Gauge Mediation of Exact Scale Breaking

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PLAN AND MOTIVATIONS

- Naturalness problem in the Standard Model (SM)
- Strategy: symmetries to protect Higgs mass
- Scale symmetry as candidate
- Review of popular scenarios where scale symmetry plays a role
  - 125 GeV scalar as a dilaton
  - Classical scale invariance and Coleman Weinberg mechanism

- In this talk: DIFFERENT APPROACH FOR SCALE INVARIANCE

EXACT (QUANTUM LEVEL) SCALE INVARIANCE IN THE UV

- Gauge mediation principle for scale invariance breaking
- Phenomenological consequences in the resulting Higgs potential

Naturalness problem in the SM

- Higgs boson discovered in July 2012
- Unique elementary scalar in the Standard Model

Hierarchy problem

- Higgs mass is unique dimensionful parameter in the SM
- Hierarchy problem: why $\Lambda_{EW} \ll M_{Plank}$?

Technical hierarchy problem

- Scalars are (quadratically) sensitive to high scale physics (e.g. M_{Planck})
- How and Why EW scale is stable under quantum corrections?
- Where is the scale of new physics?

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

New Physics and Extra symmetry protection

Expectations:

- New physics at relatively low scale, so effective cut-off is small
- Extra symmetry to protect Higgs mass

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 Symmetry in 4 dimensions

- Scaling of coordinates and operators

$$x \to e^{-\alpha} x \qquad \mathcal{O} \to e^{d_{\mathcal{O}}\alpha}\mathcal{O}$$

- Action transforms as

$$S = \int d^4x \sum_i g_i \mathcal{O}_i \quad \delta_\alpha S = \int d^4x \sum_i (d_{\mathcal{O}_i} - 4) g_i \mathcal{O}_i + \beta_i(g) \frac{\partial}{\partial g_i}\mathcal{L} = \int d^4x\, T^\mu_\mu$$

- If $d_{\mathcal{O}_i} = 4$ and $\beta_i(g) = 0$ theory is scale invariant

Non linear realization of scale invariance

- Assume that scale invariant is spontaneously broken at scale f_c
- Goldstone mode is the massless dilaton σ, which transforms as

$$\sigma \to \sigma + \alpha f_c \qquad \chi = f_c e^{\frac{\sigma}{f_c}} \to e^{\alpha}\chi$$

- NLR: Scale breaking is compensated by: $\frac{\sigma}{f_c} = \log \frac{\chi}{f_c}$

$$S_{NLR} = S - \int d^4x \frac{\sigma}{f_c} T^\mu_\mu \qquad \Rightarrow \qquad \delta_\alpha S_{NLR} = 0$$

CAN THE 125 SCALAR BE THE DILATON? GOLDBERGER, GRINSTEIN, SKIBA '07

- Higgs vev sets all the masses in the SM
- Assume Scale Invariance is spontaneously broken at a scale $f_c \simeq \Lambda_{EW}$
- $\Rightarrow$ Light scalar (the Dilaton) in the low energy spectrum
- Some amount of explicit scale breaking to provide dilaton a mass
- *The light observed scalar could be the dilaton!*
- Dilaton couplings proportional to scale anomaly
- $\Rightarrow$ e.g. Tree level fermion mass and gluon beta function

$$\mathcal{L}_{SM+Dilaton} \supset \frac{\sigma}{f_c} m_\psi \bar{\psi}\psi - \frac{\beta_{g_3}}{g_3}\frac{\sigma}{f_c} G_{\mu\nu}G^{\mu\nu}$$

MAIN OUTCOMES

- Deviations in Dilaton coupling to massless gauge boson w.r.t. the SM Higgs
- Restoration of scale invariance (new physics) not too far from EW scale (all scales naturally of order f_c)
- Typically Dilaton mass also of order f_c

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 for gravity Weinberg '76; Litim '11; ...)
- Exact scale symmetry in the UV
- Spontaneous breaking at scale f_c leads to relevant operators in the IR

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 by hand 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?

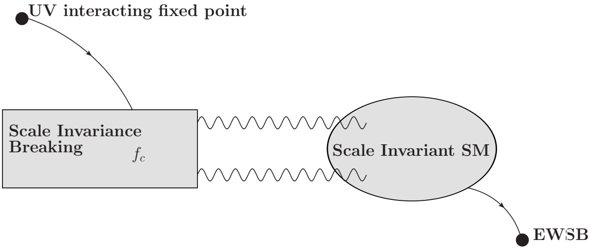
HIGGS MASS NATURALNESS AND SCALE INVARIANCE TAVARES, SCHMALTZ, SKIBA'13

- 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
- Anyway 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
- $\Rightarrow$ Add a loop of protection to Higgs mass w.r.t. previous arguments



- Scale invariance breaking is communicated to the Higgs via loops effects
- $\Rightarrow$ Relevant operators proportional to f_c are generate in Higgs potential
- The true dilaton resides in the hidden sector and has mass $\sim f_c$

SETUP

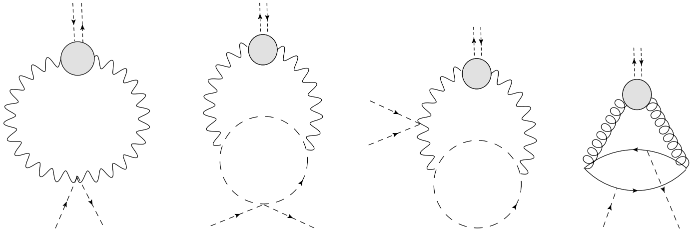
- Assume SM and Scale Breaking Sector are connected only via gauge interactions (perturbative)
- Lagrangian schematically (modular structure)

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

- 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
- $\Rightarrow$ we can simplify computation focusing on

$$\delta_{f_c} V_{loop} = V_{loop}(f_c^2) - V_{loop}(f_c^2 = 0)\,.$$

- Keep large momentum expansion of SM gauge boson two point functions

Bardin Passarino

$$8\pi^2 C_{vis}^{SU(2)} = \log(\frac{\mu^2}{p^2})b'^{(2)} + \frac{m_H^2}{4p^2}(1 + \log\frac{m_H^2}{p^2}) - 6\frac{m_t^2}{p^2} + \frac{m_W^2}{4p^2}(51 - 13\log\frac{m_W^2}{p^2})$$

$$8\pi^2 C_{vis}^{SU(3)} = \log(\frac{\mu^2}{p^2})b'^{(3)} - 6\frac{m_t^2}{p^2} + \mathcal{O}(1/p^4)$$

where $m_H^2 = 4\lambda HH^\dagger$, $m_W^2 = \frac{g_2^2}{2}HH^\dagger$ and $m_t^2 = \lambda_t^2 HH^\dagger$

- Effective potential results

$$V_{eff} = \lambda(HH^\dagger)^2 + \frac{9g_2^4\mathcal{A}_2}{16\pi^2} f_{c(2)}^2 HH^\dagger \left(4\pi^2 - \lambda_t^2(6 + 16\frac{f_{c(3)}^2\mathcal{A}_3}{f_{c(2)}^2\mathcal{A}_2}\frac{g_3^4}{g_2^4}) + (\lambda - \frac{13}{8}g_2^2)\log\frac{HH^\dagger}{f_c^2}\right)$$

- where we parameterize unknown hidden sector two point function integrals as

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

- Different $f_{c(a)}^2$ and two point functions for $SU(2)$ and $SU(3)$ hidden sectors
- $\mathcal{A}_a$ naturally at least two loop suppressed
- $\Rightarrow$ Loop suppressed $f_{c(a)}^2$ determine EW scale

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- Parameterize Higgs as $H = e^{i\xi\cdot\tau}\begin{pmatrix} 0 \\ \phi/\sqrt{2}\end{pmatrix}$
- Minimization trades $\mathcal{A}_a$ for λ and ratio $\frac{m_h^2}{\langle\phi\rangle^2}$

$$\frac{\partial V}{\partial\phi}|_{\phi=\langle\phi\rangle} = 0, \qquad \frac{\partial^2 V}{\partial\phi^2}|_{\phi=\langle\phi\rangle} = m_h^2 \qquad \Rightarrow \mathcal{A}_2(\langle\phi\rangle^2, m_h^2)\,,\ \mathcal{A}_3(\langle\phi\rangle^2, m_h^2)$$

Effective potential simplified

- $\Rightarrow$ 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 (with $f_{c(2)} = f_{c(3)} = f_c$ for simplicity)

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

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

- 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

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

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

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

- 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 SM: Banks-Zaks fixed point

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

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

- Only F' fermions t are coupled to the singlet scalar ($F' < F$)
- Compute the beta function of the couplings

$$\beta_{\alpha_g} = -2\alpha_g^2 N \left[\frac{11}{3} - \frac{2}{3}\frac{F}{N} + \alpha_y \frac{F'}{N}\right] - 2a_g^3 N^2 \left[\frac{34}{3} - \frac{F}{N}\left(\frac{13}{3} - \frac{1}{N^2}\right)\right], \quad \beta_{\alpha_y}, \quad \beta_{\alpha_\lambda}$$

- Look for $\beta_i = 0$ solution
- Compensate one loop with two loops in gauge coupling beta function

$$F = \frac{11}{2} N(1-\epsilon) \qquad \Rightarrow b_0 \sim \epsilon > 0$$

- $\Rightarrow$ There is a fixed point ($\beta_i = 0$) with couplings

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

- Stability analysis indicates that it is stable as soon as $\epsilon > 0$
- Perturbative provided $F' \geq N$

Toy model

Toy model SM

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

Toy model Hidden Sector

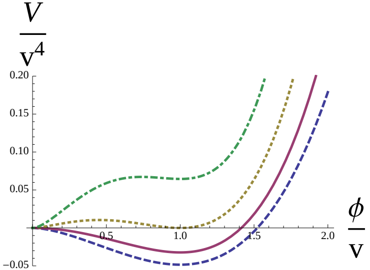
- $F - F' = 9$ are not coupled to the Higgs and can be considered part of the hidden sector
- They are coupled only to $SU(3)$ in the toy SM
- Embed $F - F' = 9$ in a gauge theory with UV fixed point
- E.g. gauge diagonal $SU(9)_L \times SU(9)_R$ group and add other fermions and/or other scalars in the hidden sector (singlets under $SU(3)_{color}$) such that $SU(9)$ has unstable UV fixed point (details in the paper)
- $SU(9)$ gauge theory breaks scale invariance spontaneously

Phenomenology of Higgs potential

- Independently from hidden sector dynamics the Higgs potential results

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

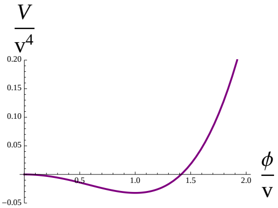
- Three different phenomenology depending on value of λ (related to hidden sector $\mathcal{A}_a$, so depending on hidden sector properties)



- 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



SM LIMIT

- $\lambda = \frac{m_h^2}{2\langle\phi\rangle^2} \simeq \frac{1}{8}$
- Recover SM potential around EWSB vacuum

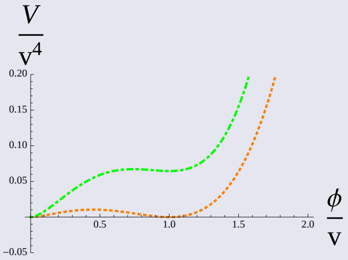
$$V = -\frac{m_h^2\langle\phi\rangle^2}{8} + \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2\langle\phi\rangle}h^3 + \frac{m_h^2}{8\langle\phi\rangle^2}h^4$$

- $\Rightarrow$ Retrofitted SM potential
- It can be achieved with $\mathcal{A}_2 = 0$ and $\mathcal{A}_3 > 0$
- $\Rightarrow$ Pure $SU(3)_c$ mediated exact scale breaking

DEGENERATE OR METASTABLE EWSB

- $\lambda \gtrsim \frac{m_h^2}{\langle\phi\rangle^2} \simeq \frac{1}{4}$ EWSB vacuum is metastable
- Compute Lifetime of EWSB vacuum
- Bounce Action should be large

$$S_{O_4} \sim \frac{2\pi^2 \langle\phi\rangle^4}{V(\langle\phi\rangle) - V(0)} \gtrsim 400$$



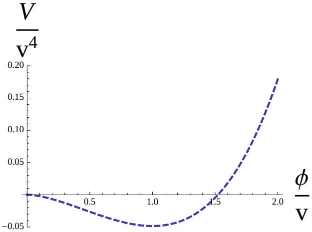
- $\Rightarrow 0.25 < \lambda \lesssim 0.45$ (using $\frac{m_h^2}{\langle\phi\rangle^2} \simeq \frac{1}{4}$) we can achieve a longlived metastable EWSB vacuum
- Enhancement of Higgs self-couplings compared with SM case
- e.g. Degenerate minima, zero vacuum energy for $\lambda = \frac{m_h^2}{\langle\phi\rangle^2}$

$$V = \frac{m_h^2}{2} h^2 + \frac{5 m_h^2}{6\langle\phi\rangle} h^3 + \frac{7 m_h^2}{24\langle\phi\rangle^2} h^4 + \mathcal{O}(h^5)$$

Log potential

- Very small λ
- Approximate potential is quadratic Logarithmic

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



- $\Rightarrow$ New mechanism for EWSB
- Similar to CW mechanism but with quadratic term
- Expansion around EWSB vacuum significantly different from SM case

$$V = -\frac{m_h^2 \langle \phi \rangle^2}{4} + \frac{m_h^2}{2} h^2 + \frac{m_h^2}{6\langle \phi \rangle} h^3 - \frac{m_h^2}{24 \langle \phi \rangle^2} h^4 + \mathcal{O}(h^5)$$

- Suppression of Higgs self-coupling compared with SM case

Summary

- Assume SM and hidden sector emanate from UV scale invariant theories
- Assume SM and hidden sector only connected by SM gauge interactions
- Scale invariance is broken in the Hidden sectors at scale f_c
- Relevant operators are generate in the Higgs potential, proportional to f_c

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

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

- New physics scale f_c is two or three loops enhanced w.r.t. EW scale

$$f_c \sim 10 - 10^2 \text{ TeV}$$

- λ and $\frac{m_h^2}{\langle\phi\rangle^2}$ related to Hidden Sector loop integrals $\mathcal{A}_a$

- Contains SM limit and possible new phenomenologies (unusual Higgs potentials and self-couplings)
- Higgs couplings with SM particles are usual ones

Outlook and conclusions

- We proposed a gauge mediation principle for exact scale breaking in SM
- Higgs mass protected from quantum corrections by UV scale invariance
- Gauge mediation structure protects Higgs mass sensitivity at two loops
- Different phenomenology in Higgs potential (*self-couplings*)
- Other Higgs couplings equal to SM case

!! SM UV-completion where only deviations are in Higgs self-coupling !!

- Given that self-couplings are only predicted possible deviations from SM
- $\Rightarrow$ LHC prospects for measuring Higgs self couplings?
- Interesting new possible shape for Higgs potential
- $\Rightarrow$ Cosmological consequences?
- New physics states in Hidden Sector quite heavy, possibly stable
- $\Rightarrow$ Heavy dark matter candidates?

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