GAUGE MEDIATION OF EXACT SCALE BREAKING

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Naturalness problem and new physics

- Higgs boson discovered in July 2012

Naturalness problem is even more timely now, given the existence of the scalar particle

POSSIBLE ROUTES:

Higgs as a Goldstone mode of a broken symmetry

- Global symmetry (Composite Models, Little Higgs)
- Scale invariance (Higgs is actually a dilaton)

Symmetry to protect Higgs mass from quant. corrections

- Supersymmetry
- Scale invariance

Scale invariance to protect Higgs mass

- The Higgs is a fundamental scalar (doublet as in the SM)
- Mass terms are forbidden in scale invariant theory
- $\Rightarrow$ Higgs mass term could be protected by scale symmetry
- But: Scale symmetry is explicitly broken by RG running (Quantum Anomaly)

TWO APPROACHES

Classical scale invariance

Bardeen '95; Meissner, Nicolai '06; ...

- Scale invariance at a classical level as a principle
- Coleman Weiberg mechanism at quantum level breaks it

Exact (quantum) scale invariance

- Theory emanates from a quantum UV fixed point analogous to asymptotic safety idea Weinberg '76, Shaposhnikov - Wetterich '09
- Exact scale symmetry in the UV

Coleman Weinberg mechanism

- Assume classical scale invariance is a principle
- $\Rightarrow$ Tree level lagrangian without dimensionful terms
- Scale symmetry is broken by quantum effects
- Example: complex scalar coupled to $U(1)$ gauge boson
- Compute effective potential and renormalize it

$$V_{eff} = \frac{\lambda}{4!}|\phi|^4 + \frac{3g^4}{64\pi^2}|\phi|^4\left(\log\frac{|\phi|^2}{\mu^2} - \frac{25}{6}\right) \qquad \frac{\partial^2 V}{\partial\phi^2}|_{\phi=0} = 0 \quad \frac{\partial^4 V}{\partial\phi^4}|_{\phi=\mu} = \lambda$$

- We imposed no generation of mass terms!
- Minimization leads to dimensional transmutation

$$\langle\phi\rangle = \mu e^{\frac{11}{6} - \frac{4\pi^2\lambda}{9g^4}}$$

- Ratio of mass over vev is a prediction of the model

$$m_\phi^2 = \frac{\partial V^2}{\partial\phi^2}|_{\phi=\langle\phi\rangle} \qquad \frac{m_\phi^2}{\langle\phi\rangle^2} = \frac{3g^4}{8\pi^2}$$

- $\Rightarrow$ Cannot work in SM

Can classical symmetry be a guiding principle in a UV complete theory?

EXACT SCALE INVARIANCE AND THE HIGGS MASS

- UV complete the theory with exact scale invariance at quantum level
- In the UV, the theory merges into a CFT
- $\Rightarrow$ Scale invariance restoration in the UV protects the Higgs mass from large radiative corrections coming from high energies
- Can this protect enough the Higgs mass?

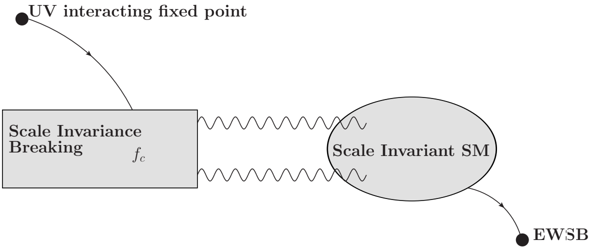
HIGGS MASS NATURALNESS AND SCALE INVARIANCE TAVARES, SCHMALTZ, SKIBA'13

- The UV fixed point cannot be free theory, otherwise it does not tame the divergences in Higgs mass
- $\Rightarrow$ One needs an interacting UV fixed point
- There exists a high scale where the running of the couplings deviates from SM towards the UV fixed point
- The Higgs mass is sensitive to this scale (naively at one loop)
- $\Rightarrow$ This scale cannot be too large (few TeV)
- At this scale we expect new physics $\Leftarrow$ Experimental constraints

?? Can we improve these features ??

IDEA: MEDIATION OF EXACT SCALE BREAKING S.ABEL, A.M '13

- Use a modular structure for the UV completion
- Split breaking of scale invariance (in a Hidden Sector) from SM sector
- Assume SM and Hidden Sector emanate from UV scale invariant theories
- Assume SM and Scale Breaking Sector (Hidden) are connected only via gauge interactions
- ⇒ Add a loop of protection to Higgs mass w.r.t. previous arguments



- Scale invariance breaking is communicated to the Higgs via loops effects
- ⇒ Operators proportional to f_c are generate in Higgs potential
- The true dilaton resides in the hidden sector

SETUP

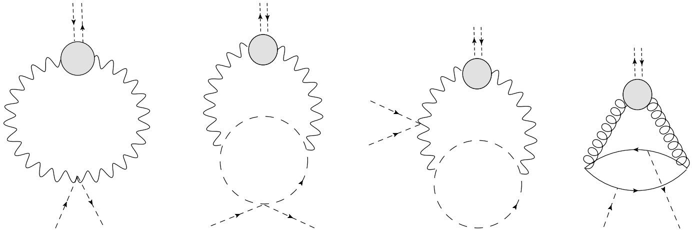
- Assume SM and Scale Breaking Sector are connected only via gauge interactions (perturbative)
- Lagrangian schematically (modular structure)

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{hid} + gA_\mu(J^\mu_{vis} + J^\mu_{hid})$$

- Parameterize hidden sector in terms of two point function

$$\langle J^\mu_{vis} J^\nu_{vis} \rangle = -(p^2\eta^{\mu\nu} - p^\mu p^\nu) C_{vis}(p^2, H^2)$$
$$\langle J^\mu_{hid} J^\nu_{hid} \rangle = -(p^2\eta^{\mu\nu} - p^\mu p^\nu) C_{hid}(p^2, f_c^2) \, .$$

- Effective potential induced by loops of gauge fields with C_{hid} insertions



Computation of Effective Potential

$$V_{tree} = \lambda (HH^\dagger)^2 \quad , \quad V_{loop} = \int \frac{d^4p}{(2\pi)^4} \log\left(1 + \frac{m_V^2}{p^2} + g^2 C_{vis}(p^2, H^2) + g^2 C_{hid}(p^2, f_c^2)\right),$$

- We are interested in relevant operators in the Higgs potential prop. to f_c
- Our assumptions imply that for $f_c \to 0$ no terms mixing the two sectors
- $\Rightarrow$ Effective potential results

$$V_{eff} = \lambda (HH^\dagger)^2 + \frac{9 g_2^4 \mathcal{A}_2}{16\pi^2} f_c^2 HH^\dagger \left(4\pi^2 - \lambda_t^2 (6 + 16 \frac{f_c^2 \mathcal{A}_3}{f_c^2 \mathcal{A}_2} \frac{g_3^4}{g_2^4}) + (\lambda - \frac{13}{8} g_2^2) \log \frac{HH^\dagger}{f_c^2}\right) .$$

- parameterize unknown hidden sector two point function integrals as

$$\mathcal{A}_a = \frac{1}{f_c^2} \int \frac{d^4p}{(2\pi)^4} \frac{1}{p^2} \left(C_{hid}^{(a)}(p^2, 0) - C_{hid}^{(a)}(p^2, f_c^2)\right) , a = SU(2), SU(3)$$

- $\mathcal{A}_a$ naturally at least two loop suppressed
- $\Rightarrow$ Loop suppressed f_c^2 determine EW scale

Effective potential simplified

- Parameterize Higgs as $H = e^{i\xi\cdot\tau}\begin{pmatrix} 0 \\ \phi/\sqrt{2} \end{pmatrix}$
- $\Rightarrow$ Effective potential can be written in terms of only physical quantities

$$V = \frac{\lambda}{4}\phi^4 + \frac{1}{4}\phi^2\left(-m_h^2 + \left(m_h^2 - 2\langle\phi\rangle^2\lambda\right)\log\left[\frac{\phi^2}{\langle\phi\rangle^2}\right]\right) .$$

- where minimization conditions implies

$$\frac{9Yg_2^4}{64\pi^2}\mathcal{A}_2 = X\frac{m_h^2}{f_c^2}\ ; \qquad Y = 13g_2^2 - 8\lambda\ ; \qquad X = \frac{2\langle\phi\rangle^2\lambda}{m_h^2} - 1$$

$$\mathcal{A}_3 = \frac{\pi^2}{18g_3^4\lambda_t^2}\left(1 + 16\frac{X}{Y}(2\pi^2 - 3\lambda_t^2) - \frac{X}{\pi^2}\log\frac{\langle\phi\rangle^2}{2f_c^2}\right)\frac{m_h^2}{f_c^2}$$

- Observations:
  - Electroweak scale two to three loops suppressed with respect to f_c

$$f_c \sim 10 - 100 \text{ TeV}$$

  - Hidden sectors ($\mathcal{A}_2$ and $\mathcal{A}_3$) related to λ and ratio $\frac{m_h^2}{\langle\phi\rangle^2}$
  - e.g.: given a value of λ, $\mathcal{A}_2$ should be > 0 or < 0 to obtain correct EWSB
  - *Higgs self coupling λ characterizes different phenomenologies*

Minimal computable case

- Assume hidden sector made of fermions and bosons with anomalous dimensions
- Matter in the Hidden Sector has mass f_c
- Matter content to compensate β function of SM gauge coupling
- C_{hid} can be computed perturbatively (1-loop) as a function of

$$n_B = \sum_{bosons} C(r_\phi) \quad , \quad n_F = \sum_{fermions} C(r_\psi) \quad , \quad \gamma_B \quad , \quad \gamma_F$$

- $\Rightarrow$ Simple expressions for $\mathcal{A}_a$ integral

$$\mathcal{A}_a = \frac{1}{(16\pi^2)^2} \left(2 \left(b_0^{SM} \right)_{(a)} + \frac{4n_B^{(a)}}{(\gamma_B^{(a)})^2} - \frac{8n_F^{(a)}}{\gamma_F^{(a)}} \right) \qquad a = SU(2), SU(3)$$

- Two independent sets of quantities for sector associated to $SU(2)$ and $SU(3)$
- $\mathcal{A}_2$ and $\mathcal{A}_3$ generically positive for this minimal perturbative model

Toy Model: Banks-Zaks fixed point

- $SU(N)$ theory with F Dirac fermions and a singlet scalar

$$\mathcal{L} = -\frac{1}{4g^2}F^2_{\mu\nu} + i\bar{\psi}\gamma.D\psi + \frac{1}{2}(\partial h)^2 - (y\bar{t}th + h.c.) - \lambda h^4$$

- Only F' fermions t are coupled to the singlet scalar ($F' < F$)
- $\Rightarrow$ There is a stable fixed point ($\beta_i = 0$) with couplings

$$4\pi N\{\alpha_{g*},\, \alpha_{y*},\, \alpha_{\lambda*}\} = 4\pi\frac{11\epsilon}{50}\left\{\frac{4}{3},\, \frac{N}{F'},\, \frac{N}{2F'}\right\} \qquad 0 < \epsilon \ll 1\,,\, F = \frac{11}{2}N(1-\epsilon)$$

Toy model SM

- Consider $SU(3)_{color}$ at a BZ fixed point, with $F = 15$ and $F' = 6$ quarks
- Toy Standard Model: $SU(3)$ gauge group with $F' = 6$ flavours coupled to a singlet scalar (the Higgs)

Toy model Hidden Sector

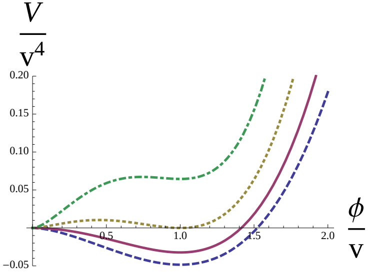
- $F - F' = 9$ not coupled to the Higgs and can be considered part of the HS
- They are coupled only to $SU(3)$ in the toy SM
- Embed $F - F' = 9$ in a gauge theory with UV fixed point

Phenomenology of Higgs potential

- Independently from hidden sector dynamics the Higgs potential results

$$V = \frac{\lambda}{4}\phi^4 + \frac{1}{4}\phi^2\left(-m_h^2 + \left(m_h^2 - 2\langle\phi\rangle^2\lambda\right)\log\left[\frac{\phi^2}{\langle\phi\rangle^2}\right]\right) .$$

- Three different phenomenology depending on value of λ (related to hidden sector $\mathcal{A}_a$, so depending on hidden sector properties)



- Expansion around EWSB vacuum

$$V = \frac{1}{4}\left(\langle\phi\rangle^4\lambda - m_h^2\langle\phi\rangle^2\right) + \frac{m_h^2 h^2}{2} + \left(\frac{m_h^2}{6\langle\phi\rangle} + \frac{2\langle\phi\rangle\lambda}{3}\right)h^3 + \left(\frac{\lambda}{3} - \frac{m_h^2}{24\langle\phi\rangle^2}\right)h^4$$

SM LIMIT: $\lambda = \frac{m_h^2}{2\langle\phi\rangle^2}$

- Recover SM potential around EWSB vacuum
  $V = -\frac{m_h^2\langle\phi\rangle^2}{8} + \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2\langle\phi\rangle}h^3 + \frac{m_h^2}{8\langle\phi\rangle^2}h^4$
- It can be achieved with $\mathcal{A}_2 \simeq 0$ and $\mathcal{A}_3 > 0 \Rightarrow$ Mainly $SU(3)_c$ mediated breaking

DEGENERATE OR METASTABLE EWSB: $\lambda \gtrsim \frac{m_h^2}{\langle\phi\rangle^2}$

- Enhancement of Higgs self-couplings compared with SM case
- e.g. Degenerate minima, zero vacuum energy for $\lambda = \frac{m_h^2}{\langle\phi\rangle^2}$
  $V = \frac{m_h^2}{2}h^2 + \frac{5m_h^2}{6\langle\phi\rangle}h^3 + \frac{7m_h^2}{24\langle\phi\rangle^2}h^4 + \mathcal{O}(h^5)$

LOG POTENTIAL: $\lambda \ll 1$

- Similar to CW mechanism but with quadratic term
- Suppression of Higgs self-coupling compared with SM case
  $V = -\frac{m_h^2\langle\phi\rangle^2}{4} + \frac{m_h^2}{2}h^2 + \frac{m_h^2}{6\langle\phi\rangle}h^3 - \frac{m_h^2}{24\langle\phi\rangle^2}h^4 + \mathcal{O}(h^5)$

Conclusions and outlook

- We proposed a gauge mediation principle for exact scale breaking in SM
- Scale invariance is broken in the Hidden sectors at scale f_c
- Gauge mediation structure protects Higgs mass sensitivity at two loops
- New physics scale f_c is two or three loops enhanced w.r.t. EW scale
- Contains SM limit and possible new phenomenologies (unusual Higgs potentials and *self-couplings*)

- Given that self-couplings are predicted possible deviations from SM
- $\Rightarrow$ LHC prospects for measuring Higgs self couplings?
- Interesting new possible shape for Higgs potential
- $\Rightarrow$ Cosmological consequences? Dorsch, Huber, No '14
- New physics states in Hidden Sector quite heavy, possibly stable
- $\Rightarrow$ Heavy dark matter candidates?

- ?? Other symmetries to protect the Higgs mass ??

Thanks for your attention!