Radiatively Induced Fermi Scale in Grand Unified Theories

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CP³ Origins

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Outline

I

Introduction

Grand Unification

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

Georgi–Glashow	Pati–Salam
• Unification of colour and electroweak interactions to e.g. SU(5) or SO(10) • Gauge-mediated proton decay • $\Lambda_\mathrm{GUT} \gtrsim 10^{15}$ GeV	• Unification of colour and lepton number to $\mathrm{SU}(4)_\mathrm{LC}$ • No proton decay via gauge interactions • Leptoquarks mediate rare kaon decay $K_\mathrm{L} \to \mu^\pm e^\mp$ • $\Lambda_\mathrm{GUT} \gtrsim 1.9 \times 10^6$ GeV

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

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  - $m_H^2 = -\lambda_H v_{\text{w}}^2$
- **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 ($\lambda_{\text{mix}} \lesssim v_{\text{w}}^2/\Lambda_{\text{GUT}}^2$)

    $\Rightarrow$ Huge hierarchy between λ_{mix} and λ_H

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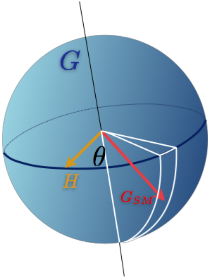
- Embed EW gauge group into G
  - If G large enough, possibility of different embeddings
  - Amount of EW breaking as $G \to H$ depends on the alignment of H wrt EW group
  - If $\sin\theta$ gives the alignment, then $v_W = \sin\theta \langle \sigma \rangle$
  - If $\theta \ll 1$, then $\langle \sigma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



[Figure: A. Meroni]

Outline: Towards a viable model

- The idea of radiative Fermi scale due to vacuum misalignment is very general
- In the following I will present a concrete (and simplest) model where this can be attained
- This postpones the hierarchy problem of the SM to a higher scale
  - Want to postpone it not just to a few TeV scale but up to the GUT scale $\Rightarrow$ Introduce a concrete unification framework
  - The simplest option turns out to be of Pati–Salam type
- This results in a phenomenologically viable model with correct low-energy spectrum

II

Elementary Goldstone Higgs

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

- The breaking $SU(4) \to Sp(4)$ can be achieved by a scalar M transforming in $6_A \in SU(4)$
  - 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$\to U(1)_Q$
  - 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 $SU(4) \to Sp(4)$ 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 $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R}$ into $\mathrm{SU}(4)$
  - 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

- Assign the SM fermions into the fundamental representation of SU(4)

$$\mathbf{L}_i = (L, \widetilde{\nu}, \widetilde{\ell})^T_{i\mathrm{L}} \sim 4, \qquad \mathbf{Q}_i = (Q, \widetilde{q}^{\mathrm{u}}, \widetilde{q}^{\mathrm{d}})^T_{i\mathrm{L}} \sim 4,$$

  where $i = 1, 2, 3$ and $\widetilde{f}_{\mathrm{L}} = (f_{\mathrm{R}})^c$
  - Need RH neutrinos to fill the lepton multiplets
- Add Yukawa terms

$$\begin{aligned}-\mathscr{L}_{\mathrm{Yuk}} =& \frac{Y^{\mathrm{u}}_{ij}}{\sqrt{2}}(Q_i^T P_\alpha Q_j)^\dagger \mathrm{Tr}[P_\alpha M] + \frac{Y^{\mathrm{d}}_{ij}}{\sqrt{2}}(Q_i^T \overline{P}_\alpha Q_j)^\dagger \mathrm{Tr}[\overline{P}_\alpha M] \\ &+ \frac{Y^{\nu}_{ij}}{\sqrt{2}}(L_i^T P_\alpha L_j)^\dagger \mathrm{Tr}[P_\alpha M] + \frac{Y^{\ell}_{ij}}{\sqrt{2}}(L_i^T \overline{P}_\alpha L_j)^\dagger \mathrm{Tr}[\overline{P}_\alpha M] + \mathrm{h.c.}\end{aligned}$$

  - The projectors P_α and $\overline{P}_\alpha$ pick the $\mathrm{SU}(2)_{\mathrm{L}}$ doublets in M
- Fermions get masses as M acquires vev, $m_f = \frac{y_f}{\sqrt{2}} v \sin\theta$

One-loop potential

- The true vacuum is determined by quantum corrections
- Calculate the one-loop potential
  - $V^{(1)}(\Phi) = \frac{1}{64\pi^2}\mathrm{Str}\left[M^4(\Phi)\left(\log\frac{M^2(\Phi)}{\mu_0^2} - C\right)\right]$
- 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 $\mathrm{SU}(4)_\chi$
  $\Rightarrow$ The natural unification scenario is à la Pati–Salam
  - Unify colour with lepton number
    $\Rightarrow \mathrm{SU}(4)_{\mathrm{LC}}$ of leptocolour
    $\Rightarrow$ The full symmetry $G = \mathrm{SU}(4)_\chi \times \mathrm{SU}(4)_{\mathrm{LC}}$
- The simplest realisation to illustrate the idea
  - M breaks $\mathrm{SU}(4)_\chi \to \mathrm{Sp}(4)_\chi$
  - 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

$$V_M = \frac{1}{2} m_M^2 \mathrm{Tr}[M^\dagger M] + \frac{\lambda_M}{4} \mathrm{Tr}[M^\dagger M]^2,$$
$$V_P = \frac{1}{2} m_P^2 \mathrm{Tr}[P^\dagger P] + \frac{\lambda_P}{4} \mathrm{Tr}[P^\dagger P]^2,$$
$$V_{MP} = \frac{\lambda_{MP}}{4} \mathrm{Tr}[M^\dagger M] \mathrm{Tr}[P^\dagger P]$$

Results

- Fix $\Lambda_{\text{GUT}} = \langle P \rangle = 2.5 \cdot 10^6$ GeV (above the experimental bound)
- Is it possible to find parameters that
  1. give the correct EW spectrum ($v \sin\theta = v_{\text{w}}$)
  2. produce the correct Higgs mass?

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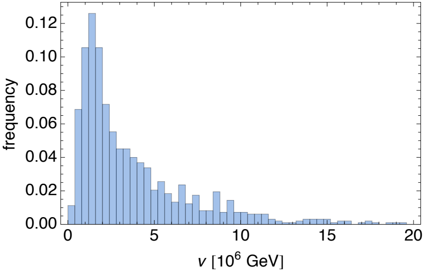
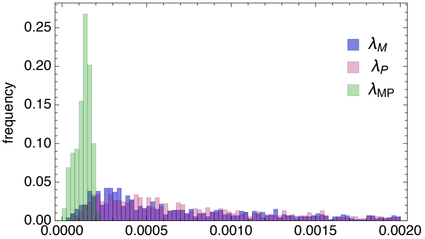
- Is it possible to find parameters that
  1. give the correct EW spectrum ($v \sin\theta = v_{\rm w}$)
  2. produce the correct Higgs mass?
- Yes!
  - Typically $v \sim \Lambda_{\rm GUT}$
  - All quartic coupings are small ($\lesssim 0.01$) **but** no large hierarchy between them
  - The mass parameters 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 ⇒ $v_w = v \sin\theta$
  - If $\theta \ll 1$, possible that $v \sim \Lambda_{\mathrm{GUT}}$
- 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 ⇒ 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)

Thank you!