# Dilaton-assisted composite Higgs model at LHC

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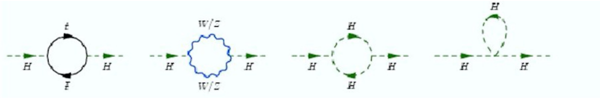
Based on arXiv:1703.05081, JHEP 1802 (2018) 102, and also;
Choi-DKH-Matsuzaki JHEP 1212 (2012) 059;PLB706 (2011) 183

# Naturalness Problem

- The SM is very successful, but unnatural ('t Hooft):
- The Higgs mass is sensitive to short-distance physics!

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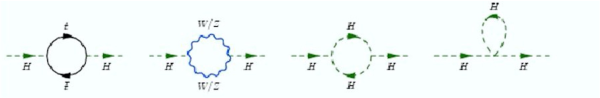


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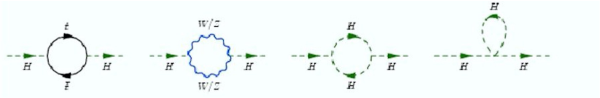


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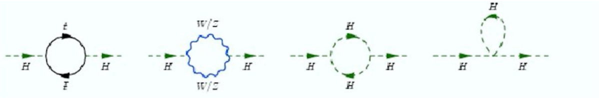


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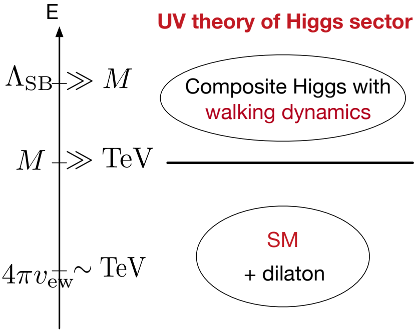
# Dilaton model (DKH 2017)

- We propose a model that Higgs boson is naturally light $\sim v_{\rm ew} \ll \Lambda_{\rm UV}$ without fine-tuning but scale symmetry.
- Furthermore the dilaton can be DM of mass $1\ \mathrm{eV} - 10\ \mathrm{keV}$.



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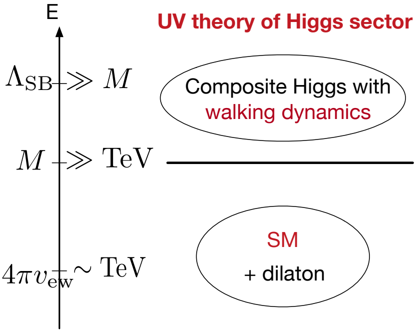

# Conformal Window

- Consider a $\mathrm{SU}(2)$ gauge theory with $N_f = 4$ and $N_s = 1$; $\alpha_* = 0.84 < \alpha_c(s) = 1.05 < \alpha_c(f) = 1.40$ at two-loop.

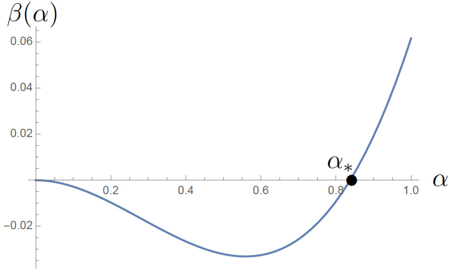


Figure: Two-loop $\beta$-function of $\mathrm{SU}(2)$ with $N_f = 4$ and $N_s = 1$.

# Near Conformal Window

- We deform the theory by partially gauging the flavor symmetry:

| | $SU(2)_1$ | $SU(2)_2$ |
|---|---|---|
| $\psi^1_{a\alpha}$ | $\square$ | $\square$ |
| $\psi^2_{a\alpha}$ | $\square$ | $\square$ |
| $\chi_{\{ab\}}$ | $\square\square$ | $1$ |

# Near Conformal Window

- It then becomes near conformal, since $\chi$SB at $\alpha_1 \approx \alpha_*$ with $\alpha_1 + \alpha_2 = \alpha_c(f)$:

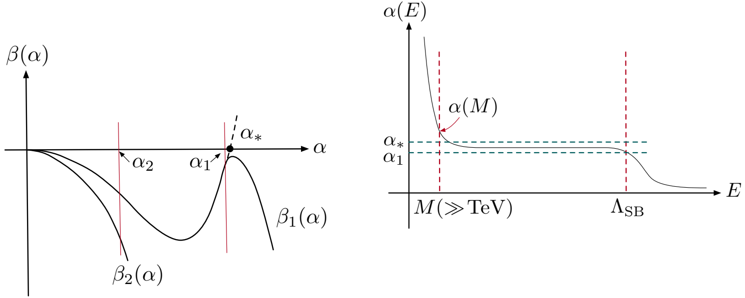


Figure: The chiral symmetry of $\psi^i$ is broken at $\alpha_1 \approx \alpha_*$.

# Near Conformal Window

- Near $\alpha_1 \approx \alpha_*$ the beta function becomes (Miransky '85; Kaplan-Lee-Son-Stephanov '09)

$$\beta(\alpha) \approx \beta_{\rm NP}(\alpha) = -\frac{2}{\pi}(\alpha - \alpha_*)^{3/2}$$

- The dynamical mass $M$ of $\chi$SB is given by the Miransky-Berezinskii-Kosterlitz-Thouless Scaling:

$$M = \Lambda_{\rm SB} \exp^{-\int_{\alpha_1} \frac{d\alpha}{\beta(\alpha)}} \approx \Lambda_{\rm SB} \exp^{-\frac{\pi}{\sqrt{\alpha_* - \alpha_1}}}$$

- The theory is almost scale-invariant for $M < E < \Lambda_{\rm SB}$, exhibiting walking dynamics.

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# A very light dilaton

- When the scale symmetry is spontaneously broken at $\alpha = \alpha_1$ or at $\Lambda_{\rm SB} \sim f$, we should have a Nambu-Goldstone boson:

$$\langle 0| D_\mu(x) |D(p)\rangle = -ifp_\mu e^{-ip\cdot x} \,,$$

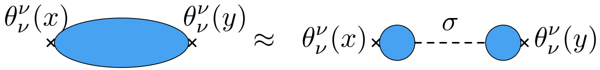
  where the dilatation current $D_\mu = x^\nu \theta_{\mu\nu}$.
- The scale symmetry is however anomalous:

$$\partial_\mu D^\mu = \theta^\mu_\mu \,.$$

  (The energy-momentum tensor is that of UV theory.)

# PCDC and Very light dilaton

- Partially conserved dilatation current (PCDC) hypothesis:




- Very light dilaton from quasi-conformal UV sector:

$$f^2 m_D^2 = -4 \langle \theta^\mu_\mu \rangle \sim M^4 \,.$$

$$m_D^2 = -\frac{4 \langle \theta^\nu_\nu \rangle}{f^2} \sim \frac{M^4}{\Lambda^2_{\rm SB}} \ll M^2 \,.$$

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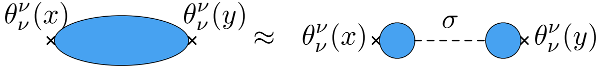


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# Dilaton effective theory

- If the scale symmetry is spontaneously broken, the theory is described at low energy by the dilaton effective Lagrangian:

$$\mathcal{L}_D^{\text{eff}} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - V_A(\chi)\,,$$

where $\chi = fe^{\sigma/f}$ describes the small fluctuations around the asymetric vacuum,

$$\theta^\mu_\mu \approx 4\mathcal{E}_{\text{vac}}\left(\frac{\chi}{f}\right)^4,$$

with $\langle\chi\rangle = f$ at the vacuum.

# Dilaton effective theory

- The dilatation current in the dilaton effective theory becomes

$$\mathcal{D}^\mu = \frac{\partial \mathcal{L}_D^{\mathrm{eff}}}{\partial(\partial_\mu \chi)} (x^\nu \partial_\nu \chi + \chi) - x^\mu \mathcal{L}_D^{\mathrm{eff}} \, .$$

The scale anomaly then takes

$$\partial_\mu \mathcal{D}^\mu = 4 V_A - \chi \frac{\partial V_A}{\partial \chi} \, .$$

- Since $\partial_\mu \mathcal{D}^\mu = -4\theta_\mu^\mu = -16\mathcal{E}_{\mathrm{vac}}(\chi/f)^4$, we get

$$V_A(\chi) = |\mathcal{E}_{\mathrm{vac}}| \left(\frac{\chi}{f}\right)^4 \left[4 \ln\left(\frac{\chi}{f}\right) - 1\right] .$$

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# Dilaton effective theory

- Under the scale transformation $M \mapsto M'$ the effective theory is covariant, since $\sigma \mapsto \sigma' = \sigma + f\ln(M'/M)$ and

$$V_A(\sigma) \to V'_A(\sigma) = \left|\mathcal{E}'_{\rm vac}\right| e^{4\sigma/f}\left(\frac{4\sigma}{f} - 1\right) ,$$

where $\mathcal{E}'_{\rm vac} = \mathcal{E}_{\rm vac}\,(M'/M)^4$.

- In terms of the shifted dilaton field, $\sigma' = \sigma + f\ln(M'/M)$, the dilaton potential becomes

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# $\mathrm{SU}(2) \times \mathrm{SU}(2)$ Composite Higgs model

- Since $\mathrm{SU}(2)$ spinors are pseudo-real, the chiral symmetry is enhanced to $\mathrm{SU}(4)_\psi \times \mathrm{SU}(2)_\chi$:

$$\begin{pmatrix} \psi_L^1 \\ \psi_L^2 \\ i\sigma^2 \psi_R^{1*} \\ i\sigma^2 \psi_R^{2*} \end{pmatrix}, \quad \begin{pmatrix} \chi_L \\ i\sigma^2 \chi_R^* \end{pmatrix}$$

- $\langle \bar{\psi}_L^i \psi_R^i + \mathrm{h.c.} \rangle \neq 0$ at $\alpha_1(\Lambda_{\mathrm{SB}})$ to break $\mathrm{SU}(4) \mapsto \mathrm{Sp}(4)$:
- There are 5 NG bosons, living on the vacuum manifold,

$$\mathcal{M} = \mathrm{SU}(4)/\mathrm{Sp}(4) \sim \mathrm{SO}(6)/\mathrm{SO}(5)$$

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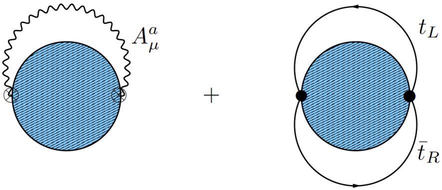
- Embed $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ into $\mathrm{SO}(5)$, the 5 NG bosons become one Higgs doublet and one singlet scalar, $\eta$.
- The SM interaction lifts the vacuum degeneracy, $U = e^{2i\phi/f_\pi}$:



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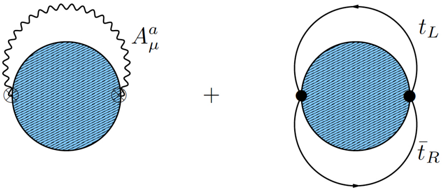

# Dilaton-Higgs coupling

- Since both Higgs boson and dilaton are from same dynamics, they will couple:

$$\mathcal{L}_H = \frac{1}{2} e^{2\sigma/f} \partial_\mu \sigma \partial^\mu \sigma + (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi, \sigma)\,.$$

- The Higgs+dilaton potential below the cutoff scale $\Lambda \sim M$ is

$$V(\sigma, \phi) = M_\phi^2 \, e^{2\sigma/f} \, \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2 + V_A(\sigma) + \mathrm{h.o.}\,,$$

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# Coleman-Weinberg mechanism and scale symmetry

- Now we further integrate out the higher frequency modes, $E > \Lambda$, the effective potential at one-loop becomes:

$$V_{\text{eff}} = V_A + \left(M_\phi^2 e^{2\sigma/f} - c_1\Lambda^2\right)\phi^\dagger\phi + \frac{\beta}{8}\left(\phi^\dagger\phi\right)^2\left[\ln\left(\frac{\phi^\dagger\phi}{v_{\text{ew}}^2}\right) - c_2\right].$$

- We impose the renormalization condition, after shifting $\sigma \to \sigma' = \sigma + \bar{\sigma}_0$,

$$m_\phi^2(\Lambda) \equiv \left.\frac{\partial^2 V_{\text{eff}}}{\partial\phi^\dagger\partial\phi}\right|_{\phi=0=\sigma'} = M_\phi^2 e^{-2\bar{\sigma}_0/f} - c_1\Lambda^2 = 0\,.$$

# Coleman-Weinberg mechanism and scale symmetry

- For any cutoff $\Lambda$ we can choose $\bar{\sigma}_0$ or $M$ such that quadratic term in the potential vanishes at the origin:

$$\left.\frac{\partial^2 V_{\text{eff}}}{\partial\phi\partial\phi^\dagger}\right|_{\sigma=0=\phi} = 0\,.$$

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- Then, the effective potential becomes

$$V_{\rm eff}(\sigma,\phi) = M_\phi^2\left(e^{2\sigma/f}-1\right)\phi^\dagger\phi + V_{\rm CW}(\phi) + V_A(\sigma)\,.$$

- At one-loop the CW potential takes

$$V_{\rm CW}^{1-\rm loop}(\phi) = \frac{1}{2}\beta\left(\phi^\dagger\phi\right)^2\left[\ln\left(\frac{\phi^\dagger\phi}{v_{\rm ew}^2}\right) - b\right]\,.$$

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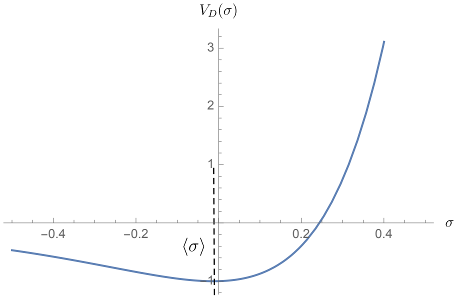
# Coleman-Weinberg mechanism and scale symmetry

- When the Higgs gets a vev, it breaks scale symmetry explicitly and the dilaton gets extra contribution.

$$V_D(\sigma) = |\mathcal{E}_{\rm vac}|\, e^{4\sigma/f}\,(4\sigma/f - 1) + V_{\rm CW}(v_{\rm ew}) + M_\phi^2 \left(e^{2\sigma/f} - 1\right) v_{\rm ew}^2 \, .$$



# Coleman-Weinberg mechanism and scale symmetry

- When the Higgs gets a vev, the dilaton also gets a vev

$$-\frac{\langle\sigma\rangle}{f} \approx \frac{M^2 v_{\rm ew}^2}{8\,|\mathcal{E}_{\rm vac}|} \ll 1\,.$$

- Higgs mass becomes with $\mathcal{E}_{\rm vac} = -cM^4$ and $\xi = M_\phi^2/M^2$

$$m_H^2 = \frac{\partial^2}{\partial\phi^\dagger\partial\phi} V\left(\langle\sigma\rangle\,,\phi\right)\Big|_{\phi=v_{\rm ew}} = \left(\frac{\xi}{4c} + \frac{\beta}{4}\right) v_{\rm ew}^2\,.$$

- Because of the scale invariance the Higgs mass is determined by the IR scale, set by the vev of Higgs fields, $\langle\phi\rangle = v_{\rm ew}$.
- The scale symmetry of UV naturally explains why $m_H \sim v_{\rm ew}$!

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- Higgs mass becomes with $\mathcal{E}_{\rm vac} = -cM^4$ and $\xi = M_\phi^2/M^2$

$$m_H^2 = \frac{\partial^2}{\partial\phi^\dagger\partial\phi} V\left(\langle\sigma\rangle\,,\phi\right)\Big|_{\phi=v_{\rm ew}} = \left(\frac{\xi}{4c} + \frac{\beta}{4}\right) v_{\rm ew}^2\,.$$

- Because of the scale invariance the Higgs mass is determined by the IR scale, set by the vev of Higgs fields, $\langle\phi\rangle = v_{\rm ew}$.
- The scale symmetry of UV naturally explains why $m_H \sim v_{\rm ew}$!

# Dark matter

- Our model consists of SM and one extra light scalar, dilaton, below the UV scale $M \gg v_{\rm ew}$.
- If the chiral symmetry is spontaneously broken near $\alpha_*$, we do have a very large separation of scales, $M \ll \Lambda_{\rm SB} \sim f$, and dilaton can be very light

$$m_D^2 = \frac{4|\mathcal{E}_{\rm vac}|}{f^2} \sim \frac{M^4}{f^2} \ll M^2 .$$

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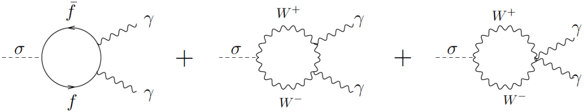
# DIlaton dark matter

- Decay of very light dilaton:




$$\Gamma(\sigma \to \gamma\gamma) \simeq \frac{\alpha_{em}^2}{36\pi^3} \frac{m_D^3}{f^2} |\mathcal{C}|^2$$

$$\tau_{\mathrm{D}} \simeq 10^{20}\,\mathrm{sec} \left(\frac{5}{\mathcal{C}}\right)^2 \left(\frac{10\,\mathrm{keV}}{m_{\mathrm{D}}}\right)^3 \left(\frac{f}{10^{12}\,\mathrm{GeV}}\right)^2 .$$

# The relic abundance of dilaton

- The light dilatons are produced non-thermally by the vacuum misalignment, $\theta_{\rm os} = \delta\sigma / f$

$$\rho_\sigma(T_{\rm os}) = \left| V_D(T_{\rm os}) - V_D^{\rm min} \right| \simeq M^4 \, {\theta_{\rm os}}^2 \, .$$

- Follwoing Choi-DKH-Matsuzaki (2012), the density at present

$$\rho_D(T_0) = \rho_D(T_{\rm os}) \cdot \frac{s(T_0)}{s(T_{\rm os})} \, .$$

The current relic density is given as

$$\Omega_\sigma^{\rm ntp} h^2 \sim 0.5 \left( \frac{\delta\sigma}{10^{-5} f} \right)^2 \left( \frac{110}{g_*(T_{\rm os})} \right) \left( \frac{M}{10 \ {\rm TeV}} \right)^4 \left( \frac{10 \ {\rm TeV}}{T_{\rm os}} \right)^3 \, .$$

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# Very light dilaton as dark matter

- The UV scale of Higgs sector in our model has to be around $M = 10 - 100\ \mathrm{TeV}$ for dilaton to be dark matter.
- The life time of dilaton $\tau_D \geq 10^{18}\ \mathrm{sec}$ and the relic abundance $\Omega_\sigma h^2 \sim 0.1$ constrain

$$m_D \sim 1\ \mathrm{eV} - 10\ \mathrm{keV} \quad \mathrm{and} \quad f \sim 10^{12-16}\ \mathrm{GeV}\ .$$

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# Conclusion

- The SM is believed to be an effective theory. But, no hint of NP is found yet at LHC.
- To solve the naturalness problem, we propose dilaton-assisted composite Higgs model, where the Higgs mass is protected by the shift symmetry and also by the scale symmetry.
- The model is based on $\mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2$ gauge theory with $N_f = 2$ bi-fundamental and $N_s = 1$ second-rank symmetric tensor Dirac spinors.

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- The UV theory is near the stable IR fixed point at the UV scale of SM. (Its IR scale, $m_{\rm dyn} \sim M$.)
- At very low energy $E \ll M$, the model contains SM and only one extra particle, very light dilaton.
- In addition to light dilaton of mass $m_D \sim 1\ {\rm eV} - 10\ {\rm keV}$ as DM the model predicts just below $M$ one heavy vector meson and two massive, oppositely charged NG bosons, which might be accessible at LHC if $M$ is a few $10\ {\rm TeV}$.
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