Unified Interpretation of Scalegenesis in Higgs Portal Scenarios

Hiroyuki Ishida (KEK)

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Collaborators: Shinya Matsuzaki (Jilin U.)
Ruiwen Ouyang (NICPB)

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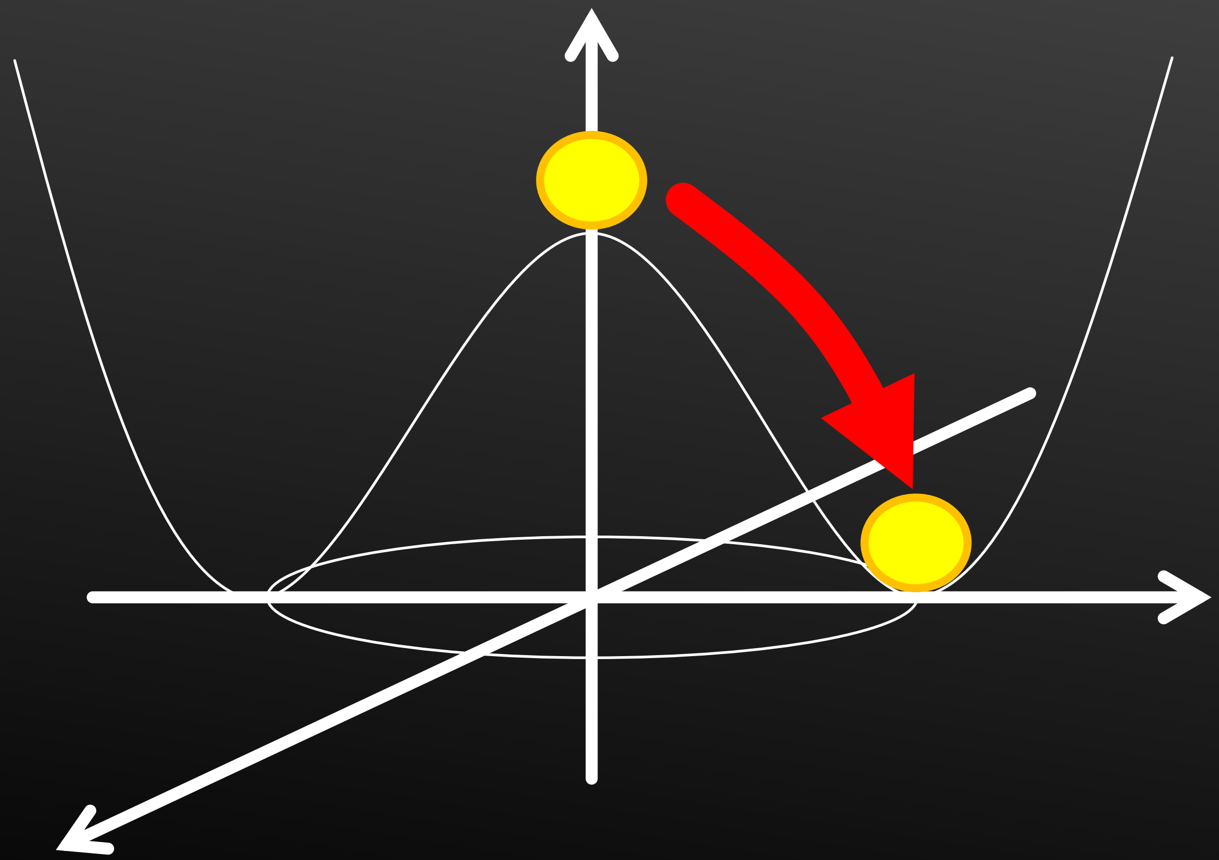
Introduction

Consequence of Higgs boson

Electroweak symmetry breaking (origin of mass)



$$V = -m_H^2 \left|H\right|^2 + \lambda_H \left|H\right|^4$$

Introduction

Consequence of Higgs boson

Electroweak symmetry breaking (origin of mass)

Higgs boson mass parameter

Negative parameter for EWSB

Unique dimensionful parameter

Radiative corrections

$$\Delta m_H^2 = -4 \sum_f m_f^2 \left(\Lambda_f^2 / v_{\mathrm{EW}}^2\right) + \left(2m_W^2 + m_Z^2 + m_H^2\right) \left(\Lambda_b^2 / v_{\mathrm{EW}}^2\right)$$

Quadratic divergence is NOT physical [Bardeen (1995)]

Introduction

Consequence of Higgs boson

Electroweak symmetry breaking (origin of mass)

Bardeen's argument (1995)

The quadratic divergence in the Higgs mass corrections can be subtracted by a boundary condition of some ultraviolet complete theory and only logarithmic divergences should be considered

$$m_h^2 = -2m_H^2 + \lambda M^2 \log\left(\mu^2/\Lambda^2\right) \cancel{+\Lambda^2}$$

Hierarchy problem can be solved unless new scale (M) is not too large

Introduction

Simple solution for fine-tuning

➡ **Classical scale invariance** [Bardeen (1995)]

RGE running of Higgs mass parameter

$$\frac{dm_H^2}{d\ln\mu} = \frac{1}{(4\pi)^2} m_H^2 \left[12\lambda_H^2 + 6y_t^2 - \frac{3}{2}g_1^2 - \frac{9}{2}g_2^2 \right]$$

Once we do not have Higgs mass parameter, hierarchy problem is always gone

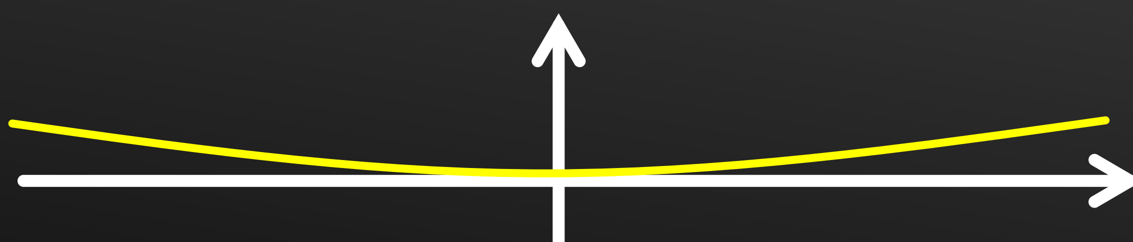
Introduction

Higgs potential w/o mass term

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

Value of quartic coupling (tree)

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



Higgs potential would be flat enough

Conformal direction

We have to rely on NP to generate scale

Introduction

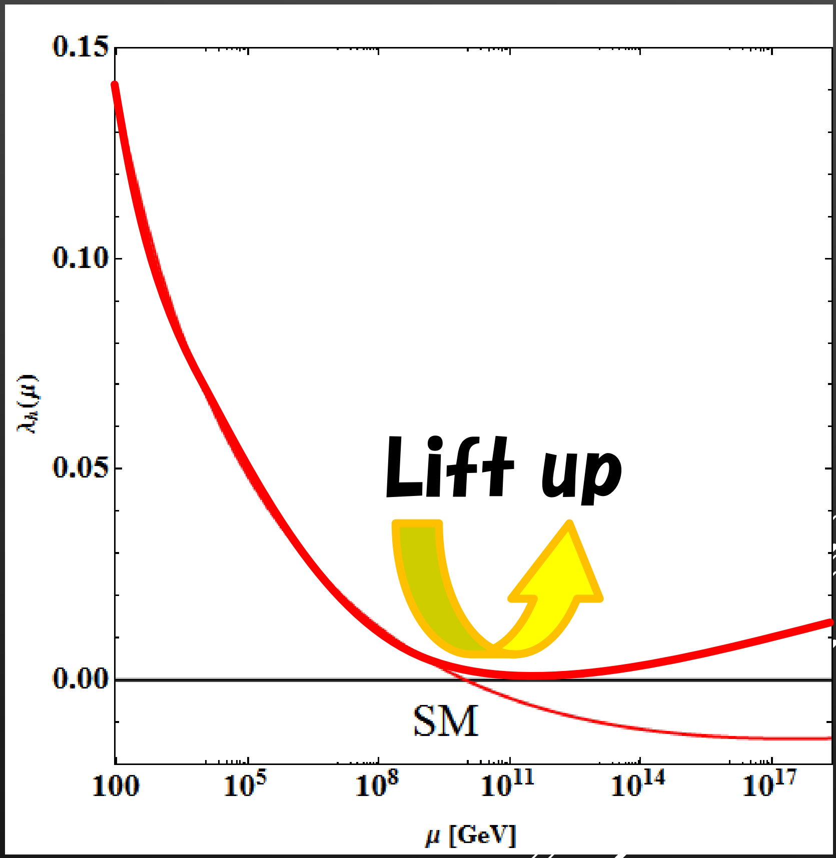
Guide(?) for NP (EW vacuum stability)

top quark contribution makes EW vacuum unstable

To consider BSM physics, to choose the conformal direction would be helpful

➡ Classical scale invariance

New scalar dof (S) helps to stabilize EW vacuum



Mixing w/ Higgs $\lambda_{\mathrm{mix}}\,|H|^2\,|S|^2$ is essential

Higgs portal scenario

Introduction

Higgs-portal scalegenesis (small summary)

Perturbative realization

Scale symmetry is broken by quantum effects such as RGE running

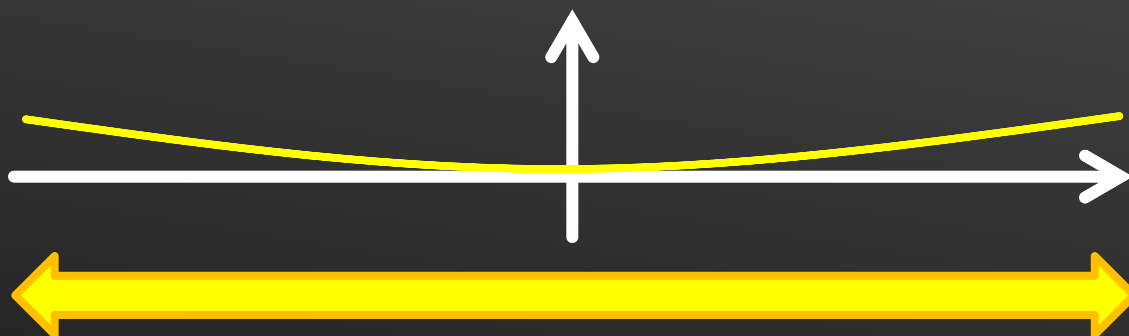
Non-perturbative realization

Scale symmetry is broken by non-perturbative scale anomaly

Introduction

Higgs-portal scalegenesis

In both of perturbative and nonperturbative types



Scale symmetry: nearly conformal direction

Predict

Light dilaton

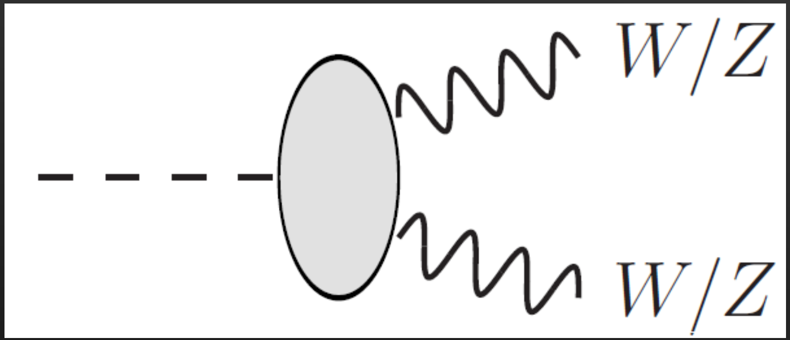
$\sim \mathcal{O}(100)$ GeV

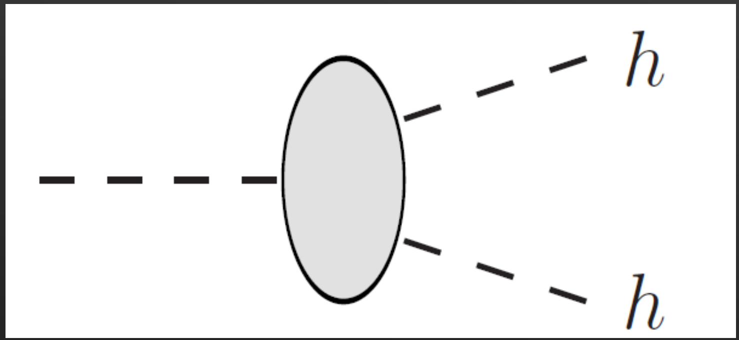
Introduction

Higgs-portal scalegenesis

Hints of light dilaton

-New resonance





-Higgs trilinear coupling [Matsuzaki, Ouyang (2018)]

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

v,η: VEV of Higgses

θ: Higgs mixing angle

a: anomalous dimension

Introduction

Higgs-portal scalegenesis

Hints of light dilaton

Our claim 1

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

Unified interpretation of Higgs portal scenarios!

Question: What is the discriminator of models?

Introduction

Higgs-portal scalegenesis

Our claim 2

Origin of scale symmetry breaking cannot directly be the origin of mass

To regard $\lambda_{\rm mix} |H|^2 |S|^2$ as Higgs mass term, negative $\lambda_{\rm mix}$ has to be required

Question: What can be the origin of negative sign?

First, let's examine with 2HDM model

Origin of negative coupling (2HDM)

Scale-invariant potential

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

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

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

Soft Z_2 breaking term

$SU(2)_{H_2}$ breaking term

Global chiral symmetry: $U(2)_{H_1} \times U(2)_{H_2}$

Origin of negative coupling (2HDM)

Scale-invariant potential

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

$c_{1,2,3}$ are real and positive

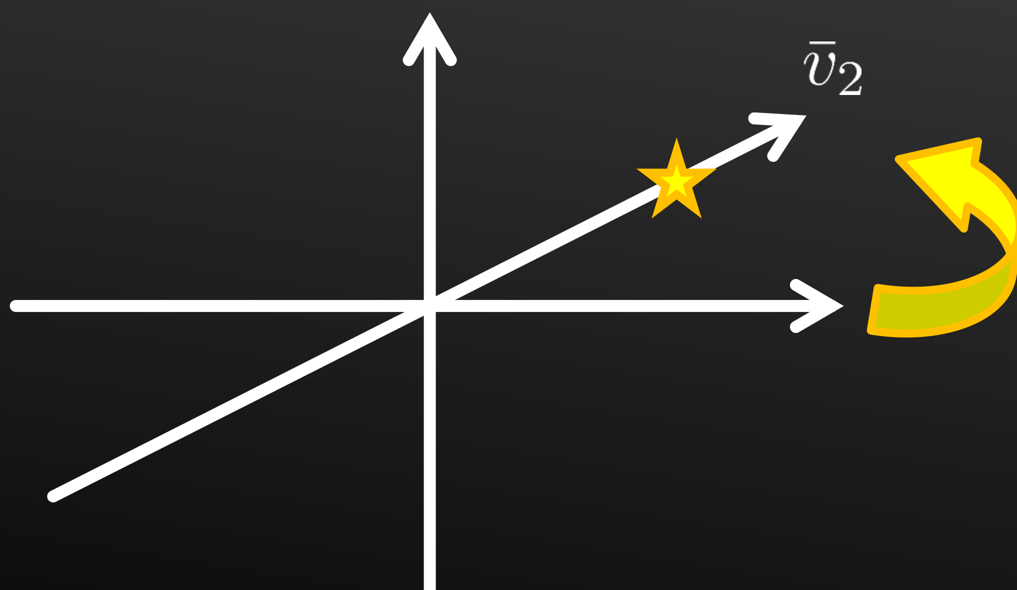
Conformal direction can be achieved by choosing $\bar{v}_2 \equiv v_2 + (c_1/c_2)\, v_1 = 0$

Direction for EWSB is deformed

Origin of negative coupling (2HDM)

Scale-invariant potential

$$V \to \frac{1}{2}\chi^2 \left(c_2 \underbrace{\left(v_2 + \frac{c_1}{c_2} v_1 \right)}_{0}^2 + \left(c_0 - \frac{c_1^2}{c_2} \right) v_1^2 \right)$$



Origin of negative coupling (2HDM)

Scale-invariant potential

Assumptions for negative portal coupling:

- Maximal isospin breaking: $c_0/c_2 \to 0$
- Soft enough $U(1)_A/Z_2$: $c_1/c_2 \ll 1$

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

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

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

Negative sign is automatically generated!

Origin of negative coupling

Bosonic seesaw mechanism

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

Mass matrix of Higgses

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

Reinterpretation of deformation

$$\bar{v}_2 \equiv v_2 + (c_1/c_2)\, v_1 = 0 \Longleftrightarrow \bar{H}_2 \simeq H_2 + (c_1/c_2)\, H_1 = 0$$

Inert Higgs

Bosonic seesaw also provides same low-energy signatures

Origin of negative coupling

Bosonic seesaw mechanism w/ hidden fermionic QCD

@chiral condensation scale $\Lambda_{\rm hQCD}$

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

$$=\chi^2\left\{c_1(\det\Sigma+\text{H.c.})+c_2\text{tr}\left[\Sigma^\dagger\Sigma\left(\frac{1-\sigma^3}{2}\right)\right]\right\}$$

$\Sigma=(H,\Theta^c)$ **w/** $\Theta\sim\bar{\psi}_R\Psi_L$

- Maximal isospin breaking: scale invariance
- Soft enough $U(1)_A/Z_2$; c_1 is originated Yukawa

  c_2 is originated hQCD

automatically incorporated! $\Rightarrow$ $c_1/c_2 \cancel{\ll 1}$

Origin of negative coupling

Bosonic seesaw mechanism w/ hidden fermionic QCD

Very origin of negative coupling would be hQCD

Fermionic hQCD predicts existence of hQCD pions

Definite discriminator of those models which is scale invariantly build along conformal direction

c_1 is small → Light hQCD pions

Prediction:

Light dilaton Light hQCD pions

Conclusions

Origin of mass

- Negative mass needs to be assumed in the SM
  - Mass parameter would have origin
  - ➥ Higgs portal extension
    - Negative coupling needs to be assumed in the most of Higgs portal scenarios
  - Conformal direction
    - ➥ Existence of light dilaton gives same low-energy signatures
      - ➥ Universality class

Conclusions

Origin of negative sign for portal coupling

- Maximal isospin breaking
- Soft enough $U(1)_A/Z_2$ breaking

Hidden Fermionic QCD dynamics would be very origin of the negative Higgs mass

Discriminator of models in universality class

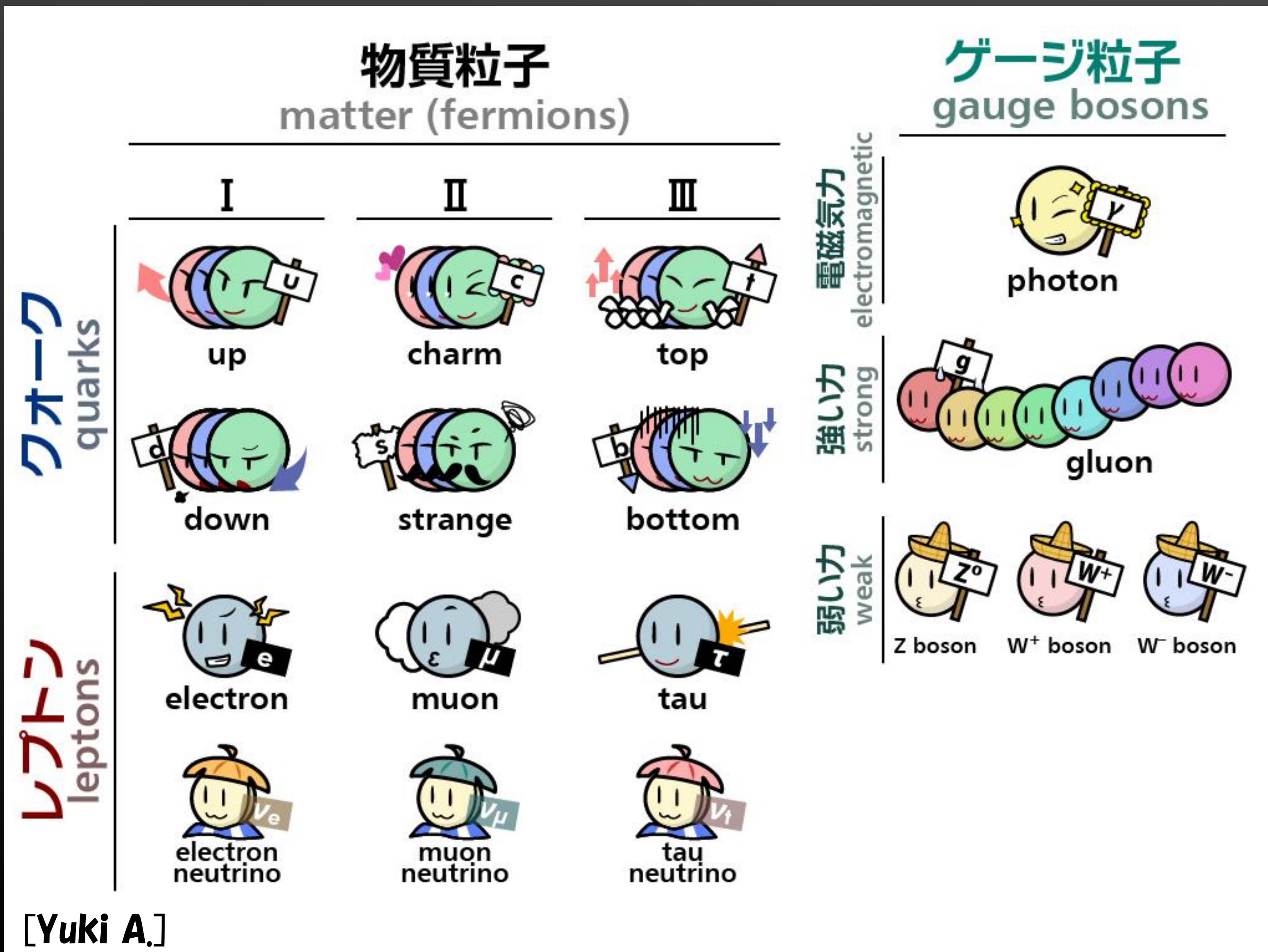
Light dilaton and pions are definite discriminators

Near and future collider experiments would observe a hint of the origin of mass!

Thank you
for your attention

Introduction

Before Higgs discovery



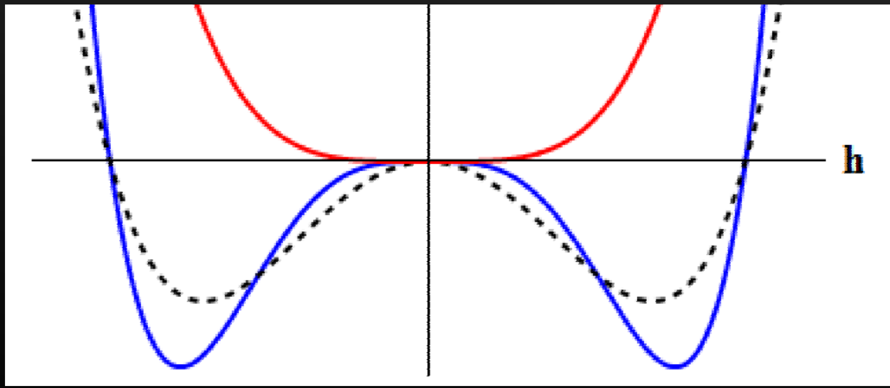
Introduction

Requirement of another dof

Quantum corrections can modify shape of potential

[Coleman, Weinberg (1973)]

Observed Higgs and top masses cannot be realized at the same time!



n_i : d.o.f of particle i

α_i : coupling of Higgs with i

C_i : constant for i

Q : renormalization scale

Introduction

How to generate scale?

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

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

Some dynamics breaks scale symmetry

$\lambda_{\text{mix}} \langle S \rangle^2$ can be regarded as Higgs mass term and triggers EWSB "Higgs-portal scalegenesis"

1. perturbative [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); Ouyang, Matsuzaki (2019)]

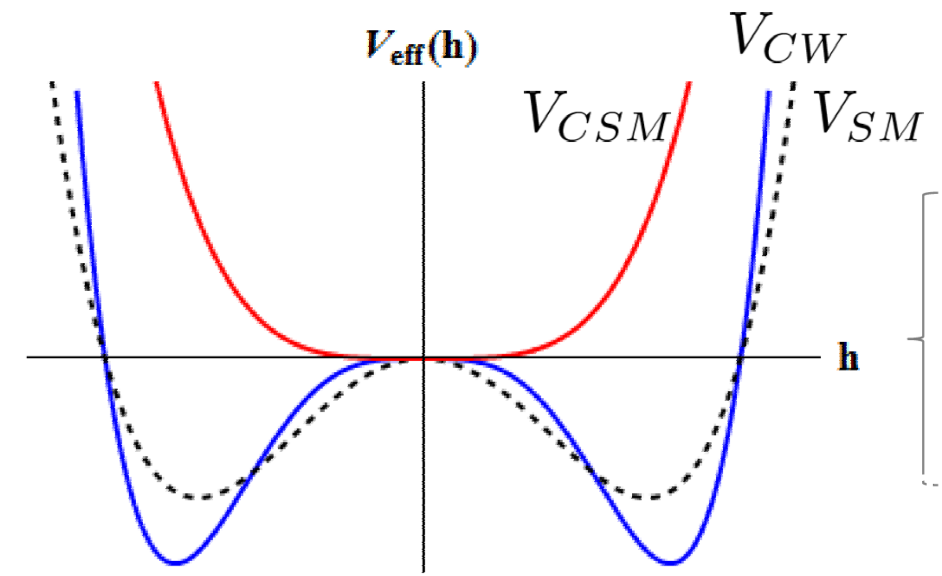
Introduction

Higgs-portal scalegenesis

Perturbative realization (CW) [Coleman, Weinberg (1973)]

$$V_{\rm CW} = \frac{1}{4}\lambda_H h^4 + \sum_i \frac{h^4}{4\pi^2} n_i \alpha_i^2 \left[\ln\left(\frac{h^2}{Q^2}\right) - C_i \right]$$

h is NOT direction of SM Higgs



n_i : d.o.f of particle i

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Introduction

Higgs-portal scalegenesis

Nonperturbative realization (scalar QCD)

[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); Ouyang, Matsuzaki (2019)]

@some scale where hidden strong int. becomes non-perturbarively large

$\langle S^\dagger S \rangle$ condensation occurs

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

Dimensional transmutation!

Origin of negative coupling

Bosonic seesaw mechanism w/ hidden fermionic QCD

[Haba, H. I., Kitazawa, Yamaguchi (2016); H. I., Matsuzaki, Yamaguchi (2016); H. I., Matsuzaki, Yamaguchi (2017); H. I., Matsuzaki, Okawa, Omura (2017)]

Visible sector

SM

Hidden sector

$$\Psi_{i(i=1,2)} = (N\,,\mathbf{1}\,,\mathbf{2}\,,1/2)$$
$$\psi = (N\,,\mathbf{1}\,,\mathbf{1}\,,0)$$

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

Yukawa coupling w/ SM Higgs

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

Origin of negative coupling

Bosonic seesaw mechanism w/ hidden fermionic QCD

Chiral structure

$$U(3)_{F_L} \times U(3)_{F_R} \xrightarrow{\Lambda_{\mathrm{hQCD}}} SU(3)_{F_V}$$

$U(1)_{F_A}$: chiral anomaly

$SU(3)_{F_L} \times SU(3)_{F_R}$: chiral condensation $\langle \bar{F} F \rangle$

8 remaining NG bosons

Explicit hidden chiral breaking is necessary

[Haba, H. I., Kitazawa, Yamaguchi (2016); H. I., Matsuzaki, Yamaguchi (2016); H. I., Matsuzaki, Yamaguchi (2017); H. I., Matsuzaki, Okawa, Omura (2017)]

Universality class of Higgs portal scalegenesis