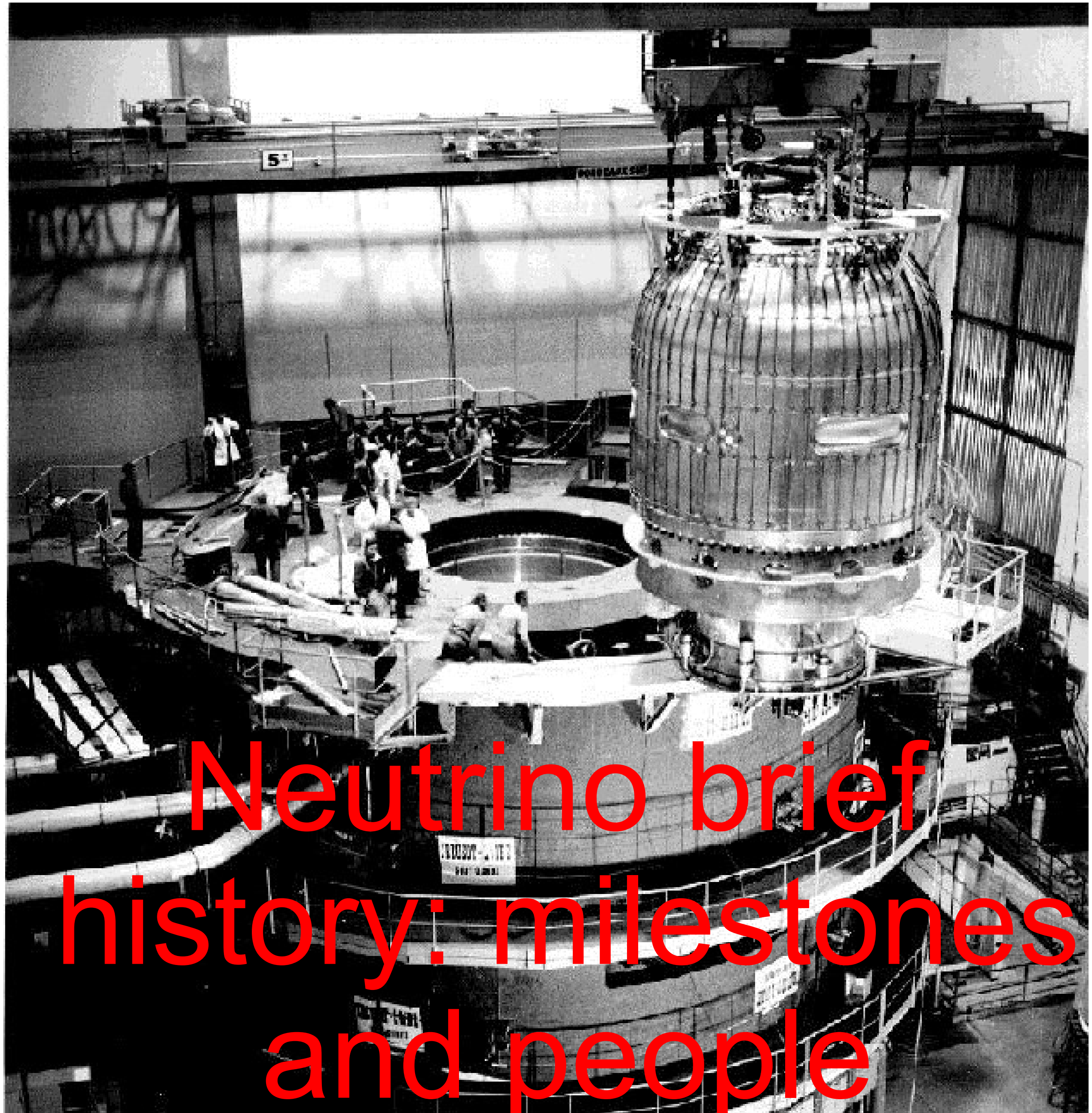
Scattering with very large momentum transfers, E_ν >> GeV the nucleon breaks up



Quark structure of the nucleon probed. Interactions on point-like quarks
⇒ raises linearly with energy (far from threshold)
⇒ CC: $\sigma_{DIS}(\nu N) = 0.67\ 10^{-38}\ cm^2 \times E_\nu\,(GeV)$
⇒ DIS X-section for antineutrinos is about 1/2



Exercise: What's the average free path in steel of 100GeV ν?
Compare with proton[$\sigma(pp) \sim 10^{-25}$ cm^2 at 100 GeV]



Neutrino brief history: milestones and people

W.Pauli

1930 - Neutrino Idea Birth Pauli's letter to Tubingen Colleagues

The neutral particle required for energy conservation in beta-decay was later named ***neutrino*** by Fermi

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

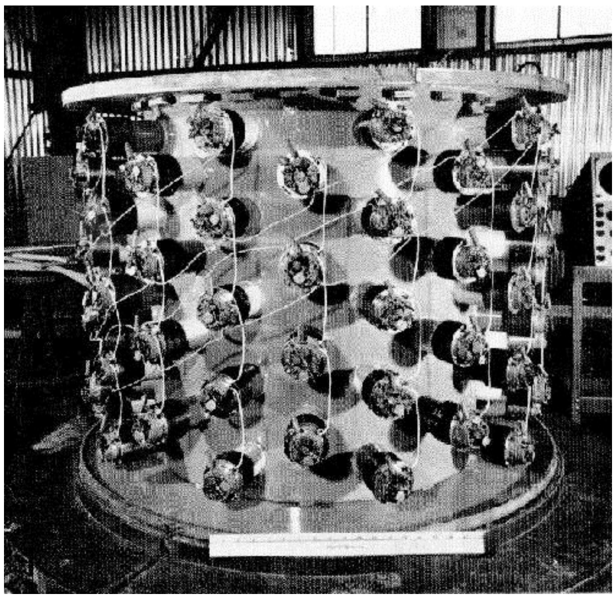
I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant
. W. Pauli

Neutrino Discovery (1956)

Reines and Cowan,1956

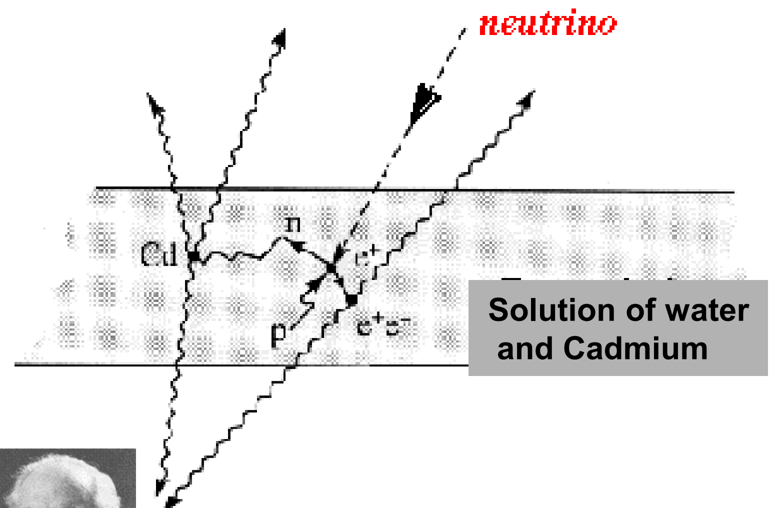
Detector at the Savannah River
nuclear reactor

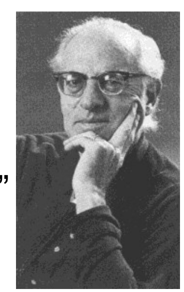


"We are happy to inform you [Pauli]
that we have definitely detected neutrinos"

The first ever observed neutrino
Interaction was a quasi-elastic process!

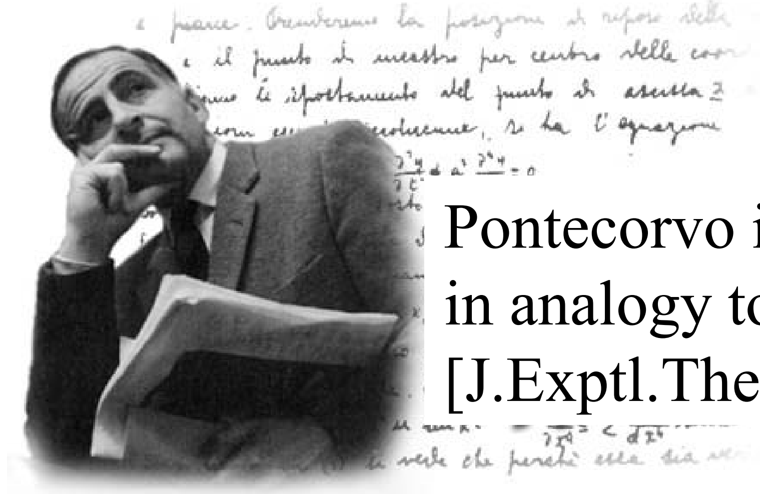
$$\bar{\nu}_e \, p \rightarrow n \, e^+$$





Reines: 1995 Nobel Prize

Bruno Pontecorvo's vision: neutrino oscillations (1957)

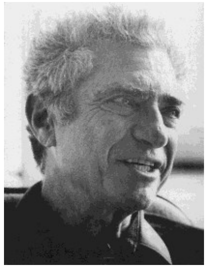


Pontecorvo idea: $\nu \Leftrightarrow \bar{\nu}$ oscillation
in analogy to $K^0 \Leftrightarrow \overline{K}^0$ oscillation
[J.Exptl.Theoret.Phys.33,1957,549]

Other neutrino flavors not known at that time

Later (1962) Maki, Nakagawa, Sakata
proposed flavor oscillation mechanism

Different neutrino species exist! (1962)

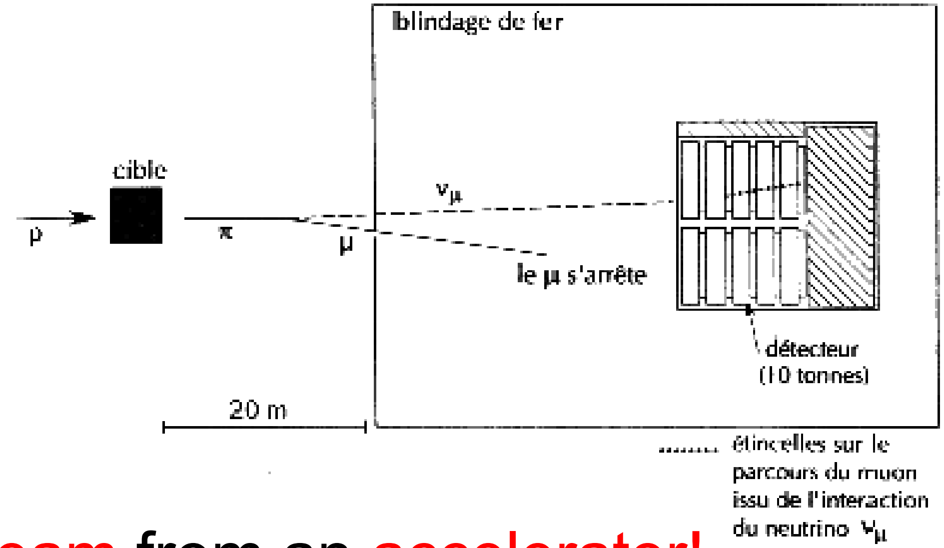


Lederman, Schwarz, and Steinberger

Nobel prize 1988

First detection of CC ν_μ interactions

$$\nu_\mu N \rightarrow \mu^- X$$



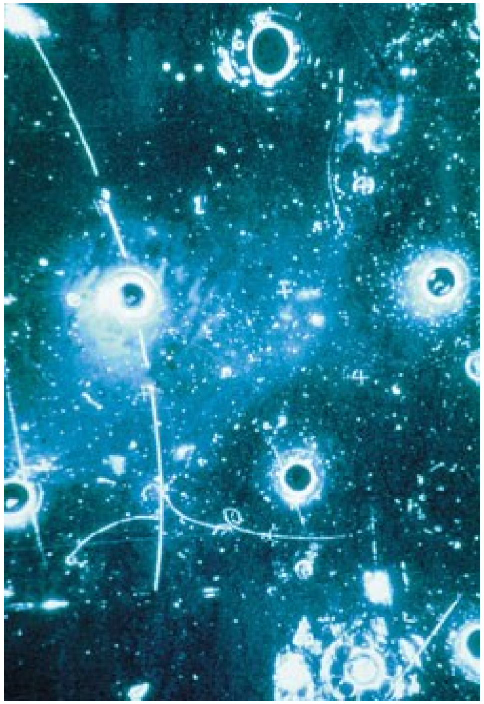
…and first neutrino beam from an accelerator!

Same principle used today in conventional neutrino beams

Discovery of NC: Gargamelle 1973 (EPS HEP prize 2009)

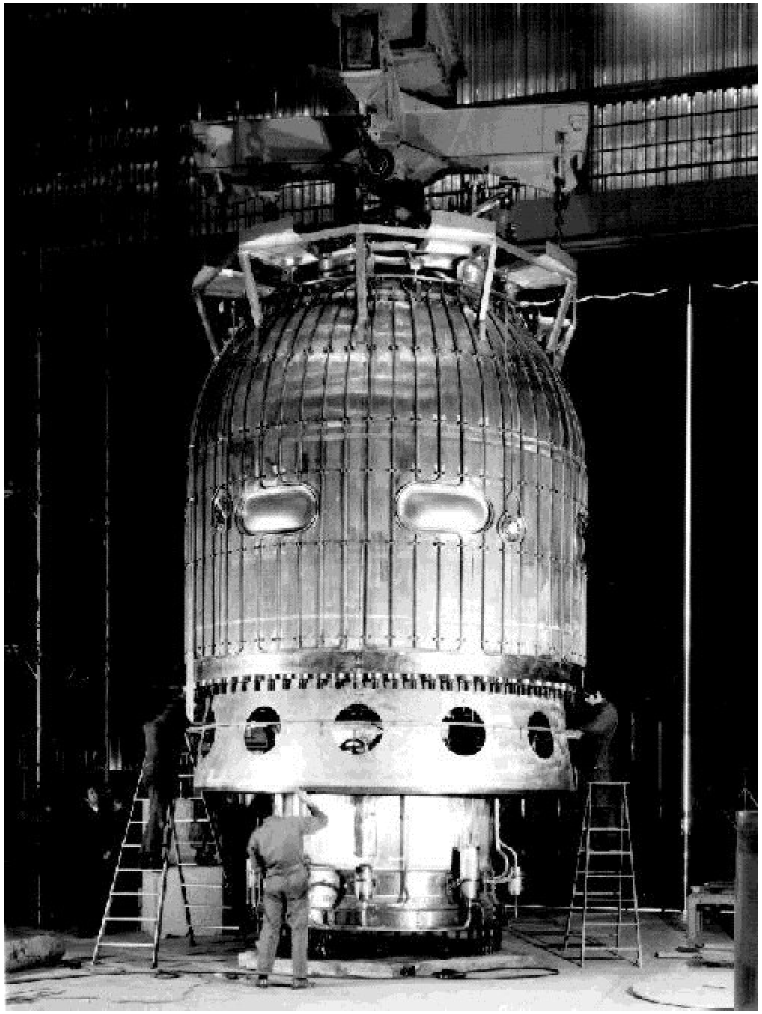
- An historic event 10 years before the discovery of the Z^0

$\nu_\mu\, e \rightarrow \nu_\mu\, e$

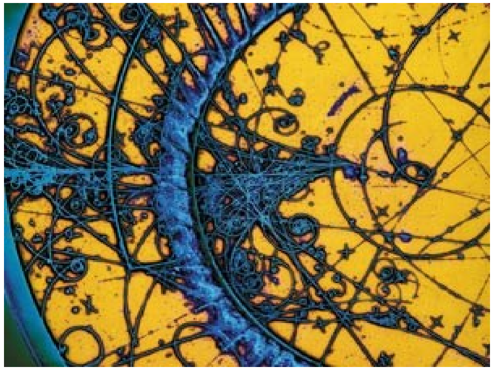


Neutrinos proved to be clean and powerful probe for the Standard Model

'70-'80:CERN Experiments explore ν-nucleon interactions

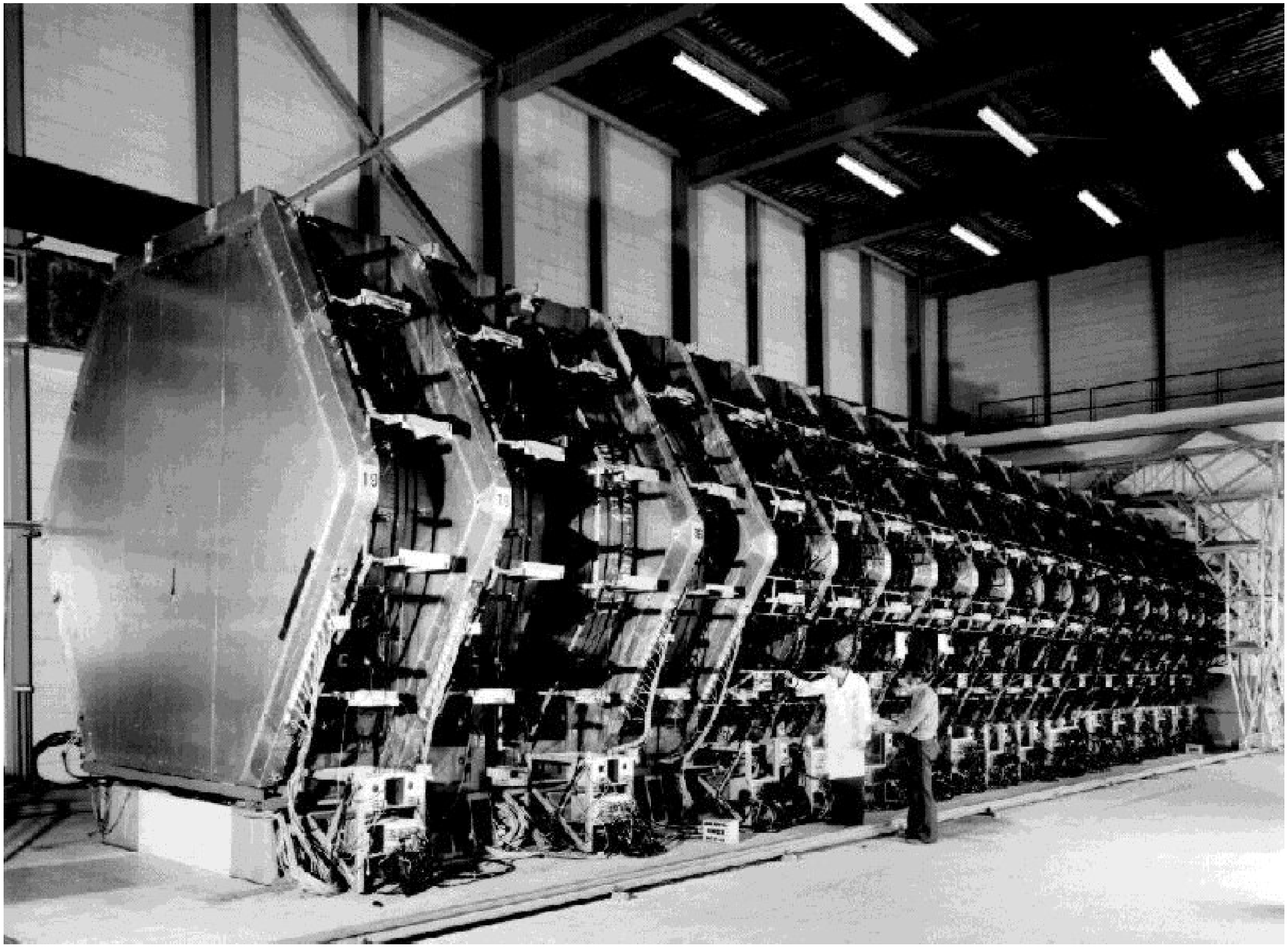


BEBC
Big
European
Bubble
Chamber

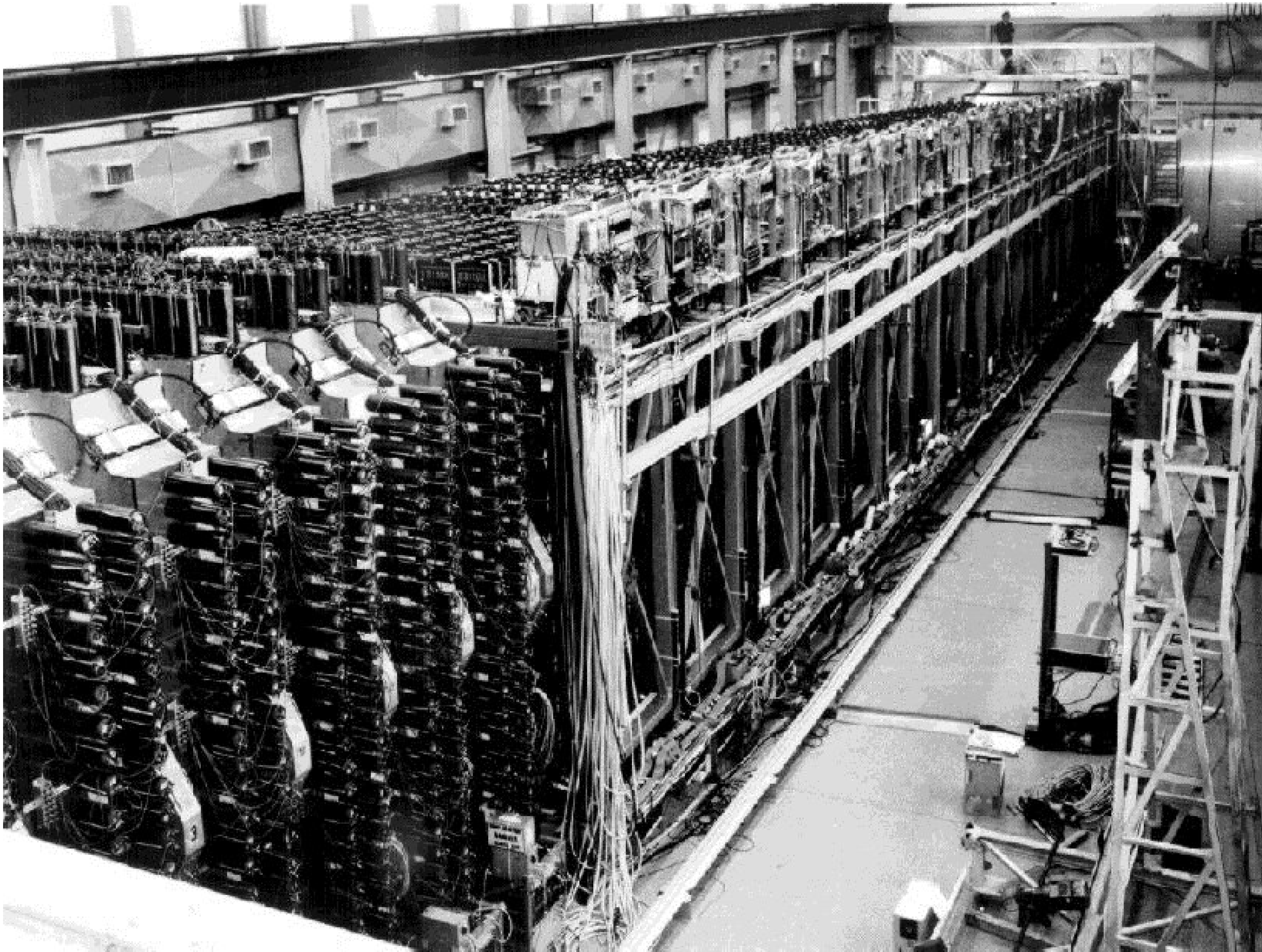


Glorious retirement in the CERN Garden

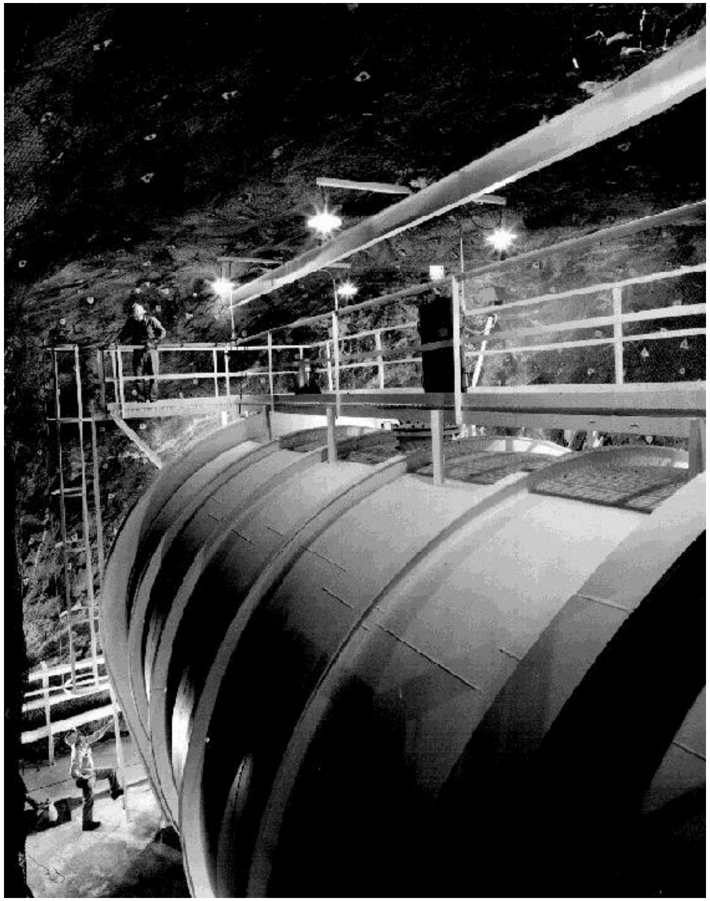
CHARM/CDHS



CHARM-II (until 1991)



Davis' perseverance: 30 years pioneering solar neutrino detection (1969 -1999)



Ray Davis and J.Bachall,
Homestake mine

Also 30 years of debate..
Solar neutrino problem

Atmospheric neutrinos observation of oscillation (1998)

Oscillations:

⇒ $m(\nu) \neq 0$

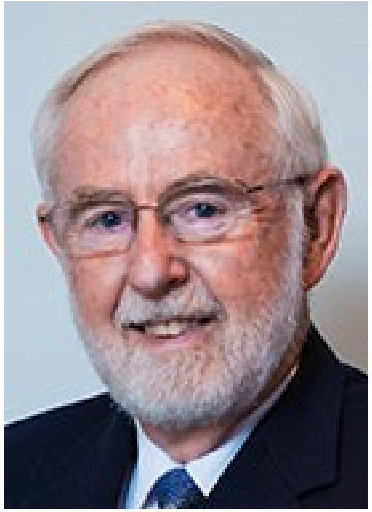
⇒ Mixing in the leptonic sector

⇒CP violation?

NEUTRINOS probe Physics Beyond SM!

2002 Nobel Prize
Koshiba
(superK Spokeman)
shared with Davis
"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

Nobel prize for physics 2015



The 2015 Nobel Prize for Physics has been awarded to Arthur B McDonald (director of SNOlab) and Takaaki Kajita (SuperKamiokande) *"for the discovery of neutrino oscillations, which shows that neutrinos have mass".*

Neutrino oscillations is still

the only experimental evidence of

Physics beyond the Standard Model

Since 1998, a series of new

exciting results confirming neutrino oscillations and providing new insights on

lepton flavour mixing

Profound implications on astrophysics and cosmology