Electroweak and Higgs physics

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大阪大学
OSAKA UNIVERSITY

OSAKA


Silk
Road
Lanzhou
蘭州市
中華人民
共和国
北京
北朝鮮
札幌
日本海
서울
大韓民国
OSAKA
日本
東京
大阪市
黄海
中国
上海
東シナ海
日本
台北

OSAKA

The second biggest urban area in Japan.

Osaka-Kyoto-Kobe-Nara

From ancient era until 19th century, this area was the center of Japan.

We now have many tourists from China, Korea, US, EU, …

OSAKA


Osaka Sushi


TAKOYAKI

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n

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J, …

There are different kinds of nice foods

Osaka University

Founded in 1724 (Kaitokudo)
in 1838 (Tekijuku)

Chartered on November 22, 1919 as
Osaka Prefectural Medical Univ.

Re-established on May 1, 1931 as
Osaka Imperial University

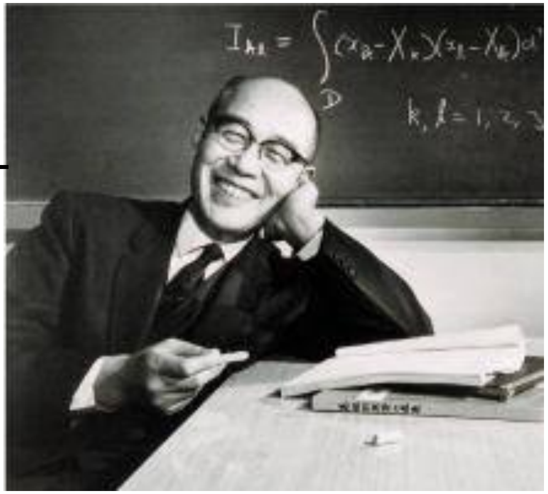
After WWII, it became **Osaka University**

Old Campus (Down Town Osaka)
School of Science
Osaka Imperial University
before WW II

New Campus (Toyonaka City)
School of Science
Osaka University

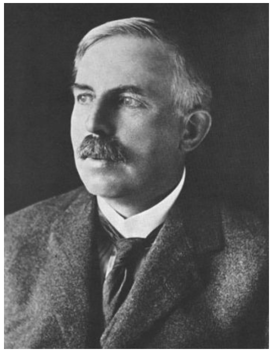
Physicists in Osaka Univ

Hideki Yukawa



Meson Theory

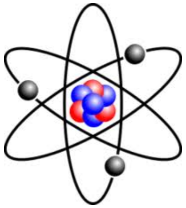
Later
professor
in Kyoto U.



Rutherford

Prof. H. Nagaoka

1st President of
Osaka Imperial University
(present Osaka Univ.)



Model of Atom

Schoichi Sakata

Sakata Model
MNS matrix

Later
professor
in Nagoya U.

Theorists in Osaka

Prof. H. Yukawa (Kyoto)

Ph. D in Osaka Univ.

Theory of Meson
1935

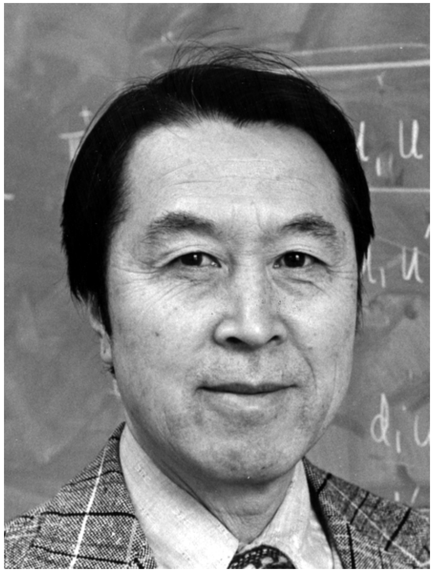
**Nobel Prize in Physics
1949**

Prof. R. Utiyama (Osaka)

Ph. D in Osaka Univ.

General gauge theories 1954
Gauge Principle for Gravity

Prof. Y. Nambu (Chicago)



**Ph. D in Univ. of Tokyo
Professor in U. of Chicago
Honorary Prof. in Osaka Univ.**

SSB 1960, Nambu-Goto String, …

**Nobel Prize in Physics
2008**

We will have a Higgs workshop “HPNP2019” in Feb 2019 in OSAKA

HPNP2019

The 4th International Workshop on
“Higgs as a Probe of New Physics”

18.-22. February 2019, Osaka University, Japan

International Advising Committee

Fawzi Boudjema (Annecy, LAPTH)	Chengwei Chiang (NTU)
Christophe Grojean (DESY)	Howard E. Haber (UC Santa Cruz)
Junji Hisano (Nagoya U.)	Pyungwon Ko (KIAS)
Stefano Moretti (U. of Southampton)	Mihoko Nojiri (KEK / Kavli IPMU)
Yasuhiro Okada (KEK)	Michael Peskin (SLAC)

Local Organizing Committee

Mayumi Aoki (Kanazawa U.)	Mitsuru Kakizaki (U. of Toyama)
Shinya Kanemura (Osaka U.), Chair	Kentarou Mawatari (Osaka U.)
Kin-ya Oda (Osaka U.)	Tetsuo Shindou (Kogakuin U.)
Hiroaki Sugiyama (Toyama Pref. U.)	Koji Tsumura (Kyoto U.)
Kei Yagyu (Seikei U.)	

Contact

Ai Sato (Secretary)
Email : hpnp2019@het.phys.sci.osaka-u.ac.jp
URL : http://www3.u-toyama.ac.jp/theory/HPNP2019/

Plan of the Lectures

1 EW Symmetry Breaking in the Standard Model (SM)

2 Physics of non-Minimal Higgs sectors

3 Higgs as a Probe of New Physics

Plan of the Lectures

1 EW Symmetry Breaking in the Standard Model (SM)
  - 1-1: Introduction
  - 1-2: Basics of Spontaneous Symmetry Breaking
  - 1-3: EW force and SM
  - 1-4: Higgs sector
  - 1-5: Properties of the Higgs boson
  - 1-6: Current situation

2 Physics of non-Minimal Higgs sectors

3 Higgs as a Probe of New Physics

Plan of the Lectures

1 EW Symmetry Breaking in the Standard Model (SM)

2 Physics of non-Minimal Higgs sectors
- 2-1: Motivation
- 2-2: Two Higgs doublet models
- 2-3: Other Models
- 2-4: Fingerprinting Higgs models
- 2-5: Decoupling/Non-decoupling
- 2-6: Radiative Corrections to Higgs couplings

3 Higgs as a Probe of New Physics

Plan of the Lectures

1 EW Symmetry Breaking in the Standard Model (SM)

2 Physics of non-Minimal Higgs sectors

3 Higgs as a Probe of New Physics
  3-1: Higgs problem and new paradigms
  3-2: BSM Phenomena and Higgs
  3-3: Neutrino Mass models and Higgs
  3-4: EW Baryogenesis and Higgs self-coupling
  3-5: Gravitational Waves as a probe of
    1st Order Phase Transition
  3-6: Towards 2030s: Golden Age

1-1 Introduction

Standard Model

Quarks and leptons
3-generations

Massive

	$SU(2)_L$	$U(1)_Y$
$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	2	1/3
u_R	1	4/3
d_R	1	−2/3
$l_L = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	2	−1
e_R	1	−2

Gauge principle: Interaction

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

Color Isospin Hypercharge

$\boxed{g_\mu^\alpha}$ Gluon W_μ^a B_μ

Spontaneous Symmetry Breaking: Mass

$$SU(2)_I \times U(1)_Y \to U(1)_{\rm em}$$

Massless

$\boxed{A_\mu}$

Photon

Massive

$\boxed{W_\mu^\pm \quad Z_\mu^0}$

Weak bosons

Standard Model

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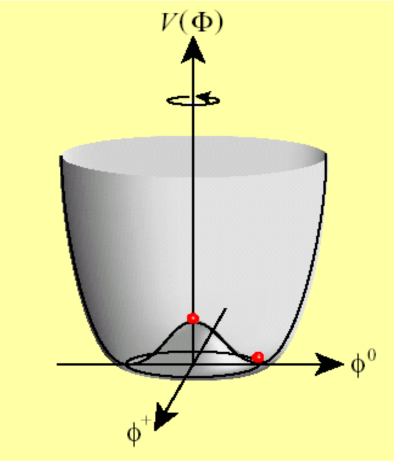
Weak bosons

Spontaneous Symmetry Breaking: Mass

$$SU(2)_I \times U(1)_Y \rightarrow U(1)_{\text{em}}$$



Tentatively introducing a scalar doublet (Higgs field)

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

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

↑

$\mu^2 < 0$

↓**VEV 246GeV**

$$\phi^0 = \frac{1}{\sqrt{2}}(v + h + iz)$$

↑

Higgs boson

LHC experiment

Discovery of a scalar particle

Mass 125 GeV, …

Spin, Pality 0^+

Coupling with many particles

hγγ, hgg, hZZ, hWW, hττ, htt, hbb, …

Identified as a Higgs boson

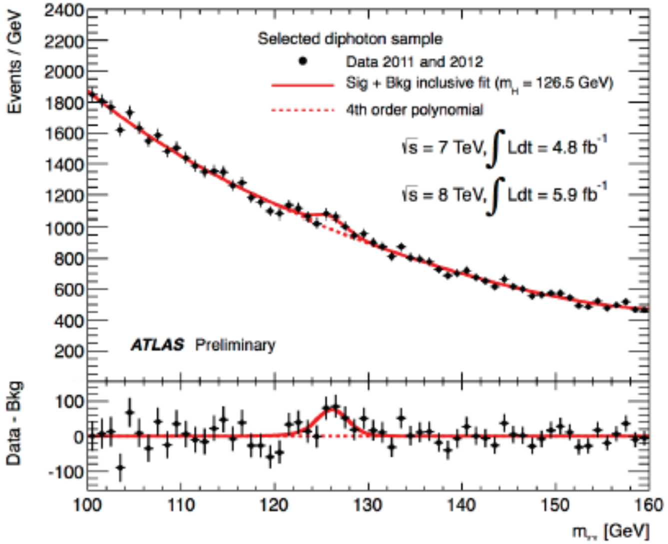
Measured couplings turned out to be consistent with the SM Higgs

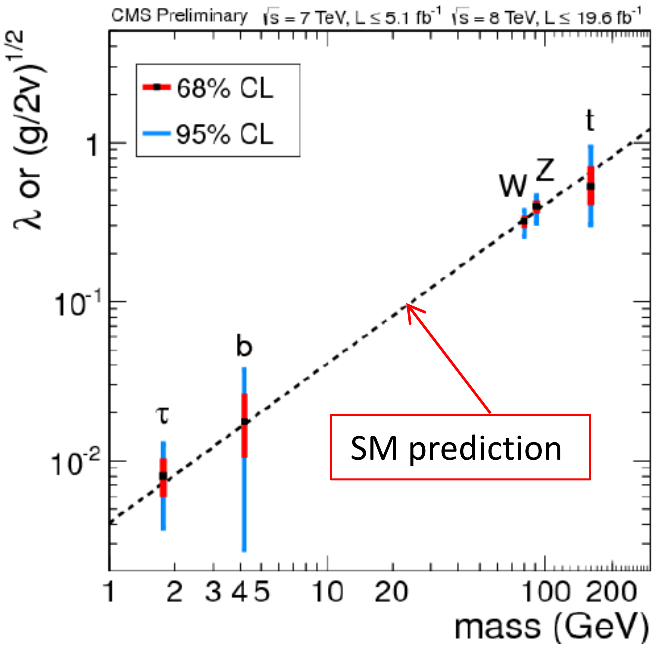
“Tentative” SM Higgs sector works well!

No BSM particle has been found

Standard Model is enough?

ATLAS/CMS
July 2012





Beyond the Standard Model

Many reasons to consider New Physics beyond SM

Unification of Law

- Paradigm of Grand Unification
- Yukawa structure (flavor physics)

Problem in the SM Higgs

- Hierarchy Problem, Shape of Higgs sector, Nature, …

BSM Phenomena

- Dark Matter
- Neutrino mass and mixing
- Baryon Asymmetry of Universe
- Inflation, Dark Energy, Gravity,…

New Physics is necessary **At which scale?**

If TeV scale, they should have connection with Higgs physics

Higgs problems

Higgs boson was found, but Higgs sector is unknown

- **Nature of Higgs boson**

$$\delta m_H^2 = \frac{\Lambda_{cutoff}^2}{16\pi^2}$$

Hierarchy Problem

New paradigm of New Physics

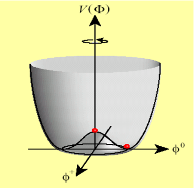
- **Structure**

Only one Higgs?

Multiplet structure, Symmetry, …

Relation to new paradigms and BSM phenomena

- **Higgs Potential**



$\mu^2 < 0$

EW Symmetry Breaking

Dynamics of EWSB

EW Phase Transition

By the discovery of *h*(125), these problems became frontier

Higgs is a key to new physics

- It is the weakest part in the SM
- Its structure remains unknown
- It relates to the physics beyond the SM
- It can be tested by current and future experiments

We can access to the new physics
via the Higgs physics!

Nature of Higgs

Higgs Nature ⇔ BSM Paradigm

– Elementary Scalar	SUSY
– Composite of fermions	Dynamical Symmetry Breaking
– A vector field in extra D	Gauge Higgs Unification
– Pseudo NG Boson	Minimal Composite Models
– ……	……

Each new paradigm predicts a specific Higgs sector
(eg. MSSM: two Higgs doublets,
Gauge-Higgs Uni.: Higgs couplings are weaker)

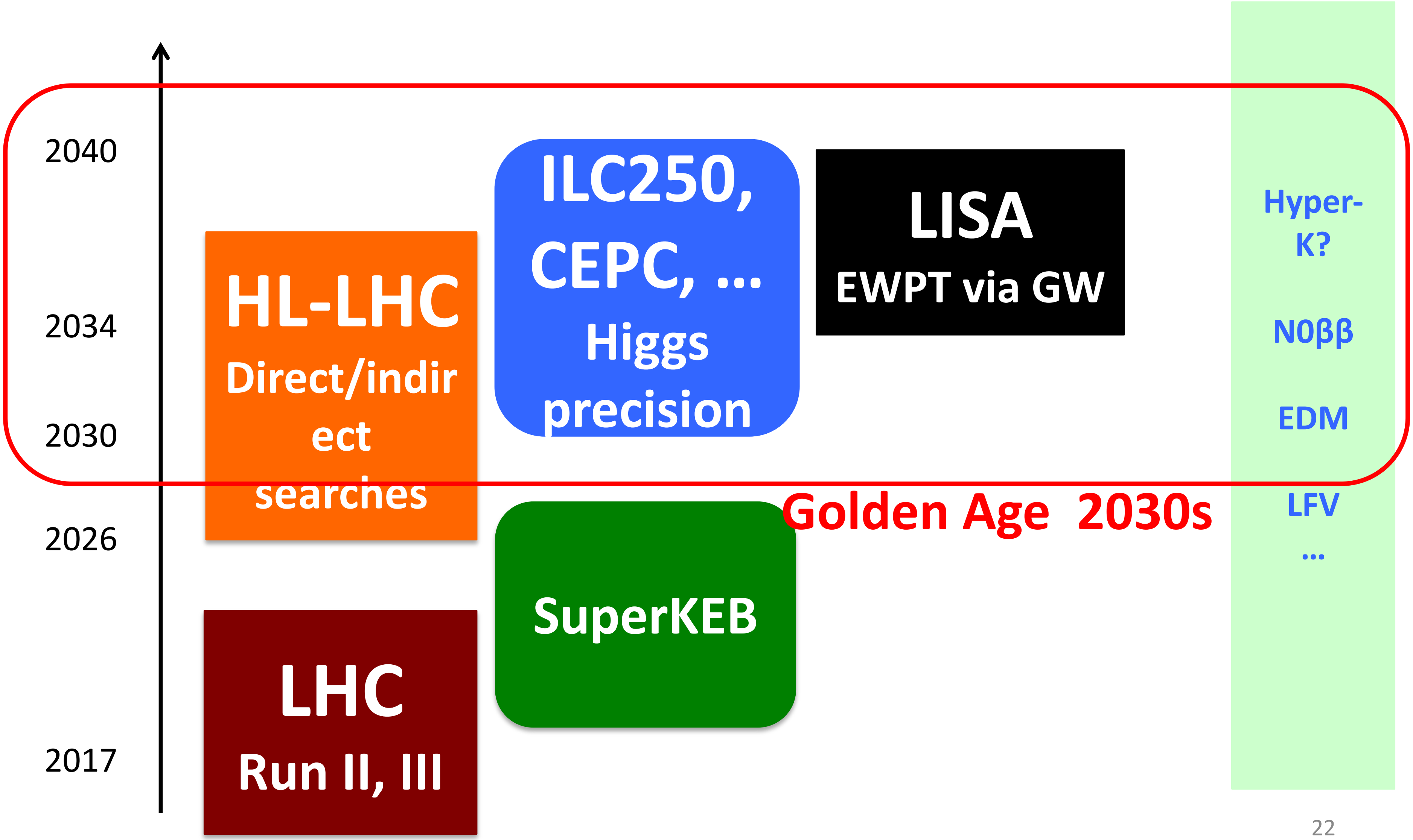
Higgs is a window to new physics

Higgs portal new physics scenarios

SUSY
Dynamical symmetry breaking
Higgs as a pNGB
Gauge Higgs Unification
CW mechanism
Higgs portal dark matter
Inert scalar models
Radiative neutrino mass models
Electroweak baryogenesis
…

It is important to experimentally determine
the Higgs sector to explore new physics beyond SM

Future experiments



2040

2034

2030

2026

2017

LHC
Run II, III

HL-LHC
Direct/indirect searches

SuperKEB

ILC250, CEPC, …
Higgs precision

LISA
EWPT via GW

Golden Age 2030s

Hyper-K?

N0ββ

EDM

LFV

…

1-2 Basics of Higgs physics

Symmetry and Vacuum

If a physics system (action) is invariant under a global transformation *G*, there is the conserved current J_μ^A for each generator T^A of *G*.

$$S = \int d^4x \mathcal{L}(\phi, \partial\phi)$$

$$\partial^\mu j_\mu^A = 0$$

$$Q^A \equiv \int d^3x j_{\mu=0}^A$$

Charge Q^A is a generator of the symmetry for the field ϕ

$$[i\epsilon_A Q^A, \phi_i] = \epsilon_A \delta^A \phi_i \quad (A = 1, 2, \cdots, \mathrm{dim}G)$$

Under G, there are two phases for vacuum

（1）Wigner Phase $$Q^A|0\rangle = 0$$

（2）Nambu-Goldstone phase
（Broken Phase） $$Q^A|0\rangle \neq 0$$

Zero mass particle appears
= Nambu-Goldstone Theorem

Global U(1) Scalar Theory

Complex field

$$\phi = \frac{\phi_1 + i\phi_2}{\sqrt{2}}$$

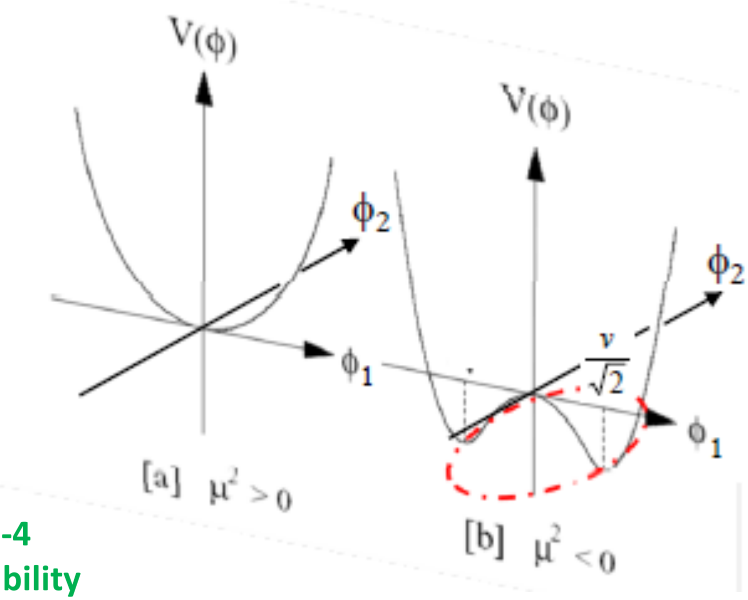
U（1）global transformation

$$\phi(x) \to \phi'(x) = e^{i\theta}\phi(x)$$

Lagrangian is invariant under the U(1)

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

Only up to dim-4 by renormalizability



For $\mu^2 < 0$, vacuum is on the circle

$$\phi_1^2 + \phi_2^2 = \frac{-\mu^2}{\lambda} = v^2$$

Using U(1) we can set the vacuum at

$$\phi_1 = v \quad \phi_2 = 0$$

$$\phi = \frac{v + \eta(x) + i\xi(x)}{\sqrt{2}}$$

No ξ^2 term

→ ξ is massless (Nambu-Goldstone boson)

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \eta)^2 + \frac{1}{2}(\partial_\mu \xi)^2 + \frac{1}{2}\underline{(2\lambda v^2)}\eta^2 + \ldots.$$

Mass term of η

Gauge Symmetry

Gauge Principle : Theory is invariant under the local gauge symmetry

System of Free Dirac Fermion

$$\mathcal{L} = \overline{\psi}(i\gamma_\mu \partial^\mu - m)\psi$$

Impose invariance under
a local U(1) gauge transformation

$$\psi(x) \to \psi'(x) = e^{i\alpha(x)}\psi(x)$$

Impossible as it is

$$\begin{aligned}\overline{\psi} i\gamma_\mu \partial^\mu \psi &\to \overline{\psi} e^{-i\alpha(x)} i\gamma_\mu \partial^\mu (e^{i\alpha(x)}\psi) \\ &= \overline{\psi} i\gamma_\mu \partial^\mu \psi - \overline{\psi}\gamma_\mu \psi \partial^\mu \alpha(x)\end{aligned}$$

Introduce the gauge field and covariant derivative

$D_\mu = \partial_\mu - ieA_\mu$ such that $D_\mu \psi \to e^{i\alpha(x)}(D_\mu \psi)$

Define the transformation of the gauge field $A_\mu \to A_\mu + \dfrac{1}{e}\partial_\mu \alpha$

$$\boxed{\mathcal{L}_{QED} = \overline{\psi}(i\gamma_\mu D^\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}}$$

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

A_μ cannot have the mass term

$$\cancel{\frac{1}{2}M^2 A_\mu A^\mu}$$

Higgs Mechanism

Case of Gauged U(1) Scalar Theory

$$\phi(x) \rightarrow \phi'(x) = e^{i\alpha(x)}\phi(x)$$

$$D_\mu = \partial_\mu - ieA_\mu$$

$$A_\mu \rightarrow A_\mu + \frac{1}{e}\partial_\mu \alpha$$

$$\mathcal{L} = (D_\mu\phi)^\dagger(D_\mu\phi) - \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Assuming $\mu^2 < 0$, expand the field around the vacuum $\phi = \frac{v + \eta(x) + i\xi(x)}{\sqrt{2}}$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\xi)^2 + \frac{1}{2}(\partial_\mu\eta)^2 + \frac{1}{2}(2\lambda v^2)\eta^2 + \frac{1}{2}e^2v^2A_\mu A^\mu - evA_\mu\partial^\mu\xi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \ldots$$

NG boson　　scalar mass　　geuge mass　　Mixing

Originally $\xi + \eta + A_\mu \times 2 =$ 4 degree of freedom（dof）

But it looks like $\xi + \eta + A_\mu \times 3 = 5$ → excess can be eliminated by the gauge transformation

Gauge transform

$$\alpha = \theta/v$$

$$\phi \rightarrow \frac{1}{2}(v + h(x))e^{i\theta(x)/v}$$

$$A_\mu \rightarrow A_\mu + \frac{1}{ev}\partial_\mu\theta$$

After SSB, ξ is unphysical,
and its original d.o.f. becomes
that of longitudinal component of A_μ

$$\boxed{\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(2\lambda v^2)h^2 + \frac{1}{2}e^2v^2A_\mu A^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \ldots}$$

1-3 EW force and the Standard Model

Nuclear Decay

Beta decays etc

$$n \rightarrow p + e^- + \overline{\nu_e}$$

$$\pi^- \rightarrow e^- + \overline{\nu}$$

$$\mu^- \rightarrow e^- + \overline{\nu_e} + \nu_\mu$$

Strange particle $\Delta S \neq 0$

$$\Sigma^+ \rightarrow n + \pi^+$$

Decay with gamma emission

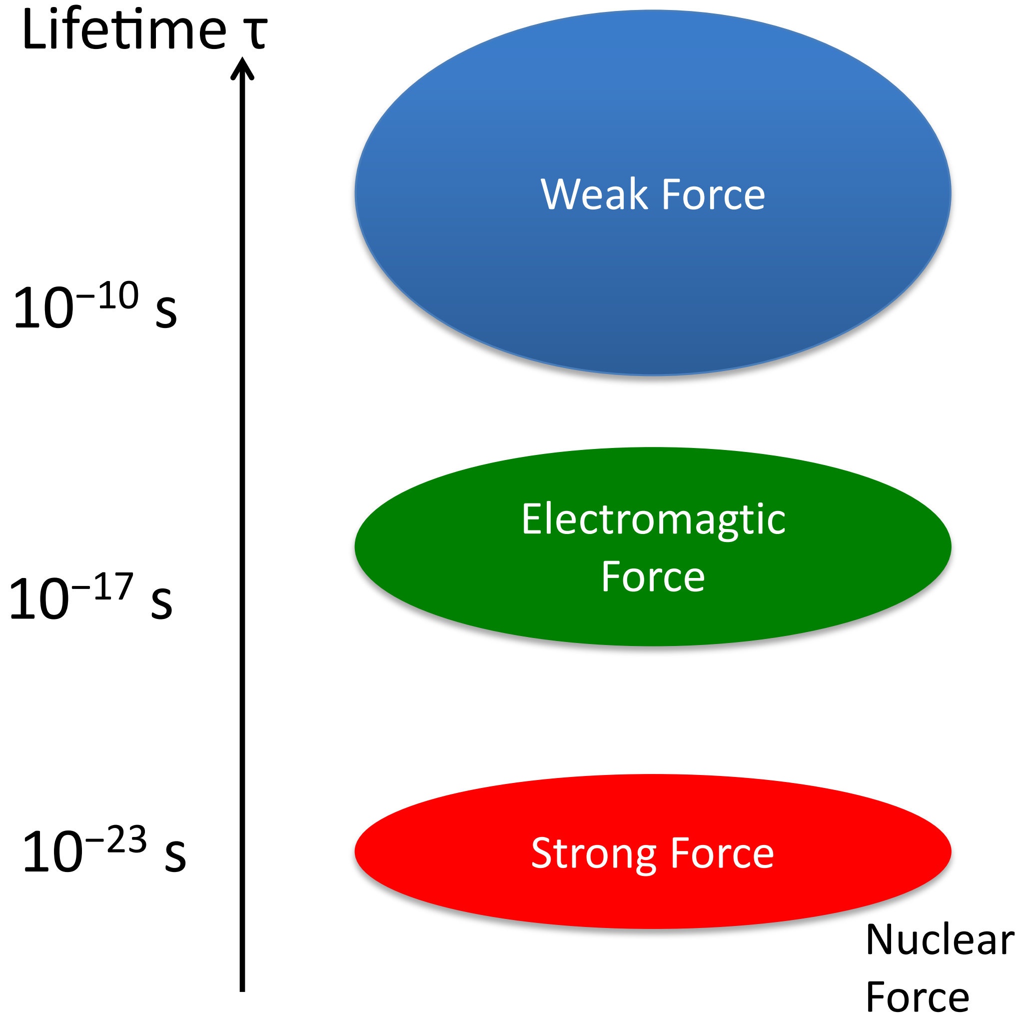
$$\pi^0 \rightarrow \gamma\gamma$$

$$\Sigma \rightarrow \Lambda\gamma$$

Other decays of Hadrons

$$\Delta^{++} \rightarrow p + \pi^+$$

$$\rho \rightarrow \pi\pi$$



Lifetime τ

10^{-10} s

Weak Force

10^{-17} s

Electromagtic Force

10^{-23} s

Strong Force

Nuclear Force

Typical Life Time for each Force

Beta decays

Beta decay of neutrons

$$n \to p + e^- + \overline{\nu_e}$$

$$\pi^+ \to \mu^+ \nu_\mu$$

$$\mu^- \to e^- + \overline{\nu_e} + \nu_\mu$$

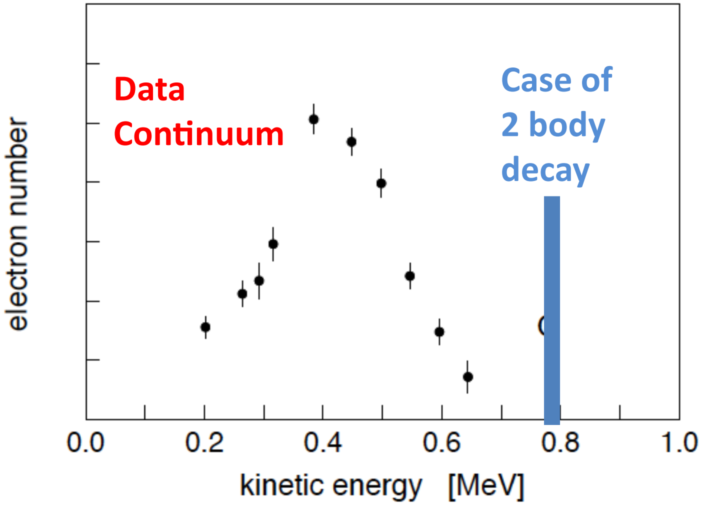
$$\Lambda \to p^+ + \pi^-$$

New force where kind of particles changes
(Not QED)

Pauli : Predicton for Neutrinos (1931)

Neutrino was introduced to explain
the continuous spectrum of
the electron energy distribution

Fermi : 4-body interaction (1934)



Distribution of *E* of the electron

Fermi Theory (1934)

Beta decay of neutrion

$$n \rightarrow p + e^- + \overline{\nu_e}$$

$\Gamma_i = 1$	γ_5	γ_μ	$\gamma_\mu\gamma_5$	$\sigma_{\mu\nu}$
S	*P*	*V*	*A*	*T*

Neutrion annihilated, and proton, electron anti-neutrino generated

Shape of Interaction $(\overline{p}\Gamma_i n)(\overline{e}\Gamma_i \nu_e)$ Fermi assumed the type *V*

Multiplication of bi-linear forms

Data: Helicity of anti-neutrino +1
Helicity of electron −1

Only left-handed
$(\nu_e)_L$, e^-_L

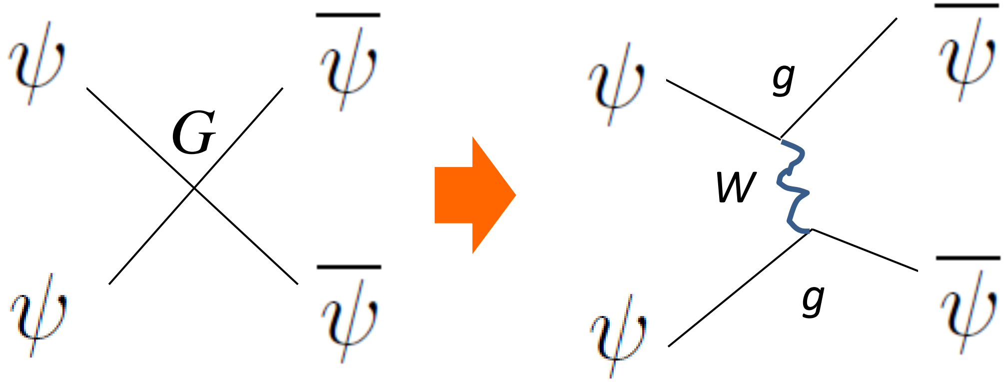
$$H \sim \frac{G}{\sqrt{2}} \left[\overline{p}\gamma_\mu(1-\lambda\gamma_5)n\right] \left[\overline{e}\gamma^\mu(1-\gamma_5)\nu_e\right]$$

Weak interaction takes the type *V*−*A*
The deviation in hadron current come from the strong interaction

$$\lambda \sim 1.25$$

Scale of weak force

$$\boxed{\frac{1}{2v^2} = \frac{g^2}{8M_W^2} = \frac{G}{\sqrt{2}}}$$



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

➡ V=246GeV

Vector field *W* which mediate the weak force has mass of O(100) GeV

If the weak force is a gauge force under a gauge symmetry ,
the gauge boson must be massless

Consider
a theory with
a broken symmtry

➡ Spontaneous symmetry breaking

Weak Force mixes with EM Force

Discovery of Strangeness（Nakano, Nishijima, Gell-Mann: 1953）

Quark Model (u, d, s)

$$\boxed{Q = I_3 + \frac{Y}{2}}$$

$Y = B + S$

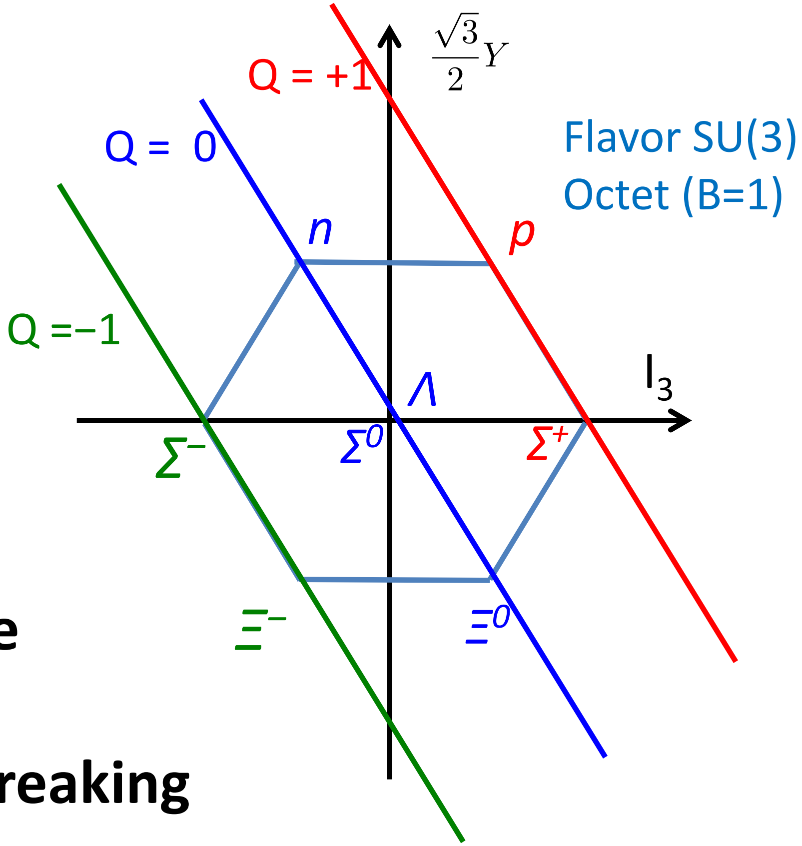
Q: Electric Charge

I_3: Isospin

Y: Hypercharge

B: Baryon Number

S: Strangeness



Isospin SU(2)$_I$ and **Hypercharge U(1)$_Y$** are fundamental, and **EM symmetry U(1)$_{EM}$** remains after Spontaneous Symmetry Breaking

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

Standard Model (Weinberg-Salam)

Electromagnetic Force

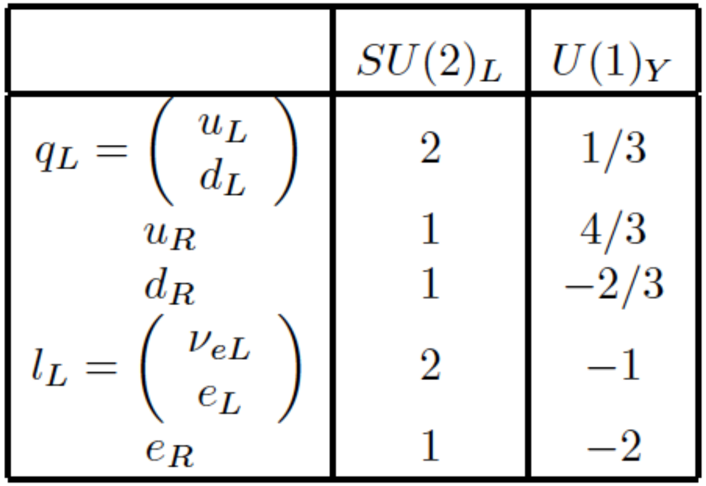
Weak Force

- P, C Violation
- Flavor is changed by the process
- FCNC suppression
- CP violation (three generation)
- Origin of mass

Explained at the same time

Particles

Quarks and Leptons $Q = I_3 + \frac{Y}{2}$



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$l_L = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	2	-1
e_R	1	-2

Gauge fields SU(2) $W_\mu^a (a = 1, 2, 3)$

U(1) B_μ

Higgs scalar field

(I=1/2, *Y*=1)

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix} \quad \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

$$\begin{array}{ccc} u_R & c_R & t_R \\ d_R & s_R & b_R \end{array}$$

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$$

$$\begin{array}{ccc} e_R & \mu_R & \tau_R \end{array}$$

3 generations

Standard Model

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
& +\overline{Q}_L i\gamma^\mu D_\mu Q_L + \overline{L}_L i\gamma^\mu D_\mu L_L \\
& +\overline{u}_R i\gamma^\mu D_\mu u_R + \overline{d}_R i\gamma^\mu D_\mu d_R + \overline{e}_R i\gamma^\mu D_\mu e_R
\end{aligned}
$$

Uniquely Determined By Gauge Principle

$$
\begin{aligned}
& -\left\{ Y_u Q_L \tilde{\Phi} u_R + Y_d Q_L \Phi d_R + Y_e Q_L \Phi e_R + (\mathrm{h.c.}) \right\} \\
& +|D_\mu \Phi|^2 - V(\Phi)
\end{aligned}
$$

Yukawa coupling

Higgs sector

Undetermined From the Principle

$$
D_\mu = \partial_\mu - igI\tau^a W^a_\mu - ig'\frac{Y}{2}B_\mu
$$

Higgs potential (not tested yet) $V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$

↑

Only the parameter of dim1

1-4　Higgs sector

Spontaneous Symmetry Breaking

Higgs Potential

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

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

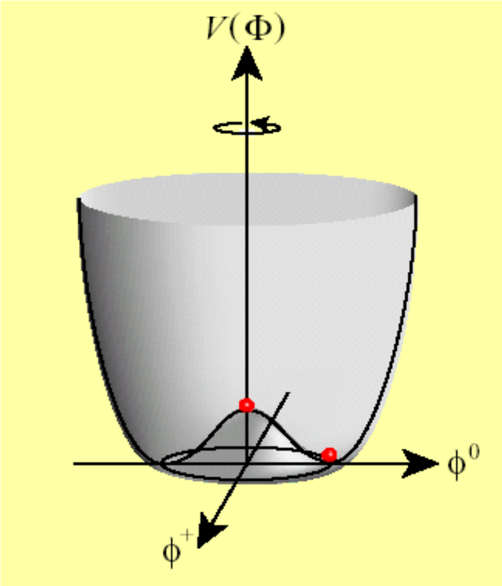
Put $\mu^2 < 0$ ⇒ Symmetry is broken

$$\boxed{\langle\phi^0\rangle = \frac{v}{\sqrt{2}} \neq 0}$$

$SU(2)_I \times U(1)_Y \to U(1)_{EM}$

$$\left.\frac{\partial V}{\partial\phi}\right|_v = 0$$

$$\left.\frac{\partial^2 V}{\partial\phi^2}\right|_v = m_h^2$$



Vacuum expectation value

$$v = \left(\frac{1}{\sqrt{2}G_F}\right)^{1/2} \simeq 246\text{GeV}$$

$$\phi^0 = \frac{1}{\sqrt{2}}(v + \underset{\uparrow}{h} + iz)$$

Higgs boson

Mass of Higgs boson *h*

$$m_h^2 = 2\lambda v^2$$

light *h* ⇔ small λ (Weak)

heavy *h* ⇔ large λ (Strong)

Higgs mechanism

Kinetic term

$$|D_\mu \Phi|^2 = \left| \left(-ig\frac{\vec{\tau}}{2} \cdot \vec{W}_\mu - \frac{i}{2} g' B_\mu \right) \Phi \right|^2$$

$$\rightarrow \frac{1}{8} \left| \begin{pmatrix} gW^3_\mu + g'B_\mu & g(W^1_\mu - iW^2_\mu) \\ g(W^1_\mu + iW^2_\mu) & -gW^3_\mu + g'B_\mu \end{pmatrix} \begin{pmatrix} 0 \\ v \end{pmatrix} \right|^2$$

$$= \frac{g^2 v^2}{8} \left[(W^1_\mu)^2 + (W^2_\mu)^2 \right] + \frac{v^2}{8} (g'B_\mu - gW^3_\mu)(g'B^\mu - gW^{3\mu})$$

$$= \left(\frac{gv}{2} \right)^2 W^+_\mu W^{-\mu} + \frac{1}{2} \left(\frac{v\sqrt{g^2 + g'^2}}{2} \right)^2 Z_\mu Z^\mu$$

$$\boxed{\frac{g'}{g} = \tan\theta_W}$$

$$e = g \sin\theta_W = g' \cos\theta_W$$

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

Gauge field	Mass eigenstate	Mass obtained
W boson	$W^\pm_\mu = \frac{1}{\sqrt{2}}(W^1_\mu \mp iW^2_\mu)$	$M_W = \frac{gv}{2}$
Z boson	$Z_\mu = \frac{gW^3_\mu - g'B_\mu}{\sqrt{g^2 + g'^2}}$	$M_Z = \frac{v\sqrt{g^2 + g'^2}}{2}$
photon	$A_\mu = \frac{g'W^3_\mu + gB_\mu}{\sqrt{g^2 + g'^2}}$	$M_A = 0$

Charged/Neutral Current

$$\mathcal{L}_{\text{int}} = \frac{g}{2\sqrt{2}}(W_\mu^- J_c^\mu + W_\mu^+ J_c^{\mu\dagger}) + eA_\mu J_{\text{em}}^\mu + \frac{g}{\cos\theta} Z_\mu J_Z^\mu$$

Charged current

$$J_c^\mu = \overline{d}^i \gamma^\mu (1-\gamma_5) u^i + \overline{e}^i \gamma_\mu (1-\gamma_5) \nu^i$$

Neutral current

$$J_Z^\mu = j^{(3)\mu} - \sin^2\theta_W J_{\text{em}}^\mu$$

$$j^{(3)\mu} = \overline{Q}_L^i \gamma_\mu \frac{\tau_3}{2} Q_L^i + \overline{L}_L^i \gamma_\mu \frac{\tau_3}{2} L_L^i$$

$$J_{\text{em}}^\mu = +\frac{2}{3}\overline{u}^i \gamma^\mu u^i - \frac{1}{3}\overline{d}^i \gamma^\mu d^i - \overline{e}^i \gamma^\mu e^i$$

Weak eigenstate basis（Not mass eigenbasis）

EW ρ parameter

Cherged Current

$$\mathcal{M}^{CC} = \frac{4G}{\sqrt{2}} J^{\rm CC}_{\mu} J^{{\rm CC}\mu\dagger}$$

$$\mathcal{M}^{CC} = \left(\frac{g}{\sqrt{2}} J^{\rm CC}_{\mu}\right)\left(\frac{1}{M_W^2}\right)\left(\frac{g}{\sqrt{2}} J^{{\rm CC}\mu\dagger}\right)$$

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

Neutral Current

$$\mathcal{M}^{NC} = \frac{4G}{\sqrt{2}} 2\rho J^{\rm NC}_{\mu} J^{{\rm NC}\mu}$$

$$\mathcal{M}^{NC} = \left(\frac{g}{\cos\theta_W} J^{\rm NC}_{\mu}\right)\left(\frac{1}{M_Z^2}\right)\left(\frac{g}{\cos\theta_W} J^{{\rm NC}\mu}\right)$$

$$\frac{\sigma(\nu_\mu N \to \nu_\mu X)}{\sigma(\nu_\mu N \to \mu^- X)} \sim 0.31$$

neutrino scattering

EW ρ parameter: the ratio of CC and NC

$$\boxed{\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W}}$$

In the SM, ρ = 1 is predicted

Experimentally ρ is very close to unity

$$\boldsymbol{\rho_{\rm exp} = 1.0004^{+0.0003}_{-0.0004}}$$

Mass of quarks and leptons

SM is a chiral theory (Left and Right have different charges)

Fermions are massless under chiral symmetry

Dirac masses are generated via Yukawa couplings and SSB

$$\overline{Q_L} Y_u \tilde{\Phi} u_R \to (\overline{u}_L, \overline{d}_L) Y_u \begin{pmatrix} \frac{v}{\sqrt{2}} \\ 0 \end{pmatrix} u_R = \frac{Y_u v}{\sqrt{2}} \overline{u}_L u_R$$

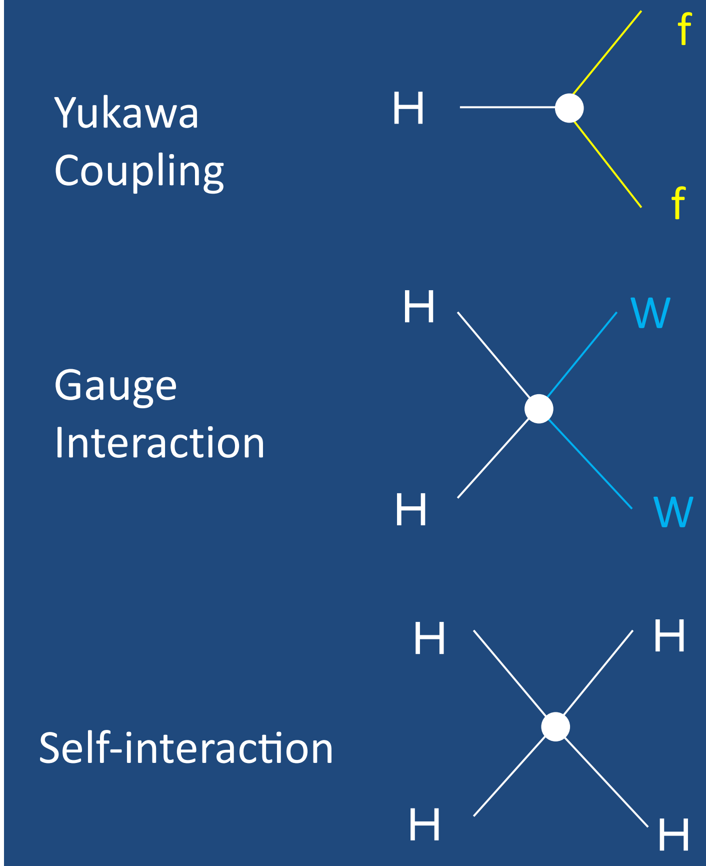
$$\overline{Q_L} Y_d \Phi d_R \to (\overline{u}_L, \overline{d}_L) Y_d \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} d_R = \frac{Y_d v}{\sqrt{2}} \overline{d}_L d_R$$

$$\overline{L_L} Y_\ell \Phi e_R \to (\overline{\nu}_L, \overline{e}_L) Y_\ell \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} e_R = \frac{Y_\ell v}{\sqrt{2}} \overline{e}_L e_R$$

$$\tilde{\Phi} = i\tau_2 \Phi$$

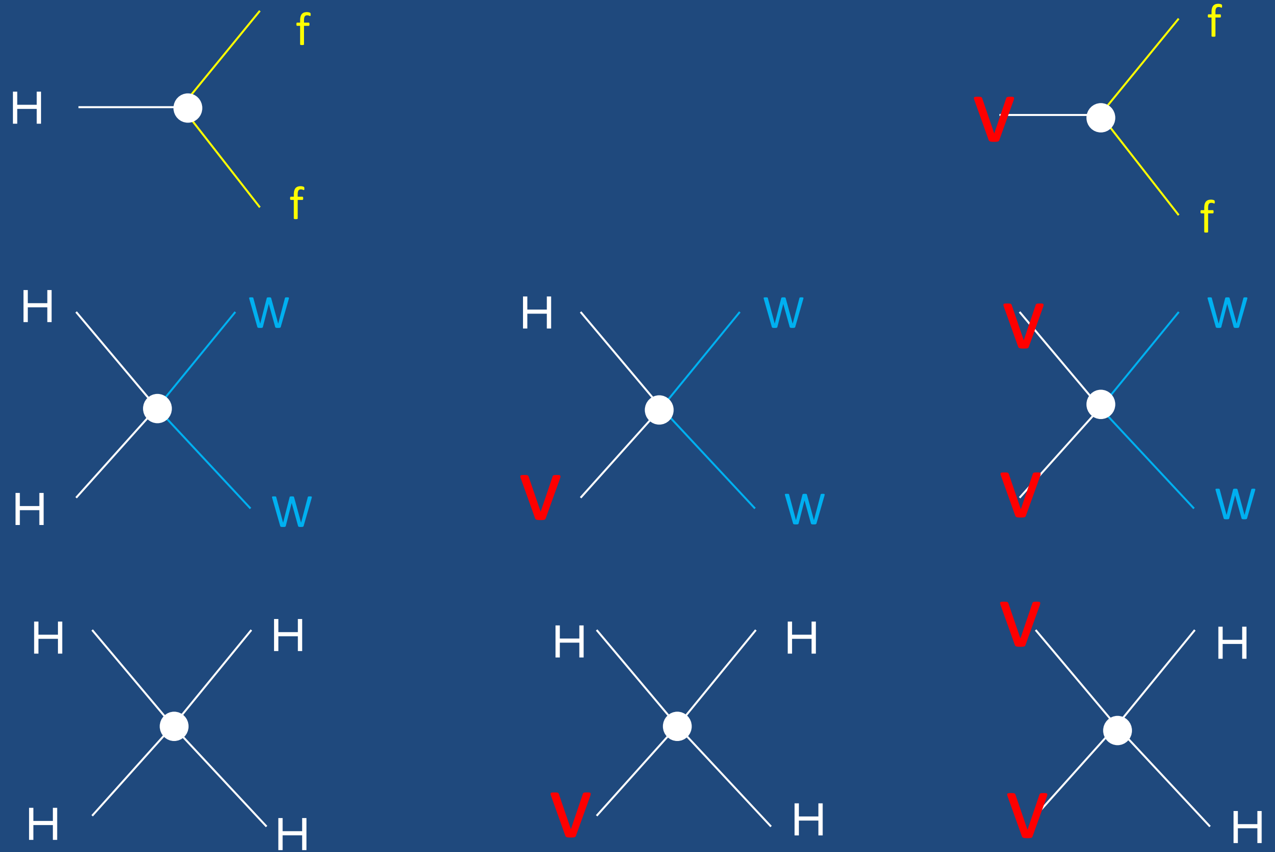
If flavor (genmeration) is taken into accout, Yukawa coupling is a matrix, and mass matrices for quarks and leptons are generated.

Higgs is Origin of Mass



Higgs is Origin of Mass

Masses of all particles come from vacuum!



Yukawa Coupling

Gauge Interaction

Self-interaction

3-point coupling

Mass

Mass-Coupling Universality

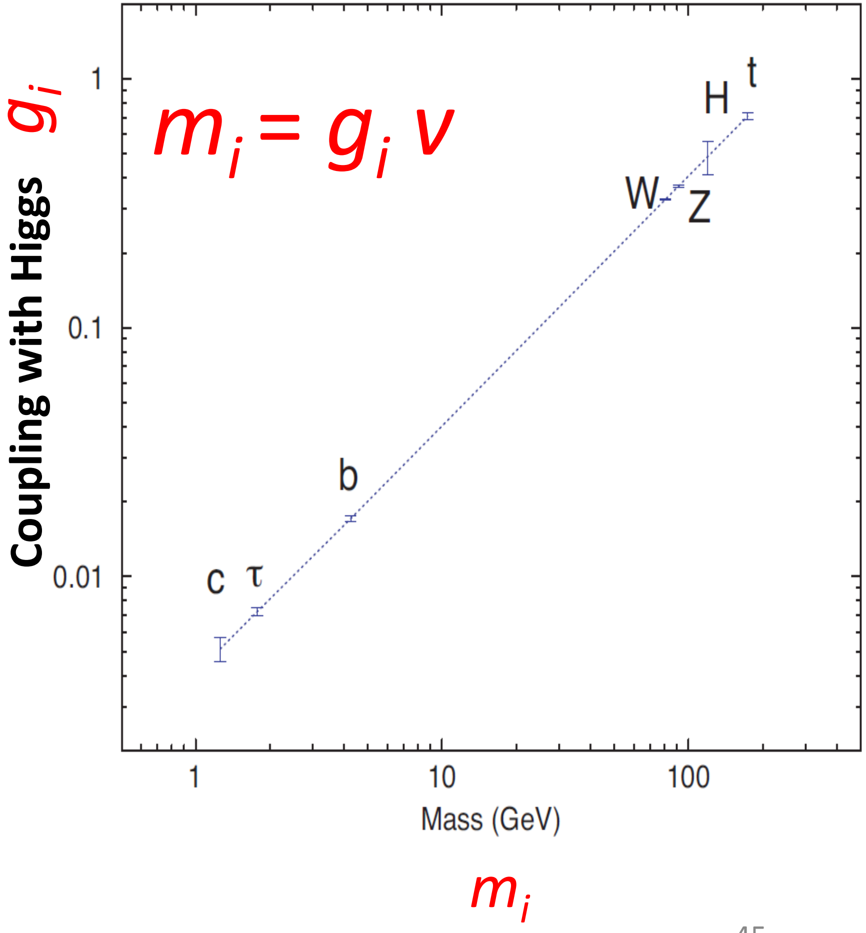
In the SM, we have the relation

$$\frac{2m_W}{g} = \frac{\sqrt{2}m_b}{y_b} = \frac{\sqrt{2}m_c}{y_c} = \frac{\sqrt{2}m_\tau}{y_\tau} = \frac{m_H}{2\sqrt{\lambda}} = v$$

SM can be tested by using this Mass-Coupling Universality

In other Higgs models (e.g. 2HDM), this relation is violated at tree level and radiative corrections

Need to measure both masses and couplings as precisely as possible

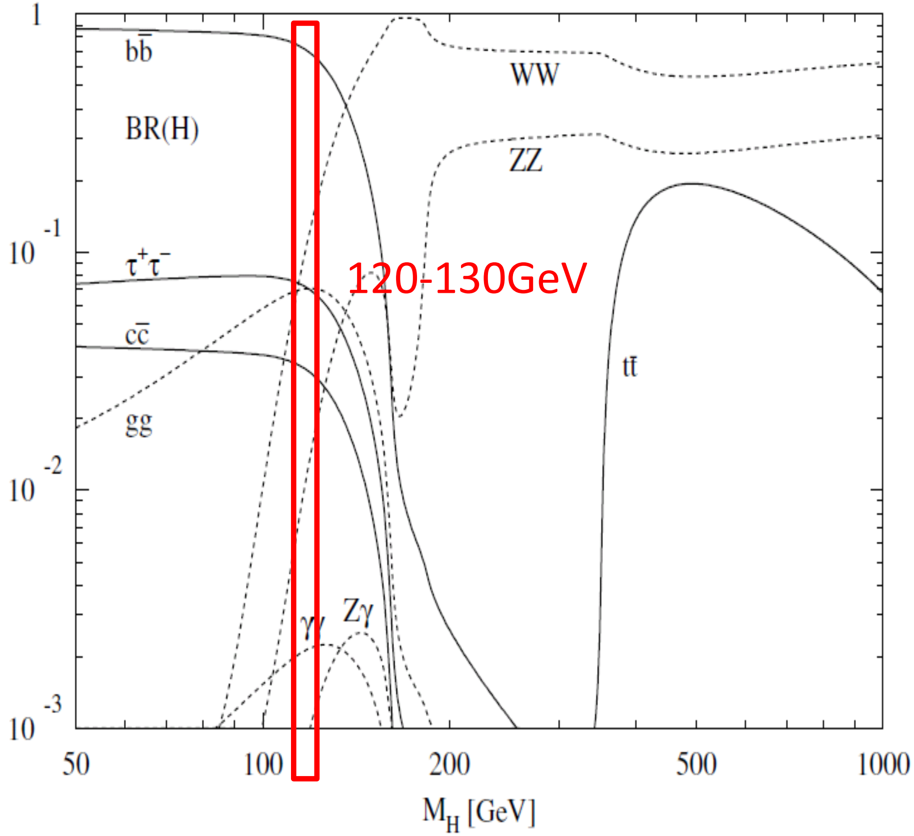


Rich decay modes for 125 GeV

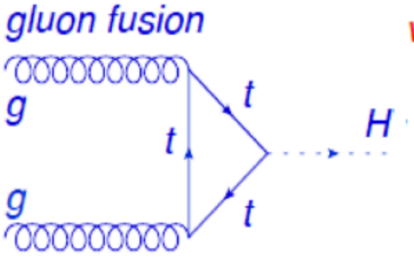
- **Higgs is origin of mass**
- **It couples to all particles**

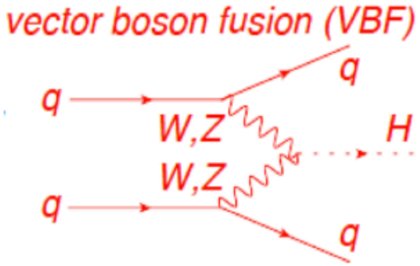
  [*hγγ, hgg* via loop]
- **Decay to various particles**
- **In particular, we are very *lucky* because *m_h*=125 GeV is ideal to test many decays**

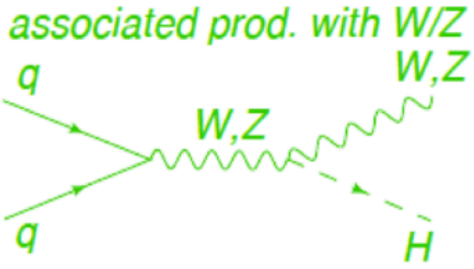
M. Spira Fortsch. Phys. 46 (1998)

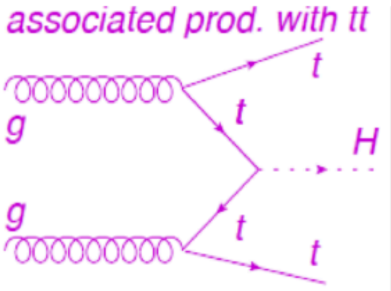


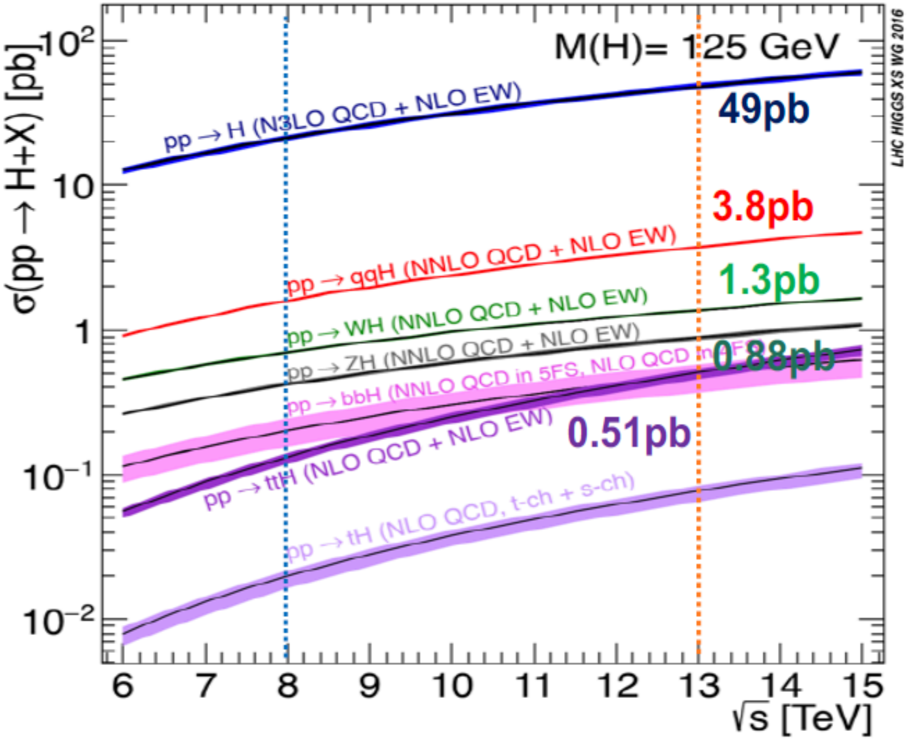
Higgs production and decay in SM

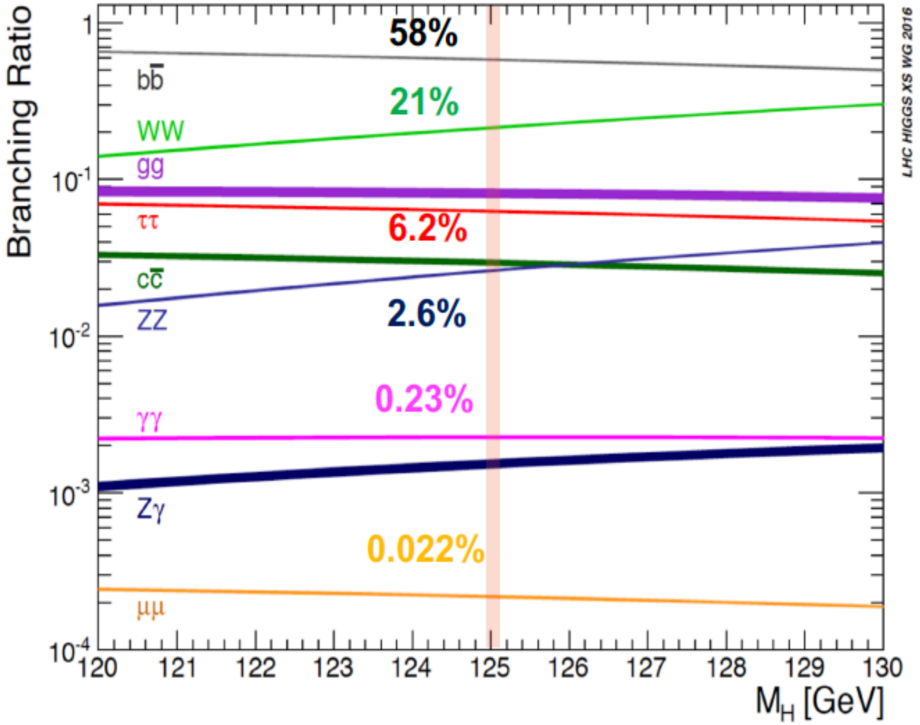

gluon fusion

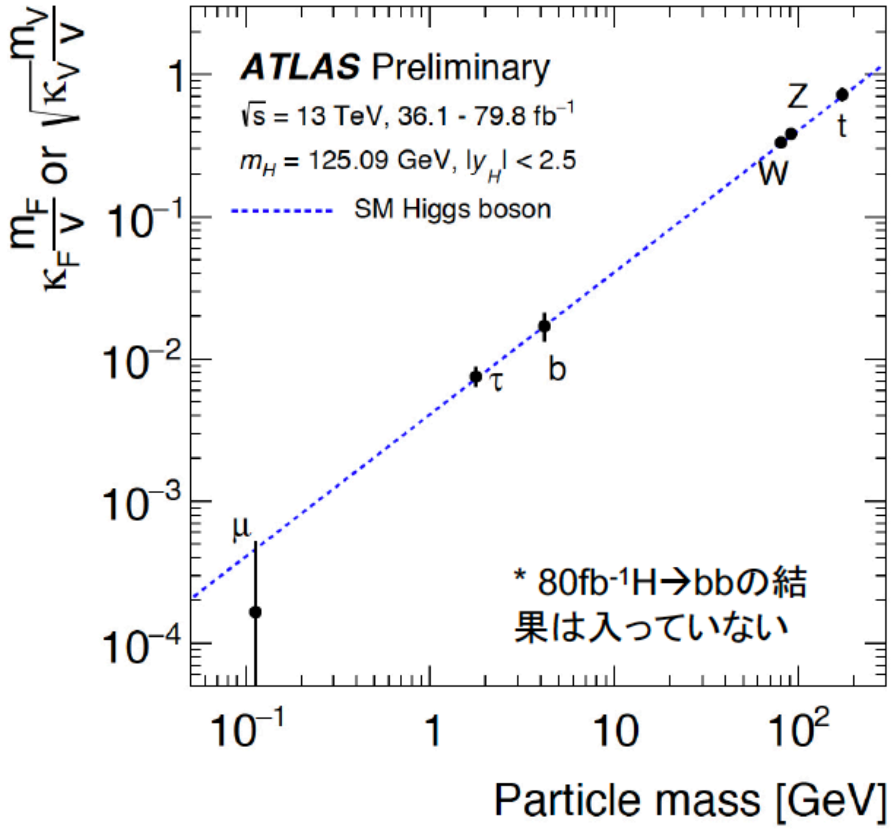

vector boson fusion (VBF)


associated prod. with W/Z

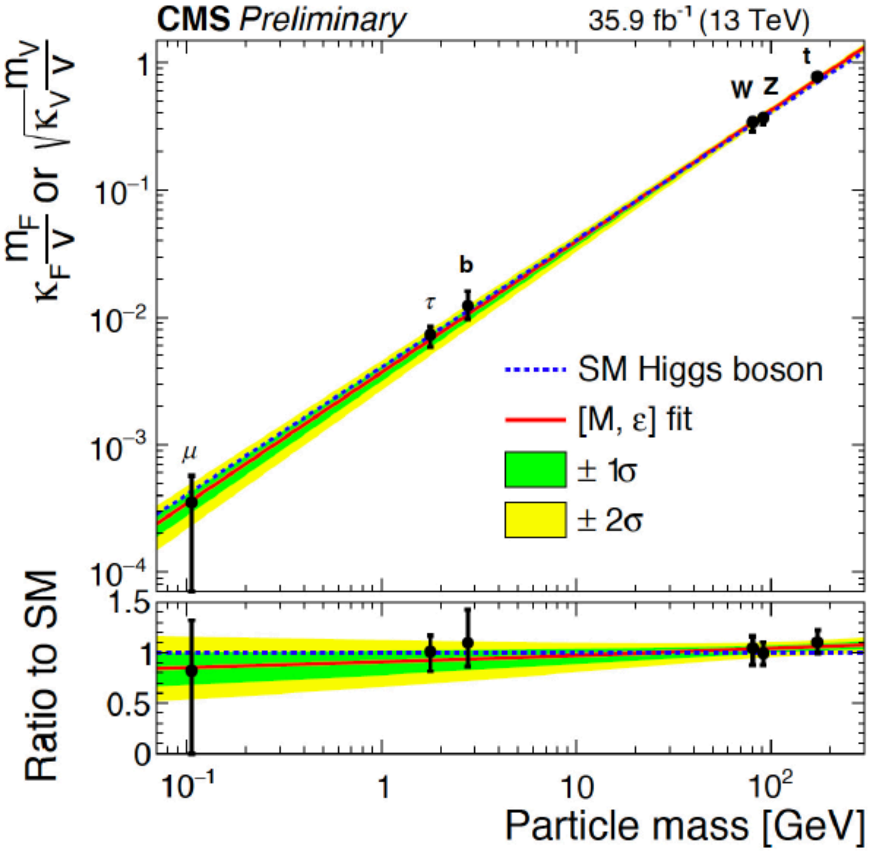

associated prod. with tt







* 80fb-1H→bbの結果は入っていない



Flavor Mixing (skip)

Ratio of leptonic decays of π (ud) and K (us)

$$\frac{\Gamma(K^+ \to \mu^+ \nu_\mu)}{\Gamma(\pi^+ \to \mu^+ \nu_\mu)} \sim 0.05$$

Reaction with ΔS = 1 is suppressed as compared to that with ΔS = 0

Explained using mixing between d and s

$$\begin{pmatrix} d \\ s \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d' \\ s' \end{pmatrix}$$

Weak eigenstates

Cabbibo angle

Mass eigenstates

$$Q_L = \begin{pmatrix} u \\ d' \cos\theta_c + s' \sin\theta_c \end{pmatrix} \qquad \frac{\Gamma(K^+ \to \mu^+ \nu_\mu)}{\Gamma(\pi^+ \to \mu^+ \nu_\mu)} = \tan^2\theta_c \qquad \boxed{\theta_c \sim 13^\circ}$$

Small deviation in the coupling of beta decays
Can also be explained

$$G_\beta = \cos^2\theta_c G_\mu \simeq \underline{0.974} G_\mu$$

Data

$$G_\mu \simeq 1.166 \times 10^{-8} \mathrm{GeV}^{-2}$$

$$G_\beta \simeq 1.136 \times 10^{-8} \mathrm{GeV}^{-2}$$

Ratio = 0.974

Flavor Changing Neutrial Current

When only u, d, s were known as quarks

Cabbibo explained charged current processes by flavor mixing

$$\boxed{\theta_c \sim 13^\circ}$$

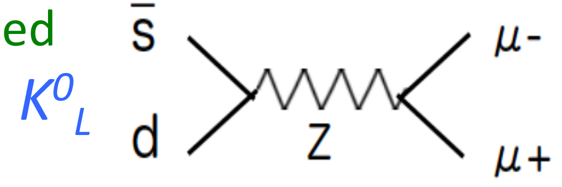
At the same time, flavor changing neutral current was predicted

$$J^{\mu}_{W^3} = \overline{Q}_L \frac{\tau_3}{2}\gamma^{\mu} Q_L \quad \sim \cdots - \sin\theta_c \cos\theta_c (\overline{d'}_L \gamma^{\mu} s'_L + (\text{h.c}))$$

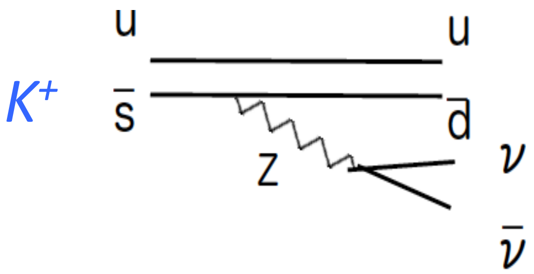
Flavor Changing Neutral Current (FCNC)

But the data shows that FCNC is very suppressed

$$B(K^0_L \to \mu^+\mu^-) \sim 10^{-8}$$



$$B(K^+ \to \pi^+\nu\overline{\nu}) \sim 10^{-10}$$



GIM Mechanism

Introduction of the second generation isospin doublet (charm quark: *c*)

$$Q_L^{(2)} = \begin{pmatrix} c \\ s \end{pmatrix} = \begin{pmatrix} c \\ -\sin\theta_c d' + \cos\theta_c s' \end{pmatrix}$$

$$J^\mu_{W^3} = \overline{Q}_L^{(2)} \frac{\tau_3}{2} \gamma^\mu Q_L^{(2)} \quad \sim \cdots + \sin\theta_c \cos\theta_c (\overline{d'}_L \gamma^\mu s'_L + (\text{h.c}))$$

Canceled with the FCNC from the 1st generation

By introduction of charm quark, neutral currents are flavor diagonal

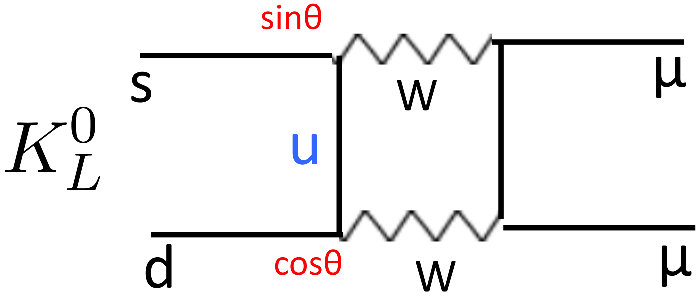
Because of the unitarity $U_d^\dagger U_d = I$, and no FCNC appear.

Glashow-Illiopoulos-Miani (GIM) mechanism (1970)

FCNC is induced via loop

Small FCNC appears by the quantum effect of charged current interaction

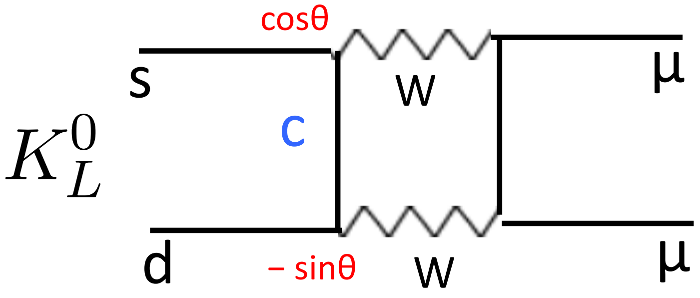
$$\mathcal{M} \sim \frac{g^2}{M_W^4}(m_c^2 - m_u^2)\sin\theta_c \cos\theta$$



It reproduces the correct order of the data

$$B(K_L^0 \to \mu^+\mu^-) \sim 10^{-8}$$

Data



Charm was discovered after 4years from GIM mechanism (1974)

FCNC and new physics

The fact of the FCNC suppression generally gives a strong constraint on new physics beyond the SM.

Extended Higgs sectors
Supersymmetric models
Technicolor
…

We see later for the case of Extended Higgs sectors

1-5 Properties of the Higgs boson

Higgs mass

Before discovery, Higgs mass was the last free parameter of the SM

There are theoretical bounds on the mass

- Unitarity
- Triviality
- Vacuum Stability

$$m_h^2 = 2\lambda v^2$$

These ideas are still useful to constrain parameters in various new physics models

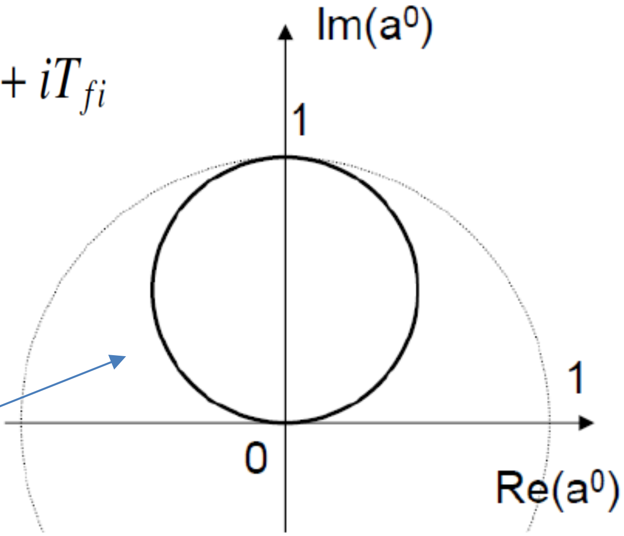
Unitarity in $W_L^+W_L^- \to W_L^+W_L^-$ elastic scatterings

S-Matrix is unitary $|S|^2 = 1$ $S_{fi} = 1_{fi} + iT_{fi}$

$$T_{fi}(s,t) = 16\pi \sum_J (2J+1) a^J_{fi}(s) P_J(\cos\theta)$$

For **2→2 elastic scatterings**,
S-wave amplitudes satisfy

$$|a^0(s)|^2 = \mathrm{Im}\left[a^0(s)\right]$$



Argand diagram

It is on the circle for unitarity

Perturbative Unitarity

If perturbation calculation is correct,
the tree-level result should be near the circle. $\boxed{|a^0| < 1}$

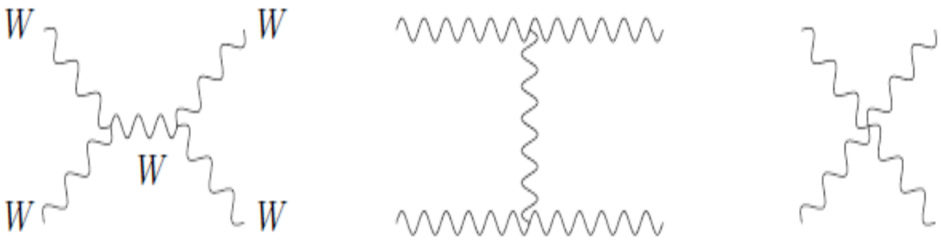
Perturbative Unitarity

Lee, Quigg, Thacker (1977)

$W_L^+ W_L^-$ **Elastic Scattering** $\epsilon_L^\mu = (p, 0, 0, E)$

$a^0(W_L^+ W_L^- \to W_L^+ W_L^-) \approx A\,E^4 + B\,E^2 + C \quad (E \to \infty)$

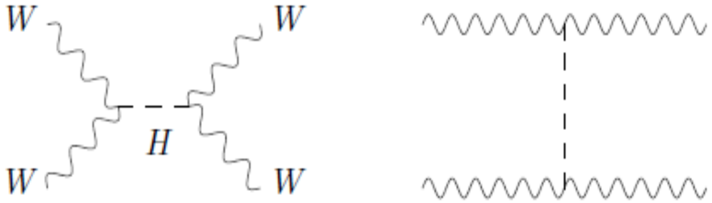
Unitarity Violation if $A, B \neq 0$



A=0 by the gauge symmetry

To make B = 0, diagrams mediated by a scalar field must be added

A Higgs field h is required to save unitarity



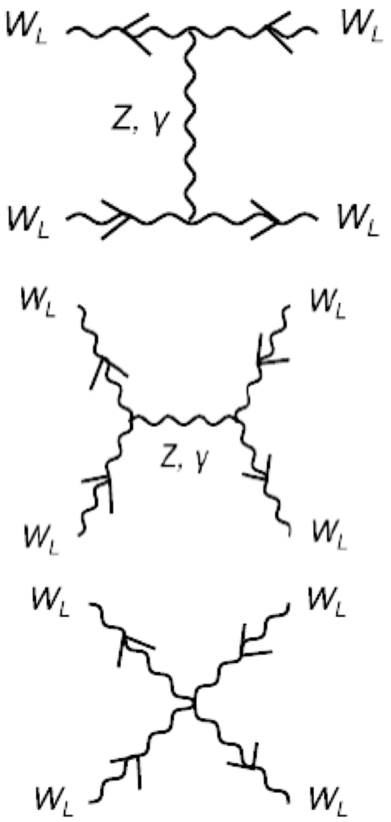
In the SM $|C| < 1 \;\Rightarrow\; m_h < 1.2$ TeV

Result without Higgs mediation

$$a^0[Z] = -\frac{g^2}{32\pi}\left\{\frac{16c_W^2}{3}\left(\frac{E}{m_W}\right)^4 - 3\left(\frac{E}{m_W}\right)^2\right\} + O(g^2),$$

$$a^0[\gamma] = -\frac{g^2}{32\pi}\frac{16s_W^2}{3}\left(\frac{E}{m_W}\right)^4 + O(g^2),$$

$$a^0[\text{接触項}] = -\frac{g^2}{32\pi}\left\{-\frac{16}{3}\left(\frac{E}{m_W}\right)^4 + 4\left(\frac{E}{m_W}\right)^2\right\} + O(g^2),$$



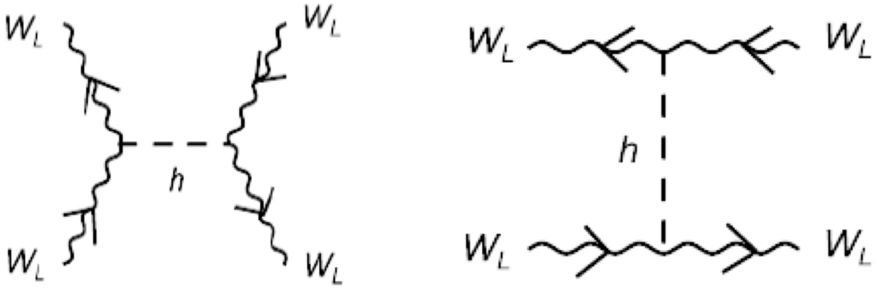
S-wave amplitude $$a^0(s) = -\frac{G_F\, s}{16\pi\sqrt{2}} + O(g^2),$$

$|a^0| < 1$ → $E < 2.5$ TeV

Unitarity is broken at high energies

Addition of the Higgs mediation

$$\boxed{g_{hWW}{}^{SM} \rightarrow \kappa\, g_{hWW}{}^{SM}}$$



$$a^0[h] = (-1+\kappa^2)\frac{G_F s}{16\sqrt{2}\pi} + \kappa^2 \frac{G_F m_h^2}{8\sqrt{2}\pi}\left\{2 + \frac{m_h^2}{s-m_h^2} - \frac{m_h^2}{s}\ln\left(1+\frac{s}{m_h^2}\right)\right\} + O(g^2)$$

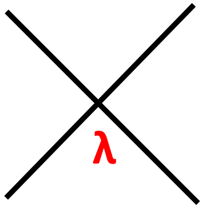
Cancellation occurs for only if κ = 1. (Namely the SM case)

S-wave amplitude $a^0(s) \sim \dfrac{G_F m_h^2}{4\pi\sqrt{2}}, \qquad (\sqrt{s} \to \infty).$

$|a^0| < 1$ → $m_h < 1.2$ TeV

Unitarity is stabilized, and the upper bound on the mass is obtained

Perturbative Unitarity



$m_h^2 = 2\lambda v^2$

Multi-Channel Unitarity $W_L^+ W_L^-, Z_L Z_L, hh, Zh$

O(4): $\varphi = (w_1, w_2, z, h)$

$$a^0 \to -\frac{G_F m_h^2}{4\pi\sqrt{2}} \times \begin{pmatrix} 1 & \frac{1}{\sqrt{8}} & \frac{1}{\sqrt{8}} & 0 \\ \frac{1}{\sqrt{8}} & \frac{3}{4} & \frac{1}{4} & 0 \\ \frac{1}{\sqrt{8}} & \frac{1}{4} & \frac{3}{4} & 0 \\ 0 & 0 & 0 & \frac{1}{2} \end{pmatrix}$$

Lee, Quigg, Thacker (1977)

$$4 \otimes 4 = 1 \oplus 9 \oplus 6$$

(1)	+ 2ww + zz + hh
$(9)_{33} + (9)_{44}$	- 2ww + zz + hh
$(9)_{33} - (9)_{44}$	zz - hh
$(9)_{34}$	zh

Eigenvalues $(\frac{3}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2})$

$$|a^0| < 1 \quad \Rightarrow \quad m_h < 1\ \text{TeV}$$

Triviality and Vacuum stability

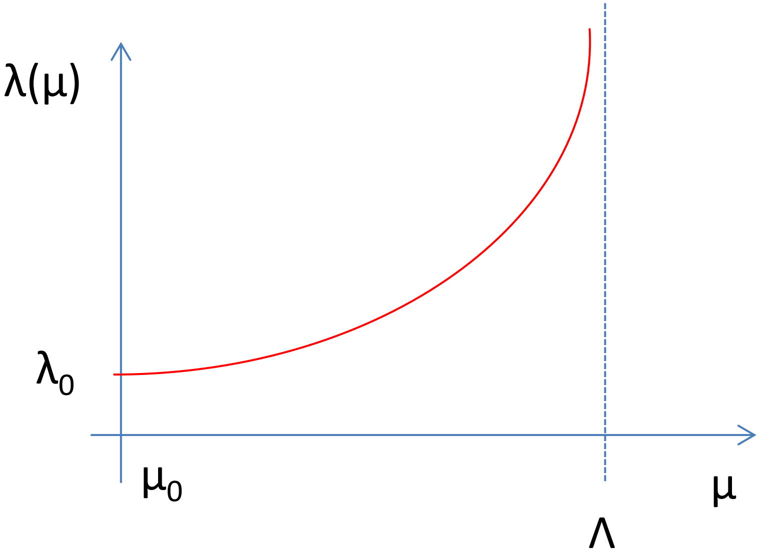
Landau Pole

The Φ^4 theory is asymptotic non-free

RGE Equation

$$16\pi^2\mu\frac{d\lambda}{d\mu} = +3\lambda^2$$

$$\boxed{\lambda(\mu) = \frac{\lambda_0}{1 - \frac{3}{16\pi^2}\lambda_0 \ln\frac{\mu}{\mu_0}}}$$



Coupling blow up and divergent at the Landau pole

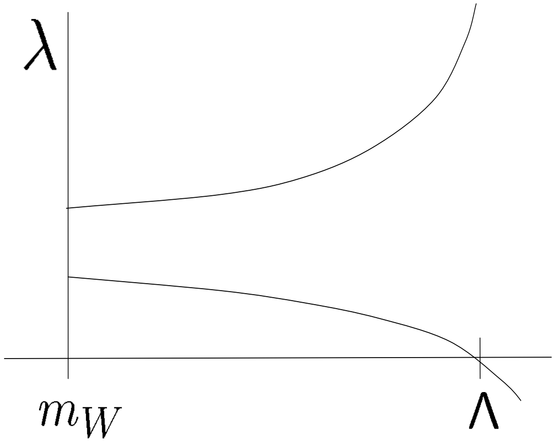
$$\Lambda = \mu_0 e^{\frac{16\pi^2}{3\lambda_0}}$$

Calculation
using perturbation
for simplicity

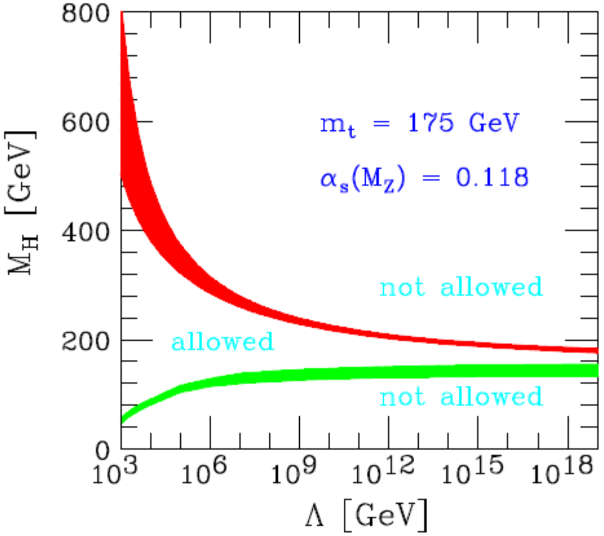
Triviality/Vacuum Stability

Require that the SM holds up to a scale Λ

- No Landau Pole
- Stable Vacuum ($\lambda > 0$)



$m_h^2 = 2\lambda v^2$



RGE of λ coupling

$y_t = O(1)$

$$16\pi^2\mu\frac{d}{d\mu}\lambda = 24\lambda^2 - 6y_t^4 + \ldots.$$

If initial value of λ is large, β-function is positive (blow up)

If the 2nd term is stronger, β-function is negative (fall down)

The Cut-off of the SM Λ

With the discovered 125 GeV Higgs boson, λ becomes negative below Planck Scale (at central value of m_t)

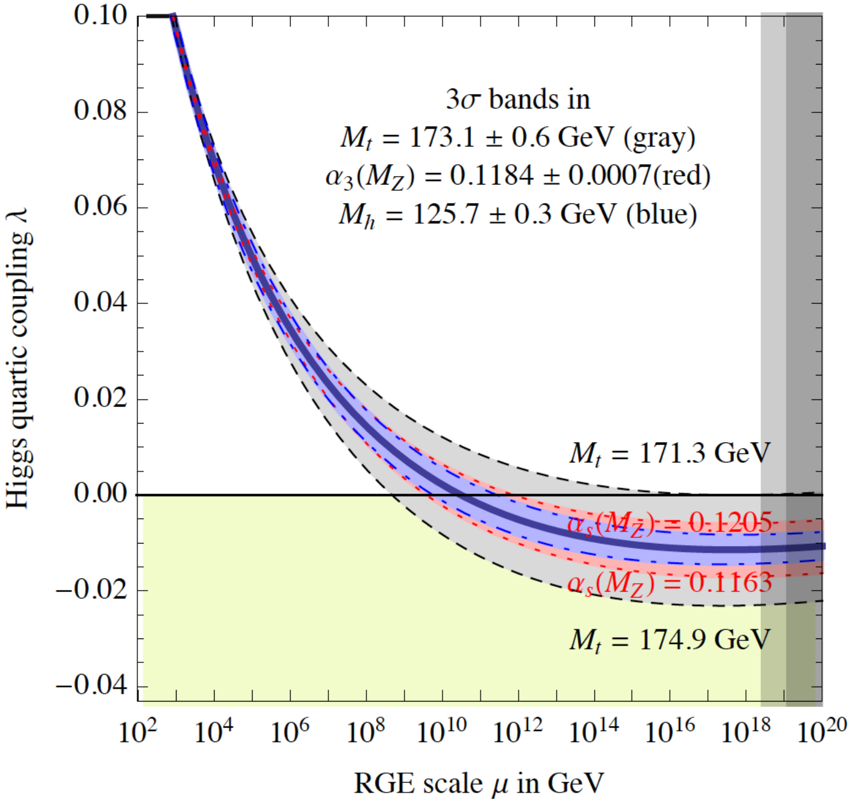
Cut off Λ = 10^7 – 10^{19} GeV

large uncertainty comes from large Δm_t

At ILC, $\Delta m_t \approx$ 30 MeV is expected

Cutoff Λ can be determined

arXiv:1205.6497, Degrassi et al



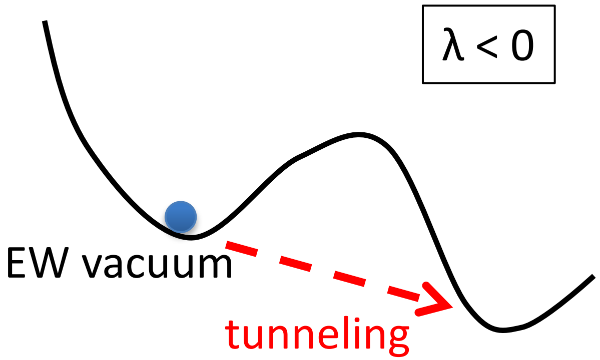
At Planck Scale, λ(M_{pl}) < 0, but the theory satisfies the condition of the meta-stable vacuum

Tunneling into the other vacuum

Decay Rate of EW vacuum
(Tunneling effect)

$$\Gamma \sim \varphi^4 e^{-S_4}$$

$$V(h) \sim \frac{\lambda(h)}{4} h^4$$



Decay Probability

$$P \sim \tau_U^4 h_t^4 e^{\frac{-8\pi^2}{3|\lambda(h_t)|}} \sim e^{560} e^{-\frac{2600}{|\lambda|/0.01}}$$

$$\beta_\lambda(h_t) \sim 0$$

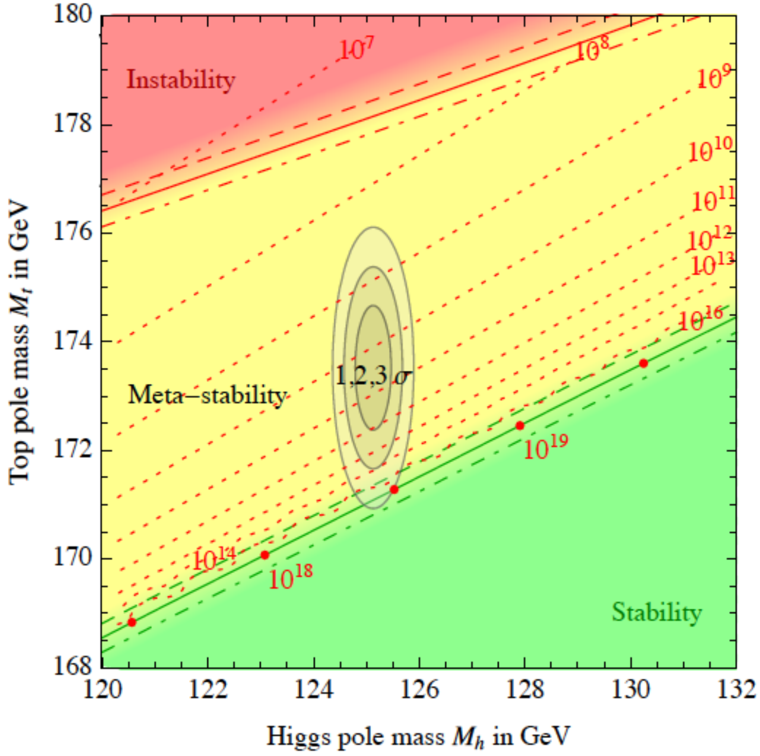
$$\tau_U^4 \sim \left(\frac{e^{140}}{M_{\mathrm{planck}}}\right)^4$$

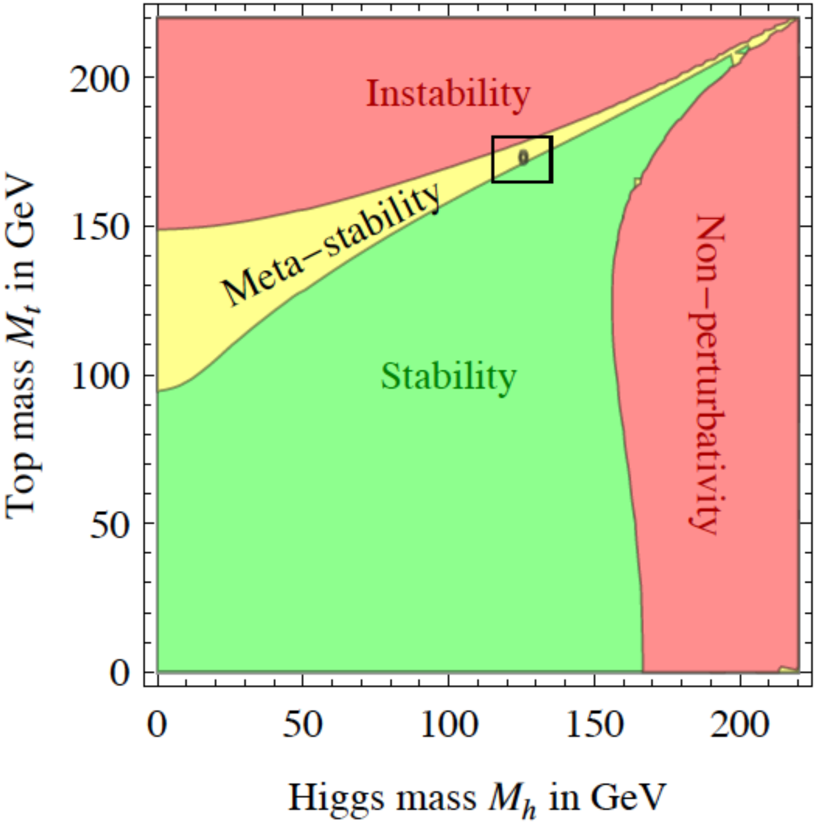
Destiny of the Universe is determined by the balance of the age of the Universe (τ_U) and the life time (τ_{EW}) of the EW vacuum

If $\lambda(h_t) = -0.01$, $\tau_U << \tau_{EW}$. Meta-stable but not dangerous

If $\lambda(h_t) < -0.05$, $\tau_U >> \tau_{EW}$. Instability and dangerous

Are we on the edge?





arXiv:1205.6497, Degrassi et al

Condition of meta-stability is satisfied. $\tau_{EW} >> \tau_U$

Part I Summary

- Higgs field is origin of mass
- Higgs is a probe of new physics
- SM Higgs sector
- Some properties (Unitarity, Vacuum stability, …)
- If SM is correct up to very high energies, the vacuum of our universe would be meta-stable.

Nambu-Goldstone Theorem

1. Lorentz and translation invariance
2. Conserved current exists
3. Symmetry is spontaneously broken

$$\partial^\mu j_\mu^A = 0$$

$$G_n = \langle 0|\mathrm{T}\phi_1(x_1)\cdots\phi_n(x_n)|0\rangle$$

$$\delta^a G_n(x_1,\cdots,x_n) = \langle 0|\mathrm{T}([iQ^a,\phi_1(x_1)\cdots\phi_n(x_n)])|0\rangle$$

$$Q^A|0\rangle \neq 0 \longrightarrow \delta^a G_n \neq 0$$

Matrix element with current

$$M_\mu^a(q,x_1,\cdots,x_n) \equiv \int d^4z\, e^{iqz}\langle 0|\mathrm{T}(J_\mu^a(z)\phi_1(x_1)\cdots\phi_n(x_n))$$

$$\lim_{q^\mu\to 0} q^\mu M_\mu^a(q,x_1,\cdots,x_n) = \lim_{q^\mu\to 0}\int d^4z\, e^{iqz}(i\partial_z^\mu)\langle 0|\mathrm{T}(J_\mu^a(z)\phi_1(x_1)\cdots\phi_n(x_n))|0\rangle$$

$$= \langle 0|\mathrm{T}([iQ^a,\phi_1(x_1)]\phi_2(x_2)\cdots\phi_n(x_n))|0\rangle + \langle 0|\mathrm{T}(\phi_1(x_1)[iQ^a,\phi_2(x_2)]\cdots\phi_n(x_n))|0\rangle$$

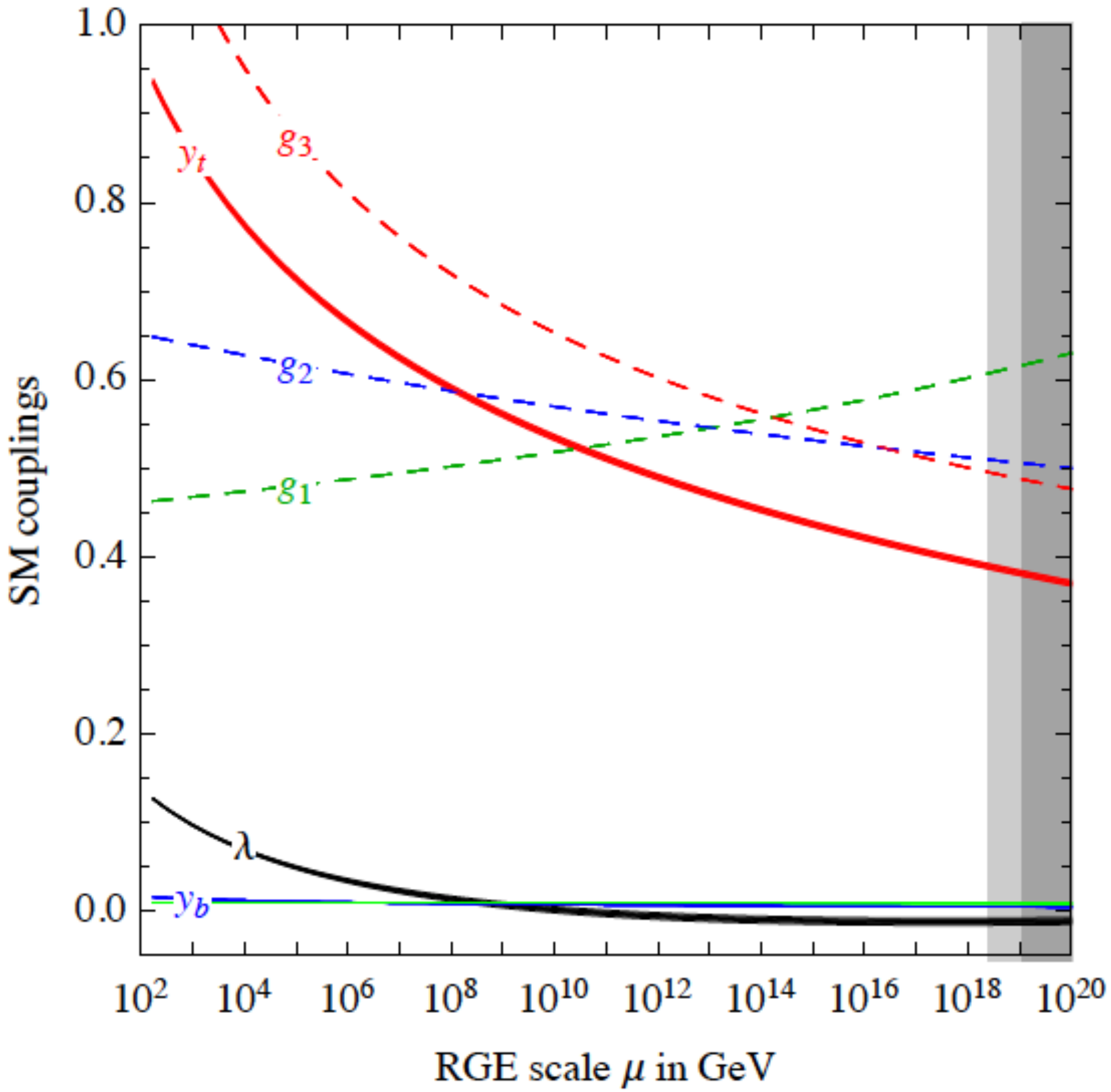
$$+\cdots+\langle 0|\mathrm{T}(\phi_1(x_1)\phi_2(x_2)\cdots[iQ^a,\phi_n(x_n)])|0\rangle = \delta^a G_n(x_1,\cdots,x_n)$$

From explicit Lorentz invariance

$$\boxed{M_\mu^a(q,x_1,\cdots,x_n) \sim \frac{q_\mu}{q^2}\delta^a G_n(x_1,\cdots,x_n)}$$

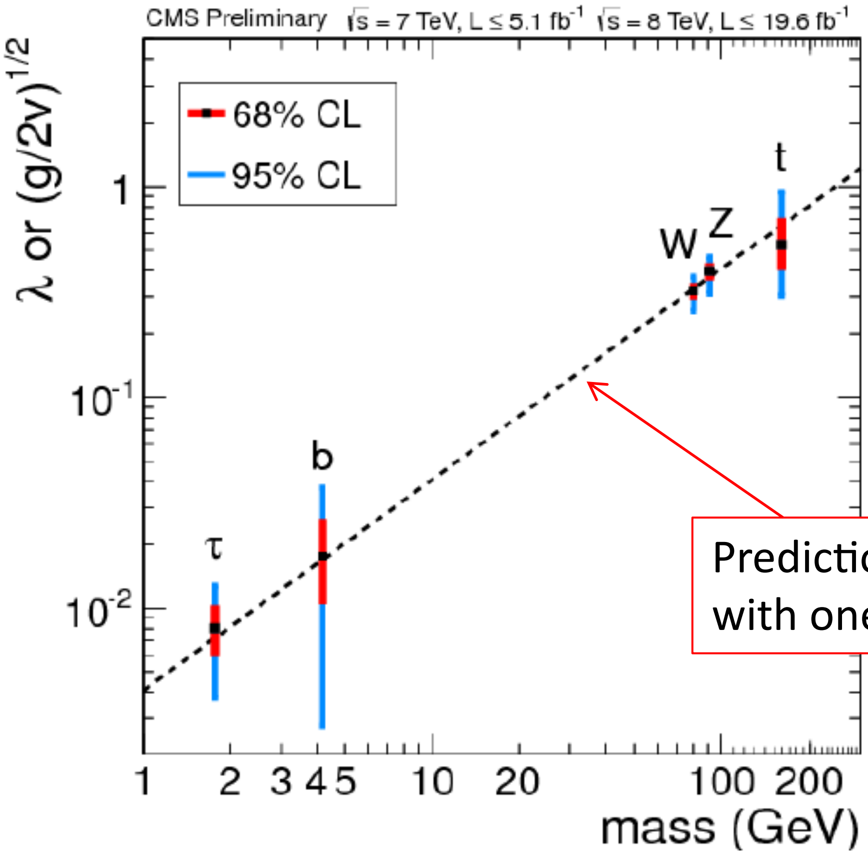
Massless particle appears and couples to the current

Nambu-Goldstone's Theorem


SM couplings
RGE scale μ in GeV
1.0
0.8
0.6
0.4
0.2
0.0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
y_t
g_3
g_2
g_1
λ
y_b

What a coincidence!

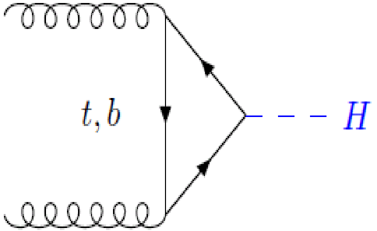
ゲージ結合と
湯川結合
の存在確認
以上の成果



Prediction in the SM
with one Higgs doublet

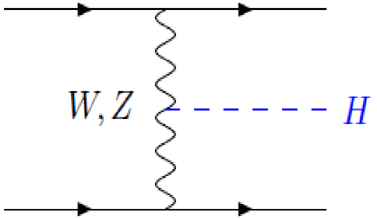
標準理論の最大の特徴：　スケールが真空期待値1個 (v=246 GeV)

Production of the SM Higgs @LHC



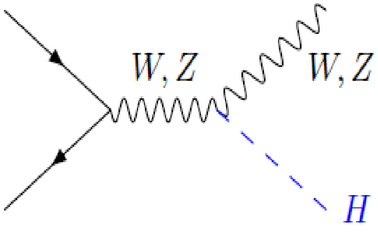
Gluon Fusion

$H\to\gamma\gamma$ (110-140GeV)
$H\to ZZ\to llll$ (140-1000GeV)
$H\to WW$ (130-170)



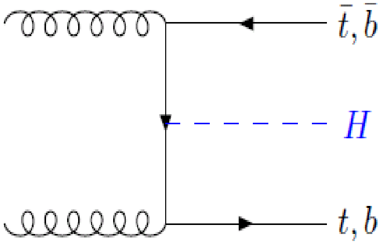
Vector Boson Fusion (VBF)

$H\to\tau\tau$ (110-140GeV)
$H\to WW$ (130-200GeV) g_{HWW}
$H\to\gamma\gamma$ (110-140GeV)
$H\to bb$ (110-140GeV) Y_b



W association

$H\to WW$ (140-170GeV) g_{HWW}



Top association

$H\to bb$ (110-130GeV) Y_t
$H\to\tau\tau$ (110-130GeV) Y_t
$H\to WW$ (130-180GeV) Y_t

Production cross section