Volume: 4 Issue: 11 Pages: 09-14

The Role of Symmetry Breaking in the Standard Model of Particle Physics

[*1] Dr. KM Nirupma Kumari

[*1] Assistant Professor, Department of Physics, Jagjiwan College Gaya, Magadh University Bodh Gaya, Bihar, India.

Article Info.
E-ISSN: 2583-6528
Impact Factor (SJIF): 6.876
Peer Reviewed Journal
Available online:
www.alladvancejournal.com

Received: 29/Oct/2025
Accepted: 02/Nov/2025

***Corresponding Author**
Dr. KM Nirupma Kumari
Assistant Professor, Department of Physics, Jagjiwan College Gaya, Magadh University Bodh Gaya, Bihar, India.

Abstract
This paper investigates the fundamental role of Spontaneous Symmetry Breaking (SSB) in the Standard Model (SM) of Particle Physics. The SM is constructed upon the principle of local gauge symmetry, which inherently requires all force carriers and matter particles to be massless, a prediction that fundamentally contradicts experimental evidence. The core objective of this study is to meticulously detail the theoretical mechanism by which the masses of the W and Z gauge bosons and all fundamental fermions are generated. We demonstrate that the Higgs mechanism, a process involving a complex scalar field acquiring a non-zero vacuum expectation value (v), spontaneously breaks the electroweak symmetry $SU(2)_L \times U(1)_Y$ down to the electromagnetic $U(1)_{em}$.This breaking is shown to provide the longitudinal polarization (and hence mass) to the weak force carriers via the Brout-Englert-Higgs mechanism and, through the Yukawa coupling, imparts mass to the fundamental fermions. The successful prediction and subsequent 2012 discovery of the remnant excitation of this field, the Higgs boson, serves as the definitive experimental validation for the SSB paradigm as the cornerstone of mass generation within the Standard Model.

Keywords: Standard Model, Spontaneous Symmetry Breaking (SSB), Higgs Mechanism, Electroweak Symmetry, Gauge Bosons, Yukawa Coupling, Mass Generation, Higgs Boson

Introduction

The Standard Model (SM) of Particle Physics represents the most accurate and empirically successful theory in modern science, describing the fundamental building blocks of matter and the forces that govern their interactions: the electromagnetic, weak nuclear, and strong nuclear forces. The framework is inherently a quantum field theory that is founded upon the principle of local gauge symmetry [Weinberg, 1995]. This central tenet dictates the existence and properties of the force-carrying particles, known as gauge bosons: the massless photon (γ) the eight massless gluons (g), and the weak force mediators ($W^{\pm}$,Z^0)

The mathematical requirement of local gauge invariance, essential for the theory's consistency and renormalizability, carries a profound physical consequence: it demands that all fundamental fields including the force carriers and the matter fields (quarks and leptons) must be massless [Griffiths, 2008].

The Mass Problem

This theoretical necessity immediately creates a severe conflict with experimental observation. While the photon and gluons are indeed massless, the weak force is known to be short-range, a property directly linked to the massive nature of its carriers. Specifically, the $W^{\pm}$ and Z^0 bosons are measured to have substantial masses (approximately 80.4 GeV/c^2 and 91.2 GeV/c^2, respectively) [Particle Data Group, 2024]. Furthermore, all fundamental matter particles, such as the electron and the top quark, are also observed to possess non-zero mass. Introducing explicit mass terms directly into the SM Lagrangian would violate the underlying gauge symmetry, thereby rendering the theory mathematically inconsistent and non-renormalizable [Quigg, 2009].

The Solution: Spontaneous Symmetry Breaking

To resolve this critical dilemma how to generate mass without destroying the fundamental gauge symmetry physicists turned to the concept of Spontaneous Symmetry Breaking (SSB). SSB is a phenomenon where the underlying laws (the Lagrangian) of a system are perfectly symmetric, but the system's lowest energy state, the vacuum, is not [Aitchison & Hey, 2012].

In the context of the SM, SSB is implemented through the Higgs mechanism [Englert & Brout, 1964; Higgs, 1964; Guralnik, Hagen, & Kibble, 1964]. This mechanism involves the introduction of a complex, scalar Higgs field that permeates all of space. By design, the potential energy of this field is constructed such that the minimum energy state (the vacuum) is attained when the field acquires a non-zero Vacuum Expectation Value (VEV). It is this non-zero VEV that spontaneously breaks the electroweak symmetry $SU(2)_L \times U(1)_Y$ down to the single remaining symmetry of electromagnetism, $U(1)_{em}$.

This paper argues that Spontaneous Symmetry Breaking, executed via the Higgs mechanism, is the critical theoretical tool required to reconcile the highly symmetric nature of the fundamental forces with the observed massive spectrum of the weak gauge bosons and all fundamental fermions. The subsequent sections will detail the theoretical underpinnings of symmetry, explain the mechanics of the Higgs field, and demonstrate precisely how the symmetry breaking process successfully generates mass for all the constituent particles of the Standard Model.

Theoretical Foundations of Symmetry

Symmetry is the most fundamental guiding principle in modern physics, postulating that the laws governing a system should remain unchanged under certain transformations. The application of symmetry principles is not merely aesthetic; it is the core mechanism used to construct the Lagrangians that define the Standard Model (SM). Understanding the distinction between different types of symmetry is essential for appreciating the necessity and mechanism of symmetry breaking.

A. Global vs. Local Symmetries

Symmetries in quantum field theory are broadly categorized based on their range of effect across spacetime:

1. Global Symmetries

A Global Symmetry is a transformation that is applied uniformly and simultaneously to a field at every single point in spacetime and leaves the system's Lagrangian (and thus its dynamics) invariant.

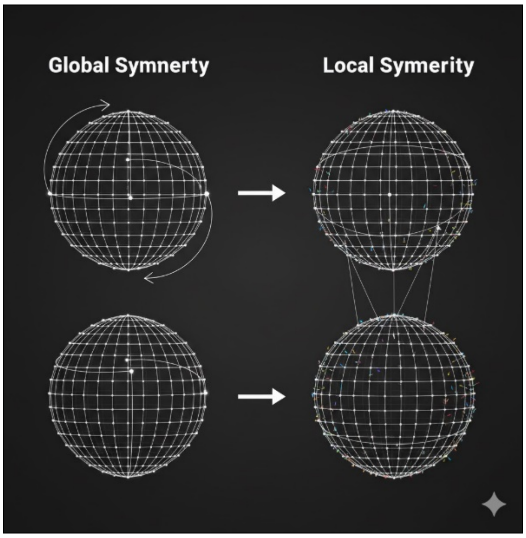
- **Example:** A global phase transformation on a charged field, $\psi(x) \to e^{i\alpha}\psi(x)$ where α is a constant, independent of the spacetime coordinates x.
- **Consequence:** Global symmetries lead to conserved quantities, as dictated by Noether's Theorem.

2. Local (Gauge) Symmetries

A Local Symmetry, or Gauge Symmetry, is a transformation where the symmetry parameter is allowed to vary from point to point in spacetime [Aitchison & Hey, 2012].

- **Example:** A local phase transformation on a charged field, $\psi(x) \to e^{i\alpha(x)}\psi(x)$, where $\alpha(x)$ is a function of the spacetime coordinates.
- **Consequence:** Local symmetry is the foundational requirement for constructing consistent theories of forces. The requirement of local invariance is so stringent that it forces the introduction of a new field the gauge boson to "correct" the Lagrangian and restore invariance.

Diagram



A simple visual comparison of a Global rotation (all points on a sphere rotate by the same angle) next to a Local rotation (each point rotates by a different, smoothly varying angle, necessitating connecting vectors to maintain the physical connection).

B. Noether's Theorem and Conserved Quantities

The profound connection between symmetry and conservation laws was mathematically established by Emmy Noether in 1915, forming a cornerstone of modern theoretical physics.

- Statement: Noether's Theorem states that for every continuous symmetry of the action (the integral of the Lagrangian) of a physical system, there exists a corresponding conserved quantity (or Noether charge) [Noether, 1918].
- **Significance:** This theorem elevated symmetry from a useful tool to a fundamental principle.
  - Time-translation symmetry → Conservation of Energy.
  - Spatial-translation symmetry → Conservation of Momentum.
  - Rotational symmetry → Conservation of Angular Momentum.
  - Global U(1) phase symmetry → Conservation of Electric Charge.

The theorem yields a conserved Noether current, denoted J^μ, whose four-divergence is zero. This formal expression directly encapsulates the mathematical rigor of the conservation principle:

$$\partial_\mu J^\mu = 0$$

Where $\partial_\mu = \left(\frac{1}{c}\frac{\partial}{\partial t}, \nabla\right)$ is the four-gradient operator, and the conservation law is valid when the fields satisfy the equations of motion.

The current J^μ itself is derived from the field's transformation under the symmetry and the derivative of the lagrangian density $\mathcal{L}$:

$$J^\mu = \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_i)}\delta\phi_i$$

The integral of the time component of the current J^0, over all space gives the conserved charge $Q: Q = \int J^0 d^3x$. the principle that charge conservation is derived from the $U(1)$ symmetry of the electromagnetic field is a direct consequence of this theorem

C. The Paramountcy of Local Gauge Symmetry

While global symmetries explain conserved charges, local gauge symmetry is the engine that generates the fundamental forces of the Standard Model.

The requirement of local invariance:

1. **Necessitates Gauge Bosons:** To maintain invariance under a local transformation, the theory must introduce a new vector field, $A_\mu(x)$ which is precisely the gauge boson (e.g., the photon for QED). This field interacts with the matter field in a way that perfectly compensates for the local changes in phase [Griffiths, 2008].
2. **Defines the Interaction:** By requiring local gauge invariance under the specific symmetry groups $SU(3)_C \times SU(2)_L \times U(1)_Y$, the entire interaction structure of the strong, weak, and electromagnetic forces is uniquely determined.
3. **Mandates Masslessness:** Critically, the very presence of the compensating gauge boson in the Lagrangian forbids the inclusion of a mass term for the gauge boson, $m^2 A_\mu A^\mu$, because such a term explicitly breaks the local gauge symmetry [Quigg, 2009].

Thus, the Standard Model, in its symmetric form, is a perfect, consistent quantum field theory for massless particles. The conflict with observed particle masses is what makes the mechanism of Spontaneous Symmetry Breaking, discussed in the following sections, a necessity.

Spontaneous Symmetry Breaking (SSB)

Spontaneous Symmetry Breaking (SSB) is the central concept that allows the Standard Model to possess massive particles while maintaining a fundamental, symmetric Lagrangian. It is the core idea that rescues the theory from its contradiction with experimental evidence.

A. Definition and Mechanism

SSB occurs when the Lagrangian (the mathematical rules governing the system) possesses a certain symmetry, but the ground state or vacuum (the lowest energy configuration of the system) does not share that symmetry.

The process is "spontaneous" because there is no explicit term in the fundamental equations that forces the system into the asymmetric state; rather, it is energetically favorable for the system to settle into one of many possible ground states.

1. The Mexican Hat Potential Analogy

The phenomenon is best understood using the classical analogy of a particle resting on a potential energy surface defined by the Higgs potential [Duff, 2004].

- **The Potential:** Consider a scalar field ϕ with a potential energy function, often referred to as the "Mexican Hat Potential" or $V(\phi)$. This potential is manifestly symmetric under rotation around the central axis (the V-axis).

$$V(\phi) = \mu^2 |\phi|^2 + \lambda|\phi|^4$$

- **Symmetric but Unstable Vacuum ($\mu^2 > 0$):** If $\mu^2 > 0$, the minimum energy (the vacuum) is at the center, $\phi = 0$. In this case, the vacuum is symmetric, matching the Lagrangian.
- **Asymmetric and Stable Vacuum ($\mu^2 < 0$):** In the case required for the Higgs mechanism, $\mu^2 < 0$. The minimum energy state is no longer at $\phi = 0$ (the peak of the hat), but rather forms a continuous ring of non-zero minimum energy states at a radius defined by

$$\phi 0 = \sqrt{-\mu 2/2\lambda}$$

- **SSB Occurs:** The system must choose one point on this valley of minima to settle into as its true ground state. Once that choice is made, the vacuum breaks the rotational symmetry of the potential. An observer standing at that chosen point can easily move along the minimum energy valley, but their local environment is no longer rotationally symmetric.

B. Goldstone's Theorem

A necessary consequence of SSB is the introduction of new particles, as formalized by Goldstone's Theorem [Goldstone, 1961]:

- **Statement:** The spontaneous breaking of a continuous global symmetry must result in the appearance of one or more massless spin-zero particles, known as Goldstone Bosons (or Nambu-Goldstone Bosons).
- **The Two Modes of Excitation:** When the system settles at the asymmetric minimum ($\phi = 0$):
  1. **Radial Mode (Higgs Boson):** Oscillations that move the field value out of the valley toward higher energy. This mode corresponds to a massive scalar particle (the physical Higgs boson).
  2. **Angular/Tangential Mode (Goldstone Bosons):** Oscillations that move the field value around the valley of the minima. Since motion along the valley requires no energy, these oscillations correspond to massless scalar particles (the Goldstone bosons).

C. The Challenge for the Standard Model

In a theory of fundamental forces like the Standard Model, Goldstone bosons pose a problem: there are no observed massless, spin-zero particles matching their properties.

This challenge is precisely where the Higgs mechanism (discussed in the next section) enters. It shows that when the broken symmetry is a local gauge symmetry (instead of a global one), the Goldstone bosons do not appear as separate particles. Instead, they are "eaten" by the gauge bosons, providing the latter with the necessary third (longitudinal) polarization component required to acquire mass. This critical result is known as the Brout-Englert-Higgs (BEH) Mechanism.

The Higgs Mechanism (SSB in Gauge Theories)

The Higgs mechanism, also known as the Brout-Englert-Higgs (BEH) mechanism, is the specific implementation of Spontaneous Symmetry Breaking (SSB) within a local gauge theory. It provides a consistent framework for gauge bosons and fermions to acquire mass while preserving the underlying gauge symmetry of the Lagrangian. This mechanism is central to the Standard Model's explanation of particle masses and culminated in the discovery of the Higgs boson in 2012.

A. The Higgs Field

To trigger electroweak symmetry breaking, the Standard

Model introduces a new fundamental field: the Higgs field (ϕ). It is a complex scalar field, meaning it has zero spin and carries no intrinsic angular momentum. Crucially, it is a doublet under the $SU(2)_L$ weak isospin symmetry and has a weak hypercharge Y = +1 [Peskin & Schroeder, 1995]:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \\ \frac{1}{\sqrt{2}}(\phi_3 + i\phi_4) \end{pmatrix}$$

This structure means the Higgs field actually comprises four real scalar degrees of freedom (ϕ_1, ϕ_2, ϕ_3, ϕ_4). The upper component (ϕ^+) is electrically charged, and the lower component (ϕ^0) is electrically neutral.

B. The Higgs Potential

The dynamics of the Higgs field are governed by its potential energy, $V(\phi)$, which is specifically designed to induce SSB. This is the famous "Mexican Hat Potential" applied to a quantum field:

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

where $\phi^\dagger\phi = (\phi^+)^*\phi^+ + (\phi^0)^*\phi^0$.

- **Parameters**
  - μ^2: A mass-like parameter.
  - λ: A self-interaction coupling constant, assumed to be positive ($\lambda > 0$).

The crucial aspect of this potential for SSB is the sign of μ^2:

- **Case 1**: $\mu^2 > 0$

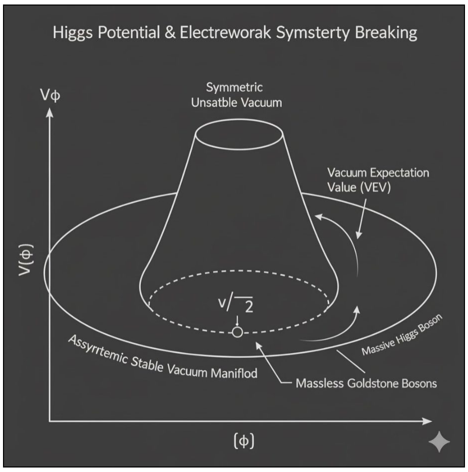
The minimum of the potential occurs at $\phi^\dagger\phi = 0$. The vacuum state is at $\phi = 0$, where the field has no value. This would imply a symmetric vacuum, leading to massless particles.

- **Case 2**: $\mu^2 < 0$ (Required for SSB)

This is the condition that drives SSB. With $\mu^2 < 0$, the origin $\phi = 0$ becomes a local maximum (the "peak" of the hat). The true minimum of the potential forms a continuous manifold of equivalent vacuum states at a non-zero value of $\phi^\dagger\phi$. The squared magnitude of the Higgs field at this minimum is:

$$|\phi|^2 = \phi^\dagger\phi = -\frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2}$$

where v is the Vacuum Expectation Value (VEV) of the Higgs field. The constant v has a value of approximately 246 GeV [Particle Data Group, 2024], and represents the strength of the Higgs field that permeates the entire universe.



C. Electroweak Symmetry Breaking: $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$

The VEV of the Higgs field is not symmetric under the full electroweak gauge group $SU(2)_L \times U(1)_Y$. To simplify the analysis, we can choose a specific direction for the VEV (though the physics is independent of this choice due to gauge freedom). Conventionally, we choose the VEV to align with the neutral component:

$$\langle\phi\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

This Choice Explicitly Breaks the $SU(2)_L \times U(1)_Y$ Symmetry

- The $U(1)_{em}$ (electromagnetic) symmetry remains unbroken because the vacuum state has zero electric charge ($Q = Y/2 + I_3 = 0/2 + 0 = 0$). The photon remains massless.
- The $SU(2)_L$ and $U(1)_Y$ symmetries are broken. This breaking is crucial for giving mass to the $W^\pm$ and Z^0 bosons, as well as fermions.

We can express the Higgs field around its vacuum expectation value by expanding it:

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

Here

- h(x) is the physical Higgs boson field (a single scalar degree of freedom), representing excitations in the radial direction of the potential, which will be massive.
- $G^+(x)$, $G^-(x)$ (the complex conjugate of G^+), and $G^0(x)$ are three Goldstone boson fields, representing excitations along the "trough" of the potential.

In a theory with local gauge symmetry, these three Goldstone bosons do not appear as physical particles. Instead, they are "absorbed" by the originally massless gauge bosons to become their longitudinal polarization components, thereby giving them mass. This is the core of the Brout-Englert-Higgs mechanism.

Mass Generation

The spontaneous breaking of the electroweak symmetry, $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$, by the Higgs field's non-zero Vacuum Expectation Value (VEV), $v \approx 246$, is the precise mechanism that endows particles with mass. This process is distinct for gauge bosons and fermions.

A. Mass for Gauge Bosons (The BEH Mechanism)

In a gauge theory, when the vacuum breaks a local symmetry, the massless Goldstone bosons predicted by Goldstone's Theorem are not physical particles. Instead, they are "absorbed" by the initially massless gauge bosons. This is the Brout-Englert-Higgs (BEH) mechanism for mass acquisition.

1. **The Absorption of Goldstone Bosons**
   - A massless vector boson (like the photon) has only two polarization states (helicity ±1).
   - A massive vector boson (like the W or Z) requires a third, longitudinal polarization state (helicity 0).

- The three Goldstone bosons (G^+, G^-, G^0) that arise from the breaking of the three components of the $SU(2)_L \times U(1)_Y$ symmetry are exactly the three degrees of freedom needed to make three of the four electroweak gauge bosons massive.

The Absorption Process can be summarized as Follows

Initial Massless Bosons	Absorbed Goldstone Bosons	Final Massive Bosons
W^1, W^2, W^3 (from $SU(2)_L$)	$G^\pm$ and a linear combination of G^0 and the B field	$W^\pm$ and Z^0
B (from $U(1)_Y$)		γ(Photon) and Z^0

2. Mass Calculation

The mixing of the W^3 and B fields gives rise to the physical Z^0 and the massless photon (γ). The resulting masses for the weak bosons are directly proportional to the Higgs VEV (v) and the relevant coupling constants (g and g'):

- **Charged Weak Bosons ($W^\pm$)**

$$M_W = \frac{1}{2} gv$$

- **Neutral Weak Boson (Z^0)**

$$M_Z = \frac{1}{2}\sqrt{g^2 + g'^2}v$$

- **Photon (y)**

$$M_\gamma = 0$$

Because the VEV v is a constant, and g and g' are large, the W and Z bosons acquire the large masses necessary to explain the short range of the weak nuclear force.

B. Mass for Fermions (Yukawa Coupling)

The mechanism for generating mass for the fundamental matter particles (quarks and leptons) is different from the gauge bosons, though still dependent on the Higgs field's VEV. Fermions acquire mass through the Yukawa Coupling.

1. The Interaction Term

Fermions are given mass through a gauge-invariant interaction term added to the Standard Model Lagrangian: the Yukawa term (L_{Yukawa}) [Quigg, 2009].

$$\mathcal{L}_{\text{Yukawa}} = -\lambda_f \overline{\psi}_L \phi \psi_R + \text{h.c.}$$

- ψ_L and ψ_R are the left-and right-handed components of the fermion field ψ_f.
- ϕ is the Higgs field.
- λ_f is the Yukawa coupling constant for that specific fermion f.

2. Mass Generation

When the Higgs field spontaneously acquires its VEV, the Higgs field ϕ in the interaction term is replaced by its constant vacuum value, $\langle\phi\rangle_0 \approx v/\sqrt{2}$. The Yukawa interaction term then simplifies to an effective mass term for the fermion:

$$\mathcal{L}_{\text{mass}} \approx -\left(\frac{\lambda_f v}{\sqrt{2}}\right)\overline{\psi}_L\psi_R + \text{h.c.} = -m_f\overline{\psi}_f\psi_f$$

The mass of the fermion, m_f, is thus defined by:

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

This result is critically important: the mass of any given fermion is not a fundamental property, but rather a direct measure of its interaction strength (λ_f) with the universal Higgs field.

3. Implications

- **Hierarchy of Masses:** The wide range of observed fermion masses (from the near-massless neutrino to the extremely heavy top quark) is explained by the vast range of Yukawa coupling constants λ_f. A small λ_f results in a low mass (e.g., the electron), while a large λ_f results in a high mass (e.g., the top quark).
- **The Higgs Boson (h):** The remaining degree of freedom in the Higgs field, h(x), is the physical, massive scalar particle that was discovered in 2012. Its mass, M_h, is also determined by the parameters of the Higgs potential ($M_h^2 = 2\lambda v^2$).

Conclusion

The central objective of this research paper was to demonstrate that Spontaneous Symmetry Breaking (SSB) is the indispensable theoretical mechanism required to construct a consistent and experimentally validated Standard Model (SM) of Particle Physics. The dilemma posed by the SM's fundamental requirement for massless particles, derived from its governing local gauge symmetries, stands in direct contradiction to the observed massive nature of the weak force carriers and fundamental fermions.

Summary of Findings

The resolution lies entirely in the Higgs mechanism, which implements SSB via a complex scalar field.

- **Symmetry Breaking:** By acquiring a non-zero Vacuum Expectation Value (VEV), $v \approx$ 246 GeV, the Higgs field spontaneously breaks the electroweak symmetry $SU(2)_L \times U(1)_Y$ down to the electromagnetic symmetry $U(1)_{em}$.
- **Mass for Gauge Bosons:** The Brout-Englert-Higgs (BEH) mechanism showed that the three Goldstone bosons arising from the broken symmetries are "absorbed" by the $W^\pm$ and Z^0 gauge bosons.

This absorption provides the necessary third, longitudinal polarization component, thereby generating their masses M_W and M_Z, which are directly proportional to the VEV v. The photon, associated with the unbroken $U(1)_{em}$ symmetry, remains massless.

- **Mass for Fermions:** Fermions acquire mass through the Yukawa coupling, an interaction term between the fermion field and the Higgs field. The resulting fermion mass m_f is determined by the arbitrary coupling constant λ_f and the Higgs VEV, $m_f = \lambda_f v/\sqrt{2}$ This explains the vast hierarchy in observed particle masses.

Wider Implications and Future Outlook

The most profound validation of this SSB paradigm came with the 2012 discovery of the physical Higgs boson at the Large Hadron Collider (LHC) [ATLAS Collaboration, 2012; CMS Collaboration, 2012]. The discovery confirmed the existence of the field responsible for mass generation and completed the particle content of the Standard Model.

Despite its monumental success, the SM and the SSB mechanism, while internally consistent, remain incomplete:

1. **Gravity:** The SM does not incorporate gravity.
2. **Dark Matter/Dark Energy:** It offers no explanation for the vast majority of the universe's energy and mass content.
3. **Hierarchy Problem:** The theory struggles to naturally explain why the Higgs boson's mass is so much lower than the Planck scale.

Many extensions to the Standard Model (e.g., Supersymmetry, Grand Unified Theories) utilize more complex gauge groups and, consequently, require further, more intricate symmetry breaking schemes at higher energy scales. Therefore, the principles of symmetry and spontaneous symmetry breaking will remain the guiding light for physicists seeking to explore and understand physics Beyond the Standard Model.

References

1. Aitchison IJR, Hey AJG. Gauge Theories in Particle Physics: A Practical Introduction. CRC Press, 2012, 2.
2. ATLAS Collaboration. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. Physics Letters B. 2012; 716(1):1–29.
3. Brout R, Englert F. Broken Symmetry and the Mass of Gauge Vector Mesons. Physical Review Letters. 1964; 13(9):321-323.
4. CMS Collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. Physics Letters B. 2012; 716(1):30-61.
5. Goldstone J. Field Theories with Superconductor Solutions. Nuovo Cimento. 1961; 19(1):154-164.
6. Griffiths DJ. Introduction to Elementary Particles (2nd ed.). Wiley-VCH, 2008.
7. Guralnik GS, Hagen CR, Kibble TWB. Global Conservation Laws and Massless Particles. Physical Review Letters. 1964; 13(20):585-587.
8. Higgs PW. Broken Symmetries and the Masses of Gauge Bosons. Physical Review Letters. 1964; 13(16):508-509.
9. Noether E. Invariante Variationsprobleme. Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse, (Original German publication of Noether's Theorem), 1918, 235-257.
10. Peskin ME, Schroeder DV. An Introduction to Quantum Field Theory. Westview Press, 1995.
11. Quigg C. Gauge Theories of the Strong, Weak, and Electromagnetic Interactions. Princeton University Press, 2009.
12. Weinberg S. The Quantum Theory of Fields, 1: Foundations. Cambridge University Press, 1995, 10.