Composite vs. elementary pseudo-Goldstone Higgs

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Outline

I Motivational notes

II Enhanced global symmetries

III Vacuum misalignment and pGB Higgs

IV Model examples

V Conclusions

Beware!

Or: I don't (a priori) mind elementary scalars, and this is not a talk about the naturalness problem!

I

Motivational notes

QCD

- QCD with two massless quarks $q = (u, d)$:

$$\mathscr{L} = \overline{q}_{\mathrm{L}} \mathrm{i} \not{D} q_{\mathrm{L}} + \overline{q}_{\mathrm{R}} \mathrm{i} \not{D} q_{\mathrm{R}}$$

  - Global $\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}}$ chiral symmetry

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- RG: gauge coupling large at low energies
  - Non-zero vev $\langle\overline{q}q\rangle\sim 4\pi f_\pi^3$
    $\Rightarrow$ dynamical masses for mesons and baryons
  - Characteristic QCD scale $4\pi f_\pi\approx m_p$

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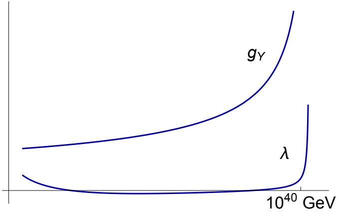
- Mass gap: pions light, only about 140 MeV
  - GB's of $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \to \mathrm{SU}_\mathrm{V}$
  - But: u, d not quite massless $\Rightarrow$ chiral symmetry explicitly broken
    $\Rightarrow$ Masses for pions $\Rightarrow$ pseudo-GB's
  - EW interactions $\Rightarrow$ Mass splitting between $\pi^\pm$ and π^0

What is disturbing with the EW sector?

- SM is not all
    - Landau poles / triviality
    - DM, matter–antimatter asymmetry, origin of neutrino masses, inflation...?



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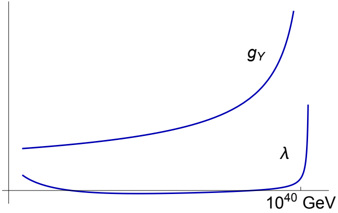


- Still the Higgs mass is light (and EWSB scale low)
  - Why is it not sensitive to the new-physics scale?
  - Why don't we observe anything else at EW scale?
- What if the real symmetry-breaking scale f were much higher?
  - EW scale $v_W = 246\,\text{GeV}$ just radiatively generated
  - Higgs a pGB related to the symmetry breaking

II

Enhanced global symmetries

Composite

- Take N_f fermions $Q = (Q_1, \ldots, Q_{N_f})$ on rep. R of gauge group G
  - Kinetic terms have global $\mathrm{SU}(N_f)_\mathrm{L} \times \mathrm{SU}(N_f)_\mathrm{R}$ symmetry
  - However, if R is (pseudo)real, the global symmetry is enhanced to $\mathrm{SU}(2N_f)$
- R real: $\mathrm{SU}(2N_f) \to \mathrm{SO}(2N_f)$
  - $\mathrm{SU}(4) \to \mathrm{SO}(4)$: Two Dirac fermions on the adjoint of $G = \mathrm{SU}(2)_\mathrm{TC}$
  - The $\mathrm{SU}(4)/\mathrm{SO}(4)$ coset does not contain the Higgs doublet
- R pseudoreal: $\mathrm{SU}(2N_f) \to \mathrm{Sp}(2N_f)$
  - $\mathrm{SU}(4) \to \mathrm{Sp}(4)$: Two Dirac fermions on the fundamental of $G = \mathrm{SU}(2)_\mathrm{TC}$
  - Minimal composite-Higgs scenario with underlying 4D fermionic model
- R complex: $\mathrm{SU}(N_f)_\mathrm{L} \times \mathrm{SU}(N_f)_\mathrm{R} \to \mathrm{SU}(N_f)_\mathrm{V}$

Elementary

- Scalar potential can have an enhanced global symmetry as well
  - E.g. SM: V_H has $\mathrm{SO}(4) \cong \mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R}$ global symmetry
- General idea [Weinberg, PRL29 (1972)]:
  - Take scalar, S, on rep. R of gauge group G
  - Write the most general potential
  - Impose renormalisability

    ⇒ Potential truncated at order 4

    ⇒ The resulting potential is "more symmetric" than G, since not all operators are allowed

Minimal scenarios for pGB Higgs

- Need 4 GB's transforming as (2,2) under $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R}$ to be able to build the SM-Higgs doublet out of GB's
- Original idea $\mathrm{SU}(3)_\mathrm{L} \times \mathrm{SU}(3)_\mathrm{R} \to \mathrm{SU}(3)_\mathrm{V}$
  [Georgi & Kaplan, PLB136B (1984)]
- SO(5)/SO(4)
  - Minimal breaking pattern: 4 GB's
  - No underlying 4D fermionic realisation
  - Minimal Composite Higgs [Agashe, Contino, Pomarol, NPB719 (2005)]
- $\mathrm{SO}(6)/\mathrm{SO}(5) \cong \mathrm{SU}(4)/\mathrm{Sp}(4)$
  - 5 GB's, $(2,2)+(1,1)$
  - 2 Dirac fermions on fundamental of SU(2)

[Katz, Nelson, Walker, JHEP0508 (2005),
Gripaios, Pomarol, Riva, Serra, JHEP0904 (2009),
Galloway, Evans, Luty, Tacchi, JHEP1010 (2010),
Barnard, Gherghetta, Ray, JHEP 1402 (2014),
Ferretti & Karateev, JHEP1403 (2014),
Cacciapaglia & Sannino, JHEP 1404 (2014)]

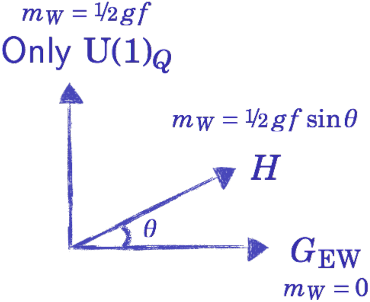
III

Vacuum misalignment and pGB Higgs

EW embedding and vacuum misalignment

- Enhanced global symmetry $G \to H$
  - Identify the $\mathrm{SU}(2) \times \mathrm{SU}(2)$ subgroup as the SM chiral group
  - Gauge $G_{\mathrm{EW}} = \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_Y$ subgroup
- What is the relative alignment of G_{EW} and H?
  - H should include at least $\mathrm{U}(1)_Q$, but is there more?
- Simplest case: this can be parameterised by an angle
  - Clever parameterisation of the vacuum: $E_\theta = \cos\theta E_0 + \sin\theta E_{\mathrm{B}}$
  - Angle θ determined by radiative effects:

$$\left.\frac{\partial V_{\mathrm{eff}}}{\partial\theta}\right|_{\mathrm{vac}} = 0$$



Sources for misalignment

- To determine the alignment, need to evaluate the radiative effects from the explicit breaking sectors to the effective potential
  - (EW) gauge interactions
  - SM-fermion masses
  - Vector-like masses for the new fermions
  - Extra scalars
  - ...
- If the model is perturbative, the one-loop effective potential can be calculated:

$$V_1 = -\frac{\mathrm{i}}{2}\int \frac{\mathrm{d}^4 k}{(2\pi)^4}\mathrm{Str}\left[\log\left(k^2 + M^2(\phi_c)\right)\right] + \text{ c.t.}$$

  - With hard Euclidean cut-off, $k_{\mathrm{E}}^2 = \Lambda^2$, this yields

$$V_1 = \frac{1}{64\pi^2}\mathrm{Str}\left[\Lambda^4\left(\log\Lambda^2 - \frac{1}{2}\right) + 2M^2(\phi_c)\Lambda^2 + M^4(\phi_c)\left(\log\frac{M^2(\phi_c)}{\Lambda^2} - \frac{1}{2}\right)\right] + \text{c.t.}$$

The role of different UV realisations

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The role of different UV realisations

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the alignment)
⇒ Ignore

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Renormalisable model: Set conter terms to cancel the divergent parts

⇒ The dominant term

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Physical cut-off: Set counter
terms at the cut-off scale
⇒ Below the cut-off effective
theory description
⇒ Dominant contributions
proportional to the cut-off

Elementary pGB's?

- Only fermions: generating the SM-fermion masses is a tricky business
  - 4f interactions / partial compositeness from extended strong dynamics?
- Extended elementary scalar sectors: can you solve the triviality and phenomenological issues, and still decouple the high-scale physics?

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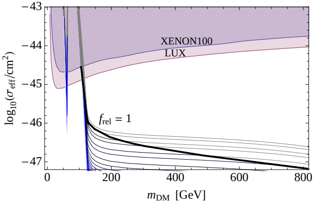
  - 4f interactions / partial compositeness from extended strong dynamics?
- Extended elementary scalar sectors: can you solve the triviality and phenomenological issues, and still decouple the high-scale physics?
- Can the extra GB's be DM?
  - Topological terms can break the apparent Z_2 symmetry in the chiral Lagrangian and make the composite pGB's unstable [Wess & Zumino, PLB37 (1971), Witten NPB223 (1983)]
    - ★ The remaining pGB in composite SU(4)/Sp(4) cannot be DM [Cacciapaglia & Sannino, JHEP1404 (2014), Duan, da Silva, Sannino, NPB592 (2001)]
  - If the pGB's are elementary, this is not a problem
    - ★ Elementary SU(4)/Sp(4) can accommodate DM [TA, Gertov, Sannino, Tuominen, PRD91 (2015)]



Elementary vs. composite Higgs

Composite	Elementary
● Dominant term $\sim \mathrm{Tr}[M^2]f^2$ ● Gauge symmetry wants to be unbroken [Peskin, NPB175 (1980), Preskill, NPB177 (1981)] ● If the SM fermions get masses via the condensate, TC-like vacuum preferred ● Need some other source to obtain a pGB Higgs	● CW potential: dominant term $\mathrm{Tr}[M^4(\log M^2 + C)]$ ● Logarithmic terms change the picture: for SM field content the opposite alignment to the composite scenario ● Non-trivial scalar sector affects the alignment [TA, Gertov, Meroni, Sannino, PRD94 (2016)] ● DM candidates?

IV

A concrete model example: Elementary SO(5)/SO(4)

[TA, Gertov, Meroni, Sannino, PRD94 (2016)]

DoF's

- Minimal coset, i.e. 4 GB's transforming as bi-doublet under $\mathrm{SU(2)_L \times SU(2)_R \cong SO(4)}$
    - Embed $\mathrm{SU(2)_L \times SU(2)_R}$ subgroup to SO(5) by identifying the left and right generators

$$(T_{\mathrm{L,R}})^a_{ij} = -\frac{\mathrm{i}}{2}\left[\frac{1}{2}\epsilon^{abc}\left(\delta^b_i\delta^c_j - \delta^b_j\delta^c_i\right) \pm \left(\delta^a_i\delta^4_j - \delta^a_j\delta^4_i\right)\right]$$

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- There are two vacua that do not break $U(1)_Q$:

$$E_0 = (0,0,0,0,1) \text{ and } E_\mathrm{B} = (0,0,1,0,0)$$

  - E_0 does not break EW, E_B breaks it completely to $U(1)_Q$
  - General vacuum a linear combination $E_\theta = \cos\theta E_0 + \sin\theta E_\mathrm{B}$

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  - General vacuum a linear combination $E_\theta = \cos\theta E_0 + \sin\theta E_\mathrm{B}$
- Parameterise the scalar DoF's as a linear sigma model around the vacuum E_θ : $\Phi = (\sigma + \mathrm{i}\Pi^a X^a)E_\theta$
- SO(5)-symmetric potential: $V_0 = \dfrac{m_\Phi^2}{2}\Phi^\dagger\Phi + \dfrac{\lambda}{4!}(\Phi^\dagger\Phi)^2$

Gauge boson and SM fermion masses

- At the SSB, $\langle\sigma\rangle = v$, EW gauge bosons get masses

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

  - Identify $v_{\mathrm{w}} = v \sin\theta$
- Writing the (SO(5)-breaking) Yukawa terms between the SM fermions and the EW doublet in Φ gives the fermions masses

$$m_f = \frac{y_f}{\sqrt{2}} v \sin\theta$$

- Both proportional to $v \sin\theta$

The CW potential

- The effective potential up to one-loop order is then
$$V_{\text{eff}} = V_0 + V_1^{\text{scalar}} + V_1^{\text{ferm}} + V_1^{\text{gauge}}$$
- In the $\overline{\text{MS}}$ scheme the contributions to the CW potential (in ϕ background) are

$$\begin{aligned}
V_1^{\mathrm{scalar}} &= \frac{1}{64\pi^2}\mathrm{Tr}\left[M^4(\phi)\left(\log\frac{M^2(\phi)}{\mu_0^2}-\frac{3}{2}\right)\right],\\
V_1^{\mathrm{gauge}} &= \frac{3}{64\pi^2}\mathrm{Tr}\left[\mu^4(\phi)\left(\log\frac{\mu^2(\phi)}{\mu_0^2}-\frac{5}{6}\right)\right],\\
V_1^{\mathrm{ferm}} &= -\frac{4}{64\pi^2}\mathrm{Tr}\left[\left(m^\dagger(\phi)m(\phi)\right)^2\left(\log\frac{m^\dagger(\phi)m(\phi)}{\mu_0^2}-\frac{3}{2}\right)\right],
\end{aligned}$$

- A convenient renormalisation condition is to require that the vev stays at the tree-level value: $\left.\dfrac{\partial V_{\text{eff}}}{\partial\sigma}\right|_{\sigma=v} = 0$

Vacuum alignment?

- Minimize V_{eff} wrt $\theta \Rightarrow$ Only solution $\theta = 0$
    - The EW does not break
    - No non-trivial alignments without further ingredients
    - Cf. composite case: top contributions would prefer $\theta = \pi/2$

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- But: Add an extra Z_2-symmetric singlet scalar, S

$$V_0 \rightarrow \frac{m_\Phi^2}{2}\Phi^\dagger\Phi + \frac{m_S^2}{2}S^2 + \frac{\lambda}{4!}(\Phi^\dagger\Phi)^2 + \frac{\lambda_{\Phi S}}{4}(\Phi^\dagger\Phi)S^2 + \frac{\lambda_S}{4!}S^2$$

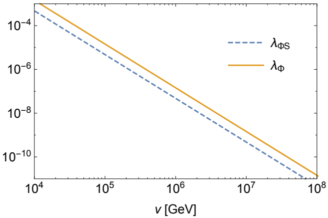
  - Now solutions for small θ for $\sin^2\theta \propto \lambda_{\Phi S}$
    $\Rightarrow$ a pGB Higgs possible with non-minimal scalar sector!
  - $\theta \ll 1$ requires tiny quartic couplings
    $\Rightarrow$ Extra scalar states are very decoupled

V

Theme and variations

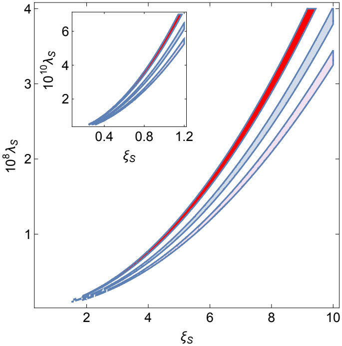
Cosmic connections: EWSB & Inflation

- Could cosmic inflation and EWSB be connected?
- Best-known example: Higgs inflation
  [Bezrukov & Shaposhnikov, PLB659 (2008)]
  - The SM Higgs inflation requires a very large non-minimal coupling to gravity $\xi R(H^\dagger H)$, $\xi \sim 10^4$
  - Unitarity of gravitational Higgs–Higgs scattering?
- Similarly for inflation driven by an additional singlet, S:
  $\xi_S \approx 49000\sqrt{\lambda_S}$
  - Inflation with $\xi_S \sim \mathcal{O}(1)$, if $\lambda_S \lesssim 10^{-8}$
- Can the extra singlet, S, required in SO(5)/SO(4) be the inflaton if non-minimally coupled to gravity?



pGB Higgs & Inflation?

- Yes, it can [TA, Sannino, Tenkanen, Tuominen, PRD 95 (2017)]
  - Inflaton would trigger EWSB
  - Symmetry breaking near the inflation scale
    $\Rightarrow$ The scalar self-couplings tiny
    $\Rightarrow$ Already a very small non-minimal coupling ($\xi < 1$) is enough
  - For $0.1 < \xi_S < 10$ and $N \approx 60$, we obtain the spectral index $n_s \approx 0.9678$ and tensor-to-scalar ratio $0.0030 < r < 0.0078$



The correct $\mathscr{P}_R$ for $N = 55, 60, 65$ (red,blue,purple)

Hierarchy between Unification and Fermi scales

- Two vastly separated energy scales: Λ_{GUT} and $v_{\mathrm{w}} = 246$ GeV
- The symmetry breaking steps are modelled via scalar sectors
  - $\langle P \rangle \sim \Lambda_{\mathrm{GUT}}$ and $\langle H \rangle = v_w$
- The SM scalar potential: $V_{\mathrm{SM}} = m_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$
  - Physical Higgs mass 125 GeV $\Rightarrow \lambda_H = 0.13$
  - $m_H^2 = -\lambda_H v_{\mathrm{w}}^2$

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

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

Pati–Salam Unification

- As an example, consider $\mathrm{SO}(6)/\mathrm{SO}(5) \cong \mathrm{SU}(4)/\mathrm{Sp}(4)$ global symmetry pattern ⇒ The natural unification scenario is à la Pati–Salam
  - Unify colour with lepton number
    $\Rightarrow \mathrm{SU}(4)_{\mathrm{LC}}$ of leptocolour
    ⇒ The full symmetry $G = \mathrm{SU}(4)_{\mathrm{glo}} \times \mathrm{SU}(4)_{\mathrm{LC}}$
- The simplest realisation to illustrate the idea
  [TA, Meroni, Sannino, Tuominen, PRD 93 (2016)]
  - $M \sim (6_{\mathrm{A}}, 1) \in G$ breaks $\mathrm{SU}(4)_{\mathrm{glo}} \to \mathrm{Sp}(4)_{\mathrm{glo}}$
  - Add another scalar multiplet to break the leptocolour: $P \sim (1,4) \in G$

Results

- Fix $\Lambda_{\rm UT} = \langle P \rangle = 2.5 \cdot 10^6$ 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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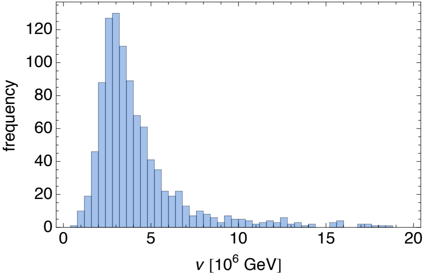
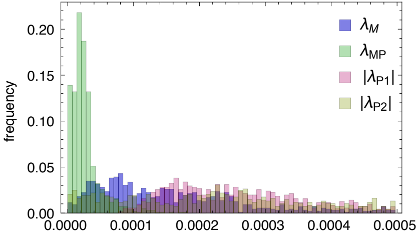
  1. give the correct EW spectrum ($v \sin\theta = v_{\mathrm{W}}$)
  2. produce the correct Higgs mass?
- Yes!
  - Typically $v \sim \Lambda_{\mathrm{UT}}$
  - All quartic coupings are small ($\lesssim 0.01$) **but** no large hierarchy between them
  - The mass parameters of the same order
  - EWSB originates from the Unification scale





Conclusions and Outlook

- Different UV realisations imply different phenomenology
  - Composite framework more famous, but elementary realisation can also provide interesting possibilities
  - In a renormalisable model, a pGB Higgs can be obtained by extending the scalar sector
- Minimal scenario SO(5)/SO(4)
  - Minimal composite Higgs, but no 4D fermionic realisation
  - With elementary scalars intriguing possibilities with e.g. inflation or unification scenarios

Possible further avenues:

- Neutrinos
  - Type I See-Saw: RH neutrinos with Majorana masses near the symmetry breaking scale?
- FIMP dark matter
  - High SSB scale ⇒ Self-couplings tiny

Thank you!