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The Quest for Physics Beyond the Standard Mode

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While the Standard Model of particle physics has been immensely successful in describing the fundamental particles and their interactions. However, several experimental and theoretical observations indicate the potential existence of physics beyond its scope. This article explores two prominent extensions: TeV scale U(1)B-L extension of the standard model and minimal supersymmetric standard model.

I. Standard Model Overview

The Standard Model (SM) stands as the leading theoretical framework in particle physics, providing an advanced understanding of elementary particles and their fundamental interactions (Khalil & Moretti, 2022). It has signi_cantly improved our understanding of observable particle behavior and o_ered comprehensive explanations for the three fundamental forces governing the universe. The SM is based on the gauge symmetry SU(3)C _SU(2)L _ U(1)Y and demonstrates exceptional consistency with experimental results. The symmetry structure forms the foundation for the fundamental forces of the universe. Speci_cally, SU(3)C represents the gauge symmetry governing quantum chromodynamics (QCD), which explains strong interactions. Meanwhile, SU(2)L _ U(1)Y corresponds to the symmetry associated with electroweak interactions.

The matter content of the SM consists of 6 leptons and 6 quarks, arranged in pairs that experience transformations under SU(2)L. This structure includes 3 generations of left-handed SU(2)L doublet pairs of quarks and leptons (fermions). Conversely, the right-handed fermions, fR, exist as SU(2)L singlets. The SM Lagrangian is given by

$$\begin{aligned}\mathcal{L}_{\rm SM} &= -\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a - \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \bar{L}_i\, iD_\mu\gamma^\mu\, L_i + \bar{e}_{Ri}\, iD_\mu\gamma^\mu\, e_{R_i} + \bar{Q}_i\, iD_\mu\gamma^\mu\, Q_i \\ &+ \bar{u}_{Ri}\, iD_\mu\gamma^\mu\, u_{R_i} + \bar{d}_{Ri}\, iD_\mu\gamma^\mu\, d_{R_i},\end{aligned} \tag{1}$$

where the components are defined as:

$$Q^i_L(3,2,1/6) = \begin{pmatrix} u^i \\ d^i \end{pmatrix}_L,\ u^i_R(3.1.2/3),\ d^i_R(3,1,-1/3),\ L^i_L(1,2,-1/2) = \begin{pmatrix} \nu^i \\ e^i \end{pmatrix}_L,\ e^i_R(1,1,-1). \tag{2}$$

The covariant derivatives D_μ are defined as follows:

$$D_\mu Q_i = \left(\partial_\mu - ig_s T_a G^a_\mu - ig_2 T_a W^a_\mu - ig_1 \frac{Y_{Q_i}}{2} B_\mu\right) Q_i, \tag{3}$$

$$D_\mu L_i = \left(\partial_\mu - ig_2 T_a W^a_\mu - ig_1 \frac{Y_{L_i}}{2} B_\mu\right) L_i, \quad D_\mu f_R = \left(\partial_\mu - ig_1 \frac{Y_{f_R}}{2} B_\mu\right) f_R. \tag{4}$$

Here, the electric charge is given by: $Q = I_{3_L} + \frac{Y}{2}$. Introducing the Higgs field $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$, with $Y_\Phi = 1$ and the following Lagrangian, invariant under the electroweak gauge symmetry:

$$\mathcal{L}_{scalar} = (D_\mu\Phi)^\dagger(D^\mu\Phi) - V(\Phi), \tag{5}$$

where the potential is formulated as:

$$V(\Phi) \equiv -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2,\ \mu^2\ ,\lambda > 0. \tag{6}$$

In the context of the SM, the absence of a right-handed component for the neutrino predicts its masslessness. We can conclude this section, by de_ning the SM as a 4-dimension QFT invariant under the Poincar group, is characterized by its local symmetry under SU(3)C _SU(2)L _U(1)Y . Its point particle makeup comprises generations of fermions (quarks and leptons) and lacks right-handed neutrinos, predicting neutrinos with zero mass. Within the SM, symmetry breaking occurs via a single Higgs doublet, and it does not o_er a candidate particle for Dark Matter. Notably, gravity is not encompassed within the SM's framework.

II. EVIDENCE FOR PHYSICS BEYOND THE SM

While the SM has been highly successful in describing a wide range of phenomena, there are several pieces of evidence that suggest the existence of physics beyond the SM. Here are some of the key indications:

1. Neutrino Masses

As advocated above, in the SM, the masses of quarks and charged leptons (including electrons) arise through Yukawa couplings with the Higgs _eld. However, neutrinos in the SM are massless because there are no right-handed neutrino _elds included in the theory. The discovery of neutrino oscillations, where neutrinos change from one avor to another as they propagate, provides strong evidence that neutrinos have non-zero masses and undergo mixing. The solar and atmospheric neutrino oscillation experiments have provided measurements for the neutrino mass-squared di_erences and also for the neutrino mixing angles. At the 3_ level, the allowed ranges are (Esteban et al., 2020).

$$
\begin{aligned}
\Delta m^2_{12} &= (7.42^{+0.21}_{0.20}) \times 10^{-5}\mathrm{eV}^2, \\
\Delta m^2_{13} &= (2.517^{+0.026}_{0.028}) \times 10^{-3}\mathrm{eV}^2, \\
|\Delta m^2_{32}| &= (2.48^{+}0.028_{-0.028}) \times 10^{-3}\mathrm{eV}^2,
\end{aligned}
$$

This phenomenon cannot be explained within the framework of the SM. To accommodate neutrino masses and mixing, various extensions to the SM have been proposed. One common approach is to introduce right-handed neutrino _elds and extend the SM with a mechanism called the seesaw mechanism. This mechanism introduces additional terms in the Lagrangian that allow for the generation of neutrino masses at the expense of introducing very heavy right-handed neutrinos. These extensions to the SM, known as neutrino mass models, can explain the observed neutrino oscillations and provide a framework to understand the origin and nature of neutrino masses. They also o_er avenues to explore physics beyond the SM and uncover new phenomena related to neutrinos. Experimental e_orts, such as neutrino oscillation experiments and neutrinoless double-beta decay experiments, are actively studying neutrinos to measure their masses, investigate their properties, and probe the mechanisms responsible for their masses and mixing.

2. Dark Matter

Most astronomers, cosmologists and particle physicists are convinced that 90% of the mass of the Universe is due to some non-luminous matter, called `Dark Matter/Energy' (Aghanim et al., 2020), as explained in Fig. 1 The presence of dark matter is strongly supported by observational evidence from various cosmological and astrophysical observations.

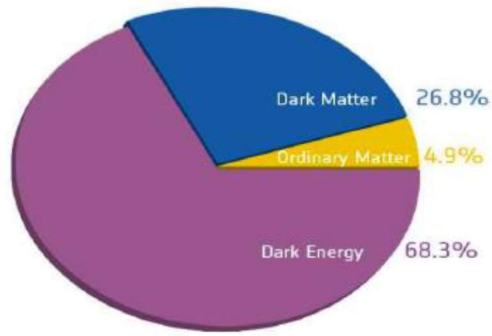

FIG. 1: Planck Observational Results: Composition of the Universe.

The discrepancy between the observed rotational velocities of galaxies and the expected velocities based on visible matter alone, as described by the following rotation curve equation, is one of the key pieces of evidence.

$$v(r) = \sqrt{\frac{G\,M(r)}{r}}$$

The observation that rotation velocities in spiral galaxies remain approximately constant at large distances from the galactic center implies the existence of additional mass beyond what is accounted for by visible matter. This discrepancy, shown in Fig. 2, can be explained by the presence of dark matter halos surrounding galaxies, which provide the necessary gravitational pull to maintain the observed velocities.

Dark matter is believed to be non-baryonic, meaning it does not consist of the same particles as ordinary matter described by the SM of particle physics. The SM can not account for the observed properties of dark matter. This has motivated the search for new particles and physics beyond the SM that could explain the nature of dark matter.

3. Higgs Vacuum Stability

In the SM, the quadratic coupling, speci_cally referring to the Higgs self-coupling parameter in the Higgs potential where MH = $\sqrt{\lambda}v$, can undergo evolution as energy scales change. This evolution is governed by quantum e_ects described through the theory of quantum _eld theory. One of the signi_cant features of the SM is the running of coupling constants with energy scale, as described by the renormalization group equations. These equations predict how the strength of interactions, including the Higgs self-coupling, changes as the energy scale at which particles interact changes. Under certain conditions and at extremely high energy scales, the renormalization group equations predict that the Higgs self-coupling could evolve towards zero or even become negative (Elias-Miro et al., 2012), as shown in Fig. 3. This phenomenon is related to the quantum corrections involving the interactions of the Higgs boson with other particles in the theory.

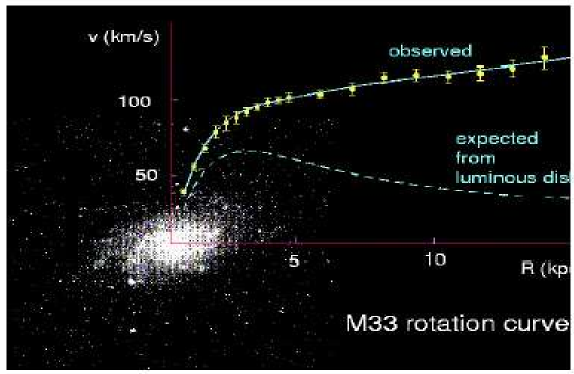

FIG. 2: Rotation curve of spiral galaxy Messier 33

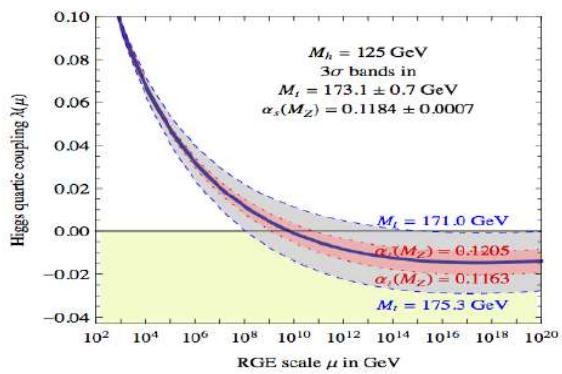

FIG. 3: The renormalization group evolutions of the SM Higgs quartic coupling, from [4].

However, it's important to note that this behavior is theoretical and subject to assumptions made within the SM framework. If the Higgs self-coupling were to turn negative at very high energies, it could imply potential instability of the Higgs _eld, indicating limitations or potential breakdown of the SM at such extreme scales. This behavior is a key motivation for exploring physics beyond the SM, as it suggests the possibility of new physics or extensions that could resolve the issues arising from the evolution of coupling constants and ensure the stability of the Higgs _eld at all energy scales.

4. Higgs Mass Hierarchy

The Higgs Mass Hierarchy refers to the observed mass of the Higgs boson and its apparent sensitivity to quantum corrections. In the SM, the Higgs mass receives quantum corrections from interactions with other particles, depicted in Fig.4. These corrections tend to push the Higgs mass to higher energy scales, potentially causing the mass to become excessively large unless there's a _ne-tuning mechanism. The measured mass of the Higgs boson, around 125 GeV, appears to sit at a precarious balance between these quantum corrections and the actual mass value. The fact that the Higgs mass seems to be relatively light compared to what quantum corrections might suggest raises the question of whether there's a natural mechanism that _nely tunes or stabilizes the Higgs mass within an acceptable range.

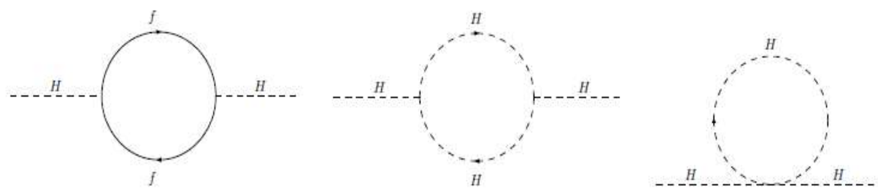

FIG. 4: One-loop radiative corrections to Higgs mass in the SM.

This hierarchy problem is seen as a motivation to explore physics beyond the SM. It suggests that there might be new symmetries, particles, or mechanisms at play that provide a natural explanation for the observed Higgs mass and its stability against quantum corrections.

5. Baryon Asymmetry (Matter- Antimatter Asymmetry)

Why is our universe made of matter and not antimatter? Neither the standard model of particle physics, nor the theory of general relativity provides an obvious explanation. In 1967, A. Sakharov showed that the generation of the net baryon number in the universe requires: Baryon number violation, Thermal non-equilibrium, and C and CP violation. All of these ingredients were present in the early Universe. However, the SM does not have su_cient CP violation to accommodate for Baryon asymmetry in our universe, which is estimated as Moretti & Khalil, (2019).

$$\frac{(n_B - n_B)}{n_\gamma} = 6.1 \times 10^{-10}. \tag{12}$$

In addition, there are a number of questions we hope will be answered: Electroweak symmetry breaking, which is not explained within the SM. Why is the symmetry group is SU(3) _ SU(2) _ U(1)? Can forces be uni_ed? Why are there three families of quarks and leptons? Why do the quarks and leptons have the masses they do? Can we have a quantum theory of gravity? Why is the cosmological constant much smaller than simple estimates would suggest?

Physics beyond the Standard Model (SM) encompasses various theoretical frameworks and directions that aim to address the limitations and open questions of the SM. Here are some prominent directions that physicists are actively exploring: Extension of gauge symmetry, Extension of Higgs Sector, Extension of Matter Content, Extension with Flavor Symmetry, Extension of Space-time dimenstions (Extra-dimensions), Extension of Lorentz Symmetry (Supersymmetry), Incorporate Gravity (Supergravity), and One dimension object (Superstring)We will focus on two possible example of extension of the SM, namely the U(1)B⊚L extension of the SM and Supersymmetry.

III. TEV SCALE B ⚜ L EXTENSION OF THE SM

The $B-L$ extension of the SM (BLSM) is based on the gauge group [5]

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

In this model, the following new particles are introduces: Three right-handed neutrinos, N_R^i, $i = 1,2,3$; with $B-L$ charge $= -1$. An extra gauge boson corresponding to $B-L$ gauge symmetry, Z'. An extra SM singlet scalar, χ with $B-L$ charge $= +2$, are introduced. The relevant part for the Lagrangian of the leptonic sector is given by

$$\begin{aligned}\mathcal{L}_{B-L} &= -\frac{1}{4}C_{\mu\nu}C^{\mu\nu} + i\,\bar{l}D_\mu\gamma^\mu l + i\,\bar{e}_R D_\mu\gamma^\mu e_R + i\,\bar{\nu}_R D_\mu\gamma^\mu\nu_R + (D^\mu\phi)^\dagger(D_\mu\phi)\\ &+ (D^\mu\chi)^\dagger(D_\mu\chi) - V(\phi,\chi) - \Big(\lambda_e\bar{l}\phi e_R + \lambda_\nu\bar{l}\tilde{\phi}\nu_R + \frac{1}{2}\lambda_{\nu_R}\bar{\nu_R^c}\chi\nu_R + \lambda_\nu\bar{\nu_R^c}\tilde{\phi}l^c + h.c.\Big),\end{aligned} \tag{13}$$

where $C_{\mu\nu} = \partial_\mu C_\nu - \partial_\nu C_\mu$ is the field strength of the $U(1)_{B-L}$. The covariant derivative D_μ is generalized by adding the term $ig''Y_{B-L}C_\mu$, where g'' is the $U(1)_{B-L}$ gauge coupling constant and Y_{B-L} is the $B-L$ quantum numbers of involved particles. The Y_{B-L} for leptons and Higgs are given by: $Y_{B-L}(l) = -1$, $Y_{B-L}(e_R) = -1$, $Y_{B-L}(\nu_R) = -1$, $Y_{B-L}(\phi) = 0$ and $Y_{B-L}(\chi) = 2$.

In order to analyze the $B-L$ and electroweak symmetry breaking, we consider the most general Higgs potential invariant under these symmetries, which is given by

$$V(\phi,\chi) = m_1^2\phi^\dagger\phi + m_2^2\chi^\dagger\chi + \lambda_1(\phi^\dagger\phi)^2 + \lambda_2(\chi^\dagger\chi)^2 + \lambda_3(\chi^\dagger\chi)(\phi^\dagger\phi), \tag{14}$$

where $\lambda_3 > -2\sqrt{\lambda_1\lambda_2}$ and $\lambda_1, \lambda_2 \geq 0$, so that the potential is bounded from below. This is the stability condition of the potential. Furthermore, in order to avoid vanishing vacuum expectation values (vevs): $v = \langle\phi\rangle = 0$ and $v' = \langle\chi\rangle = 0$ from being local minimum, one must assume that $\lambda_3^2 < 4\lambda_1\lambda_2$. As in the usual Higgs mechanism of electroweak symmetry breaking in the SM, the $B-L$ spontaneous symmetry breaking requires a negative squared masse, $m_2^2 < 0$. In this case, the following non-zero vev may be obtained [5]

$$v'^2 = \frac{-2(m_1^2 + \lambda_1 v^2)}{\lambda_3}, \quad \text{and} \quad v^2 = \frac{4\lambda_2 m_1^2 - 2\lambda_3 m_2^2}{\lambda_3^2 - 4\lambda_1\lambda_2}. \tag{15}$$

From these equations, two comments are in order: (i) For non-vanishing λ_3, the vevs v and v' are related and hence they are naturally of the same order, *i.e.*, $v \simeq \mathcal{O}(100)$ GeV and $v' \simeq \mathcal{O}(1)$ TeV. In fact, in this scenario $v' \gg v$ will require a significant fine-tuning among the input parameters: $m_{1,2}^2$ and $\lambda_{1,2,3}$. (ii) The condition of the electroweak symmetry breaking, for $\lambda_3^2 - 4\lambda_1\lambda_2 < 0$, is given by

$$m_1^2 < M_C^2 = \frac{\lambda_3 m_2^2}{2\lambda_2}. \tag{16}$$

For $m_2^2 < 0$ and $m_1^2 > M_C^2$, $U(1)_{B-L}$ is spontaneously broken while the $SU(2)_L \times U(1)_Y$ remains exact. At this stage, the following vevs are obtained [5]

$$v' = \sqrt{\frac{-m_2^2}{2\lambda_2}}, \quad \text{and} \quad v = 0.$$

The evolution from $\mathcal{O}(1)$ TeV scale down to $\mathcal{O}(100)$ GeV, may reduce the squared Higgs mass m_1^2 until eventually the minimization condition is satisfied and the electroweak gauge symmetry is broken. This scenario corresponds to two stages symmetry breaking at two different scales. Note that if $\lambda_3 < 0$, the radiative electroweak symmetry breaking can be achived with positive squared Higgs mass. Therefore, throughout this work, we will focus on the following region of mixing coupling λ_3: $0 > \lambda_3 > -2\sqrt{\lambda_1\lambda_2}$ and $\lambda_{1,2} \sim O(1)$.

As usual, we expand the scalar field χ around the $B-L$ minimum v' and write $\chi(x) = \frac{v'+H'(x)}{\sqrt{2}}$. In this case, one finds the following lagrangian for the $B-L$ Higgs (H') mass and its interaction with right handed neutrino and SM Higgs ϕ:

$$\mathcal{L}(\phi, H') = \frac{1}{2}m_{H'}^2 H'^2 - \frac{1}{2\sqrt{2}}\lambda_{\nu_R}H'\bar{\nu}_R^c\nu_R + \lambda_3\left(\frac{1}{2}H'^2\phi^2 + v'H'\phi^2\right). \tag{17}$$

Finally, after the $B-L$ gauge symmetry breaking the gauge field C_μ (will be called Z' in the rest of the paper) acquires the following mass:

$$M_{Z'}^2 = 4g''^2 v'^2. \tag{18}$$

The Lagrangian terms that describe the interactions of the Z'_μ gauge boson are given by

$$\mathcal{L}_{Z'} = -\frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \frac{1}{2}M^2_{Z'}Z'_\mu Z'^\mu + 2g''^2 Z'_\mu Z'^\mu \chi^2 + 4g''^2 v' Z'_\mu Z'^\mu \chi - ig'' J^{B-L}_\mu Z'^\mu \tag{19}$$

where $J^{B-L}_\mu = \bar{\psi}_L \gamma_\mu \psi_L + \bar{e}_R \gamma_\mu e_R + \bar{\nu}_R \gamma^\mu \nu_R$. The high energy experimental searches for an extra neutral gauge boson impose lower bounds on the Z' mass [6]:

$$M_{Z'}/g'' > 6 \text{ TeV}. \tag{20}$$

After $U(1)_{B-L}$ symmetry breaking [5], the Yukawa interaction term: $\lambda_{\nu_R}\chi\bar{\nu}^c_R\nu_R$ leads, as usual, to right handed neutrino mass: $M_R = \frac{1}{2\sqrt{2}}\lambda_{\nu_R}v'$. Also the electroweak symmetry breaking results in the Dirac neutrino mass term : $m_D = \frac{1}{\sqrt{2}}\lambda_\nu v$. Therefore, the mass matrix of the left and right-handed neutrinos is given by

$$\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}. \tag{21}$$

Since M_R is proportional to v' and m_D is proportional to v *i.e.*, $M_R > m_D$, the diagonalization of this mass matrix leads to the following masses for the light and heavy neutrinos respectively:

$$m_{\nu_L} = -m_D M_R^{-1} m_D^T, \tag{22}$$

$$m_{\nu_H} = M_R. \tag{23}$$

Thus, $B - L$ gauge symmetry can provide a natural framework for the seesaw mechanism.

IV. SUPERSYMMETRY

Supersymmetry (SUSY) represents an extension of the space-time symmetries within quantum _eld theory (Moretti & Khalil, 2019). It establishes a connection between matter particles (such as quarks and leptons) and force-carrying particles, proposing the existence of additional "superparticles" to achieve this symmetry. SUSY is a novel symmetry that establishes a relationship between bosons and fermions, as illustrated in Fig. 5.

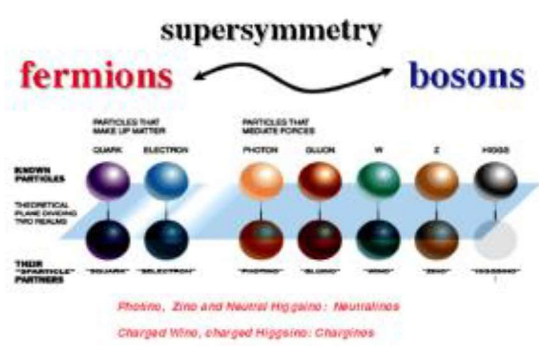

FIG. 5: Supersymmetry: Fermion-to-Boson Transformation

The Minimal Supersymmetric Standard Model (MSSM) is essentially a straightforward supersymmetrization of the SM with a minimal number of new parameters. It is the most widely studied potentially realistic SUSY model. The super_eld is a kind of a multiplet that contains both bosons and fermions. The MSSM contains three generations of quark and lepton super_elds, the super_elds necessary to gauge the SU(3)C _ SU(2)L _ U(1)Y gauge of the SM, and two SU(2) doublet Higgs super_elds. The introduction of a second Higgs doublet is necessary to give masses to both up and down type quarks (Moretti & Khalil, 2019). The particle content of the MSSM together with their quatnum numbers is presented in Table 1.

Particle	Symbol	Spin	Superpartner	Symbol	Spin
Quark	q	1/2	Squark	$\tilde{q}$	0
Neutrino	ν	1/2	Sneutrino	$\tilde{\nu}$	0
Electron	e	1/2	Selectron	$\tilde{e}$	0
Muon	μ	1/2	Smuon	$\tilde{\mu}$	0
Tau	τ	1/2	Stau	$\tilde{\tau}$	0
W	W	1	Wino	$\tilde{W}$	1/2
Z	Z	1	Zino	$\tilde{Z}$	1/2
Photon	γ	1	Photino	$\tilde{\gamma}$	1/2
Gluon	g	1	Gluino	$\tilde{g}$	1/2
Higgs	$h, A, H^0, H^{\pm}$	0	Higgsinos	$\tilde{h}, \tilde{A}, \tilde{H}^0, \tilde{H}^{\pm}$	1/2

TABLE I: The MSSM particle content.

Supersymmetry cannot be an exact symmetry of nature since if it were, it would imply the existence of mass degenerate fermion boson pairs, for which there is no experimental evidence. Thus, supersymmetry must be a broken symmetry. There are several MSSM models that are based on di_erent mechanisms of supersymmetry breaking, and each predicts di_erent experimental signatures. The model most often used to interpret experimental data is the minimal supergravity model (mSUGRA). In this model, certain universality of soft SUSY breaking terms is assumed at grand uni_cation (GUT) scale _ 1016 GeV and the renormalization group equations (RGE) are used to calculate the parameters at the electroweak.

The mSUGRA is a natural framework for studying production and decay of SUSY particles since it has only _ve free parameters. Thus one one can systematically study the whole parameter space of this model. A strong constraint on the parameters is given by the requirement of spontaneous electroweak symmetry breaking.Therefore, the parameters which remain are: m0, the common scalar mass at GUT scale, m1=2 the unifying gaugino mass, A0 the common trilinear term, tan _ = v2=v1, with v1(v2) being the Higgs vacuum expectation value of the Higgs H1(H2), and sign of the Higgs bilinear term, _H1H2 (Moretti & Khalil, 2019).

Various investigations have explored gluino masses up to 2.4 TeV, light squark masses up to 1.8 TeV, bottom squark masses up to 1.3 TeV, and top squark masses up to 1.35 TeV (Sekmen, 2022). Charginos and neutralinos comprise electroweak eigenstates of binos, winos, and higgsinos. Directly producing neutralinos and charginos yields lower cross sections. Studies targeting the lightest chargino and next-to-lightest neutralino have probed masses up to 1.35 TeV (Sekmen, 2022). However, the lower limit of the lightest neutralino remains contingent on the model and relies on assumptions about its mass correlation with other SUSY particles.

The investigation of the low energy e_ects, which might arise from supersymmetry, is another possible way of testing SUSY theories. For instance, severe constraints on the MSSM, which arise upon consideration of rare processes and precision experiments. In particular, the most stringent constraints arise from the b ! s decay width as measured by the LHCb experiment. Further, if the dark matter in the universe is made of the lightest neutralino, then e_0 can be probed by di_erent direct and indirect dark matter searches (Moretti & Khalil, 2019). Furthermore, there are indirect evidences for SUSY through departure from the SM prediction in FCNC and CP violation processes. Indeed, these processes have potentialities to exhibit manifestations of SUSY, see for instance Ref. (Moretti & Khalil, 2019).

V. CONCLUSIONS

Discovering new physics beyond the SM of particle physics would represent a signi_cant advancement in 21st-century physics. This paper provides a concise overview of the SM while exploring potential evidence that suggests the necessity of considering physics beyond the SM. Within this exploration, we explored two illustrative examples of these extensions.

The _rst extension involves augmenting the SM gauge group by introducing an additional $U(1)_{B-L}$. The second extension arises from the incorporation of supersymmetry, elevating the SM to the Minimal Supersymmetric Standard Model. Notably, both extensions e_ectively address several de_ciencies of the SM, such as accommodating neutrino masses and accounting for dark matter. Furthermore, they forecast the existence of new particles that could be experimentally probed at facilities like the Large Hadron Collider (LHC). These pursuits hold the promise of unveiling previously uncharted realms of particle physics beyond the SM paradigm.

Acknowledgements

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