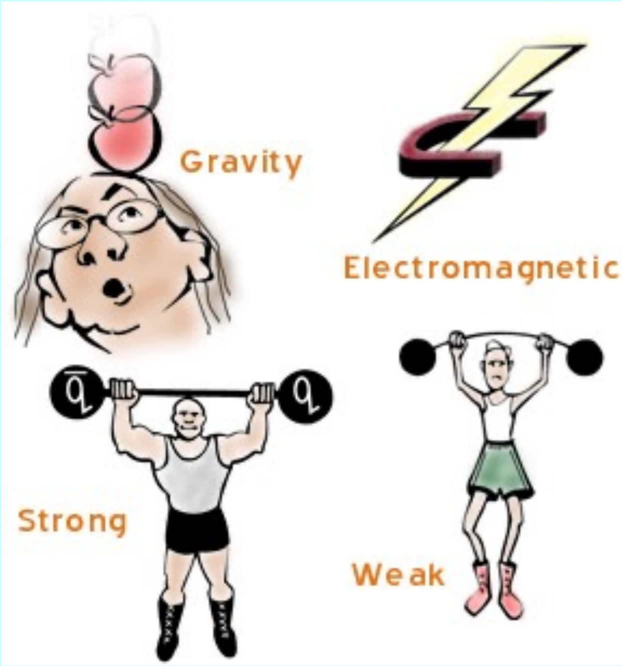
The secret of universe is the following:

Weak and Electromagnetic interaction is one $SU(2)\times U(1)$ gauge theory.

Strong interaction is a $SU(3)$ gauge theory.

This is usually called the standard model of particle physics.



What are the doublets of electroweak $SU(2)$?

What is the triplet gauge bosons of electroweak $SU(2)$?

What are the triplets of strong $SU(3)$?

In search of the interaction Lagrangian $\mathcal{L}_I$ for weak interaction.

尋找弱作用的基本作用交點 vertices.

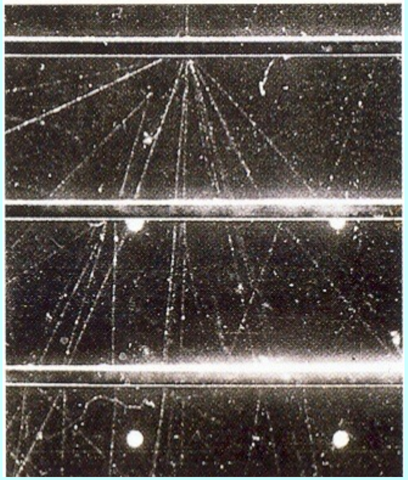
Weak interaction decay

β Decay $n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$

Pion Decay $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

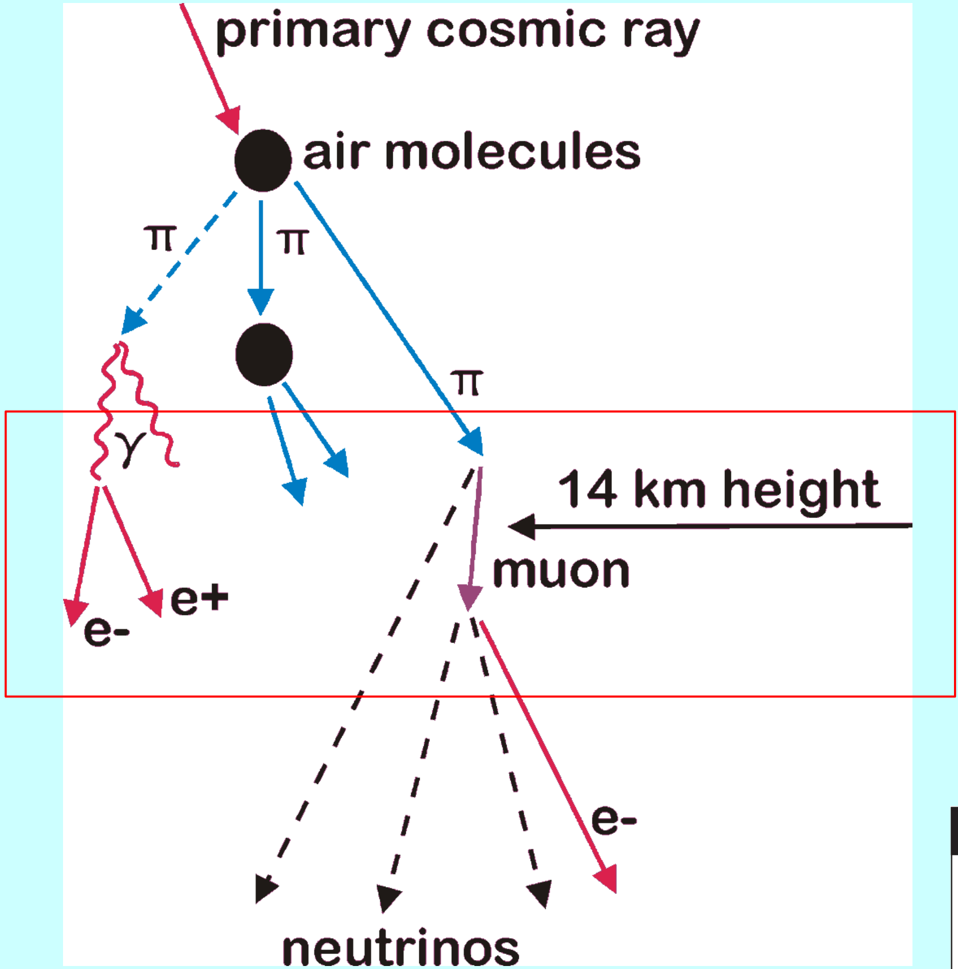
Muon Decay $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

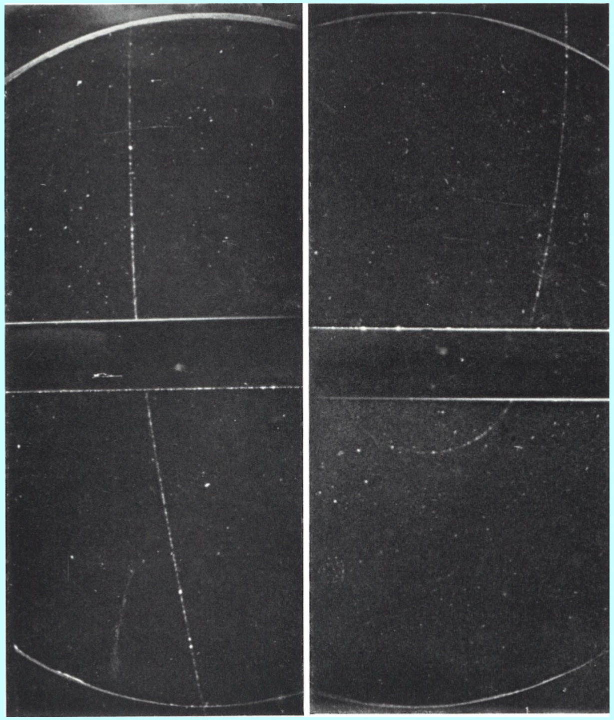
高速宇宙射線打擊高空氣體分子，產生新的基本粒子



新的基本粒子π會衰變，衰變產物主要就是緲子μ。

在地面已幾乎看不到π Pion，但緲子可以飛行到達地面，速度都是近光速等級。





緲子μ壽命也只有百萬分之一秒衰變為電子。

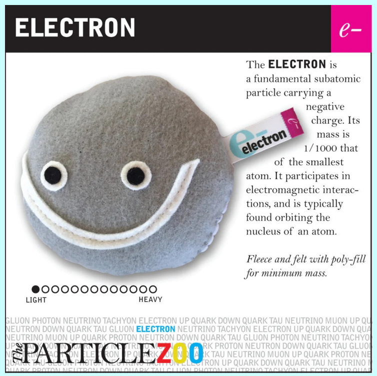
μ

$J = \frac{1}{2}$

Mass $m = 0.1134289267 \pm 0.0000000029$ u

Mass $m = 105.6583715 \pm 0.0000035$ MeV

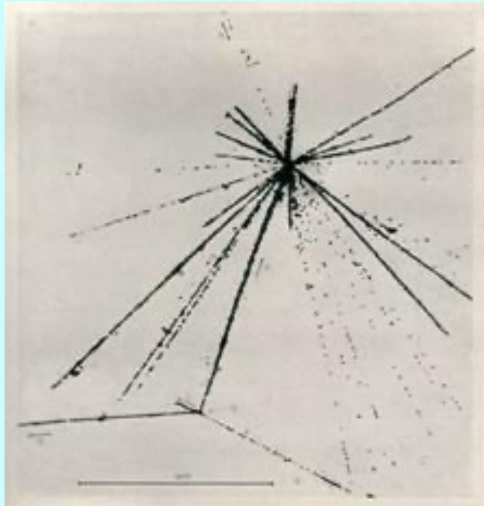
Mean life $\tau = (2.1969811 \pm 0.0000022) \times 10^{-6}$ s

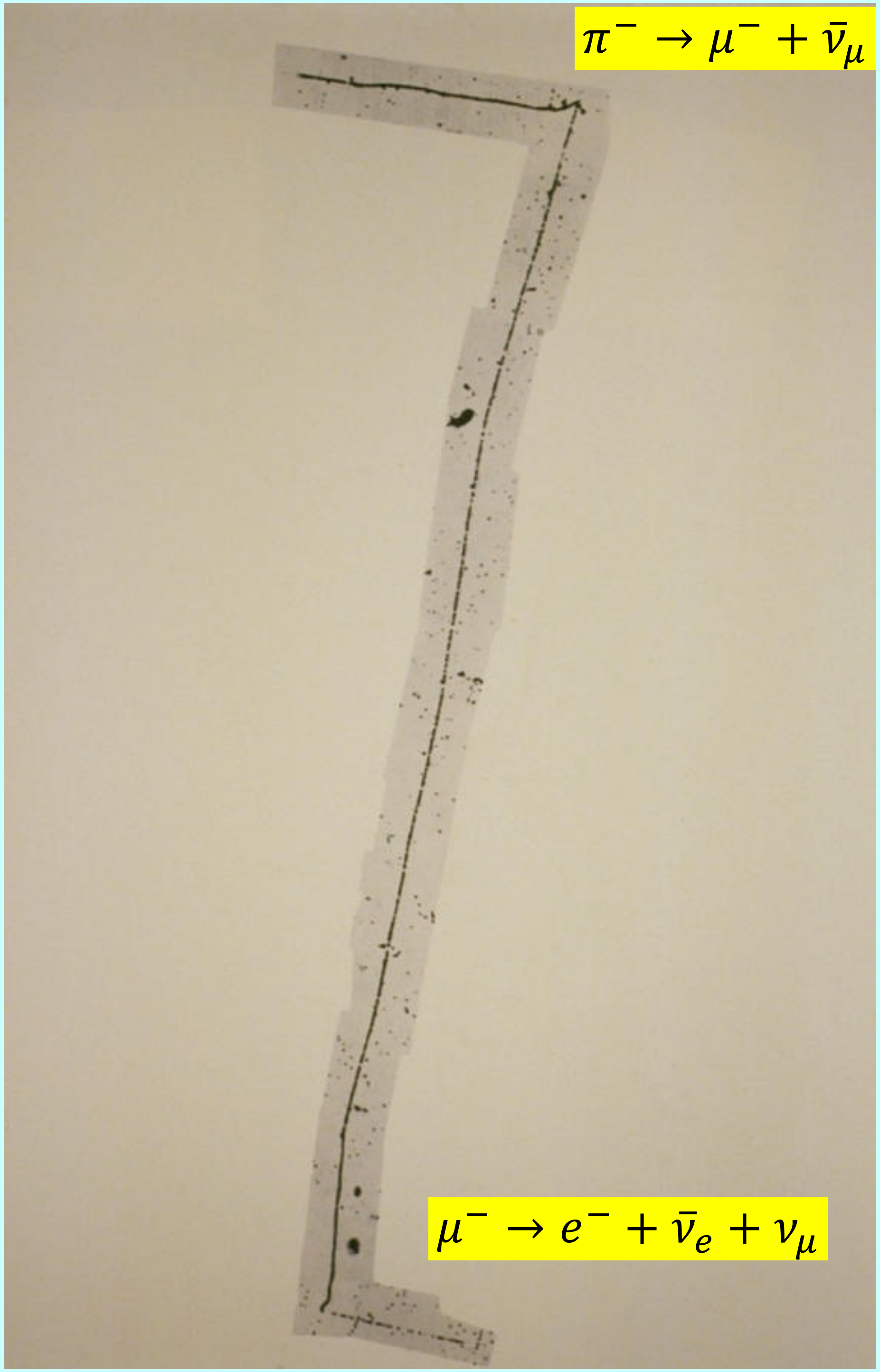


Emulsion photograph

物理學家開始使用相片膠捲軟片來觀測。

更容易攜帶到高空或高山進行實驗。

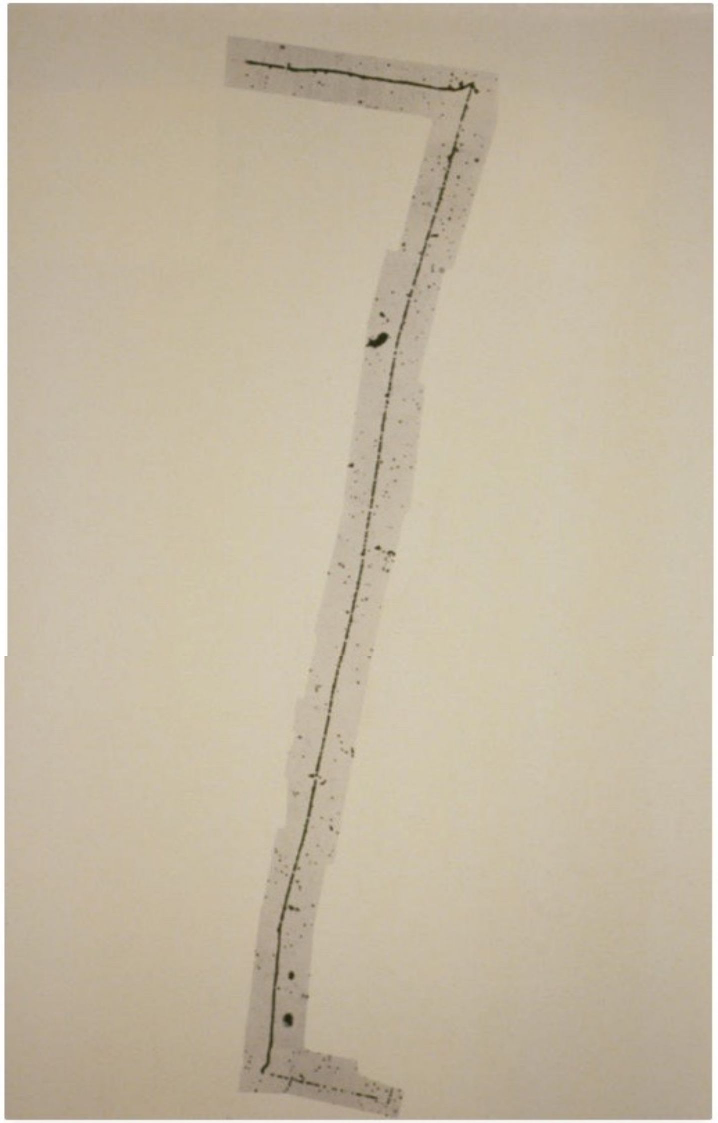




C. F. Powell

Emulsion photograph showing the classic pion-muon- electron (pi-mu-e) decay chain of a charged cosmic ray pion. The pion enters the picture at top left; it soon decays to a muon, which travels down the picture, & a neutrino, which is neutral & so leaves no track. At the bottom of the picture, the muon decays to an electron - the faint track heading to the right - & another neutrino. The muon's track, which is about 0.6 mm long, becomes denser as the muon slows down before decaying. The picture was taken in 1948 by Cecil Powell, the English physicist who pioneered the use of photo-graphic emulsions to record particle tracks.

< Back to C. Powell, P. Fowler & D. Perkins | Art > Photographs > Pion Photographs



Pion-muon-electron (pi-mu-e) Decay Chain is a photograph by C. Powell, P. Fowler & D. Perkins which was uploaded on May 2nd, 2013.

< PREV | NEXT >

Pion-muon-electron (pi-mu-e) Decay Chain

Emulsion photograph showing the classic pion-muon- electron (pi-mu-e) decay chain of a charged cosmic ray pion. The pion enters the picture at top... more

by **C. Powell, P. Fowler & D. Per...**

Title
Pion-muon-electron (pi-mu-e) Decay Chain

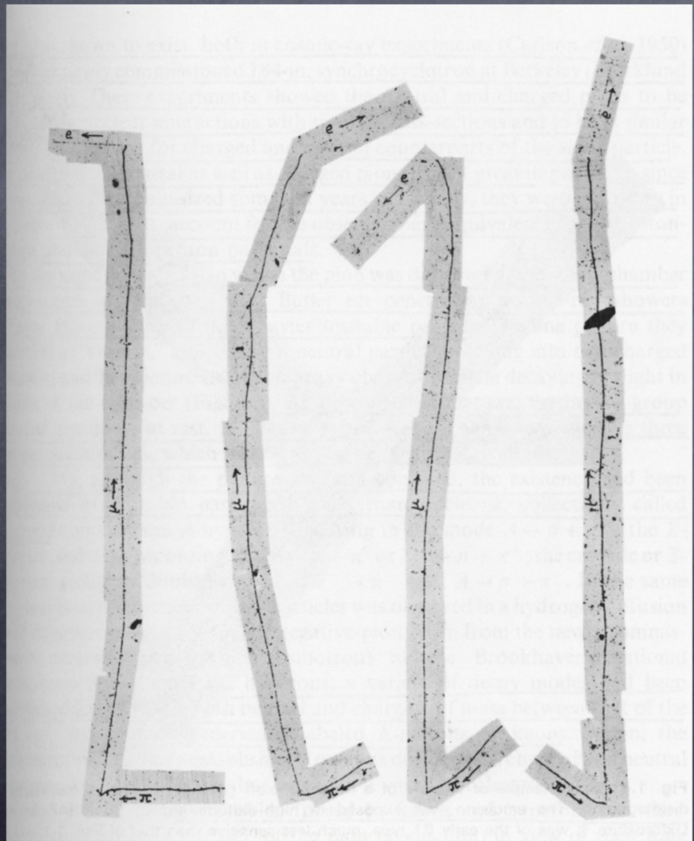
Artist
C. Powell, P. Fowler & D. Perkins

Medium
Photograph - Photograph

Description
Emulsion photograph showing the classic pion-muon- electron (pi-mu-e) decay chain of a charged cosmic ray pion. The pion enters the picture at top left; it soon decays to a muon, which travels down the picture, & a neutrino, which is neutral & so leaves no track. At the bottom of the picture, the muon

More from C. Powell, P. Fowler & D. Perkins

Pion discovery
Nobel Prize 1950

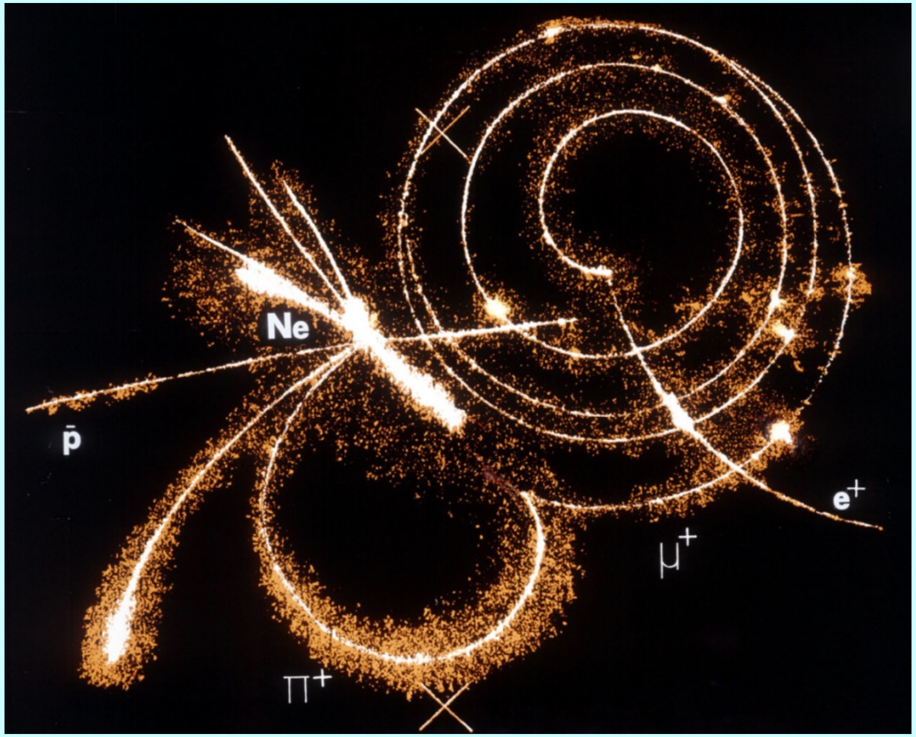


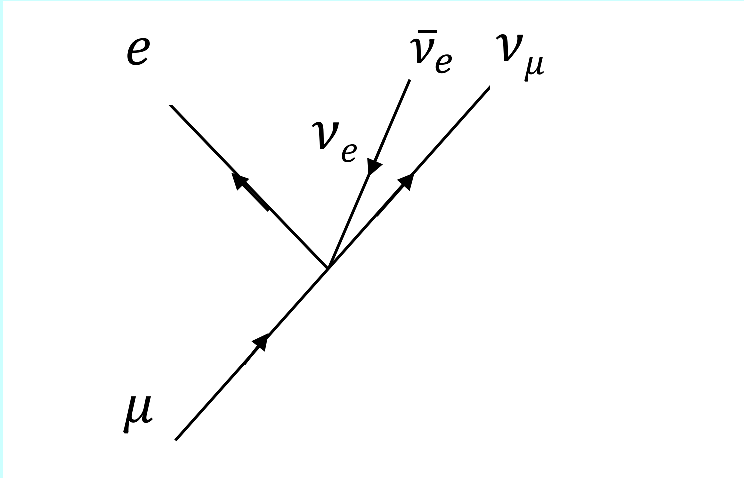
Powell

一個典型的弱交互作用的衰變

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

Muon decay





似乎可以用四隻腳的交點來描述！ Fermi theory

Positron energy spectrum in anti-muon decay

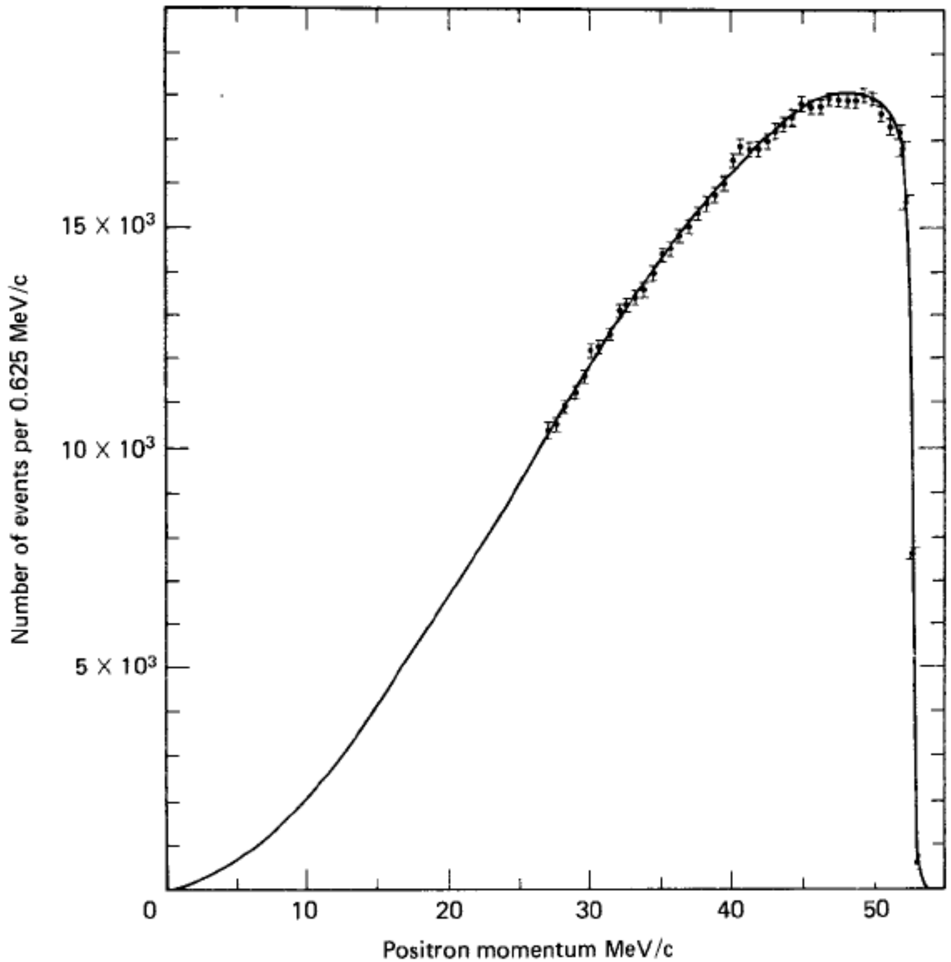
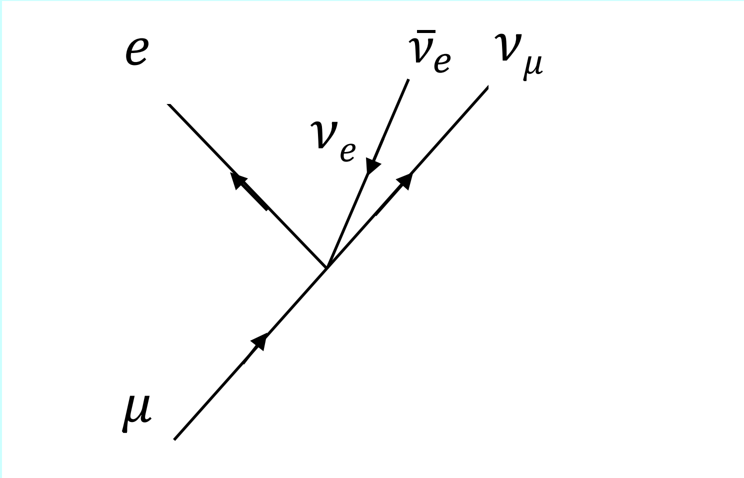


Figure 10.1 Experimental spectrum of positrons in $\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$. The solid line is the theoretically predicted spectrum based on equation (10.35), corrected for electromagnetic effects. (*Source:* M. Bardon et al., *Phys. Rev. Lett.* **14,** 449 (1965).)

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



This Fermi theory describes Weak decays very well!

But it can't be the final theory.

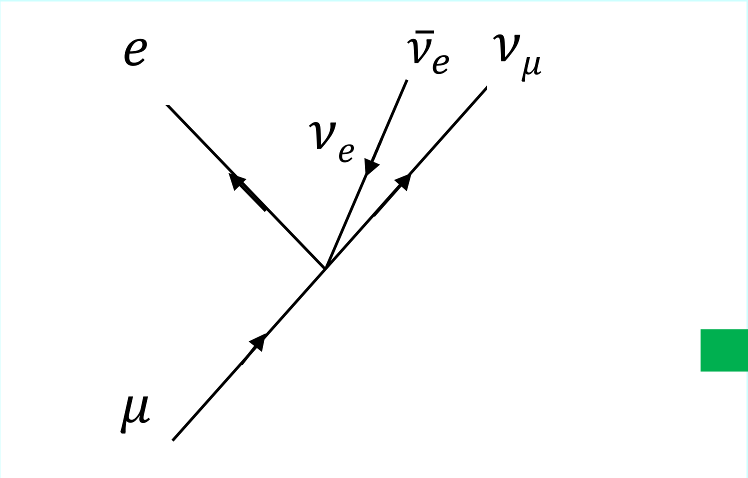
It's non-renormalizable (filled with uncontrollable infinities)!

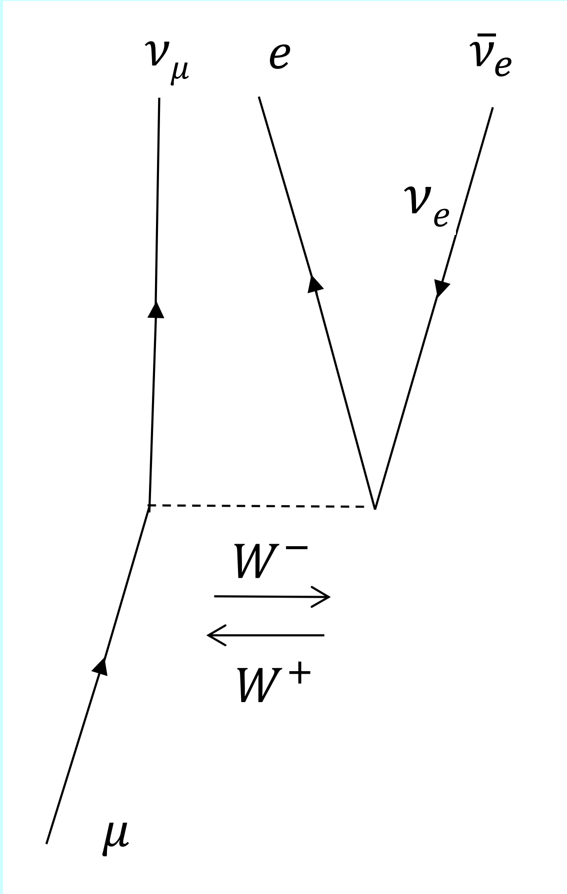
病源是在交點上聚集太多粒子。

The reason is there are too many particles at one vertex.

或許弱交互作用也可以想像如核力一樣由一個媒介子來傳播！

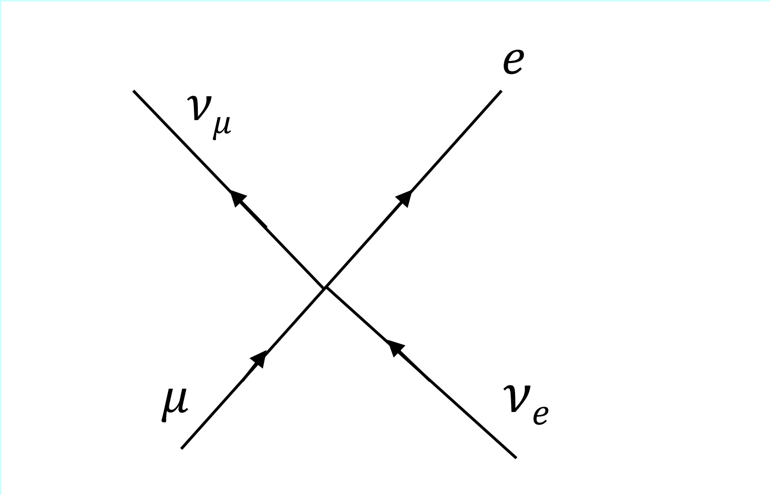
如此就可以降低交點上聚集的粒子數目。畢竟類似的QED是可重整化的。



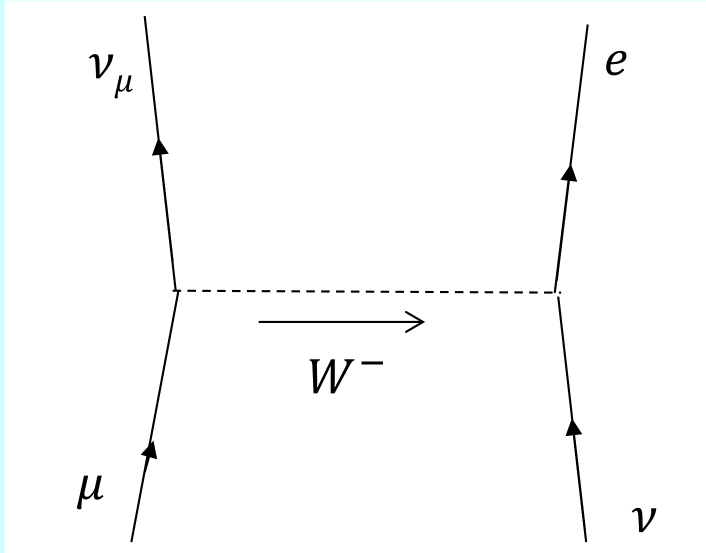


弱交互作用的媒介粒子稱為W^- boson，帶電荷-1。

反粒子稱為W^+ boson，帶電荷$+1$。



$\approx$



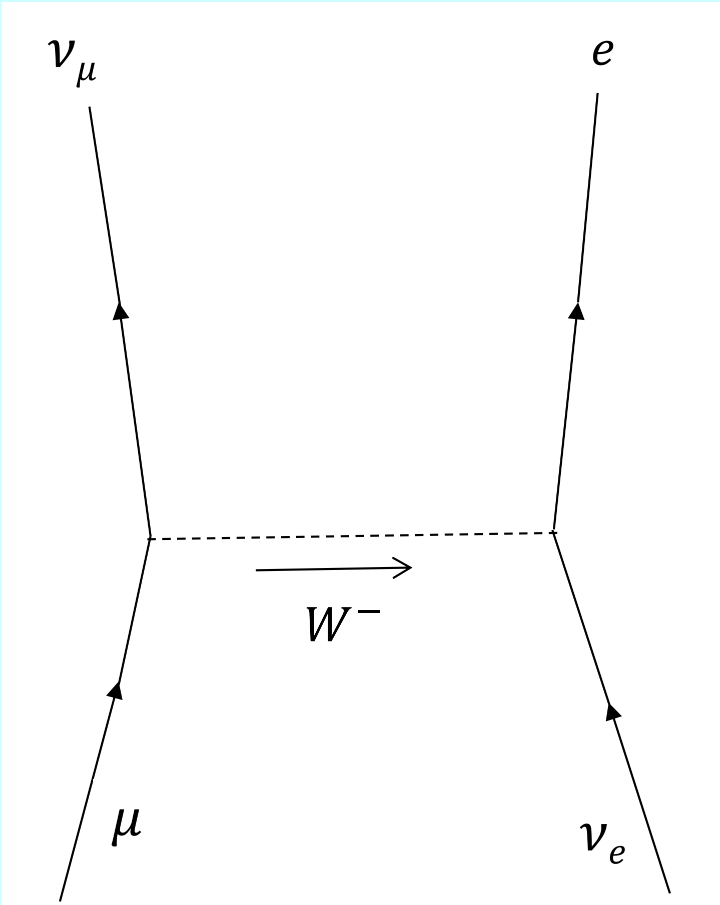
$p^2 \ll M_W^2$

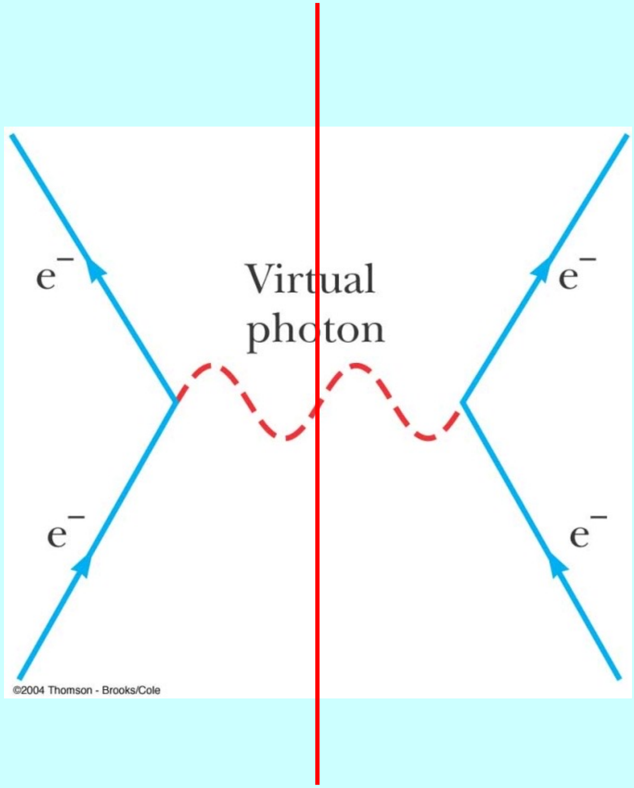
$$-\frac{i}{M_W^2} \Leftarrow \frac{i}{p^2 - M_W^2}$$

在$p^2 \ll M_W^2$時，W^-的 Propagator 看來像一個常數：$p^2 - M_W^2 \approx -M_W^2$

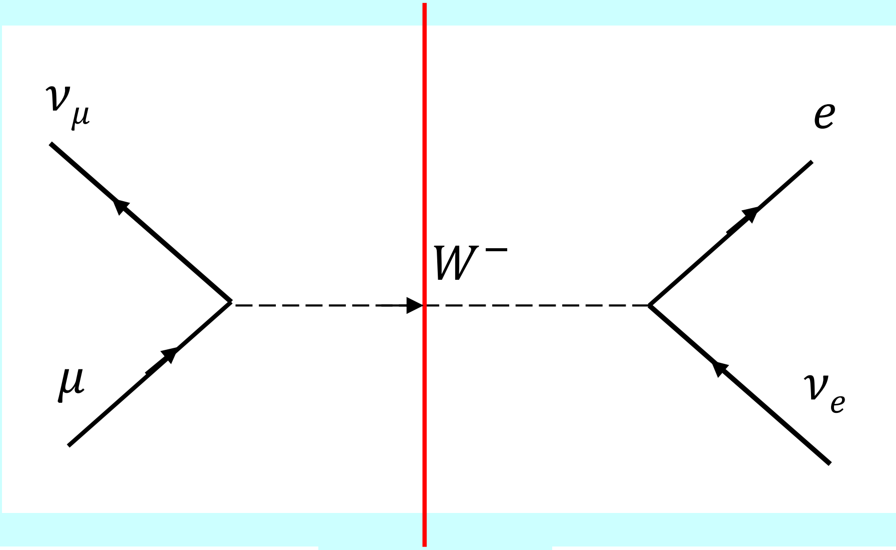
內線就近似於一個無結構的點，那就是Fermi 的理論。

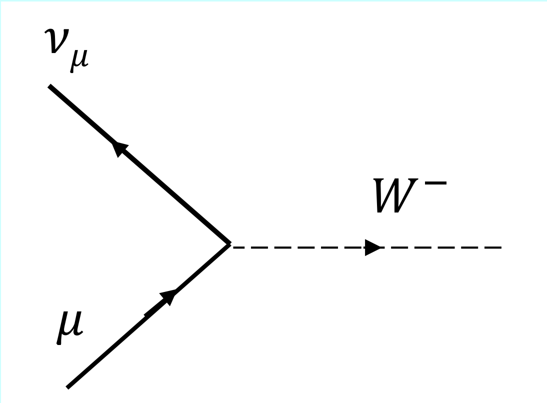
如此，這個弱作用的圖與兩個電子交換光子的電磁散射就非常類似：

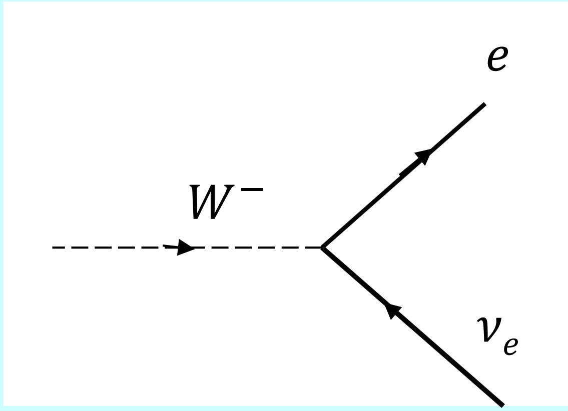


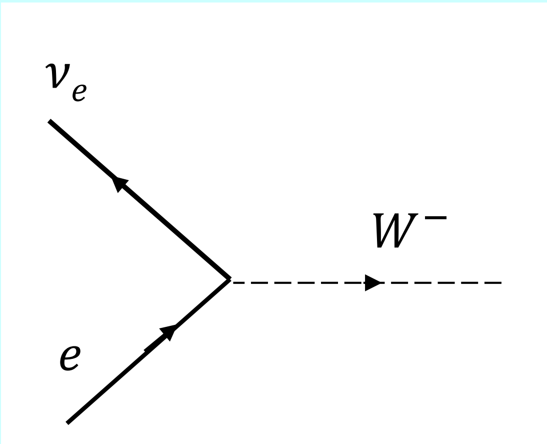


弱交互作用的媒介粒子$W^{\pm}$就扮演電磁作用中光子的角色





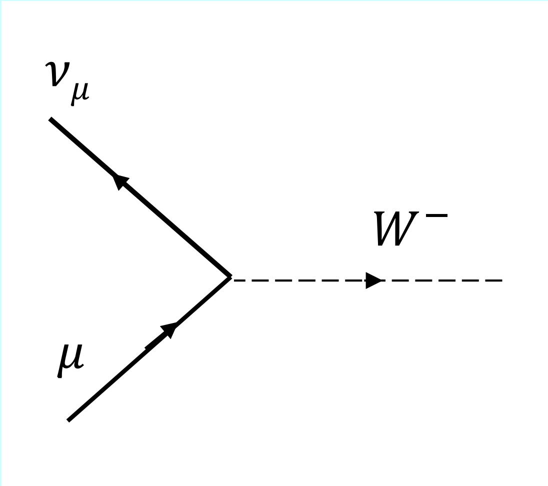


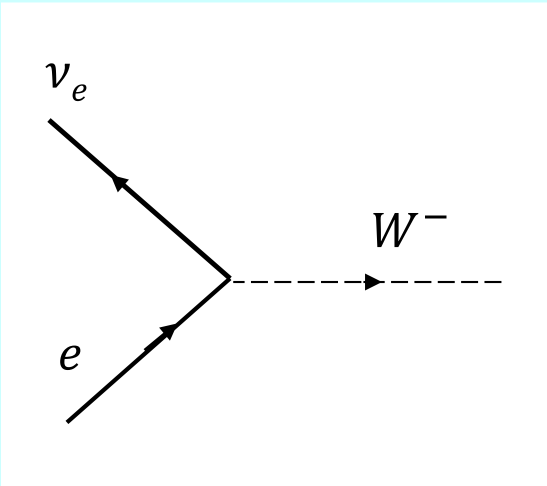


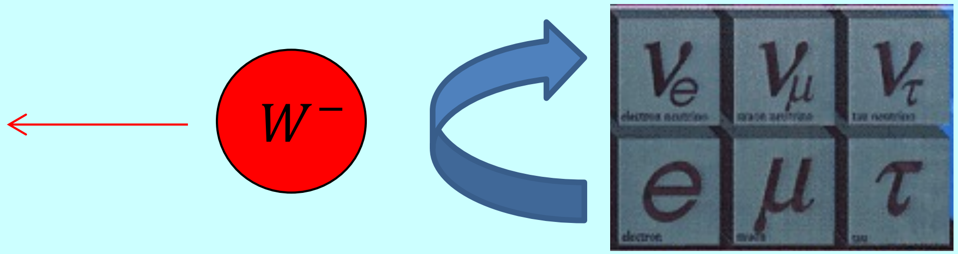
理論中也必須包含時間逆行的交點

This is part of the interaction Lagrangian $\mathcal{L}_I$ for weak interaction.

弱作用的基本作用交點 vertices.

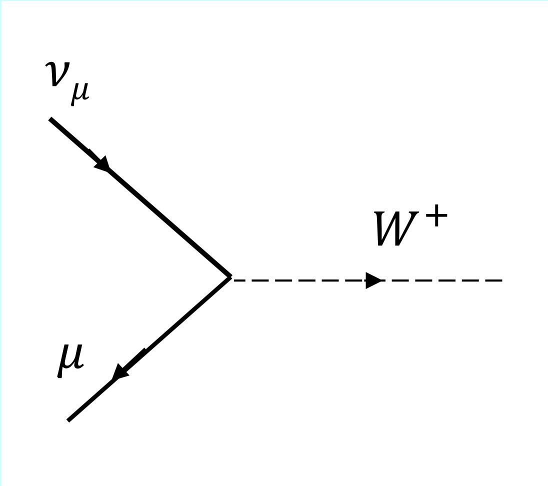


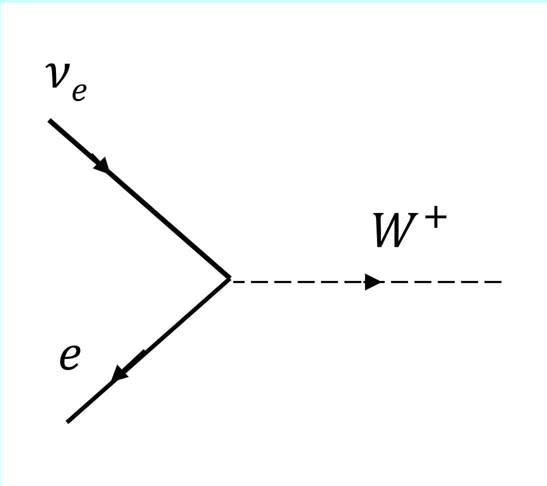


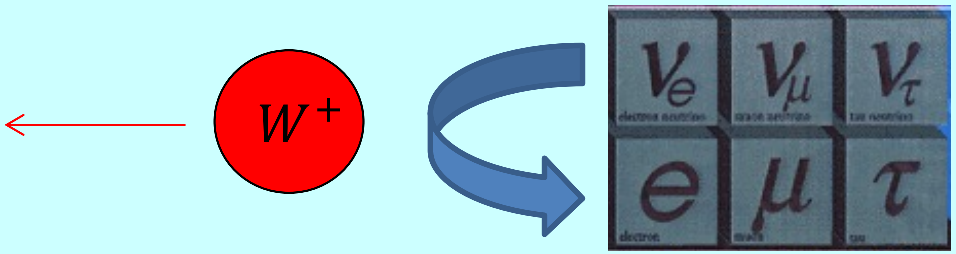


放出 W^-（或吸收 W^+）後，成對的粒子可以由下方升到上方！

Reverse the arrow:

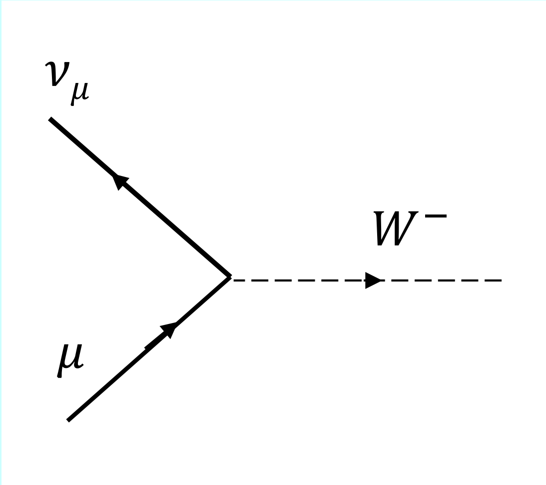


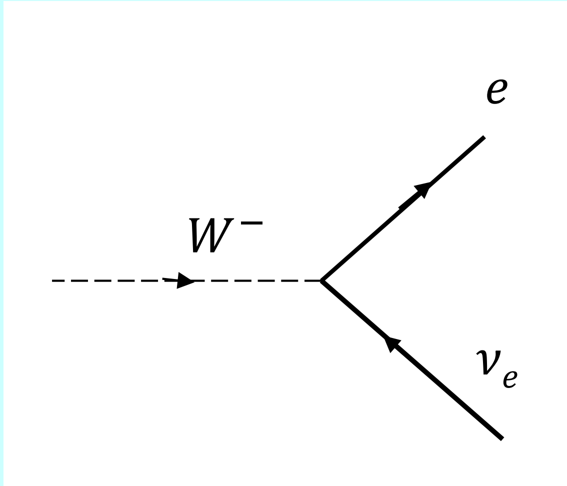




放出W^+（或吸收W^-）後，成對的粒子可以由上方降到下方！

將以上的作用元件組合，即可得出所有的弱交互作用。

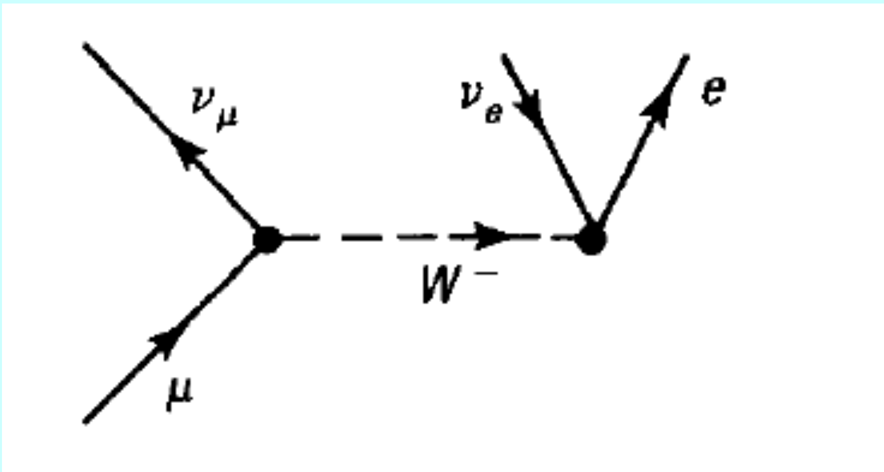




將這兩個元件組合即可以得到緲子的衰變：

W^+離開等於反粒子W^-進入。

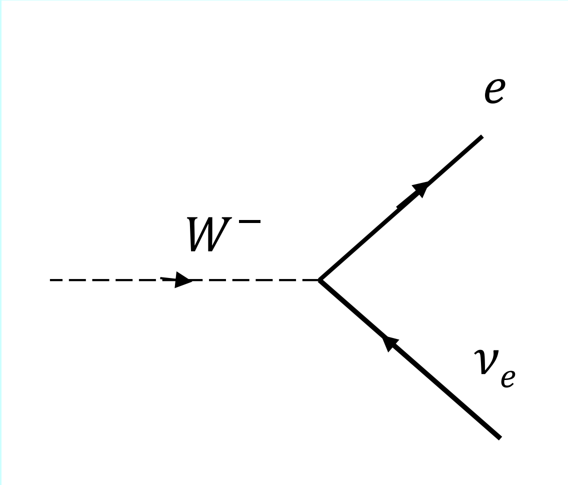
ν_e進入等於反粒子$\bar{\nu}_e$離開。



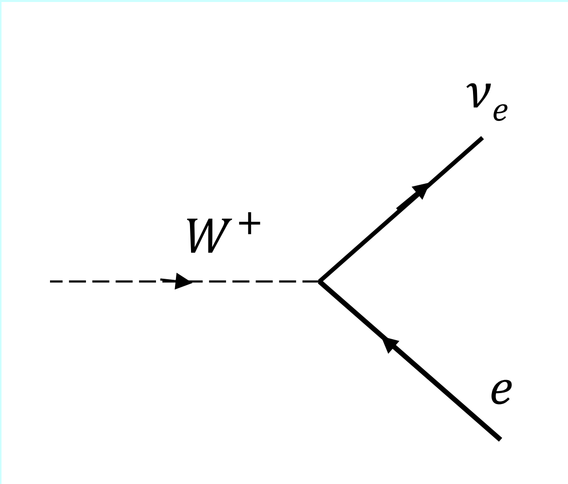
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

弱交互作用的交點可以如此紀錄：

我先忽略 Dirac structure such as γ^μ. 最後很容易就加上。

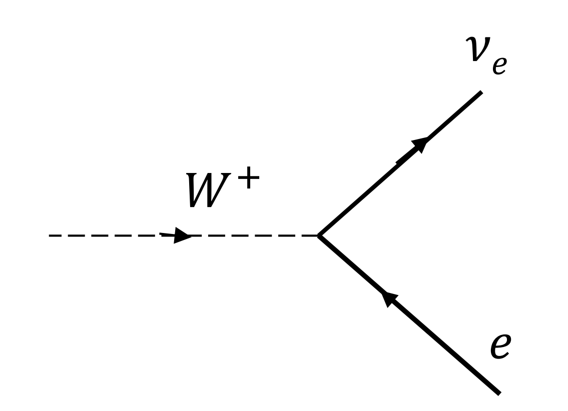


$$\frac{g}{\sqrt{2}} \cdot (\bar{e} \cdot \nu_e \cdot W^-)$$

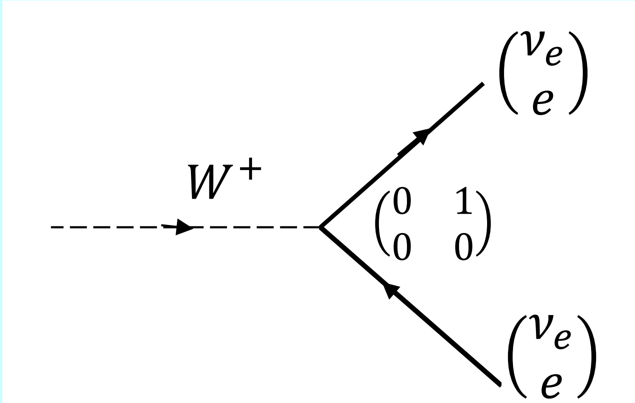


$$\frac{g}{\sqrt{2}} \cdot (\bar{\nu}_e \cdot e \cdot W^+)$$

將lepton寫成doublet$\begin{pmatrix}\nu_e\\ e\end{pmatrix}$的形式：



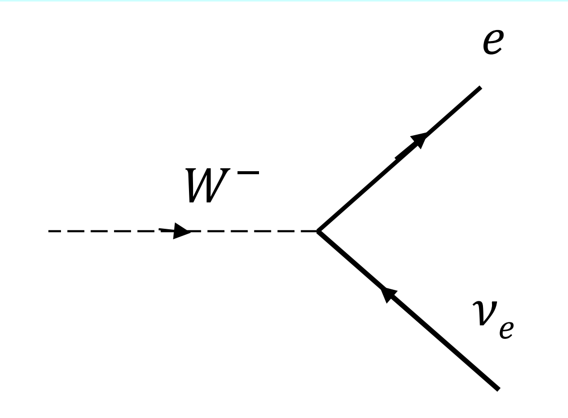
$$\frac{g}{\sqrt{2}}\cdot(\bar{\nu}_e\cdot e\cdot W^+)$$



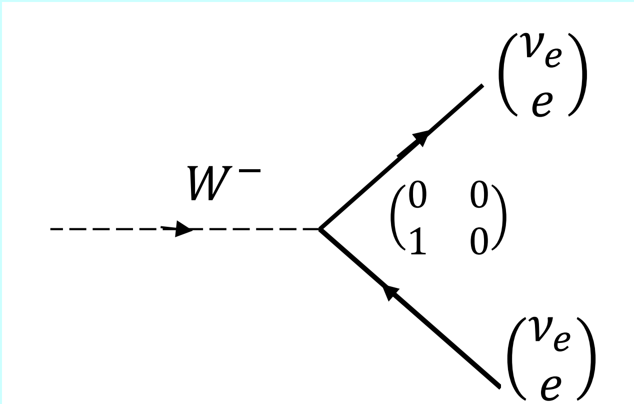
此交點可以doublet及矩陣符號表示：

$$\frac{g}{\sqrt{2}}(\bar{\nu}_e\cdot e\cdot W^+)=\frac{g}{\sqrt{2}}(\bar{\nu}_e \quad \bar{e})\begin{pmatrix}0 & 1\\ 0 & 0\end{pmatrix}\begin{pmatrix}\nu_e\\ e\end{pmatrix}\cdot W^+$$

同理：



$$\frac{g}{\sqrt{2}}\cdot(\bar{e}\cdot\nu_e\cdot W^-)$$



$$\frac{g}{\sqrt{2}}(\bar{e}\cdot\nu_e\cdot W^-)=\frac{g}{\sqrt{2}}(\bar{\nu}_e \quad \bar{e})\begin{pmatrix}0 & 0\\ 1 & 0\end{pmatrix}\begin{pmatrix}\nu_e\\ e\end{pmatrix}W^-$$

這些交點都是$\mathcal{L}_I$的項，最後都是加總在一起的。

將這兩式疊加後，弱作用的交點可以綜合寫成：

$$\frac{g}{\sqrt{2}}(\bar{\nu}_e \quad \bar{e})\left[W^+\begin{pmatrix}0 & 1\\ 0 & 0\end{pmatrix} + W^-\begin{pmatrix}0 & 0\\ 1 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ e\end{pmatrix}$$

$$= \frac{g}{\sqrt{2}}(\bar{\nu}_e \quad \bar{e})\left[W^+\left(\frac{\tau^1 + i\tau^2}{2}\right) + W^-\left(\frac{\tau^1 - i\tau^2}{2}\right)\right]\begin{pmatrix}\nu_e\\ e\end{pmatrix}$$

$$= \frac{g}{\sqrt{2}}(\bar{\nu}_e \quad \bar{e})\left[\left(\frac{W^+ + W^-}{2}\right)\tau^1 + i\left(\frac{W^+ - W^-}{2}\right)\tau^2\right]\begin{pmatrix}\nu_e\\ e\end{pmatrix}$$

$$= \frac{g}{2}(\bar{\nu}_e \quad \bar{e})(W^1\tau_1 + W^2\tau_2)\begin{pmatrix}\nu_e\\ e\end{pmatrix}$$

It could be neatly written in term of $\tau_{1,2}$ and $W^{1,2}$.

$$\tau_1 = \begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}$$

$$\tau_2 = \begin{pmatrix}0 & -i\\ i & 0\end{pmatrix}$$

$$\tau_3 = \begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}$$

引入新的符號：

$$\sqrt{2}W^1 = W^+ + W^-$$

$$\sqrt{2}W^2 = i(W^+ - W^-)$$

$$W^\pm = \frac{W^1 \mp iW^2}{\sqrt{2}}$$

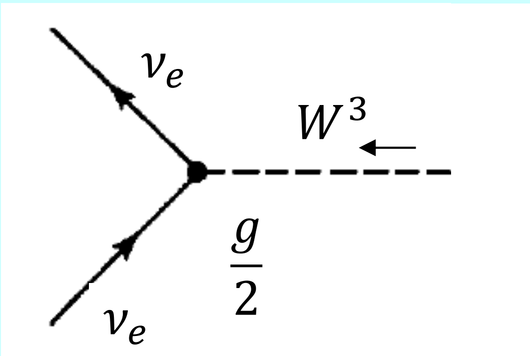
$$\frac{g}{2}(\bar{\nu}_e \quad \bar{e})(W^1\tau_1 + W^2\tau_2)\begin{pmatrix}\nu_e \\ e\end{pmatrix} \Rightarrow \frac{g}{2}(\bar{\nu}_e \quad \bar{e})(W^1\tau_1 + W^2\tau_2 + W^3\tau_3)\begin{pmatrix}\nu_e \\ e\end{pmatrix}$$

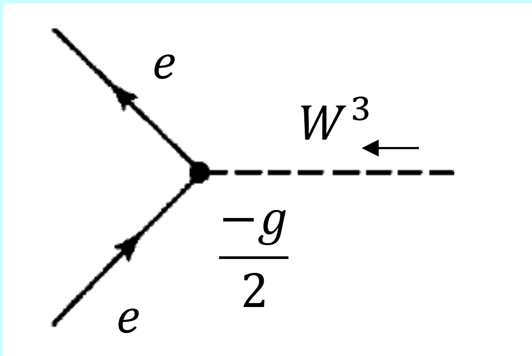
Won't you want to complete it?

We should expect a similar term for τ_3 and W^3.

$$\frac{g}{2}(\bar{\nu}_e \quad \bar{e})W^3\tau_3\begin{pmatrix}\nu_e \\ e\end{pmatrix}$$

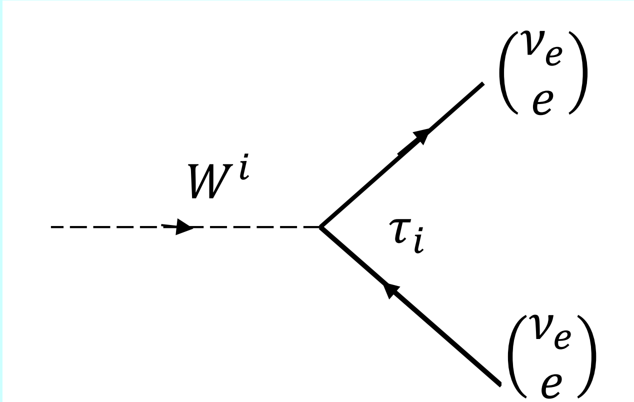
$$\frac{g}{2}(\bar{\nu}_e \quad \bar{e})W^3\begin{pmatrix}1 & 0 \\ 0 & -1\end{pmatrix}\begin{pmatrix}\nu_e \\ e\end{pmatrix} = \frac{g}{2}\bar{\nu}_e\nu_e W^3 - \frac{1}{2}\bar{e}eW^3$$





W^3 is charge neutral.

弱交互作用的完整交點：



$$\frac{g}{2}(\bar{\nu}_e \quad \bar{e})(W^1\tau_1 + W^2\tau_2 + W^3\tau_3)\begin{pmatrix}\nu_e\\ e\end{pmatrix} = \frac{g}{2}(\bar{\nu}_e \quad \bar{e})\left(\sum_{i=1}^{3} W^i\tau^i\right)\begin{pmatrix}\nu_e\\ e\end{pmatrix}$$

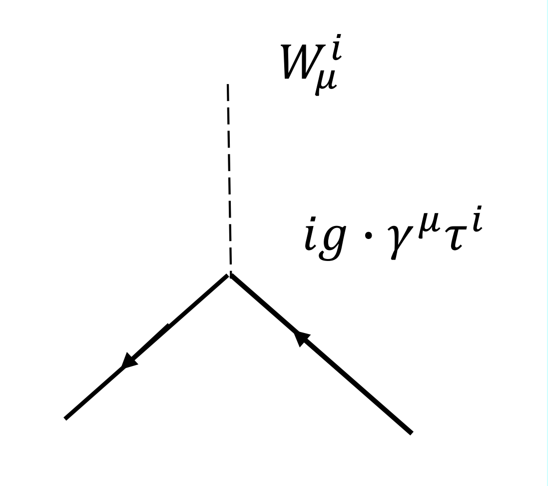
This is exactly a non-abelian $SU(2)$ gauge theory for doublet $\begin{pmatrix}\nu_e\\ e\end{pmatrix}$.

$$\frac{g}{2}(\bar{\nu}_e \quad \bar{e})\gamma^\mu\left(\sum_{i=1}^{3} W_\mu^i\tau^i\right)\begin{pmatrix}\nu_e\\ e\end{pmatrix} = \frac{g}{2}(\bar{\nu}_e \quad \bar{e})\gamma^\mu\begin{pmatrix} W_\mu^3 & W_\mu^1 - iW_\mu^2 \\ W_\mu^1 + iW_\mu^2 & -W_\mu^3\end{pmatrix}\begin{pmatrix}\nu_e\\ e\end{pmatrix}$$

Non-abelian $SU(2)$ gauge theory:

$$\mathcal{L} = \bar{\Psi} i\gamma^{\mu} D_{\mu}\Psi - m\bar{\Psi}\Psi + \frac{g}{2}\bar{\Psi}\gamma^{\mu}\boldsymbol{\tau}\cdot\boldsymbol{W}_{\mu}\Psi$$

Interaction of a doublet and the gauge boson.



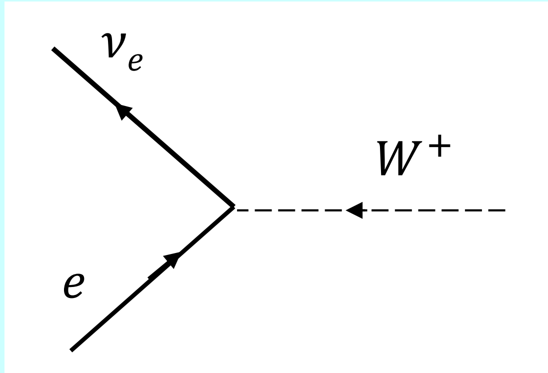
$$\mathcal{L}_I = \frac{g}{2}\bar{\Psi}\gamma^{\mu}\boldsymbol{\tau}\cdot\boldsymbol{W}_{\mu}\Psi = \frac{g}{2}(\bar{\nu}_e \quad \bar{e})\gamma^{\mu}\begin{pmatrix} W_{\mu}^{3} & W_{\mu}^{1} - iW_{\mu}^{2} \\ W_{\mu}^{1} + iW_{\mu}^{2} & -W_{\mu}^{3} \end{pmatrix}\begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

$$= \frac{g}{2}(\bar{\nu}_e \quad \bar{e})\gamma^{\mu}\begin{pmatrix} W_{\mu}^{3} & \sqrt{2}W_{\mu}^{+} \\ \sqrt{2}W_{\mu}^{-} & -W_{\mu}^{3} \end{pmatrix}\begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

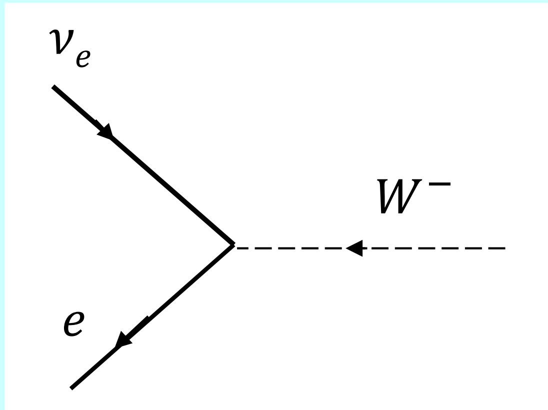
W^1, W^2不是真實可觀察的粒子，

W^+, W^-才是真實可觀察的粒子，

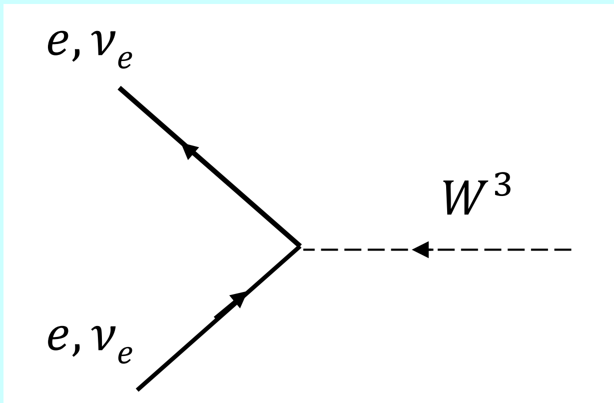
$$\frac{g}{2}(\bar{\nu}_e \quad \bar{e})\gamma^\mu \begin{pmatrix} W_\mu^3 & \sqrt{2}W_\mu^+ \\ \sqrt{2}W_\mu^- & -W_\mu^3 \end{pmatrix} \begin{pmatrix} \nu_e \\ e \end{pmatrix}$$



$$\frac{g}{\sqrt{2}} \cdot (\bar{\nu}_e \gamma^\mu e \cdot W^+ + \bar{e}\gamma^\mu \nu_e \cdot W^-)$$

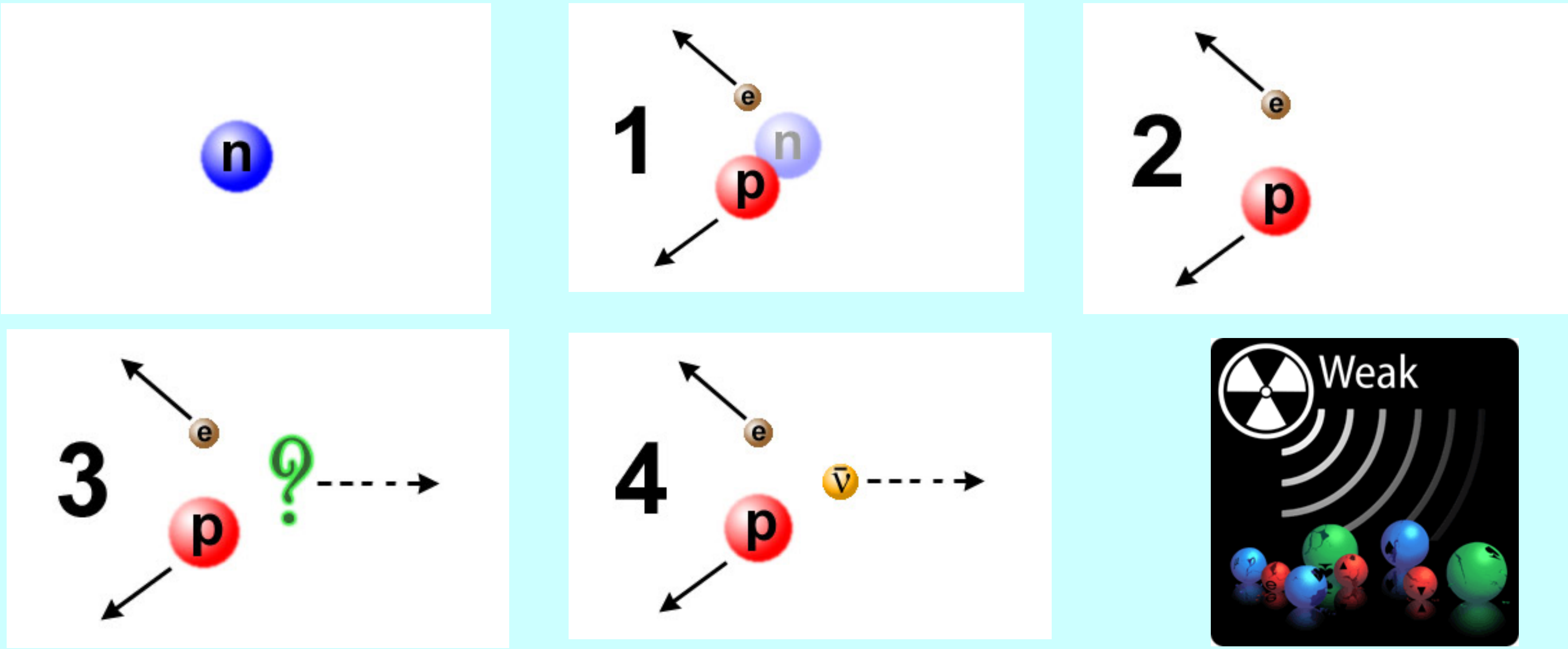


$$\frac{g}{2}\bar{\nu}_e \gamma^\mu \nu_e W^3 - \frac{g}{2}\bar{e}\gamma^\mu e W^3$$



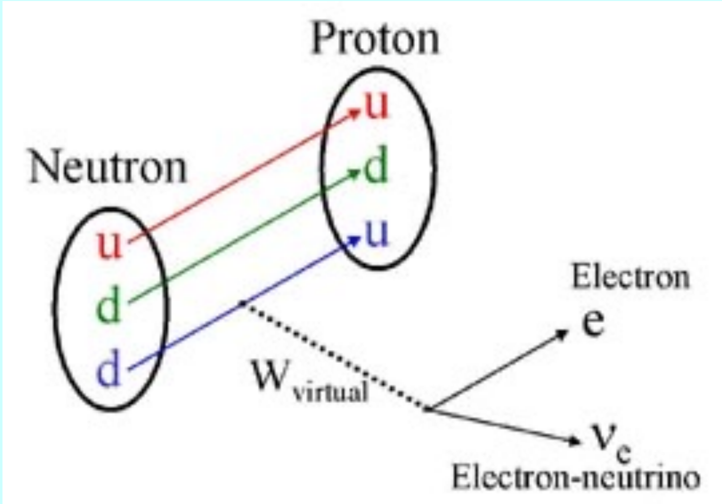
類似的結果也適用於夸克：

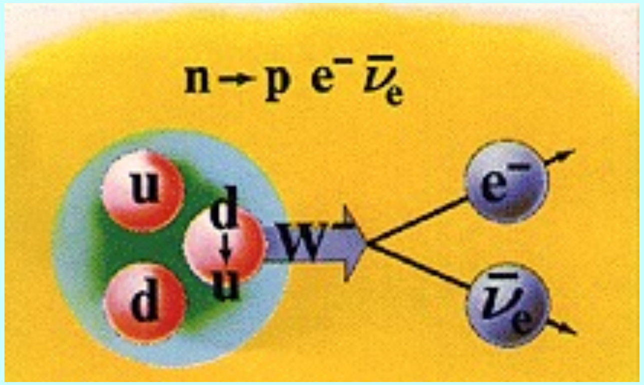
β Beta Decay $n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$



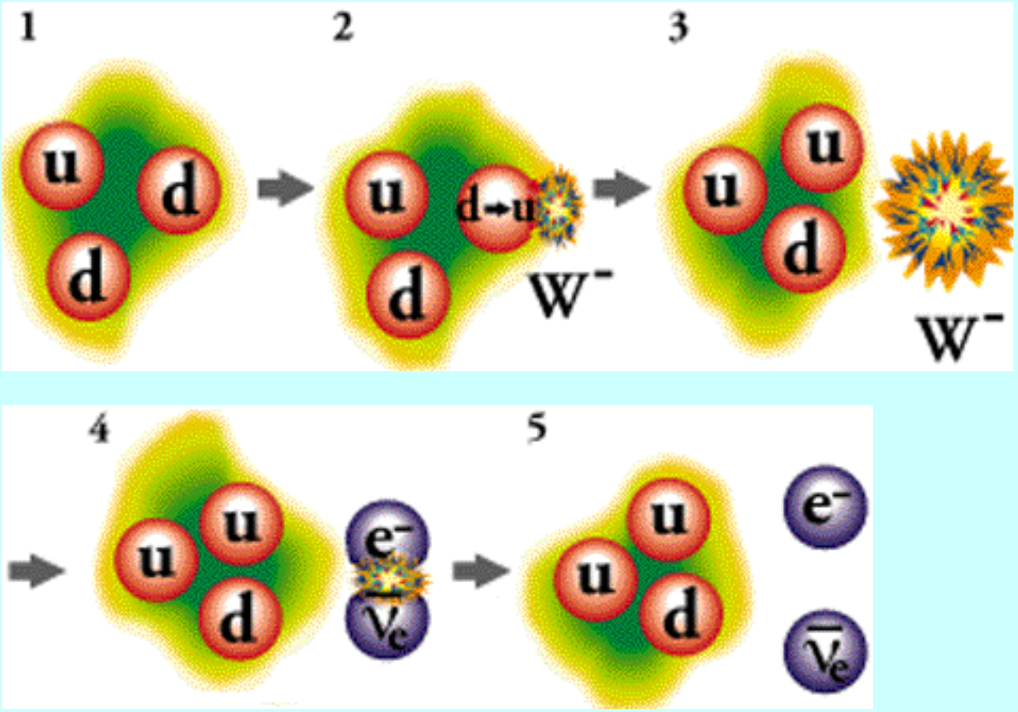
質子中子都是由夸克組成，差別在一個 *d* 夸克換成了 *u* 夸克，

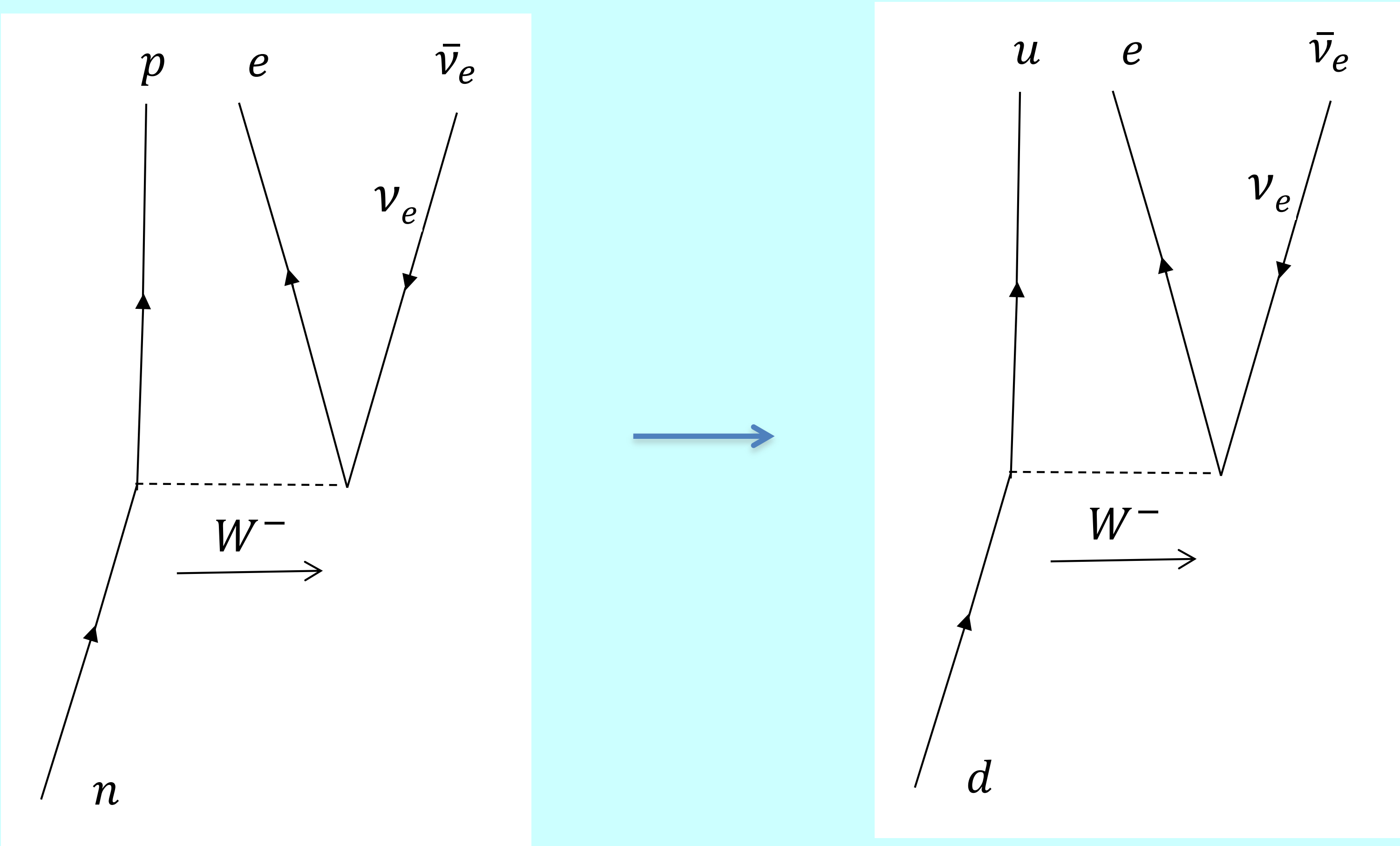
因此 β 衰變應該看成是 d 夸克換成了 u 夸克的衰變：



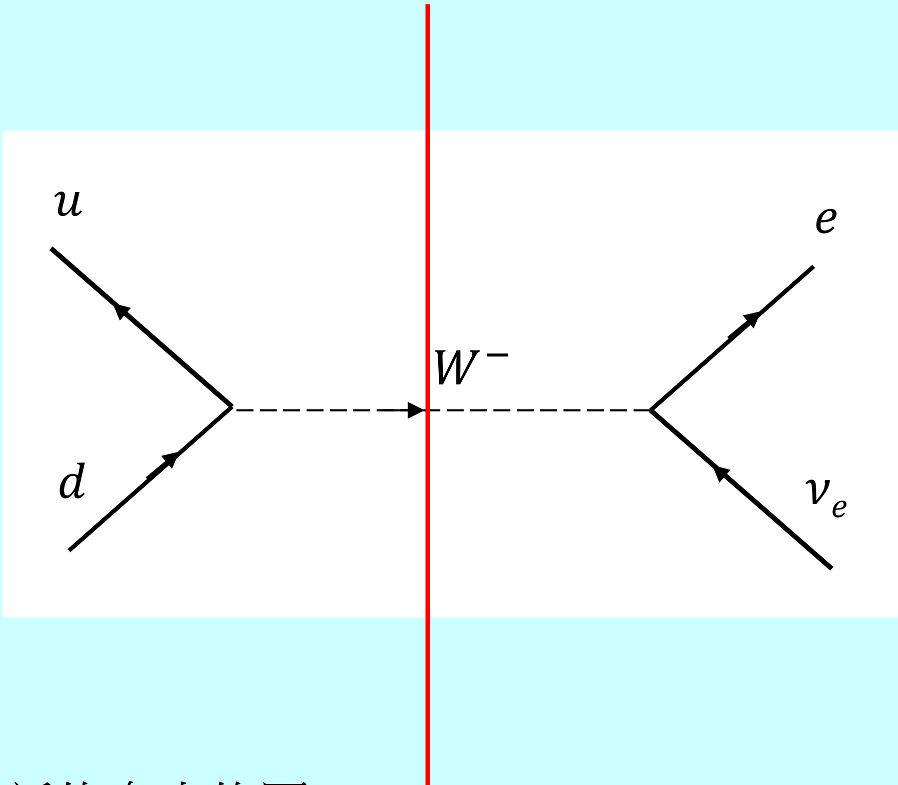


$d \rightarrow u + e^- + \bar{\nu}_e$


1
u
d
d
2
u
d→u
d
W⁻
3
u
u
d
W⁻
4
u
u
d
e⁻
$\bar{\nu}_e$
5
u
u
d
e⁻
$\bar{\nu}_e$

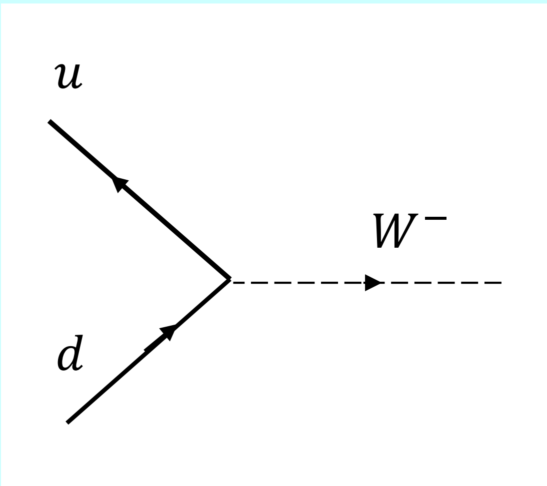


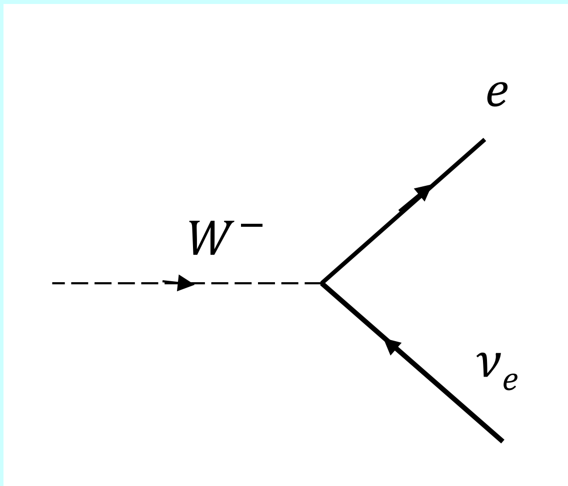
非常類似邈子衰變。

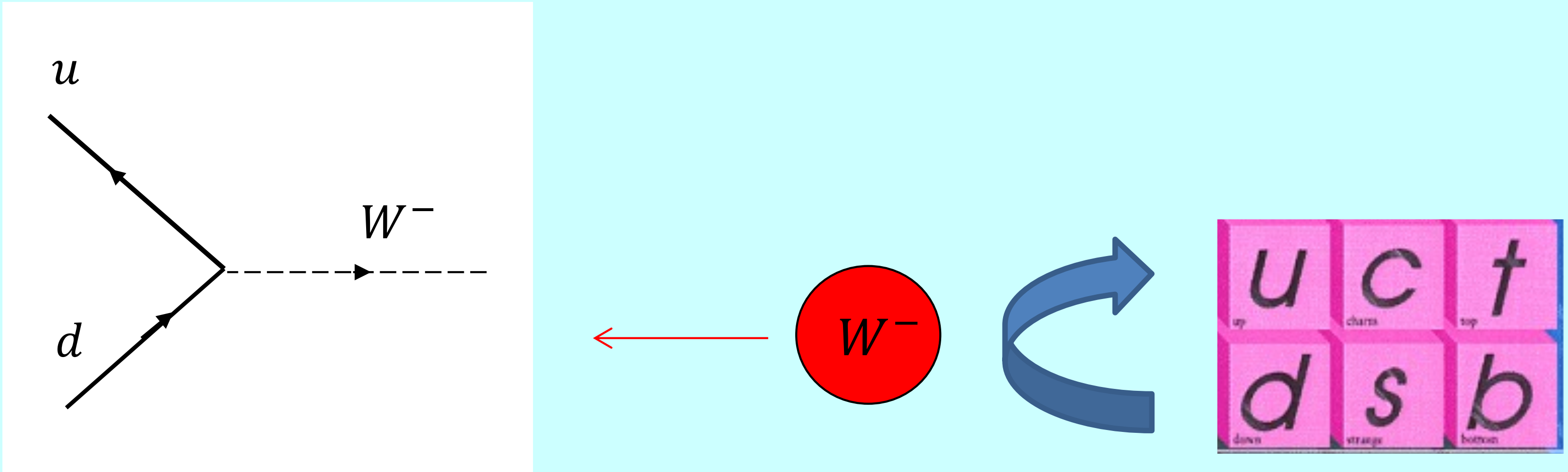


左手邊是新的夸克的圖

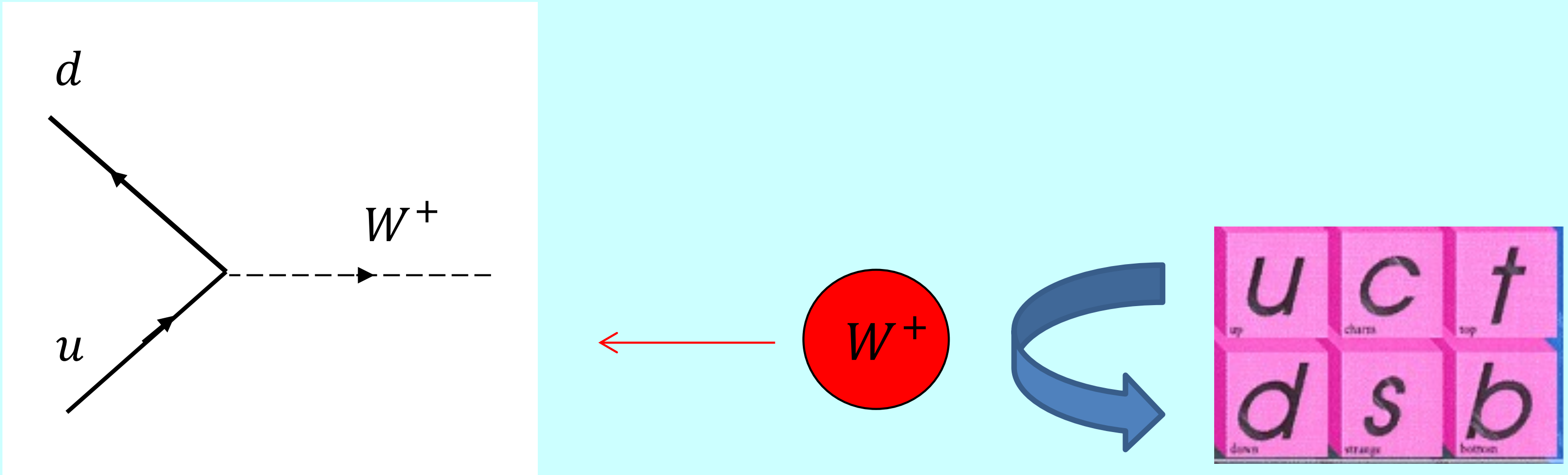
右手邊是已知的圖



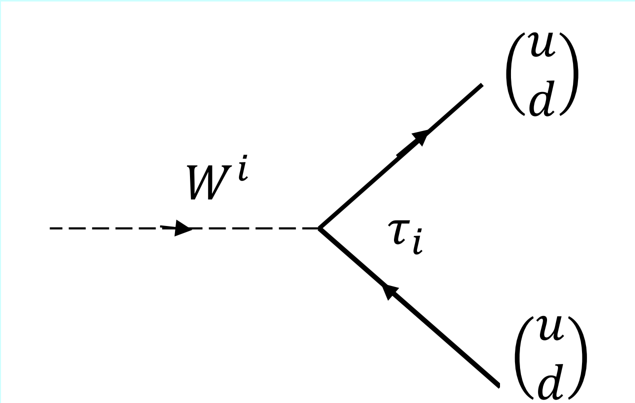




放出 W^-（或吸收 W^+）後，成對的粒子可以由下方升到上方！



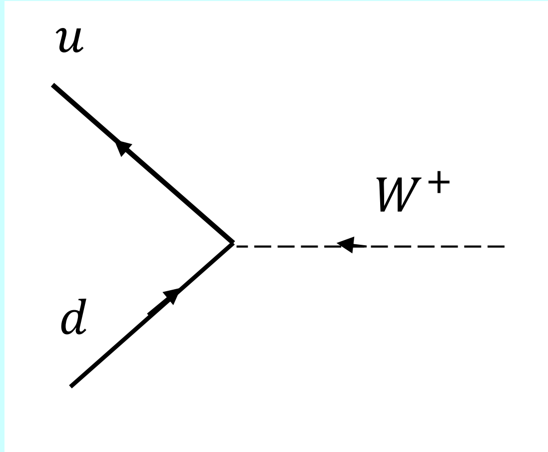
放出W^+（或吸收W^-）後，成對的粒子可以由上方降到下方！

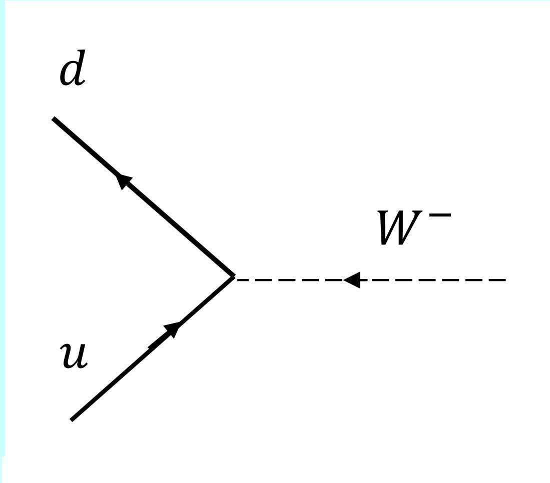


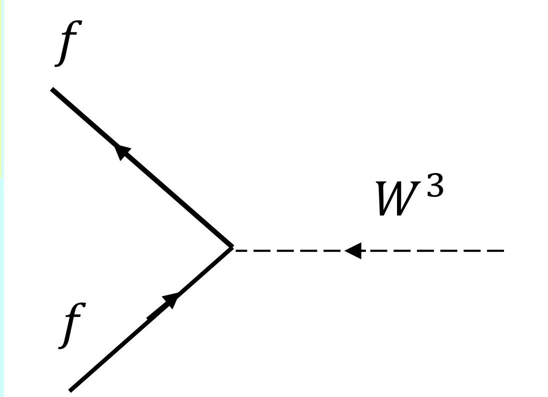
$$\frac{g}{2}\sum_{i=1}^{3}(\bar{u} \quad \bar{d})W^i\tau_i\binom{u}{d}$$

$$(\bar{u} \quad \bar{d})\begin{pmatrix} \frac{W^3}{2} & -\frac{1}{\sqrt{2}}W^+ \\ -\frac{1}{\sqrt{2}}W^- & -\frac{W^3}{2} \end{pmatrix}\binom{u}{d}$$

同樣的耦合常數，







這是規範對稱的結果，顯示交互作用完全由對稱性所控制。

Weak interaction is a $SU(2)$ (called weak $SU(2)$) gauge theory.

What are the doublets of electroweak $SU(2)$?

Quarks and Leptons respectively form three pairs of doublets.

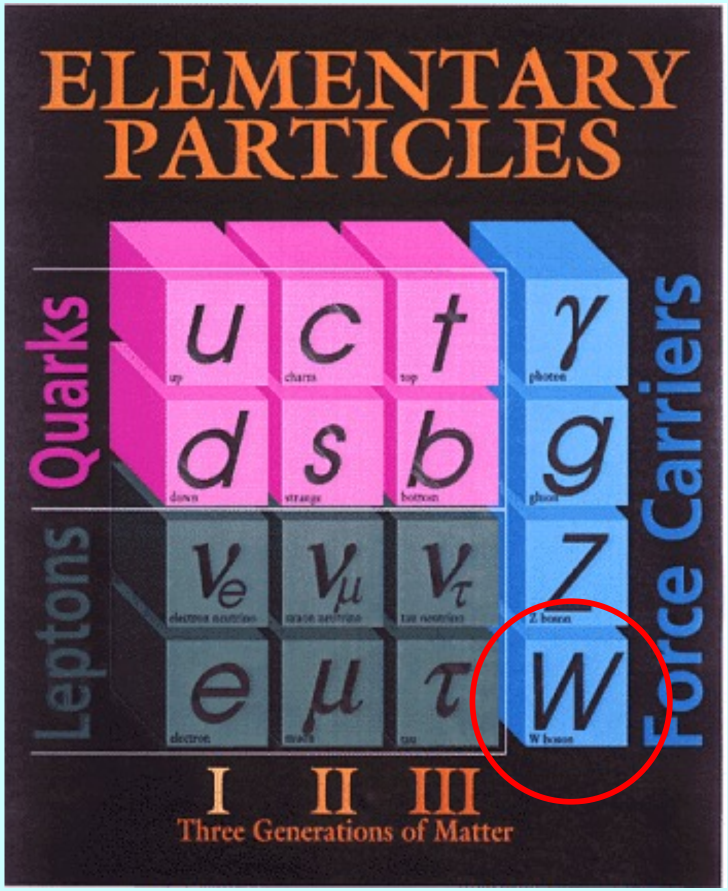
放出W^+（或吸收W^-）後， Weak $SU(2)$雙重態粒子可以由上方降到下方！

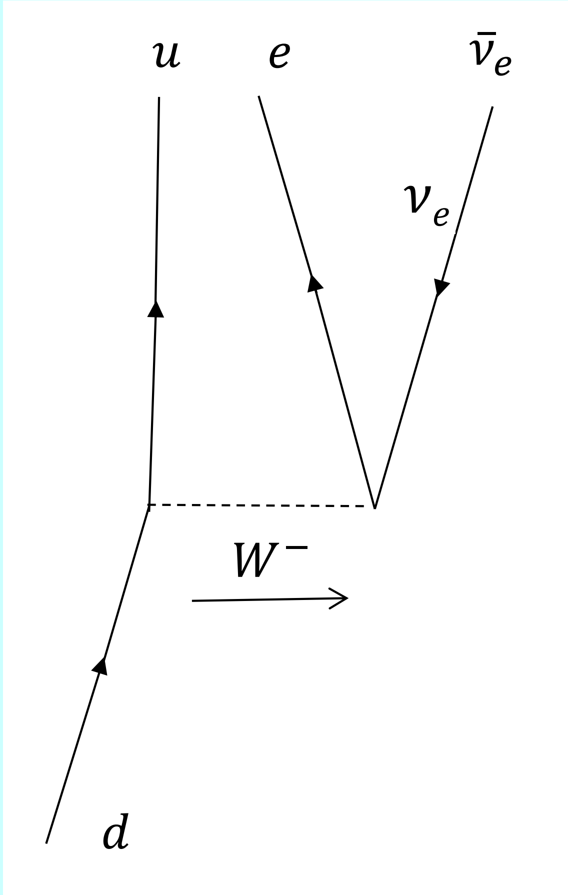
$\binom{u}{d}, \binom{c}{s}, \binom{t}{b}$ $\binom{\nu_e}{e}, \binom{\nu_\mu}{\mu}, \binom{\nu_\tau}{\tau}$

電弱統一

What is the triplet of electroweak $SU(2)$ gauge bosons?

$$(W^1 \quad W^2 \quad W^3)$$





$W^{\pm}$ bosons are the mediation particles of weak interaction.

W $J = 1$

Charge = ± 1 e

Mass $m = 80.377 \pm 0.012$ GeV

W/Z mass ratio $= 0.88145 \pm 0.00013$

$m_Z - m_W = 10.811 \pm 0.012$ GeV

$m_{W^+} - m_{W^-} = -0.029 \pm 0.028$ GeV

Full width $\Gamma = 2.085 \pm 0.042$ GeV

$\langle N_{\pi^\pm} \rangle = 15.70 \pm 0.35$

$\langle N_{K^\pm} \rangle = 2.20 \pm 0.19$

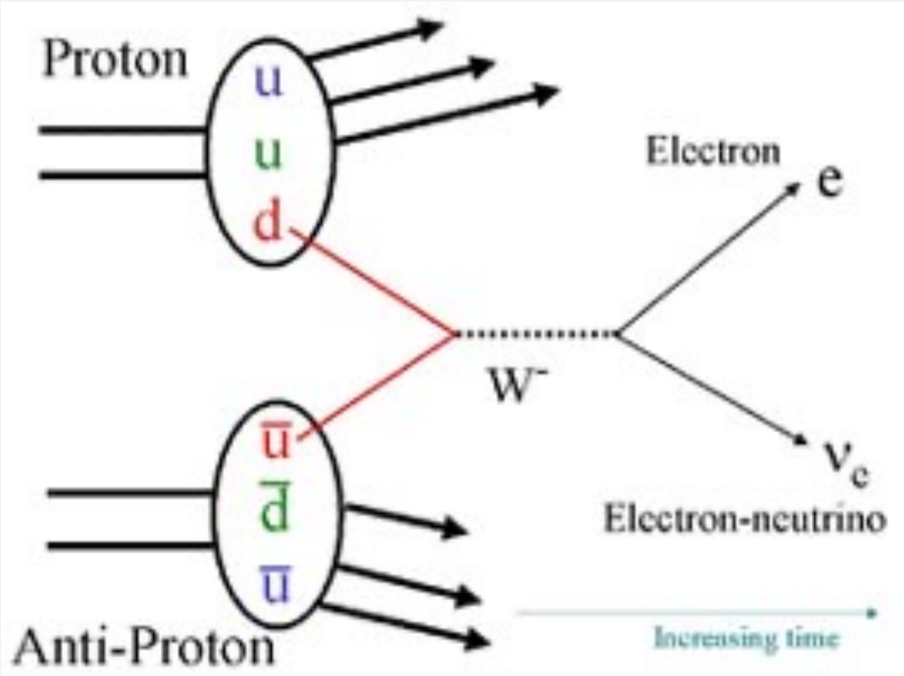
$\langle N_p \rangle = 0.92 \pm 0.14$

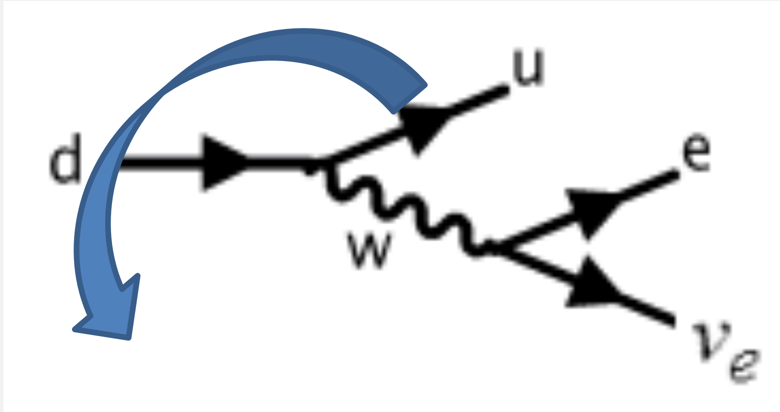
$\langle N_{\text{charged}} \rangle = 19.39 \pm 0.08$

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

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+ \nu$	[b]	(10.86 ± 0.09) %		–

W 粒子可以由質子與反質子的碰撞來產生



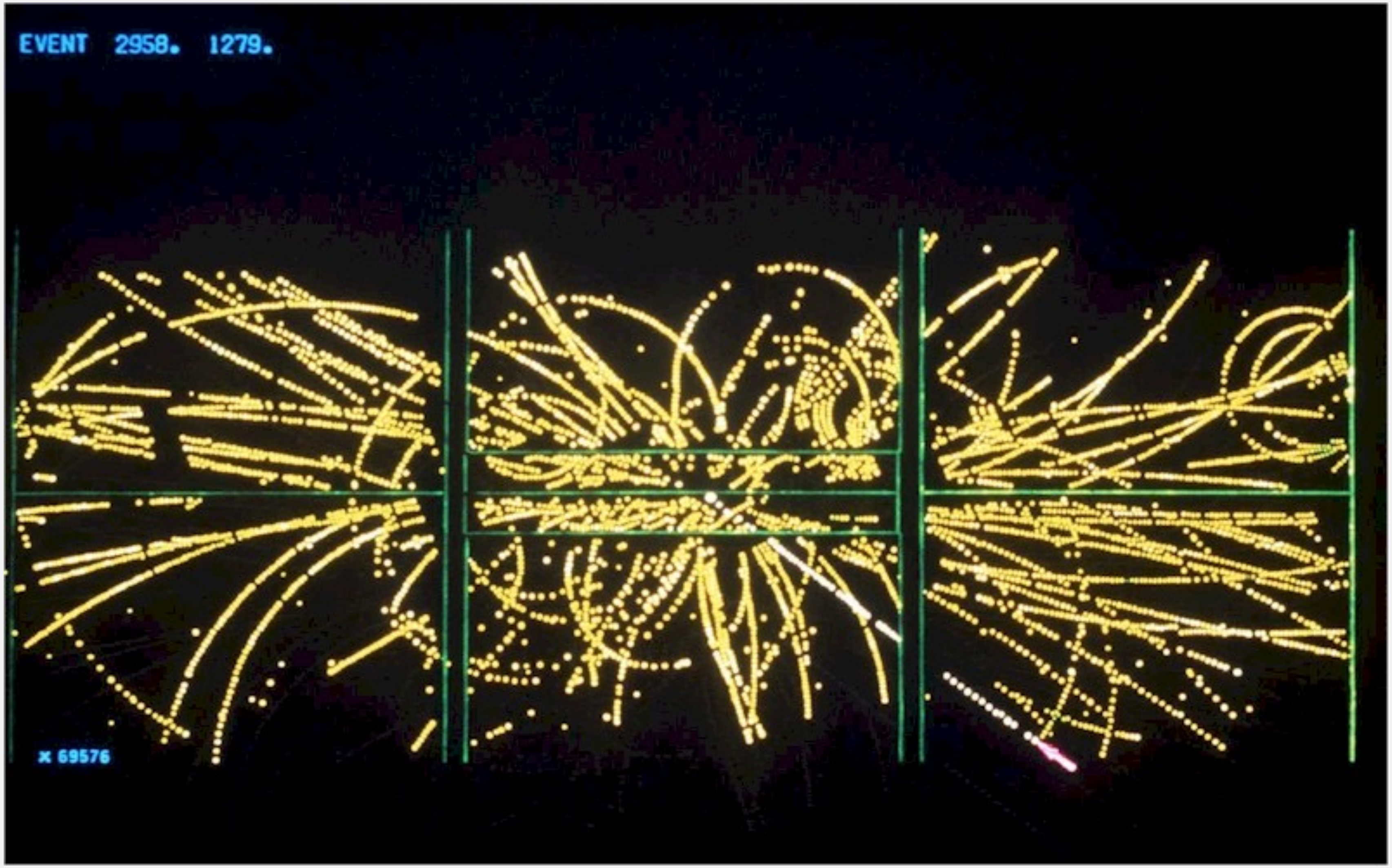


往後的外線扭成往前的外線後，
就變成反粒子！

$d + \bar{u} \rightarrow W^{-} \rightarrow e^{-} + \bar{\nu}_e$

$p + \bar{p} \rightarrow W^{-} + \text{other} \rightarrow e^{-} + \bar{\nu}_e + +\text{other}$

高速飛出的電子是W 的主要跡象



The first observation of W boson at P$\underline{P}$ collider, UA1, CERN 1983

The Nobel Prize in Physics 1984

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

Carlo Rubbia

1/2 of the prize

Italy

CERN
Geneva, Switzerland

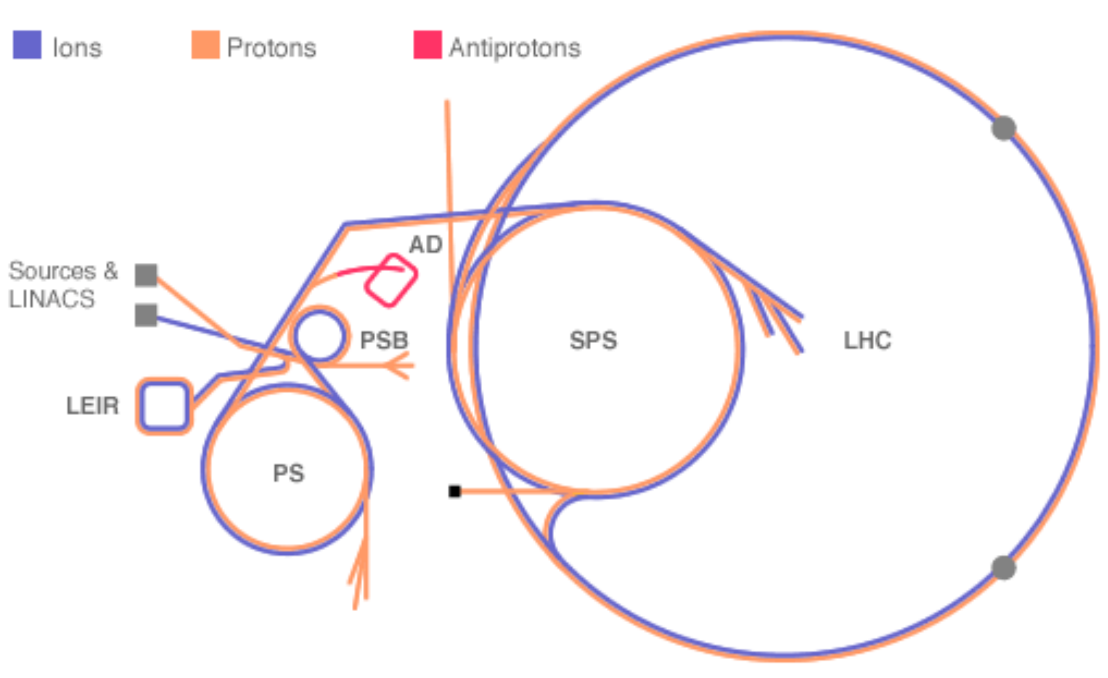
Simon van der Meer

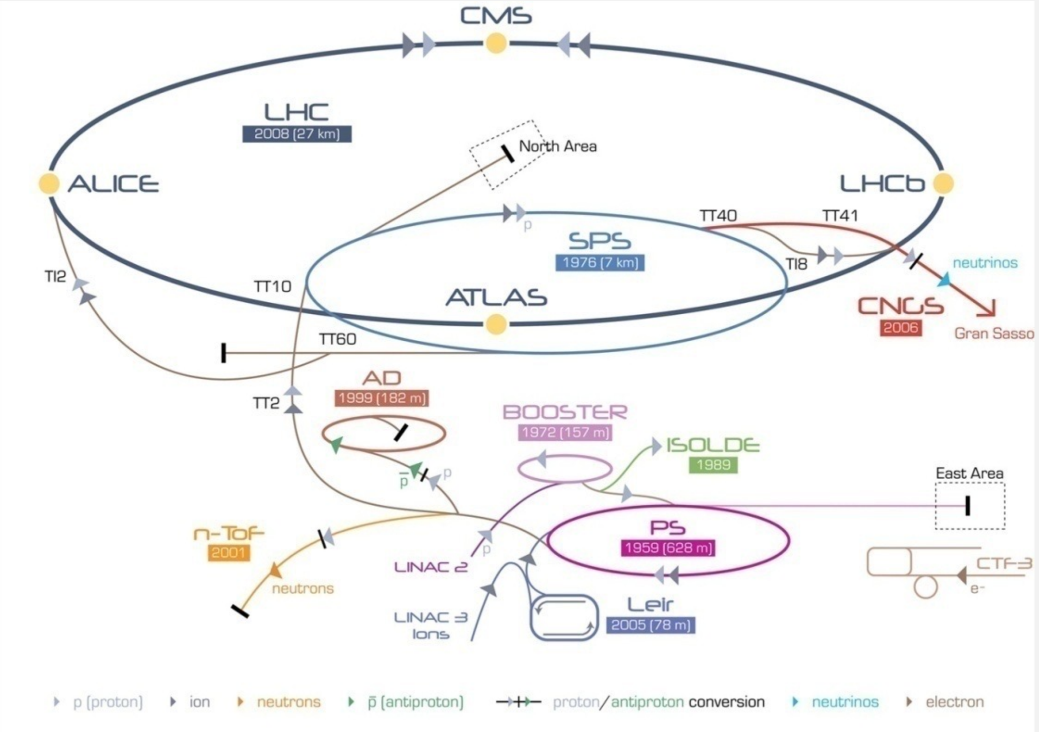
1/2 of the prize

the Netherlands

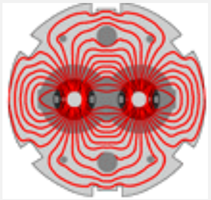
CERN
Geneva, Switzerland

CERN


Ions
Protons
Antiprotons
Sources &
LINACS
AD
PSB
SPS
LHC
LEIR
PS

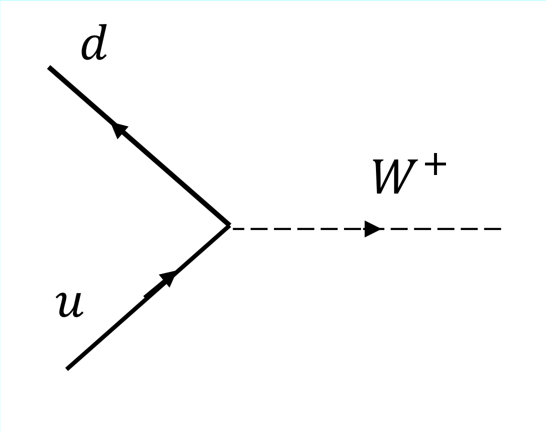

CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
LINAC 2
CTF3
e–
neutrons
LINAC 3
Ions
Leir
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
proton/antiproton conversion
neutrinos
electron

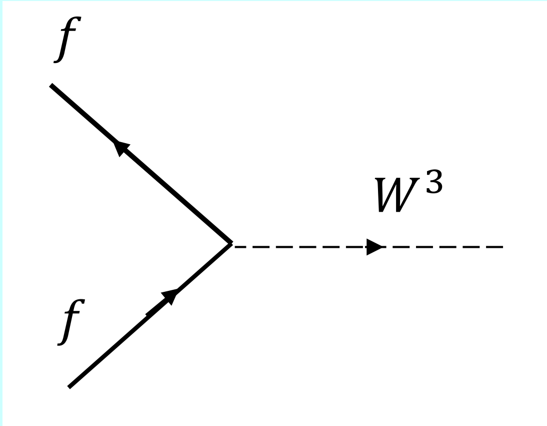
W 在 SPS 找到！

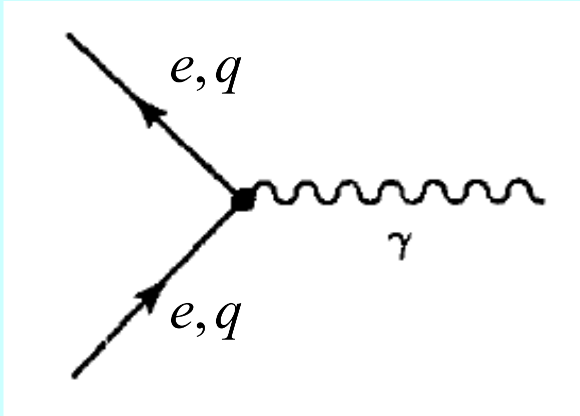


What is the charge neutral W^3 boson?

Charge neutral weak interaction was observed only in 1973.





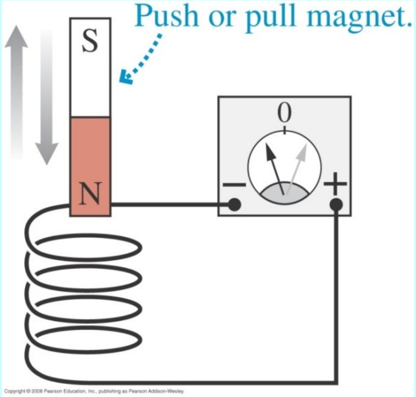


弱作用與電磁作用的結構非常類似，都可簡化為由少量的交點來描述。

兩者都是由自旋為一的波色子來媒介。

Could the charge neutral W^3 be photon?

弱作用與電磁作用可不可以統一？



磁場變化產生感應電場！

磁力與電力是內在地聯繫在一起，

必須以統一的電磁力來對待。

或許電磁力與弱作用力也是同一個力的兩個面向

電磁作用與弱作用或許可以統一成為電弱交互作用Electroweak。

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

and on a right-handed singlet

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e.$$

The largest group that leaves in matic terms $-\bar{L}\gamma^{\mu}\partial_{\mu}L-\bar{R}\gamma^{\mu}\partial_{\mu}R$ ian consists of the electronic isc on L, plus the numbers N_L, N_R right-handed electron-type lepto as we know, two of these symme tirely unbroken: the charge $Q=$ and the electron number $N=N_R$ gauge field corresponding to an metry will have zero mass,[4] and massless particle coupled to N,[5] form our gauge group out of the spin $\vec{T}$ and the electronic hyperc $+\tfrac{1}{2}N_L$.

Therefore, we shall construct ian out of L and R, plus gauge fi B_{μ} coupled to $\vec{T}$ and Y, plus a s

ANNALS OF PHYSICS: **2**, 407–434 (1957)

A Theory of the Fundamental Interactions

JULIAN SCHWINGER

Harvard University, Cambridge, Massachusetts

"The axiomatic basis of theoretical physics cannot be extracted from experience but must be freely invented."

A. Einstein.

This note is an account of some developments in an effort to find a description of the present stock of elementary particles within the framework of the theory of quantized fields[1].

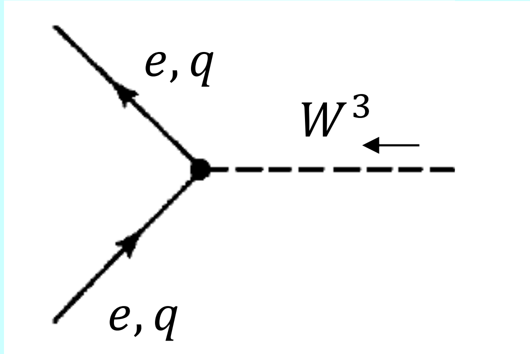
The theory of fields suggests that the spin values of ½ for F(ermi)-D(irac) fields, and of 0 and 1 for B(ose)-E(instein) fields are not only exceptional in their simplicity but are likely to be unique in the possibility of constructing a con-

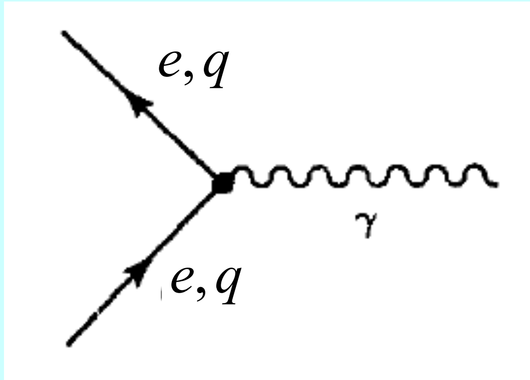
Schwinger first suggested the existence of an "isotopic" triplet of vector fields whose universal couplings would generate both the weak interactions and electromagnetism — the two oppositely charged fields mediate weak interactions and the neutral field is light [2]). A certain ambiguity beclouds the self-

Schwinger 的 iso-triplet vector field 就雷同Weak $SU(2)$ gauge theory 1957

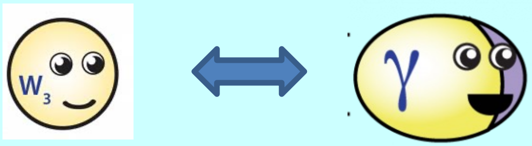
統一的電弱理論

$(W^+ \quad W^3 \quad W^-)$





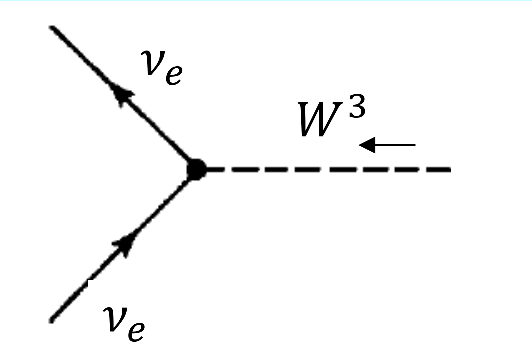
他主張電中性的W^3就是光子！

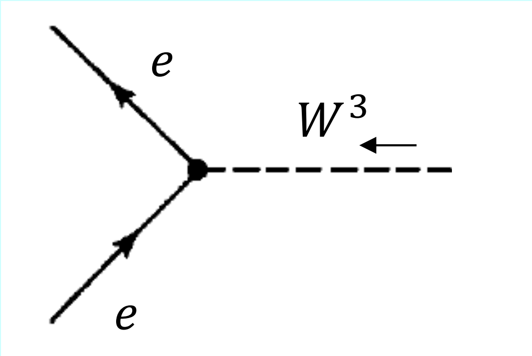


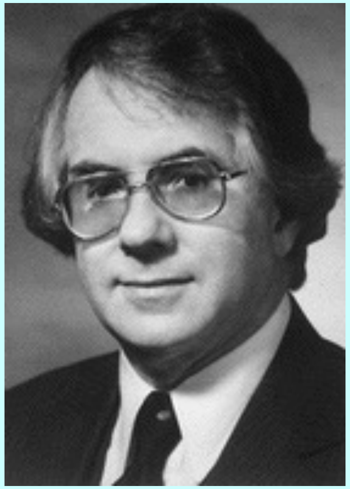
可惜，It doesn't work!

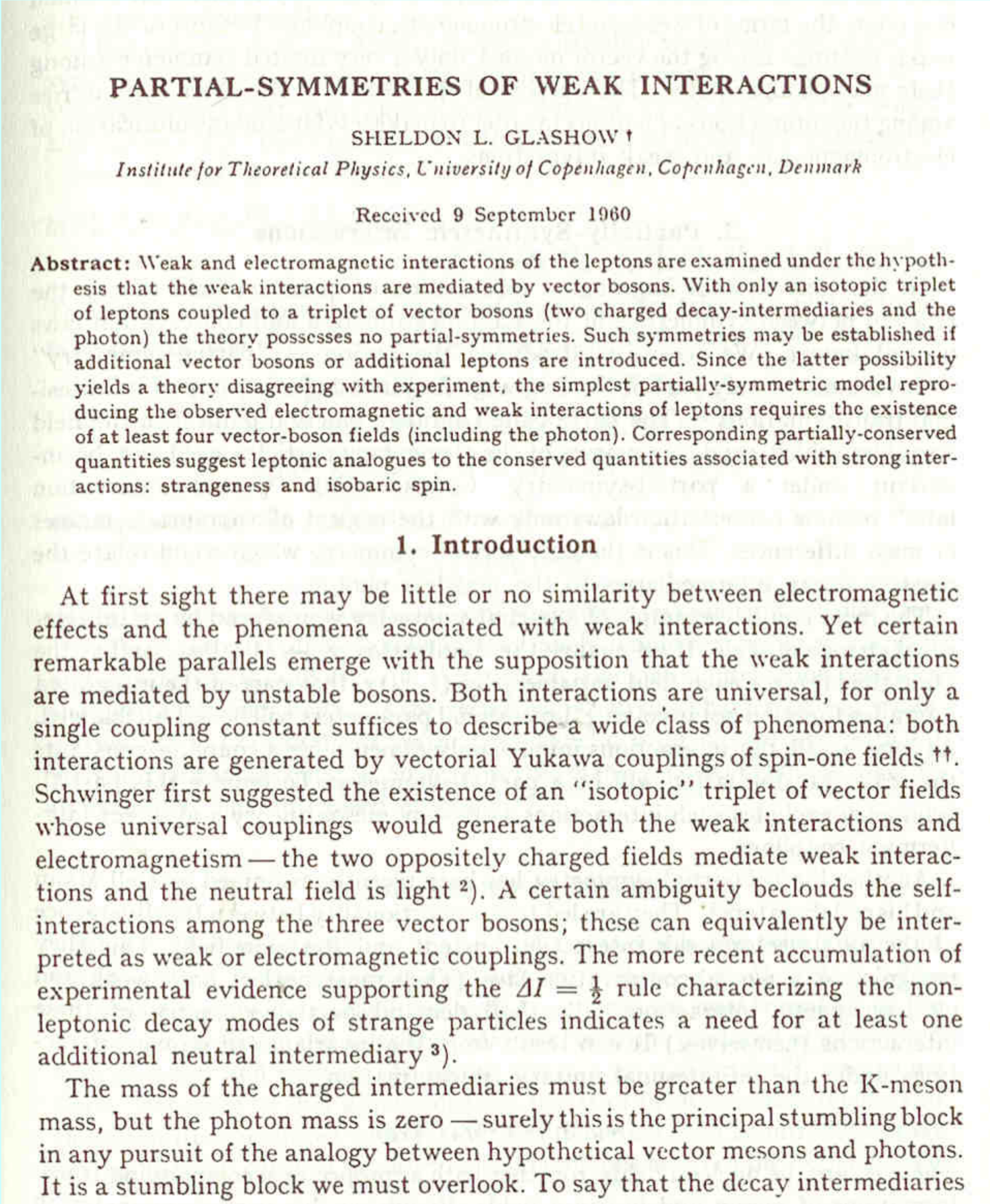
W^3與微中子的交互作用是光子沒有的！

$$\frac{g}{2}\begin{pmatrix}\bar{\nu}_e & \bar{e}\end{pmatrix} W^3 \begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\begin{pmatrix}\nu_e\\ e\end{pmatrix} = \frac{g}{2}\bar{\nu}_e\nu_e W^3 - \frac{1}{2}\bar{e}eW^3$$









PARTIAL-SYMMETRIES OF WEAK INTERACTIONS

SHELDON L. GLASHOW †

Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

Received 9 September 1960

Abstract: Weak and electromagnetic interactions of the leptons are examined under the hypothesis that the weak interactions are mediated by vector bosons. With only an isotopic triplet of leptons coupled to a triplet of vector bosons (two charged decay-intermediaries and the photon) the theory possesses no partial-symmetries. Such symmetries may be established if additional vector bosons or additional leptons are introduced. Since the latter possibility yields a theory disagreeing with experiment, the simplest partially-symmetric model reproducing the observed electromagnetic and weak interactions of leptons requires the existence of at least four vector-boson fields (including the photon). Corresponding partially-conserved quantities suggest leptonic analogues to the conserved quantities associated with strong interactions: strangeness and isobaric spin.

1. Introduction

At first sight there may be little or no similarity between electromagnetic effects and the phenomena associated with weak interactions. Yet certain remarkable parallels emerge with the supposition that the weak interactions are mediated by unstable bosons. Both interactions are universal, for only a single coupling constant suffices to describe a wide class of phenomena: both interactions are generated by vectorial Yukawa couplings of spin-one fields ††. Schwinger first suggested the existence of an "isotopic" triplet of vector fields whose universal couplings would generate both the weak interactions and electromagnetism — the two oppositely charged fields mediate weak interactions and the neutral field is light [2]). A certain ambiguity beclouds the self-interactions among the three vector bosons; these can equivalently be interpreted as weak or electromagnetic couplings. The more recent accumulation of experimental evidence supporting the $\Delta I = \frac{1}{2}$ rule characterizing the non-leptonic decay modes of strange particles indicates a need for at least one additional neutral intermediary [3]).

The mass of the charged intermediaries must be greater than the K-meson mass, but the photon mass is zero — surely this is the principal stumbling block in any pursuit of the analogy between hypothetical vector mesons and photons. It is a stumbling block we must overlook. To say that the decay intermediaries

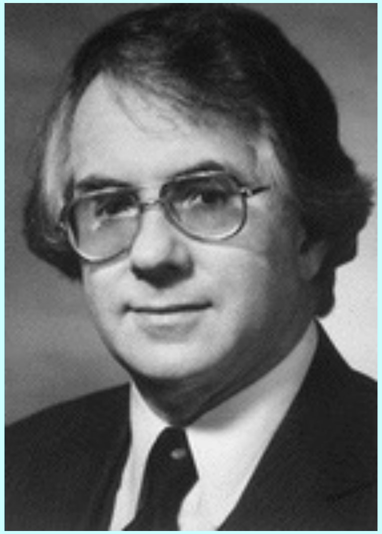
4. Partially-Symmetric Synthesis

In order to achieve a partially-symmetric theory of weak and electro-magnetic interactions, we must go beyond the hypothesis of only a triplet of vector bosons and introduce an additional neutral vector boson Z_S. It will have the same behaviour under CP as Z_3 and it is coupled to its own neutral lepton current $J_\mu^S = \psi\beta\gamma_\mu S\psi$. The three partial symmetries of section 3 are undisturbed by this new interaction provided that

$$[O, S] = 0. \qquad (4.1)$$

Glashow 建議電弱理論是一個 $SU(2) \times U(1)$ gauge theory.

$SU(2) \times U(1)$



Gauged Weak $SU(2)$

$\alpha_1, \alpha_2, \alpha_3$

三個規範子

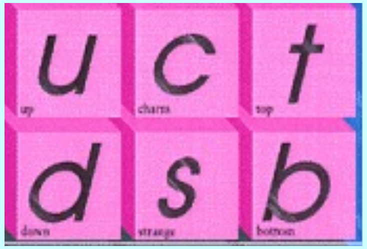
Gauged $U(1)$

θ

一個規範子

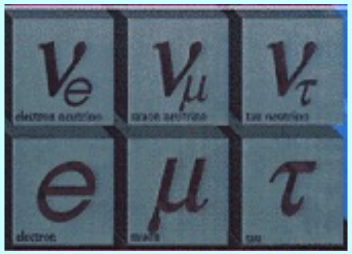
這是一個精心設計的$U(1)$：夸克與輕子以不同的Y (Hypercharge) 作phase變化

$$Q = \frac{\tau^3}{2} + Y$$



$$q' \to e^{iY\theta} q = e^{i\frac{1}{6}\theta} q$$

$$Y = \frac{1}{6}$$

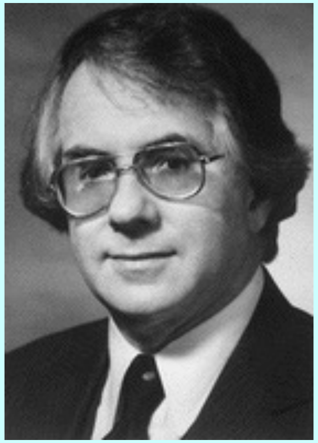


$$l' \to e^{iY\theta} l = e^{-i\frac{1}{2}\theta} l$$

$$Y = -\frac{1}{2}$$

對應於每一個連續變數，必須引進一個自旋為1的規範波色子 Gauge Boson!

Gauged $U(1)$ 也有一個規範波色子 B。



$SU(2) \times U(1)$ gauge theory

$SU(2) \times U(1)$

Gauged Isospin $SU(2)$

$\alpha_1, \alpha_2, \alpha_3$

$(W^+ \quad W^3 \quad W^-)$

Gauged $U(1)$

θ

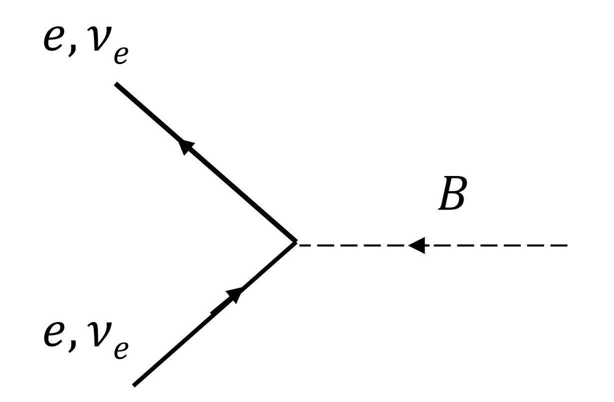
B

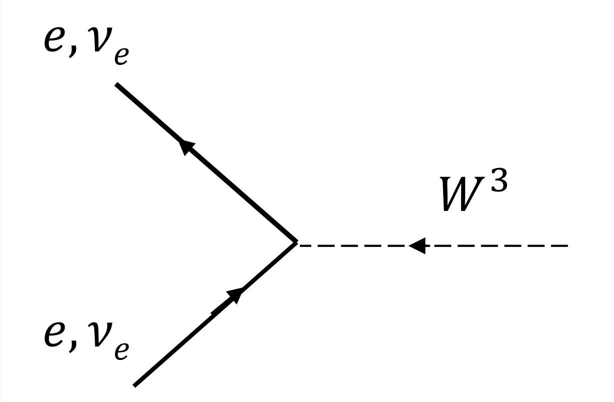
B與doublet的上下粒子作用相同，耦合常數記為$g'Y$，vertex寫成矩陣：

$$g'Y\bar{\nu}_e\nu_e B - g'Y\bar{e}eB = (\bar{\nu}_e \quad \bar{e})\begin{pmatrix} -\frac{g'}{2}B & 0 \\ 0 & -\frac{g'}{2}B \end{pmatrix}\begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

W^3的Vertex也可以寫成矩陣：

$$\frac{g}{2}\bar{\nu}_e\nu_e W^3 - \frac{g}{2}\bar{e}eW^3 = (\bar{\nu}_e \quad \bar{e})\begin{pmatrix} \frac{g}{2}W^3 & 0 \\ 0 & -\frac{g}{2}W^3 \end{pmatrix}\begin{pmatrix} \nu_e \\ e \end{pmatrix}$$





加總，這其實就產生四個interaction vertices，但讓我們保留矩陣寫法：

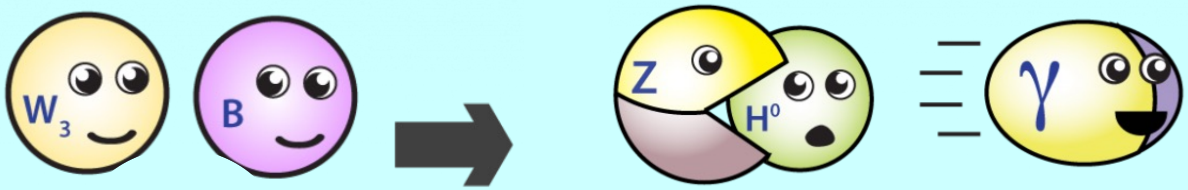
$$(\bar{\nu}_e \quad \bar{e})\begin{pmatrix} \frac{g}{2}W^3 - \frac{g'}{2}B & 0 \\ 0 & -\frac{g}{2}W^3 - \frac{g'}{2}B \end{pmatrix}\begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

The reader may wonder what has been gained by the introduction of another neutral vector meson. Neither Z_3 nor Z_S interacts with the electrical current so that neither interaction may be identified with electromagnetism. (To have chosen $J_\mu{}^S$ to be the electrical current would have violated (4.1) and lost partial-symmetry.) However, both the neutral fields have the same CP property so that linear combinations of the two fields may correspond to "particles."

Glashow提議：光子 γ 是 B 與 W^3 的線性疊加。

$$\gamma = \sin\theta_W\, W^3 + \cos\theta_W\, B$$

θ_W:Weinberg Angle



另一個正交的線性疊加是一個尚未觀察到的粒子：Z 粒子

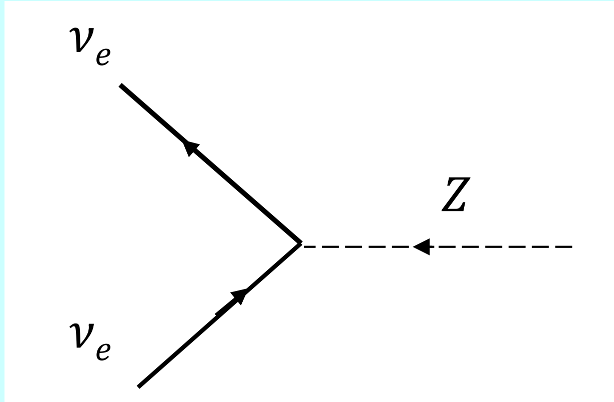
$$Z = \cos\theta_W\, W^3 - \sin\theta_W\, B$$

微中子與光子A無交互作用，因此矩陣左上角與微中子作用的是Z介子。

Z

$$(\bar{\nu}_e \quad \bar{e})\begin{pmatrix} \frac{g}{2}W^3 - \frac{g'}{2}B & 0 \\ 0 & -\frac{g}{2}W^3 - \frac{g'}{2}B \end{pmatrix}\begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

$Z + A$

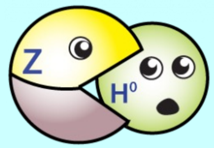


$$\frac{1}{\sqrt{g^2 + g'^2}}(gW^3 - g'B) \equiv Z$$

與Z介子垂直的線性組合即是光子A 。

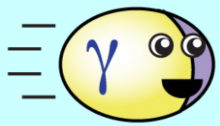
$$\frac{1}{\sqrt{g^2 + g'^2}}(g'W^3 + gB) \equiv A$$

$$\frac{1}{\sqrt{g^2+g'^2}}(gW^3-g'B)\equiv Z$$



$$W^3=\frac{1}{\sqrt{g^2+g'^2}}(gZ+g'A)$$

$$\frac{1}{\sqrt{g^2+g'^2}}(g'W^3+gB)\equiv A$$



$$B=\frac{1}{\sqrt{g^2+g'^2}}(-gZ+g'A)$$

Z與輕子的交互作用就可以由W^3, B與輕子的交互作用得出：

$$(\bar{\nu}_e \quad \bar{e})\begin{pmatrix}\frac{g}{2}W^3+\frac{g'}{2}B & 0 \\ 0 & -\frac{g}{2}W^3+\frac{g'}{2}B\end{pmatrix}\begin{pmatrix}\nu_e \\ e\end{pmatrix}$$

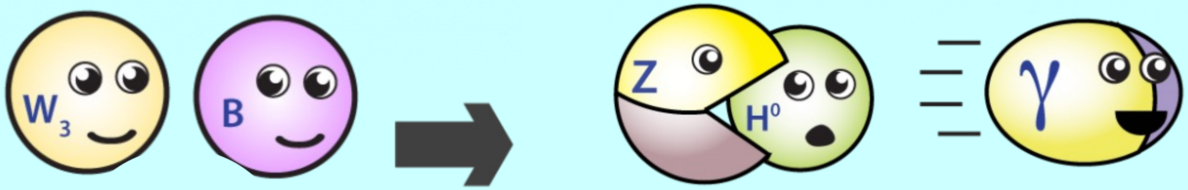
$$=(\bar{\nu}_e \quad \bar{e})\begin{pmatrix}\frac{\sqrt{g^2+g'^2}}{2}Z & 0 \\ 0 & \frac{(g'^2-g^2)}{2\sqrt{g^2+g'^2}}Z+\frac{gg'}{\sqrt{g^2+g'^2}}A\end{pmatrix}\begin{pmatrix}\nu_e \\ e\end{pmatrix}$$

Two Splendid Results: I. Weinberg Angle

$$A = \sin\theta_W\, W^3 + \cos\theta_W\, B$$

$$Z = \cos\theta_W\, W^3 - \sin\theta_W\, B$$

θ_W:Weinberg Angle



$$A = \frac{1}{\sqrt{g^2 + g'^2}}(g'W^3 + gB)$$

$$Z = \frac{1}{\sqrt{g^2 + g'^2}}(gW^3 - g'B)$$

$$\sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

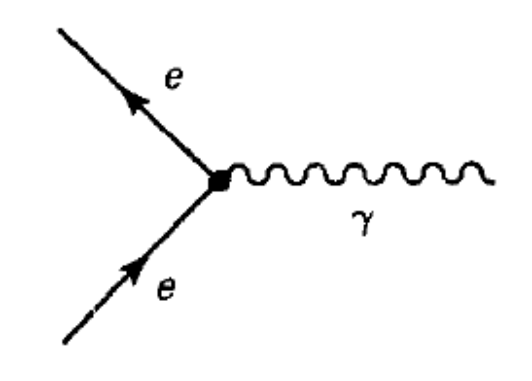
Two Splendid Results: II. Interaction vertices of leptons and neutral gauge bosons

$$\begin{pmatrix}\bar{\nu}_e & \bar{e}\end{pmatrix}\begin{pmatrix}\frac{\sqrt{g^2+g'^2}}{2}Z & 0 \\ 0 & \frac{(g'^2-g^2)}{2\sqrt{g^2+g'^2}}Z+\frac{gg'}{\sqrt{g^2+g'^2}}A\end{pmatrix}\begin{pmatrix}\nu_e \\ e\end{pmatrix}$$

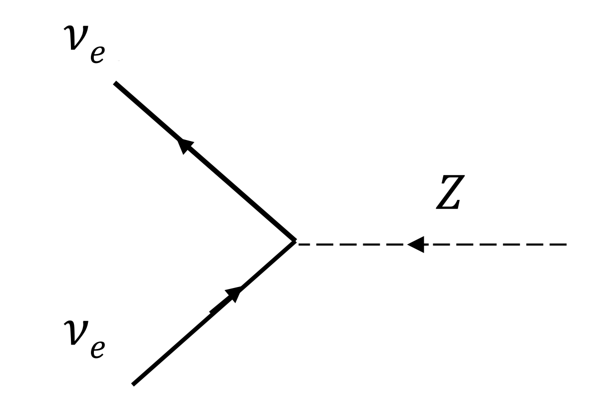
Now I put back $\gamma^{\mu\prime}$s and μ's.

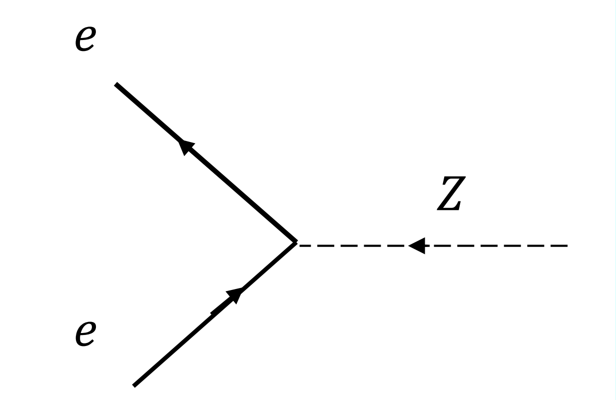
$$\frac{gg'}{\sqrt{g^2+g'^2}}\bar{e}\gamma^\mu e A_\mu = q_e \cdot \bar{e}\gamma^\mu e A_\mu$$

$$\frac{gg'}{\sqrt{g^2+g'^2}} = q_e$$

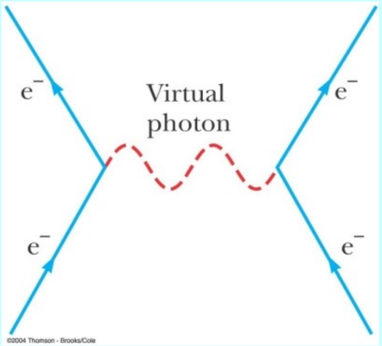


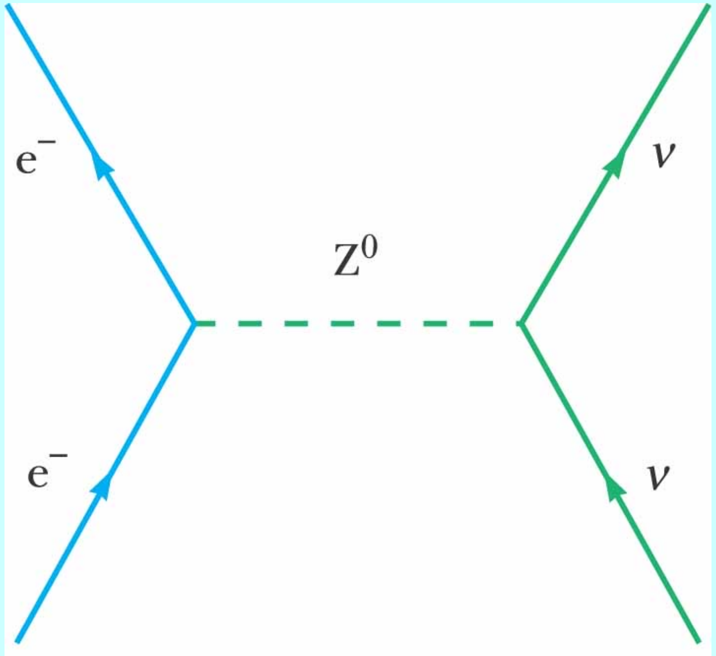
$$\frac{\sqrt{g^2+g'^2}}{2}\bar{\nu}_e\gamma^\mu\nu_e Z_\mu - \frac{(g'^2-g^2)}{2\sqrt{g^2+g'^2}}\bar{e}\gamma^\mu e Z_\mu$$





Weak Interaction through Z particle

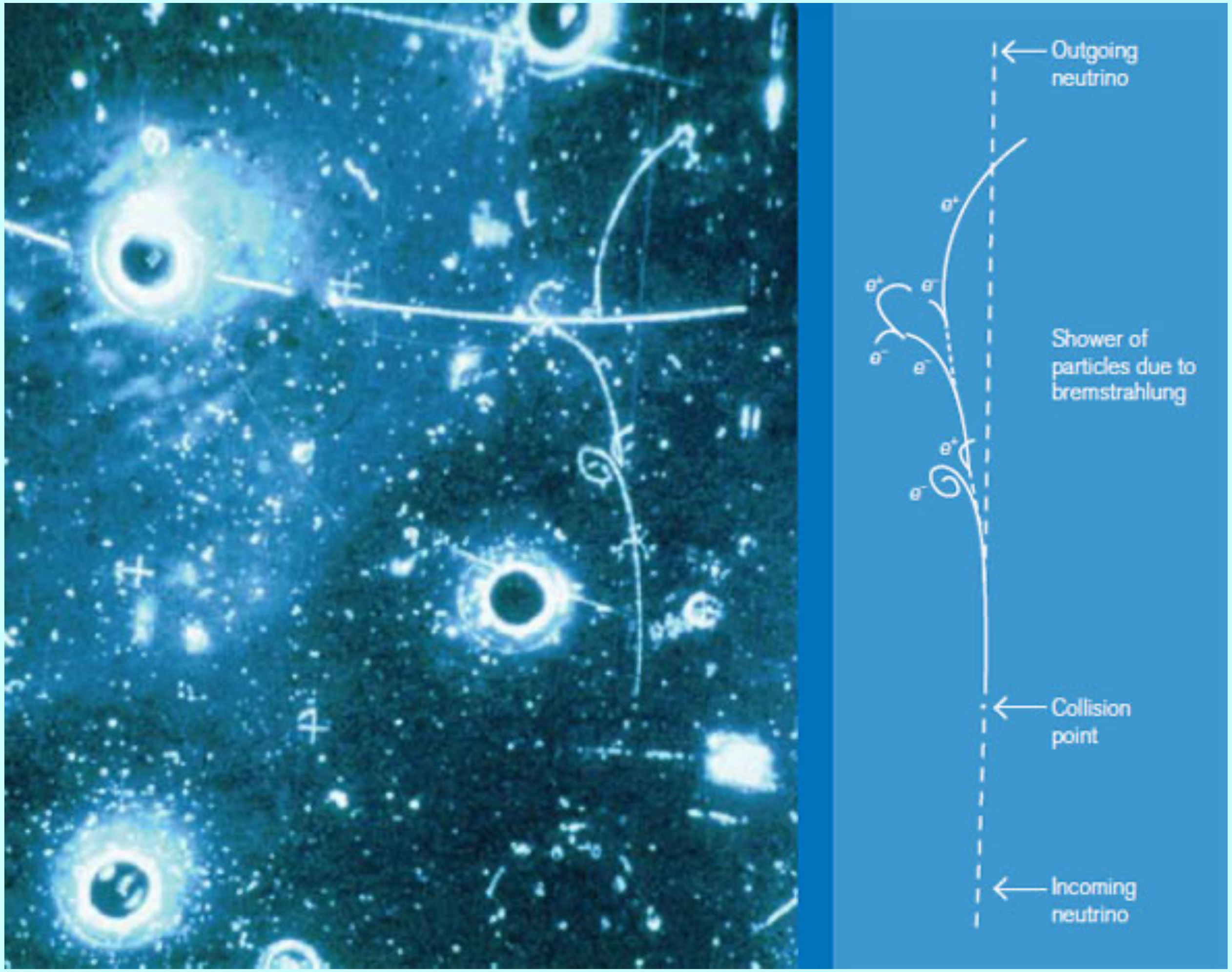


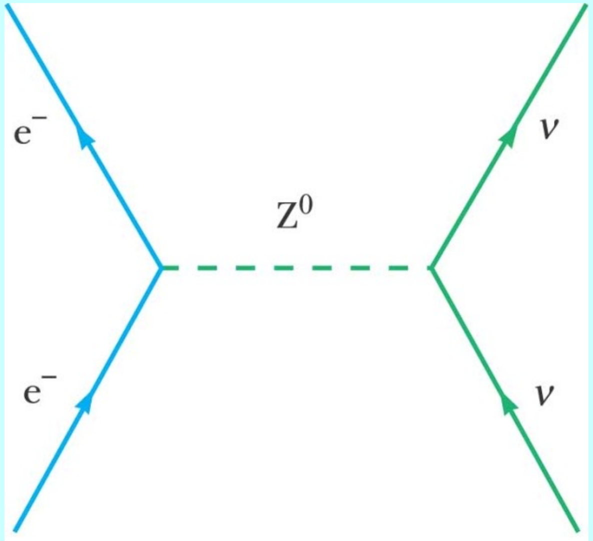


Beta衰變只需要W即可，Z的存在是依據規範對稱的原則在60年代即預測出來，70年代間接證實，80年代才直接找到。

Z^0與光子的作用很接近，難區分，但只有Z^0與微中子是有作用的！

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





Garmamelle CERN 1973

Z $J = 1$

Charge = 0

Mass $m = 91.1876 \pm 0.0021$ GeV [d]

Full width $\Gamma = 2.4952 \pm 0.0023$ GeV

$\Gamma(\ell^+ \ell^-) = 83.984 \pm 0.086$ MeV [b]

$\Gamma(\text{invisible}) = 499.0 \pm 1.5$ MeV [e]

$\Gamma(\text{hadrons}) = 1744.4 \pm 2.0$ MeV

$\Gamma(\mu^+ \mu^-)/\Gamma(e^+ e^-) = 1.0009 \pm 0.0028$

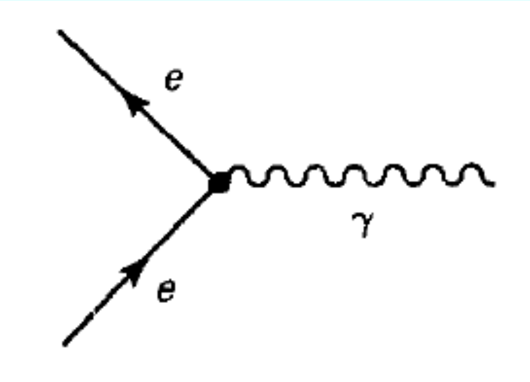
$\Gamma(\tau^+ \tau^-)/\Gamma(e^+ e^-) = 1.0019 \pm 0.0032$ [f]

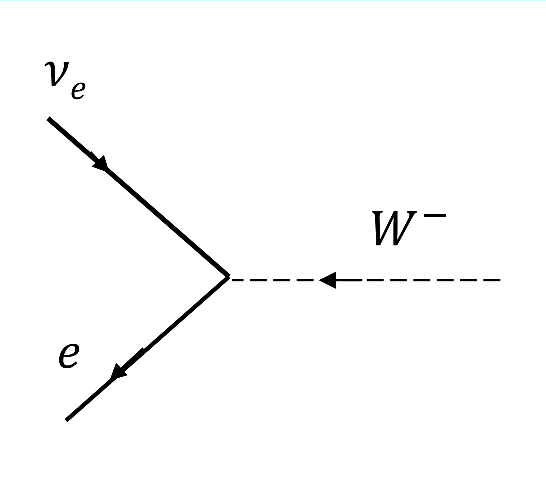
電磁作用與弱作用統一成為電弱Electroweak交互作用。

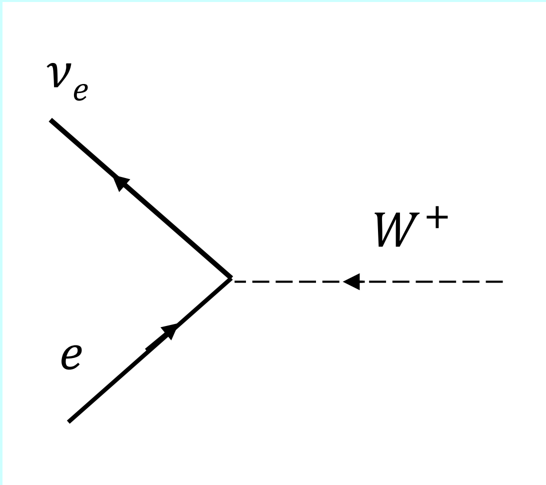
Weak and Electromagnetic interaction is one $SU(2)\times U(1)$ gauge theory.

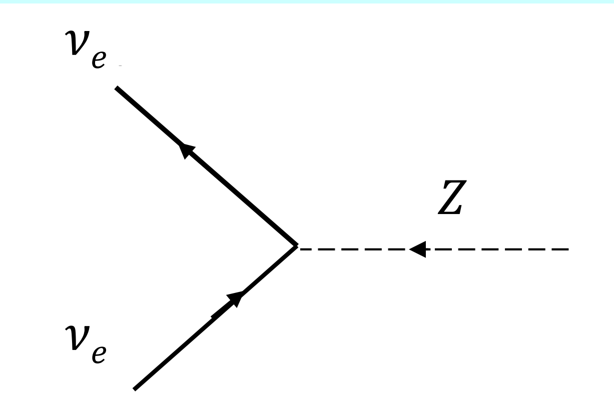
光子 γ 是 B 與 W^3 的線性疊加。疊加統一了兩個彼此分不開的交互作用。

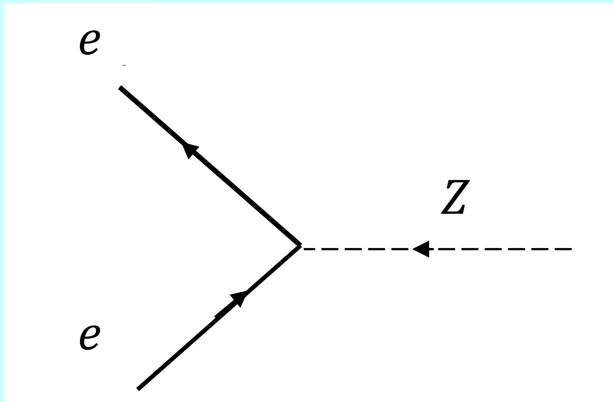
另一個正交的線性疊加是已觀察到的粒子：Z 粒子。


e
γ
e


ν_e
W^-
e


ν_e
W^+
e


ν_e
Z
ν_e


e
Z
e

夸克可以照作：

$$g'Y\bar{d}dB - g'Y\bar{u}uB = (\bar{u} \quad \bar{d})\begin{pmatrix} \frac{g'}{6}B & 0 \\ 0 & \frac{g'}{6}B \end{pmatrix}\binom{u}{d}$$

$$\frac{g}{2}\bar{\nu}_e\nu_e W^3 - \frac{g}{2}\bar{e}eW^3 = (\bar{u} \quad \bar{d})\begin{pmatrix} \frac{g}{2}W^3 & 0 \\ 0 & -\frac{g}{2}W^3 \end{pmatrix}\binom{u}{d}$$

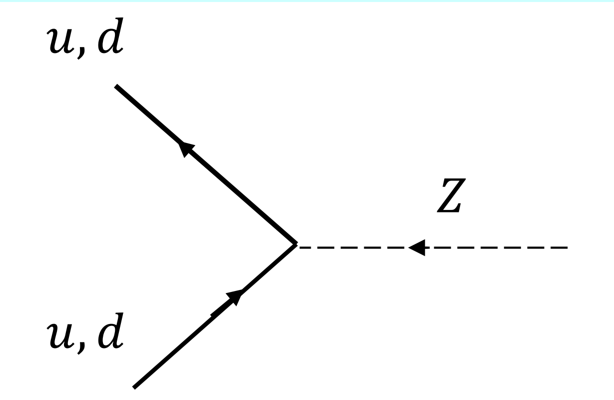
$$(\bar{u} \quad \bar{d})\begin{pmatrix} \frac{g}{2}W^3 + \frac{g'}{6}B & 0 \\ 0 & -\frac{g}{2}W^3 + \frac{g'}{6}B \end{pmatrix}\binom{u}{d}$$

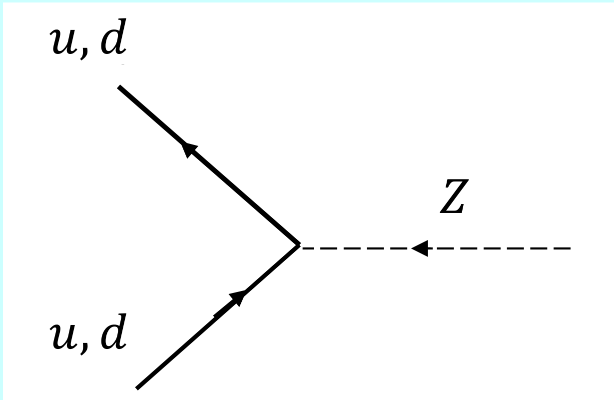
$$W^3 = \frac{1}{\sqrt{g^2 + g'^2}}(gZ + g'A)$$

$$B = \frac{1}{\sqrt{g^2 + g'^2}}(-gZ + g'A)$$

代入線性疊加公式即可：

夸克同時與光子及Z都有作用：





Feynman Rule用Covariant Derivative D_μ來推導更系統化：

$$D_\mu = \partial_\mu - \frac{i}{2} g \boldsymbol{\tau} \cdot \boldsymbol{W}_\mu - i g' Y B_\mu$$

$$\begin{pmatrix} \frac{g}{2} W^3 + g' Y B & \frac{g}{\sqrt{2}} W^+ \\ \frac{g}{\sqrt{2}} W^- & -\frac{g}{2} W^3 + g' Y B \end{pmatrix}$$

代入真實的規範粒子：

$$D_\mu = \partial_\mu - i \frac{g}{\sqrt{2}} \left(W_\mu^+ \tau^+ + W_\mu^- \tau^- \right) - i \frac{g}{2} W_\mu^3 \tau^3 - i g' Y B_\mu$$

$$= \partial_\mu - i \frac{g}{\sqrt{2}} \left(W_\mu^+ \tau^+ + W_\mu^- \tau^- \right) - i q_e Q A_\mu - i \frac{q_e}{\cos\theta_W \sin\theta_W} \left(\frac{\tau^3}{2} + Q \sin^2\theta_W \right) Z_\mu$$

$$W^3 = \cos\theta_W \, Z + \sin\theta_W \, A$$

$$B = -\cos\theta_W \, Z + \sin\theta_W \, A$$

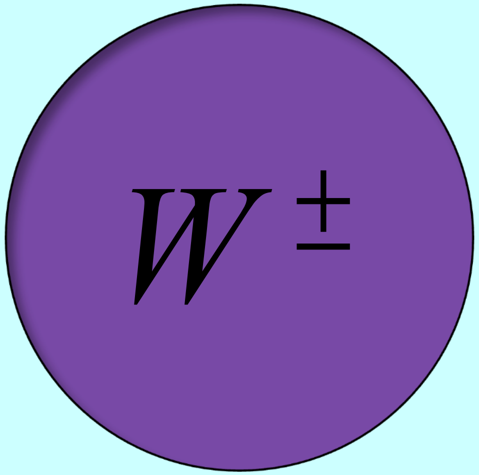
$$Q = \frac{\tau^3}{2} + Y$$

這樣的統一建議雖然美好，但還沒起飛就已墜落！

Gauge Bosons are massless, by gauge symmetry.

Gauge Bosons mass term is not gauge invariant, hence will ruin renormalization.

$m_W W_\mu^+ W^{-\mu}$ $m_Z Z_\mu Z^\mu$



規範波色子必須無質量，但W是很重的！

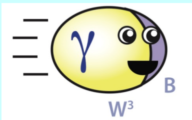
在$SU(2)$變換之下 $(W^+ \quad W^3 \quad W^-)$

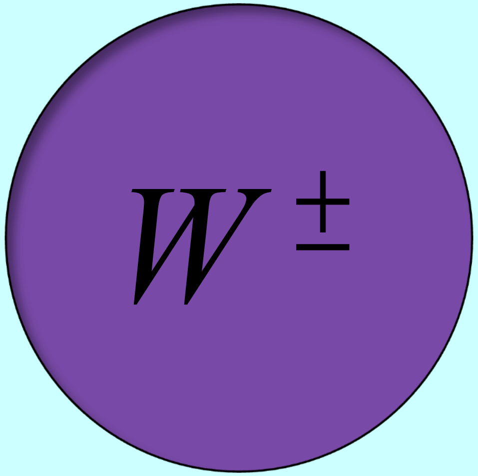
$$\delta \boldsymbol{W}_\mu = \frac{1}{g}\partial_\mu \boldsymbol{\alpha} + \boldsymbol{\alpha} \times \boldsymbol{W}_\mu$$

是屬於一個 Representation。

一個Representation中的所有基本粒子性質（質量）相等。

因此對稱性要求三個波色子性質相同！





光子中有W^3的成分

$W^\pm$與W^3三者性質相似！

為什麼 $W^\pm$ 會比 γ 重如此之多？

PARTIAL-SYMMETRIES OF WEAK INTERACTIONS

SHELDON L. GLASHOW †

Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

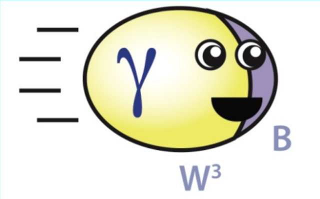
Received 9 September 1960

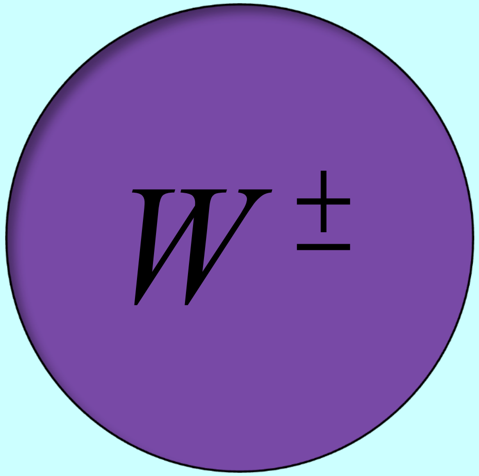
Abstract: Weak and electromagnetic interactions of the leptons are examined under the hypothesis that the weak interactions are mediated by vector bosons. With only an isotopic triplet of leptons coupled to a triplet of vector bosons (two charged decay-intermediaries and the photon) the theory possesses no partial-symmetries. Such symmetries may be established if additional vector bosons or additional leptons are introduced. Since the latter possibility yields a theory disagreeing with experiment, the simplest partially-symmetric model reproducing the observed electromagnetic and weak interactions of leptons requires the existence of at least four vector-boson fields (including the photon). Corresponding partially-conserved quantities suggest leptonic analogues to the conserved quantities associated with strong interactions: strangeness and isobaric spin.

$W^{\pm}$

The mass of the charged intermediaries must be greater than the K-meson mass, but the photon mass is zero — surely this is the principal stumbling block in any pursuit of the analogy between hypothetical vector mesons and photons. It is a stumbling block we must overlook. To say that the decay intermediaries

"The purpose of the note is to ….. make less fanciful the unification of electromagnetism and weak interaction."





$W^{\pm}$會比γ重如此之多！

規範波色子必須無質量，但$W^{\pm}$是很重的！

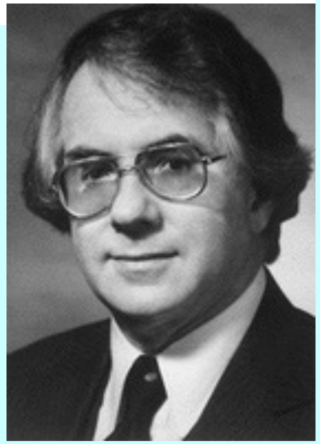
$SU(2)$ 對稱已經被破壞！

規範對稱已經被破壞！

如何優雅而不粗暴地破壞理論優美的對稱呢？

你可以暴力地直接破壞對稱：就直接容許某些項就是不是不變的。

is well known. We recently introduced the notion of "partial-symmetry" — invariance of only part of the Lagrange function under a group of infinitesimal transformations [4]). The part of the Lagrange function bilinear in the field variables which produces masses of the elementary particles need not be invariant under a partial-symmetry. Corresponding "partial-conservation laws" become conservation laws only with the neglect of appropriate masses or mass differences. This is the only sort of symmetry which could relate the massive decay intermediaries to the massless photon.



這樣的作法會使理論無法重整化 renormalizable。

如何優雅而不粗暴地破壞理論優美的對稱呢？

A MODEL OF LEPTONS*

Steven Weinberg†

Laboratory for Nuclear Science and Physics

Massachusetts Institute of Technology, Cambridg

(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the

真空破壞了對稱，給了無質量的規範粒子質量！

Steven Weinberg

The Nobel

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

Photo: University of Chicago

Yoichiro Nambu

1/2 of the prize

USA

Enrico Fermi Institute,
University of Chicago
Chicago, IL, USA

b. 1921
(in Tokyo, Japan)

Scanned at the American Institute of Physics

1969

這樣的機制已經早被提出來了。

Scanned at the American Institute of Physics

PHYSICAL REVIEW VOLUME 124, NUMBER 1 OCTOBER 1, 1961

Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity. II*

Y. NAMBU AND G. JONA-LASINIO†
Enrico Fermi Institute for Nuclear Studies and Department of Physics, University of Chicago, Chicago, Illinois

(Received May 10, 1961)

Continuing the program developed in a previous paper, a "superconductive" solution describing the proton-neutron doublet is obtained from a nonlinear spinor field Lagrangian. We find the pions of finite mass as nucleon-antinucleon bound states by introducing a small bare mass into the Lagrangian which otherwise possesses a certain type of the γ_5 invariance. In addition, heavier mesons and two-nucleon bound states are obtained in the same approximation. On the basis of numerical mass relations, it is suggested that the bare nucleon field is similar to the electron-neutrino field, and further speculations are made concerning the complete description of the baryons and leptons.

I. INTRODUCTION

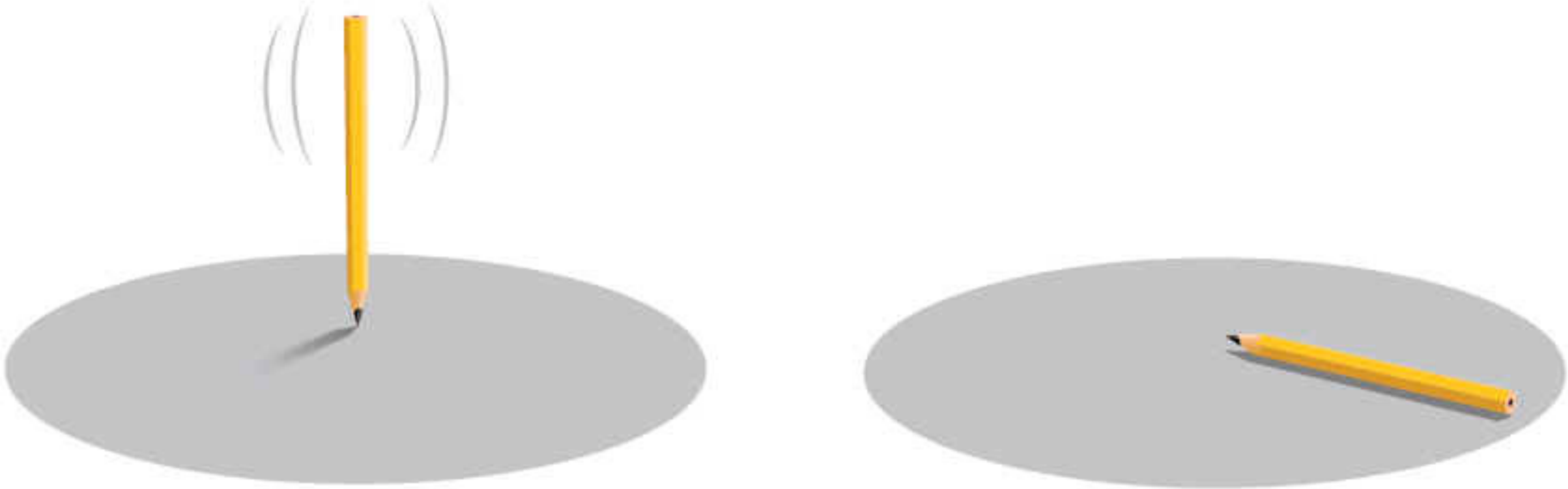
IN Part I of this paper[1] we have proposed a model of strong interactions based on an analogy with the BCS-Bogoliubov theory of superconductivity. It is characterized by a nonlinear spinor field possessing γ_5 invariance, and simulates some important features of the meson-nucleon system. The basic principle underlying the model is the idea that field theory may admit, as a result of dynamical instability, extraordinary (nontrivial) solutions that have less symmetries than are built into the Lagrangian.[2] In fact we have obtained as an extraordinary solution a massive fermion and a massless pseudoscalar boson as idealized proton and pion, together with other heavy mesons.

theory will depend on its ability to account for violation of the symmetry as well.

Finally, we face the problem of the baryon ve the lepton, the electromagnetism, and the w processes. Here our theory creates a particular incen for speculation concerning the baryon-lepton prob since the ordinary and extraordinary solutions mediately remind us of these two families of partic

We do not profess to have any clear-cut answe these problems. In the present paper we shall a content ourselves with a rather modest task. We first discuss a generalization of our model which corporates the isospin for the nucleon and guarar the existence of the pion. This can be done by

直覺的預期，如果能量有某個對稱，
作為能量的最低值的真空，應該也遵守該對稱。
事實上不是如此：



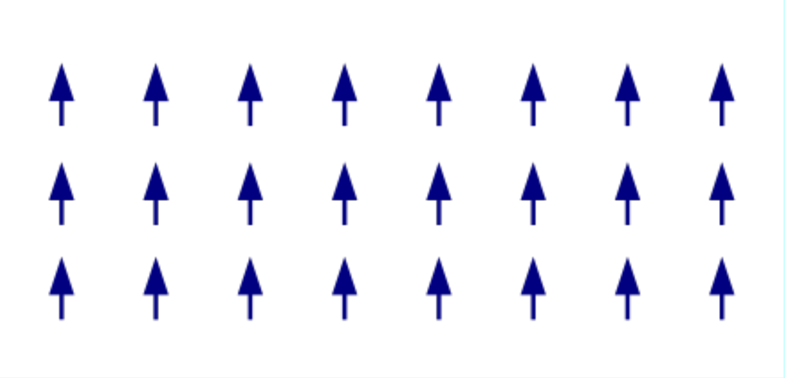
Spontaneous broken symmetry. *The world of this pencil is completely symmetrical. All directions* ***are exactly*** *equal. But this symmetry is lost when the pencil falls over. Now only one direction holds. The symmetry* ***that*** *existed before is hidden behind the fallen pencil.*

自發對稱破缺的例子在固態物理中早已被提出過了！

磁鐵的磁性就是如此

磁鐵是由一個個的小磁鐵組成，

小磁鐵彼此同向時能量最小，



$$H \propto -\sum_i \vec{s}_i \cdot \vec{s}_{i+1}$$

這個能量是旋轉對稱，isotropy似乎隱含磁鐵不可能有磁性。

能量在所有小磁鐵都同向時會是最低。

所有小磁鐵同向的狀態一定破壞旋轉對稱。

定義一總自旋：$s_z \equiv \sum_i s_{iz}$，在基態$s_z \neq 0$。

在旋轉變換下，基態不為零的s_z會變換，因此破壞旋轉不變性。

這種物理量s_z標誌了對稱的破壞，稱為Order Parameter。

在粒子物理中，扮演對稱破壞者的是純量場Φ的真空期望值$\langle\Phi\rangle$。

$$\langle\Phi\rangle = \langle 0|\Phi|0\rangle = \Phi_0$$

但在真空中，純量場的期望值可以不是零嗎？

一般的答案是真空中什麼都沒有，場的期望值自然是零！

真空的定義是基態Ground State：能量最低的狀態！

我們應該檢查一下在能量最低的狀態，$\langle\Phi\rangle$是否為零。

考慮一個複數純量場：$\Phi(x)$，

$$\mathcal{L} = \left(\partial_\mu \Phi^*\right)(\partial^\mu \Phi) - m^2\Phi^*\Phi - \lambda(\Phi^*\Phi)^2$$

Lagrangian在乘上一個相位的$U(1)$變換下是不變的： $\Phi(x) \to e^{-i\theta}\Phi(x)$

讓我先從global symmetry開始：

$U(1)$ global symmetry

$$\Psi(x) \to e^{-i\theta}\Psi(x)$$

$$\mathcal{L} = (\partial_\mu \Phi^*)(\partial^\mu \Phi) - m^2 \Phi^* \Phi - \lambda (\Phi^* \Phi)^2$$

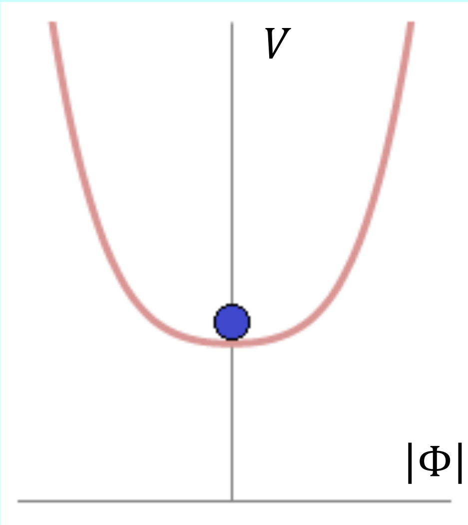
真空應該是平移對稱，因此$\langle \Phi \rangle$是一個常數。

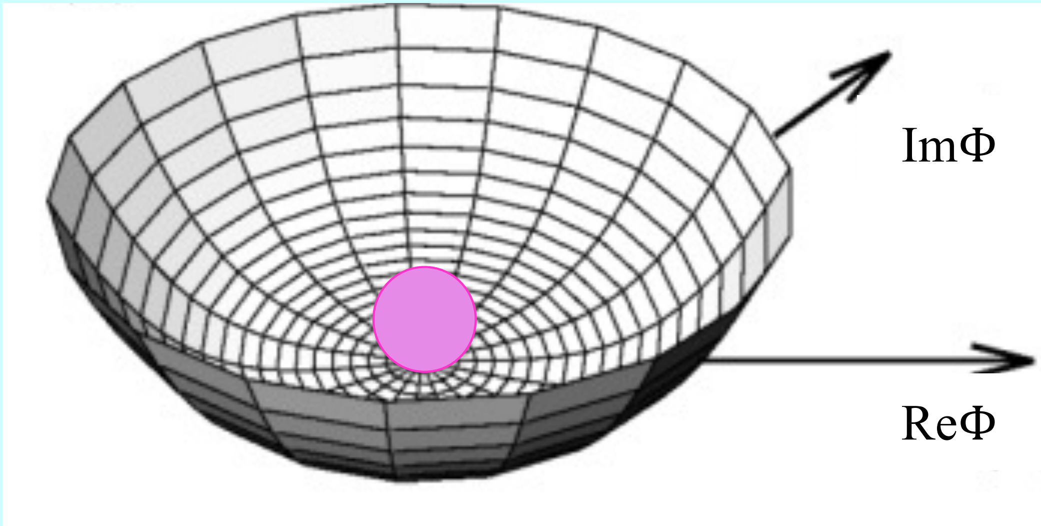
能量只要考慮無微分的項即可：

$$V = m^2 \Phi^* \Phi + \lambda (\Phi^* \Phi)^2 = m^2 |\Phi|^2 + \lambda |\Phi|^4$$

$\langle \Phi \rangle \equiv \Phi_0$是$V(\Phi_0)$的極小值。

將V對$|\Phi|$及複數Φ做圖。

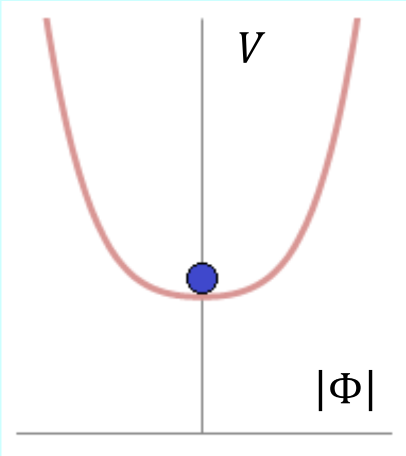


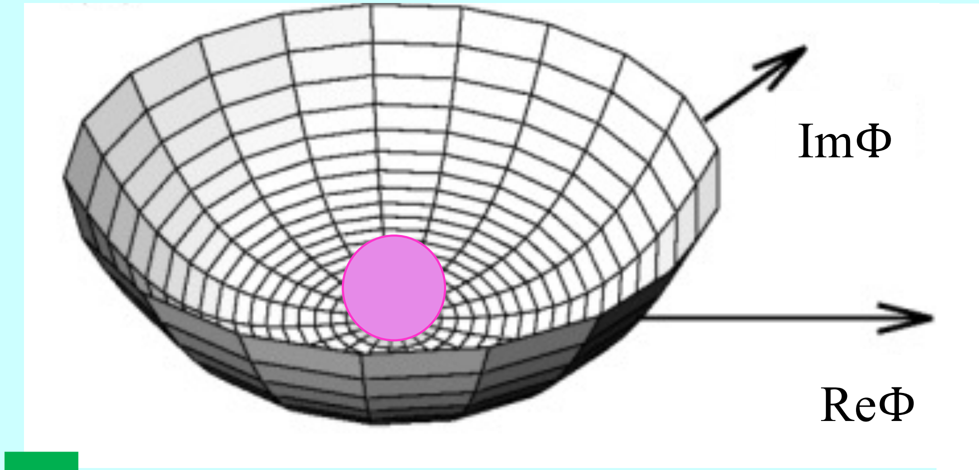


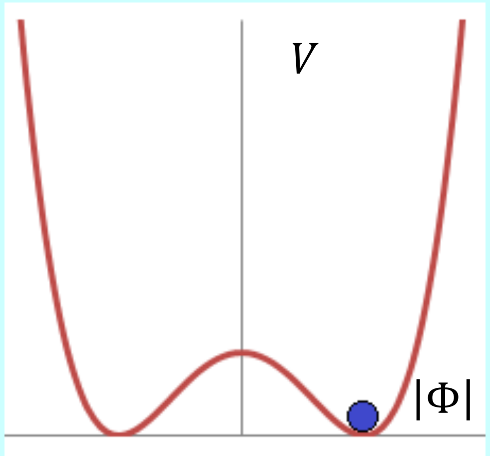
的確最低能量的狀態，場的值為零。此純量場在真空中為零。

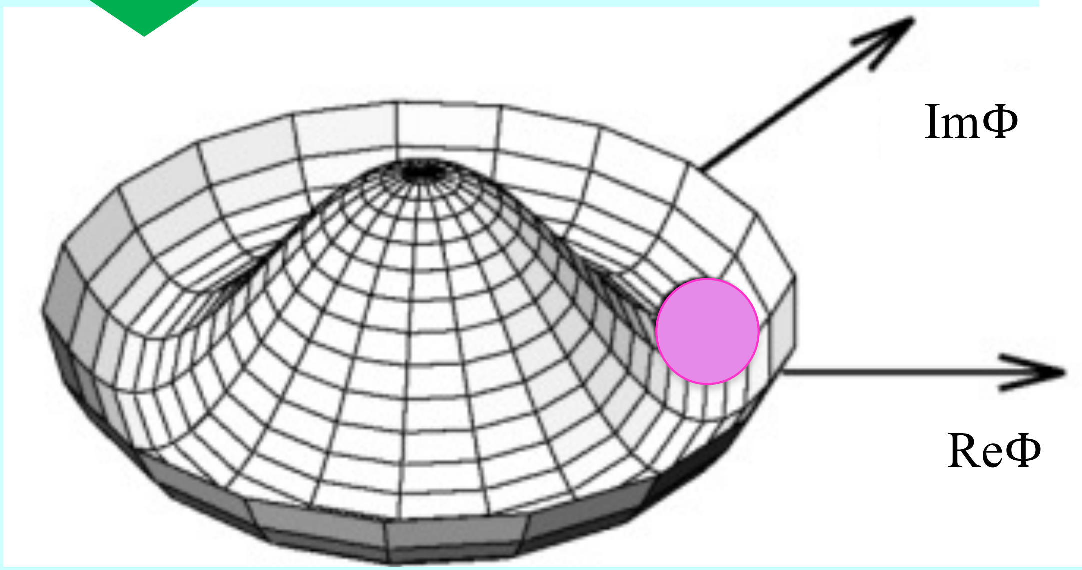
但如果平方項的係數為負數呢？

$$V = -\mu^2 \Phi^* \Phi + \lambda (\Phi^* \Phi)^2$$









現在場值為零的狀態能量並不是最低！

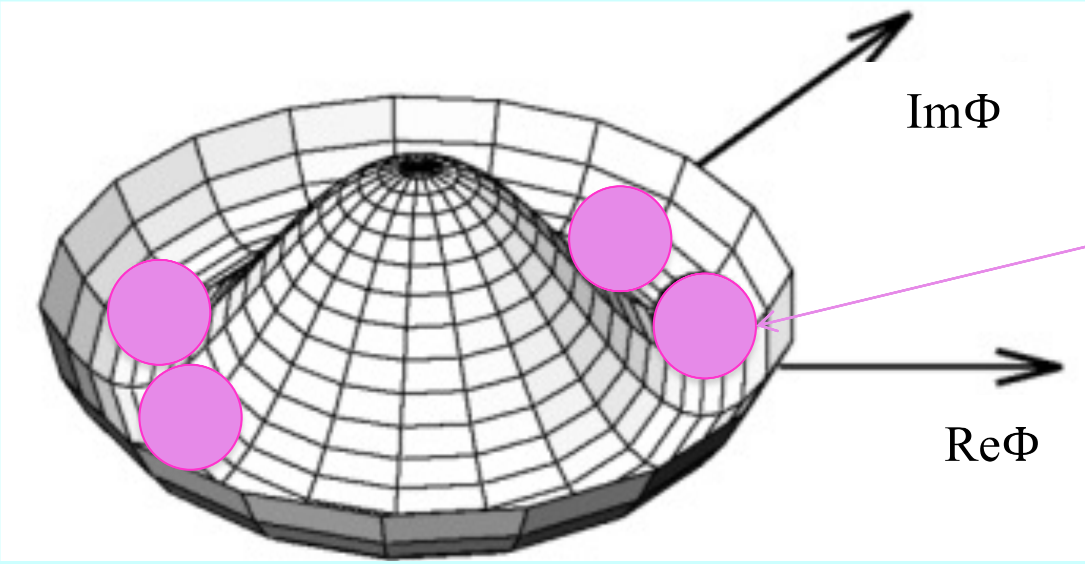
能量最低的狀態，場值不為零！

$$|\langle \Phi \rangle| = \frac{\mu}{\sqrt{2\lambda}}$$

$$|\Phi| = \frac{\mu}{\sqrt{2\lambda}}$$

而且，你現在有一整圈的最低能量態可以選擇作為真空：

但無論選了哪一個，真空中Φ值都不為零！



$$\Phi_0 = \frac{\mu}{\sqrt{2\lambda}}$$

選任何一個真空的場值，都會破壞對稱。例如：

$$\Phi_0 = \frac{\mu}{\sqrt{2\lambda}}$$

Lagrangian在乘上一個phase的$U(1)$變換下是不變的！

$$\Phi(x) \rightarrow e^{-i\theta}\Phi(x)$$

真空卻在此一變換下不是不變的！

$$\Phi_0 = \frac{\mu}{\sqrt{2\lambda}} \rightarrow e^{-i\theta}\frac{\mu}{\sqrt{2\lambda}} \neq \frac{\mu}{\sqrt{2\lambda}}$$

拉氏量、能量及運動方程式都遵守$U(1)$變換不變性，

但真空在$U(1)$變換下卻不是不變的！

能量最低的真空，破壞了能量所遵守的對稱性！

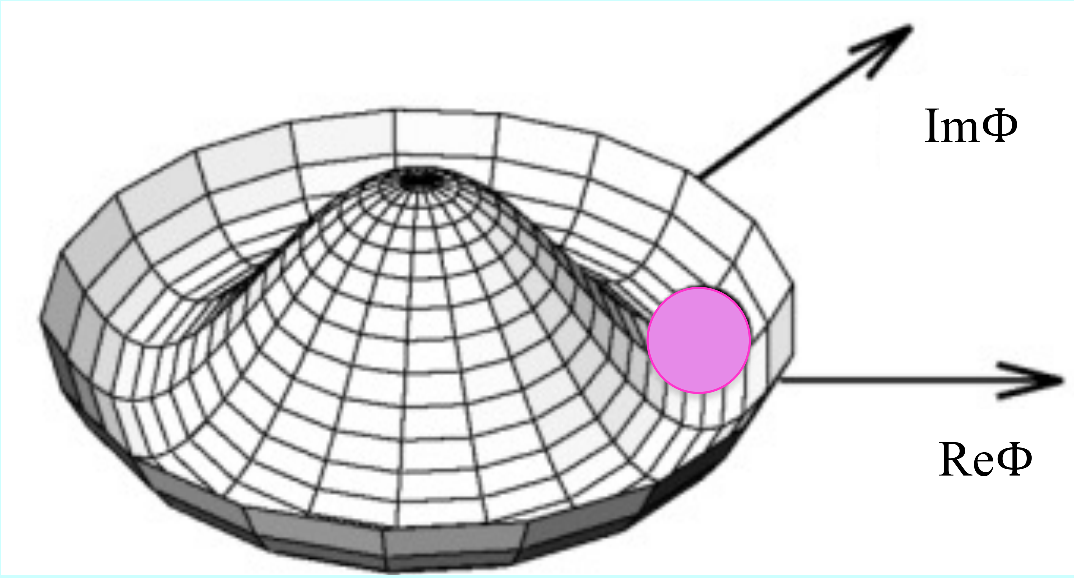
因此，表面上此系統無此對稱性，但能量及運動方程式卻偷偷地遵守！

這樣的機制稱為 Spontaneous Symmetry Breaking 自發對稱破缺

非藉由外力，而是由對稱的機制自發地破壞自己遵守的對稱。

Spontaneous Symmetry Breaking 自發對稱破缺

非藉由外力，而是由對稱的機制自發地破壞自己遵守的對稱：



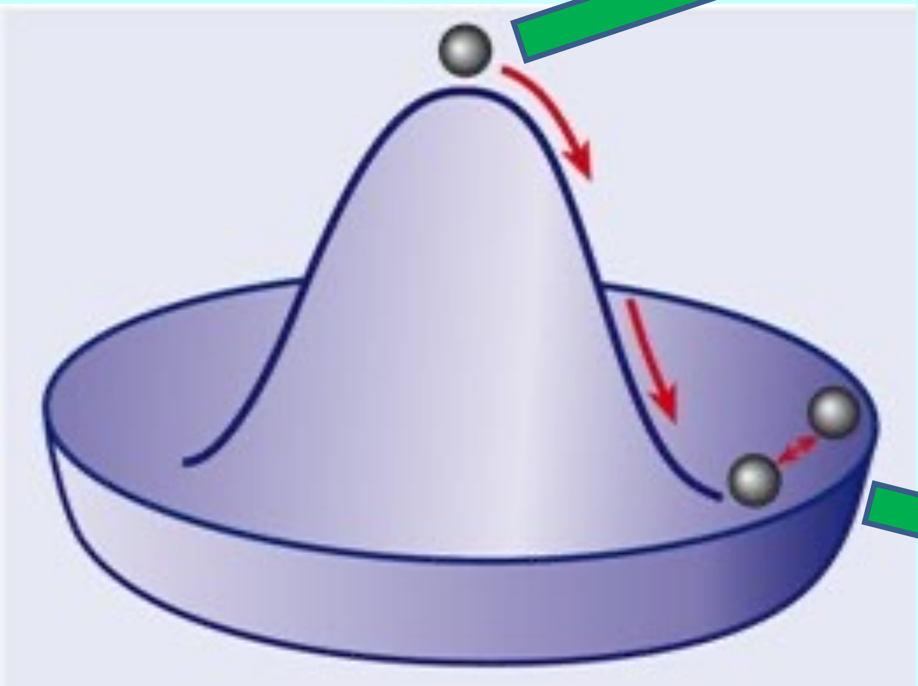
選擇那一個真空，在$U(1)$變換下都不是不變的！

所有可以選的真空都破壞能量遵守的$U(1)$對稱性！

Broken Symmetry

你的對稱感是與高度（能量）有關！

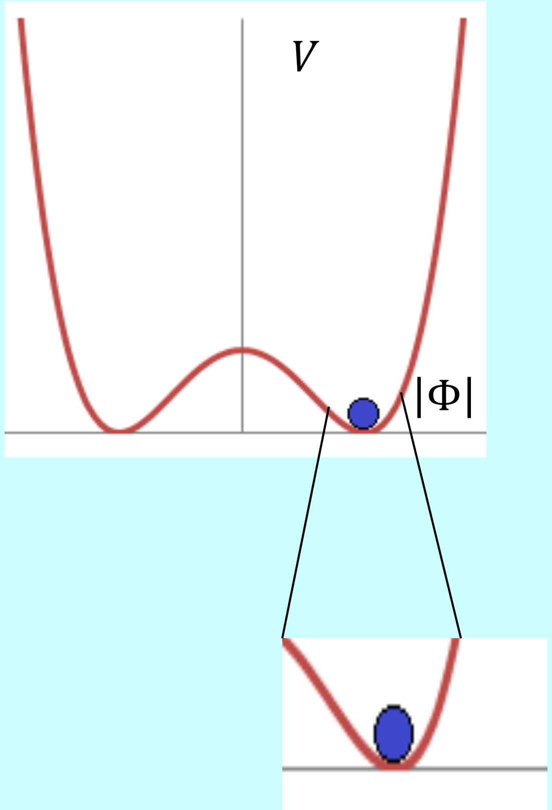
登上山頂才發現旋轉對稱！每一個方向都一樣！

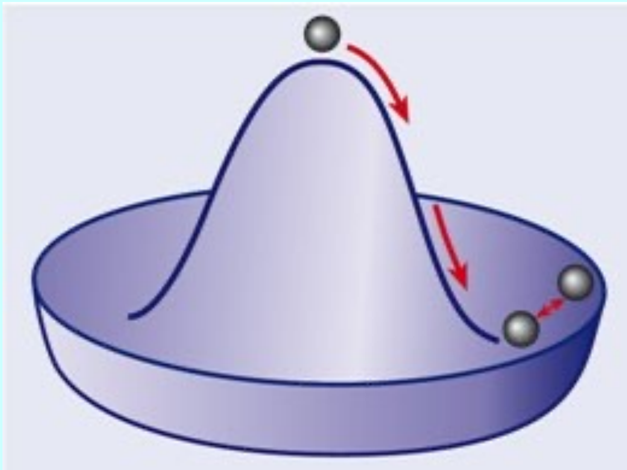


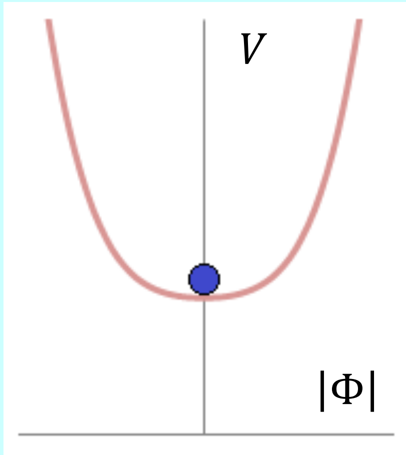
在山谷中並不會發現旋轉對稱！因為高山就矗立在一個方向！

雖然平方項的係數為負數，

$$V = -\mu^2\Phi^*\Phi + \lambda(\Phi^*\Phi)^2$$





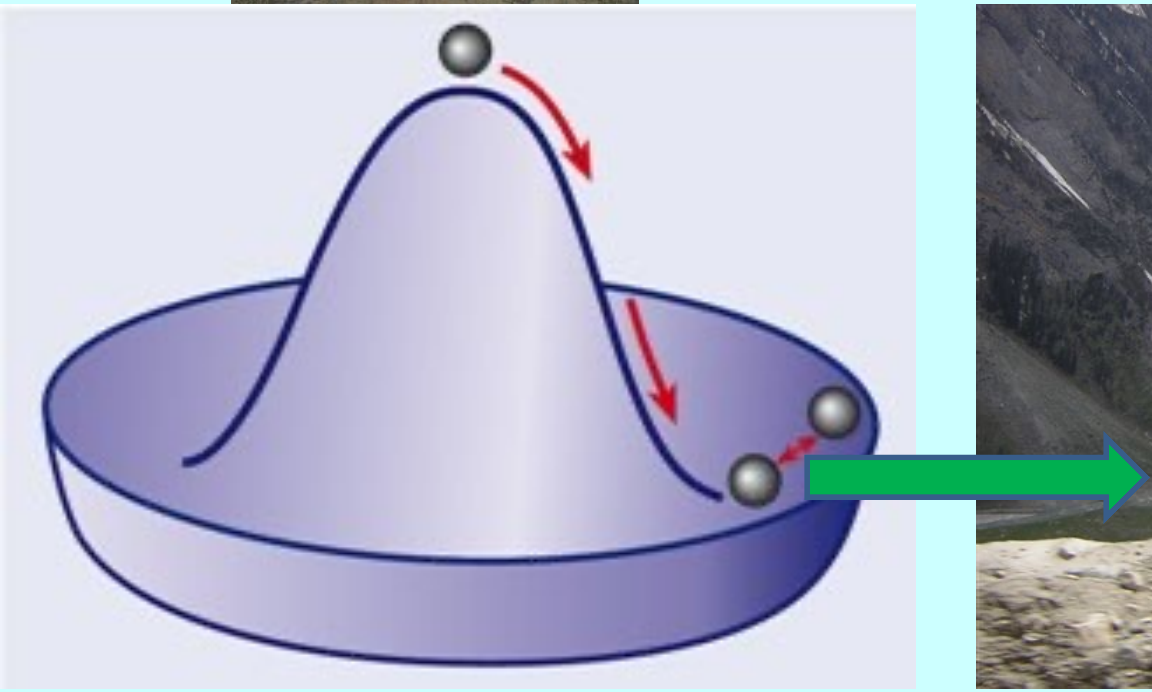


但如果站在真正的基態上看位能，當能量不大時，與簡諧振盪的位能無異。

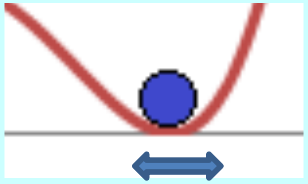
場量子化後，此簡諧振盪就會對應一個正質量的粒子Φ！

在能量不大時能否觀察到對稱？（畢竟不是每個人都能登高）

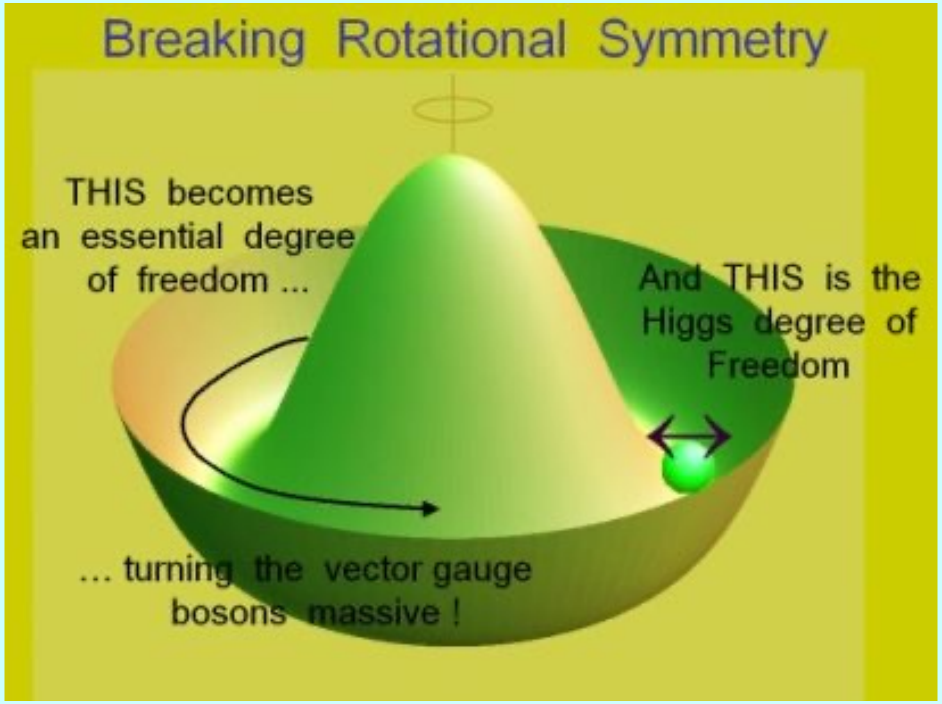
注意能量的旋轉對稱，在基態的痕跡就是一道平坦的河谷。

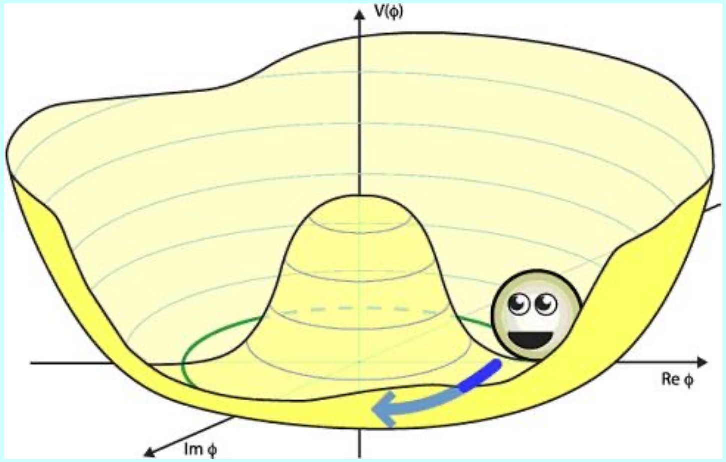


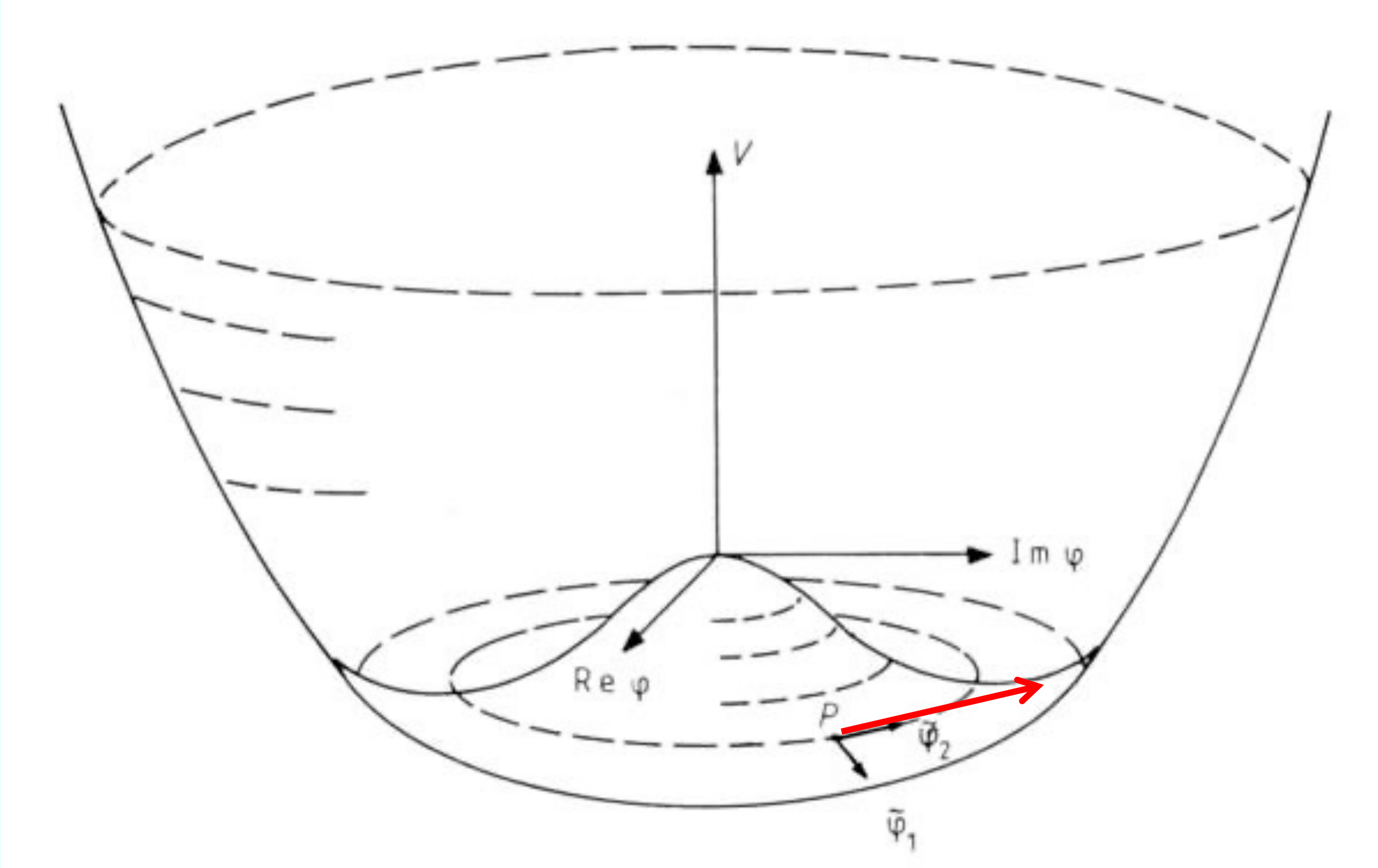
從基地（基態）出發，向著山的方向前進需要能量。



但沿著Valley的方向是平的，不需能量就能”移動”！







沿著Valley的方向是平的，不需作功就能"移動"！

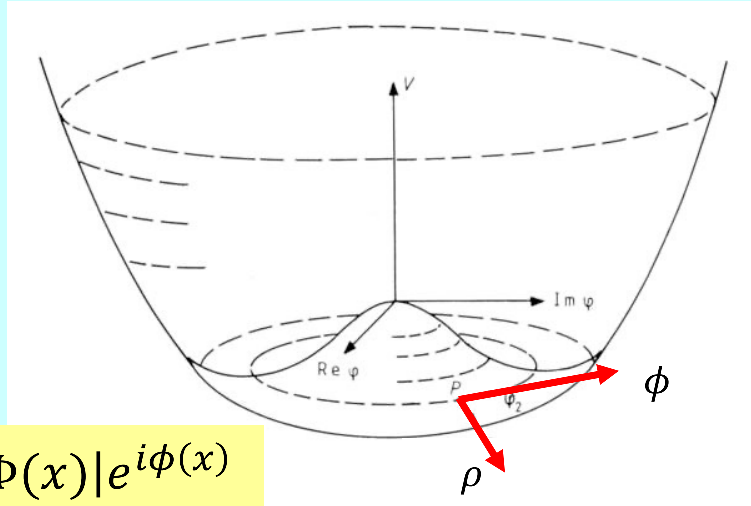
不需能量即能朝φ_2方向變化震盪，

此方向的場量子化後對應的粒子靜止能量為零。

φ_2對應一個無質量的粒子！

假設選取真空的場值為實數：

$$\Phi_0 = \frac{\mu}{\sqrt{2\lambda}} \equiv v$$



現在研究一下量子化後的粒子內容：

$$\mathcal{L} = \partial_\mu \Phi^* \partial^\mu \Phi + \mu^2 \Phi^* \Phi - \lambda (\Phi^* \Phi)^2$$

將場Φ以絕對值與幅角表示： $\Phi(x) = |\Phi(x)| e^{i\phi(x)}$

粒子是場相對真空的微小擾動，所以取$\Phi(x)$與$\Phi_0 = v$的差，才是恰當的場。

$$\Phi(x) = |\Phi(x)| e^{i\phi(x)} \equiv (\rho(x) + v) e^{i\phi(x)}$$

$$\langle \rho \rangle = \langle 0 | \rho(x) | 0 \rangle = \langle \phi \rangle = 0$$

很明顯，ϕ與ρ分別對應沿河谷與垂直河谷兩個方向場的變化的自由度！

將新的表示法代入Lagrangian後，粒子內容由場的平方項決定：

$$\mathcal{L} \supset \partial_\mu \rho \partial^\mu \rho + \mu^2 \rho^2 - 4\lambda v^2 \rho^2 + v^2 \partial_\mu \phi \partial^\mu \phi$$

注意：$\partial_\mu \rho \partial^\mu \phi$的交叉項會消掉。且位能與$\phi$無關，只由$|\Phi(x)|$決定。

$$= \partial_\mu \rho \partial^\mu \rho - \mu^2 \rho^2 + v^2 \partial_\mu \phi \partial^\mu \phi$$

場的兩個自由度，$\rho(x)$是一正質量KG場自旋零粒子，

$v\phi(x)$則是一無質量KG場自旋零粒子。

Dynamical Model of Elementary Particles Based on an Analogy with Superconductivity. I*

Y. NAMBU AND G. JONA-LASINIO†
Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Ill

(Received October 27, 1960)

It is suggested that the nucleon mass arises largely as a self-energy of some primary fermion field through the same mechanism as the appearance of energy gap in the theory of superconductivity. The idea can be put into a mathematical formulation utilizing a generalized Hartree-Fock approximation which regards real nucleons as quasi-particle excitations. We consider a simplified model of nonlinear four-fermion interaction which allows a γ_5-gauge group. An interesting consequence of the symmetry is that there arise automatically pseudoscalar zero-mass bound states of nucleon-antinucleon pair which may be regarded as an idealized pion. In addition, massive bound states of nucleon number zero and two are predicted in a simple approximation.

The theory contains two parameters which can be explicitly related to observed nucleon mass and the pion-nucleon coupling constant. Some paradoxical aspects of the theory in connection with the γ_5 transformation are discussed in detail.

The Nobel

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

Photo: University of Chicago

Yoichiro Nambu

1/2 of the prize

USA 南部陽一郎

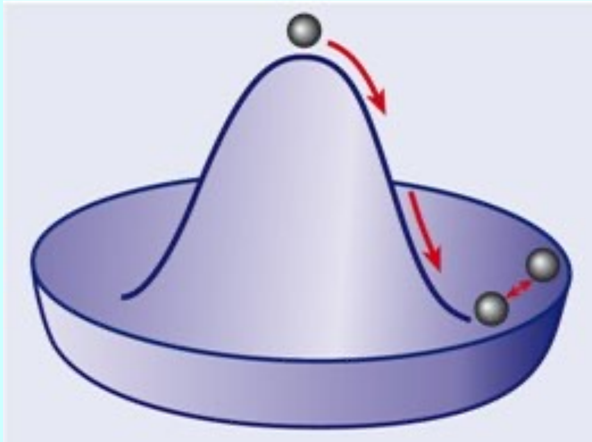
Enrico Fermi Institute, University of Chicago
Chicago, IL, USA

b. 1921
(in Tokyo, Japan)

Spontaneous Symmetry Breaking 自發對稱破缺

$U(1)$ global symmetry

$$\Psi(x) \rightarrow e^{-i\theta}\Psi(x)$$



物理定律是對稱的，但最低能量態卻不對稱！

自發對稱破缺的證據是一個對應的無質量粒子！

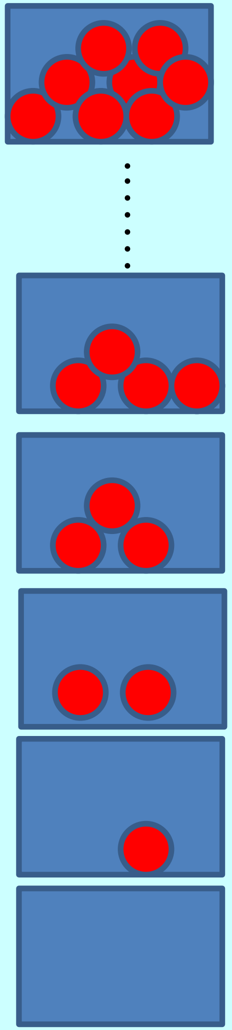
Goldstone Boson

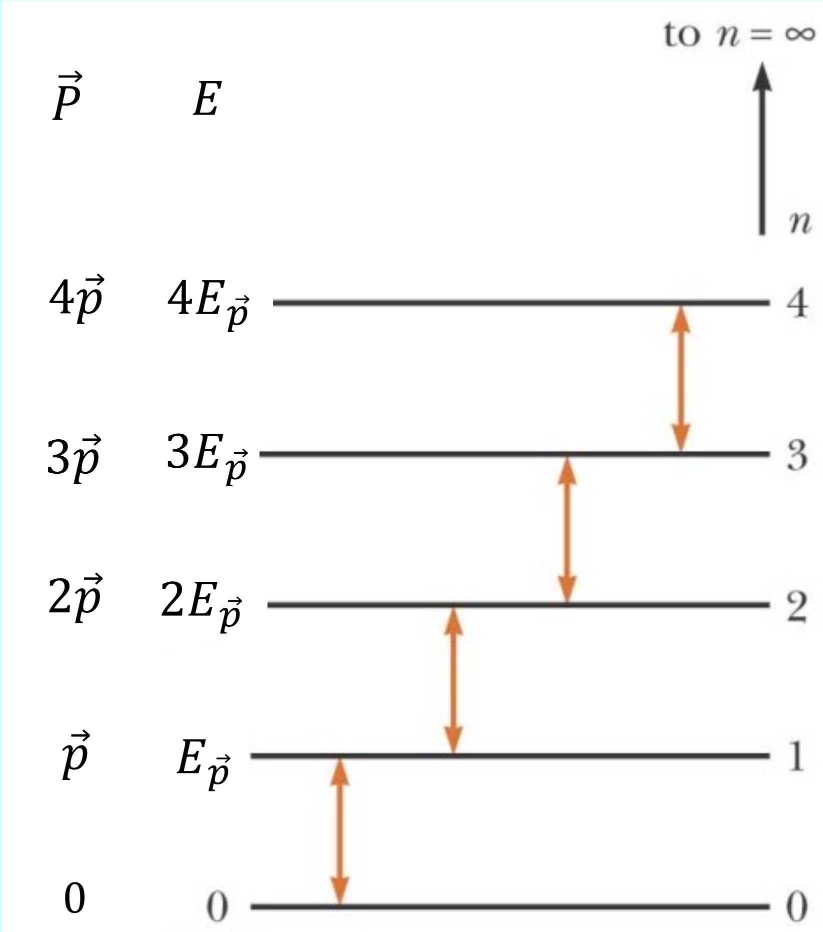
Nambu-Goldstone Boson

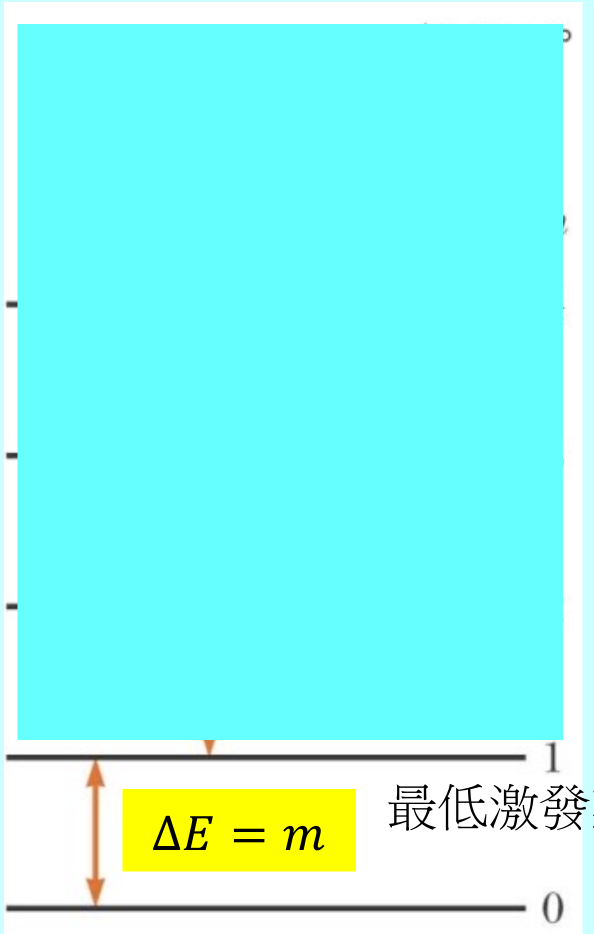
量子場就是一系列量子彈簧，其能量的本徵值為一系列的$nE_{\vec{p}}$，

這些本徵態也同時是動量的本徵態，本徵值為 $n\vec{p}$。 $E_{\vec{p}} = \sqrt{|\vec{p}|^2 + m^2}$

激發態的能量有一下限，與基態有一個energy gap。



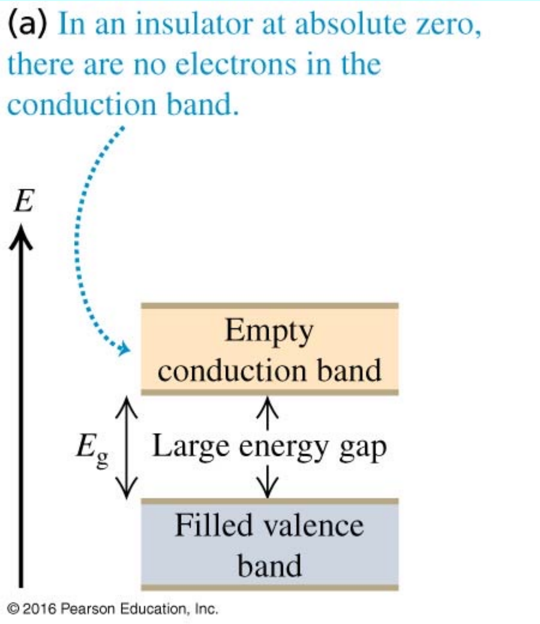


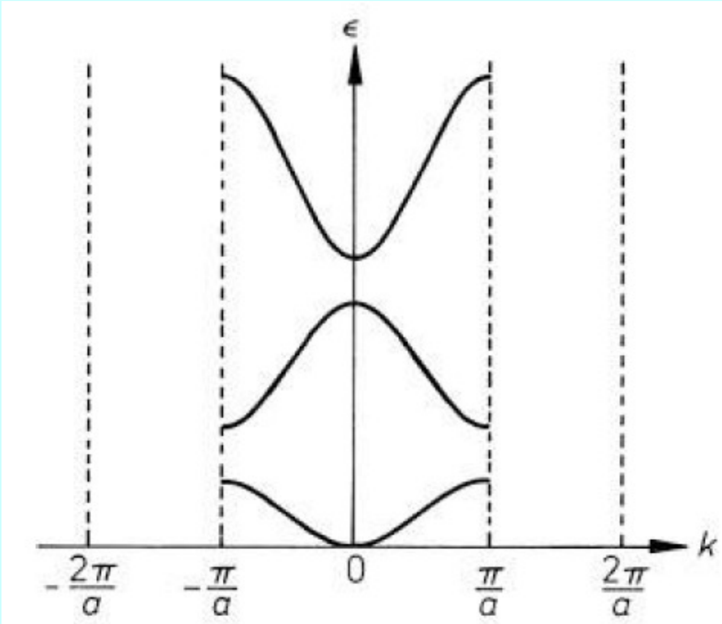


最低激發態

如果質量為零，能階是無間隙的，也就是能態是連續分布的。

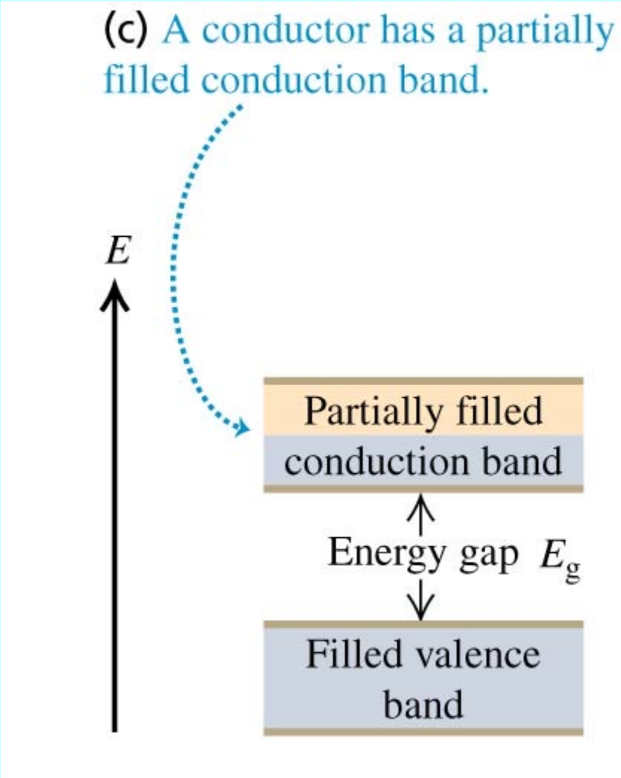
對凝態物理，能態分佈是否有間隙energy gap，至關緊要。

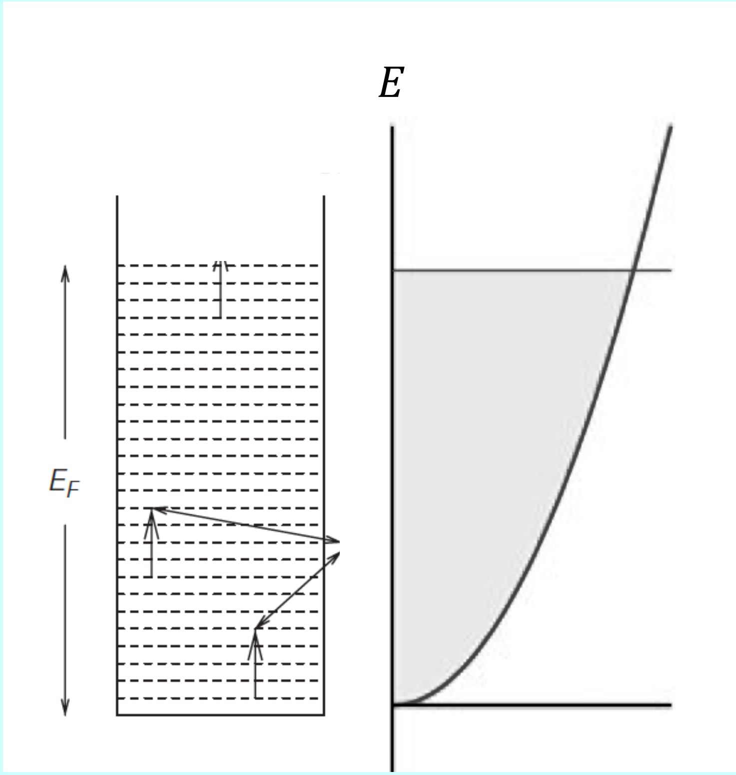




質量為零，能階是無間隙的，也就是能態是連續分布的。

只要些許能量，就能激發。





The Nobel Prize in Physics 2008

Japanese are eccentric in western eyes!

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: University of Chicago

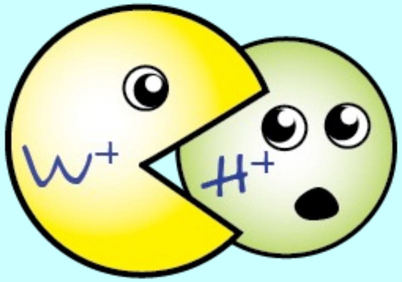
Photo: KEK

Photo: Kyoto University

Spontaneous Symmetry Breaking 自發對稱破缺

Yoichiro Nambu	Makoto Kobayashi	Toshihide Maskawa
1/2 of the prize	1/4 of the prize	1/4 of the prize
USA 南部陽一郎	Japan 小林誠	Japan 益川敏英
Enrico Fermi Institute, University of Chicago Chicago, IL, USA	High Energy Accelerator Research Organization (KEK) Tsukuba, Japan	Kyoto Sangyo University; Yukawa Institute for Theoretical Physics (YITP), Kyoto University Kyoto, Japan
b. 1921 (in Tokyo, Japan)	b. 1944	b. 1940

那無質量的 Goldstone Boson 呢？沒有看見呀？！



災難通常也是轉機！規範粒子也是沒有質量的！

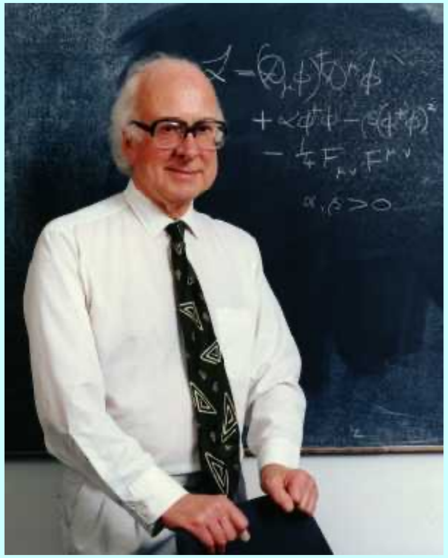
如果被破壞的對稱是規範對稱，

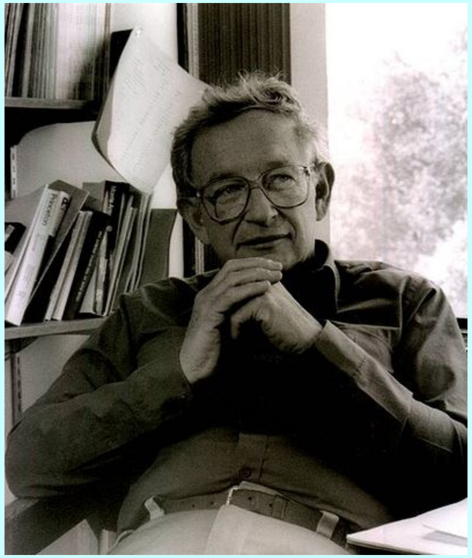
無質量自旋零 Goldstone Boson (1自由度)、與無質量自旋一Gauge boson (2自由度)

組合竟然形成一個有質量的自旋一Gauge boson (3自由度) ！

正是我們所需要，一石二鳥！一次解決兩個無質量的粒子。

Higgs Mechanism





真空中一純量場Φ的值若不為零，可以使與它有作用的規範粒子產生質量。

真空中一Φ的期望值若不為零，與它有作用的規範粒子會產生質量。

假設選取真空的場值為實數，這同時破壞了Global及Local的$U(1)$對稱：

$$\Phi_0 = \frac{\mu}{\sqrt{2\lambda}} \equiv v$$

遵守$U(1)$規範對稱的純量場Φ的動能項，就是將KG的$\mathcal{L}$中的∂_μ以D_μ取代：

$$D_\mu \Phi^\dagger D^\mu \Phi = \partial_\mu \Phi^\dagger \partial^\mu \Phi + igA_\mu \Phi^\dagger \partial^\mu \Phi - igA_\mu \partial^\mu \Phi^\dagger \cdot \Phi + g^2 A^\mu A_\mu \Phi^\dagger \Phi$$

$$D_\mu \Psi = \partial_\mu \Psi - igA_\mu \Psi$$

在真空中：$\Phi = \Phi_0 = v$，A_μ會由最後一項得到一個不為零的質量項：

$$g^2 A^\mu A_\mu \Phi^\dagger \Phi \to (g^2 v^2) A^\mu A_\mu = m^2 A^\mu A_\mu$$

規範對稱不允許這樣的質量項，但真空已破壞了規範對稱$U(1)$。

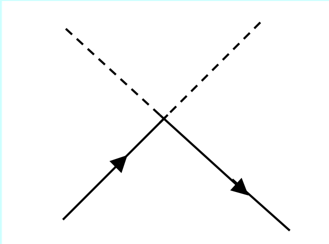
比較精準一點，就是將$D_\mu \Phi^\dagger D^\mu \Phi$以正確、真空值為零的粒子場$\rho, \phi$表示:

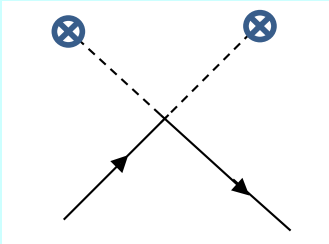
$$\Phi(x) = (\rho(x) + v) e^{i\phi(x)}$$

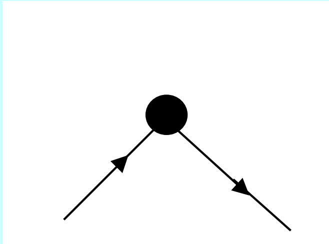
$$g^2 A^\mu A_\mu \Phi^\dagger \Phi \to g^2 (\rho + v)^2 A^\mu A_\mu$$

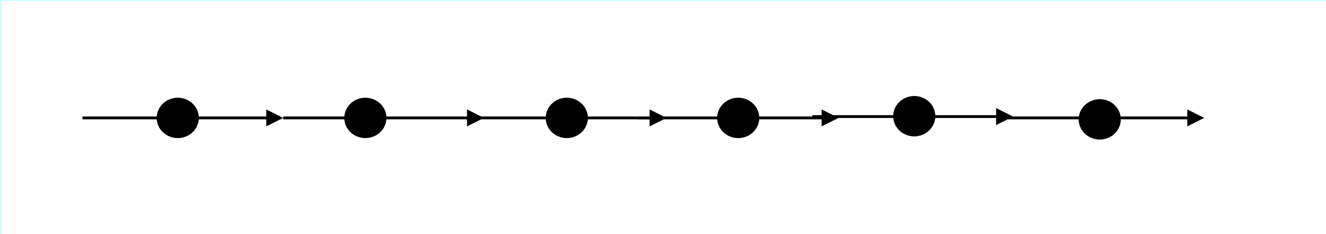
$(g^2 v^2) A^\mu A_\mu$就會自動出現。

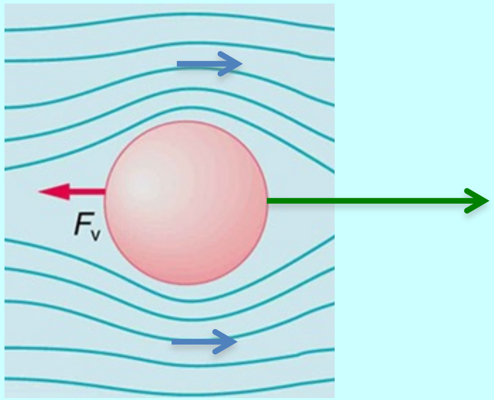
自旋為零粒子Φ與向量粒子*A*的交點vertices。



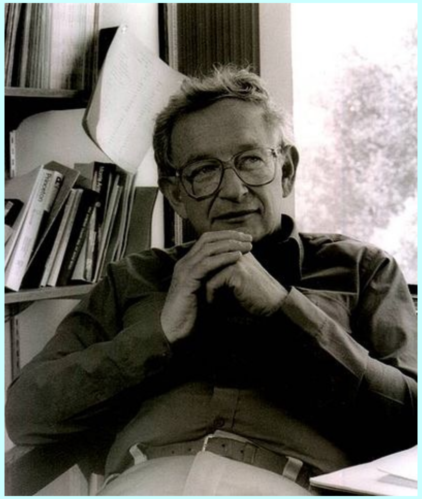








真空中不為零的場可以為與其作用的粒子帶來質量。



這個機制首先在凝態物理中寫下。

PHYSICAL REVIEW VOLUME 130, NUMBER 1 1 APRIL 1963

Plasmons, Gauge Invariance, and Mass

P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 8 November 1962)

Schwinger has pointed out that the Yang-Mills vector boson implied by associating a generalized gauge transformation with a conservation law (of baryonic charge, for instance) does not necessarily have zero mass, if a certain criterion on the vacuum fluctuations of the generalized current is satisfied. We show that the theory of plasma oscillations is a simple nonrelativistic example exhibiting all of the features of Schwinger's idea. It is also shown that Schwinger's criterion that the vector field $m \neq 0$ implies that the matter spectrum before including the Yang-Mills interaction contains $m=0$, but that the example of superconductivity illustrates that the physical spectrum need not. Some comments on the relationship between these ideas and the zero-mass difficulty in theories with broken symmetries are given.

A total of 6 people came to the similar idea!

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.[3] In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a more fundamental significance. Here we begin with a chirality-invariant Lagrangian and introduce both vector and pseudovector gauge fields, thereby guaranteeing invariance under both local phase and local γ_5-phase transformations. In this model the gauge fields themselves may break the γ_5 invariance leading to a mass for the original Fermi field. We shall show in this case

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

Recently a number of people have discussed the Goldstone theorem [1,2]: that any solution of a Lorentz-invariant theory which violates an internal symmetry operation of that theory must contain a massless scalar particle. Klein and Lee [3] showed that this theorem does not necessarily apply in non-relativistic theories and implied that their considerations would apply equally well to Lorentz-invariant field theories. Gilbert [4], however, gave a proof that the failure of the Goldstone theorem in the nonrelativistic case is of a type which cannot exist when Lorentz invariance is imposed on a theory. The purpose of this note is to show that Gilbert's argument fails for an important class of field theories, that in which the conserved currents are coupled to gauge fields.

Following the procedure used by Gilbert [4], let us consider a theory of two hermitian scalar fields

Then there is a conserved current j_μ such that

$$i[\int d^3x\, j_0(x),\ \varphi_1(y)] = \varphi_2(y). \qquad (2)$$

We assume that the Lagrangian is such that symmetry is broken by the nonvanishing of the vacuum expectation value of φ_2. Goldstone's theorem is proved by showing that the Fourier transform of $i\langle[j_\mu(x),\ \varphi_1(y)]\rangle$ contains a term $2\pi\langle\varphi_2\rangle\epsilon(k_0)k_\mu\delta(k^2)$, where k_μ is the momentum, as a consequence of Lorentz-covariance, the conservation law and eq. (2).

Klein and Lee [3] avoided this result in the non-relativistic case by showing that the most general form of this Fourier transform is now, in Gilbert's notation,

$$\text{F.T.} = k_\mu \rho_1(k^2, nk) + n_\mu \rho_2(k^2, nk) + C_3 n_\mu \delta^4(k)\ , \qquad (3)$$

where n_μ, which may be taken as (1, 0, 0, 0), picks out a special Lorentz frame. The conversation law then reduces eq. (3) to the less general form

$$\text{F.T.} = k_\mu \delta(k^2)\rho_4(nk) + [k^2 n_\mu - k_\mu(nk)]\rho_5(k^2, nk) + C_3 n_\mu \delta^4(k)\ . \qquad (4)$$

It turns out, on applying eq. (2), that all three terms in eq. (4) can contribute to $\langle\varphi_2\rangle$. Thus the Goldstone theorem fails if $\rho_4 = 0$, which is possible only if the other terms exist. Gilbert's remark that no special timelike vector n_μ is available in a Lorentz-covariant theory appears to rule out this possibility in such a theory.

There is however a class of relativistic field theories in which a vector n_μ does indeed play a part. This is the class of gauge theories, where an auxiliary unit timelike vector n_μ must be in-

[...] of the simplest such theory, quantum electrodynamics.) There seems to be no reason why the vector n_μ should not appear in the Fourier transform under consideration.

It is characteristic of gauge theories that the conservation laws hold in the strong sense, as a consequence of field equations of the form

$$j^\mu = \partial_\nu F'^{\mu\nu},$$

$$F_{\mu\nu}' = \partial_\mu A_\nu' - \partial_\nu A_\mu'\ . \qquad (5)$$

Except in the case of abelian gauge theories, the fields A_μ', $F_{\mu\nu}'$ are not simply the gauge field variables A_μ, $F_{\mu\nu}$, but contain additional terms with combinations of the structure constants of the group as coefficients. Now the structure of the Fourier transform of $i\langle[A_\mu'(x),\ \varphi_1(y)]\rangle$ must be given by eq. (3). Applying eq. (5) to this commutator gives us as the Fourier transform of $i\langle[j_\mu(x),\ \varphi_1(y)]\rangle$ the single term $[k^2 n_\mu - k_\mu(nk)]\rho(k^2, nk)$. We have thus exorcised both Goldstone's zero-mass bosons and the "spurion" state (at $k_\mu = 0$) proposed by Klein and Lee.

In a subsequent note it will be shown, by considering some classical field theories which display broken symmetries, that the introduction of gauge fields may be expected to produce qualitative changes in the nature of the particles described by such theories after quantization.

References

1) J. Goldstone, Nuovo Cimento 19 (1961) 154.
2) J. Goldstone, A. Salam and S. Weinberg, Phys. Rev. 127 (1962) 965.
3) A. Klein and B. W. Lee, Phys. Rev. Letters 12 (1964) 266.
4) W. Gilbert, Phys. Rev. Letters 12 (1964) 713.
5) J. Schwinger, Phys. Rev. 127 (1962) 324.

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

In all of the fairly numerous attempts to date to formulate a consistent field theory possessing a broken symmetry, Goldstone's remarkable theorem[1] has played an important role. This theorem, briefly stated, asserts that if there exists a conserved operator Q_i such that

$$[Q_i, A_j(x)] = \sum_k t_{ijk} A_k(x),$$

and if it is possible consistently to take $\sum_k t_{ijk} \times \langle 0|A_k|0\rangle \neq 0$, then $A_j(x)$ has a zero-mass particle in its spectrum. It has more recently been observed that the assumed Lorentz invariance essential to the proof[2] may allow one the hope of avoiding such massless particles through the introduction of vector gauge fields and the consequent breakdown of manifest covariance.[3] This, of course, represents a departure from the assumptions of the theorem, and a limitation on its applicability which in no way reflects on the general validity of the proof.

In this note we shall show, within the framework of a simple soluble field theory, that it is possible consistently to break a symmetry (in the sense that $\sum_k t_{ijk}\langle 0|A_k|0\rangle \neq 0$) without requiring that $A(x)$ excite a zero-mass particle. While this result might suggest a general procedure for the elimination of unwanted massless bosons, it will be seen that this has been accomplished by giving up the global conservation law usually

We consider, as our example, a theory which

was partially solved by Englert and Brout,[5] and bears some resemblance to the classical theory of Higgs.[6] Our starting point is the ordinary electrodynamics of massless spin-zero particles, characterized by the Lagrangian

$$\mathcal{L} = -\tfrac{1}{2}F^{\mu\nu}(\partial_\mu A_\nu - \partial_\nu A_\mu) + \tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} + \varphi^\mu \partial_\mu \varphi + \tfrac{1}{2}\varphi^\mu \varphi_\mu + ie_0 \varphi^\mu q \varphi A_\mu,$$

where φ is a two-component Hermitian field, and q is the Pauli matrix σ_2. The broken-symmetry condition

$$ie_0 q\langle 0|\varphi|0\rangle = \eta \equiv \begin{pmatrix}\eta_1\\ \eta_2\end{pmatrix}$$

Anderson-Englert-Brout-Higgs-Guralink-Hagen-Kibble (AEBHGHK) Mechanism

2010 J.J. Sakurai Prize Winners - Kibble, Guralnik, Hagen, Englert, and Brout

A Working Afternoon: Young Baron May of Oxford, Guralnik and Hagen 1961

The History of the Guralnik, Hagen and Kibble development of the Theory of Spontaneous Symmetry Breaking and Gauge Particles

Gerald S. Guralnik[1]

Physics Department[2].
Brown University, Providence — RI. 02912

Abstract

I discuss historical material about the beginning of the ideas of spontaneous symmetry breaking and particularly the role of the Guralnik, Hagen Kibble paper in this development. I do so adding a touch of some more modern ideas about the extended solution-space of quantum field theory resulting from the intrinsic nonlinearity of non-trivial interactions.

Shortly thereafter, as we were literally placing the manuscript in the envelope to be sent to PRL, Kibble came into the office bearing two papers by Higgs and the one by Englert and Brout. These had just arrived in the then very slow and unreliable (because of strikes and the peculiarities of Imperial College) mail. We were very surprised and even amazed. We had no idea that there was any competing interest in the problem, particularly outside of the United States. Hagen and I quickly glanced at these papers and thought that, while they aimed at the same point, they did not form a serious challenge to our work.

In any event, after seeing the competing EBH analyses, we unhesitatingly thought that we should do the completely honest thing and reference them, as

they were clearly relevant with examples, even if not convincing to us. Our paper was finished and typed in final form when we saw these other works and made this decision. We only altered the manuscript by adding in several places references to these just-revealed papers. Not a single thought or calculation was removed or added, nor was any change made but to the referencing in our manuscript as the result of Kibble's having pointed out the existence of these new papers. In retrospect, I wish we had added the true statement — "after this paper was completed, related work by EB and H was brought to our attention."

We were naive enough to feel that these other articles offered no threat to our insights or to the crediting of our contribution. Nearly 45 years later, it is clear that we were very wrong. An unbiased reading of all the papers should make it clear that GHK is the result of an entirely independent train of thought. Over the decades, the awareness of the need to address what in 1964 were many worrisome points has vanished because of the acceptance of the end results and the general increase in our theoretical understanding. This, in turn, has affected the appreciation of the extremely significant differences in "correctness" and "completeness" of our work relative to the others. While we were too innocent in our slowness to publish and in the way the referencing was included, we never thought that this would in any way affect our claim, since so many knew of the evolution of our work and my open discussion of it for nearly six months before we submitted it for publication.

We were sure that a clear claim had been staked for us, even without the first-publication place holder. Over the short term this was correct, but, after decades, colleagues died and many seemed to forget. A major loss in this regard and many many other ways was Paul Matthews, who was aware of the detailed evolution of our work. Initially, there seemed to be no problem getting recognition for what we did on a more than equal basis to the EB and H papers. This seemed to change around 1999, when our work began to be omitted from the references contained in important talks and papers, even by authors who had previously referenced us.

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson[3] has drawn attention: that the scalar zero-mass excitations of a superconducting neutral Fermi gas become longitudinal plasmon modes of finite mass when the gas is charged.

The simplest theory which exhibits this behavior is a gauge-invariant version of a model

about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \tag{2a}$$

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \tag{2b}$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \tag{2c}$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

$$B_\mu = A_\mu - (e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1),$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}, \tag{3}$$

into the form

$$\partial_\mu B^\mu = 0, \quad \partial_\nu G^{\mu\nu} + e^2\varphi_0^2 B^\mu = 0. \tag{4}$$

PHYSICAL REVIEW VOLUME 145, NUMBER 4 27 MAY 1966

Spontaneous Symmetry Breakdown without Massless Bosons*

PETER W. HIGGS†
Department of Physics, University of North Carolina, Chapel Hill, North Carolina
(Received 27 December 1965)

We examine a simple relativistic theory of two scalar fields, first discussed by Goldstone, in which as a result of spontaneous breakdown of $U(1)$ symmetry one of the scalar bosons is massless, in conformity with the Goldstone theorem. When the symmetry group of the Lagrangian is extended from global to local $U(1)$ transformations by the introduction of coupling with a vector gauge field, the Goldstone boson becomes the longitudinal state of a massive vector boson whose transverse states are the quanta of the transverse gauge field. A perturbative treatment of the model is developed in which the major features of these phenomena are

Spontaneous Symmetry Breaking

The Nobel Prize in Physics 2013

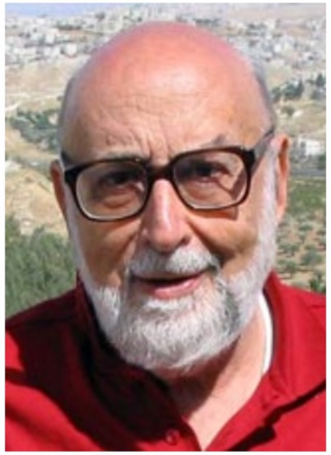


Photo: Pnicolet via Wikimedia Commons

François Englert

Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

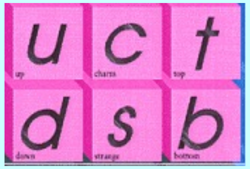
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

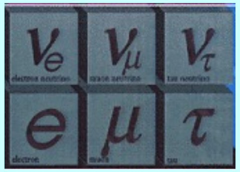
現在開始破壞SU(2)

假設有一個Weak SU(2)的double純量場：希格斯場 $H = \begin{pmatrix} H_1(x) \\ H_2(x) \end{pmatrix}$

在SU(2)變換下，希格斯場也是以與其他doublet一樣的方式變換！

$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$





$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \to U \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix} \to U \begin{pmatrix} u \\ d \end{pmatrix}$$

如同夸克與輕子，上下H電荷應該差 1

設H_2是電中性， H_1就是帶電 $+1$。

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \to \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

$$Q = \frac{\tau^3}{2} + Y$$

$$Y = \frac{1}{2}$$

注意：只有H^+與光子有交互作用！

$H^0(x)$ $H^+(x)$

設計一個$SU(2)$對稱的$\mathcal{L}$：

$$\mathcal{L} = \left(\partial_\mu H^\dagger\right)(\partial^\mu H) - m^2 H^\dagger H - \lambda\left(H^\dagger H\right)^2$$

$\mathcal{L}$在Weak $SU(2)$變換之下是不變的：

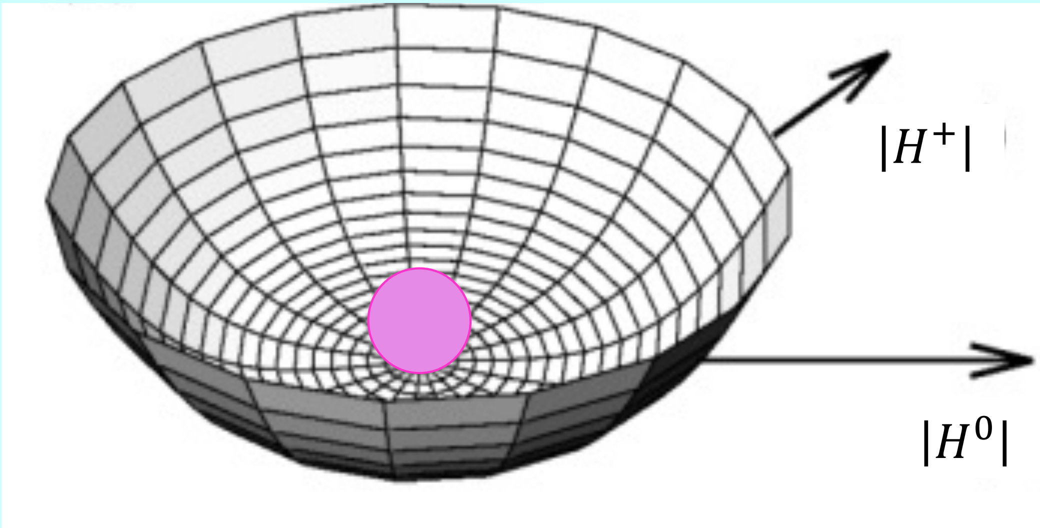
$$\begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \rightarrow U \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

$$H^\dagger H = (H^+ \quad H^0)^* \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = (H^+ \quad H^0)^* \cdot U^\dagger \cdot U \cdot \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = H^\dagger H$$

位能為：

$$V = m^2 H^\dagger H + \lambda\left(H^\dagger H\right)^2$$

$$H^\dagger H = |H^+|^2 + |H^0|^2$$



最低能量的狀態，場的值都為零。

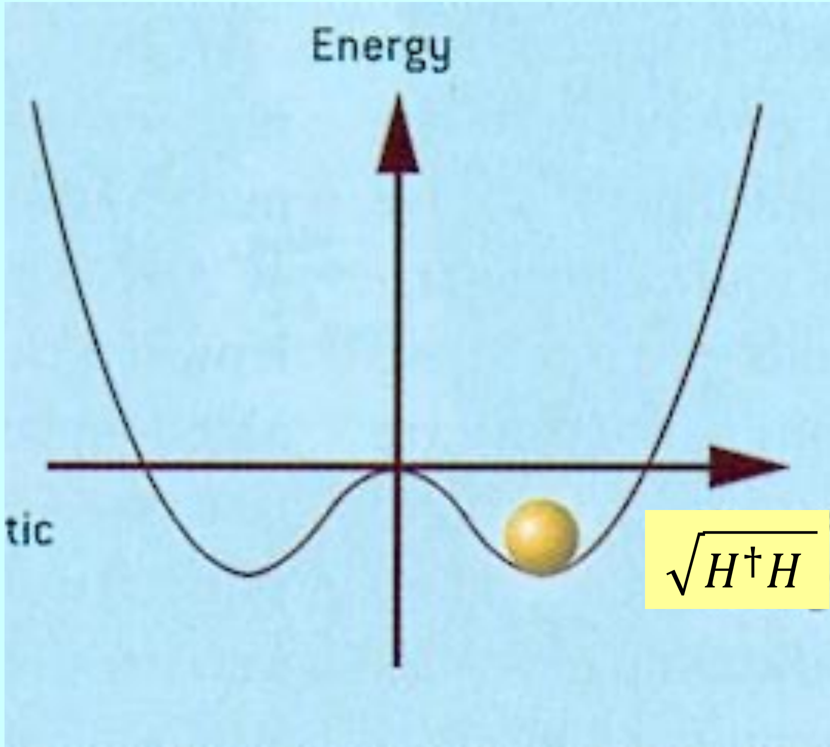
$$\begin{pmatrix}0\\0\end{pmatrix} \rightarrow U \cdot \begin{pmatrix}0\\0\end{pmatrix} = \begin{pmatrix}0\\0\end{pmatrix}$$

此真空在 Weak SU(2)變換下是不變的！

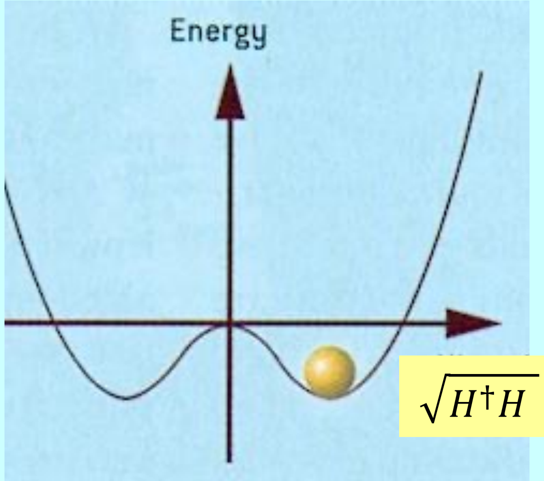
但如果二次項係數設為負數：

$$\mathcal{L} = (\partial_\mu H^\dagger)(\partial^\mu H) + \mu^2 H^\dagger H - \lambda (H^\dagger H)^2$$

$$V = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

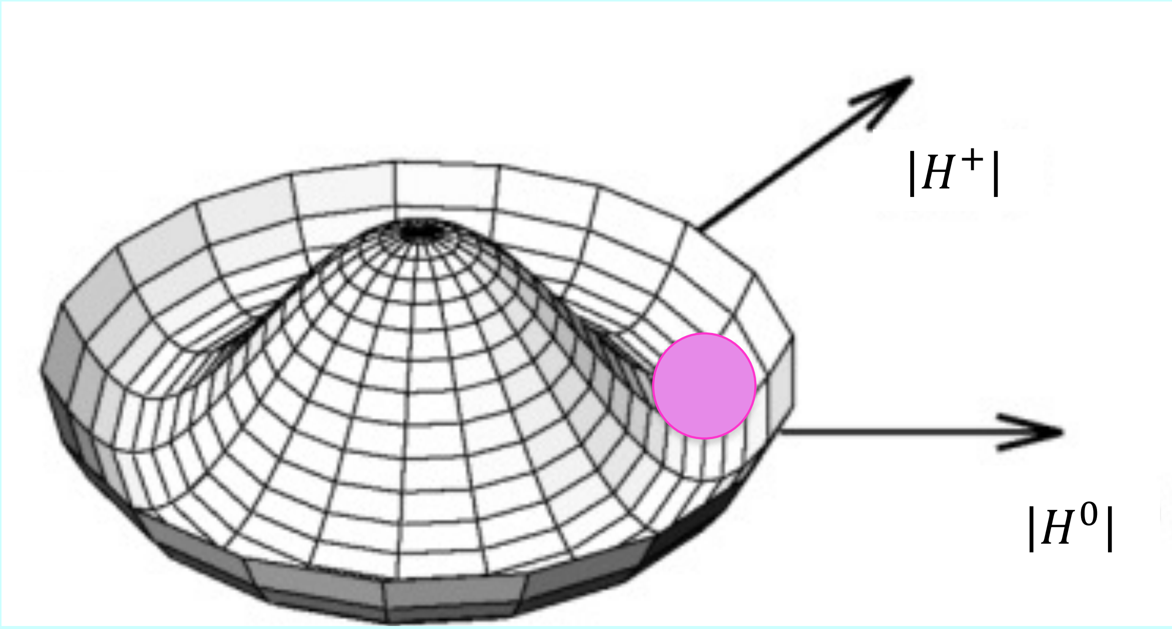


$\mathcal{L}$ Weak SU(2)變換之下還是不變的：



$$V = -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$$

$$H^\dagger H = |H^+|^2 + |H^0|^2$$

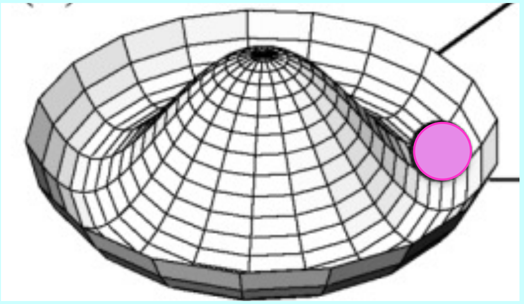


現在$\begin{pmatrix}0\\0\end{pmatrix}$的狀態能量並不是最低！

能量最低的狀態滿足：

$$|H^+|^2 + |H^0|^2 = \frac{\mu^2}{2\lambda}$$

你現在有一整圈的最低能量態可以選擇作為真空：



例如，如果選了如下的真空：

$$\begin{pmatrix}\langle H^+\rangle \\ \langle H^0\rangle\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v\end{pmatrix}$$

$$v \equiv \frac{\mu}{\sqrt{\lambda}}$$

真空中H^0場不為零！

$$\begin{pmatrix}0 \\ v\end{pmatrix} \rightarrow U \cdot \begin{pmatrix}0 \\ v\end{pmatrix} \neq \begin{pmatrix}0 \\ v\end{pmatrix}$$

能量是遵守 Weak $SU(2)$變換對稱，真空在 Weak $SU(2)$變換下卻不是不變的！

而且你選任何一個最低能量態都會是如此！

Weak $SU(2)$變換對稱、被遵守此對稱的能量、的最低態真空所破壞！

在這個真空中，規範 Weak SU(2) 被破壞，因此某些規範粒子可以有質量！

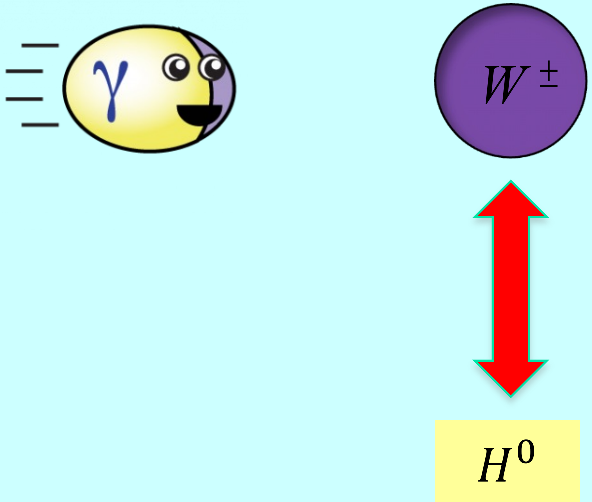
兩個希格斯場與光子及 W 的交互作用不同

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

光子不會感覺到這個在真空中值不為零的場H^0，

因為它是電中性！與光子沒有作用。

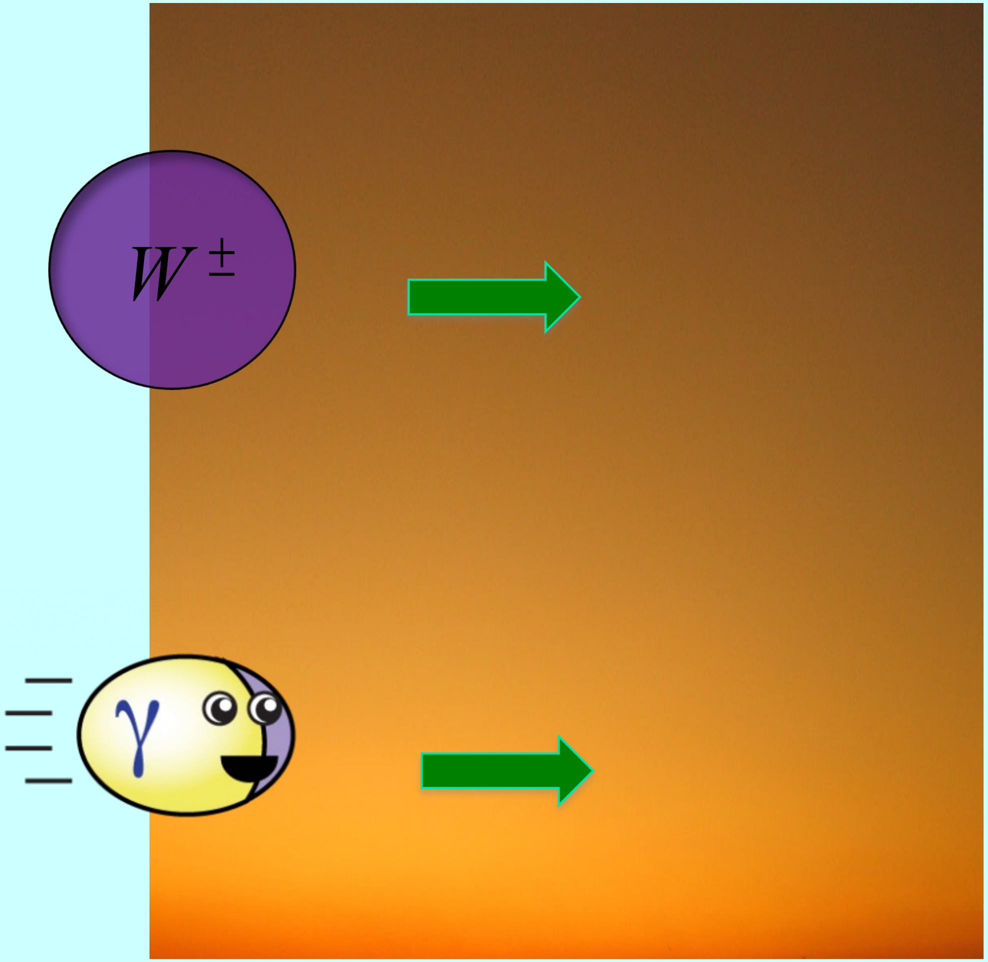
但W就會感覺到這個在真空中值不為零的場H^0。

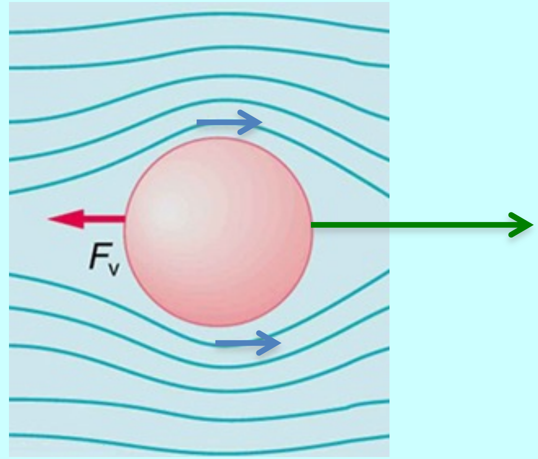


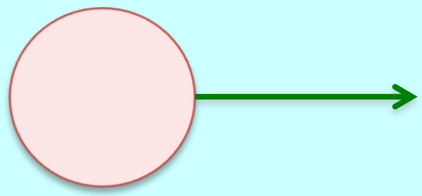
真空中一純量場的值若不為零，可以使與它有作用的規範粒子產生質量。

光子與H^0沒有作用，對真空沒有感覺。因此仍然是無質量的。

真空給有作用的 W 一個額外的慣性質量！







這可以從希格斯場的covariant derivative看得很清楚：

$$D_\mu = \partial_\mu - \frac{i}{2} g \boldsymbol{\tau} \cdot \boldsymbol{W}_\mu - i g' Y B_\mu$$

$$\left(\frac{1}{2} g \boldsymbol{\tau} \cdot \boldsymbol{W}_\mu + g' Y B_\mu\right) \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \begin{pmatrix} \frac{g}{2} W^3 + \frac{g'}{2} B & \frac{1}{\sqrt{2}} W^+ \\ \frac{1}{\sqrt{2}} W^- & -\frac{g}{2} W^3 + \frac{g'}{2} B \end{pmatrix} \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

$Z + A$

Z

除了這個變號，所有式子都與$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$一模一樣。

光子與H^0沒有交互作用。所以對真空中不為零的期望值沒有感覺。

規範場A對應的generator 2×2矩陣$Q = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$，乘在真空態等於零。

$$Q \begin{pmatrix} 0 \\ v \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v \end{pmatrix} = 0$$

代表真空態在規範場A對應的規範變換下還是不變的！

$$U(x) \begin{pmatrix} 0 \\ v \end{pmatrix} = \exp(-iQ\theta) \begin{pmatrix} 0 \\ v \end{pmatrix} \xrightarrow[\theta \to 0]{} (1 - iQ\theta) \begin{pmatrix} 0 \\ v \end{pmatrix} = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

規範對稱並沒有被趕盡殺絕：

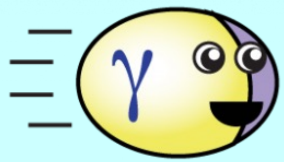
$SU(2) \times U(1)$ gauge theory

$SU(2) \times U(1)$

SSB

$U(1)_{\mathrm{EM}}$ gauge theory

$U(1)_{\mathrm{EM}}$



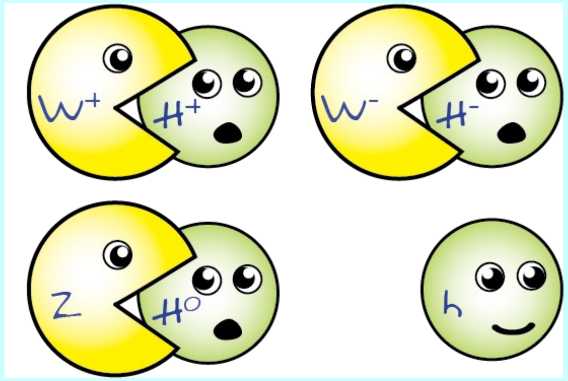
Gauged Isospin $SU(2)$

$\alpha_1, \alpha_2, \alpha_3$

Gauged $U(1)$

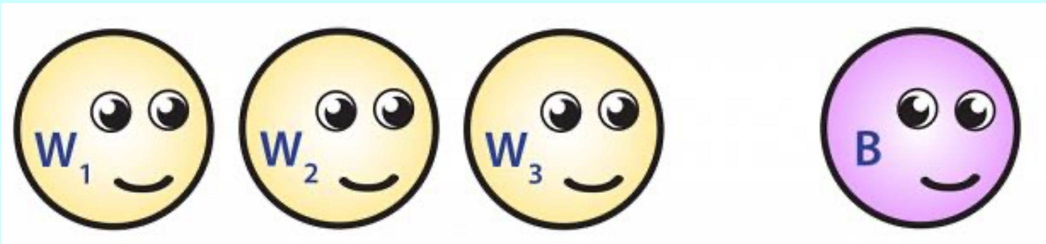
θ

$\begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$



$(W^+ \quad W^3 \quad W^-)$

B



Plug this vacuum $H = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\v\end{pmatrix}$

into kinetic energy: $(D_\mu H^\dagger)(D^\mu H)$ $\quad D_\mu = \partial_\mu - \frac{i}{2} g \boldsymbol{\tau} \cdot \boldsymbol{W}_\mu - i g' Y B_\mu$

All the other terms vanish except for:

$$\frac{1}{2}(0 \quad v)\begin{pmatrix} c_1 Z + c_2 A & \frac{1}{\sqrt{2}} W^+ \\ \frac{g}{\sqrt{2}} W^- & \frac{\sqrt{g^2+g'^2}}{2} Z \end{pmatrix}\begin{pmatrix} c_1 Z + c_2 A & \frac{g}{\sqrt{2}} W^+ \\ \frac{1}{\sqrt{2}} W^- & \frac{\sqrt{g^2+g'^2}}{2} Z \end{pmatrix}\begin{pmatrix}0\\v\end{pmatrix}$$

$$= \frac{1}{2}\begin{pmatrix} \frac{gv}{\sqrt{2}} W^- & \frac{\sqrt{g^2+g'^2}}{2} vZ \end{pmatrix}\begin{pmatrix} \frac{gv}{\sqrt{2}} W^+ \\ \frac{\sqrt{g^2+g'^2}}{2} vZ \end{pmatrix}$$

Photon A feels nothing in vacuum.

$= m_W^2 W_\mu^+ W^{-\mu} + m_Z^2 Z_\mu Z^\mu$ $\quad m_W = \frac{1}{2} g v$ $\quad m_Z = \frac{1}{2}\sqrt{g^2+g'^2}\, v$

W, Z can feel the effects of non-trivial vacuum and both received a mass.

$m_W = \cos\theta_W \, m_Z$

這樣的機制也可以用以下的圖像來代表。

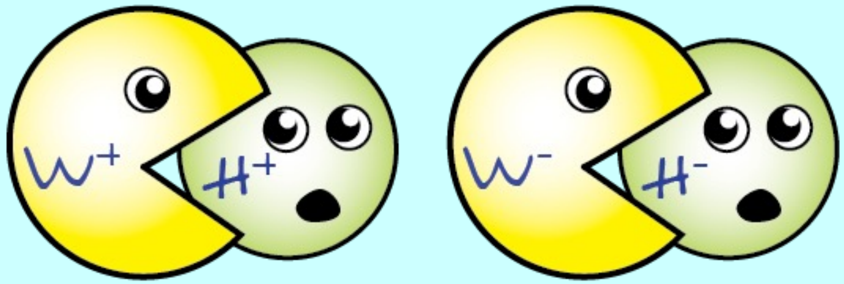
在量子場論中，無質量的自旋 1 粒子（自由度 2）與有質量的自旋 1 粒子（自由度 3）差別在自由度的數目。

自發對稱破缺的證據是一個對應的無質量粒子！

Nambu-Goldstone Boson

在此即存在三個無質量的希格斯場的自由度（對應到位能的三個河谷方向）。

本來無質量（自由度 2）的 W 波色子吃下一個無質量的希格斯場的自由度，而成為有質量的粒子（自由度 3）



結果是，$W^{\pm}$及Z因此機制得到質量，而光子γ還是保持無質量。

$M_W \approx 80\,\mathrm{GeV}$　　$M_Z \approx 90\,\mathrm{GeV}$　　而質量比$\frac{M_Z}{M_W}$是可以預測的。

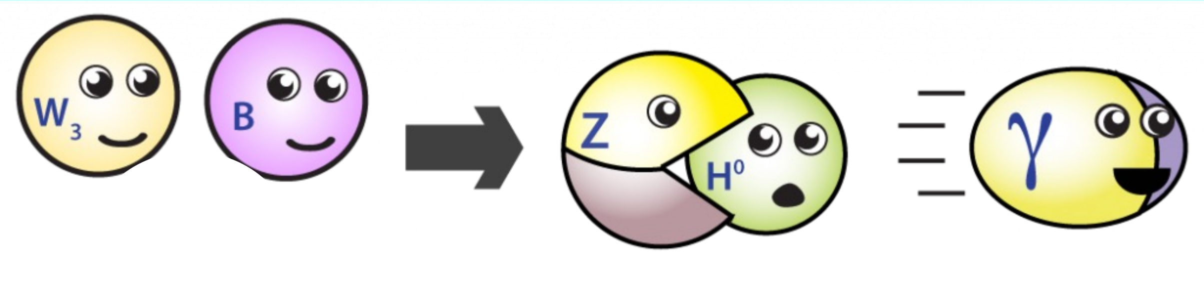
Z $J = 1$

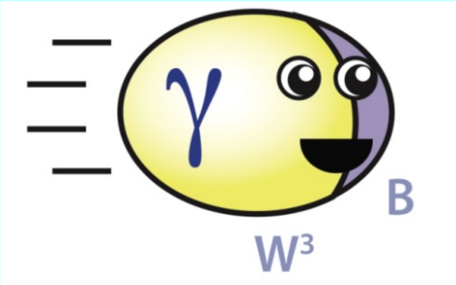
Charge = 0
Mass m = 91.1876 ± 0.0021 GeV [d]

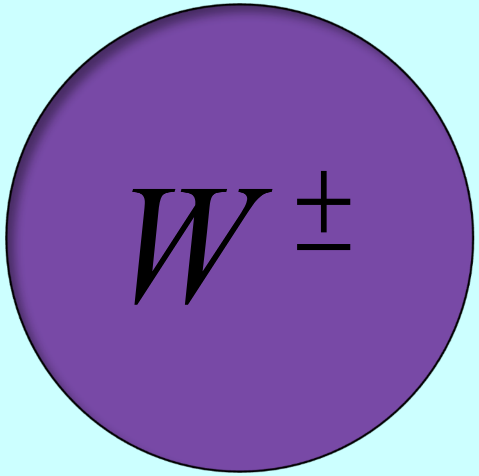
W $J = 1$

Charge = ±1 e
Mass m = 80.385 ± 0.015 GeV
$m_Z - m_W$ = 10.4 ± 1.6 GeV

光子 γ 與 Z 粒子是 B 與 W^3 的線性疊加







光子中有與W^3的成分

$W^{\pm}$與W^3三者性質相似！

$W^{\pm}$會比γ重如此之多！

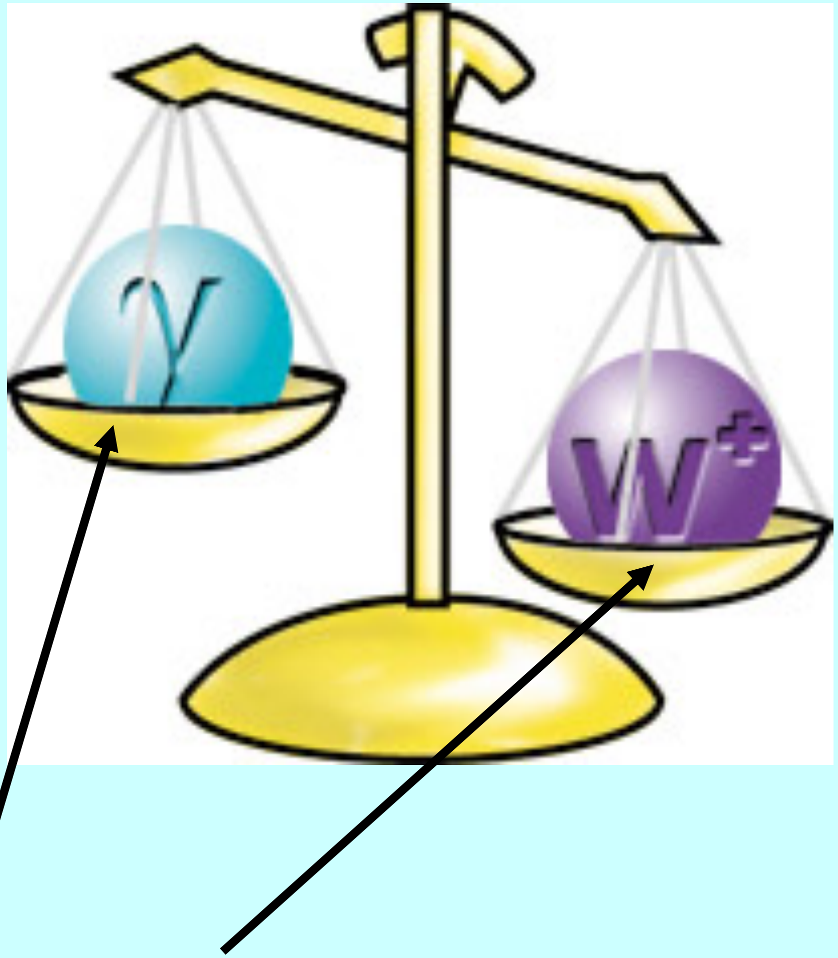
規範波色子必須無質量，但W是很重的！

SU(2) 對稱已經被破壞！

規範對稱已經被破壞！

或許SU(2)規範對稱是被真空所破壞！

為什麼 W 比 γ 重?



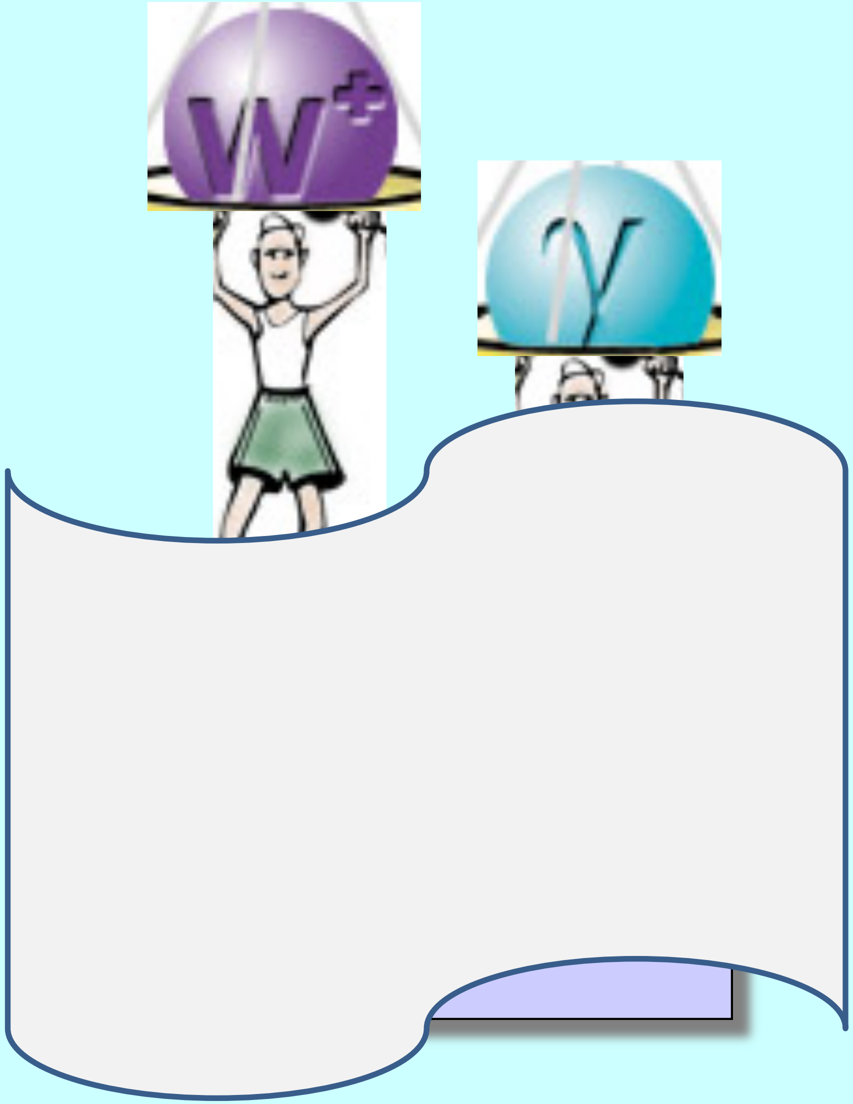
或許是 W 的基礎與 γ 的基礎不同!!!!!!! 基礎就是真空。

真空只有一個，但兩個粒子對真空的感覺不同。

或許是作為基礎的真空使兩者質量不同！

對稱的能量所得出不對稱的真空破壞了弱力與電磁力的對稱！

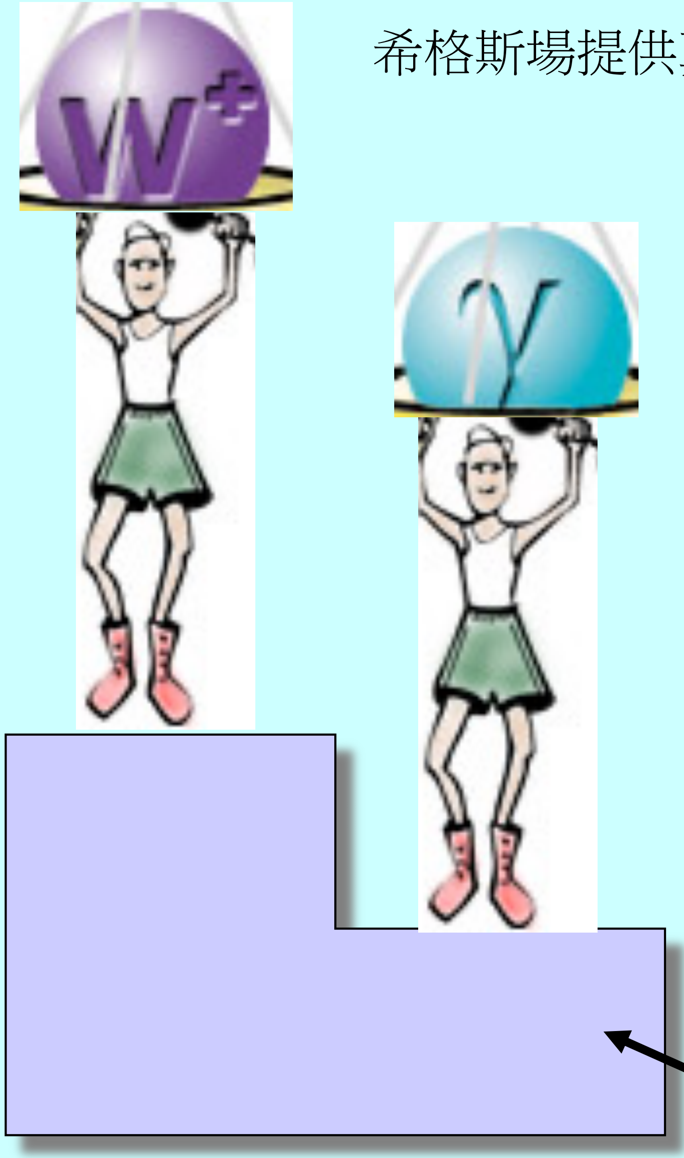
對稱的能量，得出不對稱的最低能量真空，將能量的對稱性隱藏起來：



Symmetry is hidden!

希格斯場提供真空一個結構，使得真空中的 W 比 γ 重.

Spontaneous Symmetry Breaking



Higgs Fields in Vacuum

Steven Weinberg

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L \equiv [\tfrac{1}{2}(1+\gamma_5)]\begin{pmatrix}\nu_e \\ e\end{pmatrix} \quad (1)$$

and on a right-handed singlet

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e. \quad (2)$$

The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L-\bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q=T_3-N_R-\tfrac{1}{2}N_L$, and the electron number $N=N_R+N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,[4] and there is no massless particle coupled to N,[5] so we must form our gauge group out of the electronic isospin $\vec{T}$ and the electronic hyperchange $Y\equiv N_R+\tfrac{1}{2}N_L$.

Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec{A}_\mu$ and B_μ coupled to $\vec{T}$ and Y, plus a spin-zero doublet

$$\varphi = \begin{pmatrix}\varphi^0 \\ \varphi^-\end{pmatrix} \quad (3)$$

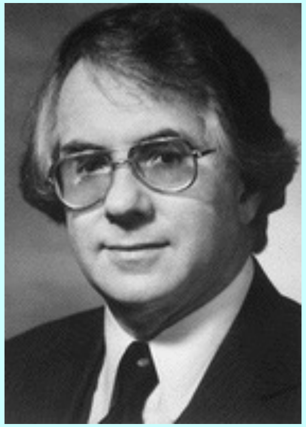
whose vacuum expectation value will break $\vec{T}$ and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under $\vec{T}$ and Y gauge transformations is

$$\mathcal{L} = -\tfrac{1}{4}(\partial_\mu\vec{A}_\nu-\partial_\nu\vec{A}_\mu+g\vec{A}_\mu\times\vec{A}_\nu)^2-\tfrac{1}{4}(\partial_\mu B_\nu-\partial_\nu B_\mu)^2-\bar{R}\gamma^\mu(\partial_\mu-ig'B_\mu)R-\bar{L}\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu-i\tfrac{1}{2}g'B_\mu)L$$

$$-\tfrac{1}{2}|\partial_\mu\varphi-ig\vec{A}_\mu\cdot\vec{t}\varphi+i\tfrac{1}{2}g'B_\mu\varphi|^2-G_e(\bar{L}\varphi R+\bar{R}\varphi^\dagger L)-M_1{}^2\varphi^\dagger\varphi+h(\varphi^\dagger\varphi)^2. \quad (4)$$

We have chosen the phase of the R field to make G_e real, and can also adjust the phase of the L and Q fields to make the vacuum expectation value $\lambda\equiv\langle\varphi^0\rangle$ real. The "physical" φ fields are then φ^-

的確，*W* 和 *Z* 得到該有的質量，而光子仍是無質量！

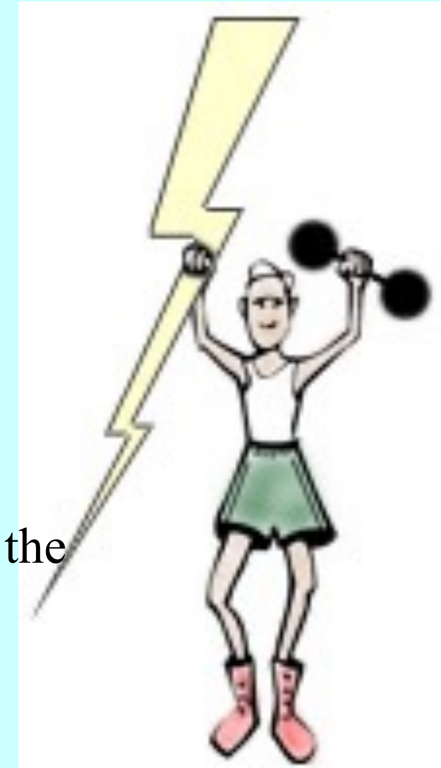
  

Glashow, Weinberg and Salem:

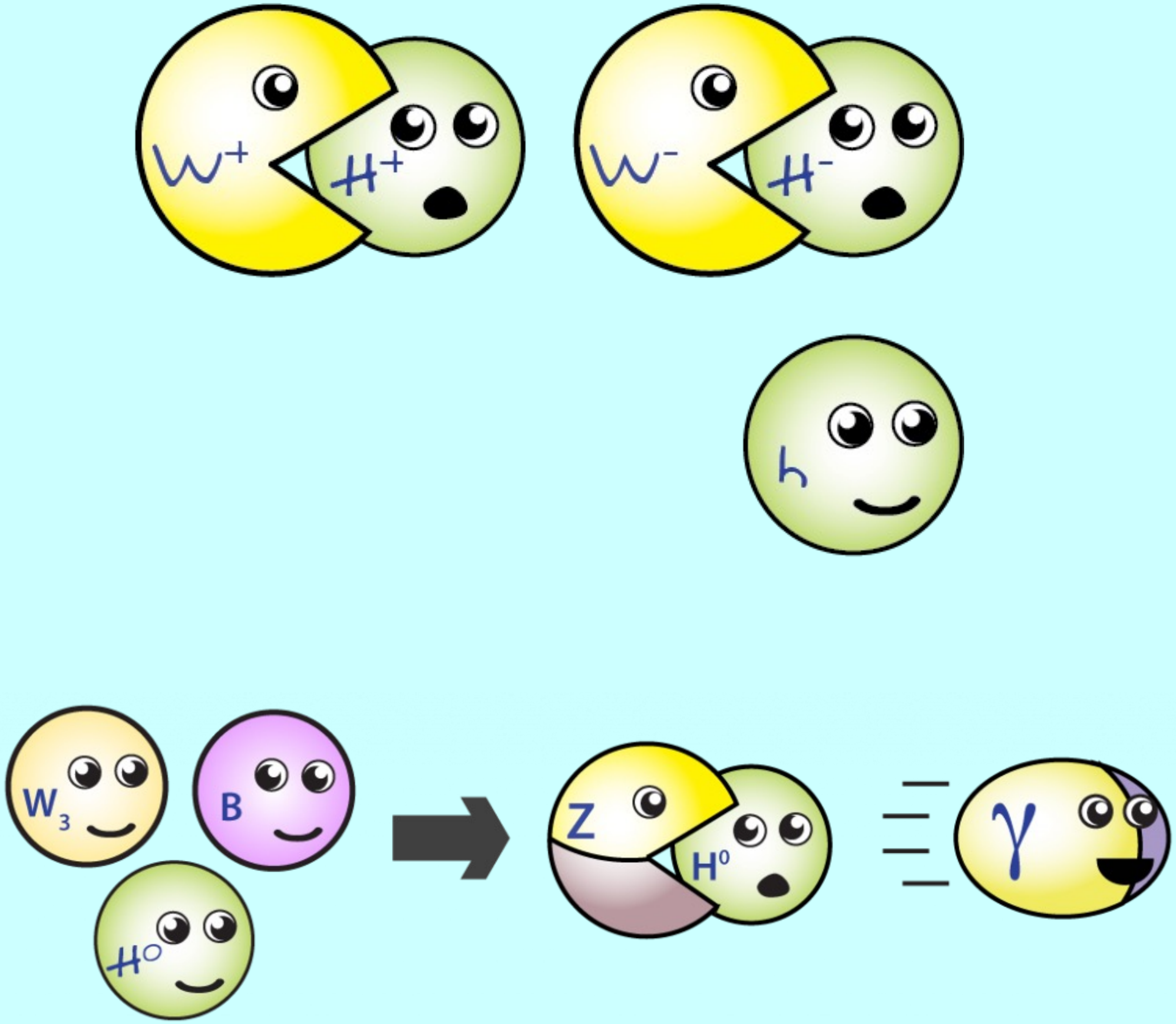
Standard Model

Twins

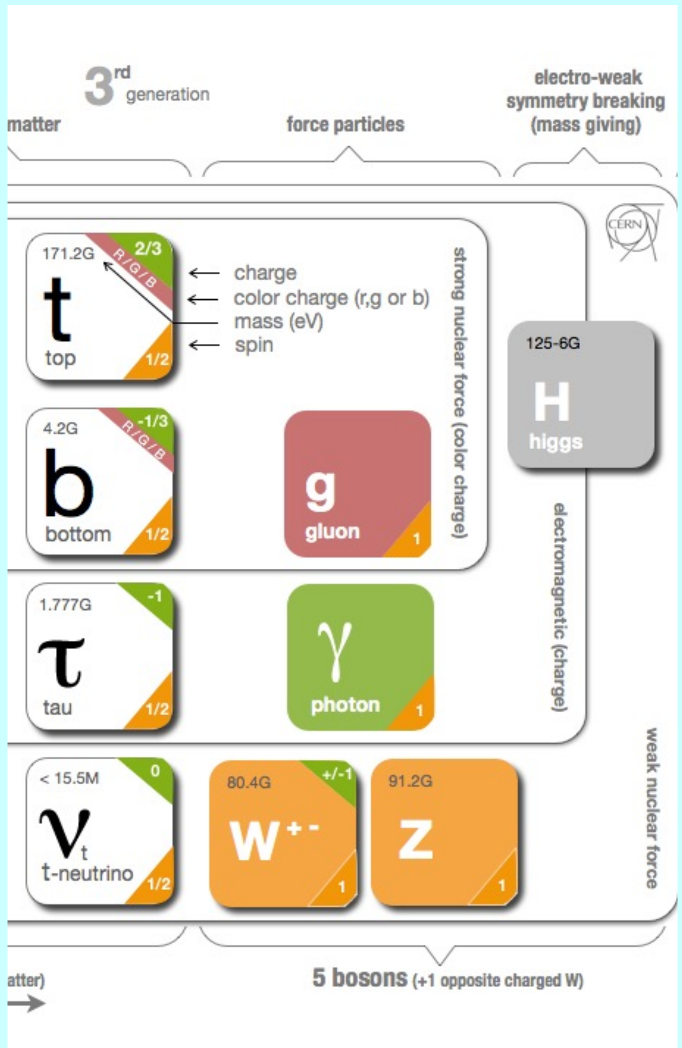
Different aspects of the same interaction.



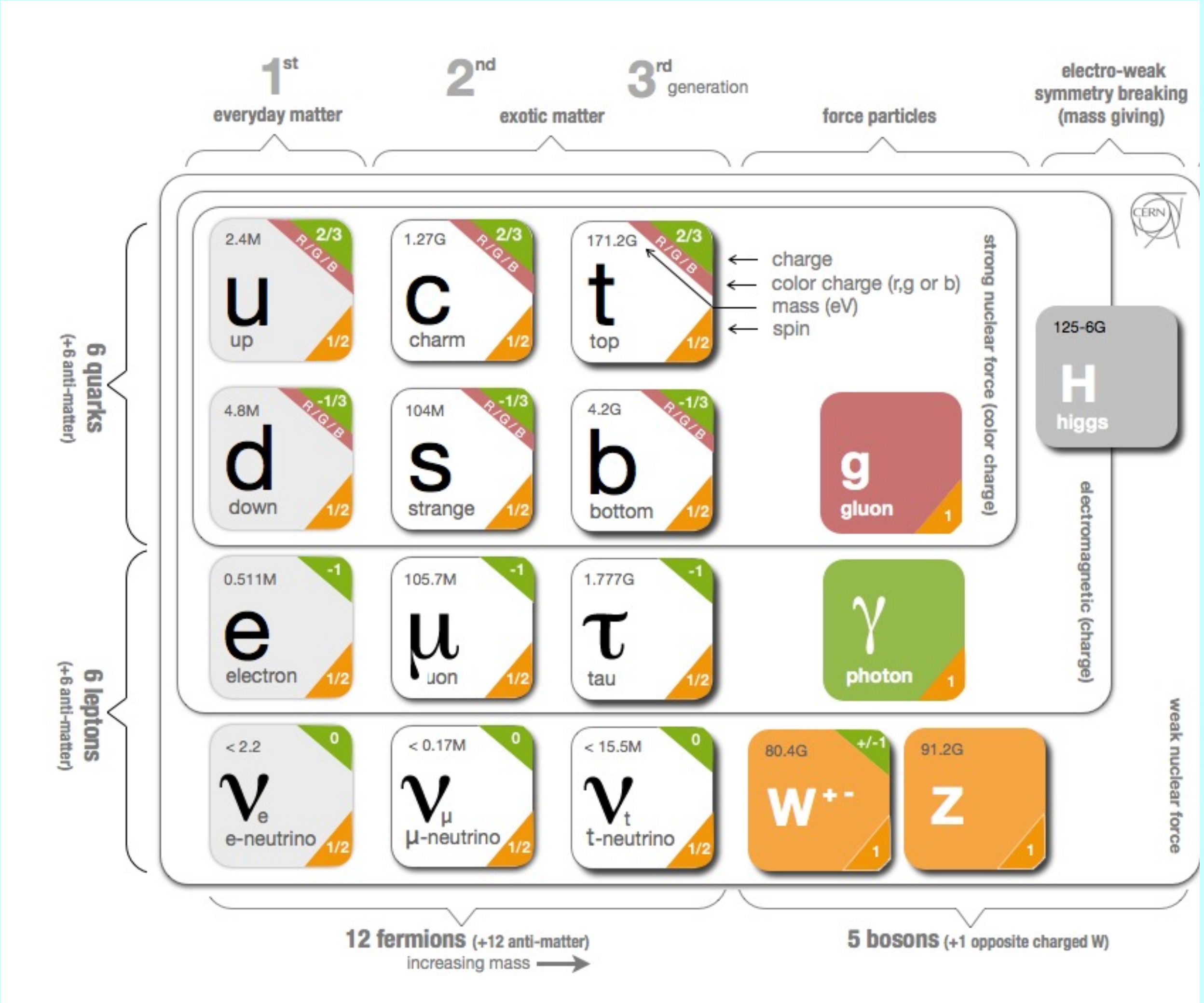
Electromagnetic and weak interactions are unified into **Electroweak**.



W+
H+
W-
H-
h
W3
B
H0
Z
H0
γ



3rd generation
matter
force particles
electro-weak symmetry breaking (mass giving)
171.2G
2/3
R/G/B
t
top
1/2
charge
color charge (r,g or b)
mass (eV)
spin
strong nuclear force (color charge)
125-6G
H
higgs
4.2G
-1/3
R/G/B
b
bottom
1/2
g
gluon
1
electromagnetic (charge)
1.777G
-1
τ
tau
1/2
γ
photon
1
< 15.5M
0
ν
t-neutrino
1/2
80.4G
+/-1
W+-
1
91.2G
Z
1
weak nuclear force
atter)
5 bosons (+1 opposite charged W)


1st everyday matter
2nd exotic matter
3rd generation
force particles
electro-weak symmetry breaking (mass giving)
2.4M 2/3 R/G/B u up 1/2
1.27G 2/3 R/G/B c charm 1/2
171.2G 2/3 R/G/B t top 1/2
charge
color charge (r,g or b)
mass (eV)
spin
4.8M -1/3 R/G/B d down 1/2
104M -1/3 R/G/B s strange 1/2
4.2G -1/3 R/G/B b bottom 1/2
g gluon 1
125-6G H higgs
0.511M -1 e electron 1/2
105.7M -1 μ uon 1/2
1.777G -1 τ tau 1/2
γ photon 1
< 2.2 0 ν e e-neutrino 1/2
< 0.17M 0 ν μ μ-neutrino 1/2
< 15.5M 0 ν t t-neutrino 1/2
80.4G +/-1 W+- 1
91.2G Z 1
strong nuclear force (color charge)
electromagnetic (charge)
weak nuclear force
6 quarks (+6 anti-matter)
6 leptons (+6 anti-matter)
12 fermions (+12 anti-matter)
increasing mass
5 bosons (+1 opposite charged W)

and

$$\varphi_1 \equiv (\varphi^0 + \varphi^{0\dagger} - 2\lambda)/\sqrt{2} \quad \varphi_2 \equiv (\varphi^0 - \varphi^{0\dagger})/i\sqrt{2}. \quad (5)$$

The condition that φ_1 have zero vacuum expectation value to all orders of perturbation theory tells us that $\lambda^2 \cong M_1^2/2h$, and therefore the field φ_1 has mass M_1 while φ_2 and φ^- have mass zero. But we can easily see that the Goldstone bosons represented by φ_2 and φ^- have no physical coupling. The Lagrangian is gauge invariant, so we can perform a combined isospin and hypercharge gauge transformation which eliminates φ^- and φ_2 everywhere[6] without changing anything else. We will see that G_e is very small, and in any case M_1 might be very large,[7] so the φ_1 couplings will also be disregarded in the following.

The effect of all this is just to replace φ everywhere by its vacuum expectation value

$$\langle\varphi\rangle = \lambda\binom{1}{0}. \quad (6)$$

The first four terms in $\mathcal{L}$ remain intact, while the rest of the Lagrangian becomes

$$-\tfrac{1}{8}\lambda^2 g^2[(A_\mu^{\ 1})^2 + (A_\mu^{\ 2})^2]$$
$$-\tfrac{1}{8}\lambda^2(gA_\mu^{\ 3} + g'B_\mu)^2 - \lambda G_e \bar{e}e. \quad (7)$$

We see immediately that the electron mass is λG_e. The charged spin-1 field is

$$W_\mu \equiv 2^{-1/2}(A_\mu^{\ 1} + iA_\mu^{\ 2}) \quad (8)$$

and has mass

$$M_W = \tfrac{1}{2}\lambda g. \quad (9)$$

The neutral spin-1 fields of definite mass are

$$Z_\mu = (g^2+g'^2)^{-1/2}(gA_\mu^{\ 3} + g'B_\mu), \quad (10)$$

$$A_\mu = (g^2+g'^2)^{-1/2}(-g'A_\mu^{\ 3} + gB_\mu). \quad (11)$$

Their masses are

$$M_Z = \tfrac{1}{2}\lambda(g^2+g'^2)^{1/2}, \quad (12)$$

$$M_A = 0, \quad (13)$$

so A_μ is to be identified as the photon field. The interaction between leptons and spin-1 mesons is

$$\frac{ig}{2\sqrt{2}}\bar{e}\gamma^\mu(1+\gamma_5)\nu W_\mu + \text{H.c.} + \frac{igg'}{(g^2+g'^2)^{1/2}}\bar{e}\gamma^\mu e A_\mu$$
$$+ \frac{i(g^2+g'^2)^{1/2}}{4}\left[\left(\frac{3g'^2-g^2}{g'^2+g^2}\right)\bar{e}\gamma^\mu e - \bar{e}\gamma^\mu\gamma_5 e + \bar{\nu}\gamma^\mu(1+\gamma_5)\nu\right]Z_\mu. \quad (14)$$

We see that the rationalized electric charge is

$$e = gg'/(g^2+g'^2)^{1/2} \quad (15)$$

and, assuming that W_μ couples as usual to hadrons and muons, the usual coupling constant of weak interactions is given by

$$G_W/\sqrt{2} = g^2/8M_W^{\ 2} = 1/2\lambda^2. \quad (16)$$

Note that then the e-φ coupling constant is

$$G_e = M_e/\lambda = 2^{1/4}M_e G_W^{\ 1/2} = 2.07\times10^{-6}.$$

The coupling of φ_1 to muons is stronger by a factor M_μ/M_e, but still very weak. Note also that (14) gives g and g' larger than e, so (16) tells us that $M_W > 40$ BeV, while (12) gives $M_Z > M_W$ and $M_Z > 80$ BeV.

by this model have to do with the couplings of the neutral intermediate meson Z_μ. If Z_μ does not couple to hadrons then the best place to look for effects of Z_μ is in electron-neutron scattering. Applying a Fierz transformation to the W-exchange terms, the total effective e-ν interaction is

$$\frac{G_W}{\sqrt{2}}\bar{\nu}\gamma_\mu(1+\gamma_5)\nu\left\{\frac{(3g^2-g'^2)}{2(g^2+g'^2)}\bar{e}\gamma^\mu e + \tfrac{3}{2}\bar{e}\gamma^\mu\gamma_5 e\right\}.$$

If $g \gg e$ then $g \gg g'$, and this is just the usual e-ν scattering matrix element times an extra factor $\tfrac{3}{2}$. If $g \simeq e$ then $g \ll g'$, and the vector interaction is multiplied by a factor $-\tfrac{1}{2}$ rather than $\tfrac{3}{2}$. Of course our model has too many

taken very seriously, but it is worth keeping in mind that the standard calculation[8] of the electron-neutrino cross section may well be wrong.

Is this model renormalizable? We usually do not expect non-Abelian gauge theories to be renormalizable if the vector-meson mass is not zero, but our Z_μ and W_μ mesons get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning. Indeed, the model Lagrangian we start from is probably renormalizable, so the question is whether this renormalizability is lost in the reordering of the perturbation theory implied by our redefinition of the fields. And if this model is renormalizable, then what happens when we extend it to include the couplings of $\vec{A}_\mu$ and B_μ to the hadrons?

I am grateful to the Physics Department of MIT for their hospitality, and to K. A. Johnson for a valuable discussion.

*This work is supported in part through funds provided by the U. S. Atomic Energy Commission under Contract No. AT(30-1)2098).

†On leave from the University of California, Berkeley, California.

[1]The history of attempts to unify weak and electromagnetic interactions is very long, and will not be reviewed here. Possibly the earliest reference is E. Fermi, Z. Physik 88, 161 (1934). ... was discussed by S. Glashow, ... (1961); the chief difference is ... symmetry-breaking terms int... therefore gets less definite pr...

[2]J. Goldstone, Nuovo Cimen... stone, A. Salam, and S. Weinb... 965 (1962).

[3]P. W. Higgs, Phys. Letters ... Rev. Letters 13, 508 (1964), ... (1966); F. Englert and R. Bro... 13, 321 (1964); G. S. Guralnik ... B. Kibble, Phys. Rev. Letters ...

[4]See particularly T. W. B. K... 1554 (1967). A similar pheno... strong interactions; the ρ-me... perturbation theory is just the... A_1 meson picks up an extra co... taneous breaking of chiral sym... Phys. Rev. Letters 18, 507 (1... 7; J. Schwinger, Phys. Letter... S. Glashow, H. Schnitzer, and... Letters 19, 139 (1967), Eq. (1...

[5]T. D. Lee and C. N. Yang, ...

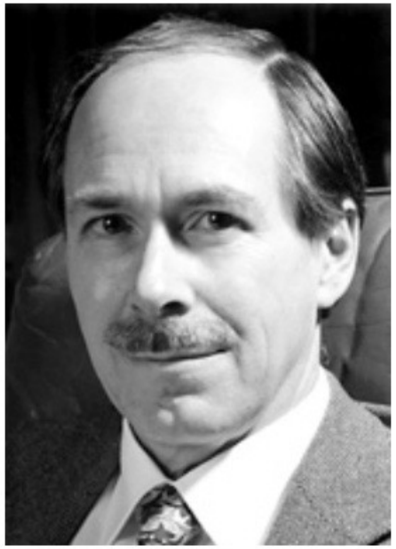
[6]This is the same sort of tr... which eliminates the nonderiv... σ model; see S. Weinberg, Ph... (1967). The $\vec{\pi}$ reappears with ... cause the strong-interaction ... ant under chiral gauge transfo...

[7]For a similar argument ap... Weinberg, Ref. 6, ...

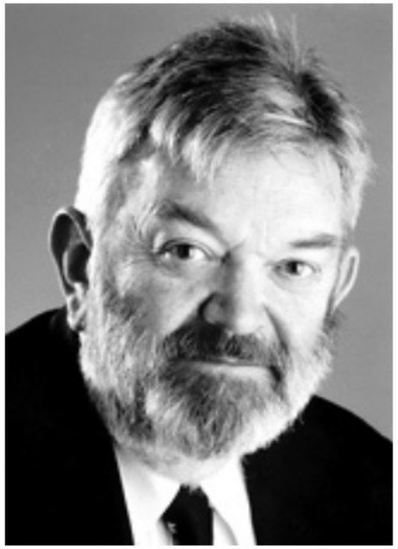
[8]R. P. Feynman and M. Gell... 193 (1957).

標準模型正式誕生！

The Nobel Prize in Physics 1999



Gerardus 't Hooft
Prize share: 1/2



Martinus J.G. Veltman
Prize share: 1/2

The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman *"for elucidating the quantum structure of electroweak interactions in physics"*

Renormalization of massless Yang-Mills fields

G. 'tHooft

Institute for Theoretical Physics, University of Utrecht, Utrecht, The Netherlands

Received 12 February 1971, Available online 25 October 2002

Renormalizable Lagrangians for massive Yang-Mills fields

G.'t Hooft

Institute for Theoretical Physics, University of Utrecht, Netherlands

Received 13 July 1971, Available online 21 October 2002

The secret of universe is the following:

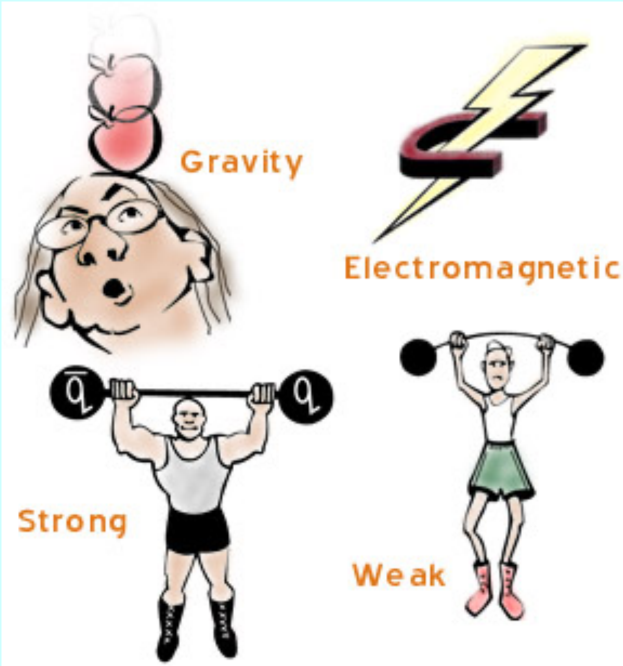
Weak and Electromagnetic interaction is one $SU(2)\times U(1)$ gauge theory.

Gauge symmetry is broken by spontaneous symmetry breaking:

Strong interaction is a $SU(3)$ gauge theory.

$SU(2)\times U(1) \rightarrow U(1)_{\mathrm{EM}}$

This is usually called the standard model of particle physics.



What are the doublets of electroweak $SU(2)$?

What is the triplet gauge bosons of electroweak $SU(2)$?

What are the triplets of strong $SU(3)$?

如何證實希格斯場的存在呢？

由水面的漣漪發現水面

由聲音的傳播驗證空氣的存在！

這些都是場的擾動。

如果我們能觀察希格斯場的擾動………

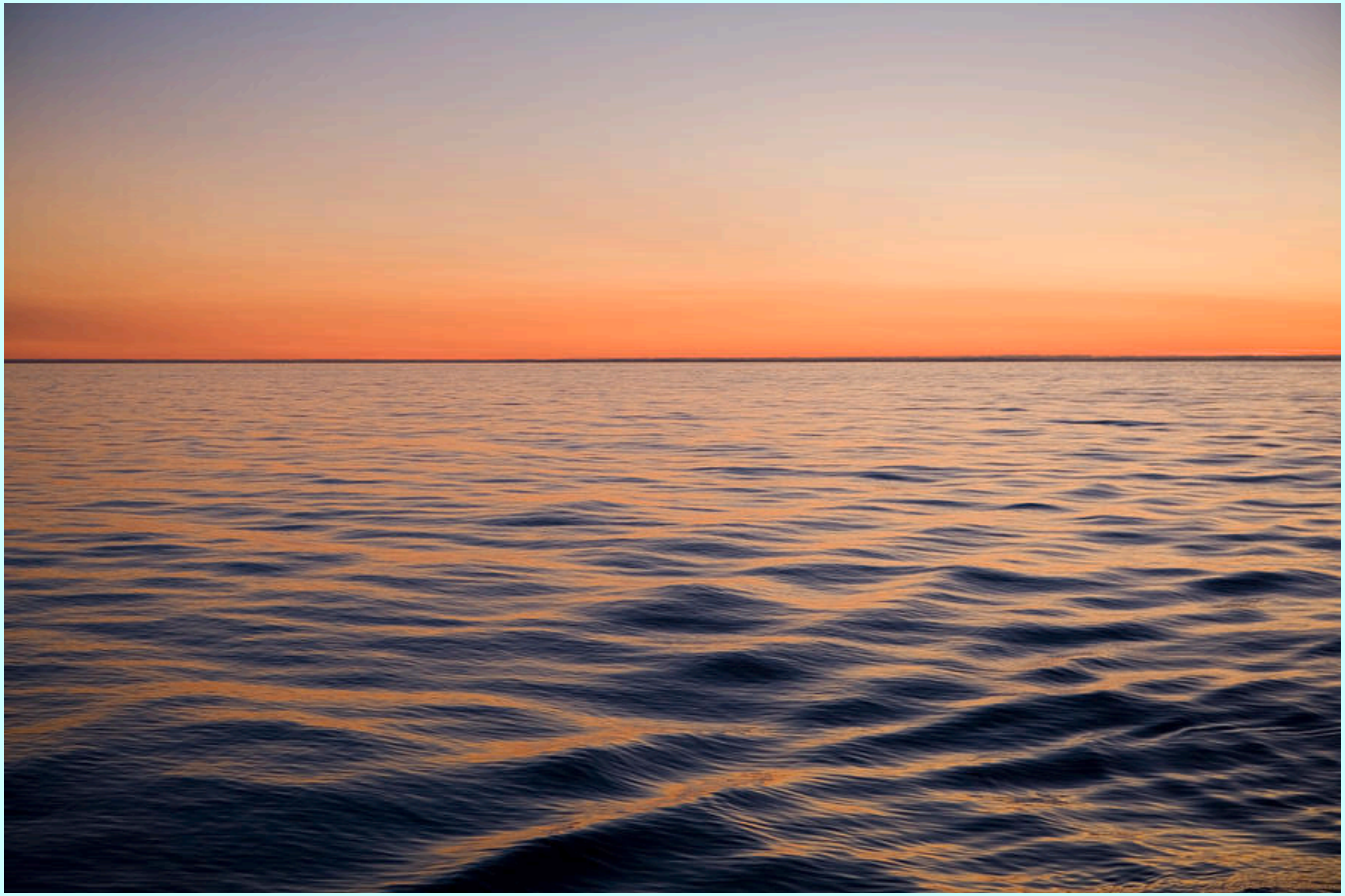
相對於真空的基態，擾動後的希格斯場就是激發態！

需要多少能量才能產生激發態？

如果是激發水面的漣漪，只要些許能量即可：

當然，也可以很壯觀：

總之是可大可小，水面的激發態是連續的。

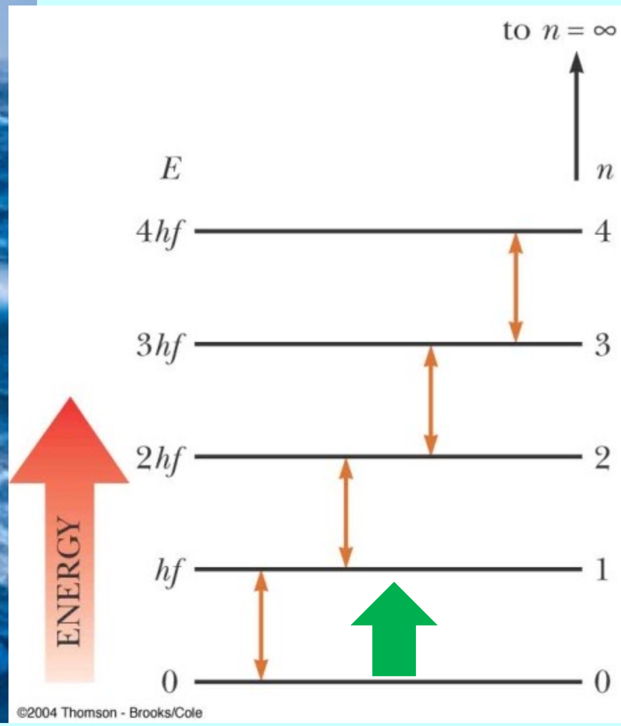


海風徐徐吹來，水面激起了細微的波紋

如果輸送一點能量給希格斯場，是否能激起相應的波浪？

答案竟是否定的。

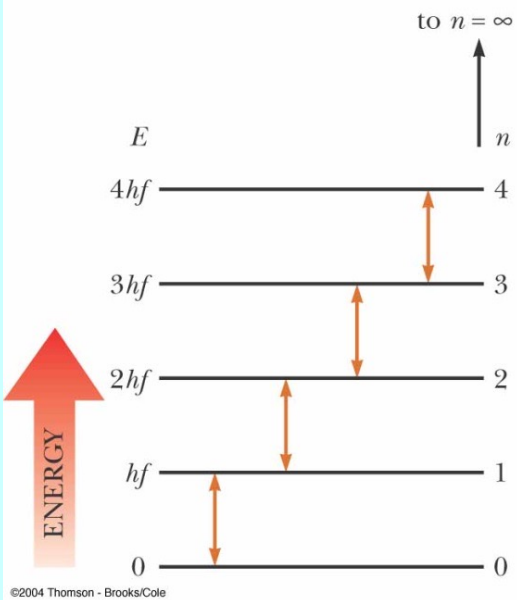
但如果我們不計一切奮力擾動激發希格斯場………



相對於真空，擾動後的希格斯場就是處於激發狀態！

激發態是何種樣貌？需要多少能量才能產生激發態？

$\begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$ 希格斯場也是一個量子場



激發態的能量不是連續的

能量的分佈像是一個一個的粒子

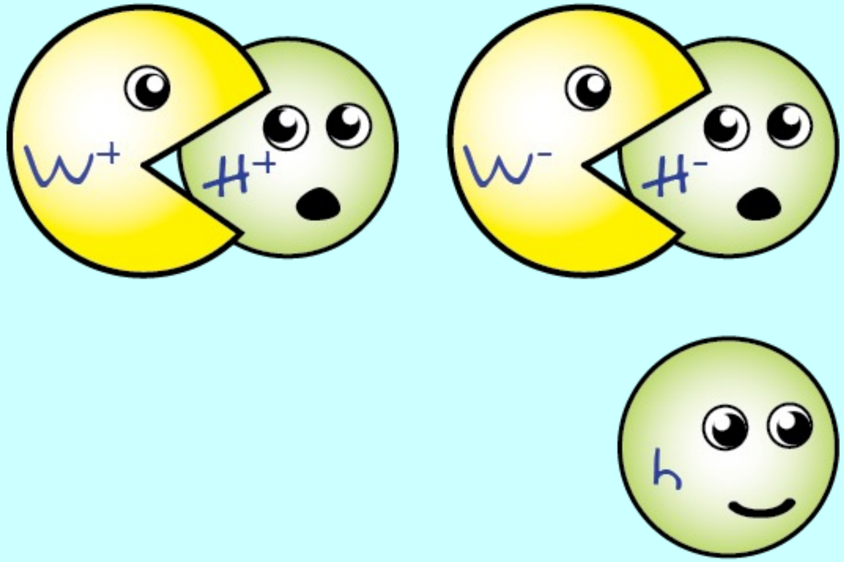
量子化的場一點都不像連續的場，反而像粒子。

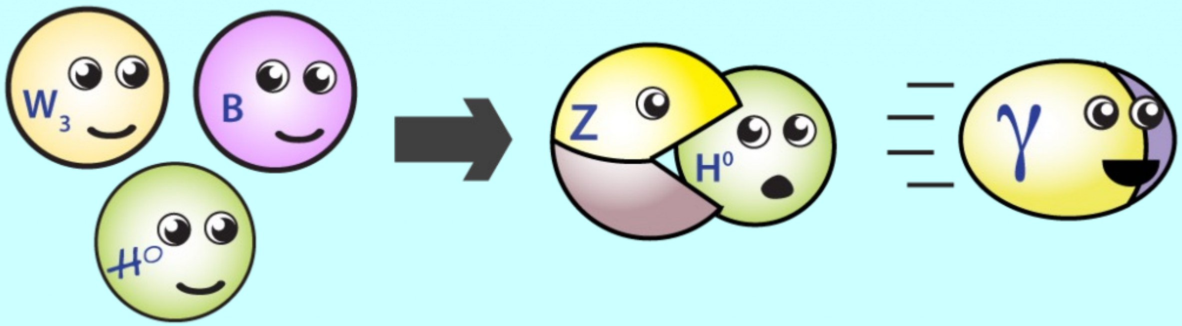
量子化的希格斯場所對應的粒子，就是希格斯粒子

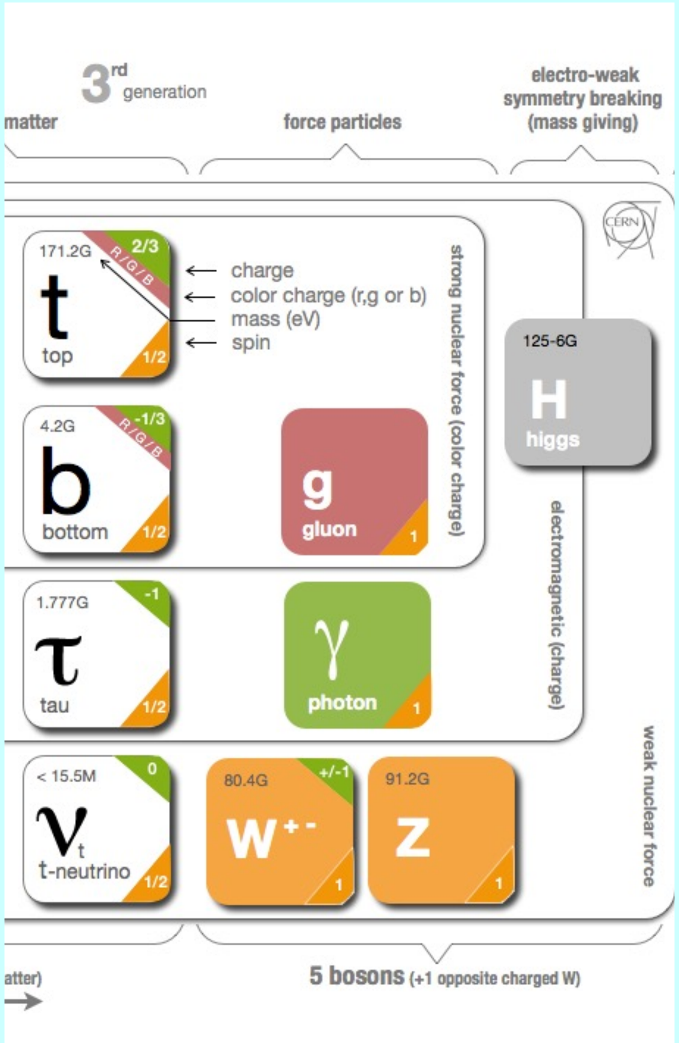
H Particle ⟷ $H(x)$ Field

因此希格斯粒子就是希格斯場的擾動或激發態。

$$\begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$



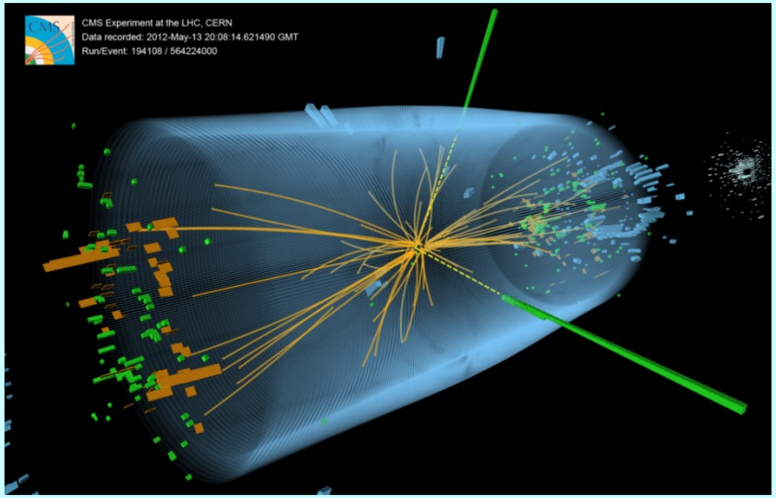


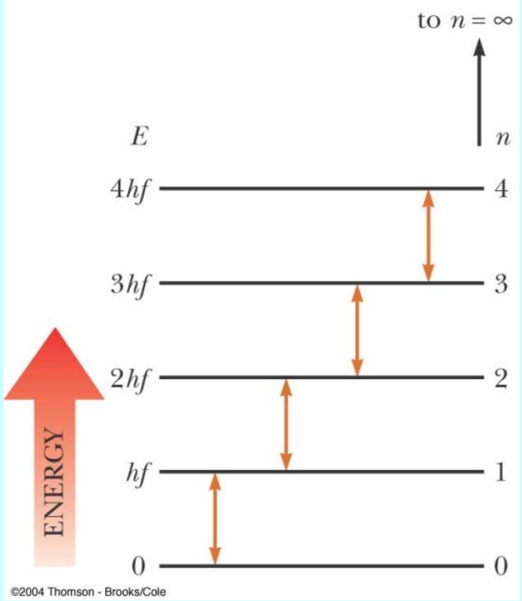


因此希格斯粒子就是希格斯場的擾動或激發態。

希格斯場預測了一個新的基本粒子─希格斯粒子。

因此希格斯粒子的發現證實了希格斯場的存在。

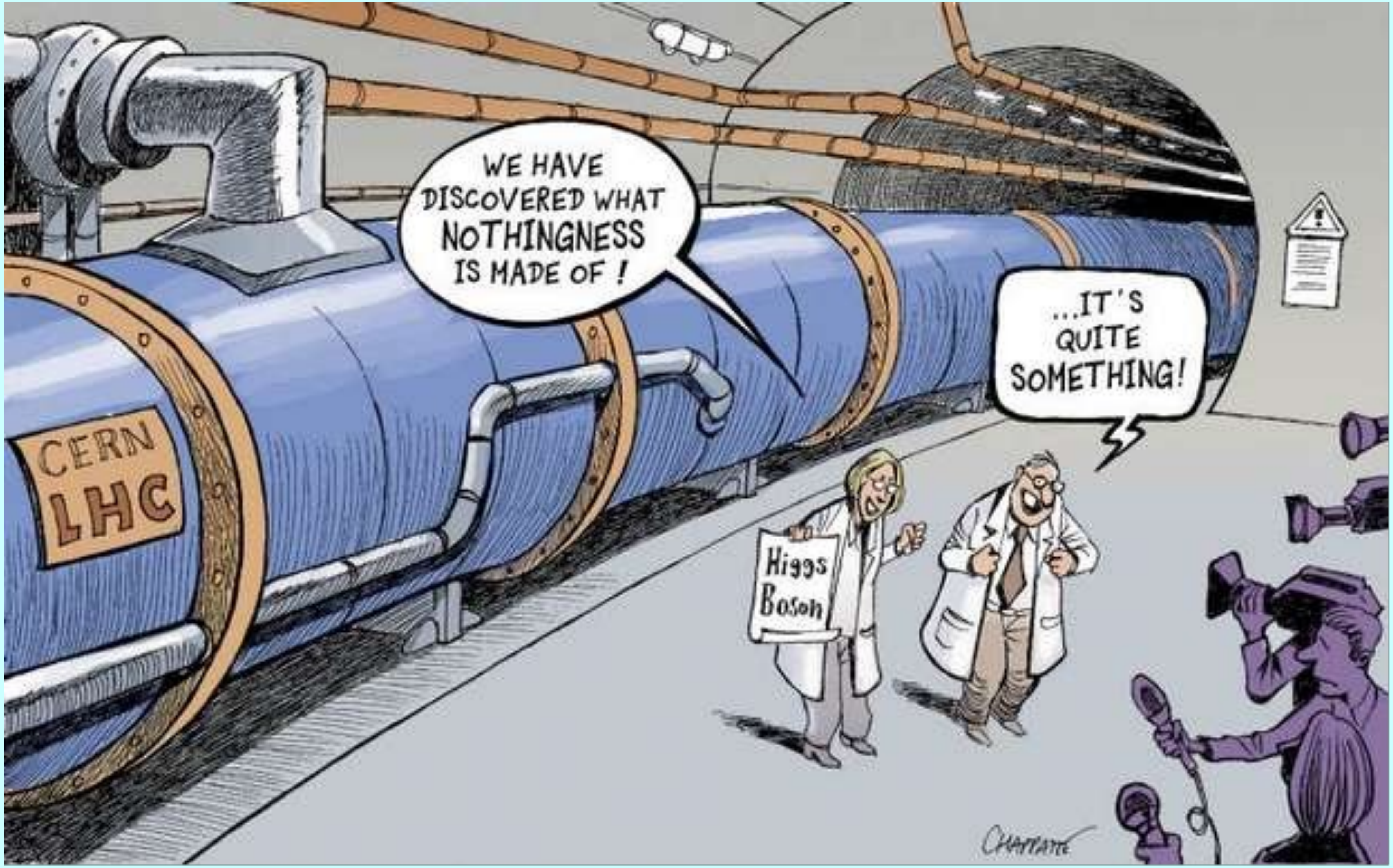




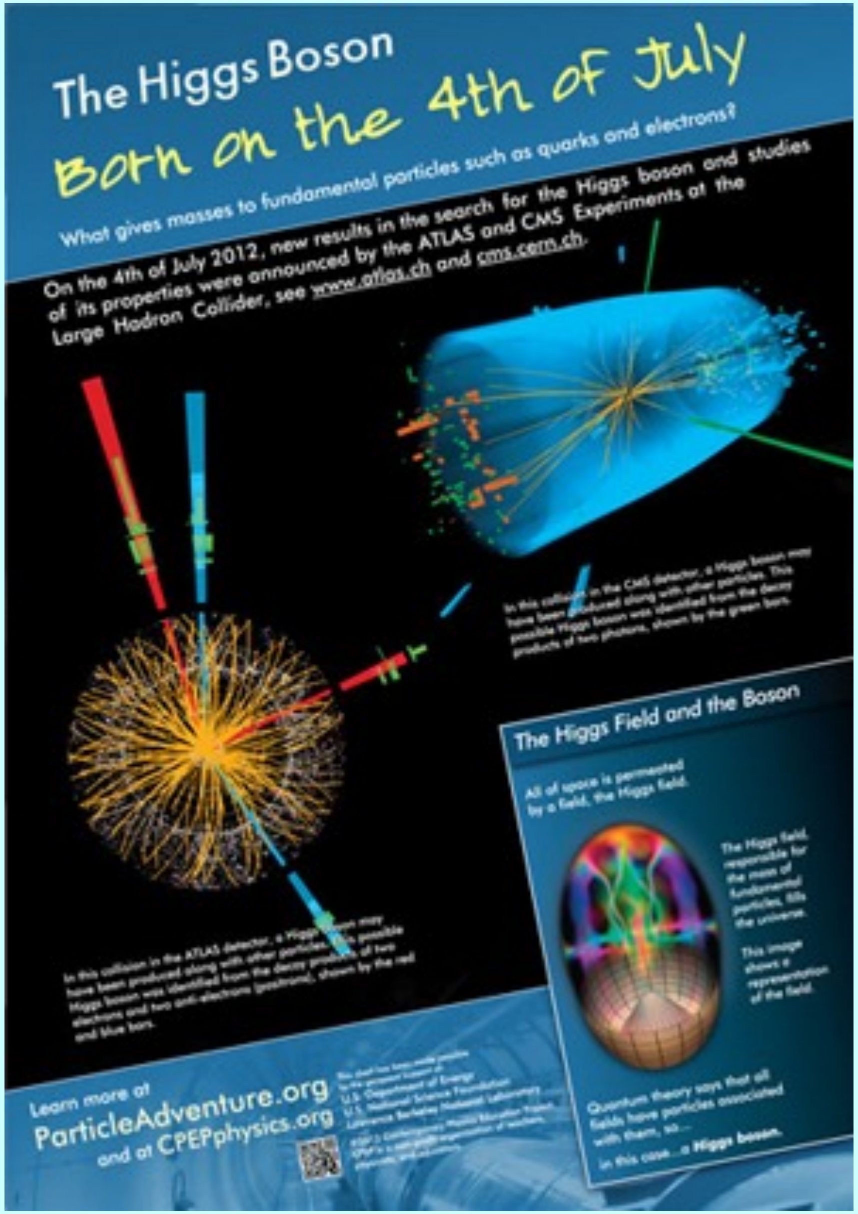
粒子的質量即對應此激發態與真空的能量差 Gap $E = mc^2$

相對的，真空中的希格斯場是絕對純粹，**沉靜無波**

要激起浪花，能量有門檻，而且驚人的高！

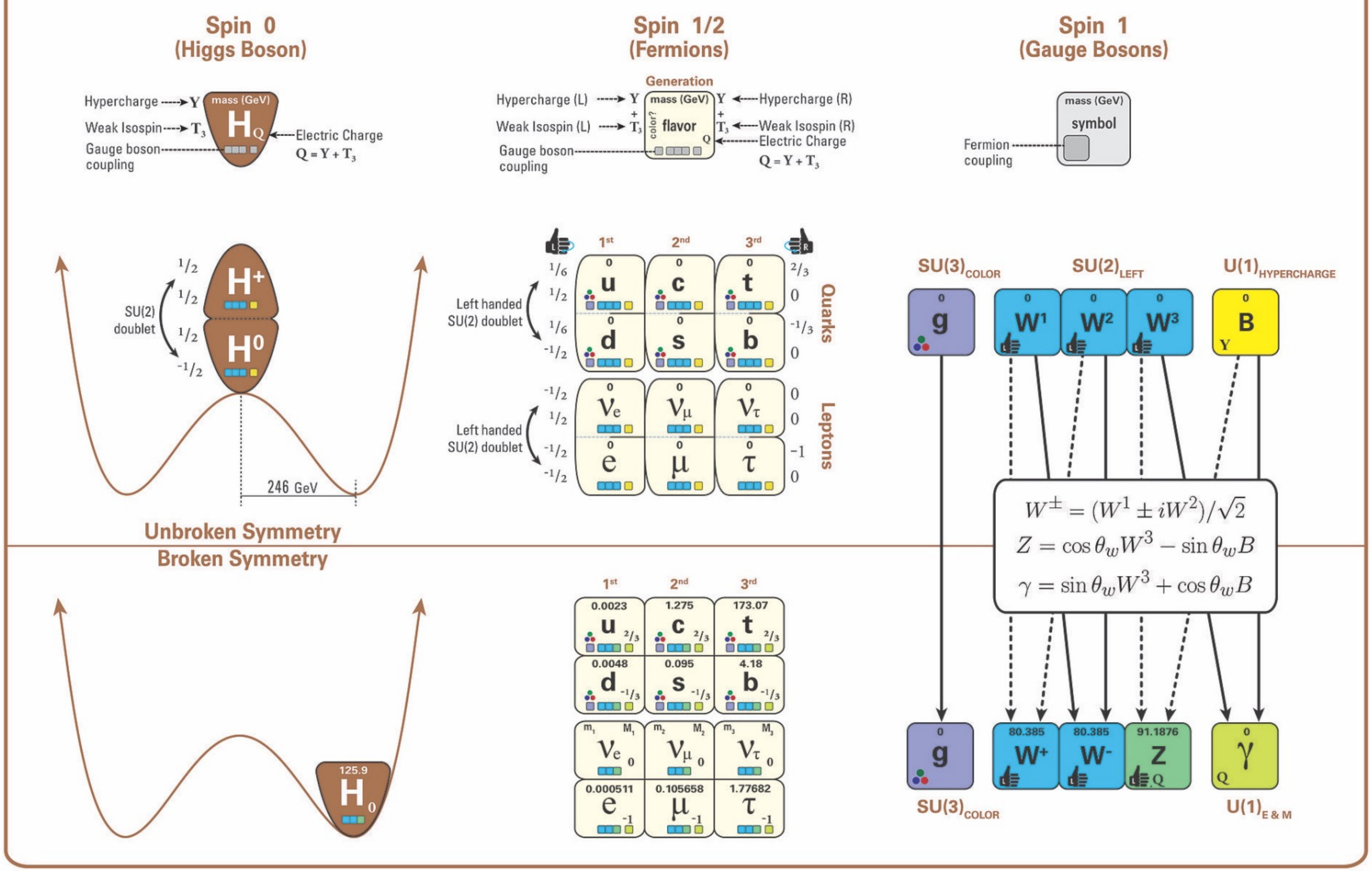

WE HAVE DISCOVERED WHAT NOTHINGNESS IS MADE OF !
...IT'S QUITE SOMETHING!
CERN LHC
Higgs Boson
CHAPPATTE

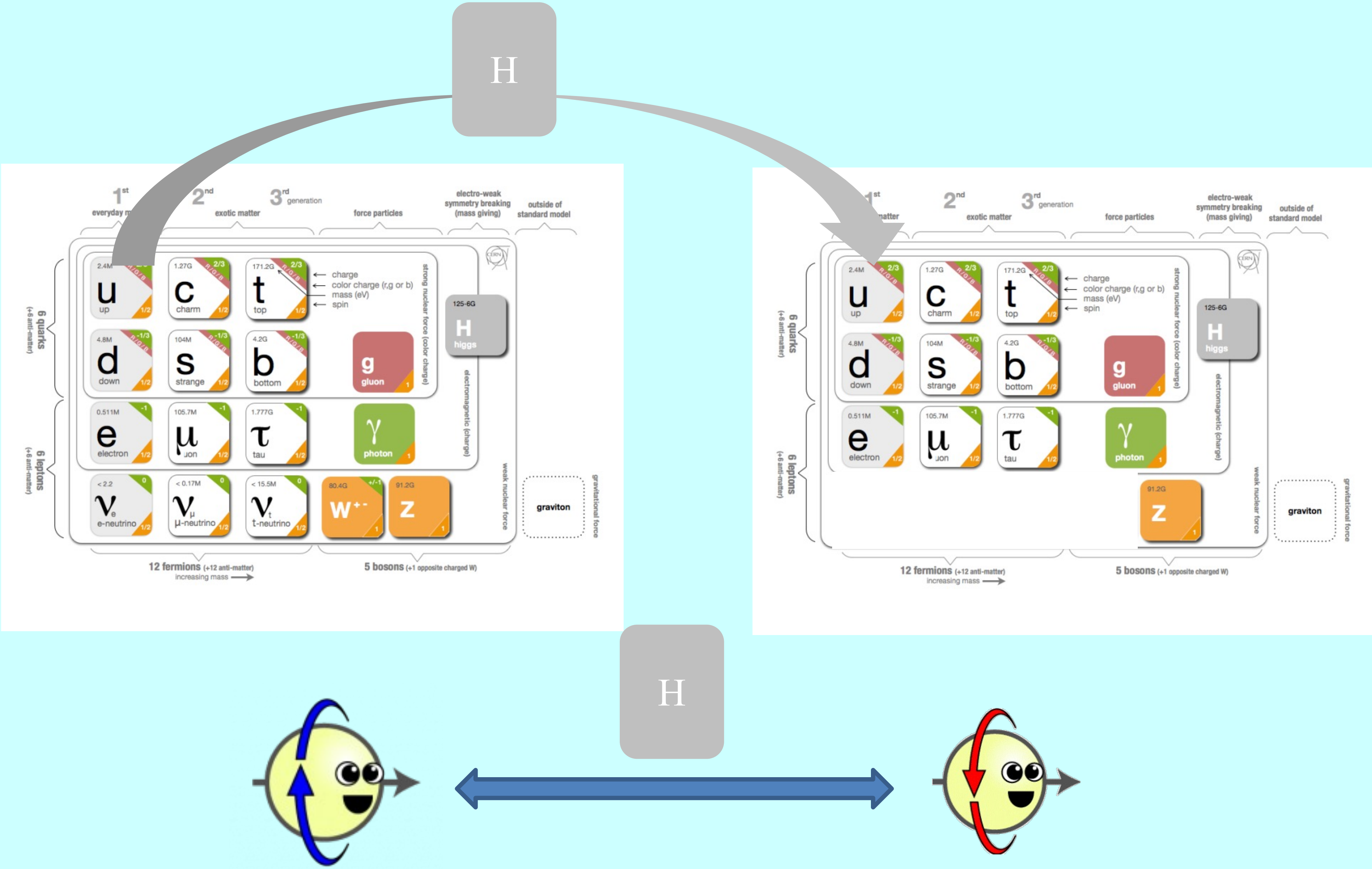
在無處不在的希格斯場之上，激發出了這個珍貴難得價值不菲的希格斯粒子



Jigsaw falling into place

The Standard Model of Particle Physics





破壞SU(2)$_L$ 規範對稱的希格斯場，也提供了費米子質量。