The Standard Model and Beyond

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The status of particle physics

Lecture 1

1. The Standard Model (SM) is the best theory of describing the nature of particle physics, which is in excellent agreement with almost of all current experiments
2. However, there are some theoretical problems & recent experimental results, which strongly suggest New Physics beyond the SM

Lecture 2

3. Many well-motivated New Physics models have been proposed
4. Many planned and on-going (collider) experiments may reveal New Physics in the near future

Lecture 1

Status of the Standard Model and its problems

1. Definition of the Standard Model

What is the Standard Model (SM)?

General theoretical framework: Gauge Field Theory

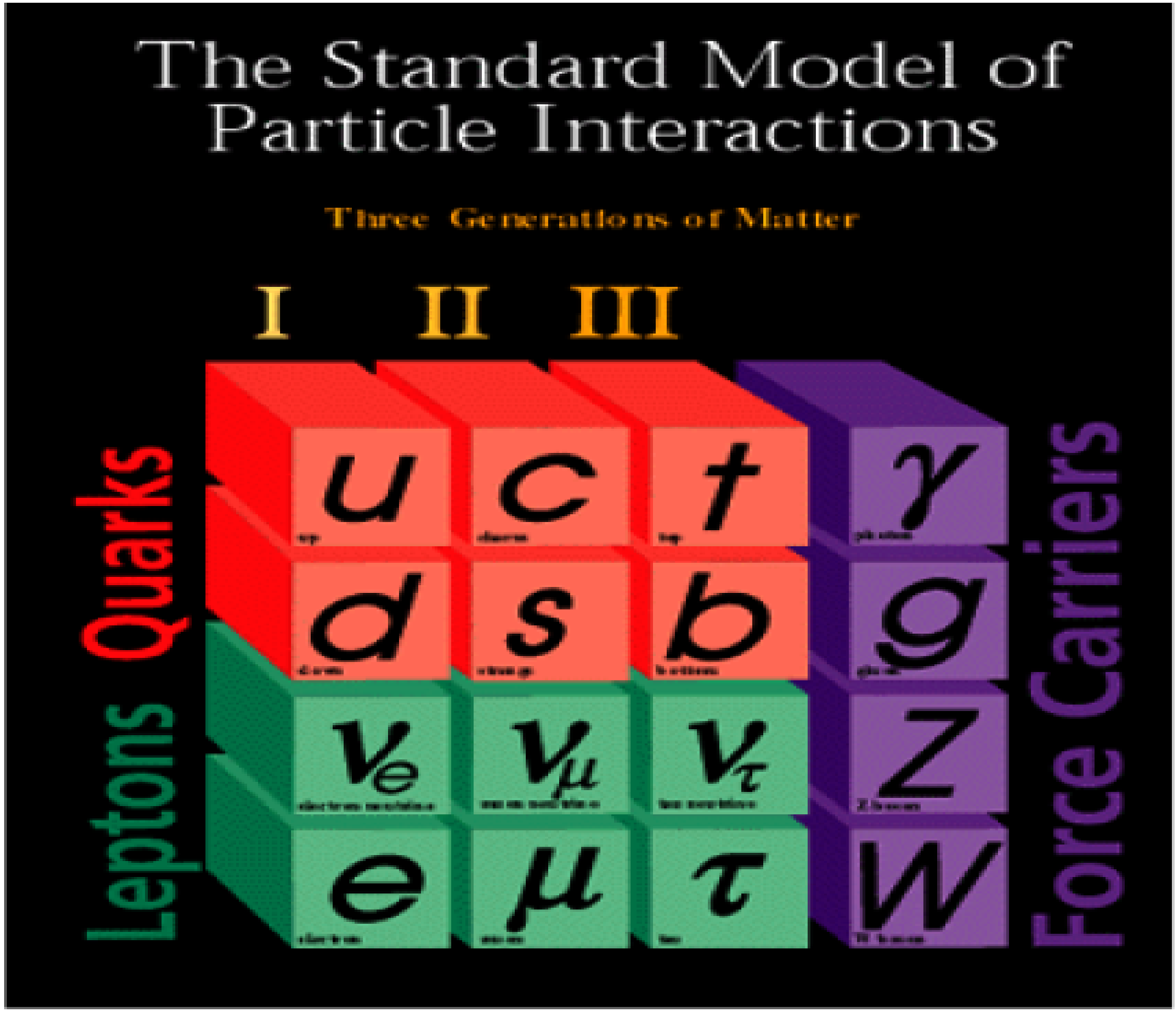
- Quantum field theory → relativity + quantum mechanics
- Gauge principle → invariance under Gauge Transformation

General definition of a model of gauge field theory

1. Define Gauge Group (U(1), SU(N) etc.)
2. Fix Particle Contents

The Standard Model

Fermions & Gauge Bosons



The Standard Model

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

QCD int. Electroweak int.

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

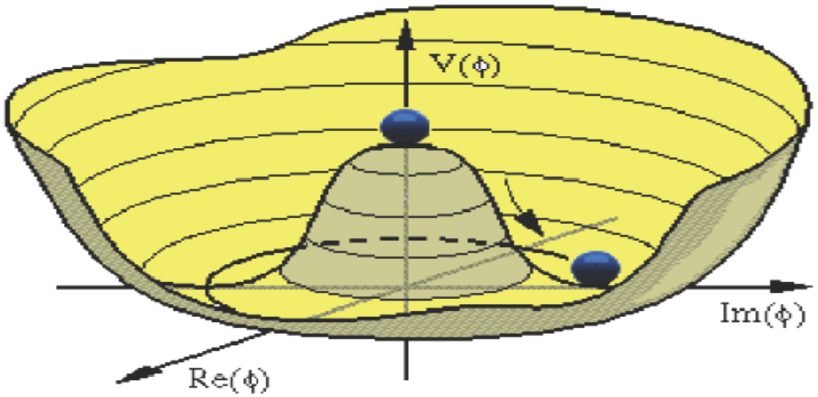
Particle contents: leptons & quarks & Higgs doublet

$$
\begin{aligned}
(\ell_L)_i &= \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L : \left(\mathbf{1},\ \mathbf{2},\ -\tfrac{1}{2} \right) \\
(q_L)_i &= \begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L : \left(\mathbf{3},\ \mathbf{2},\ \tfrac{1}{6} \right) \\
(\ell_R)_i &= e_R\ ,\ \mu_R\ ,\ \tau_R\ : \left(\mathbf{1},\ \mathbf{1},\ -1 \right) \\
(u_R)_i &= u_R\ ,\ c_R\ ,\ t_R\ : \left(\mathbf{3},\ \mathbf{1},\ \tfrac{2}{3} \right) \\
(d_R)_i &= d_R\ ,\ s_R\ ,\ b_R\ : \left(\mathbf{3},\ \mathbf{1},\ -\tfrac{2}{3} \right)
\end{aligned}
$$

Electroweak Symmetry Breaking & Higgs mechanism

Higgs doublet scalar $H: \ (\mathbf{2}, \ 1/2)$ **under** $SU(2)_L \times U(1)_Y$

Higgs potential: $V = -m^2 H^\dagger H + \frac{1}{2}\lambda (H^\dagger H)^2$



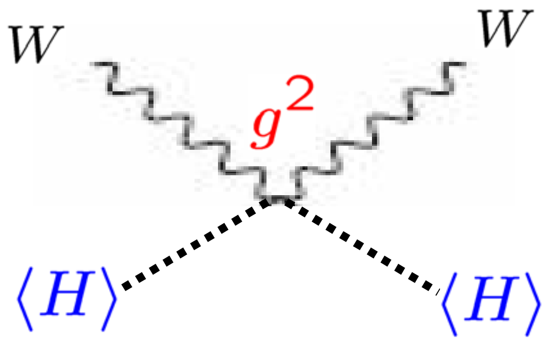
$$\langle \phi \rangle = \frac{v}{\sqrt{2}} = 174\text{GeV}$$

Electroweak symmetry breaking: $SU(2)_L \times U(1)_Y \to U(1)_{\text{EM}}$

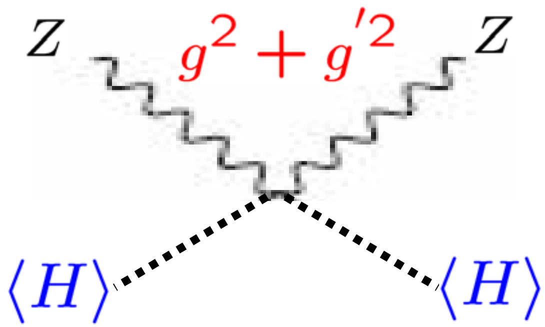
Higgs mechanism: **Massive weak gauge bosons & Higgs boson**

Fermion masses are also generated

W & Z bosons get masses through gauge coupling



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

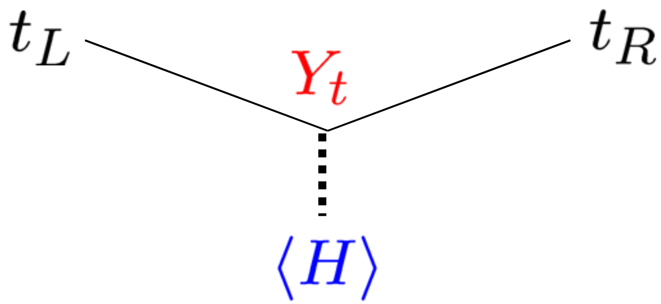


$$M_Z^2 = \frac{1}{4}(g^2 + g'^2) v^2$$

Fermions get masses through Yukawa coupling

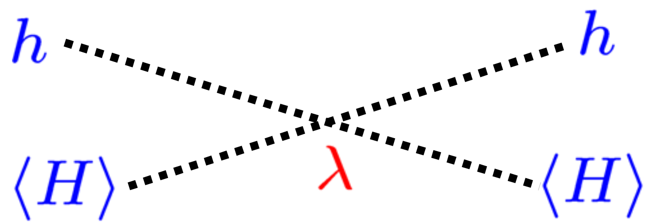
Ex) top quark mass

$$m_t = \frac{Y_t}{\sqrt{2}} v$$



Higgs boson mass

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



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

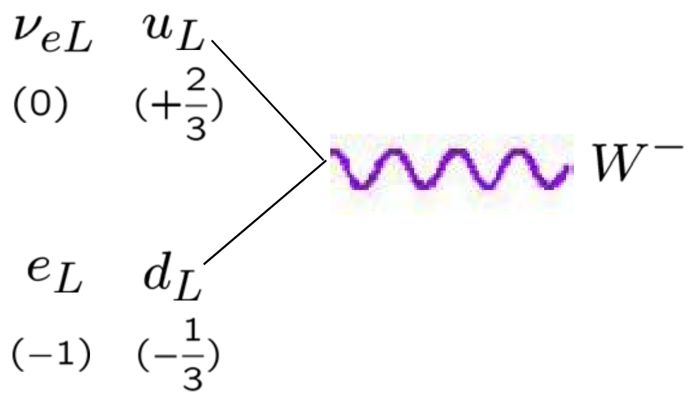
Interactions between fermions and gauge bosons

Charged current interaction

$$\mathcal{L}_{CC} = g(J^1_\mu A'^{1\mu} + J^2_\mu A'^{2\mu}) = \frac{g}{\sqrt{2}}(J^-_\mu W^{-\mu} + J^+_\mu W^{+\mu})$$

$$J^+_\mu = J^1_\mu + iJ^2_\mu = \bar{L}'\gamma_\mu\tau^+L' = \bar{\nu}_{eL}\gamma_\mu e_L = \frac{1}{2}\bar{\nu}_e\gamma_\mu(1-\gamma_5)e,$$

$$J^-_\mu = J^1_\mu - iJ^2_\mu = \bar{L}'\gamma_\mu\tau^-L' = \bar{e}_L\gamma_\mu\nu_{eL} = \frac{1}{2}\bar{e}\gamma_\mu(1-\gamma_5)\nu_e.$$



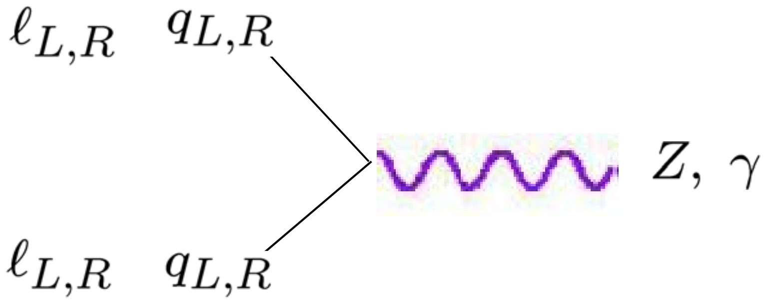
Neutral current interaction

$$\mathcal{L}_{int} = \frac{e}{s_w c_w} J_Z^\mu Z_\mu + e J_{em} A_\mu$$

$$J_Z^\mu = \bar{f}\gamma^\mu \left(T^3 P_L - Q s_w^2\right) f$$

$T^3 =$
- **+ ½ : up-type frmion**
- **- ½ :down-type fermion**

$$J_{em}^\mu = Q\bar{f}\gamma^\mu f$$



2. Experimental status on the Standard Model

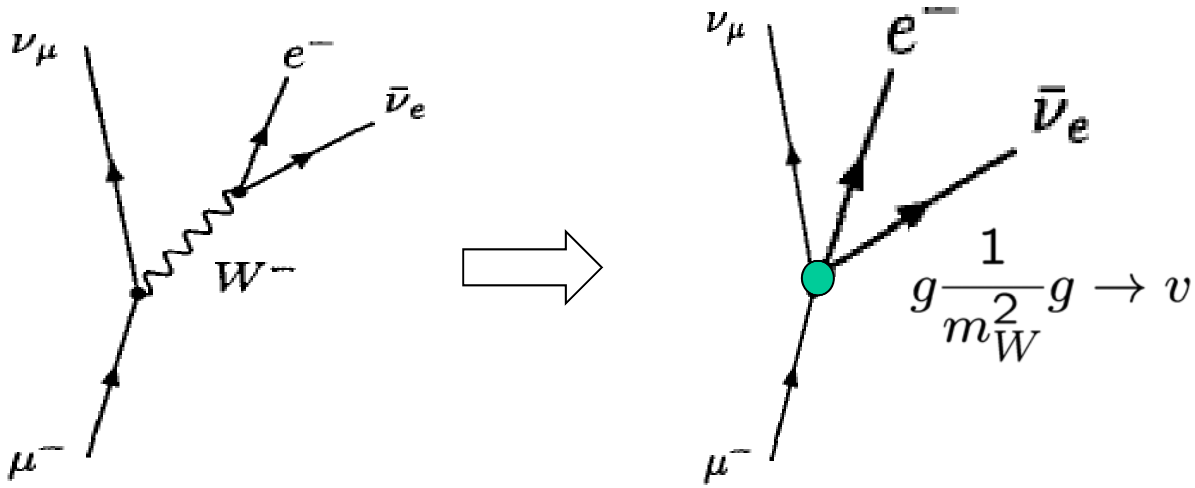
2-1. Search for weak gauge bosons

Implicit: Muon weak decay

$$\Gamma(\mu \to e + \bar{\nu}_e + \nu_\mu) = \frac{m_\mu^5 G_F}{192\pi^3}$$

$$G_F = \frac{1}{\sqrt{2}v^2} = 1.166 \times 10^{-5}\text{GeV}^{-2}$$

$$m_\mu = 1.0566\text{MeV}$$

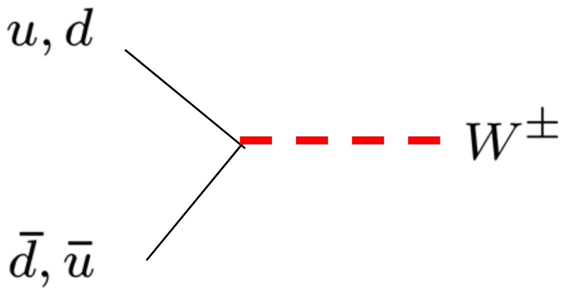


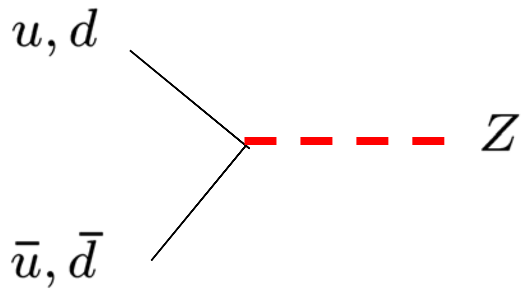
Investigation of Electroweak theory began

2-2. Direct evidence of weak gauge boson

Weak gauge bosons were discovered at CERN in 1983

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





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

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

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

Numerically consistent, Coupling universality

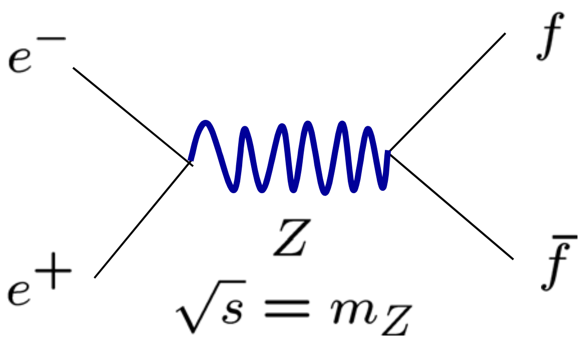
More precise measurements

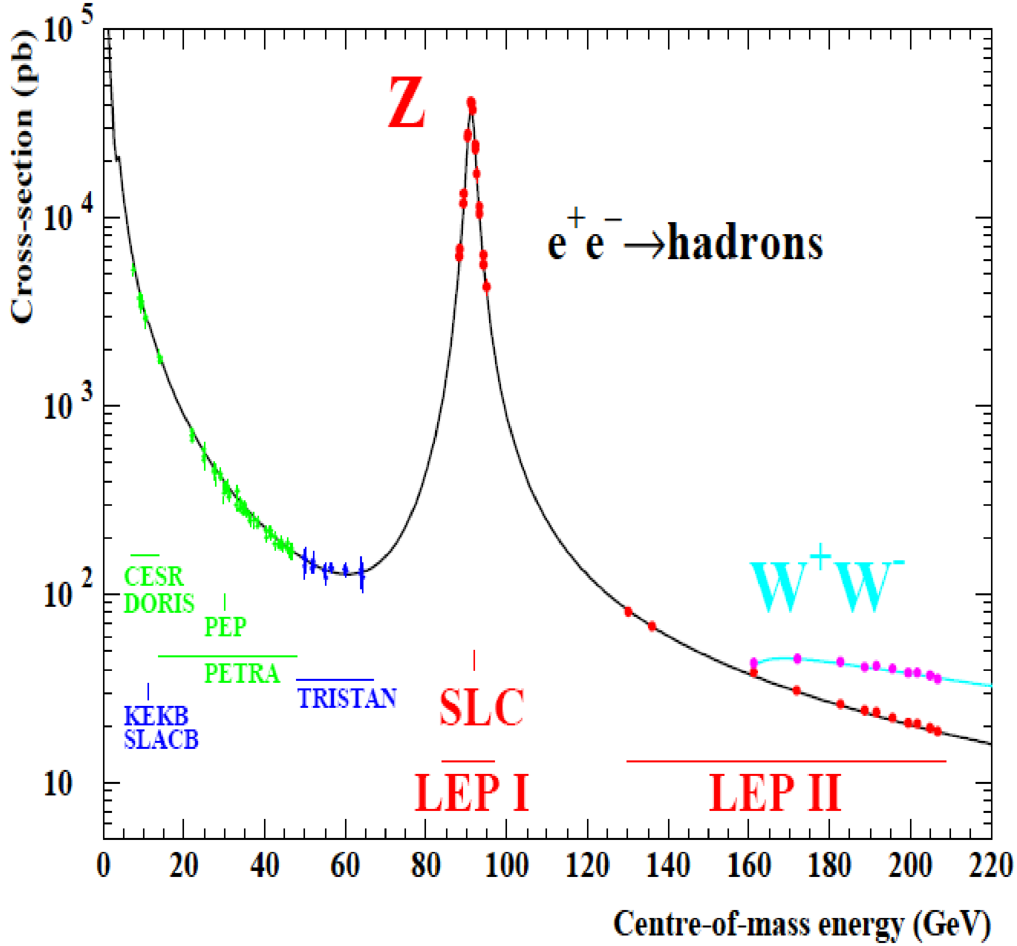
e^+e^- collider **LEP @ CERN**

SLC @ Stanford

LEP Experiment

Z-boson production at Z-pole





Z-boson production @Z-pole

Huge number of Z bosons

→ **Very precise measurements**

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

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

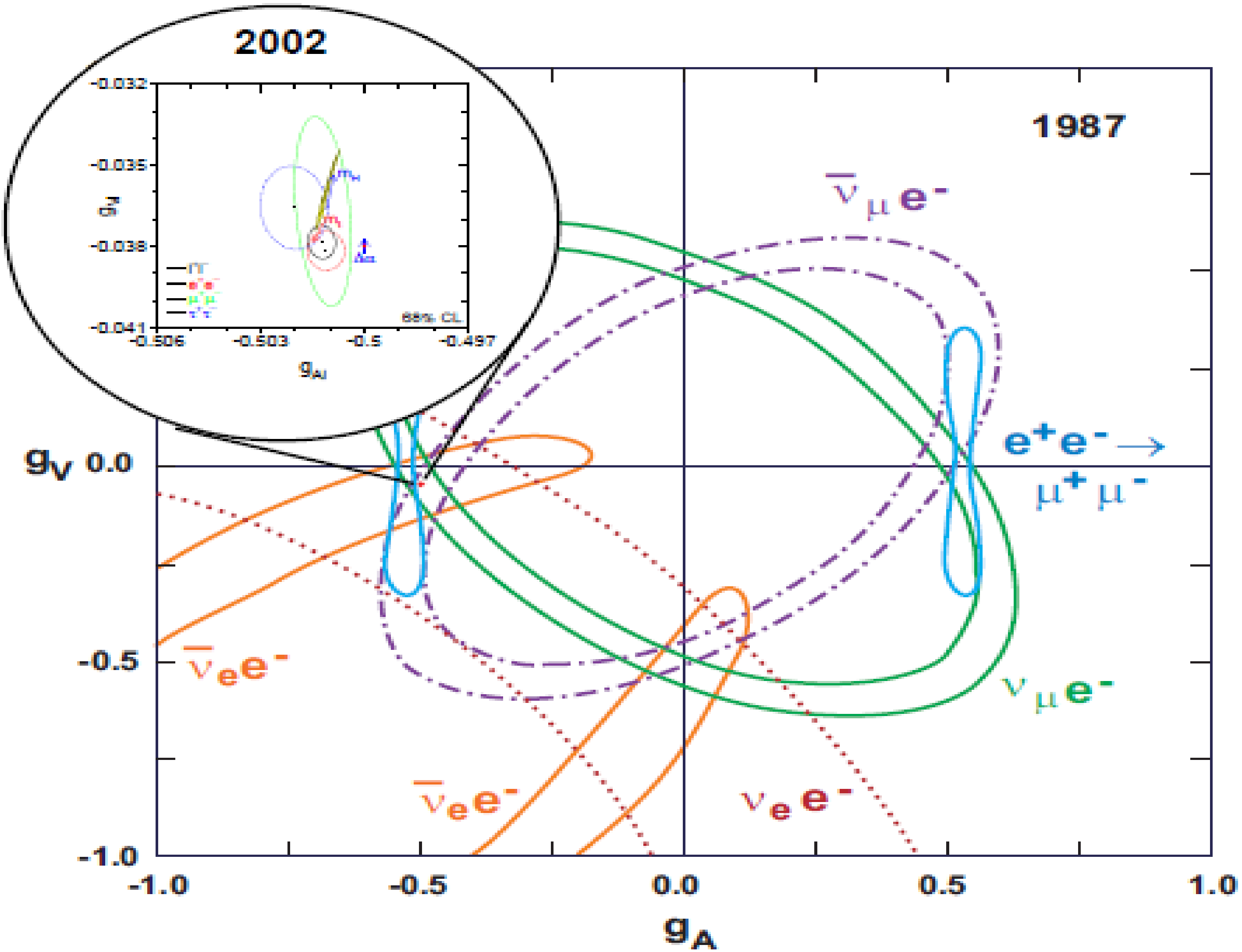
$$\begin{aligned}\Gamma(Z \to e^+e^-) &= 83.82 \pm 0.30\text{MeV}\\ \Gamma(Z \to \mu^+\mu^-) &= 83.83 \pm 0.39\text{MeV}\\ \Gamma(Z \to \tau^+\tau^-) &= 83.67 \pm 0.44\text{MeV}\\ \Gamma(total) &= 2490 \pm 7\text{MeV}\end{aligned}$$

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 $\sin^2\theta_w = 0.2315$

Numerically consistent, Coupling universality

Measurements of couplings between leptons and weak bosons



Number of neutrinos

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

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

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

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

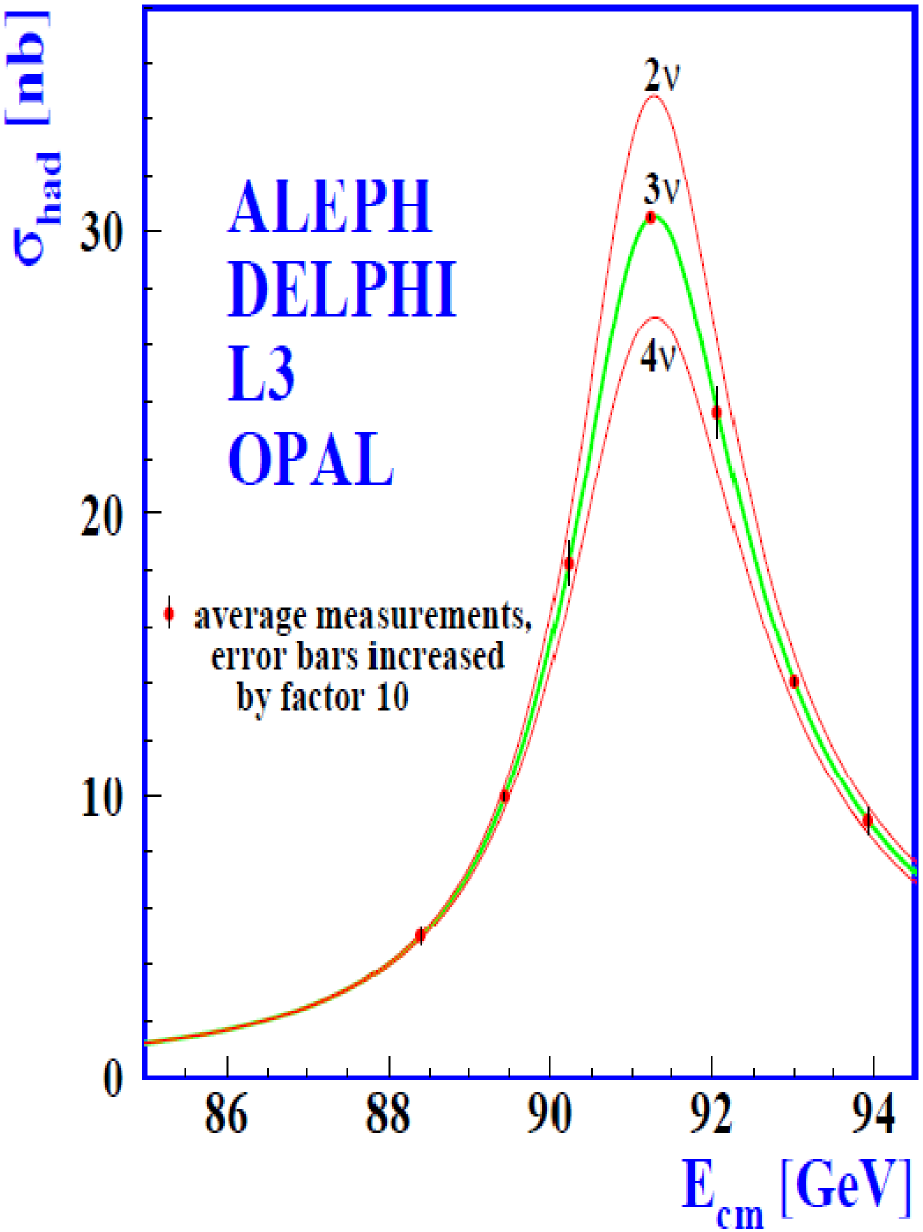
i) Z mass & total decay width from the position & width of the peak

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^- **polarized 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.) $\Gamma(\text{hadron}) = 1.741 \pm 0.006\text{GeV}$

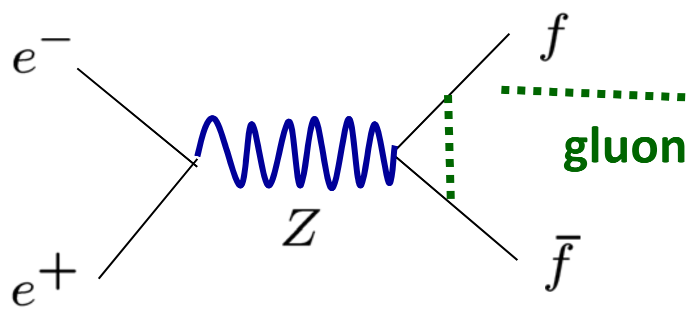
Th.) $$\Gamma(d_k\bar{d}_k) = \frac{G_F m_Z^3}{4\sqrt{2}\pi}\left(1 - \frac{4}{3}\sin^2\theta_w + \frac{8}{9}\sin^4\theta_w\right) = 0.3677\text{GeV}$$

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

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

for $\sin^2\theta_w = 0.2315$

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**

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 $W^+W^-\gamma \quad W^+W^-Z$

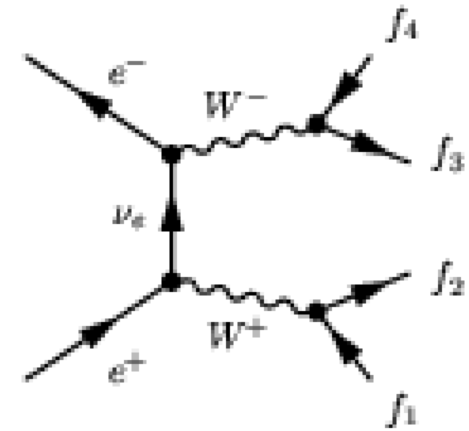
anomalous $Z\gamma\gamma, \quad ZZ\gamma, \quad ZZZ$

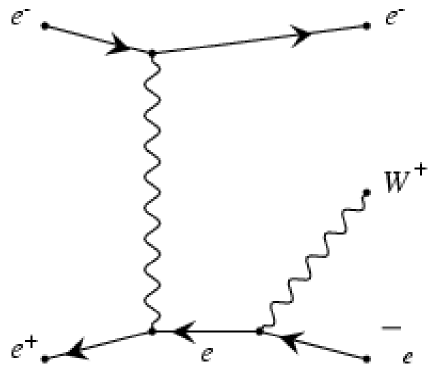
4-gauge couplings: SM $W^+W^-\gamma\gamma, \quad W^+W^-\gamma Z,$
$W^+W^-ZZ, \quad W^+W^-W^+W^-$

anomalous $ZZ\gamma\gamma$

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

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



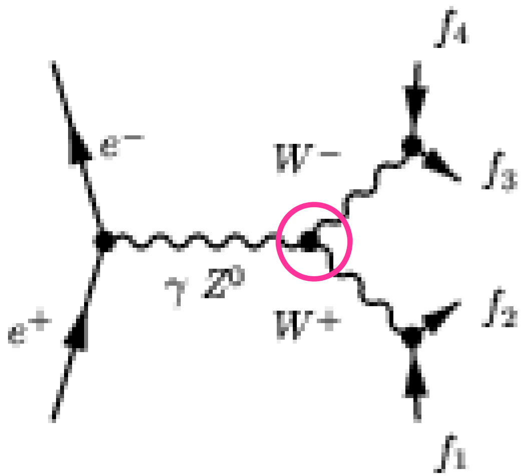


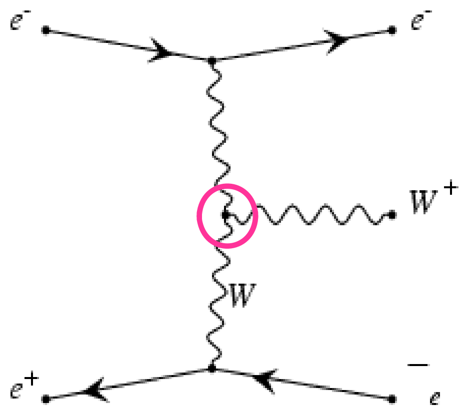
188.6 GeV

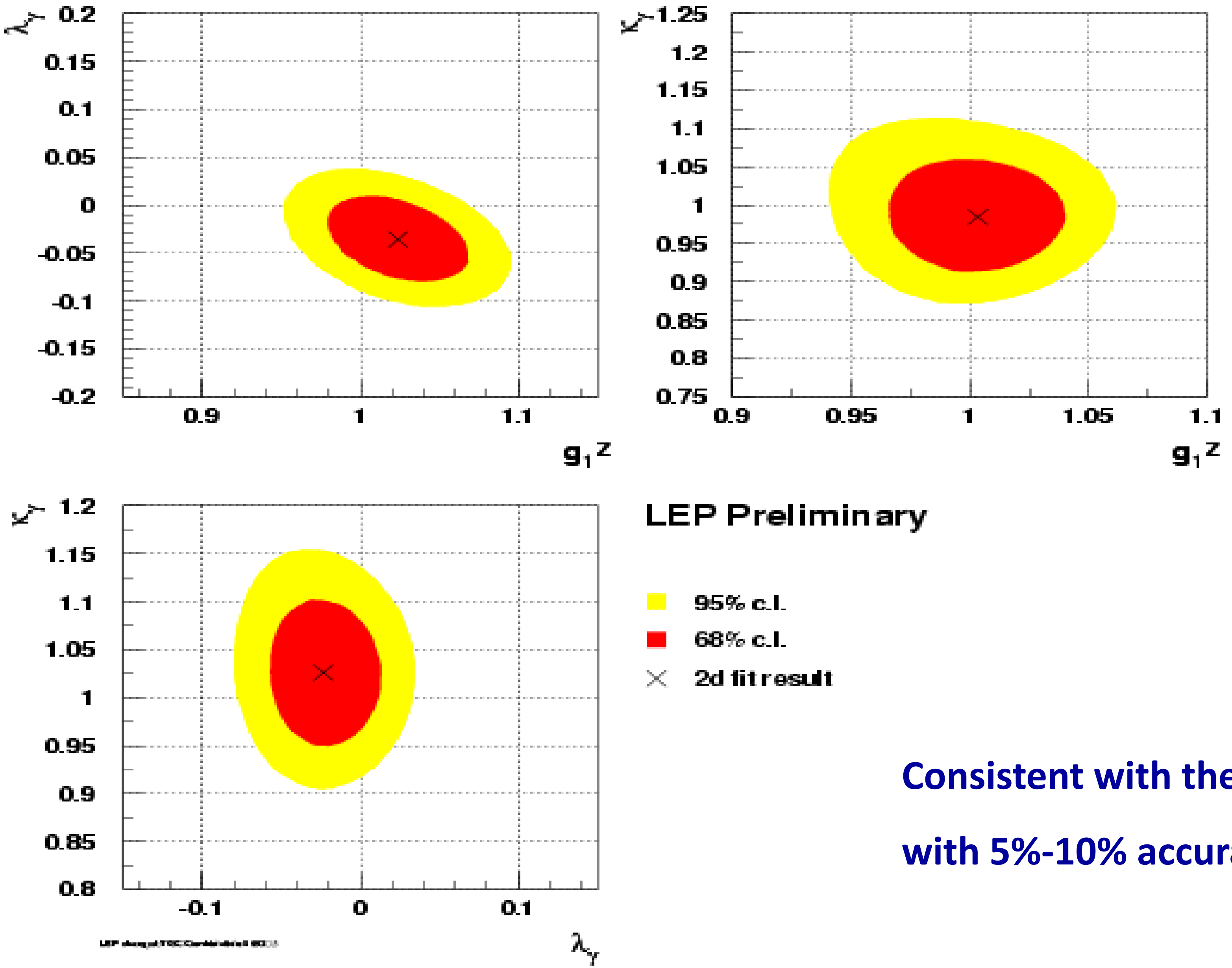
σ=15.98±0.23 pb

188.6 GeV

σ=0.60±0.09 pb





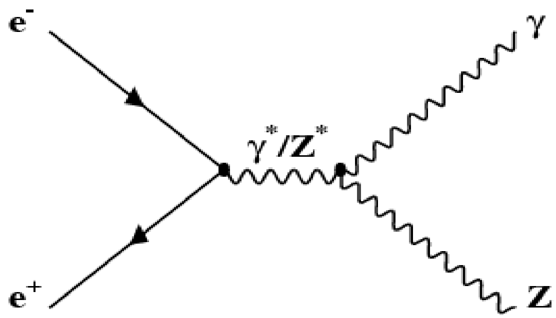


Consistent with the SM

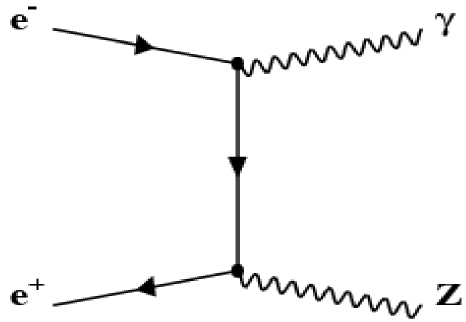
with 5%-10% accuracy

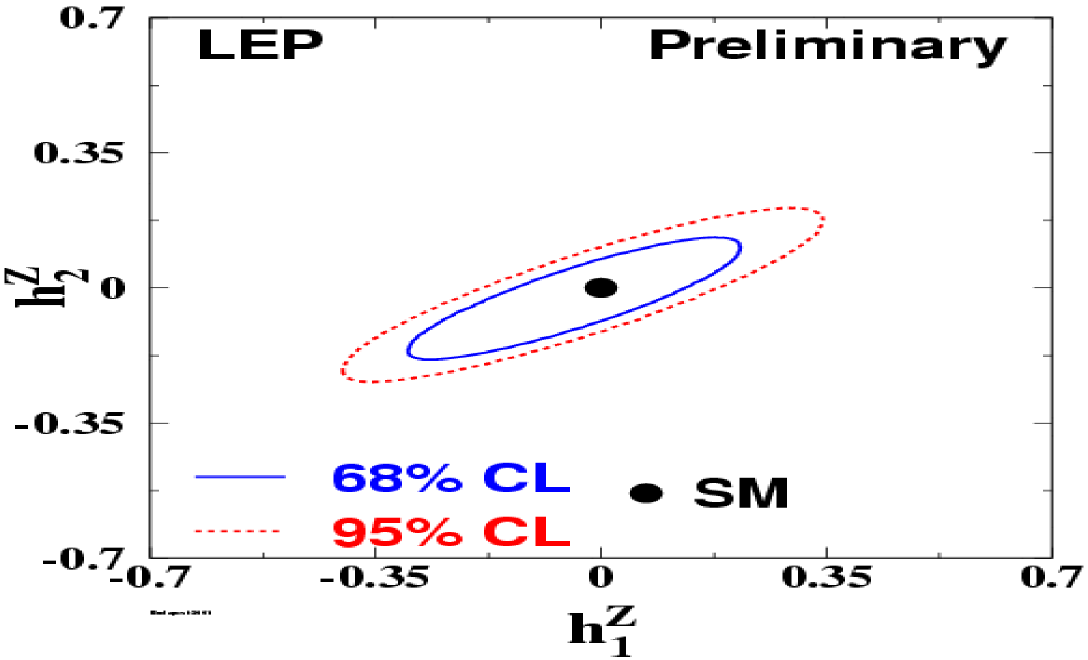
Neutral triple gauge couplings ← not exist in the SM

Search



SM background



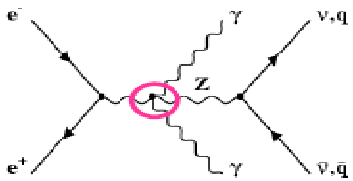


Consistent with the SM

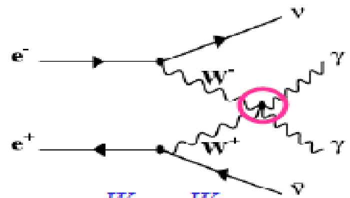
Quartic gauge couplings

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

- Anomalous couplings

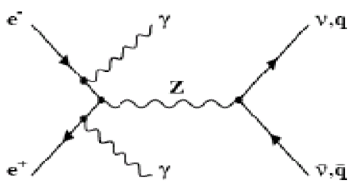


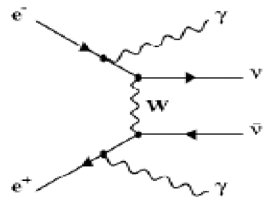
$a_0^Z \quad a_c^Z$



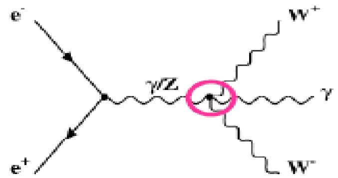
$a_0^W \quad a_c^W$

- Main diagrams

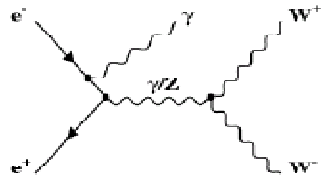


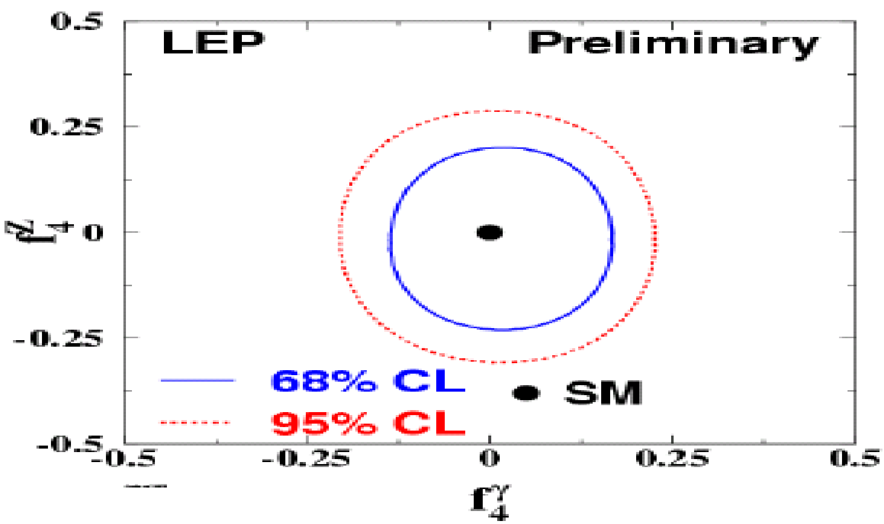


$$e^+e^- \to W^+W^-\gamma$$



$a_0^W \quad a_c^W \quad a_n$



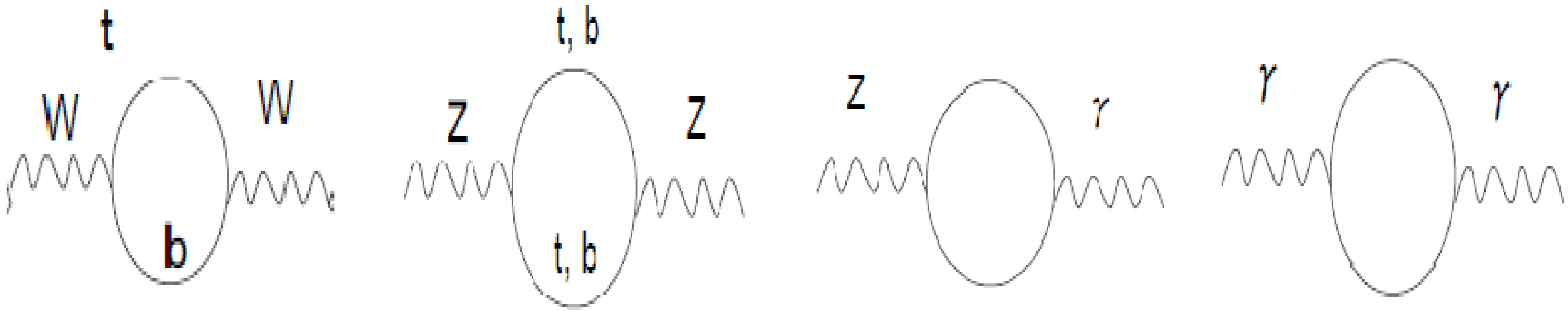


No anomalous coupling

Beyond Tree level

LEP precision measurements → beyond % level

→ level of quantum corrections



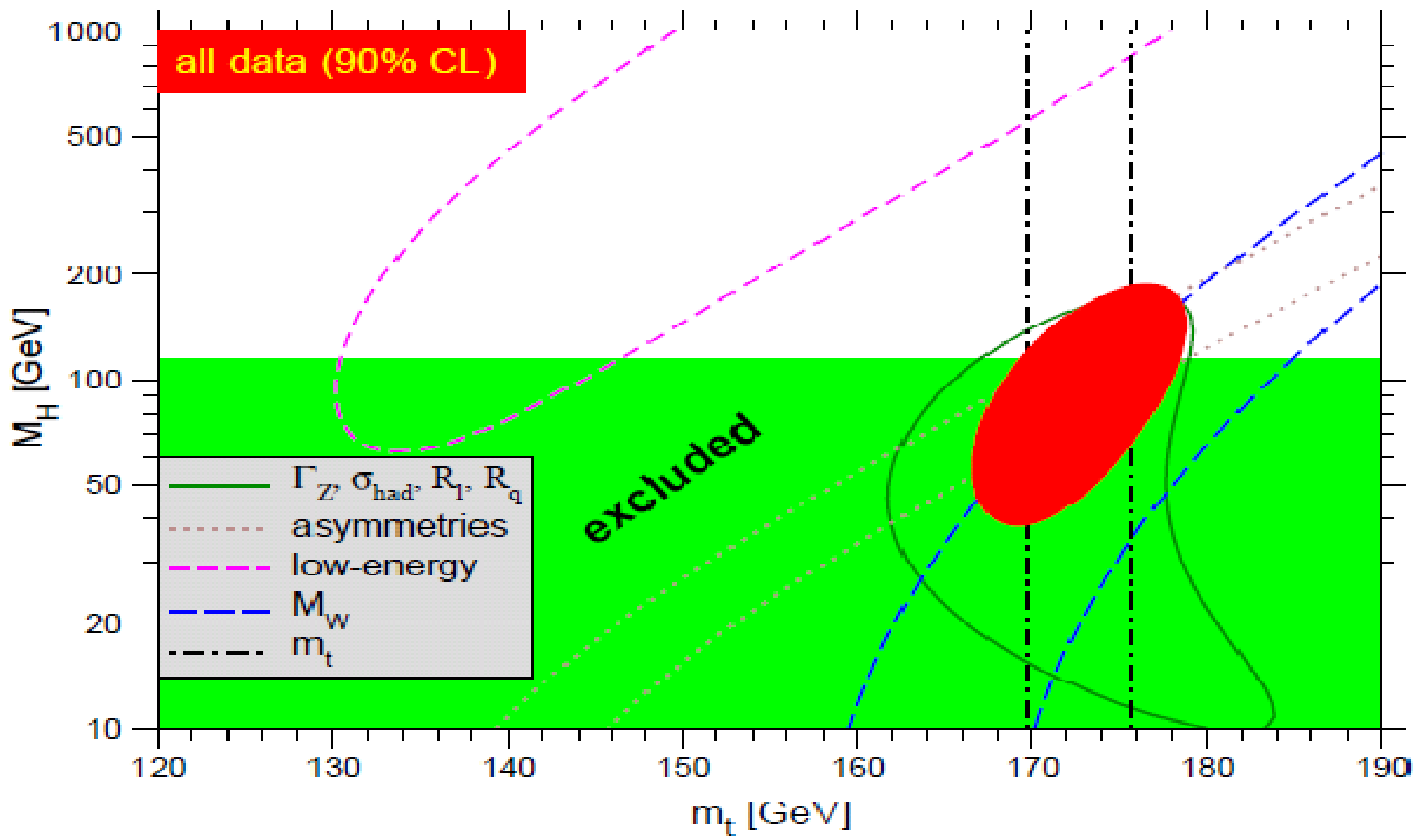
Mass ratio: $$m_Z^2 = (g^2 + g'^2)\frac{v^2}{4} + \Pi_{ZZ}(m_Z^2) \quad 91.1876 \pm 0.0021\text{GeV}$$

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

ρ parameter

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

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



Strong constraints on New Physics Models

→ **Loop corrections by New Particles should be < 1% contribution**

Ex) 4th generation leptons

Peskin & Takeuchi,

PRD 46, 381 (1992)

$$\Delta\rho = \alpha T$$

$$\Delta T_{new} = \frac{1}{16\pi s_w^2 c_w^2 m_Z^2}\left[{m_N}^2 + m_L^2 - \frac{2m_N^2 m_L^2}{{m_N}^2 - m_L^2}\ln\left(\frac{m_N^2}{m_L^2}\right)\right]$$

$$\simeq \frac{1}{12\pi s_w^2 c_w^2}\left[\frac{(\Delta m)^2}{m_Z^2}\right]$$

$$\Delta m = |m_N - m_L| \ll m_N,\ m_L$$

Mass splitting should be small

Two main structures of the Standard Model

Gauge invariance

→ very precisely checked by experiments

Matters

→ some representations under SM gauge group

all matters have been observed

Higgs mechanism

→ Higgs has not yet been observed

Origin of symmetry breaking (Higgs potential)?

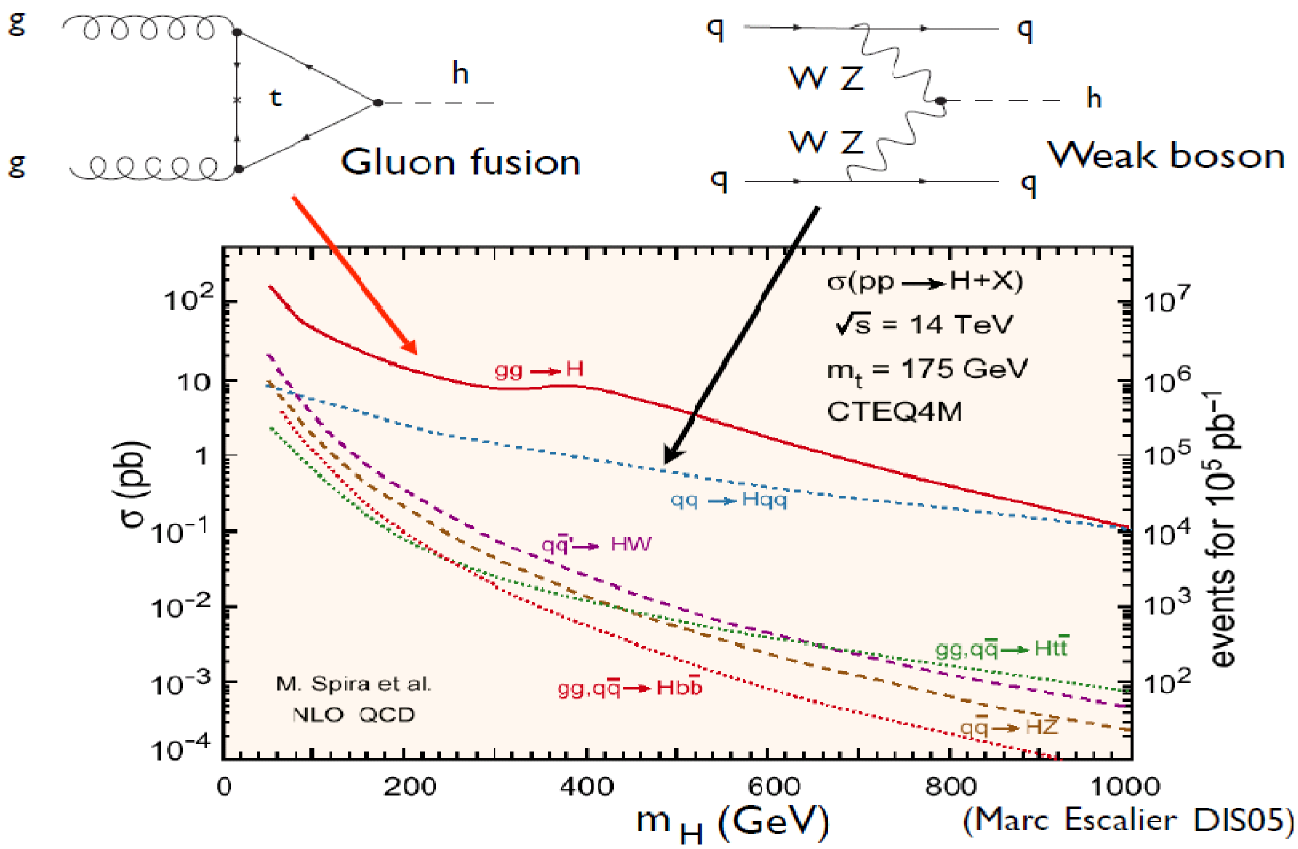
Mass generation mechanism is not yet confirmed

→ should be checked in future experiments

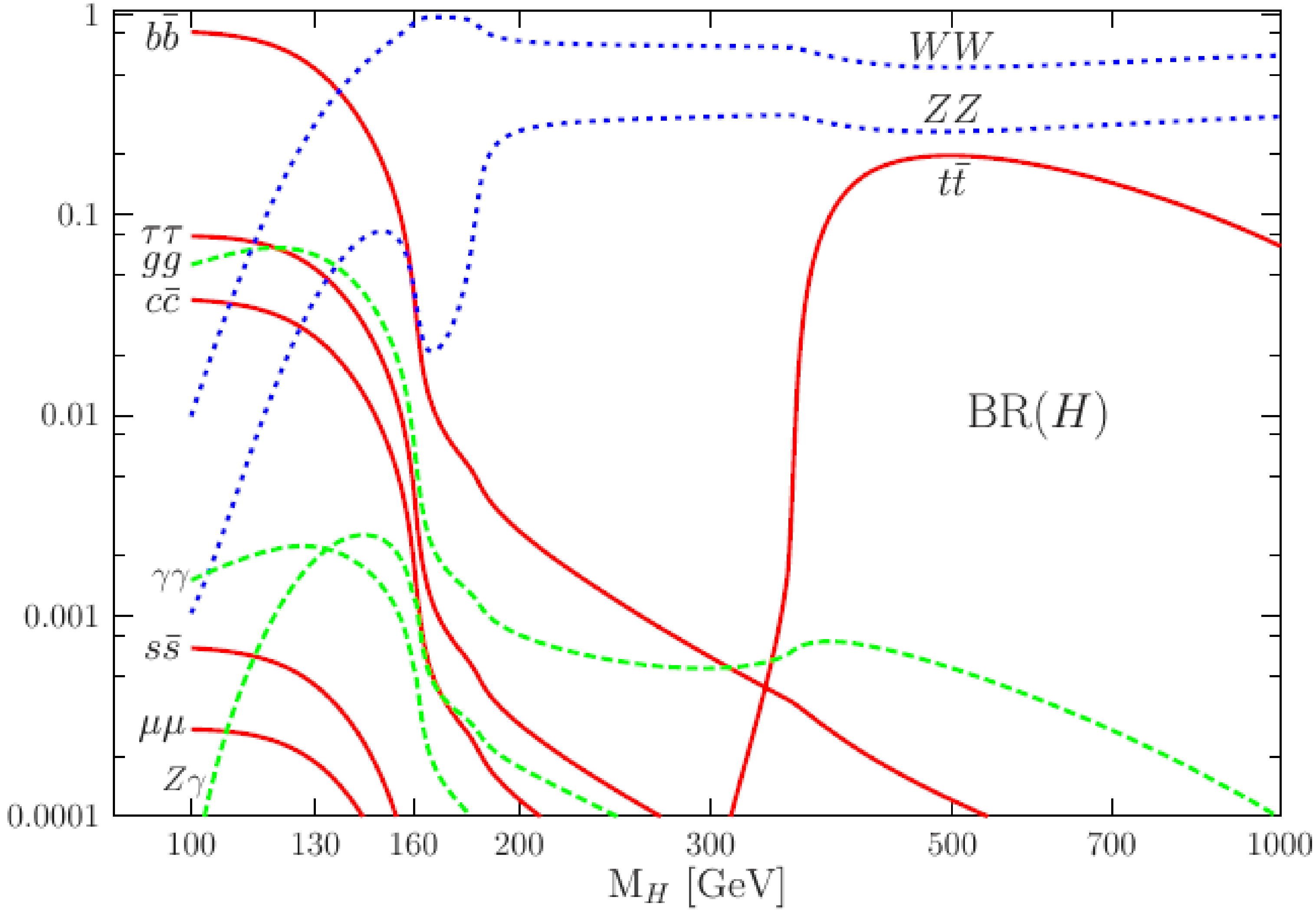
Higgs boson search at LHC

Higgs boson production dominantly by gluon fusion,

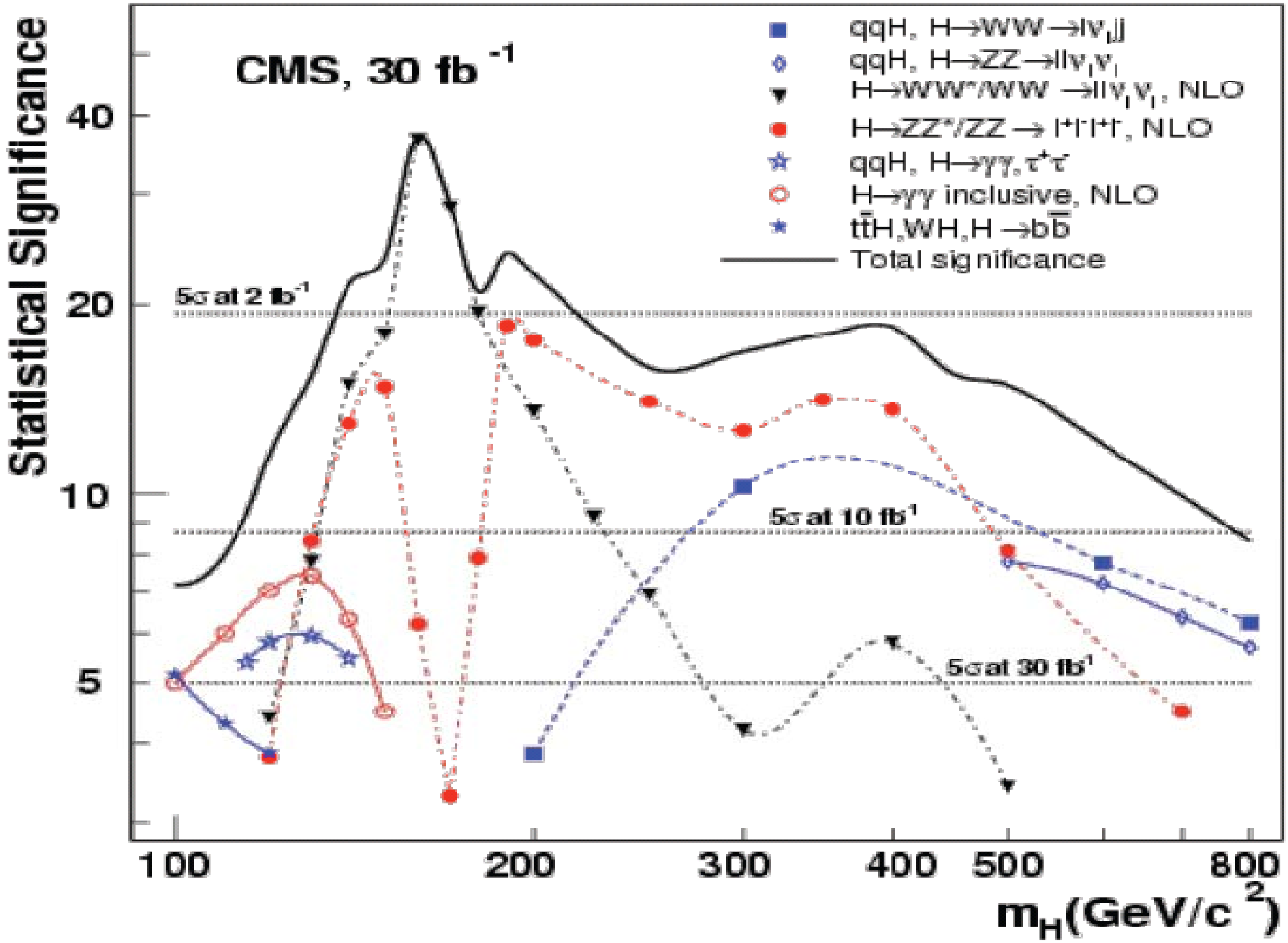
followed by week boson fusion



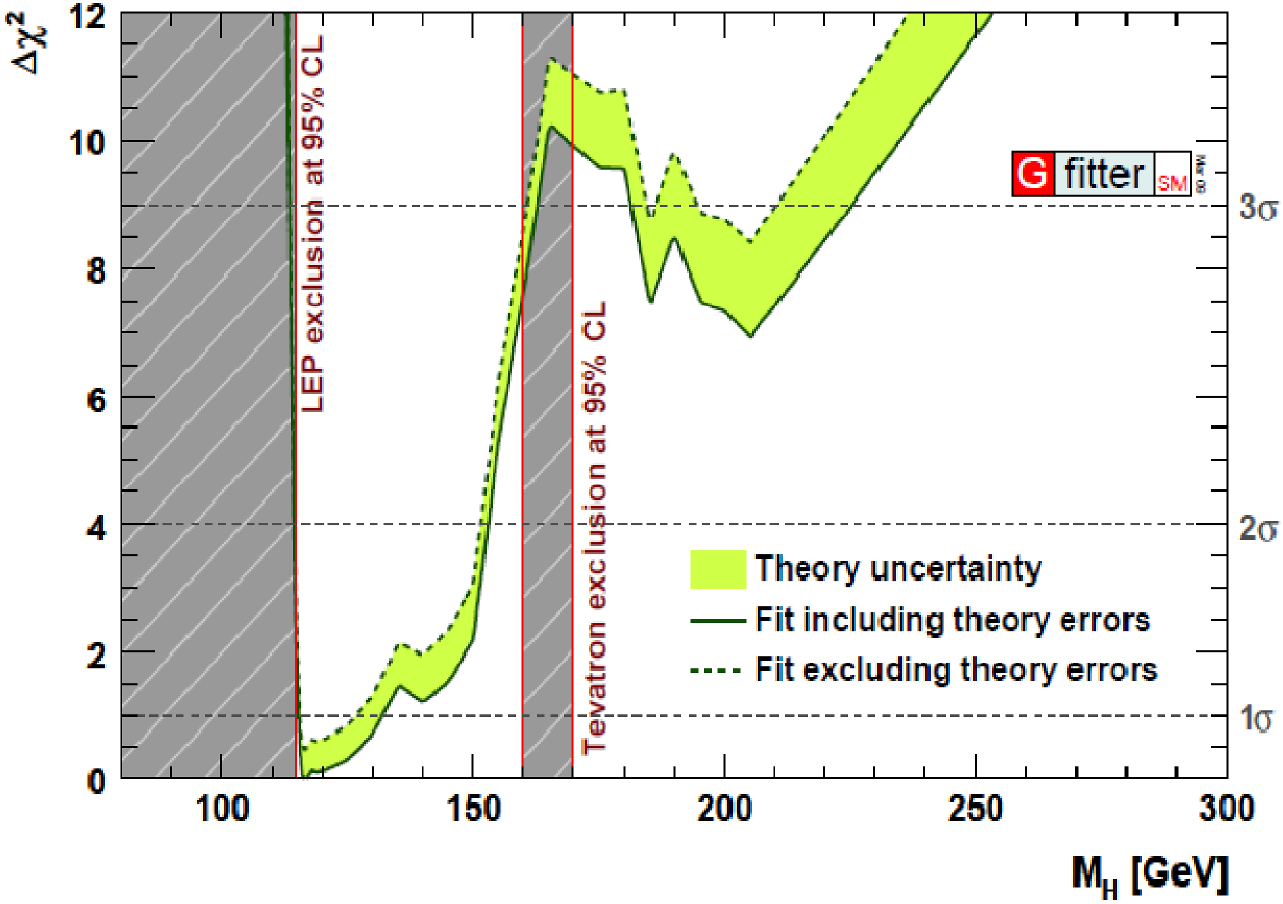
Branching fractions



Discovery potential

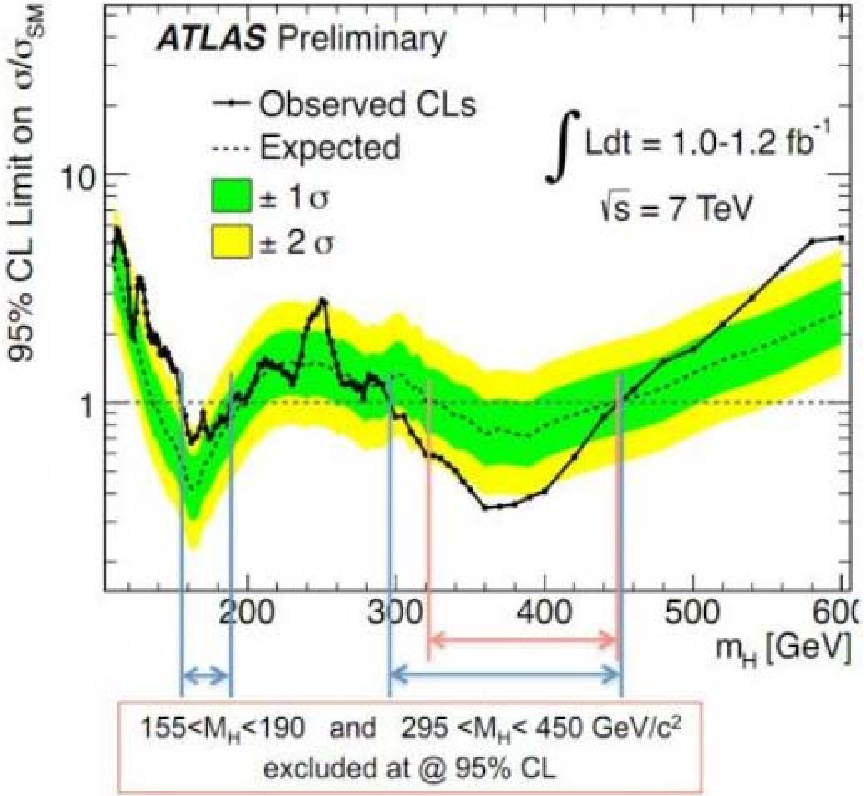


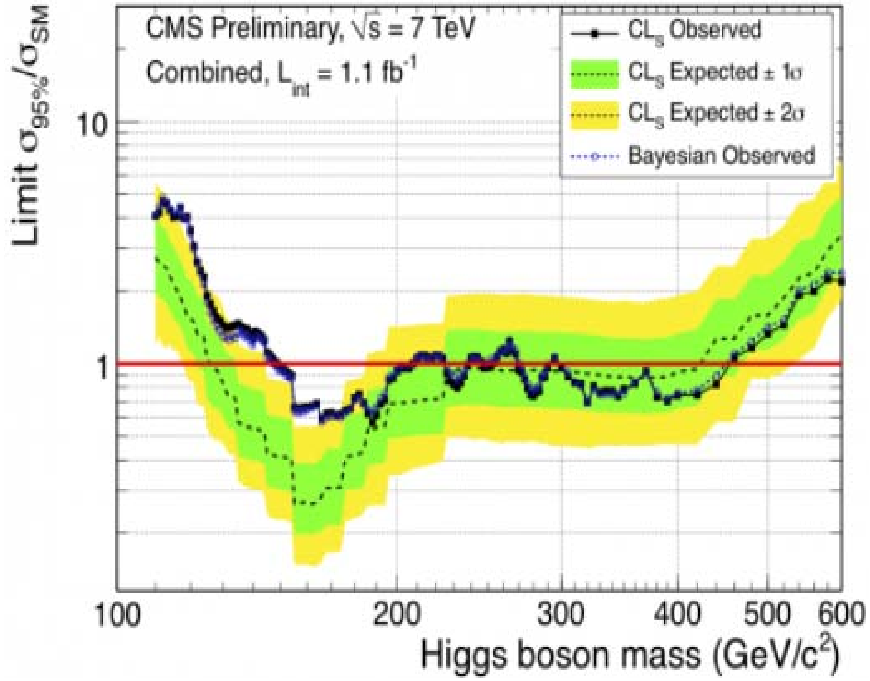
Direct Higgs mass bound by LEP & Tevatron
Fitting of Electroweak precision measurements



Higgs mass < 160 GeV seems favorable

Most recent data at LHC http://blog.vixra.org/2011/07/22/big-day-for-higgs-boson/





Window for Higgs boson mass

$$114 \text{ GeV} < m_H < 137 \text{ GeV}$$

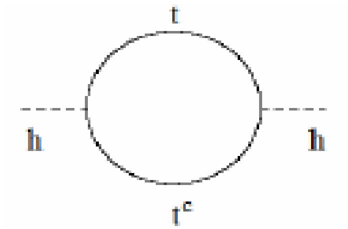
$$205 \text{ GeV} < m_H < 295 \text{ GeV}$$ ← **Disfavored by EWPM**

3. Problems in the Standard Model

(A) Theoretical (conceptual) problem

Quantum corrections of Higgs mass → quadratic divergence

$\Delta M_H^2 =$



$= Y_t^2 \Lambda^2$

$$M_{\text{Phys}}^2 = M_0^2 + \Delta M_H^2 \to \mathcal{O}(M_W^2)$$

If $\Lambda_{\text{New}} \gg M_W$ we need to explain the reason

→ hierarchy problem

(fine-tuning problem: Big # - Big# → small #)

No such a problem → New Physics around TeV

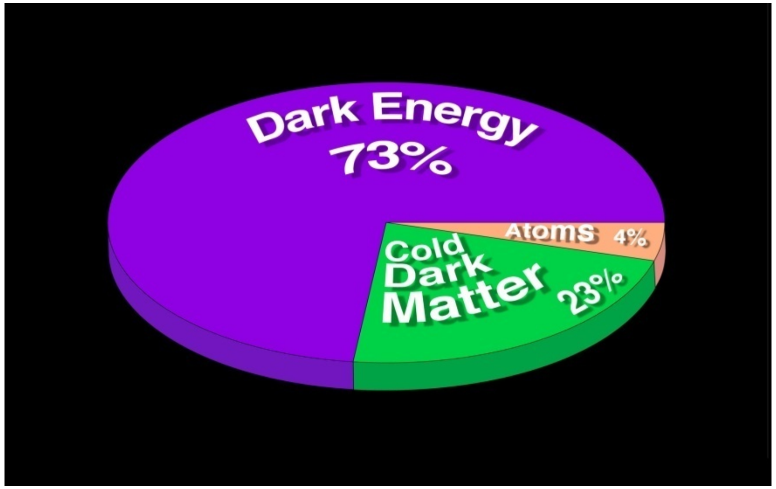
(B) Experimental observations which the SM cannot explain

Wilkinson Microwave Anisotropy Probe (WMAP) satellite has established the energy budget in the present Universe with a great accuracy

(1) Dark Matter

$$0.096 \leq \Omega_{DM} h^2 \leq 0.122$$

Massive, charge neutral, stable



Suitable candidate: weakly interacting massive particle (WIMP) → No Candidate in the SM → Need New Physics

$$\Omega h^2 = \frac{1.07 \times 10^9 x_f \mathrm{GeV}^{-1}}{\sqrt{g_*} M_{\mathrm{Pl}} \langle \sigma \mathrm{v} \rangle} \sim 0.1 \rightarrow \quad \langle \sigma v \rangle \sim \alpha^2 \left(\frac{1}{1\ \mathrm{TeV}} \right)^2$$

TeV scale New Physics is relevant to DM physics!

Neutrinos are massless in the Standard Model

(2)Neutrino Oscillation Data

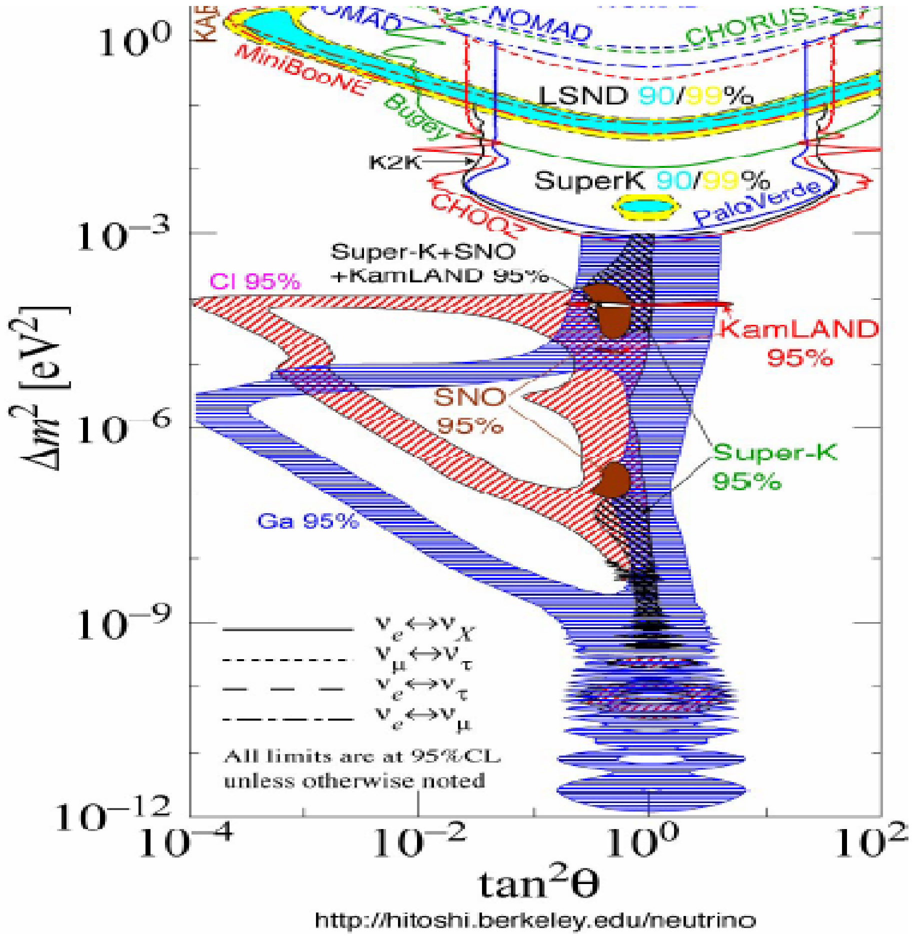
→ **Evidence of New Physics beyond the SM**

neutrino non-zero mass & flavor mixings

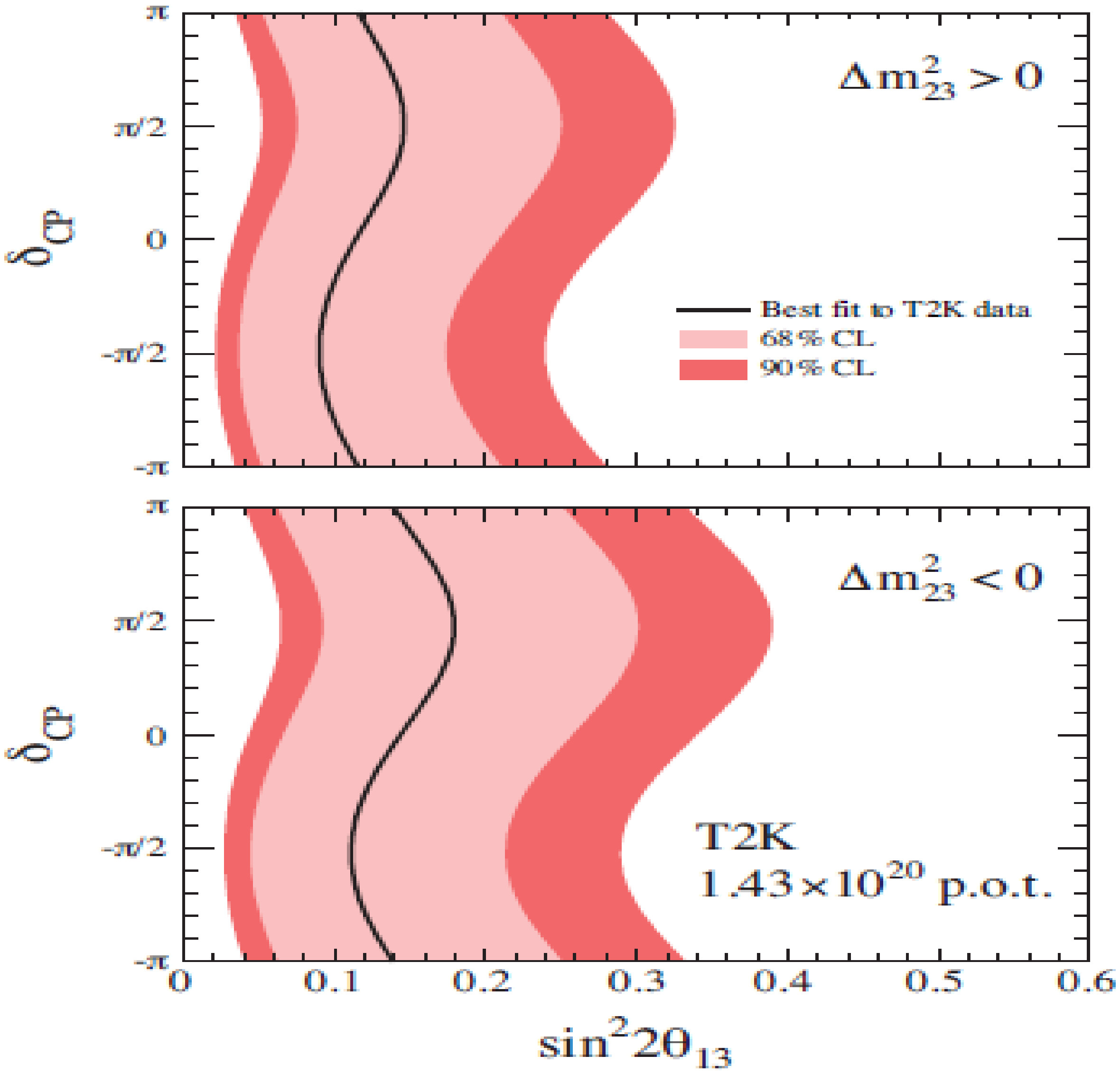
Oscillation data

$$7.2\times 10^{-5} < \Delta m^2_{12}(\mathrm{eV}^2) < 9.2\times 10^{-5}$$
$$1.4\times 10^{-3} < \Delta m^2_{23}(\mathrm{eV}^2) < 3.3\times 10^{-3}$$
$$0.25 < \sin^2\theta_{12} < 0.39$$
$$\sin^2 2\theta_{23} > 0.9$$
$$|U_{e3}| < 0.22.$$

Tiny mass scale & large mixing angles



Measurement of theta_13 at T2K



We focus on TeV scale New Physics

(1) motivated by the hierarchy problem

(2) suitable for Dark Matter Physics

TeV scale

→ **Accessible at future collider experiments!**

Large Hadron Collider (LHC)

International Linear Collider (ILC)

Examples of New Physics models

Supersymmetric models: MSSM, GUT, SUSY breaking,

Extra-dimension models: large Xdim, Warped Xdim, Universal Xdm,

gauge-Higgs model, Higgs-less model,….

non-SUSY models in 4D: Technicolor, Little Higgs models,….

Unexpected: unparticle, hidden valley, quirk models, ….

In next lectures, we will discuss

Supersymmetry (SUSY)