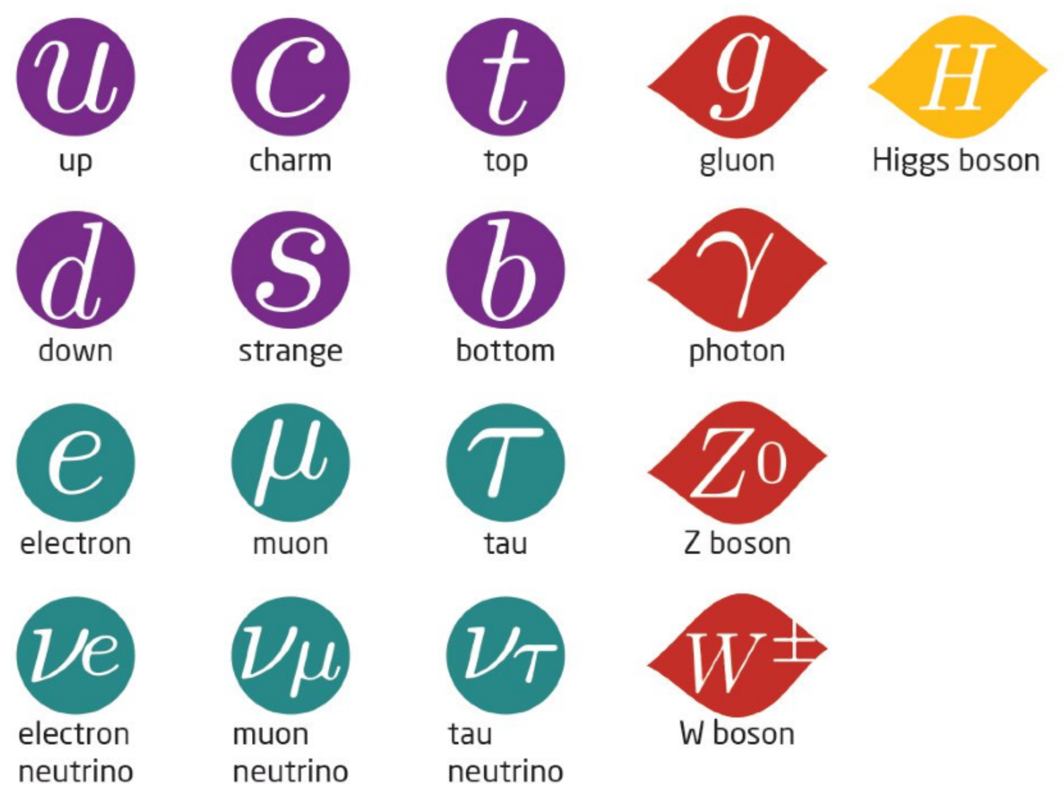
An Introduction to the Standard Model of Particle Physics



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2nd IUT CMS meeting, Shahrivar 1400

Introduction/Outline

- An old question and long-standing activity:

What the Universe is made of at the most (or at a more) fundamental level?

Elementary particles and their interaction.

In this brief lecture, we present our knowledge based on many years of experimentation and theoretical speculation.

- Outline:
    - Experimental findings
    - Theoretical framework
    - The Standard Model of particle physics
    - Electroweak symmetry breaking and the Higgs mechanism

Experimental Findings: *Fermions*

Spin 1/2 matter particles, and their anti-particles, vast range of *masses*

electron: $m = 0.510998928 \pm 0.000000011$ MeV

muon: $m = 105.6583715 \pm 0.0000035$ MeV

tau: $m = 1776.82 \pm 0.16$ MeV

muon neutrino, electron neutrino, tau neutrino

$$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{32} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}\ \mathrm{eV}^2$$

up: $m_u = 2.2^{+0.6}_{-0.4}$ MeV

down: $m_d = 4.7^{+0.5}_{-0.4}$ MeV

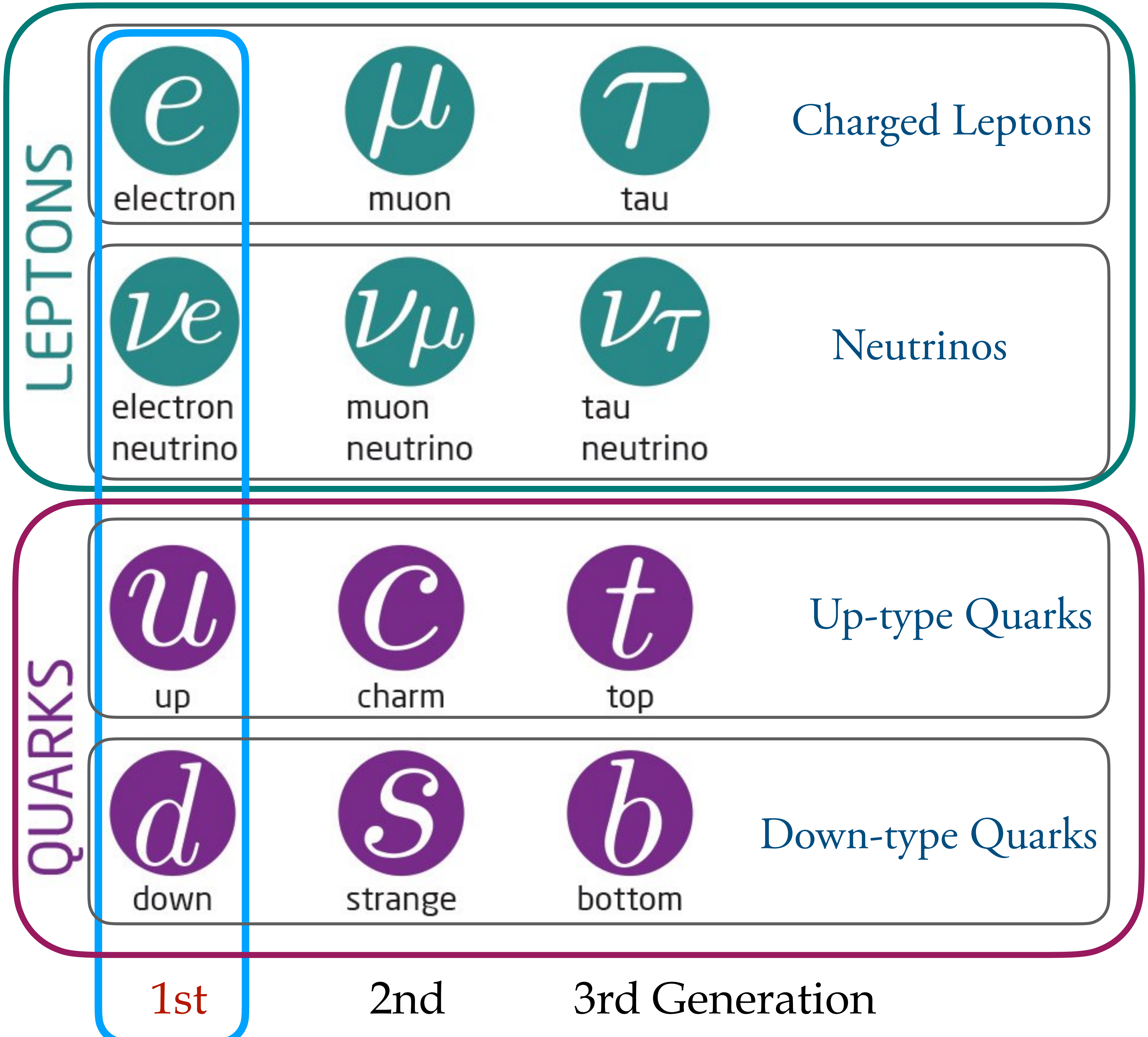
strange: $m_s = 96^{+8}_{-4}$ MeV

charm: $m_c = 1.28 \pm 0.03$ GeV

bottom: $m = 4.18^{+0.04}_{-0.03}$ GeV

top: $m = 173.1 \pm 0.6$ GeV

Experimental Findings: *Fermions*



Experimental Findings: *Gauge Bosons*

Spin 1 gauge particles and vast range of *masses* (force carriers)

$m < 1 \times 10^{-18}$ eV

Interacts with electrically charged particles

$m = 80.399 \pm 0.023$ GeV

Interacts with LH particles

$m = 91.1876 \pm 0.0021$ GeV

Interacts with all particles

$m = 0$

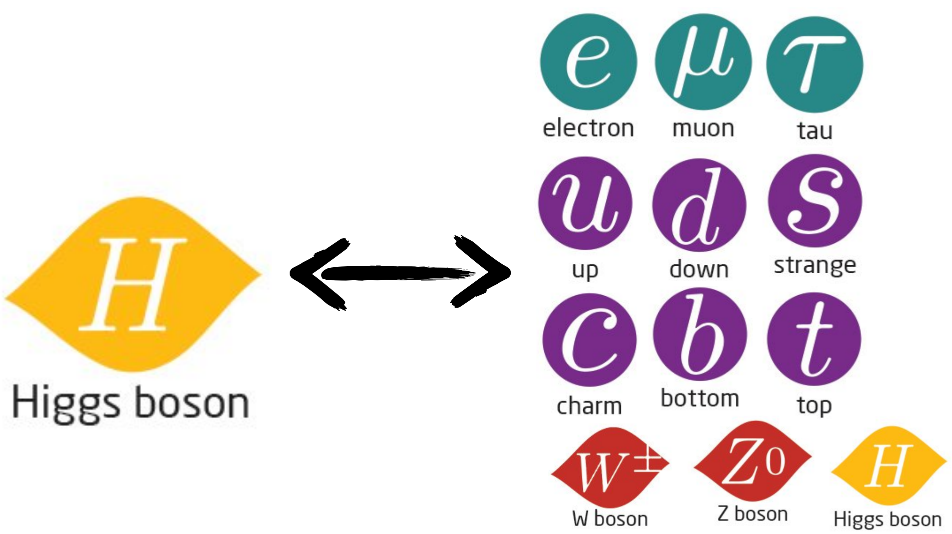
Interacts with quarks (colored particles)

Experimental Findings: *Scalar Boson*

Spin 0 particle with non-zero *mass*

$$m = 125.18 \pm 0.16 \text{ GeV}$$

◆ Interacts with massive particles,
the more massive the stronger the interaction.



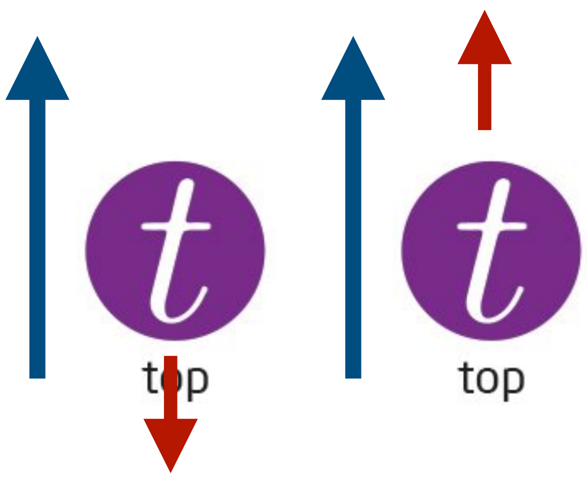
◆ The last elementary particle discovered in 2012 at the LHC

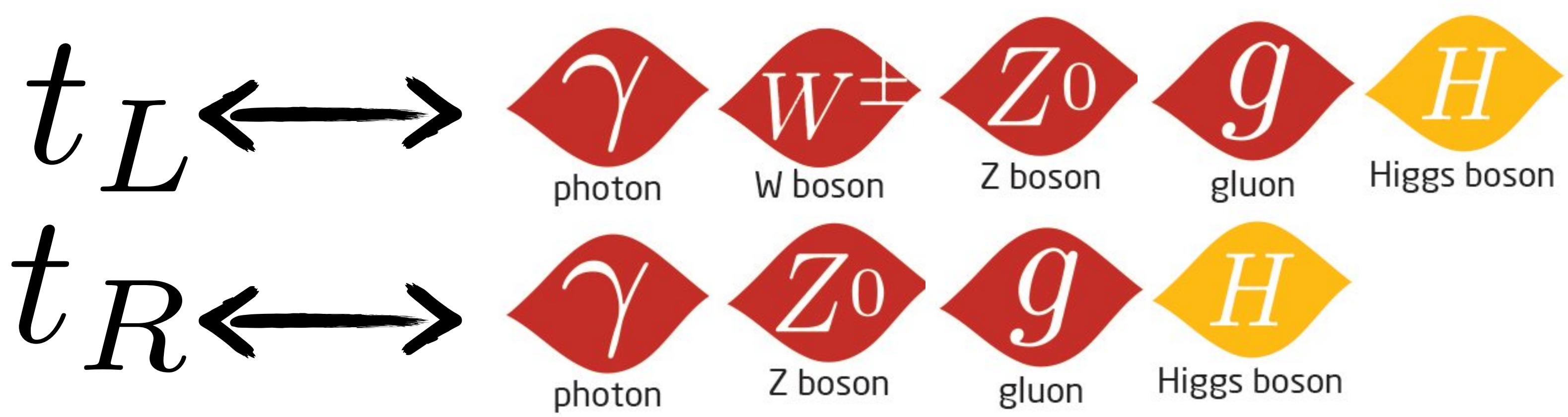
Experimental Findings

- Measured particle properties:

$$m = 173.1 \pm 0.6 \text{ GeV}$$
$$J = 1/2$$

- Spin is a vector quantity (magn.,direction). In VHE limit:





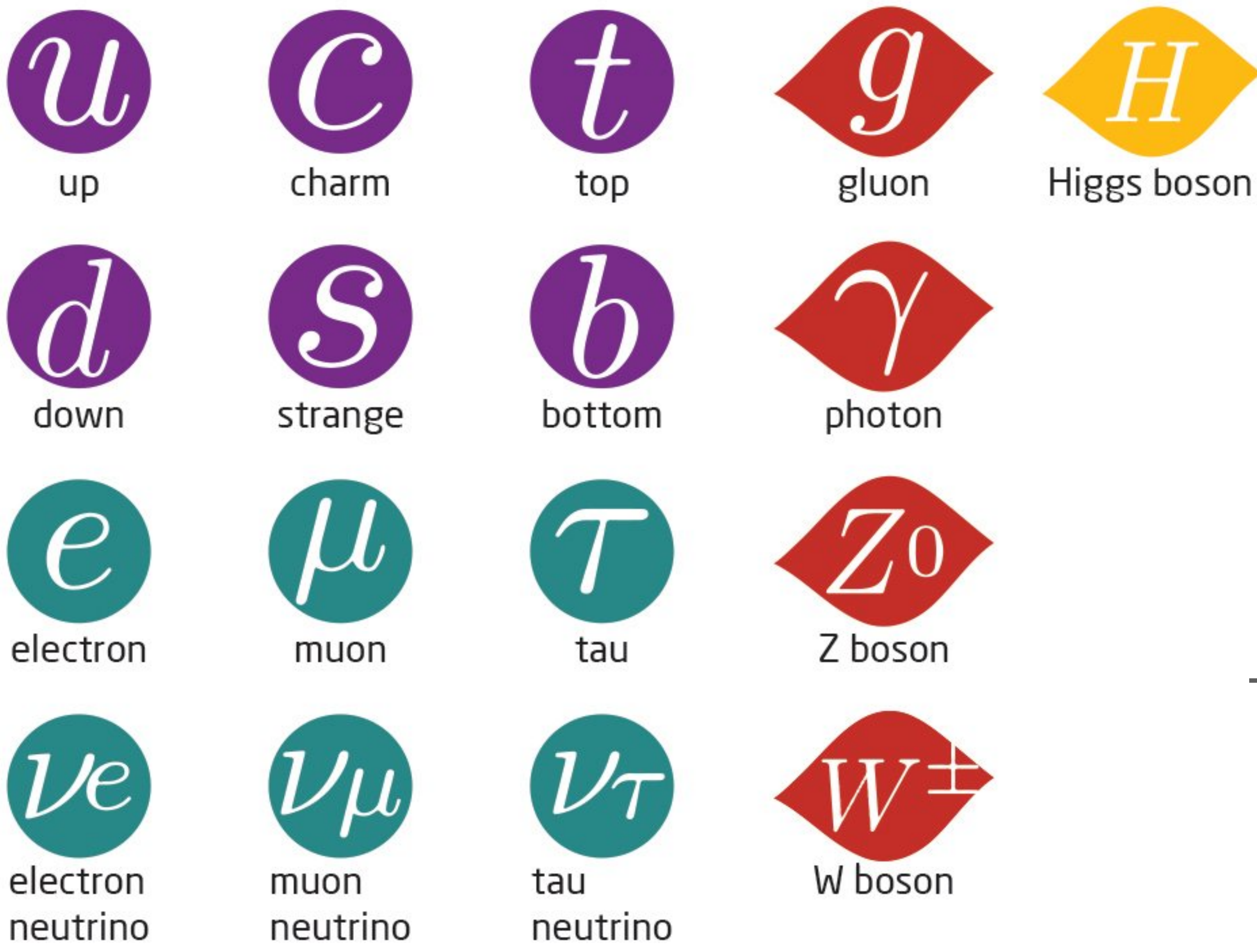
- A Dirac top quark is linear combination of both states.
- Neutrinos are left-handed
- Parameters to parametrize the strengths of interactions: quantum numbers

1/3,{R,B,G},y_t,etc,

- There are also anti-particles.

Experimental Findings

◆Experimentally, we know that what the Universe is made of at *some* fundamental level:



+ anti-particles.

◆Next question: If there is model to understand and describe elementary particles, their properties and interactions in mathematical terms?

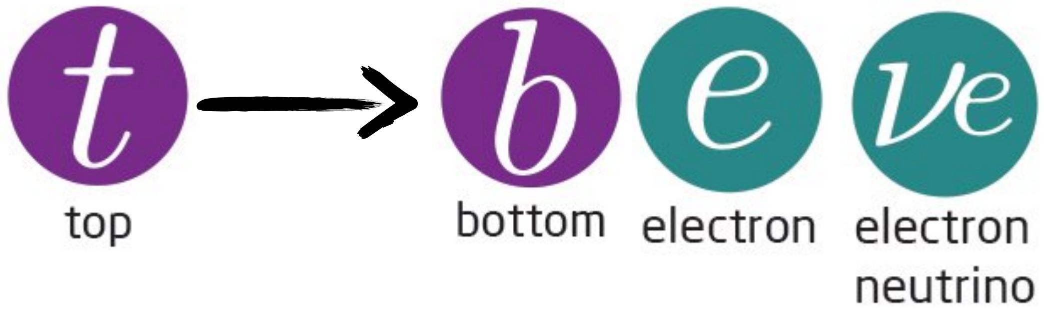
◆What is a particle?

Theoretical Framework: *Quantum Mechanics*

- A theoretical practical framework for understanding physics at the microscopic scale: Quantum Mechanics. A probabilistic understanding of subatomic phenomena.

- A particle is a *state* in the Hilbert space.

- However, single particle quantum mechanics is not applicable to particle phenomena: the number/type of particles changes in interactions.



- Thus we need a more general framework that applies the quantum rules.

Theoretical Framework: *Special Relativity*

◆Experimental data indicate that Lorentz symmetry is respected by particle phenomena.

Conservation of energy-momentum, angular momentum in interaction.

Anti-particles, DOF's,particular kinds of interactions, etc.

◆A symmetry of nature: Lorentz invariance (all inertial observers see same physics: special relativity)

◆All (physical) quantities classified by how they transform under Lorentz group *SO(1,3)*. (recall: Lorentz group is subgroup of Poincare)

◆Wigner: Unitary irreducible representations are characterized by two invariants: call them *Mass* m and *Spin* J, with *1, 2, 2J+1* DOF's. (infinite-dimensional representation)

◆Particles are in infinite-dimensional irreducible *representations* of the Lorentz group. $so(1,3) = sl(2,C) = su(2)_L \times su(2)_R$

$$(j_1, j_2) \qquad J = j_1 + j_2, j_1 + j_2 - 1, \ldots, |j_1 - j_2|$$

Theoretical Framework: *Quantum Field Theory*

- A particle is a *state* in the Hilbert space.

- A particles is in infinite-dimensional irreducible *representations* of the Lorentz group.

- A unique framework including *QM* plus *SR*: *Quantum Field Theories*

- What is a quantum field?

Infinite number of harmonic oscillators.

Natural object to describes particles.

Particles are excitations of quantum fields.

Theoretical Framework: *Quantum Field Theory*

Higgs particle: Higgs boson $J = 0$

$m = 125.18 \pm 0.16$ GeV

Higgs field: $$h(x) = \int \frac{d^3\mathbf{p}}{(2\pi)^3}\left[a_{\mathbf{p}}(t)e^{i\mathbf{p}\cdot\mathbf{x}} + a_{\mathbf{p}}(t)^{\dagger}e^{-i\mathbf{p}\cdot\mathbf{x}}\right]$$

$a_{\mathbf{p}}^{\dagger}$ Creates a Higgs particle, with momentum p and energy $E_{\mathbf{p}}^2 = |\mathbf{p}|^2 + m^2$

$(\partial_t^2 + E_{\mathbf{p}}^2)a_{\mathbf{p}}(t) = 0$ Equation of motion of a harmonic oscillator

- A Higgs particle is a *state* in the Hilbert space. $|\mathbf{p}\rangle$
- The Higgs particles is infinite-dimensional irreducible representations of the Lorentz group. $(0, 0)$

Theoretical Framework: *Quantum Field Theory*

top (anti)particle: $J = 1/2$, $m = 173.1 \pm 0.6$ GeV

top (anti) field:

$$t(x) = \sum_s \int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3} \left[a^s_{\mathbf{p}}(t) u^s_{\mathbf{p}} e^{i\mathbf{p}\cdot\mathbf{x}} + b^{s\dagger}_{\mathbf{p}}(t) v^s_{\mathbf{p}} e^{-i\mathbf{p}\cdot\mathbf{x}}\right]$$

$$\bar{t}(x) = \sum_s \int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3} \left[a^{s\dagger}_{\mathbf{p}}(t) \bar{u}^s_{\mathbf{p}} e^{-i\mathbf{p}\cdot\mathbf{x}} + b^s_{\mathbf{p}}(t) \bar{v}^s_{\mathbf{p}} e^{i\mathbf{p}\cdot\mathbf{x}}\right]$$

$a^{s\dagger}_{\mathbf{p}}$, $b^{s\dagger}_{\mathbf{p}}$ Creates a top (anti)particle, with momentum p, spin state s

$$E^2_{\mathbf{p}} = |\mathbf{p}|^2 + m^2$$

$(\partial_t^2 + E^2_{\mathbf{p}}) a_{\mathbf{p}}(t) = 0$ Equation of motion of a harmonic oscillator

- A top particle is a *state* in the Hilbert space. $|\mathbf{p}, s\rangle$
- The top particle is in infinite-dimensional irreducible representations of the Lorentz group. $(1/2, 0) + (0, 1/2)$

Theoretical Framework: *Quantum Field Theory*

Z boson particle: 

$J = 1$

$m = 91.1876 \pm 0.0021$ GeV

Z field: $$Z_\mu(x) = \sum_i \int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3} \left[\epsilon^i_{\mu,\mathbf{p}} a^i_{\mathbf{p}}(t) e^{i\mathbf{p}\cdot\mathbf{x}} + \epsilon^{i*}_{\mu,\mathbf{p}} a^{i\dagger}_{\mathbf{p}}(t) e^{-i\mathbf{p}\cdot\mathbf{x}}\right]$$

$a^{i\dagger}_{\mathbf{p}}$ Creates a Z boson, with momentum p, spin state *i*, $E^2_{\mathbf{p}} = |\mathbf{p}|^2 + m^2$

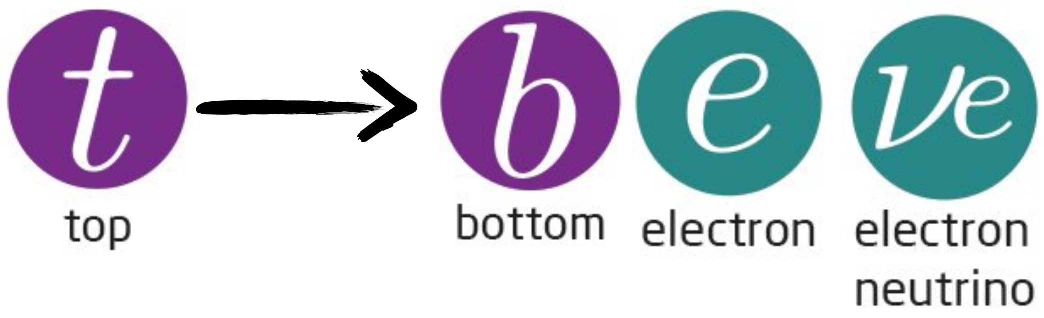
$(\partial_t^2 + E^2_{\mathbf{p}}) a_{\mathbf{p}}(t) = 0$ Equation of motion of a harmonic oscillator

- A top particle is a *state* in the Hilbert space. $|\mathbf{p}, s\rangle$
- The top particle is in infinite-dimensional irreducible representations of the Lorentz group. $(1/2, 1/2)$

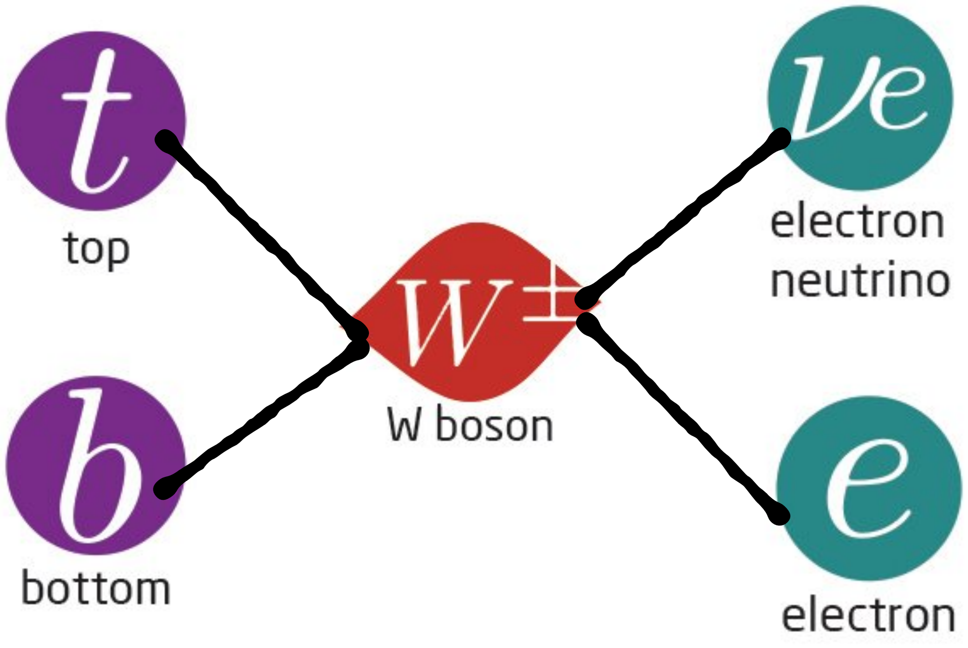
Theoretical Framework: *Quantum Field Theory*

- Interactions: non-linear terms of quantum fields in the Hamiltonian

Decay of top particle to a bottom, electron and anti-neutrino particles



$$\mathcal{H} \supset t_L(x) b_L(x) W_\mu(x) + e_L(x) \nu_L(x) W_\mu(x)$$



Theoretical Framework: *Quantum Electrodynamics*

- Electron-Photon *U(1)* interaction

Charged Dirac fermion interacting with massless photon.

electron

$$\psi(x) = \sum_s \int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3} \left[a^s_{\mathbf{p}}(t) u^s_{\mathbf{p}} e^{i\mathbf{p}\cdot\mathbf{x}} + b^{s\dagger}_{\mathbf{p}}(t) v^s_{\mathbf{p}} e^{-i\mathbf{p}\cdot\mathbf{x}}\right]$$

$$\bar{\psi}(x) = \sum_s \int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3} \left[a^{s\dagger}_{\mathbf{p}}(t) \bar{u}^s_{\mathbf{p}} e^{-i\mathbf{p}\cdot\mathbf{x}} + b^s_{\mathbf{p}}(t) \bar{v}^s_{\mathbf{p}} e^{i\mathbf{p}\cdot\mathbf{x}}\right]$$

photon

$$A_\mu(x) = \sum_i \int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3} \left[\epsilon^i_{\mu,\mathbf{p}} a^i_{\mathbf{p}}(t) e^{i\mathbf{p}\cdot\mathbf{x}} + \epsilon^{i*}_{\mu,\mathbf{p}} a^{i\dagger}_{\mathbf{p}}(t) e^{-i\mathbf{p}\cdot\mathbf{x}}\right]$$

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F_{\mu\nu} + i\gamma_\mu \bar{\psi} \partial_\mu \psi - e\gamma_\mu A_\mu \bar{\psi}\psi - m\bar{\psi}\psi$$

$$F_{\mu\nu} = -\frac{1}{4}(\partial_\mu A_\nu - \partial_\nu A_\mu)$$

- Abelian *U(1)* gauge symmetry

$$A_\mu \to A_\mu + \partial_\mu \alpha$$

$$\psi \to \psi e^{i\alpha}$$

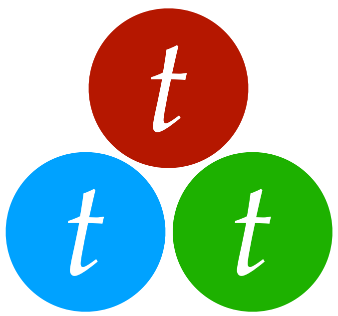
$$\bar{\psi} \to \bar{\psi} e^{-i\alpha}$$

- The unique way a charged particle interacts with massless vector particle.

Theoretical Framework: *Quantum Yang-Mills Theory*

◆ Quark-Gluon *SU(3)* interactions

Colored Dirac fermions interacting with massless gluon.



$$t^{r,g,b}(x) = \sum_s \int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3} \left[a^{r,g,b}_{s,\mathbf{p}}(t) u_{s,\mathbf{p}} e^{i\mathbf{p}\cdot\mathbf{x}} + b^{r,g,b\dagger}_{s,\mathbf{p}}(t) v_{s,\mathbf{p}} e^{-i\mathbf{p}\cdot\mathbf{x}}\right]$$

$$\bar{t}^{r,g,b}(x) = \sum_s \int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3} \left[a^{r,g,b\dagger}_{s,\mathbf{p}}(t) \bar{u}_{s,\mathbf{p}} e^{-i\mathbf{p}\cdot\mathbf{x}} + b^{r,g,b}_{s,\mathbf{p}}(t) \bar{v}_{s,\mathbf{p}} e^{i\mathbf{p}\cdot\mathbf{x}}\right]$$

$$g^a_\mu(x) = \sum_i \int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi)^3} \left[\epsilon^i_{\mu,\mathbf{p}} a^{a,i}_{\mathbf{p}}(t) e^{i\mathbf{p}\cdot\mathbf{x}} + \epsilon^{i*}_{\mu,\mathbf{p}} a^{a,i\dagger}_{\mathbf{p}}(t) e^{-i\mathbf{p}\cdot\mathbf{x}}\right]$$

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + i\gamma_\mu \bar{\psi}^I \partial_\mu \psi^I - g_s (T^a)^{IJ} \gamma_\mu g^a_\mu \bar{\psi}^I \psi^J - m\bar{\psi}^I \psi^I$$

$$G^a_{\mu\nu} = \partial_\mu g^a_\nu - \partial_\nu g^a_\mu + g_s f^{abc} A^b_\mu A^c_\nu$$

◆ Non-Abelian *SU(3)* gauge symmetry

$$g^a_\mu \to g^a_\mu - f^{abc} \alpha^b A^c_\mu$$

$$\psi^I \to e^{i\alpha^a (T^a)^{IJ}} \psi^J$$

$$\bar{\psi}^I \to e^{-i\alpha^a (T^a)^{IJ}} \bar{\psi}^J$$

Theoretical Framework: *Higgs Mechanism*

- Complex Scalar-Photon *U(1)* interaction

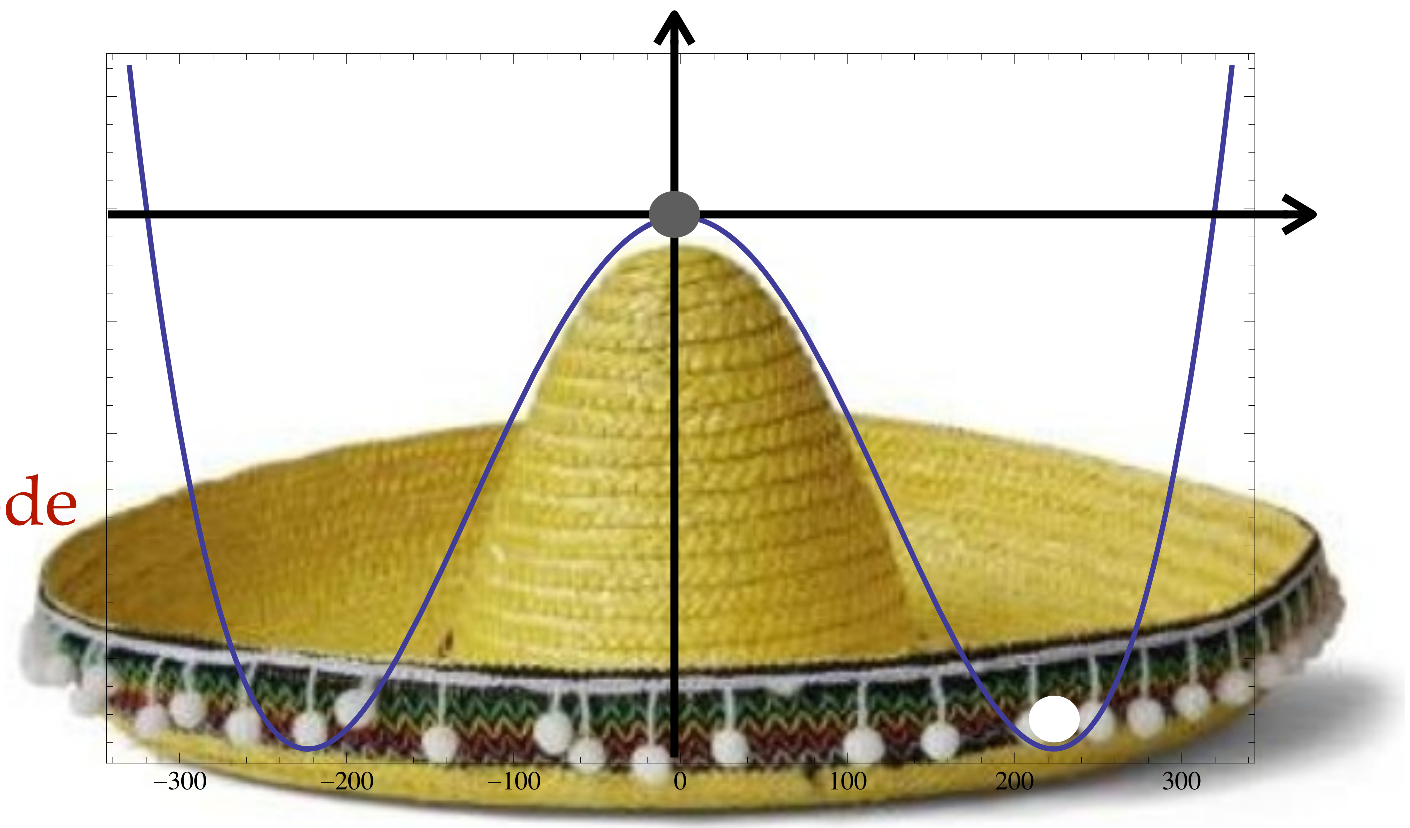
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F_{\mu\nu} + |\partial_\mu\phi|^2 - ieA_\mu(\phi^*\partial_\mu\phi - \phi\partial_\mu\phi^*) + e^2A_\mu^2|\phi|^2 - V(\phi)$$

- Abelian *U(1)* gauge symmetry $A_\mu \to A_\mu + \partial_\mu\alpha \qquad \phi \to \phi e^{i\alpha} \qquad \bar{\phi} \to \bar{\phi}e^{-i\alpha}$
- Scalar potential $V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$

$\phi = \varphi e^{i\sigma}$

Goldstone mode

Longitudinal mode



- Spontaneous symmetry breaking $\langle\phi\rangle = v$
- Photons receives a mass in the vacuum $m_A = ev$

Theoretical Framework: *Quantum Field Theory*

- A quantum field theory for particles physics?
- Particles (discovered experimentally), 90+19+1=110 dof's, 3 Interactions

$$e_L, e_R, \nu_L^e, u_L^r, u_L^g, u_L^b, u_R^r, u_R^g, u_R^b, d_L^r, d_L^g, d_L^b, d_R^r, d_R^g, d_R^b$$

$$\mu_L, \mu_R, \nu_L^\mu, c_L^r, c_L^g, c_L^b, c_R^r, c_R^g, c_R^b, s_L^r, s_L^g, s_L^b, s_R^r, s_R^g, s_R^b$$ + anti-particles

$$\tau_L, \tau_R, \nu_L^\tau, t_L^r, t_L^g, t_L^b, t_R^r, t_R^g, t_R^b, b_L^r, b_L^g, b_L^b, b_R^r, b_R^g, b_R^b$$

$$\gamma, W_T^\pm, W_L^\pm, Z_T, Z_L, g^{rb}, \cdots, h$$

- 18 Parameters: 12 mass, 2 interaction strengths, 3 mixing angles, 1 phase
- Symmetries (deduced experimentally):

  Spacetime (global) symmetries: Poincare Group *ISO(1,3)*

  Internal (gauge) symmetries: $SU(3)_c$, $U(1)_{EM}$

- Quantum field for each dof. A very messy interacting Lagrangian.
- It is the limit of an elegant model in its symmetry broking phase:

The *Standard Model*.

The Standard Model

- A particular interacting quantum field theory, explains experiments well.

Symmetry Structure:

Spacetime (global) symmetries: Poincare Group *ISO(1,3)* (Structure)

Internal (gauge) symmetries: $SU(3)_c$, $SU(2)_L$, $U(1)_Y$ (Interactions)

The field content:

Field	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$ISO(1,3)$
$L = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix}$	$(1, 2, -1)$	$(1/2, 0)$
e^c_R	$(1, 1, 2)$	$(1/2, 0)$
$Q = \begin{bmatrix} u_L \\ d_L \end{bmatrix}$	$(3, 2, 1/3)$	$(1/2, 0)$
u^c_R	$(\bar{3}, 1, -4/3)$	$(1/2, 0)$
d^c_R	$(\bar{3}, 1, 2/3)$	$(1/2, 0)$
$H = \begin{bmatrix} \sigma^1 + i\sigma^2 \\ h + i\sigma^3 \end{bmatrix}$	$(1, 2, 1)$	$(0, 0)$
g	$(8, 1, 0)$	$(1/2, 1/2)$
W	$(1, 3, 0)$	$(1/2, 1/2)$
B	$(1, 1, 0)$	$(1/2, 1/2)$

+ anti-particles

The Standard Model

- The most general renormalizable invariant Lagrangian

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W_i^{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu} \\
& + \bar{L}\gamma_\mu(i\partial_\mu + gW + Y_L g' B)L + \bar{e}_R\gamma_\mu(i\partial_\mu + Y_e g' B)e_R \\
& + \bar{Q}\gamma_\mu(i\partial_\mu + gW + Y_Q g' B + g_s g)Q + \bar{u}_R\gamma_\mu(i\partial_\mu + Y_u g' B + g_s g)u_R + \bar{d}_R\gamma_\mu(i\partial_\mu + Y_d g' B + g_s g)d_R \\
& + y_u Q\bar{u}H + y_d Q\bar{d}\tilde{H} + y_e L\bar{e}\tilde{H} \quad \textit{+ 2 families} \\
& + (\partial_\mu H - igWH - iY_H g' BH)^\dagger(\partial_\mu H - igWH - iY_H g' BH) - V(H)
\end{aligned}
$$

- The Higgs potential $V(H) = -m^2 H^\dagger H + \lambda(H^\dagger H)^2$

- Besides, there are 19 free parameters. Only 1 mass parameter.

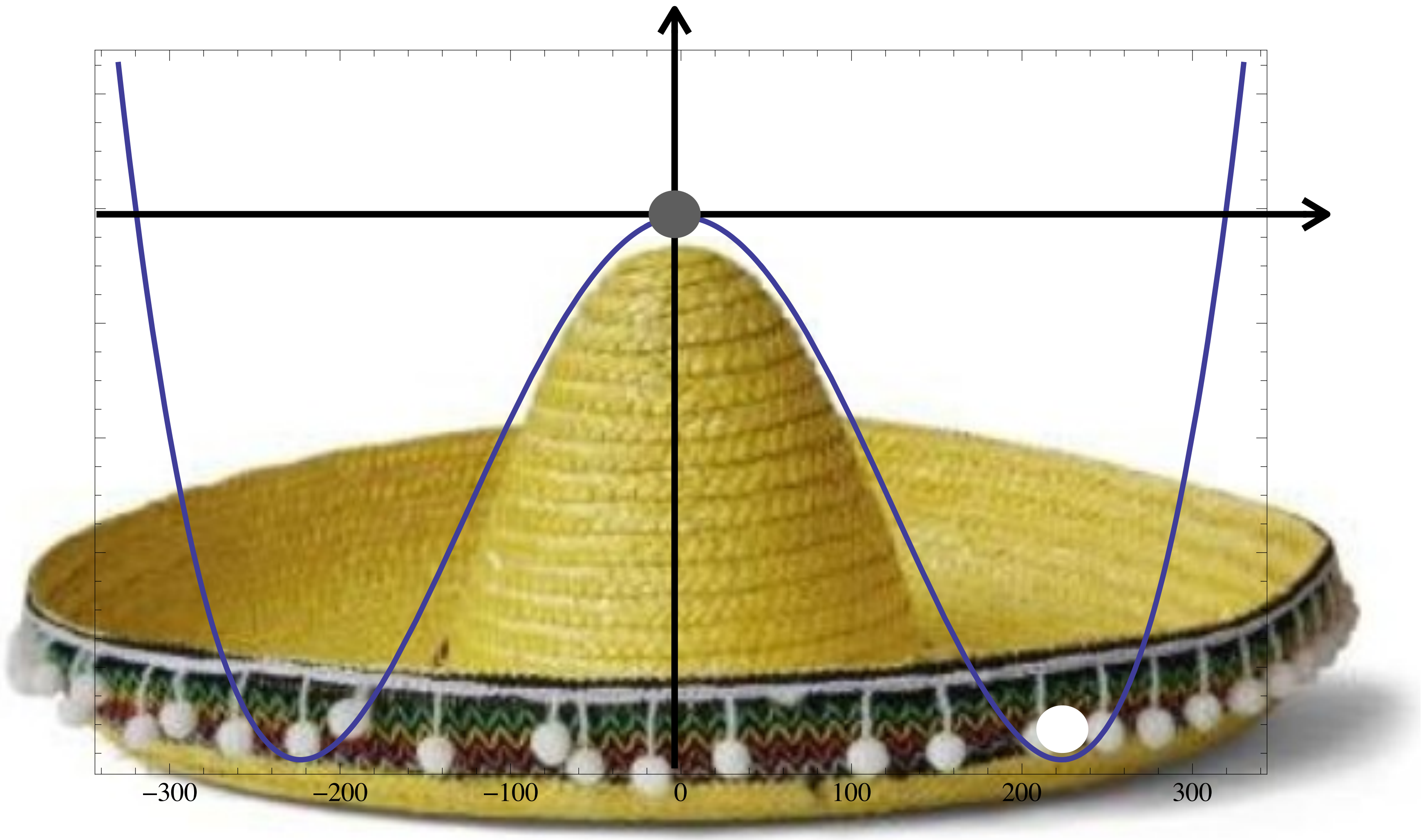
- The *strong* interaction sector is an easy piece.

- The *electroweak* sector is non-trivia, as it is accompanied with a Higgs mechanism.

The Electroweak Sector

- The Higgs potential $$V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

H: $(1, 2, 1)$



- The Higgs mechanism for the electroweak symmetry breaking $\langle H \rangle \neq 0$

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

The Electroweak Sector

- The Higgs mechanism and electroweak symmetry breaking

$$\mathcal{L} = -\frac{1}{4}(W^a_{\mu\nu})^2 - \frac{1}{4}B^2_{\mu\nu} + (D_\mu H)^\dagger(D_\mu H) + m^2 H^\dagger H - \lambda(H^\dagger H)^2$$

$$D_\mu H = \partial_\mu H - igW^a_\mu \tau^a H - \frac{1}{2}ig' B_\mu H.$$

- The Higgs field at the local minimum $H = e^{\frac{i\sigma^a \pi^a}{v}} \begin{bmatrix} 0 \\ v+h \end{bmatrix}$
- The Higgs expectation value $v = \frac{m}{\sqrt{\lambda}}$
- The Higgs-gauge interaction at the minimum

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

- The mass eigenstates

$$W^1_\mu \quad W^2_\mu$$

$$Z_\mu \equiv \cos\theta_w W^3_\mu - \sin\theta_w B_\mu$$

$$A_\mu \equiv \sin\theta_w W^3_\mu + \cos\theta_w B_\mu$$

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

The Electroweak Sector

- The Lagrangian electroweak symmetry breaking phase:

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}Z_{\mu\nu}^2 + \frac{1}{2}m_Z^2 Z^\mu Z_\mu - \frac{1}{2}\left(\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+\right)\left(\partial_\mu W_\nu^- - \partial_\nu W_\mu^-\right)$$

$$+ m_W^2 W_\mu^+ W_\mu^- - ie\cot\theta_w \Big[\partial_\mu Z_\nu \left(W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-\right)$$

$$+Z_\nu\left(-W_\mu^+\partial_\nu W_\mu^- + W_\mu^-\partial_\nu W_\mu^+ + W_\mu^+\partial_\mu W_\nu^- - W_\mu^-\partial_\mu W_\nu^+\right)\Big]$$

$$- ie\Big[\partial_\mu A_\nu \left(W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-\right)$$

$$+A_\nu\left(-W_\mu^+\partial_\nu W_\mu^- + W_\mu^-\partial_\nu W_\mu^+ + W_\mu^+\partial_\mu W_\nu^- - W_\mu^-\partial_\mu W_\nu^+\right)\Big]$$

$$- \frac{1}{2}\frac{e^2}{\sin^2\theta_w} W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}\frac{e^2}{\sin^2\theta_w} W_\mu^+ W_\nu^- W_\mu^+ W_\nu^-$$

$$- e^2\cot^2\theta_w \left(Z_\mu W_\mu^+ Z_\nu W_\nu^- - Z_\mu Z_\mu W_\nu^+ W_\nu^-\right) + e^2\left(A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-\right)$$

$$+ e^2\cot\theta_w \Big[A_\mu W_\mu^+ W_\nu^- Z_\nu + A_\mu W_\mu^- Z_\nu W_\nu^+ - W_\mu^+ W_\mu^- A_\nu Z_\nu \Big],$$

$$m_W = \frac{v}{2}g$$

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

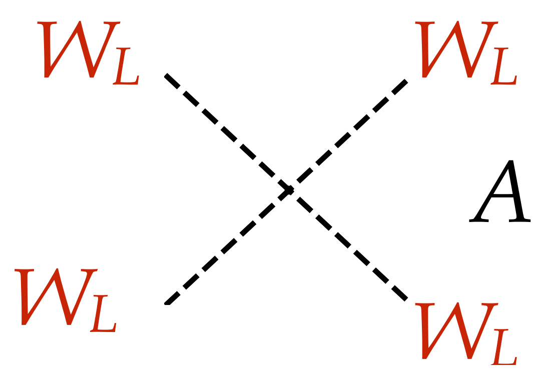
$$e = g\sin\theta_w = g'\cos\theta_w$$

The Electroweak Sector

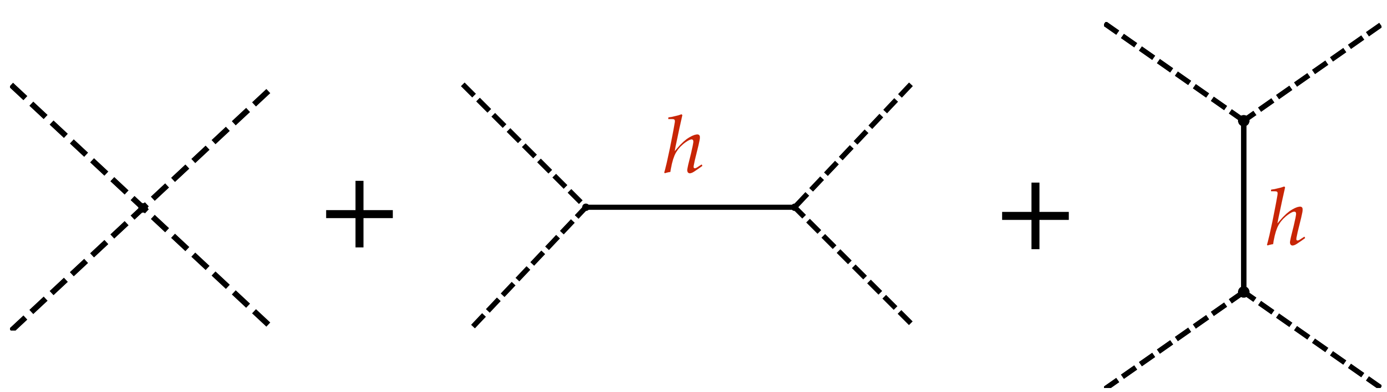
- The Lagrangian electroweak symmetry breaking phase:

$$\mathcal{L}_{\text{Higgs}} = -\frac{1}{2}h(\Box + m_h^2)h - g\frac{m_h^2}{4m_W}h^3 - \frac{g^2}{32}\frac{m_h^2}{m_W^2}h^4$$
$$+ 2\frac{h}{v}\left(m_W^2 W_\mu^+ W_\mu^- + \frac{1}{2}m_Z^2 Z_\mu^2\right) + \left(\frac{h}{v}\right)^2\left(m_W^2 W_\mu^+ W_\mu^- + \frac{1}{2}m_Z^2 Z_\mu Z_\mu\right)$$

- The Higgs particle unitarizes the scattering of longitudinal modes



$A \sim E^2/M^2_W$



$A \sim 1/E^2$

- The SM is unitary and renormalizable up to the Planck scale.

The Electroweak Sector

- Fermion-Higgs coupling: masses and interactions

$$\mathcal{L}_{\text{Yukawa}} = +y_u Q\bar{u}H + y_d Q\bar{d}\tilde{H} + y_e L\bar{e}\tilde{H}$$

- In the electroweak symmetry breaking vacuum, fermions are massive and interact with the physical Higgs particle

$$H = e^{\frac{i\sigma^a \pi^a}{v}} \begin{bmatrix} 0 \\ v+h \end{bmatrix}$$

$$\mathcal{L}_{\text{mass}} = (y_u v)u\bar{u} + (y_d v)d\bar{d} + (y_e v)e\bar{e}$$

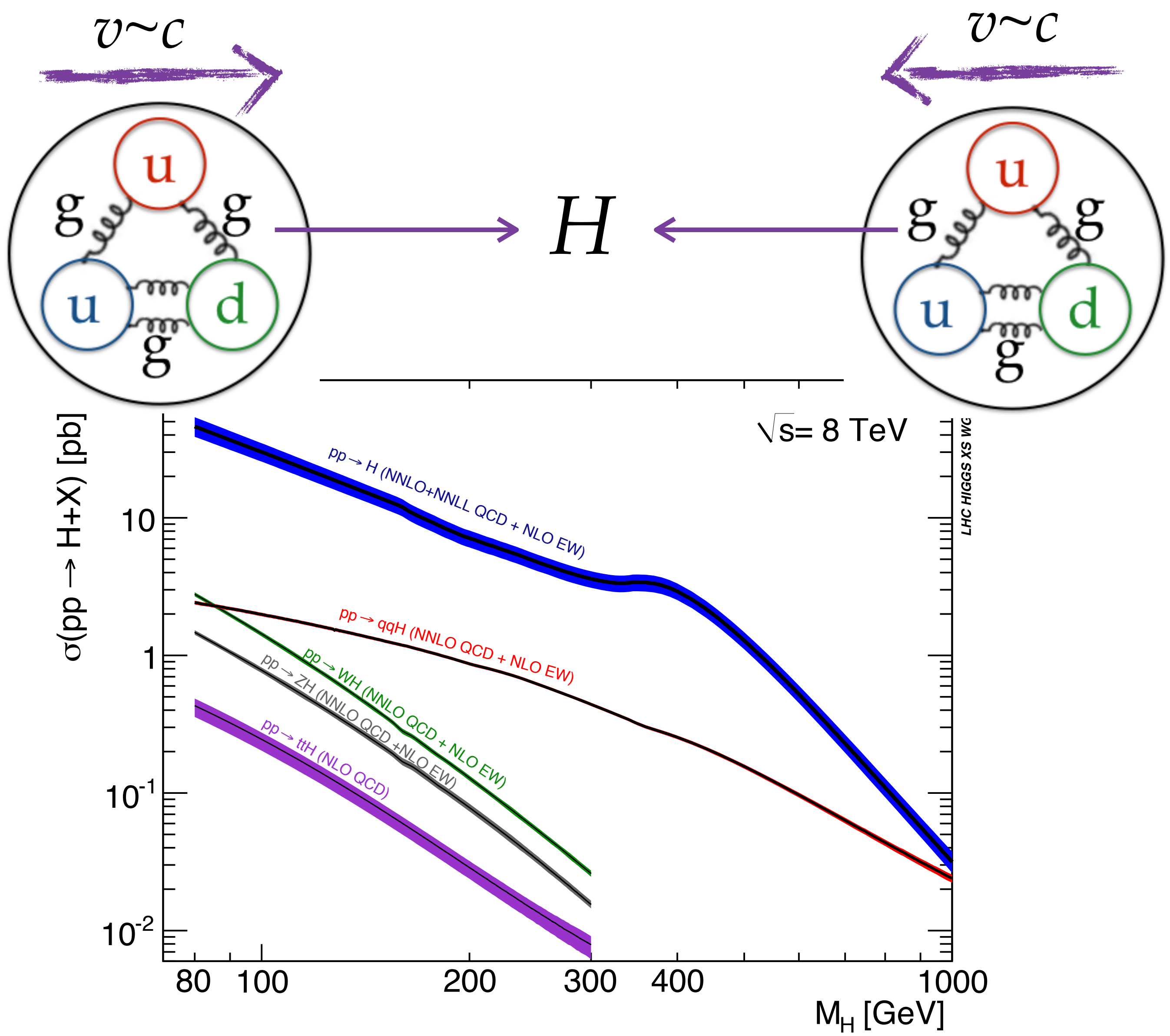
$$\mathcal{L}_{\text{int}} = y_u h u\bar{u} + y_d h d\bar{d} + y_e h e\bar{e}$$

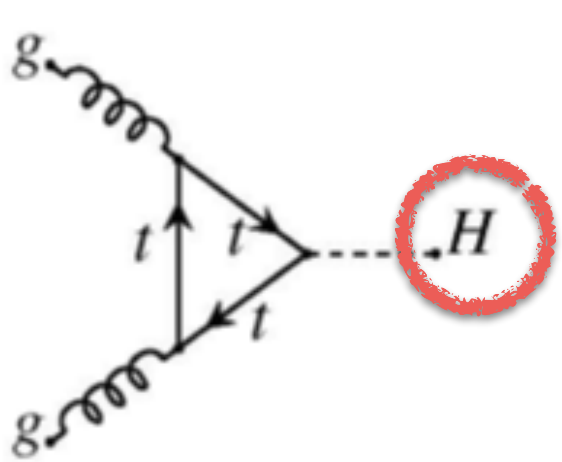
- The mass and the strengths of interaction are proportional to Yukawa couplings.
- The heavier the particle, the more strongly coupled to the Higgs.

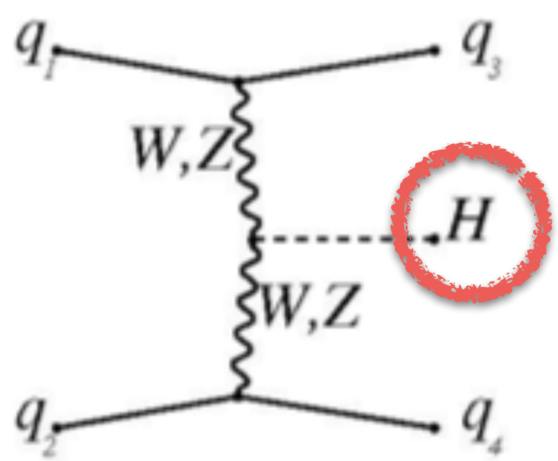
- The Higgs is the origin of the mass in the Standard Model.

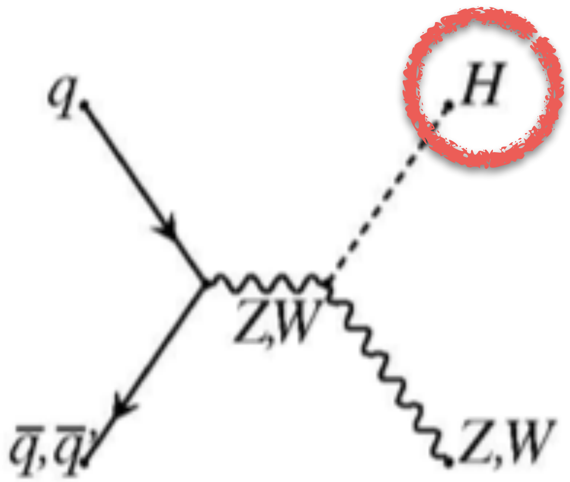
The Electroweak Sector

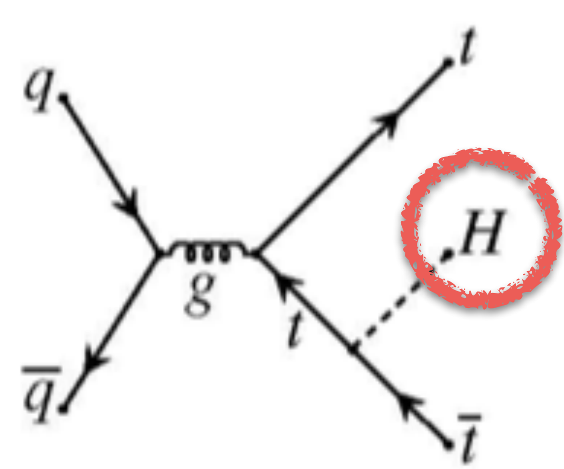
- The Higgs particles has been discovered 50 years after it was proposed.







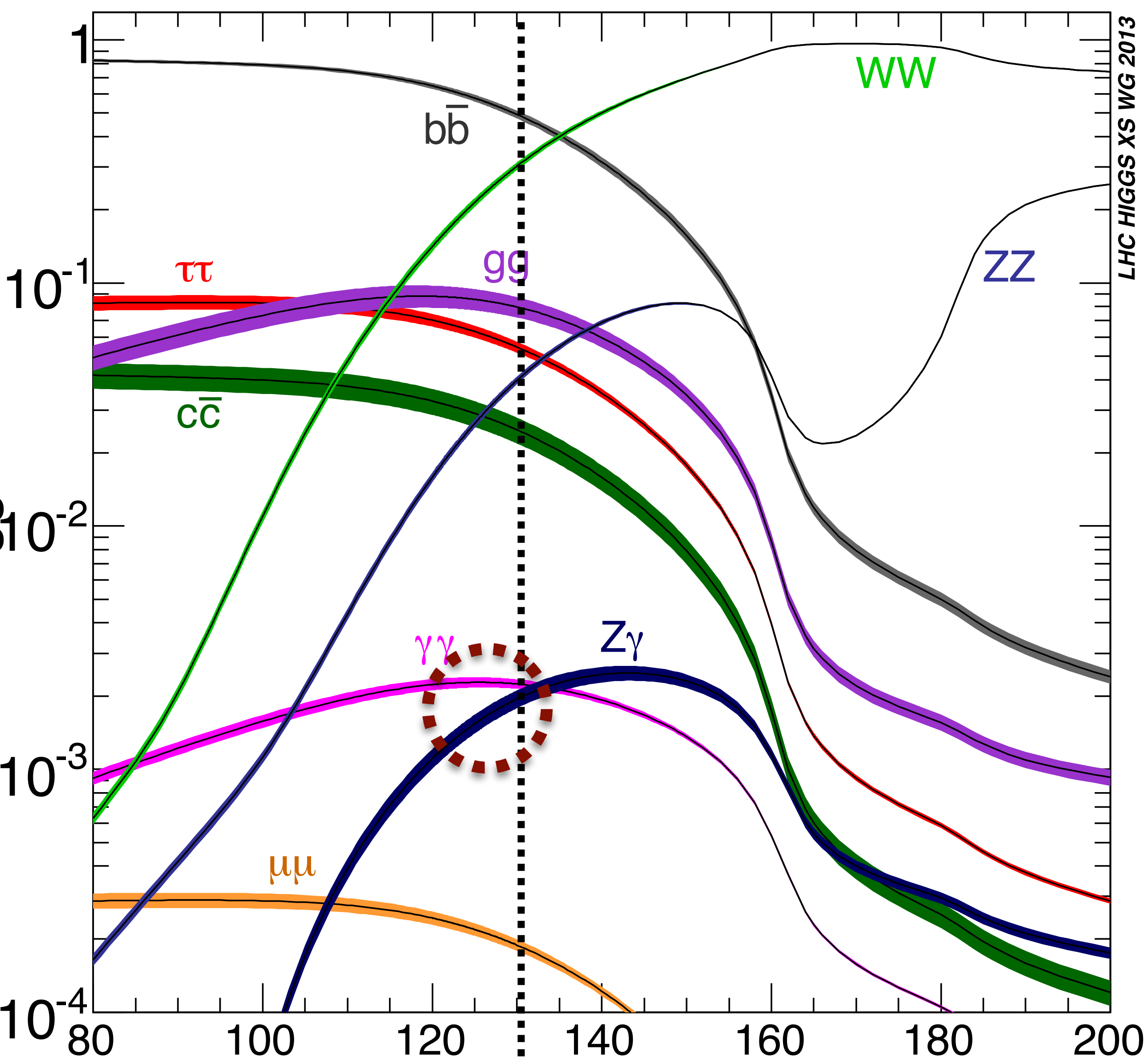


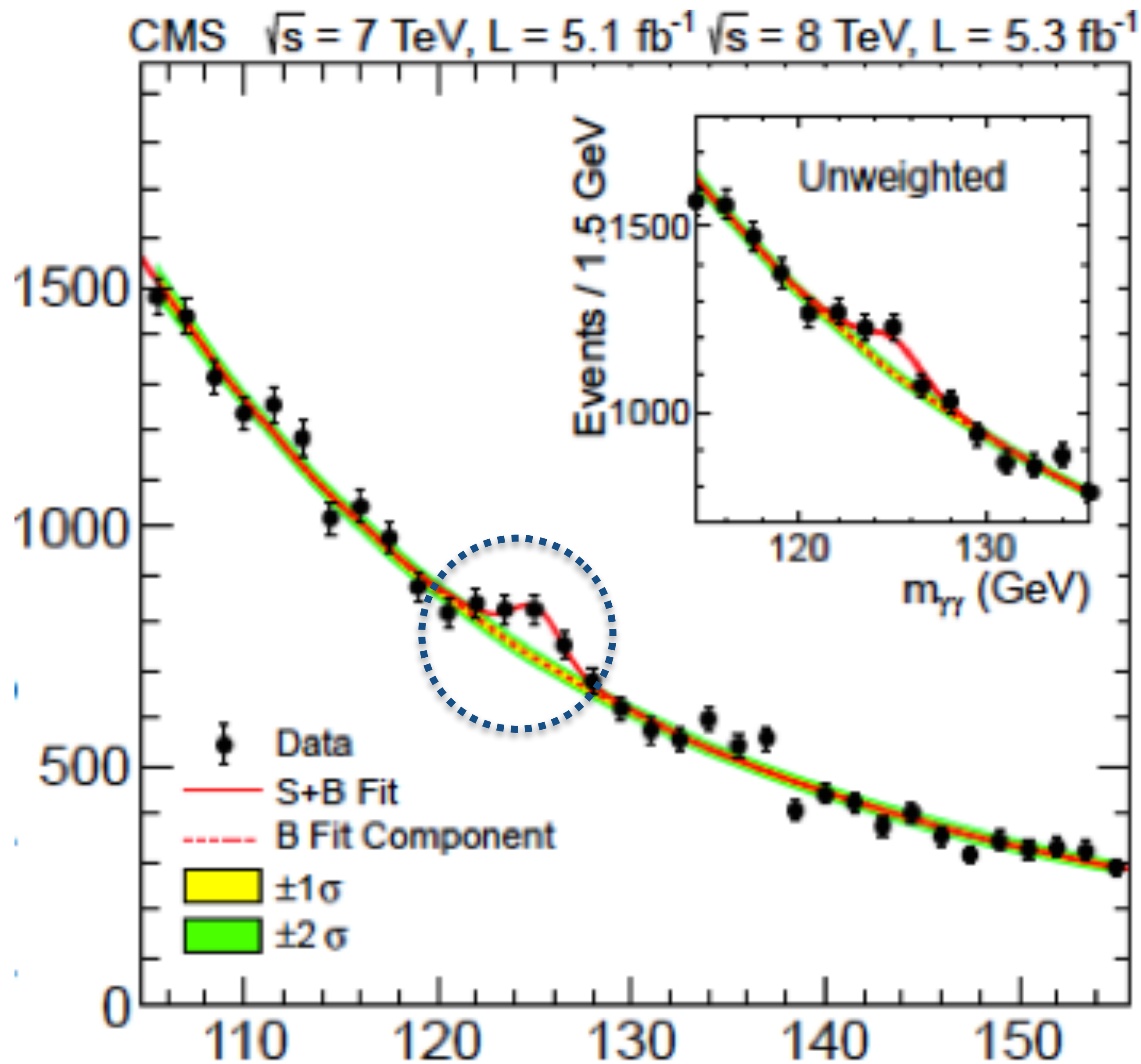


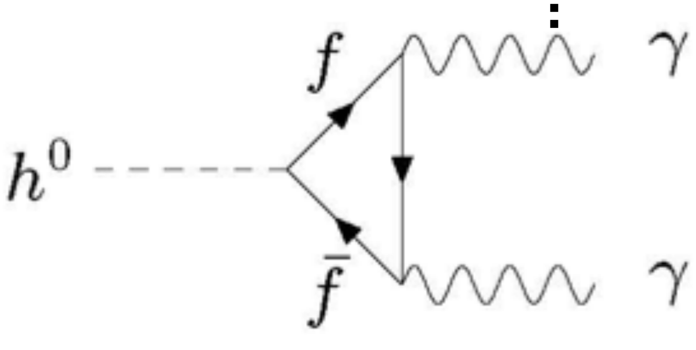
The Electroweak Sector

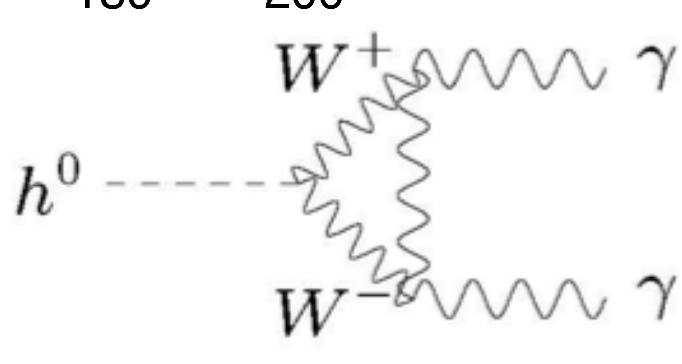
- The Higgs particles has been discovered 50 years after it was proposed.

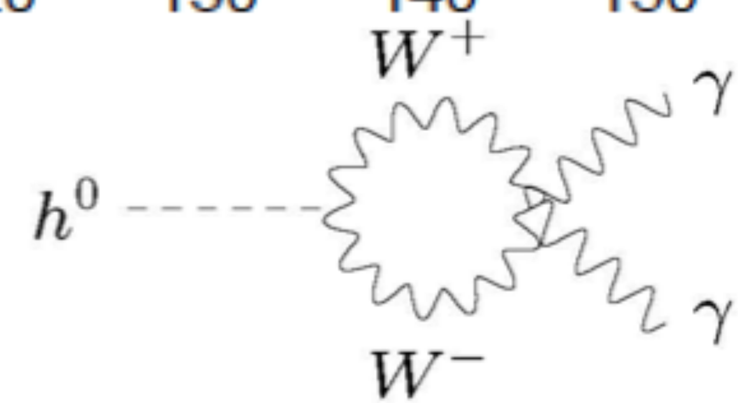
Higgs decays 10^{-22} second after its production to the SM particles.











The End