How Does Standard Model Predict?

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People have long asked,

“ What is the world made of? ”

and

“ What holds it together? ”

Elementary Particle Physics

or

High Energy Physics

Studying Fundamental Interactions (Forces)
in Nature

Leptons

- Don't feel the strong force
- Integer or Zero charge
- Flavours:

e^-	"electron" (0.511 MeV)	(1897)	In atoms
μ^-	"Muon" (206 m_e)	(1937)	First seen in Cosmic Ray
τ^-	"Tau" (17 m_μ)	(1975)	Seen at SLAC (Stanford Linear Accelerator Center)
ν_e	"electron neutrino" Pauli's explanation of Beta Decay (1930)	(1956)	
ν_μ	"Muon neutrino"	(1962)	
ν_τ	"Tau neutrino"	(2000)	

Mass

$$\nu_e < 3 \text{ eV}$$

$$\nu_\mu < 0.19 \text{ MeV}$$

$$\nu_\tau < 18.2 \text{ MeV}$$

Quarks

- Feel the strong force
- Fractionally charged

$$Q = \begin{Bmatrix} 2/3 \\ -1/3 \end{Bmatrix} \times \text{ Proton charge}$$

- Constituents of neutron and proton
  (udd) (uud)

$\begin{pmatrix} u \\ d \end{pmatrix}$ "up" "down"

- First Evidence:

Stanford Linear Accelerator Center
(Giant Electron Microscope)

- Flavors:

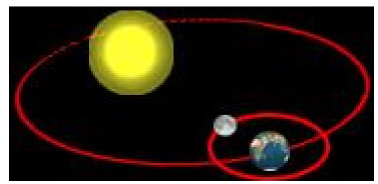
u	"up"		
d	"down"		
s	"strange"		
c	"charmed"	(1974)	
b	"bottom"	(1977)	"Beauty"
t	"top"	(1995) @ Fermilab (Tevatron)	"Truth"

Interactions

Four forces in Nature

1 Gravity

Newton ⟷



3 Weak Interaction

Beta (radioactive) decay

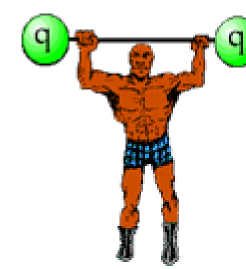
Muon decay

Time scales: $10^{-12} \sim 10^{3}$ sec

2 Electromagnetism

Faraday ⟷

4 Strong Interaction



Hold nuclei together

Particle collision

Time scales: 10^{-23} sec

The Standard Model of Particle Physics

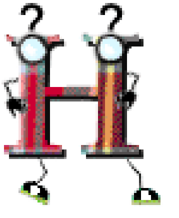
- Gauge Symmetry (Gravity is not included)

$$\underbrace{SU(3)_{\text{Color}}}_{\text{QCD}} \otimes \underbrace{SU(2)_{\text{Left}} \otimes U(1)_{\text{Hyper charge}}}_{\text{WEAK} \oplus \text{QED}}$$

(Strong Interaction)

(Unification of Weak and Electromagnetic)

Spontaneously Broken
(Higgs Mechanism)



$$U(1)_{\text{E.M.}}$$

QED
(Electromagnetic Interaction)

The Standard Model of Particle Physics

- Matter fields (make up all visible matter in the universe)
  - Fermions (Spin 1/2)

Lepton

(No Strong Interaction)

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

$$e_R^- \quad \mu_R^- \quad \tau_R^-$$

Quarks

(q)

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \; u_R \; u_R \quad c_R \; c_R \; c_R \quad t_R \; t_R \; t_R$$

$$d_R \; d_R \; d_R \quad s_R \; s_R \; s_R \quad b_R \; b_R \; b_R$$

3 families

  - Scalar (Spin 0)

    Higgs Boson (Not yet found!)

    (From Higgs Mechanism —— Spontaneous Symmetry Breaking)

The Standard Model of Particle Physics

❖ Interactions (mediated by interchanging Gauge Bosons, spin-1 force carrier)

1) Electromagnetic Interaction (QED)

Photon (massless)

2) Strong Interaction (QCD)

Gluon (massless) (1979)

3) Weak Interaction

W^+, W^- and Z Gauge Bosons (1983)

$$\left(\text{massive} \quad \begin{array}{l} M_W = 80.42 \text{ GeV} \\ M_Z = 91.187 \text{ GeV} \end{array} \qquad 1 \text{ GeV} = 10^9 \text{ eV} \right)$$

In SM, the Mass of W-boson, either $W^\pm$ or Z , arises from the Higgs Mechanism

(Without it, Gauge Bosons have to be massless from gauge principle.)

Higgs Mechanism in the SM

Two outstanding mysteries in the Electroweak theory :

- The cause of Electroweak Symmetry Breaking

  (M_W = 80 GeV, M_Z = 91 GeV)

- The origin of Flavor Symmetry Breaking

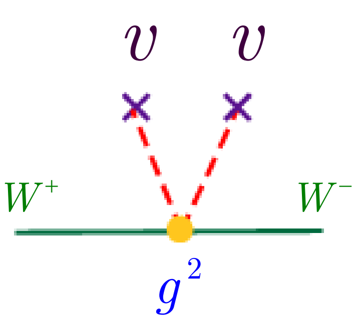
  (Quarks and Leptons have diverse masses.)

Both Symmetry Breaking are accommodated by including a fundamental weak doublet of scalar (Higgs) boson:

$$\Phi = \begin{pmatrix} \frac{v + H + i\phi^0}{\sqrt{2}} \\ i\phi^- \end{pmatrix}$$

- To generate M_W and M_Z

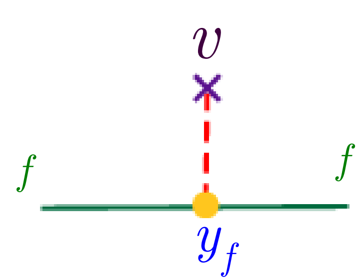
$$L_\Phi = \left(D_\mu \Phi\right)^+ \left(D^\mu \Phi\right) - \lambda\left(\Phi^+\Phi - \frac{v^2}{2}\right)^2$$



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

- To generate m_f

$$y_f \bar{F}_L \Phi f_R + \cdots$$



$$m_f = y_f \frac{v}{\sqrt{2}}$$

How does SM predict … ?

- In Quantum Mechanics

  Schrodinger Equation:

$$i\frac{\partial \Psi}{\partial t} = H\Psi$$

1. Figure out what H is.
2. Insert H in S.E.
3. Calculate Predictions

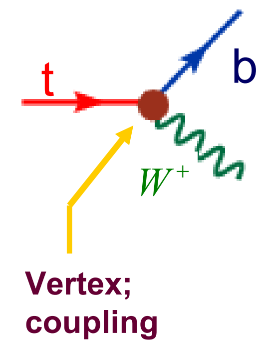
- In Relativistic Quantum Field Theory

  SM gives the Interaction Lagrangian $\mathcal{L}$

$\mathcal{L}$

⇓

Feynman Rules
Feynman Diagrams }



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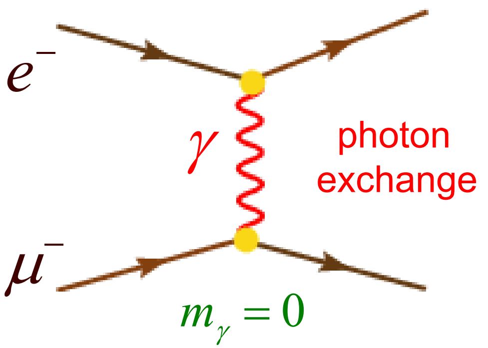
S-Matrix Elements

⇓

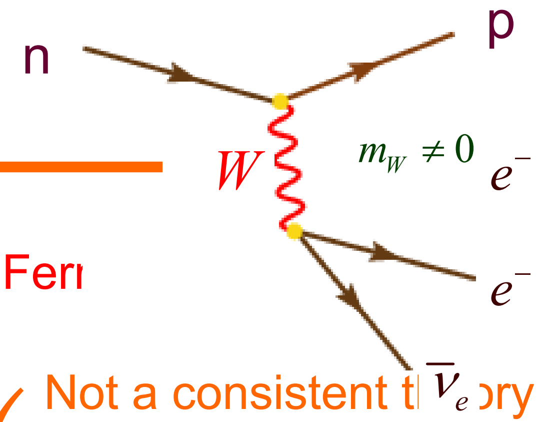
Predictions

Electro-weak Unification

Electromagnetic Interaction:



Weak Interaction: (Beta Decay)



Ferı

(Not a consistent t ory.
ndition
sions.)

Allows: Self-consistent calculations at high energy and to higher orders of perturbative theory

Prices to pay:

1) $W^\pm$ must exist — 1983
2) Simplest version requires also massive Z^0 — 1983

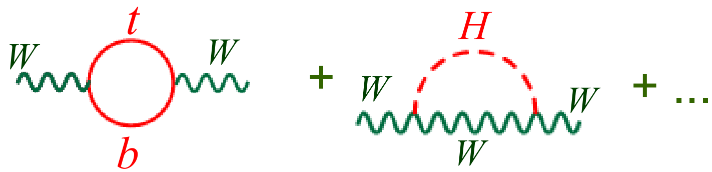
New weak charge preserving interactions — 1973

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

Some Examples of Loop Corrections

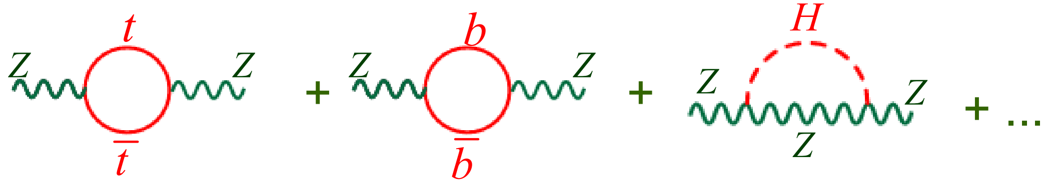
(Radiative corrections)

1) $m_W \sim$

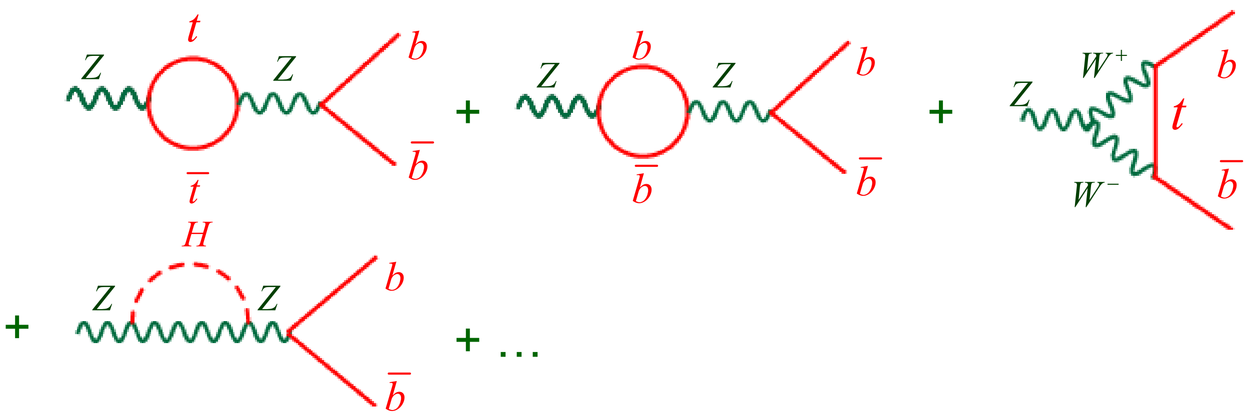


Sum over Intermediate states

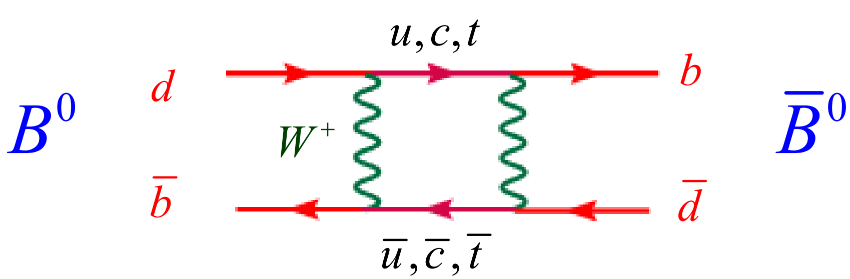
$m_Z \sim$



2) $\Gamma_{Z\to b\bar{b}} \sim$



3) $B_d - \bar{B}_d$ mixing



Free Parameters in Standard Model

$SU(3)_{\text{color}} \times SU(2)_{\text{Left}} \times U(1)_{\text{Hypercharge}}$

g_3, g_2, g_1
λ, μ

$$\left\{ \begin{array}{l} \alpha_S, \alpha_{\text{em}}, \theta_{\text{Weak mixing}} \\ V \text{(vacuum expectation value)} \\ m_H \text{(Higgs Boson mass)} \end{array} \right\}$$

This set can be traded by
$\alpha_S, \alpha_{\text{em}}, G_F, m_Z, m_H$

(3) Lepton masses
(e, μ, τ) m_ν's=0

(6) Quark masses
(u, d, s, c, b, t)

Mixing of quark weak eigenstates and mass eigenstates → 3 angles and 1 phase
(1 phase: CP violation)

(1) Strong CP phase

→ Total of 19 free parameters.
So far, all experimental data agree with the prediction of SM.

To include neutrino masses (suggested by Neutrino Oscillation data) in the SM

- For Dirac Neutrinos
  → Add 3 masses and
  3 mixing angles with
  1 CP violation phase
- For Majorana Neutrinos
  → Add 3 masses and
  3 mixing angles with
  3 CP violation phase

Quantum Electrodynamics (QED)

- Lagrangian for QED
- Feynman rules for QED
- Potential vs. Propagator (in non-relativistic limit)
- Scattering amplitudes (S-matrix elements)
- Production rate
- Life-time of particle