Brout-Englert-Higgs Mechanism and Beyond

Ajinkya Shrish Kamat

ajinkya@virginia.edu

http://people.virginia.edu/~ask4db/

University of Virginia

GPSA (Graduate Physics Students Association) Talk

11th November, 2013
Why is the Brout-Englert-Higgs Mechanism needed: a quick revisitation

- The framework that combines principles of the Quantum Mechanics and the Special Relativity is the Quantum Field Theory (QFT)
Why is the Brout-Englert-Higgs Mechanism needed: a quick revisitation

- The framework that combines principles of the Quantum Mechanics and the Special Relativity is the Quantum Field Theory (QFT)
- Lagrangian ($\mathcal{L}$) is used instead of Hamiltonian ($\mathcal{H}$)
Why is the Brout-Englert-Higgs Mechanism needed: a quick revisitation

- The framework that combines principles of the Quantum Mechanics and the Special Relativity is the Quantum Field Theory (QFT)
- Lagrangian ($\mathcal{L}$) is used instead of Hamiltonian ($\mathcal{H}$)
- Physicists knew the Quantum Electrodynamics (QED) and tried to build a theory to explain the $\beta$-decay based on similar ideas
Why is the Brout-Englert-Higgs Mechanism needed: a quick revisitation

- The framework that combines principles of the Quantum Mechanics and the Special Relativity is the Quantum Field Theory (QFT)
- Lagrangian ($L$) is used instead of Hamiltonian ($H$)
- Physicists knew the Quantum Electrodynamics (QED) and tried to build a theory to explain the $\beta$-decay based on similar ideas
- This theory agreed with experiments AT LOW ENERGY, but had BAD HIGH ENERGY BEHAVIOR
To solve this a theory of ‘weak interactions’ was put forward adding $W^\pm$ bosons as the force carriers of the weak force.
To solve this a theory of ‘weak interactions’ was put forward adding $W^\pm$ bosons as the force carriers of the weak force.

To cancel certain ‘badly behaving interactions’ a third neutral $W^0$ boson was added.

Three matrices ($T_1, T_2, T_3$) were required for this cancellation with a condition

$$[T_a, T_b] = T_a T_b - T_b T_a = i \sum c_{abc} T_c$$

⇒ SU(2) group symmetry!
A quick revision (continued..)

- To solve this a theory of ‘weak interactions’ was put forward adding $W^\pm$ bosons as the force carriers of the weak force.
- To cancel certain ‘badly behaving interactions’ a third neutral $W^0$ boson was added.
- Three matrices ($T^1, T^2, T^3$) were required for this cancellation with a condition:

$$[T^a, T^b] = T^a T^b - T^b T^a = i \sum_c \epsilon^{abc} T^c$$

$\Rightarrow SU(2)$ group symmetry!
Construct Lagrangian of (Weak + QED) → ELECTROWEAK THEORY \((SU(2) \times U(1)\) symmetry)

\(W^\mu\) and \(A^\mu\) combine to give \(W^\pm, Z^0\) and photon \(\gamma\)
Construct Lagrangian of (Weak + QED) $\rightarrow$ ELECTROWEAK THEORY ($SU(2) \times U(1)$ symmetry)

$W^\mu$ and $A^\mu$ combine to give $W^\pm$, $Z^0$ and photon $\gamma$

Meaning of having a symmetry: If the ‘Fields’ associated with all particles undergo transformation under the symmetry group (something like multiplication by $\text{Exp}(i \sum a T^a \alpha^a)$), the Lagrangian of the theory remains invariant
If we want a freedom of performing such transformations at a point in space-time without affecting fields at other space-time points (LOCAL SYMMETRY: $\alpha \rightarrow \alpha(x)$),
If we want a freedom of performing such transformations at a point in space-time without affecting fields at other space-time points (LOCAL SYMMETRY: $\alpha \rightarrow \alpha(x)$), then the $W^{\pm,0}$ mass terms $\sim M_{W}^{2} W_{\mu}^{\dagger} W^{\mu}$ cannot be added to the Lagrangian by hand.
If we want a freedom of performing such transformations at a point in space-time without affecting fields at other space-time points (LOCAL SYMMETRY: $\alpha \rightarrow \alpha(x)$), then the $W^{\pm,0}$ mass terms
\[ M_W^2 W_\mu^\dagger W^\mu \]
cannot be added to the Lagrangian by hand.

Same for mass terms like $m_f \bar{\Psi}_f \Psi_f$ of fermions (electron, neutrinos, muon etc.)
If we want a freedom of performing such transformations at a point in space-time without affecting fields at other space-time points (LOCAL SYMMETRY: $\alpha \rightarrow \alpha(x)$), then the $W^{\pm,0}$ mass terms $\sim M_W^2 W_\mu^\dagger W^\mu$ cannot be added to the Lagrangian by hand.

Same for mass terms like $m_f \bar{\Psi}_f \Psi_f$ of fermions (electron, neutrinos, muon etc.)

Because these particles MUST be massive some other mechanism is needed to give these particles their masses.
BROUT-ENGLERT-HIGGS MECHANISM

In 1964 by 3 groups: Robert Brout and François Englert; by Peter Higgs; and by Gerald Guralnik, C. R. Hagen, and Tom Kibble

Incorporated in the Standard Model by Steven Weinberg (1967) and Abdus Salam (1968)
Introduction to the Standard Model

Accounts for almost everything about Electroweak and Strong interactions of the fundamental particles in Nature (not gravitational)

\[ SU(3) \times SU(2) \times U(1) \]

LOCAL GAUGE SYMMETRY

It is important to understand how all these elementary particles get their masses or massless-ness

Ajinkya S. Kamat, ajinkya@virginia.edu

Brout-Englert-Higgs Mechanism and Beyond

GPSA talk, 11th November, 2013
Accounts for *almost* everything about Electroweak and Strong interactions of the fundamental particles in Nature (not gravitational)
Introduction to the Standard Model

Accounts for *almost* everything about Electroweak and Strong interactions of the fundamental particles in Nature (not gravitational)

\[ SU(3) \times SU(2) \times U(1) \]

LOCAL GAUGE SYMMETRY

Three generations of matter (fermions)

- **I**
  - up, 2.4 MeV/c^2
  - charm, 1.27 GeV/c^2
  - top, 171.2 GeV/c^2

- **II**
  - down, 4.8 MeV/c^2
  - strange, 104 MeV/c^2
  - bottom, 4.2 GeV/c^2

- **III**
  - photon, 0 GeV/c^2
  - Higgs boson, ? GeV/c^2

Quarks:
- mass, charge, spin, name

Leptons:
- mass, charge, spin, name

Gauge bosons:
- mass, charge, spin, name
Introduction to the Standard Model

- Accounts for *almost* everything about Electroweak and Strong interactions of the fundamental particles in Nature (not gravitational)
- $SU(3) \times SU(2) \times U(1)$ LOCAL GAUGE SYMMETRY
- It is important to understand how all these elementary particles get their masses or massless-ness
\[ SU(2) \times U(1) \] local gauge symmetry demands that \( W^\pm, Z^0 \) and fermions (spin-1/2) particles are massless.
- $SU(2) \times U(1)$ local gauge symmetry demands that $W^\pm$, $Z^0$ and fermions (spin-1/2) particles are massless.
- Observations show that these particles are massive.
\( SU(2) \times U(1) \) local gauge symmetry demands that \( W^\pm, Z^0 \) and fermions (spin-1/2) particles are massless

- Observations show that these particles are massive
- This means that in the stable state of the universe that we are in, \( SU(2) \times U(1) \) is broken
$SU(2) \times U(1)$ local gauge symmetry demands that $W^\pm$, $Z^0$ and fermions (spin-1/2) particles are massless.

Observations show that these particles are massive.

This means that in the stable state of the universe that we are in, $SU(2) \times U(1)$ is broken.

Thus, $SU(2) \times U(1)$ symmetry must have existed right after the Big Bang and soon after that.

THE SYMMETRY WAS BROKEN \textit{SPONTANEOUSLY}
SOME CONCEPTS
Perturbation Theory

- QFT is usually used with perturbation theory to study effects of ‘relatively less probable’ interactions.
Perturbation Theory

- QFT is usually used with perturbation theory to study effects of ‘relatively less probable’ interactions

- Imagine Taylor expansion: \(\frac{1}{1 - ax} \approx 1 + ax + O(a^2x^2)\)
  
  if \(ax \ll 1\)
Perturbation Theory

QFT is usually used with perturbation theory to study effects of ‘relatively less probable’ interactions.

Imagine Taylor expansion: \[ \frac{1}{1 - ax} \approx 1 + ax + \mathcal{O}(a^2x^2) \]

if \( ax \ll 1 \)

Similarly in QFT perturbation theory.
Perturbation Theory

- QFT is usually used with perturbation theory to study effects of ‘relatively less probable’ interactions

- Imagine Taylor expansion: \[ \frac{1}{1 - ax} \approx 1 + ax + \mathcal{O}(a^2x^2) \]
  if \( ax \ll 1 \)

- Similarly in QFT perturbation theory
  the fields need to have small values i.e.
  average value zero + quantum fluctuations
Covariant Derivative

In Lagrangian the kinetic terms of fields have
\((\partial \rho \phi)\), i.e. \((\partial \phi/\partial x \rho)\)

\(\partial \rho\) assumes that the difference between fields at
\(x\) and \(x+\delta x\) is due
to different space-time points

When there is LOCAL GAUGE SYMMETRY, actually their phases
might be different too:
\(\alpha(x) \neq \alpha(x+\delta x)\)

Hence, a meaningful derivative has to account for this and find effect
only due to space-time translation: COVARIANT DERIVATIVE

\[ D_{\rho} \phi = \partial_{\rho} \phi + \dot{i} g A_{\rho} \phi \]

\(A_{\rho}\) → Gauge Field (like the photon in QED)

By defining requirement when
\(\phi(x) \rightarrow \text{Exp} [\dot{i} \alpha(x)] \phi(x)\)
\(A_{\rho}(x) \rightarrow A_{\rho}(x) - (1/g) \partial_{\rho} \alpha(x)\)

Hereafter, we'll use the covariant derivative in the kinetic terms
Covariant Derivative

- In Lagrangian the kinetic terms of fields have \( (\partial_\rho \phi) \) i.e. \( (\partial \phi / \partial x^\rho) \)
Covariant Derivative

- In Lagrangian the kinetic terms of fields have \((\partial_\rho \phi)\) i.e. \((\partial \phi / \partial x^\rho)\)
- \(\partial_\rho\) assumes that the difference between fields at \(x\) and \(x + \delta x\) is due to different space-time points

\[ D_\rho \phi = \partial_\rho \phi + \dot{i} g A_\rho \phi: \text{Gauge Field (like the photon in QED)} \]
Covariant Derivative

- In Lagrangian the kinetic terms of fields have \((\partial_\rho \phi)\) i.e. \((\partial \phi / \partial x^\rho)\)

- \(\partial_\rho\) assumes that the difference between fields at \(x\) and \(x + \delta x\) is due to different space-time points

- When there is LOCAL GAUGE SYMMETRY, actually their phases might be different too: \(\alpha(x) \neq \alpha(x + \delta x)\)
Covariant Derivative

- In Lagrangian the kinetic terms of fields have \( \partial_\rho \phi \) i.e. \( \partial \phi / \partial x^\rho \)
- \( \partial_\rho \) assumes that the difference between fields at \( x \) and \( x + \delta x \) is due to different space-time points
- When there is LOCAL GAUGE SYMMETRY, actually their phases might be different too: \( \alpha(x) \neq \alpha(x + \delta x) \)
- Hence, a meaningful derivative has to account for this and find effect only due to space-time translation
Covariant Derivative

- In Lagrangian the kinetic terms of fields have \((\partial_\rho \phi)\) i.e. \((\partial \phi / \partial x^\rho)\)
- \(\partial_\rho\) assumes that the difference between fields at \(x\) and \(x + \delta x\) is due to different space-time points
- When there is LOCAL GAUGE SYMMETRY, actually their phases might be different too: \(\alpha(x) \neq \alpha(x + \delta x)\)
- Hence, a meaningful derivative has to account for this and find effect only due to space-time translation: COVARIANT DERIVATIVE

\[ D_\rho \phi = \partial_\rho \phi + \dot{\mathbf{i}} g A_\rho \phi: \text{Gauge Field (like the photon in QED)} \]
Covariant Derivative

- In Lagrangian the kinetic terms of fields have \((\partial_\rho \phi)\) i.e. \((\partial \phi / \partial x^\rho)\)
- \(\partial_\rho\) assumes that the difference between fields at \(x\) and \(x + \delta x\) is due to different space-time points
- When there is LOCAL GAUGE SYMMETRY, actually their phases might be different too: \(\alpha(x) \neq \alpha(x + \delta x)\)
- Hence, a meaningful derivative has to account for this and find effect only due to space-time translation: COVARIANT DERIVATIVE
- \(D_\rho \phi = \partial_\rho \phi + ig A_\rho \phi: A_\rho \rightarrow\) Gauge Field
  (like the photon in QED)
In Lagrangian the kinetic terms of fields have \((\partial_\rho \phi)\) i.e. \((\partial \phi / \partial x^\rho)\)

\(\partial_\rho\) assumes that the difference between fields at \(x\) and \(x + \delta x\) is due to different space-time points

When there is LOCAL GAUGE SYMMETRY, actually their phases might be different too: \(\alpha(x) \neq \alpha(x + \delta x)\)

Hence, a meaningful derivative has to account for this and find effect only due to space-time translation: COVARIANT DERIVATIVE

\[ D_\rho \phi = \partial_\rho \phi + ig A_\rho \phi: A_\rho \rightarrow \text{Gauge Field} \] (like the photon in QED)

By defining requirement when \(\phi(x) \rightarrow \text{Exp}[i\alpha(x)] \phi(x)\)

\[ A_\rho(x) \rightarrow A_\rho(x) - (1/g) \partial_\rho \alpha(x) \]
Covariant Derivative

- In Lagrangian the kinetic terms of fields have $(\partial_{\rho} \phi)$ i.e. $(\partial \phi / \partial x^{\rho})$
- $\partial_{\rho}$ assumes that the difference between fields at $x$ and $x + \delta x$ is due to different space-time points
- When there is LOCAL GAUGE SYMMETRY, actually their phases might be different too: $\alpha(x) \neq \alpha(x + \delta x)$
- Hence, a meaningful derivative has to account for this and find effect only due to space-time translation: COVARIANT DERIVATIVE
- $D_{\rho} \phi = \partial_{\rho} \phi + ig A_{\rho} \phi$: $A_{\rho} \rightarrow$ Gauge Field (like the photon in QED)
- By defining requirement when $\phi(x) \rightarrow \text{Exp}[i\alpha(x)] \phi(x)$ $A_{\rho}(x) \rightarrow A_{\rho}(x) - (1/g) \partial_{\rho} \alpha(x)$
- Hereafter, we’ll use the covariant derivative in the kinetic terms
A toy model

Consider a model with LOCAL $U(1)$ symmetry

A real gauge field $A^\rho$ (associated with force carrier spin-1 particle) and a complex scalar (associated with a spin-0 particle) field $\phi = \sqrt{2}(\phi_1 + i\phi_2)$

$A^\rho$ needs to be massive but due to LOCAL $U(1)$ GAUGE SYMMETRY mass term cannot be added by hand

Lagrangian: $L = (D^\rho \phi)^\dagger (D^\rho \phi) - \frac{1}{4} F^\rho_\sigma F_{\rho\sigma} - V(\phi)$ with potential $V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$

No higher orders of $\phi$ to ensure that all infinite interactions/diagrams can be cancelled (Renormalizability!)

Ajinkya S. Kamat, ajinkya@virginia.edu

Brout-Englert-Higgs Mechanism and Beyond

GPSA talk, 11th November, 2013
A toy model

- Consider a model with LOCAL $U(1)$ symmetry
Consider a model with LOCAL $U(1)$ symmetry

A real gauge field $A_\rho$ (associated with force carrier spin-1 particle) and a complex scalar (associated with a spin-0 particle) field

$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i \phi_2)$$
A toy model

- Consider a model with LOCAL $U(1)$ symmetry
- A real gauge field $A_\rho$ (associated with force carrier spin-1 particle) and a complex scalar (associated with a spin-0 particle) field
  \[
  \phi = \frac{1}{\sqrt{2}}(\phi_1 + i \phi_2)
  \]
- $A_\rho$ needs to be massive but due to LOCAL $U(1)$ GAUGE SYMMETRY mass term cannot be added by hand
A toy model

- Consider a model with LOCAL $U(1)$ symmetry
- A real gauge field $A_\rho$ (associated with force carrier spin-1 particle) and a complex scalar (associated with a spin-0 particle) field
  \[ \phi = \frac{1}{\sqrt{2}} (\phi_1 + i \phi_2) \]
- $A_\rho$ needs to be massive but due to LOCAL $U(1)$ GAUGE SYMMETRY mass term cannot be added by hand
- Lagrangian:
  \[ \mathcal{L} = (D_\rho \phi)^\dagger (D^\rho \phi) - \frac{1}{4} F_{\rho\sigma} F^{\rho\sigma} - V(\phi) \]
  with potential \[ V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \]
Consider a model with LOCAL $U(1)$ symmetry

A real gauge field $A_\rho$ (associated with force carrier spin-1 particle) and a complex scalar (associated with a spin-0 particle) field

$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i \phi_2)$$

$A_\rho$ needs to be massive but due to LOCAL $U(1)$ GAUGE SYMMETRY mass term cannot be added by hand

Lagrangian: $\mathcal{L} = (D_\rho \phi)\dagger (D^\rho \phi) - \frac{1}{4} F_{\rho\sigma} F^{\rho\sigma} - V(\phi)$

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

No higher orders of $\phi$ to ensure that all infinite interactions/diagrams can be cancelled (Renormalizability!)
Only case of interest: $\mu^2 > 0$  \hspace{1cm} ($\mu^2 < 0$ does not have the ‘valley’)

$V(\phi)$

$\phi_1$

$\phi_2$
Only case of interest: $\mu^2 > 0$
Stable state of the field $\phi$ is at $|\phi|^2 = \mu^2/\lambda = v^2/2$
i.e. $\phi_1^2 + \phi_2^2 = v^2 \rightarrow$ a circle
Stable state of the field $\phi$ is at $|\phi|^2 = \mu^2/\lambda = v^2/2$
i.e. $\phi_1^2 + \phi_2^2 = v^2 \rightarrow$ a circle

This is the state that all the ‘Expectation (like average) values’ (e.g. $\langle \phi \rangle$) are seen to be in
Only case of interest: $\mu^2 > 0$
Stable state (ground state) of the field $\phi$ is at $|\phi|^2 = \frac{\mu^2}{\lambda} = \frac{v^2}{2}$
i.e. $\phi_1^2 + \phi_2^2 = v^2 \rightarrow$ a circle
Stable state (ground state) of the field $\phi$ is at $|\phi|^2 = \mu^2 / \lambda = v^2 / 2$
i.e. $\phi_1^2 + \phi_2^2 = v^2 \rightarrow$ a circle

All states on this circle are *equally* stable $\Rightarrow$ we can choose any point as the ground state.
Stable state (ground state) of the field $\phi$ is at $|\phi|^2 = \mu^2 / \lambda = \nu^2 / 2$
i.e. $\phi_1^2 + \phi_2^2 = \nu^2 \rightarrow$ a circle

All states on this circle are *equally* stable $\Rightarrow$ we can choose any point as the ground state.

Choose, (say) $<\phi_1> = \nu$ and $<\phi_2> = 0$
- Stable state (ground state) of the field $\phi$ is at $|\phi|^2 = \mu^2/\lambda = v^2/2$
  i.e. $\phi_1^2 + \phi_2^2 = v^2 \rightarrow$ a circle
- All states on this circle are *equally* stable $\Rightarrow$ we can choose any point as the ground state.
- Choose, (say) $<\phi_1> = v$ and $<\phi_2> = 0$
- All classical, NOTHING QUANTUM YET
Stable state (ground state) of the field $\phi$ is at $|\phi|^2 = \mu^2/\lambda = v^2/2$
i.e. $\phi_1^2 + \phi_2^2 = v^2 \rightarrow$ a circle

All states on this circle are *equally* stable $\Rightarrow$ we can choose any point as the ground state.

Choose, (say) $<\phi_1> = v$ and $<\phi_2> = 0$

All classical, NOTHING QUANTUM YET

One problem in working with these fields: We want to use perturbation theory
And perturbation theory requires smallness of the terms in the expansion (much like Taylor expansion)
Stable state (ground state) of the field $\phi$ is at $|\phi|^2 = \mu^2/\lambda = v^2/2$
i.e. $\phi_1^2 + \phi_2^2 = v^2 \rightarrow$ a circle
All states on this circle are equally stable $\Rightarrow$ we can choose any point as the ground state.
Choose, (say) $\langle \phi_1 \rangle = v$ and $\langle \phi_2 \rangle = 0$
All classical, NOTHING QUANTUM YET
One problem in working with these fields: We want to use perturbation theory
And perturbation theory requires smallness of the terms in the expansion (much like Taylor expansion)
So the fields must have average value zero in the ground state
Define: $\phi'_1 = \phi_1 - \nu$. Thus, $\langle \phi'_1 \rangle = 0$.
Define: $\phi'_1 = \phi_1 - \nu$. Thus, $\langle \phi'_1 \rangle = 0$

The symmetry of the ground state is broken spontaneously.

$V(\phi')$

$\phi'_1$
Then

\[
(D_\rho \phi)^\dagger (D^\rho \phi) = \text{(some ‘ok’ terms)}
\]
Then

\[(D_\rho \phi)^\dagger (D^\rho \phi) = (\text{some 'ok' terms}) + \frac{g^2 v^2}{2} A_\rho A^\rho \text{ (hurray!)}\]
Then

\[(D_\rho \phi)\dagger (D^\rho \phi) = (\text{some 'ok' terms}) + \frac{g^2 v^2}{2} A_\rho A^\rho \text{ (hurray!)} \]

\[-gv A_\rho (\partial^\rho \phi_2 + g A^\rho \phi'_1) \text{ (problem again!!)} \]
Then

\[(D_\rho \phi)^\dagger (D^\rho \phi) = (\text{some ‘ok’ terms}) + \frac{g^2 v^2}{2} A_\rho A^\rho \text{ (hurray!)}\]

\[- g v A_\rho (\partial^\rho \phi_2 + g A^\rho \phi_1') \text{ (problem again!!)}\]

Don’t worry, we’re very close to the solution
Then

\[(D_\rho \phi)^\dagger (D_\rho \phi) = \text{(some 'ok' terms) } + \frac{g^2 v^2}{2} A_\rho A^\rho \text{ (hurray!)}\]

\[\text{− } g v A_\rho (\partial_\rho \phi_2 + g A^\rho \phi'_1) \text{ (problem again!!)}\]

Don’t worry, we’re very close to the solution

Try polar coordinates:

\[\phi(x) = \text{radial}(x) \exp[i \theta(x)] = \frac{1}{\sqrt{2}}(v + \eta(x)) \exp[i \theta(x)/v]\]
Then

\[(D_\rho \phi)^\dagger (D^\rho \phi) = (\text{some 'ok' terms}) + \frac{g^2 \nu^2}{2} A_\rho A^\rho \ (\text{hurray!})\]

\[- g\nu A_\rho (\partial^\rho \phi_2 + g A^\rho \phi'_1) \ (\text{problem again!!})\]

Don’t worry, we’re very close to the solution

Try polar coordinates:

\[\phi(x) = \text{radial}(x) \ \text{Exp}[i \ \theta(x)] = \frac{1}{\sqrt{2}} (\nu + \eta(x)) \ \text{Exp}[i \ \theta(x)/\nu]\]

\[\phi(x) \approx \frac{1}{\sqrt{2}} (\nu + \eta(x) + i \ \theta(x)) \text{ and} \]

\[= \frac{1}{\sqrt{2}} (\nu + \phi'_1(x) + i \ \phi_2(x))\]
Use symmetry and transform:
\[ \phi(x) \rightarrow \phi'(x) = \exp[-i \theta(x)/v] \phi(x) \]
Use symmetry and transform:

\[ \phi(x) \rightarrow \phi'(x) = \exp[-i \theta(x)/v] \phi(x) \]

So \( A_\rho(x) \rightarrow A'_\rho(x) = A_\rho(x) - (1/g) \partial_\rho \theta(x) \)
Use symmetry and transform:
\[
\phi(x) \rightarrow \phi'(x) = \exp[-i \theta(x)/v] \phi(x)
\]
So \(A_\rho(x) \rightarrow A'_\rho(x) = A_\rho(x) - (1/g) \partial_\rho \theta(x)\)

Now when \(\mathcal{L}\) is expanded there’s no \(\theta(x)\) i.e. no \(\phi_2\) and \(A_\rho\) has a mass \((g\, v)\). \(\phi_2\) ”absorbed” by \(A_\rho\)
Use symmetry and transform:
\[ \phi(x) \rightarrow \phi'(x) = \text{Exp}[-i \theta(x)/v] \phi(x) \]

\[ \text{So } A_\rho(x) \rightarrow A'_\rho(x) = A_\rho(x) - \left(\frac{1}{g}\right) \partial_\rho \theta(x) \]

Now when \( \mathcal{L} \) is expanded there’s no \( \theta(x) \) i.e. no \( \phi_2 \) and \( A_\rho \) has a mass \((g \cdot v)\). \( \phi_2 \) ”absorbed” by \( A_\rho \)

AND
Use symmetry and transform:
\[ \phi(x) \to \phi'(x) = \text{Exp}\left[ -i \frac{\theta(x)}{v} \right] \phi(x) \]

So \( A_\rho(x) \to A'_\rho(x) = A_\rho(x) - \frac{1}{g} \partial_\rho \theta(x) \)

Now when \( \mathcal{L} \) is expanded there’s no \( \theta(x) \) i.e. no \( \phi_2 \) and \( A_\rho \) has a mass \( (g \cdot v) \). \( \phi_2 \) ”absorbed” by \( A_\rho \)

AND a scalar particle associated with \( \phi'_1 \) has appeared having mass \( (\sqrt{2} \cdot \mu) \)

\( \to \) BROUT-ENGLERT-HIGGS BOSON :-}
In the Standard Model, the electroweak symmetry is $SU(2) \times U(1)$. So scalar $\phi$ is a $(2 \times 1)$ matrix instead of a number, but the calculations proceed in the same way.
In the Standard Model, the electroweak symmetry is $SU(2) \times U(1)$. So scalar $\phi$ is a $(2 \times 1)$ matrix instead of a number, but the calculations proceed in the same way.

This mechanism gives mass term for $W^\pm$ and $Z^0$ bosons, but not for the photon. So the photon is massless.
In the Standard Model, the electroweak symmetry is $SU(2) \times U(1)$. So scalar $\phi$ is a $(2 \times 1)$ matrix instead of a number, but the calculations proceed in the same way.

This mechanism gives mass term for $W^\pm$ and $Z^0$ bosons, but not for the photon. So the photon is massless.

Higgs field interacts with the fermions through Yukawa interaction

$$ \sim g_f \phi \bar{\psi}_f \psi_f = \frac{g_f v}{\sqrt{2}} \bar{\psi}_f \psi_f + \text{(interaction with } \phi') $$

→ masses of fermions (Neutrinos are still massless)
Symmetry of the Lagrangian IS NOT BROKEN but that of the GROUND STATE is broken
Clarifying Some Concepts

- Symmetry of the Lagrangian IS NOT BROKEN but that of the GROUND STATE is broken.

- Higgs boson (particle) DOES NOT give mass to the particles but the interaction with the HIGGS FIELD is responsible for that.
Clarifying Some Concepts

- Symmetry of the Lagrangian IS NOT BROKEN but that of the GROUND STATE is broken
- Higgs boson (particle) DOES NOT give mass to the particles but the interaction with the HIGGS FIELD is responsible for that
- Mass of the Higgs boson cannot be predicted theoretically even if $g$ and $v$ are known (this is where LHC discovery comes in)
Clarifying Some Concepts

▶ Symmetry of the Lagrangian IS NOT BROKEN but that of the GROUND STATE is broken

▶ Higgs boson (particle) DOES NOT give mass to the particles but the interaction with the HIGGS FIELD is responsible for that

▶ Mass of the Higgs boson cannot be predicted theoretically even if $g$ and $v$ are known (this is where LHC discovery comes in)

▶ IT IS NOT RESPONSIBLE FOR MASS OF ALL THE MATTER IN THE UNIVERSE

∼ 99.9% mass of the visible universe comes from the strong force between quarks!

▶ NOT THE GOD PARTICLE!!
Clarifying Some Concepts

- Symmetry of the Lagrangian IS NOT BROKEN but that of the GROUND STATE is broken.
- Higgs boson (particle) DOES NOT give mass to the particles but the interaction with the HIGGS FIELD is responsible for that.
- Mass of the Higgs boson cannot be predicted theoretically even if $g$ and $v$ are known (this is where LHC discovery comes in).
- IT IS NOT RESPONSIBLE FOR MASS OF ALL THE MATTER IN THE UNIVERSE.
- $\sim 99.9\%$ mass of the visible universe comes from the strong force between quarks!
Clarifying Some Concepts

- Symmetry of the Lagrangian IS NOT BROKEN but that of the GROUND STATE is broken
- Higgs boson (particle) DOES NOT give mass to the particles but the interaction with the HIGGS FIELD is responsible for that
- Mass of the Higgs boson cannot be predicted theoretically even if $g$ and $v$ are known (this is where LHC discovery comes in)
- IT IS NOT RESPONSIBLE FOR MASS OF ALL THE MATTER IN THE UNIVERSE
- $\sim 99.9\%$ mass of the visible universe comes from the strong force between quarks!
- NOT THE GOD PARTICLE!!
The Higgs boson associated with $2 \times 1$ matrix $\phi$ is the SIMPLEST case that fits in the Standard Model.
The Higgs boson associated with $2 \times 1$ matrix $\phi$ is the SIMPLEST case that fits in the Standard Model

This is what the experiments at LHC were primarily looking for
The Higgs boson associated with $2 \times 1$ matrix $\phi$ is the SIMPLEST case that fits in the Standard Model.

This is what the experiments at LHC were primarily looking for.

There can be MORE as well as MORE COMPLICATED Higgs bosons (like charged Higgs, doubly charged Higgs, etc).
The Higgs boson associated with $2 \times 1$ matrix $\phi$ is the SIMPLEST case that fits in the Standard Model

This is what the experiments at LHC were primarily looking for

There can be MORE as well as MORE COMPLICATED Higgs bosons (like charged Higgs, doubly charged Higgs, etc)

The particle discovered at LHC on July 4$^{th}$, 2012 with mass $\sim 126$ GeV is looking more and more like the Standard Model Higgs boson, although it can be an impostor
The Higgs boson associated with $2 \times 1$ matrix $\phi$ is the SIMPLEST case that fits in the Standard Model.

This is what the experiments at LHC were primarily looking for.

There can be MORE as well as MORE COMPLICATED Higgs bosons (like charged Higgs, doubly charged Higgs, etc).

The particle discovered at LHC on July 4th, 2012 with mass $\sim 126$ GeV is looking more and more like the Standard Model Higgs boson, although it can be an impostor and/or there can be (pleeeeeeaaase be there) something else BEYOND.
Many questions still unanswered: it has been proved again and again that the neutrinos DO HAVE masses
Many questions still unanswered: it has been proved again and again that the neutrinos DO HAVE masses

Clear evidence that something remains beyond the Standard Model
Many questions still unanswered: it has been proved again and again that the neutrinos DO HAVE masses

- Clear evidence that something remains beyond the Standard Model
- If neutrinos are massive then they should come in two types:
  - left-handed (travels opposite to spin)
  - right-handed (travels in direction of spin)
Many questions still unanswered: it has been proved again and again that the neutrinos DO HAVE masses.

Clear evidence that something remains beyond the Standard Model.

If neutrinos are massive then they should come in two types:
- left-handed (travels opposite to spin)
- right-handed (travels in direction of spin)

Only left-handed have been observed.
Many questions still unanswered: it has been proved again and again that the neutrinos DO HAVE masses.

Clear evidence that something remains beyond the Standard Model.

If neutrinos are massive then they should come in two types:
  - left-handed (travels opposite to spin)
  - right-handed (travels in direction of spin)

Only left-handed have been observed.

Many Grand Unified Theories (GUT) postulate right-handed neutrinos at mass $\sim 10^{16-17}$ GeV!! Cannot be detected at LHC or near future colliders.
Is it possible to have mass of the right-handed neutrino in the mass range ACCESSIBLE TO LHC
Is it possible to have mass of the right-handed neutrino in the mass range ACCESSIBLE TO LHC WITH NO NEW FUNDAMENTAL FORCES added to the Standard Model?
YES, the Electroweak-scale Right-handed Neutrino ($\text{EW}_R$) Model
(P. Q. Hung, V. V. Hoang, ASK)
YES, the Electroweak-scale Right-handed Neutrino (EW\textsubscript{\nu\textsubscript{R}}) Model

(P. Q. Hung, V. V. Hoang, ASK)

Three generations of Standard Model fermions

<table>
<thead>
<tr>
<th>Mass (MeV/c\textsuperscript{2})</th>
<th>Charge</th>
<th>Spin</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>u\textsubscript{up}</td>
<td>(\frac{1}{2})</td>
<td>(\frac{1}{2})</td>
<td>up</td>
</tr>
<tr>
<td>c\textsubscript{charm}</td>
<td>(\frac{2}{3})</td>
<td>(\frac{1}{2})</td>
<td>charm</td>
</tr>
<tr>
<td>t\textsubscript{top}</td>
<td>(\frac{1}{2})</td>
<td>(\frac{1}{2})</td>
<td>top</td>
</tr>
</tbody>
</table>

Gauge bosons

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass (GeV/c\textsuperscript{2})</th>
<th>Charge</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma)</td>
<td>(0)</td>
<td>0</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>(W\textsubscript{\pm})</td>
<td>(\pm 1)</td>
<td>(\pm 1)</td>
<td>(\frac{1}{2})</td>
</tr>
<tr>
<td>(Z)</td>
<td>(91.2)</td>
<td>0</td>
<td>(\frac{1}{2})</td>
</tr>
</tbody>
</table>

Three generations of mirror fermions

<table>
<thead>
<tr>
<th>Mass (MeV/c\textsuperscript{2})</th>
<th>Charge</th>
<th>Spin</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu\textsubscript{L})</td>
<td>(0)</td>
<td>(\frac{1}{2})</td>
<td>electron neutrino</td>
</tr>
<tr>
<td>(\nu\textsubscript{\mu})</td>
<td>(0)</td>
<td>(\frac{1}{2})</td>
<td>muon neutrino</td>
</tr>
<tr>
<td>(\nu\textsubscript{\tau})</td>
<td>(0)</td>
<td>(\frac{1}{2})</td>
<td>tau neutrino</td>
</tr>
</tbody>
</table>

Quarks

<table>
<thead>
<tr>
<th>Mass (MeV/c\textsuperscript{2})</th>
<th>Charge</th>
<th>Spin</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>d\textsubscript{down}</td>
<td>(-\frac{1}{2})</td>
<td>(\frac{1}{2})</td>
<td>down</td>
</tr>
<tr>
<td>s\textsubscript{strange}</td>
<td>(0)</td>
<td>(\frac{1}{2})</td>
<td>strange</td>
</tr>
<tr>
<td>b\textsubscript{bottom}</td>
<td>(-\frac{1}{2})</td>
<td>(\frac{1}{2})</td>
<td>bottom</td>
</tr>
</tbody>
</table>

Leptons

<table>
<thead>
<tr>
<th>Mass (MeV/c\textsuperscript{2})</th>
<th>Charge</th>
<th>Spin</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e)</td>
<td>(-1)</td>
<td>(\frac{1}{2})</td>
<td>electron</td>
</tr>
<tr>
<td>(\mu)</td>
<td>(-1)</td>
<td>(\frac{1}{2})</td>
<td>muon</td>
</tr>
<tr>
<td>(\tau)</td>
<td>(-1)</td>
<td>(\frac{1}{2})</td>
<td>tau</td>
</tr>
</tbody>
</table>

Left-handed fermion doublets

Right-handed mirror fermion doublets

Brout-Englert-Higgs Mechanism and Beyond

GPSA talk, 11\textsuperscript{th} November, 2013
YES, the Electroweak-scale Right-handed Neutrino (EW$\nu_R$) Model

(P. Q. Hung, V. V. Hoang, ASK)

Three generations of Standard Model fermions

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>c</td>
<td>t</td>
</tr>
<tr>
<td>up</td>
<td>charm</td>
<td>top</td>
</tr>
<tr>
<td>2.4 MeV/c$^2$</td>
<td>1.27 GeV/c$^2$</td>
<td>171.2 GeV/c$^2$</td>
</tr>
<tr>
<td>½</td>
<td>½</td>
<td>½</td>
</tr>
<tr>
<td>½</td>
<td>½</td>
<td>½</td>
</tr>
</tbody>
</table>

Gauge bosons

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>U$^M$</td>
<td>C$^M$</td>
</tr>
<tr>
<td>photon</td>
<td>up</td>
<td>charm</td>
</tr>
<tr>
<td>¾</td>
<td>½</td>
<td>½</td>
</tr>
</tbody>
</table>

Three generations of mirror fermions

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>s</td>
<td>b</td>
</tr>
<tr>
<td>down</td>
<td>strange</td>
<td>bottom</td>
</tr>
<tr>
<td>4.8 MeV/c$^2$</td>
<td>104 MeV/c$^2$</td>
<td>4.2 GeV/c$^2$</td>
</tr>
<tr>
<td>½</td>
<td>½</td>
<td>½</td>
</tr>
<tr>
<td>½</td>
<td>½</td>
<td>½</td>
</tr>
</tbody>
</table>

Quarks

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>μ</td>
<td>τ</td>
</tr>
<tr>
<td>electron</td>
<td>muon</td>
<td>tau</td>
</tr>
<tr>
<td>0.511 MeV/c$^2$</td>
<td>105.7 MeV/c$^2$</td>
<td>1.777 GeV/c$^2$</td>
</tr>
<tr>
<td>½</td>
<td>½</td>
<td>½</td>
</tr>
<tr>
<td>½</td>
<td>½</td>
<td>½</td>
</tr>
</tbody>
</table>

Leptons

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>V$_{Le}$</td>
<td>V$_{L\mu}$</td>
<td>V$_{Lt}$</td>
</tr>
<tr>
<td>electron neutrino</td>
<td>muon neutrino</td>
<td>tau neutrino</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>½</td>
<td>½</td>
<td>½</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z$^0$</td>
<td>V$^{Re}_R$</td>
<td>V$^{Re}_L$</td>
</tr>
<tr>
<td>Z boson</td>
<td>muon neutrino</td>
<td>tau neutrino</td>
</tr>
<tr>
<td>91.2 GeV/c$^2$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>½</td>
<td>½</td>
<td>½</td>
</tr>
</tbody>
</table>

Left-handed fermion doublets

Right-handed mirror fermion doublets

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_5^±$</td>
<td>H$_5^±$</td>
<td>H$_5^±$</td>
</tr>
<tr>
<td>Higgs boson</td>
<td>Higgs boson</td>
<td>Higgs boson</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Interacts only with mirror fermions

Interacts with Standard Model fermions and mirror fermions

Interacts with Standard Model fermions

Created by Ajinkya Kamat
Can be tested at LHC as well as neutrino experiments
Can be tested at LHC as well as neutrino experiments

We have showed that it fits well within the precision constraints on the electroweak new Physics (Nucl. Phys. B, Volume 877, Issue 2)

Many exciting possibilities in this model as well as others. Stay tuned!
Can be tested at LHC as well as neutrino experiments

We have showed that it fits well within the precision constraints on the electroweak new Physics (Nucl. Phys. B, Volume 877, Issue 2)

Our calculations also show that the a Higgs boson in this model can show properties of the Standard Model Higgs boson as seen at LHC experiments (paper under preparation)
- Can be tested at LHC as well as neutrino experiments
- We have showed that it fits well within the precision constraints on the electroweak new Physics (Nucl. Phys. B, Volume 877, Issue 2)
- Our calculations also show that the a Higgs boson in this model can show properties of the Standard Model Higgs boson as seen at LHC experiments (paper under preparation)
- Many exciting possibilities in this model as well as others. Stay tuned!
Thank You :-}