SCALAR INTERACTIONS IN THE MODIFIED LEFT-RIGHT SYMMETRY MODEL

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ABSTRACT

The Standard Model is a model of particle physics in which one Higgs particle has been confirmed with a mass of 126 GeV. In 2016 some discoveries made it possible to have other scalar particles similar to the Higgs. The modified left-right symmetric model extends the standard model with an expanded scalar sector. There are ϕ_L and Δ_L left sector scalar particles, ϕ_L and Δ_L right sector scalar particles and two singlet η and ξ scalar particles. Therefore, this research objective is to analyze of the possibility of a Higgs interaction with other scalar particles. The method of this research is using a Feynman diagram to describe the interaction terms at the Higgs Potential. The interaction probability is sought using the Feynman rule for Toy Theory. The decay rate uses the Golden Rule. When the universe's temperature reaches the mass of η, the scalar becomes non-relativistic and decays into ϕ_L and ϕ_R. The scalar ξ is scattered into ϕ_L through the η scalar propagator and into ϕ_R. The scalars Δ_L and Δ_R do not decay, they only scatter into ϕ_L and ϕ_R. The η and ξ scalars have transformed into ϕ_L in the left sector and ϕ_R in the right sector, and only ϕ_L in the sectors are likely to be detected as the Higgs Standard Model.

Keywords: Standard Model; Scalar Extension; Higgs Scalar; Modified Left-Right Symmetry

Introduction

The Standard Model of particle physics is still the most robust way to explain nearly all laboratory measurements of underlying particles that make up the ultimate building blocks of the universe.[1] This model consists of nine fermions, four gauge bosons, and one Higgs boson particle. The Higgs particle was originally hypothetical,[2] This was later proven ten years ago, in 2012, when CERN announced the discovery of a Higgs particle through this data. From this data, the statistical interpretation of the excess events is Higgs mass is equal to 126 GeV.[3,4] Higgs particles are responsible for giving particle masses by interacting with them.[5]

A fundamental concept field causes interaction between particles with no physical stuff. Every one of The Standard Model particles has an associated field. So, a field for Higgs is called a Higgs field or Scalar field.[6] The stronger a particle interacts with the Higgs field, the heavier the particle ends up being.

There was a problem in 2016. There was a big moment of excitement; there may be another Higgs, a scalar, or a pseudoscalar whose mass was about 750 GeV.[7,8,9] This new paradigm about extra Higgs may explain some mysteries that the standard model does not. The standard model unresolved problems are the hierarchy problem, the cosmological constant problem, what particles could be candidates for cold dark matter in the universe and the anomalous of the muon magnetic moments.[10] Therefore, we need extensions of the standard model to explain this problem. There are several extension models from the Standard Model with extensions in the Higgs sector such as Left-Right Symmetry,[11,12] Minimal Extension of the Standard Model,[13] CP-Mirror Extension of Standard Model,[14] and Modified Left-Right Symmetry.[15]

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Table 1. Scalar Interaction

Term	Interaction
$\lambda_1\|\phi_L\|^4$	$(a.1)\ \phi_L + \phi_L^\dagger \to \phi_L + \phi_L^\dagger$
$\lambda_2\|\eta\|^4$	$(a.2)\ \eta + \eta^\dagger \to \eta + \eta^\dagger$
$\lambda_3\|\xi\|^4$	$(a.3)\ \xi + \xi^\dagger \to \xi + \xi^\dagger$
$\lambda_4\|\Delta_L\|^4$	$(a.4)\ \Delta_L + \Delta_L^\dagger \to \Delta_L + \Delta_L^\dagger$
$\lambda_5\|\phi_R\|^4$	$(a.5)\ \phi_R + \phi_R^\dagger \to \phi_R + \phi_R^\dagger$
$\lambda_6\|\Delta_R\|^4$	$(a.6)\ \Delta_R + \Delta_R^\dagger \to \Delta_R + \Delta_R^\dagger$
$\epsilon_1(\|\phi_L\|^2 + \|\phi_R\|^2)$	$(a.7)\ \phi_L + \phi_L^\dagger \to \Delta_L + \Delta_L^\dagger$
$(\|\Delta_L\|^2 + \|\Delta_R\|^2)$	$(a.8)\ \phi_L + \phi_L^\dagger \to \Delta_R + \Delta_R^\dagger$
	$(a.9)\ \phi_R + \phi_R^\dagger \to \Delta_L + \Delta_L^\dagger$
	$(a.10)\phi_R + \phi_R^\dagger \to \Delta_R + \Delta_R^\dagger$
$\epsilon_2\|\eta\|^2(\|\phi_L\|^2 + \|\phi_R\|^2)$	$(a.11)\eta + \eta^\dagger \to \phi_L + \phi_L^\dagger$
	$(a.12)\eta + \eta^\dagger \to \phi_R + \phi_R^\dagger$
$\epsilon_3\|\eta\|^2(\|\Delta_L\|^2 + \|\Delta_R\|^2)$	$(a.13)\eta + \eta^\dagger \to \Delta_L + \Delta_L^\dagger$
	$(a.14)\eta + \eta^\dagger \to \Delta_R + \Delta_R^\dagger$
$\epsilon_4\|\xi\|^2(\|\phi_L\|^2 + \|\phi_R\|^2)$	$(a.15)\xi + \xi^\dagger \to \phi_L + \phi_L^\dagger$
	$(a.16)\xi + \xi^\dagger \to \phi_R + \phi_R^\dagger$
$\epsilon_5\|\xi\|^2(\|\Delta_L\|^2 + \|\Delta_R\|^2)$	$(a.17)\xi + \xi^\dagger \to \Delta_L + \Delta_L^\dagger$
	$(a.18)\xi + \xi^\dagger \to \Delta_R + \Delta_R^\dagger$
$\epsilon_6\|\phi_L\|^2\|\phi_R\|^2$	$(a.19)\phi_L + \phi_L^\dagger \to \phi_R + \phi_R^\dagger$
$\epsilon_7\|\eta\|^2\|\xi\|^2$	$(a.20)\eta + \eta^\dagger \to \xi + \xi^\dagger$
$\epsilon_8\|\Delta_L\|^2\|\Delta_R\|^2$	$(a.21)\Delta_L + \Delta_L^\dagger \to \Delta_R + \Delta_R^\dagger$
$\epsilon_9\eta^\dagger\xi\xi^\dagger\eta$	$(a.22)\eta^\dagger + \xi \to \xi^\dagger + \eta$

This study aims to analyze all possible interactions between scalar particles in the Modified Left-Right Symmetry Model. Original Higgs particle may interact with other new scalar particles in this Model. Scalars interaction in this Model is described by the scalar Potential, which is invariant under the gauge group.[15] All possible interactions happen, such as decay and scattering.

Methods

This research is theoretical. Scalar interactions that may occur can be identified by analyzing the Higgs Potential. The interaction terms at the Higgs Potential are depicted using a Feynman diagram. After that, the interaction probability is sought using the Feynman rule for Toy Theory. Meanwhile, the decay rate uses the Golden Rule shown by Equation (1)

$$\Gamma = \frac{S}{2\hbar}\int |\mathcal{M}|^2(2\pi)^4\delta^4(p_1 - p_2 - \cdots - p_n) \times \prod_{j=2}^{n} 2\pi\delta\left(p_j^2 - m_j^2c^2\right)\theta\left(p_j^0\right)\frac{d^4p_j}{(2\pi)^4} \quad (1)$$

The symbol m_j is the mass of the first particle, p_j is the momentum of the fourth particle, and S is a statistical factor that corrects double counting when there are identical particles.

The Model

The Modified Left-Right Symmetry Model is invariant under the gauge group $SU(3) \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_Y$. This model is an extension of the Standard Model with an additional scalar. The scalar $\phi_L \sim (\mathbf{1},\mathbf{2},\mathbf{1},-1)$ is originally Higgs in the Standard Model and its dual scalar in the right sector was $\phi_R \sim (\mathbf{1},\mathbf{1},\mathbf{2},-1)$. Additional scalars ini this Model are two scalar singlet $\eta \sim(\mathbf{1},\mathbf{1},\mathbf{1},0)$ and $\xi \sim(\mathbf{1},\mathbf{1},\mathbf{1},-2)$; and scalar doublet $\Delta_L \sim \left(\mathbf{1},\mathbf{2},\mathbf{1},\frac{1}{3}\right)$ with its dual $\Delta_R \sim \left(\mathbf{1},\mathbf{1},\mathbf{2},\frac{1}{3}\right)$.[15] By some spontaneous symmetry breaking down to Standard Model at low energy. This symmetry-breaking schema as shown in Figure 1.

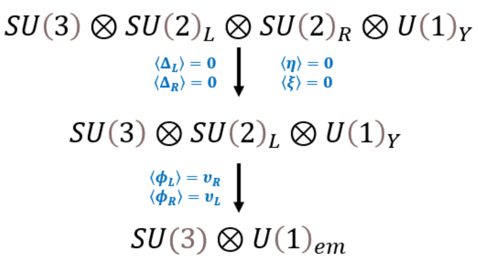

Figure 1. Symmetry Breaking Schema

The symmetry breaking pattern $SU(3) \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_Y$ down to $SU(3) \otimes SU(2)_L \otimes U(1)_Y$ happens when the scalar singlet, namely η and ξ, and doublet scalar Δ_L and Δ_R gain nonzero Vacuum Expectation Value (VEV). After that, the symmetry breaks down to $SU(3) \otimes U(1)_{em}$ when the scalars ϕ_L and ϕ_R gain the VEV. The electroweak symmetry is broken at scale $\langle \phi_L^0 \rangle = v_L$ and The gauge group $SU(2)_R$ is broken at scale $\langle \phi_R^0 \rangle = v_R$ where in general $v_L < v_R$.[15,16] The order of values is v_L around 10^2 GeV, while the order v_R of the lowest values is around 10 TeV.[17]

Scalar Interactions

In a high energy, or instead in the post-inflation re-heating period, the universe is dominated by radiation.[18] One of the contributions of radiation energy is scalar field kinetic energy.[19] The kinetic energy of the scalar field comes from scalar interactions. Table 1 is the list of possible interactions.

The scalars have not taken its VEV, so it has not been mass and is still relativistic. The interactions shown in table 1 are interactions in the form of scattering of crossing processes which do not affect the temperature asymmetry of the two sectors.

The next stage is spontaneous symmetry breaking when the universe's temperature is around 10^4 GeV.[20] The scalars $\Delta_L.\Delta_R,\eta$, and ξ take their VEV so the Higgs potential shown by Equation (2)

$$
\begin{aligned}
V = & -\mu_1^2|\phi_L|^2 - \mu_2^2 h_\eta^2 - \mu_3 h_\xi^2 - \frac{1}{2}\mu_4^2 h_{\Delta_L}^2 \\
& -\mu_5^2|\phi_R|^2 - \frac{1}{2}\mu_6^2 h_{\Delta_R}^2 + \lambda_1|\phi_L|^4 \\
& +\lambda_2 h_\eta^4 + \lambda_3 h_\xi^4 + \frac{1}{4}\lambda_4 h_{\Delta_L}^4 + \lambda_5|\phi_R|^4 \\
& +\frac{1}{4}\lambda_6 h_{\Delta_R}^4 + \frac{1}{2}\epsilon_1 h_{\Delta_L}^2(|\phi_L|^2 + |\phi_R|^2) \\
& +\frac{1}{2}\epsilon_1 h_{\Delta_R}^2(|\phi_L|^2 + |\phi_R|^2) \\
& +\epsilon_2 h_\eta^2(|\phi_L|^2 + |\phi_R|^2) \\
& +\frac{1}{2}\epsilon_3 h_\eta^2(h_{\Delta_L}^2 + h_{\Delta_R}^2) \\
& +\epsilon_4 h_\xi^2(|\phi_L|^2 + |\phi_R|^2) \\
& +\frac{1}{2}\epsilon_5 h_\xi^2(h_{\Delta_L}^2 + h_{\Delta_R}^2) \\
& +\epsilon_6|\phi_L|^2|\phi_R|^2 + \epsilon_7 h_\eta^2 h_\xi^2 \\
& +\frac{1}{4}\epsilon_8 h_{\Delta_L}^2 h_{\Delta_R}^2 + \epsilon_9 h_\eta^2 h_\xi^2 + \alpha_1|\phi_L|^2 h_\eta \\
& +\alpha_2 h_\xi^2 h_\eta + \frac{1}{2}\alpha_3 h_{\Delta_L}^2 h_\eta + \alpha_4|\phi_R|^2 h_\eta \\
& +\frac{1}{2}\alpha_5 h_{\Delta_R}^2 h_\eta + \alpha_6 h_\eta^3 + h.c. \qquad (2)
\end{aligned}
$$

The scalars $\Delta_L.\Delta_R,\eta$, and ξ acquire their masses as shown by Equation (3)

$$
\begin{aligned}
m_{\Delta_L} &= \frac{1}{2}\mu_4^2 \\
m_{\Delta_R} &= \frac{1}{2}\mu_6^2 \\
m_\xi &= \mu_3^2 \\
m_\eta &= \mu_2^2 \qquad (3)
\end{aligned}
$$

Based on Equation (1), Table 2 shows the possible η decay modes.

Table 2. The Decay Process of scalar η

No.	**Term**	**η Decay Modes**
$(a.23)$	$\alpha_1|\phi_L|^2 h_\eta$	$h_\eta \to \phi_L^\dagger + \phi_L$
$(a.24)$	$\alpha_4|\phi_R|^2 h_\eta$	$h_\eta \to \phi_R^\dagger + \phi_R$

The Feynman diagram illustrating the two modes of scalar η decay is shown in Figure 2

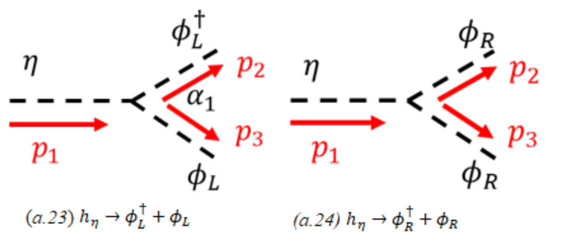

Figure 2. Feynman Diagram of η decay modes

The amplitude of the decay $\eta \to \phi_L^\dagger + \phi_L$ associated with a Feynman Diagram Figure 1 is shown by Equation (4)

$$
iM_{(a.23)} = \frac{-i\alpha_1}{2}(2\pi)^4\delta^4(p_1 - p_2 - p_3) \quad (4)
$$

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The delta function of $(2\pi)^4\delta^4(p_1 - p_2 - p_3)$ imposes energy-momentum conservation at the vertex. It is zero unless the coming momenta, p_1, equals the sum of outgoing momenta, $p_2 + p_3$. According to the Golden Rule for decay[21], Equation (5) shows the decay rate of $\eta \rightarrow \phi_L^\dagger + \phi_L$.

$$\Gamma_{(a.23)} = \frac{S|\mathbf{p_2}||M_{(a.23)}|^2}{8\,\pi\hbar m_\eta^2} = \frac{\alpha_1^2}{128\,\pi\hbar m_\eta} \qquad (5)$$

Statistical factor S is $1/2!$ because of the decay of η into two identical scalars. The magnitude of the momentum $|\mathbf{p_2}|$ obtained by using $|\mathbf{p_2}| = |\mathbf{p_3}|$, so that $|\mathbf{p_2}| = \frac{1}{2}m_\eta$. In the same way, the decay rate of $h_\eta \rightarrow \phi_R^\dagger + \phi_R$ can be obtained $\Gamma_{(a.24)}$ The total decay rate of the two modes possible scalar decays η is shown by Equation (6)

$$\Gamma_{\eta(a.23+a.24)} = \frac{\alpha_1^2 + \alpha_4^2}{128\,\pi\hbar m_\eta} \qquad (6)$$

The lifetime τ_η of the scalar η is the inverse of the decay rate Γ_η.

By combining the terms in equation (3) we can obtain eight scattering processes mediated by scalar η as shown in Figure 3.

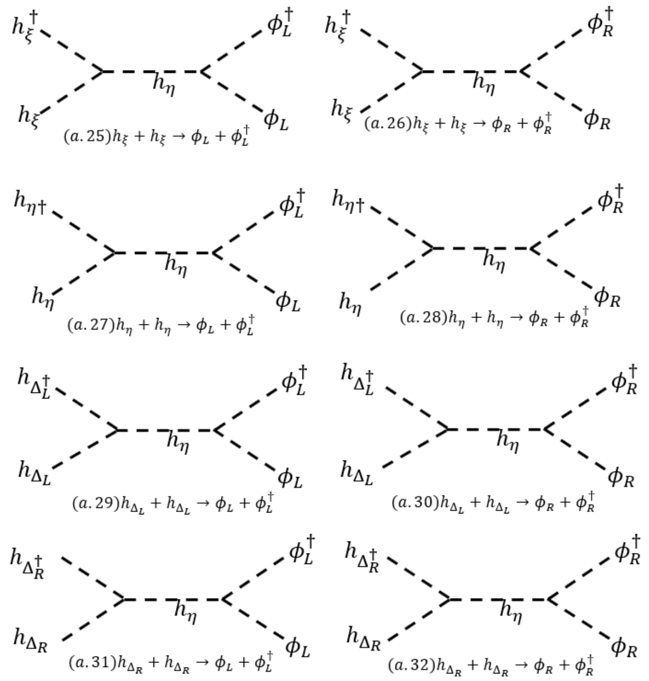

Figure 3. Feynman Diagram of Scalar Scattering Mediated by η

The scalars $\Delta_L.\Delta_R, \eta$, and ξ become nonrelativistic at the temperature of the left-sector a that less than or equal to the mass of the double scalar Δ_L, $T_L \leq m_{\Delta_L}$. Moreover, right-sector temperatures are less than or equal to the mass of the scalar $\Delta_R, T_R \leq m_{\Delta_R}$. All the processes in Figure 2 can take place only go in one direction. The magnitude of the scattering probability of the eight processes mediated via scalar η is shown by Equation (7-14)

$$M_{a.25} = \frac{\alpha_1\alpha_2}{2((p_1 + p_2)^2 - m_\eta^2)} \qquad (7)$$

$$M_{a.26} = \frac{\alpha_4\alpha_2}{2((p_1 + p_2)^2 - m_\eta^2)} \qquad (8)$$

$$M_{a.27} = \frac{\alpha_1\alpha_6}{2((p_1 + p_2)^2 - m_\eta^2)} \qquad (9)$$

$$M_{a..28} = \frac{\alpha_4\alpha_6}{2((p_1 + p_2)^2 - m_\eta^2)} \qquad (10)$$

$$M_{a.29} = \frac{\alpha_1\alpha_3}{2((p_1 + p_2)^2 - m_\eta^2)} \qquad (11)$$

$$M_{a.30} = \frac{\alpha_4\alpha_3}{2((p_1 + p_2)^2 - m_\eta^2)} \qquad (12)$$

$$M_{a.31} = \frac{\alpha_1\alpha_5}{2((p_1 + p_2)^2 - m_\eta^2)} \qquad (13)$$

$$M_{a.32} = \frac{\alpha_4 \alpha_5}{2((p_1+p_2)^2 - m_\eta^2)} \qquad (14)$$

After the universe's temperature decreases, the symmetry breaks down to $SU(3) \otimes U(1)_{em}$. The scalar ϕ_L takes the value of VEV $\upsilon_L = 264$ GeV[22]. At the same time, the scalar ϕ_R takes the value VEV with υ_R. After all scalars take VEV and have mass, the dynamics of scalar particles is described by the equation (15)

$$\begin{aligned} V &= \lambda_1 h_L^4 + \lambda_2 h_\eta^4 + \lambda_3 h_\xi^4 + \frac{1}{4}\lambda_4 h_{\Delta_L}^4 \\ &+ \lambda_5 h_R^4 + \frac{1}{4}\lambda_6 h_{\Delta_R}^4 + \frac{1}{2}\epsilon_1 h_{\Delta_L}^2 h_L^2 \\ &+ \frac{1}{2}\epsilon_1 h_{\Delta_L}^2 h_R^2 + \frac{1}{2}\epsilon_1 h_{\Delta_R}^2 h_L^2 + \frac{1}{2}\epsilon_1 h_{\Delta_R}^2 h_R^2 \\ &+ \epsilon_2 h_\eta^2 h_L^2 + \epsilon_2 h_{\Delta_L}^2 h_R^2 + \frac{1}{2}\epsilon_3 h_\eta^2 (h_{\Delta_L}^2 + h_{\Delta_R}^2) \\ &+ \frac{1}{2}\epsilon_4 h_\xi^2 (h_L^2 + h_R^2) + \frac{1}{2}\epsilon_5 h_\xi^2 (h_{\Delta_L}^2 + h_{\Delta_R}^2) \\ &+ \frac{1}{4}\epsilon_6 h_L^2 h_R^2 + \epsilon_7 h_\eta^2 h_\xi^2 + \frac{1}{4}\epsilon_8 h_{\Delta_L}^2 h_{\Delta_R}^2 \\ &+ \epsilon_9 h_\eta^2 h_\xi^2 + \alpha_1 h_L^2\, h_\eta + \alpha_2 h_\xi^2\, h_\eta \\ &+ \frac{1}{2}\alpha_3 h_{\Delta_L}^2\, h_\eta + \frac{1}{2}\alpha_4 h_R^2\, h_\eta \\ &+ \frac{1}{2}\alpha_5 h_{\Delta_R}^2\, h_\eta + \alpha_6 h_\eta^3 + h.c. \end{aligned} \qquad (15)$$

Possible interactions after all scalars take VEV are similar to those in Tables 1 and 2, but with the difference that all scalar particles have mass.

The interaction of scalar particles in the Modified Left-Right Symmetry Model can be identified by reviewing the Higgs potential equation. The interactions that occur after the universe has experienced a period of post-reheating inflation are dominated by radiation due to one of them being scalar scattering. Scattering processes involving scalars η and ξ cause interactions between sectors and cause the temperature between sectors to remain the same, such as scattering modes $(a.2), (a.3), (a.20)$, and $(a.22)$.

As the universe's energy decreases and spontaneous breaking occurs the first stage and the scalar fields $\Delta_L . \Delta_R, \eta$, and ξ obtain zero VEV. It is assumed that the constant is $\mu_6 \approx \mu_4$ so the mass m_{Δ_R} is in the same order as m_{Δ_L}. If $\mu_3 > \mu_2$, the mass scalars ratio is $m_\xi > m_\eta$. The scalar η has the most massive mass, so it tends to decay into other scalars. When the universe's temperature equals the mass η, this scalar becomes non-relativistic. It begins to decay into ϕ_L and ϕ_R. If the coupling constant $\alpha_1 > \alpha_4$ is assumed, then the scalar η decay rate into double ϕ_L is greater than the process of decay of the scalar η into double ϕ_R, so $\Gamma_{(a.23)} > \Gamma_{(a.24)}$. The lifetime τ_η of the scalar η is inversely proportional to its mass. The possibility of scalar Higgs decay to scalar Higgs also exists in the two scalar real-singlet extension models from the Standard Model.[23]

Based on equation (2), The scalar ξ is scattered into ϕ_L via mode (a.25) with the propagator η scalar, their form of terms $\alpha_1 |\phi_L|^2\, h_\eta + \alpha_2 h_\xi^2\, h_\eta$. The scalar ξ is scattered into ϕ_R via mode (a.26) with the propagator η scalar their form of terms $\alpha_4 |\phi_R|^2\, h_\eta + \alpha_2 h_\xi^2\, h_\eta$. Probabilities magnitude of these two scattering modes is affected by the difference of coupling constant α_1 and α_4 which makes $M_{a.25} > M_{a.26}$. This causes the abundance of the scalar ϕ_L to be greater than the scalar ϕ_R.

The scalars Δ_L and Δ_R do not decay, only scatter. The process of scattering the scalar Δ_L into a scalar ϕ_L only occurs in the left sector. Scattering the scalar Δ_R into a scalar ϕ_R only occurs in the right sector. Compared to the amplitude, the probability of scattering ϕ_L in the left sector is greater than that of scattering ϕ_R in the right sector. Scalar Δ_L and Δ_R, which do not decay, could be dark matter candidates. Scalars, which can be candidate for dark matter, were also investigated by reviewing the massive scalar field, which could not reach equilibrium between its classical and quantum dynamics during inflation.[24]

At cosmic energy is on the order of 10^4 GeV, the scalar η and ξ have changed to ϕ_L in the left and to ϕ_R in the right sectors. The detected scalars are probably only ϕ_L in the left sector and to ϕ_R in the right sector. Roughly speaking, based on the experiment in LHC,[3] only one Higgs particle has been detected. the detected Higgs is a Higgs scalar with a mass of 126 GeV is a ϕ_L in this Model.

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But the scalar ϕ_R not been detected. Meanwhile, the LHC Run 2 project managed to find signs of Higgs particles that have a larger mass than ϕ_L, which may be scalars $\phi_R, \eta, \xi, \Delta_L$ or Δ_R.

Conclusion

On the Modified Left-Right Symmetry Model, interactions are primarily dominated by radiation from scalar scattering after the post-reheating inflation period. As the universe's energy decreases and spontaneous symmetry breaks, the scalar fields Δ_L, Δ_R, η, and ξ attain a zero value. When the universe's temperature reaches the mass of η, the scalar becomes non-relativistic and decays into ϕ_L and ϕ_R. The scalar ξ is scattered into ϕ_L through the η scalar propagator and into ϕ_R. The scalars Δ_L and Δ_R do not decay, they only scatter into ϕ_L and ϕ_R. The η and ξ scalars have transformed into ϕ_L in the left sector and ϕ_R in the right sector, and only ϕ_L in the sectors are likely to be detected as the Higgs Standard Model.

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