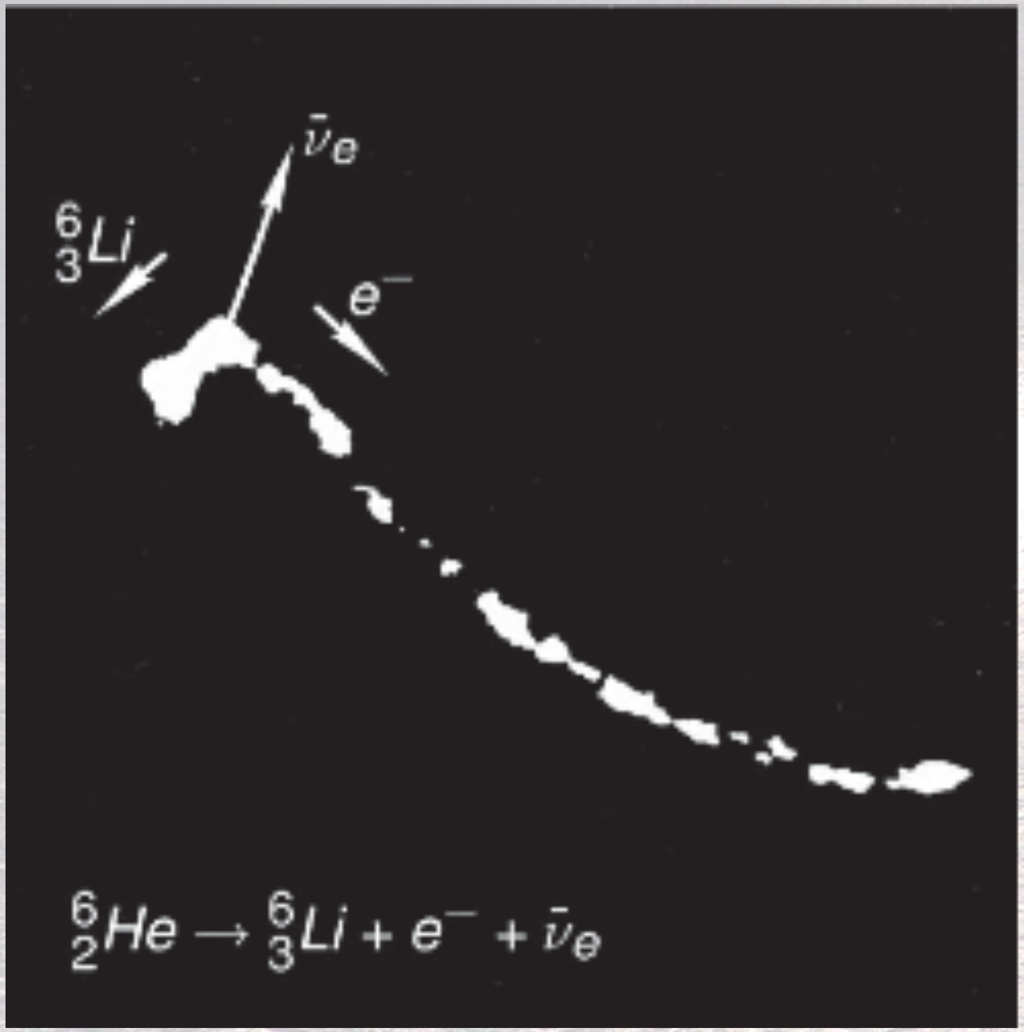
First cloud chamber image of β decay
J. Csikai and A. Szalay, Budapest, fall 1956



Introduction to Experimental Neutrino Physics

International School of Physics E. Fermi

Varenna, 2023

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Outline (I)

- Quick review of relevant neutrino physics
  - Neutrinos in the SM and low energy Fermi effective theory
  - Charged and Neutral currents
  - Interaction with Leptons and Hadrons
  - Mixing and oscillation; neutrino propagation through matter
  - Dirac and Majorana mass terms

- Neutrino phenomenology from 0 eV up to PeV scale
  - Zero threshold processes
  - Low energy nuclear processes
  - Scattering on electrons
  - Elastic, quasi elastic, resonant, deep inelastic scattering on nucleon and nuclei

Outline (II)

- Experimental techniques
  - Radiochemistry
  - Water/Ice (and D_2O) Cherenkov detectors
  - Organic scintillators
  - Sampling calorimeters
  - LAr
  - Accelerator experiments

Disclaimer

- The list of items shown before clearly exceeds what may be discussed thoroughly in only 5 hours.

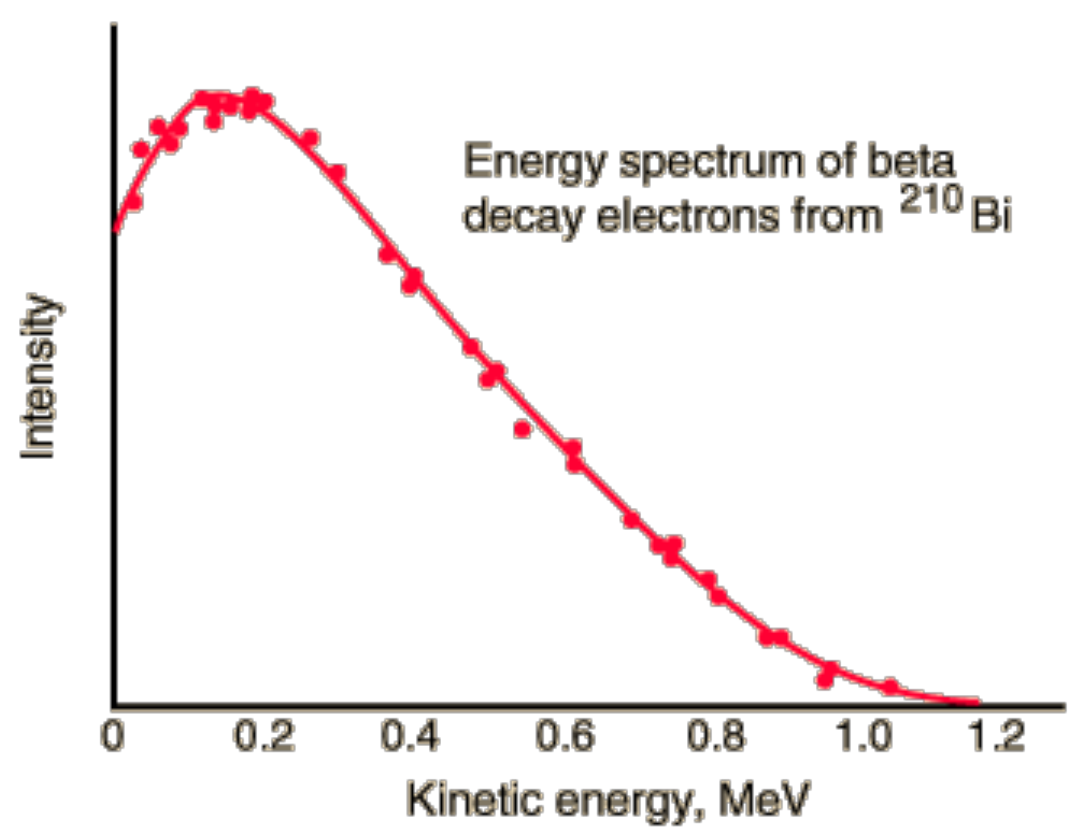
- Therefore:
  - I assume you are somewhat familiar with basic neutrino physics and the basics of the Standard Model. I hope the first part is mostly a recall of known things.
    - I will focus on key points or on some points often mis-understood
  - I will fly quickly over some of the slides: they are meant to be just a reference for home work
  - If I go too quick, you complain and we focus on fewer topics

A touch of history

- **Indirect** evidence of neutrinos dates back to ***early discovery of radioactivity***

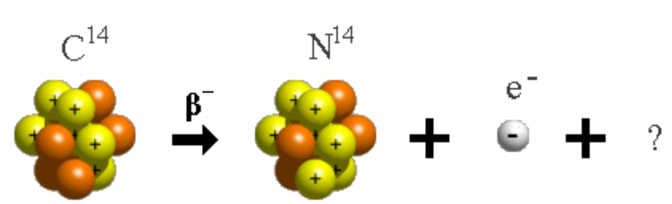
  - Becquerel (1896) discovers β radioactivity, .i.e. the spontaneous emission of an electron off an atomic nucleus [Rutherford, 1899].
  - Several experiments in the period 1911-1927 [O. Hahn, L. Meitner, Chadwick, Ellis-Wooster] prove that the ***e^- spectrum is continuous***, contradicting two-body kinematics.
    - N. Bohr dares saying: "*Maybe in β decays energy is conserved only on average*"

  - Even worse, the β decay, e.g., of ^{14}C (and of all nuclei with an even number of nucleons) **violates statistics,** if the final state is made of a single e^-



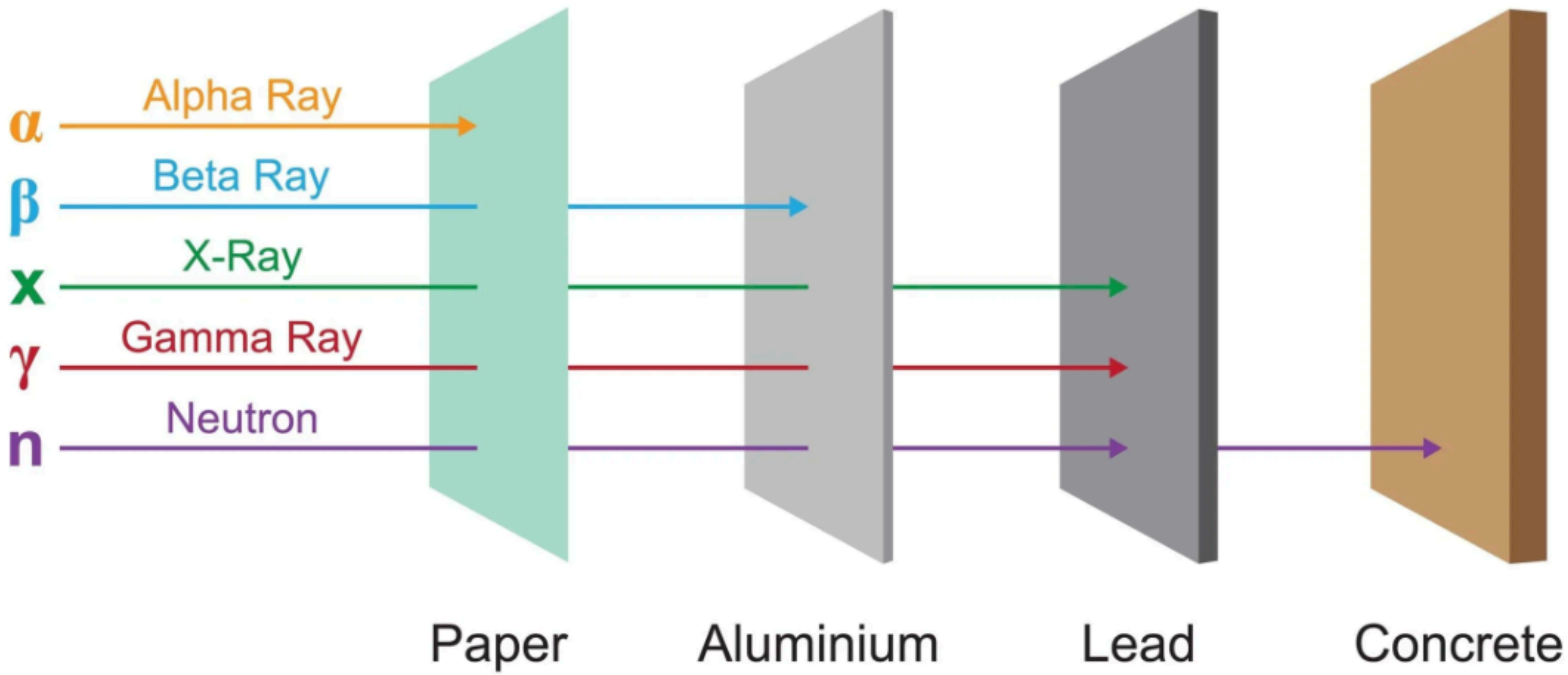
$$^{14}\mathrm{C} \rightarrow {}^{14}\mathrm{N} + e^-$$

boson boson fermion

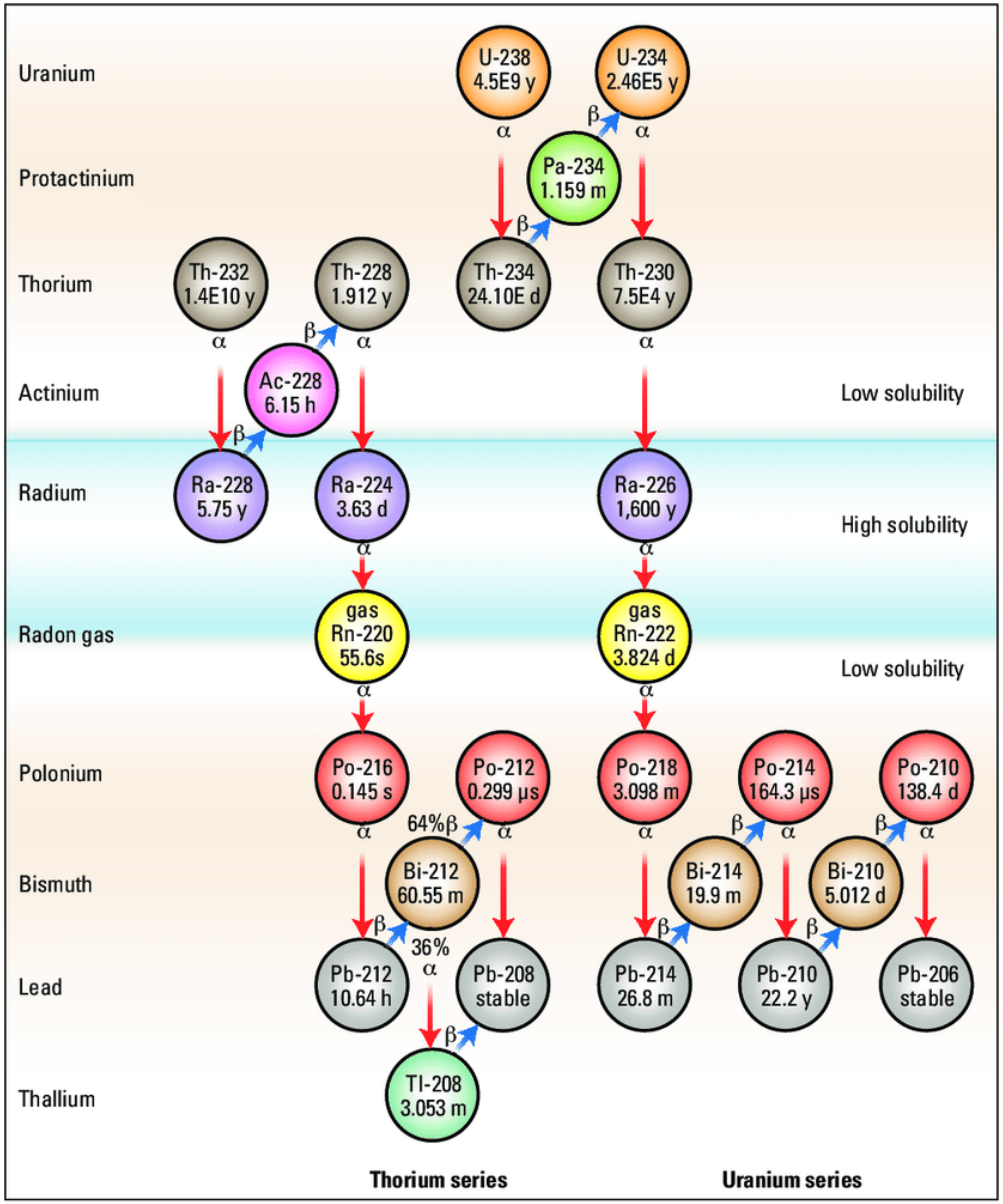


Avoiding historical miopia

- The problem WAS difficult !



The problem WAS difficult



Pauli and Fermi

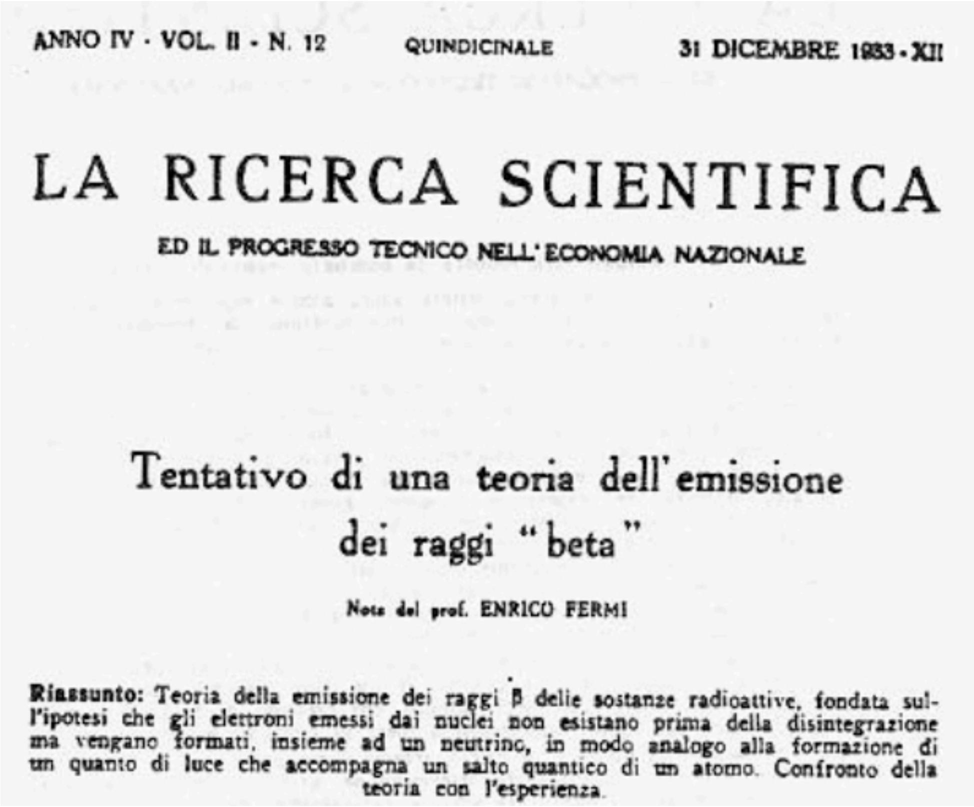
W. Pauli

E. Fermi

- Both problems are solved by a single idea: **a three-body final state** obtained by adding a **light neutral spin ½ particle**
  - Pauli letter, **1930**

- The discovery of the **neutron** (1932, Chadwick) clarifies nuclear structure:
  - The nucleus is made of protons and neutrons (Heisenberg model, 1932-1933)
  - No electrons are within the nucleus
  - The neutrons are not the neutrinos (neutrons are heavy and strong interacting)

- These ideas, in the hands of **Enrico Fermi**, bring to the first **"attempt"** to describe weak interactions:
  - Many breakthroughs in a single paper:
    - **It is the first Quantum Field Theory beyond QED**
    - Neutrinos and electrons ***are not in the nucleus***, but are **created** by the interaction
    - Explains the Q^5 behaviour of some β decays life-times



ANNO IV · VOL. II · N. 12 QUINDICINALE 31 DICEMBRE 1933 · XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del prof. ENRICO FERMI

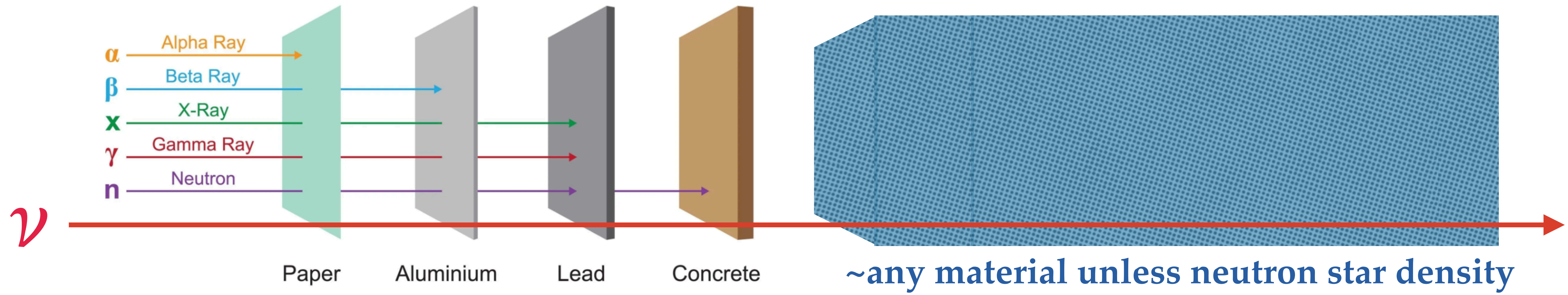
Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

Fermi theory

- Fermi theory is a blessing which gives the "desperate remedy" a convincing theoretical framework
  - But it almost killed neutrino physics at its infancy
  - Bethe and others compute the neutrino-matter cross sections and the result is despairing
    - **$\sim 10^{-42}$ - 10^{-44} cm^2 @ 1 MeV**

MEAN FREE PATH IN WATER

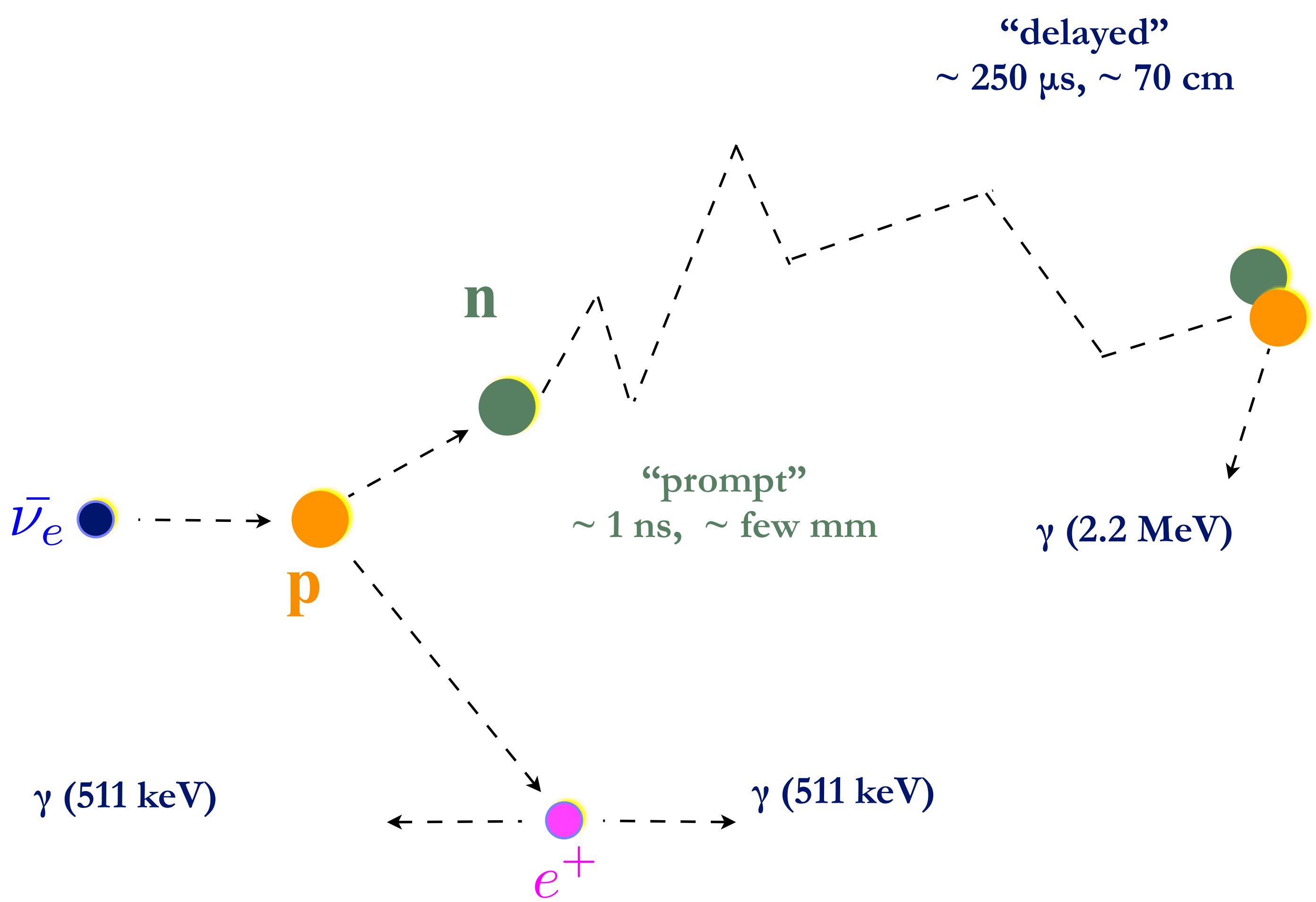
$$\lambda = \frac{1}{n\sigma} \simeq \frac{1}{6\ 10^{23} \cdot 10^{-42}} = 1.7\ 10^{18}\ cm = 1.7\ ly$$



~any material unless neutron star density

Inverse β decay

- Historically and physically, is a key process for neutrino physics
  - "The golden channel" for anti-neutrino detection at low energy
    - Large cross section, clean signature of final state
  - First detection by Reines and Cowan was done using this technique



First detection of (anti)-neutrinos (I)

- Key point: **ν-matter cross sections are (always) small**
  - To detect some νs you need a **huge integrated luminosity,** which is obtained with large **detector masses,** very large ν **fluxes,** and **patience.**

- ν detection was at first made possible by the development of **fission reactors**

  - **Reines and Cowan, 1956** (after several attempts, including the "idea" to use atomic bombs explosions!)

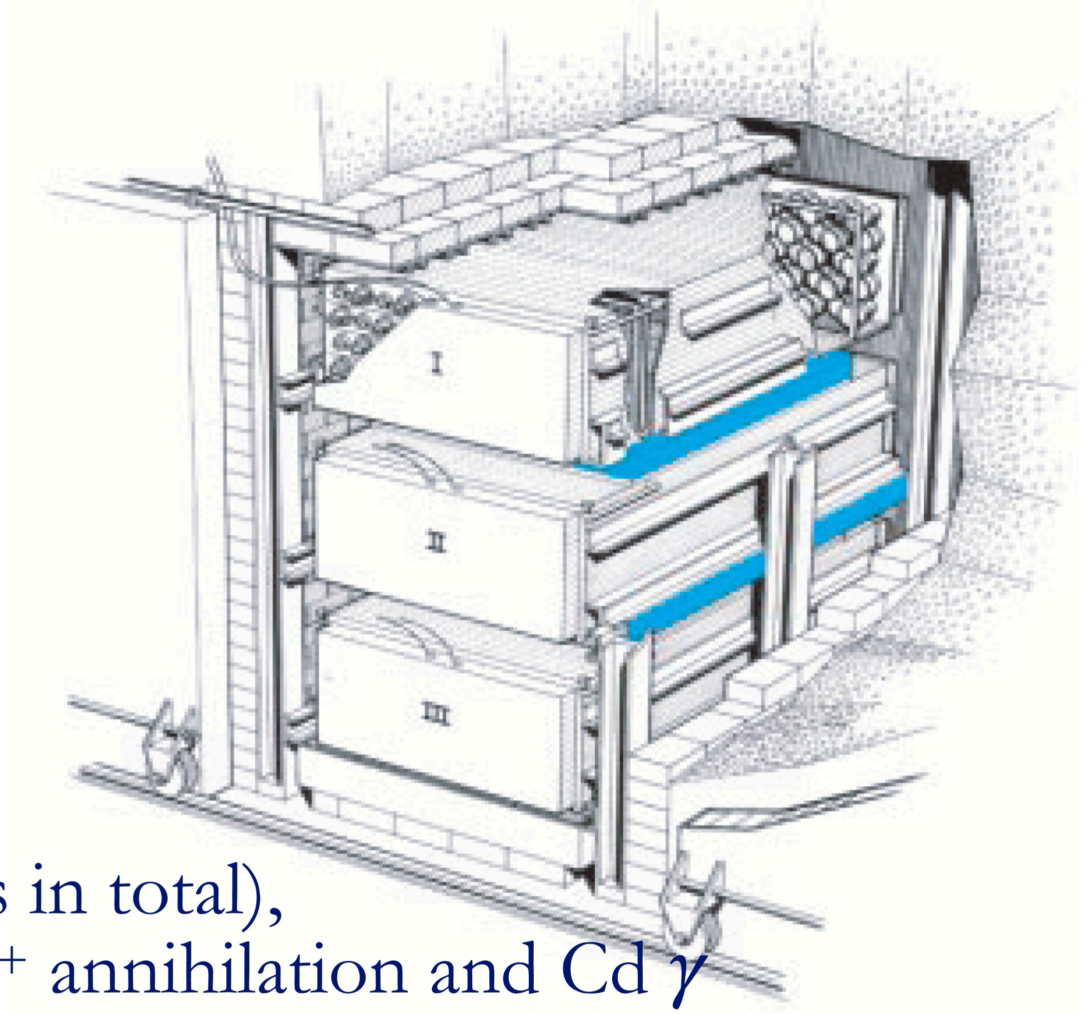
  - **Each U fission yields 200 MeV on average, and 6 ν_e**
    - Flux: ~ **2. 10^{20} s^{-1} GW^{-1},** isotropic, $\langle E_\nu \rangle \simeq 0.5$ MeV
    - About ~ **4. 10^{12} s^{-1} cm^{-2}** for 1 GW reactor at **20 m from the core**
    - For comparison **solar neutrinos:** ~ **6.5 10^{10} s^{-1} cm^{-2} on Earth**

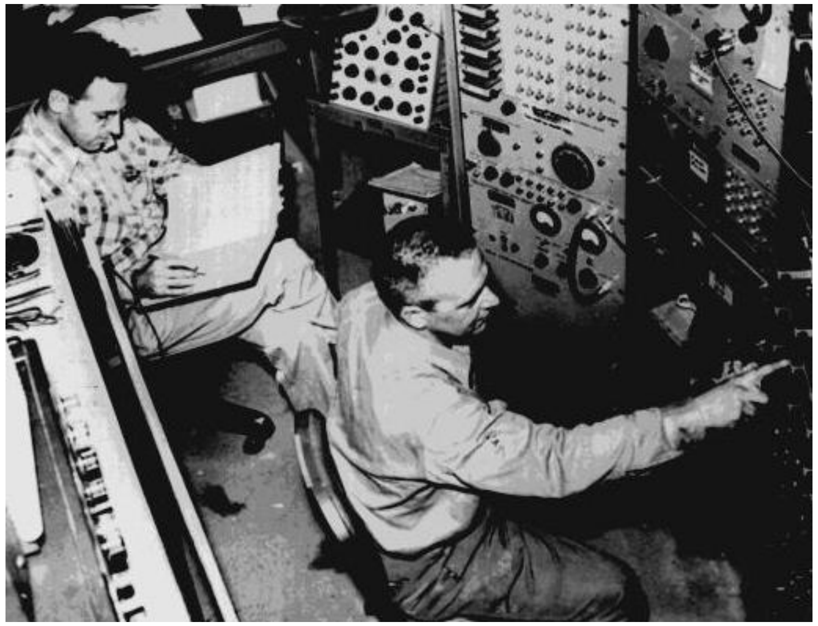
First detection of (anti)-neutrinos (II)

- A first conceptual drawing to detect ν from nuclear explosions in 1952. Never done.
- First detection at Hanford fission reactor in 1953.
  - **300 lit of liquid scintillator observed by photomultipliers**
    - At that time, a record. Largest detector before was about 10 litres.
    - Neutrons and photons from reactor successfully shielded by lead and borated-paraffin
    - **Lesson learned: cosmic rays make a substantial background,** 10 times more than signal.
      - *"The lesson of the work was clear: It is easy to shield out the noise men make, but impossible to shut out the cosmos. Neutrons and gamma rays from the reactor, which we had feared most, were stopped in our thick walls of paraffin, borax and lead, but the cosmic ray mesons penetrated gleefully, generating backgrounds in our equipment as they passed or stopped in it. We did record neutrino-like signals, but the cosmic rays with their neutron secondaries generated in our shields were 10 times more abundant than were the neutrino signals. We felt we had the neutrino by the cottails, but our evidence would not stand up in count."*
- **No surprise:** today most **low energy ν experiments are underground**
  - The group had to develop **technologies** that are still crucial today
    - Improve quality and stability of liquid scintillator and large scale production
    - **Low radioactivity** components, shielding and **tagging of external radiation**
    - **Electronics to detect delayed coincidence**

First detection of (anti)-neutrinos (III)

- Conclusive result at Savanah River in 1956
  - Two plastic tanks filled with water (blue)
    - $\Rightarrow \nu$ target (protons)
  - Cadmium dissolved in water
    - $\Rightarrow$ Cd has a **huge neutron capture cross section** and emits high energy γ
  - Between the water tanks, 3 large liquid scintillators detectors (I, II e III) (4200 litres in total), each equipped with 110 PMTs to detector e^+ annihilation and Cd γ
  - Each ν **event in the water produces**:
    - A positron, whose annihilations yields two back-to-back γs $\Rightarrow$ fast coincidence in tanks I and II.
    - A neutron, captured by Cd $\Rightarrow$ again signals in tanks I or II, delayed by 3-10 μs.
    - No signal in tank III because Tank II is a good shield



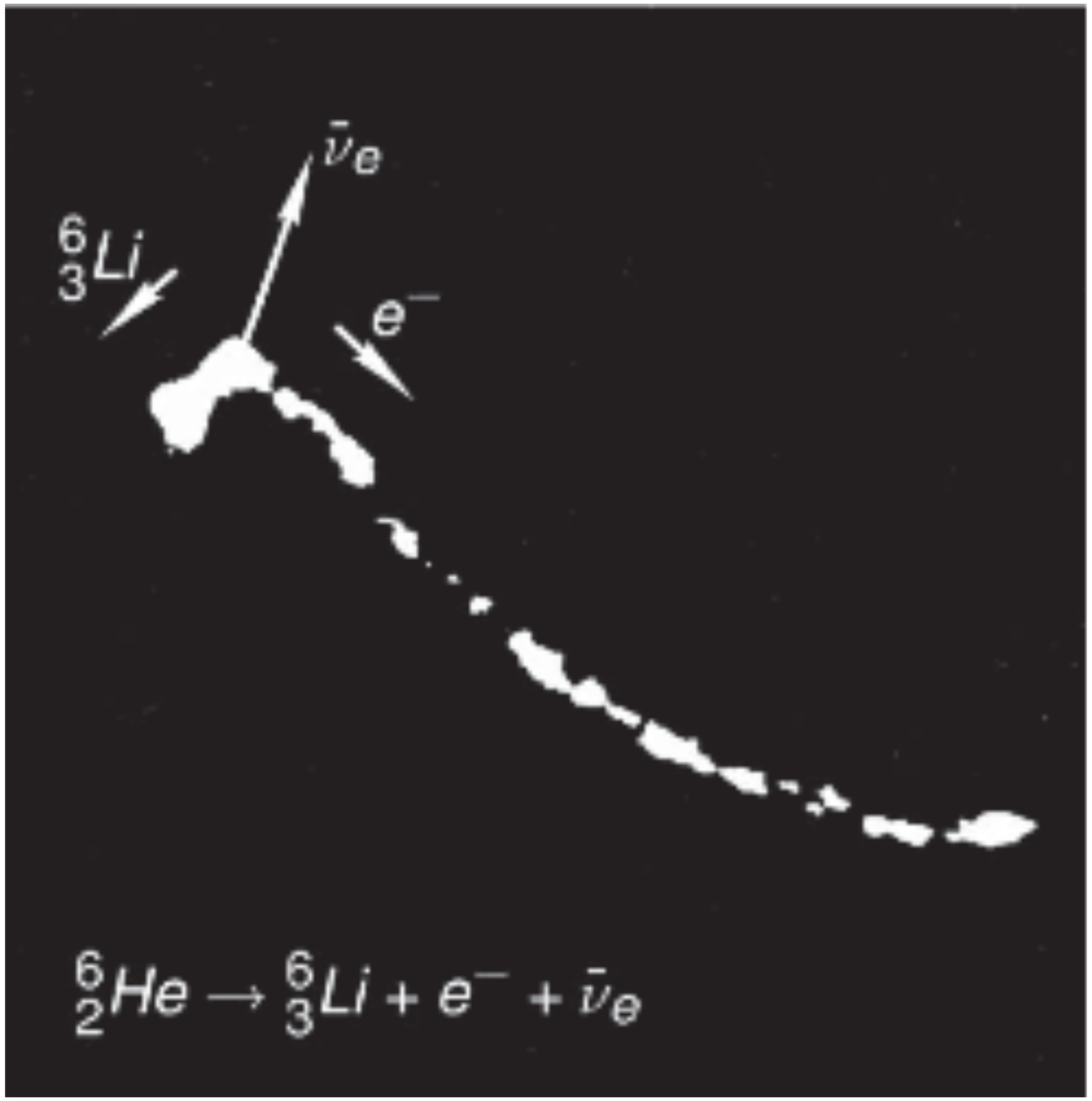


Historical note

- First visual image of a β decay (^{6}He in a cloud chamber)
  - Clearly showing that it is a 3-body final state
  - Obtained in Hungary in 1956, a few weeks before Soviet invasion, which stopped completely this activity

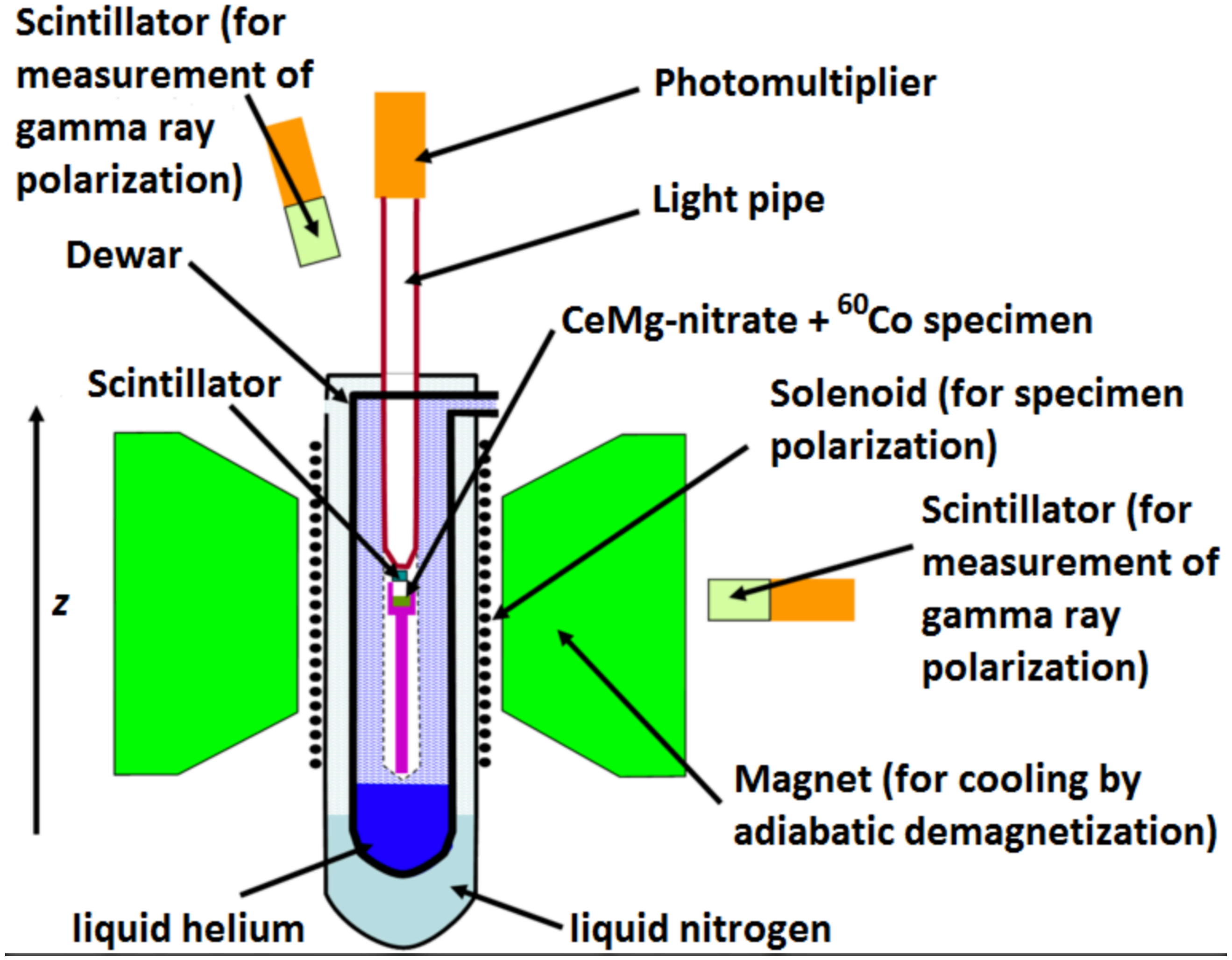
J. Csikai
A. Szalay

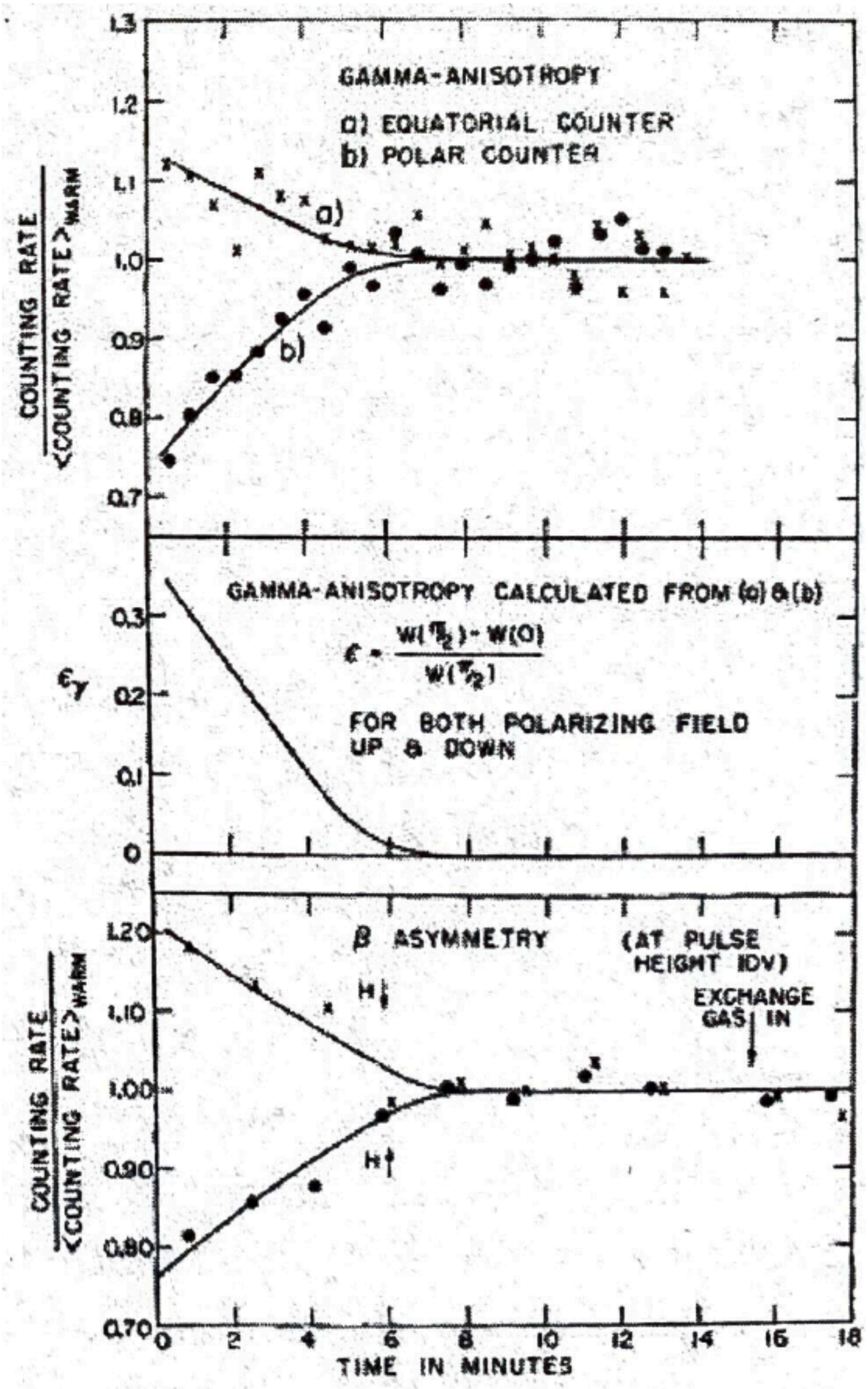
C. Budapest, fall 1956



Discovery of parity violation (1956)

- **C.S. Wu (1956)**
  - She measures the angular distribution of e^- emitted in ultra-cold polarised **^{60}Co** ***β*-decays** and discovers **parity violation**
    - She never got the Nobel prize she deserved

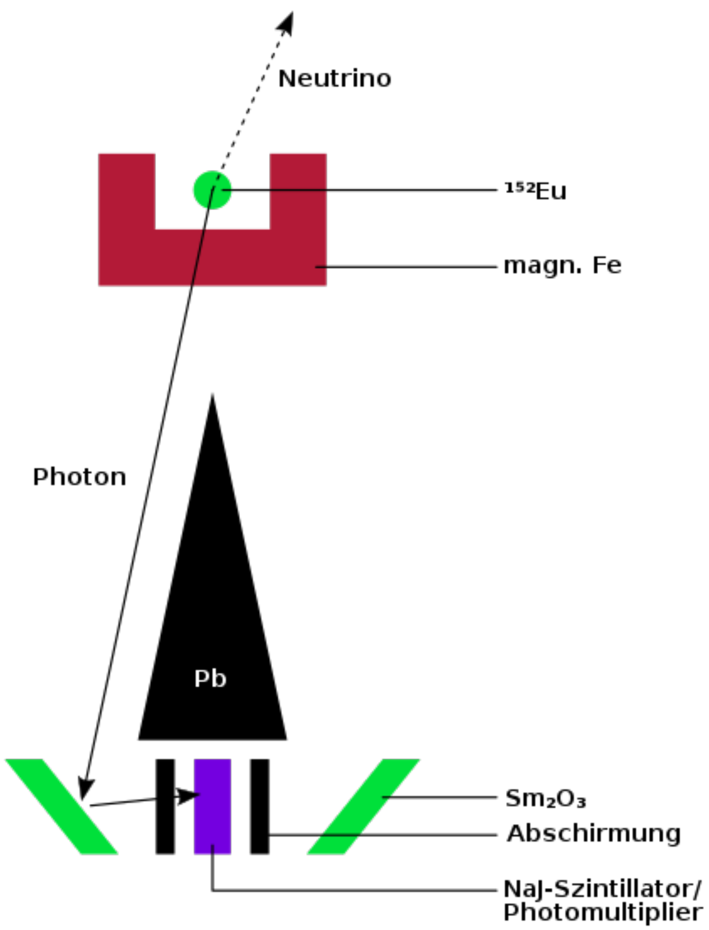




Neutrino helicity (1958)

M. Goldhaber

- Goldhaber, Grodzinns and Sunyar (1958)
  - ν emitted in β-decay have **fixed helicity**
  - A beautiful trick transfers helicity to a detectable γ



$$^{152m}\mathrm{Eu} + e^- \rightarrow \nu + ^{152}\mathrm{Sm}^*$$

$$0^- + \tfrac{1}{2} = \tfrac{1}{2} + 1^-$$

j_z p

τ = 3 10^{-14} s

$$^{152}\mathrm{Sm}^* \rightarrow ^{152}\mathrm{Sm} + \gamma \; (963\ keV)$$

$$1^- = 0^+ + 1^-$$

p

3 crucial points:

- neutrino helicity is transferred to photon helicity
- neutrino recoil is the same as photon recoil
- Sm-152 decays fast, it is not disturbed by crystal

Recalling SPINORs properties

- A spinor is a 2-component quantity transforming under Lorentz transformations Λ as:

$$\xi = \begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix} \rightarrow L(\Lambda)\xi$$

- Where L(Λ) $\in$ SL(2$\mathbb{C}$) is a complex 2x2 matrix defined as:

$$\frac{1}{2} Tr\left(\bar{\sigma}_\mu L \sigma_\nu L^\dagger\right) = 2 g_{\mu\rho} \Lambda^\rho_\nu$$

2 SOLUTIONS for each Λ

With $\sigma_0 = \bar{\sigma}_0 = I$ and $\sigma_i = -\bar{\sigma}_i$ are Pauli matrices.

- A Dirac spinor is a 4-component quantity transforming under Lorentz transformations Λ as:

$$\psi(x) = \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \chi_1 \\ \chi_2 \end{pmatrix} \rightarrow L(\Lambda)\, \psi(\Lambda^{-1} x)$$

where $L(\Lambda) = e^{\left(\frac{1}{2}\omega_{\mu\nu}\sigma^{\mu\nu}\right)}$ $\sigma^{\mu\nu} = \frac{1}{2}[\gamma^\mu, \gamma^\nu]$

Lorentz transformation of spinor bilinear

- It can be proved that, given a Dirac spinor, the following bilinear have the transformation properties below:

$\bar{\psi}\psi$	SCALAR
$\bar{\psi}\gamma^5\psi$	PSEUDO SCALAR
$\bar{\psi}\gamma^\mu\psi$	VECTOR
$\bar{\psi}\gamma^5\gamma^\mu\psi$	PSEUDO VECTOR (AXIAL VECTOR)
$\bar{\psi}\sigma^{\mu\nu}\psi$	TENSOR

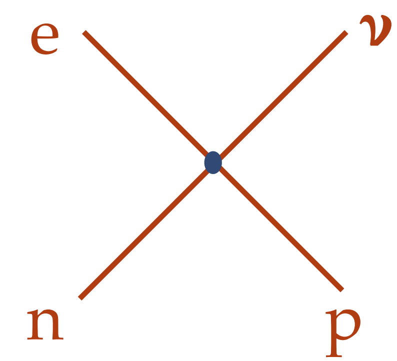
where:

$$\bar{\psi} = \psi^\dagger\gamma^0$$

Fermi weak interactions

- Assuming **point-like 4-fermion interaction** the Fermi Hamiltonian reads:

$$H_W = \frac{G_F}{\sqrt{2}} \hat{J}^{\dagger}_{\mu} \hat{J}^{\mu}$$



LOWEST ORDER DIAGRAM FOR NEUTRON DECAY IN FERMI THEORY

- Original Fermi theory (1934): $\hat{J}^{\mu} = \bar{n}\gamma^{\mu}p + \bar{\nu}\gamma^{\mu}e$ **pure "VECTOR" current**

- Gell-Mann - Feynman V-A (1958): $\hat{J}^{\mu} = \bar{n}\gamma^{\mu}(g_V + g_A\gamma^5)p + \bar{\nu}\gamma^{\mu}(1-\gamma^5)e$

  Phys.Rev. 109 (1958) 193-198

  Developed after discovery of PARITY violation

  "VECTOR" - "AXIAL" current

  - Note 1: the ratio of axial/vector couplings to **leptons** is fixed by the theory
  - Note 2: **that of hadrons is NOT**
    - We see later that the coupling to quarks is the same as that of leptons, **but strong interactions have substantial effects,** especially **on the axial coupling.**

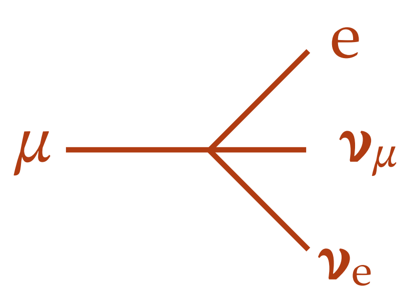
Universal weak interactions

- Gell-Mann and Feynman introduce two key ideas:
  - The weak current has a V-A structure
  - The interaction is **universal**, i.e. it explains leptons and hadrons weak interactions, assuming that all hadrons are coupled to weak interactions.
  - Many results: chiefly

$$H_W = \frac{G_F}{\sqrt{2}}\, \bar{\nu}_\mu \gamma^\alpha (1-\gamma^5)\mu \; \bar{e}\gamma_\alpha (1-\gamma^5)\nu_e$$

    - μ lifetime is calculated at % level

$$\tau = \frac{1}{\Gamma} = \frac{G_F^2 m_\mu^5}{192\pi^3}$$



$$\tau = \frac{1}{\Gamma} = \frac{G_F^2 m_\mu^5}{192\pi^3}\left[1 - \frac{\alpha}{2\pi}\left(\pi^2 - \frac{25}{4}\right)\right]$$

WITH LEADING QED CORRECTIONS

    - Weak interactions are responsible also of processes not involving neutrinos:
      - The fact that K^+ decays both in 2 and 3 pions (violating parity) is explained

$K^+ \rightarrow \pi^+\pi^+\pi^-$ BR 5.6% (Phase space is small)

$K^+ \rightarrow \pi^+\pi^0$ BR 20.7%

V-A structure

- The **V-A structure** of weak interactions is based on solid experimental evidence
  - For example a scalar or pseudo-scalar interaction terms would say:

$$\frac{\Gamma(\pi^+ \to e^+\nu_e)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)} = 5.5$$

WRONG !

  - **V-A predicts:**

THEORY (tree level)

$$\frac{\Gamma(\pi^+ \to e^+\nu_e)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)} = \frac{m_e^2(m_\pi^2 - m_e^2)^2}{m_\mu^2(m_\pi^2 - m_\mu^2)^2} = 1.26\ 10^{-4}$$

EXPERIMENT PDG 2020

$$\frac{\Gamma(\pi^+ \to e^+\nu_e)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)} = 1.230 \pm 0.004\ 10^{-4}$$

- **TWIST** experiment has made a high precision test with **10^{10} polarised muons**
  - The Michel parameters parameterise the general combination of the possible S+P+V+A+T interaction terms.
  - The Michel parameters ϱ and δ, which for a pure V − A interaction should be 3/4, are measured to be:
    - $\varrho = 0.74977 \pm 0.00012(\text{stat.}) \pm 0.00023(\text{syst.})$
    - $\delta = 0.75049 \pm 0.00021(\text{stat.}) \pm 0.00027(\text{syst.})$

Phys. Rev. D 85, 092013 (2012)

Hadronic weak decays

- Weak decays of hadrons are affected by strong interactions. We can classify the main hadronic weak matrix elements as:

  - **Leptonic decays:** $< 0|J_\mu^{(h)}|h >$ e.g. $\pi^+ \to \mu^+ \nu_\mu$
  - **Semi-leptonic decays:** $< h'|J_\mu^{(h)}|h >$ e.g. nuclear β decay, $\Lambda \to p e^- \bar{\nu}_e$
  - Semi-leptonic with **two hadrons in FS:** $< h' h''|J_\mu^{(h)}|h >$ e.g. $K^- \to \pi^+ \pi^- e^- \bar{\nu}_e$
  - **Meson oscillations:** $< h'|J_\mu^{(h)} J^{(h)\mu\dagger}|h >$ e.g. $K^0 \leftrightarrow \bar{K}^0, D^0 \leftrightarrow \bar{D}^0, B^0 \leftrightarrow \bar{B}^0$
  - Hadronic with two hadrons in final state: $< h' h''|J_\mu^{(h)} J^{(h)\mu\dagger}|h >$ e.g. $\Lambda \to p \pi^-$

- Generally, $\mathbf{J}_\mu = \mathbf{V}_\mu - \mathbf{A}_\mu$, but these **operators cannot be written exactly** because of **strong interactions**

Standard model (I)

- In the SM weak currents are **Noether currents** of the **gauge group $SU(2)_L$**, acting on L components of **fermion fields doublets,** e.g.

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \to \exp\left(ig\alpha_i \frac{\sigma_i}{2}\right) \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$$

- Leaving to others the complete construction of the model, we recall some key features:
  - The group SU(2) has **three generators,** one of which is a **neutral current**
    - This neutral current is **NOT the photon.** We must add another U(1) to the gauge group

$$SU(2)_L \times U_Y(1)$$

  - If the two neutral fields are rotated by θ_W **angle, electro-weak unification** is obtained:

$$g \sin\theta_W = g' \cos\theta_W = e \quad Y(e_L) = Y(\nu_{eL}) = -1 \quad Y(e_R) = -2 \quad Y(\nu_{eR}) = 0$$

N.B. !

  - **A weak neutral current is indeed predicted:**

$$\bar{\nu}_{eL}\gamma_\mu Q_Z \nu_{eL} Z^\mu + \bar{e}_L \gamma_\mu Q_Z e_L Z^\mu$$

  - with strength:

$$Q_Z = \frac{e}{\sin\theta_W \ \cos\theta_W}\left(T_3 - Q\sin^2\theta_W\right)$$

Standard Model (II)

- The complete SM Lagrangian **(before symmetry breaking)** reads:

$$\mathcal{L}_{SM} = \mathcal{L}_{YM} + \mathcal{L}_k + \mathcal{L}_{cc} + \mathcal{L}_{nc}$$

- with:

3 LEPTON families (f=1..3)

$$\ell^f_L = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$$

3 QUARK families (f=1..3)

$$q^f_L = \begin{pmatrix} u_L \\ d'_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s'_L \end{pmatrix} \quad \begin{pmatrix} t_L \\ b'_L \end{pmatrix}$$

- $\mathcal{L}_{YM}$ is the Yang-Mills term for gauge fields (not shown)
- $\mathcal{L}_k$ is the kinetic (massless) term for all fermions

$$\mathcal{L}_k = i\bar{\ell}^f_L \partial\!\!\!/ \ell^f_L + i\bar{q}^f_L \partial\!\!\!/ q^f_L + i\bar{e}^f_R \partial\!\!\!/ e^f_R + i\bar{\nu}^f_R \partial\!\!\!/ \nu^f_R + i\bar{u}^f_R \partial\!\!\!/ u^f_R + i\bar{d}^f_R \partial\!\!\!/ d^f_R$$

- is the coupling term of fermions to charged W **(charged current)**

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left(\bar{\nu}^f_L \gamma^\mu e^f_L + V^{CKM}_{fg} \bar{u}^f_L \gamma^\mu d^g \right) W^+_\mu + h.c.$$

- is the coupling term of fermions to photon and Z **(neutral current)**

$$\mathcal{L}_{nc} = eQ\bar{\psi}\gamma_\mu \psi A^\mu + Q_Z \bar{\psi}\gamma_\mu \psi Z^\mu$$

where ψ is any SM fermion and Q is its electric charge.

Accidental symmetries: lepton and baryon numbers

- Without Yukawa interaction, the Lagrangian for fermion fields may be written in the compact form:

$$\mathcal{L}_f = \sum_k^5 \bar{\psi}_k i \not{D} \psi_k$$

- Where k=1..5 runs over 5 possible representations of the $SU(2)_L \times U_Y(1)$ gauge group:

$\psi_1 = e_R \; (\mathbf{1}, -2)$	$\psi_2 = \ell_L \; (\mathbf{2}, -1)$	$\psi_3 = u_R \; (\mathbf{1}, 4/3)$	$\psi_4 = d_R \; (\mathbf{1}, -2/3)$	$\psi_5 = q_L \; (\mathbf{2}, 1/3)$
SU(2) singlet, Y=-2	**SU(2) doublet, Y=-1**	**SU(2) singlet, Y=4/3**	**SU(2) singlet, Y=-2/3**	**SU(2) doublet, Y=⅓**

- Masses are forbidden by gauge symmetry, so there are therefore 5 accidental global U(1) symmetries:

$$\psi_k \rightarrow e^{i\Phi_k} \psi_k$$

- Which correspond to the following Noether currents:

$$J_1^\mu = \bar{e}_R \gamma^\mu e_R$$
$$J_2^\mu = \bar{\nu}_L \gamma^\mu \nu_L + \bar{e}_L \gamma^\mu e_L$$
$$J_3^\mu = \bar{u}_R \gamma^\mu u_R$$
$$J_4^\mu = \bar{d}_R \gamma^\mu d_R$$
$$J_5^\mu = \bar{d}_L \gamma^\mu d_L + \bar{u}_L \gamma^\mu u_L$$

WHICH WE MAY REGROUP AS

$$J_Y^\mu = \sum_{k=1}^5 \frac{Y_k}{2} J_k^\mu$$

$U_Y(1)$ gauge symmetry. Not new!

$$J_\ell^\mu = J_1^\mu + J_2^\mu = \bar{\nu} \gamma^\mu \nu + \bar{e} \gamma^\mu e$$

LEPTON NUM.

$$J_b^\mu = \frac{1}{3}(J_3^\mu + J_4^\mu + J_5^\mu) = \frac{1}{3}(\bar{u}\gamma^\mu u + \bar{d}\gamma^\mu d)$$

BARYON NUM.

$$J_{\ell 5}^\mu = J_1^\mu - J_2^\mu = \bar{\nu}\gamma^\mu \gamma_5 \nu + \bar{e}\gamma^\mu \gamma_5 e$$
$$J_{b5}^\mu = \frac{1}{3}(J_3^\mu + J_4^\mu - J_5^\mu) = \frac{1}{3}(\bar{u}\gamma^\mu \gamma_5 u + \bar{d}\gamma^\mu \gamma_5 d)$$

NOT OBSERVED !

Lepton number

- The **Yukawa interaction** changes the picture:
  - J^μ_Y J^μ_b J^μ_ℓ remain conserved currents, in agreement with observations
  - J^μ_{b5} $J^\mu_{\ell 5}$ are not compatible with mass terms, and disappear
- With **three families,** global baryon number and individual lepton numbers are conserved, while individual are not in case of **mixing**
  - CKM matrix breaks "individual" baryon numbers, preserving global lepton number;
  - Without neutrino mixing, individual lepton numbers are conserved
    - Because of the accidental symmetry, neutrino mass is NOT generated by radiative corrections
  - **PMNS matrix** breaks "individual" lepton number, preserving global lepton number;
- Most relevant test of baryon and lepton number conservation:

$$\tau(p \to e^+\pi^0) > 1.6\ 10^{34}\ y$$

$$\tau(^{136}Xe \to ^{136}Ba + 2e^-) > 1.07\ 10^{26}\ y$$

$$BR(\mu^- \to e^-\gamma) < 4.2\ 10^{-13}$$

Neutrino mass (I)

- The Standard Model was built assuming massless neutrinos
  - A choice that was well motivated by the facts that, experimentally:

$$m_{\nu_e} \leq 1.1\ eV \qquad m_{\nu_\mu} \leq 0.19\ MeV \qquad m_{\nu_\tau} \leq 18.2\ MeV$$

All neutrinos are much lighter than W,Z and corresponding charge leptons

- This creates no problem:
  - **W and Z are coupled** to ν_L and $\overline{\nu}_R$, not to ν_R and $\overline{\nu}_L$
    - Right-handed components of all fermions are SU(2) singlet (i.e. Y=0);
  - Being neutrinos neutral and colour-less, they do not carry any other gauge charge
    - They right handed components can be omitted from the theory with no consequence
    - The choice is consistent, i.e. renormalisation does not re-introduce the mass, **because mass-less neutrinos brings an additional accidental symmetry**
  - ν_R are effectively decoupled and can be ignored

Neutrino mass (II)

- To build a **mass term,** you must introduce ν_R and ν_L into the theory:
  - **Option 1:** do the same as for u-quarks, i.e. add proper Yukawa coupling to Higgs doublet

ELECTRON MASS

$$\mathcal{L}_Y = -y_e\,(\bar{\nu}_{eL}, \bar{e}_L)\begin{pmatrix}\Phi^+\\ \Phi^0\end{pmatrix} e_R^- + h.c.$$

'Dirac' NEUTRINO MASS

$$-y_\nu\,(\bar{\nu}_{eL}, \bar{e}_L)\begin{pmatrix}\Phi^{0*}\\ -\Phi^-\end{pmatrix} \nu_R^- + h.c.$$

  - After spontaneous symmetry breaking:

$$-m\,(\bar{\nu}_L\nu_R + \bar{\nu}_R\nu_L) \qquad m = \frac{y_\nu v}{\sqrt{2}}$$

  - **Option 2:** Being ν_R not related to SU(2) gauge symmetry, they do not need to have a gauge invariant mass term
    - They admit, therefore, with M very large: $-\frac{1}{2}M\,(\bar{\nu}_R^c\nu_R + \bar{\nu}_R\nu_R^c)$
    - In general, the mass term can be:

$$\mathcal{L}_\nu = -\frac{1}{2}\,(\bar{\nu}_L^c\;\bar{\nu}_R)\begin{pmatrix}0 & m\\ m & M\end{pmatrix}\begin{pmatrix}\nu_L\\ \nu_R^c\end{pmatrix} + h.c.$$

    - where: M ≫ m. The terms proportional to m are the same as Dirac mass term [note that $\bar{\nu}_L^c\nu_R^c = \bar{\nu}_R\nu_L$]

Neutrino mass (III)

- The mass term can be diagonalised:

$$m_1 = \frac{1}{2}\left(M + \sqrt{M^2 + 4m^2}\right) \qquad m_2 = \frac{1}{2}\left(M - \sqrt{M^2 + 4m^2}\right)$$

- With M ≫ m [e.g. **m ~ 200 GeV** and **M ~ 10^{16} GeV**]:

$$m_1 \simeq M \qquad m_2 \simeq \frac{m^2}{M} \ll m$$

SEE-SAW mechanism

  - One of the two neutrinos is very heavy and not observable, while the other one is very light without assuming very small Yukawa couplings.
    - **m_2 goes "naturally" to meV scale**

- The diagonalised mass term is that of 2 Majorana neutrinos:

  - with: $$-\frac{1}{2}m_1\left(\bar{\nu}_1^c\nu_1 + \bar{\nu}_1\nu_1^c\right) - \frac{1}{2}m_2\left(\bar{\nu}_2^c\nu_2 + \bar{\nu}_2\nu_2^c\right)$$

$$\nu_1 = \nu_L \sin\theta + \nu_R^c \cos\theta \qquad \nu_2 = -i\nu_L \cos\theta + i\nu_R^c \sin\theta \qquad \text{with} \qquad \tan 2\theta = \frac{2m}{M} \ll 1$$

  - with very small θ ν_1 is an almost pure very heavy right handed neutrino, and ν_2 is the standard model one with very small mass.

Mixing

- With more than one SM neutrino, the model is easily generalised
  - n families (n=3) and k RH components (k is unknown)
    - **m** becomes a **k × n matrix**, while **M** becomes a **k × k matrix**
    - **CP violating phases come from both matrices,** in general.

- In the simplest case with k=n=3, the SM neutrinos are related to **mass eigenstates** by a **3 × 3** unitary matrix:

$$|\nu_\alpha >= U_{\alpha i}|\nu_i > \qquad \text{where } |\nu_i > \text{ are mass eigenstates.}$$

and where U is often parametrised as:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_D} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_D} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Low energy neutrino - electron interaction

- At low energy ($q^2 \ll M_W$), the effective neutrino-electron interaction reads:

$$H_W^{\text{eff}} = \frac{G_F}{\sqrt{2}} \{[\bar{e}\gamma_\mu(1-\gamma_5)\nu_e]\,[\bar{\nu}_e\gamma^\mu(1-\gamma_5)e] + \rho\,[\bar{\nu}_\ell\gamma_\mu(1-\gamma_5)\nu_\ell]\,[\bar{e}\gamma^\mu(g_V - g_A\gamma_5)e]\}$$

  - where:

$$g_V = g_L + g_R = -\frac{1}{2} + 2\sin^2\theta_W \qquad g_A = g_L - g_R = -\frac{1}{2} \qquad \rho = 1$$

- After Fierz transformation of the first term we can write:

$$H_W^{\text{eff}} = \frac{G_F}{\sqrt{2}} \{[\bar{\nu}_\ell\gamma_\mu(1-\gamma_5)\nu_\ell]\,[\bar{e}\gamma^\mu(c_V - c_A\gamma_5)e]\}$$

  - where:
    - for $\nu_e e^-$ scattering: $c_V = 1 + \rho g_V \qquad c_A = 1 + \rho g_A$
    - for $\nu_\ell e^-$ scattering: $c_V = \rho g_V \qquad c_A = \rho g_A$

Neutrino - electron interaction

- **Differential cross section** as a function of e⁻ recoil momentum:

$$\frac{d\sigma}{dT'_e} = \frac{2G_F^2\, m_e}{\pi}\left[c_L^2 + c_R^2\left(\frac{E'_\nu}{E_\nu}\right)^2 - c_L c_R \frac{m_e}{E_\nu}\frac{E_\nu - E'_\nu}{E_\nu}\right]$$

  - where $T'_e = E'_e - m_e = E'_\nu - E_\nu$ is the electron recoil energy.

- The **total cross section** reads:

$$\sigma = \frac{2G_F^2\, m_e\, E_\nu}{\pi}\left[c_L^2 + \frac{1}{3}c_R^2 - \frac{1}{2}c_L c_R \frac{m_e}{E_\nu}\right]$$

  - For anti-neutrinos the formula is the same with c_L and c_R exchanged.

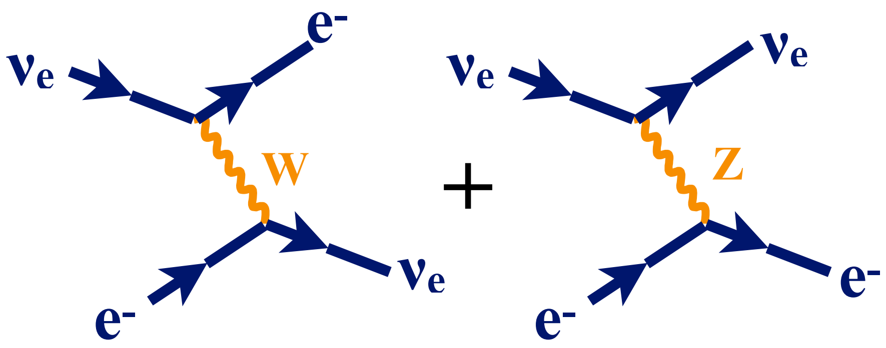
TREE level cross sections $\sin^2\theta_W = 0.2312$ $\overline{\text{MS}}$

	c_L	c_R	σ [10^{-44} cm^2]
ν_e e⁻	$\frac{1}{2} + \sin^2\theta_W$	$\sin^2\theta_W$	0.95 E_ν [MeV]
ν_μ e⁻	$-\frac{1}{2} + \sin^2\theta_W$	$\sin^2\theta_W$	0.16 E_ν [MeV]
$\bar{\nu}_e$ e⁻	$\sin^2\theta_W$	$\frac{1}{2} + \sin^2\theta_W$	0.23 E_ν [MeV]
$\bar{\nu}_\mu$ e⁻	$\sin^2\theta_W$	$-\frac{1}{2} + \sin^2\theta_W$	0.078 E_ν [MeV]

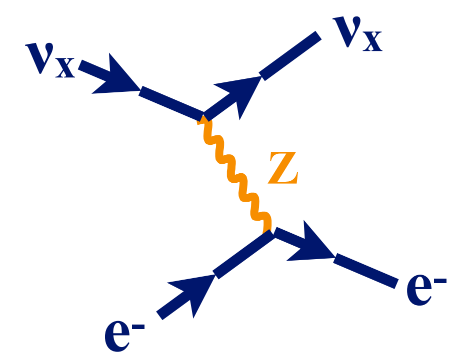
- **QED** and **EW radiative corrections** are at **few %** level and **are relevant** for high precision solar neutrino experiments and future experiments.

Example: neutrino detection in Borexino

- Elastic scattering on e⁻: detects **all ν** flavours, with a **larger cross-section for ν_e**

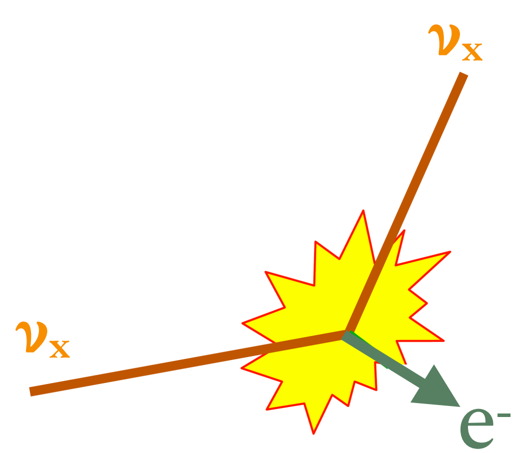


$$\xi = \sin^2\theta_W \simeq 0.23$$



$$\sigma(\nu_e e^-) = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2}+\xi\right)^2+\frac{\xi^2}{3}\right]$$

9.5 10^{-45} cm^2 @ 1 MeV

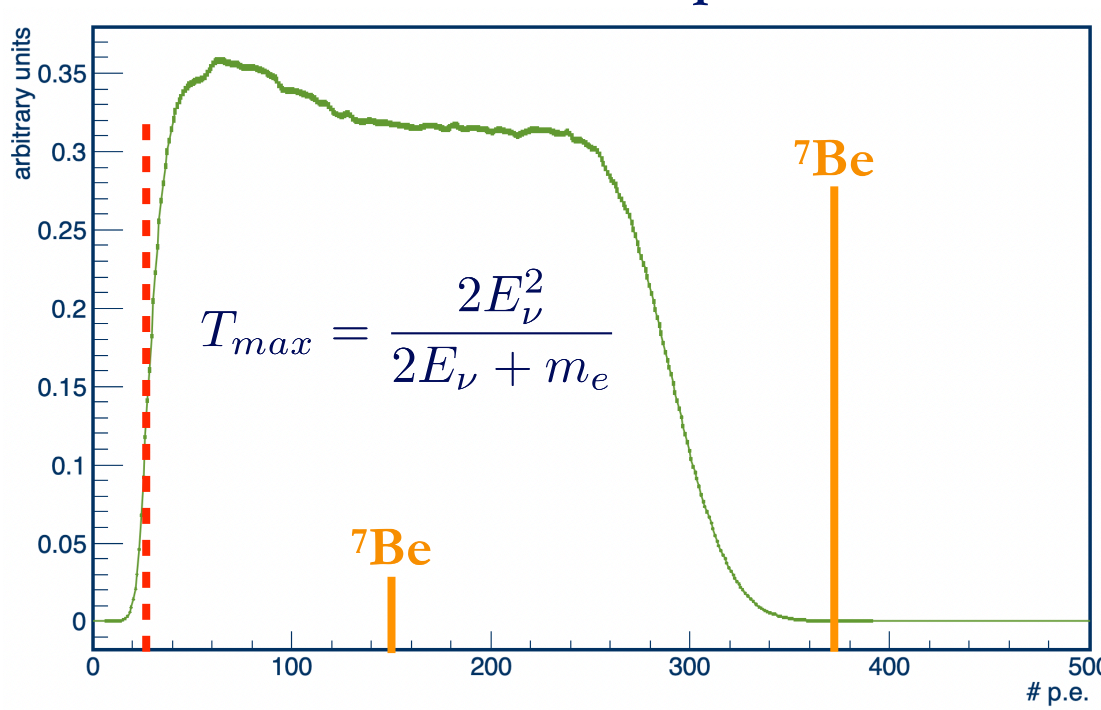


$$\sigma(\nu_x e^-) = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2}-\xi\right)^2+\frac{\xi^2}{3}\right]$$

1.6 10^{-45} cm^2 @ 1 MeV

- The e⁻ is scattered in the **liquid scintillator:**
  - path: **few mm**
  - physics thresh.: **very small**
  - triggering thresh.: **~40 keV** (dep.)
  - analysis thresh.: **~ 200 keV**

SIGNATURE: 'Compton' shoulders



Neutrino-nucleon scattering

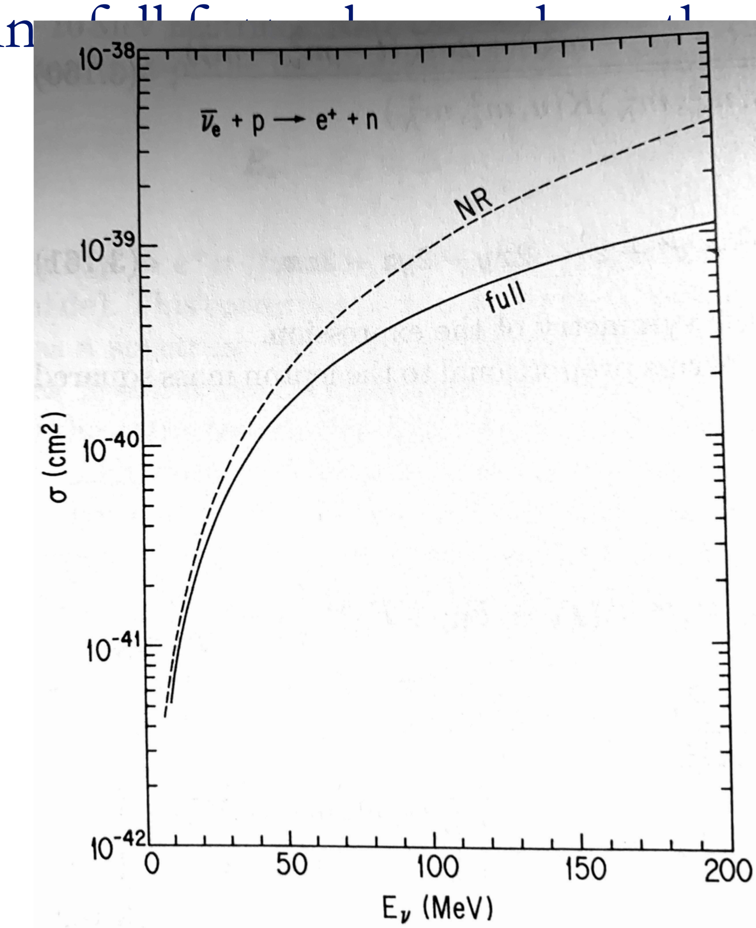
- CC ν-nucleon scattering is, for historical reasons, called "inverse β decay" (also, quasi-elastic)
    - At low E$_\nu$ ($\lesssim$ 100 MeV), only ν_e are active, being μ and τ too heavy

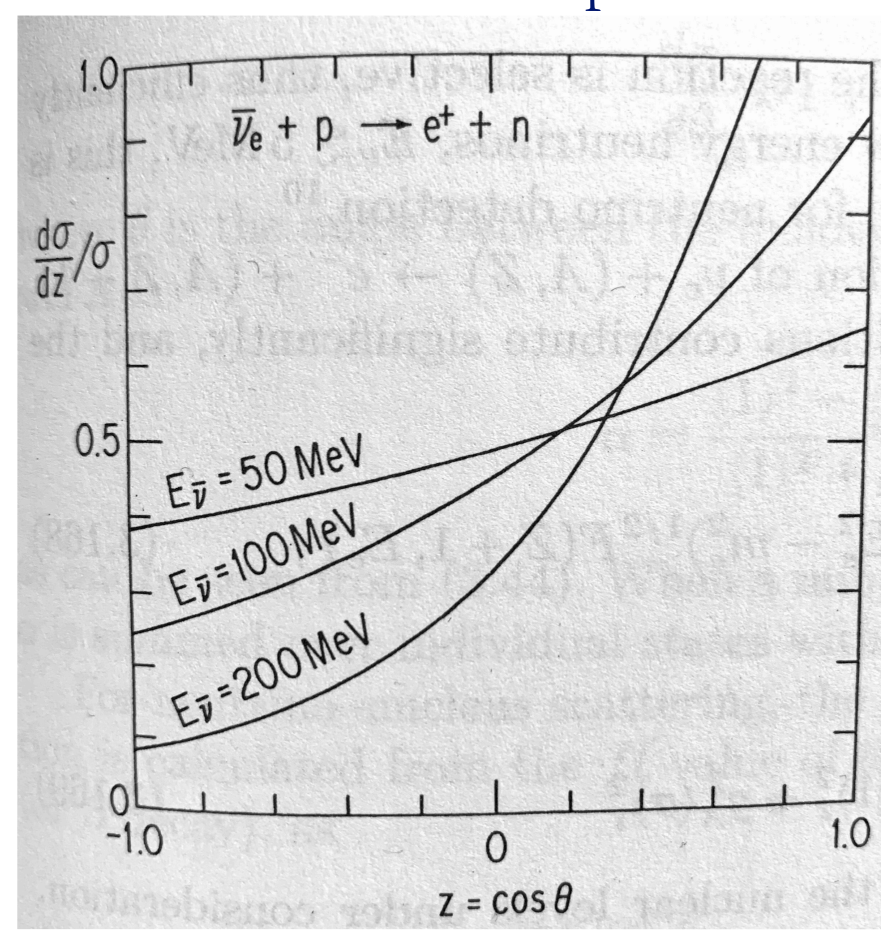
      $\bar{\nu}_e + p \to e^+ + n$ $\qquad$ $\nu_e + n \to e^- + p$

    - At very low E$_\nu$ ($\lesssim$ 30 MeV), the cross section is well reproduced by:

$$\sigma(\bar{\nu}_e p \to e^+ n) = \sigma(\nu_e n \to e^- p) = \frac{G_F^2 E_e p_e}{\pi} |U_{ud}|^2 (1+3g_A^2) \simeq 9.3\, 10^{-42} \left(\frac{E_\nu}{10\ MeV}\right)^2 \text{cm}^2$$

    - While in the region E$_\nu$ ~ 30 - 100 MeV the nucleon form factors become important. Without writin … plots:

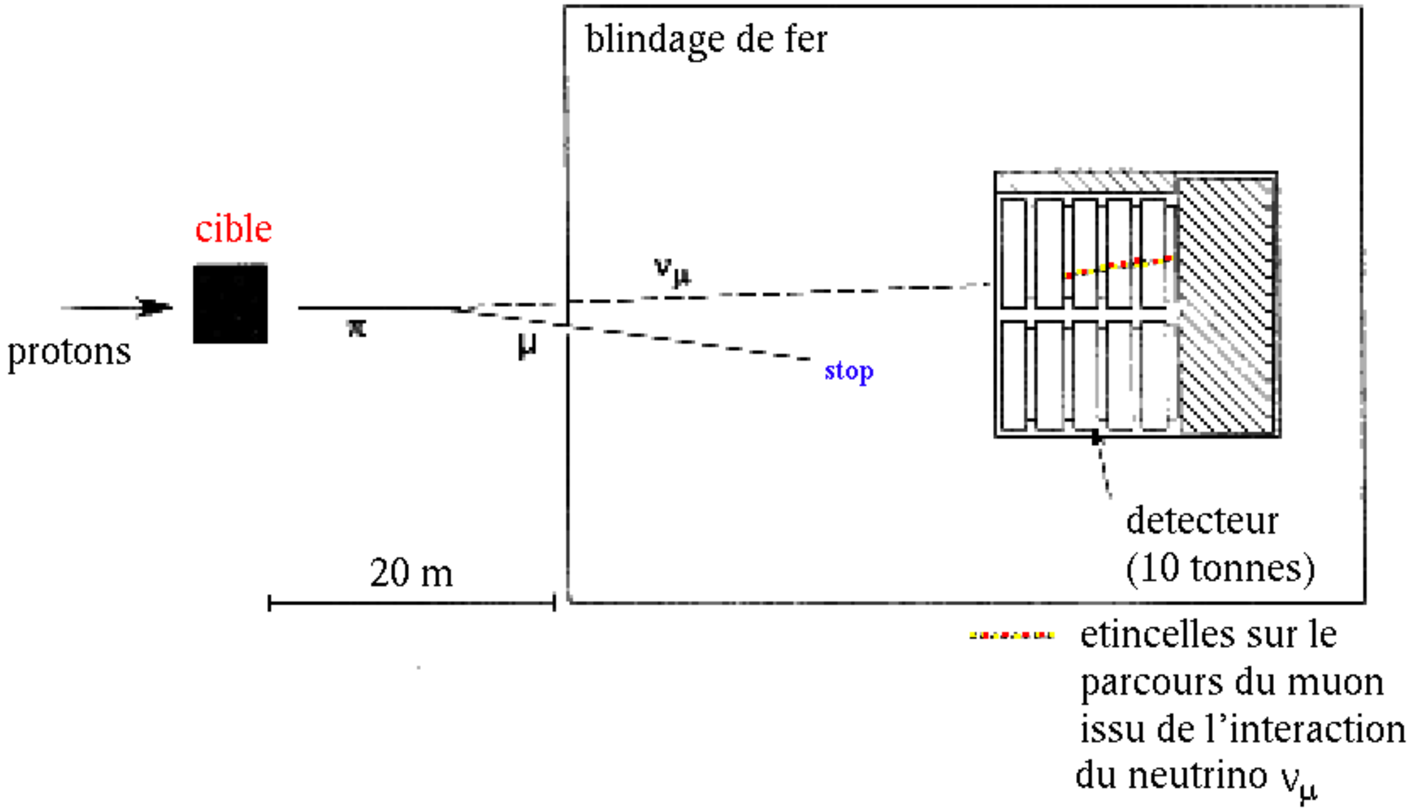




2 neutrino flavours (I)

- How do we know that the neutrinos emitted in pion decay (accompanying a muon) is the same as in β decay ?

  - 1959: M. Schwartz proposes to build a neutrino beam from pion decay
  - 1962: L. Lederman, M. Schwartz and J. Steinberger build a large spark chamber (using 10 tons of neon gas) to identify muons in neutrino interactions.
  - The idea is still the one we use today to produce neutrino beams with accelerators
  - There was no pion momentum selection



2 neutrino flavours (II)

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

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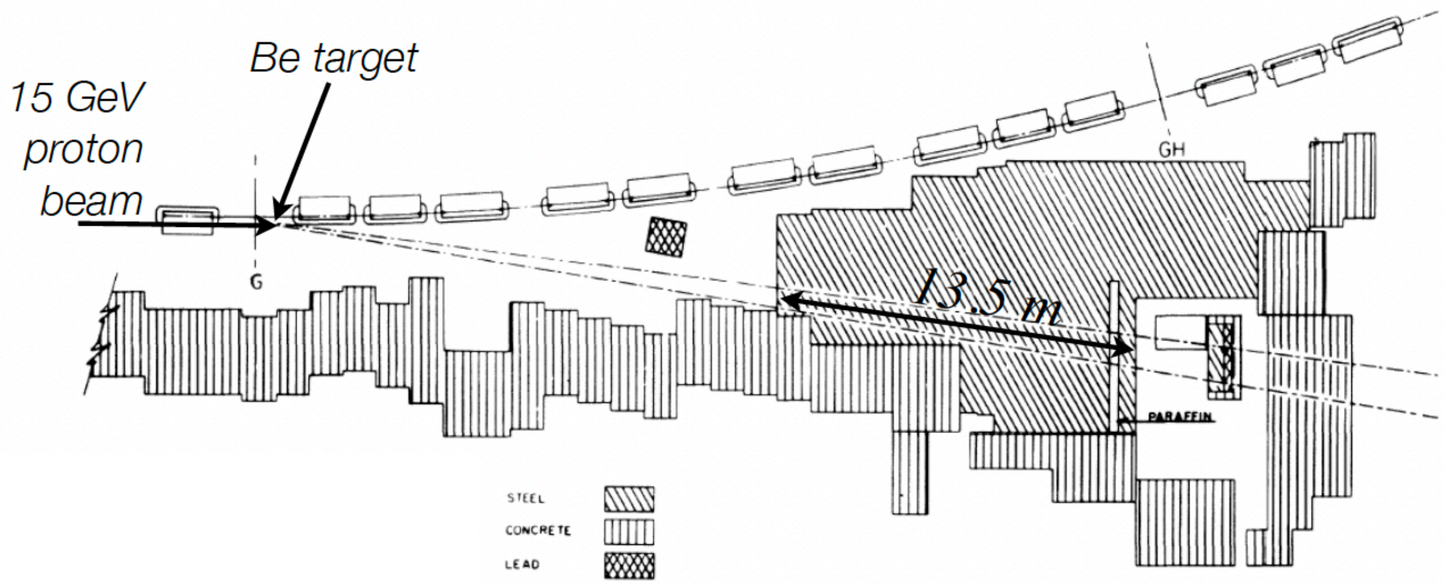
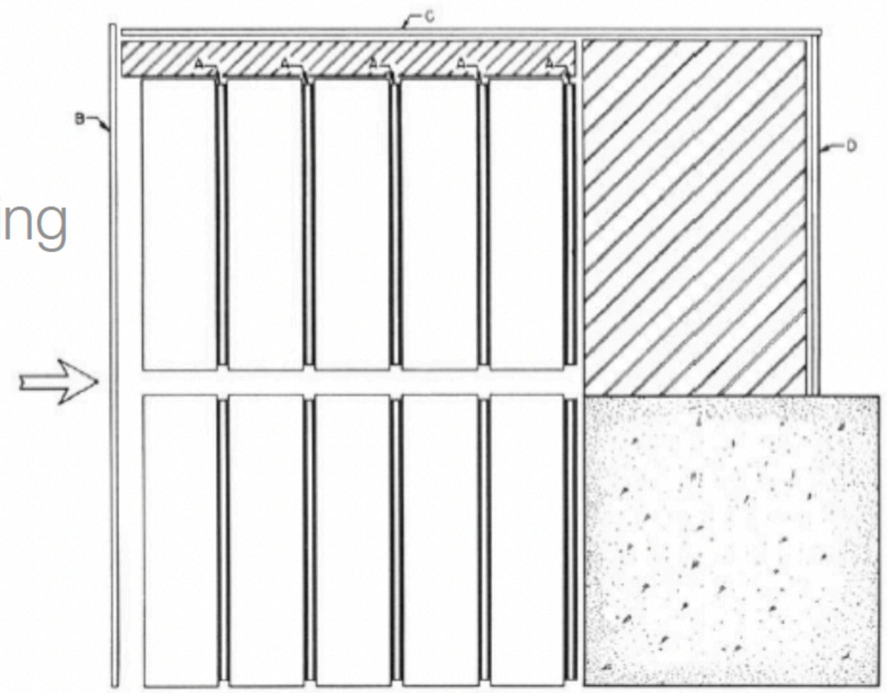


FIG. 1. Plan view of AGS neutrino experiment.

B,C,D vetos against entering tracks



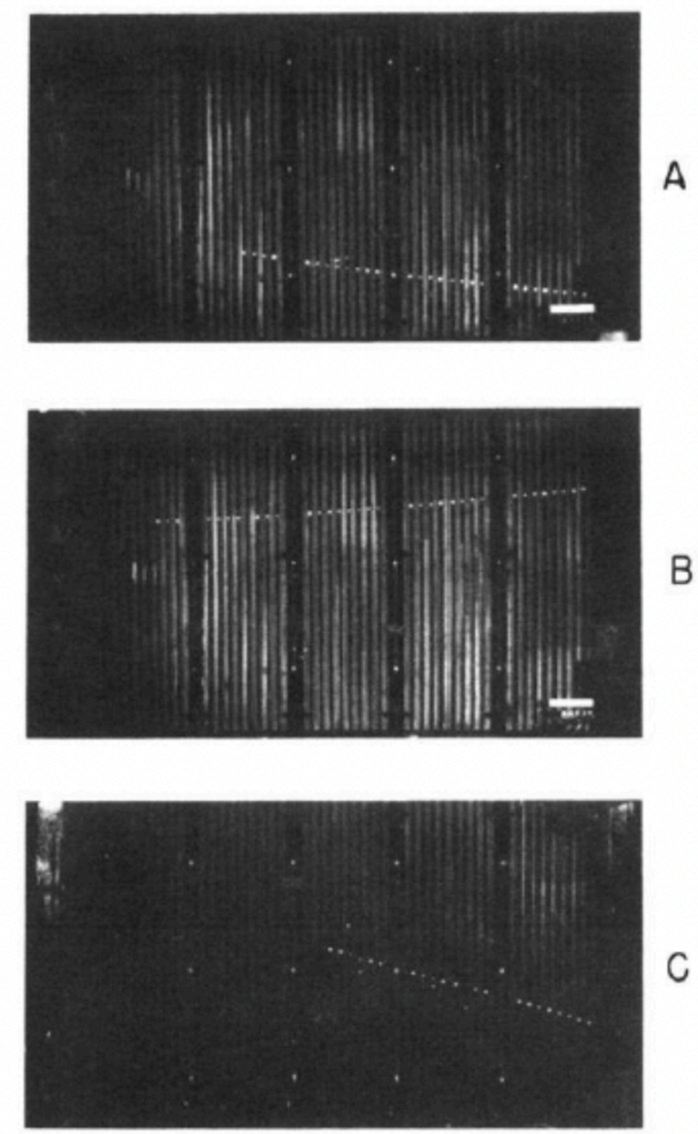
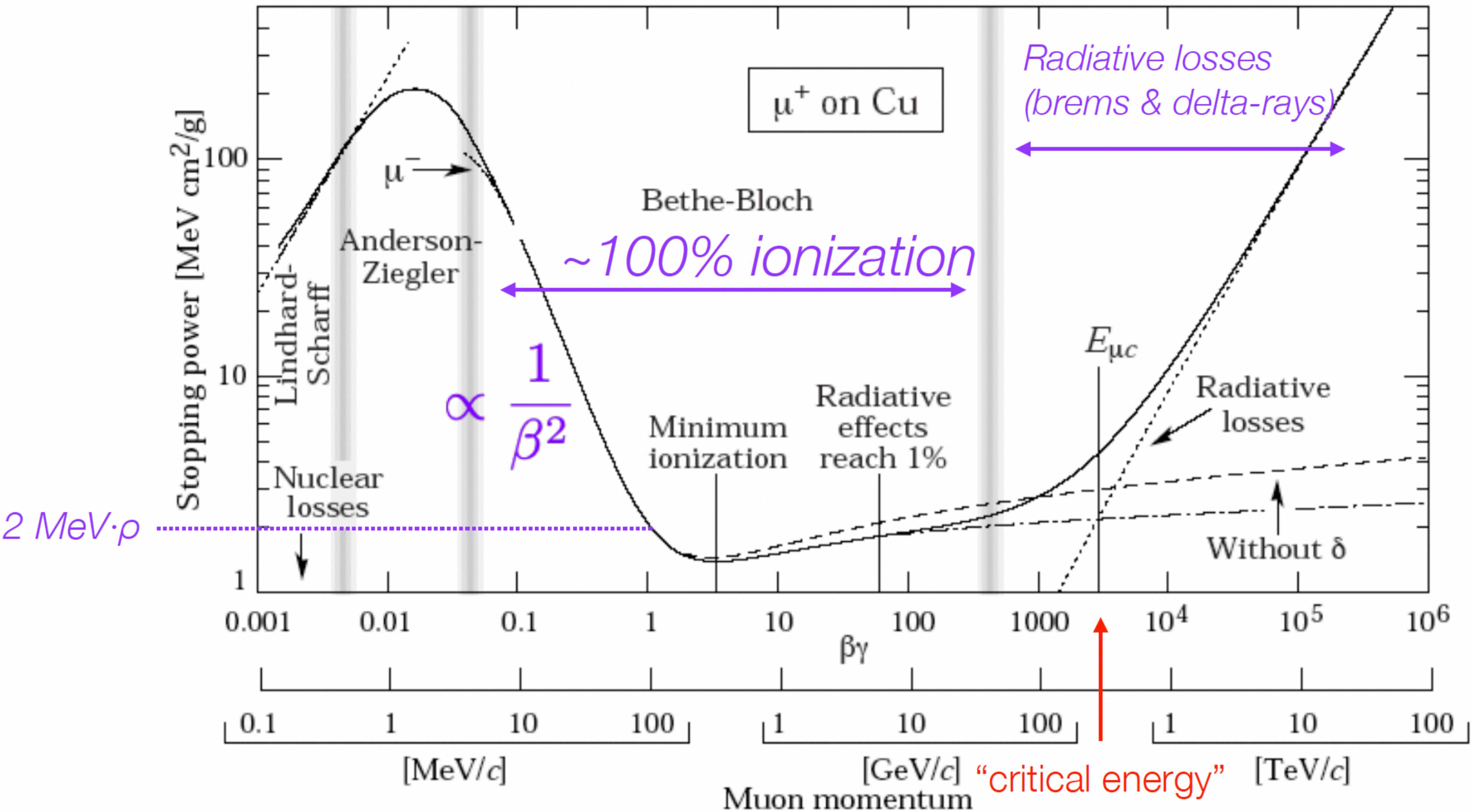


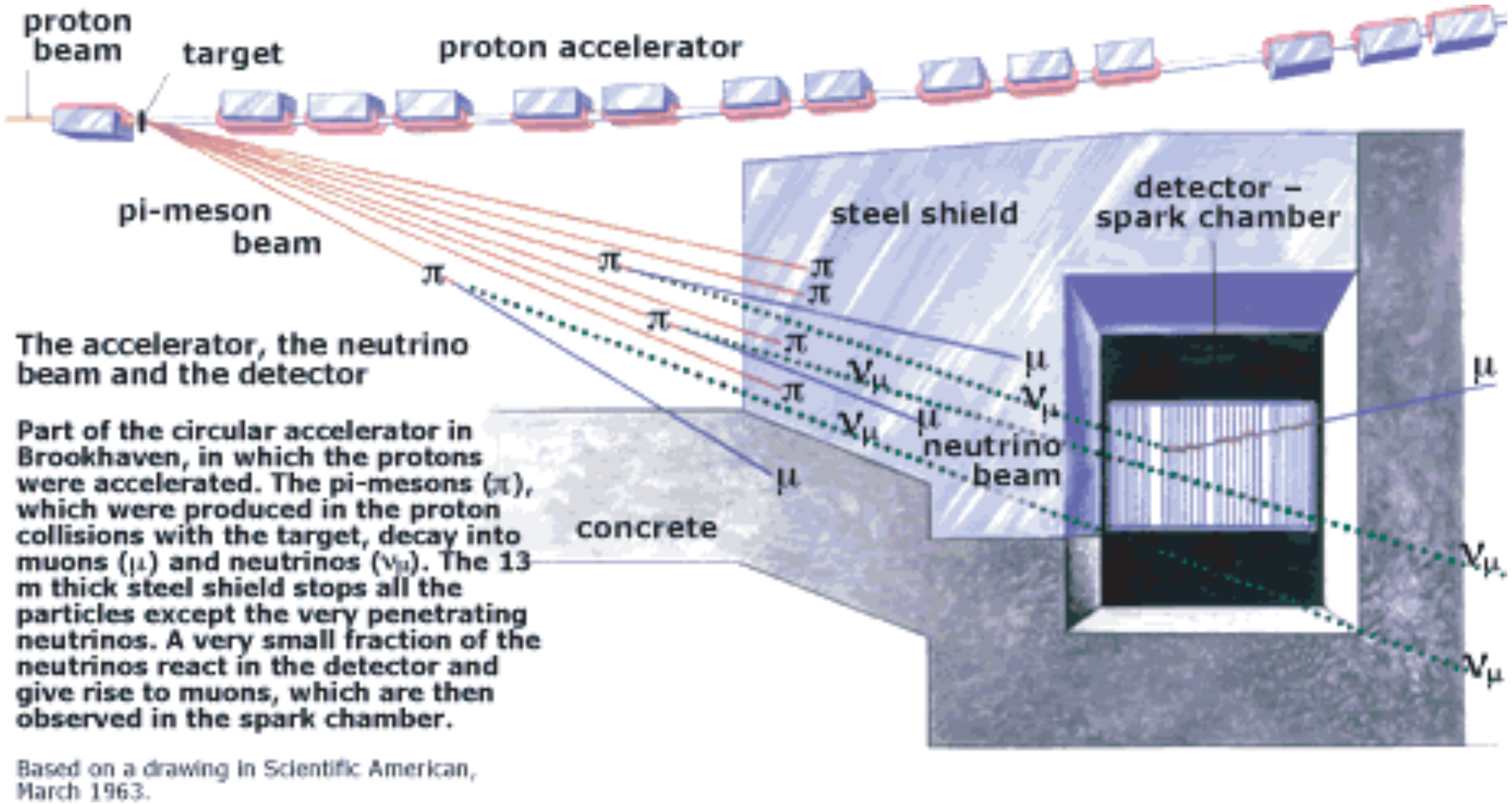
FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and δ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with δ ray.

Intermezzo: Bethe-Bloch



$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

2 neutrino flavours (II)



- Results:
  - 64 events detected
    - 34 events with a single long track p>300 MeV
    - 22 multi-tracks
      - Of which, 8 compatible with electron showers, 6 neutrons, 2 electrons from the beam
  - **There exists a different neutrino type that produces muons and not electrons in nuclear interactions**

Discovery of neutral currents

- In 1968 Weinberg completes the Standard Model in the form we know today, adopting also GIM mechanism prescription
- 3 fundamental predictions (plus many many more….)

  - **Neutral currents must exists,** and their coupling is fixed by theory

$$\bar{\nu}_{eL}\gamma_\mu Q_Z \nu_{eL} Z^\mu + \bar{e}_L \gamma_\mu Q_Z e_L Z^\mu$$

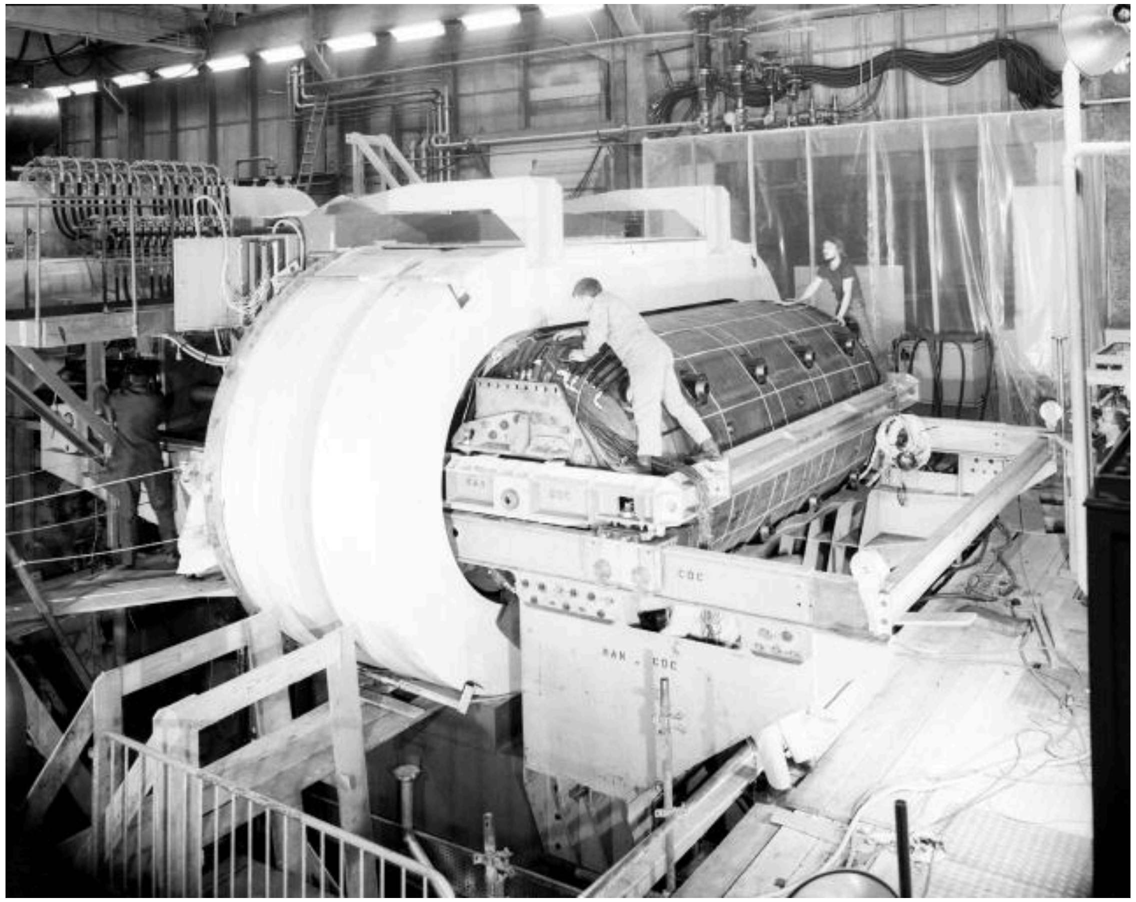
$$Q_Z = \frac{e}{\sin\theta_W \ \cos\theta_W}\left(T_3 - Q\sin^2\theta_W\right)$$

  - Fermions are organised in **doublets**, so at least **charm quark must exist**
    - Additional third family fermions are not mandatory and will come later, although they are actually required if you want CP violation in the SM

  - **There exist 2 gauge bosons,** whose mass is fixed by the theory **once neutral current strength is measured (to get the Weinberg angle)**

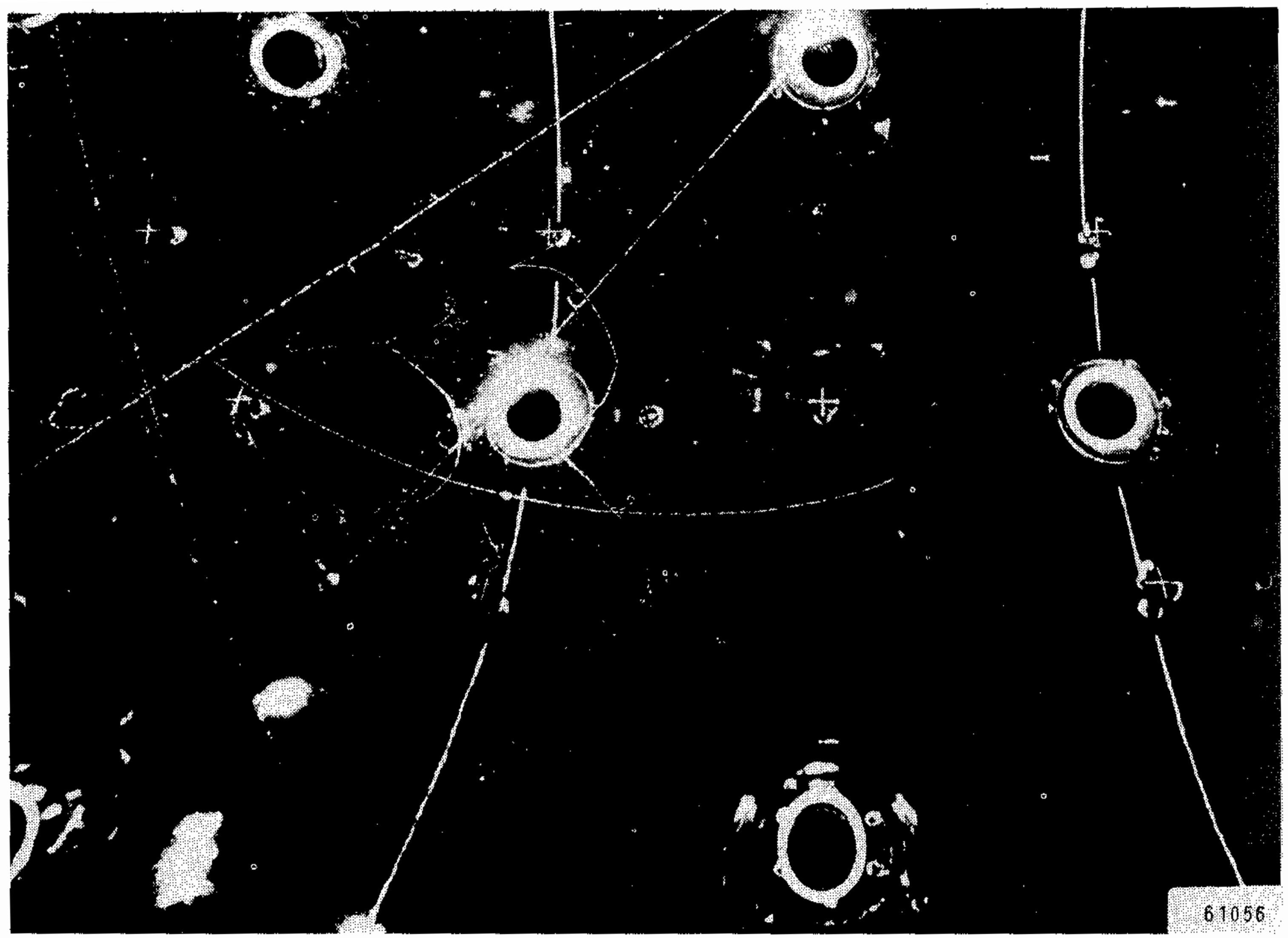
Gargamelle experiment

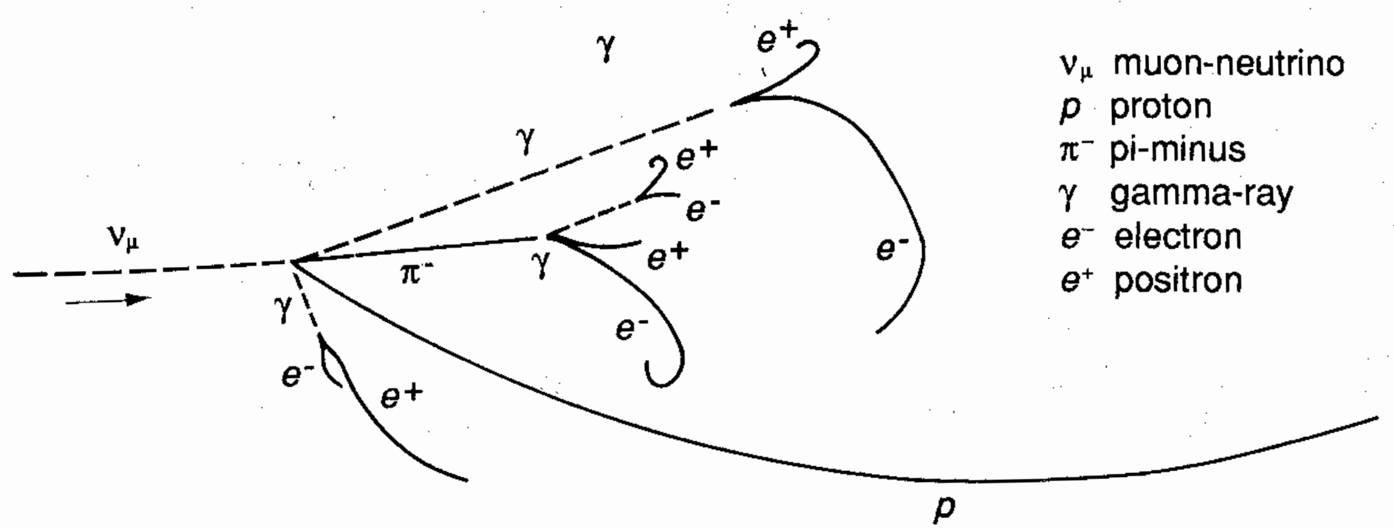
- The successful detection of neutral currents depends on two crucial technological improvements/achievements
  - **The magnetic horn,** which allows more intense and purer beams
    - It focalise mesons of one size and delocalise the other ones
  - The fast, high volume, and high density **bubble chamber,** to visualise events
    - 6.2 m^3 of liquid freon **(CF_3Br)** with a **density of 1.5 g/cm^3**
  - Ideas that are **still the key of more modern efforts** such as SBN at Fermilab, DUNE, T2K, HK



Magnetic horn to focalise the beam

Neutral current event in the bubble chamber





Results of Gargamelle

- **Run with both neutrinos and anti-neutrinos**
  - ν run: 102 NC, 428 CC, 15 neutrons
  - $\bar{\nu}$ run: 64 NC, 148 CC, 12 neutrons
  - Possible backgrounds
    - **Cosmic rays.** Excluded by means of asymmetries
    - CC with **lost muon because of low momentum:** good agreement with calculations
    - Direct and indirect **neutrons:** significant but much smaller than signal
  - **ALL these are still a key issue for today's experiments!**

- **Final result of Gargamelle:**
  - *"We have observed events without secondary muon or electr induced by neutral penetrating particles. We are not able to explain the bulk of the signal by any known background."*
    - **(NC/CC) = 0.21 ± 0.03**
    - **(NC/CC) = 0.45 ± 0.09**
    - **$\sin\vartheta_w$** in range **0.3 - 0.4**

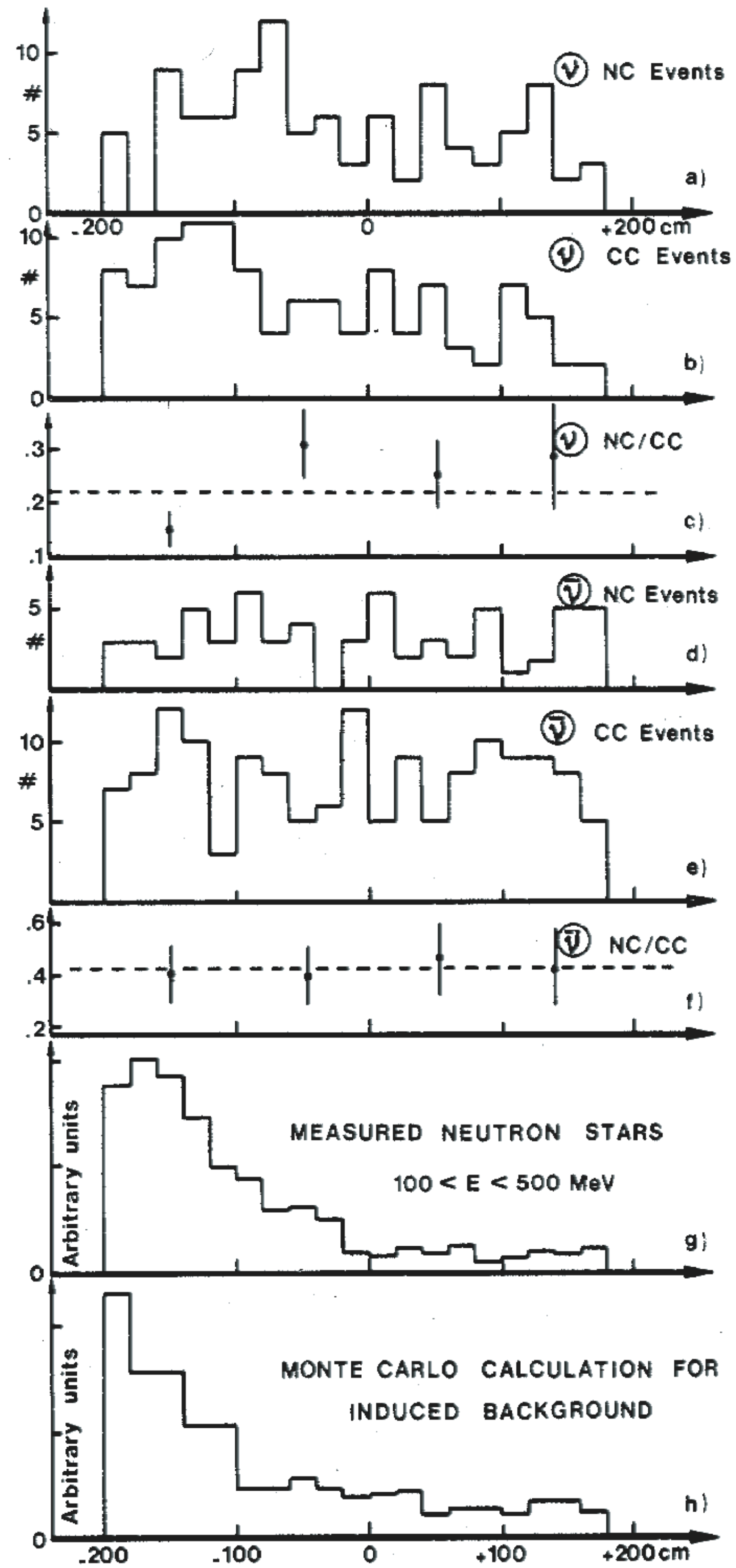
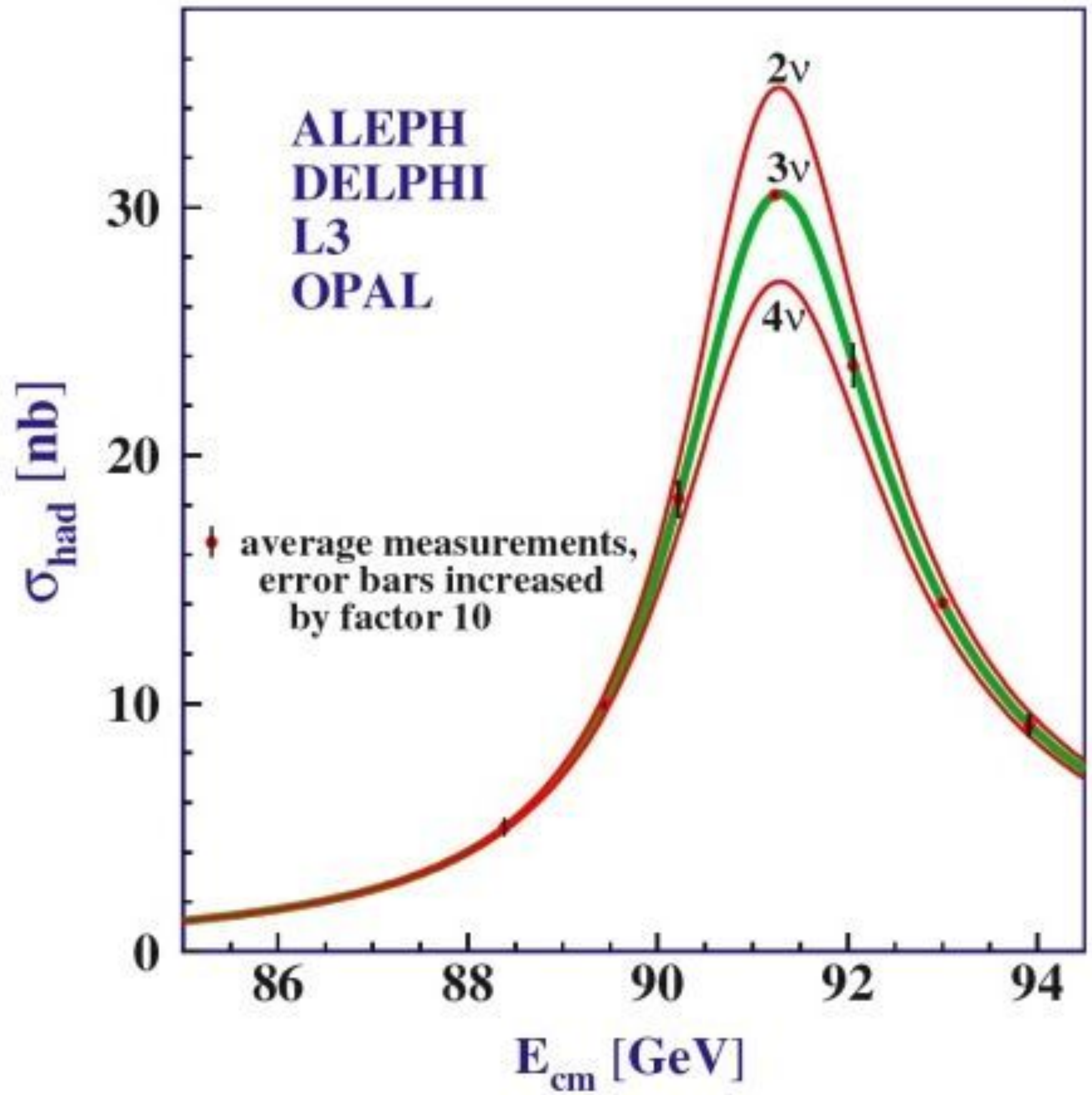


Fig. 1. Distributions along the ν-beam axis. a) NC events in ν. b) CC events in ν (this distribution is based on a reference sample of ~ 1/4 of the total ν film). c) Ratio NC/CC in ν (normalized). d) NC in $\bar{\nu}$. e) CC events in $\bar{\nu}$. f) Ratio NC/CC in $\bar{\nu}$. g) Measured neutron stars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

Three neutrinos



$$\Gamma_{tot} = \Gamma_e + \Gamma_\mu + \Gamma_\tau + \Gamma_{had} + \Gamma_{inv}$$ **Measured**

$\Gamma_e \quad \Gamma_\mu \quad \Gamma_\tau \quad \Gamma_{had}$ **Measured (adding up all events with hadrons in FS)**

$\Gamma_{inv} = 3\Gamma_\nu$ Can be checked