Lectures on The Standard Model and Beyond

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Who am I?

Nobuchika Okada
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Specialization: Theoretical Particle Physics and Cosmology

Education:

03/1998	Ph.D, Physics, Tokyo Metropolitan University, Japan Thesis: A Supersymmetric Composite Model of Quarks with Dynamical Supersymmetry Breaking Advisor: Professor Hisakazu Minakata
03/1995	M.Sc, Physics, Tokyo Metropolitan University, Japan
03/1993	B.Sc, Physics, Tokyo Institute of Technology, Japan

Positions Held

08/2019–present	Professor, University of Alabama, Tuscaloosa, USA
08/2014–07/2019	Associate Professor, University of Alabama, Tuscaloosa, USA
09/2009–07/2014	Assistant Professor, University of Alabama, Tuscaloosa, USA
09/2002–08/2009	Assistant Professor, Theory Group, KEK, Japan (Tenured Position) (KEK: High Energy Accelerator Research Organization, Japan)
09/2001–08/2002	Postdoctoral Fellow, University of Maryland, College Park, USA
01/2001–08/2001	COE Research Associate, KEK, Japan
04/1998–12/2000	Japan Society for the Promotion of Science (JSPS) Postdoctoral Research Fellow, KEK, Japan
04/1996–03/1998	JSPS Research Fellow (for Graduate Students), Japan

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04/1996–03/1998	JSPS Research Fellow (for Graduate Students), Japan

More importantly:

You can call me Nobu/Nobuchika

Feel free to contact me at okadan@ua.edu

Day 1

The Standard Model

Status of the Standard Model

The Standard Model (SM) is the best theory in describing the nature of elementary particle physics, which is in excellent agreement with almost of all current experimental results (including LHC results) as of TODAY

However,

There are problems that the SM cannot answer

Physics beyond the SM (BSM Physics) is strongly suggested by both experimental & theoretical points of view

General features of BSM: New particles

New Interactions

The Standard Model

The best theory that we know in describing elementary particle phenomena at the energy scale up to O(1 TeV)

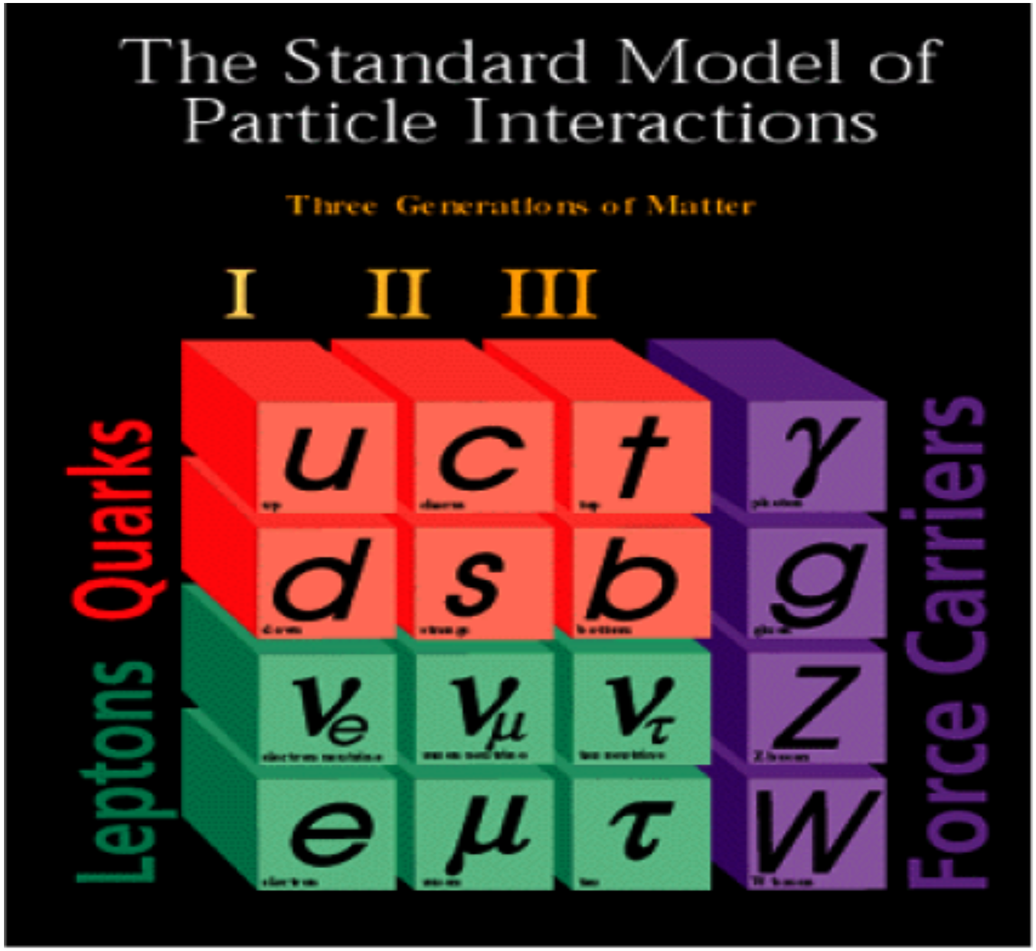
Elementary particles (*as of today*)

- Matters: quarks & leptons
- Gauge bosons: mediate interactions (gauge interactions)
- Higgs boson: origin of mass

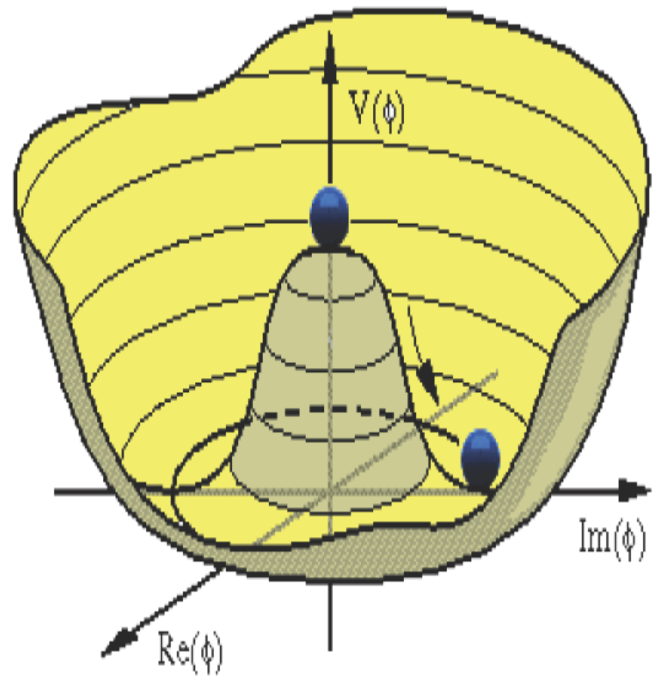
Theoretical Tech: Gauge Field Theories
(Quantum Field Theory + Gauge Invariance)

The Standard Model

Fermions & Gauge Bosons



Higgs field &
Higgs potential



The Standard Model

⊂ Spontaneously Broken Chiral Gauge Theory

"Spontaneously Broken": Spontaneous gauge symmetry breaking
Higgs mechanism

"Chiral gauge theory":

Chiral fermions involved
Left-handed and right-handed fermions interacts differently
Chiral symmetry forbids fermion masses

General definition of a model of gauge field theory

1. Define Gauge Group (U(1), SU(N) etc.)

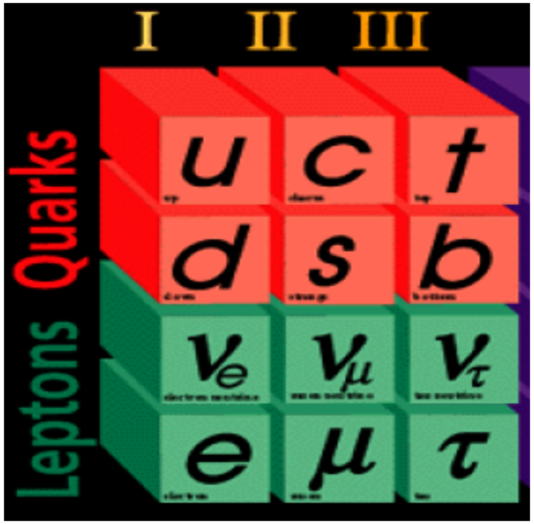
2. Fix Particle Contents

Particle content of the SM

Gauge group: $\underbrace{SU(3)_c}_{\textbf{QCD int.}} \times \underbrace{SU(2)_L \times U(1)_Y}_{\textbf{Electroweak int.}}$

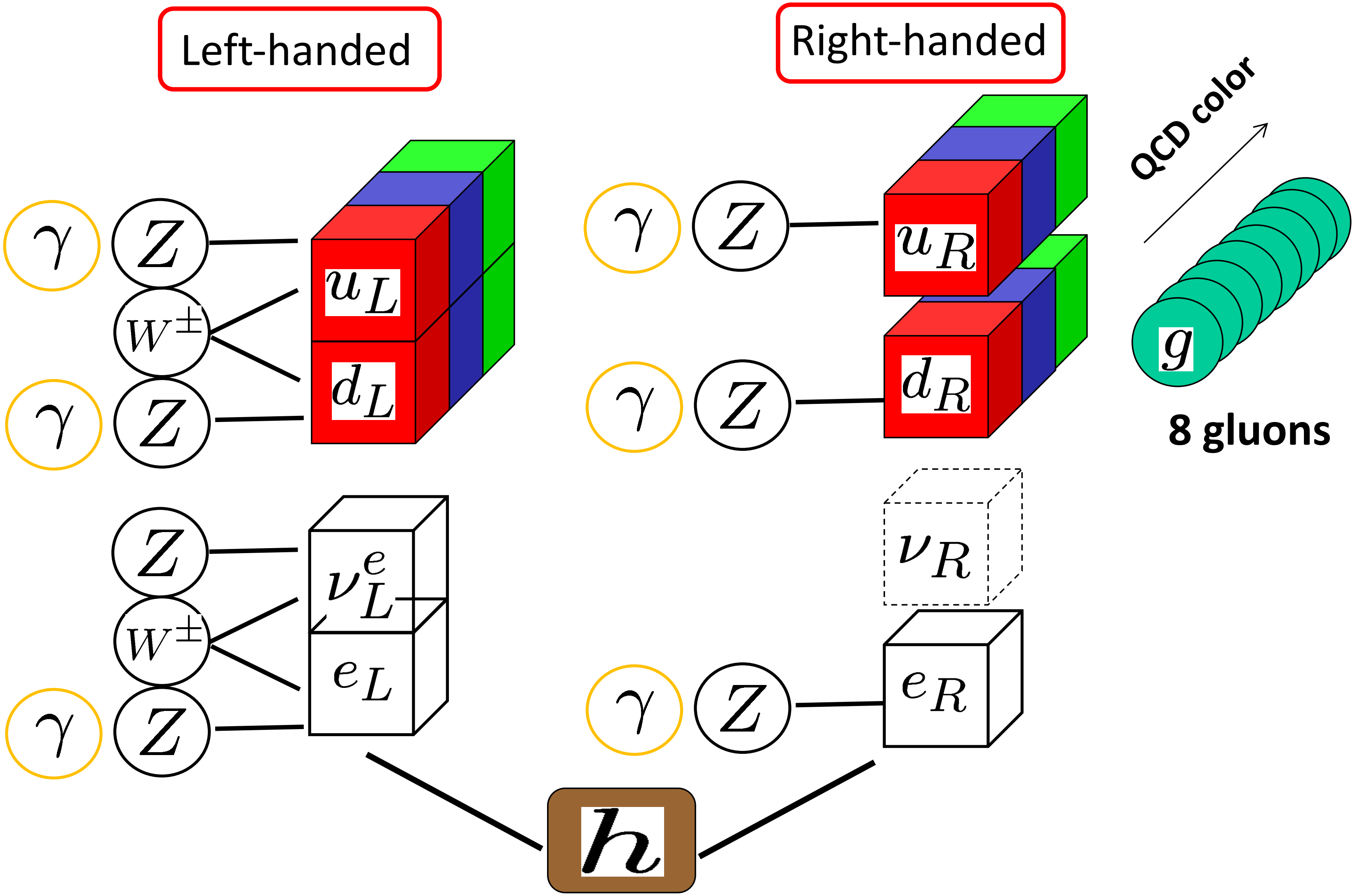
Gauge fields: **gluon** $W,\ Z,\ \gamma$

i =1,2,3	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$	**3**	**2**	1/6
u_R^i	**3**	**1**	2/3
d_R^i	**3**	**1**	-1/3
$l_L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$	**1**	**2**	-1/2
e_R^i	**1**	**1**	-1
$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix}$	**1**	**2**	-1/2



Electric charge operator: $Q_L = \frac{1}{2}\sigma^3 + Y_L,\ \ Q = Y_R$

The structure of the SM (1st generation)

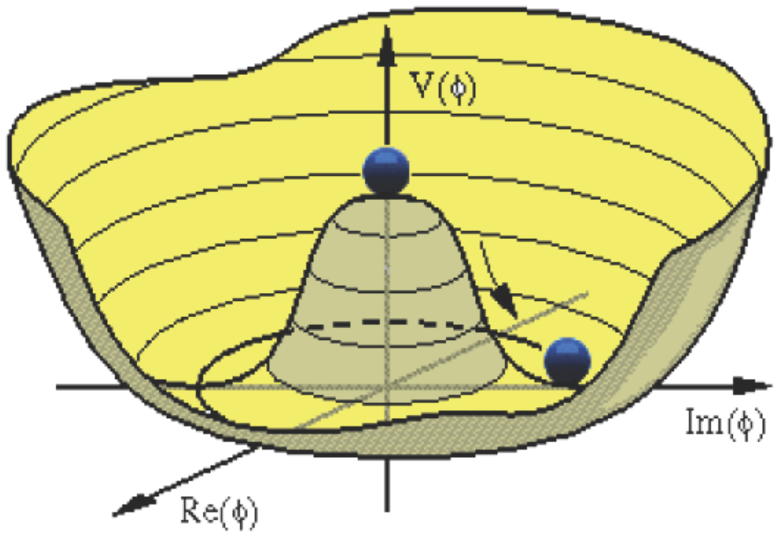


Higgs field

The Higgs scalar field plays the crucial role in the SM to generate particle masses (Higgs Mechanism)

Higgs potential

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



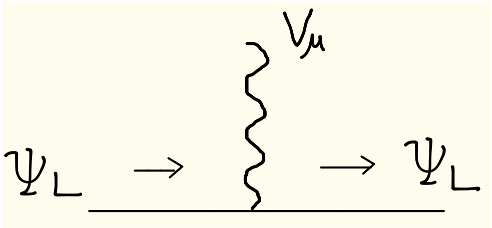
$$\langle \phi \rangle = \frac{v}{\sqrt{2}} = 174\text{GeV}$$

Vacuum of the SM, Higgs field *condenses* with non-zero vacuum expectation value
→ generating masses for particles coupling to the Higgs VEV

Interactions in the SM

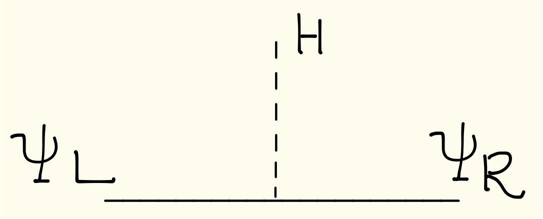
1. Gauge interactions (strong, weak, electromagnetic)

Chirality conserving: $g\,\overline{\psi_{L,R}}\gamma^{\mu}\psi_{L,R}V_{\mu}$



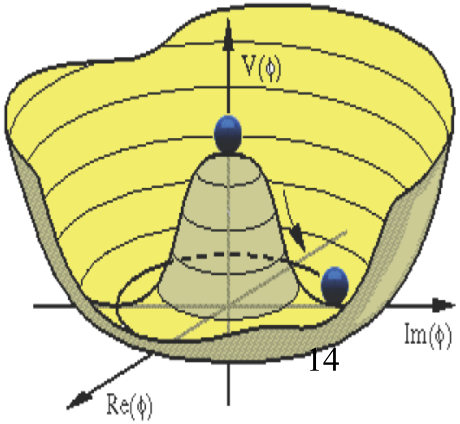
2. Yukawa interaction

Chirality flipping: $Y\,\overline{q_R}H^{\dagger}Q_L$



3. Self-interaction of Higgs

Higgs potential: $V = \lambda\left(H^{\dagger}H - \frac{v_{\rm EW}^2}{2}\right)^2$



Fundamental forces in Nature

4 fundamental forces

- Gravity interaction
- Strong interaction (QCD)
- Weak interaction
- Electromagnetic int. (QED)

Very precisely measured & checked

More interactions in the SM

Yukawa interaction
crucial for generating fermion masses

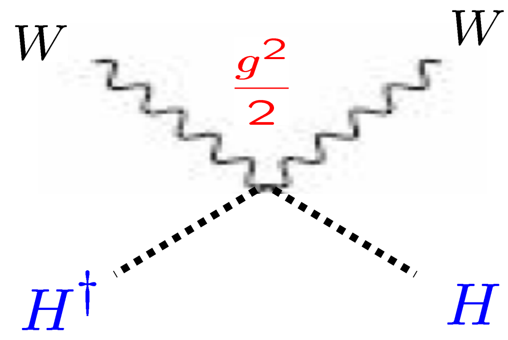
Higgs self-interaction
crucial for Higgs potential and VEV

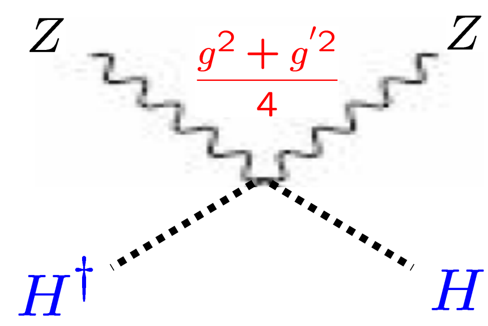
Need experimental confirmations!

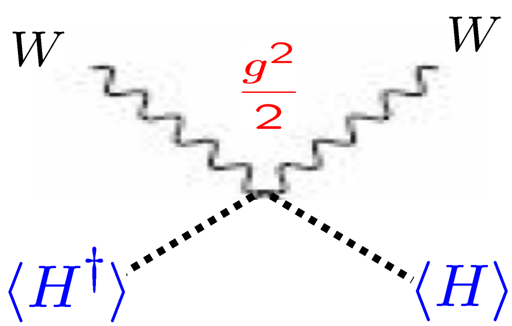
EW symmetry breaking and mass generation mechanism

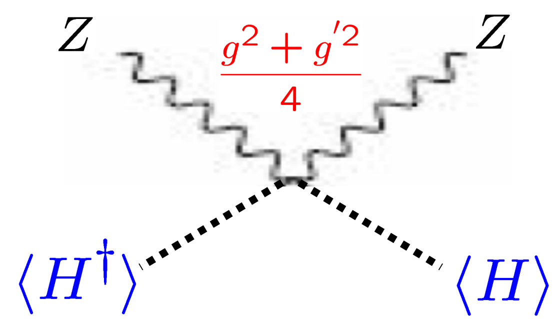
W & Z bosons get masses through gauge coupling

Gauge interaction
of Higgs doublet





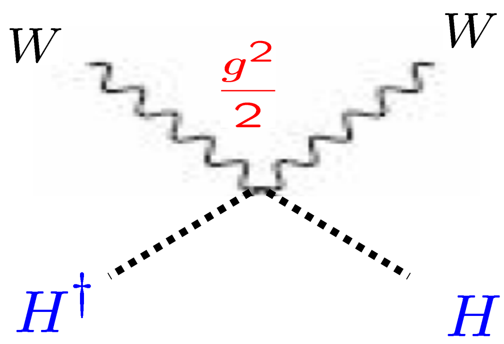




$$M_W^2 = \frac{1}{4} g^2 v^2$$

$$M_Z^2 = \frac{1}{4} (g^2 + g'^2) v^2$$

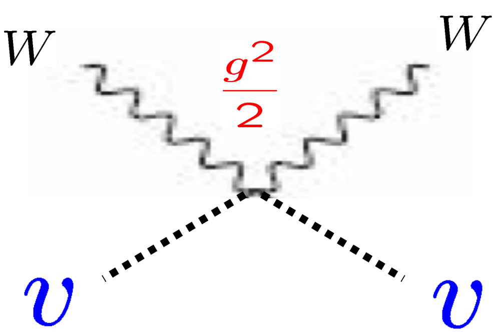
Gauge interaction of Higgs doublet



Unitary Gauge

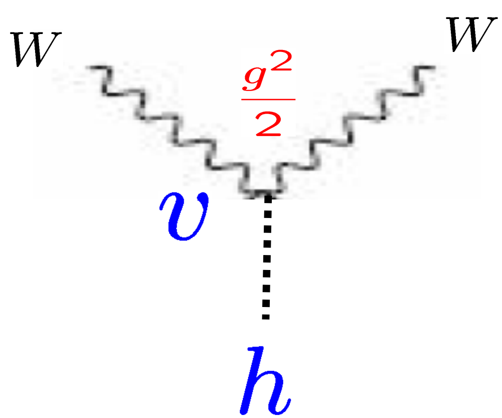
$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} v + h(x) \\ 0 \end{pmatrix}$$

Pick up Two VEVs



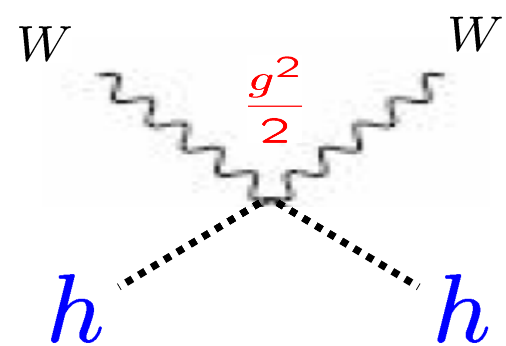
W boson mass

Pick up one VEV



3 point interaction

Pick up NO VEV

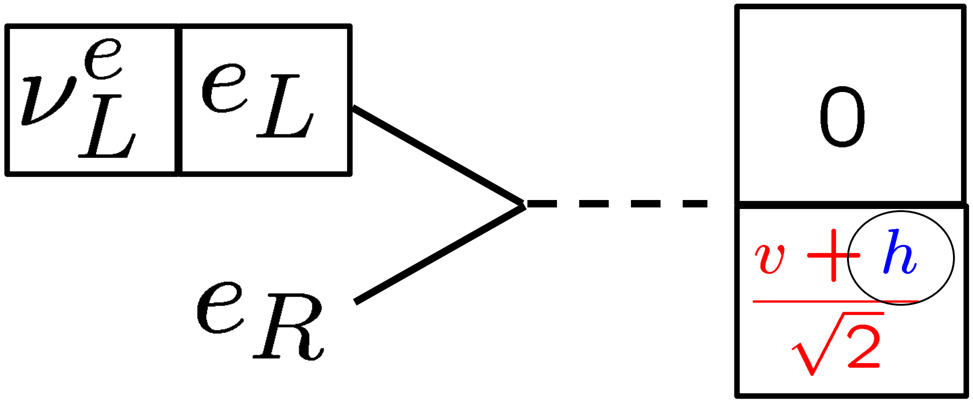


4 point interaction

Fermions get masses through Yukawa coupling

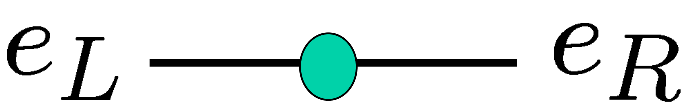
Example: electron mass

$$\tilde{H} = i\sigma^2 H^\dagger$$



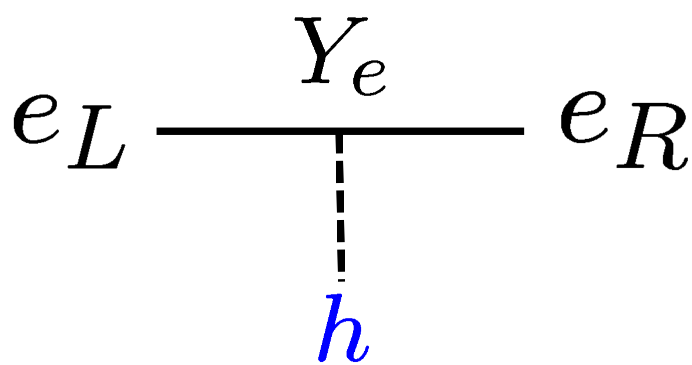
$$m_e = \frac{Y_e}{\sqrt{2}} v$$

Pick up one VEV

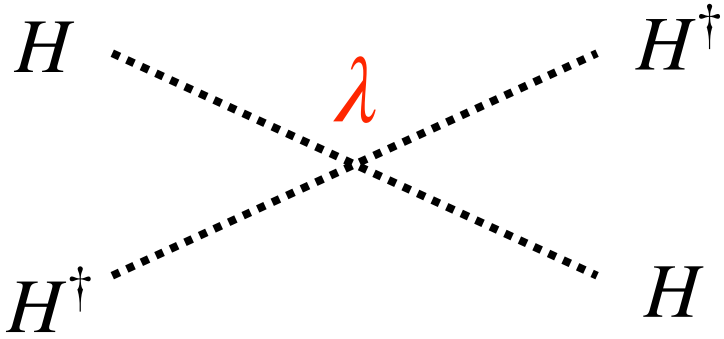


$$m_e = \frac{Y_e}{\sqrt{2}} v$$

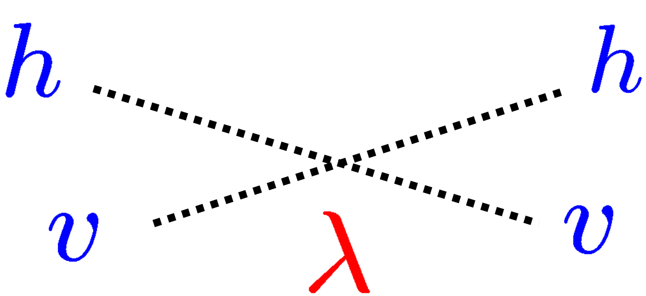
Pick up NO VEV



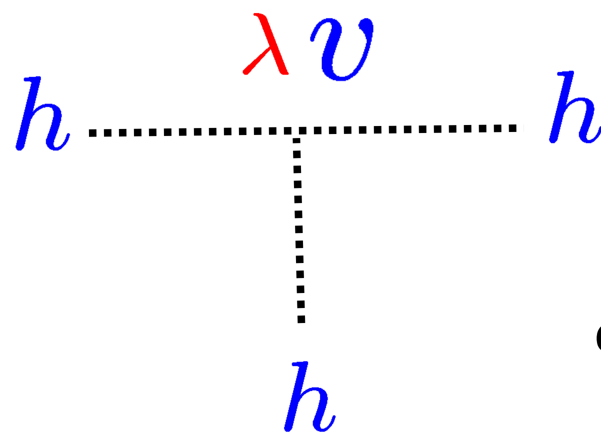
Higgs boson mass via the Higgs quartic coupling



$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} v + h(x) \\ 0 \end{pmatrix}$$

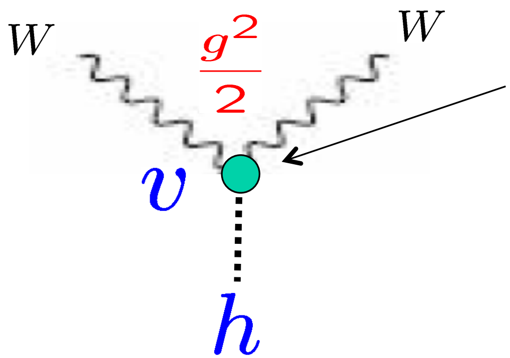


$$m_h^2 = \lambda v^2$$



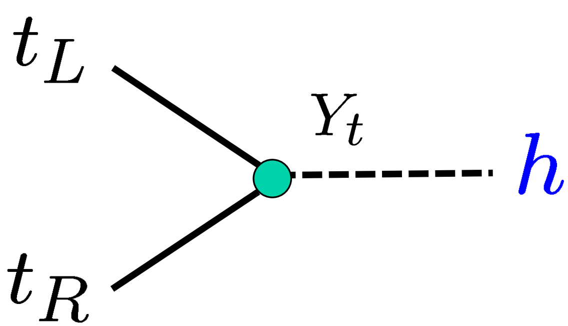
etc.

Towards experimental confirmation of the mass generation mechanism

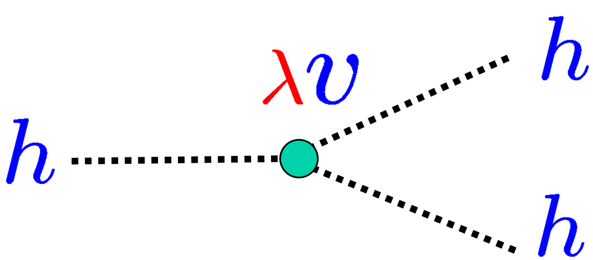


Measure the coupling precisely and compare it to the theory prediction

$$C_{exp} \overset{???}{=} \frac{m_W^2}{2v}$$



$$Y_{exp} \overset{???}{=} \frac{m_t}{v}$$



$$\lambda_{exp} \overset{???}{=} \frac{m_h^2}{v^2}$$

More details on Higgs Mechanism

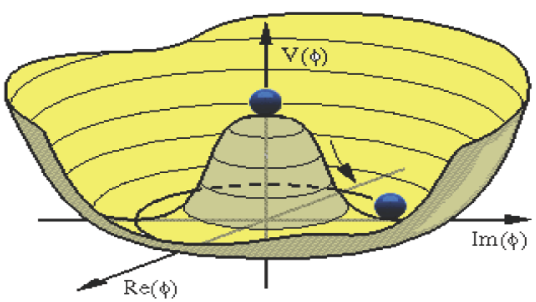
$$H(x) = \begin{pmatrix} H^0(x) \\ H^-(x) \end{pmatrix}$$ with Electric charge operator: $Q = \frac{1}{2}\sigma^3 + Y$

- $SU(2)_L \times U(1)_Y$ transformation

$$H(x) \;\rightarrow\; \exp\left(i\,\alpha^a(x)\frac{\sigma^a}{2} \right) \exp\left(i\,\left(-\frac{1}{2}\right)\,\beta(x) \right) H(x)$$

- Higgs potential

$$V(H) = -\,\mu^2\,H^\dagger H + \lambda\,(H^\dagger H)^2, \qquad (\mu^2 > 0,\ \lambda > 0)$$



$$\langle H \rangle = \begin{pmatrix} \frac{v}{\sqrt{2}} \\ 0 \end{pmatrix}, \qquad v = 246\,\mathrm{GeV}$$

For Unitary Gauge discussion, Non-Linear/Polar parametrization is more convenient:

$$H(x) = \begin{pmatrix} H^0(x) \\ H^-(x) \end{pmatrix} \to H(x) = \exp\left(i \frac{\pi^a(x)\sigma^a}{2v} \right) \frac{1}{\sqrt{2}} \begin{pmatrix} v + h(x) \\ 0 \end{pmatrix}$$

$$h(x) = \sqrt{2}\,\mathrm{Rm}\, H^0(x)$$

$$\pi^1(x) = \frac{1}{\sqrt{2}} \left(H^-(x) + H^{-*}(x) \right)$$

$$\pi^2(x) = \frac{i}{\sqrt{2}} \left(H^{-*}(x) - H^-(x) \right)$$

$$\pi^3(x) = \sqrt{2}\,\mathrm{Im}\, H^0(x)$$

These π^a are would-be Nambu-Goldstone bosons:
They are massless NG modes associated with $SU(2)_L \times U(1)_Y \to U(1)_{EM}$ symmetry breaking in the global limit.

Unitary Gauge: Remove the would-be NG modes by suitable choice of $\alpha(x)^a$ and $\beta(x)$

Matching the degree of freedom before/after symmetry breaking?

Symmetric Case

D.O.F

$W_\mu^a \ (a = 1,2,3), \ B_\mu$ — all massless: $3 \times 2 + 1 \times 2 = 8$

H — Complex doublet: $2 \times 2 = 4$

Broken Case

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp i W_\mu^2\right)$$

$$Z_\mu = c_W W_\mu^3 - s_W B_\mu$$

3 massive vector bosons: $3 \times 3 = 9$

$$m_W = \frac{1}{2} g\, v,\ m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v$$

$$\tan\theta_W = g'/g$$

$$A_\mu = s_W W_\mu^3 + c_W B_\mu,$$

1 massless photon: $1 \times 2 = 2$

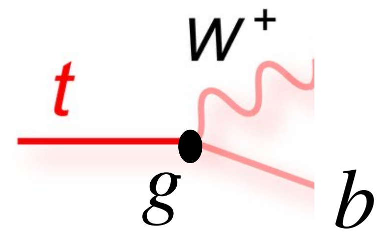
h — 1 real scalar (Higgs boson): 1

Higgs Mechanism: 3 would-be NG modes are "eaten"
by the longitudinal modes of W and Z

Theoretical observation of this structure

example 1: top quark decay ($t \to bW^+$) if $m_t \gg m_W$

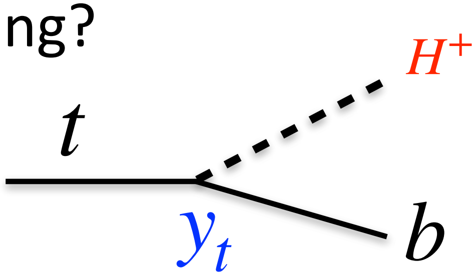
top quark decays to W+b
through SU(2) gauge interaction



$$\Gamma(t \to bW) = \frac{m_t^3}{16\pi v^2}\left(1 - \frac{m_W^2}{m_t^2}\right)^2\left(1 + 2\frac{m_W^2}{m_t^2}\right) \to \frac{m_t^3}{16\pi v^2}$$

Independent of SU(2) gauge coupling?

$$\Gamma(t \to bW) \to \frac{m_t^3}{16\pi v^2} = \frac{y_t^2}{32\pi} m_t$$

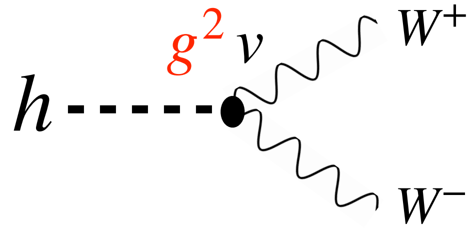


Top quark decays to would-be NG boson through
Yukawa coupling

Theoretical observation of this structure

example 2: Higgs boson decay ($h \to W^+W^-$) if $m_h \gg m_W$

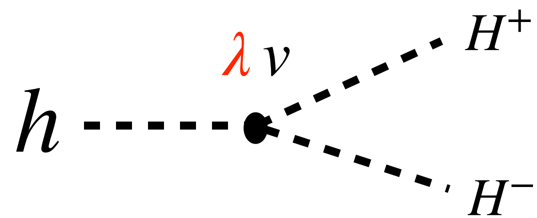
Higgs boson decays to W^+W^- through SU(2) gauge interaction



$$\Gamma(h \to W^+W^-) = \frac{m_h^3}{16\pi v^2}\sqrt{1 - \frac{4m_W^2}{m_h^2}}\left(1 - \frac{4m_W^2}{m_h^2} + \frac{12m_W^4}{m_h^4}\right) \to \frac{m_h^3}{16\pi v^2}$$

Independent of SU(2) gauge coupling?

$$\Gamma(h \to W^+W^-) \to \frac{m_h^3}{16\pi v^2} = \frac{\lambda^2 v^2}{64\pi m_h}$$



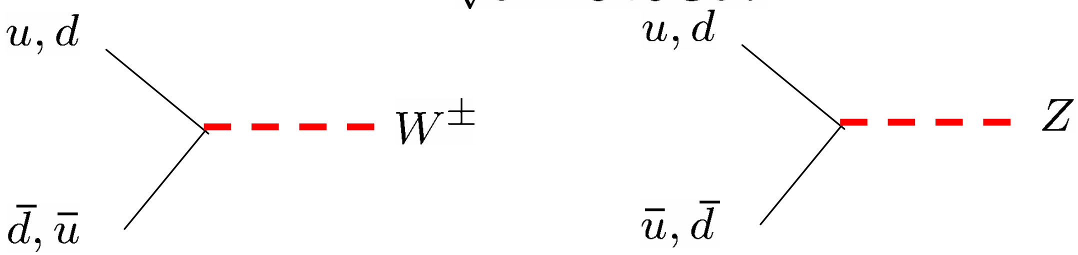
Higgs decays to would-be NG bosons through self-quartic coupling

Success of the SM before LHC

(i) Direct evidence of weak bosons

Weak gauge bosons were discovered at CERN in 1983

$p\bar{p}$ **collider with** $\sqrt{s} = 540\mathrm{GeV}$



Exp.) $M_W = 80.33 \pm 0.15\mathrm{GeV}$

$$\begin{aligned}
\Gamma(W^+ \to e^+\nu) &= 224 \pm 15\mathrm{MeV} \\
\Gamma(W^+ \to \mu^+\nu) &= 215 \pm 19\mathrm{MeV} \\
\Gamma(W^+ \to \tau^+\nu) &= 226 \pm 127\mathrm{MeV} \\
\Gamma(W^+ \to e^+\nu) &= \Gamma(W^- \to e\bar{\nu})
\end{aligned}$$

Theory) $\Gamma(W^+ \to e^+\nu_e) = \dfrac{G_F M_W^3}{6\sqrt{2}\pi} = 226\mathrm{MeV}$

Consistency (numerical), Coupling universality

(ii) More precise measurements of EW gauge interactions

LEP e^+e^- **collider**

Exp.) $M_Z = 91.187 \pm 0.007\text{GeV}$

$$
\begin{aligned}
\Gamma(Z \to e^+e^-) &= 83.82 \pm 0.30\text{MeV} \\
\Gamma(Z \to \mu^+\mu^-) &= 83.83 \pm 0.39\text{MeV} \\
\Gamma(Z \to \tau^+\tau^-) &= 83.67 \pm 0.44\text{MeV} \\
\Gamma(total) &= 2490 \pm 7\text{MeV}
\end{aligned}
$$

Th.)

$$
\begin{aligned}
\Gamma(Z \to e^+e^-) &= \frac{G_F M_Z^3}{12\sqrt{2}\pi}(1 - 2\sin^2\theta_w)^2 + 4\sin^4\theta_w) \\
&= 83.4\text{MeV}
\end{aligned}
$$

for $\sin^2\theta_w = 0.2315$

Number of neutrinos

Exp.) $\Gamma(\text{invisible}) = 498.3 \pm 4.2\text{MeV}$

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{3\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{\mu\mu}}{(E-M_Z)^2+\Gamma_t^2/4}$$

$$\sigma(e^+e^- \to \text{hadrons}) = \frac{3\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{\text{had}}}{(E-M_Z)^2+\Gamma_t^2/4}$$

$$\Gamma(\text{invisible}) = \Gamma_t - 3\Gamma_{ee} - \Gamma_{\text{had}}$$

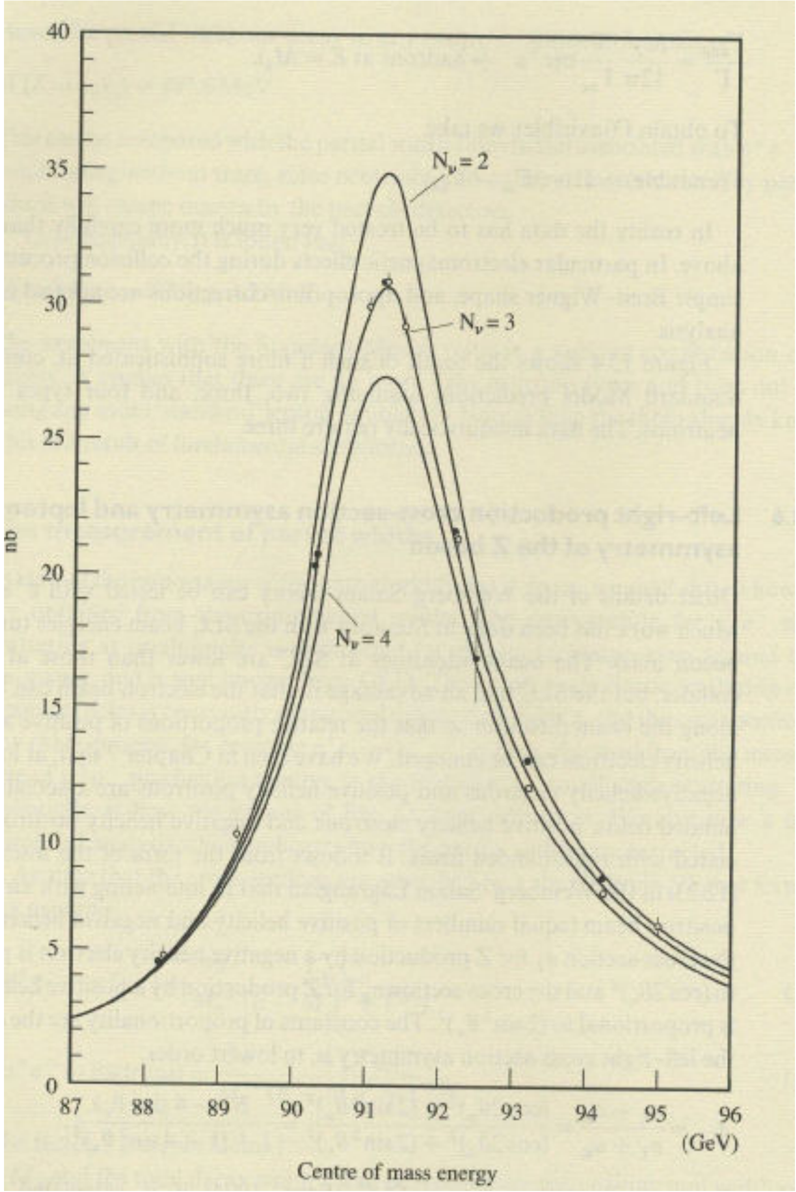
i) Z mass & total decay width from the position & width of the peak

ii) Measure cross sections at Z-pole

Th.)
$$\Gamma(Z\to\nu_e\bar{\nu}_e) = \Gamma(Z\to\nu_\mu\bar{\nu}_\mu) = \Gamma(Z\to\nu_\tau\bar{\nu}_\tau) = \frac{G_F m_Z^3}{12\sqrt{2}\pi} = 165.9\text{MeV}$$

$$\Gamma(\text{invisible}) = 497.6\text{MeV}$$

Number of neutrinos = 3



Left-right production cross section asymmetry & lepton decay asymmetry of the Z-boson

SLC @ Stanford e^- **polarization beam**

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{2(1 - 4\sin^2\theta_w)}{1 + (1 - 4\sin^2\theta_w)^2}$$

Exp.)
$$\begin{aligned} A_{LR} &= 0.1628 \pm 0.0099 \\ &\rightarrow \sin^2\theta_w = 0.2292 \pm 0.0013 \end{aligned}$$

Independent of $\frac{m_W^2}{m_Z^2} = \cos^2\theta_w$

Hadronic decays of the Z and W bosons

Exp.) $\Gamma(\text{hadron}) = 1.741 \pm 0.006\text{GeV}$

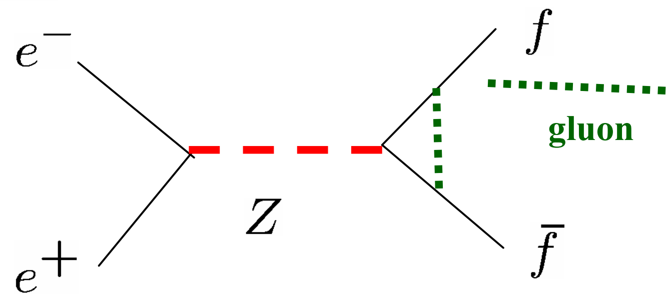
Th.) $$\Gamma(d_k\bar{d}_k) = \frac{G_F m_Z^3}{4\sqrt{2}\pi}\left(1 - \frac{4}{3}\sin^2\theta_w + \frac{8}{9}\sin^4\theta_w\right) = 0.3677\text{GeV}$$

$$\Gamma(u_k\bar{u}_k) = \frac{G_F m_Z^3}{4\sqrt{2}\pi}\left(1 - \frac{8}{3}\sin^2\theta_w + \frac{32}{9}\sin^4\theta_w\right) = 0.2583\text{GeV}$$

for $\sin^2\theta_w = 0.2315$

$$\Gamma(\text{hadron}) = 1.6737\text{GeV}$$

Consider QCD corrections:

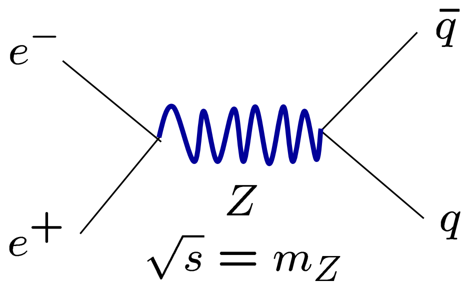


$$f = 1 + \frac{\alpha_s}{\pi} + 1.411\left(\frac{\alpha_s}{\pi}\right)^2 - 12.8\left(\frac{\alpha_s}{\pi}\right)^3 \simeq 1.038$$

$\Gamma(\text{hadron}) \to f\Gamma(\text{hadron}) = 1.737\text{GeV}$ ← **more consistent**

(ii) More precise measurements of EW gauge interactions

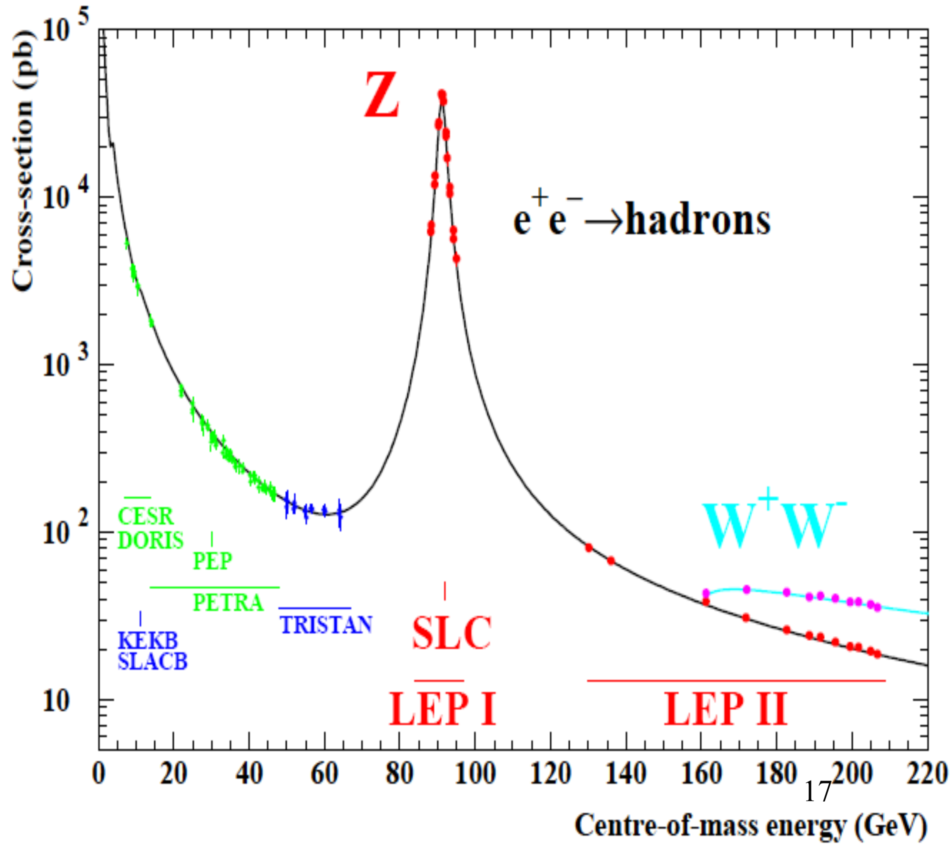
(Ex) LEP Experiment



Z-boson production @Z-pole

Huge number of Z bosons

→ Very precise measurements



Triple & Quartic Gauge couplings at LEP2 LEP → LEP2: E= m_Z → 200 GeV

i) Test of non-Abelian nature of SM gauge sector

ii) Probe for new physics ← anomalous coupling ← not exists in SM

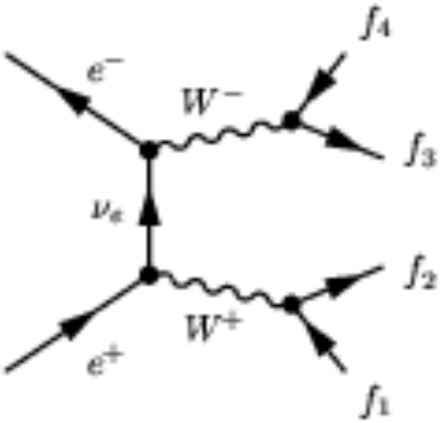
3-gauge couplings: SM $W^+W^-\gamma \quad W^+W^-Z$

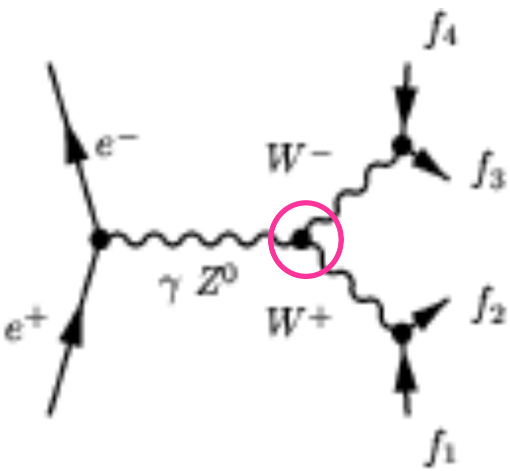
anomalous $Z\gamma\gamma, \quad ZZ\gamma, \quad ZZZ$

4-gauge couplings: SM $W^+W^-\gamma\gamma, \quad W^+W^-\gamma Z,$
$W^+W^-ZZ, \quad W^+W^-W^+W^-,$

anomalous $ZZ\gamma\gamma$

$e^+e^- \to W^+W^-$

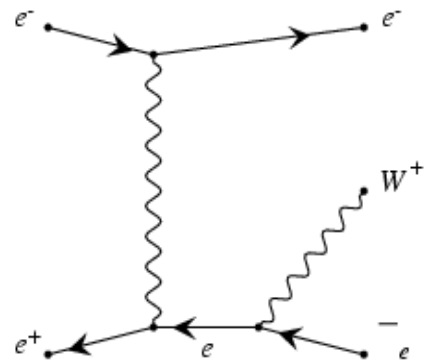


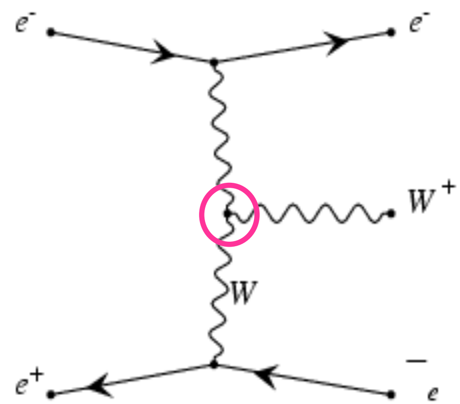


188.6 GeV

σ=15.98±0.23 pb

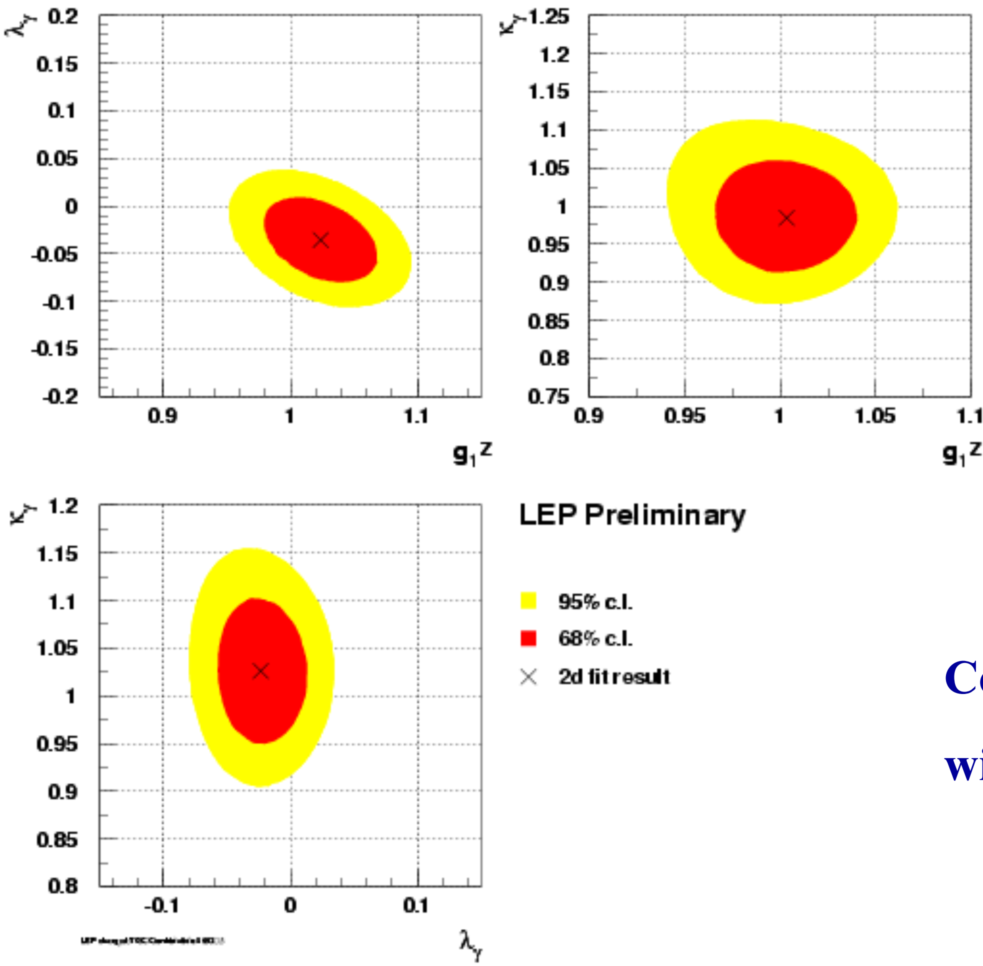
$e^+e^- \to We\nu_e$





188.6 GeV

σ=0.60±0.09 pb

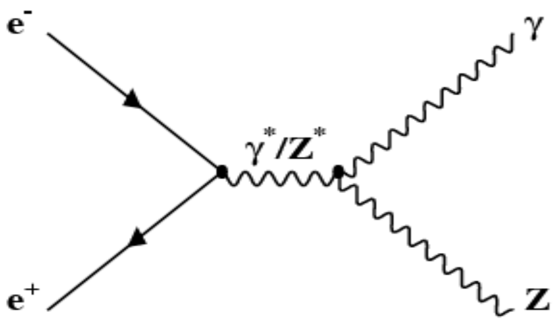


Consistent with the SM

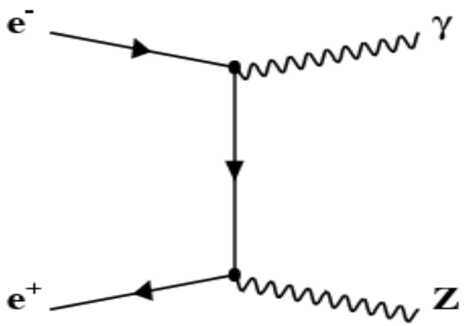
with 5%-10% accuracy

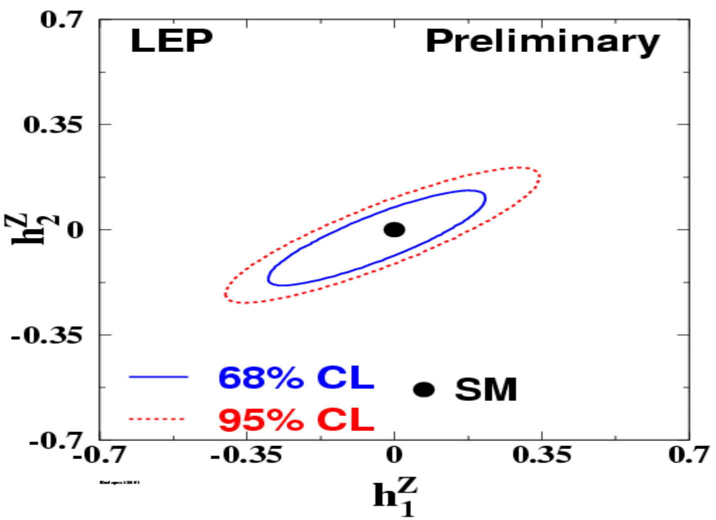
Neutral triple gauge couplings ← not exist in the SM

Search



SM background



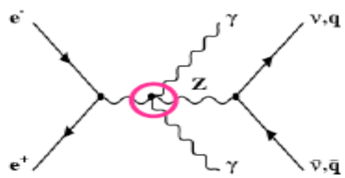


Consistent with the SM

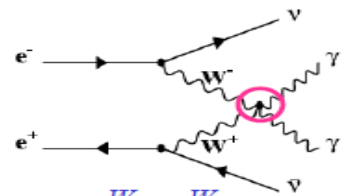
Quartic gauge couplings

$$e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma,\ q\bar{q}\gamma\gamma$$

- Anomalous couplings

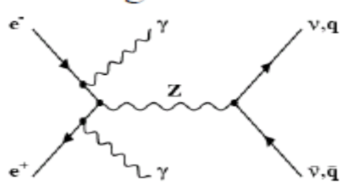


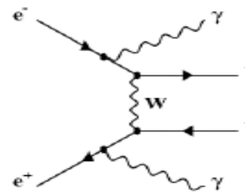
$a_0^Z \ a_c^Z$



$a_0^W \ a_c^W$

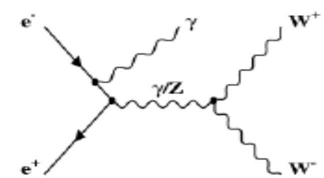
- Main diagrams

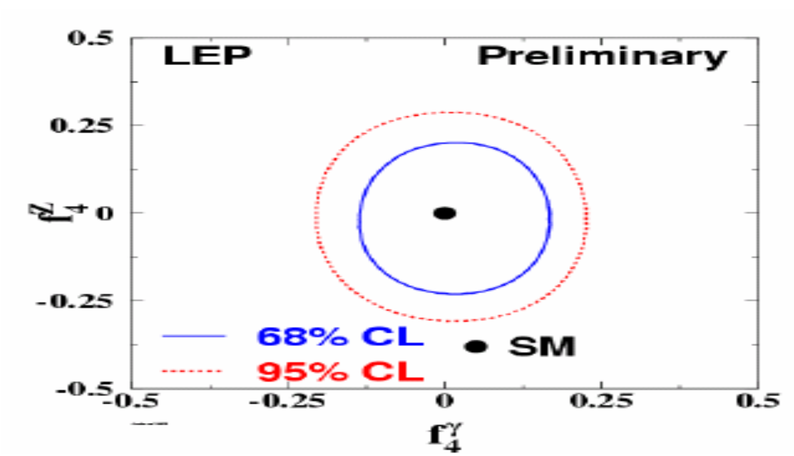




$$e^+e^- \rightarrow W^+W^-\gamma$$

$a_0^W \ a_c^W \ a_n$



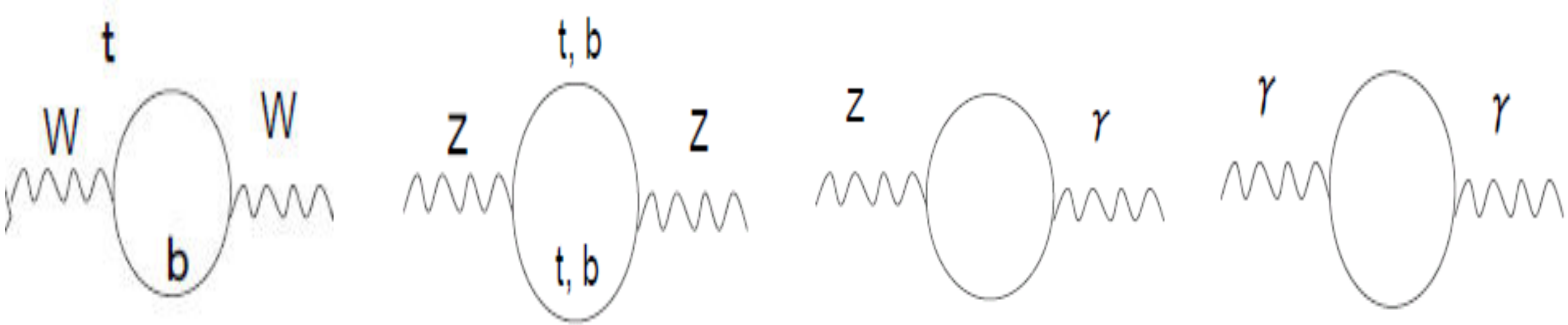


No anomalous coupling

Beyond Tree level

LEP precision measurements → beyond % level

→ level of quantum corrections



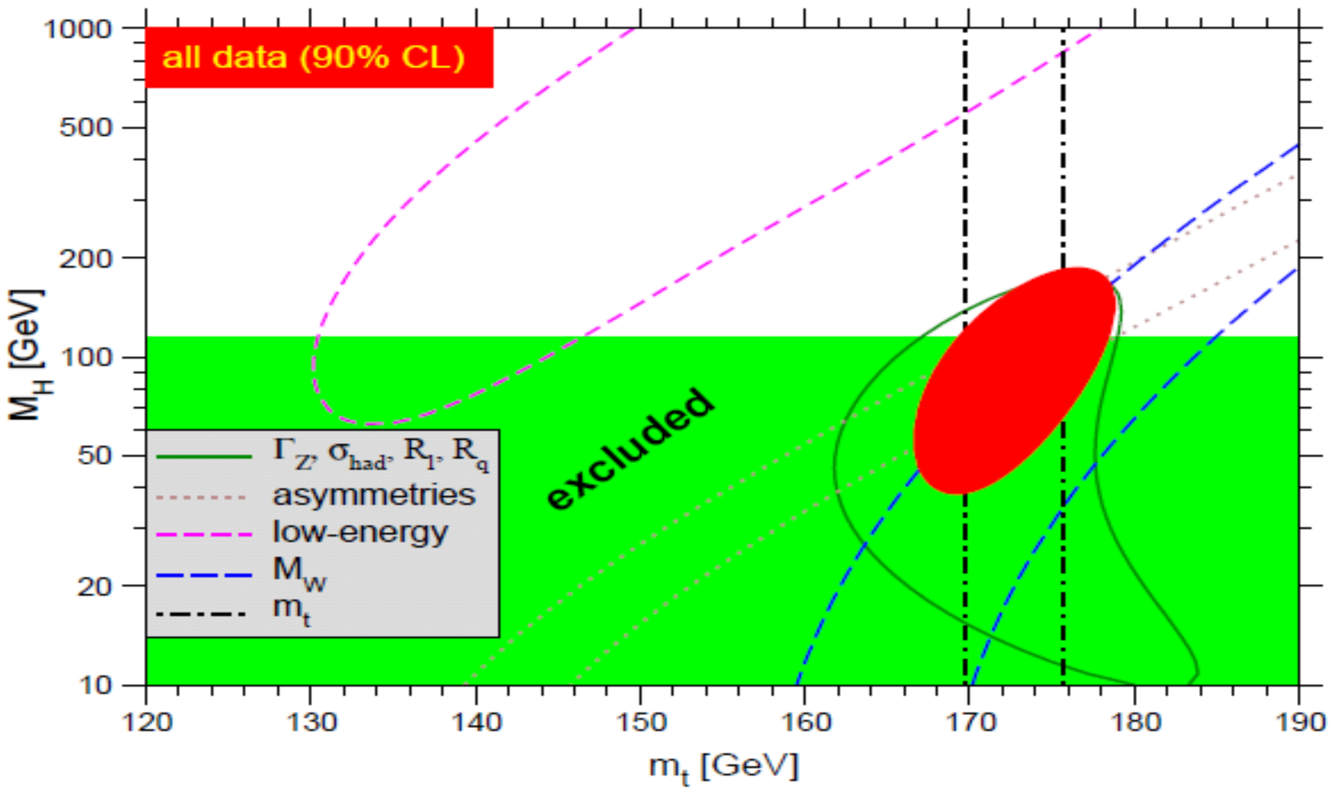
Mass ratio: $m_Z^2 = (g^2 + g'^2)\frac{v^2}{4} + \Pi_{ZZ}(m_Z^2)$ 91.1876 ± 0.0021GeV

$m_W^2 = g^2\frac{v^2}{4} + \Pi_{WW}(m_W)$ 80.454 ± 0.059GeV

ρ parameter

$$\rho - 1 = \frac{m_W^2}{m_Z^2 \cos^2\theta_w} - 1 = \frac{e^2}{s_w^2 c_w^2 m_Z^2}\left[\Pi_{11} - \Pi_{33}\right]$$

$$= \frac{3G_F}{8\sqrt{2}\pi^2}\left[m_t{}^2 + m_b^2 - \frac{2m_t^2 m_b^2}{m_t{}^2 - m_b^2}\ln\left(\frac{m_t^2}{m_b^2}\right) + m_W^2 \ln\left(\frac{m_H^2}{m_W^2}\right) - m_Z^2 \ln\left(\frac{m_H^2}{m_Z^2}\right)\right]$$



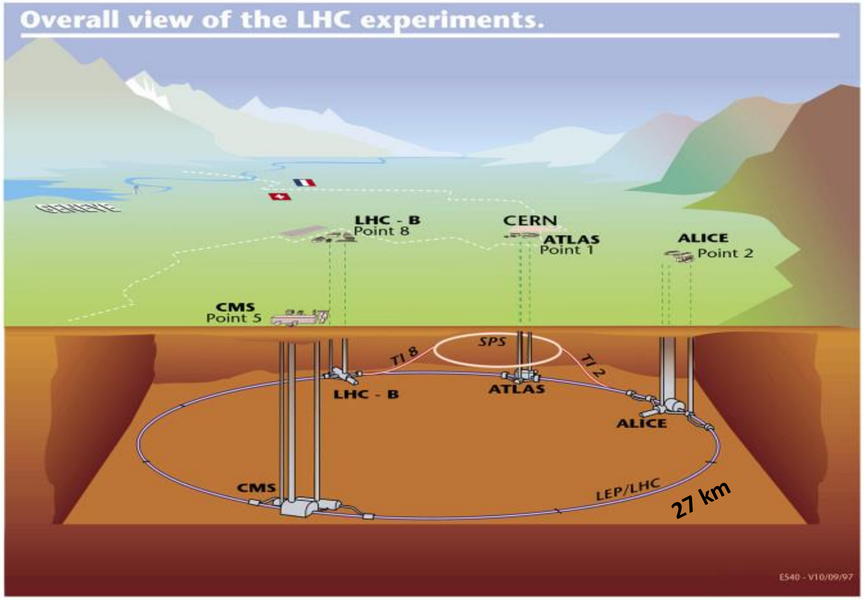
Before LHC:

All particles have been observed (except Higgs boson)

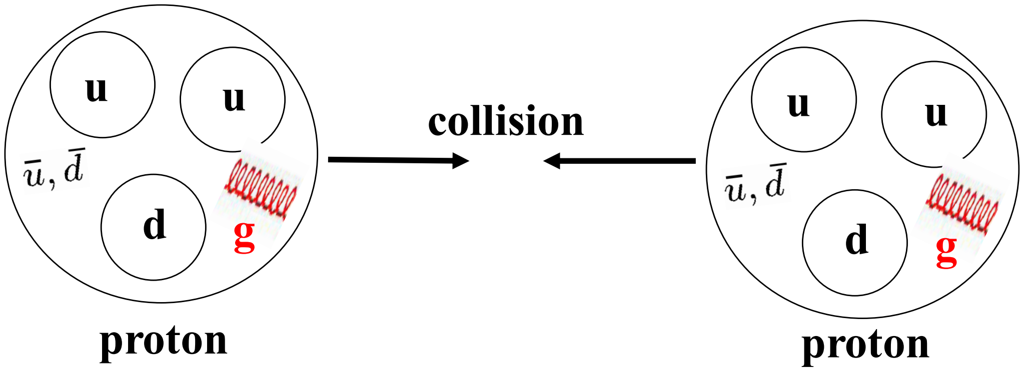
The nature of the gauge interaction has been precisely checked

After LHC?

New particle search at Large Hadron Collider (LHC)



Proton-Proton collider $\sqrt{s} = 13 - 14\,\text{TeV}$



Initial states:

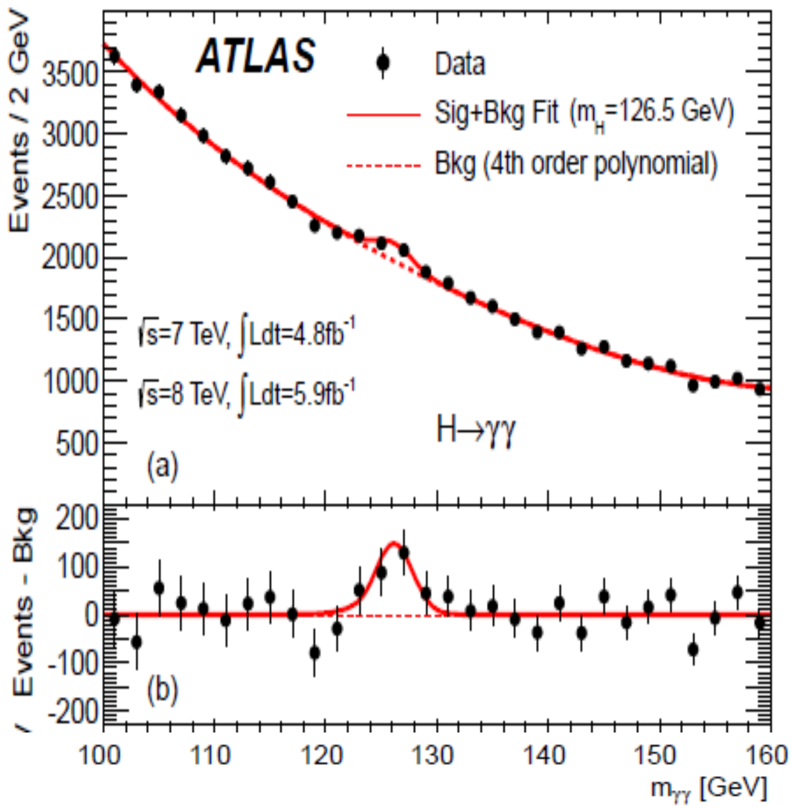
$$gg, gq, g\bar{q}, q\bar{q}, qq', \ldots$$

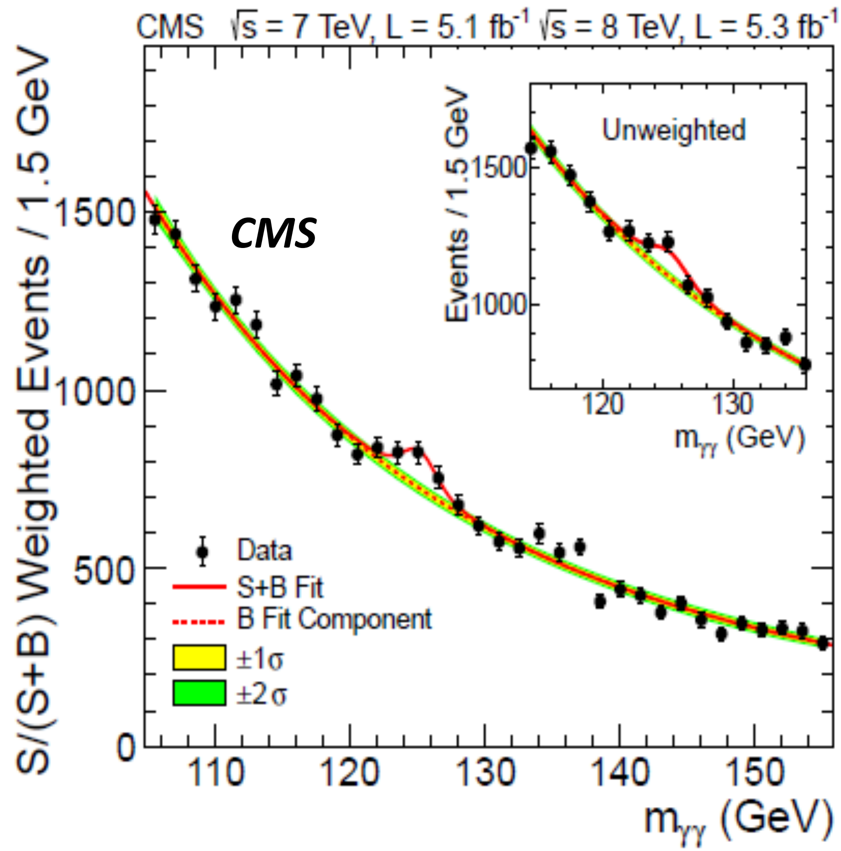
Discovery of a new scalar particle (Higgs boson)!

- A new scalar particle, most likely the Higgs boson, has been discovered independently by ATLAS and CMS collaborations

- First announcement on July 4th, 2012
  "Higgsdependence" Day

A new scalar particle, most likely Standard Model Higgs boson has been discovered at LHC through a variety of decay modes.





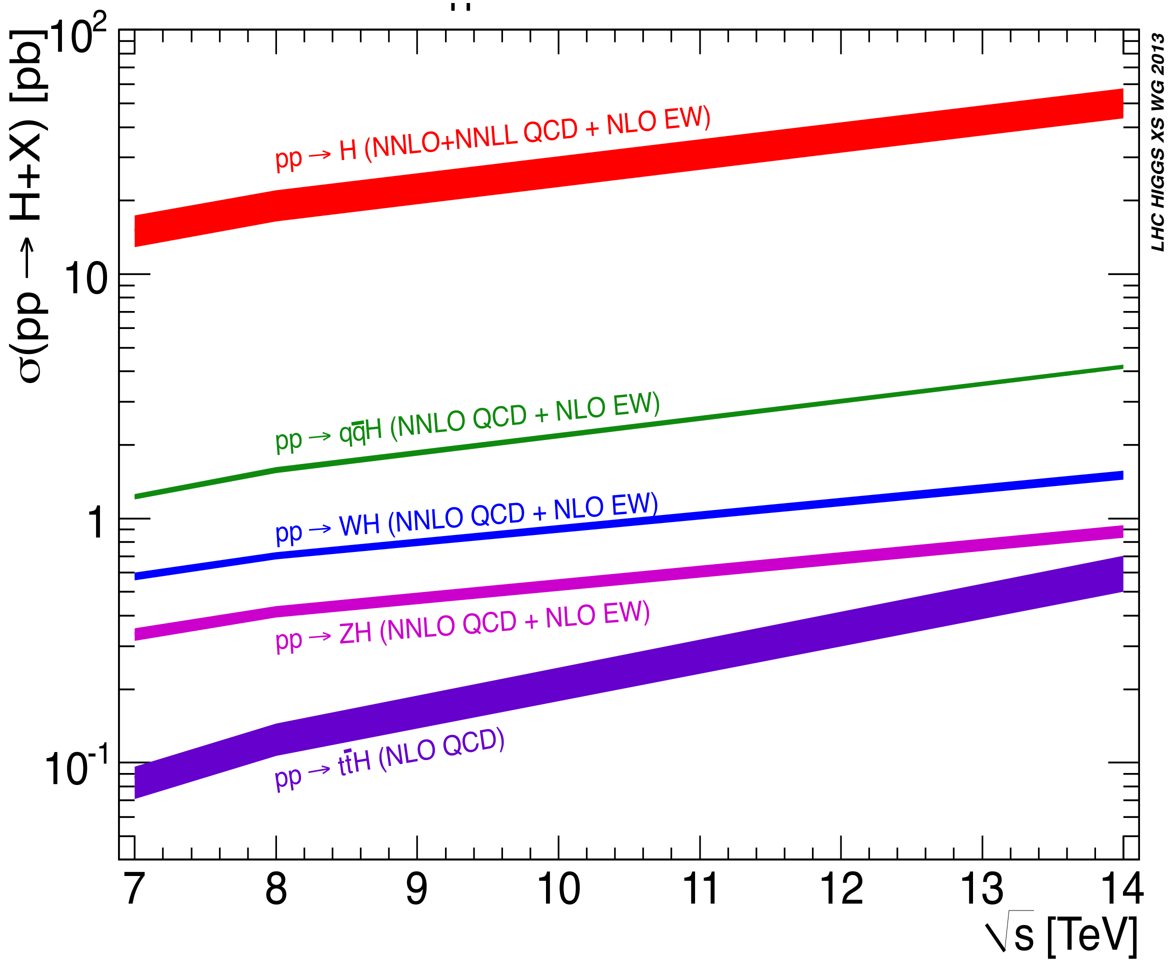
$$m_h = 126.0 \pm 0.4(\text{stat.}) \pm 0.4(\text{syst.})\ \text{GeV}$$

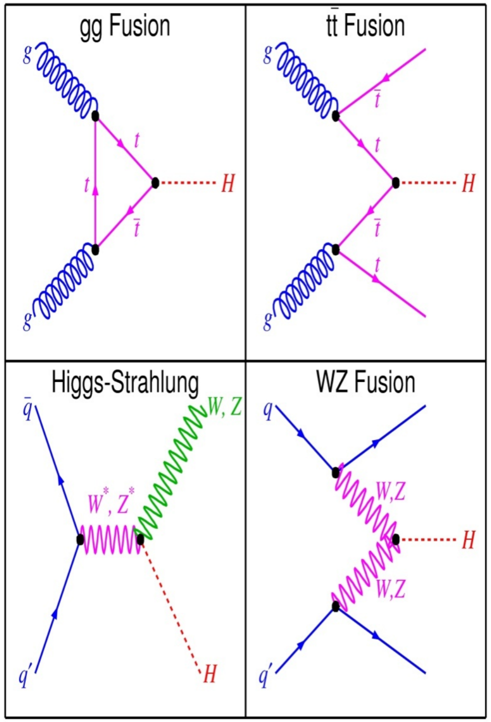
$$m_h = 125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})\ \text{GeV}$$

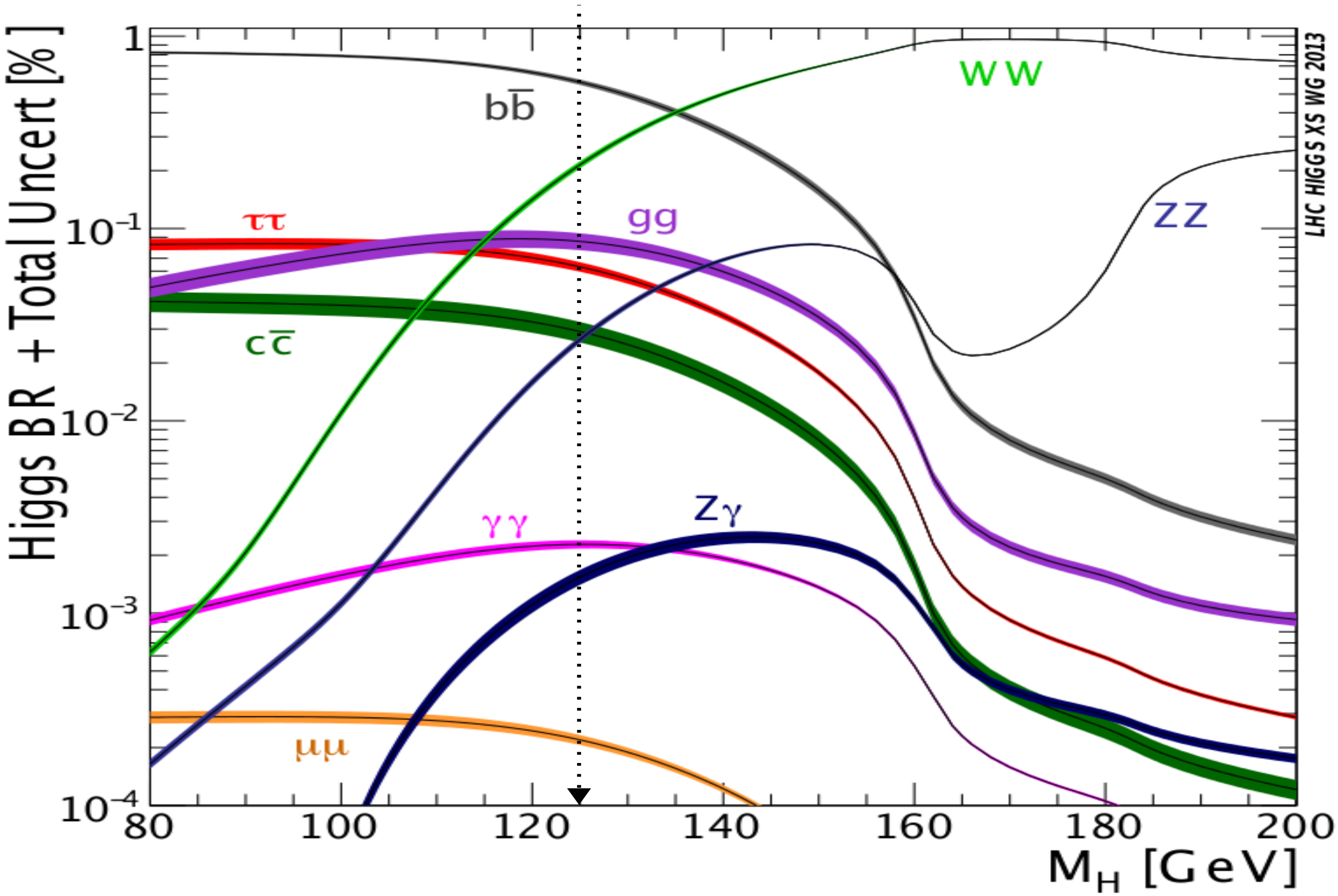
Measurements of Higgs boson couplings

➢ Variety of productions processes & decay modes

For mh=125.5 GeV





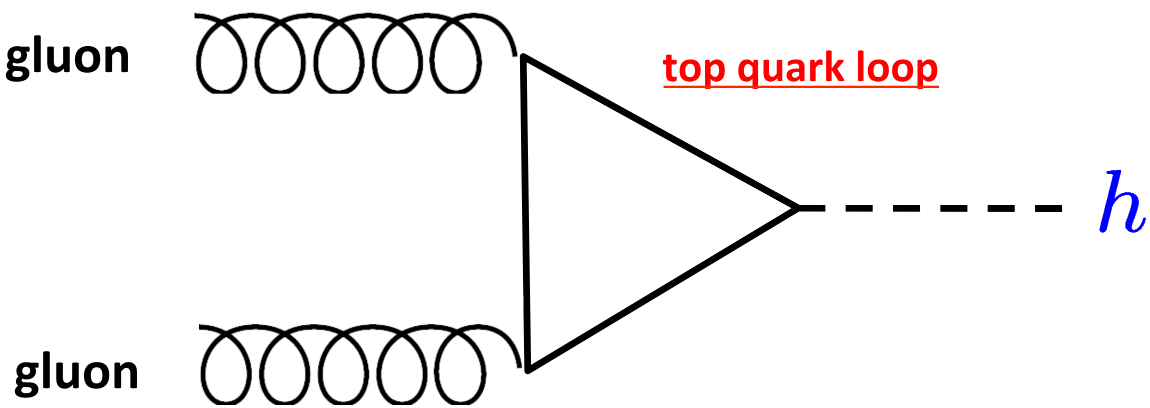


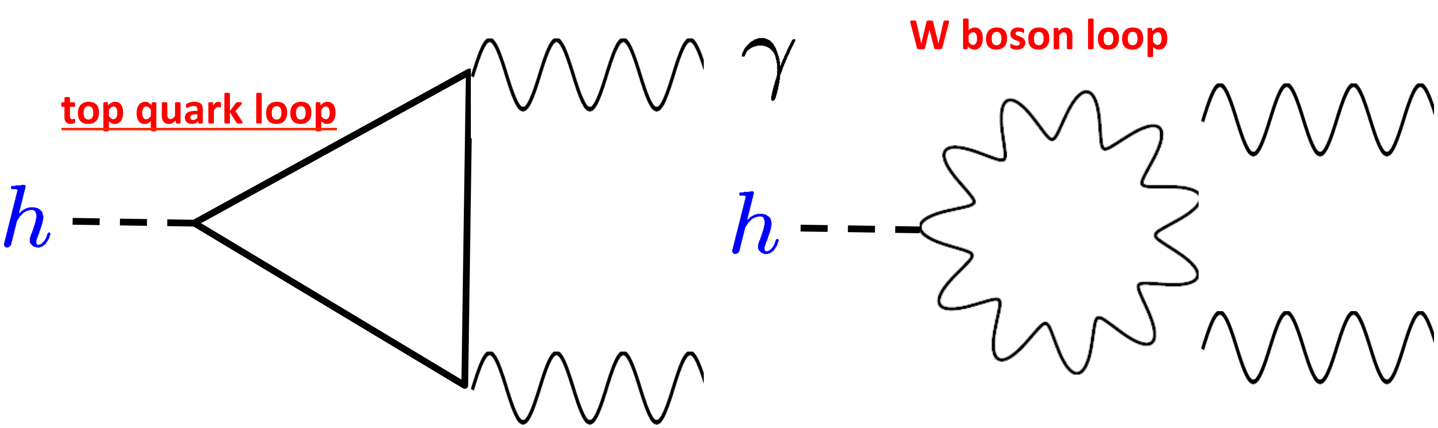
Observed mh=125-126 GeV is ideal to explore Higgs boson properties with variety of decay modes!

* Imagine what if mh > 160 GeV

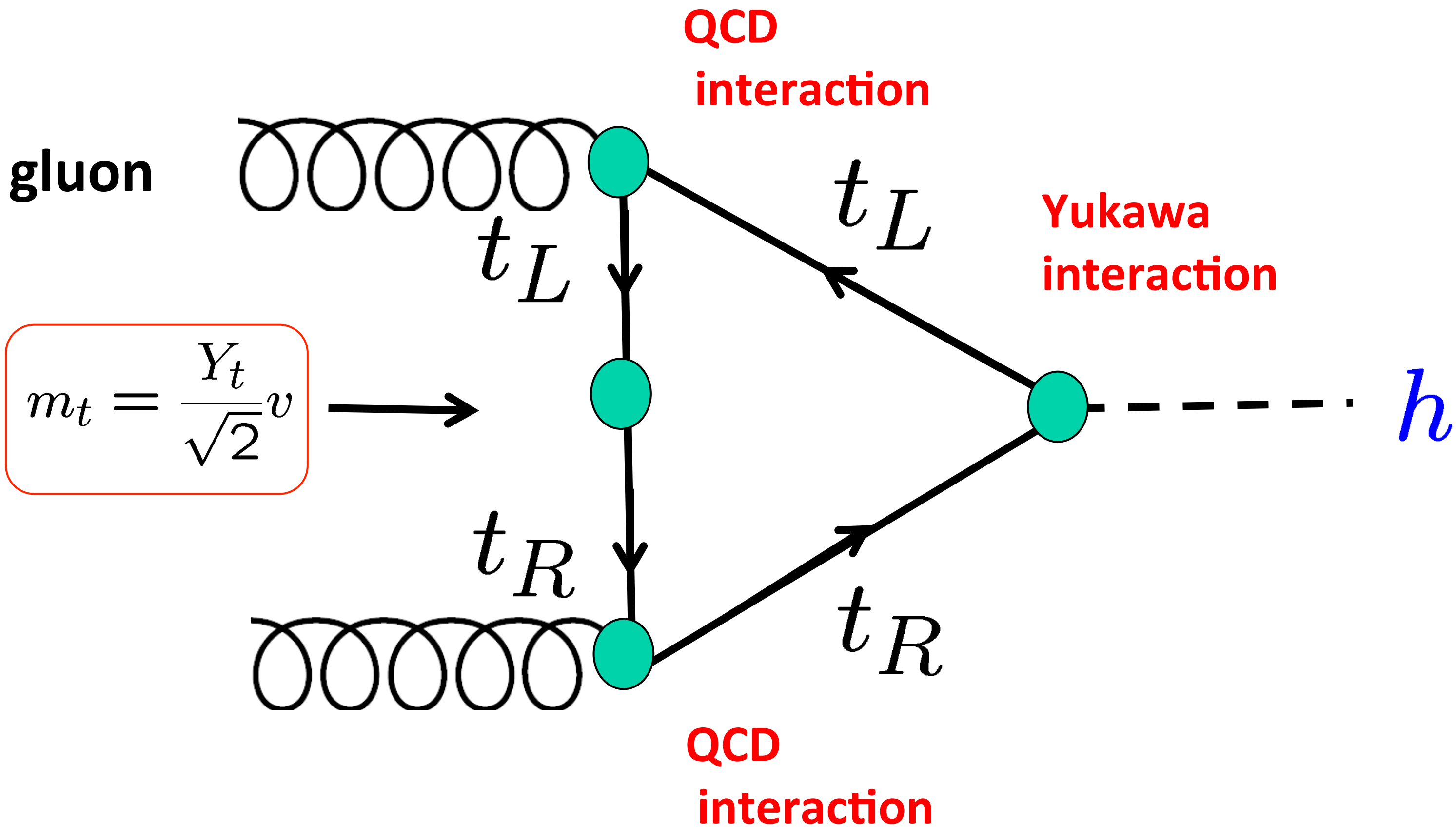
Early stage of Higgs physics at LHC

1. Main production mode: gluon fusion
2. Primary discovery mode: Higgs decay to diphoton



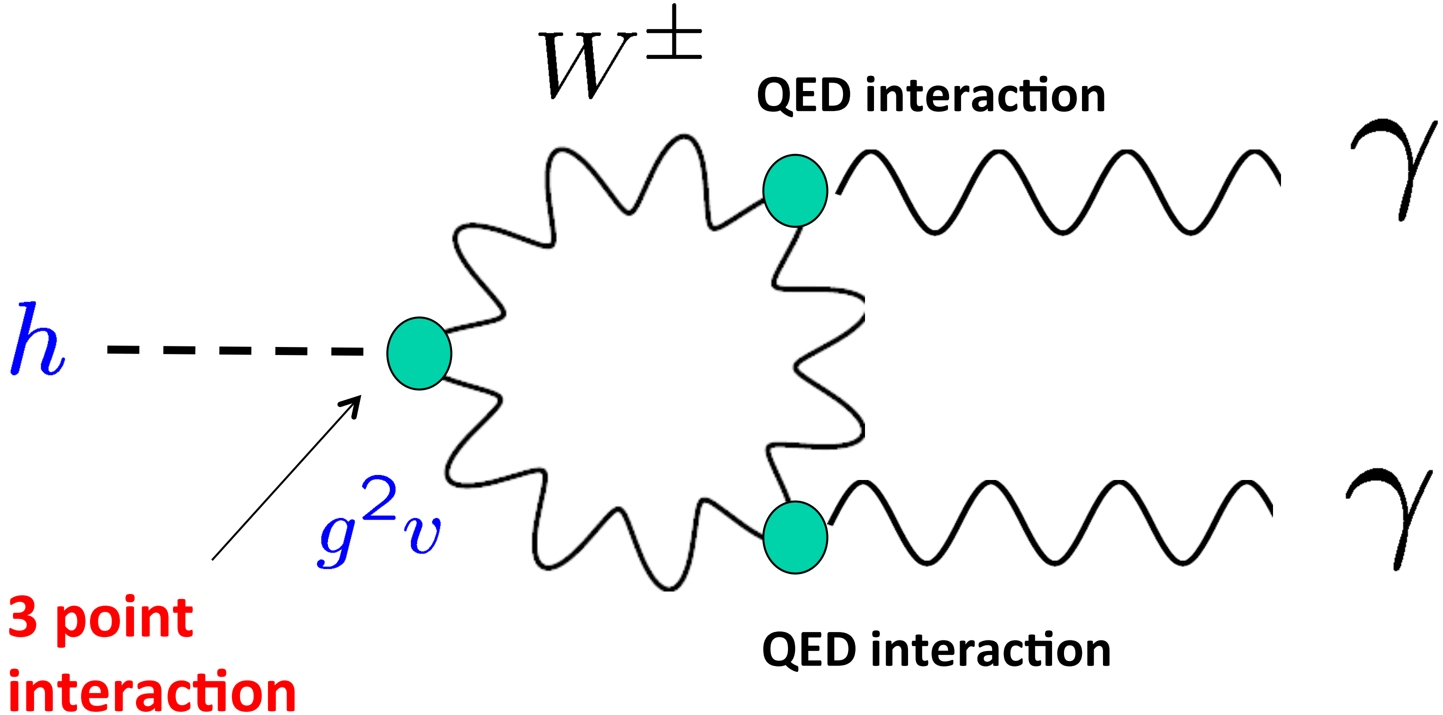


More theoretical description



We need a mass insertion (Symmetry Breaking) to close the loop!

W boson loop



We need a VEV insertion (Symmetry Breaking) to close the loop!

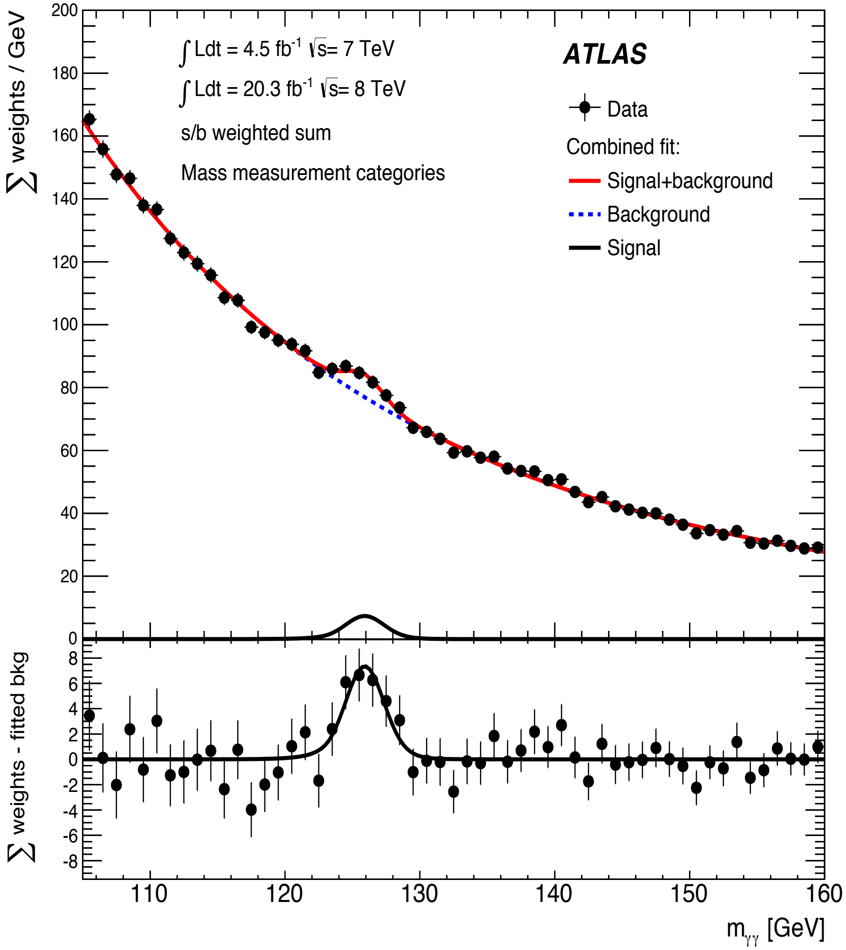
- Without EW symmetry breaking, the loop diagrams cannot be induced.

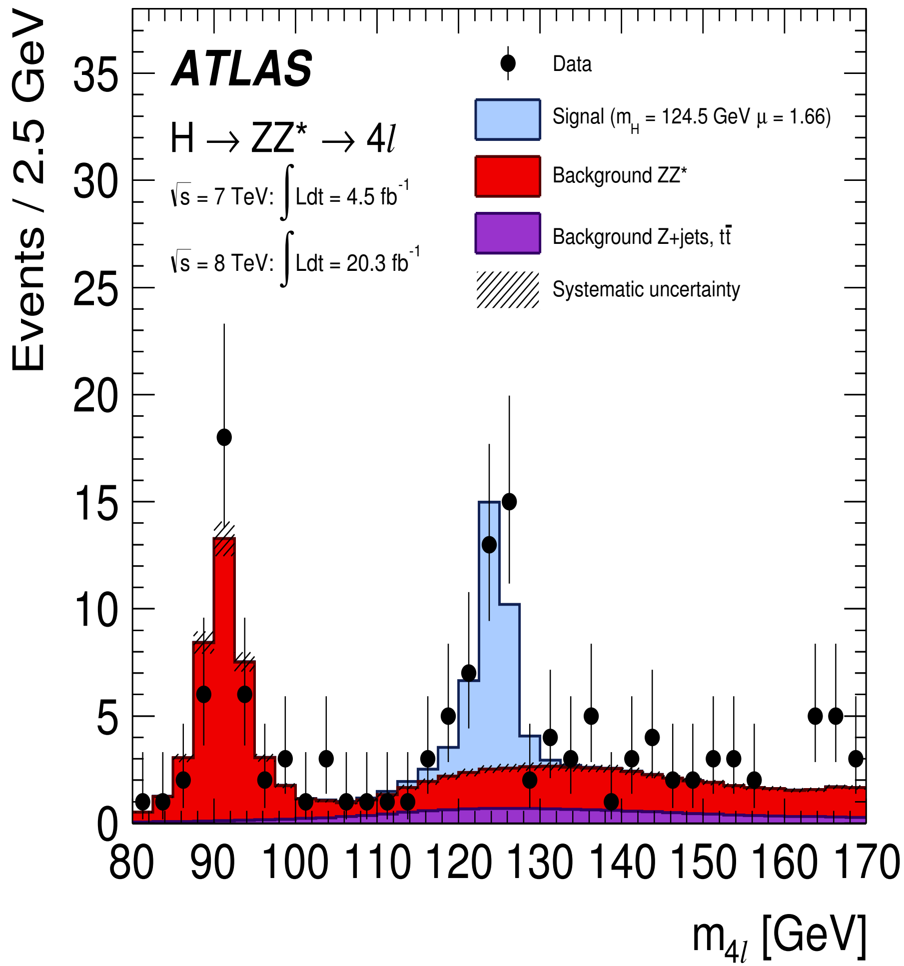
- The new particle discovered at LHC is a particle which has something to do with EW symmetry breaking.

- It is most likely the long-sought Higgs boson of the Standard Model

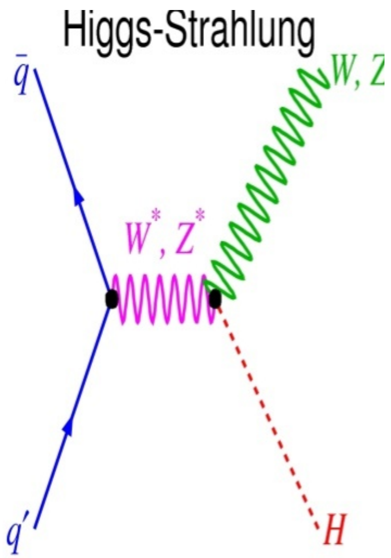
Higgs boson mass measurement via h → diphoton, ZZ*→4l

ATLAS results (arXiv: 1406.3827)

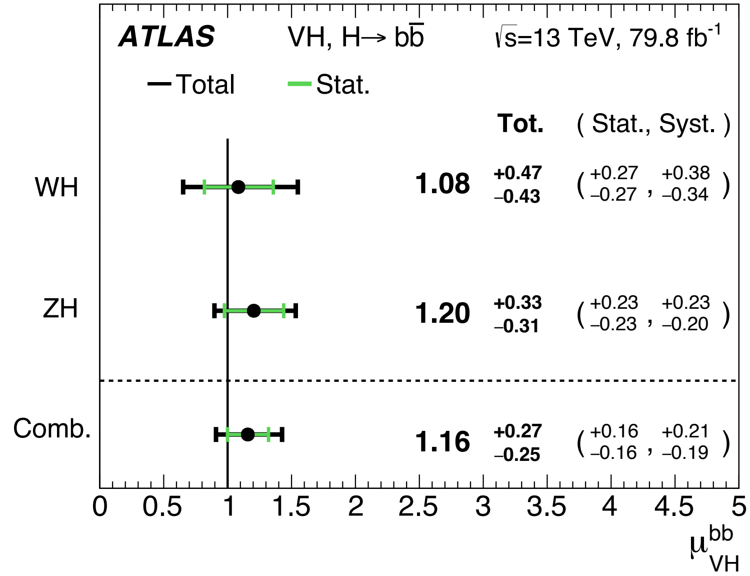




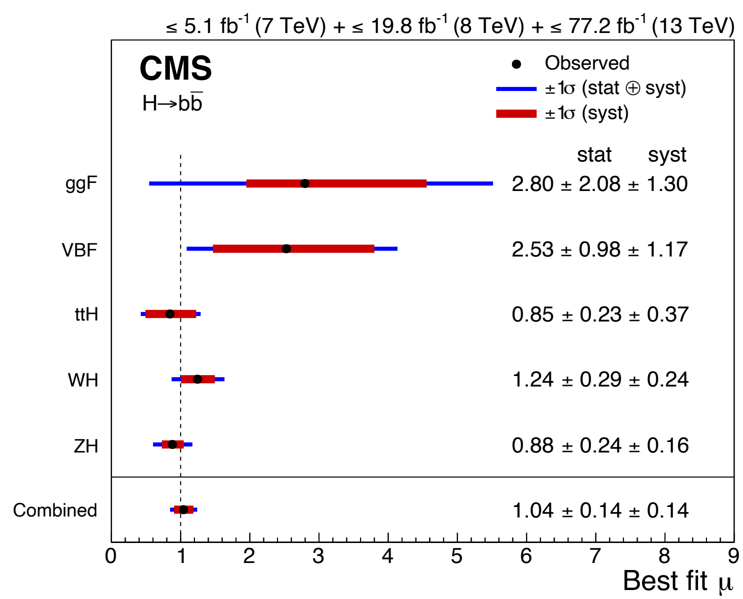
Observation of $H \to b\bar{b}$ decay



arXiv:1808.08238v2



arXiv:1808.08242v2



Future of the Standard Model

The gauge structure of the Standard Model was tested with high precision even before the LHC

The final missing particle of the Standard Model, the Higgs boson, was discovered at the LHC

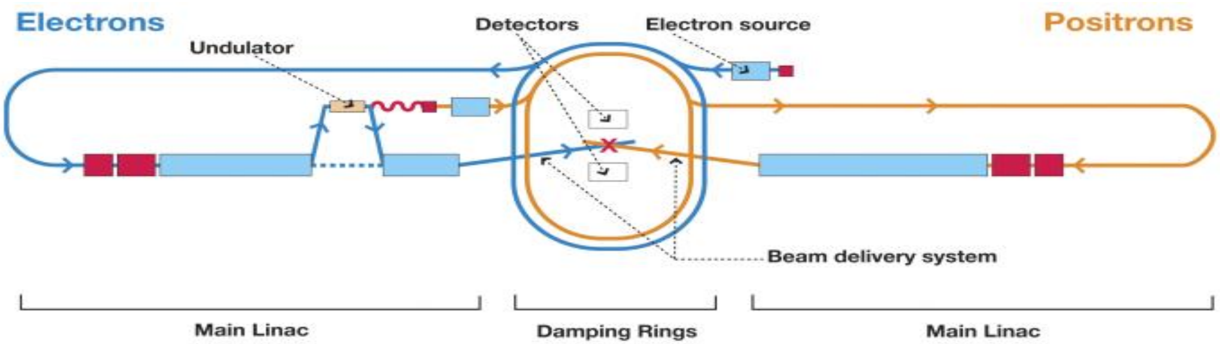
To complete and stress test the Standard Model, we must measure Higgs properties with much higher precision

This is one of the most important directions in particle physics for the coming decades

What do we need to achieve this goal?

Higgs Factory!

International Linear Collider (ILC) from 20XX ?



Lepton collider

Initial states: e^+e^- elementary particle

colliding particle energy is fixed and tunable

$$\sqrt{s} = 250 \text{ GeV} - 1 \text{ TeV}$$

polarized beam option

ILC: more precise measurements

→ Higss boson properties, discriminate New Physics Models

For details, see Junping's lecture (Lecture I)!

Summary

Status of the Standard Model

The Standard Model (SM) is the best theory in describing the nature of elementary particle physics, which is in excellent agreement with almost of all current experimental results (including LHC Run results) as of TODAY

Discussion Day 1 completed!
Let's continue to Day 2

However,
There are problems that the SM cannot answer
Physics beyond the SM (BSM Physics) is strongly suggested by both experimental & theoretical points of view

Thank you

for your attention!