Underlying conformally extended standard models

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based on: 1907.09176

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@ SYSU: Composite 2019: Hunting New Physics in Higgs, Dark Matter, Neutrinos, Composite Dynamics and Extra-Dimensions., 11/21/2019 - 11/24/2019

Introduction

☆ Discovery of Higgs boson in 2012

--- last piece of particles predicted in SM

--- very successful SM pheno. so far

--- but, NOT the end of the story!

still lots of stuff left needed to account for

e.g. neutrino masses (mixing),
dark matter, baryon asymmetry, etc

No clear BSM signal seen yet, though…
(2012 was already 7 years ago….)

☆ In particular,
SM involves unsatisfactory stuff on theoretical ground:

--- origin of mass is given "by hand"

--- why mH^2 <0 (dynamical origin?) and O(100 GeV)^2?
(related to gauge hierarchy problem)

One way to tackle the dynamical origin of mass

- Classical scale invariance [Bardeen (1995)]

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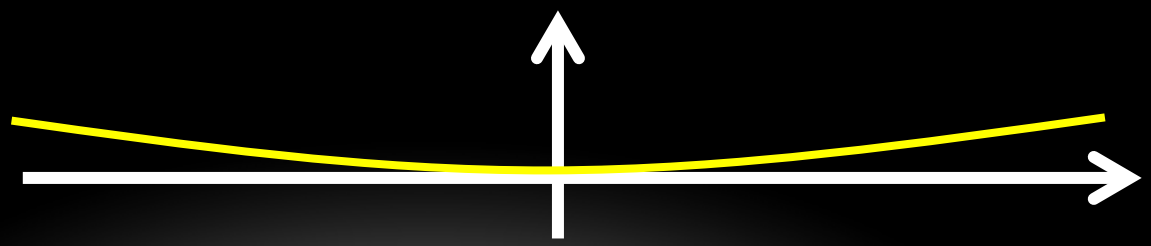
Higgs potential w/o mass term = ideal limit for scale-inv.

$$V = -\cancel{m_H^2}\,|H|^2 + \lambda_H\,|H|^4$$

In reality, it's not so bad: a hint from observation:

$$\lambda_H = \left(m_h^2/2v_{\rm EW}^2\right) \simeq 1/8 \ll 1$$



Higgs potential would be flat enough

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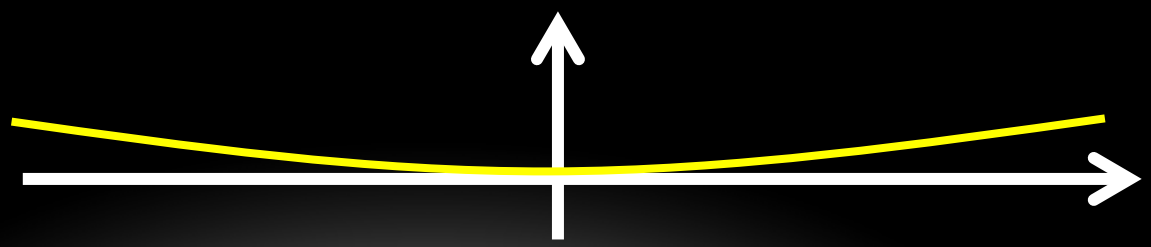

The SM seems to be oriented to nearly conformal direction

Let’s go along the conformal direction beyond SM, covering SM!

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Generic and simplest Conformal extension:

$$\lambda_{\rm mix} |H|^2 |S|^2$$

$$\lambda_{\rm mix} |H|^2 \langle S \rangle^2$$

Some dynamics spontaneously breaks scale symmetry

$\lambda_{\rm mix} \langle S \rangle^2$ can be regarded as Higgs mass term and triggers EWSB

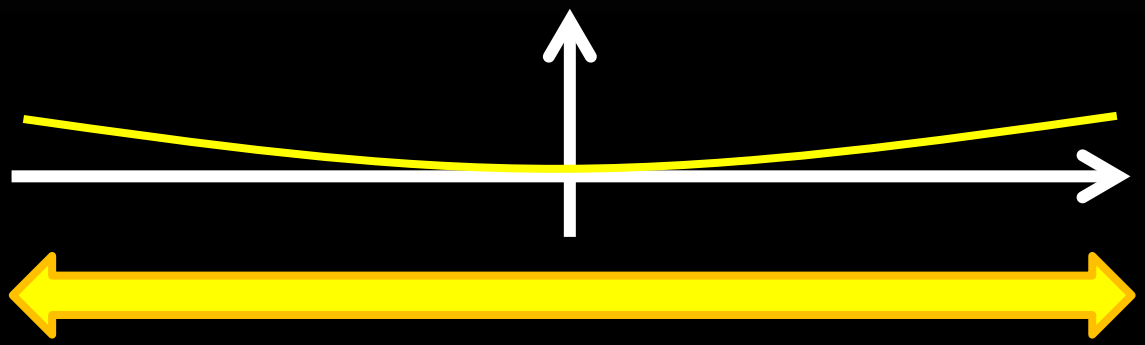
called "Higgs-portal scalegenesis"

1. perturbative a la CW [Coleman, Weinberg (1973); Gildener, Weinberg (1976)]
2. non-perturbative

[Kubo, Lim, Lindner (2014); Hur, Ko (2011); Holthausen et al. (2013); Heikinheimo et al. (2014); Hambye, Strumia (2013); Kubo, Yamada (2016); Kubo, Yamada (2016); Kubo, Soesanto, Yamada (2018); S.M., Ouyang (2019)]

In Higgs-portal scalegenesis

both of perturbative and nonperturbative types work along



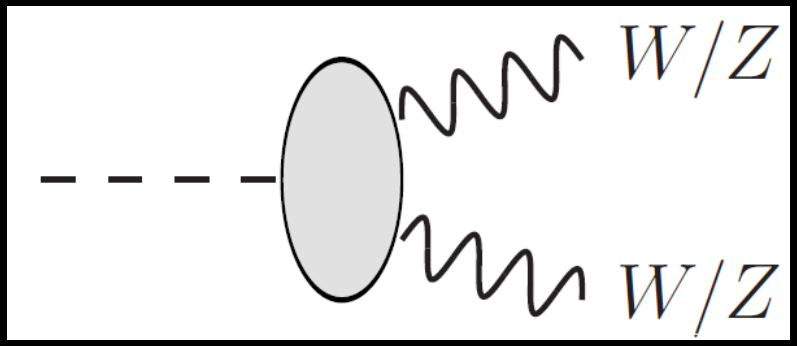
(approximate) scale symmetry: nearly conformal direction

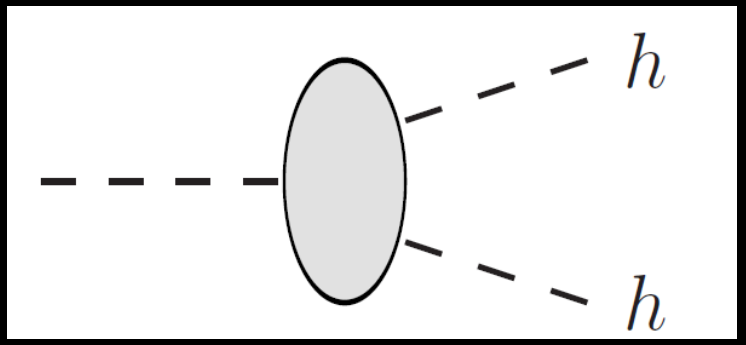
predicts

Light dilaton, e.g.

Higgs-portal scalegenesis thus generically predicts

- a light new scalar (dilaton) resonance (w/ mass ~ EW scale)





[S.M. Ouyang (2018)]

- significant effect on Higgs trilinear coupling

$$\lambda_{h'h'h'} = -4\sin^3\theta\left[\lambda_\chi + \left(1+\frac{13}{12}a\right)\lambda_a\right]\eta + \cos^3\theta\lambda_H v - \sin\theta\cos\theta\lambda_{H\chi}\left(v\sin\theta - \eta\cos\theta\right)$$

v,η: VEVs of Higgs & dilaton

θ: Higgs mixing angle

a: anomalous dimension for E.M.T

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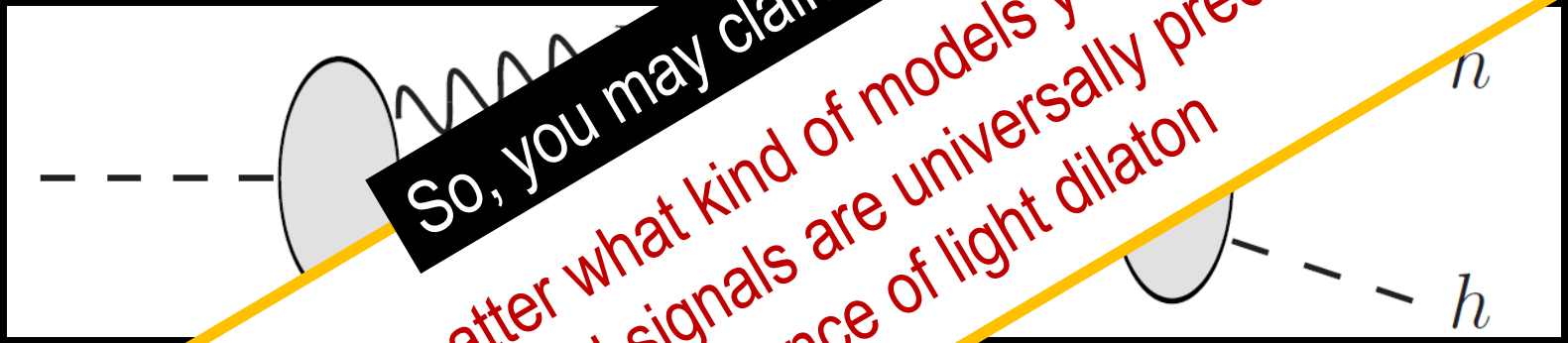

So, you may claim that..

No matter what kind of models you have, experimental signals are universally predicted by existence of light dilaton

[S.M. Ouyang (2018)]

- trilinear coupling

$$\lambda_{h'h'h'} = \left[\left(1+\frac{13}{12}a\right)\lambda_a\right]\eta$$
$$+ \lambda_H v$$
$$- \sin\theta\cos\theta\lambda_{H\chi}\left(v\sin\theta - \eta\cos\theta\right)$$

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How can we distinguish this “universality” class?

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Should not it be provided by a dynamical origin of the Higgs portal interaction?

$$\lambda_{\rm mix} \, |H|^2 \, |S|^2$$

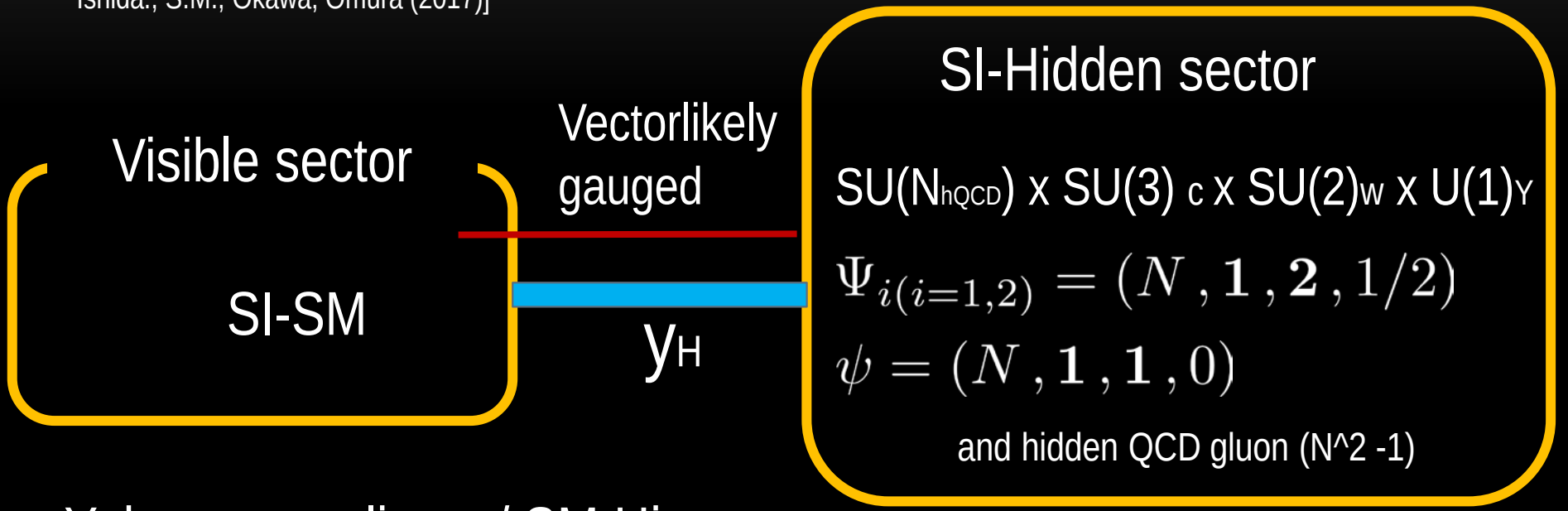
Actually, this guy again has to be "negative"…

$$\lambda_{\rm mix} < 0 \text{ by hand, s.t. } m_H^2 < 0$$

A very origin of portal coupling (hidden QCD)

Hidden fermionic QCD

[Haba, Ishida, Kitazawa, Yamaguchi (2016); Ishida., S.M., Yamaguchi (2016); Ishida., S.M., Yamaguchi (2017); Ishida., S.M., Okawa, Omura (2017)]



Yukawa coupling w/ SM Higgs

$$\mathcal{L}_{\rm Yukawa} = -y_H \bar{F}_L \cdot \begin{pmatrix} 0 & H \\ H^\dagger & 0 \end{pmatrix} \cdot F_R + \text{H.c.}$$

$$F_{L/R} \equiv (\Psi\,, \psi)$$

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@ $\Lambda_{\rm hQCD}$ = O(1) TeV

* SSB of SU(3)L x SU(3)R → SU(3)V by $\langle \bar{F}_i F_j \rangle \sim \Lambda^3_{\rm hQCD} \delta_{ij}$

--- dimensional transmutation – scale generation

* Chiral mesons generated

$$F_{L/R} \equiv (\Psi\,, \psi)$$

$$\mathcal{L}_{\rm Yukawa} = -y_H \bar{F}_L \cdot \begin{pmatrix} 0 & H \\ H^\dagger & 0 \end{pmatrix} \cdot F_R + \text{H.c.}$$

$\Lambda_{\rm hQCD}$ ⟶ $-\chi^2 \left[c_1 (H_1^\dagger \Theta + \text{H.c.}) + c_2 |\Theta|^2 \right]$

$\Theta \sim \bar{\psi}_R \Psi_L$

$\chi \sim G^2/\bar{F}F$ or admixture

* <Θ>=0 & c2 > 0 ← ensured by Vafa-Witten theorem

* No direct HHXX coupling: ← X = composite dilaton

$$F_{L/R} \equiv (\Psi\,, \psi)$$

$$\mathcal{L}_{\rm Yukawa} = -y_H \bar{F}_L \cdot \begin{pmatrix} 0 & H \\ H^\dagger & 0 \end{pmatrix} \cdot F_R + \text{H.c.}$$

$\Lambda_{\rm hQCD}$ ⟶

$$-\chi^2 \left[c_1 (H_1^\dagger \Theta + \text{H.c.}) + c_2 |\Theta|^2 \right]$$

$$\Theta \sim \bar{\psi}_R \Psi_L$$

Integrate out a heavy Θ w/ O(1) TeV mass

Portal int. dynamically generated ⟶

$$V \approx -\left(\frac{c_1^2}{c_2}\right) \chi^2 |H_1|^2$$

* <Θ>=0 & c2 > 0 ← ensured by Vafa-Witten theorem

* No direct HHXX coupling: ← X = composite dilaton

Thus, very and natural origin of portal coupling
can be supplied by

hidden fermionic QCD

-- w/ a definite discriminator
along the conformal direction:

Portal coupling has to be phenomenologically small

c1 ~ yH [origin]:

$$\mathcal{L}_{\text{Yukawa}} = -y_H \bar{F}_L \cdot \begin{pmatrix} 0 & H \\ H^\dagger & 0 \end{pmatrix} \cdot F_R + \text{H.c.}$$

signaled by small enough hidden chiral breaking
= light hQCD pions

Conclusion

The issue is to interpret "Quest for Origin of Mass"

-- put in by hand, in the SM

-- explore the dynamical origin, along the nearly SI, conformal SM

- Any sort of conformal extensions,
  based on Higgs-portal scalegenesis, involve

  a light dilaton, giving universal low-energy signatures,
  hence form "*universality class*"

- Degeneracy in models disassociated by the very origin of the Higgs portal -- hidden fermionic QCD
  – light hQCD pions

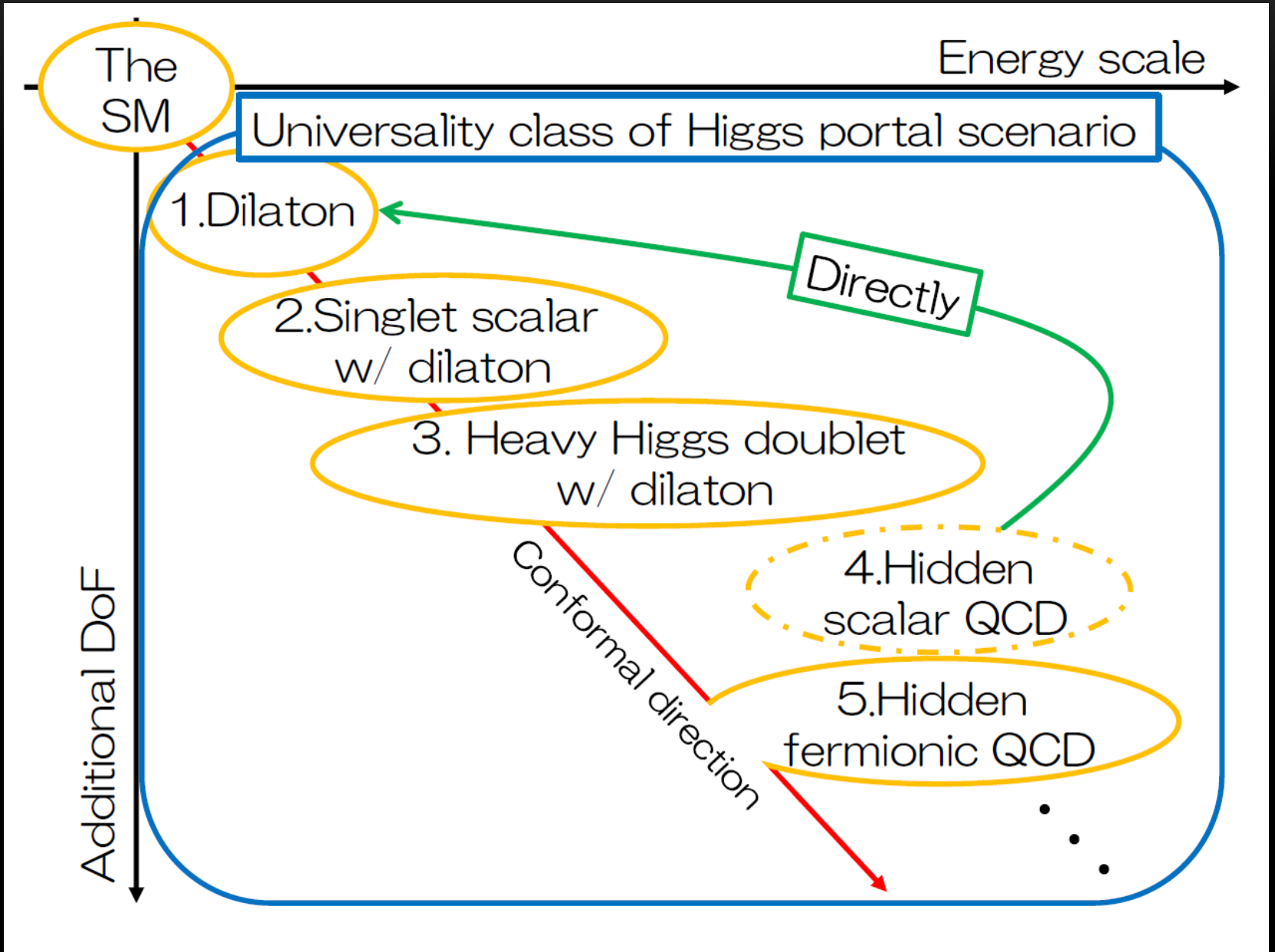
Comments added:

* Light chiral pions with mass O(500 GeV) for $\lambda_{\rm hQCD} = \mathcal{O}(1)\,{\rm TeV}$ may show up in near future collider exps., via EW production and decay processes. [for more details, ref. to the paper]

* Many future works left:
  -- thermal history regarding the hQCD scenario;
  -- possible gravitational wave signals discriminating the universality class
  -- detailed collider simulations for light dilaton and pions
  -- extension to Planck scale generation along the universality class,
  -- and so forth..

Backup slides

Universality class of Higgs portal scalegenesis



Origin of portal coupling (warm-up by 2HDM)

Consider a scale-invariant potential w/ singlet χ and 2HDs $H_{1,2}$

$$V \supset \chi^2 \left[c_0 \left| H_1 \right|^2 + c_1 \left(H_1^\dagger H_2 + \text{H.c.} \right) + c_2 \left| H_2 \right|^2 \right]$$

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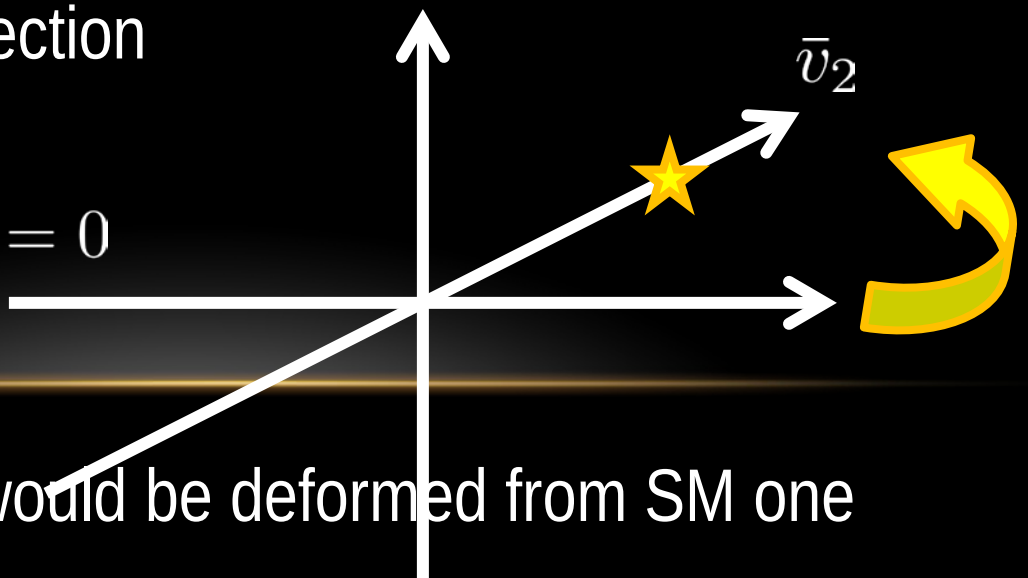
The potential can be minimized:

$$V \to \frac{1}{2} \chi^2 \left(c_2 \underline{\left(v_2 + \frac{c_1}{c_2} v_1 \right)^2} + \left(c_0 - \frac{c_1^2}{c_2} \right) v_1^2 \right)$$

0

keeping conformal direction achieved by

$$\bar{v}_2 \equiv v_2 + (c_1/c_2)\, v_1 = 0$$



Hence EWSB vacuum would be deformed from SM one

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Make Higgs-chiral structure manifested:

$$\Sigma \equiv (H_1 \, , H_2^c)$$

$$V \ni \chi^2 \left[\left(\frac{c_0 + c_2}{2} \right) \text{tr} \left[\Sigma^\dagger \Sigma \right] + c_1 (\det \Sigma + \text{H.c.}) + \left(\frac{c_0 - c_2}{2} \right) \text{tr} \left[\Sigma^\dagger \Sigma \sigma^3 \right] \right]$$

$U(2)_L$ x $U(2)_R$ w/ soft breaking by c1 [$U(1)_A$] and c0-c2 [$SU(2)_R$]

* Assume inert H_2, i.e. $c_2 > 0$, s.t. $\langle H_2 \rangle = 0$

*Take maximal Higgs-isospin violation limit

*Take soft/small enough mixing/breaking $U(1)_A/Z_2$

But, sounds still ad hoc?

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$$c_0/c_2 \ll 1 \text{ and } c_1/c_2 \ll 1, \text{ with } c_2 > 0$$

$$V \supset \chi^2 \left[c_0 |H_1|^2 + c_1 \left(H_1^\dagger H_2 + \text{H.c.} \right) + c_2 |H_2|^2 \right]$$

EoM $H_2 \simeq -(c_1/c_2) H_1$

$$V \approx -(c_1^2/c_2) \chi^2 |H_1|^2$$

$= \lambda_{mix}$

Negative portal coupling is dynamically generated!

This is called "bosonic seesaw mechanism"

[Calmet (2003); Kim (2005); Haba, Kitazawa, Okada (2009); Antipin, Redi, Strumia (2015); Haba, Ishida., Okada, Yamaguchi (2016); Haba. Ishida., Kitazawa, Yamaguchi (2016); Ishida, S.M., Yamaguchi (2016); Ishida., S.M., Yamaguchi (2017); Haba, Yamada (2017); Haba, Yamada (2017); Ishida., S.M., Okawa, Omura (2017)]

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Mass matrix of Higgses

$$\begin{pmatrix} 0 & c_1 \\ c_1 & c_2 \end{pmatrix} \xrightarrow{\text{diagonalization}} \begin{pmatrix} -\frac{c_1^2}{c_2} & 0 \\ 0 & c_2 \end{pmatrix}$$