Low-scale gauge unification of families and forces

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April 7, 2021

Café com Física – Universidade de Coimbra

To appear in 2105.xxxx

PTDC/FIS-PAR/31000/2017

Outline

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Introduction

Large mass and mixing hierarchies found in Nature

- $m_t\ ,\ m_h\ , m_z\ , m_w \sim 10^2$ GeV (EW scale)
- $m_t \sim 10^2 m_c \sim 10^{4.6} m_u$
- $m_t \sim 10^{1.6} m_b \sim 10^{3.2} m_s \sim 10^{4.8} m_d$
- $m_t \gtrsim 10^{11} m_\nu$
- $m_e \gtrsim 10^5 m_\nu$
- $m_\tau \sim 10^{1.2} m_\mu \sim 10^{3.5} m_e$

$$V_{\mathrm{CKM}} \sim \begin{pmatrix} \cos\theta_c & \sin\theta_c & 0 \\ -\sin\theta_c & \cos\theta_c & 0 \\ 0 & 0 & 1 \end{pmatrix} + \text{Perturbations}\ .$$

- Why are there small mixing angles in the quark sector and not in the lepton sector?

What is the origin of the strong and electroweak interactions?

$$\mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}} \subset \boldsymbol{G}$$

- Can $\boldsymbol{G}$ unify the strong and electroweak interactions?
- Why are the $g_{\mathrm{SU}(3)}$, $g_{\mathrm{SU}(2)}$ and $g_{\mathrm{U}(1)}$ gauge couplings so different?
- What is the $\boldsymbol{G}$ unification scale Λ_0?
- Can the $\boldsymbol{G}$ breaking mechanism explain the EW scale?
- Can $\boldsymbol{G}$ unify matter?
- Can $\boldsymbol{G}$ unify families / offer an explanation for the flavour structure?
- **What is the gauge group $\boldsymbol{G}$** and which predictions does it bring along?

Historical perspective

The idea of Grand Unification proposed by H. Georgi and S. Glashow in 1974

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

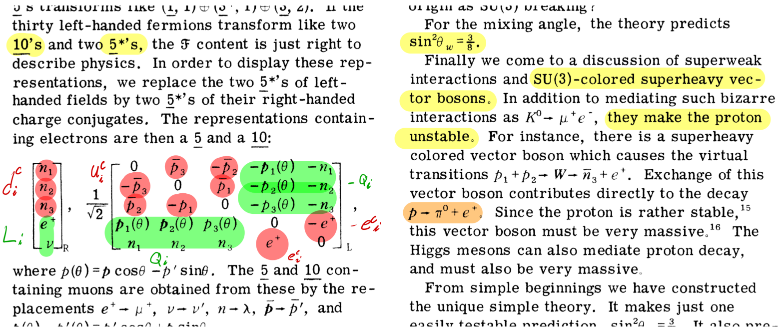
We present a series of hypotheses and speculations leading inescapably to the conclusion that SU(5) is the gauge group of the world—that all elementary particle forces (strong, weak, and electromagnetic) are different manifestations of the same fundamental interaction involving a single coupling strength, the fine-structure constant. Our hypotheses may be wrong and our speculations idle, but the uniqueness and simplicity of our scheme are reasons enough that it be taken seriously.

Our starting point is the assumption that *weak and electromagnetic forces are mediated by the vector bosons of a gauge-invariant theory with spontaneous symmetry breaking.* A model describing the interactions of leptons using the

of the GIM mechanism with the notion of colored quarks[4] keeps the successes of the quark model and gives an important bonus: Lepton and hadron anomalies cancel so that the theory of weak and electromagnetic interactions is renormalizable.[5]

The next step is to include strong interactions. We assume that *strong interactions are mediated by an octet of neutral vector gauge gluons* associated with local color SU(3) symmetry, and that there are no fundamental strongly interacting scalar-meson fields.[6] This insures that parity and hypercharge are conserved to order α,[7] and does not lead to any new anomalies, so that the theory remains renormalizable. The strongest binding forces are in color singlet states which may explain why observed hadrons

- $G = \mathrm{SU}(5)$ describing an hypothetical universal force



$\underline{5}$'s transforms like $(1,1)\oplus(3^*,1)\oplus(3,2)$. If the thirty left-handed fermions transform like two $\underline{10}$'s and two $\underline{5}^*$'s, the $\mathfrak{F}$ content is just right to describe physics. In order to display these representations, we replace the two $\underline{5}^*$'s of left-handed fields by two $\underline{5}^*$'s of their right-handed charge conjugates. The representations containing electrons are then a $\underline{5}$ and a $\underline{10}$:

$$
\begin{array}{c} d_i^c \\ \\ L_i \end{array}
\begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ e^+ \\ \nu \end{bmatrix}_R ,\quad
u_i^c \;\; \frac{1}{\sqrt{2}}
\begin{bmatrix}
0 & \bar{p}_3 & -\bar{p}_2 & -p_1(\theta) & -n_1 \\
-\bar{p}_3 & 0 & \bar{p}_1 & -p_2(\theta) & -n_2 \\
\bar{p}_2 & -\bar{p}_1 & 0 & -p_3(\theta) & -n_3 \\
p_1(\theta) & p_2(\theta) & p_3(\theta) & 0 & -e^+ \\
n_1 & n_2 & n_3 & e^+ & 0
\end{bmatrix}_L ,
\begin{array}{c} -Q_i \\ \\ -e_i^c \end{array}
$$

Q_i $\quad e_i^c$

where $p(\theta) = p\cos\theta - p'\sin\theta$. The $\underline{5}$ and $\underline{10}$ containing muons are obtained from these by the replacements $e^+ \to \mu^+$, $\nu \to \nu'$, $n \to \lambda$, $\bar{p} \to \bar{p}'$, and $p(\theta) \to p'(\theta) = p'\cos\theta + p\sin\theta$

origin as SU(5) breaking?

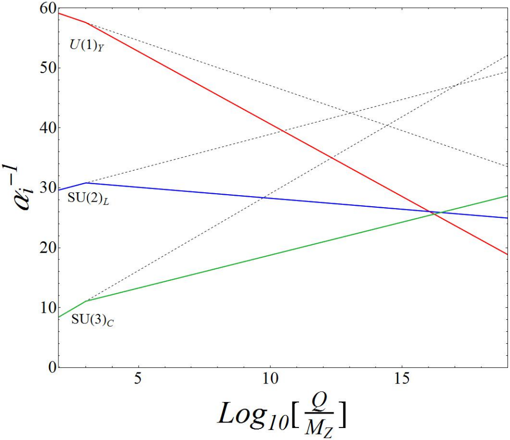
For the mixing angle, the theory predicts $\sin^2\theta_w = \frac{3}{8}$.

Finally we come to a discussion of superweak interactions and SU(3)-colored superheavy vector bosons. In addition to mediating such bizarre interactions as $K^0 \to \mu^+ e^-$, they make the proton unstable. For instance, there is a superheavy colored vector boson which causes the virtual transitions $p_1 + p_2 \to W \to \bar{n}_3 + e^+$. Exchange of this vector boson contributes directly to the decay $p \to \pi^0 + e^+$. Since the proton is rather stable,[15] this vector boson must be very massive.[16] The Higgs mesons can also mediate proton decay, and must also be very massive.

From simple beginnings we have constructed the unique simple theory. It makes just one easily testable prediction, $\sin^2\theta_w = \frac{3}{8}$. It also pre-

- All known matter to date embedded in $\mathbf{5} \oplus \mathbf{10}$ **but not unified**
- Strong and electroweak interactions in the same footing
- Quarks can be transformed into leptons via $SU(5)$ gauge bosons interchange $\to$ **prediction for proton decay**

Gauge coupling unification in $\mathrm{SU}(5)$



- **Dashed lines:** Georgi-Glashow (GG) model ($\alpha_i^{-1} = \frac{4\pi}{g_i^2}$)
- **Solid lines:** Minimal supersymmetric extension with GG embedding
- Suggests $\Lambda_0 \sim \mathcal{O}(10^{16}\ \mathrm{GeV})$ **consistently with proton decay**

Matter unification in $\mathrm{SO}(10)$ by Fritzsch and Minkowski in 1975

ANNALS OF PHYSICS **93**, 193–266 (1975)

Unified Interactions of Leptons and Hadrons*

HARALD FRITZSCH AND PETER MINKOWSKI

California Institute of Technology, Pasadena, California 91125

Received March 19, 1975

It is suggested that a unifying description of leptons and hadrons can be obtained within a nonabelian gauge theory where the gauge group is a symmetry group of a set of massless elementary fermions (leptons, quarks). We investigate the consequences of such an approach for the strong, electromagnetic, and weak interactions. We study both gauge theories with and without fermion number conservation, e.g., theories based on the groups $SU_n \times SU_n$ ($n = 8, 12, 16$) and SO_n ($n = 10, 14$).

1. INTRODUCTION

In this paper, we show how several hypotheses proposed during the last few years about nonabelian gauge theories for the weak and electromagnetic interactions [1], permanently confined colored quarks [2, 3] and color octet vector

- Besides forces, each matter generation is also unified in a single $\mathbf{16}$
- Possible interpretation: **leptons as a fourth colour**
- Offers right-handed neutrinos $\to$ seesaw mechanism

$$(\mathbf{16})_1 = \begin{pmatrix} \bar{u} & \bar{u} & \bar{u} & \bar{\nu}_e & u & u & u & \nu_e \\ \bar{d}' & \bar{d}' & \bar{d}' & e^+ & d' & d' & d' & e^- \end{pmatrix}_L$$

$$(\mathbf{16})_2 = \begin{pmatrix} \bar{c} & \bar{c} & \bar{c} & \bar{\nu}_\mu & c & c & c & \nu_\mu \\ \bar{s}' & \bar{s}' & \bar{s}' & \mu^+ & s' & s' & s' & \mu^- \end{pmatrix}_L$$

EW singlets EW doublets

The SO_{10} theory described above has the following features.

(a) Since SO_{10} has the subgroup $SU_4{}^c \times SU_2 \times SU_2$, the parity transformation is an automorphism of the gauge group and the Lagrangian is parity invariant. Parity must be broken spontaneously.

(b) The SU_5 model of [11] is a subtheory of the SO_{10} model, since SO_{10} contains SU_5. The $\mathbf{(16)}$ representation breaks up under SU_5 as $\mathbf{(1)} + \mathbf{(\bar{5})} + \mathbf{(10)}$.

The breakup of the SO_{10} group can proceed in two different ways, given by the diagram

$$\begin{tikzcd}
 & SO_{10} \arrow[dl] \arrow[dr] & \\
SU_4^c \times SU_2^L \times SU_2^R \arrow[dr] & & SU_5 \arrow[dl] \\
 & SU_3^c \times SU_2 \times U_1 &
\end{tikzcd}$$

Gürsey, Ramond and Sikivie propose the first exceptional E_6 unification model in 1976

Volume 60B, number 2 PHYSICS LETTERS 5 January 1976

A UNIVERSAL GAUGE THEORY MODEL BASED ON E_6 ☆

F. GÜRSEY and P. RAMOND*

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and

P. SIKIVIE

Department of Physics and Astronomy, University of Maryland, College Park, MD. 20742, USA

Received 29 October 1975

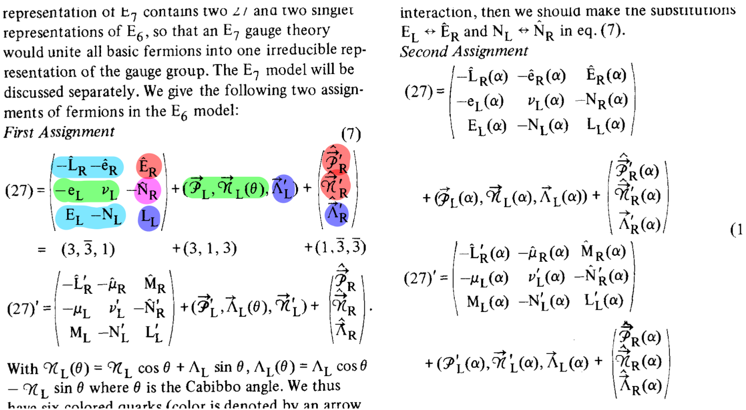
A universal gauge theory based on E_6 is suggested as a model for the unification of strong, electromagnetic and weak interactions. Left and right components of six quarks (3 light, 3 charmed) and nine leptons (including heavy charged and neutral leptons) are fitted into two 27-dimensional representations of E_6. Two different assignments are proposed. The Weinberg angle and the R ratio are derived and the stability of the proton is discussed.

Following the interpretation [1, 2] of the quark color group $SU^c(3)$ as a subgroup of the automorphism group G_2 of the octonion algebra and the identification of the exceptional observables of Jordan, von Neumann and Wigner [3] (JNW) with the operators acting on charge space of elementary particles, we are led to consider the Exceptional Lie Groups as

$$(27) = (\bar{3}, 3, 1^c) + (3, 1, 3^c) + (1, \bar{3}, \bar{3}^c)$$

$$(78) = (8, 1, 1^c) + (1, 8, 1^c) + (1, 1, 8^c) + (\bar{3}, \bar{3}, 3^c) + (3, 3, \bar{3}^c). \qquad (1)$$

The 27 representation, which is complex, can be re-


representation of E_7 contains two 27 and two singlet representations of E_6, so that an E_7 gauge theory would unite all basic fermions into one irreducible representation of the gauge group. The E_7 model will be discussed separately. We give the following two assignments of fermions in the E_6 model:

First Assignment (7)

$$(27) = \begin{pmatrix} -\hat{L}_R & -\hat{e}_R & \hat{E}_R \\ -e_L & \nu_L & -\hat{N}_R \\ E_L & -N_L & L_L \end{pmatrix} + (\vec{\mathcal{P}}_L, \vec{\mathcal{N}}_L(\theta), \vec{\Lambda}'_L) + \begin{pmatrix} \hat{\vec{\mathcal{P}}}'_R \\ \hat{\vec{\mathcal{N}}}'_R \\ \hat{\vec{\Lambda}}'_R \end{pmatrix}$$

$$= (3, \bar{3}, 1) \qquad + (3, 1, 3) \qquad + (1, \bar{3}, \bar{3})$$

$$(27)' = \begin{pmatrix} -\hat{L}'_R & -\hat{\mu}_R & \hat{M}_R \\ -\mu_L & \nu'_L & -\hat{N}'_R \\ M_L & -N'_L & L'_L \end{pmatrix} + (\vec{\mathcal{P}}'_L, \vec{\Lambda}_L(\theta), \vec{\mathcal{N}}'_L) + \begin{pmatrix} \hat{\vec{\mathcal{P}}}_R \\ \hat{\vec{\mathcal{N}}}_R \\ \hat{\vec{\Lambda}}_R \end{pmatrix}.$$

With $\mathcal{N}_L(\theta) = \mathcal{N}_L \cos\theta + \Lambda_L \sin\theta$, $\Lambda_L(\theta) = \Lambda_L \cos\theta - \mathcal{N}_L \sin\theta$ where θ is the Cabibbo angle. We thus have six colored quarks (color is denoted by an arrow

interaction, then we should make the substitutions $E_L \leftrightarrow \hat{E}_R$ and $N_L \leftrightarrow \hat{N}_R$ in eq. (7).

Second Assignment

$$(27) = \begin{pmatrix} -\hat{L}_R(\alpha) & -\hat{e}_R(\alpha) & \hat{E}_R(\alpha) \\ -e_L(\alpha) & \nu_L(\alpha) & -N_R(\alpha) \\ E_L(\alpha) & -N_L(\alpha) & L_L(\alpha) \end{pmatrix}$$

$$+ (\vec{\mathcal{P}}_L(\alpha), \vec{\mathcal{N}}_L(\alpha), \vec{\Lambda}_L(\alpha)) + \begin{pmatrix} \hat{\vec{\mathcal{P}}}'_R(\alpha) \\ \hat{\vec{\mathcal{N}}}'_R(\alpha) \\ \hat{\vec{\Lambda}}'_R(\alpha) \end{pmatrix} \qquad (1$$

$$(27)' = \begin{pmatrix} -\hat{L}'_R(\alpha) & -\hat{\mu}_R(\alpha) & \hat{M}_R(\alpha) \\ -\mu_L(\alpha) & \nu'_L(\alpha) & -\hat{N}'_R(\alpha) \\ M_L(\alpha) & -N'_L(\alpha) & L'_L(\alpha) \end{pmatrix}$$

$$+ (\mathcal{P}'_L(\alpha), \vec{\mathcal{N}}'_L(\alpha), \vec{\Lambda}_L(\alpha) + \begin{pmatrix} \hat{\vec{\mathcal{P}}}_R(\alpha) \\ \hat{\vec{\mathcal{N}}}_R(\alpha) \\ \hat{\vec{\Lambda}}_R(\alpha) \end{pmatrix}$$

- Contains the $\mathbf{16}$ of $\mathrm{SO}(10)$ plus new lepton doublets, sterile neutrinos and singlet quarks
- Both lepton doublets and singlet quarks are vector-like
- The lepton doublets have the same quantum numbers as Higgs doublets
- Supersymmetry $\Rightarrow$ **possibility for Higgs-matter unification**

PHYSICAL REVIEW D **95,** 075031 (2017)

Reviving trinification models through an E_6-extended supersymmetric GUT

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(Received 9 November 2016; published 25 April 2017)

We present a supersymmetric (SUSY) model based on trinification $[SU(3)]^3$ and family $SU(3)_F$ symmetries embedded into a maximal subgroup of E_8, where the sectors of light Higgs bosons and leptons are unified into a single chiral supermultiplet. The common origin of gauge trinification and of the family symmetry from E_8 separates the model from other trinification-based GUTs, as it protects, in particular, the Standard Model fermions from gaining mass until the electroweak symmetry is broken. Furthermore, it allows us to break the trinification symmetry via vacuum expectation values in SU(3)-adjoint scalars down to a left-right symmetric theory. Simultaneously, it ensures the unification of the gauge and Yukawa couplings as well as proton stability. Although the low-energy regime (e.g., mass hierarchies in the scalar sector determined by a soft SUSY-breakin[…] to revive the once very popular trinifica

DOI: 10.1103/PhysRevD.95.075031

PHYSICAL REVIEW D **99,** 035041 (2019)

Scale hierarchies, symmetry breaking, and particle spectra in SU(3)-family extended SUSY trinification

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(Received 26 July 2018; published 27 February 2019)

A unification of left-right $SU(3)_L \times SU(3)_R$, color $SU(3)_C$, and family $SU(3)_F$ symmetries in a maximal rank-8 subgroup of E_8 is proposed as a landmark for future explorations beyond the Standard Model (SM). We discuss the implications of this scheme in a supersymmetric (SUSY) model based on the trinification gauge $[SU(3)]^3$ and global $SU(3)_F$-family symmetries. Among the key properties of this model are the unification of SM Higgs and lepton sectors, a common Yukawa coupling for chiral fermions, the absence of the μ problem, gauge couplings unification, and proton stability to all orders in perturbation theory. The minimal field content consistent with a SM-like effective theory at low energies is composed of one E_6 **27-plet** per generation as well as three gauge and one family SU(3) octets inspired by the fundamental sector of E_8. The details of the corresponding (SUSY and gauge) symmetry-breaking […] effective low-energy scenarios are

Eur. Phys. J. C (2020) 80:1162
https://doi.org/10.1140/epjc/s10052-020-08710-4

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Theoretical Physics

Prospects for new physics from gauge left-right-colour-family grand unification hypothesis

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Received: 13 September 2020 / Accepted: 20 November 2020 / Published online: 17 December 2020

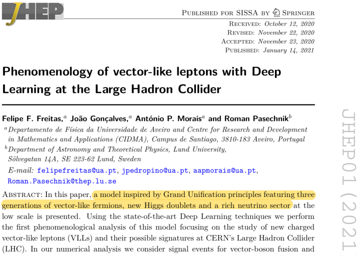
Abstract Given the tremendous phenomenological success of the Standard Model (SM) framework, it becomes increasingly important to understand to what extent its specific structure dynamically emerges from unification principles. In this study, we present a novel anomaly-free supersymmetric (SUSY) Grand Unification model based upon gauge trinification $[SU(3)]^3$ symmetry and a local $SU(2)_F \times U(1)_F$ family symmetry, with particle spectra and gauge symmetries inspired by a possible reduction pattern $E_8 \to E_6 \times SU(2)_F \times U(1)_F$, with subsequent $E_6 \to [SU(3)]^3$ symmetry breaking step. In this framework, higher-dimensional operators of E_6 induce the threshold corrections in the gauge and Yukawa interactions leading, in particular, to only two distinct Yukawa couplings in the fundamental sector of the resulting $[SU(3)]^3 \times SU(2)_F \times U(1)_F$ Lagrangian. Among the appealing features emergent in this framework are the Higgs-matter unification and a unique minimal three Higgs doublet scalar sector at the electroweak scale as well as tree-

achieved, a consensual explanation for the observed features of the particle spectra and interactions observed in nature is still lacking. Along these lines, while over the past forty years the strong and electroweak (EW) interactions have been extensively probed and confirmed in various experiments, their origin at a more fundamental level is still unknown. Besides, the existing SM framework is not capable of explaining some of the observed phenomena such as the specific patterns and hierarchies in its fermion spectra nor contains a suitable candidate for Dark Matter. At last, but not least, it cannot explain the observed matter-antimatter asymmetry in the Universe.

Typically, these problems are addressed separately in different contexts. In order to describe the origin of the SM gauge interactions one typically refers to Grand Unified Theories (GUTs) where larger continuous symmetries contain the SM gauge group, e.g. SU(5), SO(10), or E_6 [3–13]. A common procedure to resolve the flavour problem in minimal

Emergent features from Higgs-matter unification

- Three generations of up- and down-type Higgs doublets
- Only first and second generation quark masses are generated at tree-level
- Masses of leptons and first generation quarks are radiatively induced
- Cabibbo mixing generated at tree-level while small CKM elements are of radiative nature
- Model predicts three generations of VLL doublets and up to two generations of VLQ singlets at TeV scale


JHEP
PUBLISHED FOR SISSA BY SPRINGER
RECEIVED: October 12, 2020
REVISED: November 22, 2020
ACCEPTED: November 23, 2020
PUBLISHED: January 14, 2021

Phenomenology of vector-like leptons with Deep Learning at the Large Hadron Collider

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ABSTRACT: In this paper, a model inspired by Grand Unification principles featuring three generations of vector-like fermions, new Higgs doublets and a rich neutrino sector at the low scale is presented. Using the state-of-the-art Deep Learning techniques we perform the first phenomenological analysis of this model focusing on the study of new charged vector-like leptons (VLLs) and their possible signatures at CERN's Large Hadron Collider (LHC). In our numerical analysis we consider signal events for vector-boson fusion and

JHEP01(2021)

- Proton decay constrains the Unification scale $\Lambda_0 > 10^{16}$ GeV
- Soft-SUSY breaking in the usual way but constrained by VLQ searches $\Lambda_{\rm SUSY} \gtrsim 100$ TeV
- Gauge coupling unification is only achievable with large **650** and **2430** E_6 representations
- **The model is inspired on the E_8 symmetry but not really worked out**
- **SUSY-E_8 is an extraordinary candidate for the ultimate Higgs-matter-force unification in a single field**

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Nuclear Physics B 960 (2020) 115209

NUCLEAR PHYSICS B

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Exceptional unification of families and forces

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Received 19 August 2020; received in revised form 2 October 2020; accepted 4 October 2020
Available online 6 October 2020
Editor: Tommy Ohlsson

Abstract

This work considers the remarkable suggestion that the three families of quarks and leptons may be unified, together with the Higgs and gauge fields of the Standard Model (SM), into a single "particle", namely the **248** vector superfield of a ten-dimensional E_8 super Yang Mills (SYM) theory. Towards a realistic model along these lines, a class of orbifoldings based on $T^6/(\mathbb{Z}_N \times \mathbb{Z}_M)$ are proposed and explored, that can in principle break E_8 SYM down to the minimal supersymmetric standard model (MSSM), embedded in a larger group such as E_6, $SO(10)$ or $SU(5)$, together with other gauge group factors which can be broken by Wilson lines. A realistic model based on $T^6/(\mathbb{Z}_6 \times \mathbb{Z}_2)$ is presented. The orbifold breaks E_8 SYM down to a Pati-Salam gauge group in 4d, together with other gauge groups, which are subsequently broken to the

Outline

Defining the model

The E_8 group as a unified force and its adjoint $\mathbf{248}$ as a unified field.

$$E_8 \to E_6 \times \mathrm{SU}(3) \to \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$$

$$\mathbf{248} \to (\mathbf{78}, 1) \oplus (1, \mathbf{8}) \oplus (\mathbf{27}, \mathbf{3}) \oplus (\overline{\mathbf{27}}, \overline{\mathbf{3}})$$

> No Witten and gauge anomalies

> Standard matter must be embedded in $(\mathbf{27}, \mathbf{3})$

> The anti-chiral representation $(\overline{\mathbf{27}}, \overline{\mathbf{3}})$ is an unavoidable problem in 4d

- All matter would become vector-like due to mass terms as

$$M\,(\mathbf{27}, \mathbf{3})\,(\overline{\mathbf{27}}, \overline{\mathbf{3}}) \supset M(e_i e_i^c + \nu_i \nu_i^c + u_i u_i^c + d_i d_i^c + \cdots)$$

Defining the model

The E_8 group as a unified force and its adjoint $\mathbf{248}$ as a unified field.

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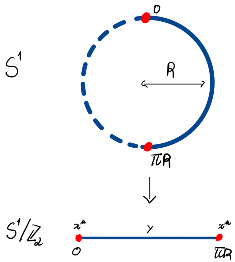
One needs a a theory in higher space-time dimensions where the compactification procedure projects-out unwanted matter

Example of a $S^1/\mathbb{Z}_2$ orbifold that compactifies 5d $\to$ 4d in the fixed points 0 and πR



- Identify $\mathcal{T} : y \to y + 2\pi R$
- Periodic boundary conditions $\Phi(x^\mu, y + 2\pi R) = \mathcal{T}\Phi(x^\mu, y)$
- Particle in a box analogy

> Identify points on the circle under the action $\theta : y \to -y$

$$\Phi(x^\mu, -y) = \omega\Phi(x^\mu, y) \qquad \text{with eignevalue} \qquad \omega = \pm 1$$

> $\mathbb{Z}_2$ even and odd modes expansion

$$\sum_{n=-\infty}^{\infty} \Phi_+^{(n)}(x^\mu) \cos\frac{ny}{R} \qquad \sum_{n=-\infty}^{\infty} \Phi_-^{(n)}(x^\mu) \sin\frac{ny}{R} \qquad m_n = (n/R)^2 \qquad m_0 = 0$$

- Mode expansion yields an infinite tower of particles $\rightarrow$ Kaluza-Klein (KK) modes
- Only the 4d $\Phi_{+}^{(0)}(x^{\mu})$ mode is massless
- Only part of the original $\Phi(x^{\mu}, y)$ sits in each of the fixed points
  - $\Phi_{+}^{(n)}(x^{\mu})$ in $y = 0$
  - $\Phi_{-}^{(n)}(x^{\mu})$ in $y = \pi R$
- **Symmetry broken in the fixed points**

Our model

$\mathcal{N}=1$ **SYM theory with a single E_8 vector superfield $\mathcal{V}_{(\mathbf{248})}(x,z_i)$ in 10d**

- Consider the orbifold $\mathbb{T}_6/(\mathbb{Z}_3\times\mathbb{Z}_3)$ by identifying (analogous to $\mathbb{Z}_2$ above)

$$\mathbb{Z}_3:\ (x,z_1,z_2,z_3)\sim(x,\omega^2 z_1,\omega^2 z_2,\omega^2 z_3),\quad \mathcal{V}_{(\mathbf{248})}\to e^{2i\pi q_8^F/3}\,\mathcal{V}_{(\mathbf{248})}$$
$$\mathbb{Z}_3:\ (x,z_1,z_2,z_3)\sim(x,\omega^3 z_1,\omega z_2,\omega^2 z_3),\quad \mathcal{V}_{(\mathbf{248})}\to e^{2i\pi q_8^C/3}\,\mathcal{V}_{(\mathbf{248})}$$

- $\mathbb{T}_6$ torus lattice defined by the translations (periodic boundary conditions)

$$\tau_i^1: z_i\to z_i+2\pi R_i,\quad \tau_i^2: z_i\to z_i+2\pi e^{i\pi/3}R_i,\quad \mathcal{V}(x,z_i)=U_i^r\,\mathcal{V}(x,z_i+\tau_i^r)$$

- Non-trivial gauge U_i^r transformations called Wilson lines

- Wilson lines further break the symmetry as they generate effective VEVs in extra-dim gauge vectors (scalars)

$$\text{4d vector:} \quad V(x,z_i) = \tilde{V}(x,z_i),$$

$$\text{4d scalars:} \quad \phi_i(x,z_i) = \tilde{\phi}(x,z_i) + \sum_r \alpha_i^{ar}\tau_i^r T_a,$$

Model completely defined with:

1. 3 R_i (scales)
2. 15 arbitrary Wilson line dimensionless parameters (VEVs)
3. 1 single gauge coupling

$$\mathbb{Z}_3: \ (x, z_1, z_2, z_3) \sim (x, \omega^2 z_1, \omega^2 z_2, \omega^2 z_3), \quad E_8 \to E_6 \times \mathrm{SU}(3)_\mathrm{F}$$

$$\mathbb{Z}_3: \ (x, z_1, z_2, z_3) \sim (x, \omega^3 z_1, \omega z_2, \omega^2 z_3), \quad E_8 \to E_6 \times \mathrm{SU}(3)_\mathrm{C}$$

$$\mathbb{Z}_3 \times \mathbb{Z}_3 : E_8 \to \mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R} \times \mathrm{SU}(3)_\mathrm{F}$$

	V	ϕ_1	ϕ_2	ϕ_3
$\mathcal{V}_{(\mathbf{8},\mathbf{1},\mathbf{1},\mathbf{1})}$	$1, 1$	$\omega^2, 1$	ω^2, ω	ω^2, ω^2
$\mathcal{V}_{(\mathbf{1},\mathbf{8},\mathbf{1},\mathbf{1})}$	$1, 1$	$\omega^2, 1$	ω^2, ω	ω^2, ω^2
$\mathcal{V}_{(\mathbf{1},\mathbf{1},\mathbf{8},\mathbf{1})}$	$1, 1$	$\omega^2, 1$	ω^2, ω	ω^2, ω^2
$\mathcal{V}_{(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{8})}$	$1, 1$	$\omega^2, 1$	ω^2, ω	ω^2, ω^2
$\mathcal{V}_{(\bar{\mathbf{3}},\mathbf{3},\mathbf{3},\mathbf{1})}$	$1, \omega^2$	ω^2, ω^2	$\omega^2, 1$	ω^2, ω
$\mathcal{V}_{(\mathbf{3},\bar{\mathbf{3}},\bar{\mathbf{3}},\mathbf{1})}$	$1, \omega$	ω^2, ω	ω^2, ω^2	$\omega^2, 1$

	V	ϕ_1	ϕ_2	ϕ_3
$\mathcal{V}_{(\mathbf{1},\bar{\mathbf{3}},\mathbf{3},\mathbf{3})}$	$\omega, 1$	$1, 1$	$1, \omega$	$1, \omega^2$
$\mathcal{V}_{(\mathbf{3},\mathbf{3},\mathbf{1},\mathbf{3})}$	ω, ω	$1, \omega$	$1, \omega^2$	$1, 1$
$\mathcal{V}_{(\bar{\mathbf{3}},\mathbf{1},\bar{\mathbf{3}},\mathbf{3})}$	ω, ω^2	$1, \omega^2$	$1, 1$	$1, \omega$
$\mathcal{V}_{(\mathbf{1},\mathbf{3},\bar{\mathbf{3}},\bar{\mathbf{3}})}$	$\omega^2, 1$	$\omega, 1$	ω, ω	ω, ω^2
$\mathcal{V}_{(\bar{\mathbf{3}},\bar{\mathbf{3}},\mathbf{1},\bar{\mathbf{3}})}$	ω^2, ω^2	ω, ω^2	$\omega, 1$	ω, ω
$\mathcal{V}_{(\mathbf{3},\mathbf{1},\mathbf{3},\bar{\mathbf{3}})}$	ω^2, ω	ω, ω	ω, ω^2	$\omega, 1$

Table: Decomposition of $\mathcal{V}_{\mathbf{248}}$: adjoint fields, Higgs and leptons, quarks, mirror Higgs and mirror fermions, mirror quarks, and exotics.

Zero modes from orbifolding

$$\begin{aligned} V_\mu &: (\mathbf{8},\mathbf{1},\mathbf{1},\mathbf{1}) + (\mathbf{1},\mathbf{8},\mathbf{1},\mathbf{1}) + (\mathbf{1},\mathbf{1},\mathbf{8},\mathbf{1}) + (\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{8}), \\ \phi_1 &: (\mathbf{1},\bar{\mathbf{3}},\mathbf{3},\mathbf{3}), \\ \phi_2 &: (\bar{\mathbf{3}},\mathbf{1},\bar{\mathbf{3}},\mathbf{3}), \\ \phi_3 &: (\mathbf{3},\mathbf{3},\mathbf{1},\mathbf{3}). \end{aligned}$$

> **Choose, without loss of generality, generic $\langle\phi_1\rangle$ while $\langle\phi_{2,3}\rangle = 0$**

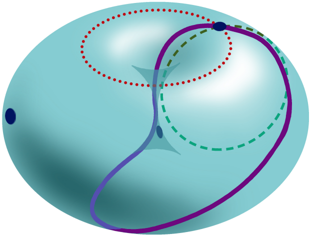
> **always preserves one $\mathrm{SU}(3)$ $\rightarrow$ identify with colour**

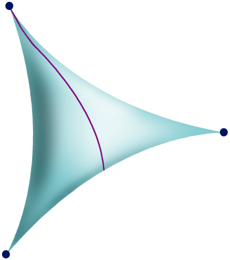
$$V_\mu : \Delta_C + \Delta_L + \Delta_R + \Delta_F, \quad \phi_1 : \mathbf{L}, \quad \phi_2 : \mathbf{Q}_R, \quad \phi_3 : \mathbf{Q}_L.$$

> Align $\langle\phi_1\rangle$ to preserve $\mathrm{SU}(2)\times\mathrm{U}(1) \rightarrow$ 9 zero and 6 non-zero parameters

$$\begin{aligned} V_\mu &: G_\mu + W_\mu + B_\mu, \\ \phi_1 &: L_i + e_i^c + h_{ui} + h_{di} + \varphi_i + \nu_i^c, \qquad i = 1,2,3 \\ \phi_2 &: u_i^c + d_i^c + D_i^c, \\ \phi_3 &: Q_i + D_i. \end{aligned}$$

$\mathbb{T}_2/\mathbb{Z}_3$ example: 1 complex extra-dimension visualization





- E_8 in the bulk $\rightarrow$ anomaly free ✓
- $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ **at the fixed points** $\rightarrow$ **anomaly free** ✓

Unique and simple $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R} \times \mathrm{SU}(3)_\mathrm{F}$ superpotential

$$\mathcal{W} = g\phi_1\phi_2\phi_3 = g\epsilon^{ijk}\mathbf{L}^{l}{}_{mi}\mathbf{Q}_{R}{}^{m}{}_{j}\mathbf{Q}_{Llk}$$

- g is the universal gauge-Yukawa coupling (up to CGC)
- $\mathbf{L}^3$ absent due to anti-symmetry $\rightarrow$ **no tree-level lepton masses**
- Absence of bilinear terms $\rightarrow$ **no μ-problem**

Wilson line effective VEVs in $\langle \mathbf{L} \rangle \sim \langle \varphi_i \rangle$, $\langle \nu_i^c \rangle$ yield $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$

$$\begin{aligned}\mathcal{W} =& g\varepsilon^{ijk}\Big(h_{ui}u_j^c Q_k + h_{di}d_j^c Q_k \\ &+ [\varphi_i + \langle\varphi_i\rangle] D_j^c D_k + [\nu_i^c + \langle\nu_i^c\rangle] d_j^c D_k \\ &+ e_i^c u_j^c D_k + L_i Q_j D_k^c\Big),\end{aligned}$$

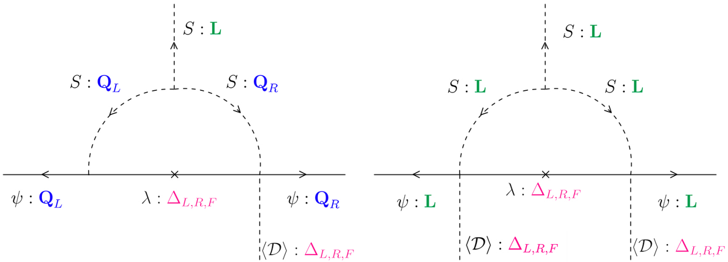
- First line: 2nd and 3rd generation quark masses
- **u and d quarks massless at tree-level**
- Second line: VLQ masses via $\langle\varphi\rangle$ and $d^c - \bar{D}$ mixing through $\langle\nu^c\rangle$

Wilson lines induce D-term SUSY breaking

$$\langle \mathcal{D}_A \rangle = \sum_{ij} \langle\nu_i^c\rangle^\dagger t_A \langle\nu_j^c\rangle + \langle\varphi_i\rangle^\dagger t_A \langle\varphi_j\rangle + \langle\varphi_i\rangle^\dagger t_A \langle\nu_j^c\rangle + \langle\nu_i^c\rangle^\dagger t_A \langle\varphi_j\rangle \neq 0,$$

- $\langle \mathcal{D}_A \rangle$ **further induces radiative masses for leptons, u and d quarks**

Chiral fermions



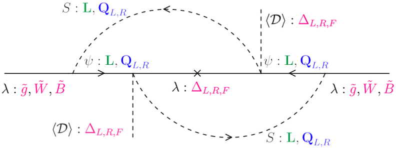
- **Quark and lepton masses are of SUSY-breaking origin and of radiative nature**

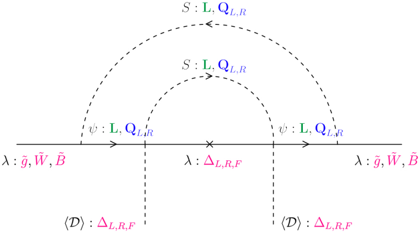
$$m_{t,c} \propto \left(g + \tilde{g}_1 \frac{\langle \mathcal{D} \rangle}{\Lambda^2} \right) \langle h_{ui} \rangle \quad m_{b,s} \propto \left(g + \tilde{g}_2 \frac{\langle \mathcal{D} \rangle}{\Lambda^2} \right) \langle h_{di} \rangle \quad m_{u,d} \propto \tilde{g}_{3,4} \frac{\langle \mathcal{D} \rangle}{\Lambda^2} \langle h_{(u,d)i} \rangle$$

$$m_{e,\mu,\tau} \propto \tilde{g}_5 \frac{\langle \mathcal{D} \rangle^2}{\Lambda^4} \langle h_{di} \rangle \qquad m_{\nu_i} \propto \tilde{g}_6 \frac{\langle \mathcal{D} \rangle^2}{\Lambda^4} \frac{\langle h_{ui} \rangle^2}{\langle \nu^c \rangle}$$

- Rich flavour structure with 6 different $\langle h_{ui} \rangle$ and $\langle h_{di} \rangle$ VEVs
- **Possible explanation for observed hierarchies from first principles**

- Broken gauginos and scalar masses are of tree-level origin generated close to the compactification scale $1/R$
- $\langle \mathcal{D} \rangle$ preserves the SM and cannot directly give masses to SM-partner gauginos
- **Realized at two-loop order**





$$m_g \propto g^4 l^2 \frac{\langle \mathcal{D} \rangle^{5/2}}{\Lambda^4}$$

Outline

Predicting the unification scale

> **The E_8 theory contains a single, universal, gauge coupling g_8**

> **The SM must emerge form the geometrical properties of the 10d space-time**

1. three $\mathbb{T}_6$ radii
2. six Wilson lines / effective VEVs

> **Several KK modes that contribute to the RG-running of the theory**

Power law running for a given parameter $\mathcal{P}$

$$\beta_{\mathcal{P}}^{(1)} \to \beta_{\mathcal{P}}^{(1)} + [S(\mu,\delta) - 1]\,\tilde{\beta}_{\mathcal{P}}^{(1)} \qquad S(\mu,\delta) = X_\delta \left(\frac{\mu}{\mu_{\mathrm{KK}}}\right)^{\delta} \text{ for } \mu \geqslant \mu_{\mathrm{KK}}$$

$X_\delta = \frac{2\pi^{\delta/2}}{\delta\Gamma(\delta/2)}$ comes from an integral regulator [Dienes et al. Phys. Lett. B436(1998), 55-65]

$\delta \to$ number of extra dimensions

$\mu_{\mathrm{KK}} \to$ the KK modes scale

Defining the scales:

$$\{\mathrm{E}_8\}_{10\mathrm{d}} \xrightarrow{\Lambda_0} \{\mathrm{E}_6 \times \mathrm{SU}(3)_\mathrm{C}\}^{\mathrm{KK}}_{6\mathrm{d}} \xrightarrow{\Lambda_1} \{\mathrm{E}_6 \times \mathrm{SU}(3)_\mathrm{C}\}^{0}_{6\mathrm{d}} \xrightarrow{\Lambda_2}$$
$$\{\mathrm{U}(1)_\mathrm{Y} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{C}\}^{\mathrm{KK}-1}_{4\mathrm{d}} \xrightarrow{\Lambda_3} \{\mathrm{U}(1)_\mathrm{Y} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{C}\}^{\mathrm{KK}-2}_{4\mathrm{d}} \xrightarrow{\Lambda_4}$$
$$\{\mathrm{U}(1)_\mathrm{Y} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{C}\}^{0}_{4\mathrm{d}} \xrightarrow{\Lambda_5} \{\mathrm{U}(1)_\mathrm{Y} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{C}\}^{0}_{4\mathrm{d}-\mathrm{NHDM}}$$

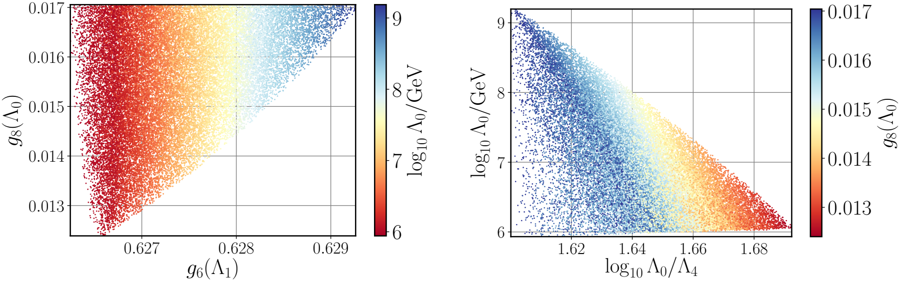
- $\Lambda_0 = 1/R_1$ is the GUT scale and where 10d $\to$ 6d compactification
- Λ_1 is where E_8 KK modes wear out
- $\Lambda_2 = 1/R_{2,3}$, 6d $\to$ 4d and $E_6 \to SU(3)_L \times SU(3)_R \times SU(3)_F$
- $\Lambda_3 \approx \Lambda_2$ Wilson-lines scale with SUSY and quartification breaking
- Λ_4 lightest KK modes wear out
- $\Lambda_5 \sim \mathcal{O}(\mathrm{TeV})$ scale of new physics

Fast power-law running in the region $\Lambda_0 \to \Lambda_1$

$$\beta^{(1)}_{g_{3,6}}(\mu) \approx \frac{\tilde{b}_{3,6}}{16\pi^2}\left[\frac{\pi^2}{3}\left(\frac{\mu}{\Lambda_1}\right)^6 - 1\right] g^3_{3,6}\,, \quad \tilde{b}_{3,6} = -5\,, \qquad g_3(\Lambda_0) = g_6(\Lambda_0) = g_8$$

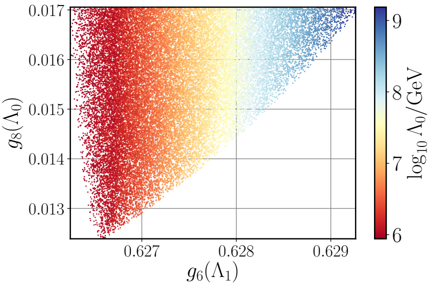
Numerical scan

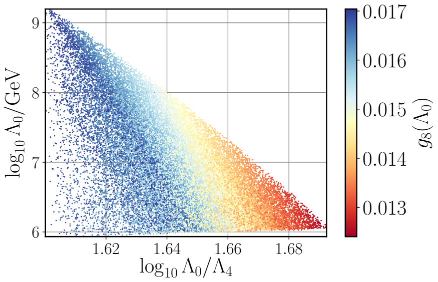
$\log_{10}\frac{\Lambda_0}{\text{GeV}}$	$\log_{10}\frac{\Lambda_1}{\text{GeV}}$	$\log_{10}\frac{\Lambda_2}{\text{GeV}}$	$\log_{10}\frac{\Lambda_3}{\text{GeV}}$	$\log_{10}\frac{\Lambda_4}{\text{GeV}}$	$\log_{10}\frac{\Lambda_5}{\text{GeV}}$	$g_8(\Lambda_0)$	$g_6(\Lambda_2)$	$g_{1,2,3}(m_Z)$
calculated	*calculated*	*calculated*	$[\Lambda_4, \Lambda_4^{1.15}]$	$[4, 15]$	3.0	*calculated*	*calculated*	*SM values*



1. High predictive power with $g_6(\Lambda_1) \approx 0.63$ and $0.01 < g_8(\Lambda_0) < 0.02$
2. **Full low scale unification of families, forces, Higgs and matter :**

$$\mathbf{1000\ TeV} \lesssim \Lambda_0 \lesssim \mathbf{1000\ PeV}$$



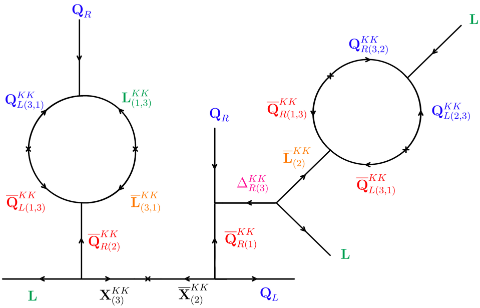


1. High predictive power with $g_6(\Lambda_1) \approx 0.63$ and $0.01 < g_8(\Lambda_0) < 0.02$
2. **Full low scale unification of families, forces, Higgs and matter :**

$$\mathbf{1000\ TeV} \lesssim \Lambda_0 \lesssim \mathbf{1000\ PeV}$$

3. What about proton decay?

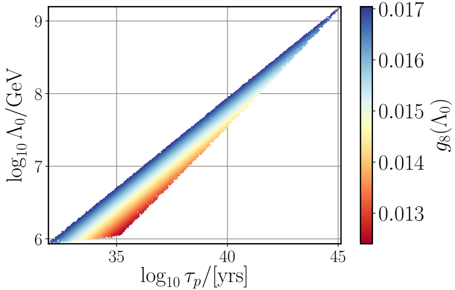
Leading order contribution that generates $L_i Q_k u_f^{c\dagger} d_l^{c\dagger} (\delta_f^i \delta_l^k - \delta_l^i \delta_f^k)$ operators



1. Highly suppressed by two loops and internal KK propagators
2. Involves two different generations thus the decay is to Kaons
3. With the flipped embedding proton decay only takes place at E_8 level

Decay width to Kaons and leptons

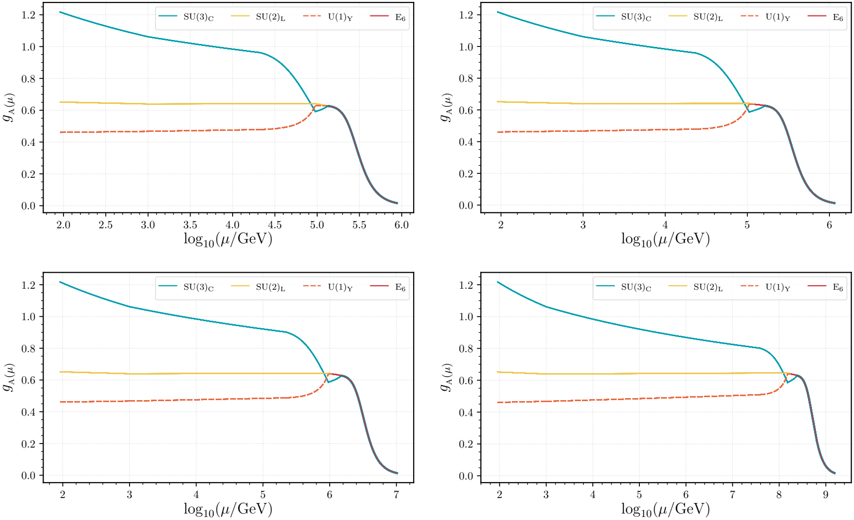
$$\Gamma_{p\to K+L} \sim g^{18} l^4 \left\langle \tilde{\nu}^{c\dagger s} \tilde{\nu}^{c}_{s} \right\rangle^2 \frac{m_p^5}{\Lambda_0^8},$$



- All points satisfy $\tau_{p\to K+L} > 1.1 \times 10^{32}$ yrs with $l = 0.08$

$$\boxed{\mathrm{O}(10^{32}) \lesssim \tau_{p\to K+L}/\mathrm{yrs} \lesssim \mathrm{O}(10^{45})}$$

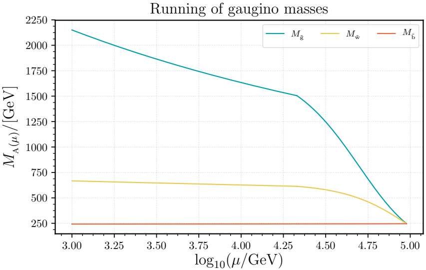
- **Model consistent with low-scale Grand Unification**


SU(3)C
SU(2)L
U(1)Y
E6
$g_{\mathrm{A}}(\mu)$
$\log_{10}(\mu/\mathrm{GeV})$

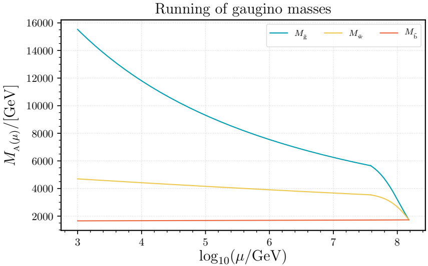
Gaugino masses

Gaugino masses are radiatively generated at two-loop at the Λ_3 scale and one can estimate

$$m_g(\Lambda_3) \approx 6^{5/2} g_3^4 l^2 \Lambda_3$$



(a) Lower Λ_0 with $l = 0.015$



(b) Larger Λ_0 with $l = 0.001$

KK modes relevant for keeping the lower unification scenario viable

Outline

Generating the electroweak scale

Proof of concept analysis:

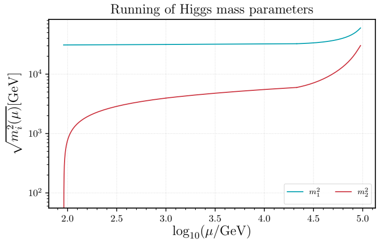
- Consider only the two lightest Higgs doublets H_u and H_d below Λ_3 scale
- Remaining scalars heavier than Λ_3 (up to a factor of 30)
- **Consider an effective 2HDM-like theory with exotic fermions**

$$V(H_u, H_d) = m_1^2 H_d^\dagger H_d + m_2^2 H_u^\dagger H_u + \lambda_1 (H_d^\dagger H_d)^2 + \lambda_2 (H_u^\dagger H_u)^2 + \lambda_3 (H_d^\dagger H_d)(H_u^\dagger H_u) \\ + \lambda_4 (H_d^\dagger H_2)(H_u^\dagger H_d) + \frac{1}{2}\lambda_5 \left[(H_u^\dagger H_d)^2 + \text{h.c.}\right] + m_{12}^2 \left(H_u^\dagger H_d + \text{h.c.}\right)$$

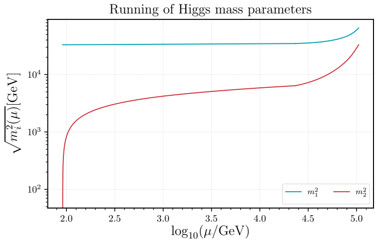
$$\mathcal{L} \supset y_t u^c Q H_u + y_b d^c Q H_d + y_{\tilde{b}1} \tilde{b} \tilde{H}_d H_d + y_{\tilde{b}2} \tilde{b} \tilde{H}_u H_u + y_{\tilde{w}1} \tilde{w} \tilde{H}_d H_d + y_{\tilde{w}2} \tilde{w} \tilde{H}_u H_u \\ + M_{\text{E}} \tilde{H}_u \tilde{H}_d + M_{\text{EL}} \tilde{H}_u L + \text{h.c.}$$

$$-\lambda_1 \approx -\lambda_2 \approx -\lambda_3 \approx \lambda_4 \approx \lambda_5 \approx \frac{1}{4} g_2^2 \,, \quad y_{\tilde{b}1} \approx y_{\tilde{b}2} \approx y_{\tilde{w}1} \approx \sqrt{2} g_1 \,, \quad y_{\tilde{w}2} \approx \sqrt{2} g_2 \,.$$

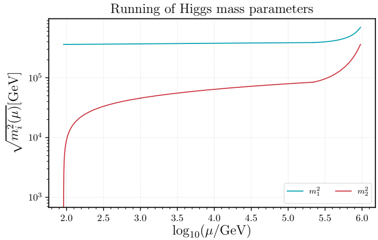
[Morais, Pasechnik, Porod, Eur.Phys.J.C 80 (2020) 12, 1162]



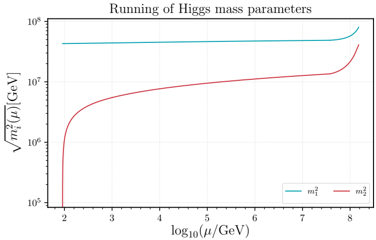
(a) $\sqrt{-m_{H_u}^2} = 186$ GeV, $m_{H_d} = 30.9$ TeV, $m_2 = 30.3$ TeV, $m_1 = 60.1$ TeV, $m_g = 1$ TeV.



(b) $\sqrt{-m_{H_u}^2} = 162$ GeV, $m_{H_d} = 33.1$ TeV, $m_2 = 33.2$ TeV, $m_1 = 65.0$ TeV, $m_g = 1$ TeV.



(c) $\sqrt{-m_{H_u}^2} = 161$ GeV, $m_{H_d} = 361$ TeV, $m_2 = 362$ TeV, $m_1 = 700$ TeV, $m_g = 1$ TeV.

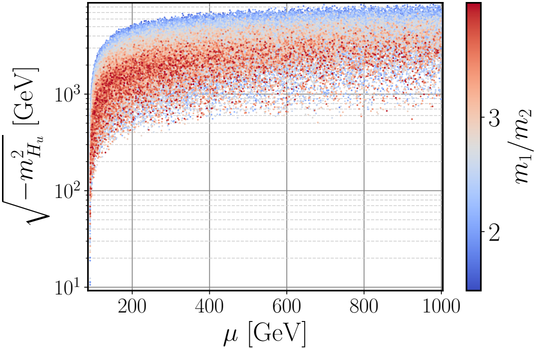


(d) $\sqrt{-m_{H_u}^2} = 155$ GeV, $m_{H_d} = 42.9$ PeV, $m_2 = 41.1$ PeV, $m_1 = 80.0$ PeV, $m_g = 173$ TeV.

Elecroweak symmetry can be radiatively generated with the correct size

The 4 scenarios shown feature $m1/m2 \approx 2$. How generic is this and how often REWSB holds?

Λ_3/TeV	m_1/GeV	m_2/GeV	m_g/GeV	y_t	y_b
100	$[0.1\Lambda_3, \Lambda_3]$	$[\frac{1}{4}m_1, m_1]$	$[300, 3000]$	$[0.6, 0.85]$	$[0.3, 0.6]$



- **Plenty of solutions with REWSB**
- The model features a light Higgs boson mostly aligned with H_{u1} while the remaining are of order Λ_3
- The third-lightest Higgs can induce FCNCs **if lighter than $150\ \mathrm{TeV}$**

  [Branco, Ferreira, Lavoura, Rebelo, Sher, Silva, Phys. Rept.516(2012), 1-102]
- FCNC condition may be met somewhere between scenarios (b) and (c)
- Radiative stability of the Higgs mass may point towards $\Lambda_0 \sim \mathcal{O}(10^6\ \mathrm{GeV})$

Outline

Concluding remarks

- **We have built the first model featuring a complete low-scale unification of the SM with stable proton**
- Our model proposes a common, first principles, description of the family replication and gauge interactions found in nature
- Highly predictive power with $g_6(\Lambda_1) \approx 0.63$ and $0.01 < g_8(\Lambda_0) < 0.02$
- Full calculation of the particle spectrum will fix the freedom of the model

Either rules it out or results in concrete and well defined new physics predictions with precise determination of scales, masses and couplings

Concluding remarks

- **We have built the first model featuring a complete low-scale unification of the SM with stable proton**
- Our model proposes a common, first principles, description of the family replication and gauge interactions found in nature
- Highly predictive power with $g_6(\Lambda_1) \approx 0.63$ and $0.01 < g_8(\Lambda_0) < 0.02$
- Full calculation of the particle spectrum will fix the freedom of the model

Either rules it out or results in concrete and well defined new physics predictions with precise determination of scales, masses and couplings

Manpower needed!!