

Radiatively Induced Fermi Scale in Grand Unified Theories

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CP³ Origins

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In collaboration with A. Meroni, F. Sannino, and K. Tuominen
[arXiv:1511.01910](https://arxiv.org/abs/1511.01910)

[Phys.Rev. D91 \(2015\) 9, 095021](#) (TA, H. Gertov, F. Sannino, K. Tuominen)

[Phys.Rev. D92 \(2015\) 9, 095003](#) (H. Gertov, A. Meroni, E. Molinaro, F. Sannino)

Outline

- I Introduction
- II Elementary Goldstone Higgs
- III Pati–Salam Unification
- IV Conclusion and Outlook

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Introduction

Grand Unification

- Why is the SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$?
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Two time-honoured schemes

Georgi–Glashow	Pati–Salam
<ul style="list-style-type: none">• Unification of colour and electroweak interactions to e.g. $SU(5)$ or $SO(10)$• Gauge-mediated proton decay• $\Lambda_{\text{GUT}} \gtrsim 10^{15}$ GeV	<ul style="list-style-type: none">• Unification of colour and lepton number to $SU(4)_{\text{LC}}$• No proton decay via gauge interactions• Leptoquarks mediate rare kaon decay $K_L \rightarrow \mu^\pm e^\mp$• $\Lambda_{\text{GUT}} \gtrsim 1.9 \times 10^6$ GeV

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- The SM scalar potential: $V_{\text{SM}} = m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$
 - ▶ Higgs mass 125 GeV $\Rightarrow \lambda_H = 0.13$
 - ▶ $m_H^2 = -\lambda_H v_w^2$

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- **But:** SM feels the GUT scalars via portal interaction $\lambda_{\text{mix}} H^\dagger H \text{Tr}[P^\dagger P]$
 - ▶ $\langle P \rangle$ induces a mass term $\sim \lambda_{\text{mix}} \Lambda_{\text{GUT}}^2$ for H
 - ▶ λ_{mix} has to be highly suppressed ($\lambda_{\text{mix}} \lesssim v_w^2 / \Lambda_{\text{GUT}}^2$)
 \Rightarrow Huge hierarchy between λ_{mix} and λ_H

Emergent Fermi scale due to vacuum misalignment

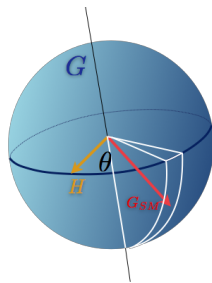
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- Embed EW gauge group into G
 - ▶ If G large enough, possibility of different embeddings
 - ▶ Amount of EW breaking as $G \rightarrow H$ depends on the alignment of H wrt EW group
 - ▶ If $\sin \theta$ gives the alignment, then $v_W = \sin \theta \langle \sigma \rangle$
 - ▶ If $\theta \ll 1$, then $\langle \sigma \rangle \gg v_W$
- Pushes origin of EWSB and new physics to higher scales!



[Figure: A. Meroni]

II

Elementary Goldstone Higgs

$SU(4) \rightarrow Sp(4)$ breaking pattern

- The breaking $SU(4) \rightarrow Sp(4)$ can be achieved by a scalar M transforming in $\mathfrak{6}_A \in SU(4)$
 - ▶ Leaves behind 5 GB's, Π_i
 - ▶ These decompose as $(2,2) + (1,1)$ under $SU(2)_L \times SU(2)_R$
 \Rightarrow Allows for SM-like Higgs bi-doublet of GB's
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- Freedom of different alignments between EW group and $Sp(4)$
 - ▶ GB-like vacuum E_{GB} leaves EW intact
 - ▶ Higgs-like vacuum E_H breaks $EW \rightarrow U(1)_Q$
 - ▶ In general, a superposition of these $E = \cos\theta E_{GB} + \sin\theta E_H$

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 - ▶ In general, a superposition of these $E = \cos\theta E_{GB} + \sin\theta E_H$
- Composite-Higgs scenario of $SU(4) \rightarrow Sp(4)$ breaking already studied [[Cacciapaglia & Sannino 2014](#)]
 - ▶ $SU(2)_{TC}$ gauge group with 2 Dirac fermions

Electroweak gauge sector

- Embed the full chiral symmetry group of the SM $SU(2)_L \times SU(2)_R$ into $SU(4)$
 - Gauge the EW symmetry \Rightarrow This breaks the global symmetry explicitly

- As M acquires vev, the EW bosons get masses

$$m_W^2 = \frac{1}{4}g^2 v^2 \sin^2 \theta, \text{ and } m_Z^2 = \frac{1}{4}(g^2 + g'^2)v^2 \sin^2 \theta$$

- The vacuum angle θ is *a priori* a free parameter

Standard Model fermions

- Since we have elementary scalars, we can give the Standard Model fermions masses without invoking further dynamics
- For the quantum vacuum analysis, the top quark is the dominant
- We add Yukawa term

$$\mathcal{L}_{\text{Yuk}} = y_t (Qt^c)_\alpha^\dagger \text{Tr}[P_\alpha M] + \text{h.c.}$$

- ▶ The projectors P_α pick the components of M transforming as $\text{SU}(2)_L$ doublet
- ▶ Similarly, we add interactions for other SM fermions
- The top gets mass as M acquires vev, $m_t = \frac{y_t}{\sqrt{2}} v \sin \theta$

One-loop potential

- The true vacuum is determined by quantum corrections
- Calculate the one-loop potential
 - ▶ $V^{(1)}(\Phi) = \frac{1}{64\pi^2} \text{Str} \left[M^4(\Phi) \left(\log \frac{M^2(\Phi)}{\mu_0^2} - C \right) \right]$
- The electroweak and fermion (top) sectors break the global SU(4) symmetry at one-loop level
 - ▶ Picks a preferred value for the vacuum angle θ
 - ▶ Gives mass to the pseudo-Goldstone boson Π_4
 - ▶ Mixing between σ and Π_4

III

Pati-Salam Unification

Symmetry structure

- Global symmetry of the scalar sector $SU(4)_\chi$
 - ⇒ The natural unification scenario is à la Pati–Salam
 - ▶ Unify colour with lepton number
 - ⇒ $SU(4)_{LC}$ of leptocolour
 - ⇒ The full symmetry $G = SU(4)_\chi \times SU(4)_{LC}$
- The simplest realisation to illustrate the idea
 - ▶ M breaks $SU(4)_\chi \rightarrow Sp(4)_\chi$
 - ▶ Add another scalar multiplet, P , to break the leptocolour

The scalar potential

- The simplest scalar potential is $V = V_M + V_P + V_{MP}$, where

$$V_M = \frac{1}{2} m_M^2 \text{Tr}[M^\dagger M] + \frac{\lambda_M}{4} \text{Tr}[M^\dagger M]^2,$$

$$V_P = \frac{1}{2} m_P^2 \text{Tr}[P^\dagger P] + \lambda_{P1} \text{Tr}[P^\dagger P]^2 + \lambda_{P2} \text{Tr}[P^\dagger P P^\dagger P],$$

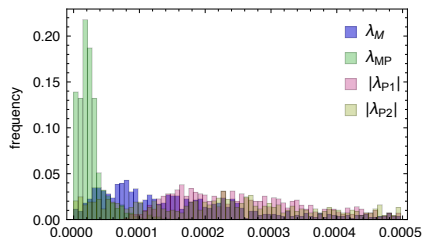
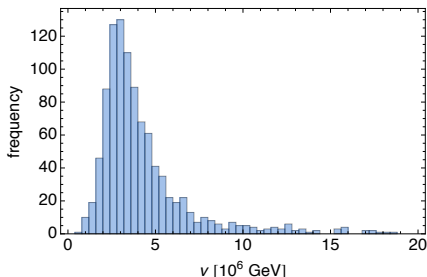
$$V_{MP} = \frac{\lambda_{MP}}{4} \text{Tr}[M^\dagger M] \text{Tr}[P^\dagger P]$$

Results

- Fix $\Lambda_{\text{GUT}} = \langle P \rangle = 2.5 \cdot 10^6 \text{ GeV}$
(above the experimental bound)
- Is it possible to find parameters that
 - 1 give the correct EW spectrum
($v \sin \theta = v_W$)
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- Is it possible to find parameters that
 - 1 give the correct EW spectrum ($v \sin \theta = v_W$)
 - 2 produce the correct Higgs mass?
- Yes!
 - ▶ Typically $v \sim \Lambda_{\text{GUT}}$
 - ▶ All quartic couplings are small ($\lesssim 0.01$) **but** no large hierarchy between them
 - ▶ The mass parameters of the same order



Conclusions and Outlook

- Vast hierarchy between the Fermi and the unification scale
- No hierarchy problem if the Fermi scale generated radiatively
 - ▶ Extended global symmetry & vacuum misalignment $\Rightarrow v_W = v \sin \theta$
 - ▶ If $\theta \ll 1$, possible that $v \sim \Lambda_{\text{GUT}}$
- Viable realisation within the Pati–Salam framework
 - ▶ Quartic scalar couplings small, but of the same order

Possible further avenues:

- Dark Matter
 - ▶ One more EW-singlet GB \Rightarrow a DM candidate
- Neutrinos
 - ▶ Natural inclusion of right-handed neutrinos because of SU(4) global symmetry (either type I or II see-saw easily realised)
- Inflation
 - ▶ $\lambda_i \ll 1 \Rightarrow$ Higgs inflation with $\xi = \mathcal{O}(1)$ non-minimal coupling?

Thank you!