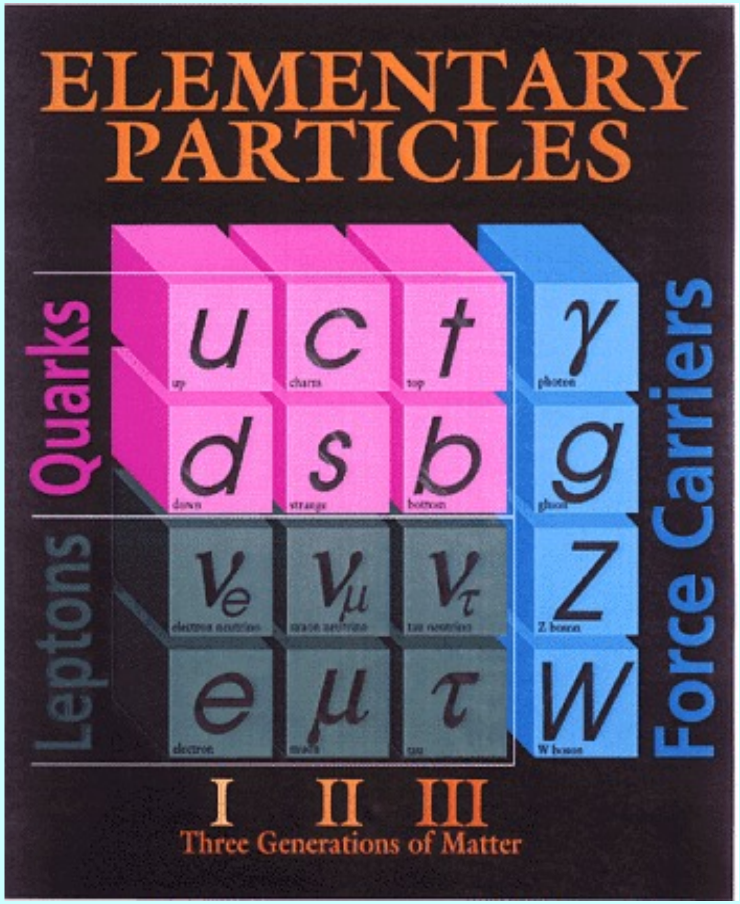
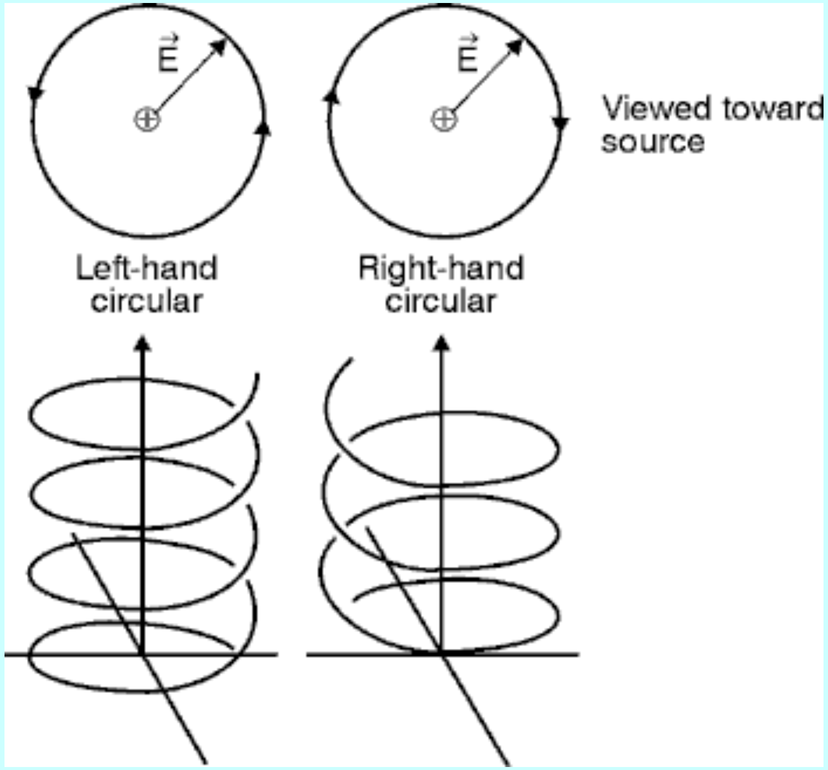
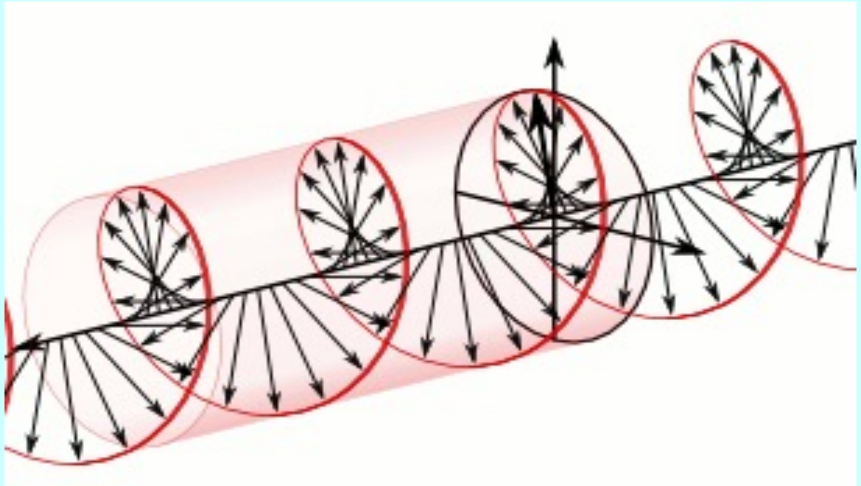


Now we have a good understanding of gauge bosons including their masses.

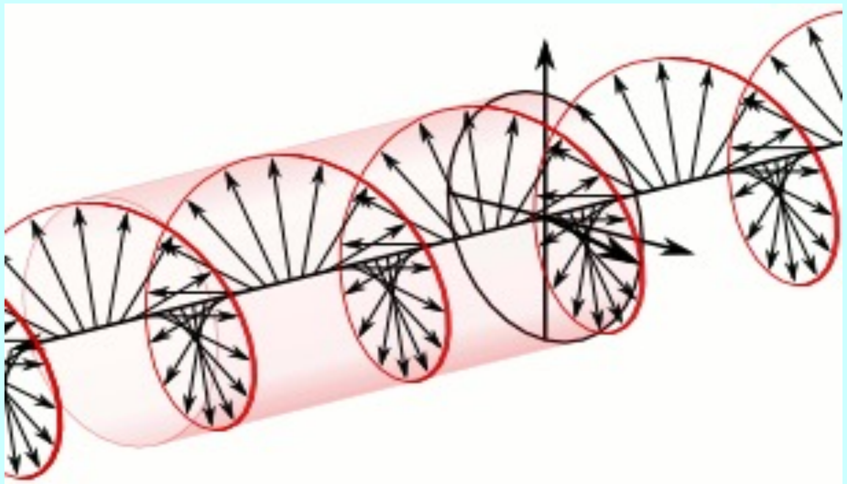
But fermions are still massless. That is actually pretty good. Why?

Circular Polarized Light





右手旋 Right-Handed

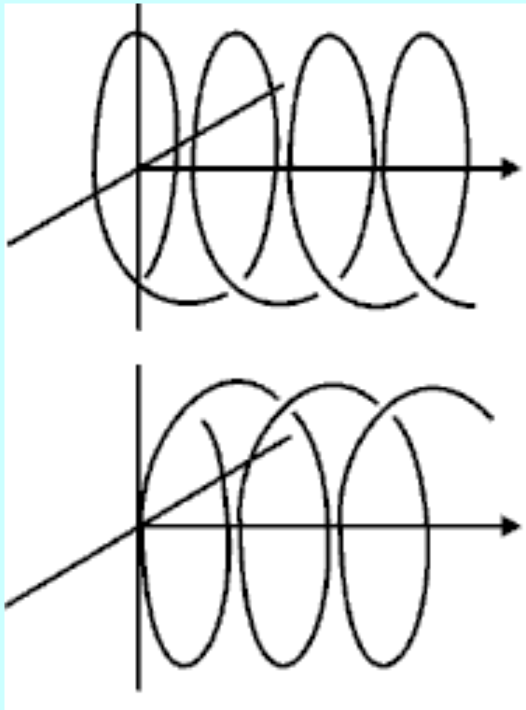


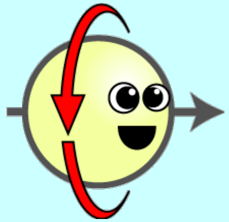
左手旋 Left-Handed

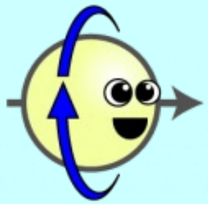
關鍵是場的旋轉軸與場傳播方向的關係。


PHOTON
γ
His eyes red from traveling so fast, the PHOTON is a quanta of visible light, a wave/particle that communicates the electromagnetic force, traveling at the speed of light (duh). With a mass and electric charge of zero, it also carries microwaves, radio waves and x-rays.
Acrylic felt with poly fill for minimum mass.
$10.49
LIGHT
HEAVY
The PARTICLE ZOO


ELECTRON
e−
The ELECTRON is a fundamental subatomic particle carrying a negative charge. Its mass is 1/1000 that of the smallest atom. It participates in electromagnetic interactions, and is typically found orbiting the nucleus of an atom.
Acrylic felt with poly fill for minimum mass.
$10.49
LIGHT
HEAVY
The PARTICLE ZOO

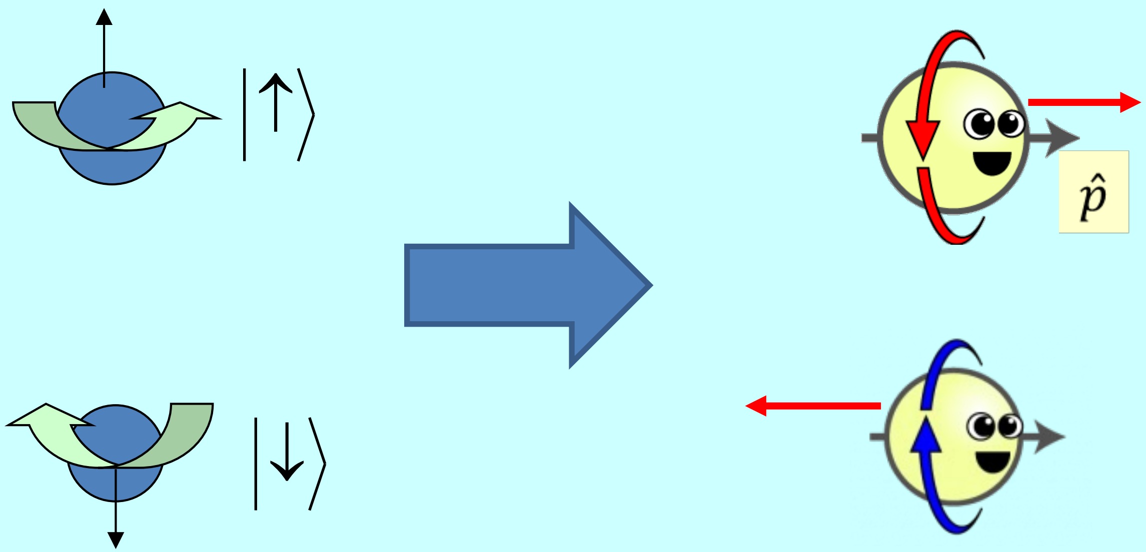






傳播中的電子也有自旋

Spin states　　　　Helicity螺旋性 States



自旋角動量只能選一個方向，要求電子為其本徵態。

S_z自旋向上及自旋向下的兩個態通常是在電子靜止時使用比較方便

當電子以動量$\vec{p}$運動，比較方便是取動量方向的自旋$\vec{S}\cdot\hat{p}$來選電子的自旋態

$\vec{S}\cdot\hat{p}=\frac{1}{2}$的電子態稱為右手旋 right-handed，

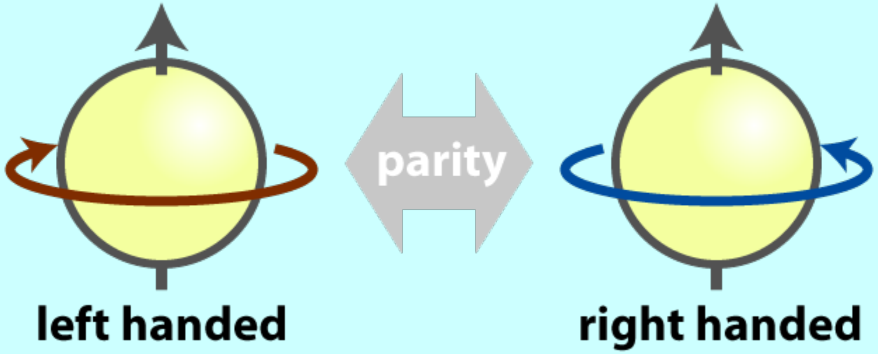
$$\vec{S}\cdot\hat{p}=\vec{S}\cdot\frac{\vec{p}}{p}$$

$\vec{S}\cdot\hat{p}=-\frac{1}{2}$的電子態稱為左手旋 left-handed

$\vec{S}\cdot\hat{p}$稱為螺旋度 Helicity。

在鏡射變換下左手旋與右手旋的態會互換。

$$\vec{S}\cdot\hat{p} = \vec{S}\cdot\frac{\vec{p}}{p}$$



In 1957 we found neutrino has only one helicity.

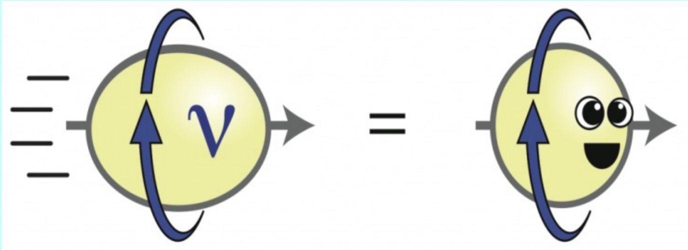
Helicity of Neutrinos*

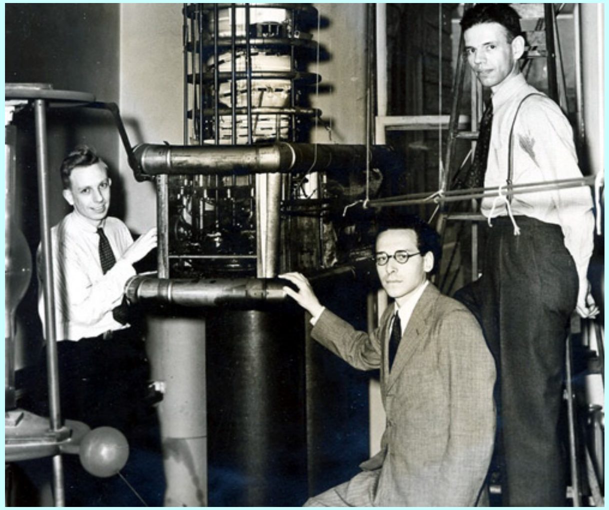
M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

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).

Our method may be illustrated by the following simple example: take a nucleus A (spin $I=0$) which decays by allowed orbital electron capture, to an excited state of a nucleus $B(I=1)$, from which a γ ray is emitted to the ground state of $B(I=0)$. The conditions necessary for resonant scattering are best fulfilled for those γ rays which are emitted opposite to the neutrino, which have an energy comparable to that of the neutrino, and which are emitted before the recoil energy is lost. Since the orbital electrons captured by a nucleus are almost entirely s electrons (K, L_I, $\cdots$ electrons of spin $S=\frac{1}{2}$), the substates of the daughter nucleus

A 1958 ex. by Goldhaber et al measured the helicity of neutrino!

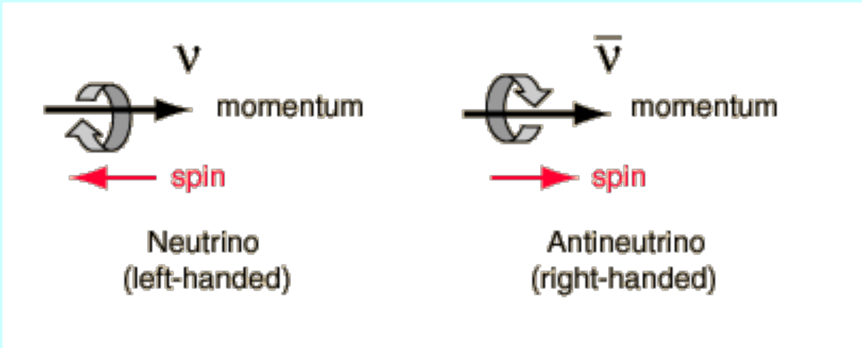




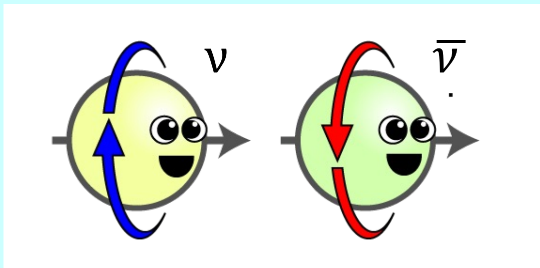
所有微中子都是左手旋！

沒有右手旋的微中子！

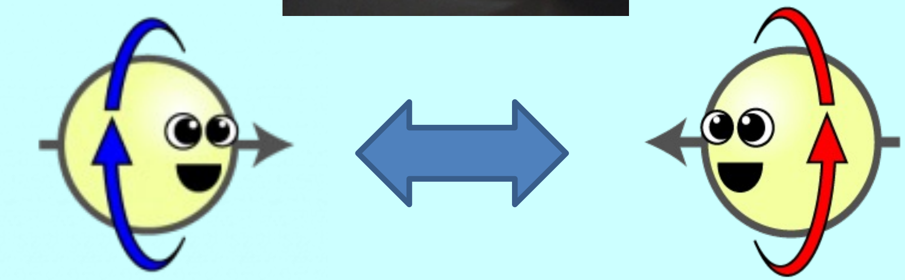
反微中子只有右手旋。



左旋微中子

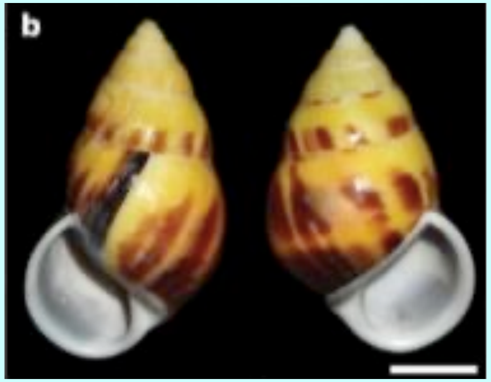


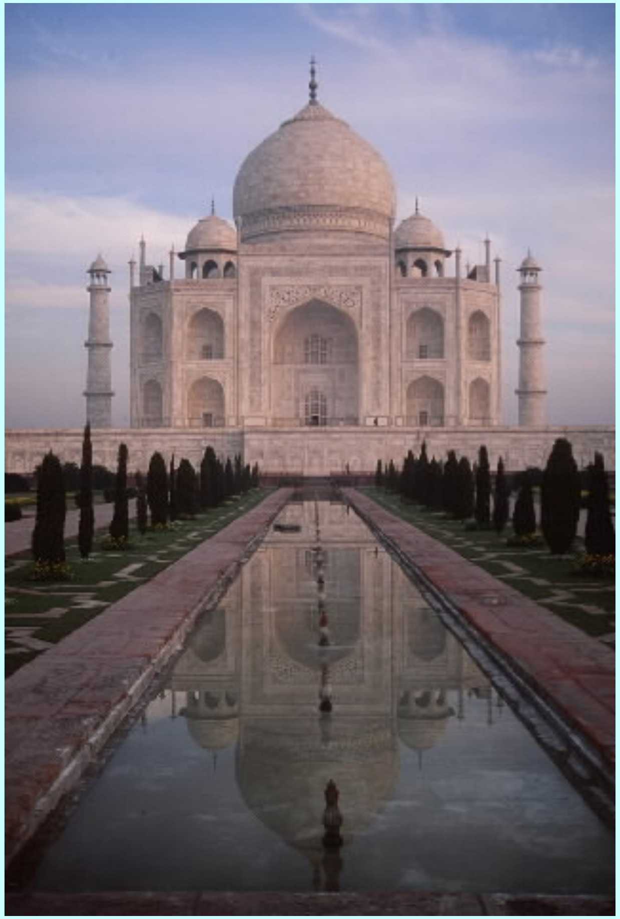
在鏡射變換下左右旋態會互換



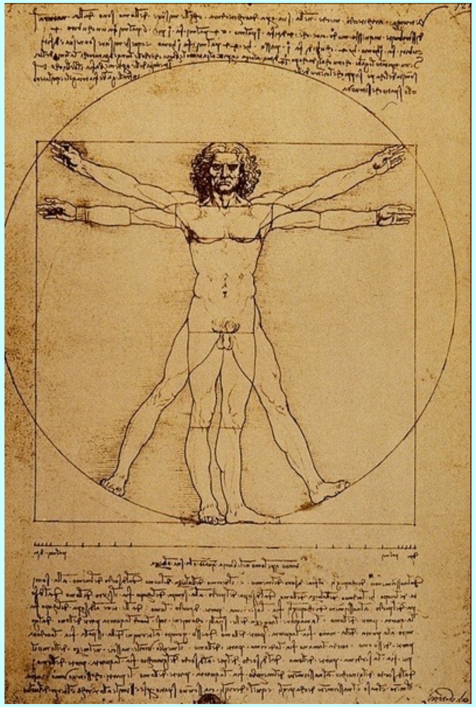
$$\vec{S}\cdot\hat{p} \rightarrow -\vec{S}\cdot\hat{p}$$

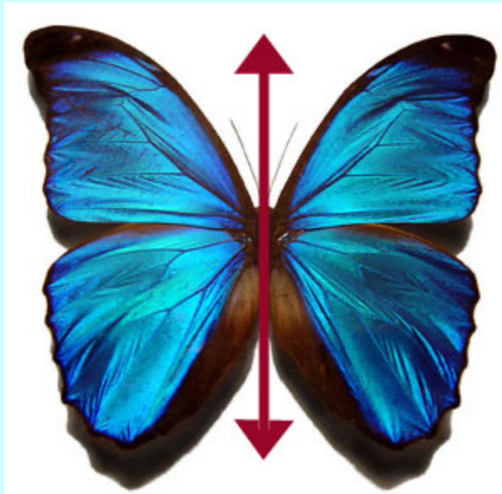
鏡射變換並不對稱。





Left and right coiling Euhadra snails





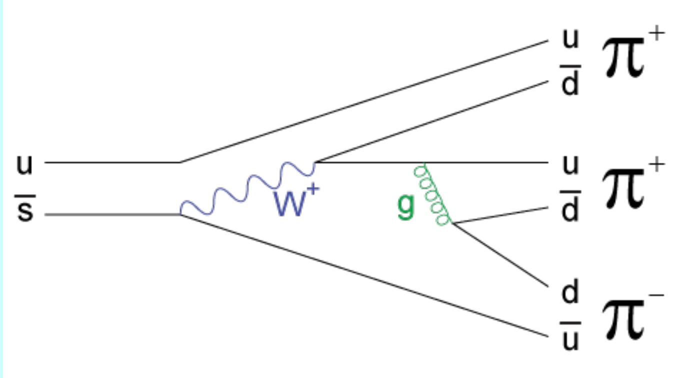
At the fundamental level, it is hard to believe God favor left over right or right or left.

I don’t believe that the Lord is a weak left-hander, and I am ready to bet a very large sum that the experiments will give symmetric results.

Pauli’s letter to Weisskopf 3 days before he was told the news

$\tau - \theta$ puzzle

$$\Theta^{+} \rightarrow \pi^{+} + \pi^{0}$$
$$\tau^{+} \rightarrow \pi^{+} + \pi^{-} + \pi^{+}$$



由衰變產物的共振曲線發現粒子。

τ and θ 具有幾乎一樣的質量與半衰期。

如此沒有個性的兩顆粒子！

But Theta decays into 2 pions.

Tau decays into 3 pions.

$$\Theta^{+} \rightarrow \pi^{+} + \pi^{0}$$
$$\tau^{+} \rightarrow \pi^{+} + \pi^{-} + \pi^{+}$$

所有基本粒子都有一個內在的Parity，即是$\hat{P}$ 的本徵值。

LIGHT UNFLAVORED MESONS
($S = C = B = 0$)

For $I = 1$ (π, b, ρ, a): $u\overline{d}$, $(u\overline{u} - d\overline{d})/\sqrt{2}$, $d\overline{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\overline{u} + d\overline{d}) + c_2(s\overline{s})$

$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^{\pm} \to \ell^{\pm}\nu\gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

π^+ DECAY MODES			Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$		[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$		[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$		[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$		[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$			$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$			$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$			$< 5 \times 10^{-6}$	90%	70
Lepton Family number (*LF*) or Lepton number (*L*) violating modes					
$\mu^+\overline{\nu}_e$	*L*	[d]	$< 1.5 \times 10^{-3}$	90%	30
$\mu^+\nu_e$	*LF*	[d]	$< 8.0 \times 10^{-3}$	90%	30
$\mu^- e^+ e^+ \nu$	*LF*		$< 1.6 \times 10^{-6}$	90%	30

π^0

$I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 134.9766 \pm 0.0006$ MeV (S = 1.1)
$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV
Mean life $\tau = (8.4 \pm 0.5) \times 10^{-17}$ s (S = 2.6)
$c\tau = 25.1$ nm

For decay limits to particles which are not established, see the appropriate Search sections (A^0 (axion) and Other Light Boson (X^0) Searches, etc.).

π^0 DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ	(98.823 ± 0.034) %	S=1.5	67
$e^+e^-\gamma$	(1.174 ± 0.035) %	S=1.5	67
γpositronium	$(1.82 \pm 0.29) \times 10^{-9}$		67
$e^+e^+e^-e^-$	$(3.34 \pm 0.16) \times 10^{-5}$		67
e^+e^-	$(6.46 \pm 0.33) \times 10^{-8}$		67

π的parity是-1: Pseudo-scalar particles

τ and θ 具有幾乎一樣的質量與半衰期。

$$\Theta^+ \to \pi^+ + \pi^0$$

$$\tau^+ \to \pi^+ + \pi^- + \pi^+$$

$$(-1)^2 = 1$$

$$(-1)^3 = -1$$

But Theta decays into a parity even state.

Tau decays into a parity odd state.

根據鏡射對稱，parity值不變，τ 應該$P = -1$，而 θ應該$P = -1$。 。

τ and θ是兩顆不同的粒子。

How could two different particles look so similar?

$\tau - \theta$ puzzle

Rochester Conference

Feynman的室友實驗學家Block提醒了他，說不定鏡射並不對稱！

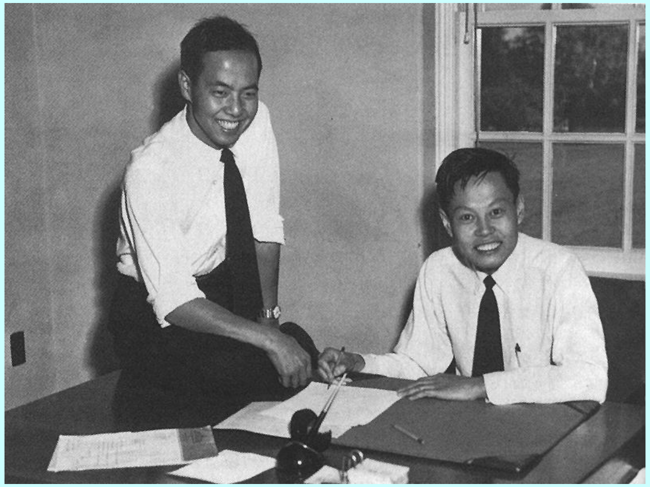
Could it be that the theta and tau are different parity states of the same particle which has no definite parity, that parity is not conserved.

Feynman at Rochester 1956

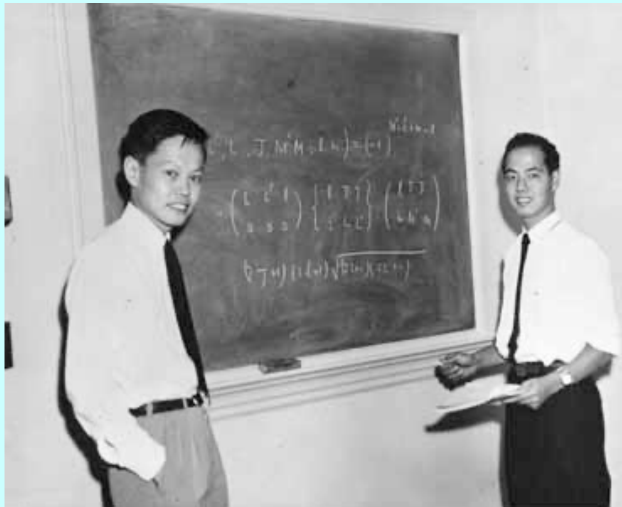
楊振寧帶著這個點子去找他長期合作的李政道。

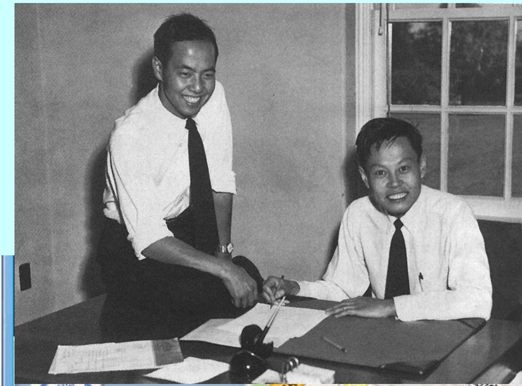

Scanned at the American Institute of Physics

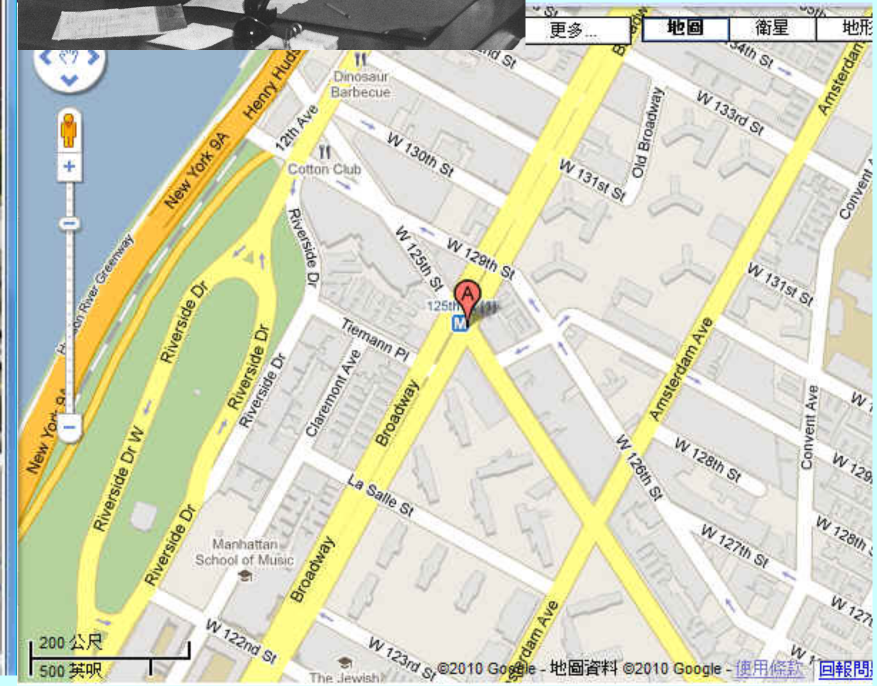

Scanned at the American Institute of Physics




Scanned at the American Institute of Physics


Scanned at the American Institute of Physics





..many fine Chinese restaurants. Finding they are not open yet, they retired to the nearby White Rose Café. They discussed the possibility that parity is conserved in strong interaction that produced tau and theta, yet violated in the weak interaction by which they decay.

Approximate Symmetry, Partial Symmetry

李政道帶著這點子與吳健雄討論：

到底有沒有實驗驗證過β衰變是否是鏡射對稱。

吳健雄塞給了李政道一本一千頁的β衰變光譜大全。

原來的標題：Is parity conserved in weak interaction?

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that

PRESENT EXPERIMENTAL LIMIT ON PARITY NONCONSERVATION

If parity is not strictly conserved, all atomic and nuclear states become mixtures consisting mainly of the state they are usually assigned, together with small percentages of states possessing the opposite parity. The fractional weight of the latter will be called $\mathfrak{F}^2$. It is a quantity that characterizes the degree of violation of parity conservation.

$$\theta^+ \rightarrow \pi^+ \pi^0 \qquad \tau^+ \rightarrow \pi^+ \pi^+ \pi^-$$

also the most accurate verification of the conservation of parity in strong and electromagnetic interactions. We shall see, however, that even this high degree of accuracy is not sufficient to supply an experimental proof of parity conservation in the weak interactions. For such a proof an accuracy of $\mathfrak{F}^2<10^{-24}$ is necessary.

QUESTION OF PARITY CONSERVATION IN β DECAY

At first sight it might appear that the numerous experiments related to β decay would provide a verification that the weak β interaction does conserve parity. We have examined this question in detail and found this to be not so. (See Appendix.) We start by writing down the five usual types of couplings. In addition to these we introduce the five types of couplings that conserve angular momentum but do not conserve parity. It is then apparent that the classification of β decays into allowed transitions, first forbidden, etc., proceeds exactly as usual. (The mixing of parity of the *nuclear states* would not measurably affect

POSSIBLE EXPERIMENTAL TESTS OF PARITY CONSERVATION IN β DECAYS

The above discussion also suggests the kind of experiments that could detect the possible interference between C and C' and consequently could establish whether parity conservation is violated in β decay. A relatively simple possibility is to measure the angular distribution of the electrons coming from β decays of oriented nuclei. If θ is the angle between the orientation of the parent nucleus and the momentum of the electron, an asymmetry of distribution between θ and $180°-\theta$ constitutes an unequivocal proof that parity is not conserved in β decay.

To be more specific, let us consider the allowed β transition of any oriented nucleus, say Co^{60}. The angular distribution of the β radiation is of the form (see Appendix):

$$I(\theta)d\theta=(\text{constant})(1+\alpha\cos\theta)\sin\theta d\theta, \qquad (2)$$

1956 Wu *et al.*: correlation between spin vector $\vec{J}$ of polarized ^{60}Co and direction $\hat{p}_e$ of outgoing β particle

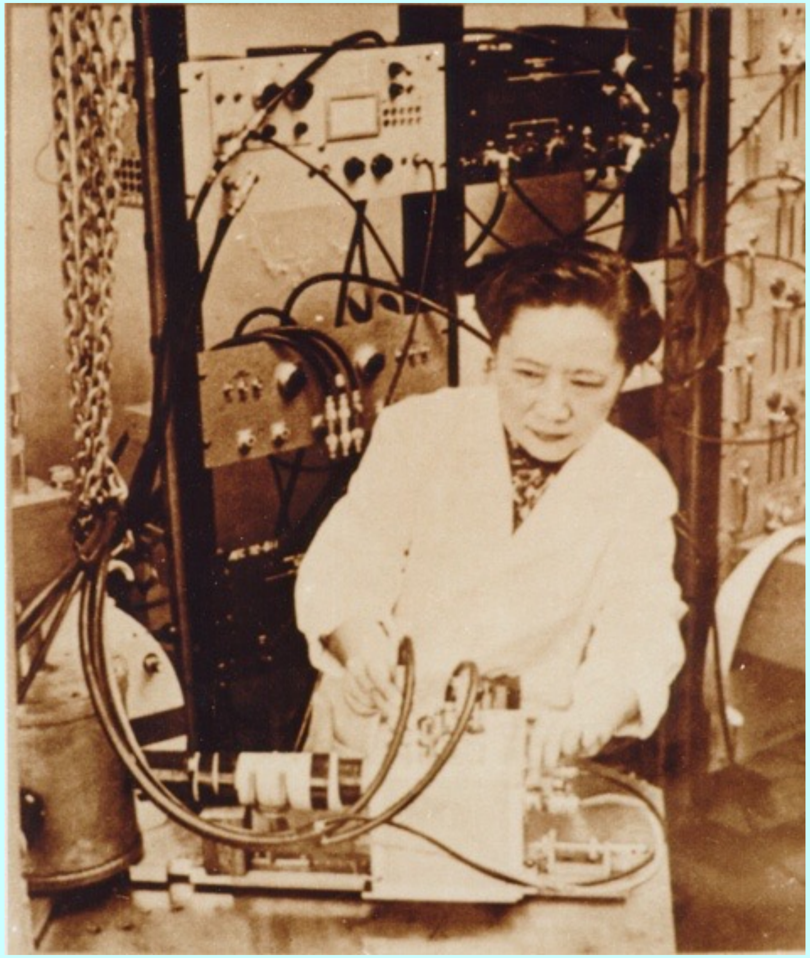
Parity leaves spin (axial vector) unchanged $\mathcal{P} : \vec{J} \rightarrow \vec{J}$

Parity reverses electron direction $\mathcal{P} : \hat{p}_e \rightarrow -\hat{p}_e$

Correlation $\vec{J} \cdot \hat{p}_e$ is *parity violating*

以原子核的固定自旋方向為軸，衰變產物電子動量的角分布。

C.S. Wu




Scanned at the American
Institute of Physics


Scanned at the American
Institute of Physics

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,
National Bureau of Standards, Washington, D. C.

(Received January 15, 1957)

In a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would provide the necessary evidence for parity conservation or nonconservation. In beta decay, one could measure the angular distribution of the electrons coming from beta decays of polarized nuclei. If an asymmetry in the distribution between θ and $180°-\theta$ (where θ is the angle between the orientation of the parent nuclei and the momentum of the electrons) is observed, it provides unequivocal proof that parity is not conserved in beta decay. This asymmetry effect has been observed in the case of oriented Co^{60}.

It has been known for some time that Co^{60} nuclei can be polarized by the Rose-Gorter method in cerium magnesium (cobalt) nitrate, and the degree of polarization detected by measuring the anisotropy of the succeeding gamma rays.[2] To apply this technique to the present problem, two major difficulties had to be over-

to surface heating effects, and the gamma-ray anisotropy alone provides a reliable measure of nuclear polarization. Specimens were made by taking good single crystals of cerium magnesium nitrate and growing on the upper surface only an additional crystalline layer containing Co^{60}. One might point out here that since the allowed beta decay of Co^{60} involves a change of spin of

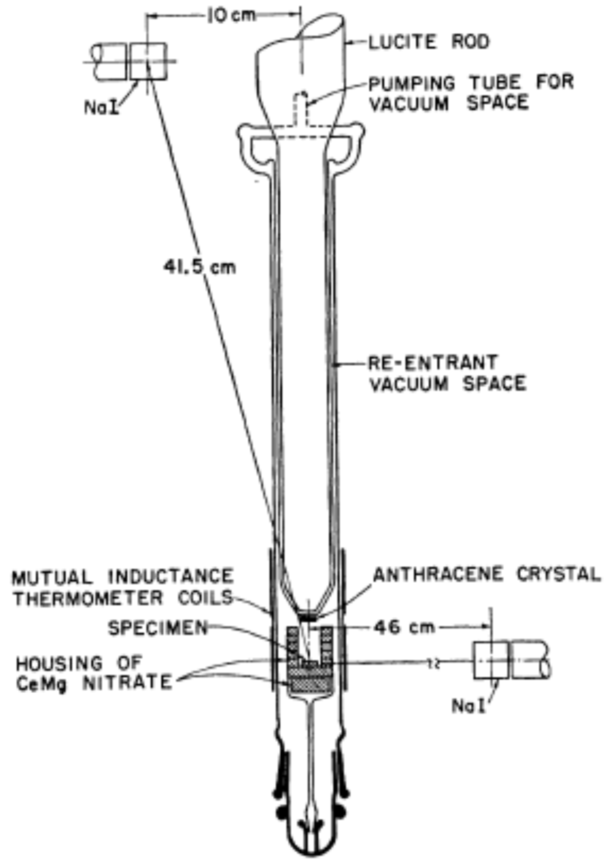
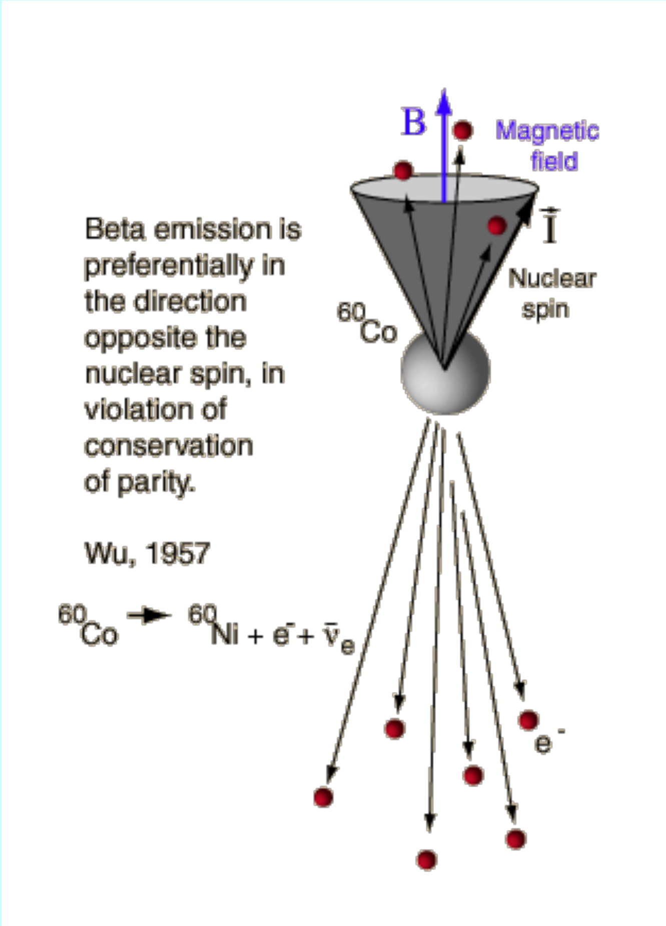


Fig. 1. Schematic drawing of the lower part of the cryostat.

How to check Parity violation?



Polarize the nucleus, and observe if there is any anisotropy in beta decays.

In beta decay of Cobalt 60, most electrons are emitted in direction opposite to nuclear spin. In mirror world, most are parallel.

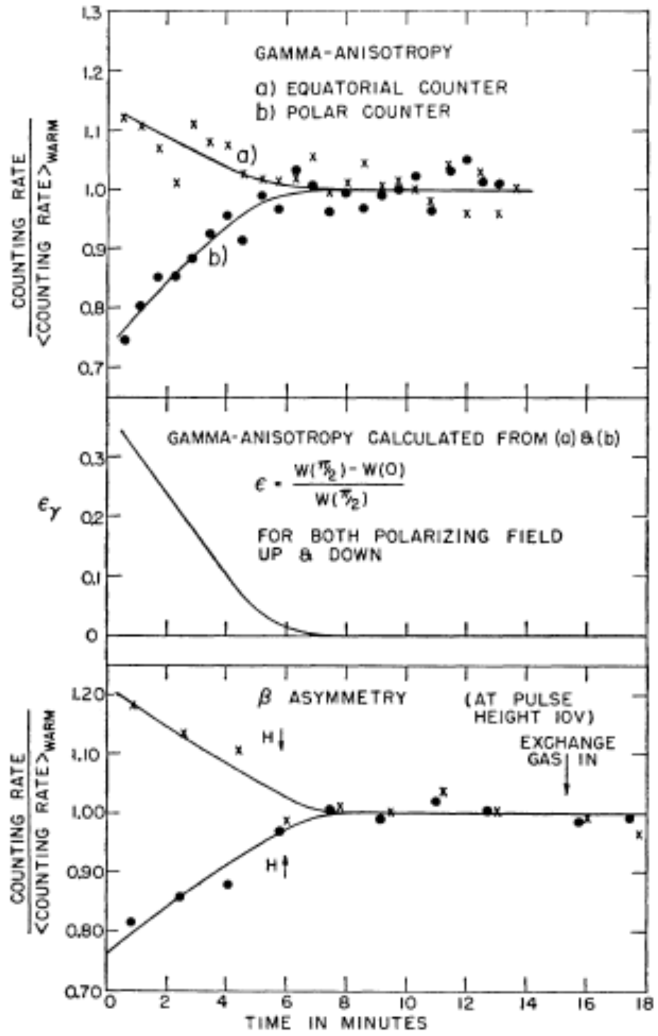


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

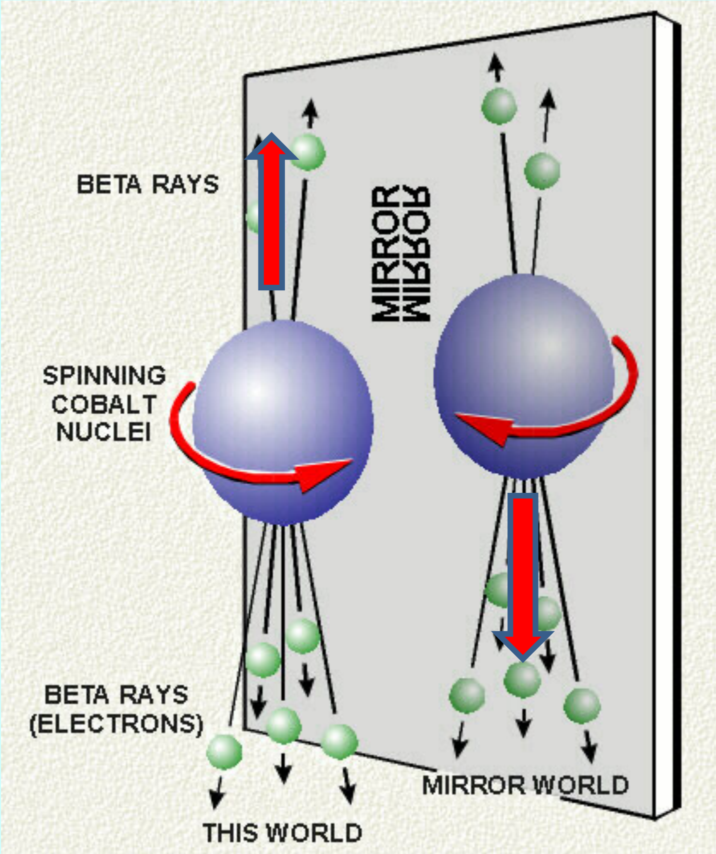
tropic g value. If the symmetry axis of a crystal is not set parallel to the polarizing field, a small magnetic field will be produced perpendicular to the latter. To check whether the beta asymmetry could be caused by such a magnetic field distortion, we allowed a drop of $CoCl_2$ solution to dry on a thin plastic disk and cemented the disk to the bottom of the same housing. In this way the cobalt nuclei should not be cooled sufficiently to produce an appreciable nuclear polarization, whereas the housing will behave as before. The large beta asymmetry was not observed. Furthermore, to investigate possible internal magnetic effects on the paths of the electrons as they find their way to the surface of the crystal, we prepared another source by rubbing $CoCl_2$ solution on the surface of the cooling salt until a reasonable amount of the crystal was dissolved. We then allowed the solution to dry. No beta asymmetry was observed with this specimen.

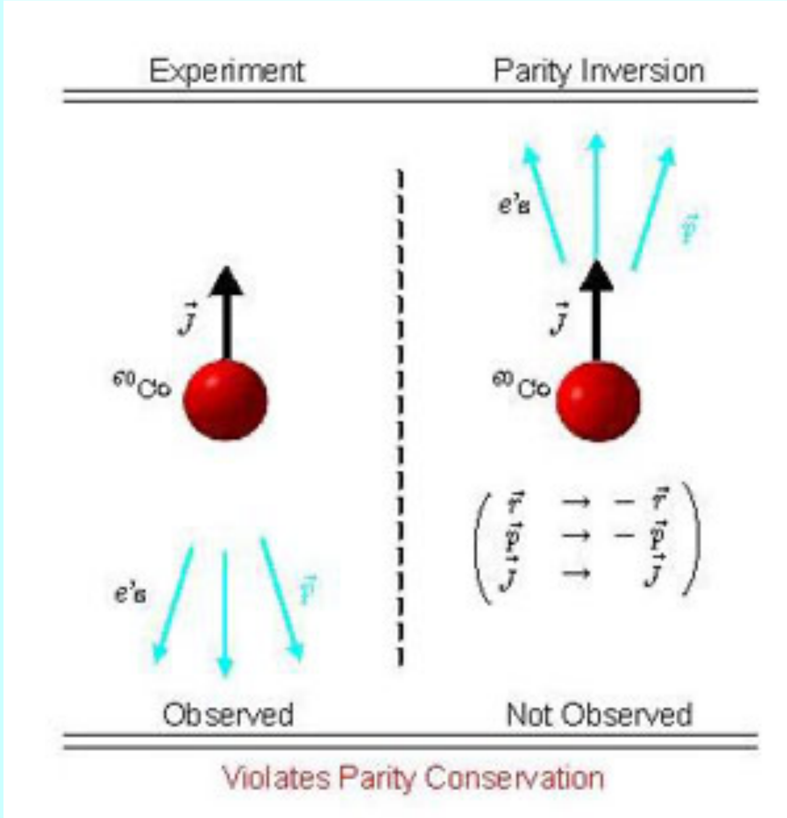
More rigorous experimental checks are being initiated, but in view of the important implications of these observations, we report them now in the hope that they may stimulate and encourage further experimental investigations on the parity question in either beta or hyperon and meson decays.

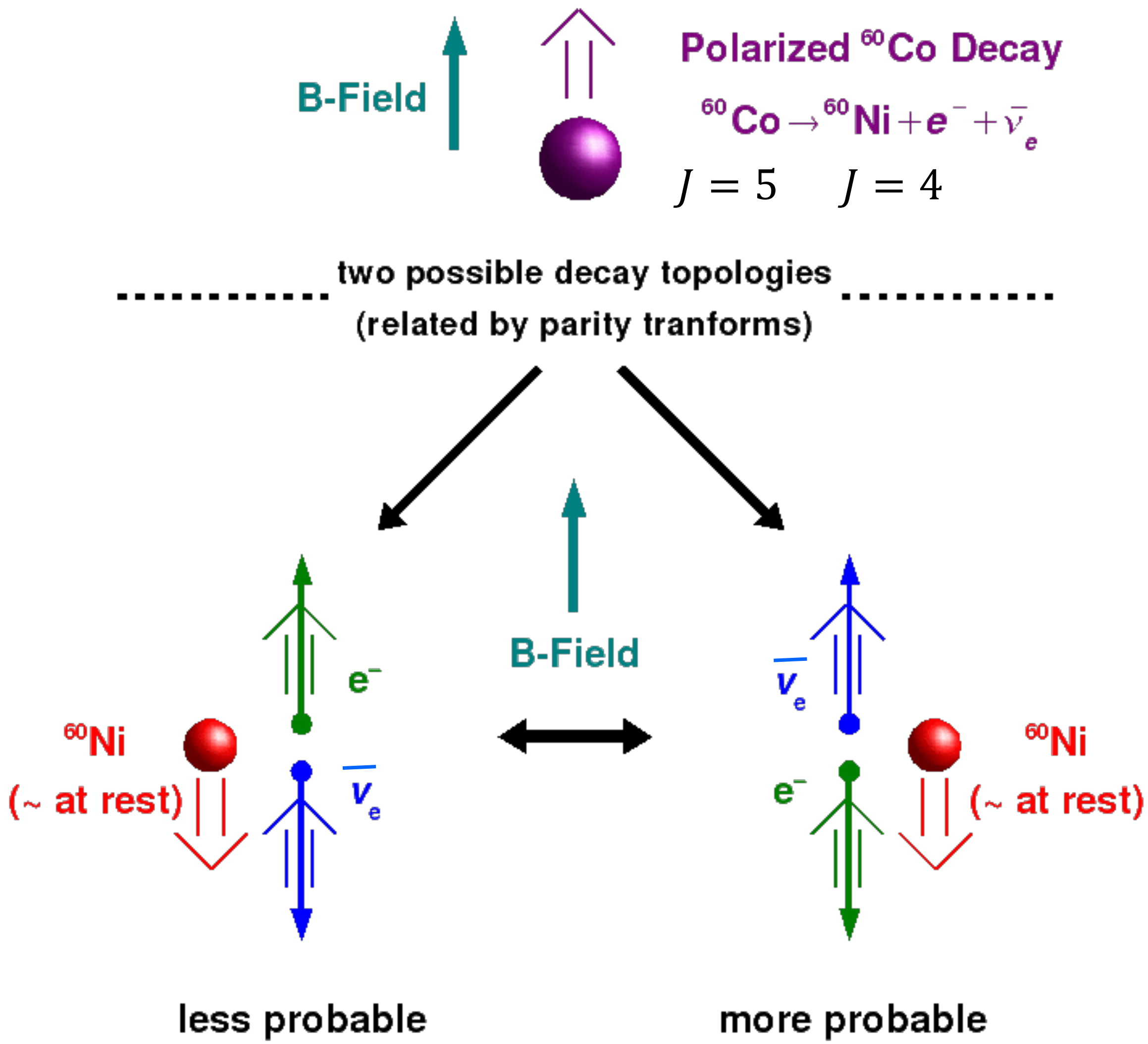
The inspiring discussions held with Professor T. D. Lee and Professor C. N. Yang by one of us (C. S. Wu) are gratefully acknowledged.

* Work partially supported by the U. S. Atomic Energy Commission.

[1] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).
[2] Ambler, Grace, Halban, Kurti, Durand, and Johnson, Phil. Mag. **44**, 216 (1953).
[3] Lee, Oehme, and Yang, Phys. Rev. (to be published).

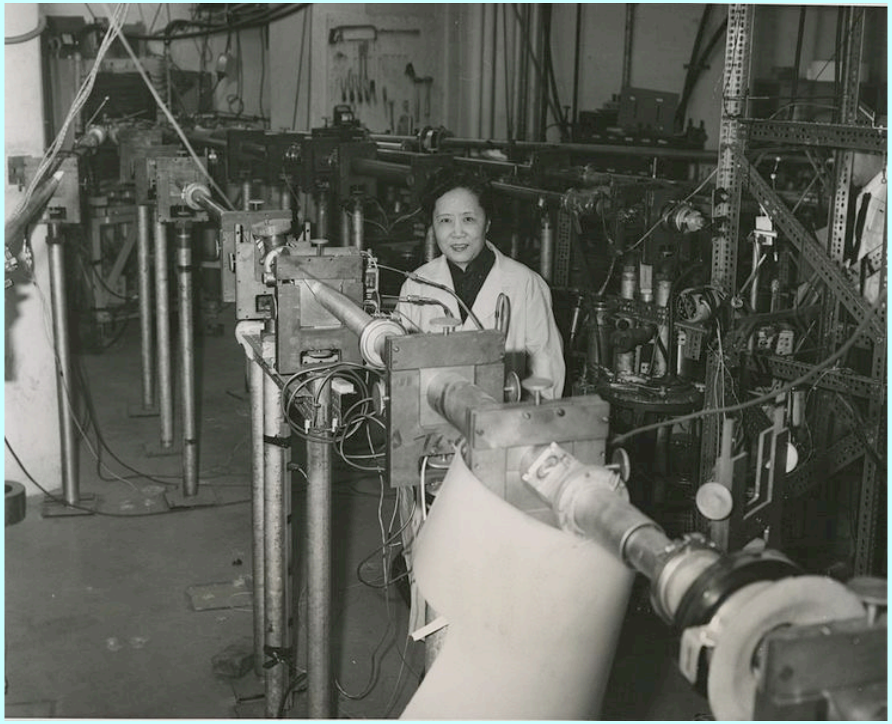

BETA RAYS
MIRROR
SPINNING
COBALT
NUCLEI
BETA RAYS
(ELECTRONS)
THIS WORLD
MIRROR WORLD


Experiment
Parity Inversion
e's
$\vec{J}$
^{60}Co
$\vec{p}$
Observed
Not Observed
Violates Parity Conservation



Polarized ^{60}Co Decay
$^{60}Co \rightarrow {}^{60}Ni + e^{-} + \bar{\nu}_e$
$J = 5 \quad J = 4$
B-Field
two possible decay topologies
(related by parity tranforms)
B-Field
e⁻
$\bar{\nu}_e$
^{60}Ni
(~ at rest)
$\bar{\nu}_e$
e⁻
^{60}Ni
(~ at rest)
less probable
more probable


Dr. Wu



[4] Their arguments are as follows: From the He^6 recoil experiment and from Eq. (A-4) of reference 1 one concludes that $(|C_A|^2+|C_A'|^2)/(|C_T|^2+|C_T'|^2)\lesssim\frac{1}{3}$. Hence, by comparing Eq. (16) of reference 3 [see also Eq. (A-6) of reference 1], one concludes that the present large asymmetry is possible only if both conservation of parity and invariance under charge conjugation are violated.

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

Richard L. Garwin,† Leon M. Lederman, and Marcel Weinrich

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)

Lee and Yang[1-3] have proposed that the long held space-time principles of invariance under charge conjugation, time reversal, and space reflection (parity) are violated by the "weak" interactions responsible for decay of nuclei, mesons, and strange particles. Their hypothesis, born out of the $\tau-\theta$ puzzle,[4] was accompanied by the suggestion that confirmation should be sought (among other places) in the study of the successive reactions

$$\pi^+\rightarrow\mu^++\nu, \quad (1)$$

$$\mu^+\rightarrow e^++2\nu. \quad (2)$$

They have pointed out that parity nonconservation implies a polarization of the spin of the muon emitted from stopped pions in (1) along the direction of motion and that furthermore, the angular distribution of electrons in (2) should serve as an analyzer for the muon polarization. They also point out that the longitudinal

VI. The measured g value and the angular distribution in (2) lead to the very strong probability that the spin of the μ^+ is $\frac{1}{2}$.[7]

VII. The energy dependence of the observed asymmetry is not strong.

VIII. Negative muons stopped in carbon show an asymmetry (also leaked backwards) of $a\sim-1/20$, i.e., about 15% of that for μ^+.

IX. The magnetic moment of the μ^-, bound in carbon, is found to be negative and agrees within limited accuracy with that of the μ^+.[8]

X. Large asymmetries are found for the e^+ from polarized μ^+ beams stopped in polyethylene and calcium. Nuclear emulsion (as a target in Fig. 1) yields an asymmetry of about half that observed in carbon.

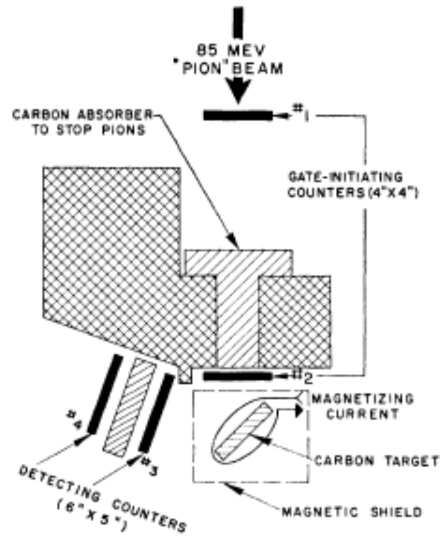


Fig. 1. Experimental arrangement. The magnetizing coil was close wound directly on the carbon to provide a uniform vertical field of 79 gauss per ampere.

Lederman聽說了Wu的結果，一月四日招集了Lee與其他同事討論測量邈子衰變的電子方向的測量來驗證鏡射破壞，一月八日就得到結果。

假如衰變的反微中子右旋比左旋多，那麼反向離開的緲子較多右旋，

收集同一方向離開的緲子，其自旋，如Wu實驗的原子核，是被極化的！

Figure 4.10 Decay of π^- at rest.

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

觀察這些緲子衰變時，電子動量相對於緲子自旋的角度分布。

Lederman很快發現非同向性！$\langle \vec{J}_\mu \cdot \vec{p}_e \rangle \neq 0$

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that

PRESENT EXPERIMENTAL LIMIT ON PARITY NONCONSERVATION

If parity is not strictly conserved, all atomic and nuclear states become mixtures consisting mainly of the state they are usually assigned, together with small percentages of states possessing the opposite parity. The fractional weight of the latter will be called $\mathfrak{F}^2$. It is a quantity that characterizes the degree of violation of parity conservation.

$$\theta^+ \rightarrow \pi^+ \pi^0$$

$$\tau^+ \rightarrow \pi^+ \pi^+ \pi^-$$

Nobel in just one year.

The Nobel Prize in Physics 1957

"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"

Chen Ning Yang

1/2 of the prize

China

Institute for Advanced Study
Princeton, NJ, USA

b. 1922

Tsung-Dao Lee

1/2 of the prize

China

Columbia University
New York, NY, USA

b. 1926

Theta and tau 是同一個粒子 K^+.

Leptonic and semileptonic modes

$\Gamma_1 \quad K^+ \rightarrow e^+ \nu_e$

$\Gamma_2 \quad K^+ \rightarrow \mu^+ \nu_\mu$

$\Gamma_3 \quad K^+ \rightarrow \pi^0 e^+ \nu_e$

Called K^+_{e3}.

$\Gamma_4 \quad K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$

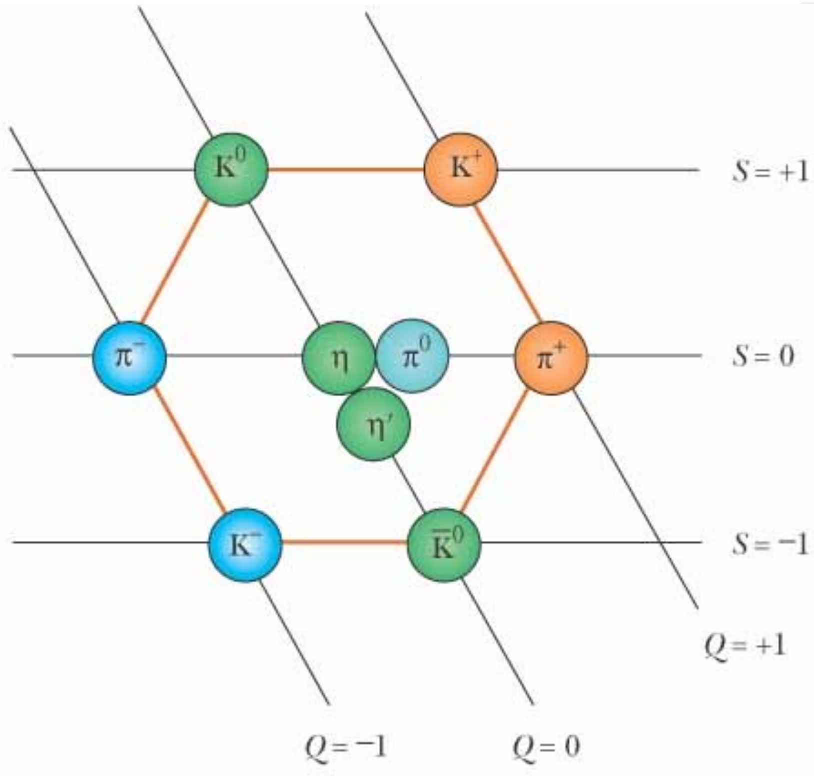
Called $K^+_{\mu 3}$.

$\Gamma_5 \quad K^+ \rightarrow \pi^0 \pi^0 e^+ \nu_e$

$\Gamma_6 \quad K^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$

$\Gamma_7 \quad K^+ \rightarrow \pi^+ \pi^- \mu^+ \nu_\mu$

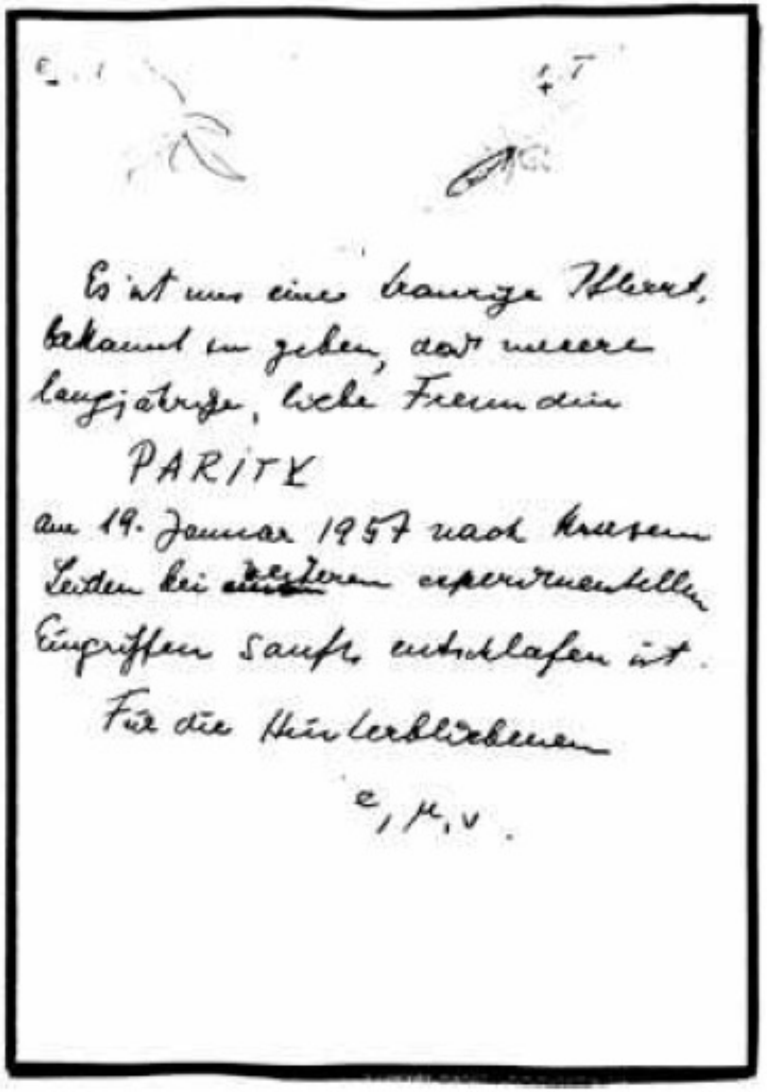
$\Gamma_8 \quad K^+ \rightarrow \pi^0 \pi^0 \pi^0 e^+ \nu_e$



Hadronic modes

Γ_9	$K^+ \rightarrow \pi^+ \pi^0$	(20.68 ± 0.13) %
Γ_{10}	$K^+ \rightarrow \pi^+ \pi^0 \pi^0$	(1.761 ± 0.022) %
Γ_{11}	$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	(5.59 ± 0.04) %

Pauli's Reaction to the Downfall of Parity



Es ist uns eine traurige Pflicht, bekannt zu geben, daß unsere langjährige, liebe Freundin

PARITY

am 19. Januar 1957 nach kurzem Leiden bei weiteren experimentellen Eingriffen sanft entschlafen ist.

Für die Hinterbliebenen

e, μ, ν.

Pauli's Reaction to the Downfall of Parity

Es ist uns eine traurige Pflicht, bekannt zu geben, daß unsere langjährige ewige Freundin

PARITY

den 19. Januar 1957 nach kurzen Leiden bei weiteren experimentellen Eingriffen sanfte entschlafen ist.

Für die hinterbliebenen

$e \quad \mu \quad \nu$

It is our sad duty to announce that our loyal friend of many years

PARITY

went peacefully to her eternal rest on the nineteenth of January 1957, after a short period of suffering in the face of further experimental interventions.

For those who survive her,

$e \quad \mu \quad \nu$

I don't believe that the Lord is a weak left-hander, and I am ready to bet a very large sum that the experiments will give symmetric results.

Pauli's letter to Weisskopf 3 days before he was told the news

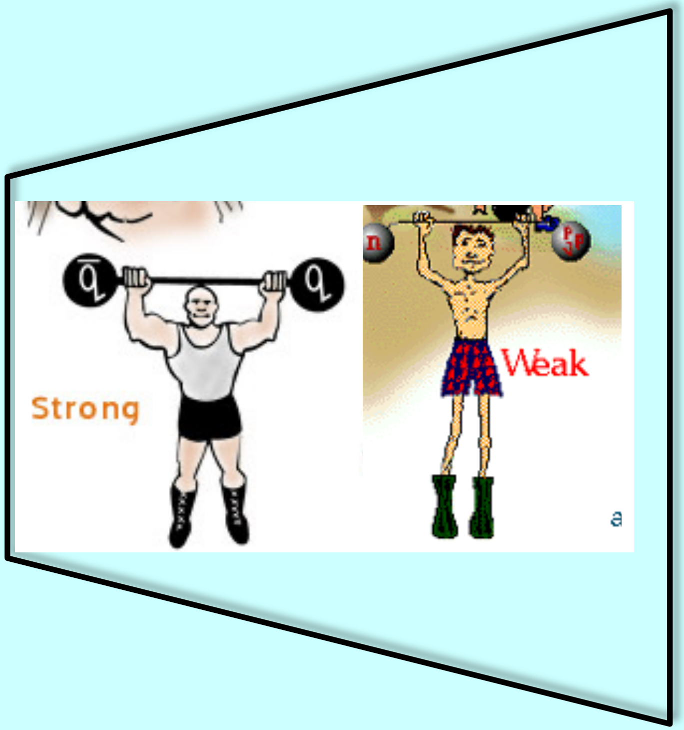
Now after the first shock is over, I begin to collect myself. I was to give a lecture at 8:15PM on the "past and recent history of the neutrino". At 5:00PM the mail brought me the three experimental papers. Now where shall I start? It is good that I did not make a bet

Pauli's letter to Weisskopf 10 days later

The Lord is indeed a weak left-hander.

What shocks me is not the fact that "god is just left-handed" but the fact that in spite of this he exhibits Himself as left/right symmetric when he expresses Himself strongly. How can the strength of an interaction produce or create symmetry?

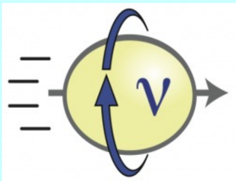
The strong interaction is parity symmetric while the weak interaction is not.

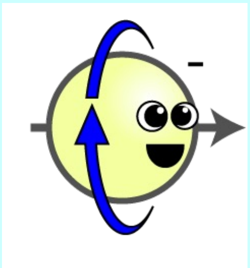


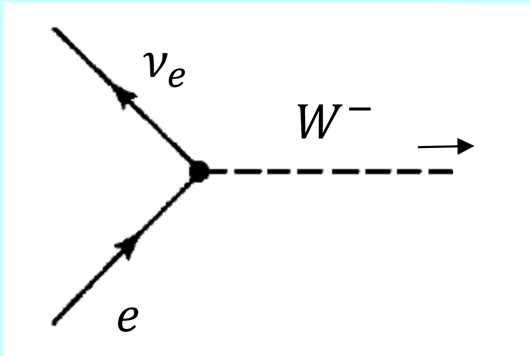
In a certain sense, a rather complete theoretical structure has been shattered at its base and we are not sure how the pieces will be put together! Rabi

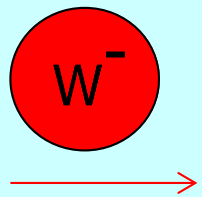
The symmetry is broken. The problem now is how bad.

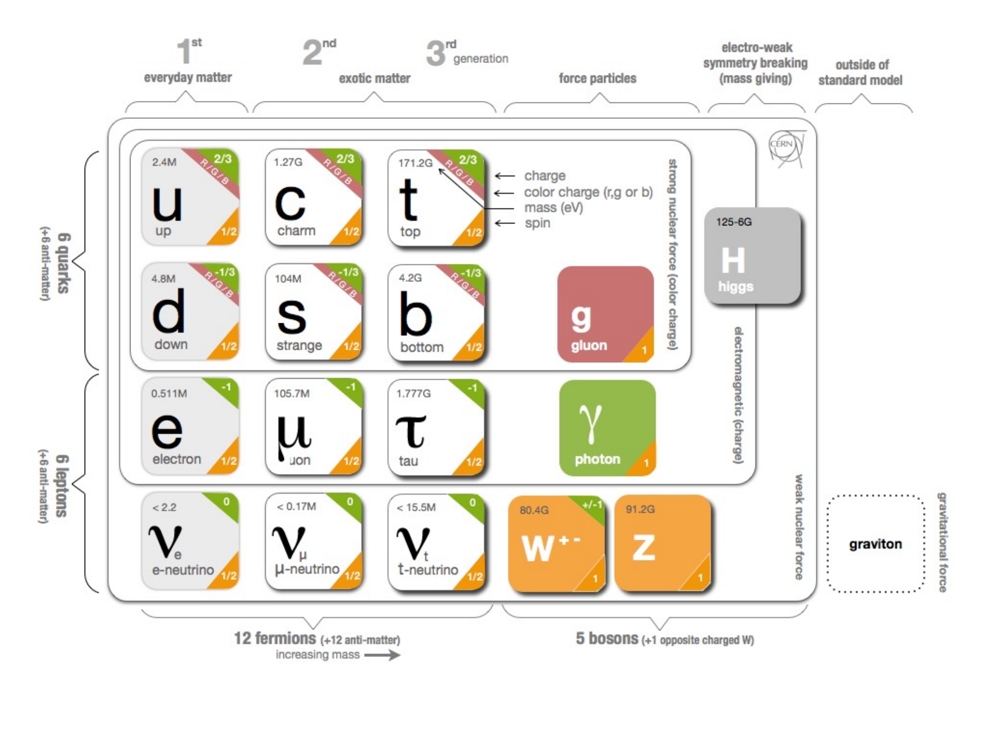
如果微中子是左旋，在這個交點中的電子只能是左旋。

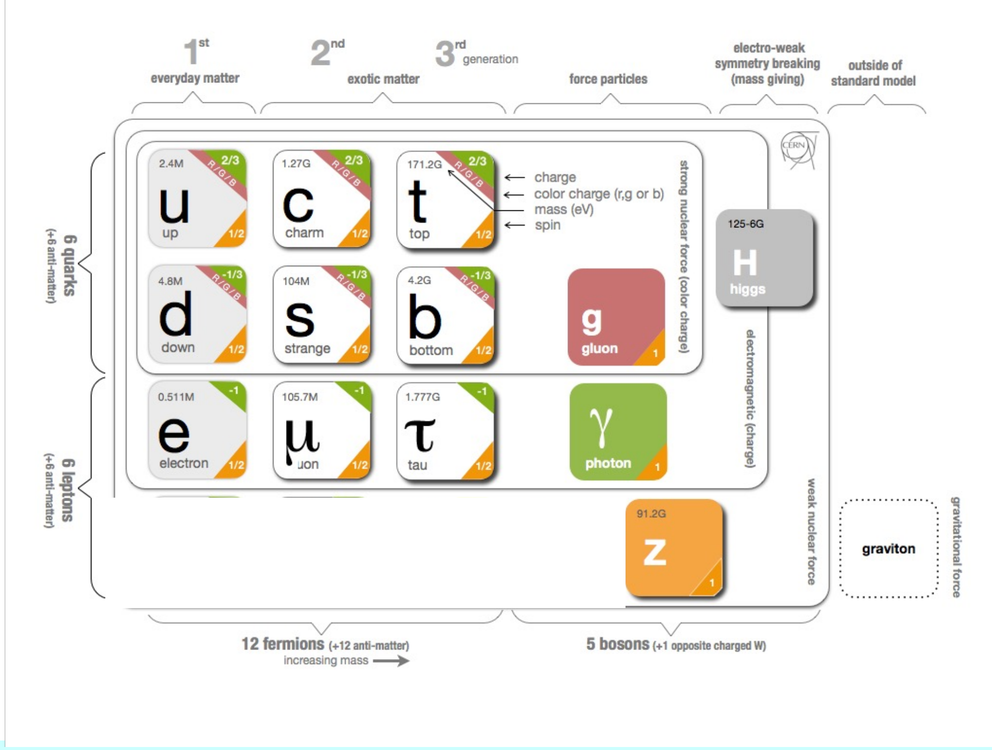




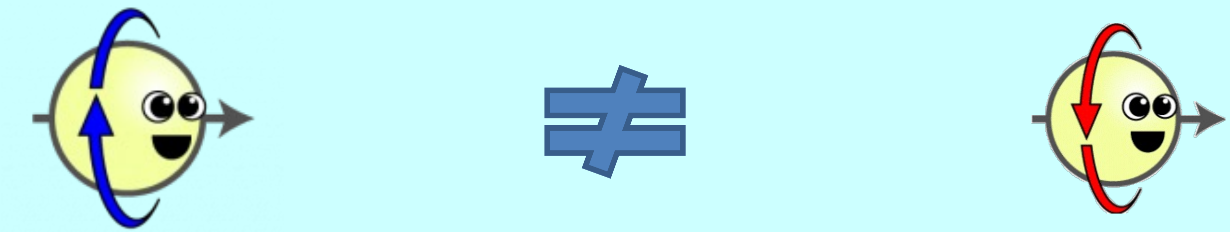








左右旋的費米子，弱交互規範作用是不同的。



這樣的交互作用稱為 Chiral.（弱作用是能分辨左右的）

Left-handed fermions act differently from Right handed Fermions.

Dirac find it's possible for 4 by 4 matrices $\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu}$

$$p^\mu p_\mu - m^2c^2 = (\gamma^\kappa p_\kappa + mc)(\gamma^\lambda p_\lambda - mc) = 0$$

Pick the first order factor: $\gamma^\mu p_\mu - mc = 0$

Make the replacement and put in the wave function:

$$p^\mu \to i\partial_\mu$$

$i\gamma^\mu \partial_\mu \psi - m\psi = 0$ Dirac Equation

If γ's are 4 by 4 matrices, *Ψ* must be a 4 component column:

$$i\left(\gamma^0 \frac{\partial \psi}{\partial t} + \gamma^i \frac{\partial \psi}{\partial x^i}\right) - m\psi = 0$$

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$

Note that it consists of 4 Equations.

Again, suppose the momentum relation can be factored into linear combinations of p's:

$$p^\mu p_\mu - m^2c^2 = (\beta^\kappa p_\kappa + mc)\left(\gamma^\lambda p_\lambda - mc\right)$$

Expand the right-hand side:

$$p^\mu p_\mu - m^2c^2 = \beta^\kappa \gamma^\lambda p_\kappa p_\lambda - mc(\beta^\kappa - \gamma^\kappa)p_\kappa - m^2c^2$$

Now for massless fermion: $m = 0$

$$p^\mu p_\mu = \beta^\kappa \gamma^\lambda p_\kappa p_\lambda$$

It is now possible that:

$$\beta^\kappa \neq \gamma^\kappa$$

$$p^\mu p_\mu = \beta^\kappa \gamma^\lambda p_\kappa p_\lambda$$

We can now choose 2 by 2 matrices : $\beta^\kappa = \left(1, \sigma^i\right) \neq \gamma^\kappa = \left(1, -\sigma^i\right)$

$p^\mu p_\mu = \beta^\kappa \gamma^\lambda p_\kappa p_\lambda$ is satisfied.

We get 2 equations for massless fermion, which are 2 component columns.

$\beta^\mu \partial_\mu \psi = 0$ $\gamma^\mu \partial_\mu \psi = 0$

Massless fermions contain only half the degrees of freedom.

This is result can been seen another way using γ^5:

$$\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3$$

$$\gamma^5\gamma^0 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3\gamma^0 = (-1)^3\gamma^0(i\gamma^0\gamma^1\gamma^2\gamma^3) = -\gamma^0\gamma^5$$

γ^5 anticomutes with all the other γ^μ.

$$\{\gamma^5, \gamma^0\} = 0$$

$(\gamma^5)^2 = I$ $\quad$ γ^5 is a projector can have eigenvalues of just ± 1.

Consider a massless fermion:

$$i\gamma^\mu \partial_\mu \psi = 0$$

Note that we have a matrix γ^5 that anticommute with all the Dirac Matrices:

$$\{\gamma^\mu, \gamma^5\} = 0 \qquad \gamma^\mu \gamma^5 = -\gamma^5 \gamma^\mu$$

We can multiply the Dirac Eq. by γ^5 and it will pass all the γ^μ to reach ψ.

$$i\gamma^5 \gamma^\mu \partial_\mu \psi = 0 \qquad i\gamma^\mu \partial_\mu (\gamma^5 \psi) = 0$$

$\gamma^5 \psi$ satisfy the same Dirac Eq. as ψ.

We can project ψ into two part: $\psi_L = P_L \psi \equiv \frac{1-\gamma^5}{2}\psi$ $\quad \psi_R = P_R \psi \equiv \frac{1+\gamma^5}{2}\psi$

Both parts satisfy Dirac Eq. independently. We usually say they are decoupled.

$$i\gamma^\mu \partial_\mu \left[\left(\frac{1 \pm \gamma^5}{2}\right)\psi\right] = 0 \qquad i\gamma^\mu \partial_\mu \psi_L = 0 \qquad i\gamma^\mu \partial_\mu \psi_R = 0$$

Without mass ψ_L, ψ_R can be seen as two different particles.

To describe ψ_L and ψ_R, two components are quite enough.

In the basis called Weyl representation, γ^5 is diagonal.

$$\gamma^5 = \begin{pmatrix} -I & 0 \\ 0 & I \end{pmatrix} \quad \gamma^0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}$$

and:

In this rep, $P_{L,R}$ are projections into the top and lower two components respectively.

$$\psi_L = P_L\psi \equiv \begin{pmatrix} I & 0 \\ 0 & 0 \end{pmatrix} \psi = \begin{pmatrix} \psi_L \\ 0 \end{pmatrix} \quad \psi_R = P_R\psi \equiv \begin{pmatrix} 0 & 0 \\ 0 & -I \end{pmatrix} \psi = \begin{pmatrix} 0 \\ \psi_R \end{pmatrix} \quad \psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

2 components $\psi_{L,R}$ are called Weyl spinors.

For massless fermion, Dirac Eq. decompose into two separate equations one for ψ_L, one ψ_R :

$$i\gamma^\mu \partial_\mu (P_L\psi) = i \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \partial_0 \begin{pmatrix} \psi_L \\ 0 \end{pmatrix} + i \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix} \partial_i \begin{pmatrix} \psi_L \\ 0 \end{pmatrix} = 0$$

$$\bar{\sigma}^\mu \partial_\mu \psi_L = 0$$

$$\bar{\sigma}^\mu = (1, -\sigma^i)$$

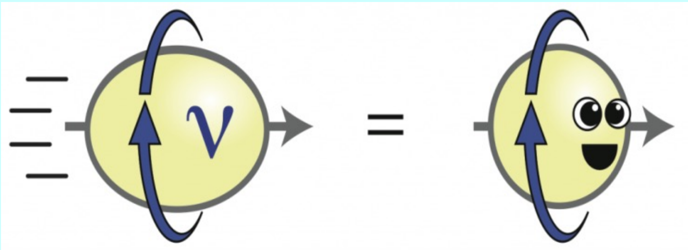
$$i\gamma^\mu \partial_\mu (P_R\psi) = 0$$

$$\sigma^\mu \partial_\mu \psi_R = 0$$

$$\sigma^\mu = (1, \sigma^i)$$

ψ_L and ψ_R are separate or decoupled.

Massless fermion contains only half the degrees of freedom.



A pure left-handed or a pure right-handed must be massless.

$\bar{\sigma}^\mu \partial_\mu \psi_L = 0$ $\sigma^\mu \partial_\mu \psi_R = 0$

$$\bar{\sigma}^{\mu}\partial_{\mu}\psi_L = 0$$

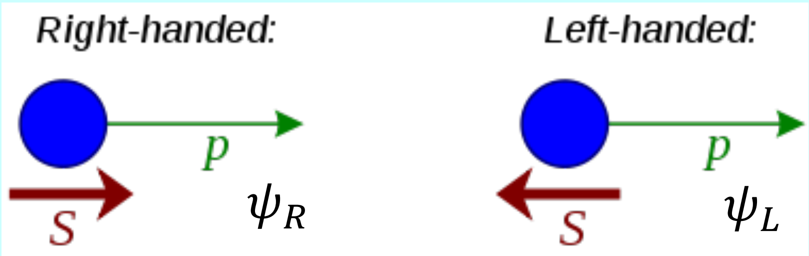
For plane wave $\bar{\sigma}^{\mu}p_{\mu}\psi_L = 0$

$$p_0\psi_L + \vec{\sigma}\cdot\vec{p}\,\psi_L = 0 \qquad p_0 = |\vec{p}| \qquad \frac{1}{2}\vec{\sigma}\cdot\hat{p}\,\psi_L = -\frac{1}{2}\psi_L$$

Helicity $\vec{s}\cdot\hat{p} = \frac{1}{2}\hbar\vec{\sigma}\cdot\hat{p}$ is the spin along the direction of the particle momentum.

In the massless limit, ψ_L, ψ_R correspond to eigenstates of helicity.

$$\frac{1}{2}\vec{\sigma}\cdot\hat{p}\,\psi_R = \frac{1}{2}\psi_R \qquad \vec{s}\cdot\hat{p} = \frac{1}{2}\hbar \qquad \vec{s}\cdot\hat{p} = -\frac{1}{2}\hbar$$



The state whose $\vec{s}$ points in the same direction as $\vec{p}$ is called right-handed particles.

The state whose $\vec{s}$ points in opposite direction as $\vec{p}$ is called left-handed particles.

They are separate particles (if massless, we said we will pretend at the moment they are).

We can keep using Dirac field and its Lagrangian density.

Dirac eq. can be derived from the following Lagrangian.

$$\mathcal{L} = \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi \qquad \bar{\psi} \equiv \psi^{\dagger}\gamma^{0}$$

First calculation $\delta\mathcal{L}$ with respect to any $\delta\psi$,$\delta\bar{\psi}$.

$$\delta\mathcal{L} = \delta\bar{\psi} \cdot \frac{\partial\mathcal{L}}{\partial\bar{\psi}} + \frac{\partial\mathcal{L}}{\partial\psi} \cdot \delta\psi = \delta\bar{\psi} \cdot \left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi + \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m\right) \cdot \delta\psi$$

Observe that if $\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi = 0$, then $\bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m\right) = 0$, and hence $\delta\mathcal{L} = 0$ for any $\delta\psi$.

Therefore, $\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi = 0$ is the equation of motion of the Lagrangian.

$$\mathcal{L} = \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi$$

The Dirac Lagrangian can be written in terms of bispinors $\psi_{L,R}$:

$$\psi_L = P_L\psi \equiv \frac{1-\gamma^5}{2}\psi = \begin{pmatrix}\psi_L \\ 0\end{pmatrix}$$

$$\psi_R = P_R\psi \equiv \frac{1+\gamma^5}{2}\psi = \begin{pmatrix}0 \\ \psi_R\end{pmatrix}$$

$$\mathcal{L} = \bar{\psi}i\gamma^\mu\partial_\mu(P_L + P_R)\psi = \bar{\psi}i\gamma^\mu\partial_\mu P_L\psi + \bar{\psi}i\gamma^\mu\partial_\mu P_R\psi$$

$$\bar{\psi}i\gamma^\mu\partial_\mu\psi_L = \bar{\psi}i\gamma^\mu\partial_\mu P_L\psi = \bar{\psi}i\gamma^\mu\partial_\mu\left(\frac{1-\gamma^5}{2}\right)\psi_L$$

$$= \psi^{*T}\gamma^0 i\left(\frac{1+\gamma^5}{2}\right)\gamma^\mu\partial_\mu\psi_L = \psi^{*T}\left(\frac{1-\gamma^5}{2}\right)\gamma^0 i\gamma^\mu\partial_\mu\psi_L = (P_L\psi)^\dagger\gamma^0 i\gamma^\mu\partial_\mu\psi_L$$

$$i\bar{\psi}_L\gamma^\mu\partial_\mu\psi_L$$

$$i\bar{\psi}_L\gamma^\mu\partial_\mu\psi_L + i\bar{\psi}_R\gamma^\mu\partial_\mu\psi_R$$

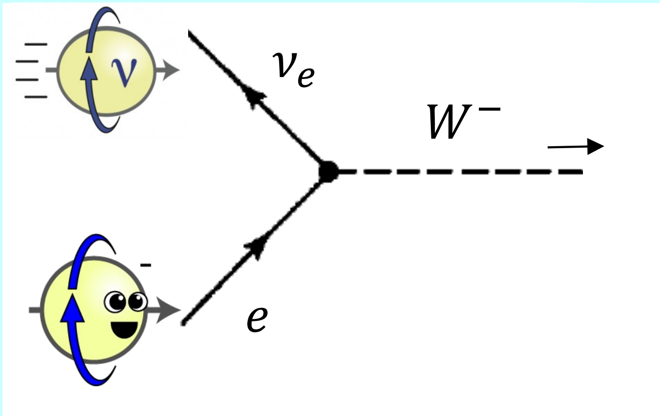
At two sides of γ^μ fermions are of the same handedness, both ψ_L or both ψ_R.

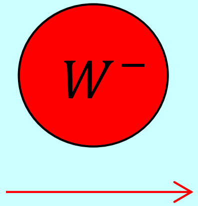
As expected, kinetic energy γ^μ terms decouple $\psi_{L,R}$.

Note that gauge boson interaction is also a γ^μ term and thus also decouple $\psi_{L,R}$.

$$\frac{g}{2}\bar{\psi}\gamma^\mu \boldsymbol{\tau}\cdot\boldsymbol{W}_\mu\psi = \frac{g}{2}\bar{\psi}_L\gamma^\mu \boldsymbol{\tau}\cdot\boldsymbol{W}_\mu\psi_L + \frac{g}{2}\bar{\psi}_R\gamma^\mu \boldsymbol{\tau}\cdot\boldsymbol{W}_\mu\psi_R$$

如果微中子是左旋，在這個交點中的電子只能是左旋。





The Lagrangian can also be written in terms of Two component Weyl spinors:

$$\mathcal{L} = \bar{\psi} i\gamma^{\mu}\partial_{\mu}(P_L + P_R)\psi \quad = \bar{\psi} i\gamma^{\mu}\partial_{\mu}P_L\psi + \bar{\psi} i\gamma^{\mu}\partial_{\mu}P_R\psi$$

Note that $\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$ $\quad \bar{\psi} = \begin{pmatrix} \psi_R^{\dagger} & \psi_L^{\dagger} \end{pmatrix}$ $\quad P_L\psi = \begin{pmatrix} \psi_L \\ 0 \end{pmatrix}$ $\quad P_R\psi = \begin{pmatrix} 0 \\ \psi_R \end{pmatrix}$

and remember in this basis:

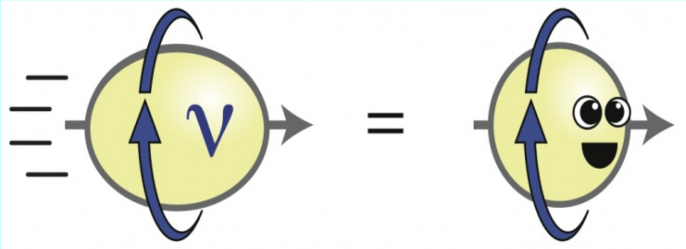
$$\gamma^0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}$$

We can directly plug this decomposition of ψ into the Lagrangian:

and get the Lagrangian for the left-handed and right-handed Weyl spinors:

$$\mathcal{L} = i\psi_L^{\dagger}\sigma^{\mu}\partial_{\mu}\psi_L + i\psi_R^{\dagger}\sigma^{\mu}\partial_{\mu}\psi_R$$

所有微中子都是左手旋！



$\bar{\sigma}^{\mu}\partial_{\mu}\psi_L = 0$ Solve the equation of motion by Fourier Transformation.

$$\psi_L = \int \frac{d^3p}{(2\pi)^3}\left[a u(\vec{p}) e^{-ipx} + b^{\dagger} v(\vec{p}) e^{ipx}\right]$$ And quantize it.

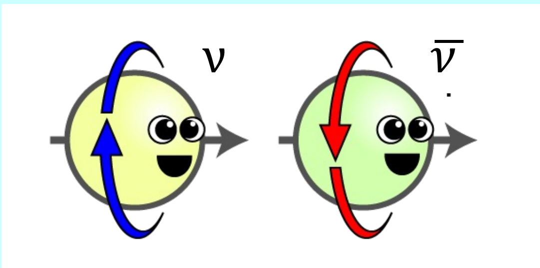
Peskin p61

For $p = (p^0, 0, 0, p^0)$

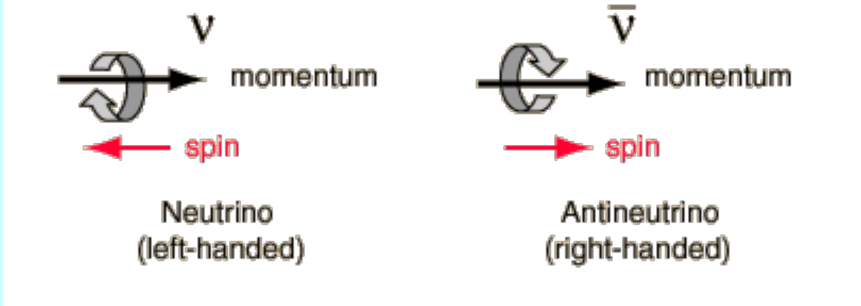
$(-p^0 - p^0\sigma^3)u = 0$ $\quad u = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ $\quad a$ annihilate a fermion of J_Z eigenvalues $-\frac{1}{2}$.

$(p^0 + p^0\sigma^3)v = 0$ $\quad v = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ $\quad b^{\dagger}$ create an antifermion of J_Z eigenvalues $+\frac{1}{2}$.

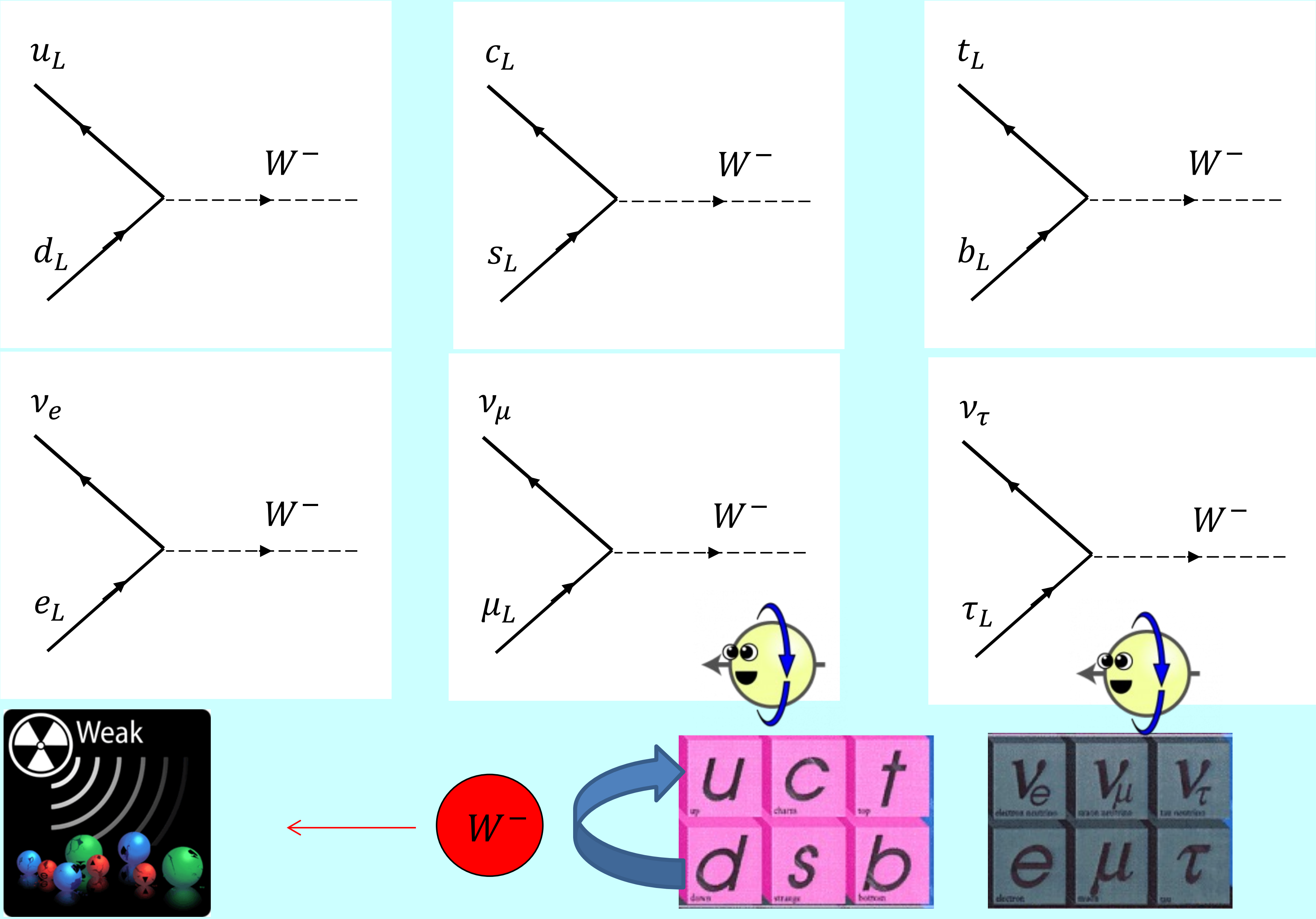
左旋微中子



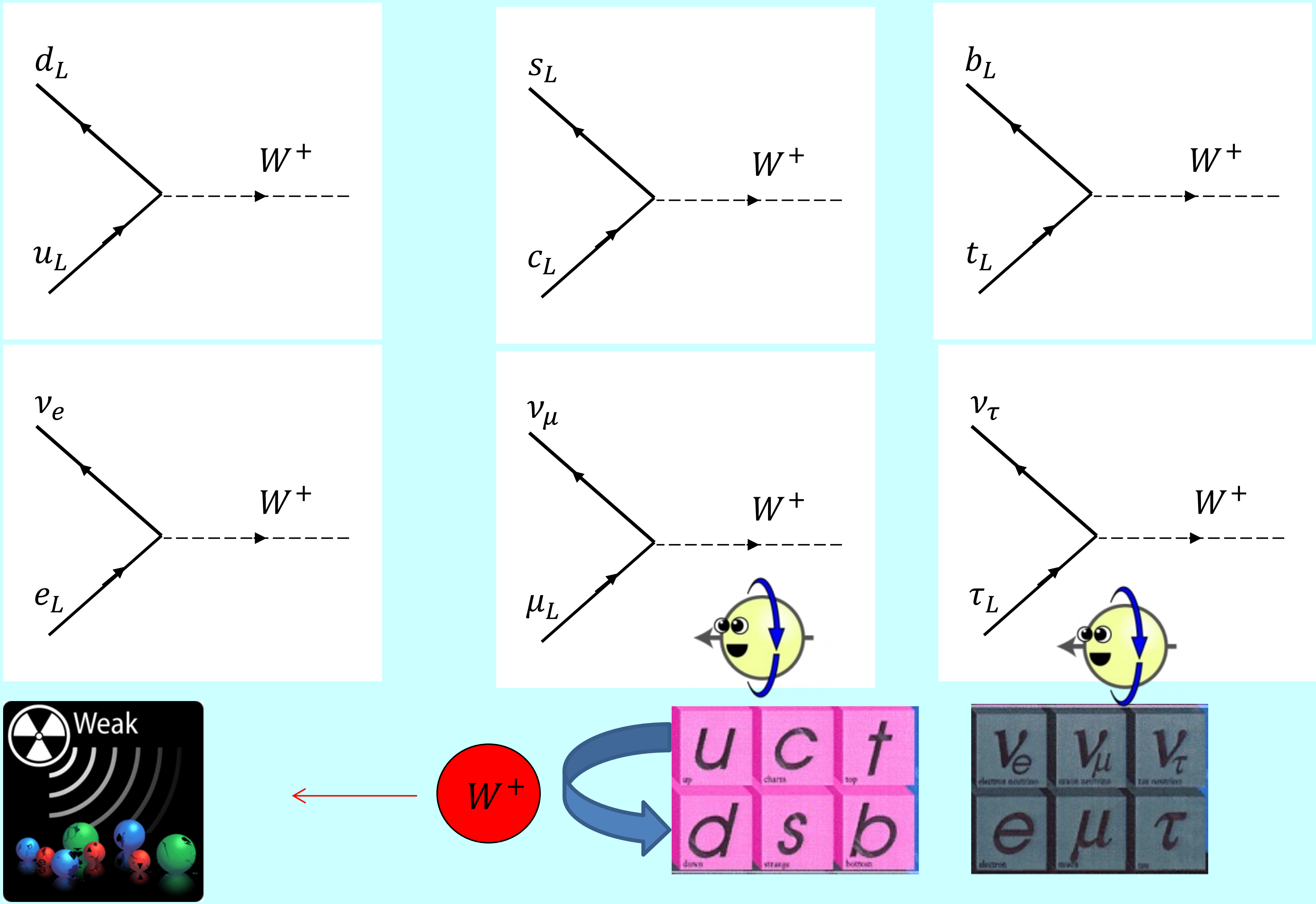
反微中子只有右手旋。



只有左旋粒子才與 W 有交互作用



只有左旋粒子才與 W 有交互作用

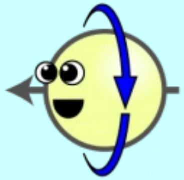


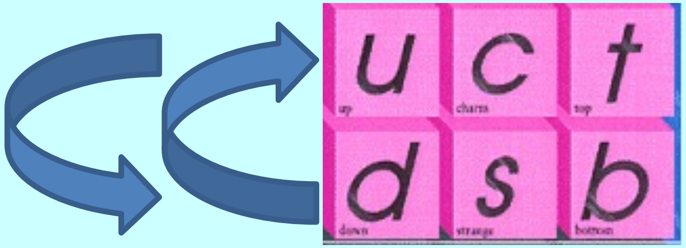
弱交互作用不是 Weak $SU(2)$ gauge interaction

而是 Left-Handed Weak $SU(2)_L$ gauge interaction

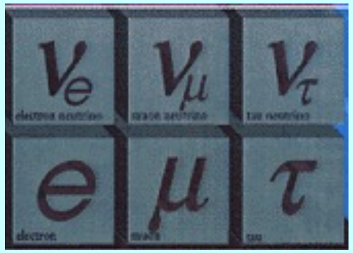
W 是 Left-Handed Weak $SU(2)_L$的規範粒子！

For left-handed weak $SU(2)_L$, left-handed particles are doublets.





L

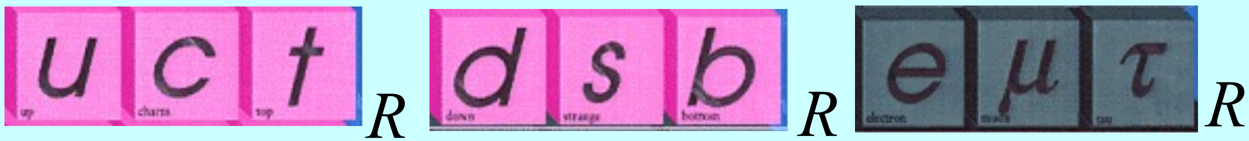


L

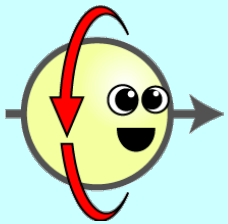
$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \to U \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e_L \end{pmatrix} \to U \begin{pmatrix} \nu_e \\ e_L \end{pmatrix}$$

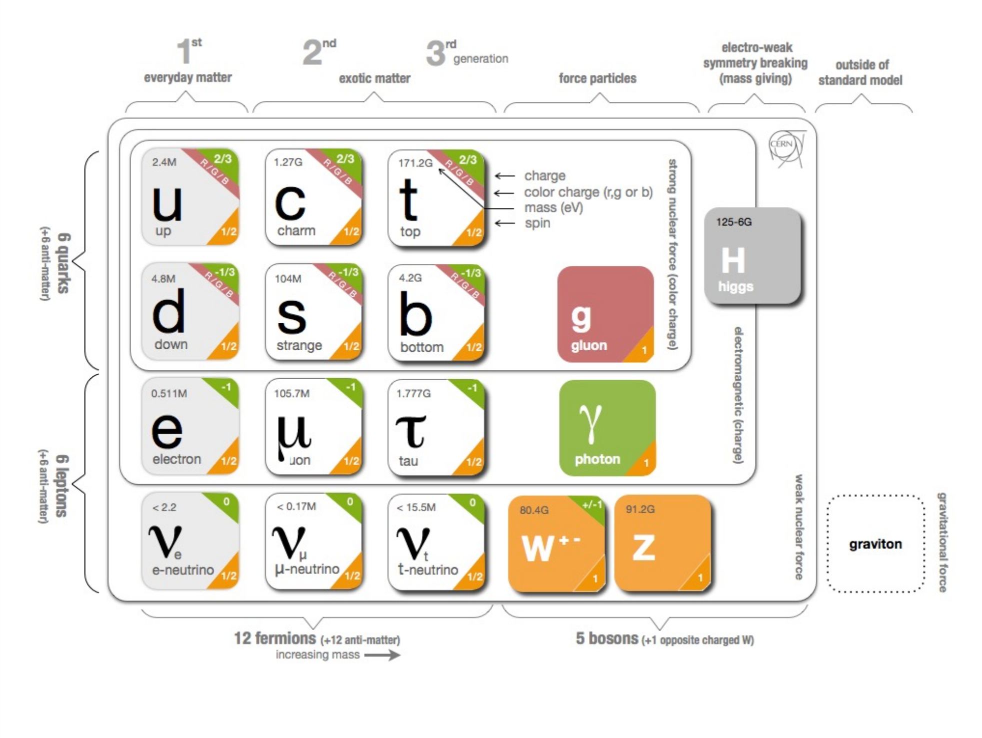
For Left-Handed Weak $SU(2)_L$, right-handed particles are singlets.

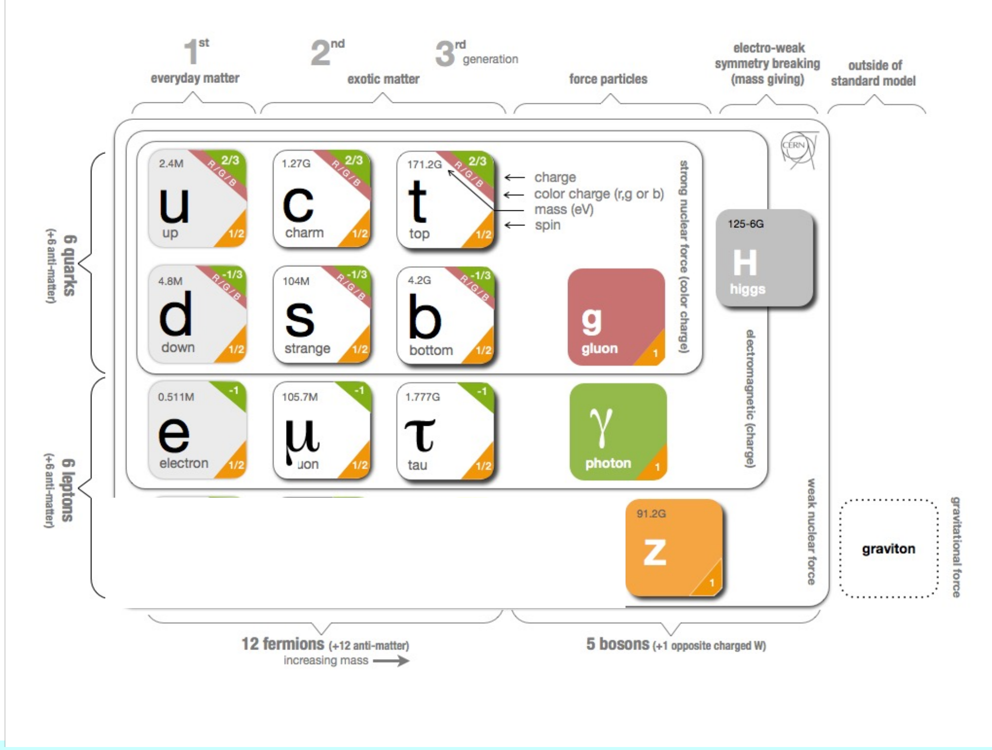


Singlet

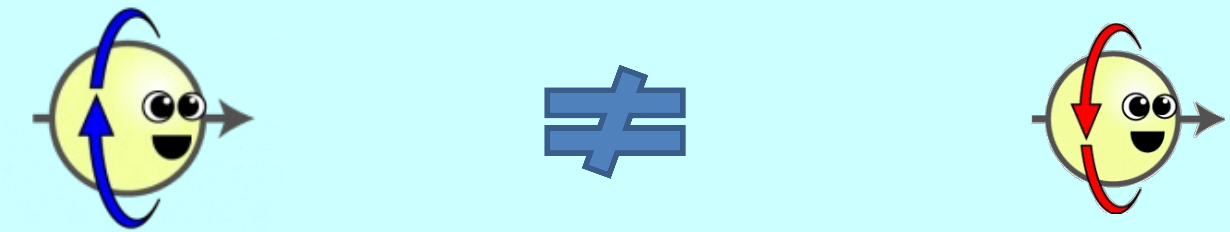


W與右旋粒子無作用！





左右旋的費米子，弱交互規範作用是不同的。



這樣的交互作用稱為 Chiral. （弱作用是能分辨左右的）

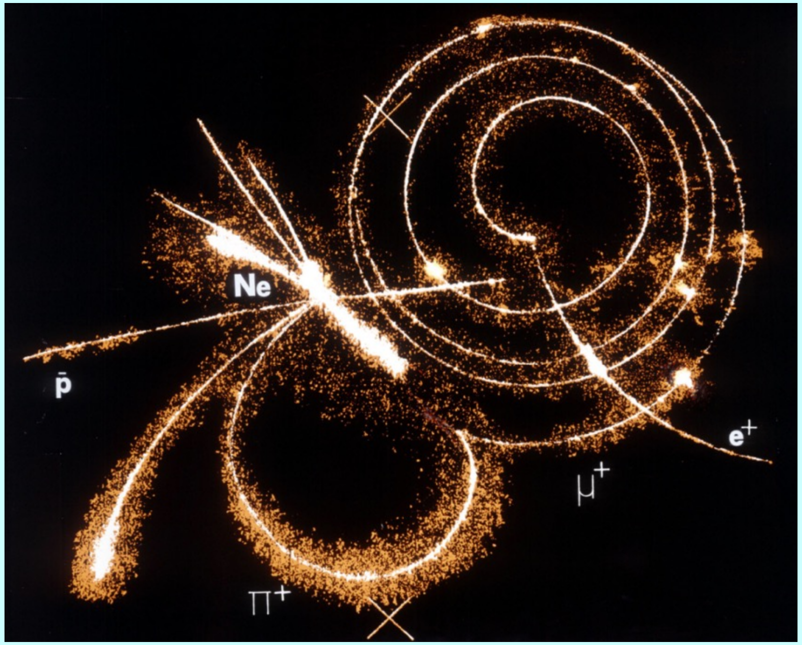
Left-handed fermions act differently from Right handed Fermions.

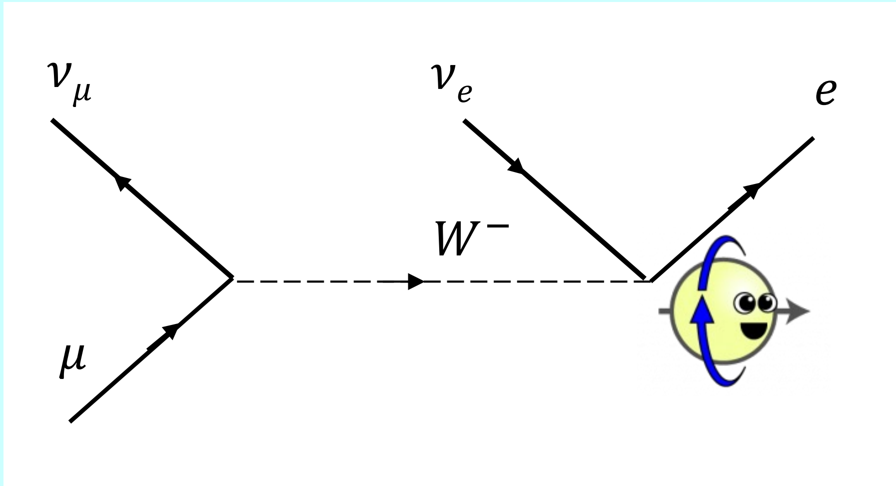
R

L

右旋的電子，完全沒有弱交互作用。

例如緲子衰變。Muon decay





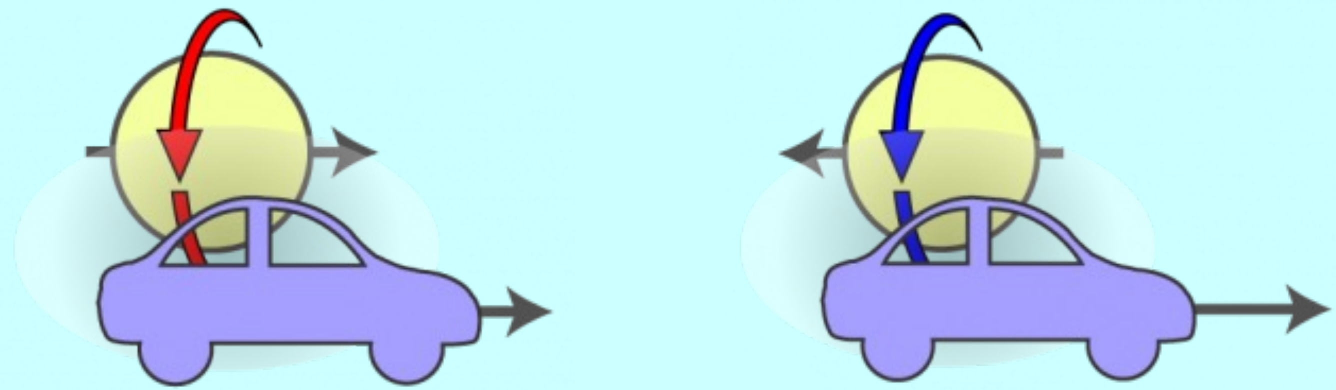
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

Experiments discover all the particles participating the interaction are left-handed.

我們宇宙是左右不對稱。 Mirror symmetry is broken!

對任一有質量的費米子我一定可以找到一個座標系比它運動得更快。

在此新座標系中觀察，粒子的動量改變方向，而自旋並不改變！



因此在此新座標系中觀察，本來的右旋費米子就變成左旋費米子！

Weak singlet e_R

Weak Doublet $\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$

此費米子的弱交互作用，在新座標系中觀察與在原來座標系中，是不同的。

弱交互作用在羅倫茲變換下，不是不變的！這當然不能允許。

除非你永遠無法跑得比它快！那此費米子是無質量的。

從弱作用規範對稱的角度來看，電子、夸克質量是不被允許的。

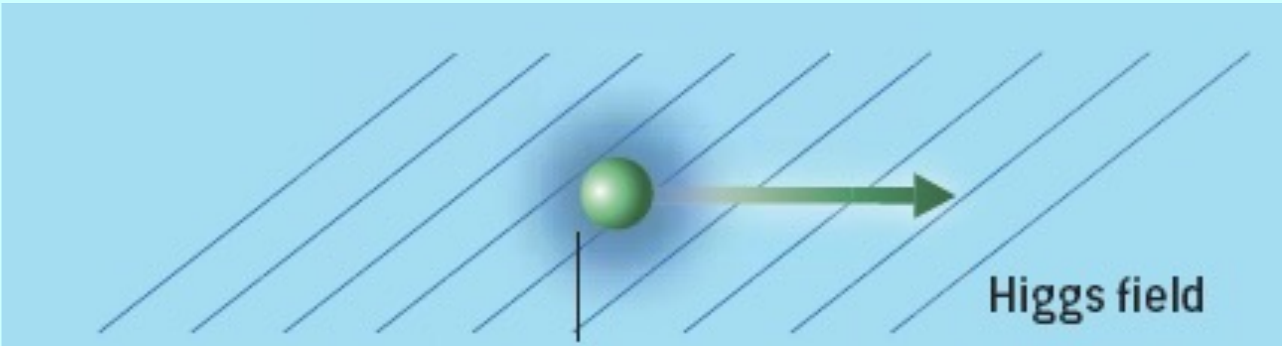
Fermion Masses are forbidden by the chiral weak symmetry!

Fermion Masses are forbidden by the chiral weak symmetry!

It helps to think that fermions are born massless, ie. intrinsically chiral.

生下來是無質量，本質上是Chiral，質量是外在機制所賦予。

Fermion masses are added on by external mechanism.



Let’s start with chiral fermions.

What does a mass do in QFT?

Still start with Dirac field and its Lagrangian density which contains masses:

$$\mathcal{L} \supset m\bar{\psi}\psi = m\bar{\psi}(P_L + P_R)\psi$$

$$m\bar{\psi}_L\psi_R + m\bar{\psi}_R\psi_L$$

$$\psi_L \equiv \begin{pmatrix} \psi_L \\ 0 \end{pmatrix}$$

The mass term mixes $\psi_{L,R}$.

The Mysteries of

MASS

Physicists are hunting for an elusive particle that would reveal the presence of a new kind of field that permeates all of reality. Finding that Higgs field will give us a more complete understanding about how the universe works

By Gordon Kane

Most people think they know what mass is, but they understand only part of the story. For instance, an elephant is clearly bulkier and weighs more than an ant. Even in the absence of gravity, the elephant would have greater mass—it would be harder to push and set in motion. Obviously the elephant is more massive because it is made of many more atoms than the ant is, but what determines the masses of the individual atoms? What about the elementary particles that make up the atoms—what determines their masses? Indeed, why do they even have mass?

We see that the problem of mass has two independent aspects. First, we need to learn how mass arises at all. It turns out mass results from at least three different mechanisms, which I will describe below. A key player in physicists' tentative theories about mass is a new kind of field that permeates all of reality, called the Higgs field. Elementary particle masses are thought to come about from the interaction with the Higgs field. If the Higgs field exists, theory demands that it have an associated particle, the Higgs boson. Using particle accelerators, scientists are now hunting for the Higgs.

The second aspect is that scientists want to know why different species of elementary particles have their specific quantities of mass. Their intrinsic masses span at least 11 orders of magnitude, but we do not yet know why that should be so [*see illustration on page 44*]. For comparison, an elephant and the smallest of ants differ by about 11 orders of magnitude of mass.

What *Is* Mass?

ISAAC NEWTON presented the earliest scientific definition of mass in 1687 in his landmark *Principia*: "The quantity of matter is the measure of the same, arising from its density and bulk conjointly." That very basic definition was good enough for Newton and other scientists for more than 200 years. They understood that science should proceed first by describing how things work and later by understanding why. In recent years, however, the *why* of mass has become a research topic in physics. Understanding the meaning and origins of mass will complete and extend the Standard Model of particle physics, the well-established theory that describes the known elementary particles and their interactions. It will also resolve mysteries such as dark matter, which makes up about 25 percent of the universe.

The foundation of our modern understanding of mass is far more intricate than Newton's definition and is based on the Standard Model. At the heart of the Standard

MALE AFRICAN ELEPHANT (about 6,000 kilograms) and the smallest species of ant (0.01 milligram) differ in mass by more than 11 orders of magnitude—roughly the same span as the top quark and the neutrino. Why the particle masses should differ by such a large amount remains a mystery.

BRYAN CHRISTIE DESIGN

$$\mathcal{L} \supset m\bar{\psi}\psi = m\bar{\psi}(P_L + P_R)\psi \quad m\bar{\psi}_L\psi_R + m\bar{\psi}_R\psi_L$$

Plug in Weyl spinors:

$$\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} \qquad \bar{\psi} = \begin{pmatrix} \psi_R^\dagger & \psi_L^\dagger \end{pmatrix}$$

The Mysteries of MASS

Physicists are hunting for an elusive particle that would reveal the presence of a new kind of field that permeates all of reality. Finding that Higgs field will give us a more complete understanding about how the universe works

By Gordon Kane

Most people think they know what mass is, but they understand only part of the story. For instance, an elephant is clearly bulkier and weighs more than an ant. Even in the absence of gravity, the elephant would have greater mass—it would be harder to push and set in motion. Obviously the elephant is more massive because it is made of many more atoms than the ant is, but what determines the masses of the individual atoms? What about the elementary particles that make up the atoms—what determines their masses? Indeed, why do they even have mass?

We see that the problem of mass has two independent aspects. First, we need to learn how mass arises at all. It turns out mass results from at least three different mechanisms, which I will describe below. A key player in physicists' tentative theories about mass is a new kind of field that permeates all of reality, called the Higgs field. Elementary particle masses are thought to come about from the interaction with the Higgs field. If the Higgs field exists, theory demands that it have an associated particle, the Higgs boson. Using particle accelerators, scientists are now hunting for the Higgs.

The second aspect is that scientists want to know why different species of elementary particles have their specific quantities of mass. Their intrinsic masses span at least 11 orders of magnitude, but we do not yet know why that should be so [*see illustration on page 44*]. For comparison, an elephant and the smallest of ants differ by about 11 orders of magnitude of mass.

What *Is* Mass?

ISAAC NEWTON presented the earliest scientific definition of mass in 1687 in his landmark *Principia*: "The quantity of matter is the measure of the same, arising from its density and bulk conjointly." That very basic definition was good enough for Newton and other scientists for more than 200 years. They understood that science should proceed first by describing how things work and later by understanding why. In recent years, however, the *why* of mass has become a research topic in physics. Understanding the meaning and origins of mass will complete and extend the Standard Model of particle physics, the well-established theory that describes the known elementary particles and their interactions. It will also resolve mysteries such as dark matter, which makes up about 25 percent of the universe.

The foundation of our modern understanding of mass is far more intricate than Newton's definition and is based on the Standard Model. At the heart of the Standard

MALE AFRICAN ELEPHANT (about 6,000 kilograms) and the smallest species of ant (0.01 milligram) differ in mass by more than 11 orders of magnitude—roughly the same span as the top quark and the neutrino. Why the particle masses should differ by such a large amount remains a mystery.

BRYAN CHRISTIE DESIGN

The mass of a fermion equals

$$\mathcal{L} \supset m\psi_L^\dagger\psi_R + m\psi_R^\dagger\psi_L$$

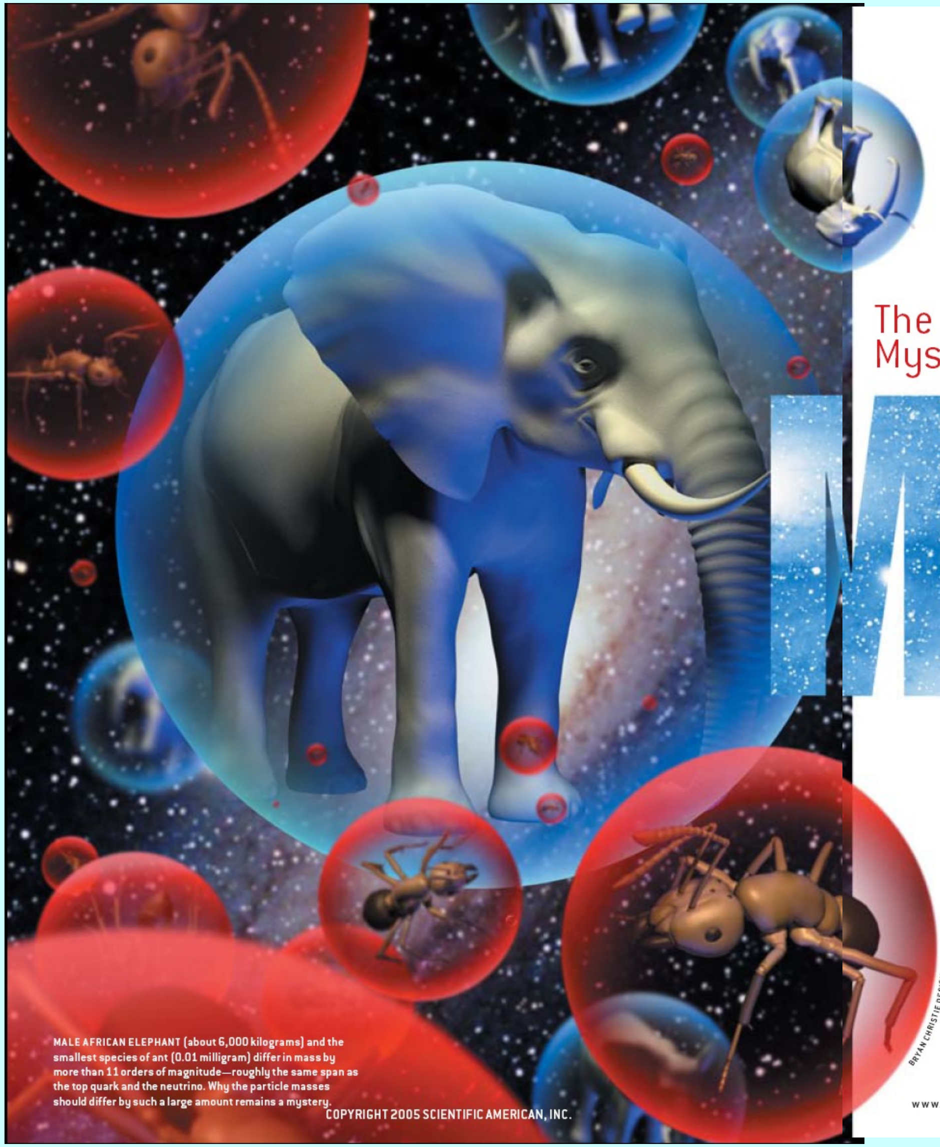
Unlike kinetic energy terms that decouples $\psi_{L,R}$, the mass term mixes them.

$$i\psi_L^\dagger\sigma^\mu\partial_\mu\psi_L + i\psi_R^\dagger\sigma^\mu\partial_\mu\psi_R$$

Massless Fermions could contain just ψ_L or ψ_R.

Massive Fermions usually contain both ψ_L and ψ_R, called Dirac Mass.

參與能分辨左右的弱作用的費米子，原本都應該沒有質量的！對稱不允許。



MALE AFRICAN ELEPHANT (about 6,000 kilograms) and the smallest species of ant (0.01 milligram) differ in mass by more than 11 orders of magnitude—roughly the same span as the top quark and the neutrino. Why the particle masses should differ by such a large amount remains a mystery.

BRYAN CHRISTIE DESIGN

The Mysteries of MASS

Physicists are hunting for an elusive particle that would reveal the presence of a new kind of field that permeates all of reality. Finding that Higgs field will give us a more complete understanding about how the universe works

By Gordon Kane

Most people think they know what mass is, but they understand only part of the story. For instance, an elephant is clearly bulkier and weighs more than an ant. Even in the absence of gravity, the elephant would have greater mass—it would be harder to push and set in motion. Obviously the elephant is more massive because it is made of many more atoms than the ant is, but what determines the masses of the individual atoms? What about the elementary particles that make up the atoms—what determines their masses? Indeed, why do they even have mass?

We see that the problem of mass has two independent aspects. First, we need to learn how mass arises at all. It turns out mass results from at least three different mechanisms, which I will describe below. A key player in physicists' tentative theories about mass is a new kind of field that permeates all of reality, called the Higgs field. Elementary particle masses are thought to come about from the interaction with the Higgs field. If the Higgs field exists, theory demands that it have an associated particle, the Higgs boson. Using particle accelerators, scientists are now hunting for the Higgs.

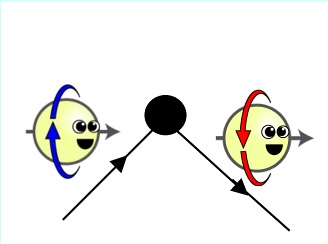
The second aspect is that scientists want to know why different species of elementary particles have their specific quantities of mass. Their intrinsic masses span at least 11 orders of magnitude, but we do not yet know why that should be so [*see illustration on page 44*]. For comparison, an elephant and the smallest of ants differ by about 11 orders of magnitude of mass.

What *Is* Mass?

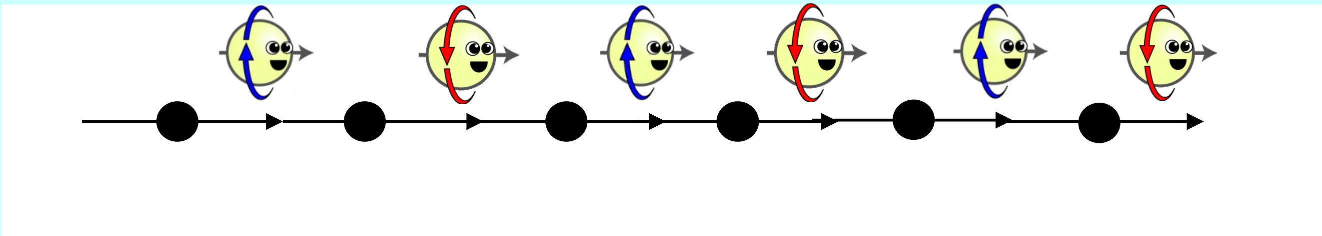
ISAAC NEWTON presented the earliest scientific definition of mass in 1687 in his landmark *Principia*: "The quantity of matter is the measure of the same, arising from its density and bulk conjointly." That very basic definition was good enough for Newton and other scientists for more than 200 years. They understood that science should proceed first by describing how things work and later by understanding why. In recent years, however, the *why* of mass has become a research topic in physics. Understanding the meaning and origins of mass will complete and extend the Standard Model of particle physics, the well-established theory that describes the known elementary particles and their interactions. It will also resolve mysteries such as dark matter, which makes up about 25 percent of the universe.

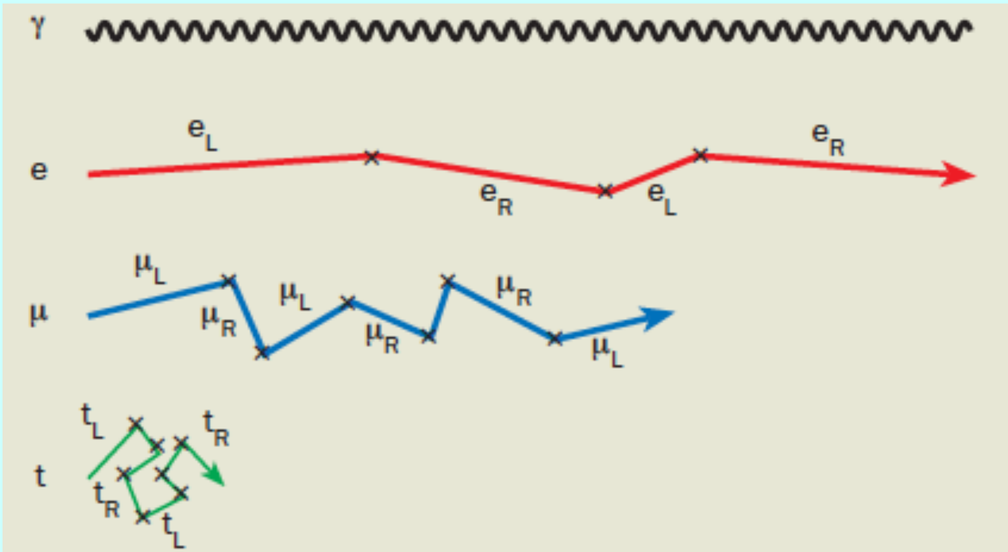
The foundation of our modern understanding of mass is far more intricate than Newton's definition and is based on the Standard Model. At the heart of the Standard

Consider mass term $m\psi_L^\dagger\psi_R + m\psi_R^\dagger\psi_L$ as vertices,



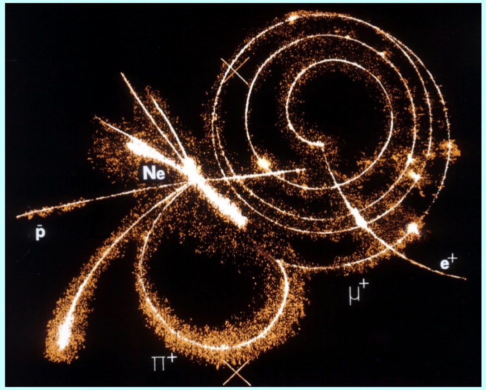
propagation of massive fermion looks like:

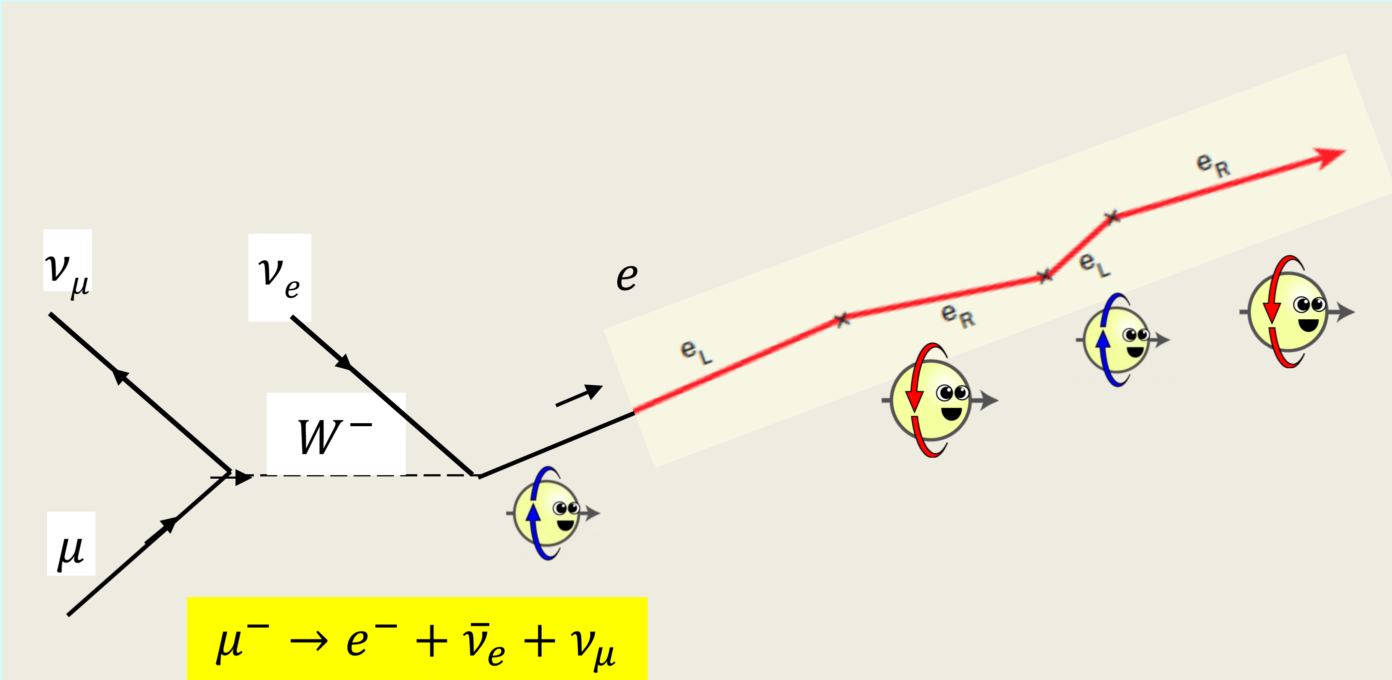




 $_R$

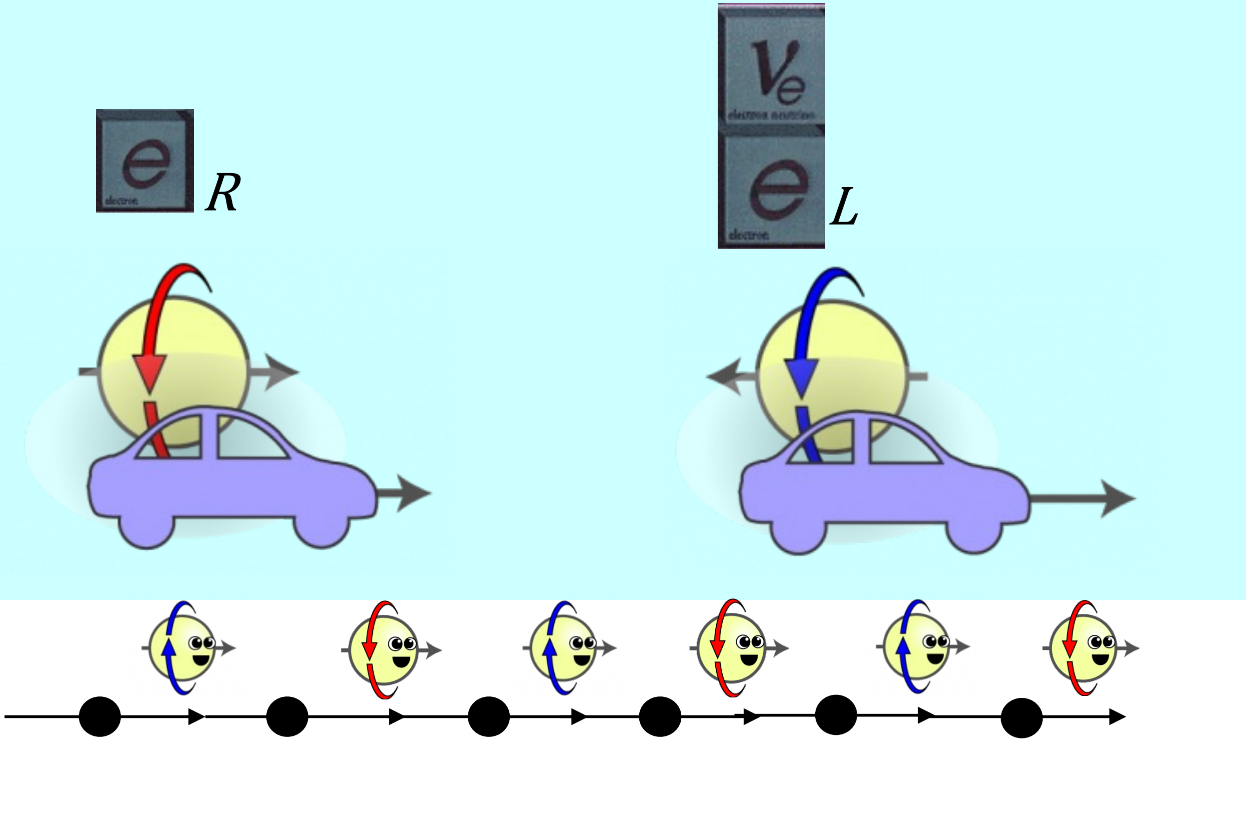
右旋的電子，完全沒有弱交互作用。





All the particles participating the interaction are left-handed.

The right-handedness of electron are developed later when propagating after interaction!



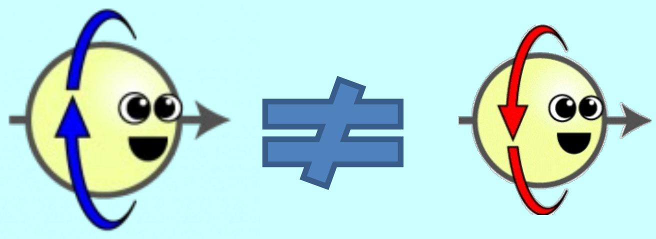
質量是一個左手旋費米子與右手旋費米子必須共同參與的機制！

Mass is a mechanism the right-handed and left-handed particles have to participate together. Without partners of opposite handedness, partciles will be massless.

真實的有質量的電子必須同時是左手旋又是右手旋。它必須有伴！

真實傳播的電子必須同時又是singlet又是doublet。

可見在真實世界，分類的規則被破壞了。這個破壞者就是希格斯場。



$m_e\bar{e}_L e_R + m_e\bar{e}_R e_L$

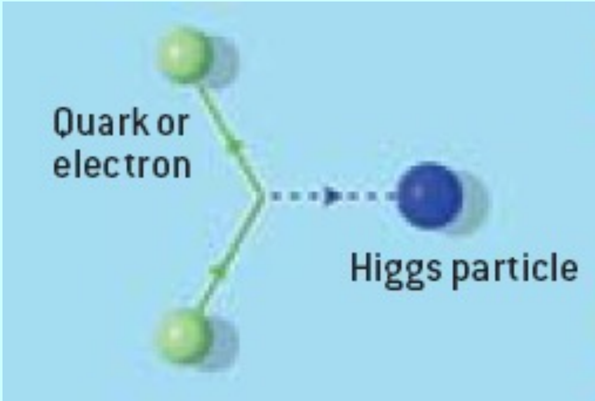
e_L is part of a doublet and e_R is a singlet. The electron mass is not invariant

所有參加 Chiral 弱作用的費米子根據Weak $SU(2)_L$ 對稱性都不能有質量。

所有參加 Chiral 弱作用的費米子都有質量

Weak $SU(2)_L$對稱必須被破壞！

But we have already break $SU(2)_L$ gauge symmetry by Higgs mechanism.



$$H = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$ $$L = \begin{pmatrix} \nu_e \\ e_L \end{pmatrix}$$ $$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$m_e \bar{e}_R e_L + \mathrm{h.c.} \Rightarrow y_e\, \bar{e}_R \left(H^\dagger L\right) + \mathrm{h.c}$$ $$y_d\, \bar{d}_R \left(H^\dagger Q\right) + \mathrm{h.c}$$

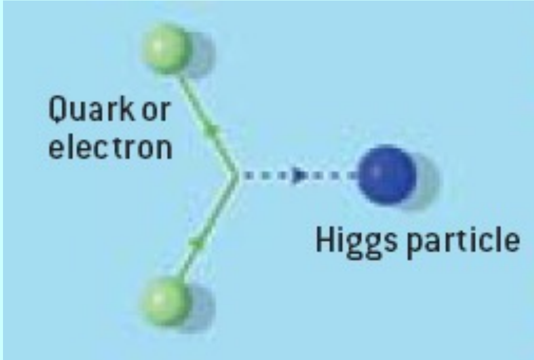
Yukawa Coupling

This is both gauge invariant and Lorentz invariant.

Plug in the non-trivial VEV: $\begin{pmatrix} \langle H^+ \rangle \\ \langle H^0 \rangle \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

$$\left(\frac{1}{\sqrt{2}} y_e v\right) \bar{e}_R e_L + \mathrm{h.c}$$ $$m_e = \frac{1}{\sqrt{2}} y_e v$$ $$m_d = \frac{1}{\sqrt{2}} y_d v$$

How about u quark mass? We need a new doublet Higgs. Not really.



$$H = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$ $$\widetilde{H} = i\tau_2 H^* = \begin{pmatrix} H^{0*} \\ -H^- \end{pmatrix}$$

$\widetilde{H}$ is also a doublet just like H.

$$H \to e^{-i\left(\frac{\tau_1}{2}\cdot\theta_1 + \frac{\tau_2}{2}\cdot\theta_2 + \frac{\tau_3}{2}\cdot\theta_3\right)} H$$

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad \tau_{1,3}\tau_2 = -\tau_2\tau_{1,3}$$

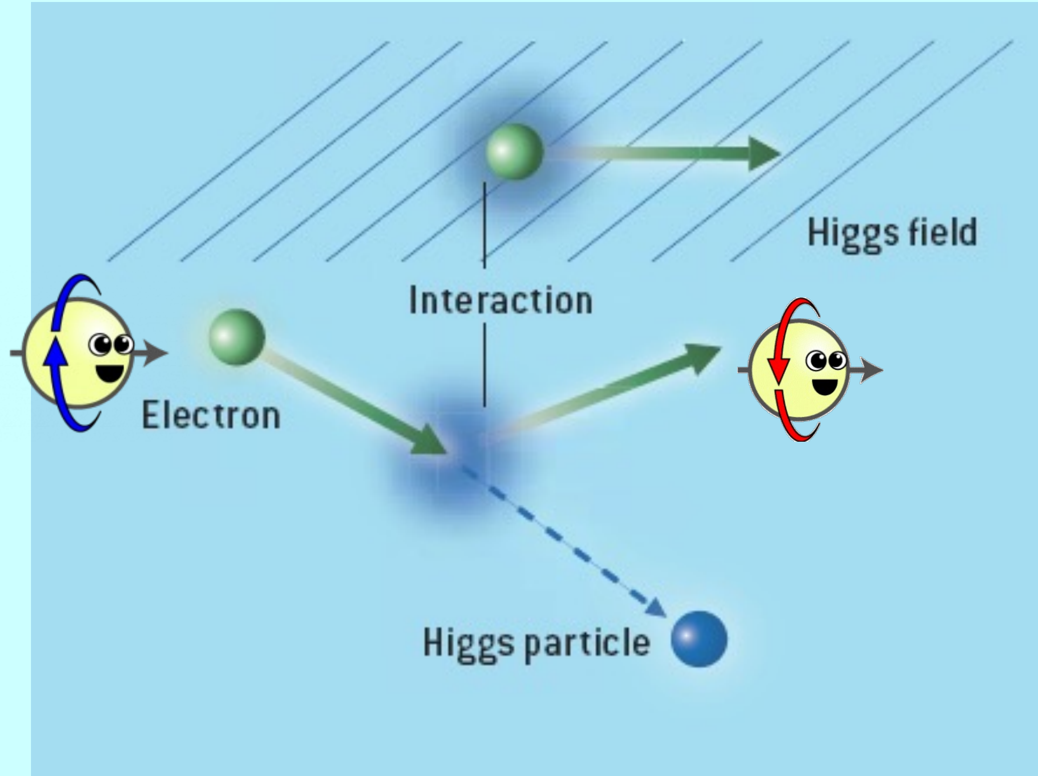
$$\tau_2 H^* \to \tau_2 e^{i\left(\frac{\tau_1}{2}\cdot\theta_1 + \frac{-\tau_2}{2}\cdot\theta_2 + \frac{\tau_3}{2}\cdot\theta_3\right)} H^* = e^{i\left(\frac{-\tau_1}{2}\cdot\theta_1 + \frac{-\tau_2}{2}\cdot\theta_2 + \frac{-\tau_3}{2}\cdot\theta_3\right)} \tau_2 H^* = U\tau_2 H^*$$

$$y_u\, \bar{u}_R \left(\widetilde{H}^\dagger Q\right) + \mathrm{h.c}$$

This is both gauge invariant and Lorentz invariant.

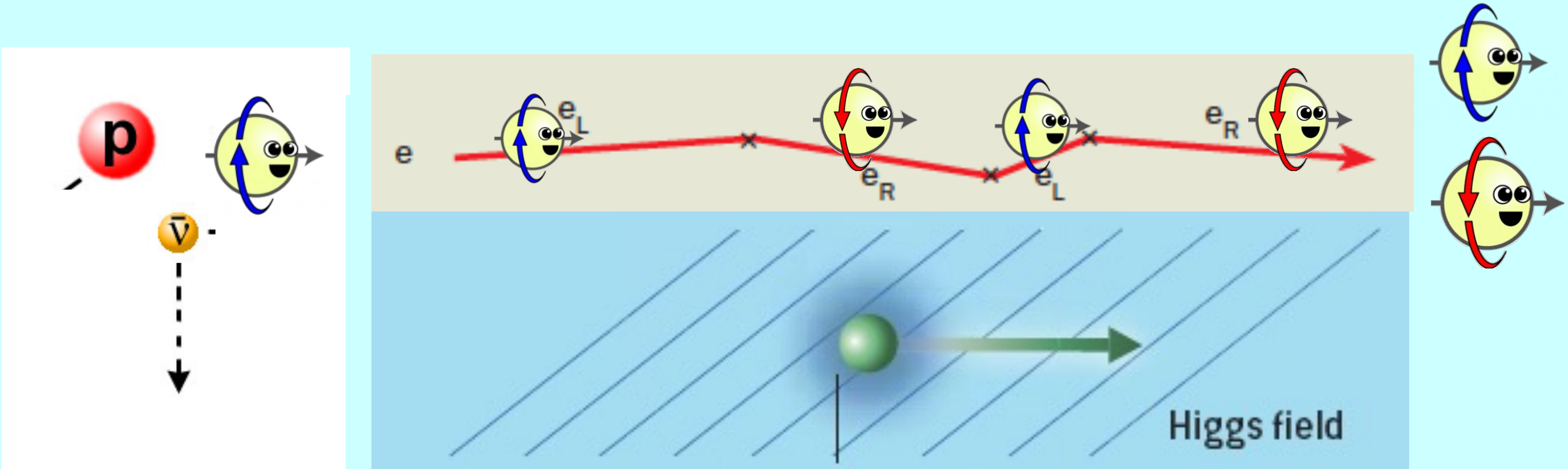
Plug in the non-trivial VEV: $$\begin{pmatrix} \langle H^{0*} \rangle \\ -\langle H^- \rangle \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$$\left(\frac{1}{\sqrt{2}} y_u v\right) \bar{u}_R u_L + \mathrm{h.c} \qquad m_u = \frac{1}{\sqrt{2}} y_u v$$

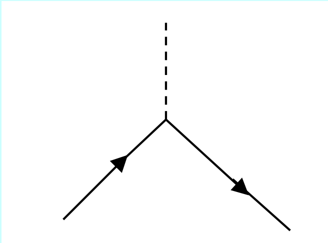


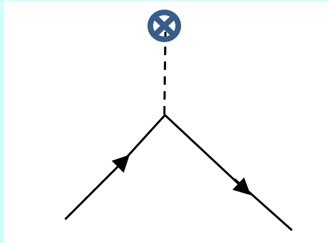
希格斯場或粒子與費米子有交互作用，可將左手旋粒子變成右手旋粒子！

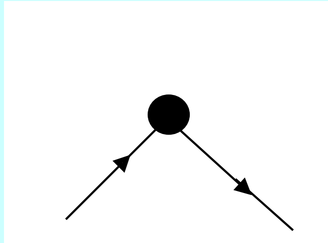
電子從衰變剛剛產生時，是左手旋。

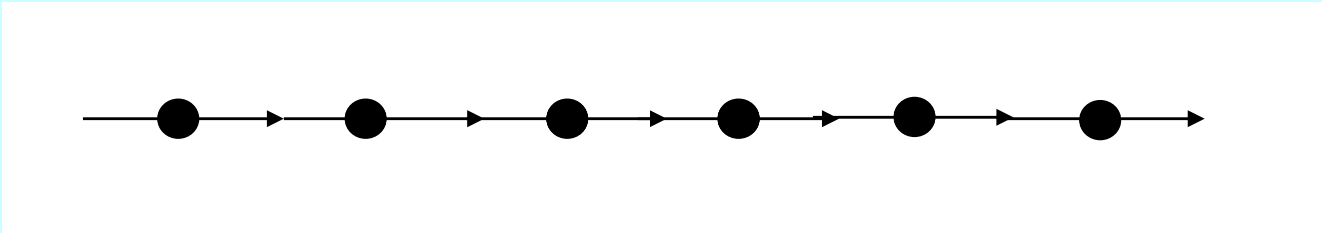


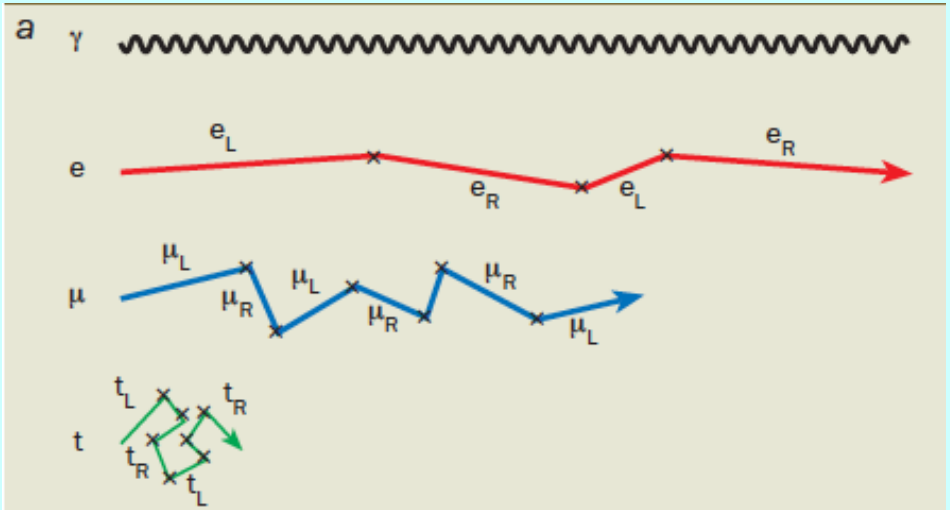
飛了一陣子，被觀測到時，左手旋右手旋都出現了！





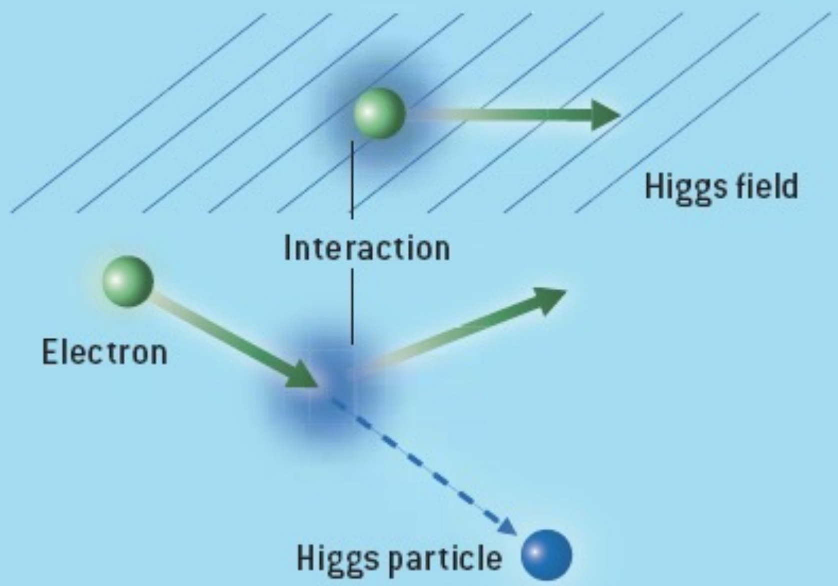





a
γ
e
e_L
e_R
e_L
e_R
μ
$μ_L$
$μ_R$
$μ_L$
$μ_R$
$μ_R$
$μ_L$
t
t_L
t_R
t_R
t_L

CAUSING TWO PHENOMENA

Two completely different phenomena—the acquisition of mass by a particle (*top*) and the production of a Higgs boson (*bottom*)—are caused by exactly the same interaction. This fact will be of great use in testing the Higgs theory by experiments.



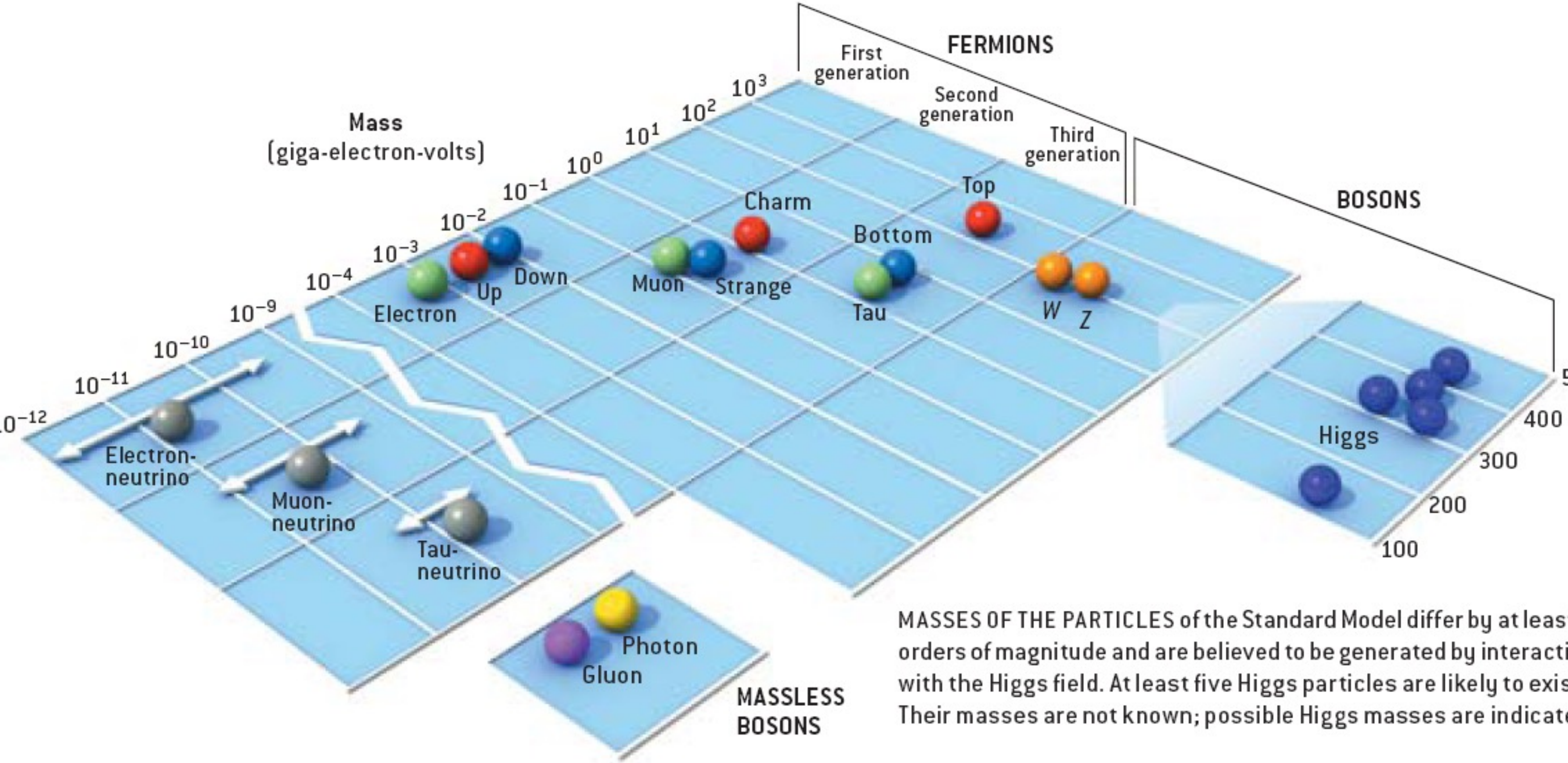
$y_e\ \bar{e}_R(H^\dagger L)$ $y_d\ \bar{e}_R(H^\dagger Q)$ $y_u\ \bar{u}_R(\tilde{H}^\dagger Q)$

$$m_e = \frac{1}{\sqrt{2}} y_e v$$

$$m_d = \frac{1}{\sqrt{2}} y_d v$$

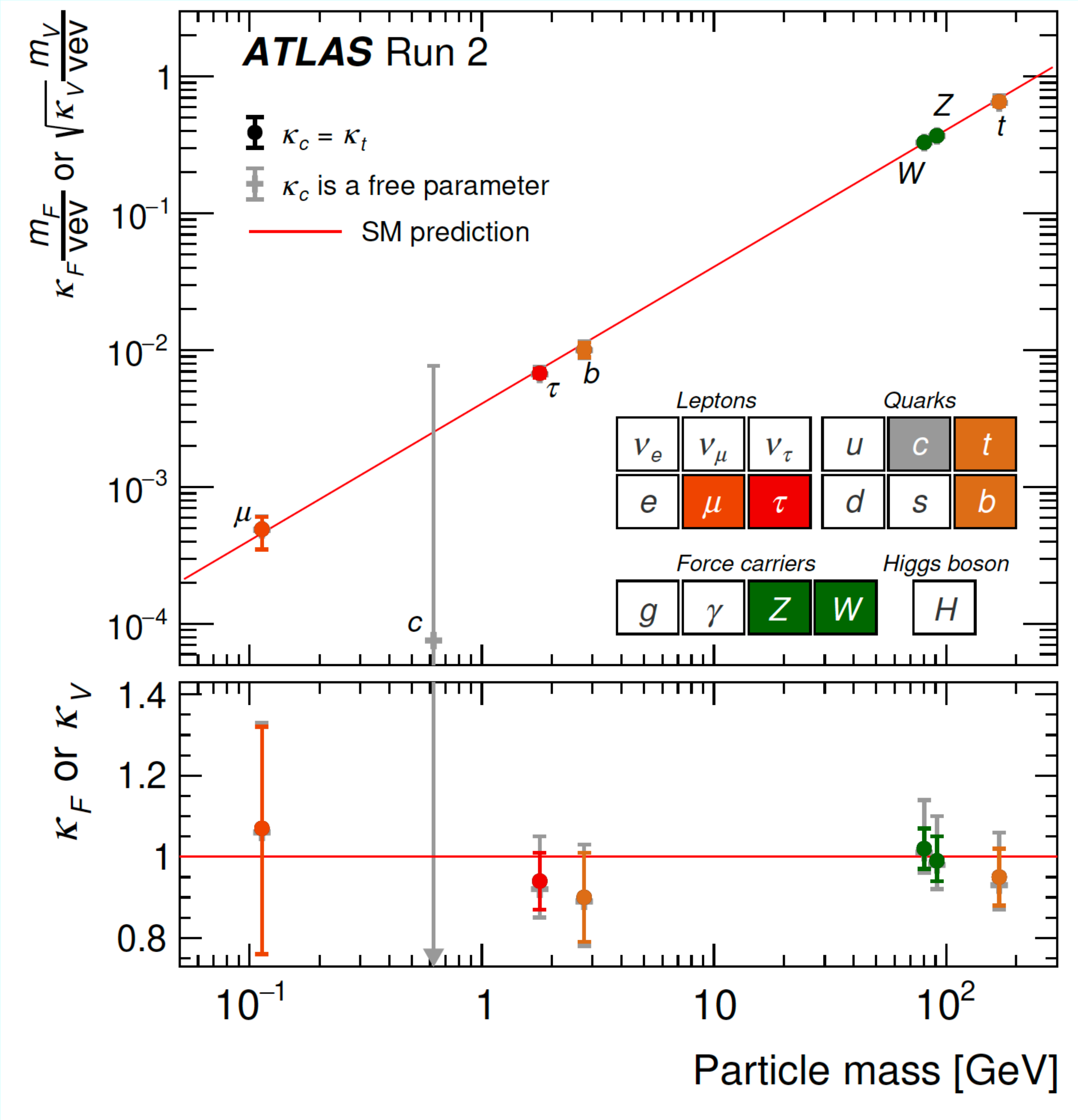
$$m_u = \frac{1}{\sqrt{2}} y_u v$$

費米子的質量及此粒子與 Higgs 粒子的交互作用是同一回事！



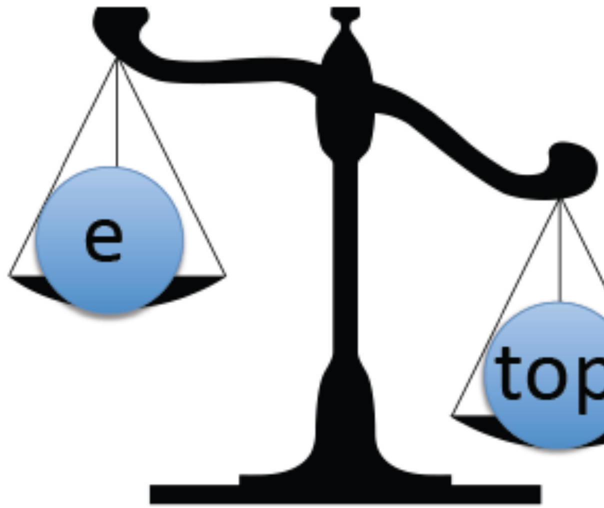
MASSES OF THE PARTICLES of the Standard Model differ by at least 11 orders of magnitude and are believed to be generated by interactions with the Higgs field. At least five Higgs particles are likely to exist. Their masses are not known; possible Higgs masses are indicated.

基本粒子質量m的分布就反映它們跟希格斯粒子的作用強度y！



ATLAS Run 2
$\kappa_c = \kappa_t$
κ_c is a free parameter
SM prediction
Leptons
Quarks
Force carriers
Higgs boson
ν_e ν_μ ν_τ u c t
e μ τ d s b
g γ Z W H
$\kappa_F \frac{m_F}{\text{vev}}$ or $\sqrt{\kappa_V}\frac{m_V}{\text{vev}}$
κ_F or κ_V
Particle mass [GeV]

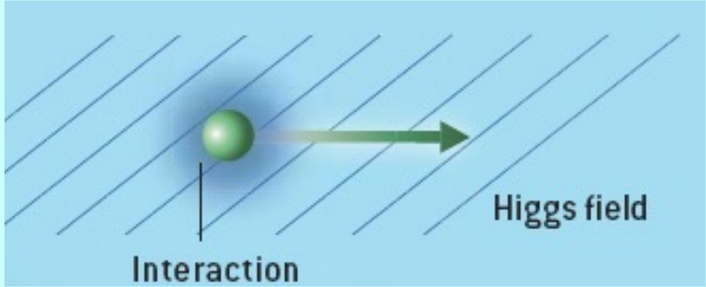
Masses for particles



The more a particle interacts with the Higgs boson, the heavier it is

It is Higgs field, not Higgs boson that gives everything its mass!

所有的費米子都是藉著與真空中的希格斯場交互作用而得到質量。

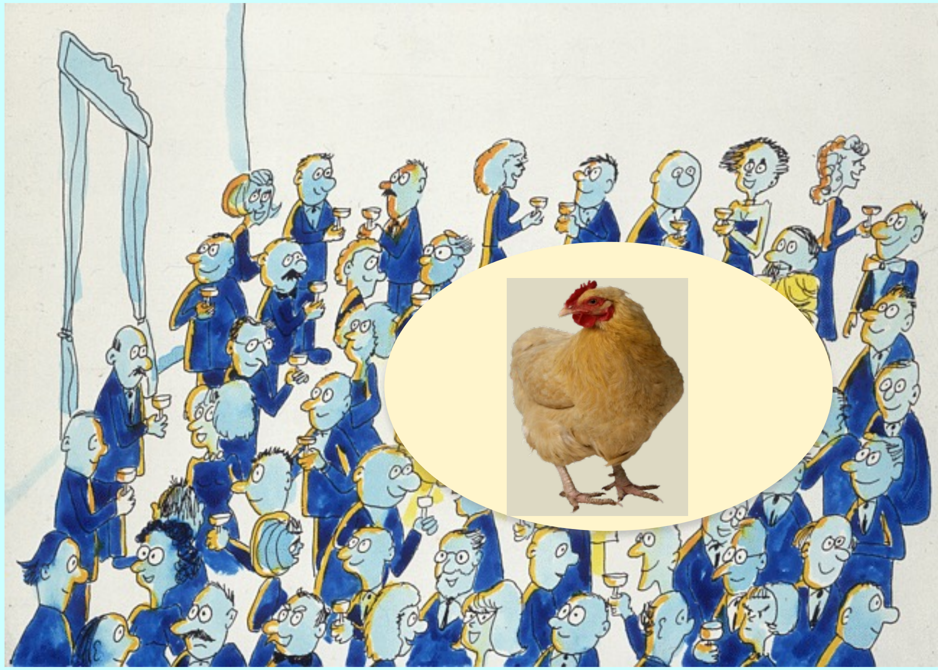


不是希格斯粒子。

Vacuum is not trivial!

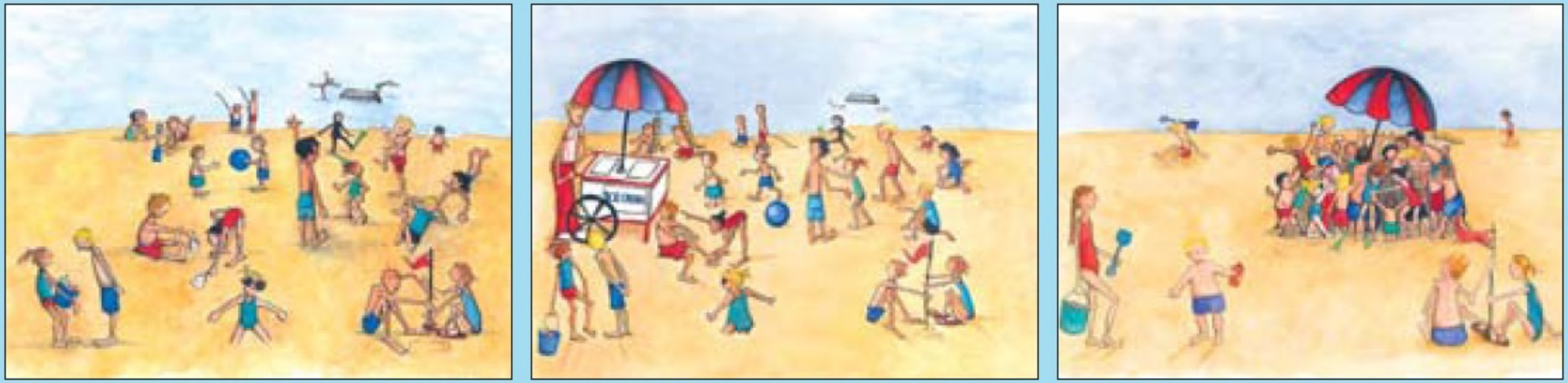
受歡迎，與希格斯場交互作用強的粒子，走起來就會較慢，慣性大！

不受歡迎，交互作用弱的粒子，慣性小，走起來就會較快！



- Theories say that elementary particles acquire mass by interacting with a quantum field that permeates all of reality. Experiments at particle accelerators may soon detect direct evidence of this so-called Higgs field.

HOW THE HIGGS FIELD GENERATES MASS



"Empty" space, which is filled with the Higgs field, is like a beach full of children.

A particle crossing that region of space is like an ice cream vendor arriving ...

... and interacting with kids who slow him down—as if he acquires "mass."

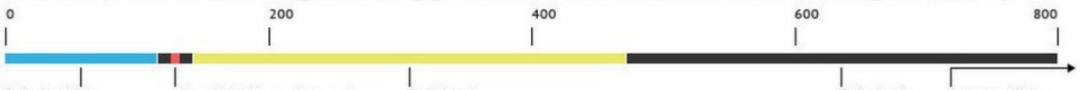
The Higgs Boson:
The Missing Particle of the Standard Model

The modern Standard Model of particle physics presupposes the existence of a particle responsible for the mass of other particles. The discovery of a similar particle was announced on July 4, 2012

The Higgs Field is a hypothetical universal field comprising Higgs bosons

Other elementary particles slow down, while contacting this field. Consequently, the particles acquire mass

History of searching for Higgs Boson in various mass ranges (GeV)



Ruled out by LEP * measurements

before 2001

up to 114 GeV

The LHC ** registered a particle with specifications similar to the Higgs Boson in the 125-126 GeV mass range

Ruled out by LHC ** measurements

as of 2011

141-470 GeV

Ruled out by indirect measurements

470 GeV and more

Incompatible with the Standard Model

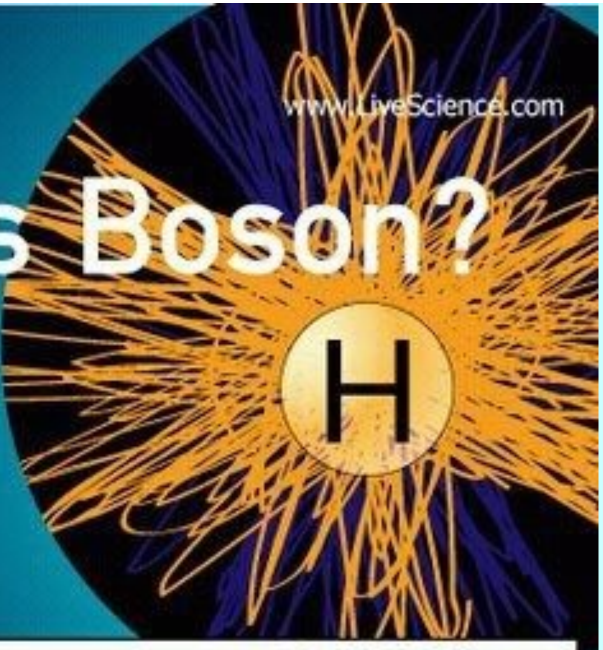
over 800 GeV

* LEP – Large Electron Positron Collider, the predecessor of the LHC (was located inside the same tunnel)

** LHC – Large Hadron Collider, the largest particle accelerator in terms of its energy levels. Searching for the Higgs Boson is one of its main tasks

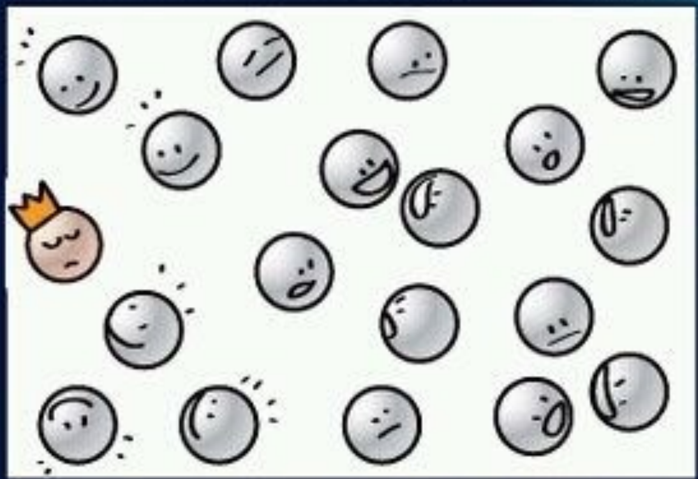
LIVE SCIENCE.

What is a Higgs Boson?

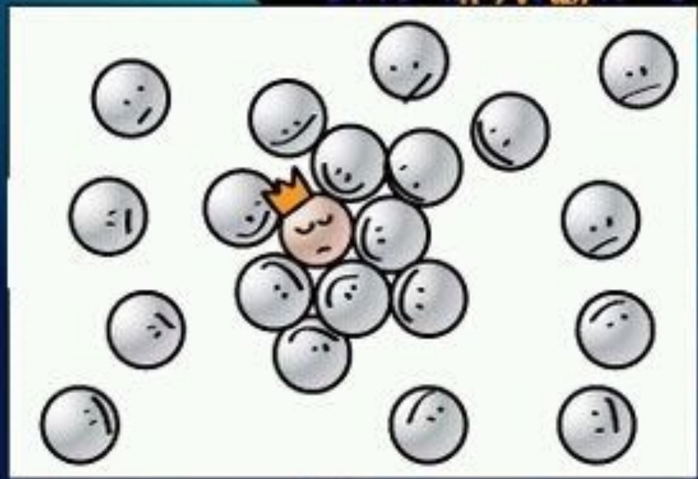


The elusive Higgs boson, if found, would complete the Standard Model of physics. It is thought that matter obtains mass by interacting with the Higgs field. If Higgs did not exist, according to the model, everything in the universe would be massless.

The "cocktail party" analogy



Imagine a party where guests are evenly spaced around the room. The room of guests represents the Higgs field, which is everywhere in the universe. Suddenly a celebrity enters. Guests notice the celebrity and rush in closer to be near her, forming a tight knot.



As the celebrity passes through the room, the concentrated clump of guests surrounding her gives the group additional momentum. The clump is harder to stop than one guest alone would be, and so we can say that the clump has acquired mass.

SOURCE: CERN

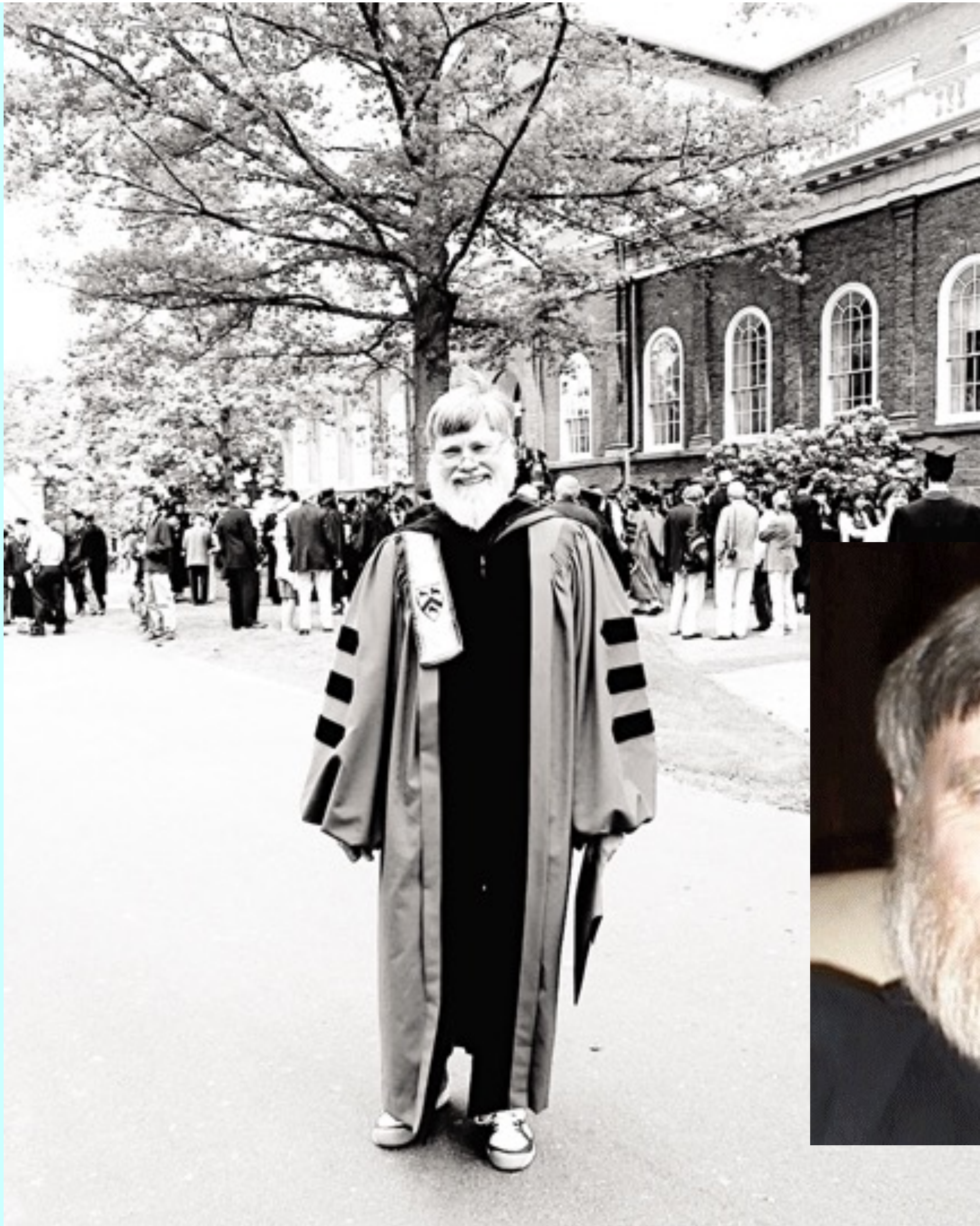
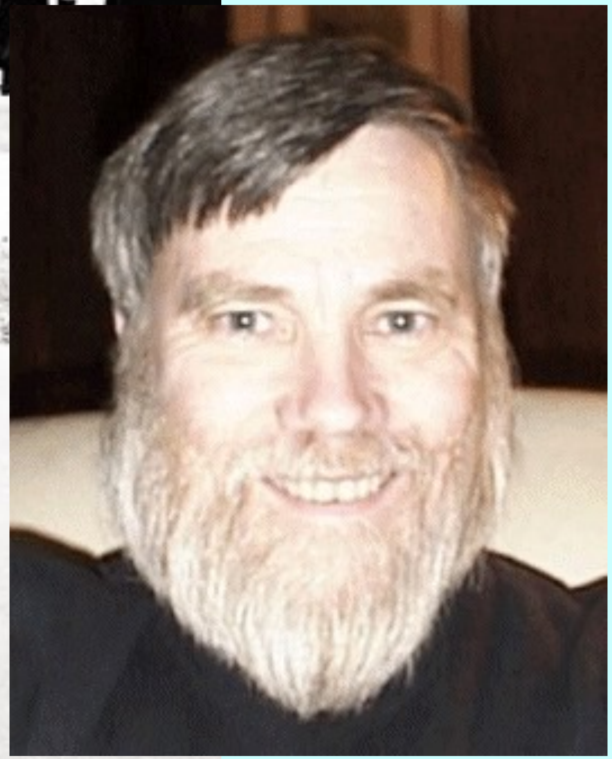
Why I would be very sad if a Higgs boson were discovered*†

Howard Georgi
Lyman Laboratory of Physics
Harvard University
Cambridge, MA 02138

Abstract

I explain the difference between the Higgs mechanism and the Higgs, discuss various options for spontaneous $SU(2) \times U(1)$ symmetry breaking and quark and lepton mass generation, and speculate about chiral gauge theories.

為什麼，假如希格斯粒子被發現了，我會覺得非常失望？

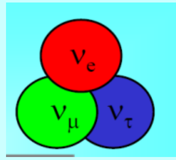



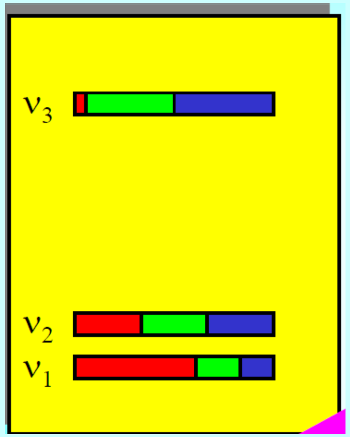
Pontecorvo發現，風味微中子可能不是可永久保存的定態！

固定風味微中子
(Flavor eigenstates)

Mixing

配方



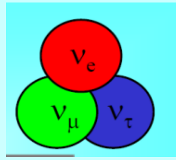


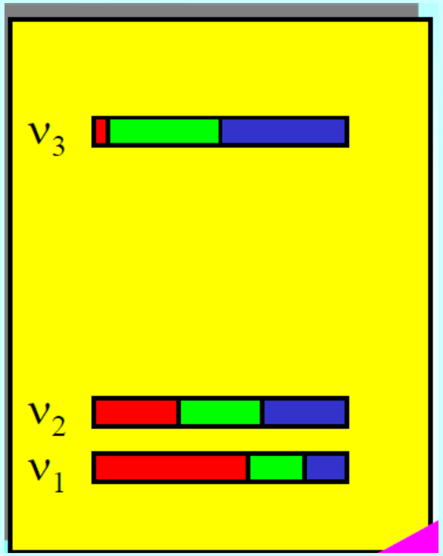
可以持久保存的微中子
（mass eigenstates）

如果微中子有質量：

可以持久保存的微中子必須是 風味微中子 的混合（疊加）！

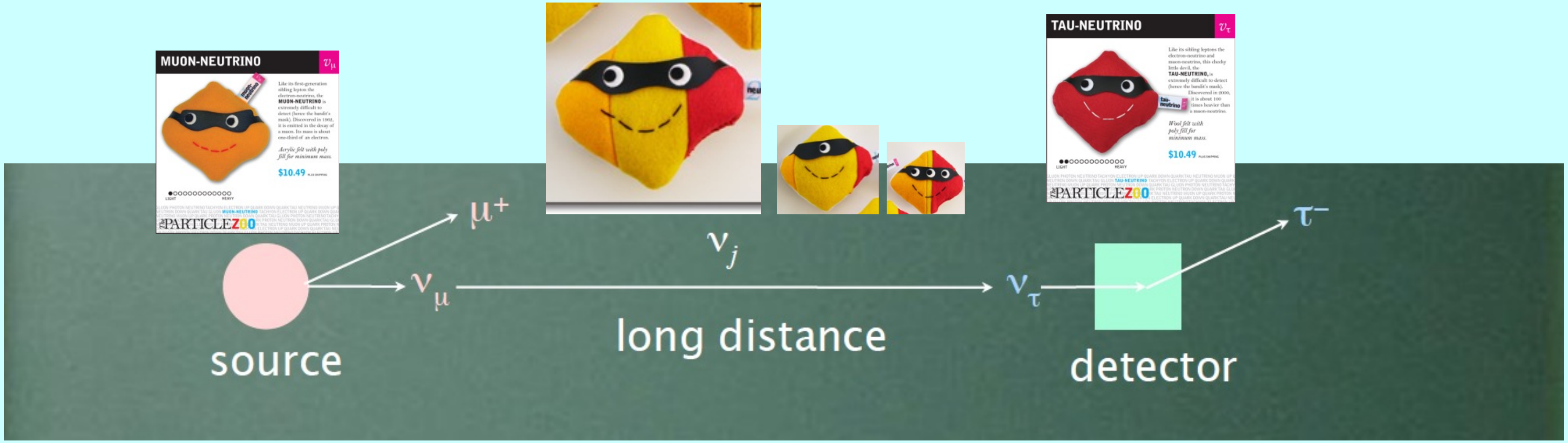
Mixing





Neutrinos in their mass eigenstates, which are a combination of their flavor (orange, yellow, red) eigenstates

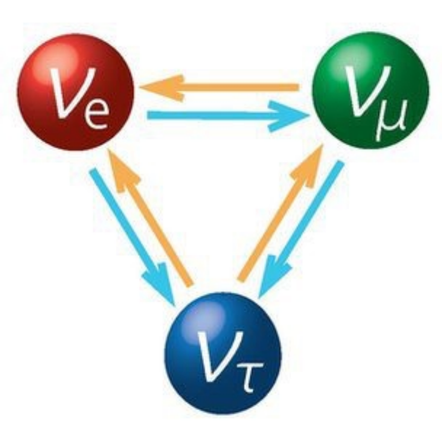
如果是如此，長程旅行，風味微中子一定會變味！



長途旅行，微中子必須以定態的面貌出現，

如果三個定態質量不同，到了遠方，就會有其他風味的微中子顯露出來！

Neutrino Oscillation!

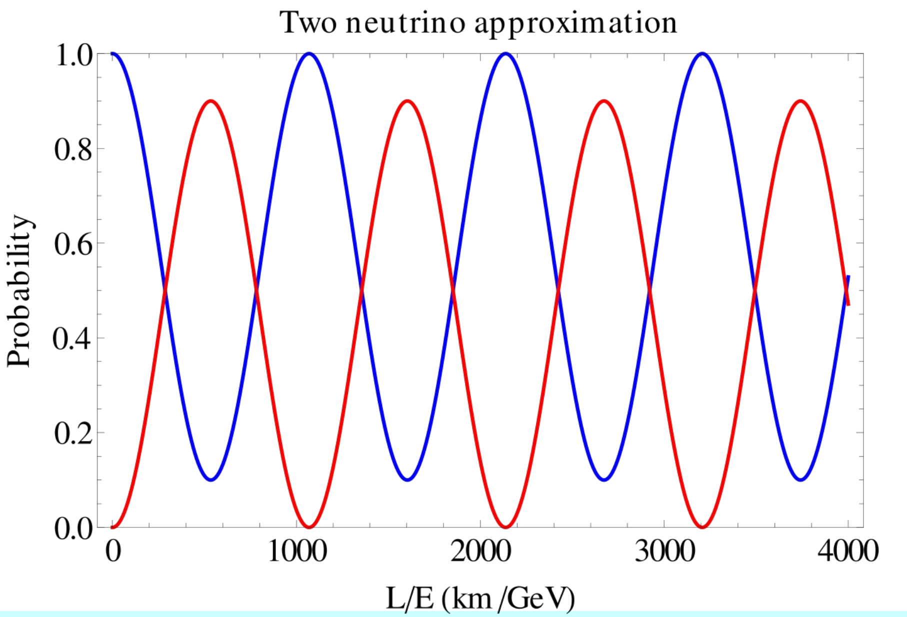


不同風味的微中子的質量差 ↔ Neutrino Oscillation

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \frac{(m_1^2 - m_2^2)L}{4E}$$

L = Distance to Source [m]

E_ν = Neutrino Energy [MeV]

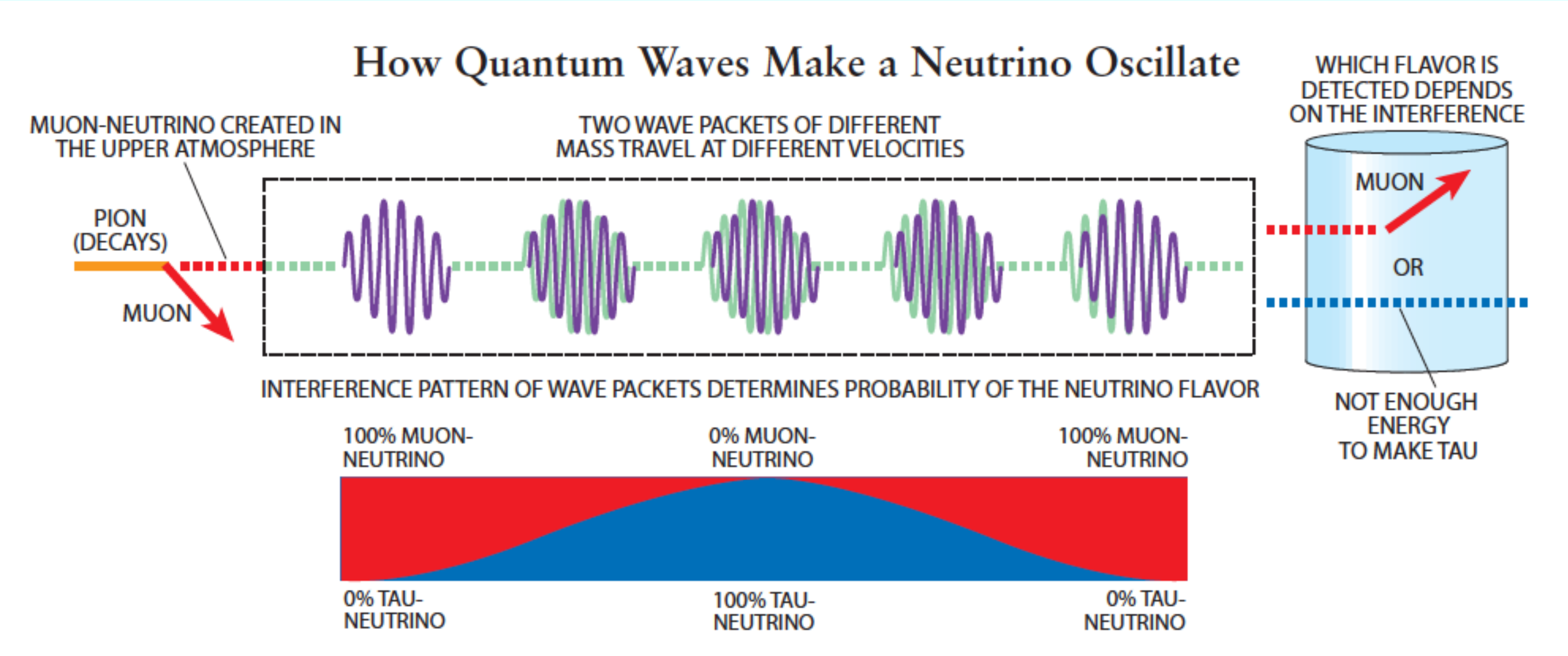


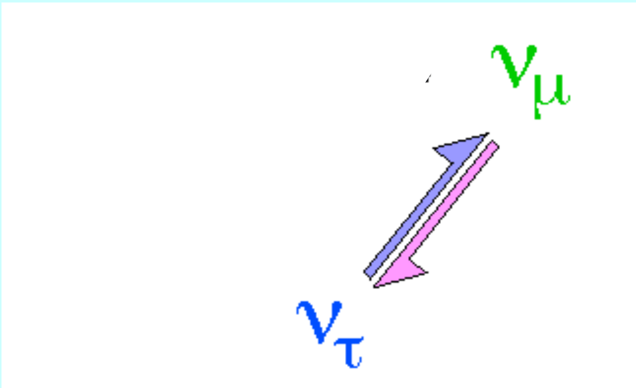
微中子變味的機率是距離的震盪函數。

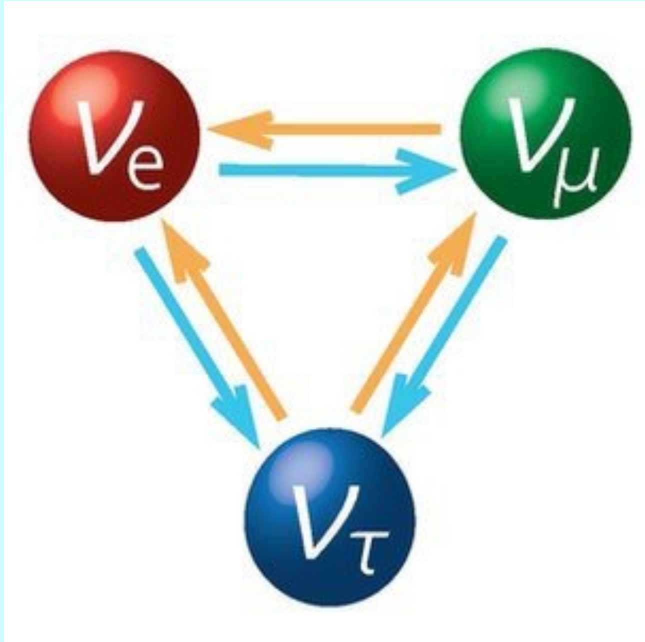
有質量差自然有質量。

量到微中子震盪就相當於量到微中子質量。

四川的變臉表演


How Quantum Waves Make a Neutrino Oscillate
MUON-NEUTRINO CREATED IN THE UPPER ATMOSPHERE
TWO WAVE PACKETS OF DIFFERENT MASS TRAVEL AT DIFFERENT VELOCITIES
WHICH FLAVOR IS DETECTED DEPENDS ON THE INTERFERENCE
PION (DECAYS)
MUON
MUON
OR
NOT ENOUGH ENERGY TO MAKE TAU
INTERFERENCE PATTERN OF WAVE PACKETS DETERMINES PROBABILITY OF THE NEUTRINO FLAVOR
100% MUON-NEUTRINO
0% MUON-NEUTRINO
100% MUON-NEUTRINO
0% TAU-NEUTRINO
100% TAU-NEUTRINO
0% TAU-NEUTRINO


ν_μ
ν_τ



會變臉的微中子一定是有質量的！

Neutrino Properties

See the note on "Neutrino properties listings" in the Particle Listings.

Mass $m < 2$ eV (tritium decay)

Mean life/mass, $\tau/m > 300$ s/eV, CL = 90% (reactor)

Mean life/mass, $\tau/m > 7 \times 10^9$ s/eV (solar)

Mean life/mass, $\tau/m > 15.4$ s/eV, CL = 90% (accelerator)

Magnetic moment $\mu < 0.29 \times 10^{-10}\ \mu_B$, CL = 90% (reactor)

Number of Neutrino Types

Number $N = 2.984 \pm 0.008$ (Standard Model fits to LEP data)

Number $N = 2.92 \pm 0.05$ (S = 1.2) (Direct measurement of invisible Z width)

Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Mass, Mixing, and Oscillations" by K. Nakamura and S.T. Petcov in this *Review*.

$\sin^2(2\theta_{12}) = 0.846 \pm 0.021$

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2

$\sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018}$ (normal mass hierarchy)

$\sin^2(2\theta_{23}) = 1.000^{+0.000}_{-0.017}$ (inverted mass hierarchy)

$\Delta m^2_{32} = (2.44 \pm 0.06) \times 10^{-3}$ eV^2 [i] (normal mass hierarchy)

$\Delta m^2_{32} = (2.52 \pm 0.07) \times 10^{-3}$ eV^2 [i] (inverted mass hierarchy)

$\sin^2(2\theta_{13}) = (9.3 \pm 0.8) \times 10^{-2}$

Stable Neutral Heavy Lepton Mass Limits

Mass $m > 45.0$ GeV, CL = 95% (Dirac)

Mass $m > 39.5$ GeV, CL = 95% (Majorana)

Neutral Heavy Lepton Mass Limits

Mass $m > 90.3$ GeV, CL = 95%

(Dirac ν_L coupling to e, μ, τ; conservative case(τ))

Mass $m > 80.5$ GeV, CL = 95%

(Majorana ν_L coupling to e, μ, τ; conservative case(τ))

Massive Fermions usually contain both ψ_L and ψ_R.

But it is not a must! We can generate a ψ_R from ψ_L.

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad \sigma_{1,3}\sigma_2 = -\sigma_2\sigma_{1,3}$$

$$\frac{1}{2}\vec{\sigma} \cdot \hat{p}\, \psi_L = -\frac{1}{2}\psi_L \quad \frac{1}{2}\vec{\sigma} \cdot \hat{p}\, \psi_R = \frac{1}{2}\psi_R$$

Try the complex conjugate of ψ_L. $i\sigma_2\psi_L^*$

$$\vec{\sigma} \cdot \hat{p}(\sigma_2\psi_L^*) = (\sigma_1 p_1 + \sigma_2 p_2 + \sigma_3 p_3)(\sigma_2\psi_L^*)$$

$$= \sigma_2(-\sigma_1 p_1 + \sigma_2 p_2 - \sigma_3 p_3)(\psi_L^*) = \sigma_2(-\sigma_1^* p_1 - \sigma_2^* p_2 - \sigma_3^* p_3)\psi_L^*$$

$$= \sigma_2(-\vec{\sigma} \cdot \hat{p}\, \psi_L)^* = \frac{1}{2}\sigma_2\psi_L^*$$

$i\sigma_2\psi_L^* \sim \psi_R$ is a right-handed field!

$\frac{m}{2}\bar{\psi}\psi$ $\quad$ $\psi \equiv \begin{pmatrix} \psi_L \\ i\sigma_2\psi_L^* \end{pmatrix}$ Majorana mass

The mass term mixes ψ_L with ψ_L^*. It mean fermion and anti-fermion are mixed.

This kind of mass term is only for charge neutral particle, such as neutrino.

Or use Weyl spinors:

The mass of a fermion equals

$\mathcal{L} \supset m\psi_L^\dagger\psi_R + m\psi_R^\dagger\psi_L$ $\quad$ $i\sigma_2\psi_L^* \sim \psi_R$

$im\psi_L^\dagger\sigma_2\psi_L^* - im\psi_L^T\sigma_2\psi_L$ $\quad$ $-im\psi_L^T\sigma_2\psi_L + \mathrm{h.c.}$

$\psi_L \equiv \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$ $\quad$ $\psi_L^T\sigma_2\psi_L = (\psi_1, \psi_2)\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} = -i(\psi_1\psi_2 - \psi_2\psi_1)$

Massive Neutral Fermions could contain just ψ_L or ψ_R.

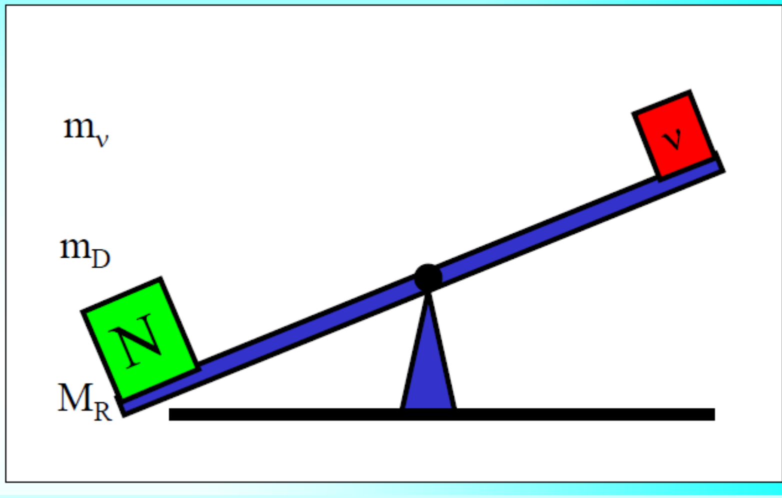
Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

Why is neutrino mass so small?

The smallness of neutrino mass may indicate it arise from a new scale other than EW.

See-saw

P. Minkowski
T. Yanagida
M. Gell-Mann, P. Ramond, R. Slansky
S. L. Glashow
R.N. Mohapatra, G. Senjanovic



Seesaw mechanism of neutrino mass consists of Majorana mass terms:

$$\sim (\nu_L^T \quad \nu_R^T) \cdot \sigma_2 \cdot \begin{pmatrix} 0 & m_\nu^D \\ m_\nu^D & M_R \end{pmatrix} \cdot \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

The eigenvalues are respective $\frac{(m_\nu^D)^2}{M_R}$ and M_R

If m_D is weak scale $\sim 10^3 \mathrm{GeV}$, a $M_R \sim 10^{14} \mathrm{GeV}$ will give small enough neutrino mass.

But a high energy seesaw means the new mechanism is beyond our reach of detection.