Dark Matter, Dark Energy & Neutrino Mass
暗物质，暗能量和中微子质量

Chao-Qiang Geng

耿朝強

國立清華大學
NATIONAL TSING HUA UNIVERSITY

理论物理前沿暑期讲习班——暗物质，中微子与粒子物理前沿

中山大学广州校区南校园 *2017*年*7*月*3-28*日

中山大學
SUN YAT-SEN UNIVERSITY

Lecture 1: Introduction to Particle Physics and Cosmology

Lecture 2: Some Basic Backgrounds of the Standard Model of Particle Physics

Lecture 3: Neutrino Mass Generation

Lecture 4: Theoretical Understanding of Dark Matter Detections

Lecture 5: Dark Energy and Gravitational Waves

Lecture 2: Some Basic Backgrounds of the Standard Model of Particle Physics

Outline

- Introduction
- Some basic concepts
- Anomalies in four-dimension
- Uniqueness of fermion representations and charges in the standard model
- Family problem
- Broken symmetry and mass generation

- # Introduction

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Standard groups

Strong Interaction ($SU(3)_C$)

Electroweak Interaction ($SU(2)_L \times U(1)_Y$)

$$Q = T_{3L} + \frac{Y}{2}$$

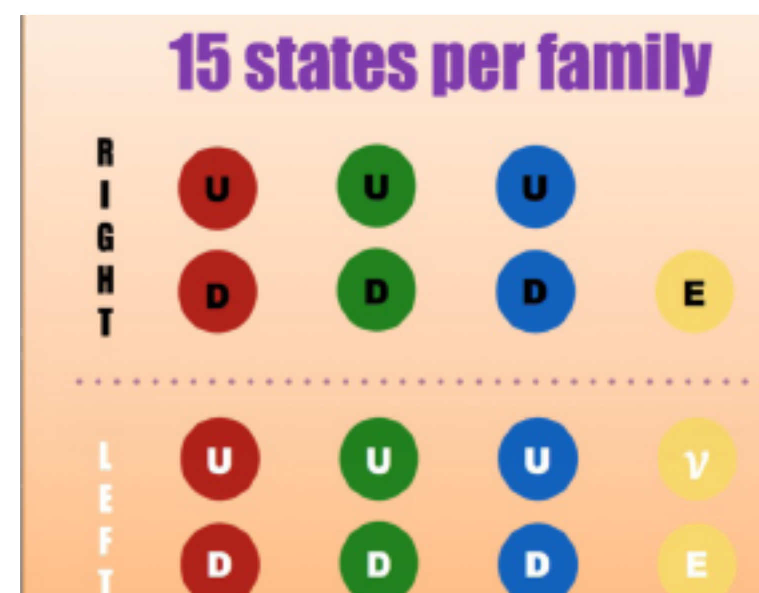
$SU(3)_C \times SU(2)_L \times U(1)_Y$ —$\langle H \rangle$→ $SU(3)_C \times U(1)_{EM}$

Higgs Mechanism

				$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$SU(3)_C$	$U(1)_{EM}$
Q_L :	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	3	2	$\frac{1}{3}$	$\begin{pmatrix} 3 \\ 3 \end{pmatrix}$	$\begin{pmatrix} \frac{2}{3} \\ -\frac{1}{3} \end{pmatrix}$
U_R :	u_R	c_R	t_R	3	1	$\frac{4}{3}$	3	$\frac{2}{3}$
D_R :	d_R	s_R	b_R	3	1	$-\frac{2}{3}$	3	$-\frac{1}{3}$
L_L :	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	1	2	-1	$\begin{pmatrix} 1 \\ 1 \end{pmatrix}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
E_R :	e_R	μ_R	τ_R	1	1	-2	1	-1
H				1	2	1		

Questions:

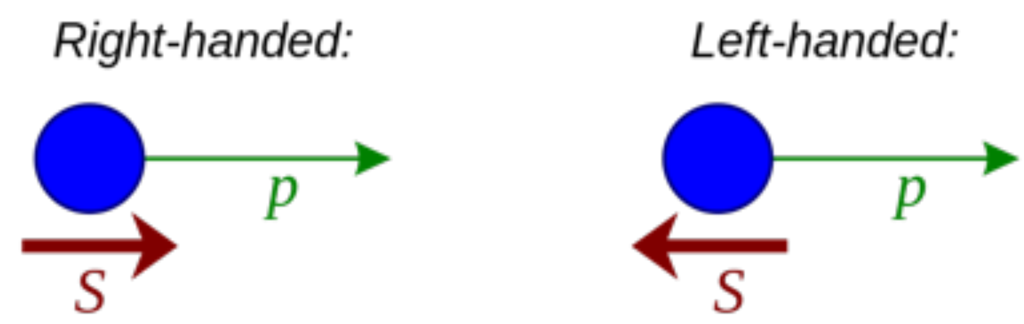
1. Why are there 15 states of quarks and leptons?
2. Why are the electric charges of particles quantized?
3. Are these quantum numbers unique?
4. Why are there three fermion generations?
5. How to generate the fermion masses?



- Some basic concepts

Chirality and Helicity

The helicity of a particle is right-handed if the direction of its spin is the same as the direction of its motion. It is left-handed if the directions of spin and motion are opposite.



$$h_p \propto \vec{s} \cdot \vec{p}$$

The chirality of a particle is determined by whether the particle is in a right- or left-handed.

For massless particles—such as photon, gluon, and graviton—chirality is the same as helicity; a given massless particle appears to spin in the same direction along its axis of motion regardless of point of view of the observer.

For massive particles—such as electrons, quarks and neutrinos—chirality and helicity must be distinguished. In the case of these particles, it is possible for an observer to change to a reference frame that overtakes the spinning particle, in which case the particle will then appear to move backwards, and its helicity (which may be thought of as 'apparent chirality') will be reversed.

A massless particle moves with c, so a real observer (who must always travel at less than c) cannot be in any reference frame where the particle appears to reverse its relative direction, meaning that all real observers see the same chirality. Because of this, the direction of spin of massless particles is not affected by a Lorentz boost (change of viewpoint) in the direction of motion of the particle, and the sign of the projection (helicity) is fixed for all reference frames: the helicity of massless particles is a relativistic invariant (i.e. a quantity whose value is the same in all inertial reference frames).

Dirac Fermion; Majorana Fermion; and Weyl Fermion

Dirac neutrino mass

$$\mathcal{L}_D = -m_D \overline{\nu_L} \nu_R + \text{h.c.}$$

Dirac Equation: $(i\gamma^\mu \partial_\mu - m)\Psi = (\gamma^\mu p_\mu - m)\Psi = 0$

在Dirac表象下， $\bar{\gamma}^0 = \begin{pmatrix} \sigma_0 & 0 \\ 0 & -\sigma_0 \end{pmatrix}, \quad \bar{\gamma}^i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix}$

Dirac Fermion

其中σ_0是二阶单位矩阵， σ_i是泡利矩阵： $\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$

在Weyl表象下，Dirac方程的解可以写为$\Psi = (\psi_R, \ \psi_L)^T$， $\gamma^0 = \begin{pmatrix} 0 & \sigma_0 \\ \sigma_0 & 0 \end{pmatrix}, \quad \gamma^i = \begin{pmatrix} 0 & -\sigma_i \\ \sigma_i & 0 \end{pmatrix}.$

$$\begin{cases} (i\partial_t - \boldsymbol{p}\cdot\boldsymbol{\sigma})\psi_R - m\psi_L = 0 , \\ (i\partial_t + \boldsymbol{p}\cdot\boldsymbol{\sigma})\psi_L - m\psi_R = 0 . \end{cases}$$

Weyl Fermions

在Majorana表象下，正反粒子等同的粒子 $\Psi^c(x) = \Psi(x)$

Majorana neutrino mass $\nu \leftrightarrow \bar{\nu}$

$$\mathcal{L}_M = -m_M \overline{\nu^c} \nu \ + \text{h.c.}$$

Dirac 方程式为纯实的方程，
因此方程和解都是实的。

Majorana Fermion

$$\begin{cases} (i\partial_t - \boldsymbol{p}\cdot\boldsymbol{\sigma})\psi_R - im_R\sigma_2\psi_R^* = 0 , \\ (i\partial_t + \boldsymbol{p}\cdot\boldsymbol{\sigma})\psi_L + im_L\sigma_2\psi_L^* = 0 . \end{cases}$$

$$\tilde{\gamma}^0 = i\begin{pmatrix} 0 & -\sigma_1 \\ \sigma_1 & 0 \end{pmatrix}, \quad \tilde{\gamma}^1 = i\begin{pmatrix} 0 & \sigma_0 \\ \sigma_0 & 0 \end{pmatrix},$$

$$\tilde{\gamma}^2 = i\begin{pmatrix} \sigma_0 & 0 \\ 0 & -\sigma_0 \end{pmatrix}, \quad \tilde{\gamma}^3 = i\begin{pmatrix} 0 & \sigma_2 \\ -\sigma_2 & 0 \end{pmatrix} .$$

Global, Local (gauge), Abelian and Non-Abelian Symmetries

In physics, a global symmetry is a symmetry that holds at all points in the spacetime under consideration, as opposed to a local symmetry which varies from point to point.

$\psi \to e^{iq\theta}\psi$ and $\bar{\psi} \to e^{-iq\theta}\bar{\psi}$

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

$\theta = constant$

U(1) global symmetry

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

$\theta = \theta(x)$

U(1) local symmetry or gauge symmetry

$$\mathcal{L} \to \bar{\mathcal{L}} = e^{-iq\theta(x)}\bar{\Psi}(i\gamma^\mu\partial_\mu - m)(e^{iq\theta(x)}\Psi)$$
$$= e^{-iq\theta(x)}e^{iq\theta(x)}\bar{\Psi}(i\gamma^\mu\partial_\mu - m - q\gamma^\mu\partial_\mu\theta(x))\Psi \neq \mathcal{L}$$

Gauge Invariant

$$\mathcal{L} = \bar{\Psi}(i\gamma^\mu D_\mu - m)\Psi$$

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

$$\Psi \to \Psi' = e^{iq\theta(x)}\Psi$$

$$D_\mu\Psi' = e^{iq\theta(x)}D_\mu\Psi$$

$$A_\mu \to A'_\mu = A_\mu + \partial_\mu\theta(x)$$

$$\mathcal{L} \to \bar{\mathcal{L}} = e^{-iq\theta(x)}e^{iq\theta(x)}\bar{\Psi}(i\gamma^\mu D_\mu - m)\Psi = \mathcal{L}$$

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\Psi}(i\gamma^\mu D_\mu - m)\Psi$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

Gauge invariant principle results in the existence of a massless vector boson field A_μ in gauge symmetry !

$\psi \to \Omega(\theta)\,\psi$

1. $\Omega(\theta)=e^{i\theta}$ Abelian U(1) symmetry $\xrightarrow[\theta=\theta(x)]{}$ gauge U(1): QED

2. $\Omega(\theta)=e^{i/2\tau_j\theta_j}$ Non-Abelian SU(2) symmetry $\xrightarrow[\theta_i=\theta_i(x)]{}$ $SU(2)_L$ in the SM

$\psi = \binom{u}{d}$

Non-Abelian local symmetry ≡ Yang-Mill gauge symmetry

τ_j (j=1,2,3) Pauli matrices $[\tau^i,\tau^j] = i\epsilon^{ijk}\tau^k$

$$\mathcal{L} = -\frac{1}{4}F^{i\mu\nu}F^i_{\mu\nu} + \bar{\Psi}(i\gamma^\mu D_\mu - m)\Psi$$

$$D_\mu = \partial_\mu - ig\frac{\tau^j}{2}A^j_\mu$$

$$F^i_{\mu\nu} = \partial_\mu A^i_\nu - \partial_\nu A^i_\mu + g\epsilon_{ijk}A^j_\mu A^k_\nu$$

Massless Yang-Mill fields

3. $\Omega(\theta)=e^{i/2\lambda_\alpha\theta_\alpha}$ Non-Abelian SU(3) symmetry $\xrightarrow[\theta_\alpha=\theta_\alpha(x)]{}$ $SU(3)_C$ $\psi=\begin{pmatrix}r\\y\\g\end{pmatrix}$

λ_α (α=1,2,...8) Gell-Mann matrices $[\lambda^\alpha,\lambda^\beta] = if^{\alpha\beta\gamma}\lambda^\gamma$

$$\mathcal{L}_{QCD} = -\frac{1}{4}F^{\alpha\mu\nu}F^\alpha_{\mu\nu} + \bar{\Psi}(i\gamma^\mu D_\mu - m)\Psi$$

$$D_\mu = \partial_\mu - ig\frac{\lambda^\alpha}{2}A^\alpha_\mu$$

$$F^\alpha_{\mu\nu} = \partial_\mu A^\alpha_\nu - \partial_\nu A^\alpha_\mu + gf_{\alpha\beta\gamma}A^\beta_\mu A^\gamma_\nu$$

Massless Gluon fields

Chiral symmetry

Massless Dirac fermion field ψ exhibits chiral symmetry

Dirac Equation: $(i\gamma^\mu\partial_\mu - m)\psi = 0 \xrightarrow{m\to 0} i\gamma^\mu\partial_\mu\psi = 0 \xrightarrow{\gamma^5} i\gamma^\mu\partial_\mu(\gamma^5\psi) = 0$

∴ both ψ and $\gamma^5\psi$ are solutions of Dirac equation.

Two linear combinations: $\psi_L = 1/2(1-\gamma^5)\psi$ and $\psi_R = 1/2(1+\gamma^5)\psi$ ⟵ $\psi = \psi_L + \psi_R$

In QED with one Dirac field:

$$\mathcal{L} = i\bar{\psi}\not{D}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - m\bar{\psi}\psi \qquad (1)$$

$$F^{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu\,, \quad D_\mu = \partial_\mu - ieA_\mu$$

$$(1) \implies U(1)_{\text{vector}} : \psi \longrightarrow e^{i\alpha}\psi$$

$$m \longrightarrow 0 \implies U(1)_{\text{axial vector}} : \psi \longrightarrow e^{i\beta\gamma_5}\psi$$

Using $\psi_L = \frac{1}{2}(1-\gamma_5)\psi\,, \quad \psi_R = \frac{1}{2}(1+\gamma_5)\psi$ notations: ⟵ **Chiral Fermions**

$$(1) \implies \mathcal{L} = i\bar{\psi}_L\not{D}\psi_L + i\bar{\psi}_R\not{D}\psi_R - m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$m \longrightarrow 0 \quad U(1)_L : \psi_L \longrightarrow e^{ia}\psi_L \qquad U(1)_R : \psi_R \longrightarrow e^{ib}\psi_R$$

☜ **Chiral symmetries**

$$U(1)_V = U(1)_{L+R}\,, \quad U(1)_A = U(1)_{L-R}$$

Chiral symmetry

QCD

Vector Gauge Theory

	$SU(3)_C$ ×	$U(n_f)_L$ ×	$U(n_f)_R$
q	3	n_f	1
$\bar{q}$	$\bar{3}$	1	$\bar{n}_f$

Global Symmetries: $U(n_f)_L \times U(n_f)_R$ ← Chiral Global Flavor Symmetries

The Lagrangian of QCD

$$\mathcal{L}_{QCD} = -\sum_i \bar{q}_i \left(\gamma^\mu \frac{1}{i} D_\mu + m_i\right) q_i - \frac{1}{4} G_a^{\mu\nu} G_{a\mu\nu}$$

which is invariant under a large global symmetry transformation $\mathcal{L}_{QCD} \xrightarrow{U(n_f)_L \times U(n_f)_R} \mathcal{L}_{QCD}$

$$n_f = 2, \quad q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \to e^{i\alpha_{iL} T_i} \begin{pmatrix} u \\ d \end{pmatrix}_L ; \quad \begin{pmatrix} u \\ d \end{pmatrix}_R \to e^{i\alpha_{iR} T_i} \begin{pmatrix} u \\ d \end{pmatrix}_R \qquad T_i = (\tau_i, 1)$$

$SU(3)_C \times U(2)_L \times U(2)_R \equiv SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_L \times U(1)_R$ ← $U(n) = SU(n) \times U(1)$

	$SU(3)_C$	$U(2)_L$	$U(2)_R$	$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)_L$	$U(1)_R$
q	3	2	1	3	2	1	1	0
$\bar{q}$	$\bar{3}$	1	2	$\bar{3}$	1	2	0	-1

$\equiv SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{V=L+R} \times U(1)_{A=L-R}$

$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)_{V=L+R}$	$U(1)_{A=L-R}$
3	2	1	1	1
$\bar{3}$	1	2	-1	1

Instanton effect: $U(1)_A \to Z_4$

$< u\bar{u}d\bar{d} > \neq 0$

$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_B$

$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)_B$
3	2	1	1/3
$\bar{3}$	1	2	-1/3

$U(1)_V = 3U(1)_B \qquad q_i \to \exp\left[\frac{i}{3}\alpha_B\right] q_i \qquad J_B^\mu = \frac{1}{3}\sum_i \bar{q}_i \gamma^\mu q_i$

$\mathcal{L}_{SM} \xrightarrow{U(1)_B} \mathcal{L}_{SM}$

$\langle \bar{u}u \rangle = \langle \bar{d}d \rangle \neq 0 \qquad SU(2)_L \times SU(2)_R \to SU(2)_{V=L+R}$

this leads to three Goldstone bosons which are pseudoscalar: $\pi^\pm, \pi^0$

$SU(3)_C \times SU(2)_{V=L+R} \times U(1)_B$

$SU(3)_C$	$SU(2)_{V=L+R}$	$U(1)_B$
3	2	1/3
$\bar{3}$	2	-1/3

- Anomalies in four-dimension

The triangular anomaly

In QED with one Dirac field:

$$\mathcal{L} = i\bar{\psi}\not{D}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - m\bar{\psi}\psi \qquad (1)$$

$$F^{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu\,, \quad D_\mu = \partial_\mu - ieA_\mu$$

$$(1) \quad \Longrightarrow \quad U(1)_{\text{vector}} \; : \; \psi \longrightarrow e^{i\alpha}\psi$$

$$m \longrightarrow 0 \quad \Longrightarrow \quad U(1)_{\text{axial vector}} \; : \; \psi \longrightarrow e^{i\beta\gamma_5}\psi$$

According to *Noether's Theorem*, gauge invariants imply the existence of conserved currents:

$$J_\mu = \bar{\psi}\gamma_\mu\psi\,, \qquad \partial_\mu J^\mu = 0\,,$$

$$J_{5\mu} = \bar{\psi}\gamma_\mu\gamma_5\psi\,, \qquad \partial_\mu J_5^\mu = 2mJ_5 \xrightarrow{m \longrightarrow 0} 0$$

where $J_5 = i\bar{\psi}\gamma_5\psi$

The anomaly phenomenon is that

S.Adler,PR177,2426(1969);
J.S.Bell,R.Jackiw,Nuovo Cimen A60,47 (1969)

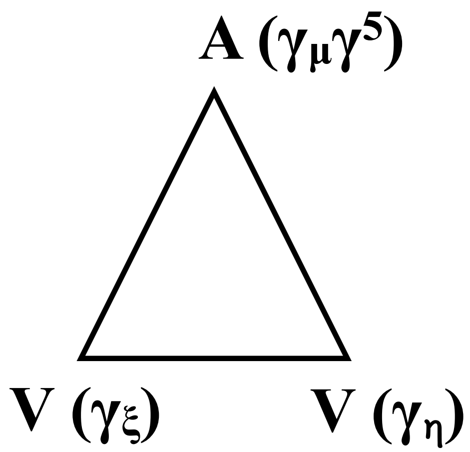
$$\partial_\mu J_5^\mu = \partial_\mu(\bar{\psi}\gamma_\mu\gamma_5\psi) = 2mJ_5 + \frac{\alpha_0}{2\pi}\tilde{F}^{\mu\nu}F_{\mu\nu}$$

$$m \longrightarrow 0 \quad \longrightarrow \frac{\alpha_0}{2\pi}\tilde{F}^{\mu\nu}F_{\mu\nu}$$

$(\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta})$

Quantum Level

— Adler-Bell-Jackiw (ABJ) or axial *Anomaly*



— *Triangle Anomaly*

This anomalous result $\Longrightarrow$ an understanding of $\pi \to 2\gamma$

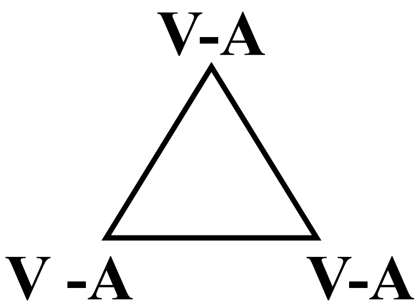
$U(1)$ problem in QCD

No problem in QED the axial-vector current doesn't couple to the photon (γ).

If we introduce a gauge boson which couples to the axial-vector current, such a theory will not be *renormalizable* since the gauge invariance – a necessary requirement for renormalizability — is lost due to $\partial_\mu J_5^\mu \neq 0$.

Electroweak theory: $V - A$ gauge coupling

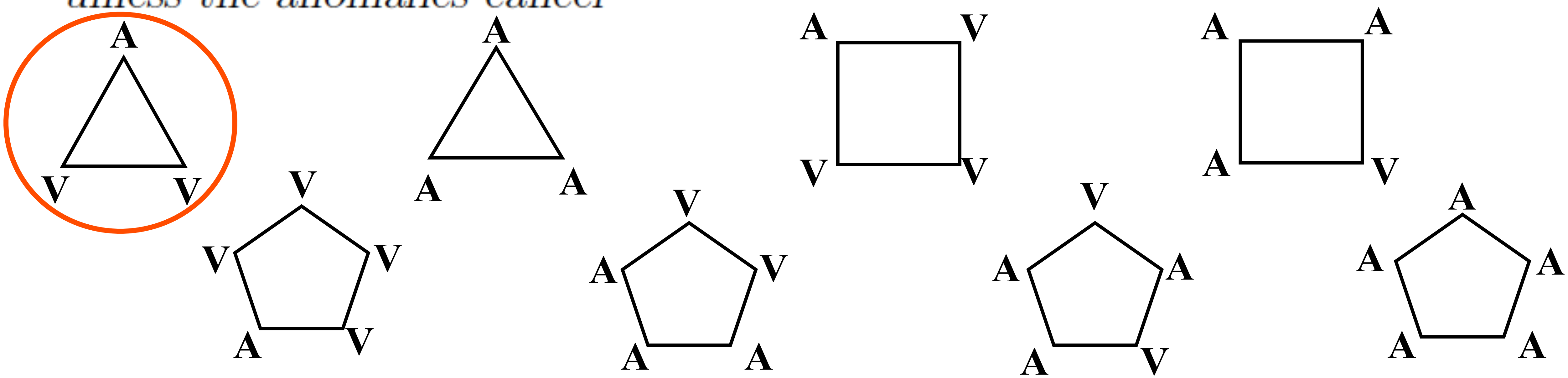
One must consider a fermion triangle with a $V - A$ current at each vertex.



This diagram is again anomalous.

Unless it cancels when summing over the fermion species running around the loop, the anomaly spoils conservation of the $V - A$ current.

- *Any gauge theory with non-vectorlike gauge coupling is inconsistent unless the anomalies cancel*



<u>Two useful theorems:</u>

- Once the AVV triangle anomaly is cancelled, then so are all the others.
- Radiative corrections do not renormalize the anomaly.

$\Longrightarrow$ *Only AVV triangle graph is needed to consider.*

For example: any gauge theory

$$\begin{aligned} J_a^\mu &= \bar{\psi}\gamma^\mu t_a \psi \\ &= \frac{1}{2}\bar{\psi}\gamma^\mu t_a^L(1-\gamma_5)\psi + \frac{1}{2}\bar{\psi}\gamma^\mu t_a^R(1+\gamma_5)\psi \end{aligned}$$

where t_a $(a = 1, 2, \cdots, N)$ are the generators of the gauge group.

$$\begin{aligned} Anomaly-free \iff \mathcal{A} &\equiv Tr\left[\{t_a^L, t_b^L\}, t_c^L\right] - Tr\left[\{t_a^R, t_b^R\}, t_c^R\right] \\ &= 0 \end{aligned}$$

△ Real representations are <u>*safe*</u>.

△ $SU(2)$, $SO(2k+1)$ $(k>2)$, $SO(4k)$ $(k>2)$, $Sp(2k)$, G_2, F_4, E_7, E_8 have only real reps. — <u>*safe*</u>.

△ $SO(4k+2)$ $(k>2)$, E_6 have complex reps. — <u>*safe*</u>.

△ $SU(N)$ $(N>2)$ are not <u>*safe*</u>.

For $(\square, Y)$ under SU(N)×U(1)$_Y$:
or $(\bar{\square}, Y)$

$$\begin{aligned} [SU(N)]^3 &: \mathcal{A}(\square) = 1\,, \quad \mathcal{A}(\bar{\square}) = -1 \\ [SU(N)]^2\, U(1)_Y &: \mathcal{A}(\square) = Y\,, \quad \mathcal{A}(\bar{\square}) = Y \\ [U(1)_Y]^3 &: \mathcal{A} = Y^3 \end{aligned}$$

Particles $(i=1,2,3)$	$SU(3)_C$	$\times$	$SU(2)_L$	$\times$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_L^i$	3		2		$\frac{1}{3}$
$u_L^{c\,i}$	$\overline{3}$		1		$-\frac{4}{3}$
$d_L^{c\,i}$	$\overline{3}$		1		$\frac{2}{3}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L^i$	1		2		-1
$e_L^{c\,i}$	1		1		2

Triangle anomalies in the standard model:

$$
\begin{aligned}
[SU(3)_C]^3 &= 2-1-1=0 \\
[SU(3)_C]^2\,U(1)_Y &= 2\cdot\frac{1}{3}+1\cdot(-\frac{4}{3})+1\cdot\frac{2}{3}=0 \\
[SU(2)_L]^3 &\equiv 0 \\
[SU(2)_L]^2\,U(1)_Y &= 3\cdot\frac{1}{3}-1=0 \\
[U(1)_Y]^3 &= TrY^3 \\
&= 3\cdot 2\cdot(\frac{1}{3})^3+3\cdot 1\cdot(-\frac{4}{3})^3+3\cdot 1\cdot(\frac{1}{3})^3 \\
&\quad +2\cdot(-1)^3+1\cdot(2)^3=0
\end{aligned}
$$

Particles $(i=1,2,3)$	$SU(3)_C$	×	$SU(2)_L$	×	$U(1)_Y$	× $U(1)_B$ 重子數	× $U(1)_L$ 輕子數	= $U(1)_{B+L}$	× $U(1)_{B-L}$
$\begin{pmatrix} u \\ d \end{pmatrix}_L^i$	3		2		$\frac{1}{3}$	1/3	0	1/3	1/3
$u_L^{c\,i}$	$\overline{3}$		1		$-\frac{4}{3}$	-1/3	0	-1/3	-1/3
$d_L^{c\,i}$	$\overline{3}$		1		$\frac{2}{3}$	-1/3	0	-1/3	-1/3
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L^i$	1		2		-1	0	1	1	-1
$e_L^{c\,i}$	1		1		2	0	-1	-1	1

Global Symmetries

Global Symmetries

$U(1)_B$: $q_i \to \exp\left[\frac{i}{3}\alpha_B\right] q_i \qquad J_B^\mu = \frac{1}{3}\sum_i \bar{q}_i\gamma^\mu q_i \qquad \mathcal{L}_{SM} \xrightarrow{U(1)_B} \mathcal{L}_{SM}$ 重子數守恆

$U(1)_L$: $\ell_i \to \exp(i\alpha_L)\ell_i \qquad J_L^\mu = \sum_i \bar{\ell}_i\gamma^\mu \ell_i \qquad \mathcal{L}_{SM} \xrightarrow{U(1)_L} \mathcal{L}_{SM}$ 輕子數守恆

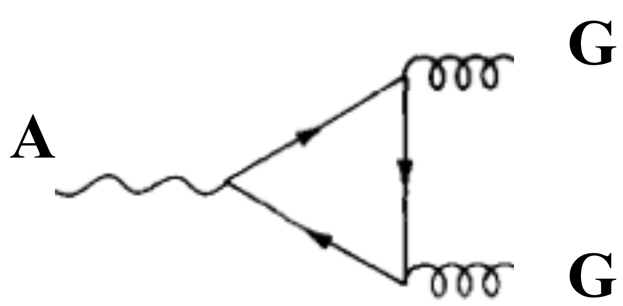
At the quantum level, however, neither $U(1)_L$ or $U(1)_B$ are good symmetries, because of the chiral nature $SU(2)_L$.

$$[SU(2)_L]^2\, U(1)_B = 3\times\frac{1}{3}+1\times 0 = 1 \qquad [SU(2)_L]^2\, U(1)_L = 3\times 0 + 1\times 1 = 1$$

$$[SU(2)_L]^2\, U(1)_{B+L} = 3\times\frac{1}{3}+1\times 1 = 2 \qquad [SU(2)_L]^2\, U(1)_{B-L} = 3\times\frac{1}{3}-1\times 1 = 0$$

$$\mathcal{L}_{SM} \xrightarrow{U(1)_{B-L}} \mathcal{L}_{SM}$$

- The mixed gauge-gravitational anomaly



The triangle with one axial-current and two energy-momentum tensors is anomalous

$$D_\mu J_5^\mu \;=\; -\frac{1}{384\pi^2}(TrQ)\; R_{\mu\nu\sigma\tau}\tilde{R}^{\mu\nu\sigma\tau}$$

R.Delbourgo,A.Salam,PLB40,381(72); T.Eguchi,P.Freund,PRL37,1251(76)

$R_{\mu\nu\sigma\tau}$ is the Riemann curvature tensor and $\tilde{R}^{\mu\nu\sigma\tau} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}R^{\sigma\tau}_{\alpha\beta}$.

In four dimensions, the standard $SU(2)_L \times U(1)_Y$ theory cannot be coupled to gravity unless the sum of hypercharges (Y) of the Weyl fermions vanishes:

$$Tr\,Y \;=\; 0$$

L.Alvarez-Gaume, E.Witten, NPB234 (1983) 269

In the SM: $TrY = 3\cdot 2\cdot(\frac{1}{3}) + 3\cdot 1\cdot(-\frac{4}{3}) + 3\cdot 1\cdot(\frac{2}{3}) + 1\cdot 2\cdot(-1) + 1\cdot 1\cdot 2 = 0.$

Remarks:

- $U(1)$ — *unsafe*, unless $TrQ = 0$.
- G — *safe*. $\quad G \longrightarrow U(1)\times g\,, \qquad TrQ \equiv 0$

Example:

$SU(3)_C$	$\times SU(2)_L$	$\times U(1)_Y$
3	2	1/3
$\overline{3}$	1	−4/3
$\overline{3}$	1	2/3
1	2	−1
1	1	2
1	1	y_i

$i = 1, \cdots, n$

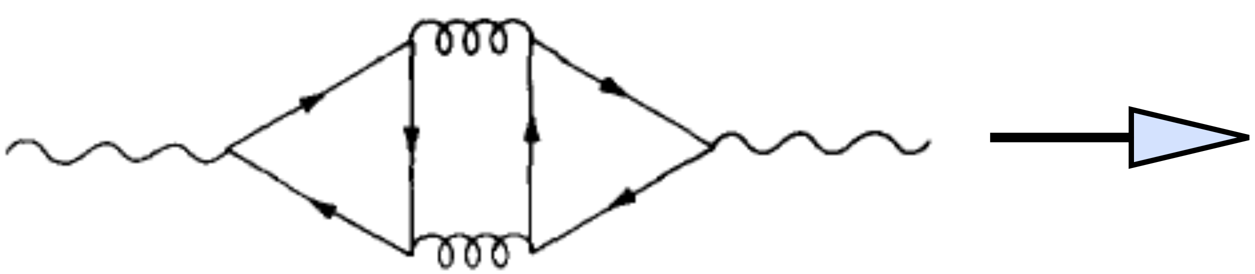
$$\Sigma_{i=1}^{n} y_i^3 = 0$$

$$\Sigma_{i=1}^{n} y_i \neq 0$$

$$Q = T_{3L} + \frac{Y}{2} \implies Tr\, Q \neq 0$$

Existing massless electrically charged fermions:

L.Alvarez-Gaume, E.Witten, NPB234 (1983) 269



$$m_\gamma^2 \sim \alpha G_N^2 \Lambda^6 (Tr\, Q)^2$$

G_N — Newton's constant

Λ — an ultraviolet cut off

$$m_\gamma \leq (10^6\ km)^{-1} \sim 10^{-25}\ GeV \implies \Lambda \leq 10^5\ GeV$$

- The global Witten $SU(2)$ anomaly

E.Witten,PLB117(1982)324

Any $SU(2)$ gauge theory with an odd number of left-handed fermion doublets is mathematically inconsistent.

The fermion integration for N massless Weyl fermion doublets, ψ:

$$\int (\mathcal{D}\psi \mathcal{D}\bar{\psi})_{\text{Weyl}}\, e^{\bar{\psi} i D \psi} = det^{N/2} iD(A) \longrightarrow (-1)^N det^{N/2} iD(A^U)$$

a topologically nontrivial gauge transformation U

where $A^U_\mu = U^{-1} A_\mu U - iU^{-1}\partial_\mu U$.

The number of the doublets, N, has to be *even*, otherwise the theory is ill-defined.

In the SM, for each family, $N = 3$ (quark) $+ 1$ (lepton) $= 4$ — even.

Remarks:

- $\Pi_4(G) = Z_2$, $G = Sp(2N), SU(2) = Sp(2)$ — *unsafe*.
- $\Pi_4(G) = 0$, G: all the simple compact Lie groups except $Sp(2N)$ — *safe*.

Π_4(G) is the 4th homotopy group

Question: For $G \longrightarrow SU(2) \times g$, is Witten $SU(2)$ anomaly free?

Triangle Anomaly-free of $G \Longrightarrow$ Witten $SU(2)$ Anomaly-free

CQG, Zhao,Marshak,OKubo PRD36(1987)1953

(a) $SO(10) \rightarrow SU(4)_C \times SU(2)_L \times SU(2)_R$

16	4	2	1
	$\bar{4}$	1	2

N= even

(b) $SU(3) \rightarrow SU(2) \times U(1)$

3	2	1
	1	-2

N= odd

- Uniqueness of fermion representations and charges in the SM

$SU(3)$	$\times$	$SU(2)$	$\times$	$U(1)$
3		2		$Q_i\,,\ i=1,\cdots,j$
3		1		$Q'_i\,,\ i=1,\cdots,k$
$\overline{3}$		1		$\overline{Q}_i\,,\ i=1,\cdots,l$
$\overline{3}$		2		$\overline{Q}'_i\,,\ i=1,\cdots,m$
1		2		$q_i\,,\ i=1,\cdots,n$
1		1		$\overline{q}_i\,,\ i=1,\cdots,p$
$\cdots$		$\cdots$		$\cdots$

☜ ***arbitrary***

The triangular anomaly-free conditions:

$$[SU(3)]^3 \ : \ \sum_{i=1}^{j} 2 + \sum_{i=1}^{k} 2 - \sum_{i=1}^{l} 1 - \sum_{i=1}^{m} 2 = 0\ , \tag{1}$$

$$[SU(3)]^2 U(1) \ : \ 2\sum_{i=1}^{j} Q_i + \sum_{i=1}^{k} Q'_i + \sum_{i=1}^{l} \overline{Q}'_i + 2\sum_{i=1}^{m} \overline{Q}'_i = 0\ , \tag{2}$$

$$[SU(2)]^2 U(1) \ : \ 3\sum_{i=1}^{j} Q_i + 3\sum_{i=1}^{m} \overline{Q}'_i + \sum_{i=1}^{n} q_i = 0\ , \tag{3}$$

$$[U(1)]^3 \ : \ 6\sum_{i=1}^{j} Q_i^3 + 3\sum_{i=1}^{k} Q_i'^3 + 3\sum_{i=1}^{l} \overline{Q}_i^3 + 6\sum_{i=1}^{m} \overline{Q}_i'^3 + 2\sum_{i=1}^{n} q_i^3 + \sum_{i=1}^{p} \overline{q}_i^3 = 0. \tag{4}$$

The global Witten $SU(2)$ anomaly-free condition: $3j + 3m + n = 0 \mod 2$ (5)

The mixed anomaly-free condition:

$$[U(1)] : 6\sum_{i=1}^{j} Q_i + 3\sum_{i=1}^{k} Q'_i + 3\sum_{i=1}^{l} \overline{Q}_i + 6\sum_{i=1}^{m} \overline{Q}'_i + 2\sum_{i=1}^{n} q_i + \sum_{i=1}^{p} \overline{q}_i = 0\ . \tag{6}$$

The minimal solusions are: ☞ ***Minimality Condition with Chiral Fermions!***

CQG&R.Marshak, PRD39(1989)693

- $j = k = l = m = n = p = 0$ NO *fermions*
- $j = 1\,,\ k = 0\,,\ l = 2\,,\ m = 0\,,\ n = 1\,,\ p = 1$

(a) $Q_1 = 0\,,\ \ \bar{Q}_1 = -\bar{Q}_2\,,\ \ q_1 = \bar{q}_1 = 0$ No *electroweak forces!*

(b) $Q_1 = -\frac{q_1}{3}\,,\ \bar{Q}_1 = \frac{4q_1}{3}\,,\ \bar{Q}_2 = -\frac{2q_1}{3}\,,\ \bar{q}_1 = -2q_1$

$q_1 = -1$ in unit of e → The *standard model* with *one family*

Table 1. The quantum numbers of quark and lepton representations under $SU(3)_C \times SU(2)_L \times U(1)_Y$ and $SU(3)_C \times U(1)_{EM}$

Particles $(i = 1, 2, 3)$	$SU(3)_C$	$\times$	$SU(2)_L$	$\times$	$U(1)_Y$	$\rightarrow$	$SU(3)_C$	$\times$	$U(1)_{EM}$
$\begin{pmatrix} u \\ d \end{pmatrix}_L^i$	3		2		$\frac{1}{3}$		$\begin{pmatrix} 3 & 2/3 \\ 3 & -1/3 \end{pmatrix}$		
$u_L^{c\,i}$	$\overline{3}$		1		$-\frac{4}{3}$		$\overline{3}$		$-2/3$
$d_L^{c\,i}$	$\overline{3}$		1		$\frac{2}{3}$		$\overline{3}$		$1/3$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L^i$	1		2		-1		$\begin{pmatrix} 1 & 0 \\ 1 & -1 \end{pmatrix}$		
$e_L^{c\,i}$	1		1		2		1		1

Why the three anomaly cancellations, especially the global Witten $SU(2)$ and mixed gauge-gravitational ones, should be satisfied?

⟶ **New Physics!**

Unified Theory: G —— Triangle $\mathcal{A}$nomaly free

⬇

No global Witten $SU(2)$ and
mixed gauge-gravitational anomalies
when G breaks down $SU(3)_C \times SU(2)_L \times U(1)_Y$

It is very natural to think that the standard model comes from some form of New Physics unless the $\mathcal{A}$nomaly Cancellations are ACCIDENTS.

• Family problem

Why are there three fermion generations?

1. Family Symmetry (gauged)?

$$SU(3) \times SU(2) \times U(1) \times SU(2)$$

$$\Downarrow$$ Anomaly free + minimality

Left-right symmetric model

$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)$
3	2	1	$\frac{1}{3}$
$\bar{3}$	1	2	$-\frac{1}{3}$
1	2	1	-1
1	1	2	1

1 family: quarks & leptons

CQG,PRD39(1989)2402

$$SU(3) \times SU(2) \times U(1) \times SU(3)$$

$$\Downarrow$$ Anomaly free + minimality

Chiral-color model

P.Frampton,S.Glashow, PRL58(1987)2168

$SU(3)_L$	$SU(3)_R$	$SU(2)_L$	$U(1)$
3	1	2	$\frac{1}{3}$
1	$\bar{3}$	1	$-\frac{4}{3}$
1	$\bar{3}$	1	$\frac{2}{3}$
1	1	2	-1
1	1	1	2
$\bar{3}$	1	1	q
1	3	1	$-q$
$\bar{3}$	1	1	$-q-\frac{2}{3}$
1	3	1	$q+\frac{2}{3}$

one family of quarks and leptons

exotic fermions

2. Preon models

	$SU(N)_{MC}$	$\times$	$SU(N+4)_F$	$\times$	$U(1)_F$
F^{ia}	$\square$		$\square$		$(N+2)$
$\bar{S}_{ij}$	$\overline{\square\square}$		1		$-(N+4)$

CQG&R.Marshak, PRD35(1987)2278

In the Higgs phase: the most attractive channel (MAC)

$$F^{ia}\bar{S}_{ij} = (\square;\square,(N+2)) \times (\overline{\square\square};1,-(N+4)) \rightarrow (\bar{\square};\square,-2)$$

$$SU(N)_{MC}\times SU(N+4)_F\times U(1)_F \rightarrow \widetilde{SU}(N)_F\times SU(4)_F\times\tilde{U}(1)_F$$

$$(\begin{smallmatrix}\square\\\square\end{smallmatrix},1,2(N+4)),\ (\square,\square,N+4)$$

complementarity

In the confining phase: the t'Hooft anomaly-free conditions

	Preons	$SU(N)_{MC}$	$\times$ $SU(N)_F$	$\times$ $SU(4)_F$	$\times$ $\tilde{U}(1)_F$
$F^{ia}\rightarrow$	p_1'	$\square$	$\square$	1	$2(N+4)$
	p_1''	$\square$	1	$\square$	$N+4$
$\bar{S}_{ij}\rightarrow$	p_2	$\overline{\square\square}$	1	1	$-2(N+4)$

Composites					Indices	
$p_1'p_1''p_2$	1	$\square$	$\square$	$N+4$	l_1	$\rightarrow$ $l_1=1$
$p_1'p_1'p_2$	1	$\square\square,\begin{smallmatrix}\square\\\square\end{smallmatrix}$	1	$2(N+4)$	l_2, l_2'	$\rightarrow$ $l_2=0$, $l_2'=1$
$p_1''p_1''p_2$	1	1	$\square\square,\begin{smallmatrix}\square\\\square\end{smallmatrix}$	0	l_3, l_3'	$\rightarrow$ $l_3=l_3'=0$

For N=15, $(\begin{smallmatrix}\square\\\square\end{smallmatrix},1,38)$ and $(\square,\square,19)$ under $SU(15)_F\times SU(4)_F\times\tilde{U}(1)_F$.

Gauging the subgroup SU(5) of $SU(15)_F$:

$$\square\rightarrow\bar{5}+10\ ,$$

$$\begin{smallmatrix}\square\\\square\end{smallmatrix}\rightarrow 5+\overline{10}+\overline{45}+45$$

☞ **$N_g=3$ of chiral fermions**

$$\bar{5}+10$$

3. High-dimensional spacetime

In an extra dimensional theory, there are many types of chiral anomalies

M.Bershadsky, C.Vafa hep-th/9703167

For D spacetime dimensions:

$$\Pi_D(G)=Z_n \rightarrow c_D[N(p_{L_D})-N(p_{R_D}) = 0 \bmod n$$

where $\Pi_D(G)$ is the D-th homotopy group, similar to the Witten SU(2) global anomaly in D=4:

$\Pi_4(SU(2))=Z_2$; $N(2_{L4})-N(2_{R4})=0 \bmod 2$ $(c_4=1)$

For D=6: **Global gauge anomalies**

$$\Pi_6(SU(3))=Z_6 \quad \Pi_6(SU(2))=Z_{12} \rightarrow N(3_{L6})-N(3_{R6}) = 0 \bmod 6 \ (c_6=1) \quad N(2_{L6})-N(2_{R6}) = 0 \bmod 6 \ (c_6=2)$$

In the SM: $N(3_{L6})=N(3_{R6})$; $N(2_{L6})=4$, $N(2_{R6})=0$

B.A.Dobrescu, E.Poppitz, PRL87(2001)031801

$\rightarrow$ $N_g = 0 \bmod 3$ ☞ $N_g = 3$ (minimal value)

4. A toy model

$\mathcal{A}$-free + $\mathcal{M}$inimality: $SU(N) \times SU(2) \times U(1)$

$N = 2k$

$SU(N)$	$\times SU(2)$	$\times U(1)$
N	2	0
$\overline{N}$	1	-1
$\overline{N}$	1	1

$N = 2k + 1$

$SU(N)$	$\times SU(2)$	$\times U(1)$
N	2	$1/N$
$\overline{N}$	1	$-1/N - 1$
$\overline{N}$	1	$-1/N + 1$
1	2	-1
1	1	2

↓

$SU(N)_C$	$\times SU(2)_L$	$\times SU(2)_R$
N	2	1
$\overline{N}$	1	2

N=12 →

$SU(12)_C$	$\times SU(2)_L$	$\times SU(2)_R$
12	2	1
$\overline{12}$	1	2

CQG,hep-ph/0101329

$$\downarrow$$
$$SU(12)_C \times SU(2)_L \times SU(2)_R$$
$$\downarrow$$
$$SU(8)_C \times SU(4)_{C1} \times SU(2)_L \times SU(2)_R \times U(1)$$
$$\downarrow$$
$$SU(4)_{C3} \times SU(4)_{C2} \times SU(4)_{C1} \times SU(2)_L \times SU(2)_R \times U(1) \times U(1)$$
$$\downarrow$$
$$\downarrow$$
$$SU(4)_C \times SU(2)_L \times SU(2)_R$$
$$\downarrow$$
$$\downarrow$$
$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

three quark and lepton families

with right-handed neutrinos

A note on the color number: N_c

Particles $(i=1,2,3)$	$SU(N)_C \times SU(2)_L \times U(1)_Y$			$\rightarrow$	$SU(N)_C \times U(1)_{EM}$	
$\begin{pmatrix} u \\ d \end{pmatrix}_L^i$	N	2	$\frac{1}{N}$		$\begin{pmatrix} N \\ N \end{pmatrix}$	$\begin{pmatrix} \frac{N+1}{2N} \\ -\frac{N-1}{2N} \end{pmatrix}$
$u_L^{c\,i}$	$\overline{N}$	1	$-\frac{N+1}{N}$		$\overline{N}$	$-\frac{N+1}{2N}$
$d_L^{c\,i}$	$\overline{N}$	1	$\frac{N-1}{N}$		$\overline{N}$	$\frac{N-1}{2N}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L^i$	1	2	-1		$\begin{pmatrix} 1 \\ 1 \end{pmatrix}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
$e_L^{c\,i}$	1	1	2		1	1

← $Q_u = e(N+1)/(2N)$

← $Q_d = -e(N-1)/(2N)$

C.Chow, T.M.Yan, PRD53, 5105(1996); R.Shrock, PRD53, 6465(1996)

V.A.Kovalchuk, JETP Lett. 48 (1988) 11

R.Marshak, "Conceptual foundations of modern particle physics," Singapore, WS (1993)

For $\pi^0 \rightarrow \gamma\gamma$, the decay width:

$$\Gamma_{\pi^0 \rightarrow \gamma\gamma} \propto N(Q_u^2 - Q_d^2) \xrightarrow{Q_u^2 - Q_d^2 = e^2/N} e^2$$

☞ independent on the color number N!

The result is true for any anomalous process.

BUT: $R \equiv \sigma(e^+e^- \rightarrow \text{hadron})/\sigma(e^+e^- \rightarrow \mu^+\mu^-) = N\, \Sigma Q_u^2 \propto N$ ☞ dependent on the color number N!

5. A geometrical origin

One starts with a theory in $d > 4$ dimensions but then assumes that the extra dimensions somehow compactify, leaving a 4-dimensional theory.

The d = 10 heterotic superstring

This string theory has an associated $E_8 \times E_8$ gauge symmetry and is supersymmetric. The chiral fermions in the $d = 10$ theory are gauginos of one of the E_8 groups (the other E_8 acts as a hidden sector), sitting in the 248 dimensional adjoint representation.

A. Candelas, G. Horowitz, A. Strominger, and E. Witten, Nucl. Phys. B258, 46 (1985).

D. Gross, J. Harvey, E. Martinec, and R. Rohm, Nucl. Phys. B255, 257 (1985); B267, 75 (1986).

The 10-dimensional space of the theory compactifies down to $d = 4$ Minkowski space times a 6-dimensional Calabi-Yau space.

$$E_8 \longrightarrow E_6 \times SU(3)$$

$$248 = (78,1) \oplus (27,3) \oplus (\bar{27},\bar{3}) + (1,8)$$

After Calabi-Yau compactification, the 4-dimensional chiral matter E_6.

The 27-dimensional representation of E_6 when decomposed in terms of its SO(10) subgroup contains the 16-dimensional representation, appropriate for a family of quarks and leptons, plus a 10 and a singlet.

6. LEP experiments

ALEPH, DELPHI, L3, and OPAL

The invisible width Γ_{inv} is assumed to be due to N_ν light neutrino species each contributing the neutrino partial width Γ_ν as given by the Standard Model.

$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\rm SM}$$

☞ $N_\nu = 3.00 \pm 0.08$

Other experiments supporting 3 families

LHC: Higgs mass

Planck: Active neutrino number

7. CP violation in the SM

M. Kobayahsi and K. Maskawa, "CP Violation in the Renormalizable Theory of Weak Interactions", Progr. Theor. Phys. **49** (1973) 652.

→ observable or physical phases : $\frac{n(n+1)}{2} - (2n-1) = \frac{(n-1)(n-2)}{2}$

For two generations $(n=2)$ → no phase + 1 angle

For three generations $(n=3)$ → one phase + 3 angles

☞ 三代夸克之存在 CP對稱性破缺

Nobel Physics Prize 2008

Broken Symmetry

破缺的對稱性

「發現對稱破缺的起源，預測自然界存在三代夸克」

"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: SCANPIX

Yoichiro Nambu

Photo: Kyodo/Reuters

Makoto Kobayashi

Photo: Kyoto University

Toshihide Maskawa

- Broken symmetry and mass generation

什麼是對稱性？ "symmetry"一词是一个十六世纪的拉丁词语，由希腊语"syn-"（一起）和"metron"（度量）派生而来的.

世界的結構的美是多方面的，所以對於這個美的感受也是多方面的，比如說我看電視有時候有一個老鷹栽倒水裡頭抓一個魚，它的速度，準確，是妙不可言的。所以中國的詩人，西方的詩人，在描寫這個老鷹能夠準確地來抓一個小動物，就有很多有名的詩句，這個是一種美

—— 楊振寧

對稱性是一種觀念，這種觀念在幾千年來一直引導人類理解和創造世界上各種事物之規律，美妙，及完善。

Hermann Weyl (in his book "Symmetry")

"I heave the basketball; I know it sails in a parabola, exhibiting perfect *symmetry*, which is interrupted by the basket. Its funny, but it is always interrupted by the basket." *Michael Jordan (former Chicago Bull)*

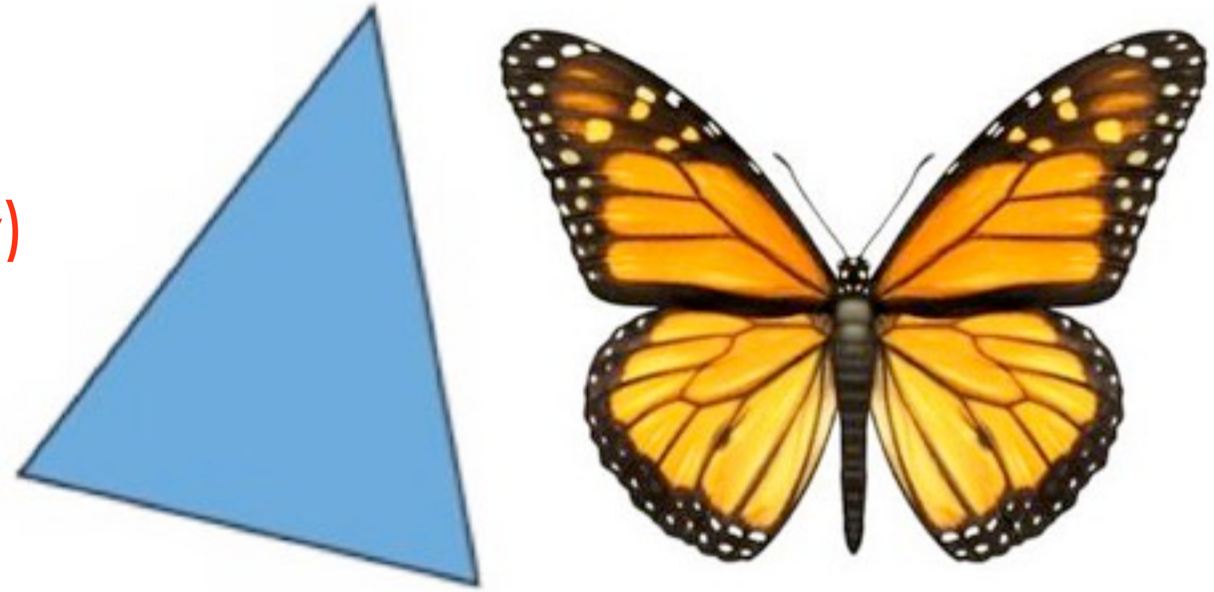
Noether's Theorem

Symmetries ⟷ Conservation Laws

Symmetry Transformation	Conserved Charge
time translation $t \to t + a$	Energy
space translation $\vec{x} \to \vec{x} + \vec{b}$	Momentum
rotation	Angular momentum
...	...

反射类(Reflective)

镜面对称(mirror symmetry)



旋转类(Rotational)

平移类(Translational)


台北市音樂季
TAIPEI CITY GOVERNMENT
National Concert Hall
National Theatre
Cultural Activity Center of Taipei

中國文學：

舉頭望明月

低頭思故鄉

英文：*palindromes* 回文

"Madam, I'm Adam"

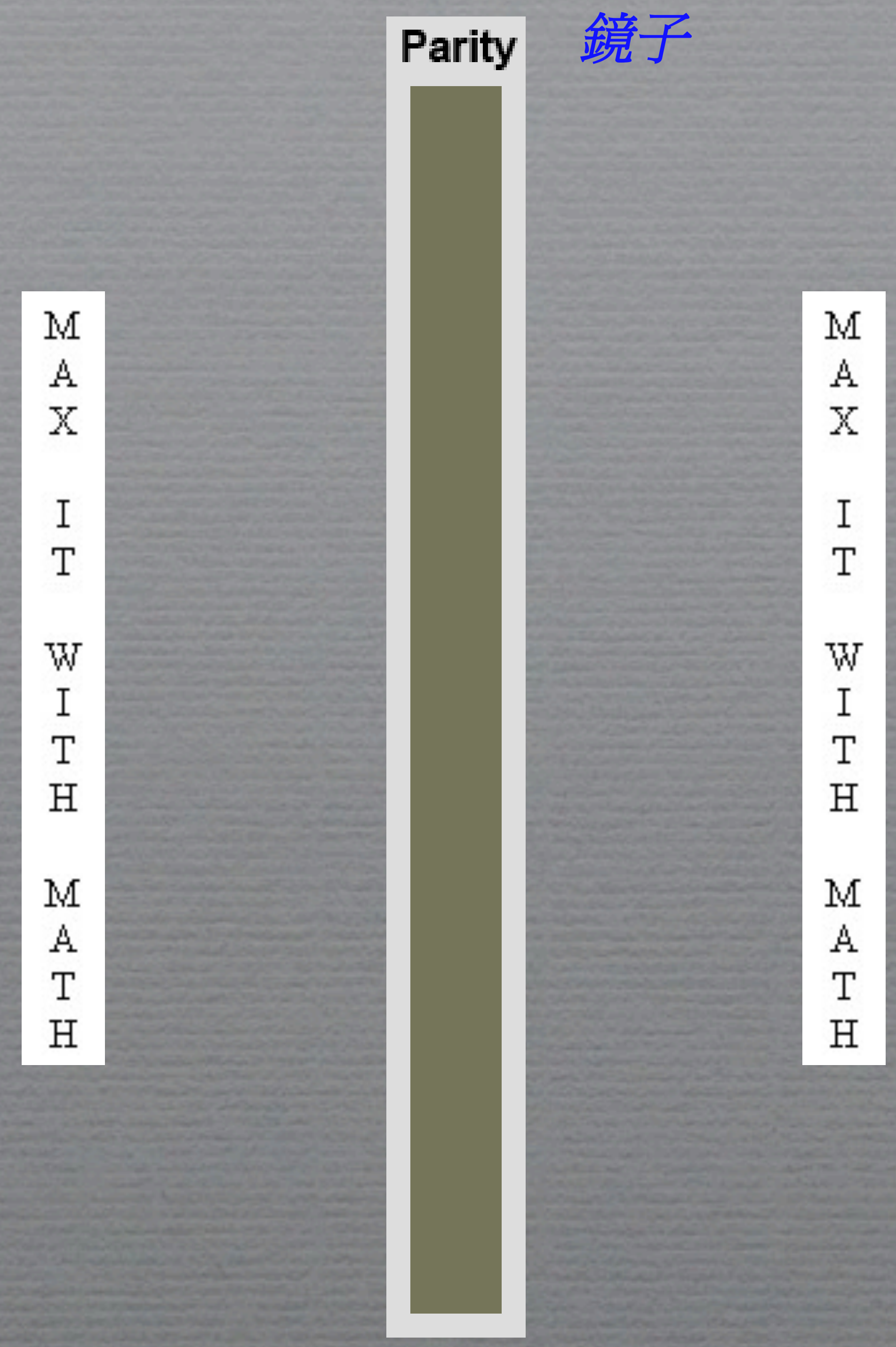
生物：基因 ***the male-defining Y*** – 染色體

About 6 million (out of 50 million) of the Y's DNA letters from palindromic sequences.

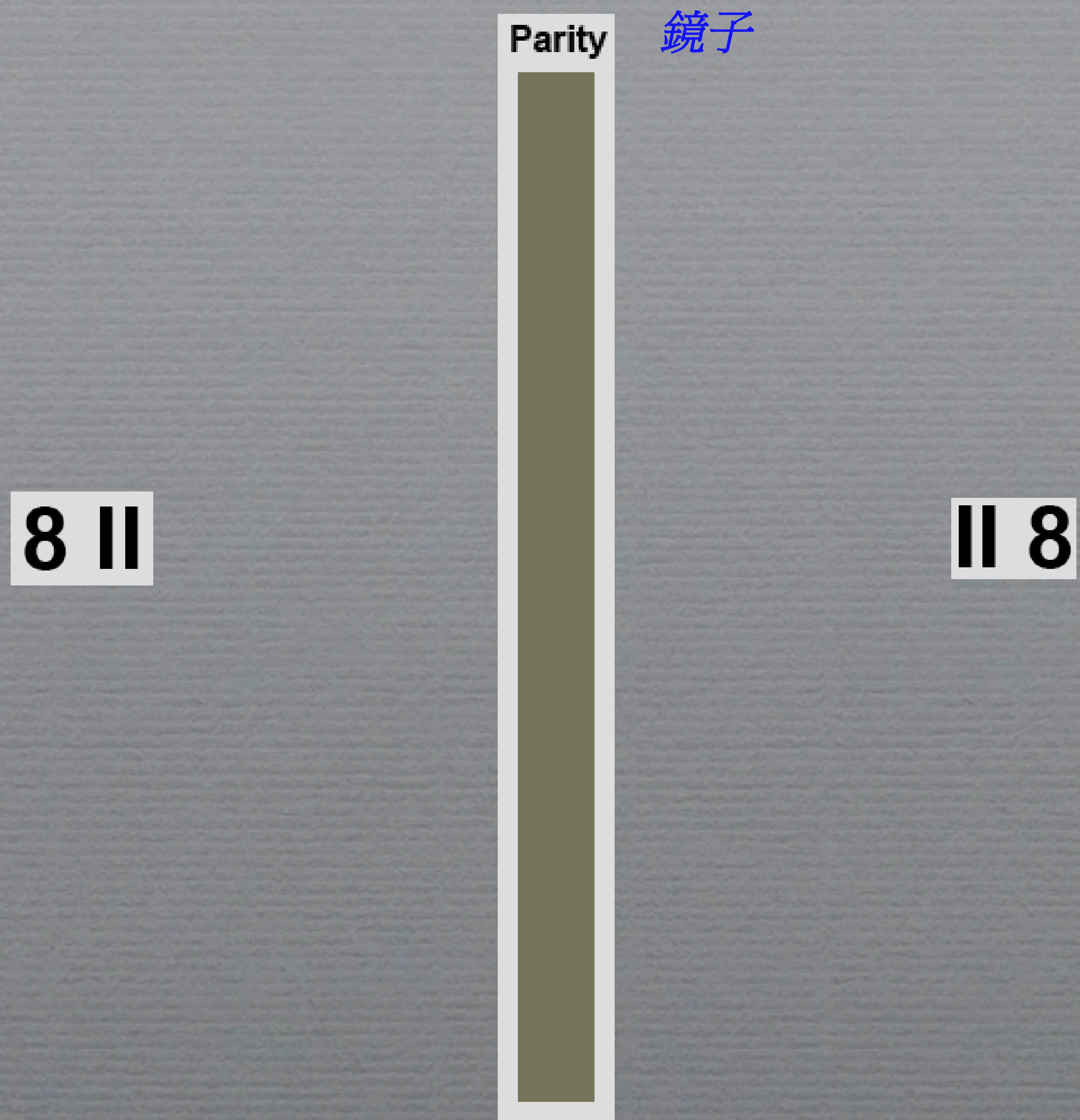
Does this look right to you?

A disconcerting experience for even the harshest critic.

對稱一定會美嗎？



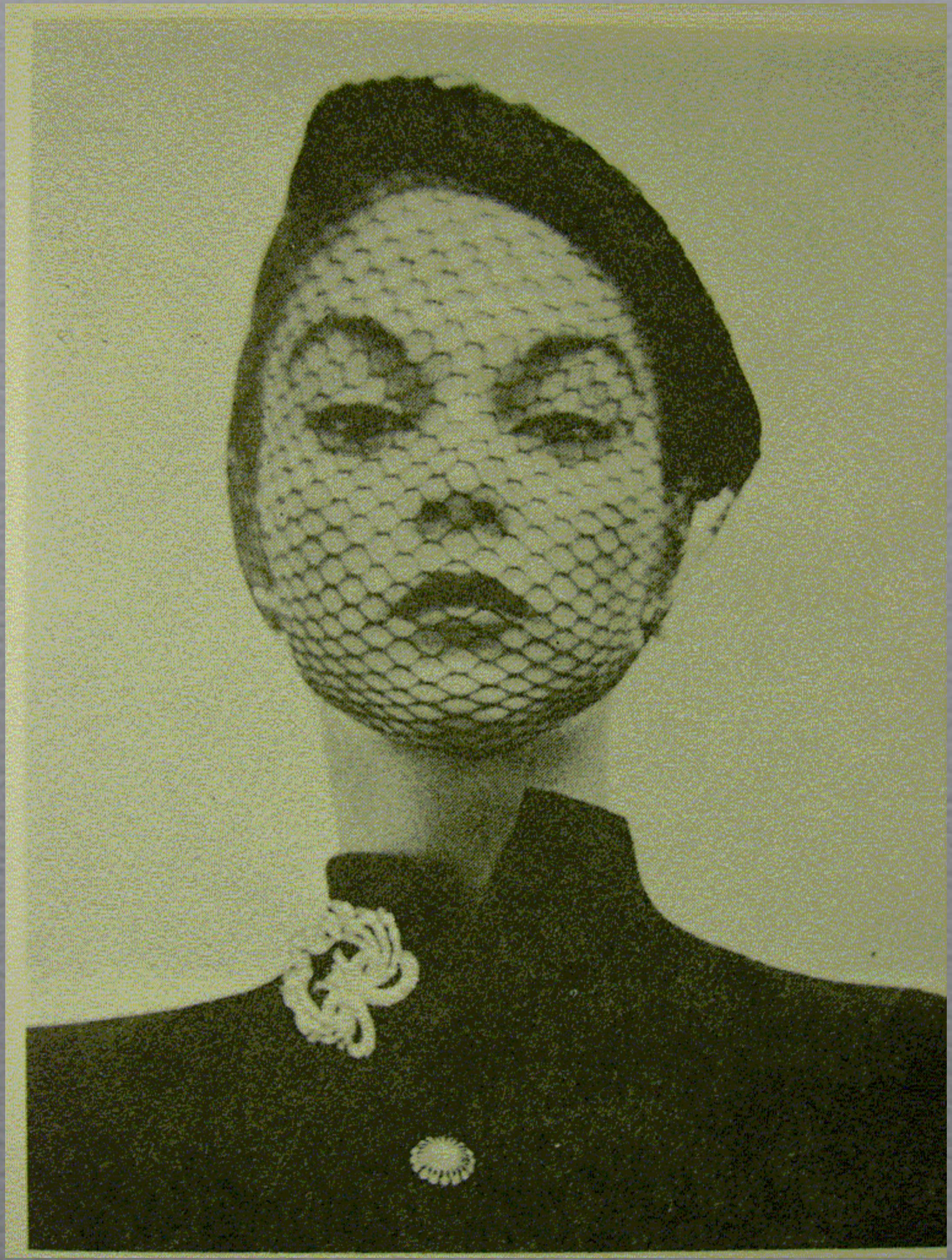
對稱一定會美嗎？

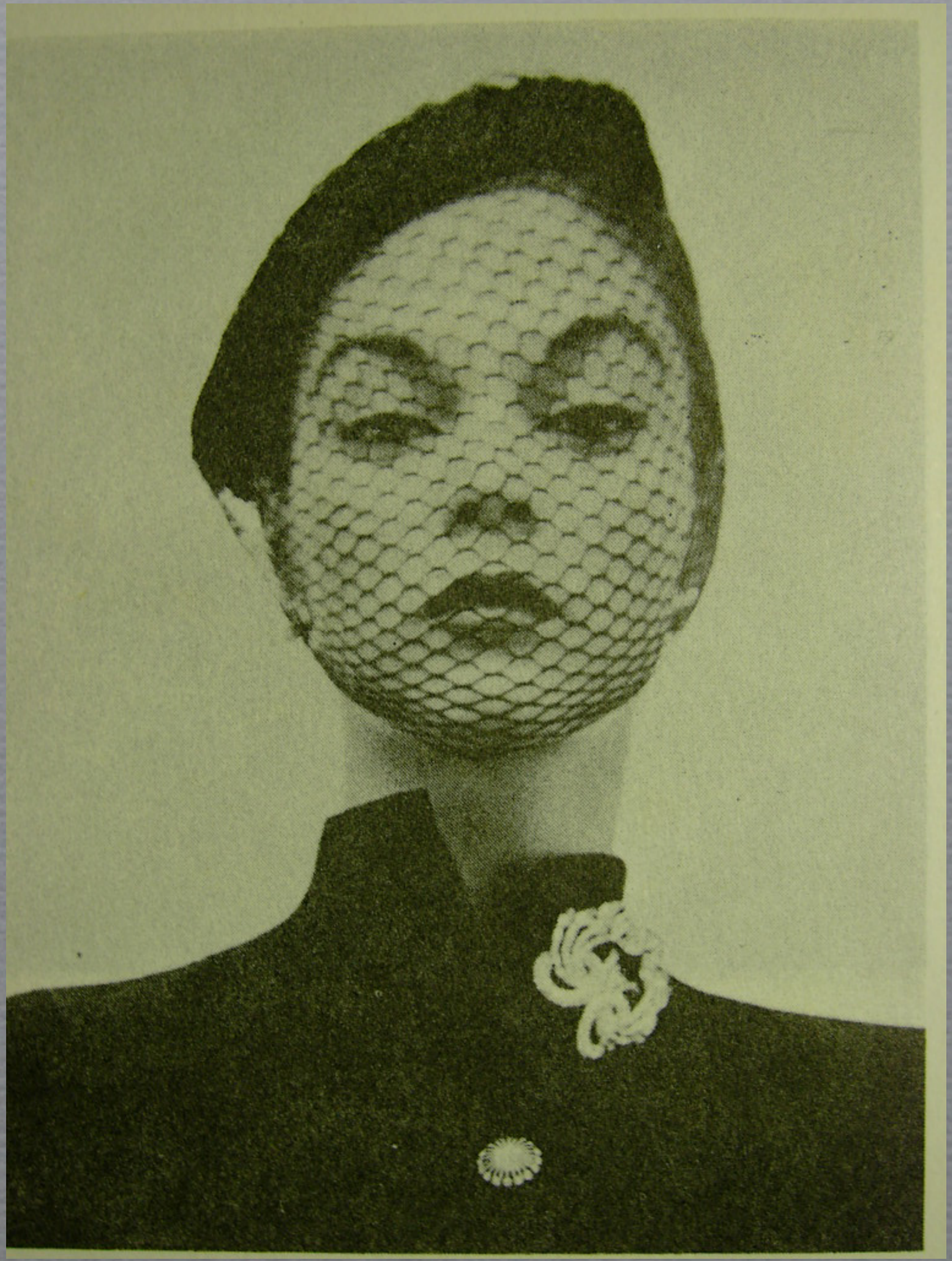


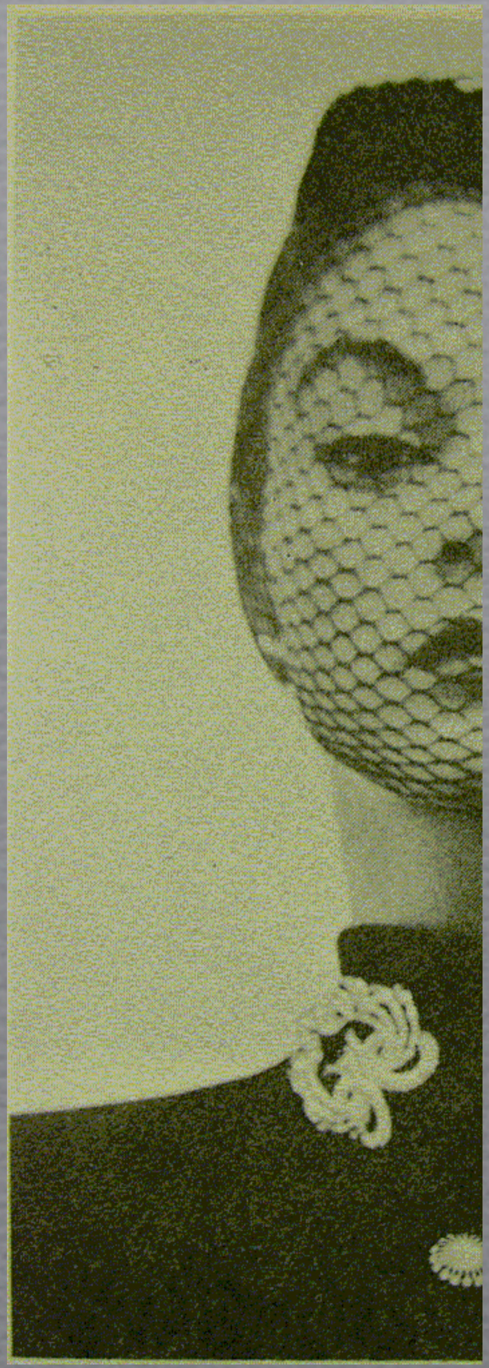
美： *Maximally violated?*　　答案？

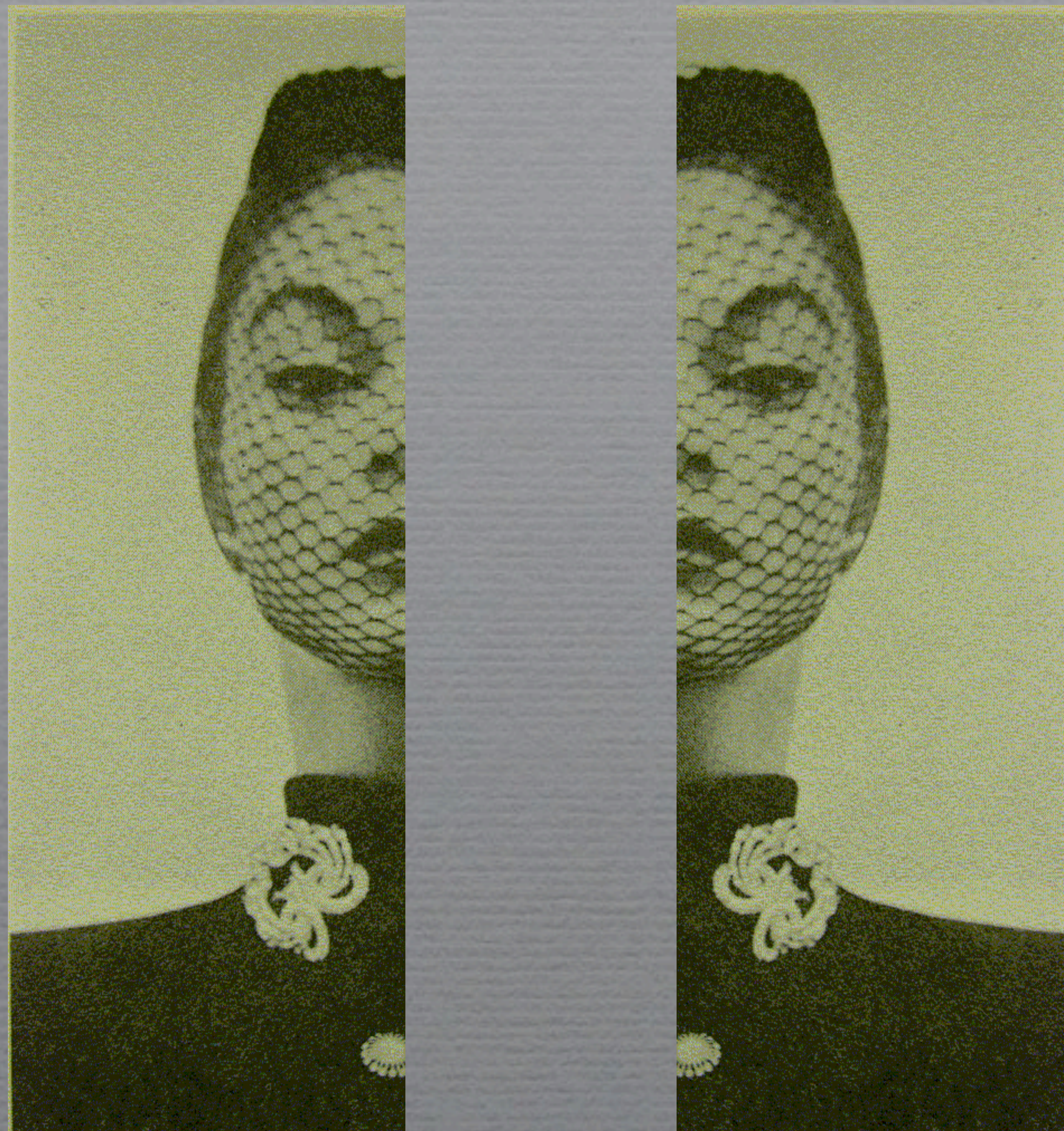
or preserved?

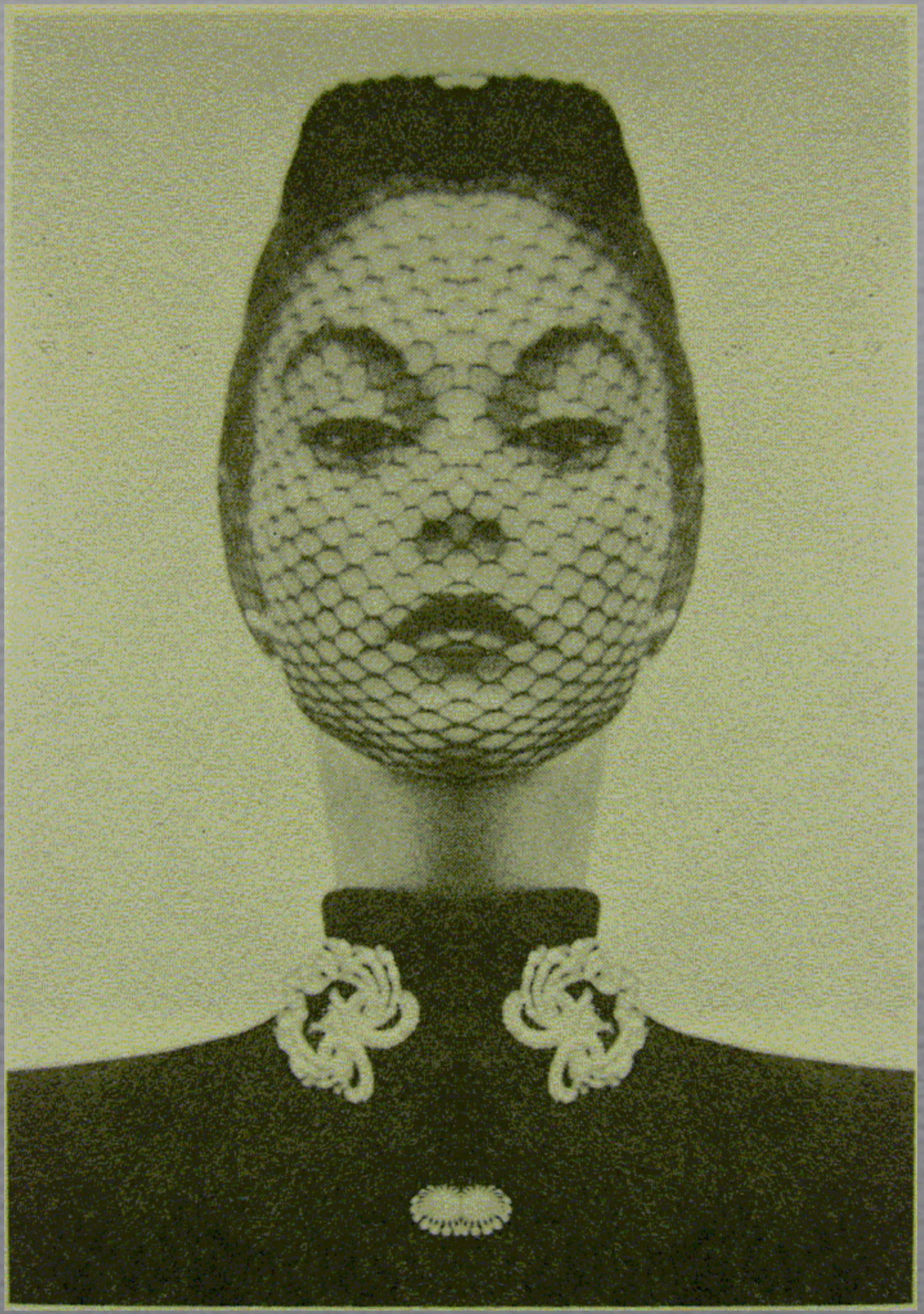
左 ↔ 右











完全左右對稱

美麗嗎？

王菲

NO.156
2000年10月28日~11月03日
每套100元
精采生活
八卦糾紛特集
李靖打官
明星跑法院高人
演唱會
主辦單位要
全裸

對稱的王菲

張柏芝

張柏芝＝林青霞＋張曼玉

對稱的張柏芝

還美麗嗎？

對稱性 → 不可區分性

對稱性破壞 → 可區分性

- 兩大問題? → 機會

I. 手征規范對稱性之破缺 ← 連續對稱性

The Higgs Particle ← LHC大強子對撞機

II.宇宙物質與反物質之不對稱性

為什麼普通物質是由物質構成？

物質

反物質

分立對稱性

1. Baryon number violation
2. C and CP violation
3. A departure from thermal equilibrium

1967: Sakharov (the Nobel Peace Prize 1975)

連續對稱性之破缺：

Symmetry lies hidden under spontaneous violations

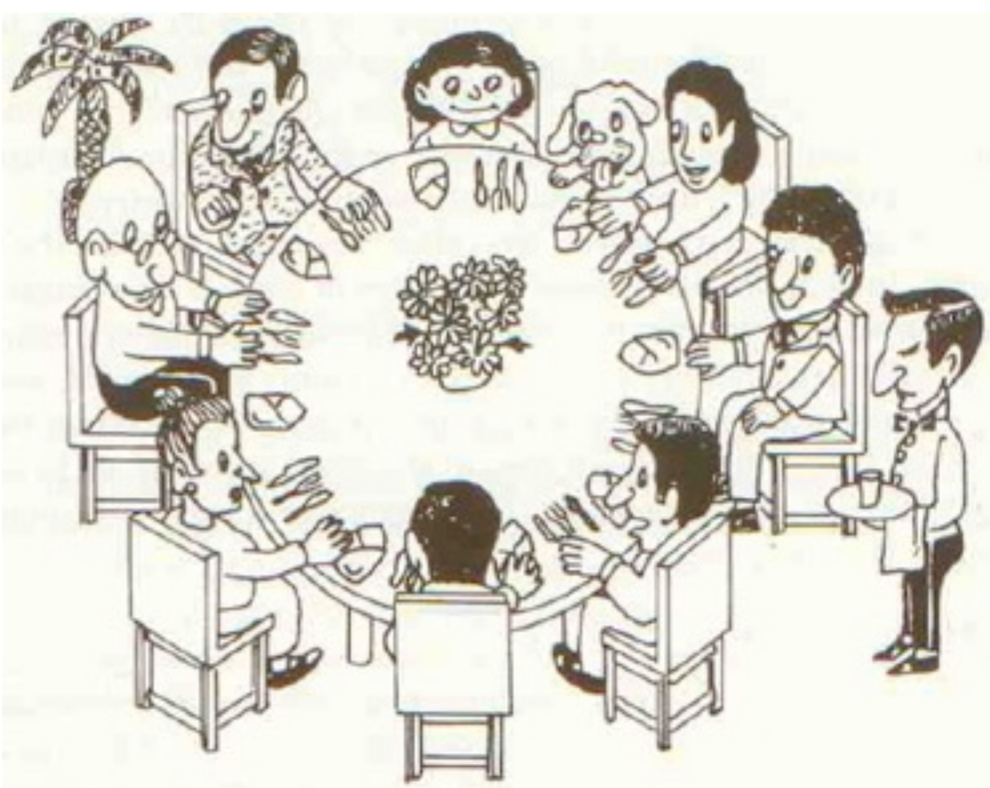
Pencil balanced on end has rotational symmetry about vertical axis.

Symmetry is broken when pencil falls over.

自發對稱性破缺

Special direction is specified.

But, underlying law of gravity is still symmetrical.



Spontaneous symmetry breaking — Salam's analogy.

From ``Quarks'', by Y. Nambu 1981 (Japanese); 1985(English)

In the 1960s, Yoichio Nambu pioneered a radical idea:

the symmetry of a beautiful theory could be subtly broken.

Nambu **showed that even if a theory appears symmetrical, it could actually be unstable if a lower energy state exists in which that symmetry is broken. Perhaps, he said, our infant universe was originally symmetrical but was also unstable. Suddenly, this symmetry broke, and the universe burst into a lower energy state,unleashing a tidal wave of energy.This could be the origin of the Big Bang.**

Nambu was the first to introduce spontaneous symmetry violation into elementary particle physics.

Y. Nambu, "A 'Superconductor' Model of Elementary Particles and its Consequencies", Talk given at a conference at Purdue (1960), reprinted in "Broken Symmetries, Selected Papers by Y. Nambu", ed:s T. Eguchi and K. Nishijima, World Scientific (1995).

Y. Nambu and G. Jona-Lasinio, "A Dynamical Model of Elementary Particles based on an Analogy with Superconductivity I", Phys. Rev. **122** (1961) 345;
Y. Nambu and G. Jona-Lasinio, "A Dynamical Model of Elementary Particles based on an Analogy with Superconductivity II", Phys. Rev. **124** (1961) 246;

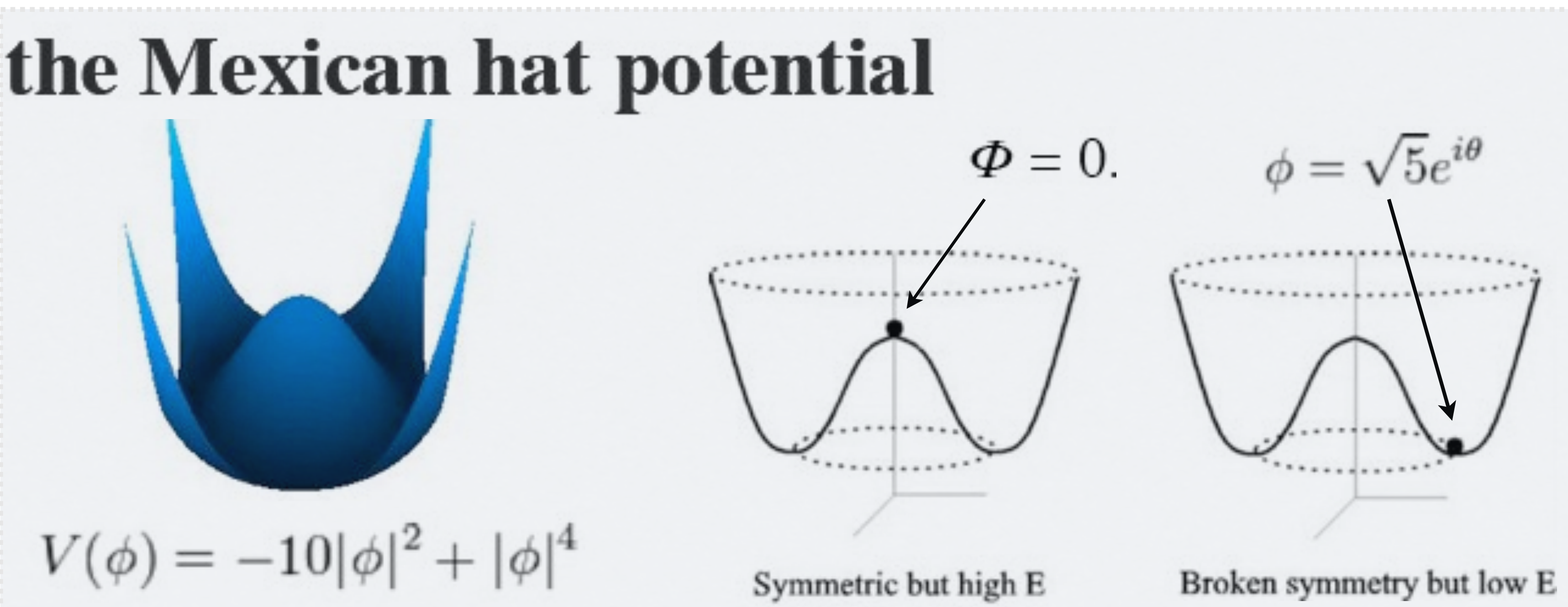
The action for a meson field ϕ interacting with a Dirac fermion field ψ is

$$S[\phi,\psi] = \int d^dx\ [\mathcal{L}_{\text{meson}}(\phi) + \mathcal{L}_{\text{Dirac}}(\psi) + \mathcal{L}_{\text{Yukawa}}(\phi,\psi)]$$

$$= \int d^dx \left[\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) + \bar{\psi}(i\partial\!\!\!/ - m)\psi - g\bar{\psi}\phi\psi\right]$$

For a (renormalizable) self-interacting field: $V(\phi) = \mu^2\phi^2 + \lambda\phi^4$

Lagrangian exhibits spontaneous symmetry breaking (SSB) when $\mu^2<0$



Minimum $V(\Phi)$

- $\Phi=0$ → symmetric, no broken symmetry
- $\Phi=\Phi_0=(-\mu^2/2\lambda)^{1/2}$ → broken symmetry, SSB

In the Standard Model, Φ_0 is responsible for the fermion masses: $g\phi_0\bar{\psi}\psi$

$\tilde{\phi} = \phi - \phi_0$ ***is known as the Higgs field.***

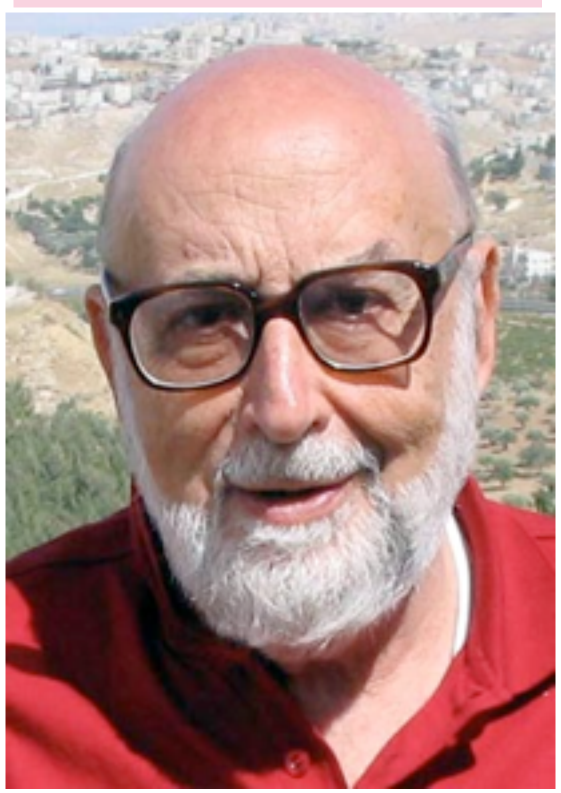
The Nobel Prize in Physics 2013

發現一個理論機制（希格斯機制）：

亞原子粒子質量起源 | 預測希格斯玻色子

"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"

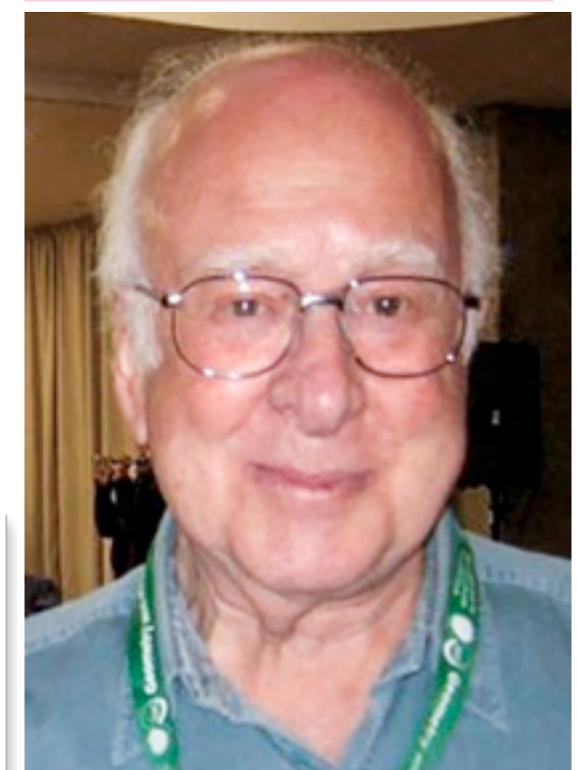
François Englert



Born: November 6, 1932
Etterbeek, Belgium

Prize amount:
SEK 8 million
(1USD=6.5SEK;
1SEK=0.94RMB)

Peter W. Higgs



Born: May 29, 1929
Newcastle upon Tyne, United Kingdom

The Nobel Prize in Physics 2013

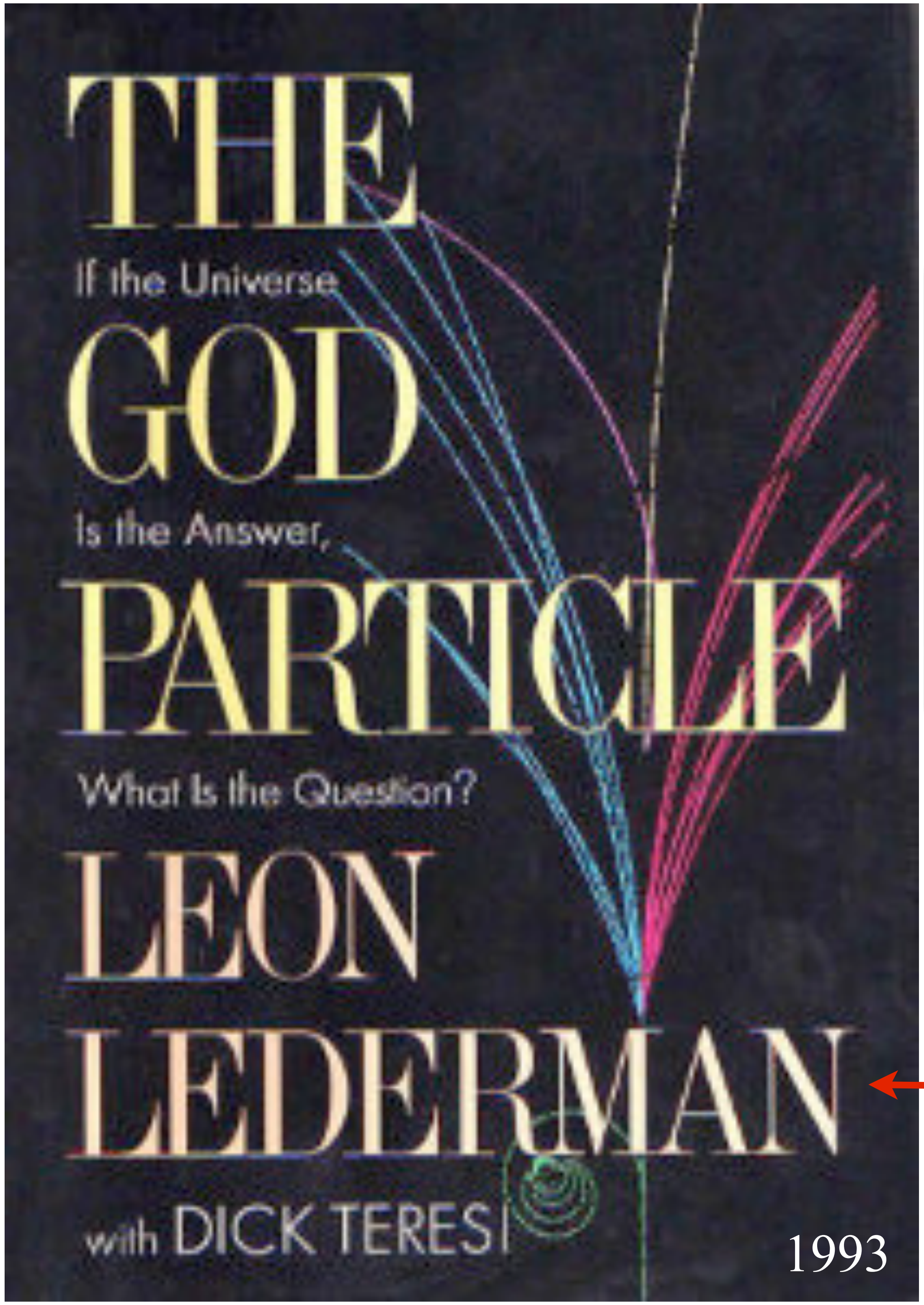
發現一個理論機制（希格斯機制）：

亞原子粒子質量起源 | 預測希格斯玻色子

"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"

July 4, 2012

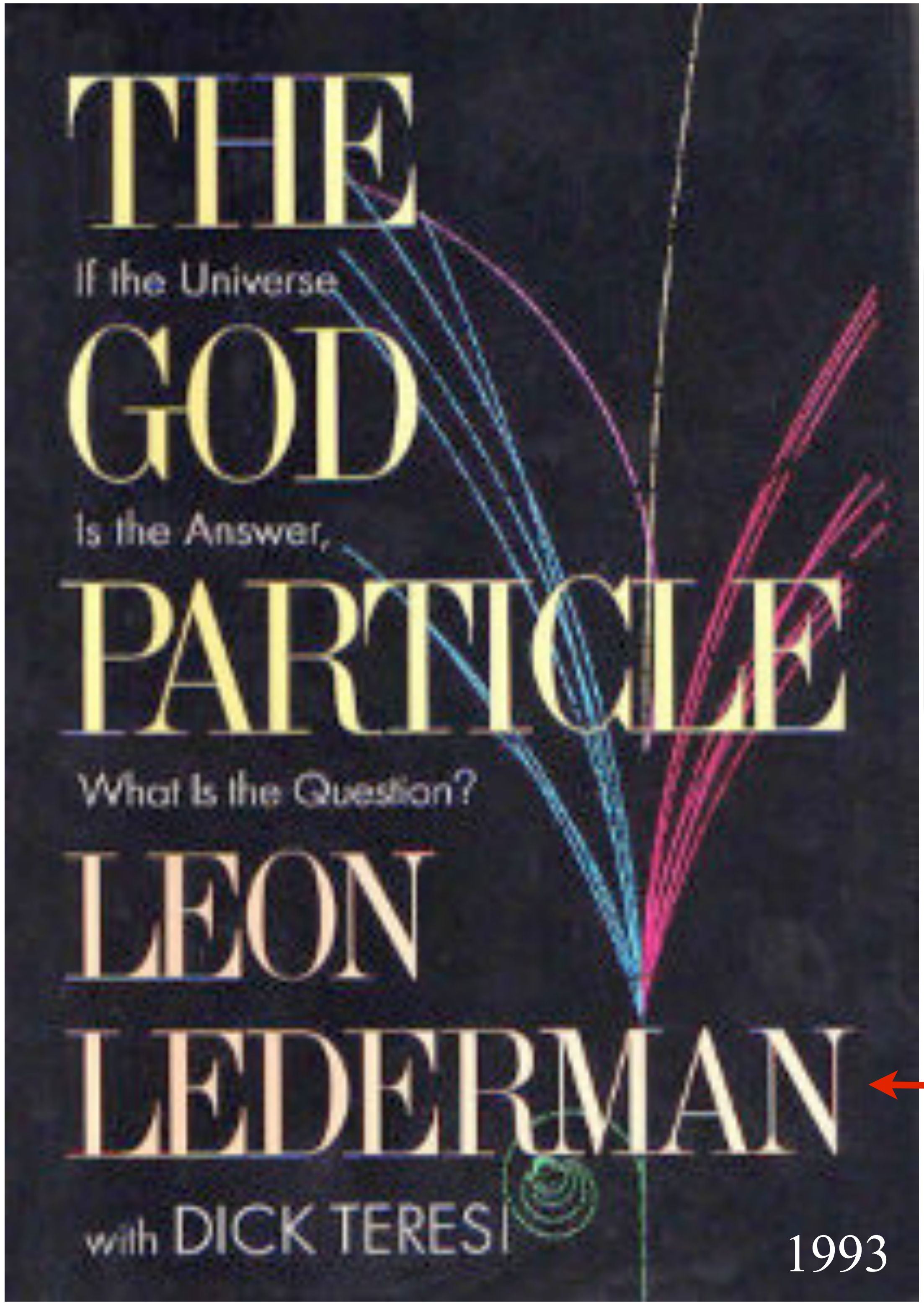
The God Particle: Higgs Boson
上帝粒子：希格斯玻色子



如果宇宙
是答案，
它的問題是什麼？

1988年Nobel
物理學獎

The *Goddamn* Particle: Higgs Boson
上帝詛咒的粒子：希格斯玻色子

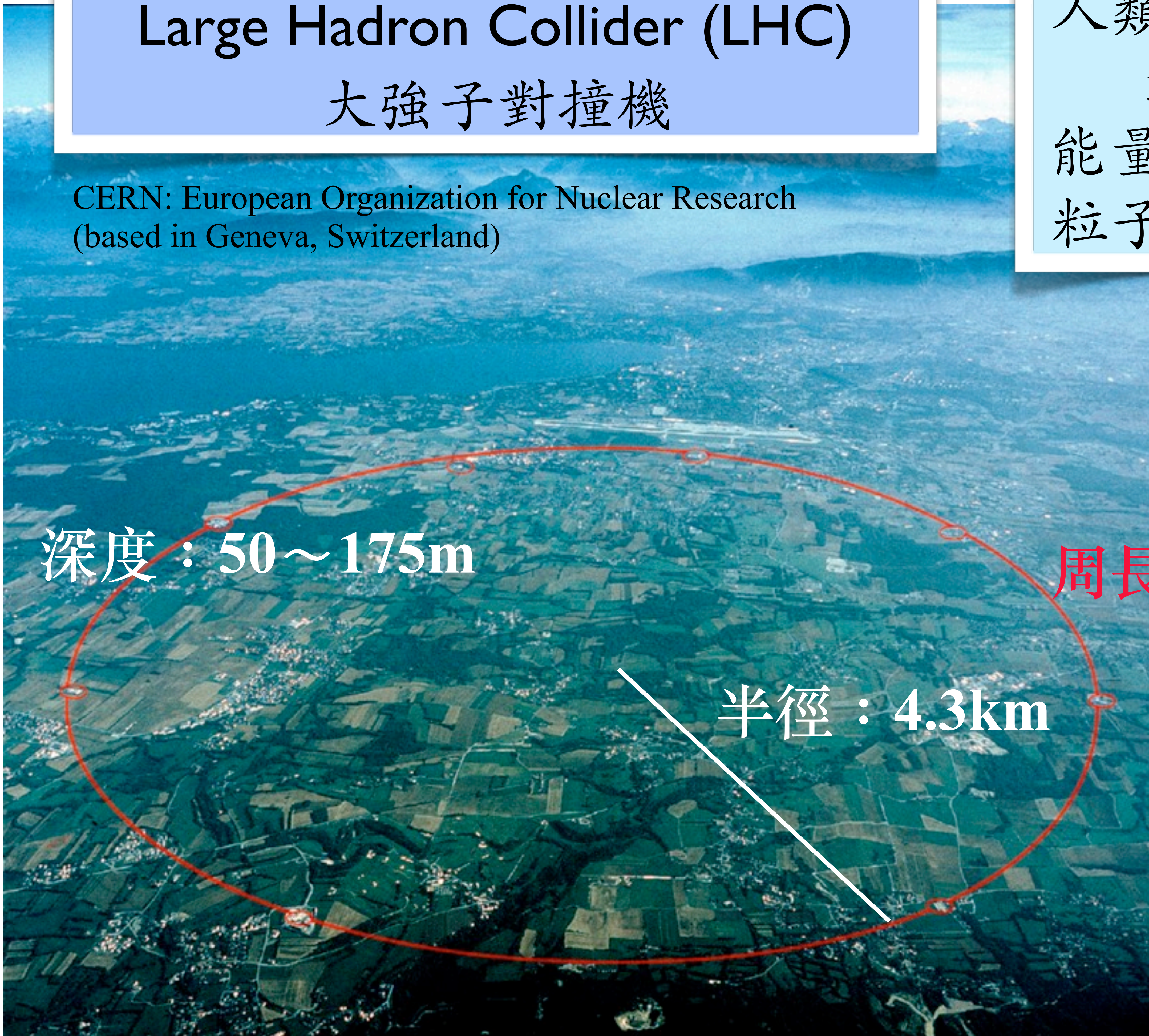


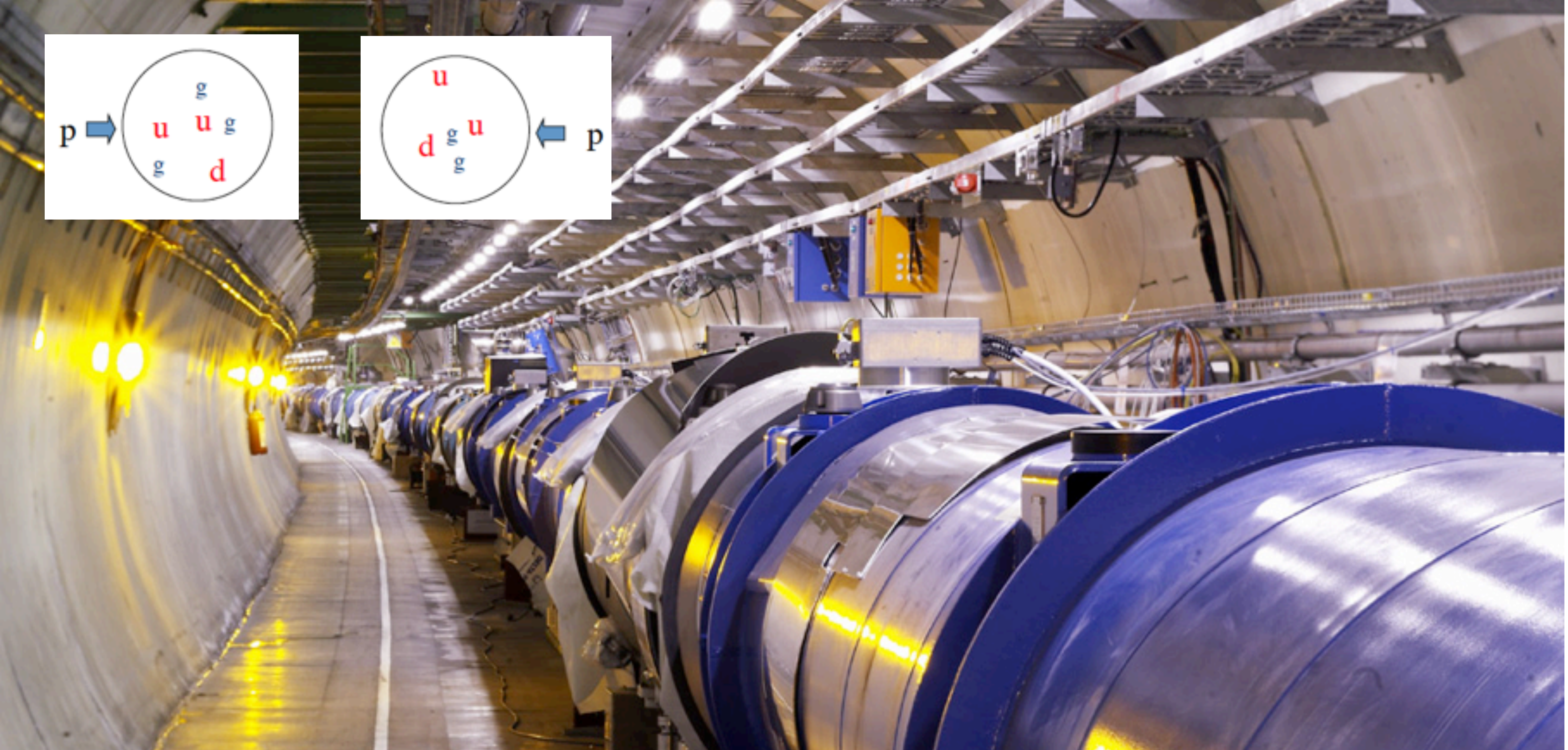
如果宇宙
是答案，
它的問題是什麼？

1988年Nobel
物理學獎

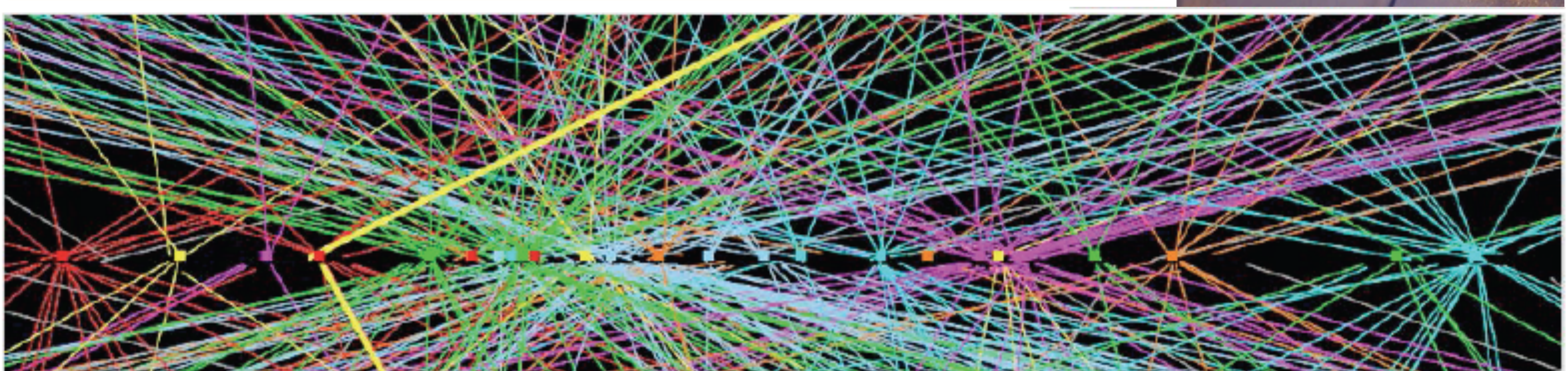
Large Hadron Collider (LHC)
大強子對撞機

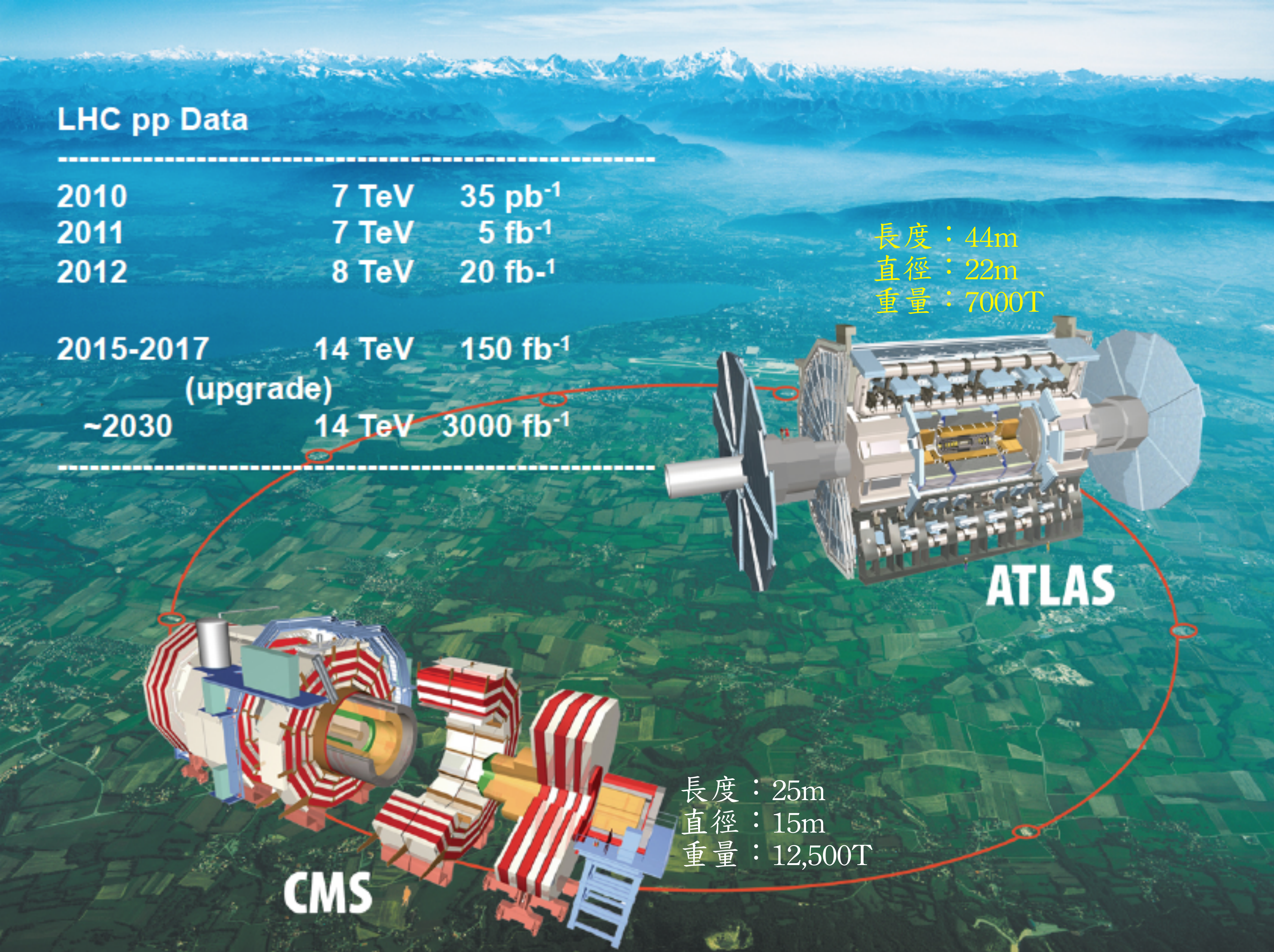
人類歷史上
最大
能量最高的
粒子加速器





幾倍的**10^{12}** 質子，每個質子以 **v=0.99999999c**的速度運動
每秒鐘旋繞27公里的LHC環（1.9K，真空～10^{-13}atm）**11000** 次
~10^9 碰撞/秒



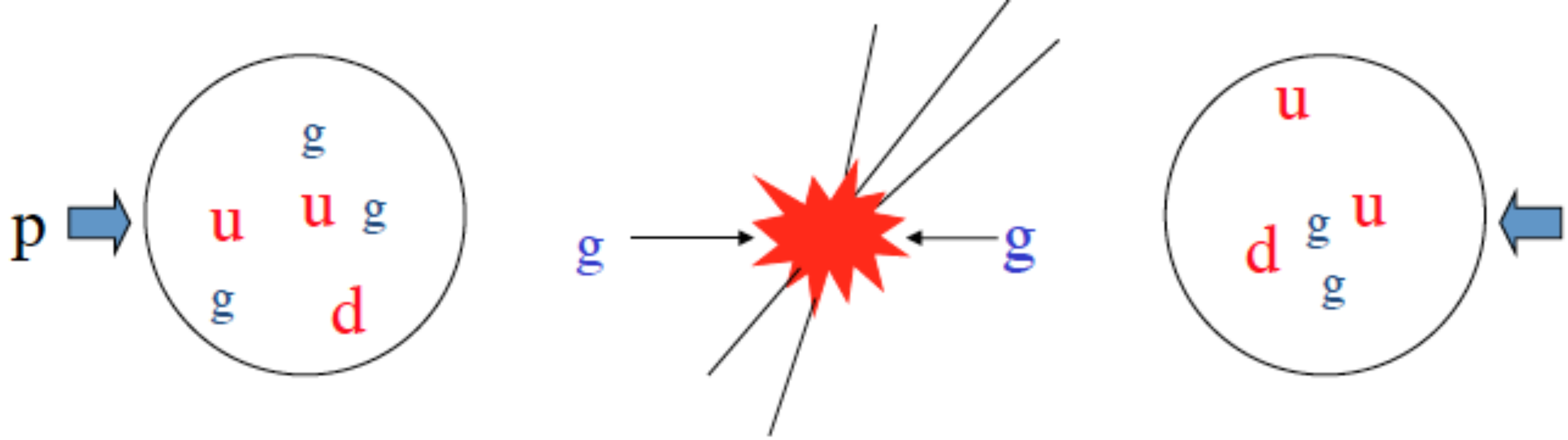

LHC pp Data
2010 7 TeV 35 pb-1
2011 7 TeV 5 fb-1
2012 8 TeV 20 fb-1
2015-2017 14 TeV 150 fb-1
(upgrade)
~2030 14 TeV 3000 fb-1
長度：44m
直徑：22m
重量：7000T
ATLAS
CMS
長度：25m
直徑：15m
重量：12,500T

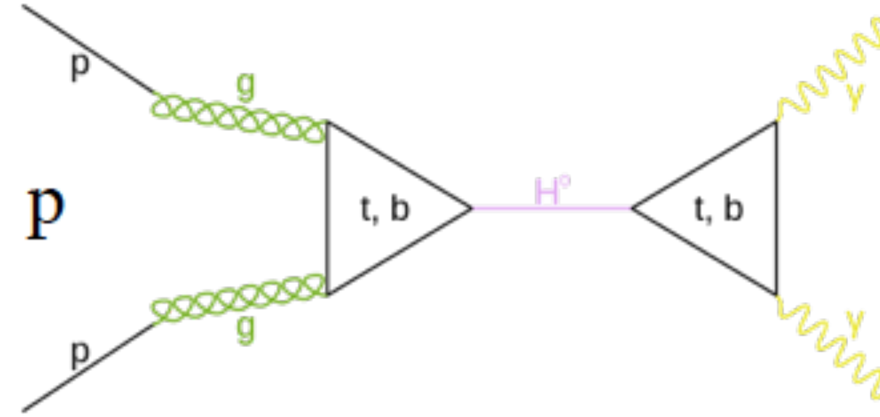
CMS Collaboration: 1740 Ph.D.s + 1535 students (845 for Ph.D.) + 790 engineers from 179 institutes in 41 countries.

ATLAS collaboration: 3000 signing authors (including 1000 students) from 174 institutes in 38 countries

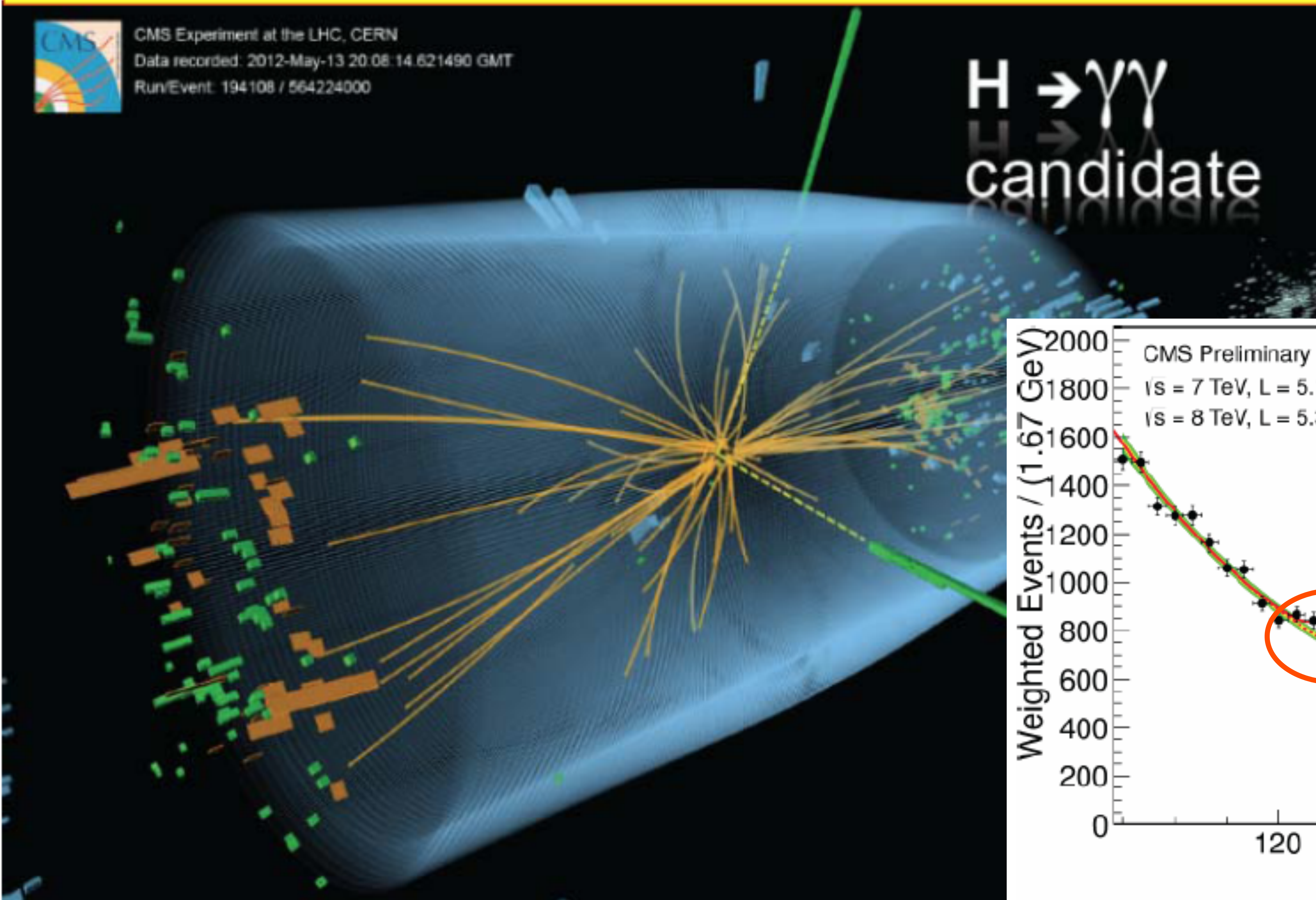
CMS Collaboration: 1740 Ph.D.s + 1535 students (845 for Ph.D.) + 790 engineers from 179 institutes in 41 countries.

ATLAS collaboration: 3000 signing authors (including 1000 students) from 174 institutes in 38 countries

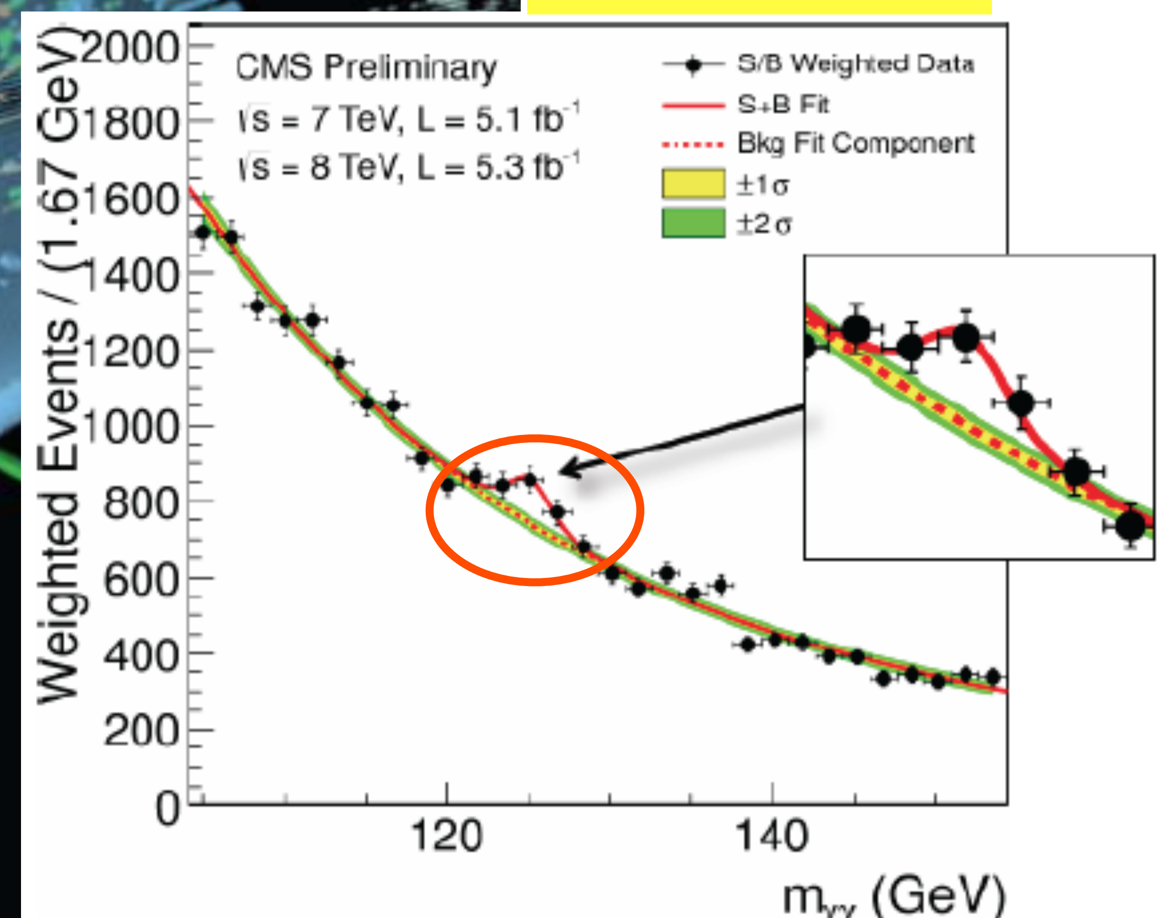




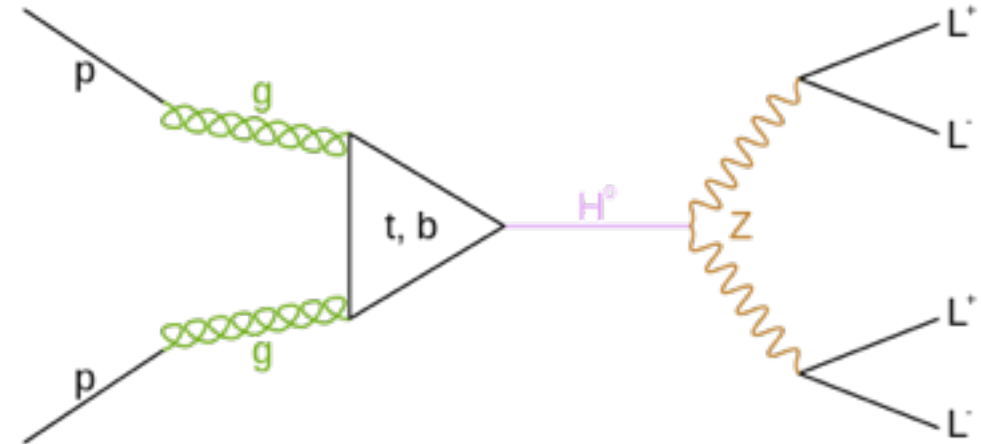
Reconstructed $p\,p \rightarrow H \rightarrow \gamma\,\gamma$ **event in CMS detector**



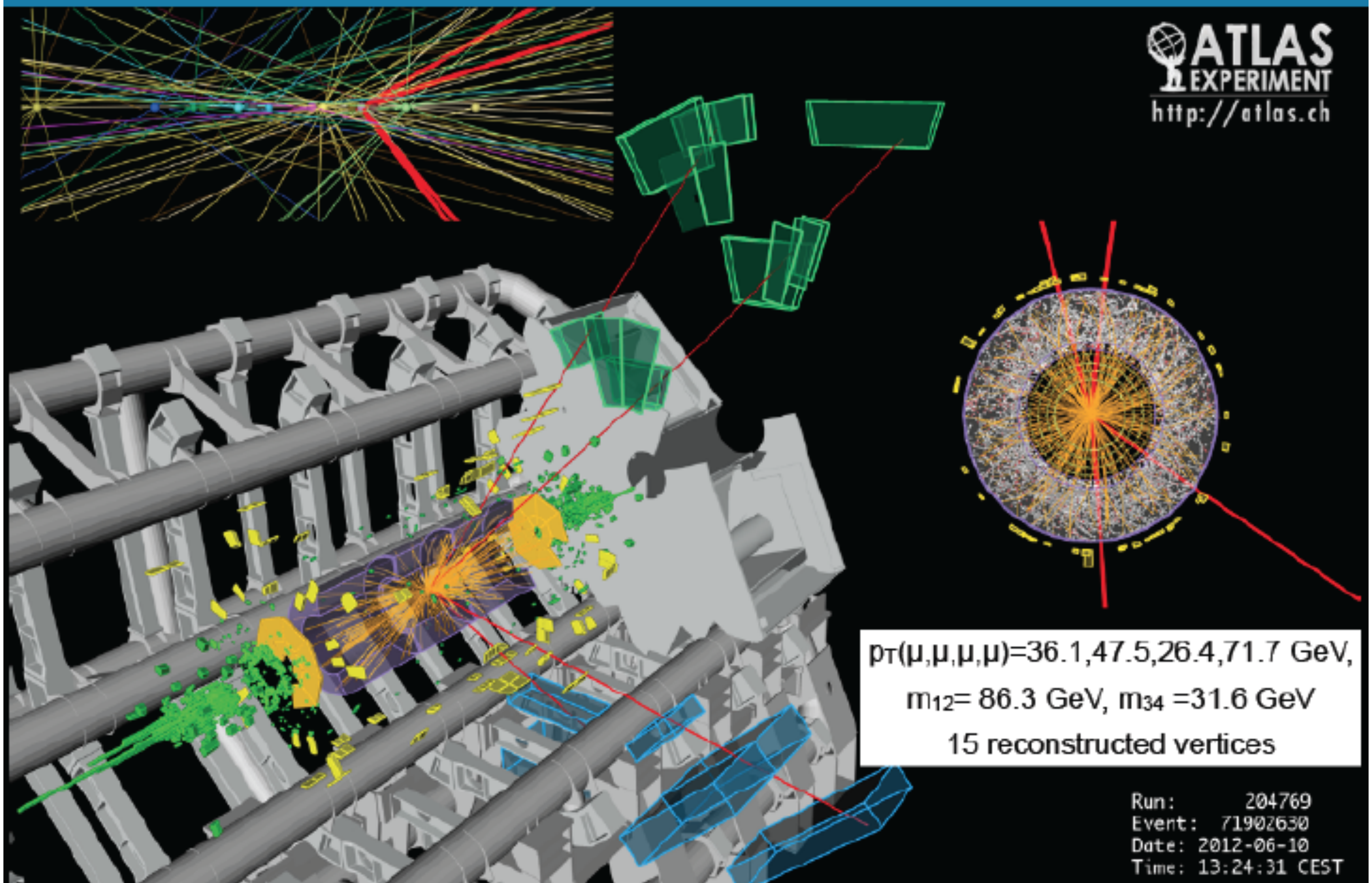
m_H=126 GeV



$H \rightarrow ZZ^{(*)} \rightarrow 4l\ (e/\mu)$



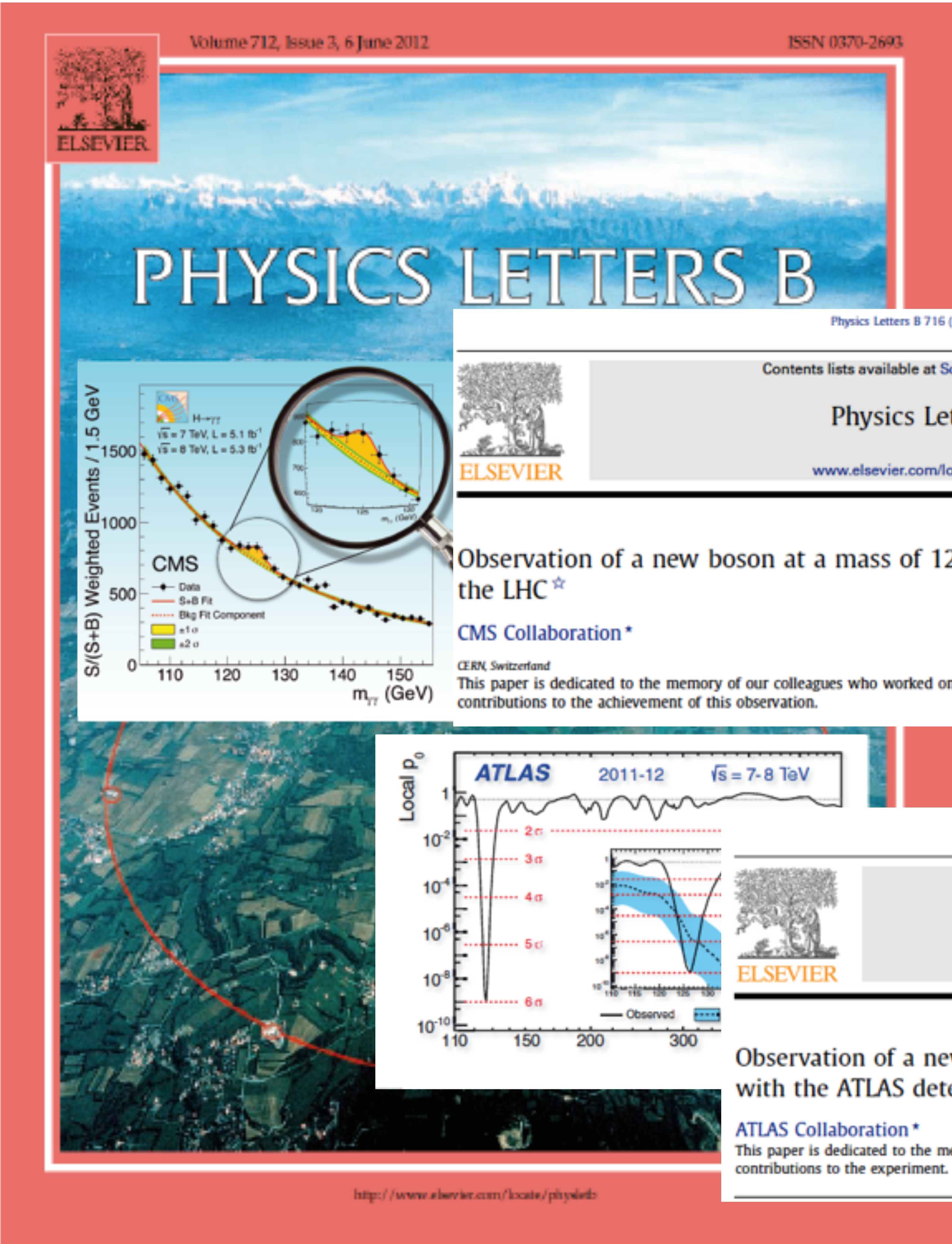
μμμμ candidate with m_{4l} = 125.1 GeV



Higgs Boson has been found at the LHC

m_H=126 GeV
lifetime=1.56x10^{-22}s

Peter Higgs in the LHC tunnel in 2012



Physics Letters B 716 (2012) 30–61

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

Physics Letters B 716 (2012) 1–29

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

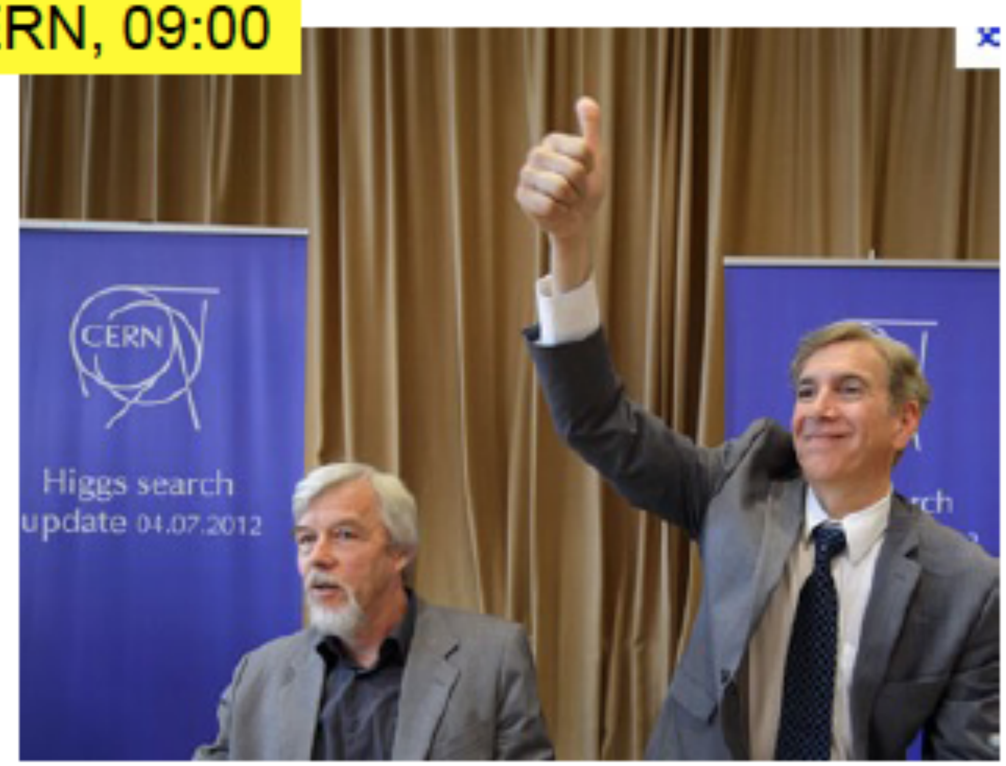
This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

ATLAS Collabo

G. Aad[48], T
R. Aben[105]
B.S. Achary
P. Adragna
S.P. Ahlen
G. Akimoto
I.N. Aleksar
M. Alhroob
S.E. Allwoo
A. Altheim
V.V. Ammo
L.S. Ancu[17]
A. Andreaz
A. Angeram
M. Antonell
R. Apolle
E. Arik[19a,*]
G. Artoni[13]
A. Astbury
R. Avramid
C. Bacci[134]
J. Backus M
T. Bain[158]
Sw. Banerje
A. Barbaro
T. Barillari
A. Baroncel
P. Barrillon
J.R. Batley
P.H. Beauch
M. Becking
C.P. Bee[83],

4 July 2012 CERN and Melbourne

CERN, 09:00

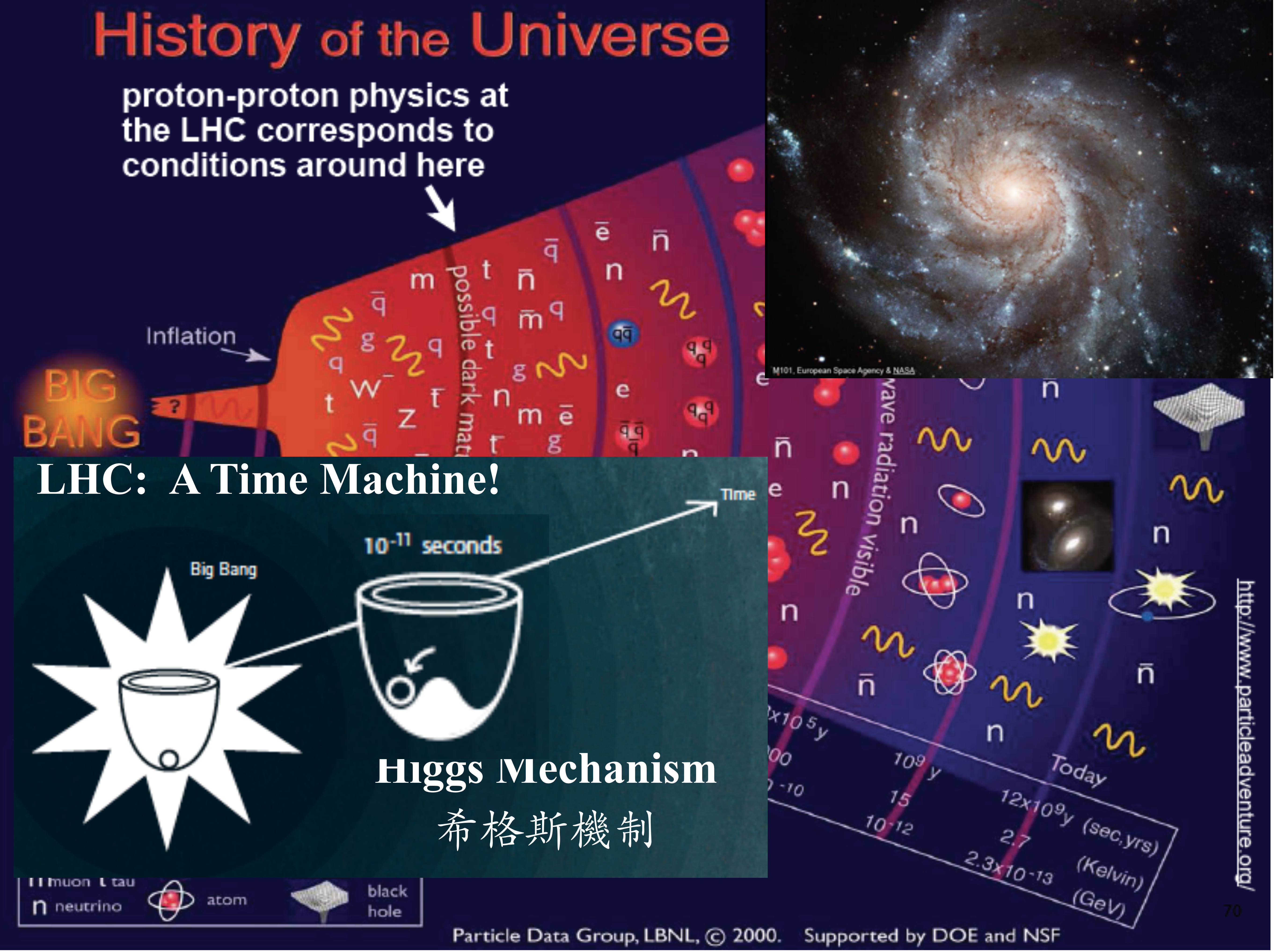


ICHEP 2012, Melbourne, 19:00

What is the Higgs boson?

Why is the Higgs boson so important?

ATLAS 探測器發言人


History of the Universe
proton-proton physics at the LHC corresponds to conditions around here
Inflation
BIG BANG
possible dark matter
wave radiation visible
M101, European Space Agency & NASA
LHC: A Time Machine!
Time
10^{-11} seconds
Big Bang
Higgs Mechanism
希格斯機制
Today
$12x10^9$y (sec,yrs)
2.7 (Kelvin)
$2.3x10^{-13}$ (GeV)
10^9y
15
10^{-12}
muon tau
neutrino
atom
black hole
http://www.particleadventure.org/
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

The story begins in 1964 …

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

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)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

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 used by Goldstone[2] himself: Two real[4] scalar fields φ_1, φ_2 and a real vector field A_μ interact through the Lagrangian density

$$L = -\tfrac{1}{2}(\nabla\varphi_1)^2 - \tfrac{1}{2}(\nabla\varphi_2)^2 - V(\varphi_1^{\,2}+\varphi_2^{\,2}) - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}, \qquad (1)$$

where

$$\nabla_\mu\varphi_1 = \partial_\mu\varphi_1 - eA_\mu\varphi_2,$$

$$\nabla_\mu\varphi_2 = \partial_\mu\varphi_2 + eA_\mu\varphi_1,$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu,$$

e is a dimensionless coupling constant, and the metric is taken as $-+++$. L is invariant under simultaneous gauge transformations of the first kind on $\varphi_1 \pm i\varphi_2$ and of the second kind on A_μ. Let us suppose that $V'(\varphi_0^{\,2}) = 0$, $V''(\varphi_0^{\,2}) > 0$; then spontaneous breakdown of U(1) symmetry occurs. Consider the equations [derived from (1) by treating $\Delta\varphi_1$, $\Delta\varphi_2$, and A_μ as small quantities] governing the propagation of small oscillations about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

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

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

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

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

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

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}, \qquad (3)$$

into the form

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

Equation (4) describes vector waves whose quanta have (bare) mass $e\varphi_0$. In the absence of the gauge field coupling ($e = 0$) the situation is quite different: Equations (2a) and (2c) describe zero-mass scalar and vector bosons, respectively. In passing, we note that the right-hand side of (2c) is just the linear approximation to the conserved current: It is linear in the vector potential, gauge invariance being maintained by the presence of the gradient term.[5]

When one considers theoretical models in which spontaneous breakdown of symmetry under a semisimple group occurs, one encounters a variety of possible situations corresponding to the various distinct irreducible representations to which the scalar fields may belong; the gauge field always belongs to the adjoint representation.[6] The model of the most immediate interest is that in which the scalar fields form an octet under SU(3): Here one finds the possibility of two nonvanishing vacuum expectation values, which may be chosen to be the two $Y = 0$, $I_3 = 0$ members of the octet.[7] There are two massive scalar bosons with just these quantum numbers; the remaining six components of the scalar octet combine with the corresponding components of the gauge-field octet to describe

massive vector bosons. There are two $I = \tfrac{1}{2}$ vector doublets, degenerate in mass between $Y = \pm 1$ but with an electromagnetic mass splitting between $I_3 = \pm\tfrac{1}{2}$, and the $I_3 = \pm 1$ components of a $Y = 0$, $I = 1$ triplet whose mass is entirely electromagnetic. The two $Y = 0$, $I = 0$ gauge fields remain massless: This is associated with the residual unbroken symmetry under the Abelian group generated by Y and I_3. It may be expected that when a further mechanism (presumably related to the weak interactions) is introduced in order to break Y conservation, one of these gauge fields will acquire mass, leaving the photon as the only massless vector particle. A detailed discussion of these questions will be presented elsewhere.

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.[9]

---

[1] P. W. Higgs, to be published.

[2] J. Goldstone, Nuovo Cimento 19, 154 (1961); J. Goldstone, A. Salam, and S. Weinberg, Phys. Rev. 127, 965 (1962).

[3] P. W. Anderson, Phys. Rev. 130, 439 (1963).

[4] In the present note the model is discussed mainly in classical terms; nothing is proved about the quantized theory. It should be understood, therefore, that the conclusions which are presented concerning the masses of particles are conjectures based on the quantization of linearized classical field equations. However, essentially the same conclusions have been reached independently by F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964): These authors discuss the same model quantum mechanically in lowest order perturbation theory about the self-consistent vacuum.

[5] In the theory of superconductivity such a term arises from collective excitations of the Fermi gas.

[6] See, for example, S. L. Glashow and M. Gell-Mann, Ann. Phys. (N.Y.) 15, 437 (1961).

[7] These are just the parameters which, if the scalar octet interacts with baryons and mesons, lead to the Gell-Mann–Okubo and electromagnetic mass splittings: See S. Coleman and S. L. Glashow, Phys. Rev. 134, B671 (1964).

[8] Tentative proposals that incomplete SU(3) octets of scalar particles exist have been made by a number of people. Such a rôle, as an isolated $Y = \pm 1$, $I = \tfrac{1}{2}$ state, was proposed for the κ meson (725 MeV) by Y. Nambu and J. J. Sakurai, Phys. Rev. Letters 11, 42 (1963). More recently the possibility that the σ meson (385 MeV) may be the $Y = I = 0$ member of an incomplete octet has been considered by L. M. Brown, Phys. Rev. Letters 13, 42 (1964).

[9] In the theory of superconductivity the scalar fields are associated with fermion pairs; the doubly charged excitation responsible for the quantization of magnetic flux is then the surviving member of a U(1) doublet.

SPLITTING OF THE 70-PLET OF SU(6)

Mirza A. Baqi Bég
The Rockefeller Institute, New York, New York

and

Virendra Singh*
Institute for Advanced Study, Princeton, New Jersey
(Received 18 September 1964)

1. In a previous note,[1] hereafter called I, we proposed an expression for the mass operator responsible for lifting the degeneracies of spin-unitary spin supermultiplets [Eq. (31)-I]. The purpose of the present note is to apply this expression to the 70-dimensional representation of SU(6).

The importance of the 70-dimensional representation has already been underlined by Pais.[2] Since

$$\underline{35} \otimes \underline{56} = \underline{56} \oplus \underline{70} \oplus \underline{700} \oplus \underline{1134}, \qquad (1)$$

it follows that $\underline{70}$ is the natural candidate for accommodating the higher meson-baryon resonances. Furthermore, since the SU(3)⊗SU(2) content is

$$\underline{70} = (\underline{1}, \underline{2}) + (\underline{8}, \underline{2}) + (\underline{10}, \underline{2}) + (\underline{8}, \underline{4}), \qquad (2)$$

we may assume that partial occupancy of the $\underline{70}$ representation has already been established through the so-called y octet[2] $(\tfrac{3}{2})^-$. Recent experiments appear to indicate that some $(\tfrac{1}{2})^-$ states may also be at hand.[3] With six masses at one's disposal, our formulas can predict the masses of all the other occupants of $\underline{70}$ and also provide a consistency check on the input. Our discussion of the $\underline{70}$ representation thus appears to be of immediate physical interest.

The story begins in 1964 . . .

VOLUME 13, NUMBER 16 — PHYSICAL REVIEW LETTERS — 19 OCTOBER 1964

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)

"an essential feature" of the theory "is the prediction of incomplete multiplets of scalar and vector bosons"

The story begins in 1964 . . .

with Englert and Brout; Higgs; Hagen, Guralnik and Kibble

page 321-323

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

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)

page 508-509

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

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)

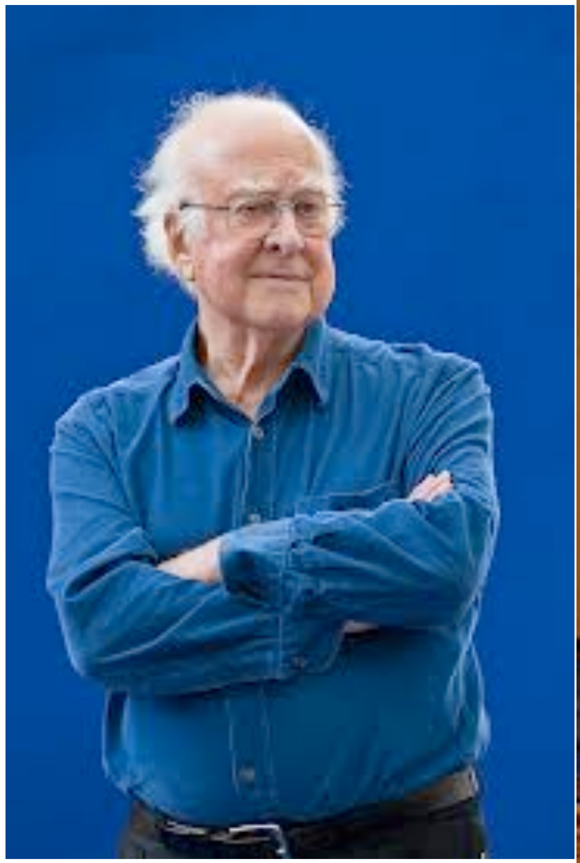
page 585-587

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

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)

J. J. Sakurai Prize in 2010



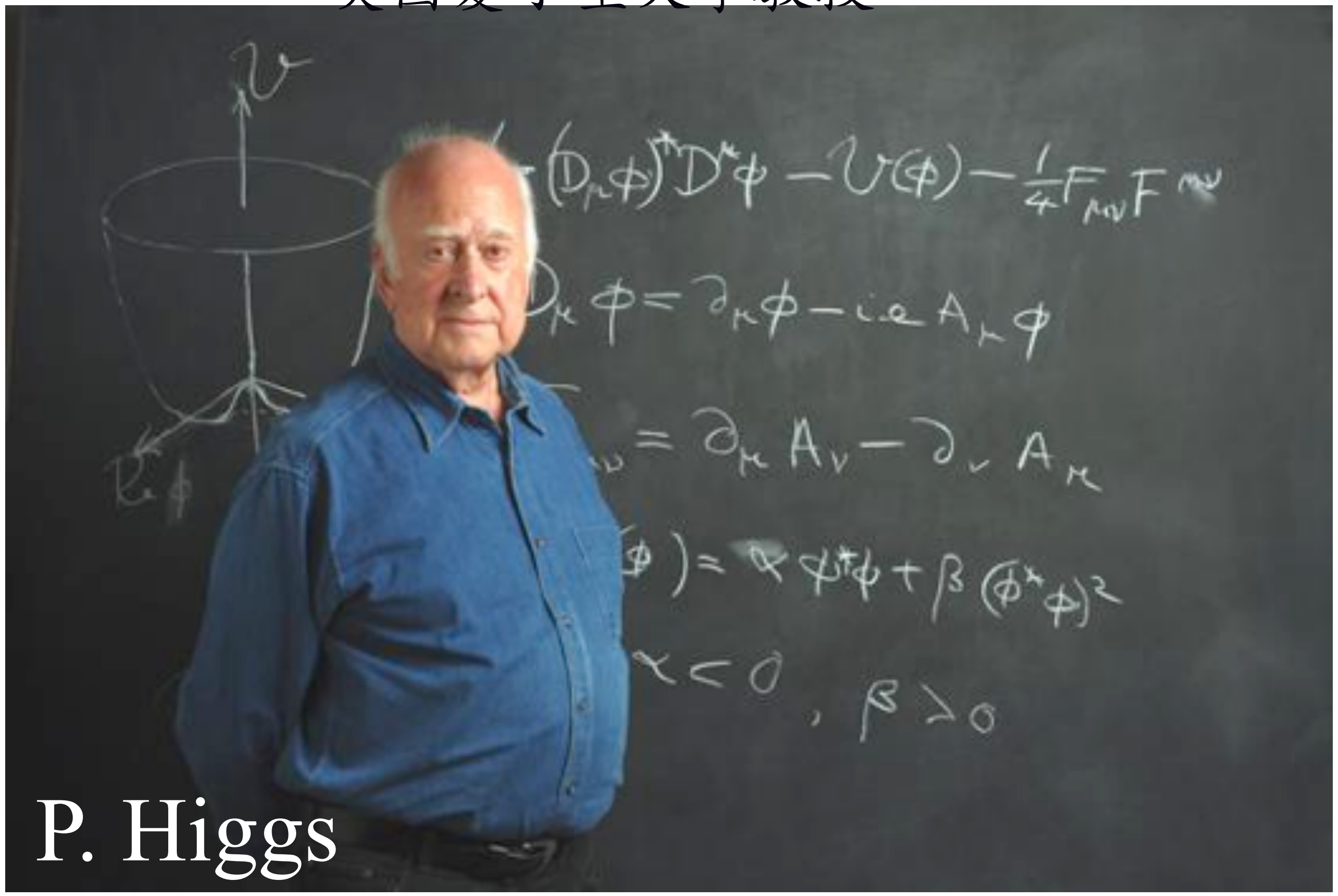
Higgs
81

Kibble, *Guralnik*, *Hagen*, *Englert*, *and* *Brout*
78 **74** **73** **78** **82**

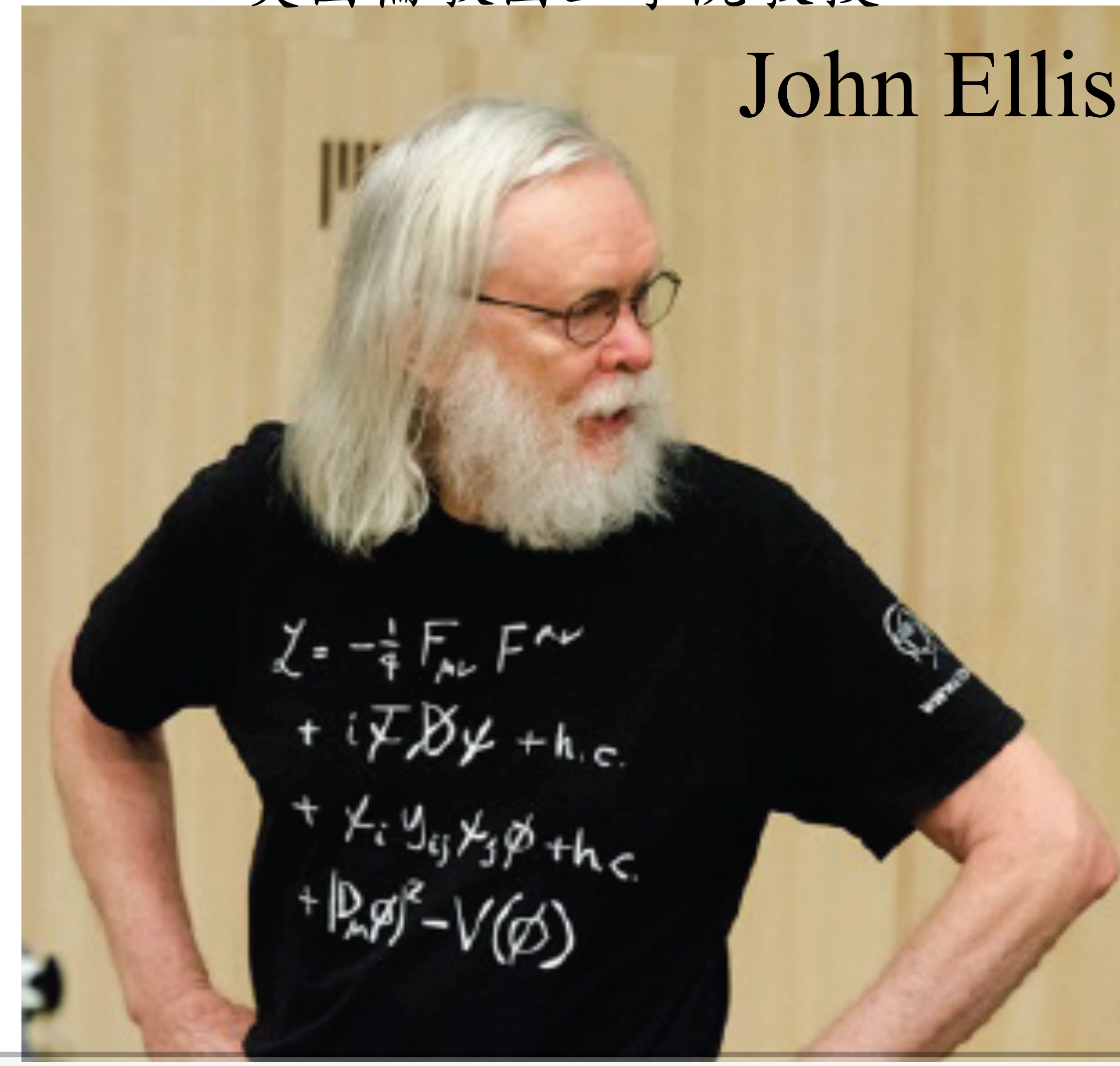
deceased at age 78 (2014) (Guralnik)

deceased at age 83 (2011) (Brout)

英國愛丁堡大學教授



英國倫敦國王學院教授



Citation summary results	Citeable papers	Published only
Total number of papers analyzed:	11	8
Total number of citations:	7,109	7,108
Average citations per paper:	646.3	888.5
h_{HEP} index [?]	5	5

博士論文: **Some Problems in the Theory of Molecular Vibrations**

導師: **Charles Coulson** (數學，化學物理)

一共發表20篇左右論文，早期的論文是發表在**Journal of Chemical Physics**上（很少引用數）

Citation summary results	Citeable papers	Published only
Total number of papers analyzed:	796	643
Total number of citations:	58,236	55,495
Average citations per paper:	73.2	86.3
h_{HEP} index [?]	124	121

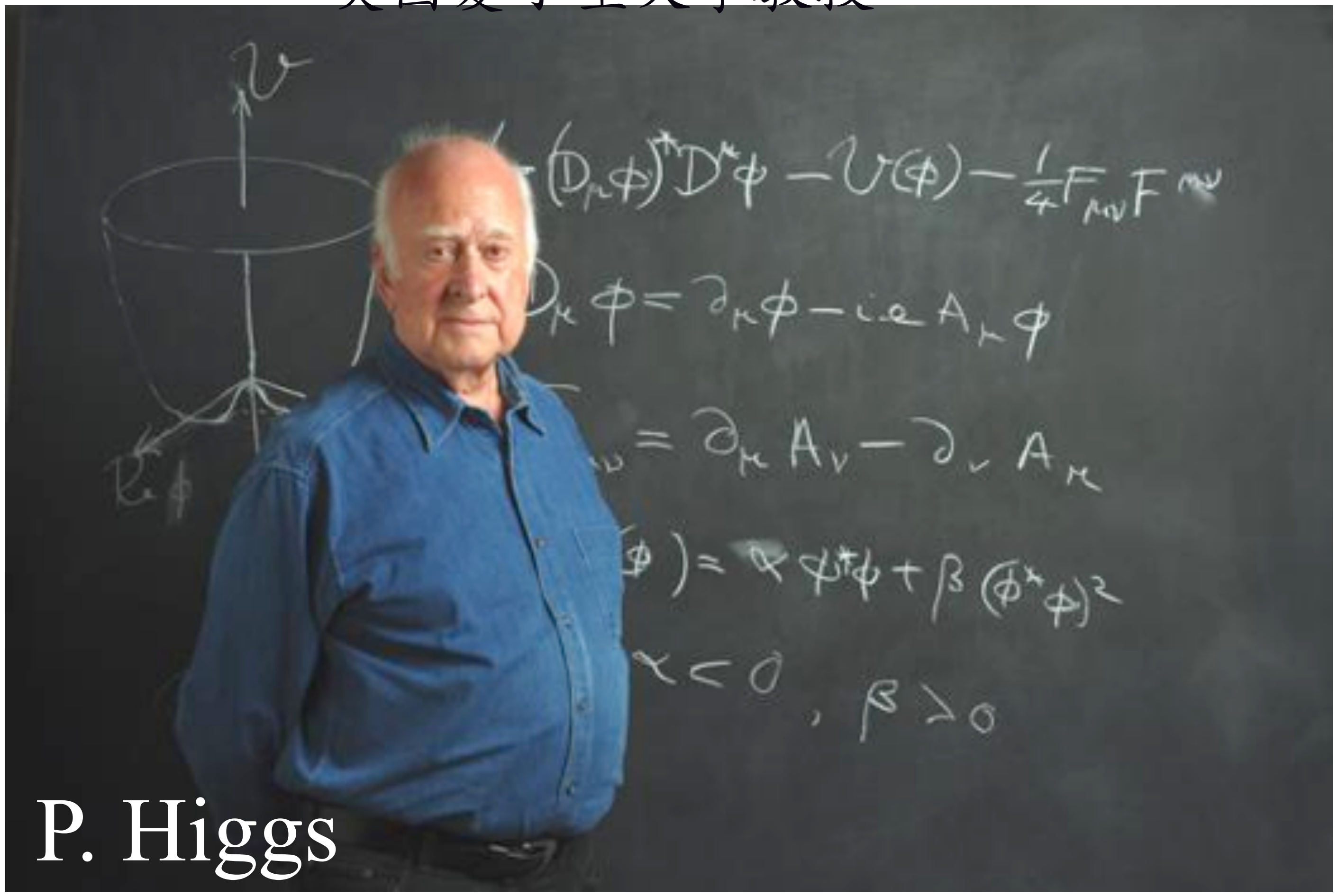
A Phenomenological Profile of the Higgs Boson

John R. Ellis (CERN), Mary K. Gaillard (CERN & Orsay, LPT), Dimitri V. Nanopoulos (CERN). Oct 1975. 62 pp.

Published in **Nucl.Phys. B106 (1976) 292**

Cited by 946 records 500+

英國愛丁堡大學教授



1. **Broken symmetries, massless particles and gauge fields**
(2584) Peter W. Higgs (Edinburgh U.). Sep 1964. 2 pp.
Published in **Phys.Lett. 12 (1964) 132-133**
DOI: 10.1016/0031-9163(64)91136-9
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 2584 records 1000+

2. **Broken Symmetries and the Masses of Gauge Bosons**
(2453) Peter W. Higgs (Edinburgh U.). Oct 1964. 2 pp.
Published in **Phys.Rev.Lett. 13 (1964) 508-509**
DOI: 10.1103/PhysRevLett.13.508
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Phys. Rev. Lett. Server
Detailed record - Cited by 2453 records 1000+

3. **Spontaneous Symmetry Breakdown without Massless Boso**
(1910) Peter W. Higgs (North Carolina U.). May 1966. 8 pp.
Published in **Phys.Rev. 145 (1966) 1156-1163**
DOI: 10.1103/PhysRev.145.1156
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 1910 records 1000+

Electroweak Theory

Steven Weinberg, Sheldon Glashow, Abdus Salam

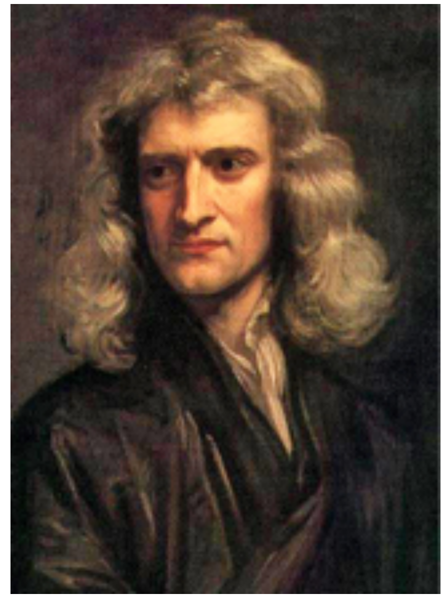
A Model of Leptons
Steven Weinberg (MIT, LNS). Nov 1967. 3 pp.
Published in **Phys.Rev.Lett. 19 (1967) 1264-1266**
Cited by 8641 records 1000+

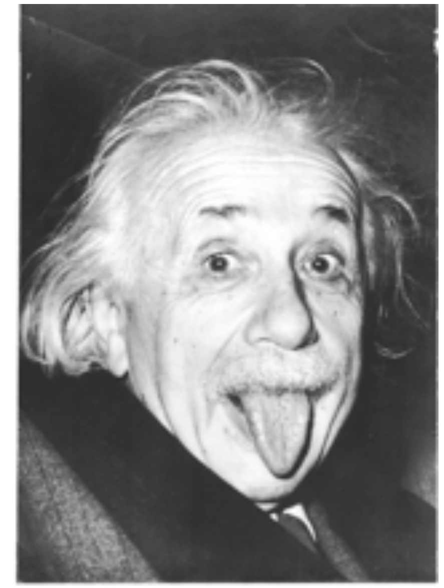
1979年Nobel
物理學獎

Origin of Mass:
（質量的來源）

What is Mass?

Newton: F=ma

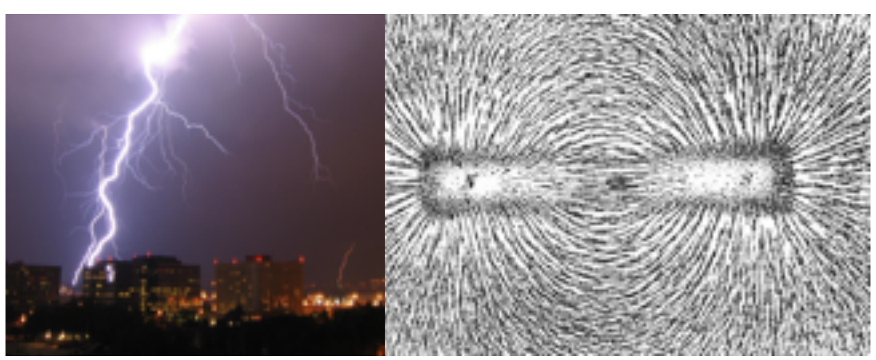




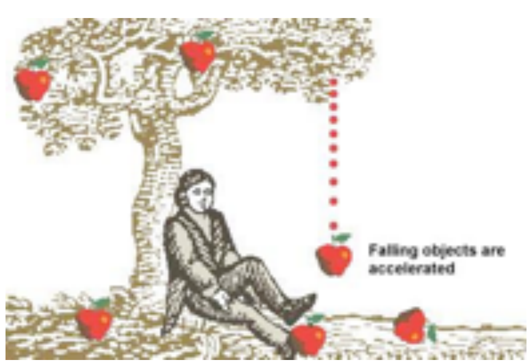
Einstein: $E=mc^2$

But they all forgot to tell us how particles get masses!

Electro-Magnetic Field



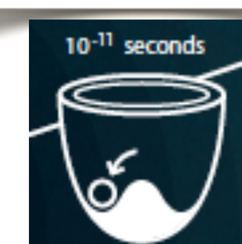
Gravitation Field



no source

Higgs field → **Mass** → **Matter**, **$W^{\pm}$, Z**

Higgs Mechanism
希格斯機制



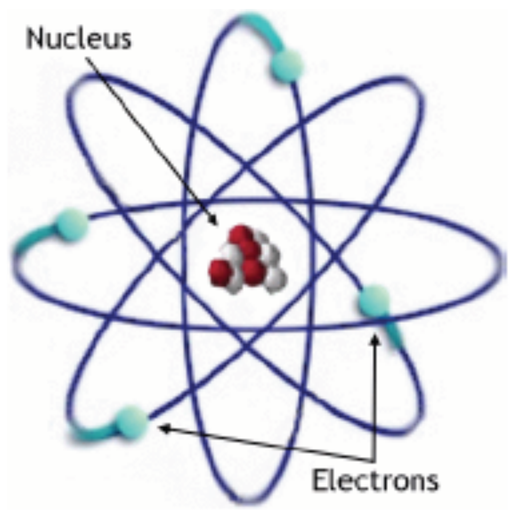
↓

Higgs Boson: H

If there were no Higgs boson:

♠ **there would be no atoms** $\because\ m_e=0$

☐ **electron would escape at the speed of light**



Radius is proportional to 1/mass(electron)

♣ **weak interactions would not be weak** $\because\ M_{W,Z}=0$

☐ **Life would not be possible: everything would be radioactive**

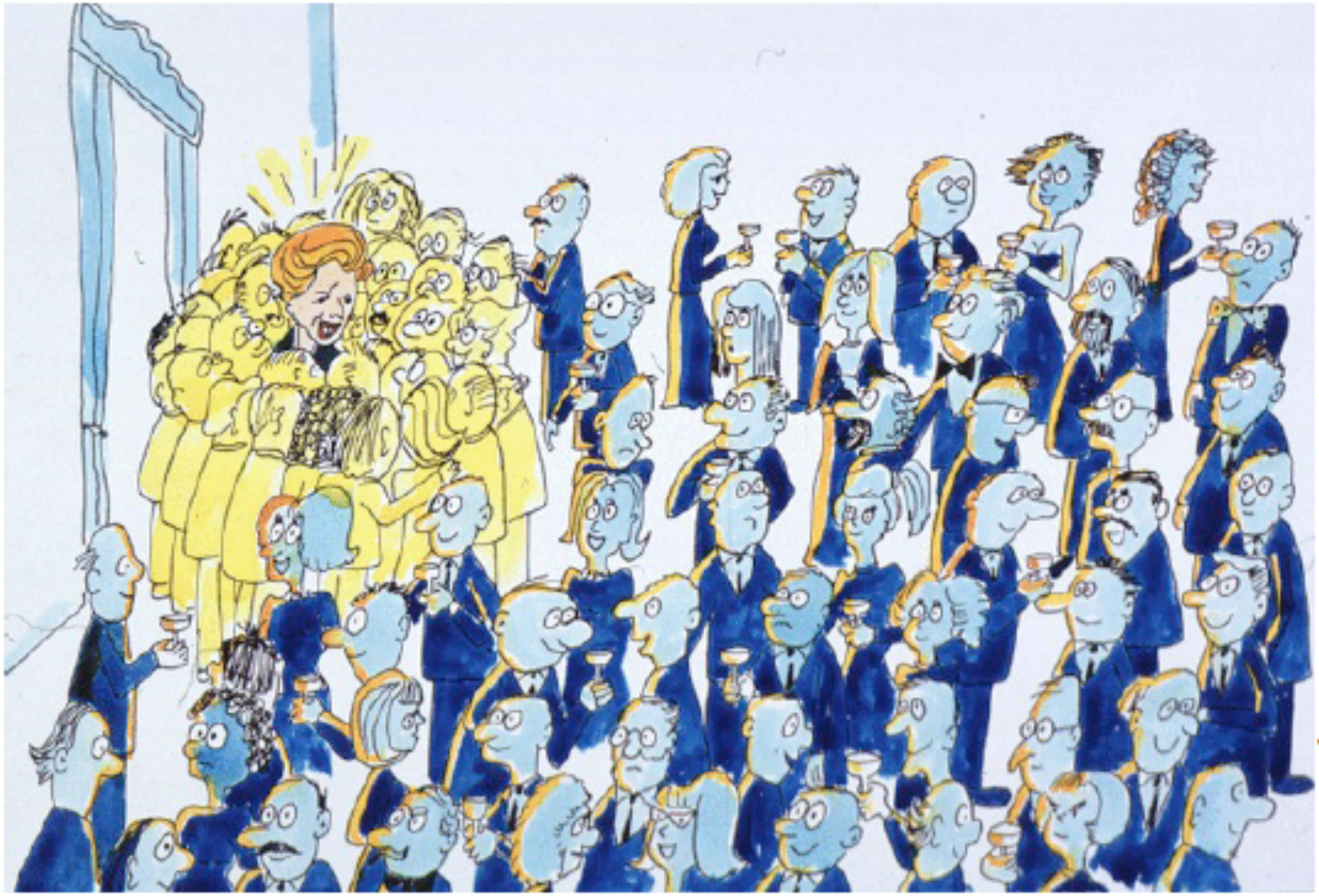
Higgs Mechanism 希格斯機制

Higgs Mechanism 希格斯機制

From David Miller, UCL. Cartoon courtesy of CERN

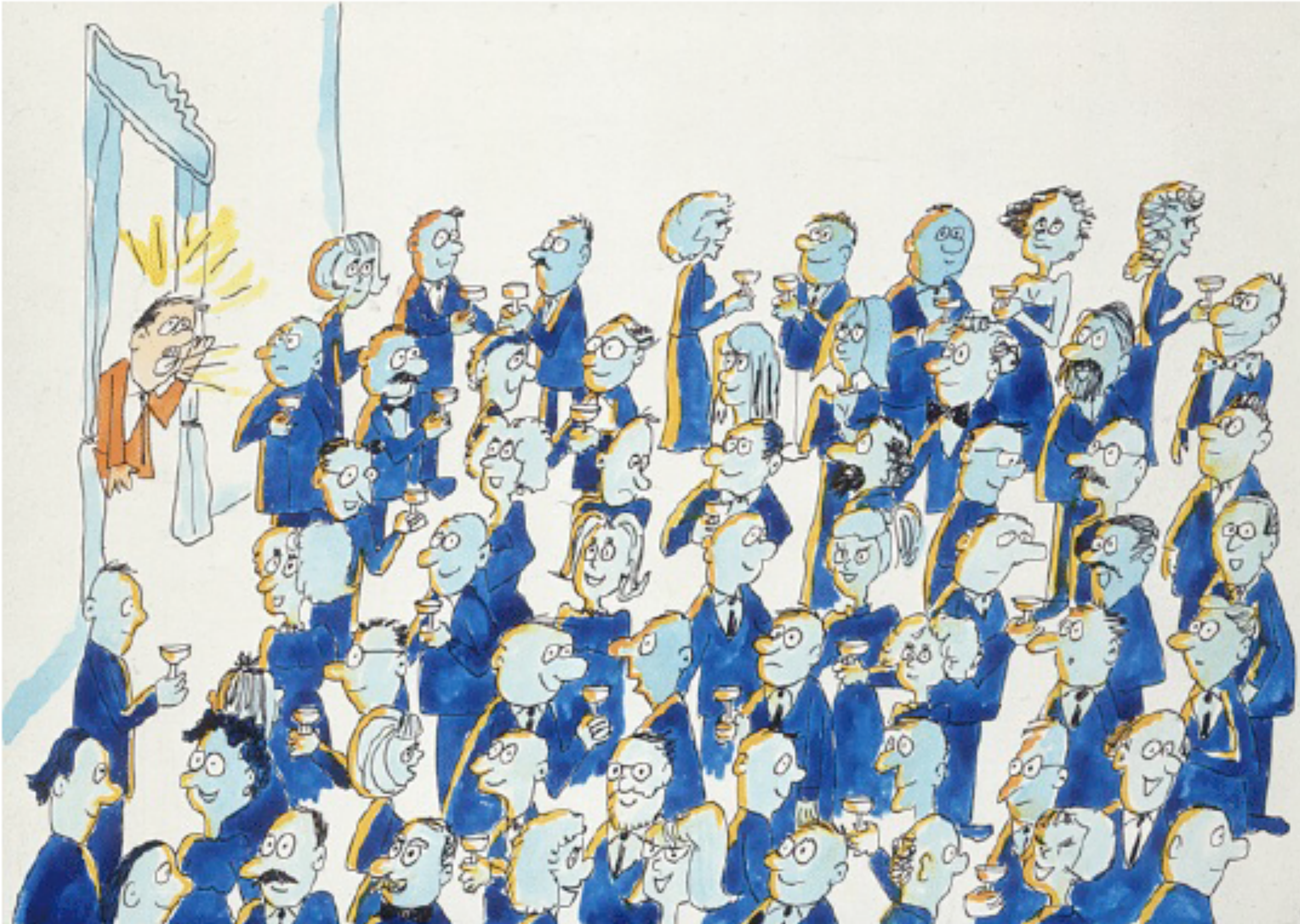
To understand the Higgs mechanism, imagine that a room full of journalists chattering quietly is like space filled with the Higgs field ...

Higgs Mechanism 希格斯機制



From David Miller, UCL. Cartoon courtesy of CERN

... a well-known person walks in, creating a disturbance as she moves across the room and attracting a cluster of journalists with each step. This increases her resistance to movement, in other words, she acquires mass, just like a particle moving through the Higgs field...



From David Miller, UCL. Cartoon courtesy of CERN

... if a rumour crosses the room, ...

From David Miller, UCL. Cartoon courtesy of CERN

... it creates the same kind of clustering, but this time among the journalists themselves. In this analogy, these clusters are the Higgs particles.

分立對稱性之破缺

- *P*： 宇稱 或 空間反演 $x \longleftrightarrow -x$
- *T*： 時間反演 $t \longleftrightarrow -t$
- *C*： 粒子和反粒子交換 或 電荷共軛

粒子 ⟷ 反粒子

粒子物理：三種非常重要的分立對稱性 -- *C*, *P*, 和 *T* 宇稱

很多年來,物理學的規律被認為是 P, C,和 T,守恆的

在電磁作用中, P , C 和 T 是守恆的！
同樣在強作用中,P, C 和 T 也是守恆的！

在弱作用中,它們是守恆的嗎？

眾所周知, 美國著名華人物理學家李政道和楊振寧博士在1956年指出：在弱作用力中, P 和 C是極大破壞的！為此他們榮獲1957年的NOBEL物理學獎

1964年，在美國BNL國家實驗室，Fitch和Cronin等人發現了 反常的中性 K介子弱衰變 ：→ CP 破壞。

--Fitch和Cronin榮獲了1980年的NOBEL物理學獎

1998年，在FNAL (KTeV) 和CERN (CPLEAR)分別觀測到了在弱作用T破壞現象。

弱交互作用力：**P**，**C**，**CP** 和 **T** 都是破壞的

Is the weak interaction God’s mistake?

Creation of Adam (Michelangelo, in Sistine Ceiling)

上帝創造的第一個男人：亞當

God's right hand, on the right, touches life into Adam's left.

Right=對, Left 拉丁文 Sinister = Evil 邪惡，罪過

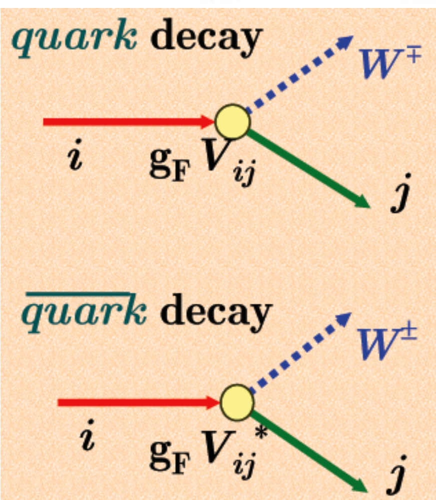
M. Kobayahsi and K. Maskawa, "CP Violation in the Renormalizable Theory of Weak Interactions", Progr. Theor. Phys. **49** (1973) 652.

Yukawa interactions: $Y = \sum_{i,j} h^d_{ij} \bar{Q}_L \phi D_R + h^u_{ij} \bar{Q}_L \tilde{\phi} U_R + h^e_{ij} \bar{L}_L \phi E_R + h.c.$

$\Phi=\Phi_0=(-\mu^2/2\lambda)^{1/2}$
SSB

$$V_L^{d+} M_d V_R^d = M_d^{diag.} \ , \ D_{L(R)_j} = (V^d_{L(R)})_{ji} D'_{L(R)_i}$$
$$V_L^{u+} M_u V_R^u = M_u^{diag.} \ , \ U_{L(R)_j} = (V^u_{L(R)})_{ji} U'_{L(R)_i}$$

Gauge couplings $W^\pm$: $\sum_i \bar{U}_{Li} \gamma_\lambda D_{Li} \longrightarrow \sum_{ij} \bar{U}'_{Lj} \gamma_\lambda V_{ji} D'_{Li}$



$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$ – Kobayashi-Maskawa (KM) matrix

$V = (V_L^u)^+ V_L^d \ , \ (V^+ V = 1)$

→ rot. angles : $\frac{n(n-1)}{2}$

→ phases : $n^2 - \frac{n(n-1)}{2} = \frac{n(n+1)}{2}$

$u_L^i \to e^{i\phi_i} u_L^i \ , \quad d_L^i \to e^{i\theta_i} d_L^i \longrightarrow V_{ij} \to V_{ij}\, e^{i(\theta_j - \phi_i)}$

⇒ observable or physical phases : $\frac{n(n+1)}{2} - (2n-1) = \frac{(n-1)(n-2)}{2}$

For three generations $(n=3)$ → one phase + 3 angles → 三代夸克之存在 CP對稱性破缺

但是，CKM之CP破缺機制不能解識
「宇宙物質與反物質之不對稱性」

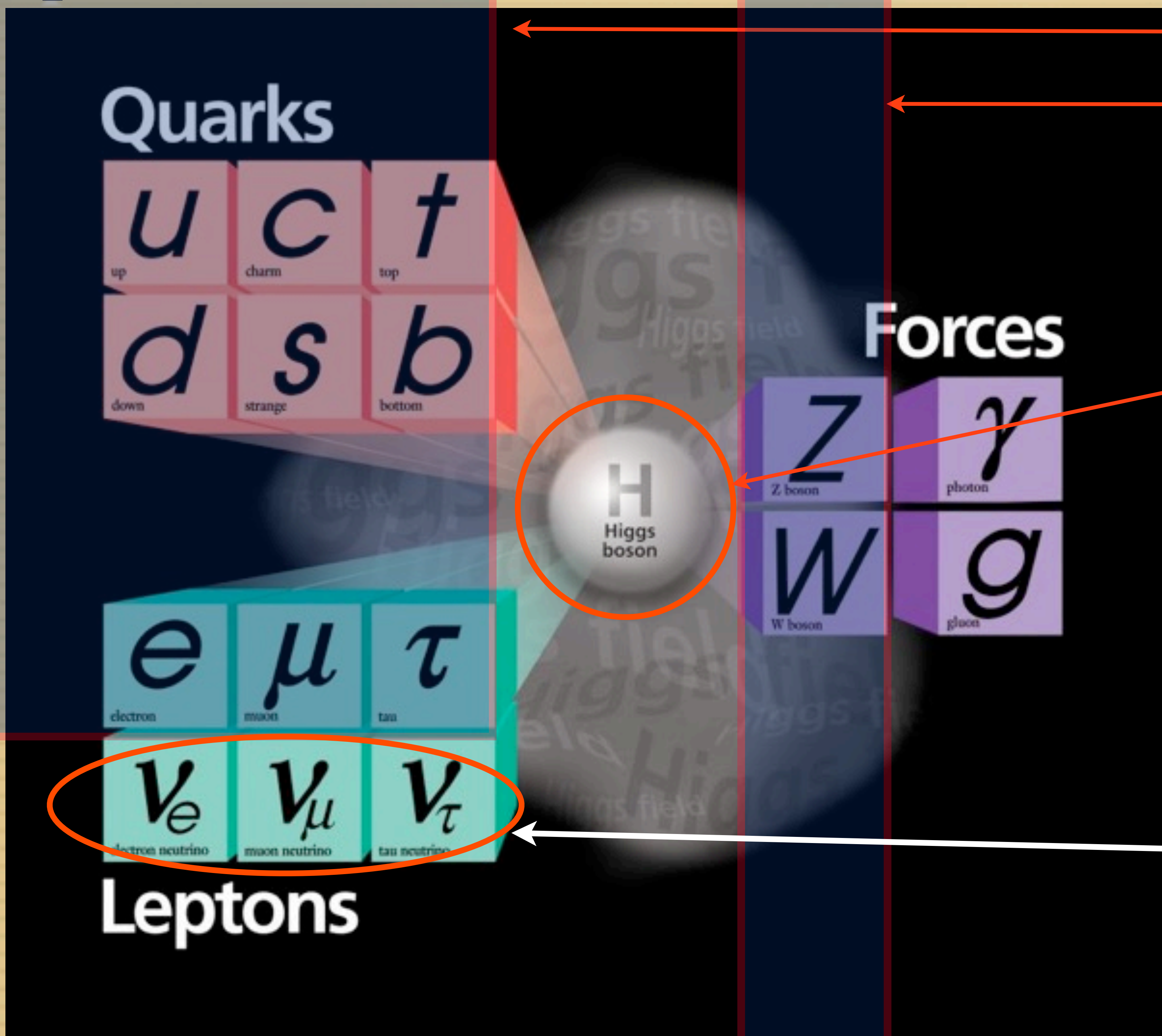
Spontaneous symmetry breaking

粒子物理標準模型
The Standard Model in Particle Physics

Fermion | Boson

Standard Matter | Higgs | Force

spin 1/2 | 0 | 1

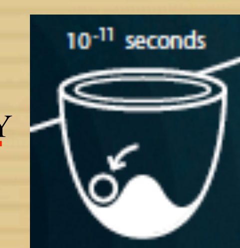


masses

$SU(3)_c \times U(1)_{EM}$

Higgs Mechanism

$SU(3)_c \times SU(2)_L \times U(1)_Y$



Neutrino Oscillation
2015 Nobel: Kajita & McDonald

標準模型無法提供微中子質量

New Physics beyond the SM

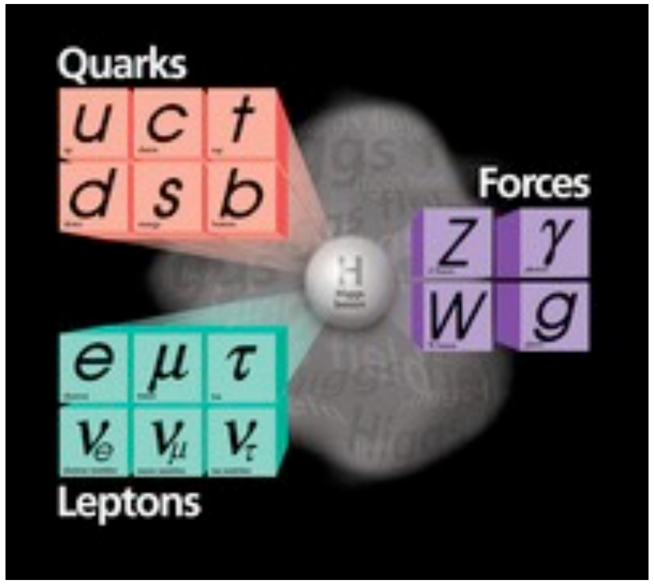
- **The standard model:** $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$Q_L : \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad L_L : \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$U_R : u_R \quad c_R \quad t_R$$

$$D_R : d_R \quad s_R \quad b_R \qquad E_R : e_R \quad \mu_R \quad \tau_R$$

Higgs : H^0 Gauge Bosons : $W^\pm$, Z, γ, g



Yukawa interactions: $\mathcal{L}_{\rm Yukawa} = -\Gamma^u_{ij}(\bar{u},\bar{d})_{{\rm L}i}\Phi u_{{\rm R}j} - \Gamma^d_{ij}(\bar{u},\bar{d})_{{\rm L}i}\tilde{\Phi} d_{{\rm R}j} + {\rm h.c.}\ .$

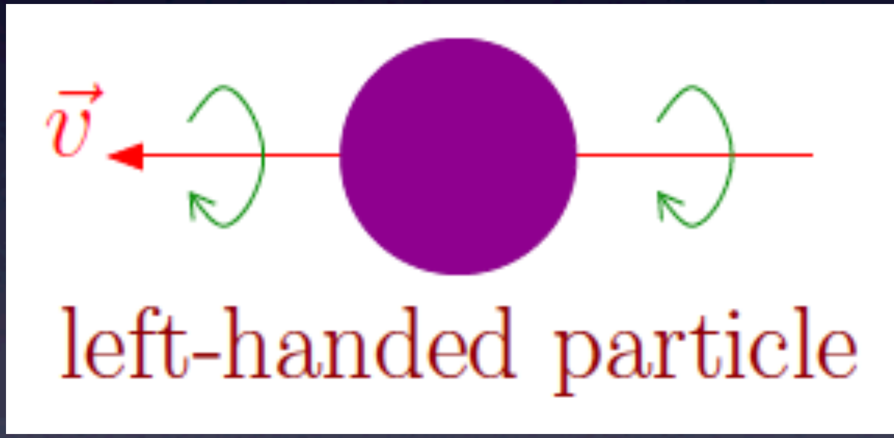
$$\Phi \to \frac{1}{\sqrt{2}}\begin{pmatrix} v+H \\ 0 \end{pmatrix} \longrightarrow M^{u,d}_{ij} = \frac{1}{\sqrt{2}}\Gamma^{u,d}_{ij} v\ .$$

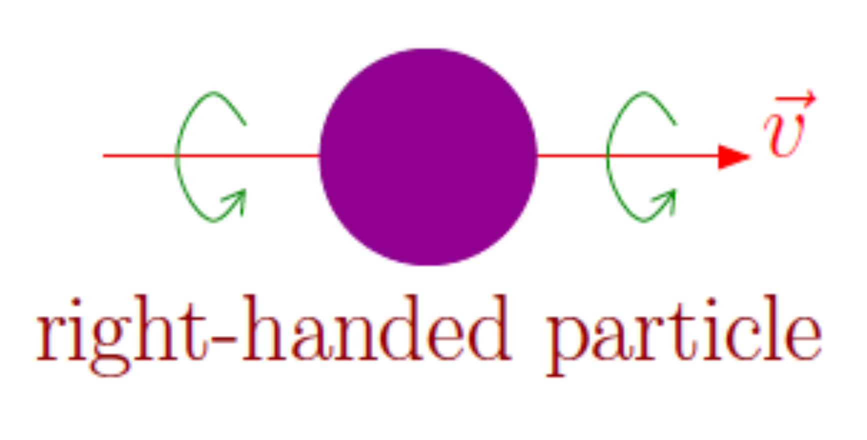
$$(U^{u,d}_{\rm L})^\dagger M^{u,d} U^{u,d}_{\rm R} = \mathcal{M}^{u,d}$$

$$\mathcal{L}^{\rm eff}_{\rm Yukawa} = -\sum_i m_i \bar{q}_i(x) q_i(x)\left[1 + \frac{H(x)}{v}\right]$$

- **What about neutrinos?**
- **Do neutrinos get their masses like charged fermions?**
- 在標準模型中，微中子質量必須是零。

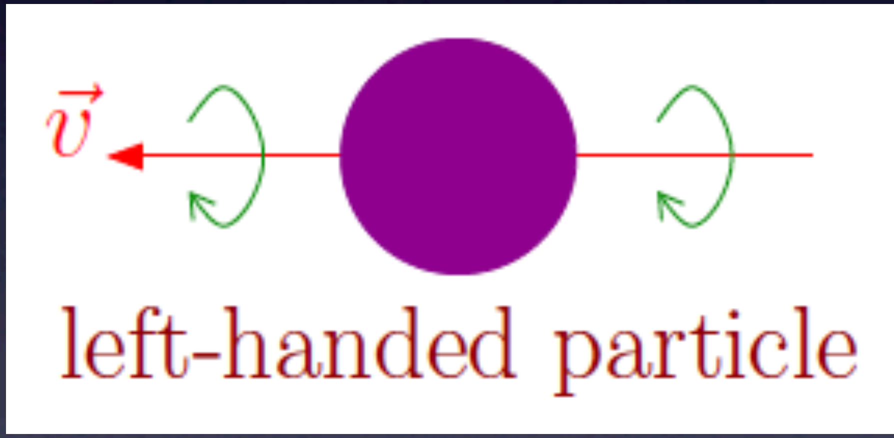
Why does the Standard Model require MASSLESS neutrinos?





Why does the Standard Model require MASSLESS neutrinos?

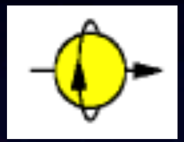
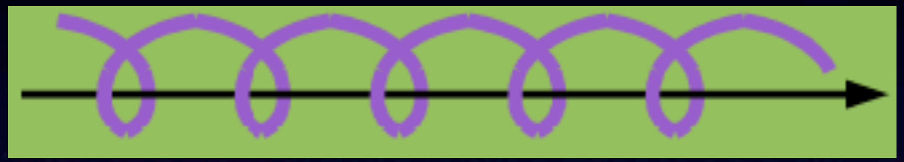
- All neutrinos left-handed ⇒ massless



Why does the Standard Model require MASSLESS neutrinos?

- All neutrinos left-handed ⇒ massless

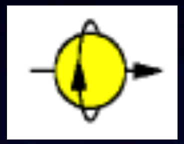
left-handed

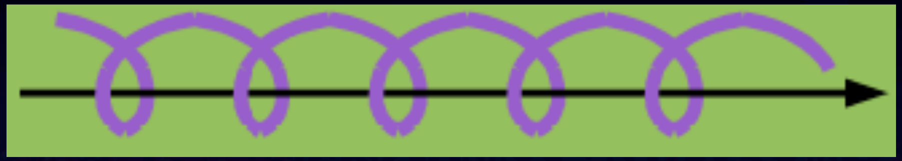




Why does the Standard Model require MASSLESS neutrinos?

- All neutrinos left-handed
- If they have mass, can't go at speed of light.

left-handed





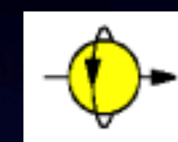
A massive particle

Why does the Standard Model require MASSLESS neutrinos?

- All neutrinos left-handed
- If they have mass, can’t go at speed of light.

A massive particle

right-handed

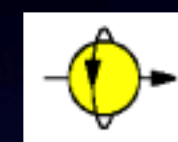


Why does the Standard Model require MASSLESS neutrinos?

- All neutrinos left-handed ⇒ massless
- If they have mass, can’t go at speed of light.

right-handed

A massive particle



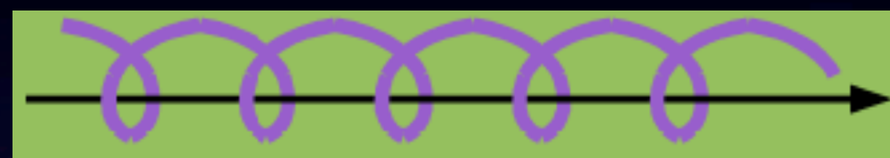
- Now neutrino right-handed??

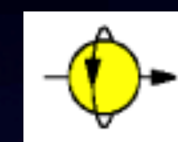
  ⇒ contradiction ⇒ can’t have a mass

Why does the Standard Model require MASSLESS neutrinos?

- All neutrinos left-handed ⇒ massless
- If they have mass, can't go at speed of light.

right-handed





A massive particle

- Now neutrino right-handed??

  ⇒ contradiction ⇒ can't have a mass

Strictly left-handed neutrinos ⟺ Massless Neutrinos

謝謝！