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Gauge Unification from Split Supersymmetric String Models

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We discuss the unification of gauge coupling constants in non-supersymmetric open string vacua that possess the properties of Split Supersymmetry, namely the Standard Model with Higgsinos at low energies and where the Standard model spectrum is always accompanied by right handed neutrinos. These vacua achieve partial unification of two out of three (namely SU(3)$_c$, SU(2), U(1)) running gauge couplings, possess massive gauginos and light Higgsinos at low energies and also satisfy $sin^2\theta_w(M_s) = 3/8$. These vacua are based on four dimensional orbifold $Z_3 \times Z_3$ compactifications of string IIA orientifolds with D6-branes intersecting at angles, where the (four dimensional) chiral fermions of the Standard Model appear as opens strings streching between the intersections of seven dimensional objects the so called D6-branes.

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1. Introduction

Recently, ATLAS and CMS experiments shed light on Higgs properties by combining the 2011 & 2012 results from LHC run 1. Their results in May 2015 clearly show an improvement in precision (see also talk by G.Tonelli in the school) of the experiments determing the Higgs mass (see figure 1 - taken from [1]) . The value of the Higgs mass is well below the value supported

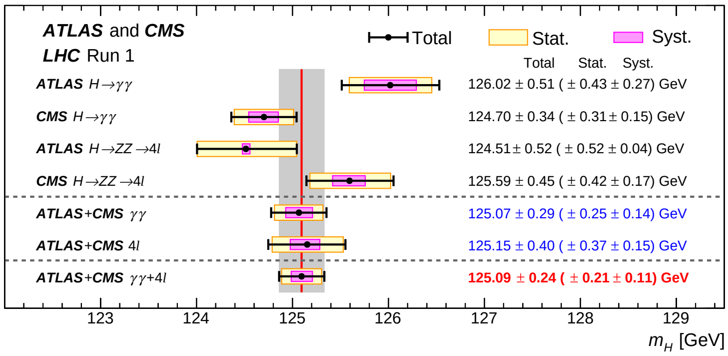

Figure 1: Summary of Higgs boson mass measurements from the individual analyses of ATLAS and CMS and from the combined analysis . The systematic (narrower, magenta-shaded bands), statistical (wider, yellow-shaded bands), and total (black error bars) uncertainties are indicated. The (red) vertical line and corresponding (gray) shaded column indicate the central value and the total uncertainty of the combined measurement, respectively. *The value of the Higgs mass is well below the value supported from the Standard model (SM), thus suggesting the existence of another framework where the SM is embedded, that can be a string theory with a high (as the one we are discussing in this talk) or a low string scale (e.g. from extra dimensions).*

from the Standard model (SM), thus suggesting the existence of another framework where the SM is embedded, that can be a string theory with a high or a low string scale (e.g. from extra dimensions). The SM is an incomplete theory for the following reasons : 1) does not incorporate gravity, 2) does not describe dark matter and dark energy. In fact, cosmological observations tell us that the standard model explains about 5% of the matter present in the universe. About $\approx 27\%$ should be dark matter, which can behave just like other matter, but which only interacts weakly (if at all) with the Standard Model fields and also 3) SM does not predict a mass for the neutrinos. At the SM $m_\nu = 0$, but measurements however indicated that neutrinos spontaneously change flavour, which implies that neutrinos have a mass. This necessitates an extension of the standard model, which not only needs to explain how neutrinos get massive, but also why their mass is so small. The solution to these problems is that the SM may be extended.

1.1 *High Scale N=1 Supersymmetry*

The first possibility is to use $N = 1$ Supersymmetry (SUSY) in gauge theories to promote the SM to a Supersymmetric Standard Model (SSM), e.g. to the so called Minimal Supersymmetric Standard Model (MSSM) [2], such that for every Standard Model particle there exists its supersymmetric (susy) partner (s-particle partner) with the same charge but with different spin (a boson acquires an s-fermion susy partner and a fermion an s-boson susy partner). N=1 SUSY solves the gauge hierarchy problem and the running gauge couplings for the $SU(3)_c$, $SU(2)$ $U(1)_Y$ gauge group, corresponding to the strong, weak and hypercharge gauge couplings, unify [3] at the unification scale [4] of

$$M_{GUT} \approx 2 \cdot 10^{16} \; GeV, \tag{1.1}$$

as seen in figure (2). In a gauge theory context, there is no fundamental reason from first principles

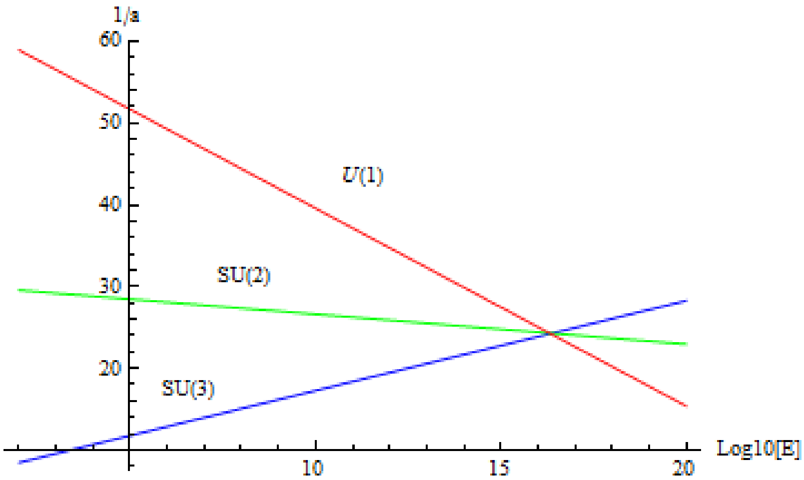

Figure 2: Unification of running gauge coupling constants in the MSSM at tree level

why the unification scale should be so high, if not by accident. However in N=1 supersymmetric vacua arising from the (perturbative) Heterotic String Theories the unification string scale M_{string} is fixed to be, larger than its gauge theory counterpart ([5]) in eqn.(1.1),

$$M_{string} \stackrel{def}{=} \frac{2e^{(1-\gamma)/2}3^{-3/4}}{\sqrt{2\pi\alpha'}} \approx 0.7 \; g_{string} \; 10^{18} \; GeV \tag{1.2}$$

It appears, though, that M_{string} is two (2) orders of magnitude larger than the unification of the SUSY gauge theory scale M_{GUT}. Several explanations were invoked to reconcile the apparent discrepancy, to name afew : threshold corrections, extra states etc.(e.g. see [6]).

2. D-branes in String Theory and the Gauge Couplings constant problem

The above problems could be solved if we focus our attention to a string theory where the string scale is a free parameter and could be lowered) so that it can be closer to the GUT scale of eqn.(1.1). This goal can be achieved in theories which are compactifications of type I theories, namely compactifications of 10 dimensional IIA orientifolds with D6-branes intersecting at angles [7, 16]. On such string vacua [8], [9], [10], [11], supersymmetry is already broken at the string scale, by construction, and at low energies the (chiral spectrum of the) SM survives to low energies. In these constructions, better known as the models of the Madrid group [8], [9], the SM appears in a global configuration and subsequently gets localized in a string model construction, by satisfying the ultraviolet tadpole constraints (the cancellation of cubic gauge anomalies) of the underlying string theory. In these constructions, chiral fermions of the SM appear as open strings stretching between intersecting D6-branes as in fig. (3). In (3) the five stack SM model of [9] is depicted. The gauge group of the model is the SM one, $SU(3)_c \times SU(2)_w \times U(1)_Y$. All extra U(1)'s, beyond the hypercharge that are originally present at the string scale gets a mass from their non-zero couplings to Green-Schwarz couplings or some other mechanism. The chiral spectrum of the model may be obtained by solving simultaneously the intersection constraints (that determine the multiplicity of the chiral fermions) coming from the existence of the different sectors and the RR tadpole cancellation conditions. The SM chiral spectrum of the SM get its mass from a set of two-Higgses and the right handed neutrino gets a Dirac mass. In this model, by construction the string/unification can be found at a high scale while Baryon number survives at low energies as a global symmetry by construction, avoiding the baryon number decay problems of heterotic orbifold contructions/F-theory constructions. It has been shown recently [12], that this model explains the latest CERN particle physics decay experiment $b \to s\, l^+\, l^-$ and predicts a new boson Z' with non-negligible couplings to the first two quark generations and a mass in the range [3.5, 5.5] TeV with the possibility to discover such a state directly during the next LHC runs via Drell-Yan production in the di-electron or di-muon decay channels.

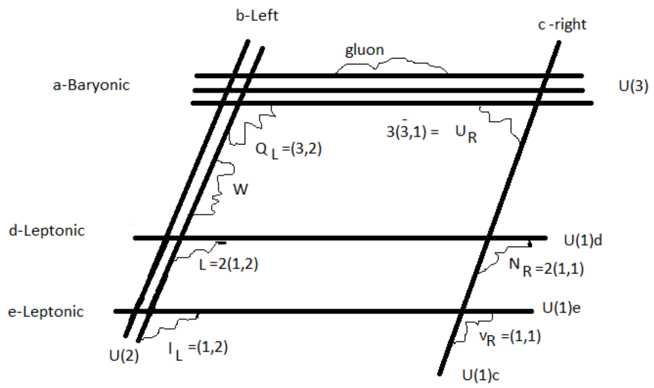

Figure 3: The stringy Standard model includes the chiral fermions (CF) of the Standard Model and the right handed neutrinos. CF appear as open strings stretching between intersecting D6-branes in the 5-stack model of [9]. Baryon number is conserved as the corresponding gauge boson receives a string scale mass. This model predicts an extra Z' gauge boson between 3.5-5.5 TeV [12] and also accommodates the recent anomalies observed in the $b \to sl^+l^-$ transitions observed by the LHCb collaboration.

2.1 Split Susy in String Theory - Explicit realizations

Split SUSY in gauge theories (from now on named global Split Susy) [13] has a number of features :

1) does not solve the Gauge Hierarchy problem but keeps the unification and dark matter candidate,

2) it achieves partial unification of two out of three SM gauge couplings at $\approx 10^{16}$ GeV,

3) All superpartners are considered massive,
4) Higgsinos, gauginos remain at low energy,
5) there is a light and a heavy Higgs and the SM (assumed to exists as a result of fine tuning).
Split supersymmetry in string theory on the other hand was introduced during November 2004 in [14], [15]. In [14] where global (quiver) models were constructed, it was argued that *String Theory can achieve Split Susy* if a number of conditions are satisfied, namely :
i) $sin^2\theta_w = 3/8$ at the string unification scale M_s
ii) there is partial unification of two (2) out of three (3) gauge couplings of the SM,
iii) there are light gauginos and iv) there are light Higgsinos, surviving to low energies
The 5th condition of global Split Susy did not appear in the present models of string theory. In our work [15] we proposed that for intersecting D6-brane Split Susy models, gauginos could get massive from loop corrections while specific string models with $sin^2\theta = 3/8$ at M_s were proposed, arising from new four dimensional constructions [16] based on chiral four dimensional T6/($Z3 \times Z3$) orientifold compactifications of IIA theory that satisfy the criteria i) - iv).

3. Non-supersymmetric Standard Model Gauge unification in Split Susy string models

Our orientifold constructions [16] are based on IIA theory compactified on the $\mathbf{T^6}/(\mathbf{Z_3}\times\mathbf{Z_3})$ orbifold, where the latter symmetry is generated by the twist generators (where $\alpha = e^{\frac{2\pi i}{3}}$) θ : $(z_1,z_2,z_3) \to (\alpha z_1, \alpha^{-1}z_2, z_3)$, $\omega : (z_1,z_2,z_3) \to (z_1, \alpha z_2, \alpha^{-1}z_3)$, where θ, ω get associated to the twists $\upsilon = \frac{1}{3}(1,-1,0)$, $u = \frac{1}{3}(0,1,-1)$. Here, $z^i = x^{10-2i} + ix^{11-2i}$, $i = 1,2,3$ are the complex coordinates on the T^6, which we consider as being factorizable for simplicity, e.g. $T^6 = T^2 \otimes T^2 \otimes T^2$. In addition, to the orbifold action the IIA theory is modded out by the orientifold action ΩR that combines the worldsheet parity Ω and the antiholomorphic operation $R : z^i \to \bar{z}^i$. and the ΩR action is along the horizontal directions across the six-torus. The model contains nine kinds of orientifold planes, that correspond to the orbit $\mathscr{O}$ consisting of the actions of ΩR, $\Omega R\theta$, $\Omega R\omega$, $\Omega R\theta^2$, $\Omega R\omega^2$, $\Omega R\theta\omega$, $\Omega R\theta^2\omega$, $\Omega R\theta\omega^2$, $\Omega R\theta^2\omega^2$. The closed string spectrum contains gravitational multiplets and orbifold moduli and is not of any interest to us in the present review. In order to cancel the RR crosscap tadpoles introduced by the introduction of the orientifold planes we introduce N $D6_a$-branes of open strings wrapped along three-cycles that are taken to be products of one-cycles along the three two-tori of the factorizable T^6. A D6-brane a - associated with the equivalence class of wrappings (n^I, m^I), $I = 1,2,3$, - is mapped under the orbifold and orientifold action to its images

$$a \leftrightarrow \begin{pmatrix} n_a^1, m_a^1 \\ n_a^2,\ m_a^2 \\ n_a^3,\ m_a^3 \end{pmatrix},\ \theta a \to \begin{pmatrix} -m_a^1,\ (n-m)_a^1 \\ (m-n)_a^2,\ -n_a^2 \\ n_a^3,\ m_a^3 \end{pmatrix},\ \Omega R a \to \begin{pmatrix} (n-m)_a^1,\ -m_a^1 \\ (n-m)_a^2,\ -m_a^2 \\ (n-m)_a^3,\ -m_a^3 \end{pmatrix}. \tag{3.1}$$

The $Z_3 \times Z_3$ orientifold models are subject to the cancellation of untwisted RR tadpole conditions [16] given by

$$\sum_a N_a Z_a = 4, \tag{3.2}$$

where

$$Z_a = 2m_a^1 m_a^2 m_a^3 + 2n_a^1 n_a^2 n_a^3 - n_a^1 n_a^2 m_a^3 - n_a^1 m_a^2 n_a^3 - m_a^1 n_a^2 n_a^3 - m_a^1 m_a^2 n_a^3 - m_a^1 n_a^2 m_a^3 - n_a^1 m_a^2 m_a^3 \tag{3.3}$$

The gauge group U(N_a) produced by N_a coincident D6$_a$-branes comes from the $a(\tilde{a})$ sector, the sector made from open strings stretched between the a-brane and its images under the orbifold action. Also, we get three adjoint N=1 chiral multiplets. In the $a(\mathscr{O}b)$ sector - strings stretched between the brane a and the orbit images of brane b - will localize I_{ab} fermions in the bifundamental $(N_a, \bar{N}_b)$ where

$$I_{ab} = 3(Z_a Y_b - Z_b Y_a), \tag{3.4}$$

and (Z,Y) are the effective wrapping numbers with Y_a given by

$$Y_a = m_a^1 m_a^2 m_a^3 + n_a^1 n_a^2 n_a^3 - n_a^1 n_a^2 m_a^3 - n_a^1 m_a^2 n_a^3 - m_a^1 n_a^2 n_a^3 \tag{3.5}$$

The sign of I_{ab} denotes the chirality of the associated fermion, where we choose positive intersection numbers for left handed fermions. In the sector ab' - strings stretching between the brane a and the orbit images of brane b, there are $I_{ab'}$ chiral fermions in the bifundamental (N_a, N_b), with

$$I_{ab'} = 3(Z_a Z_b - Z_a Y_b - Z_b Y_a), \tag{3.6}$$

Chiral fermions in symmetric (S) and antisymmetric (A) representations of $U(N_a)$ from open strings stretching between the brane a and its orbit images $(\mathscr{O}a)$ appear as,

$$(A_a) = 3(Z_a - 2Y_a), \tag{3.7}$$

$$(A_a + S_a) = \frac{3}{2}(Z_a - 2Y_a)(Z_a - 1) \tag{3.8}$$

Also, from open strings stretched between the brane a and its orbifold images we get non-chiral massless fermions in the adjoint representation,

$$(Adj)_L : \prod_{i=1}^{3} (L_{[a]}^I)^2 \ , \tag{3.9}$$

where

$$L_{[a]}^I = \sqrt{(m_a^I)^2 + (n_a^I)^2 - (m_a^I)(n_a^I)} \tag{3.10}$$

Adjoint massless matter, including fermions and gauginos that are massless at tree level are expected to receive string scale masses from loops once supersymmetry is broken [8]. The evolution of the one loop renormalization group equations (ERGE) for the $SU(3)_c$, $SU(2)_w$, $U(1)_Y$ gauge couplings in the absence of one-loop string threshold corrections (see [17] and also [16]) are given by

$$\begin{aligned}
\frac{1}{a_s(M_z)} &= \frac{1}{a_s(M_s)} - \frac{b_3}{2\pi} \ln\left(\frac{M_Z}{M_s}\right), \\
\frac{sin^2\theta_w(M_Z)}{a_{em}(M_Z)} &= \frac{1}{a_w(M_s)} - \frac{b_2}{2\pi} \ln\left(\frac{M_Z}{M_s}\right), \\
\frac{cos^2\theta_w(M_Z)}{a_{em}(M_Z)} &= \frac{1}{a_Y(M_s)} - \frac{b_1}{2\pi} \ln\left(\frac{M_Z}{M_s}\right),
\end{aligned} \tag{3.11}$$

$$\frac{2}{3}\frac{1}{\alpha_s(M_Z)} + \frac{2sin^2\theta_w(M_Z) - 1}{\alpha_{em}(M_Z)} = \frac{B}{2\pi} \ln \frac{M_Z}{M_s} \ , \tag{3.12}$$

and $B = -(\frac{2}{3}b_3 + b_2 - b_Y)$; b_3, b_2, b_1 are the β-function coefficients for strong, weak and hypercharge gauge couplings respectively. The string scale gets calculated from eqn. (3.12). For a theory which accommodates the SM and a number of extra particles below a scale M_s

$$(b_1,\, b_2,\, b_3) \;=\; (\frac{20}{9}n_G + \frac{1}{6}n_H + N_1,\; \frac{4}{3}n_G + \frac{1}{6}n_H + N_2 - \frac{22}{3},\; \frac{4}{3}n_G - 11 + N_3), \tag{3.13}$$

where N_1, N_2, N_3 the contribution of the beyond the SM particles; the rest of the terms in (3.13) are the Standard model contributions; n_G the number of generations; n_H the number of Higgses. *It appears [15] that in a non-supersymmetric string model, the value of the string scale which depends on the variable B is independent of the number of Higgses as their dependence cancels out. In table (1), we can clearly see that the string unification scale, if we have either the SM with right handed neutrinos at low energy or the SM accompanied by 3 pairs of hisggsinos, the string scale value is fixed at* $M_s = 5.1 \times 10^{13}$ *Gev independent of the number of Higgses present as their dependence cancels out in the combination* $b_2 - b_1$ *of* B.

Spectrum at low energies	$\beta_{coefficents}$	M_s
SM	$(b_1,b_2,b_3) = (\frac{20}{3} + \frac{1}{6}n_H, -\frac{10}{3} + \frac{1}{6}n_H, -7),\ B = \frac{44}{3}$	$M_s \approx 5.1 \cdot 10^{13}$
$SM + 3$ *pairs of* H_u, H_d *Higgsinos*	$(b_1,b_2,b_3) = (\frac{26}{3} + \frac{1}{6}n_H, -\frac{4}{3} + \frac{1}{6}n_H, -7),\ B = \frac{44}{3}$	$M_s \approx 5.1 \cdot 10^{13}$

Table 1: Value of the string scale M_s in Split Sysy models. All models possess $\sin^2\theta_w$ =3/8 at M_s.

The input values of the inverse gauge couplings at low energy (i.e. at m_Z = 91.1876 GeV) for the SM have been fixed by taking the recent PDG data [18]

$$\alpha_1^{-1}(m_Z) \;=\; 59.01 \pm 0.02\,, \tag{3.14}$$
$$\alpha_2^{-1}(m_Z) \;=\; 29.57 \pm 0.02\,, \tag{3.15}$$
$$\alpha_3^{-1}(m_Z) \;=\; 8.45 \pm 0.05\,. \tag{3.16}$$
$$\tag{3.17}$$

$a_2(M_Z) = a_{em}\, sin^2\theta(M_Z)$,

3.1 A Split Susy example

The minimal choice of obtaining the SM gauge group and chiral spectrum originates from a three stack $U(3)_a \times U(2)_b \times U(1)_c$ gauge group with D6-branes intersecting at angles at the string scale [15, 16]. The choice of wrapping numbers

$$(Z_a, Y_a) = \Big(1,\ 0\Big),\ (Z_b, Y_b) = \Big(1,\ 1\Big),\ (Z_c, Y_c) = \Big(-1,\ 1\Big) \tag{3.18}$$

satisfies the RR tadpoles (3.2) and corresponds to the spectrum seen in table (2).

The D-brane model [15] of table (2) has a non-supersymmetric spectrum. The Higgses come from vanishing intersections and can be understood as part for the massive spectrum that organize itself in terms of massive N=2 hypermultiplets. The Higgs fields become subsequently tachyonic in order to participate in electroweak symmetry breaking (for a more detailed discussion of these issues see [8, 9, 10]). All fermions become massive from the Yukawa couplings

Matter	Intersection	$(SU(3)\times SU(2))_{(Q_a,Q_b,Q_c)}$	$U(1)^Y$
$\{Q_L\}$	$ab*$	$3(\bar{3},2)_{(-1,\,-1,\,0)}$	$1/6$
$\{u_L^c\}$	A_a	$3(3,1)_{(-2,\,0,\,0)}$	$-2/3$
$\{d_L^c\}$	ac	$3(3,1)_{(1,\,0,\,-1)}$	$1/3$
$\{L\}$	bc	$3(1,2)_{(0,\,1,\,-1)}$	$-1/2$
$\{H_d\}$	bc	$3(1,2)_{(0,\,1,\,-1)}$	$-1/2$
$\{H_u\}$	$bc*$	$3(1,\bar{2})_{(0,\,-1,\,-1)}$	$1/2$
$\{e_L^+\}$	A_b	$3(1,1)_{(0,\,-2,\,0)}$	1
$\{N_R\}$	S_c	$9(1,1)_{(0,\,0,\,2)}$	0
$\{C_1\}$	ac	$3(3,1)_{(1,\,0,\,-1)}$	$1/3$
$\{C_2\}$	$ac*$	$3(\bar{3},1)_{(-1,\,0,\,-1)}$	$-1/3$

Table 2: A three generation 4D non-supersymmetric model with the chiral fermion content of N=1 Supersymmetric Standard Model on top of the table, in addition to N_R's. There are three pairs of H_u, H_d Higgsinos. This model has the structure of models coming from gauge mediation scenarios and exhibits the spectrum of Split Supersymmetry with the SM and Higgsinos at low energy. The spartners are part of the massive spectrum with mass of of order M_s. and possess $sin^2\theta = 3/8$ at M_s.

$$\lambda_d(Q_L)(d_L^c)\langle\tilde{H}_d\rangle \;+\; \lambda_\nu L N_R\langle\tilde{H}_u\rangle \;+\frac{\lambda_e}{M_s}Le_L^c\langle\tilde{H}_d\rangle+(\lambda_H H_u H_d+\lambda_C C_1 C_2)\langle\tilde{N}_R\rangle, \tag{3.19}$$

where the Higgs fields have the quantum numbers

$$\tilde{H}_u=(1,2,1)_{(0,-1,-1)},\;\; \tilde{H}_d=(1,2,1)_{(0,1,1)}\ . \tag{3.20}$$

Lets us now examine gauge coupling unification using the models of table (2) as a representative example. They are non-supersymmetric but they respect

$$\sin^2\theta_W \overset{M_s}{=} \frac{3}{8}\ . \tag{3.21}$$

as $a_2 = a_3$ at M_s. Thus at the unification scale where the gauge couplings $SU(2)_w$, $SU(3)_c$ meet, we have the standard SU(5) GUT relation

$$(5/3)a_Y = a_s = a_w = a_2 = a_3 \tag{3.22}$$

This relation 'solves' the following stringy relation among the gauge coupling constants

$$\frac{1}{a_Y}=\frac{2}{3}\frac{1}{a_s}+\frac{1}{a_w}\ . \tag{3.23}$$

For the Split Susy spectrum of model of table (2) we find

$$(b_1, b_2, b_3) = (\frac{29}{3}, -\frac{1}{3}, -7) \tag{3.24}$$

We get a stringy version of unification of interactions, where two out of three of gauge couplings

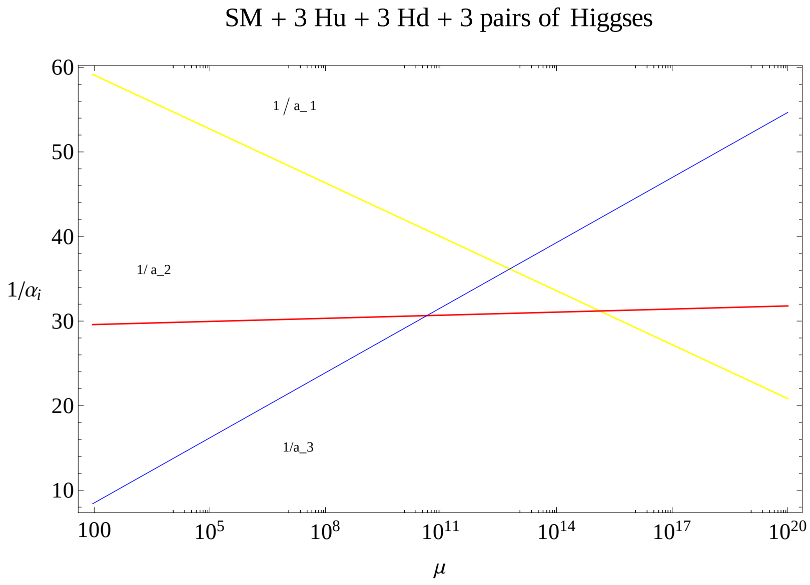

Figure 4: Gauge coupling evolution with the energy for the stringy Split Susy Standard model.

unify.

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