Vacuum Alignment and Radiatively Induced Fermi Scale

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CP³ Origins

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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 Raising the origin of the Fermi scale

III Goldstone-boson Higgs and Unification

IV Conclusion

I

Introduction

Unbearable lightness of being

- Why is the Fermi scale so low and the Higgs so light?
  - Large hierarchy between e.g. Λ_{GUT} or M_{Planck}
- Hierarchy problem could be solved by introducing new sector of strong dynamics
  - Perfect example: QCD
  - The Higgs mass is light compared to the natural scale $4\pi v_w$
  - Cannot produce fermion masses without further extensions
- Invoke some new symmetry protecting Higgs mass
  - SUSY is the time-honored example along this line
  - Requires a large amount of new, still unobserved, particles
  - New hierarchy problem with the SUSY-breaking scale

Unification

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 • $\Lambda_{\text{GUT}} \gtrsim 10^{15}$ GeV	• Unification of colour and lepton number to $SU(4)_{\text{LC}}$ • No proton decay via gauge interactions • Leptoquarks mediate rare kaon decay $K_{\text{L}} \to \mu^{\pm} e^{\mp}$ • $\Lambda_{\text{GUT}} \gtrsim 1.9 \times 10^{6}$ 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 $\Rightarrow \lambda_H = 0.13$
  - $m_H^2 = -\lambda_H v_{\text{w}}^2$

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  - $m_H^2 = -\lambda_H v_{\rm w}^2$
- **But:** SM feels the GUT scalars via portal interaction $\lambda_{\rm mix} H^\dagger H\, {\rm Tr}[P^\dagger P]$
  - $\langle P \rangle$ induces a mass term $\sim \lambda_{\rm mix} \Lambda_{\rm GUT}^2$ for H
  - $\lambda_{\rm mix}$ has to be highly suppressed ($\lambda_{\rm mix} \lesssim v_{\rm w}^2/\Lambda_{\rm GUT}^2$)

    $\Rightarrow$ Huge hierarchy between $\lambda_{\rm mix}$ and λ_H

II

Raising the origin of the Fermi scale

Emergent Fermi scale due to vacuum misalignment

- Enlarge the symmetry of the SM scalar sector to G
  - SSB $G \to H$ via a scalar vev $\langle\sigma\rangle$
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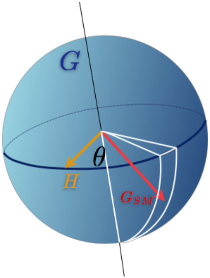
- Embed EW gauge group into G
  - If G large enough, possibility of different embeddings
  - Amount of EW breaking as $G \to H$ depends on the alignment of H wrt EW group
  - If $\sin\theta$ gives the alignment, then $v_\mathrm{W} = \sin\theta \, \langle \sigma \rangle$
  - If $\theta \ll 1$, then $\langle \sigma \rangle \gg v_\mathrm{W}$
- Pushes origin of EWSB and new physics to higher scales!



[Figure: A. Meroni]

Elementary vs. composite Higgs

Composite

- Physical cut-off $\Lambda \sim 4\pi f$ (compositeness scale) $\Rightarrow$ Below Λ dominant contributions to effective potential $\sim M^2\Lambda^2$
- Top corrections prefer SM-like vacuum $\theta = \pi/2$
- Need extra explicit breaking to get small θ
- [Peskin,'80 & Preskill '81]

Elementary

- Renormalisable $\Rightarrow$ One-loop corrections calculable and given by the Coleman–Weinberg potential $\sim M^4\left(\log\frac{M^2}{\mu_0^2} - C\right)$
- Top corrections prefer Goldstone-boson-like vacuum $\theta = 0$
- Heavy scalars important for the vacuum alignment $\Rightarrow$ No extra explicit breaking needed

III

Goldstone-boson Higgs and Unification

$\mathrm{SU}(4) \to \mathrm{Sp}(4)$ breaking pattern

- The breaking $\mathrm{SU}(4) \to \mathrm{Sp}(4)$ achieved by a scalar M in $6_{\mathrm{A}} \in \mathrm{SU}(4)$
  - Leaves behind 5 GB's, Π_i
  - These decompose as $(2,2)+(1,1)$ under $\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}}$
    $\Rightarrow$ Allows for SM-like Higgs bi-doublet of GB's
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- 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 and SM fermions

- Embed $\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}}$ into SU(4)
  - Gauge the EW symmetry ⇒ Breaks SU(4) explicitly
- As M acquires vev, the EW bosons get masses

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

- Elementary scalars ⇒ masses for SM fermions without further dynamics
- For the vacuum analysis, the top quark is dominant
- The top gets mass as M acquires vev, $m_t = \frac{y_t}{\sqrt{2}} v \sin\theta$
- The vacuum angle θ is *a priori* a free parameter

One-loop potential

- The true vacuum is determined by quantum corrections
- Calculate the one-loop Coleman–Weinberg 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 EW and 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

    $\Rightarrow$ pGB Higgs

Simplest unification scenario

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

Results

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

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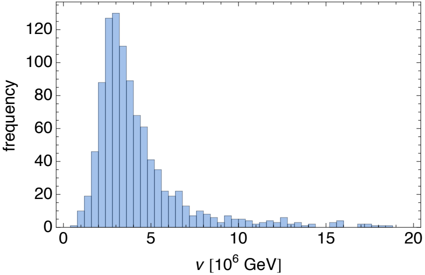
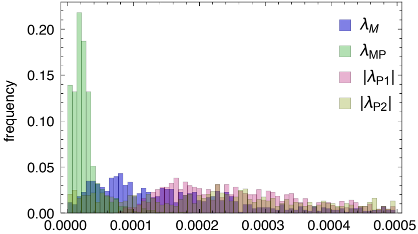
- Is it possible to find parameters that
  1. give the correct EW spectrum ($v \sin\theta = v_{\text{w}}$)
  2. produce the correct Higgs mass?
- Yes!
  - Typically $v \sim \Lambda_{\text{GUT}}$
  - All quartic coupings are small ($\lesssim 0.01$) **but** no large hierarchy between them
  - The mass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





Conclusions

- Vast hierarchy between the Fermi and the unification scale
- No hierarchy problem if the Fermi scale generated radiatively
  - Extended global symmetry & vacuum misalignment $\Rightarrow v_w = v \sin\theta$
  - Vacuum alignment different for elementary and composite scalars
- Viable realisation connecting unification and Fermi scalers within the Pati–Salam framework
  - If $\theta \ll 1$, possible that $v \sim \Lambda_{\mathrm{GUT}}$
  - Quartic scalar couplings tiny ($\sim \sin^2\theta$), but of the same order

Thank you!