Lecture I:

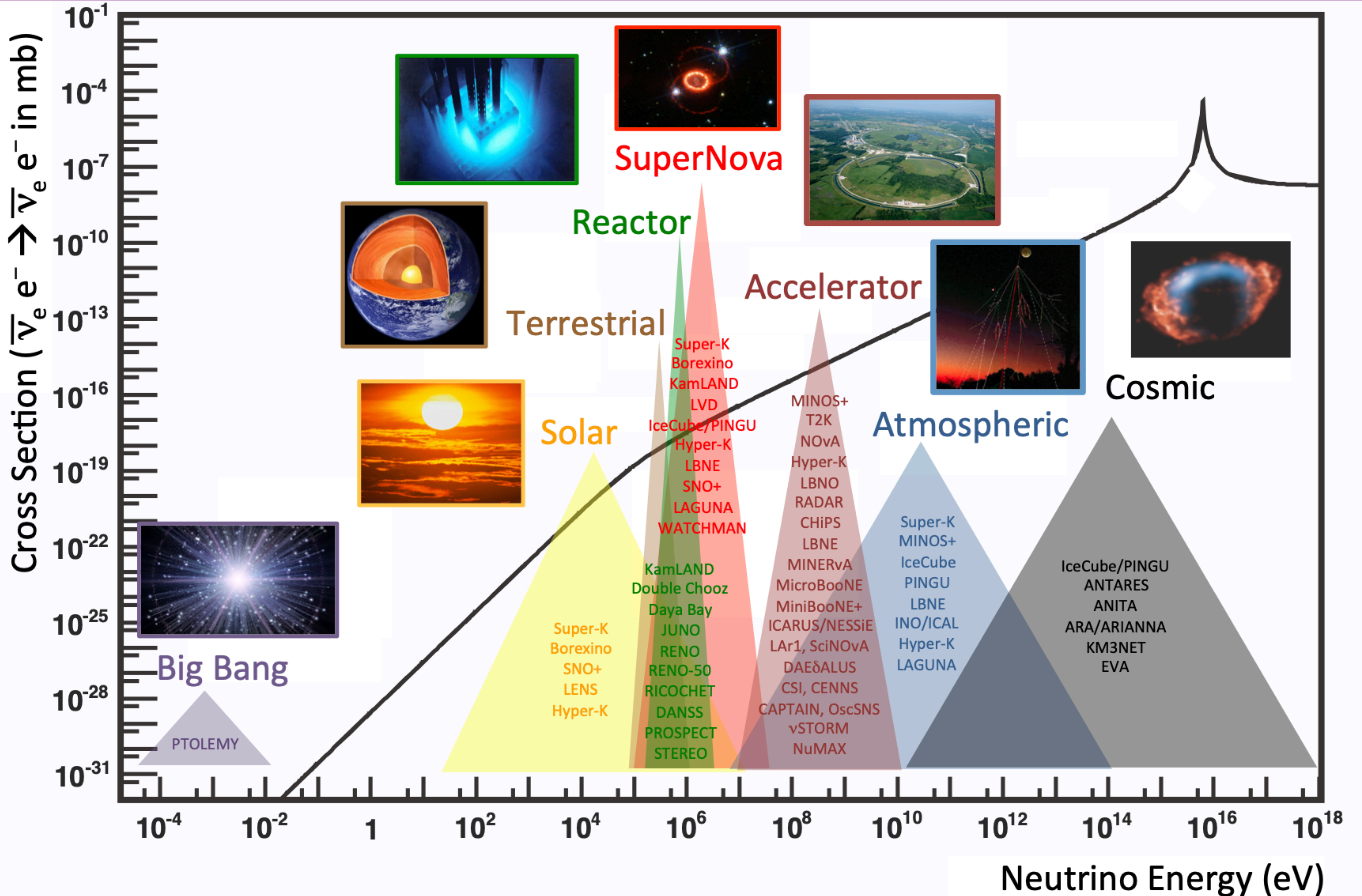
A century of surprises from $\beta-$decay to neutrinos in the SM

"*Nature* uses only the longest threads to weave her patterns, so each *small piece of* her *fabric* reveals the organization of the entire tapestry."

Richard Feynman

Neutrinos have a Ubiquitous Presence

Span many orders of magnitude in energy and x-section

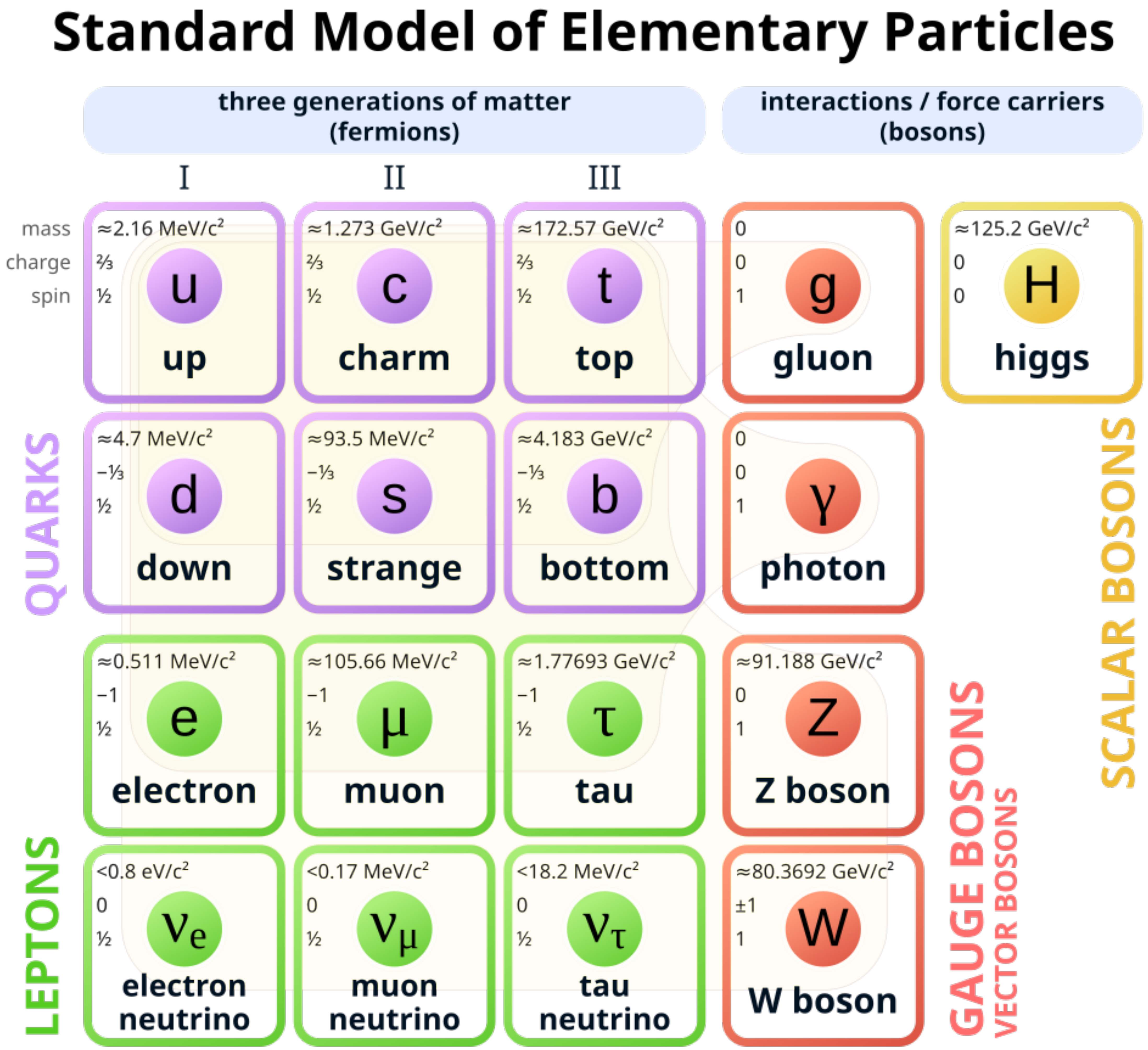


[Snowmass (2013), e-print:1401.6077]

$1\ \text{mb} = 10^{-27}\ \text{cm}^2$

The Neutrino Paved The Way

The best description we have of fundamental particles and interactions



$$\mathrm{SU}(3)_c \times \boxed{\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y}$$

Based on:

Lorentz Invariance

Gauge Invariance

With:

spontaneous symmetry breaking

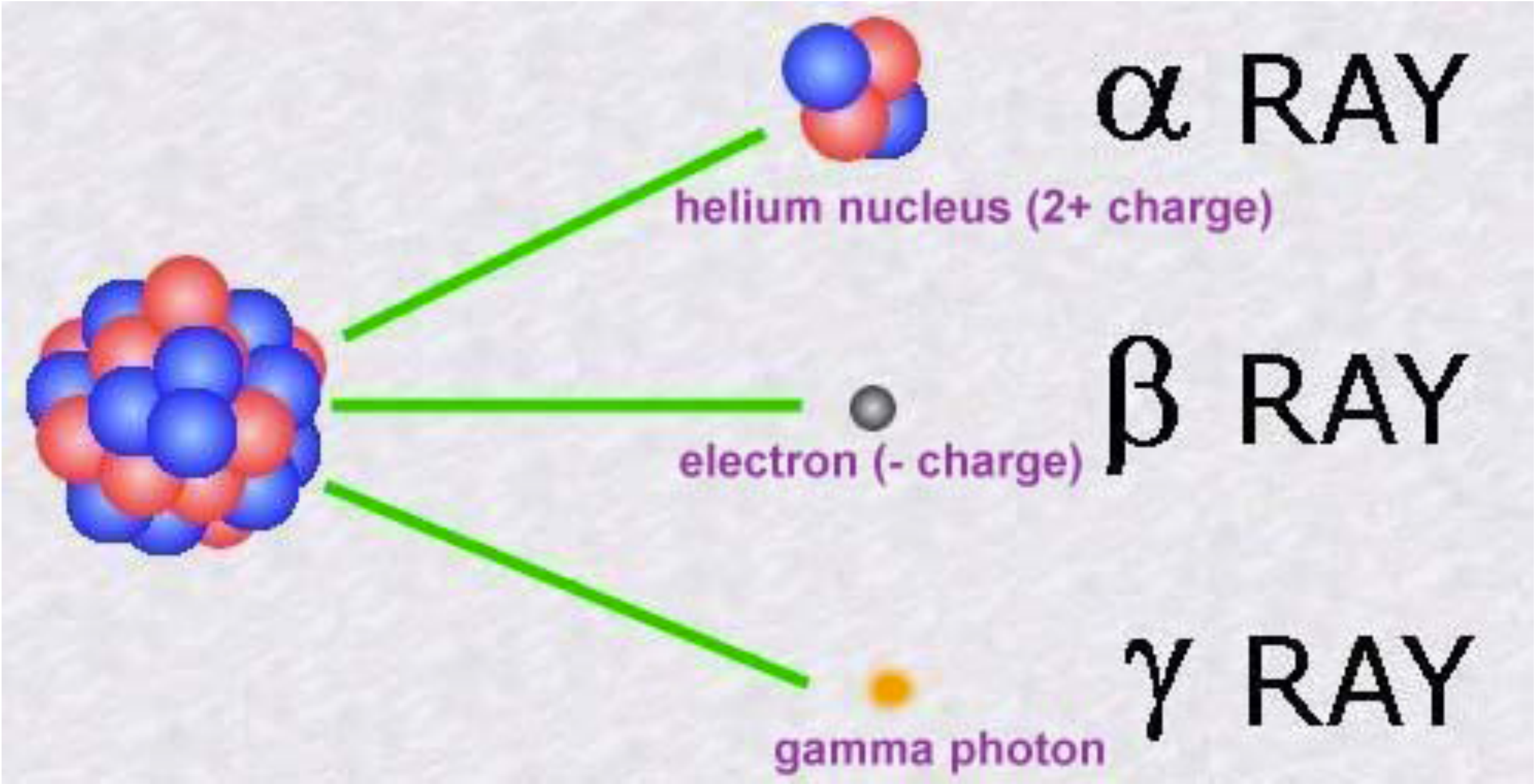
$$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \rightarrow \mathrm{U}(1)_{em}$$

How the Neutrino Was Born

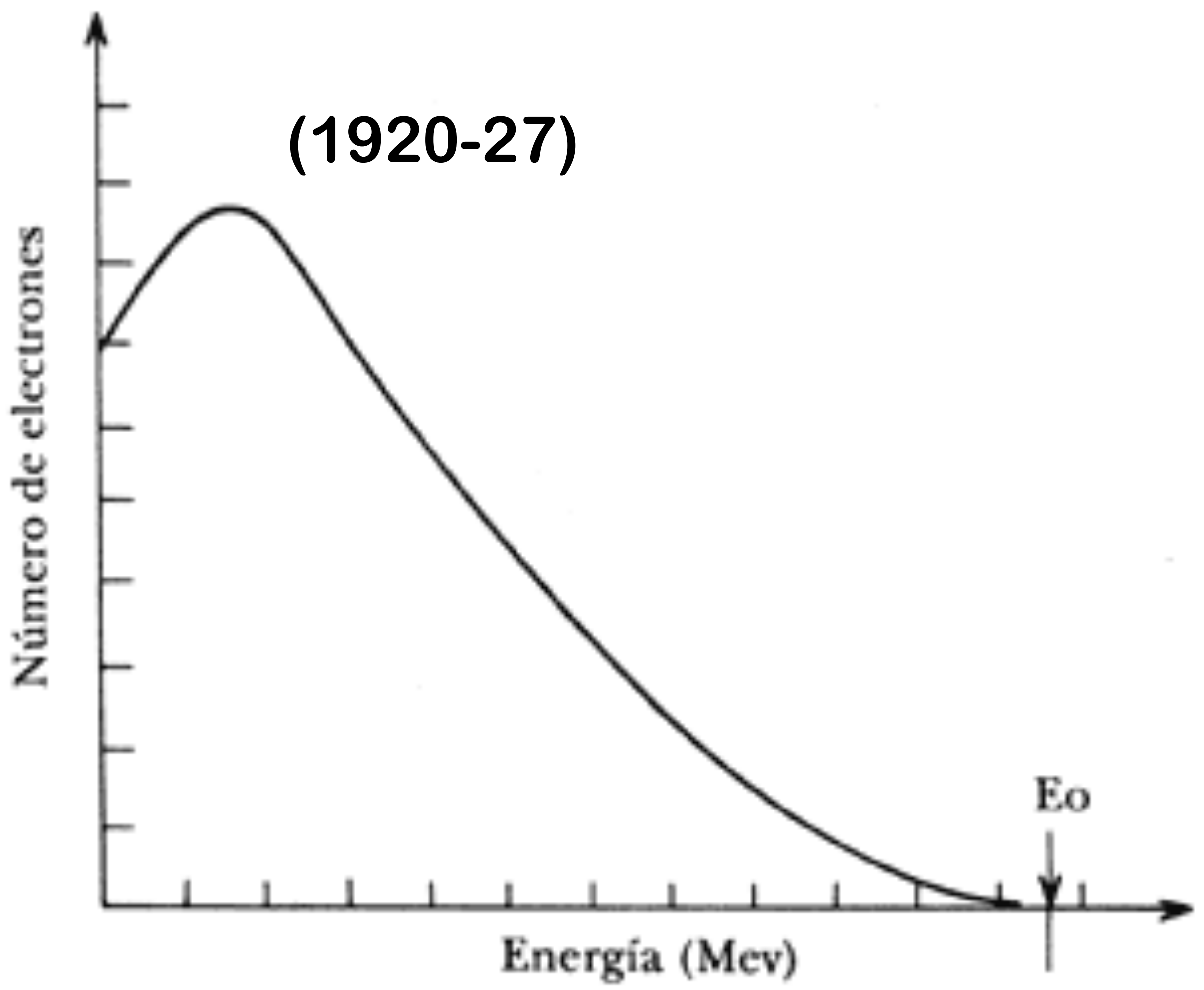
A puzzling question regarding β decays

Ernest Rutherford

James Chadwick



discovered in 1899



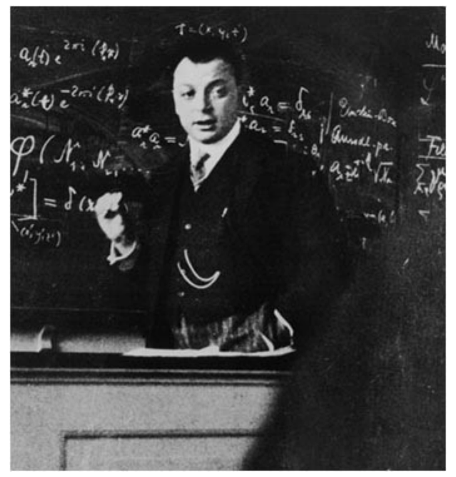
electron energy spectrum should be monochromatic … but was not !

$$A(N,Z) \rightarrow A(N-1,Z+1) + e-$$

How the Neutrino Was Born

"I have done a terrible thing"

"It is difficult to find a case where the word 'intuition' characterizes a human achievement better than in the case of the neutrino invention by Pauli"
Bruno Pontecorvo



Wolfgang Pauli

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Dear radioactive ladies and gentlemen,

As the bearer of these lines [...] will explain more exactly, considering the 'false' statistics of N-14 and Li-6 nuclei, as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the energy theorem. Namely [there is] 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 additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass. The continuous β-spectrum would then become understandable by the assumption that in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant. [...]

But I don't feel secure enough to publish anything about this idea, so I first turn confidently to you, dear radioactives, with a question as to the situation concerning experimental proof of such a neutron, if it has something like about 10 times the penetrating capacity of a γ ray.

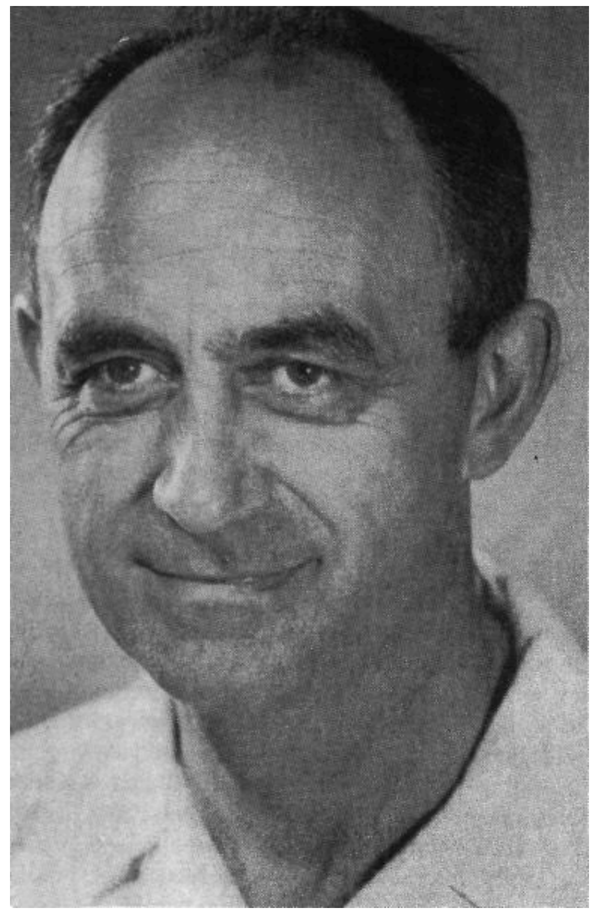
I admit that my remedy may appear to have a small a priori probability because neutrons, if they exist, would probably have long ago been seen. However, only those who wager can win, and the seriousness of the situation of the continuous β-spectrum can be made clear by the saying of my honored predecessor in office, Mr. Debye, [...] "One does best not to think about that at all, like the new taxes." [...] So, dear radioactives, put it to test and set it right. [...]

Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With many greetings to you, also to Mr. Back, your devoted servant,

W. Pauli

How the Neutrino was Born

Fermi's "too speculative" idea



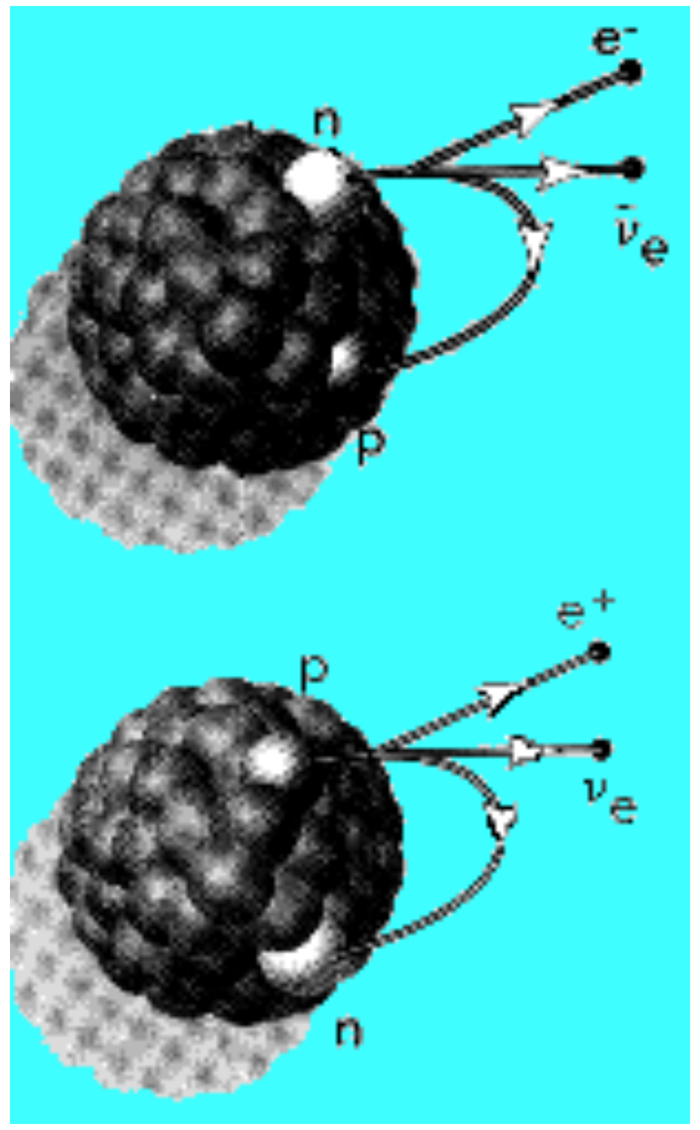
Enrico Fermi

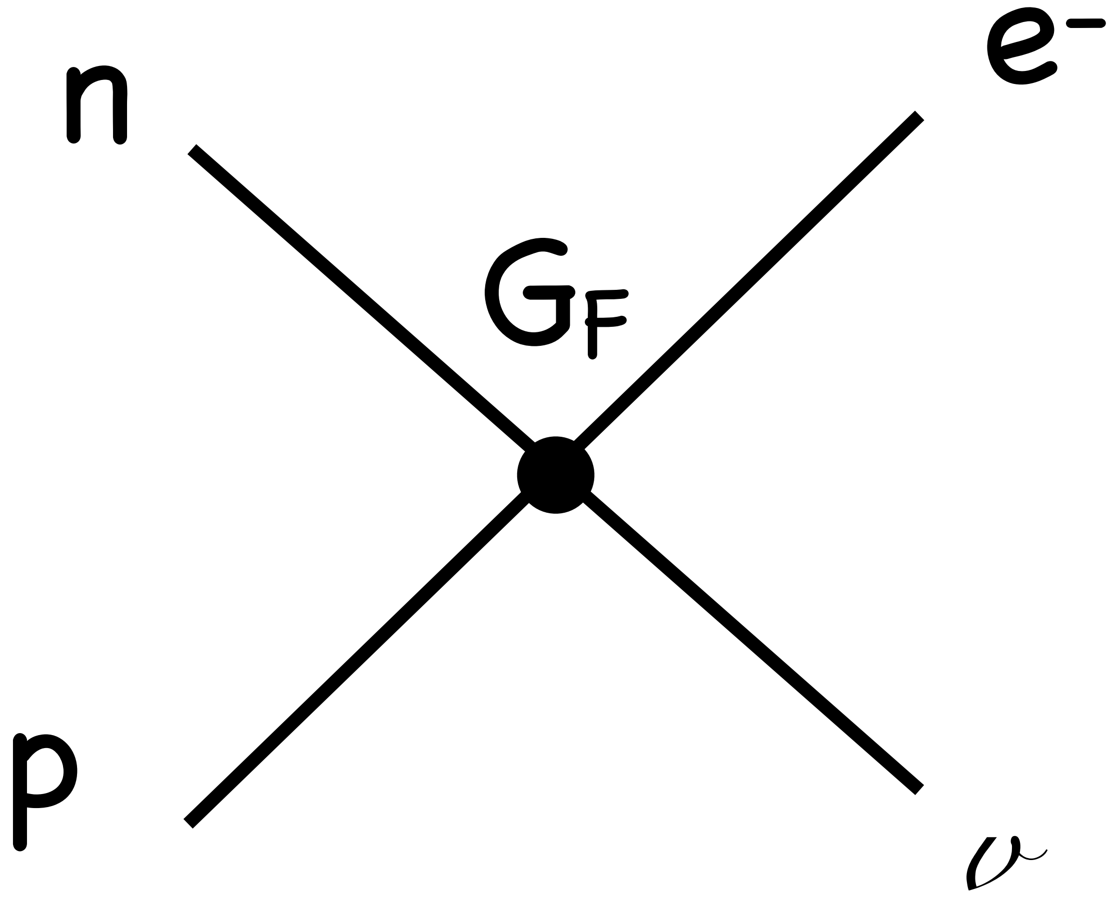
1932 - discovery of the neutron by Chadwick

1934 - discovery of β^+ decay by Joliot-Curie

- Fermi starts to call Pauli's particle neutrino ("*little neutron*") and proposes his theory for the "beta ray emission"

"contained speculations too remote from reality to be of interest to the reader" **(Nature refusal)**





$$G_F = 1.166 \times 10^{-5}\,\mathrm{GeV}^{-2}$$

$$\frac{1}{\sqrt{G_F}} \sim \mathcal{O}\,(\text{few } 10^2\,\mathrm{GeV})$$

sets the energy scale of weak interactions (Z, W in the SM have to be massive)

How the Neutrino was Born

“There is no practically possible way of observing the neutrino”

H. Bethe and R. Peierls

$$n \rightarrow e^- + p + \nu$$

$$\nu + p \rightarrow e^+ + n$$

inverse beta decay (IBD)

$$\sigma(\nu + p \rightarrow e^+ + n) \sim 10^{-38}\,\text{cm}^2 \qquad @\,1\ \text{GeV}$$

How the Neutrino was Born

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inverse beta decay (IBD)

$$\sigma(\nu + p \to e^+ + n) \sim 10^{-38}\,\text{cm}^2 \qquad @\,1\ \text{GeV}$$

$$\lambda \sim \frac{1}{n\sigma}$$

mean free path

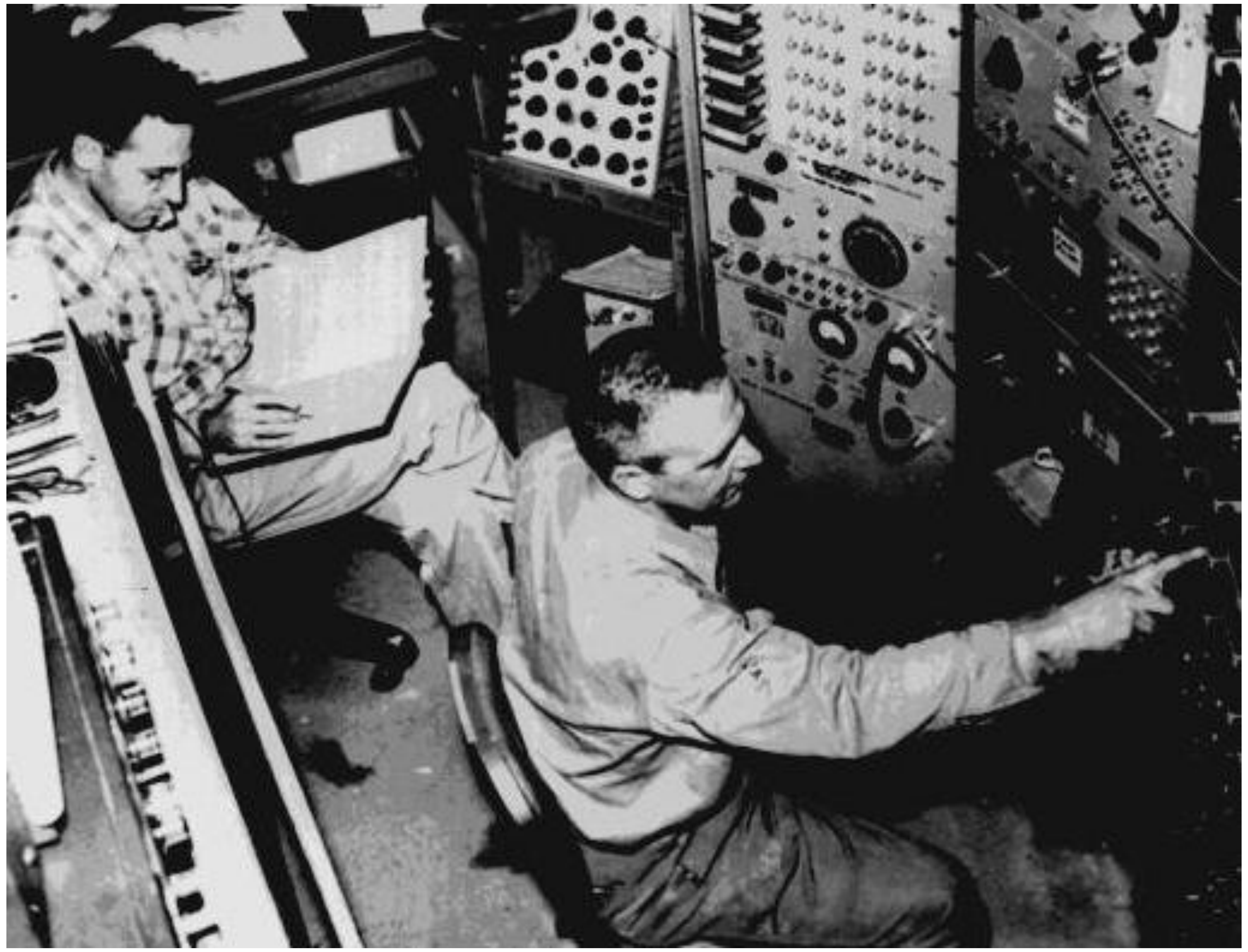
$n \sim 10^{23}\,\text{protons/cm}^3 \quad \lambda_{H_2O} \sim 10^{15}\,\text{cm} \quad \sim 10^{-3}\,\text{light} - \text{years}$

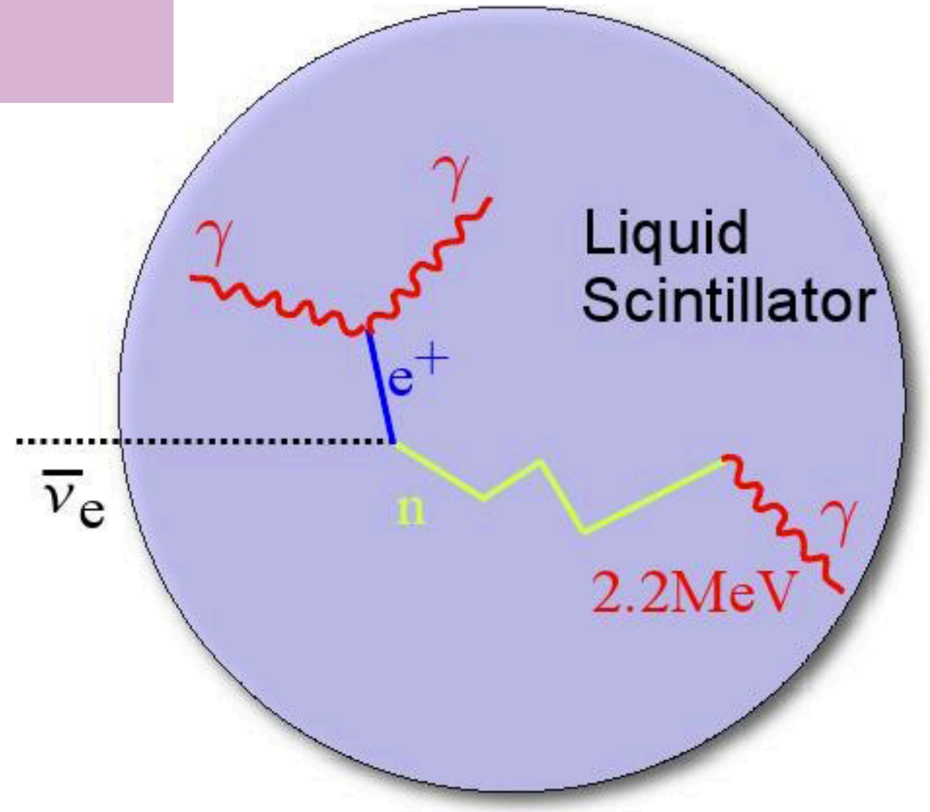
$n \sim \text{proton/cm}^3 \quad \lambda_{\text{interstellar}} \sim 10^{38}\,\text{cm} \quad \sim 10^{20}\,\text{light} - \text{years}$

Detecting the First Neutrino

The electron neutrino

Savannah River, South Carolina, EUA

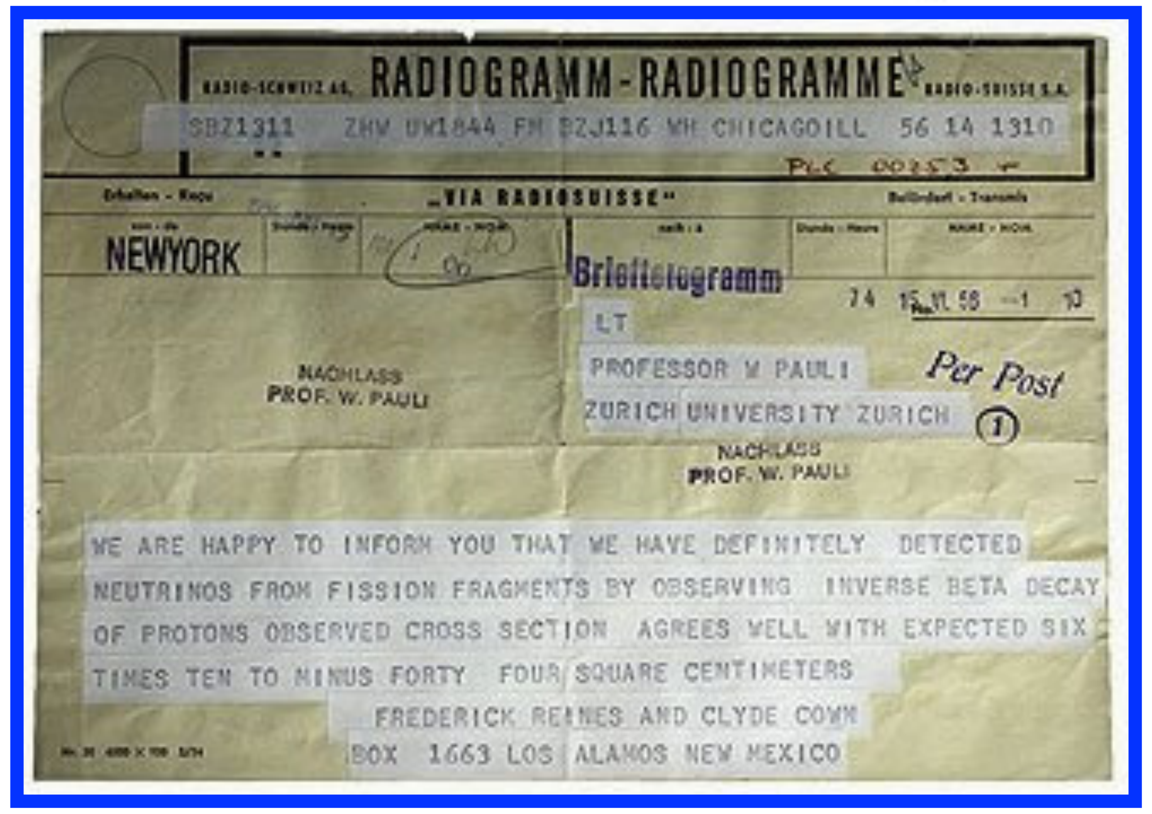




$$\overline{\nu}_e + p \rightarrow e^+ + n$$

↓ 207 μs

$$n + p \rightarrow d + \gamma$$



RADIO-SCHWEIZ AG. RADIOGRAMM - RADIOGRAMME RADIO-SUISSE S.A.

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"VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

NACHLASS PROF. W. PAULI

Per Post

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

C.L. Cowan Jr, et al. Science 124, 103 (1956)

F. Reines and C.L. Cowan Jr, Nature 178, 446 (1956)

Start of Digression :

Lorentz Transformations
&
Fermion Quantum Fields

Free Fermion Fields

Dirac equation

using natural units ($c = \hbar = 1$)

mass of the fermion

$$(i\gamma_\mu \partial^\mu - m)\psi = 0$$

- ψ is a 4 component Dirac spinor

Geral Lorentz transformation : Rotation + Boost

$$x \to \Lambda x \qquad \psi(x) \to S(\Lambda)\,\psi(\Lambda^{-1}x)$$

Free Fermion Fields

Dirac equation

mass of the fermion

$$(i\gamma_\mu \partial^\mu - m)\psi = 0$$ - ψ is a 4 component Dirac spinor

Geral Lorentz transformation : Rotation + Boost

$$x \to \Lambda x \qquad \psi(x) \to S(\Lambda)\,\psi(\Lambda^{-1}x)$$

Using the Chiral representation :

$$\gamma^0 = \begin{pmatrix} 0 & I_2 \\ I_2 & 0 \end{pmatrix} \qquad \gamma^i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix} \qquad \gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} -I_2 & 0 \\ 0 & I_2 \end{pmatrix}$$

$$\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$ **Pauli matrices**

Free Fermion Fields

Dirac equation

$$S(\Lambda_{\text{rot}}) = \begin{pmatrix} e^{i\vec{\phi}\cdot\vec{\sigma}/2} & 0 \\ 0 & e^{i\vec{\phi}\cdot\vec{\sigma}/2} \end{pmatrix}$$

$$\vec{\phi} = \phi\,\hat{n}$$

angle of rotation

General rotation

$$S(\Lambda_{\text{bost}}) = \begin{pmatrix} e^{\vec{\chi}\cdot\vec{\sigma}/2} & 0 \\ 0 & e^{-\vec{\chi}\cdot\vec{\sigma}/2} \end{pmatrix}$$

$$\vec{\chi} = \chi\,\hat{\beta}$$

$$\chi = \tanh(\beta)$$

rapidity

General boost

Free Fermion Fields

Dirac equation

$$S(\Lambda_{\text{rot}}) = \begin{pmatrix} e^{i\vec{\phi}\cdot\vec{\sigma}/2} & 0 \\ 0 & e^{i\vec{\phi}\cdot\vec{\sigma}/2} \end{pmatrix}$$

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$$\vec{\chi} = \chi\,\hat{\beta}$$

$$\chi = \tanh(\beta)$$

rapidity

General boost

$$P_L = \frac{1}{2}(I - \gamma^5) = \begin{pmatrix} I_2 & 0 \\ 0 & 0 \end{pmatrix} \qquad P_R = \frac{1}{2}(I + \gamma^5) = \begin{pmatrix} 0 & 0 \\ 0 & I_2 \end{pmatrix}$$

chiral projectors

chiral components

irreducible representations of the Lorentz group - 2 component Weyl spinors

$$\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} \qquad \psi_L = P_L\,\psi \qquad \psi_R = P_R\,\psi$$

4 component Dirac spinor is reducible

Free Fermion Fields

Dirac equation

$$S(\Lambda_{\text{rot}}) = \begin{pmatrix} e^{i\vec{\phi}\cdot\vec{\sigma}/2} & 0 \\ 0 & e^{i\vec{\phi}\cdot\vec{\sigma}/2} \end{pmatrix}$$

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$$\vec{\chi} = \chi\,\hat{\beta}$$

$$\chi = \tanh(\beta)$$

rapidity

General boost

$$\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

chiral components

$$\psi_L \to e^{i\vec{\phi}\cdot\vec{\sigma}/2}\,\psi_L \qquad \psi_R \to e^{i\vec{\phi}\cdot\vec{\sigma}/2}\,\psi_R$$

rotate the same way

$$\psi_L \to e^{\vec{\chi}\cdot\vec{\sigma}/2}\,\psi_L \qquad \psi_R \to e^{-\vec{\chi}\cdot\vec{\sigma}/2}\,\psi_R$$

boot differently

Free Fermion Fields

Dirac equation

$$S(\Lambda_{\text{rot}}) = \begin{pmatrix} e^{i\vec{\phi}\cdot\vec{\sigma}/2} & 0 \\ 0 & e^{i\vec{\phi}\cdot\vec{\sigma}/2} \end{pmatrix}$$

$$\vec{\phi} = \phi\,\hat{n}$$

angle of rotation

General rotation

$$S(\Lambda_{\text{bost}}) = \begin{pmatrix} e^{\vec{\chi}\cdot\vec{\sigma}/2} & 0 \\ 0 & e^{-\vec{\chi}\cdot\vec{\sigma}/2} \end{pmatrix}$$

$$\vec{\chi} = \chi\,\hat{\beta}$$

$$\chi = \tanh(\beta)$$

rapidity

General boost

$$\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

chiral components

$$\psi_L \rightarrow e^{i\vec{\phi}\cdot\vec{\sigma}/2}\psi_L \qquad \psi_R \rightarrow e^{i\vec{\phi}\cdot\vec{\sigma}/2}\psi_R$$

rotate the same way

$$\psi_L \rightarrow e^{\vec{\chi}\cdot\vec{\sigma}/2}\psi_L \qquad \psi_R \rightarrow e^{-\vec{\chi}\cdot\vec{\sigma}/2}\psi_R$$

boot differently

but $H = \gamma^0(-i\gamma^i\partial_i + m)$ $\quad [H, \gamma^5] \neq 0$ **chirality is not a good quantum number !**

Free Fermion Fields

Bilinear Covariants

most general form of currents consistent with Lorentz covariance

$$\overline{\psi}\,(4 \times 4)\,\psi$$

$$\overline{\psi} \equiv \psi^{\dagger}\gamma^{0}$$

Adjoint spinor (undergoes inverse Lorentz Transformation)

Free Fermion Fields

Bilinear Covariants

most general form of currents consistent with Lorentz covariance

$$\bar{\psi}\,(4\times 4)\,\psi$$

		Space Inversion (Parity) $\mathbf{x} \rightarrow -\mathbf{x}$
$\bar{\psi}\psi$	Scalar	unchanged
$\bar{\psi}\gamma^{\mu}\psi$	Vector	space components change sign
$\bar{\psi}\sigma^{\mu\nu}\psi$	Tensor	
$\bar{\psi}\gamma^{5}\psi$	Pseudo-scalar	change sign
$\bar{\psi}\gamma^{5}\gamma^{\mu}\psi$	Axial-vector	space components don’t change sign

Free Fermion Fields

Dirac equation

$$(i\gamma_\mu \partial^\mu - m)\psi = 0 \qquad H = \gamma^0(-i\gamma^i \partial_i + m)$$

4 independent states with $p_\mu = (E, \vec{p}) \qquad E = \sqrt{\vec{p}^2 + m^2}$

$$(\gamma^\mu p_\mu - m)\, u_s(\vec{p}) = 0 \qquad (\gamma^\mu p_\mu + m)\, v_s(\vec{p}) = 0 \qquad s = 1,2$$

Do we have another good quantum number to describe these states?

Free Fermion Fields

Dirac equation

$$(i\gamma_\mu \partial^\mu - m)\psi = 0 \qquad H = \gamma^0(-i\gamma^i\partial_i + m)$$

4 independent states with $p_\mu = (E, \vec{p}) \qquad E = \sqrt{\vec{p}^2 + m^2}$

$$(\gamma^\mu p_\mu - m)\, u_s(\vec{p}) = 0 \qquad (\gamma^\mu p_\mu + m)\, v_s(\vec{p}) = 0 \qquad s = 1,2$$

we can choose them to be eigenstates of the helicity projector operator

helicity

$$P_\pm = \frac{1}{2}\left(I \pm \frac{\vec{\Sigma}\cdot\vec{p}}{|\vec{p}|}\right) = \frac{1}{2}\begin{pmatrix} I_2 \pm \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} & 0 \\ 0 & I_2 \pm \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} \end{pmatrix} = \frac{1}{2}\begin{pmatrix} I_2 \pm h & 0 \\ 0 & I_2 \pm h \end{pmatrix}$$

Free Fermion Fields

Dirac equation

$(i\gamma_\mu \partial^\mu - m)\psi = 0$ $\qquad$ $H = \gamma^0(-i\gamma^i \partial_i + m)$

4 independent states with $\qquad p_\mu = (E, \vec{p}) \qquad E = \sqrt{\vec{p}^2 + m^2}$

$(\gamma^\mu p_\mu - m)\, u_s(\vec{p}) = 0 \qquad (\gamma^\mu p_\mu + m)\, v_s(\vec{p}) = 0 \qquad s = 1,2$

we can choose them to be eigenstates of the helicity projector operator

$$P_\pm = \frac{1}{2}\left(I \pm \frac{\vec{\Sigma} \cdot \vec{p}}{|\vec{p}\,|}\right) = \frac{1}{2}\begin{pmatrix} I_2 \pm h & 0 \\ 0 & I_2 \pm h \end{pmatrix}$$

$$hu_\pm = \pm\, u_\pm$$

$$hv_\pm = \mp\, v_\pm$$

$[H, \vec{\Sigma} \cdot \vec{p}] = [\vec{p}, \vec{\Sigma} \cdot \vec{p}] = 0$ $\qquad$ helicity is a good quantum number but it is not Lorentz invariant !

Free Fermion Fields

Dirac equation

$$(i\gamma_\mu \partial^\mu - m)\psi = 0$$

$$\Sigma^i \equiv -\gamma^0\gamma^5\gamma^i$$

if m = 0 (massless particle)

$$\frac{\vec{\Sigma}\cdot\vec{p}}{|\vec{p}\,|}\psi = \frac{\Sigma^i p_i}{|\vec{p}\,|}\psi = -\gamma^0\gamma^5\frac{\gamma^i p_i}{|\vec{p}\,|}\psi = -\gamma^0\gamma^5\frac{\gamma^0 E}{|\vec{p}\,|}\psi = \gamma^5\psi$$

chirality and helicity

are equivalent

in this case helicity is Lorentz invariant !

Free Fermion Fields

Dirac equation

$$(i\gamma_\mu \partial^\mu - m)\psi = 0$$

$$\Sigma^i \equiv -\gamma^0\gamma^5\gamma^i$$

if m = 0 (massless particle)

$$\frac{\vec{\Sigma}\cdot\vec{p}}{|\vec{p}\,|} = \frac{\Sigma^i p_i}{|\vec{p}\,|}\psi = -\gamma^0\gamma^5\frac{\gamma^i p_i}{|\vec{p}\,|}\psi = -\gamma^0\gamma^5\frac{\gamma^0 E}{|\vec{p}\,|}\psi = \gamma^5\psi$$

chirality and helicity are equivalent

But in general ($m \neq 0$)

in this case helicity is Lorentz invariant !

$$P_\mp = P_{L/R} + \mathcal{O}\left(\frac{m}{E}\right)P_{R/L}$$

Free Fermion Fields

Dirac equation

if m = 0 (massless particle)

$$P_{\mp} = P_{L/R}$$

only 2 independent states now with $p_\mu = (|\vec{p}|, \vec{p})$

$$\gamma^\mu p_\mu u_+(\vec{p}) = 0 \qquad \gamma^\mu p_\mu v_+(\vec{p}) = 0$$

OR

$$\gamma^\mu p_\mu u_-(\vec{p}) = 0 \qquad \gamma^\mu p_\mu v_-(\vec{p}) = 0$$

Fermion Fields

Dirac Fields

$$\psi(x) = \sum_{s,\vec{p}} \left[a_s(\vec{p})\, u_s(\vec{p}) e^{-ipx} + b_s^\dagger(\vec{p})\, v_s(\vec{p}) e^{ipx} \right]$$

$$\psi(x)_L = \sum_{\vec{p}} \left[a_L(\vec{p})\, u_L(\vec{p}) e^{-ipx} + b_L^\dagger(\vec{p})\, v_L(\vec{p}) e^{ipx} \right]$$

creates antifermion with helicity h = +1 with amplitude ~ 1
creates antifermion with helicity h = -1 with amplitude ~ m/E

Fermion Fields

Dirac Fields

$$\psi(x) = \sum_{s,\vec{p}} \left[a_s(\vec{p})\, u_s(\vec{p}) e^{-ipx} + b_s^\dagger(\vec{p})\, v_s(\vec{p}) e^{ipx}\right]$$

$$\psi(x)_L = \sum_{\vec{p}} \left[a_L(\vec{p})\, u_L(\vec{p}) e^{-ipx} + b_L^\dagger(\vec{p})\, v_L(\vec{p}) e^{ipx}\right]$$

creates antifermion with helicity h = +1 with amplitude ~ 1
creates antifermion with helicity h = -1 with amplitude ~ m/E

$$\overline{\psi(x)}_L = \sum_{\vec{p}} \left[a_L^\dagger(\vec{p})\, \overline{u}_L(\vec{p}) e^{+ipx} + b_L(\vec{p})\, \overline{v}_L(\vec{p}) e^{-ipx}\right]$$

creates fermion with helicity h = -1 with amplitude ~ 1
creates fermion with helicity h = +1 with amplitude ~ m/E

Fermion Fields

Dirac Fields

$$\psi(x)^c = \mathscr{C}\psi(x)\mathscr{C} = \sum_{s,\vec{p}} \left[\mathscr{C}a_s(\vec{p})\mathscr{C}\, u_s(\vec{p})e^{-ipx} + \mathscr{C}b_s^\dagger(\vec{p})\mathscr{C}\, v_s(\vec{p})e^{ipx}\right]$$

$$= \sum_{s,\vec{p}} \left[b_s(\vec{p})\, u_s(\vec{p})e^{-ipx} + a_s^\dagger(\vec{p})\, v_s(\vec{p})e^{ipx}\right]$$ **charge conjugate spinor**

$$= C\,\overline{\psi}^T = i\gamma^2\psi^*$$

$$C = i\gamma^2\gamma^0$$

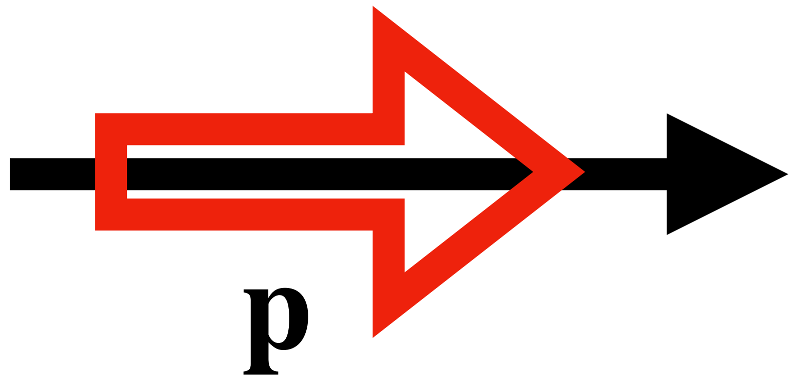
End of Digression

Neutrino Helicity

Is the neutrino left- or right-handed?

1958: Experiment by M. Goldhaber, L. Grodzins and A.W. Sunyar

Maurice Goldhaber   Lee Grodzins   Andrew Sunyar

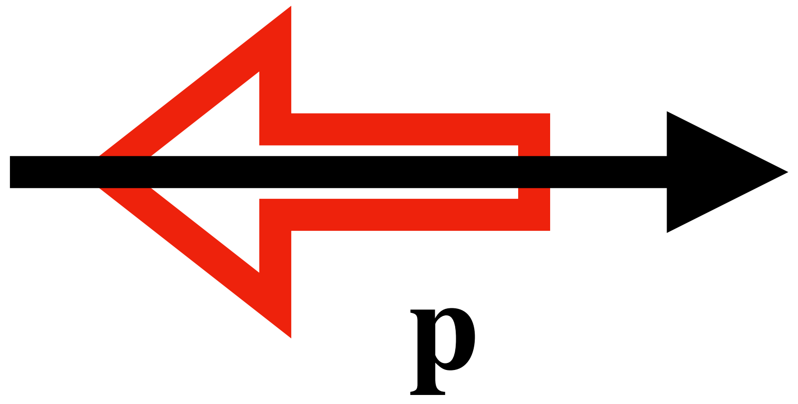


particle momentum

$\sigma \cdot \hat{\mathbf{p}}$ parallel

right-handed = positive helicity (h=+1)

OR



particle momentum

$\sigma \cdot \hat{\mathbf{p}}$ anti-parallel

left-handed = negative helicity (h=-1)

free spin 1/2 particle

Helicity of Neutrinos

The neutrino is left-handed

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

$$^{152}\mathrm{Sm}^* \rightarrow {}^{152}\,\mathrm{Sm} + \gamma$$

$$J(^{152}\mathrm{Eu}) = \mathrm{J}(^{152}\mathrm{Sm}) = 0 \qquad L(e^-) = 0$$

Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

angular momentum conservation $\quad S_z(e^-) = S_z(\nu) + S_z(\gamma) \qquad S_z(\nu) = -\frac{1}{2}S_z(\gamma)$

momentum conservation $\quad \vec{p}(^{152}\mathrm{Eu}) \simeq \vec{\mathrm{p}}(^{152}\mathrm{Sm}^{(*)}) \simeq 0$

$$\vec{p}_\nu = -\vec{p}_\gamma$$

$$\Rightarrow \quad \overrightarrow{S_\nu} \cdot \vec{p}_\nu = \frac{1}{2}\vec{S}_\gamma \cdot \vec{p}_\gamma$$

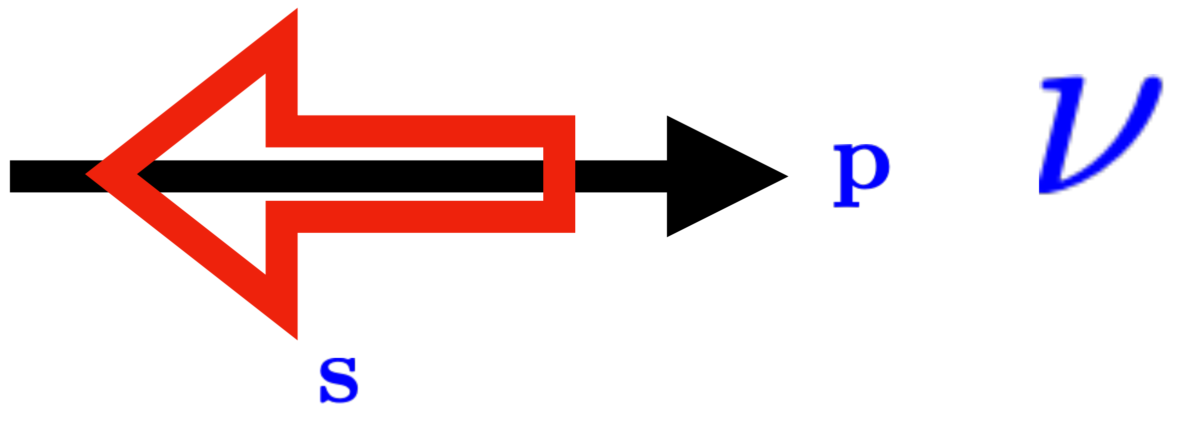
helicity of ν = 1/2 helicity of γ

leads to a V-A current

Helicity and Chirality

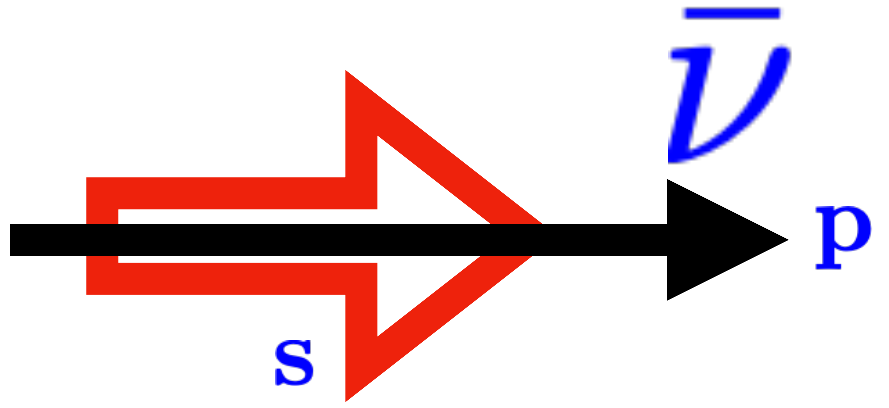
Some Consequences for pion decay

neutrinos have negative helicity



$h = -1$

antineutrinos have positive helicity



$h = +1$

if massless only need

$$\nu_L = \frac{1}{2}(1 - \gamma_5)\nu$$

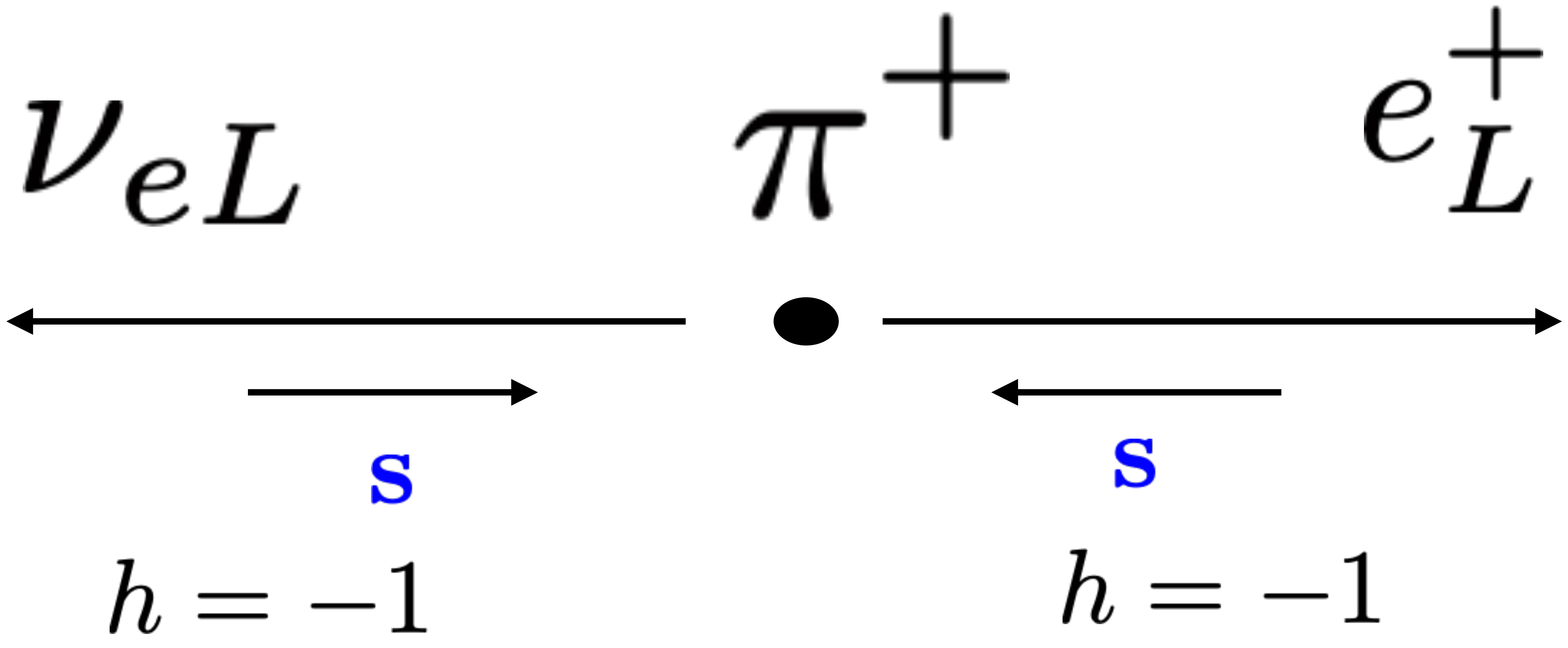
negative chirality field

Dirac Equation

	Chirality	Helicity	Amplitude
particle	L = negative chirality	h = -1	~ 1
		h = +1	$\sim \frac{m}{E}$
antiparticle		h = -1	$\sim \frac{m}{E}$
		h = +1	~ 1

Helicity and Chirality

Some Consequences for pion decay

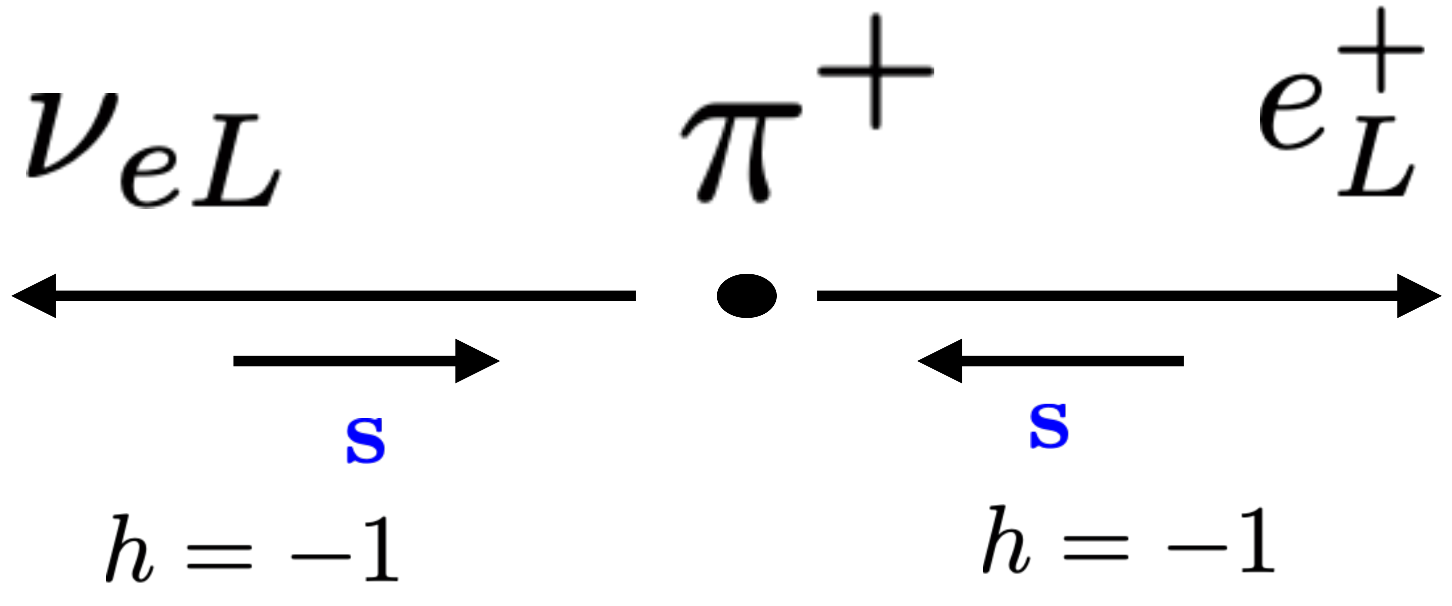


by angular momentum conservation

$$\mathcal{A}(\pi^+ \rightarrow \nu_{eL} + e^+_L) \propto m_e$$

Helicity and Chirality

Some Consequences for pion decay



by angular momentum conservation

$$\mathcal{A}(\pi^+ \to \nu_{eL} + e^+_L) \propto m_e$$

helicity suppressed

$$R_\pi \equiv \frac{\Gamma(\pi^+ \to \nu_{eL} + e^+_L)}{\Gamma(\pi^+ \to \nu_{\mu L} + \mu^+_L)} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \sim 10^{-4}$$

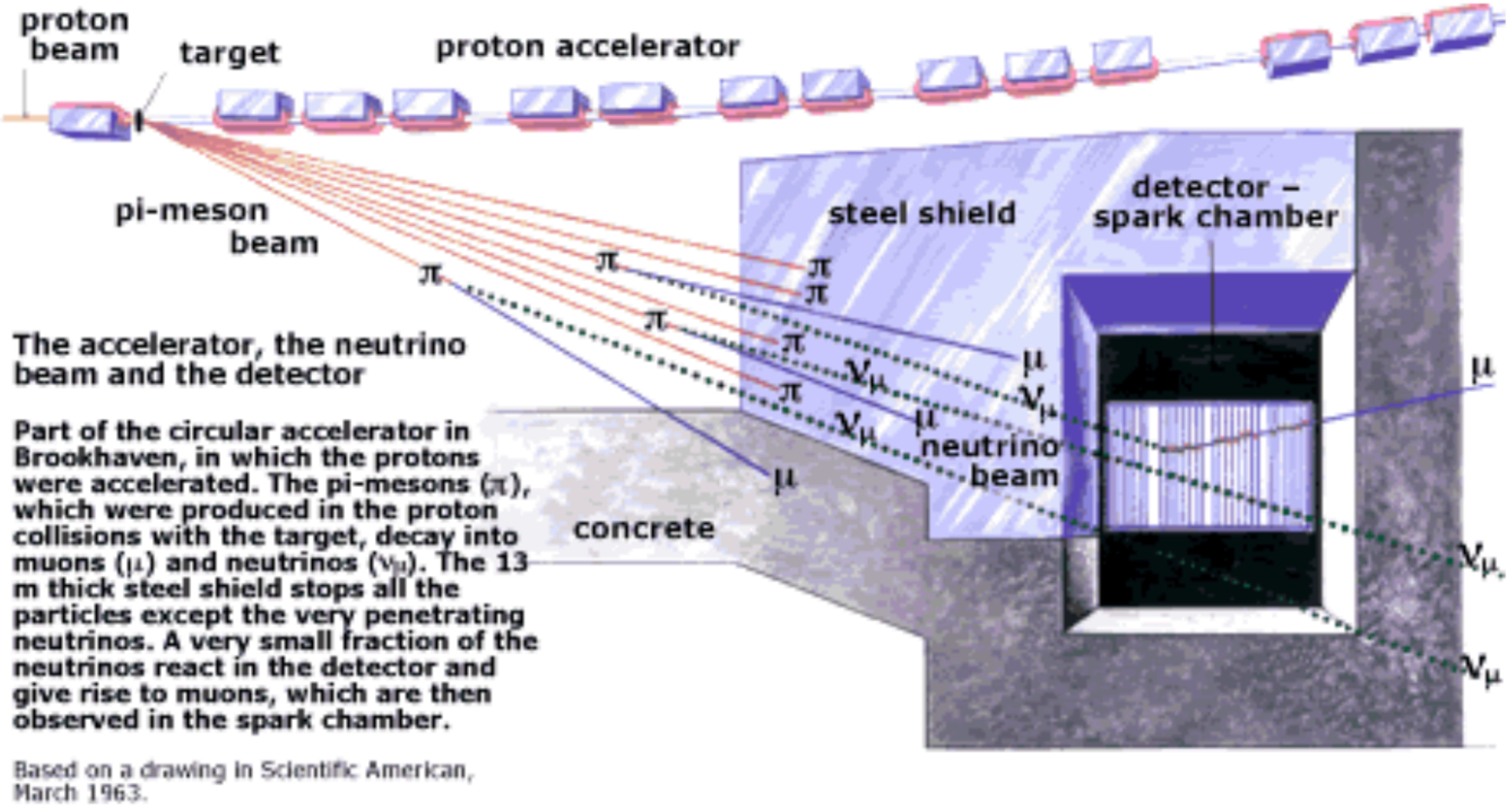
phase space factor

There is a Second Flavor

The muon neutrino

1962 : J. Steinberger, L. Lederman & M. Schwartz

$$p + p \to \pi + X \qquad \pi \to \mu + \nu_\mu$$



neutrinos produced together with a muon give rise to muons not electrons

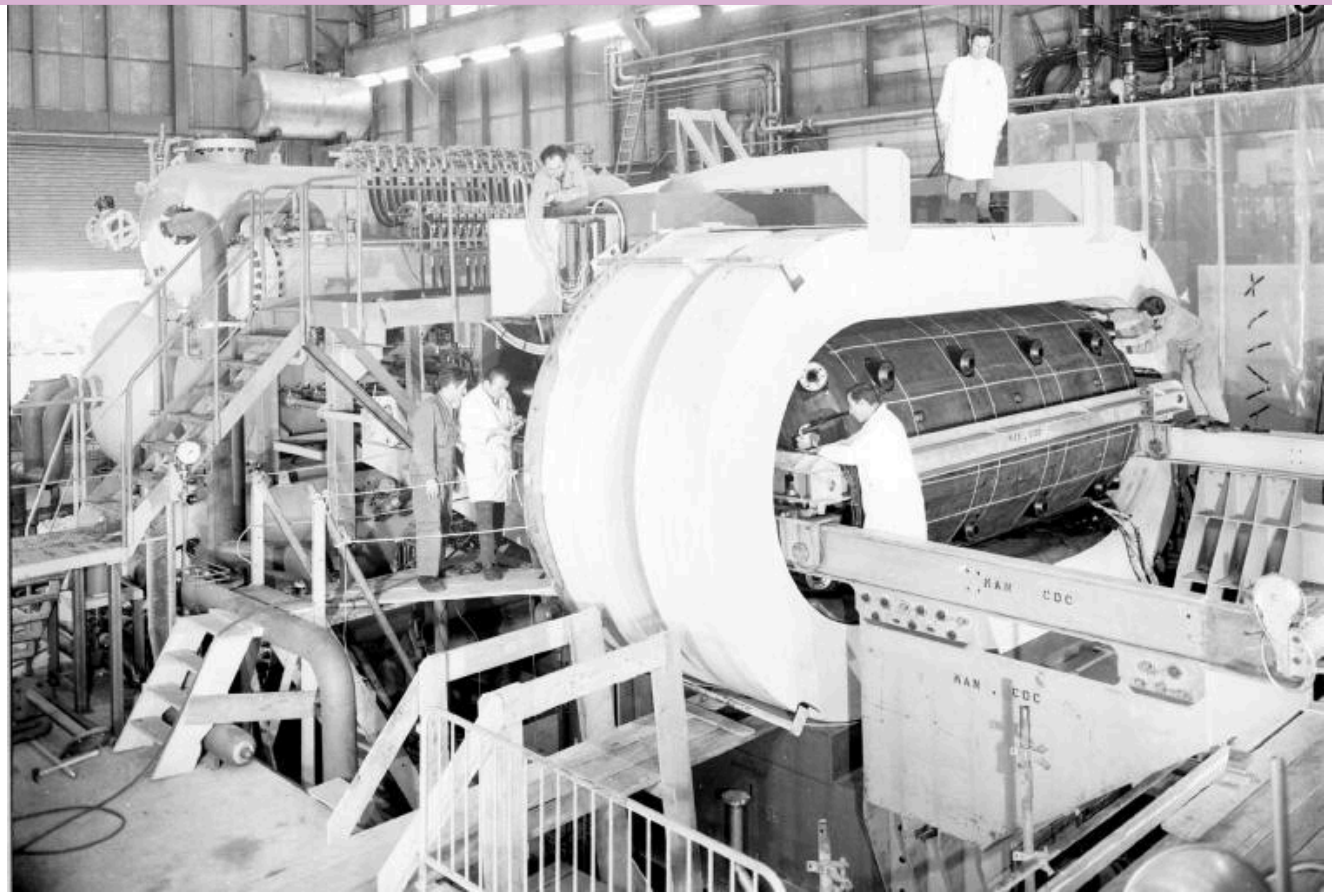
$$\nu_\mu + N \to \mu + Y$$

51 neutrino interactions were registered with a muon observed in the spark chamber

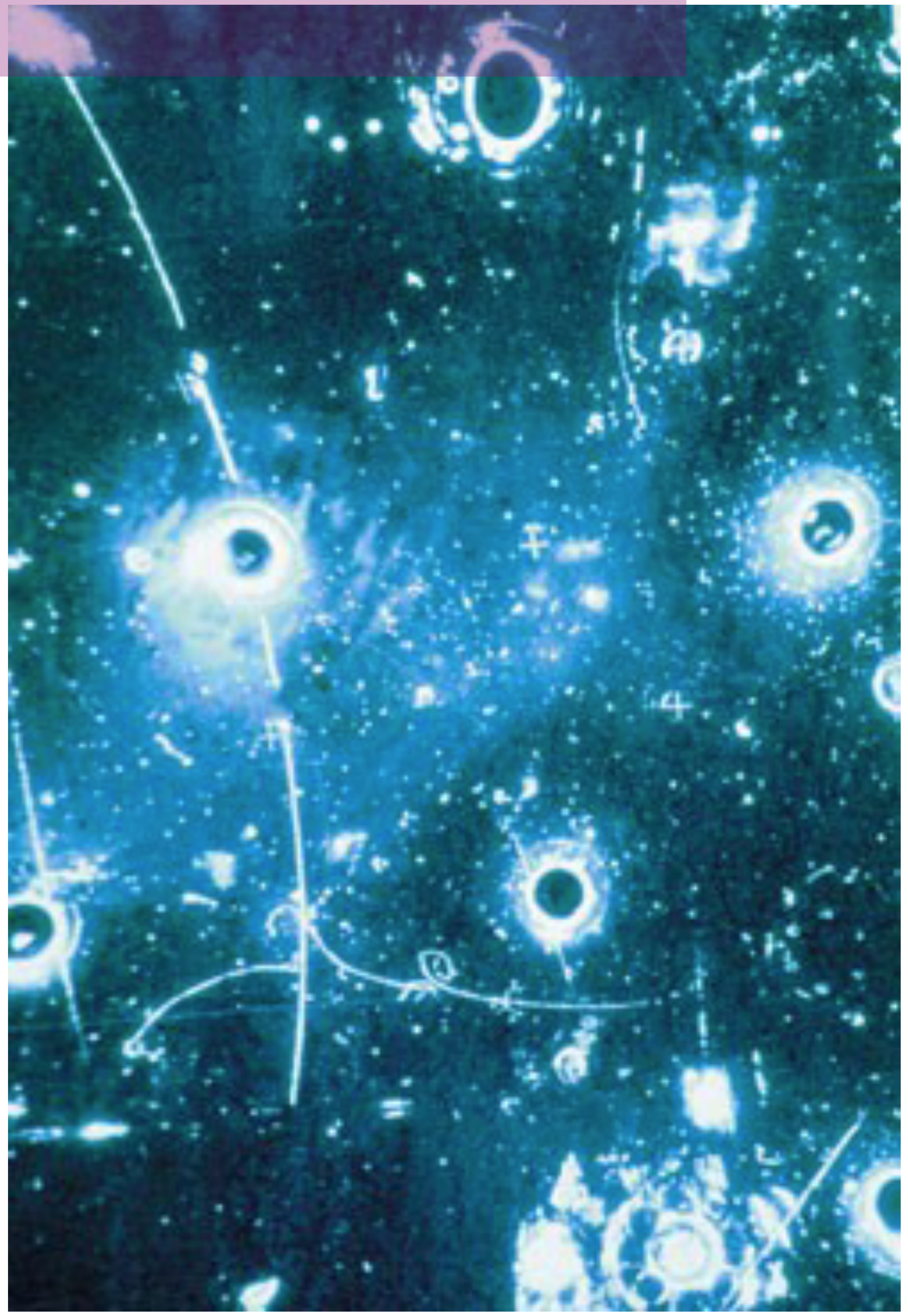
$$\nu_\mu \neq \nu_e$$

The Discovery of Neutral Currents

Neutrinos as probes



1973 : Gargamelle Bubble Chamber (CERN)



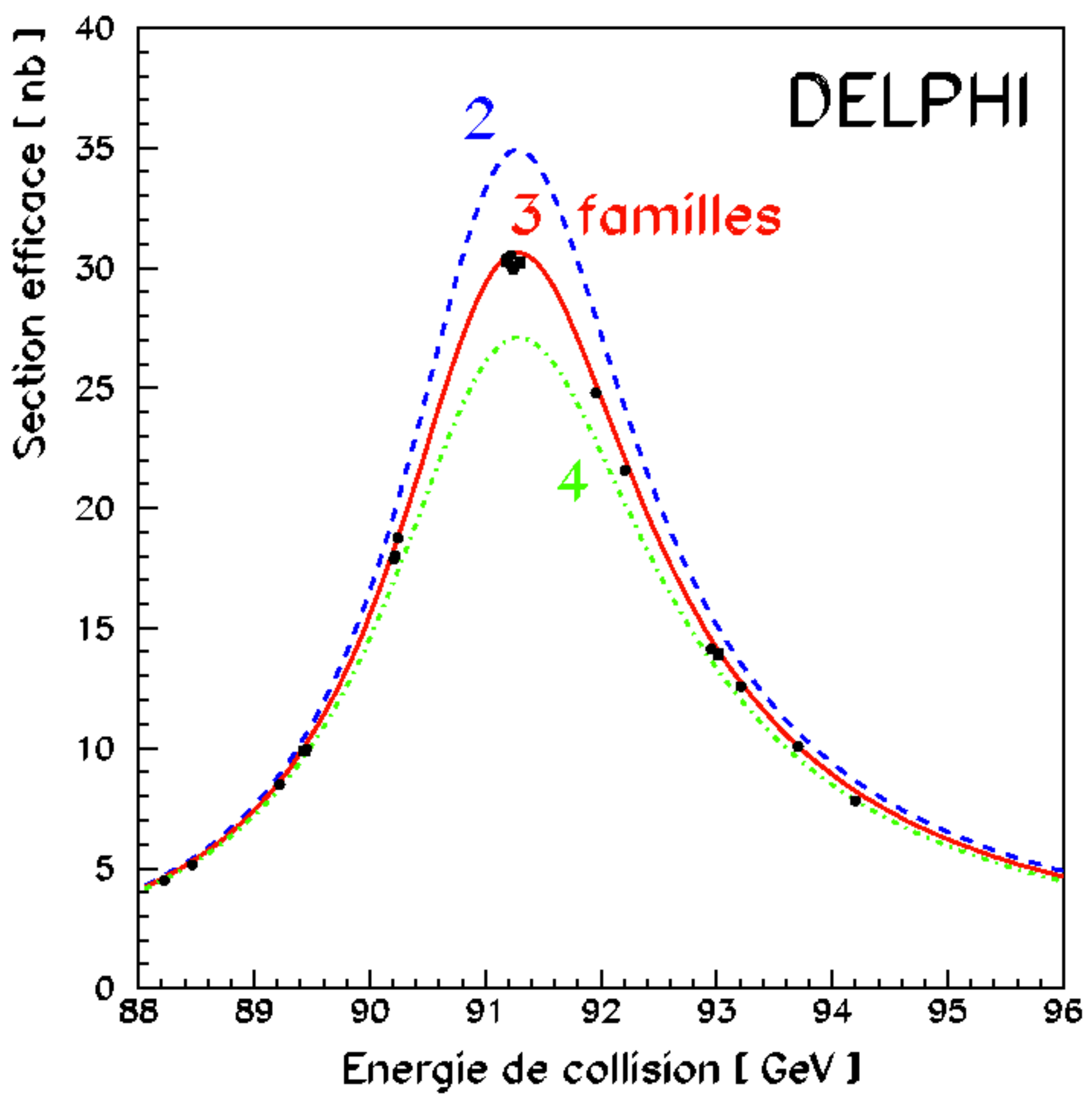
$$\nu_\mu + N \rightarrow \nu_\mu + \text{hadrons}$$

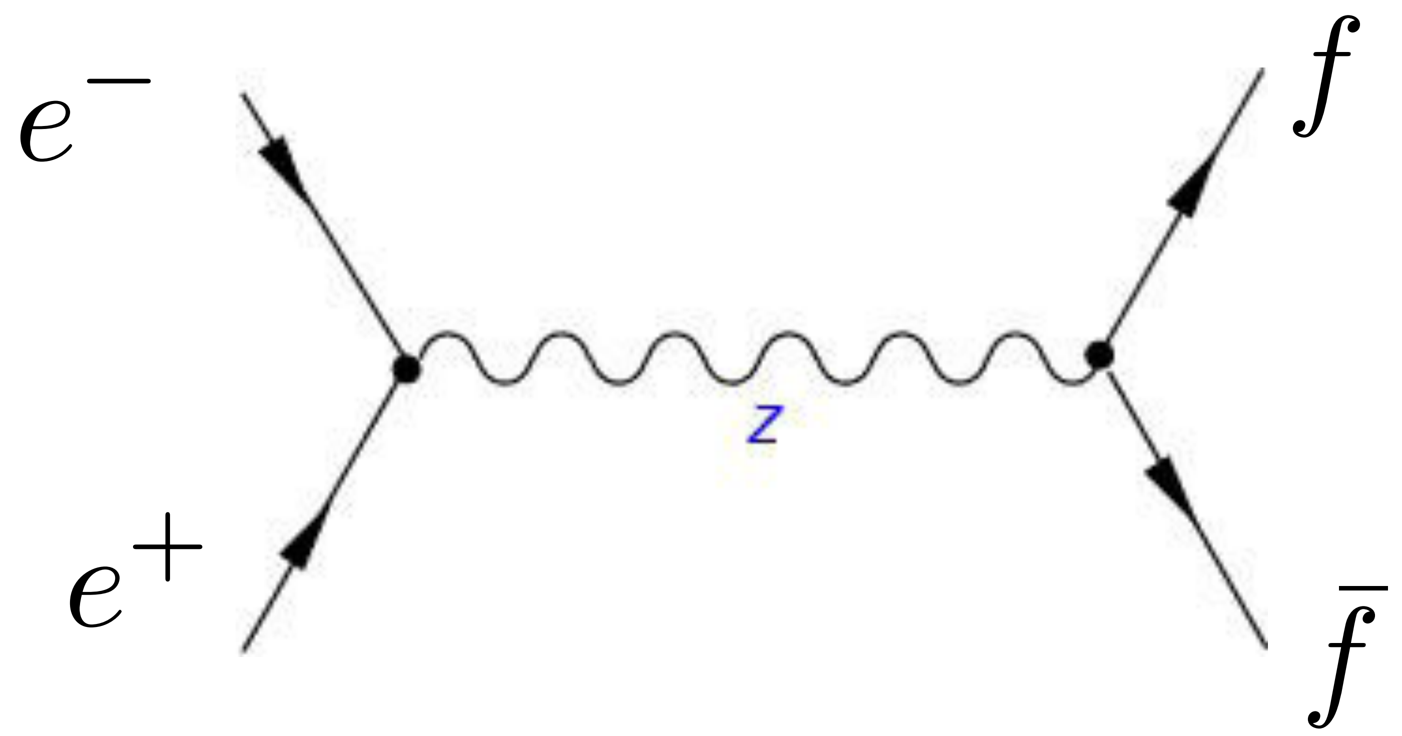
$$\bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu + \text{hadrons}$$

There is a Third Flavor

The tau neutrino

1989: LEP I experiments @ CERN determined the number of light neutrino species





$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_Z} = 3.10 \pm 0.10$$

Today $N_\nu = 2.9963 \pm 0.0074$

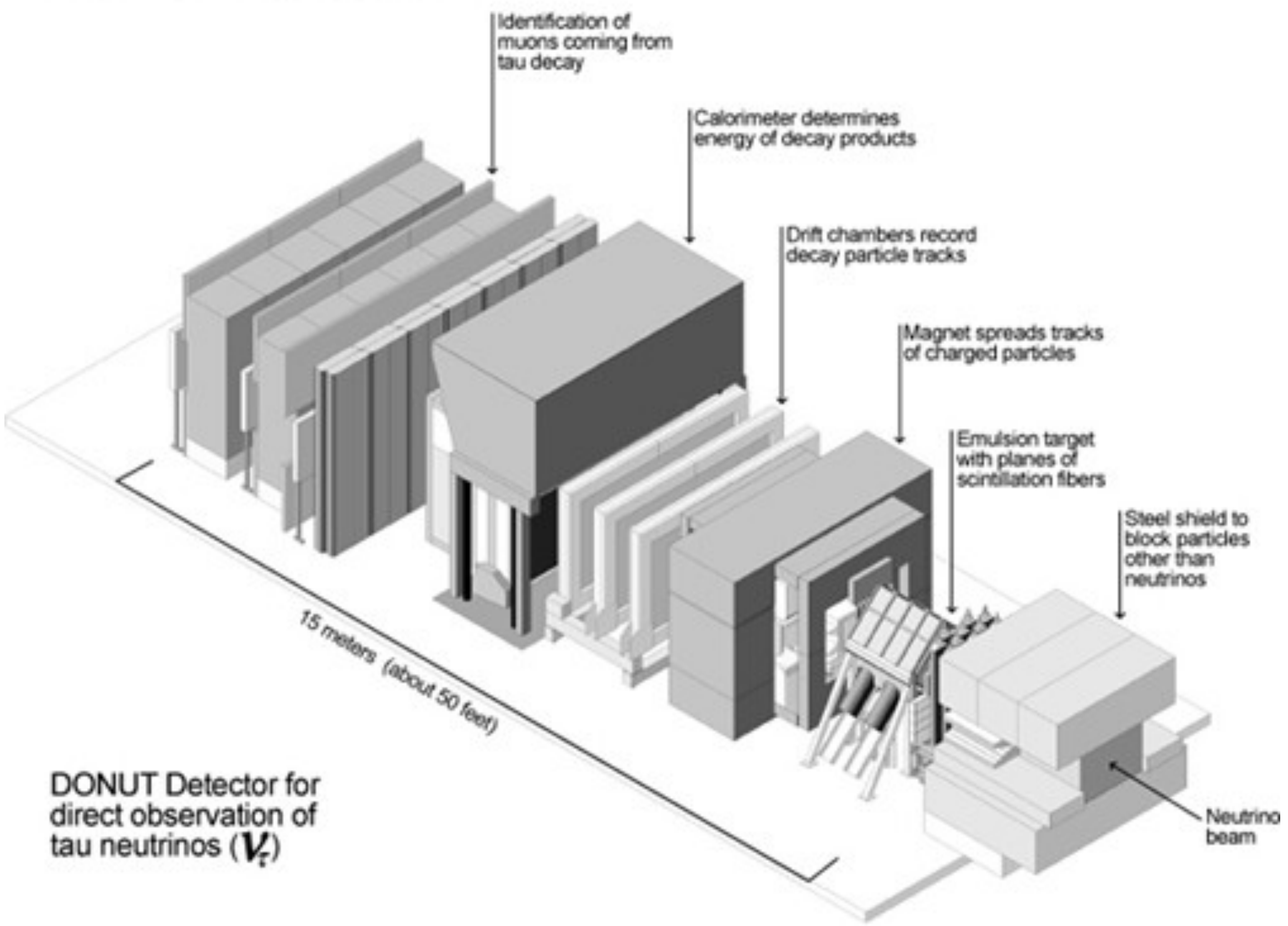
Z^0 invisible decay width

There is a Third Flavor

The tau neutrino

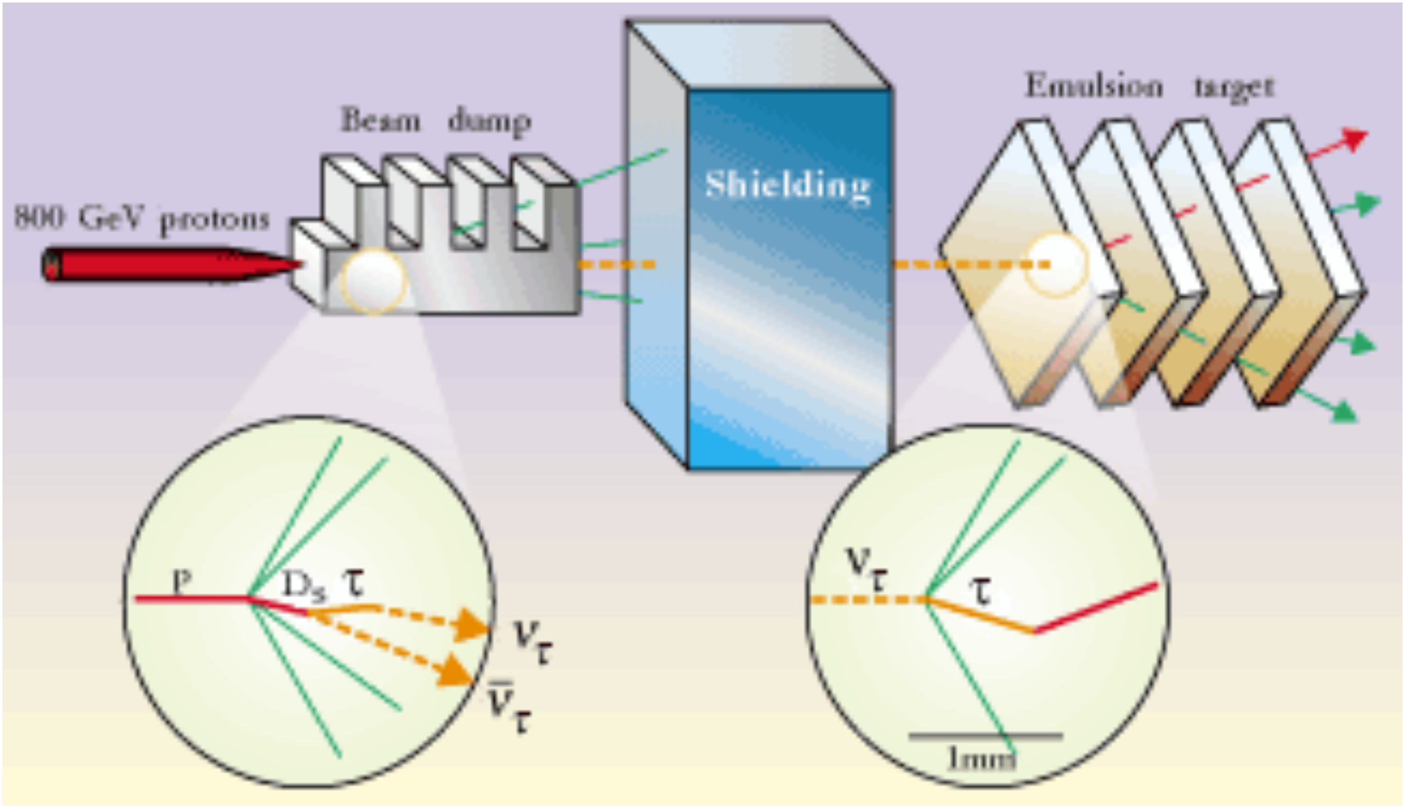
2000 : DONUT Collaboration @ Fermilab

DONUT Detector

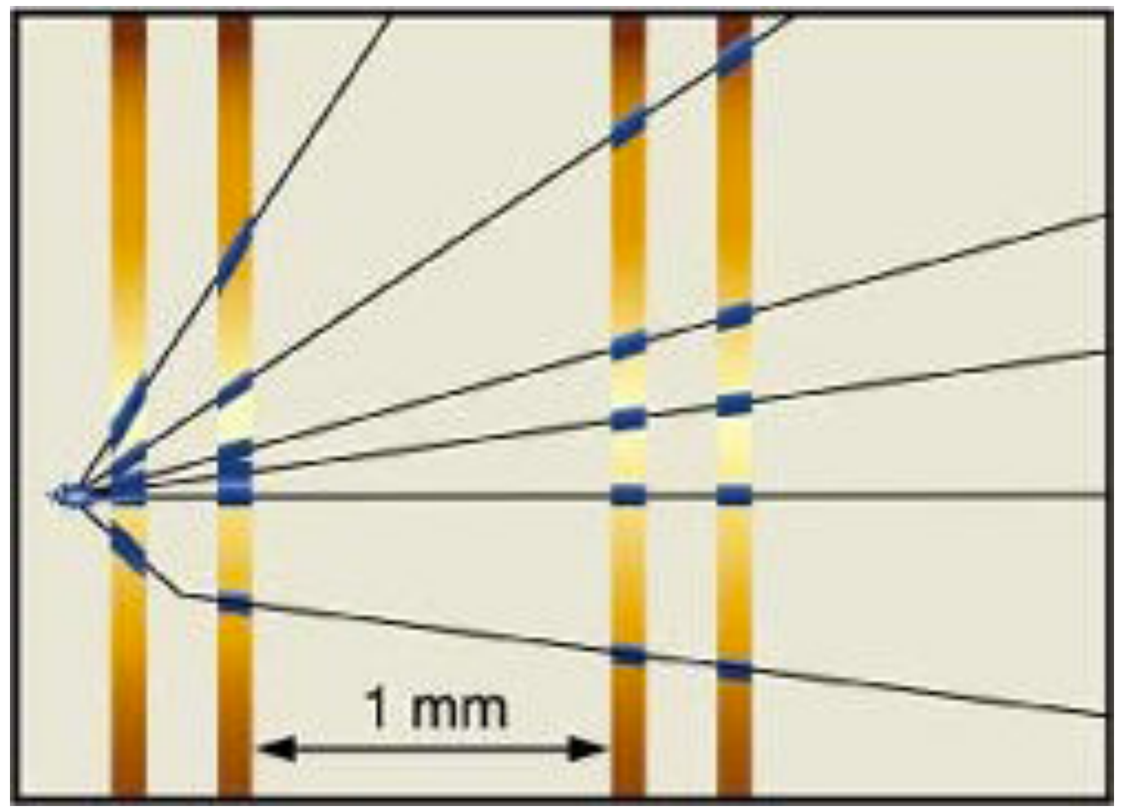


DONUT Detector for direct observation of tau neutrinos (ν_τ)

$$D_s \to \tau + \nu_\tau$$



$$\tau \to \nu_\tau + \pi$$



$$\nu_e \neq \nu_\mu \neq \nu_\tau$$

$$\nu_\tau + N \to \tau + X$$

neutrinos produced together with a tau give rise to taus

Neutrinos in the Standard Model

Symmetry Transformations

SM is based on the gauge symmetry group

$$\mathbf{SU(3)_c} \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y} \to \mathbf{SU(3)_c} \times \mathbf{U(1)_{em}}$$

I_{1L}, I_{2L}, I_{3L} $\quad [I_{iL}, I_{jL}] = i\epsilon_{ij}I_{kL}$ generators of $\mathrm{SU(2)_L}$ (weak isospin)

Y generator of $\mathrm{U(1)_Y}$ (hypercharge)

$$Q_{\mathrm{em}} = Y + I_{3L}$$

Left chiral fermion fields transform as weak isospin doublets

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$$

$\nu_{eL} \rightarrow Q_{\mathrm{em}}(\nu_e) = 0 \quad I_{3L} = 1/2$

$e_L \rightarrow Q_{\mathrm{em}}(e) = -1 \quad I_{3L} = -1/2$

$$(\mathbf{1}, \mathbf{2}, -\mathbf{1/2})$$

Neutrinos in the Standard Model

Symmetry Transformations

SM is based on the gauge symmetry group

$$\mathrm{SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3) \times U(1)_{em}}$$

I_{1L}, I_{2L}, I_{3L} $\quad [I_{iL}, I_{jL}] = i\epsilon_{ijk} I_{kL}$ generators of $\mathrm{SU(2)_L}$ (weak isospin)

Y generator of $\mathrm{U(1)_Y}$ (hypercharge)

$$Q_{\rm em} = Y + I_{3L}$$

Right chiral fermion fields transform as weak isospin singlets

$e_R \longrightarrow \quad Q_{\rm em}(e) = -1 \quad I_{3L} = 0 \qquad (\mathbf{1}, \mathbf{1}, -\mathbf{1})$

neutrino fields enter only in $SU(2)_L$ doublets $\quad \nu_{eR}$ ✗

Neutrinos in the Standard Model

3 generations of fermions

LEPTONS

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix} = L_\alpha \qquad (\mathbf{1}, \mathbf{2}, -\mathbf{1/2})$$

$$e_R \quad \mu_R \quad \tau_R = E_\alpha \qquad (\mathbf{1}, \mathbf{1}, -\mathbf{1})$$

Neutrinos in the Standard Model

3 generations of fermions

LEPTONS

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix} = L_\alpha \qquad (1, 2, -1/2)$$

$$e_R \quad \mu_R \quad \tau_R = E_\alpha \qquad (1, 1, -1)$$

QUARKS

$$\begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix} \quad \begin{pmatrix} c^i_L \\ s^i_L \end{pmatrix} \quad \begin{pmatrix} t^i_L \\ b^i_L \end{pmatrix} = Q^i_\alpha \qquad (3, 2, 1/6)$$

$$u^i_R \quad c^i_R \quad t^i_R = U^i_\alpha \qquad (3, 1, 2/3)$$

$$d^i_R \quad s^i_R \quad b^i_R = D^i_\alpha \qquad (3, 1, -1/3)$$

Neutrinos in the Standard Model

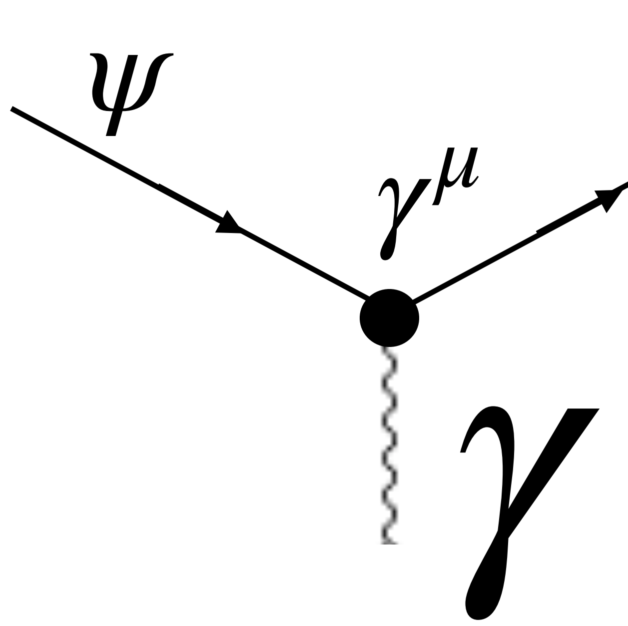
Gauge Interactions

In analogy to Quantum Electrodynamics (QED) - invariant under $\mathbf{U(1)}_{\text{em}}$ gauge symmetry

gauge field associated with $\mathbf{U(1)}_{\text{em}}$

$$\partial_\mu \rightarrow D_\mu = \partial_\mu - iqA_\mu$$

gauge coupling associated with $\mathbf{U(1)}_{\text{em}}$



Neutrinos in the Standard Model

Gauge Interactions

In analogy to Quantum Electrodynamics (QED) - invariant under $\mathrm{U(1)_{em}}$ gauge symmetry

gauge field associated with $\mathrm{U(1)_{em}}$

$$\partial_\mu \to D_\mu = \partial_\mu - iqA_\mu$$

gauge coupling associated with $\mathrm{U(1)_{em}}$

gauge fields associated with $\mathrm{SU(2)_L}$

$$D_\mu = \partial_\mu - ig\overrightarrow{I_L} \cdot \overrightarrow{W_\mu} - ig'\frac{Y}{2}B_\mu$$

gauge field associated with $\mathrm{U(1)_Y}$

gauge coupling associated with $\mathrm{U(1)_Y}$

gauge coupling associated with $\mathrm{SU(2)_L}$

Gauge Symmetry → Massless Fields

Neutrinos in the Standard Model

Higgs Mechanism

Introduce a $\mathrm{SU}(2)_L$ of complex scalar fields

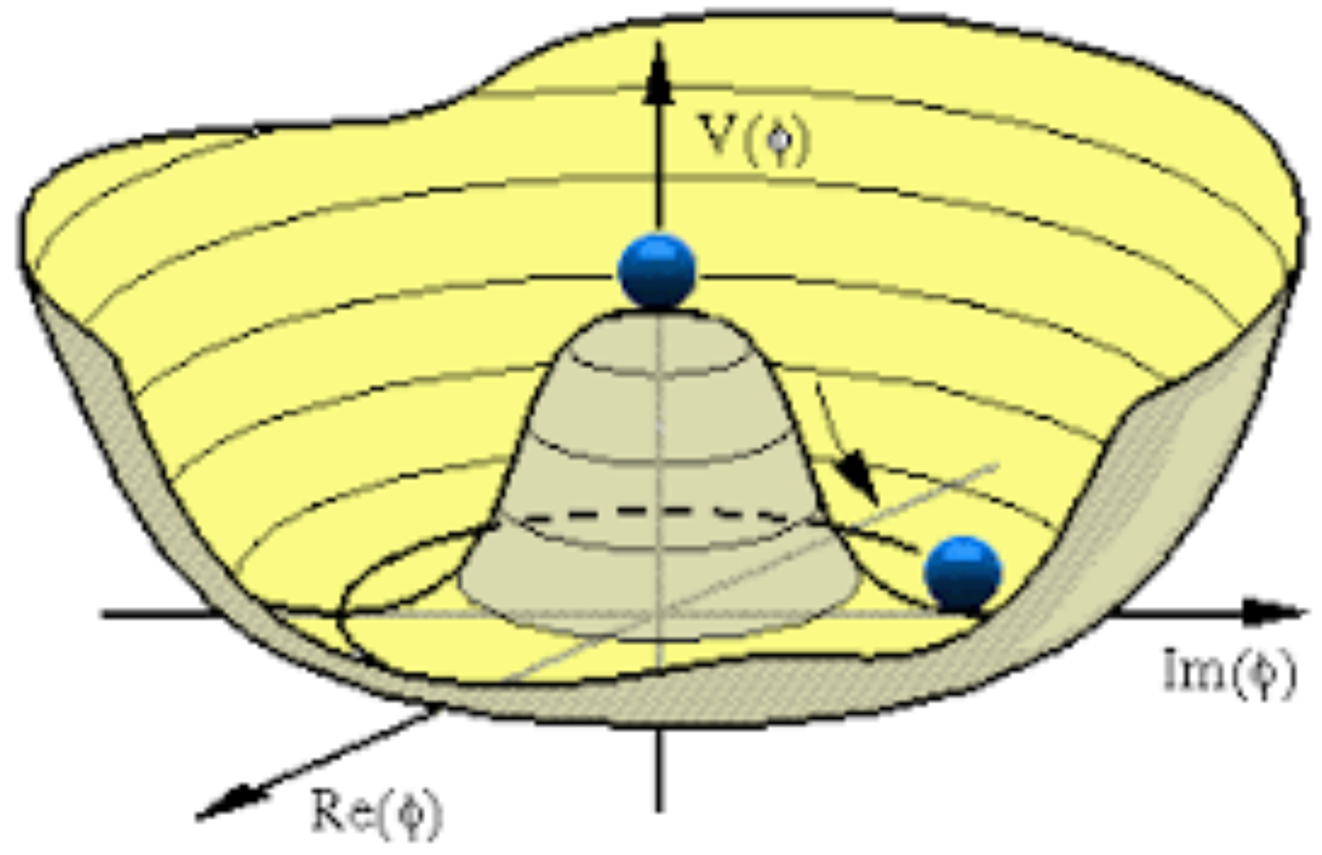
$$\phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} \xrightarrow{\text{EWSB}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

Higgs boson (H)

vacuum expectation value (vev) (v)

$$(\mathbf{1}, \mathbf{2}, \mathbf{1/2})$$

To give mass to gauge fields through spontaneous electroweak symmetry breaking (EWSB) — Higgs mechanism



Neutrinos in the Standard Model

Electroweak Gauge Bosons

Introduce a $\mathrm{SU(2)_L}$ of complex scalar fields

EWSB

$$\phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

Higgs boson

vacuum expectation value (vev)

To give mass to gauge fields through spontaneous electroweak symmetry breaking (EWSB) — Higgs mechanism

The gauge bosons become linear combinations of the gauge fields

- charged $W^{\pm}$ (CC, i.e. charged current interactions) $m_W = \frac{v}{2} g$
- neutral Z (NC, i.e. neutral current interactions) $m_Z = \frac{v}{2}\sqrt{g^2 + g'^2}$
- photon (EM, i.e. electromagnetic interactions) remain massless

Neutrinos in the Standard Model

Fermion Masses

$$m\bar{\psi}\psi = m\bar{\psi}(P_L + P_R)\psi = m\bar{\psi}_R\psi_L + \mathrm{h.c.}$$

chirality flipping term (needs both L & R)

This is not gauge invariant!

Neutrinos in the Standard Model

Fermion Masses

$$m\,\overline{\psi}\psi = m\,\overline{\psi}(P_L + P_R)\psi = m\,\overline{\psi}_R\psi_L + \mathrm{h.c.}$$

chirality flipping term (needs both L & R)

This is not gauge invariant!

Fortunately the ϕ can also fix this via Yukawa couplings to fermions

$$-\mathscr{L}_Y = Y^{\ell}_{\alpha\beta}\,\overline{L}_\alpha E_\beta\,\phi + Y^{d}_{\alpha\beta}\,\overline{Q}_\alpha D_\beta\,\phi + Y^{u}_{\alpha\beta}\,\overline{Q}_\alpha U_\beta\,\tilde{\phi} + \mathrm{h.c.}$$

This is gauge invariant !

Masses & Mixing in the SM

Biunitary Transformation

down quarks | Yukawa Matrix (complex) | down quarks

$$\overline{\begin{pmatrix}\circ & \circ & \circ\end{pmatrix}_L}\, V_L^{d\dagger} \;\; V_L^{d} \begin{pmatrix}\circ & \circ & \circ \\ \circ & \circ & \circ \\ \circ & \circ & \circ\end{pmatrix} V_R^{d\dagger} \;\; V_R^{d} \begin{pmatrix}\circ \\ \circ \\ \circ\end{pmatrix}_R$$

rotated

L fields

diagonal mass matrix

rotated

R fields

and similar to up quarks

Neutrinos in the Standard Model

Fermion Masses

$$m\,\overline{\psi}\psi = m\,\overline{\psi}(P_L + P_R)\psi = m\,\overline{\psi}_R\psi_L + \mathrm{h.c.}$$

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This is gauge invariant !

$$\tilde{\phi} = i\sigma_2\phi^*$$

$$\phi = \begin{pmatrix}\phi^+\\ \phi_0\end{pmatrix} \xrightarrow{\text{EWSB}} \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+H\end{pmatrix}$$

$$m_u\,\overline{u}_L u_R + m_d\,\overline{d}_L d_R + m_c\,\overline{c}_L c_R + \ldots + h.c.$$

$$m_{U\alpha} = \frac{v}{\sqrt{2}}y^U_{\alpha\alpha} \quad m_{D_\alpha} = \frac{v}{\sqrt{2}}y^D_{\alpha\alpha}$$

after diagonalization of $Y^{u,d}$

QUARK MASSES

$$V_{CKM} = V_L^{u\dagger}V_L^d$$

will impact CC interactions

Neutrinos in the Standard Model

Fermion Masses

$$m\,\overline{\psi}\psi = m\,\overline{\psi}(P_L + P_R)\psi = m\,\overline{\psi}_R\psi_L + \mathrm{h.c.}$$

chirality flipping term (needs both L & R)

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$$-\mathscr{L}_Y = Y^{\ell}_{\alpha\beta}\,\overline{L}_\alpha E_\beta\,\phi + Y^{d}_{\alpha\beta}\,\overline{Q}_\alpha D_\beta\,\phi + Y^{u}_{\alpha\beta}\,\overline{Q}_\alpha U_\beta\,\tilde{\phi} + \mathrm{h.c.}$$

$$\tilde{\phi} = i\sigma_2\phi^*$$

$$\phi = \begin{pmatrix}\phi^+\\ \phi_0\end{pmatrix} \xrightarrow{\text{EWSB}} \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+H\end{pmatrix}$$

$$m_e\,\overline{e}_L e_R + m_\mu\,\overline{\mu}_L\mu_R + m_\tau\,\overline{\tau}_L\tau_R + h.c.$$

$$m_\alpha = \frac{v}{\sqrt{2}}y^{\ell}_{\alpha\alpha}$$

after diagonalization of Y^{ℓ}

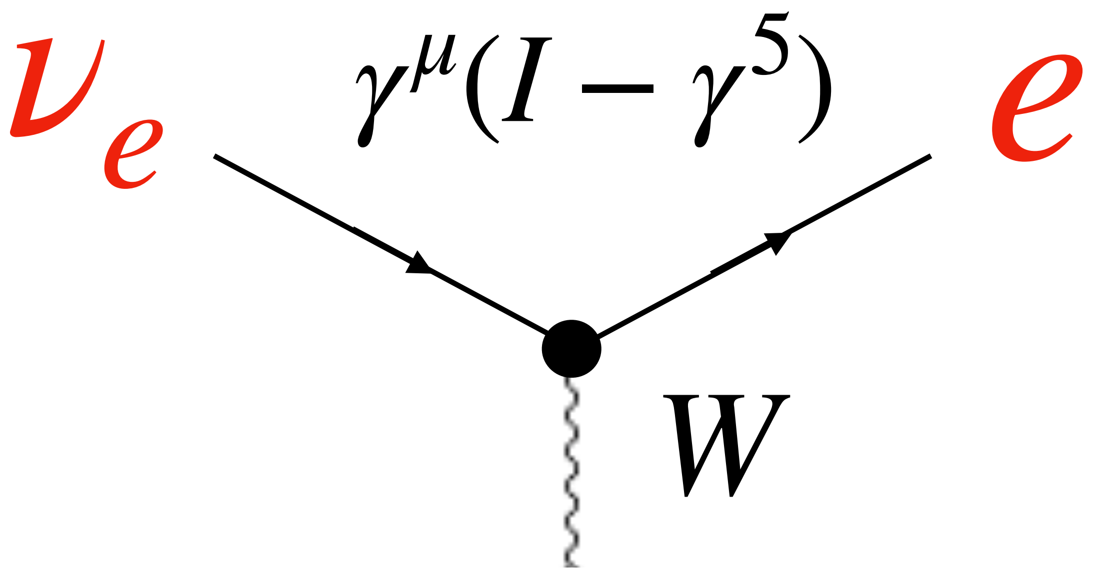
CHARGED LEPTON MASSES

Neutrinos do not have mass (no R component)

Neutrinos in the Standard Model

Neutrino Interactions with Gauge Bosons

Charged Current Interaction (CC)

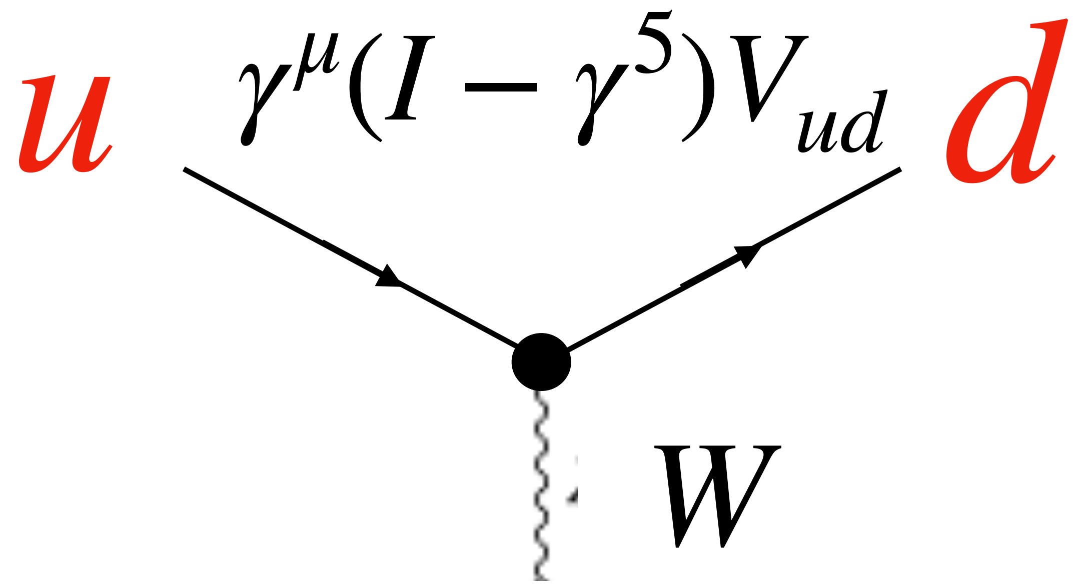


Flips up $\longleftrightarrow$ down components of the L doublets

No mixing (massless neutrinos!)

mass basis = interaction basis

This will change with mass!



Flips up $\longleftrightarrow$ down components of the L doublets

Via CKM mixing matrix

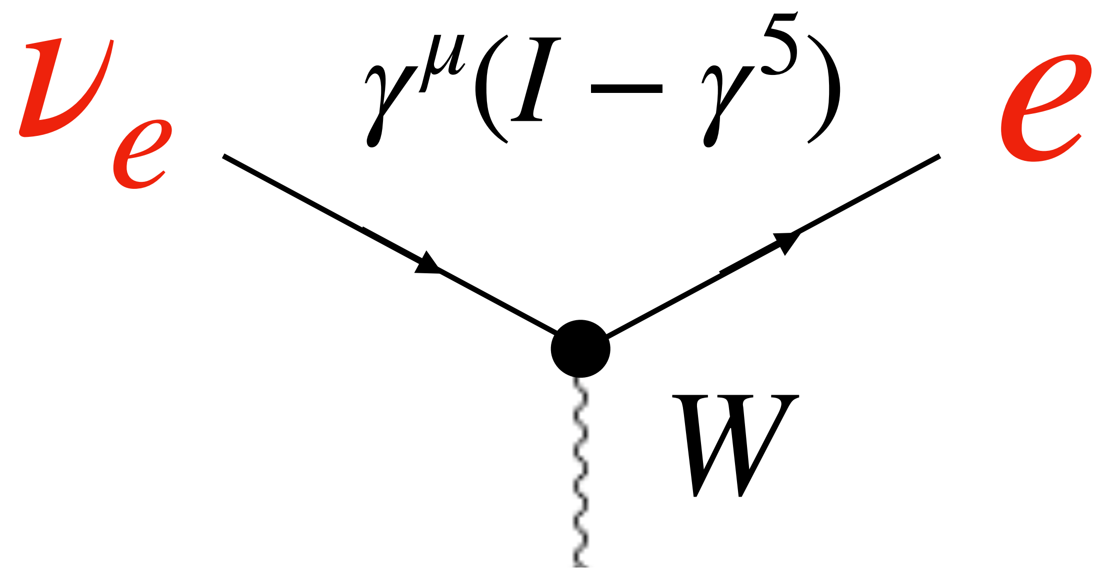
in the mass basis

mass basis $\neq$ interaction basis

Neutrinos in the Standard Model

Neutrino Interactions with Gauge Bosons

Charged Current Interaction (CC)



Flavor diagonal in the

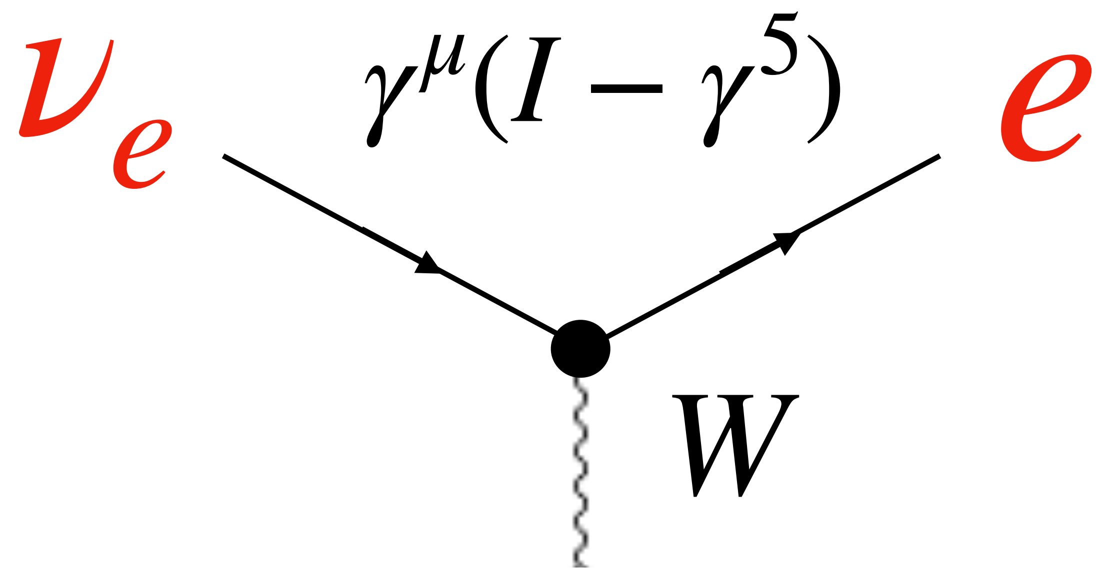
interaction basis

allows the concept of neutrino flavor = flavor of the charged lepton connected to the same CC vertex

Neutrinos in the Standard Model

Neutrino Interactions with Gauge Bosons

Charged Current Interaction (CC)



Flavor diagonal in the interaction basis

$$L_\alpha \to e^{i\theta_\alpha} L_\alpha \qquad E_\alpha \to e^{i\theta_\alpha} E_\alpha$$

3 accidental global $U(1)_{L\alpha}$ symmetries of the SM

particles (antiparticles)	L_e	L_μ	L_τ
$e^-, \nu_e \ (e^+, \bar{\nu}_e)$	-1 (+1)	0	0
$\mu^-, \nu_\mu \ (\mu^+, \bar{\nu}_\mu)$	0	-1 (+1)	0
$\tau^-, \nu_\tau \ (\tau^+, \bar{\nu}_\tau)$	0	0	-1 (+1)

$$L \equiv L_e + L_\mu + L_\tau$$

Total Lepton Number

define neutrino (antineutrino) according to the convention above (conserve Family Lepton Number)

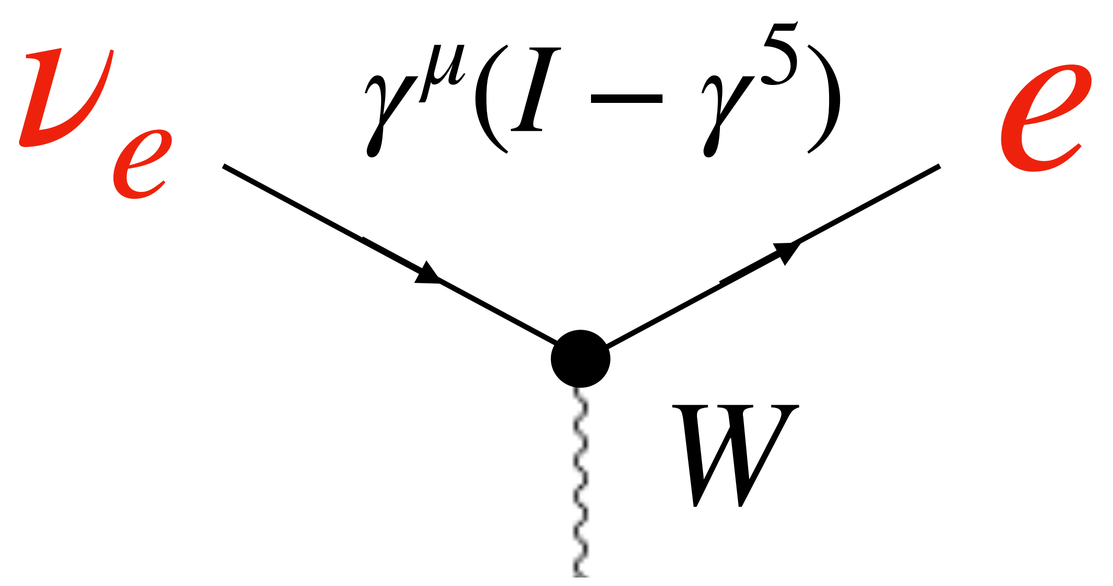
Neutrinos in the Standard Model

Neutrino Interactions with Gauge Bosons

$$L_\alpha \to e^{i\theta_\alpha} L_\alpha \qquad E_\alpha \to e^{i\theta_\alpha} E_\alpha$$

3 accidental global $U(1)_{L\alpha}$ symmetries of the SM

Charged Current Interaction (CC)



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$\mu^-, \nu_\mu \ (\mu^+, \bar{\nu}_\mu)$	0	-1 (+1)	0
$\tau^-, \nu_\tau \ (\tau^+, \bar{\nu}_\tau)$	0	0	-1 (+1)

Flavor diagonal in the interaction basis

$$L \equiv L_e + L_\mu + L_\tau$$

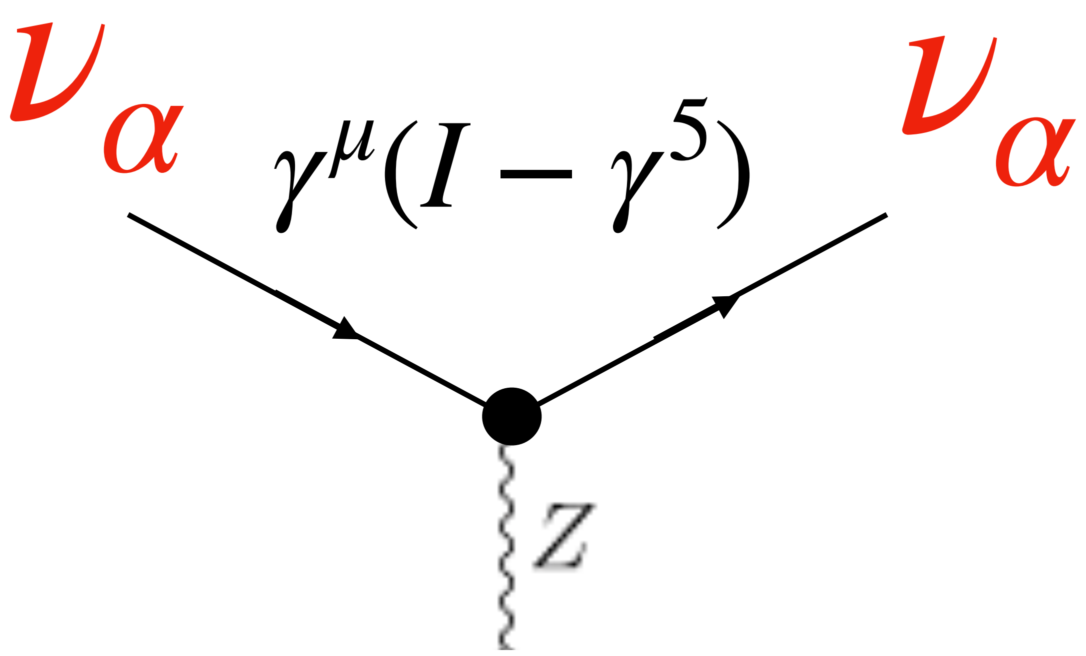
Total Lepton Number

These accidental symmetries prevents neutrinos from acquiring mass via loop corrections …

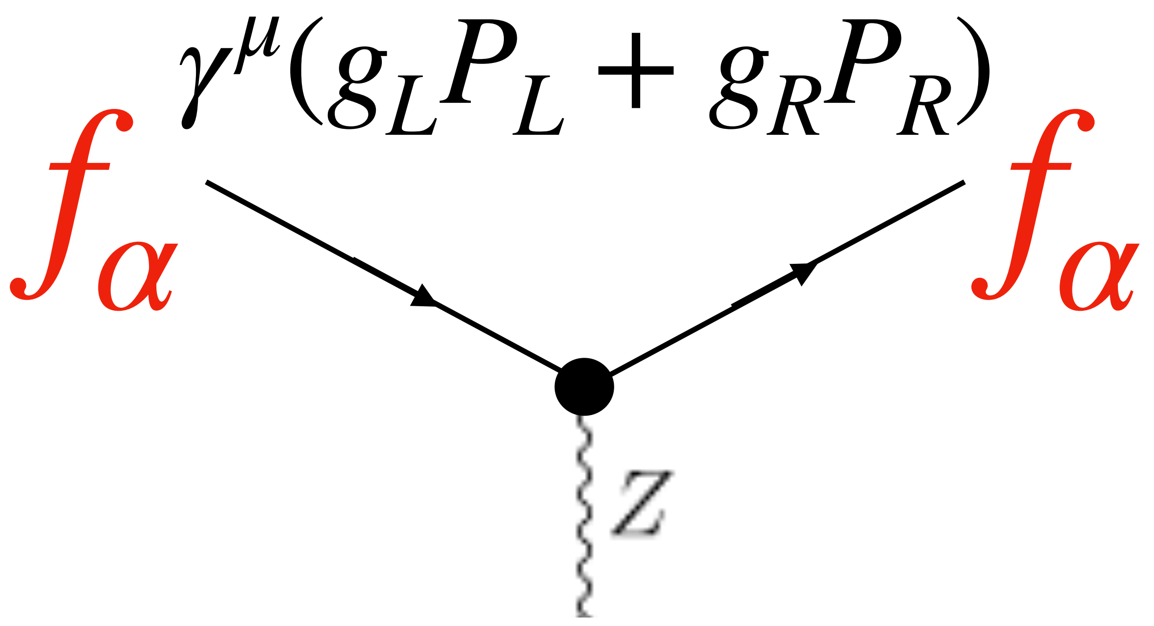
Neutrinos in the Standard Model

Neutrino Interactions with Gauge Bosons

Neutral Current (NC)



Couples only to L component



$$g_L = I_{3L} - Q\sin^2\theta_W$$
$$g_R = -\,Q\sin^2\theta_W$$

Couples only to both L & R components

No flavor changing neutral currents

only neutrinos/antineutrinos of left chirality participate of CC or NC interactions
This will not change with mass!