Very light dilaton and naturally light Higgs boson

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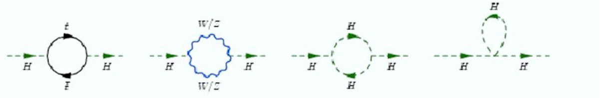
Cosmological probes of BSM, Benasque

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!



$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\Lambda^2$$

$\approx$ - (200 GeV)^2 for Λ = 10^3 GeV

$\approx$ - (200 GeV)^2 . 10^{32} for Λ = 10^{19} GeV

- SM is fine-tuned unless there is NP at $4\pi v_{\rm ew} \sim 1$ TeV.
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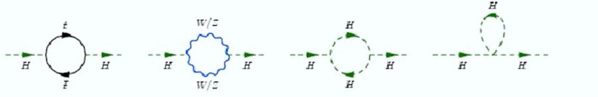

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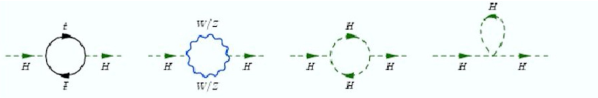

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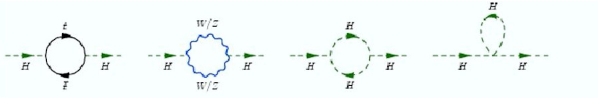

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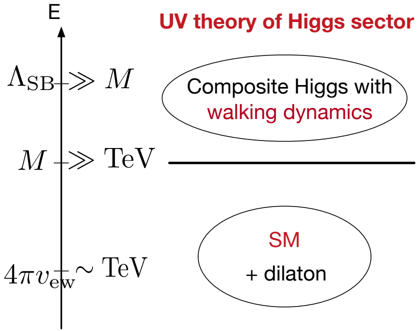
Dilaton model (DKH 2017)

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



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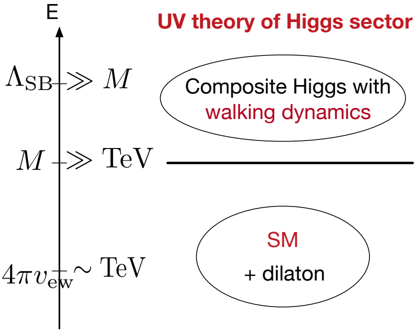

Light dilaton as a Nambu-Goldstone boson

- Consider a $\mathrm{SU}(N)$ gauge theory with infrared fixed point, studied by Casewell (1974) and also by Banks-Zaks (1982)
- The two-loop beta function with N_f fundamental Dirac fermions and N_s Dirac fermions in the second-rank symmetric tensor representation.

$$\beta(\alpha) \equiv \mu \frac{\partial \alpha}{\partial \mu} = -b\alpha^2 - c\alpha^3 \,,$$

with the coefficient b and c, known as

$$\begin{aligned} 6\pi b &= 11N - 2N_f - 2N_s(N+2) \\ 24\pi^2 c &= 34N^2 - 10NN_f - 3\left(N - \frac{1}{N}\right) N_f \\ &\quad -10NN_s(N+2) - \frac{6}{N}(N-1)(N+2)N_s(N+2) \,. \end{aligned}$$

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Conformal Window

- If $b > 0$, the theory is asymptotically free.
- If $c < 0$, there will be an IR fixed point, $\alpha_* = -\frac{b}{c}$, if chiral symmetry is unbroken.
- The chiral symmetry will be broken if $\alpha_c < \alpha_*$

$$\alpha_c(f) = \frac{2\pi}{3}\frac{N}{N^2-1}, \quad \alpha_c(s) = \frac{2\pi}{3}\frac{N}{(N+2)(N-1)}.$$

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Conformal Window

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

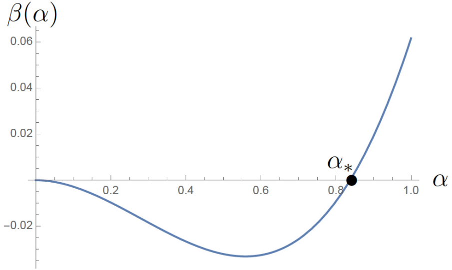

Figure: Two-loop β-function of $\mathrm{SU}(2)$ with $N_f = 4$ and $N_s = 1$.

Near Conformal Window

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

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

Near Conformal Window

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

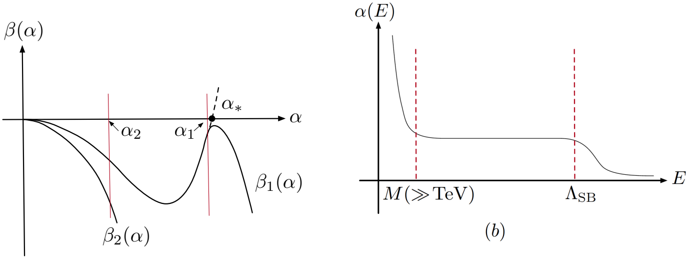

Figure: The chiral symmetry of ψ^i is broken at $\alpha_1 \approx \alpha_*$.

Near Conformal Window

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

$$\beta(\alpha) \approx \beta_{\rm NP}(\alpha) = -\frac{2\alpha_1}{\pi}\left(\frac{\alpha}{\alpha_1} - 1\right)^{3/2}$$

- The dynamical mass M of χSB is given by the Miransky-Berezinskii-Kosterlitz-Thouless Scaling:

$$M = \Lambda_{\rm SB}(\alpha_1)\exp\left(-\frac{\pi}{\sqrt{\alpha_*/\alpha_1 - 1}}\right)$$

- 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.)

A very light dilaton

- Consider WT identity:

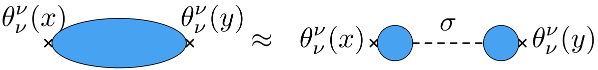
$$\int_x \partial^\mu \langle 0| \mathrm{T} D_\mu(x)\theta^\nu_\nu(y) |0\rangle = \langle 0[D, \theta^\nu_\nu] |0\rangle + \int_x \langle 0| \mathrm{T}\partial^\mu D_\mu(x)\theta^\nu_\nu |0\rangle$$

$$-4 \langle \theta^\nu_\nu \rangle \approx \int_{x,p} \langle 0| \partial^\mu D_\mu(x) \ |D(p)\rangle \ \frac{i}{p^2 - m_D^2} \langle D(p)| \theta^\nu_\nu(y) |0\rangle$$

PCDC and Very light dilaton

- Partially conserved dilatation current (PCDC) hypothesis:

$$f^2 m_D^2 = -4\,\langle \theta_\mu^\mu \rangle \approx -16\,\mathcal{E}_{\rm vac} \sim M^4\,.$$



- Very light dilaton from quasi-conformal UV sector:

$$m_D^2 = -\frac{4\,\langle \theta_\nu^\nu \rangle}{f^2} \sim \frac{M^4}{\Lambda_{\rm SB}^2} \ll M^2\,.$$

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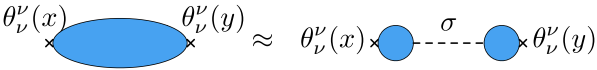

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Dilaton effective theory

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

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

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

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

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

Dilaton effective theory

- The dilatation current in the dilaton effective theory becomes

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

The scale anomaly then takes

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

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

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- 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 $\mathcal{E}'_{\rm vac} = \mathcal{E}_{\rm vac} \left(M'/M\right)^4$.

- In terms of the shifted dilaton field, $\sigma' = \sigma + f \ln\left(M'/M\right)$, 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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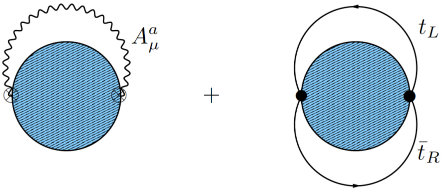
- Embed $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ into $\mathrm{SO}(5)$, the 5 NG bosons become one Higgs doublet and one singlet scalar, η.
- The SM interaction lifts the vacuum degeneracy, $U = e^{2i\phi/f_\pi}$:



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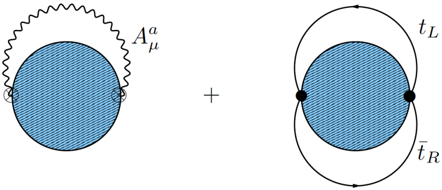

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- The Higgs potential becomes

$$V_0(\phi) = M_\phi^2 \phi^\dagger \phi + \lambda(M) \left(\phi^\dagger \phi\right)^2 + \cdots ,$$

- $M_\phi^2 = \xi M^2$ with $\xi \sim \alpha_{\rm ew}$ or $\frac{y_t^2}{4\pi}$ and $\lambda(M) \sim \alpha_{\rm ew}$ or $y_t^2/(4\pi)$.
- We gauge $\mathrm{U}(1)_\psi$ to remove the SM singlet Goldstone boson η that gives a heavy vector meson, $M_\psi \sim g_\psi M$.

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Dilaton-Higgs coupling

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

$$\begin{aligned} 0 &= \int_x \partial^\mu \langle 0| \, T\left\{\mathcal{D}_\mu(x)\phi^\dagger\phi(0)\right\}|0\rangle \\ &= \langle 0| \left[\mathcal{D}, \phi^\dagger\phi(0)\right]|0\rangle + \int_x \langle 0| \, T\left\{\theta^\mu_\mu(x)\phi^\dagger\phi(0)\right\}|0\rangle \,. \end{aligned}$$

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Scale symmetry and naturalness

- The model has SM plus a very light dilaton with one heavy vector and two massive scalars only below $M \approx 10 - 100\ \mathrm{TeV}$, above which SM is UV complete!

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

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

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

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

Scale symmetry and naturalness

- The model has SM plus a very light dilaton with one heavy vector and two massive scalars only below $M \approx 10 - 100\ \mathrm{TeV}$, above which SM is UV complete!

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

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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 Λ we can choose $\bar{\sigma}_0$ or M such that quadratic term in the potential vanishes at the origin:

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

- It is the only renormalization condition, consistent with the scale symmetry.
- One can always shift $\sigma \to \sigma + \bar{\sigma}_0$ to keep this condition.

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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

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

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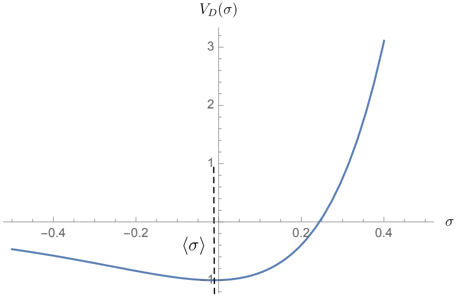
Coleman-Weinberg mechanism and scale symmetry

- 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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Dark matter

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

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

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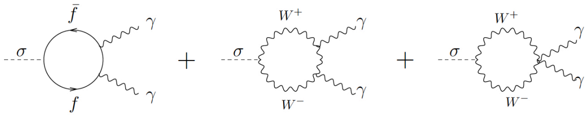
Dark matter dilaton

- Decay of very light dilaton:



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

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

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 $\tau_D \geq 10^{18}$ sec and the relic abundance $\Omega_\sigma h^2 \sim 0.1$ constrain

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- No hint of NP is found yet at LHC, though we believe there should be one above the electroweak scale.
- 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.
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- The UV theory is near the stable IR fixed point at the UV scale of SM. (Its IR scale, $m_{\mathrm{dyn}} \sim M$.)
- 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 $m_D \sim 1\ \mathrm{eV} - 10\ \mathrm{keV}$ 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 $10\ \mathrm{TeV}$.
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