Neutrinos physics

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- Introduction
- Neutrino oscillations
- The nature of the neutrino

Highly selective in terms of exp. results (and theoretical details …)

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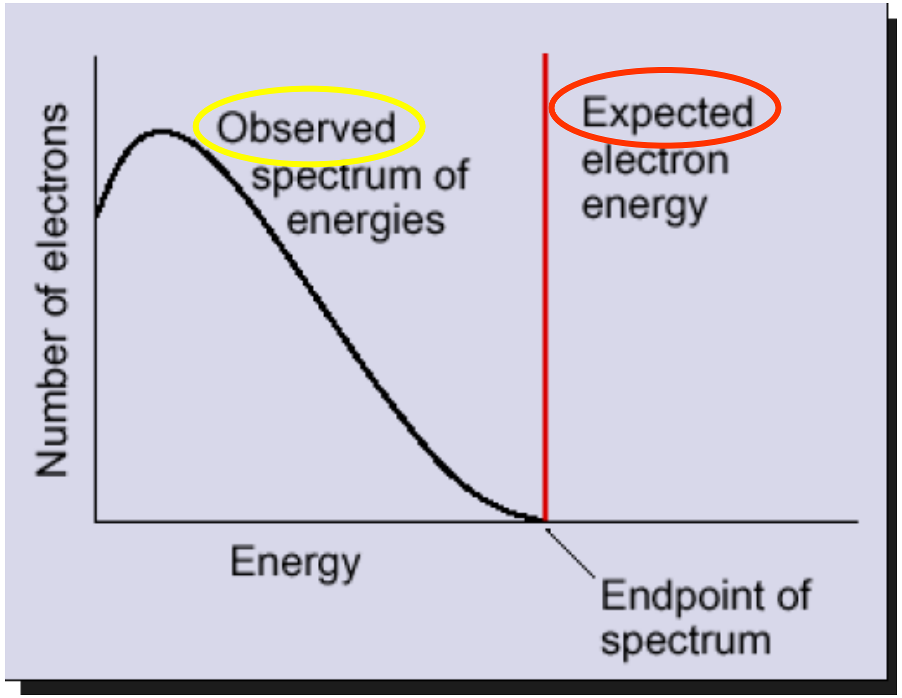
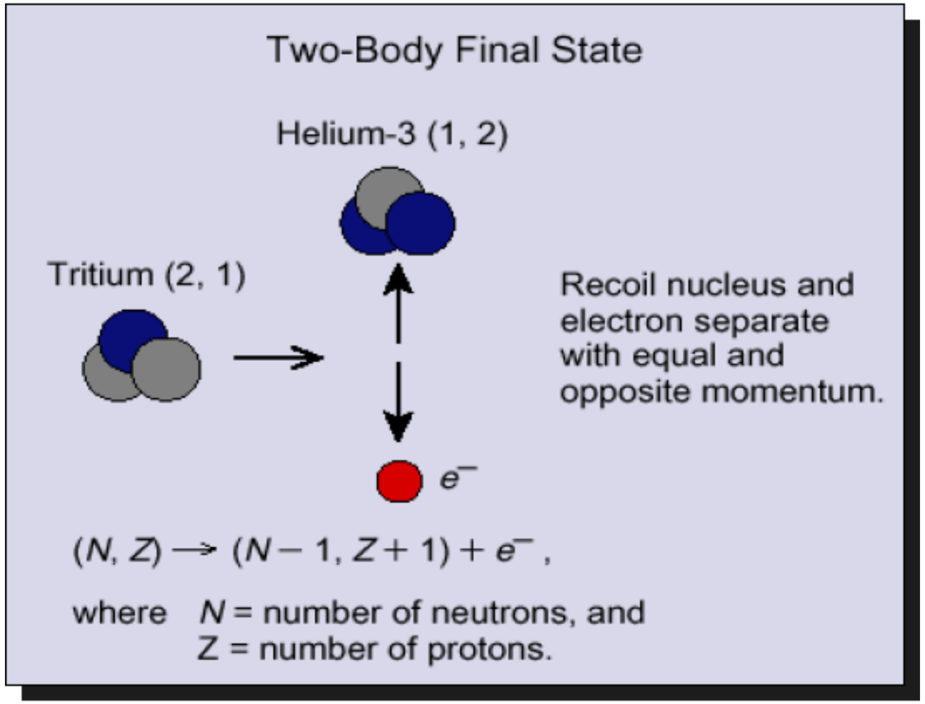
Introduction

The β decay





If **β** decay proceeds through n→p e^- the energy conservation predicts a monochromatic spectrum

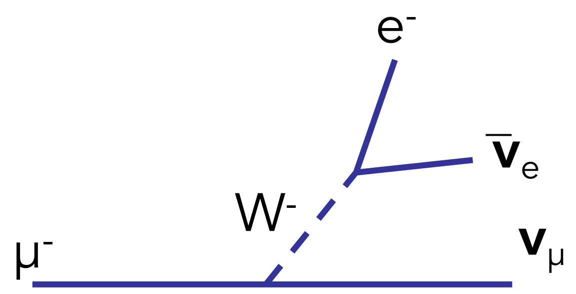
1914 Chadwick observes a continuous spectrum …

→ Energy conservation is violated (Bohr) or an other particle is in the game (Pauli) :

β decay : n→p $e^-\bar{\nu}_e$

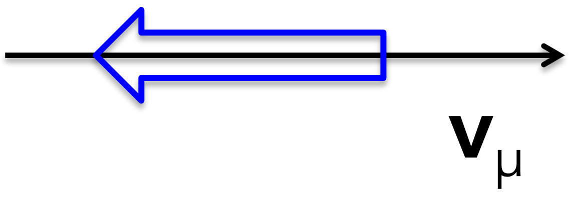
The weak interaction

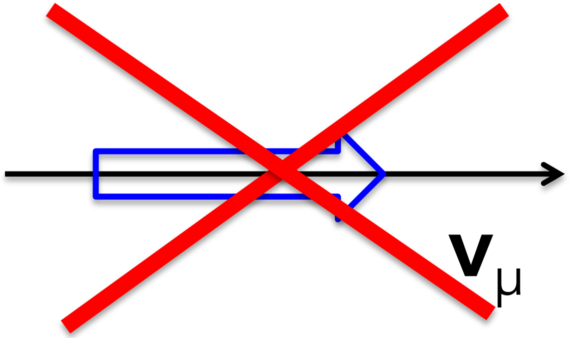
matrix element for the Feynman graph:



$$M = \left(\frac{g}{\sqrt{2}} \bar{u}_{\nu_\mu} \gamma^\mu \frac{1}{2}(1-\gamma_5) u_\mu \right) \frac{1}{M_W^2 - q^2} \left(\frac{g}{\sqrt{2}} \bar{u}_e \gamma_\mu \frac{1}{2}(1-\gamma_5) u_{\nu_e} \right)$$

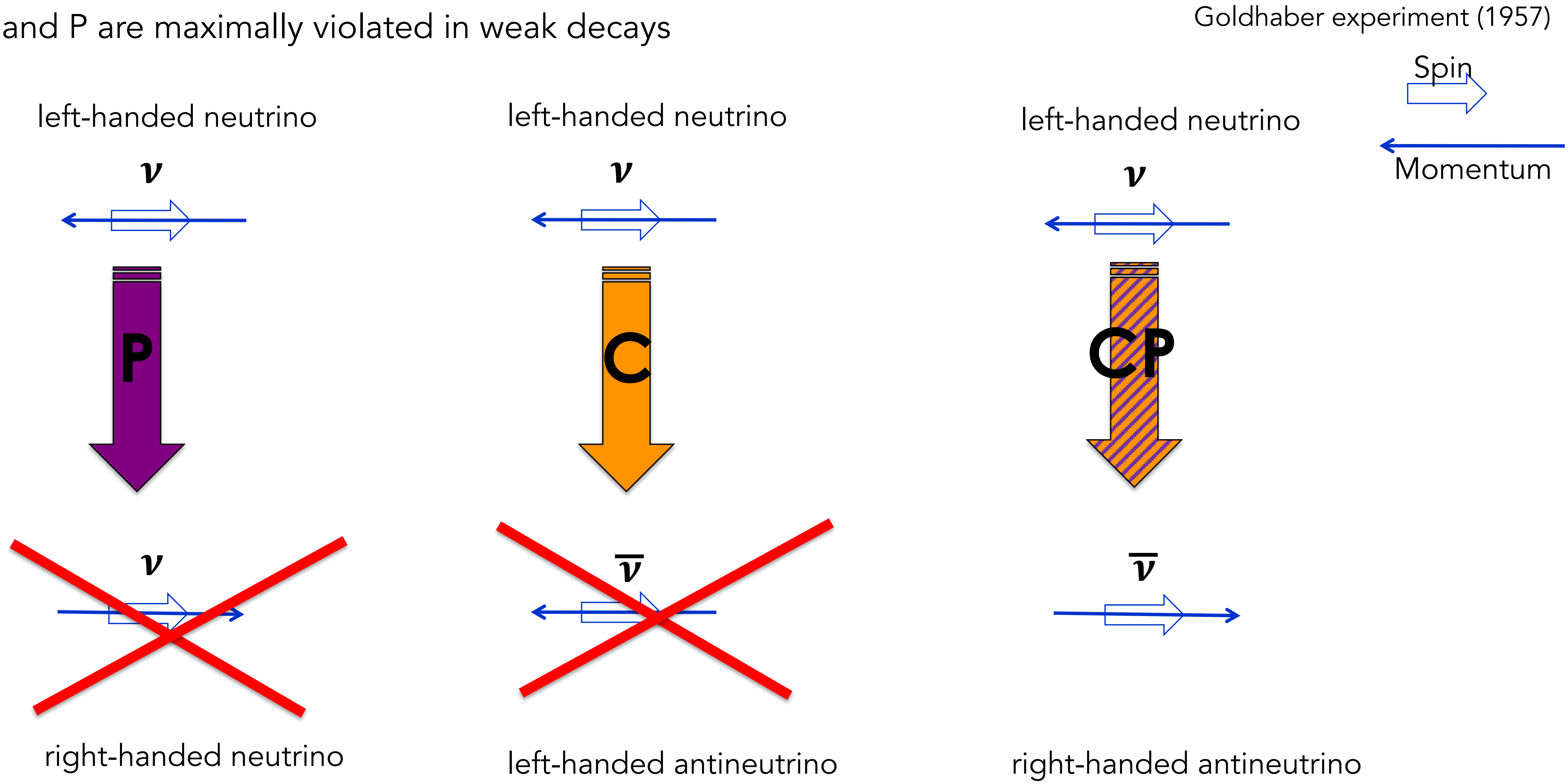
$$G_F = \frac{\sqrt{2}}{8} \frac{g^2}{M_W^2}$$





Lectures from Alexander Korchin

C and P are maximally violated in weak decays

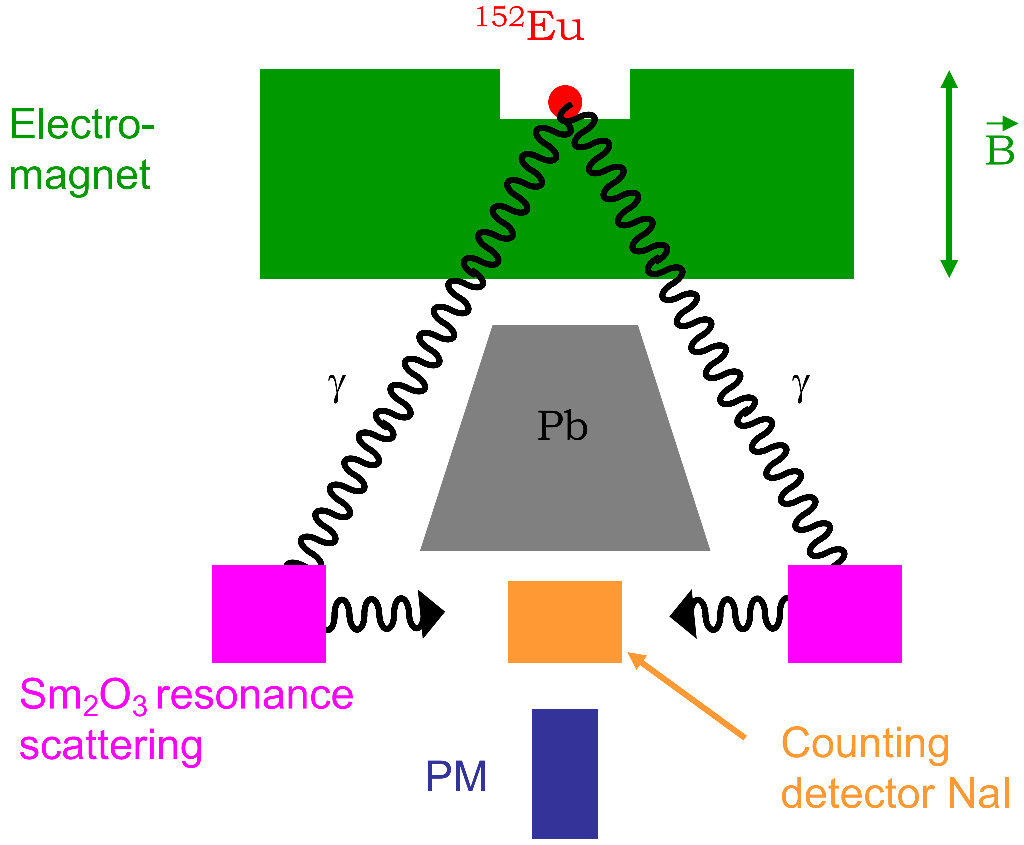


The **ν** is left-handed (the anti-neutrino is right-handed)

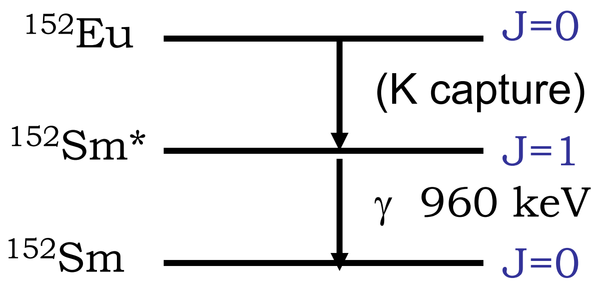
Experimental evidence for the neutrinos helicity:

Goldhaber *et al*
Phys. Rev. 109, 1015-1017 (1958)

Experimental set-up:



$$^{152}\mathrm{Eu}(J=0) + e^- \rightarrow {}^{152}\mathrm{Sm}^*(J=1) + \nu$$
(K capture)
$$\hookrightarrow {}^{152}\mathrm{Sm}(J=0) + \gamma$$

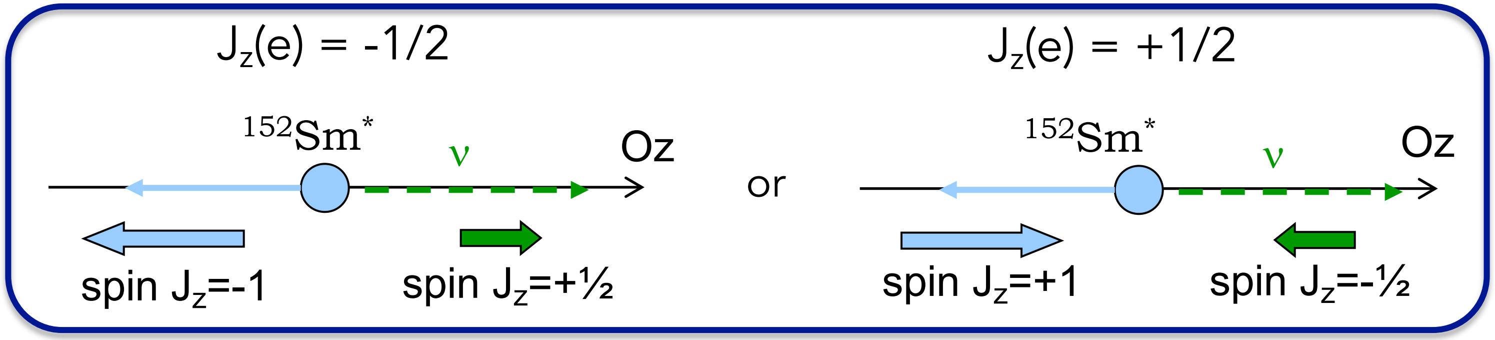


γ emitted in the direction of the momentum of the Sm* are selected

$^{152}Eu(J=0) + e^- \rightarrow ^{152}Sm^*(J=1) + \nu$

initial state: $J_i = 1/2 \Rightarrow J_f = 1/2$ and J_z given by the electron

In order to get $J_f = 1/2$, the projection of the spin of the Sm* and of the ν should be opposite (same helicities)



$J_z(Sm^*)=0$ forbidden by the decay mode

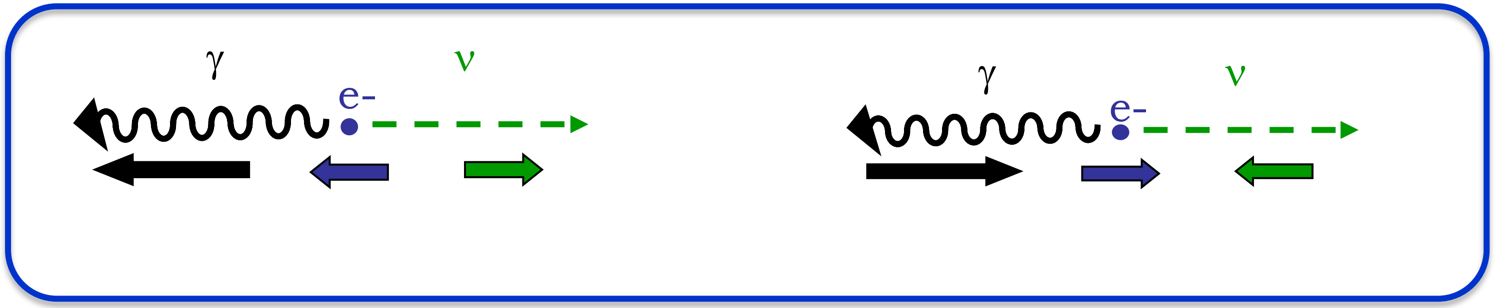
$^{152}Sm^*(J=1) \rightarrow ^{152}Sm(J=0) + \gamma$

$J_z=+/-1$ $J_z=0$ $J_z=+/-1$

γ emitted forward in the ^{152}Sm direction are selected ⇒ the 3 final state particles (Sm, γ and ν) are collinear.

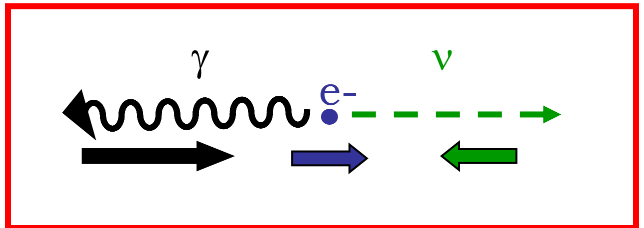
helicities of the final state particles : $S(\nu)=\pm 1/2$, $S(\gamma)= \pm 1$, $S(e)= \pm 1/2$

⇒ two possible configurations :



The γ and ν helicities are the same.

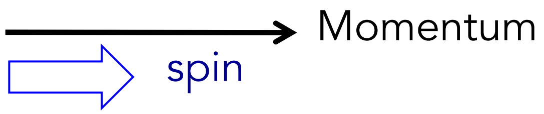
The γ polarization is measured to measure the neutrinos helicity. One sees only left handed neutrinos :



$\pi \rightarrow \ell\ \nu_\ell$

Spin of the pion : 0

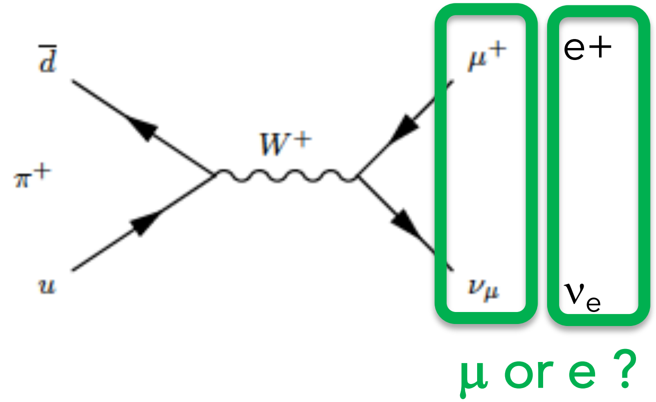
Spin of the lepton and neutrino : ½

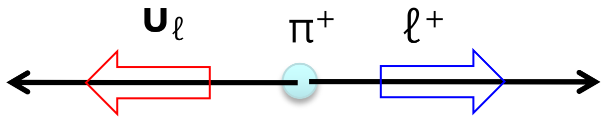


m_e = 0.5 MeV

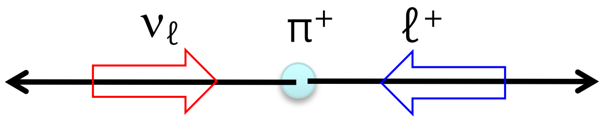
m_μ = 105 MeV

m_π = 135 MeV





Right handed neutrino



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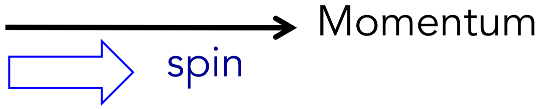

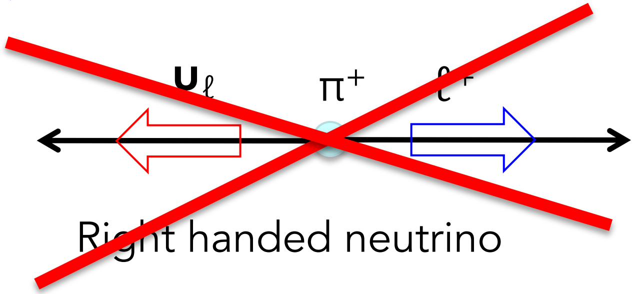

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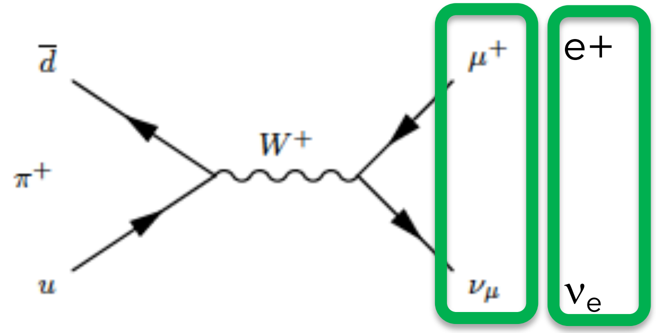
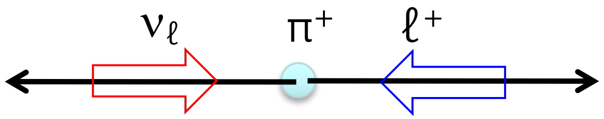


μ or e ?

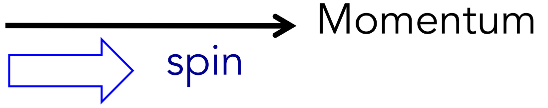


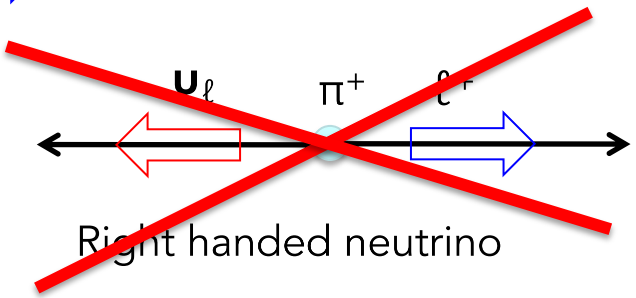
Left handed neutrino

if the ℓ^+ is massless this is not possible !

$\pi \rightarrow \ell\ \nu_\ell$

Spin of the pion : 0
Spin of the lepton and neutrino : ½





$$\Gamma = \frac{1}{8\pi} G^2 f_\pi^2 m_\pi m_\ell^2 \left(1 - \frac{m_\ell^2}{m_\pi^2}\right)^2$$

$$\frac{\Gamma_e}{\Gamma_\mu} \propto \left(\frac{m_e}{m_\mu}\right)^2 \frac{1}{\left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2} \sim 1.27\ 10^{-4}$$

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m_μ = 105 MeV
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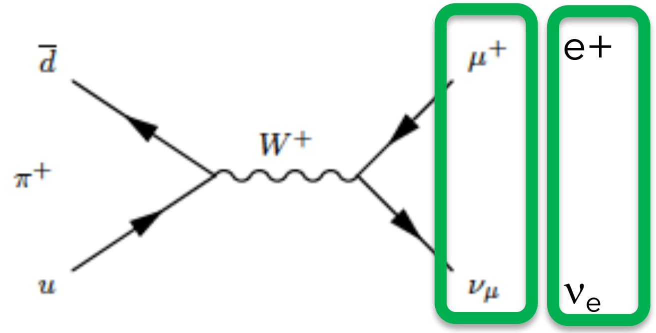
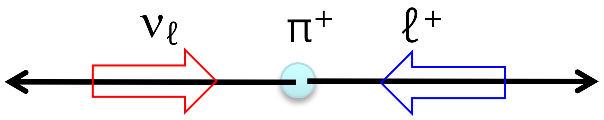


μ or e ?



Left handed neutrino

if the ℓ^+ is massless this is not possible !

Measurement:

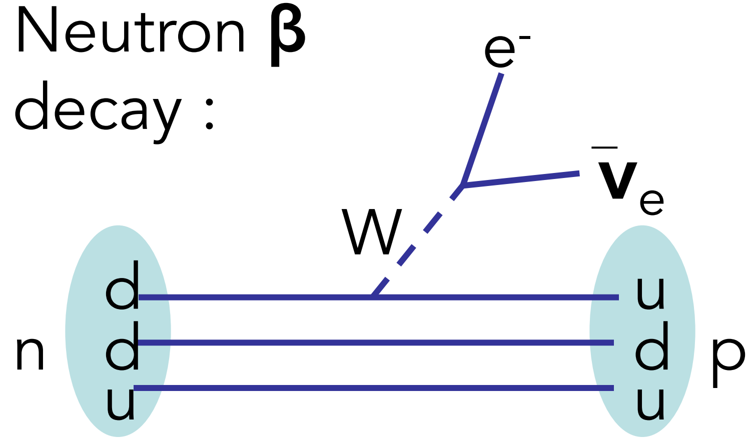
$$\frac{\Gamma\left(\pi^+ \rightarrow e^+ \nu_e\right)}{\Gamma\left(\pi^+ \rightarrow \mu^+ \nu_\mu\right)} = (1.230 \pm 0.004)\ 10^{-4}$$

Despite the much larger phase space, the electronic mode is strongly disfavored

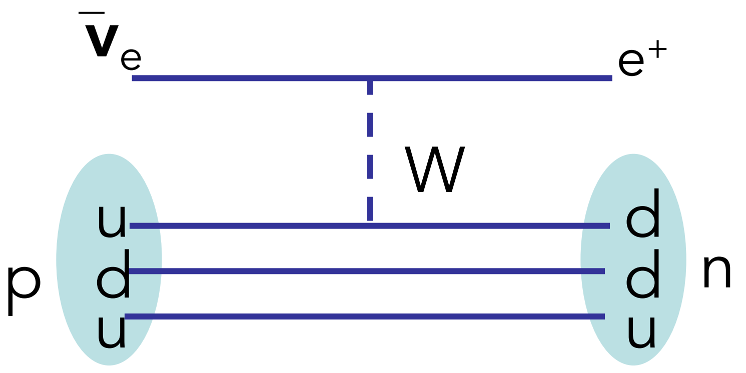
How to detect a **ν** ?

If **ν** are produced by **β** decay, they can be detected using the inverse reaction.

Neutron **β** decay :



Inverse **β** decay :



Maxim Titov's first lecture

$\sigma(\bar{\nu}p) \sim 10^{-43}\text{cm}^2$ $E_\nu \sim$ 3 MeV

$\lambda = \frac{1}{N_A \varrho \sigma}$

$\lambda(Pb) \sim \frac{1}{6 10^{23}(\text{nucleon}/g) \times 11.35\ (\frac{g}{cm^3}) \times 10^{-43}\text{cm}^2} \sim 1.5\ 10^{16}$ m

~ 1.5 light year

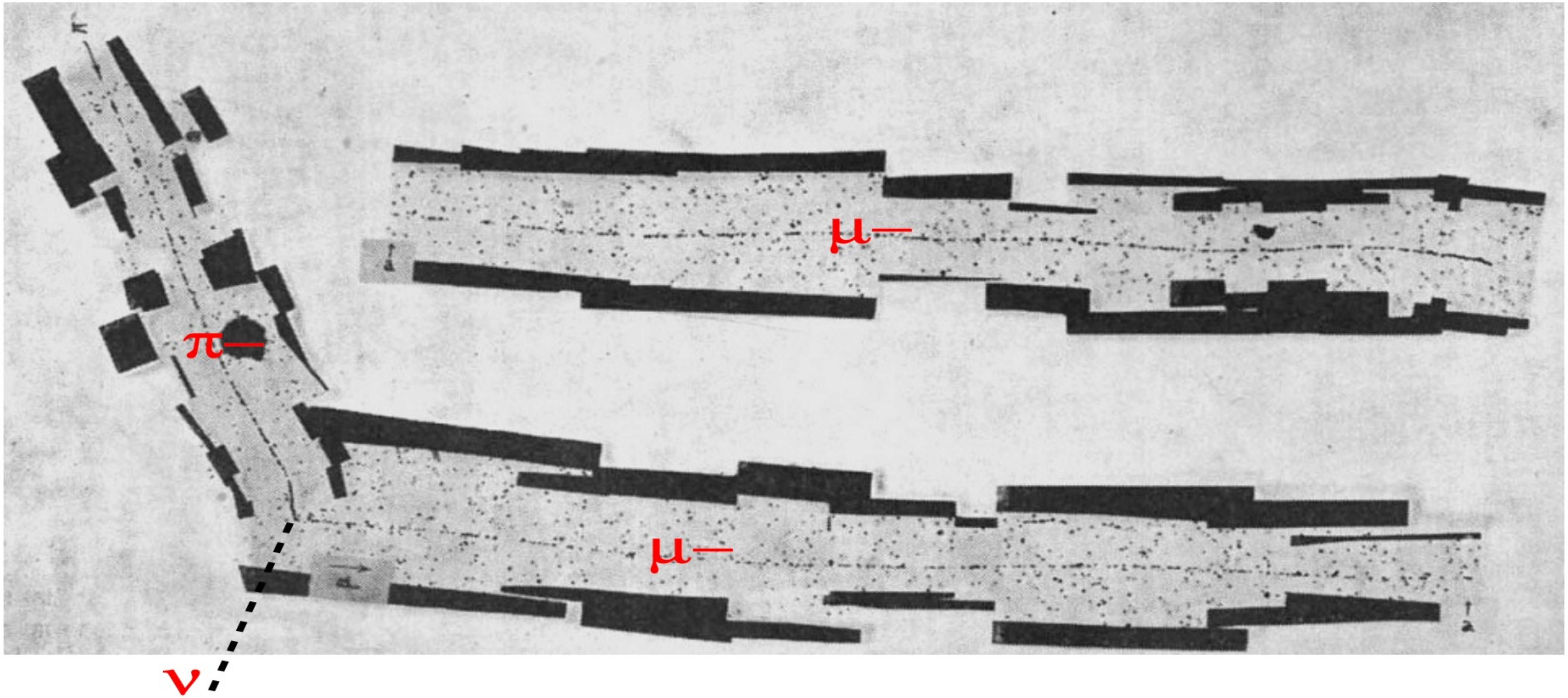
Requirements:

- Intense neutrino sources
- Large mass detectors

Sun (~10^{11} ν / cm² /s)
Cosmic rays interactions
Reactors
Accelerators

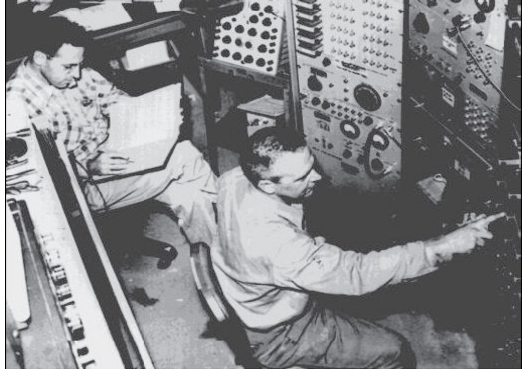
How to detect a **ν** ?

but also :

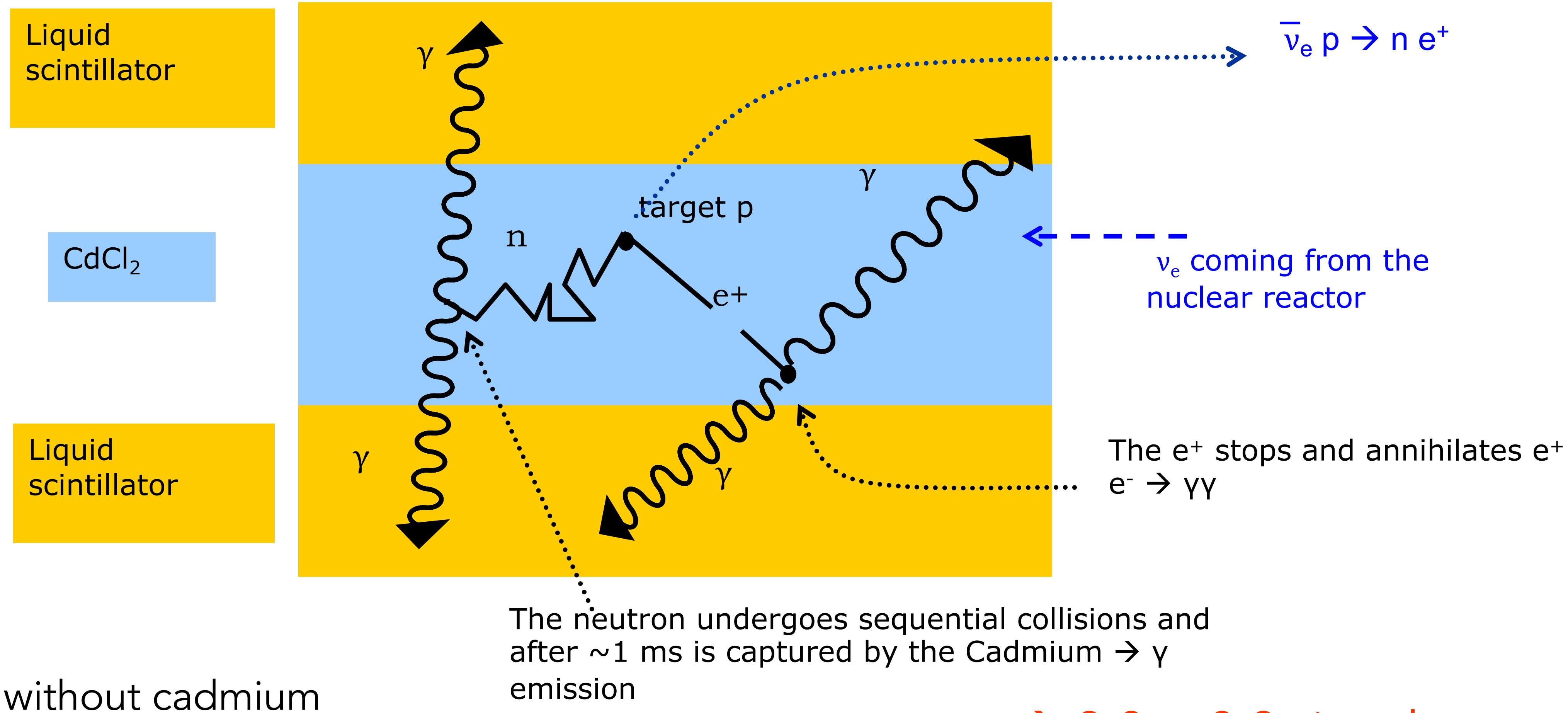


1947 : Cecil Powell takes emulsion photos aboard high altitude RAF flights
→ Pion discovery

Direct experimental evidence of ν_e



- around 1930, Pauli and Fermi made the hypothesis of the $\boldsymbol{\nu_e}$
- In 1956, Reines-Cowan experiment : experimental evidence using a nuclear reactor : search for the $\bar{\nu}_e\, p \rightarrow n\, e^+$ reaction



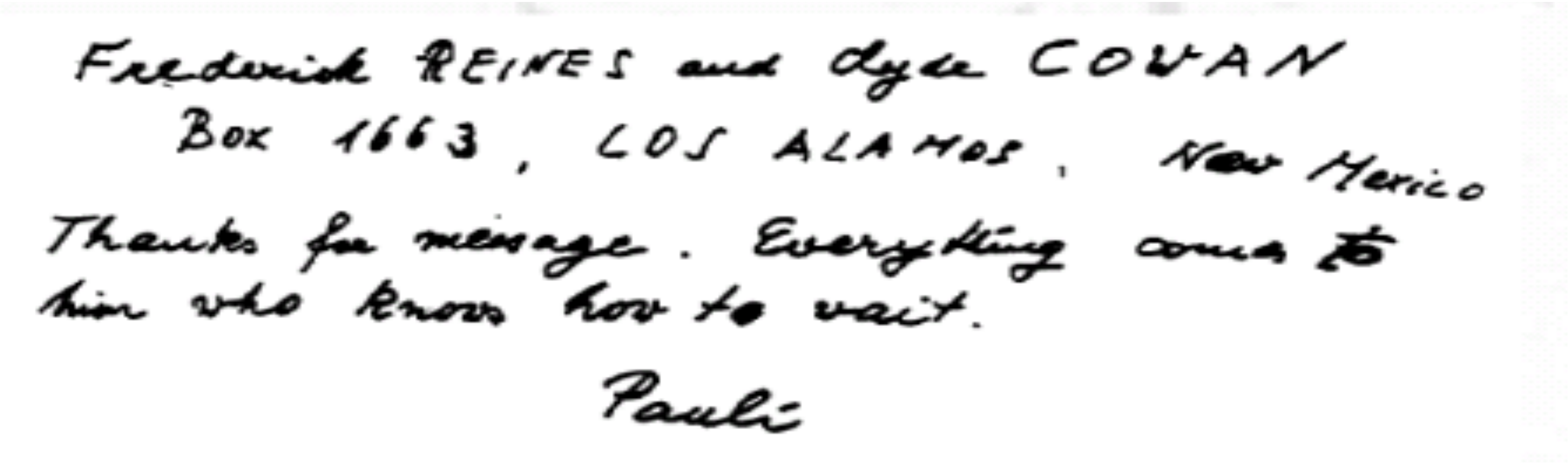
- Checks :
  - Target without cadmium
  - data taking with nuclear reactor OFF

→ 3.0 ±0.2 signal events/hour

Pauli (1930) : "I have done a terrible thing. I have proposed a particle that cannot be detected. It is something no theorist should ever do."

Reines and Cowan to Pauli (1956) : *"We are happy to inform you that we have definitely detected neutrinos … "*

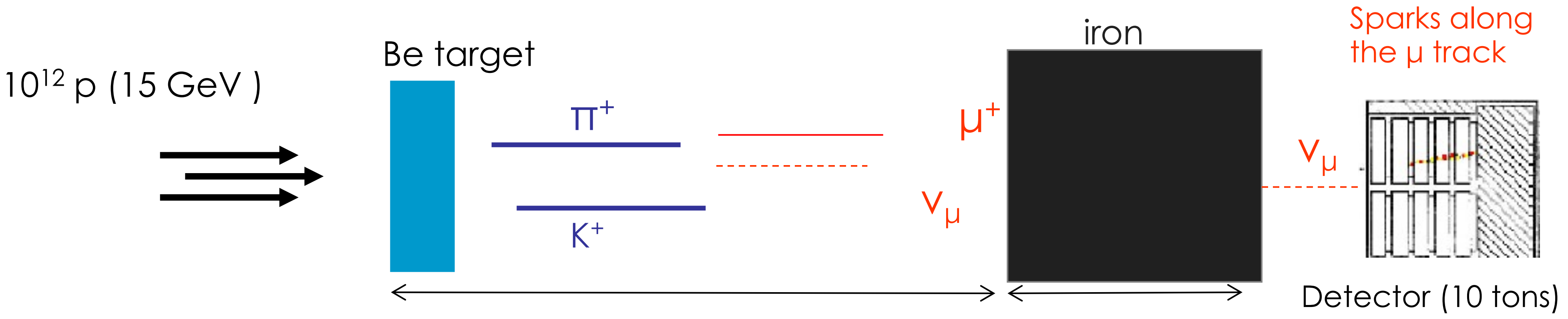
Answer from Pauli : *"Thanks for the message. Everything comes to him who knows how to wait. "*

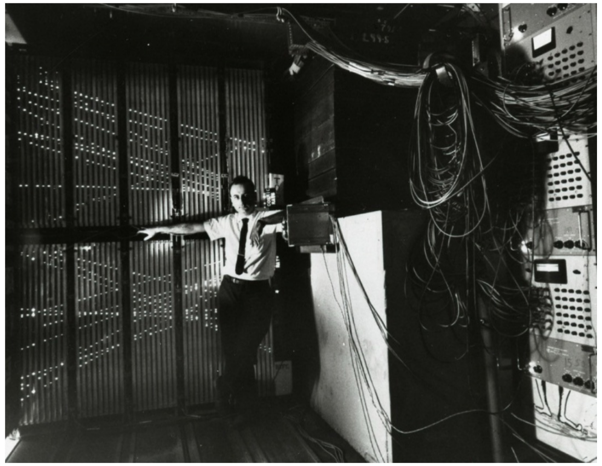

Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to
him who knows how to wait.
Pauli

Three kinds of neutrinos :

Lepton number conservation : crucial !

- In 1962 : Schwartz, Lederman et Steinberger experiment at BNL : $\boldsymbol{\nu_\mu \neq \nu_e}$





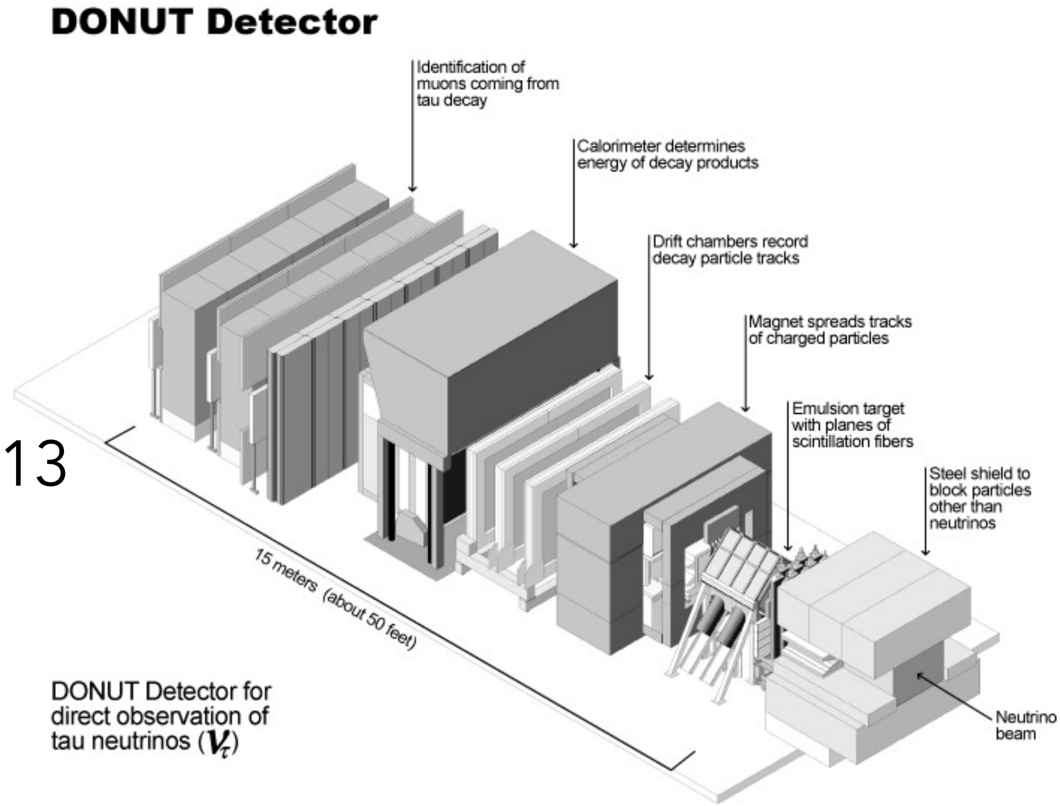
40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as μ

- in 2000 the third neutrino (DONUT) at Fermilab :

$D_s \rightarrow \tau\nu_\tau$ ν_τ beam

$\nu_\tau + N \rightarrow \tau + X$

lifetime 2.9 × 10−13

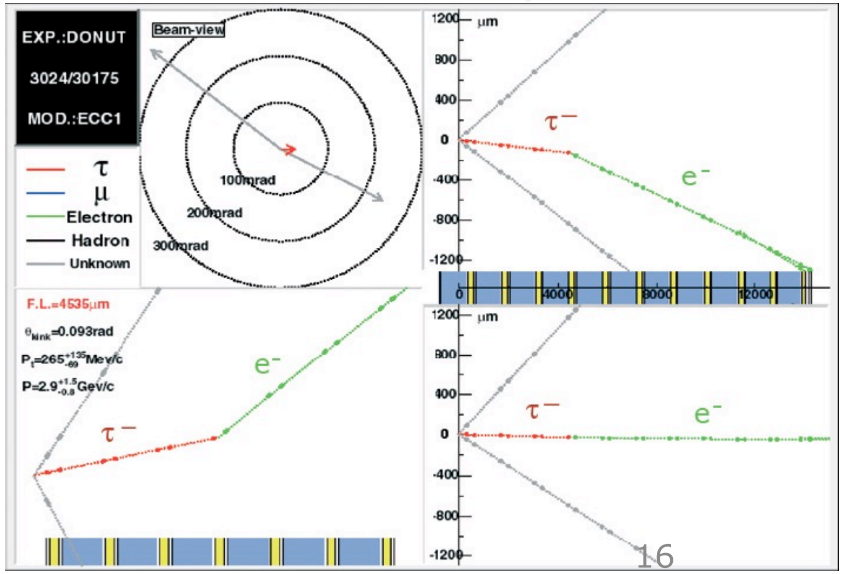


3 years of data taking :

→ 6 millions of events recorded

→ 1000 candidate events

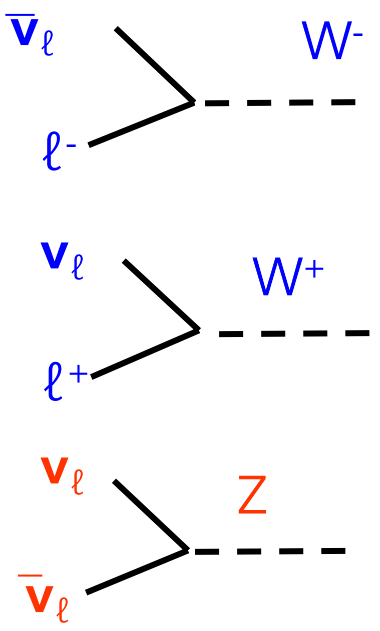
→ 4 unambiguous ν_τ signal events



MH

SM neutrino interactions

Neutrinos only couple to the weak bosons Z and W :

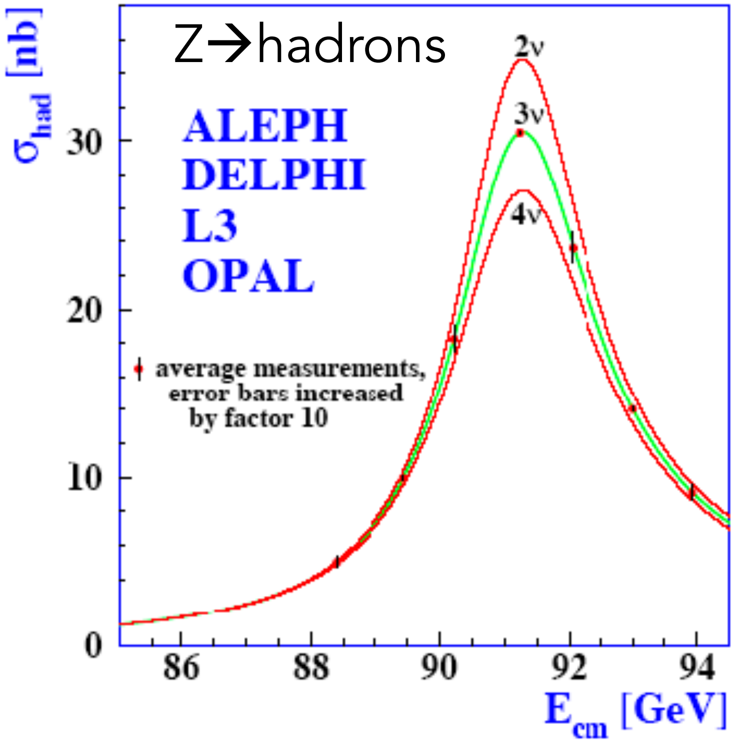


$$L_W = \frac{1}{\sqrt{2}} g \left(\overline{\ell_L} \gamma_\mu \nu_L \right) W^{+\mu} + \frac{1}{2} \frac{g}{\cos\theta_W} \left(\overline{\nu_L} \gamma_\mu \nu_L \right) Z^\mu$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \quad \text{and} \quad (e)_R \, (\mu)_R \, (\tau)_R$$

$N_\nu = 2.9840 \pm 0.0082$

3 types of light neutrinos

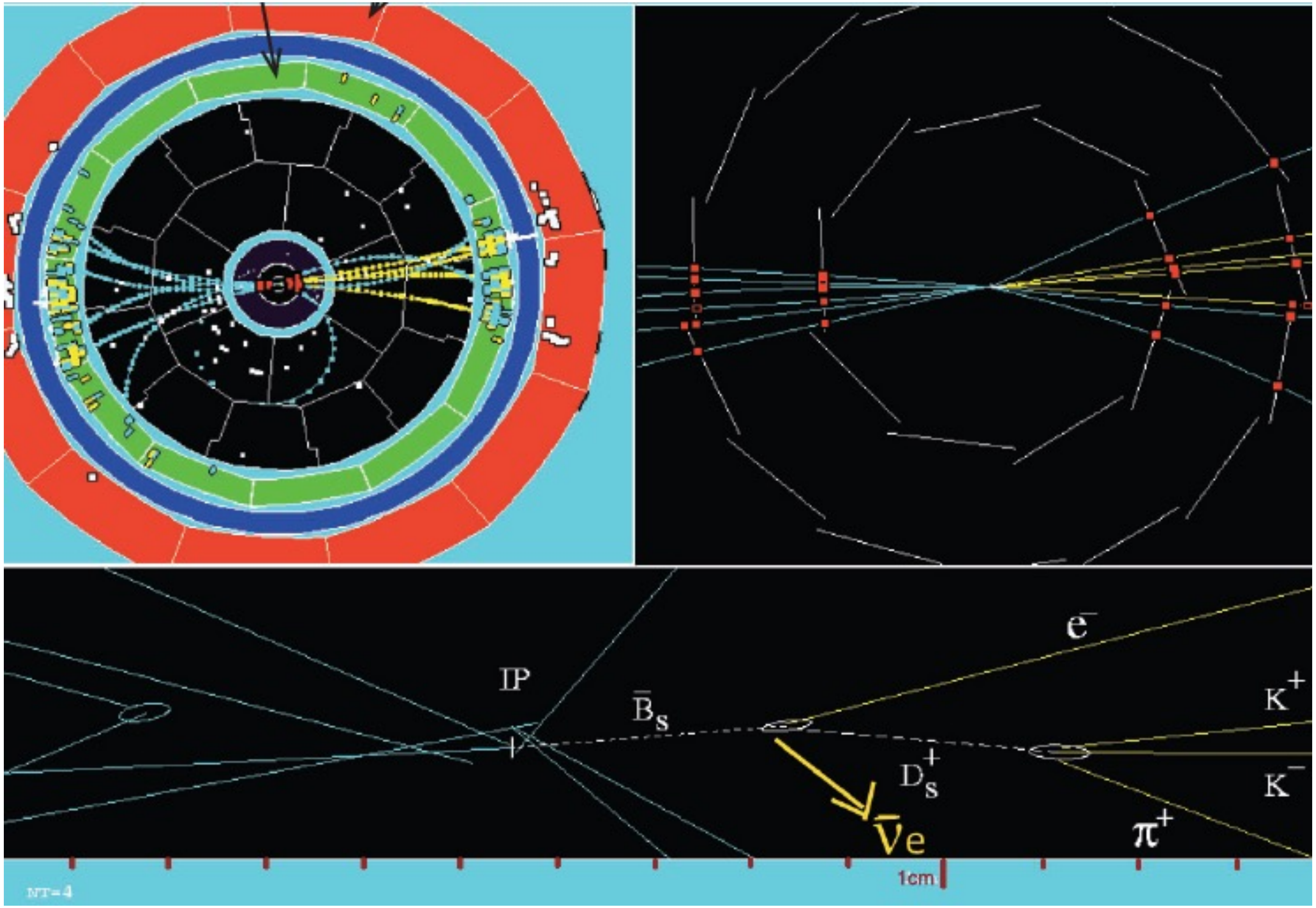


Up to now (implicit) hypothesis $m_\nu=0$

The only distinction between **ν** and **ν̄** : helicity

How to detect a **ν** ?

but also :



Leptogenesis (Majorana neutrinos)

Very heavy
neutrino N

N can decay into ℓ^+ or ℓ^-

N created at the big bang time

$N \rightarrow \ell^+ \phi^-$

$N \rightarrow \ell^- \phi^+$

Higgs field before SSB $\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$

CP violation $\Rightarrow \Gamma(N \rightarrow \ell^+ \phi^-) \neq \Gamma(N \rightarrow \ell^- \phi^+)$

unequal amount of matter and antimatter in the leptonic sector

Helicity/Chirality :

Projection of the spin in the momentum direction

- Helicity: definition for the helicity operator : $H = \frac{\sigma . p}{|\vec{p}|}$ with $\sigma = \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & \vec{\sigma} \end{pmatrix}$ 4×4

- Chirality:
  If ψ is a solution for the Dirac equation, on can write: $\psi = \psi_{CL} + \psi_{CR}$
  Definition: chirality operators *Left* ou *Right* (CL,CR) :

$$P_{CL} = \frac{1-\gamma_5}{2} = \begin{pmatrix} 0 & 0 \\ 0 & \mathbf{1} \end{pmatrix}$$

$$P_{CR} = \frac{1+\gamma_5}{2} = \begin{pmatrix} \mathbf{1} & 0 \\ 0 & 0 \end{pmatrix}$$

$$\gamma_5 = \begin{pmatrix} \mathbf{1} & 0 \\ 0 & -\mathbf{1} \end{pmatrix} \quad 4 \times 4$$

(for the chiral representation)

Algebra :

$$P_{CL}^2 = P_{CL}, \quad P_{CR}^2 = P_{CR}, \quad P_{CL} + P_{CR} = 1, \quad P_{CL}P_{CR} = 0$$

$$\psi_{CL} = P_{CL}\psi \qquad \overline{\psi}_{CL} = \overline{\psi}P_{CR}$$

$$\psi_{CR} = P_{CR}\psi \qquad \overline{\psi}_{CR} = \overline{\psi}P_{CL}$$

$$P_{CL}\gamma^\mu = \gamma^\mu P_{CR} \qquad P_{CR}\gamma^\mu = \gamma^\mu P_{CL}$$

Link between helicity and chirality

- Chirality is the "correct" quantity (it appears in the Lagrangian and in addition the helicity in not Lorentz invariant) but what is measured in the processes is the helicity

- One can show that:

$$\psi_{CL} = \frac{a}{2}\psi_{HR} + \frac{b}{2}\psi_{HL}$$

$$\psi_{CR} = \frac{b}{2}\psi_{HR} + \frac{a}{2}\psi_{HL}$$

with

$$a = 1 - \frac{p}{E+m}$$

$$b = 1 + \frac{p}{E+m}$$

ψ_{CR}, ψ_{CL} are the eigenvectors of H

ψ_{CR} corresponds to the eigenvalue +1

ψ_{CL} corresponds to the eigenvalue -1

- for m<<E: a = 1 - β and b = 1 + β

  $\beta \sim 1$: a = 0 and b = 2

  and thus : $\psi_{CL}=\psi_{HL}$ and $\psi_{CR}=\psi_{HR}$

for E>>m : Helicity $\equiv$ Chirality

4.2 V-A structure:

Let's take an electromagnetic current : $\bar{\psi}\gamma^{\mu}\psi$:

(γ^{μ} is a vector, parity = -1)

$$\bar{\psi}\gamma^{\mu}\psi = \bar{\psi}\left(P_{CL} + P_{CR}\right)\gamma^{\mu}\left(P_{CL} + P_{CR}\right)\psi =$$

$$\cancel{\bar{\psi}P_{CL}\gamma^{\mu}P_{CL}\psi} + \bar{\psi}P_{CR}\gamma^{\mu}P_{CL}\psi + \bar{\psi}P_{CL}\gamma^{\mu}P_{CR}\psi + \cancel{\bar{\psi}P_{CR}\gamma^{\mu}P_{CR}\psi} =$$

$$\bar{\psi}_{CL}\gamma^{\mu}\psi_{CL} + \bar{\psi}_{CR}\gamma^{\mu}\psi_{CR}$$

$$\bar{\psi}\gamma^{\mu}\psi = \bar{\psi}_{CL}\gamma^{\mu}\psi_{CL} + \bar{\psi}_{CR}\gamma^{\mu}\psi_{CR}$$ selects ψ_{CL}, ψ_{CR}

$\Rightarrow$ for the electromagnetic interaction : ψ_{CL} - ψ_{CL} and ψ_{CR} - ψ_{CR} couplings

Let's take a weak coupling $\bar{\psi}\gamma^{\mu}(1-\gamma_5)\psi$:

$\gamma^{\mu}\gamma^{5}$ is vector-axial, parity +1
$\gamma^{\mu}(1-\gamma_5)$: V-A structure

$$\bar{\psi}\gamma^{\mu}\left(1-\gamma_5\right)\psi = \bar{\psi}\left(P_{CL} + P_{CR}\right)\gamma^{\mu}\left(1-\gamma_5\right)\left(P_{CL} + P_{CR}\right)\psi =$$

$$2\bar{\psi}\left(P_{CL} + P_{CR}\right)\gamma^{\mu}\left(P_{CL}^2 + \cancel{P_{CL}P_{CR}}\right)\psi =$$

$$2\bar{\psi}P_{CL}\gamma^{\mu}P_{CL}\psi + 2\bar{\psi}P_{CR}\gamma^{\mu}P_{CL}\psi = 2\bar{\psi}\gamma^{\mu}\cancel{P_{CR}P_{CL}}\psi + 2\bar{\psi}_{CL}\gamma^{\mu}\psi_{CL}$$

$$\bar{\psi}\gamma^{\mu}\left(1-\gamma_5\right)\psi = 2\bar{\psi}_{CL}\gamma^{\mu}\psi_{CL}$$

$\Rightarrow$ for the weak interaction : ψ_{CL} - ψ_{CL} coupling only

This form for the current leads to maximal parity violation
(the V-A structure allows only left handed neutrinos)

Validation of the $\gamma^{\mu}(1-\gamma_5)$ expression for the weak currents