Particle Physics

Dr Victoria Martin, Spring Semester 2013

Lecture 17: Electroweak and Higgs

HIGGS BOSON

The **HIGGS BOSON** is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe gets its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland, which collides particles at 99.99% the speed of light, will detect the elusive Higgs Boson

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Wool felt, fleece with gravel fill for maximum mass.

- ★Weak Isospin and Weak Hypercharge
- ★Weak Isospin and Weak Hypercharge currents
- ★γ $W^{\pm}$ Z^0 bosons
- ★Spontaneous Symmetry Breaking
- ★The Higgs mechanism and the Higgs boson

Weak Isospin and Hypercharge

- QED couples to electric charge; QCD couples to colour charge...
- Electroweak force couples to two "charges".
  - **Weak Isospin:** total and third component T, T_3. Depends on **chirality**
  - **Weak Hypercharge,** Y In terms of electric charge Q: $Y = 2\,(Q - T_3)$
    - All right-handed fermions have $T=0,\ T_3=0$
    - All left-handed fermions have $T=½,\ T_3=\pm ½$
    - All left-handed antifermions have $T=0,\ T_3=0$
    - All right-handed antifermions have $T=½,\ T_3(\bar{f})=-T_3(f)$

Lepton	T	T_3	Y	Quark	T	T_3	Y
$\nu_{eL}, \nu_{\mu L}, \nu_{\tau L}$	½	+½	-1	u_L, c_L, t_L	½	+½	⅓
e_L, μ_L, τ_L	½	–½	-1	d_L, s_L, b_L	½	– ½	⅓
ν_R	0	0	0	u_R, c_R, t_R	0	0	4/3
e_R, μ_R, τ_R	0	0	-2	d_R, s_R, b_R	0	0	–⅔

Weak Isospin Doublets

Lepton	T	T_3	Y	Quark	T	T_3	Y
$\nu_{e\mathrm{L}}, \nu_{\mu\mathrm{L}}, \nu_{\tau\mathrm{L}}$	½	+½	-1	$\mathrm{u_L, c_L, t_L}$	½	+½	⅓
$e_\mathrm{L}, \mu_\mathrm{L}, \tau_\mathrm{L}$	½	–½	-1	$\mathrm{d_L, s_L, b_L}$	½	– ½	⅓
ν_R	0	0	0	$\mathrm{u_R, c_R, t_R}$	0	0	4/3
$e_\mathrm{R}, \mu_\mathrm{R}, \tau_\mathrm{R}$	0	0	-2	$\mathrm{d_R, s_R, b_R}$	0	0	–⅔

- Neutrinos and left-handed charged leptons from a "**weak isospin doublet**":

$$\chi_\mathrm{L} = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_\mathrm{L} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_\mathrm{L} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_\mathrm{L} \quad T = 1/2; \; \begin{matrix} T_3 = +1/2 \\ T_3 = -1/2 \end{matrix}$$

- Doublet consists of "charged current flavour change pair".
  - ➡They have the same total weak isospin T=½.
  - ➡They are differentiated by the third component T_3=±½.
- Left-handed up-type quarks and left-handed down-type quarks also form isospin doublets

$$\begin{pmatrix} \mathrm{u} \\ \mathrm{d} \end{pmatrix}_\mathrm{L} \quad \begin{pmatrix} \mathrm{c} \\ \mathrm{s} \end{pmatrix}_\mathrm{L} \quad \begin{pmatrix} \mathrm{t} \\ \mathrm{b} \end{pmatrix}_\mathrm{L} \qquad T = 1/2; \; \begin{matrix} T_3 = +1/2 \\ T_3 = -1/2 \end{matrix}$$

Weak Isospin Currents

- Weak Isospin and Weak Hypercharge couple to a different set of bosons.

- Weak isospin doublets χ_L couple to a set of **three** W-bosons: W^1, W^2, W^3, with SU(2) symmetry described by the 3 Pauli matrices:

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

- The W-bosons current is:

$$(j^{Wi})^{\mu} = [g_W T] \, \overline{\chi_{\mathrm{L}}} \, \gamma^{\mu} \, \tau_i \, \chi_{\mathrm{L}}$$

$\tau_{1,2,3}$: Pauli Matrix
χ_L: weak isospin doublet column vector spinors
$\overline{\chi_L}$: weak isospin doublet row vectors spinors
T : weak isospin charge of the doublet
g_W: weak coupling constant

- e.g for the W^1 boson and the electron doublet:

$$(j^{W1})^{\mu} = [g_W T] \, (\nu_e \; e^-)_{\mathrm{L}} \, \gamma^{\mu} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_{\mathrm{L}}$$

- Strength of the fermion interaction with W-bosons is: $g_W T$

Weak Hypercharge Current

- Particles with weak hypercharge couple to **one** ***B***-boson: $\boldsymbol{B^0}$ with U(1) symmetry.

- Use electron as an example:

$$j_\mu^Y = (\frac{1}{2} g'_W \, Y_e)\, \bar{e}\gamma^\mu e = \frac{1}{2} g'_W (Y_{e\mathrm{L}} \bar{e}_{\mathrm{L}} \gamma^\mu e_{\mathrm{L}} + Y_{e\mathrm{R}} \bar{e}_{\mathrm{R}} \gamma^\mu e_{\mathrm{R}})$$

Y_e : weak hypercharge of electron
$Y_{e\mathrm{L}}$: weak hypercharge of left-handed electron
$Y_{e\mathrm{R}}$: weak hypercharge of right-handed electron
e: Electron spinor
e_{L}: Left-handed electron spinor (u)
e_{R}: Right-handed electron spinor (u)
$\bar{e}_{\mathrm{L}}$: Left-handed electron spinor ($\bar{u}$)
$\bar{e}_{\mathrm{R}}$: Right-handed electron spinor ($\bar{u}$)
g'_W: coupling constant

- Strength of the fermion interaction with bosons is: $g'_W Y/2$

Physical Bosons

- The physical W^+, W^-, Z^0, γ bosons are linear superpositions of the W^1, W^2, W^3 and B^0 bosons.
  - Use $\cos\theta_W$ and $\sin\theta_W$ to ensure the states are properly normalised

$$W^+ = \frac{1}{\sqrt{2}}(W^1 - iW^2) \qquad W^- = \frac{1}{\sqrt{2}}(W^1 + iW^2)$$

$$Z^0 = W^3 \cos\theta_W - B^0 \sin\theta_W \qquad \gamma = W^3 \sin\theta_W + B^0 \cos\theta_W$$

- The coupling of the W^+, W^- bosons are

$$\tfrac{1}{\sqrt{2}}(g_W T) = \tfrac{1}{2\sqrt{2}} g_W$$

  - No $(1-\gamma^5)$ term: it integrated into the definition of the χ_L doublet.

The Photon

$$\gamma = W^3 \sin\theta_W + B^0 \cos\theta_W$$

- The electron current associated with the γ is:

$$\begin{aligned}
&(j^{W3})^\mu \sin\theta_W + (j^Y)^\mu \cos\theta_W \\
&\quad = \left[g_W T \sin\theta_W\right] \overline{\chi_{\mathrm{L}}}\gamma^\mu \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \chi_{\mathrm{L}} + \left[\tfrac{1}{2} g'_W Y_e \cos\theta_W\right] \overline{e}\gamma^\mu e \\
&\quad = -\left[\tfrac{1}{2} g_W \sin\theta_W\right] \overline{e_{\mathrm{L}}}\gamma^\mu e_{\mathrm{L}} + \left[\tfrac{1}{2} g'_W \cos\theta_W\right] (-\overline{e_{\mathrm{L}}}\gamma^\mu e_{\mathrm{L}} - 2\overline{e_{\mathrm{R}}}\gamma^\mu e_{\mathrm{R}}) \\
&\quad = -\left[\underbrace{\tfrac{1}{2} g_W \sin\theta_W + \tfrac{1}{2} g'_W \cos\theta_W}_{=e}\right] \overline{e_{\mathrm{L}}}\gamma^\mu e_{\mathrm{L}} - \left[\underbrace{g'_W \cos\theta_W}_{=e}\right] \overline{e_{\mathrm{R}}}\gamma^\mu e_{\mathrm{R}}
\end{aligned}$$

- Consistent with the photon coupling if $e = g'_W \cos\theta_W = g_W \sin\theta_W$

$\sin^2\theta_W$ and Z-boson couplings

- The mixing angle between g_W and g'_W is not a prediction of the model, it must be measured experimentally.

$$\sin^2\theta_W = \frac{g'^2_W}{g^2_W + g'^2_W} \approx 0.23$$

- The Z-boson the orthogonal mixture to the γ:

$$Z^0 = W^3 \cos\theta_W - B^0 \sin\theta_W$$

- predicts the couplings of the Z^0 boson in terms of T_3 and $Y = 2\,(Q - T_3)$
- e.g. for electron:

$$\begin{aligned}(j^Z)^\mu &= \frac{g_W}{\cos\theta_W}\left[(T_3 - Q\sin^2\theta_W)(\overline{e_{\rm L}}\gamma^\mu e_{\rm L}) - (Q\sin^2\theta_W)(\overline{e_{\rm R}}\gamma^\mu e_{\rm R})\right] \\ &= \frac{g_Z}{2}\,\bar{e}\,\gamma^\mu\,(c_V^e - c_A^e\gamma^5)\,e\end{aligned}$$

- if:

$$g_Z = \frac{g_W}{\cos\theta_W} \qquad c_V = T_3 - 2Q\sin^2\theta_W \qquad c_A = T_3$$

Summary of Electroweak Unification

- We have recovered the behaviour of the $W^{\pm}$, Z and γ

  - ➡ We introduced an SU(2) symmetry (3 bosons) coupling to weak isospin with a coupling constant g_W
  - ➡ We introduced a U(1) symmetry (1 boson) coupling to weak hypercharge with a coupling constant g'_W
  - ➡ Together predicts four bosons we identify with W^+, W^-, Z and γ
  - ➡ Electroweak Theory is often called **SU(2)** ⊗ **U(1)** model

- All of the properties of electroweak interactions described by:
  - the intrinsic charges of the fermions
  - the SU(2) ⊗ U(1) symmetry
  - g_W and g'_W: free parameters that need to be measured

- Along with QCD, Electroweak Theory is the Standard Model.

The Higgs Mechanism: Introduction

- The Higgs Mechanism was proposed in 1964 separately by Higgs and Brout & Englert.
- It introduces an extra field, ϕ, which interacts with the electroweak currents. The potential of the field is:

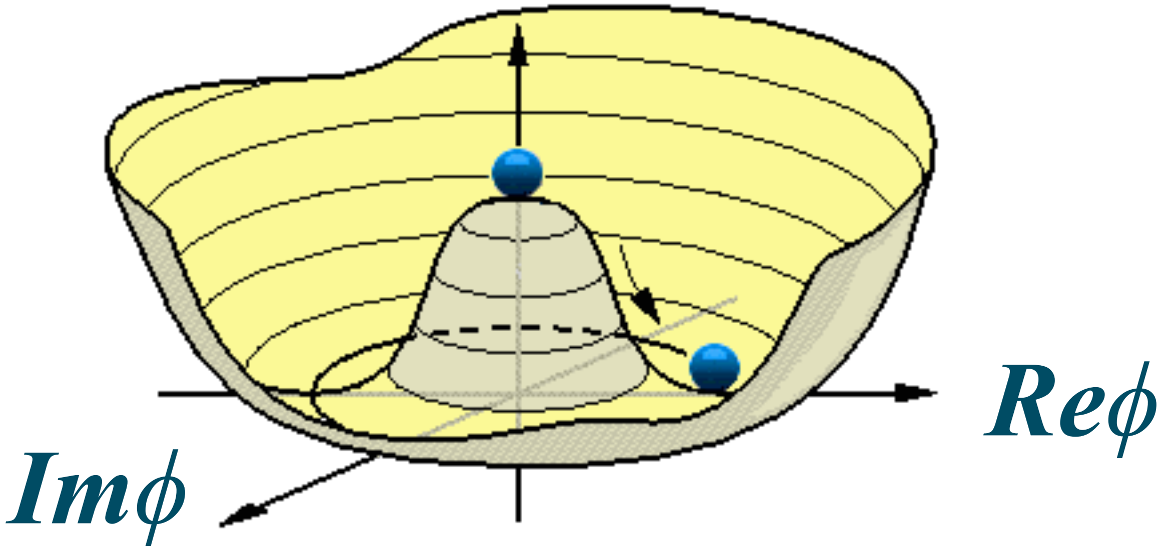
$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \qquad \text{with } \mu^2 > 0, \lambda > 0$$

- The Higgs mechanism allows the ***W*** and ***Z*** bosons to have a mass. (Otherwise forbidden by the external symmetries.)

- Provides an explanation for fermion masses (***e*, *μ*, *τ*, u, d, s, c, t, b**).

- P.W. Higgs pointed out that a further consequence would be the existence of a spin-0 boson: the Higgs boson, ***H***.

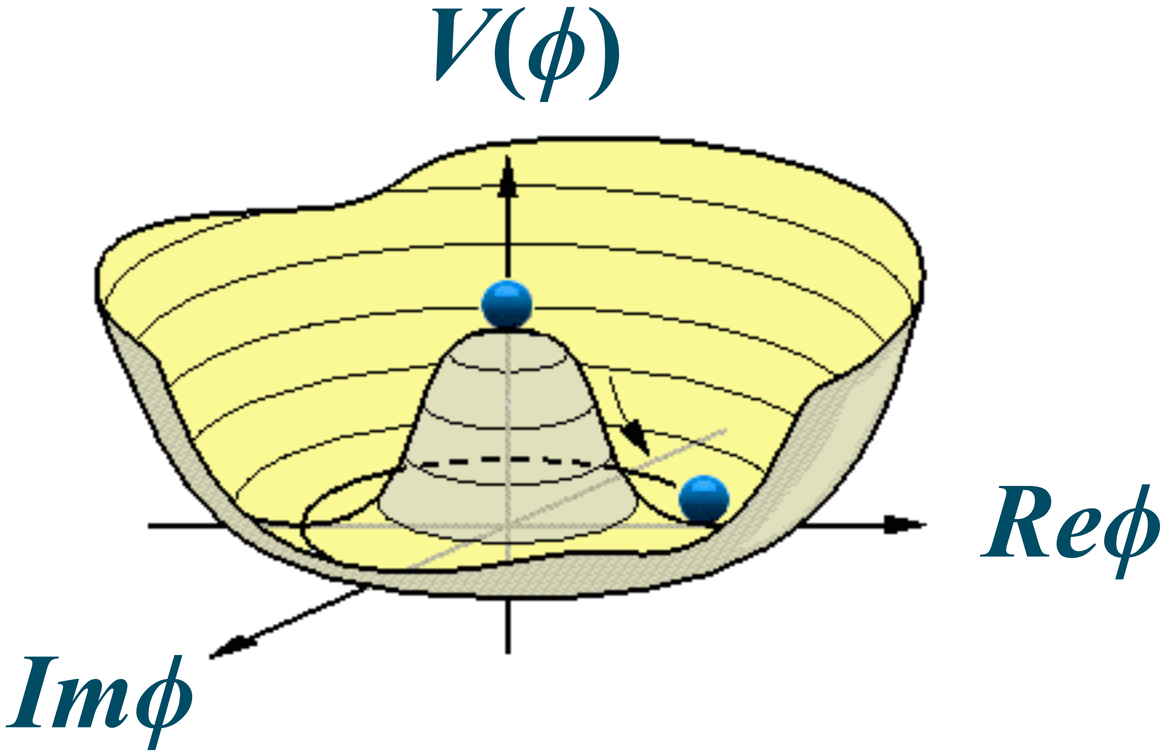
Spontaneous Symmetry Breaking



- Start with a system that has an intrinsic symmetry
  - ➡ Choosing a particular ground state configuration the symmetry is broken
  - ➡ If the choice is arbitrary, i.e. no external agent is responsible for the choice, then the symmetry is "spontaneously" broken
- Everyday example: A circle of people are sitting at a dining table with napkins between them. The first person who picks up a napkin, either with their left or right hand spontaneously breaks the L/R symmetry. All the others must do the same if everyone is to end up with a napkin.
- Physics example: In a domain inside a ferromagnet all the spins align in a particular direction. If the choice of direction is random, the underlying theory has a rotational symmetry which is spontaneously broken. The presence of an external magnetic explicitly breaks the symmetry and defines a preferred direction.

Higgs Potential

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



- ϕ is complex function.
- $V(\phi)$ is symmetric: the maximum symmetry occurs at $\phi=0$.
- A circle of values minimise the potential at $\phi=\phi_0 \equiv -v/\sqrt{2}$ with $|\phi_0| = \frac{\mu}{\sqrt{2\lambda}}$
  - Any coordinate around the circle minimise the potential: $\arg(\phi_0) = [0,2\pi)$
- The choice of which complex value of ϕ_0 is chosen spontaneously breaks the symmetry.
- The value of v, related to the value of $|\phi|$ at the minimum of the potential known as the vacuum expectation value. Measured to be $v = 246$ GeV

Standard Model Higgs Field

- In the Standard Model, the Higgs field is a complex isospin doublet:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \qquad T = 1; \quad \begin{matrix} T_3 = +1 \\ T_3 = \ \ 0 \end{matrix}$$

ϕ^+ : +ve charged field

ϕ^0 : neutral field

ϕ_0 : minimum of field

- Higgs field has four degrees of freedom.

- In the Higgs mechanism (when the symmetry is spontaneously broken) three of these degrees of freedom are used to give mass to W^+, W^-, Z^0.
- This fixes three of the degrees of freedom: two charged and one neutral.

- The minimum of the potential ϕ_0 for ground state can then be written in terms of the remaining free parameter:

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

- Where **v** is related to the value of ϕ which minimises V: $v = \frac{\mu}{\sqrt{2\lambda}}$

Introducing the Higgs Boson

- Consider a fluctuation of the Higgs field about its minimum:

$$\phi(x) = \phi_0 + h(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

- Substitute $\phi(x) = \frac{1}{\sqrt{2}}(v + h(x))$ into ***V(ϕ)*** and expand to second order in ***h(x):***

$$V(\phi) = -\mu^2 \left(\frac{v + h(x)}{\sqrt{2}} \right)^2 + \lambda \left(\frac{v + h(x)}{\sqrt{2}} \right)^4 = \ldots = V(\phi_0) + \underbrace{\lambda v^2 h^2}_{= \frac{1}{2} m_H^2} + \mathcal{O}(h(x)^3)$$

- In quantum field theory a term quadratic in the field describes a particle's mass.
- This fluctuation around the minimum of the potential describes a spin-0 particle with a mass $m = \sqrt{2\lambda} v$

- **The Higgs boson!**

Higgs Couplings

- The Higgs mechanism predicts that the Higgs boson interacts with the *W* and *Z* bosons and massive fermions, in proportion to their mass.

- The dotted line is the prediction.

- The points are the measured values from the CMS collaboration at the LHC.