Institute of Theoretical Physics
Chinese Academy of Sciences

# Nature of Higgs Boson
# Shape of Higgs Potential

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Based on collaborations with Hao-Lin Li, Ming-Lei Xiao, Zhe Ren,
Ling-Xiao Xu, Shou-hua Zhu, Yu-Hui Zheng, Jing Shu, Saha, Agrawal, C.-P. Yuan

电弱相变与Higgs物理专题研讨会

**IHEP-CAS Zoom Conference**
**July 31, 2020**

# Outline

- Overview on nature of Higgs boson
- Fundamental Higgs potential: SMEFT description

  Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **JHY** , Yu-Hui Zheng, 2007.07899

  Hao-Lin Li, Zhe Ren, Jing Shu, Ming-Lei Xiao, **JHY** , Yu-Hui Zheng, 2005.00008

  Tyler Corbett, Aniket Joglekar, Hao-Lin Li, **JHY**, JHEP 1805 (2018) 061

- PNGB Higgs potential: EW chiral Lagrangian

  Hao-Lin Li, Ling-Xiao Xu, **JHY,** Shou-hua Zhu, JHEP 1904.05359

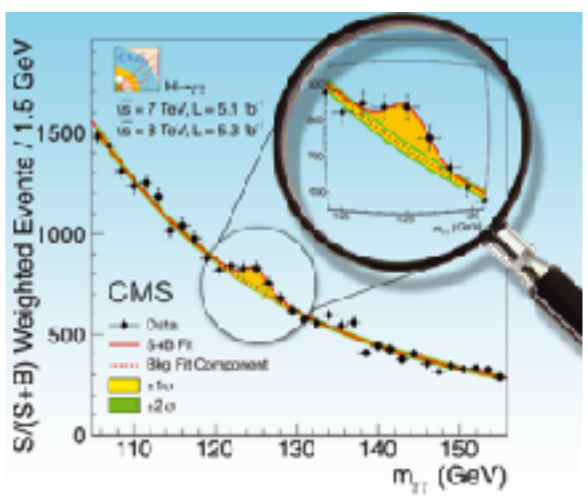
  Yong-Hui Qi, **JHY**, Shouhua Zhu, 1912.13058

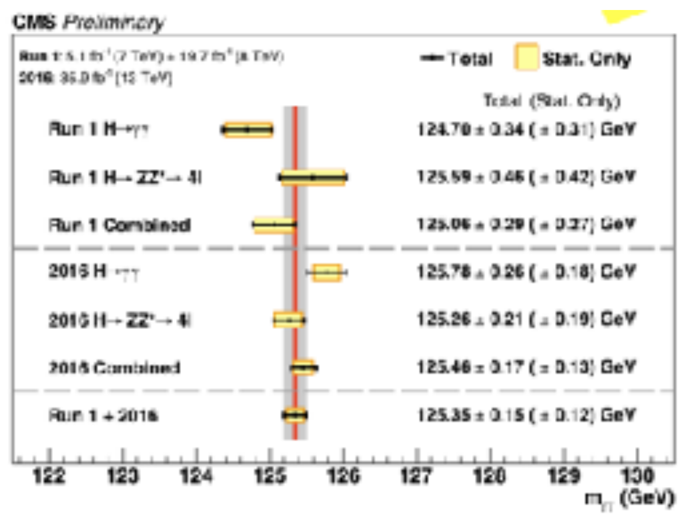
- How to determine shape of Higgs potential

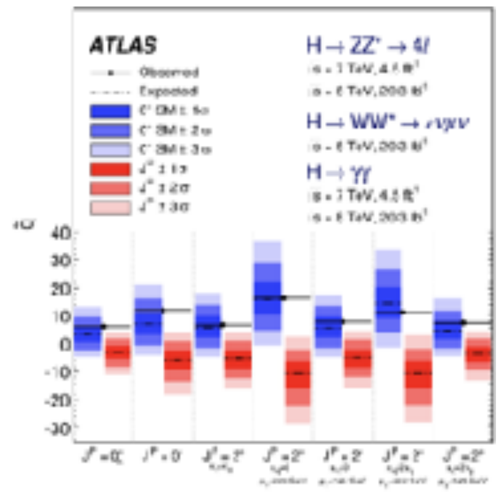
  Pankaj Agrawal, Debashis Saha, Ling-Xiao Xu, **JHY,** C.-P. Yuan, PRD 101 (2020) 075023

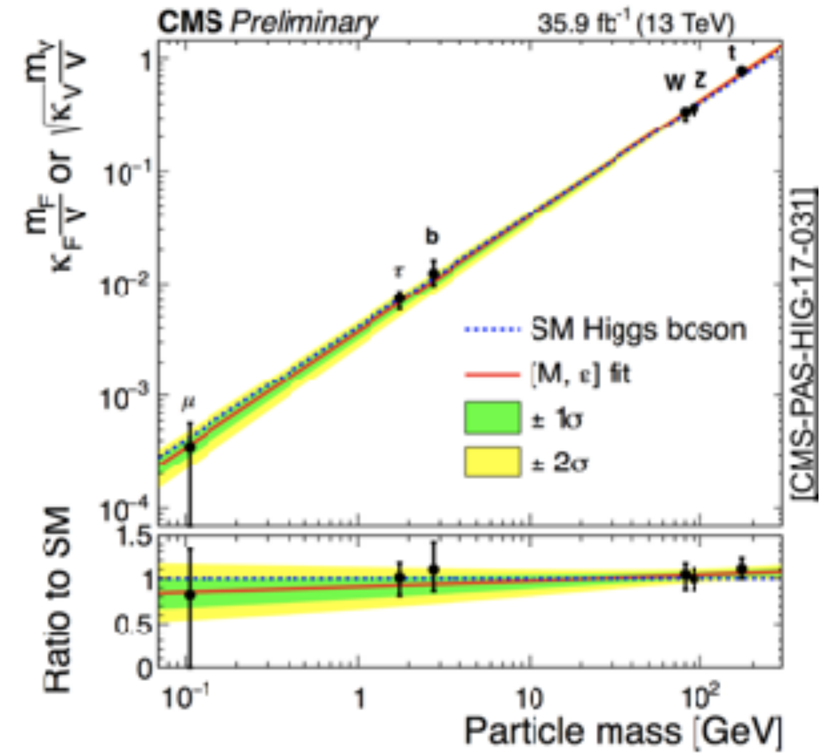
- Summary and outlook

# Higgs Boson




Discovery

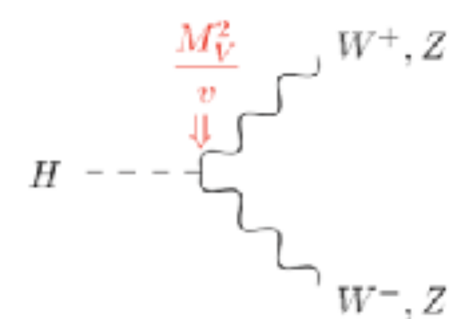
Mass

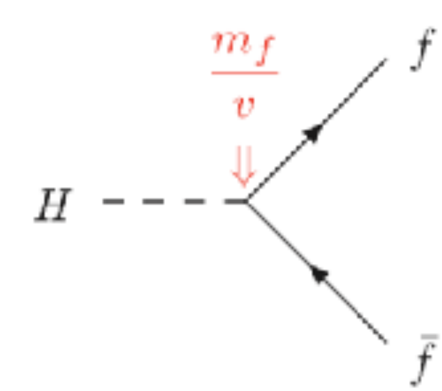
Spin

Couplings

125 GeV

$0^+$



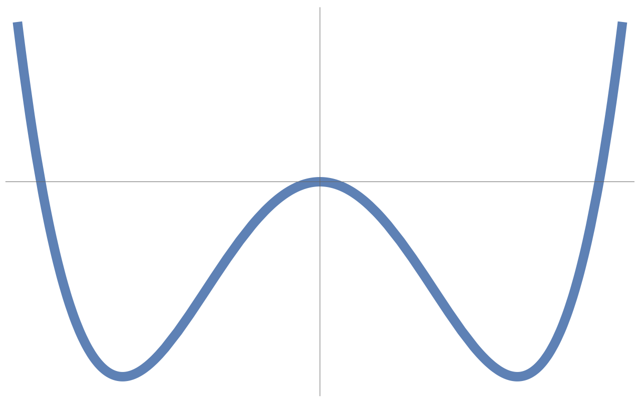



# Nature of Higgs Boson

However, nature of Higgs boson undetermined …

## Fundamental

weak dynamics at TeV

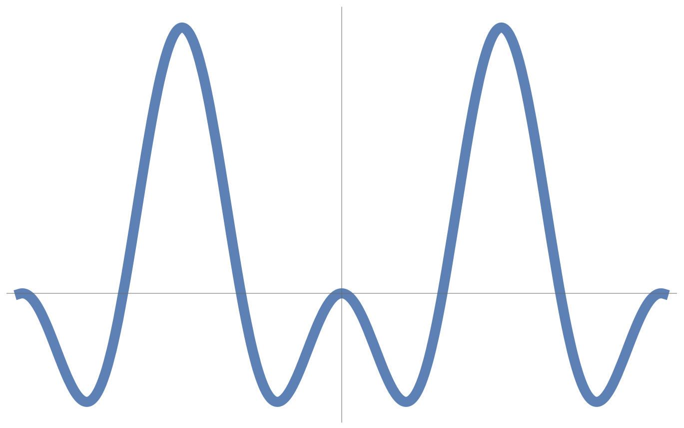


$$V(\phi) = -m^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

Landau-Ginzburg description

## Composite

strong dynamics at TeV



Microscopic theory?

# Higgs or no Higgs

Before the Higgs discovery …

Standard Model

weak dynamics at EW scale

Technicolor

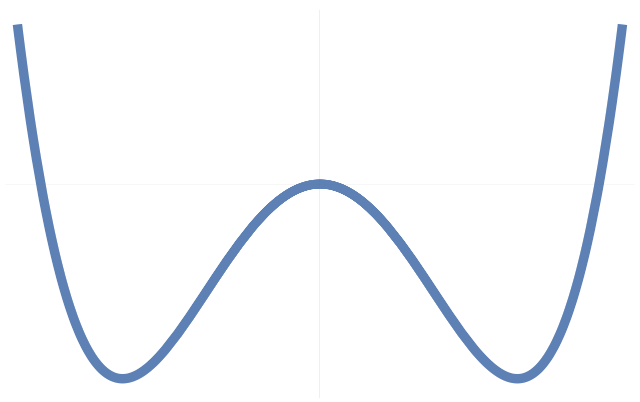
strong dynamics at EW scale

# Fundamental/Composite Higgs

An important task for HL-LHC and future collider

## Fundamental

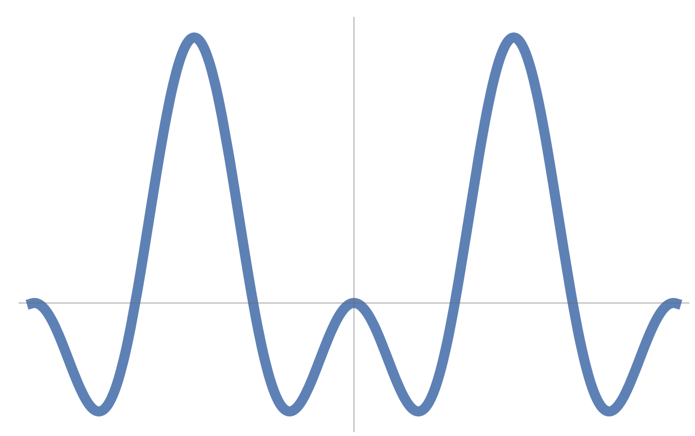
weak dynamics at TeV



$$V(\phi) = -m^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

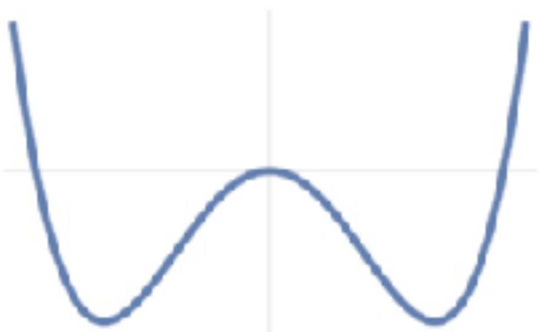
## Composite

strong dynamics at TeV



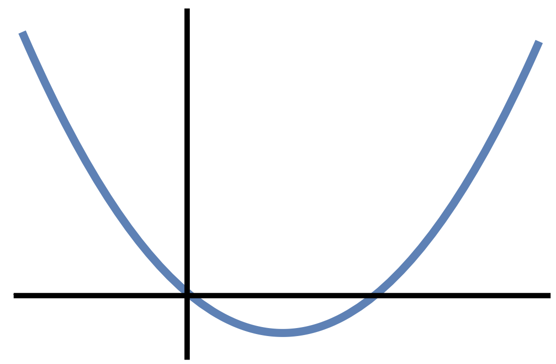
# Shape of Higgs Potential

Landau-Ginzburg Higgs



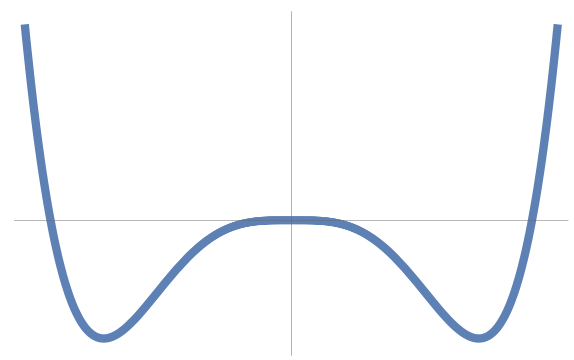
$V(\phi) = -m^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$

Tadpole-induced Higgs



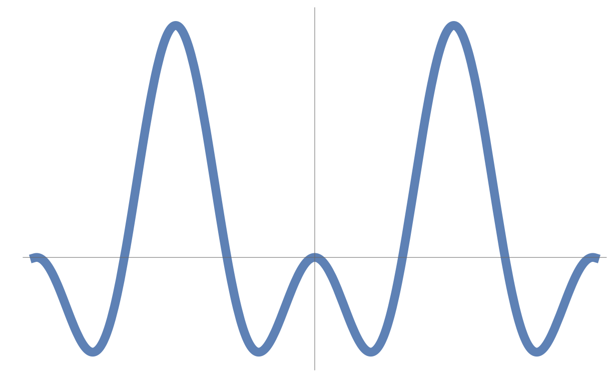
$V(\phi) = -\mu^3\sqrt{\phi^\dagger\phi} + m^2\phi^\dagger\phi$

Coleman Weinberg Higgs



$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2 \log\frac{\phi^\dagger\phi}{\mu^2}$

Pseudo-Goldstone Higgs



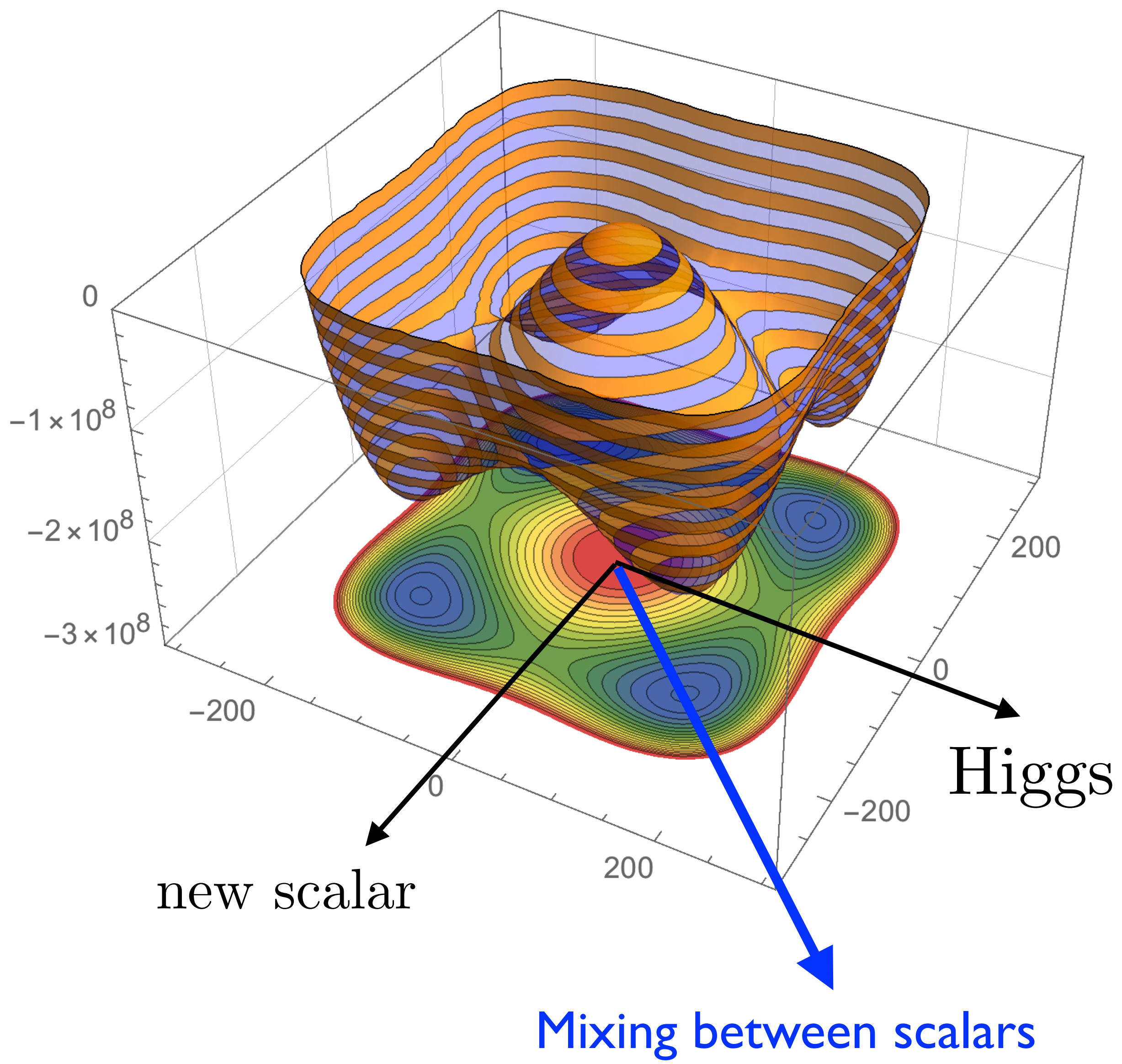
$V(\phi) = -a\sin^2(\phi/f) + b\sin^4(\phi/f)$

Fundamental | Partial Fund. | Conformal | Full Composite

Shape of Higgs potential: very different!

# Shape of Scalar Potential

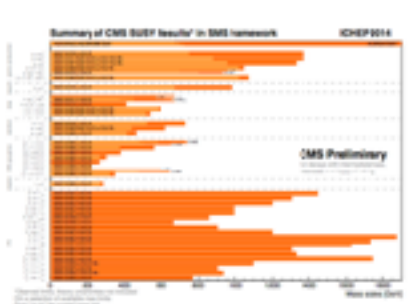
Shape of Higgs potential could be further modified



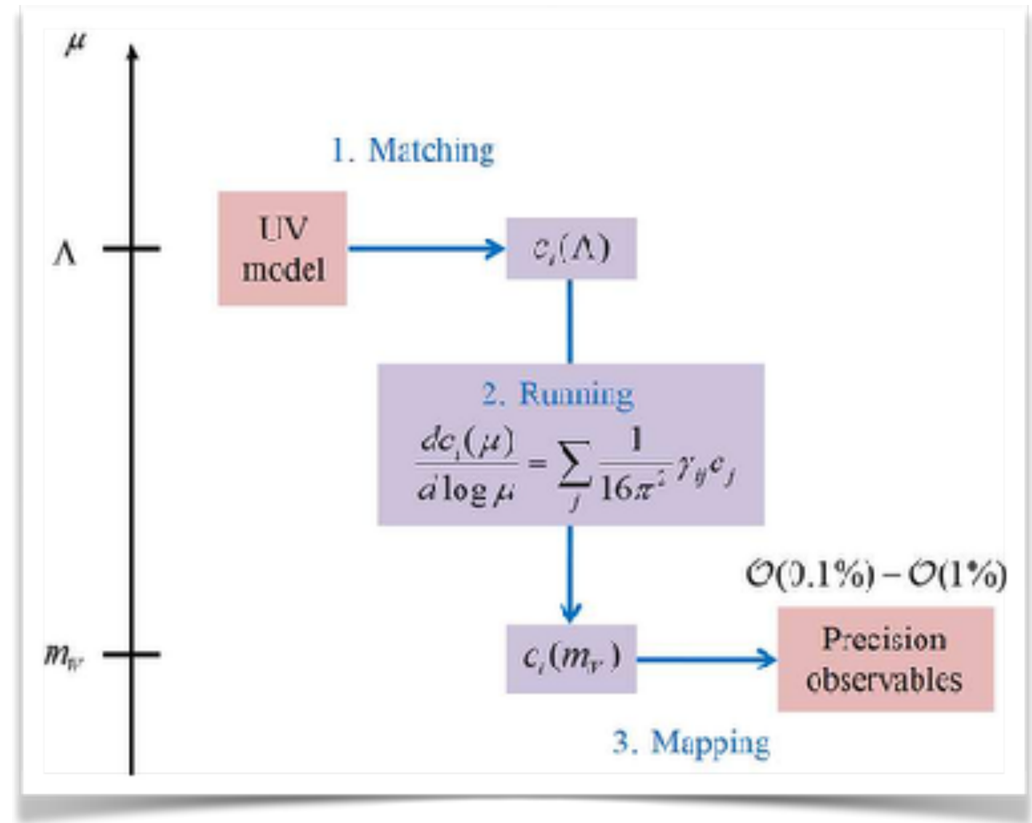

phase transition

# Scale of New Physics

LHC Searches

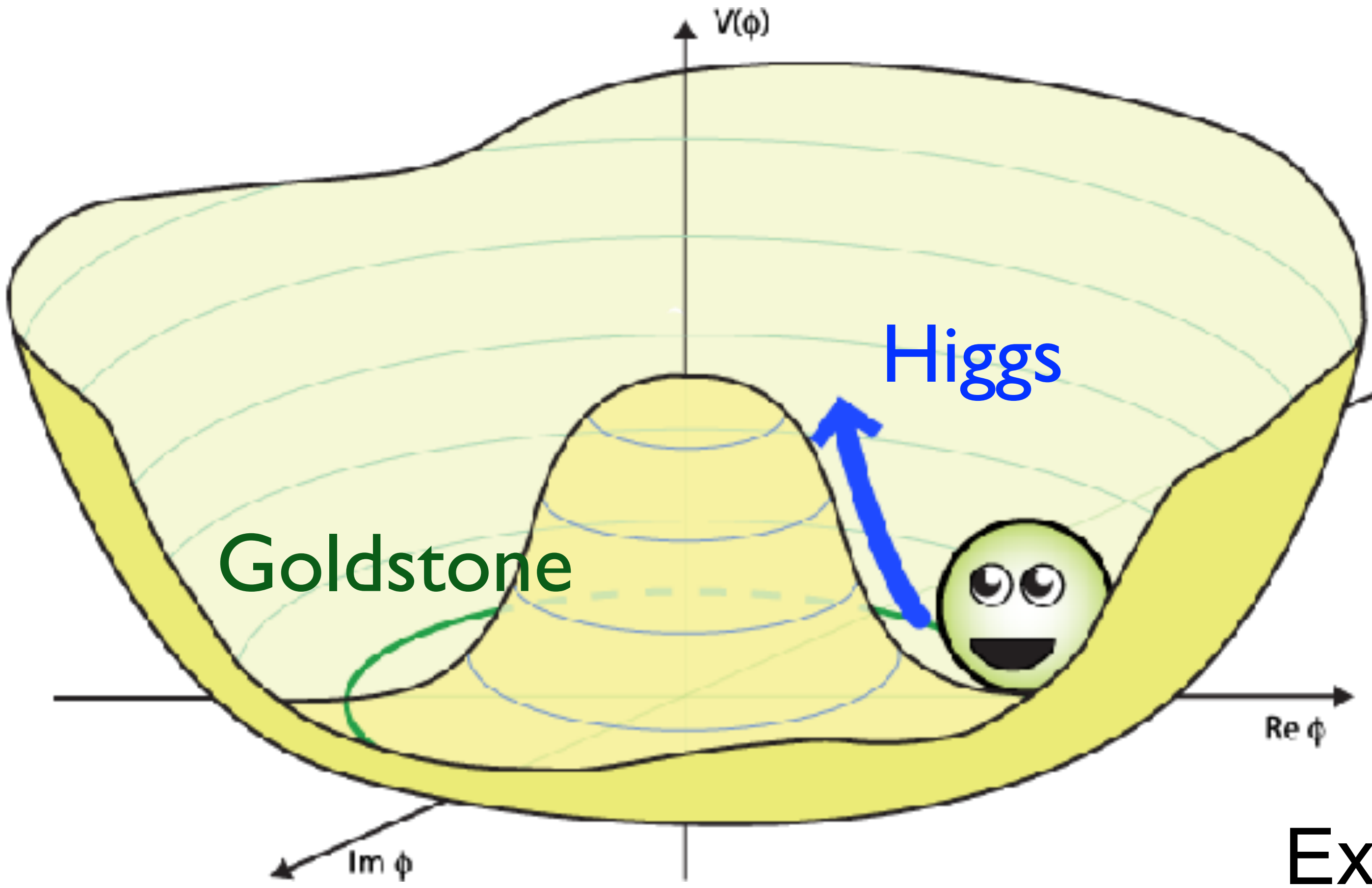


EFT description




Shape of Higgs potential at EW scale with heavy d.o.f integrate-out

# (1) Fundamental Higgs




Standard Model
Extended scalar sector
Supersymmetry
Left-right Model
GUT model
…

# UV Models

**Scalar Extension**

- Higgs Singlet
- Higgs Doublet
- Higgs Triplet
- Type-II seesaw
- Minimal Dark Matter
- …

**Fermion Extension**

- Type-I seesaw
- Vectorlike fermion
- Heavy 4th gen.
- Vectorlike top
- Singlet-doublet dark matter
- …

**Gauge Extension**

- U(1) extensions
- SU(2) extensions
- G331
- Pati-Salam
- GUT
- …

# EFT Framework

**UV model**

$$\mathcal{L} = \mathcal{L}^{\text{eff}}_{\text{Gravity}} + \underbrace{\mathcal{L}_{\text{QCD}} + \mathcal{L}_{\text{QED}} + \mathcal{L}_{\text{EW}}}_{\mathcal{L}_{SM}} + \mathcal{L}^{NP}_{\text{heavy}}$$

Integrate out TeV heavy states

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**SMEFT**

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{C_i^{(5)}}{\Lambda_{NP}} Q_i^{(5)} + \frac{C_i^{(6)}}{\Lambda_{NP}^2} Q_i^{(6)} + \cdots$$

Electroweak symmetry breaking

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**Higgs EFT**

$$\begin{aligned}\mathcal{L} = {} & \frac{1}{2}(\partial_\mu h)^2 - V(h) \\ & + \frac{v^2}{4}\mathrm{Tr}\left[(\partial_\mu U)^\dagger \partial^\mu U\right]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right) \\ & - \frac{v}{\sqrt{2}}\left(\bar{t}_L, \bar{b}_L\right) U \left(1 + c_1\frac{h}{v} + c_2\frac{h^2}{v^2} + \cdots\right)\begin{pmatrix} y_t t_R \\ y_b b_R \end{pmatrix} + \text{h.c.}\end{aligned}$$

$m_W$

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**LEFT**

$$\mathcal{L}_{\text{LEFT}} = \mathcal{L}_{\text{QED+QCD}} + \frac{C_i^{(5)}}{M_W} O_i^{(5)} + \frac{C_i^{(6)}}{M_W^2} O_i^{(6)} + \cdots$$

# SMEFT

## Dimension-5

$\epsilon_{ij}\epsilon_{mn}(L^i C L^m)H^j H^n$

[Weinberg, 1979]

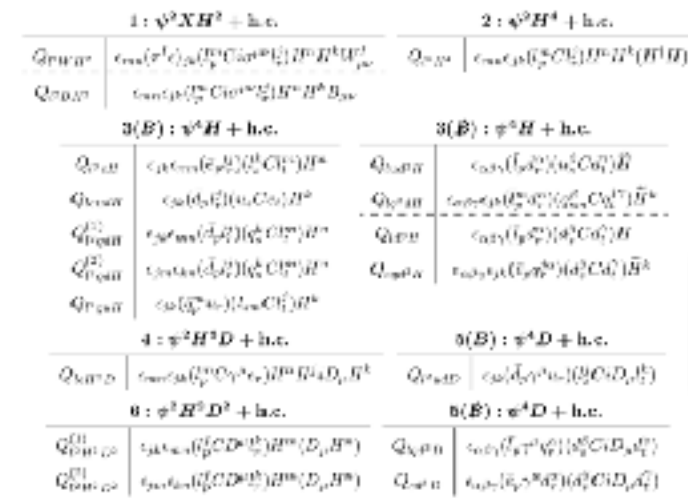
2

## Dimension-6

84

[Buchmuller, Wyler, 1986] [Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

## Dimension-7

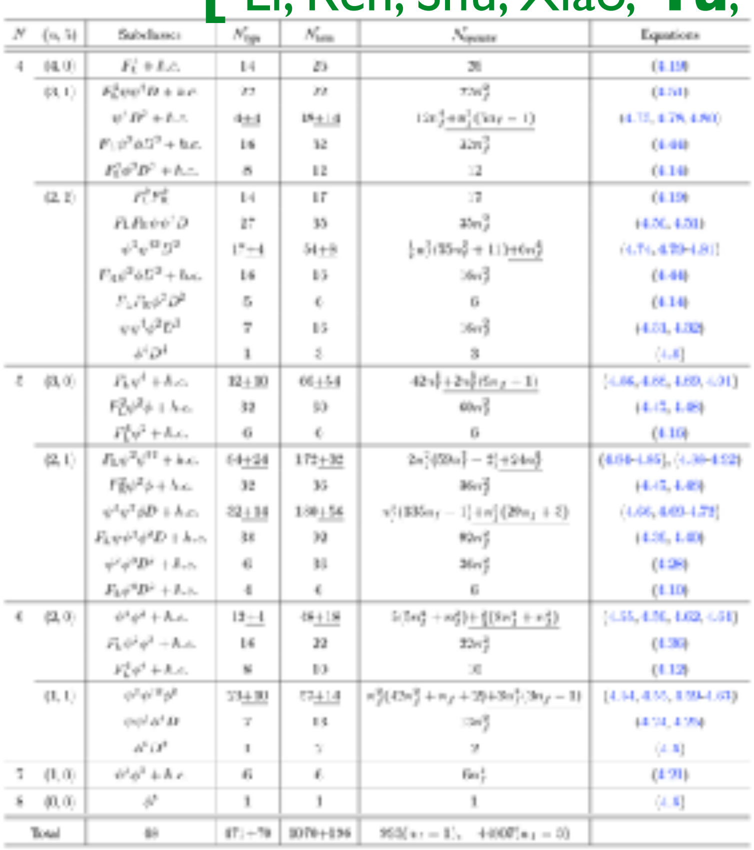


30

[Lehman, 2014]

## Dimension-8

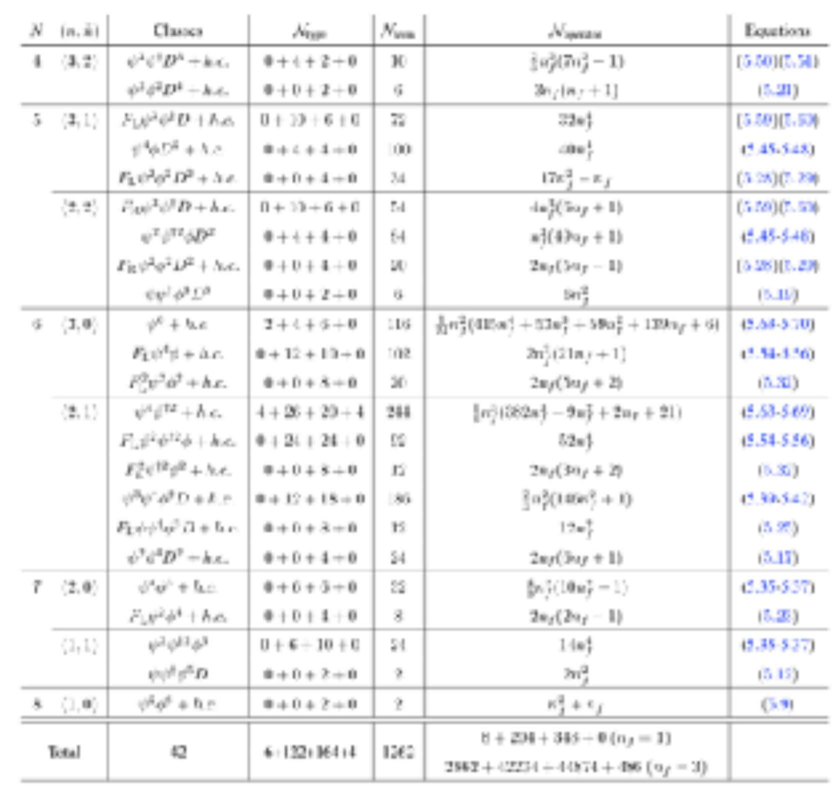
[ Li, Ren, Shu, Xiao, **Yu**, Zheng, **2020**]



993

## Dimension-9

[ Li, Ren, Xiao, **Yu**, Zheng, **2020**]



560

Jiang-Hao Yu

# How to Write Complete SMEFT?

[ Li, Ren, Shu, Xiao, **Yu**, Zheng, **2020**]
[ Li, Ren, Xiao, **Yu**, Zheng, **2020**]

## Define building block

EOM: decompose into irreps under Lorentz group

$\phi \in (0,0), \quad \psi_\alpha \in (1/2,0), \quad \psi^\dagger_{\dot\alpha} \in (0,1/2),$

$F_{L\alpha\beta} = \frac{i}{2} F_{\mu\nu}\sigma^{\mu\nu}_{\alpha\beta} \in (1,0), \quad F_{R\dot\alpha\dot\beta} = -\frac{i}{2} F_{\mu\nu}\bar\sigma^{\mu\nu}_{\dot\alpha\dot\beta} \in (0,1),$

$D_{\alpha\dot\alpha} = D_\mu \sigma^\mu_{\alpha\dot\alpha} \in (1/2,1/2),$

$$(D^{r-|h|}\Phi)^{\dot\alpha^{r+h}}_{\alpha^{r-h}} \in \left(\frac{r-h}{2}, \frac{r+h}{2}\right)$$

$\partial\psi = \left(1, \frac{1}{2}\right) + \left(0, \frac{1}{2}\right)$

$\partial F_L = \left(\frac{1}{2}, \frac{1}{2}\right) \oplus \left(\frac{3}{2}, \frac{1}{2}\right)$

$\partial^2\phi = (0,0) + (0,1) + (1,0) + (1,1)$

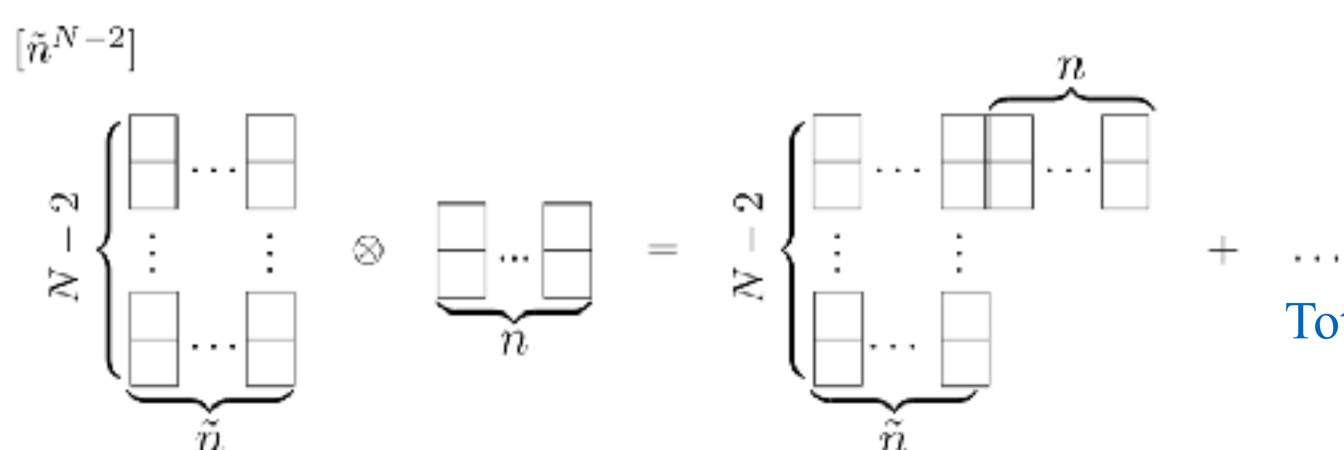
## Operator form

IBP: decompose Lorentz structure into irreps of SU(N)

$$\mathcal{M} = (\epsilon^{\alpha_i\alpha_j})^{\otimes n} (\tilde\epsilon_{\dot\alpha_i\dot\alpha_j})^{\otimes\tilde n} \prod_{i=1}^{N} (D^{r_i-|h_i|}\Phi_i)^{\dot\alpha_i^{r_i+h_i}}_{\alpha_i^{r_i-h_i}} \in [\mathcal{M}]_{N,n,\tilde n} = [\mathcal{A}]_{N,n,\tilde n} \oplus [\mathcal{B}]_{N,n,\tilde n}$$

$$\epsilon^{\alpha_i\alpha_j} \to \sum_{k,l} \mathcal{U}^i_k \mathcal{U}^j_l \epsilon^{\alpha_k\alpha_l}, \quad \tilde\epsilon_{\dot\alpha_i\dot\alpha_j} \to \sum_{k,l} \mathcal{U}^{\dagger k}_{\ i} \mathcal{U}^{\dagger l}_{\ j} \tilde\epsilon_{\dot\alpha_k\dot\alpha_l}. \qquad \square\!\!\square = [1^2] \qquad \bar{\square\!\!\square} = [1^{N-2}]$$

## SSYT



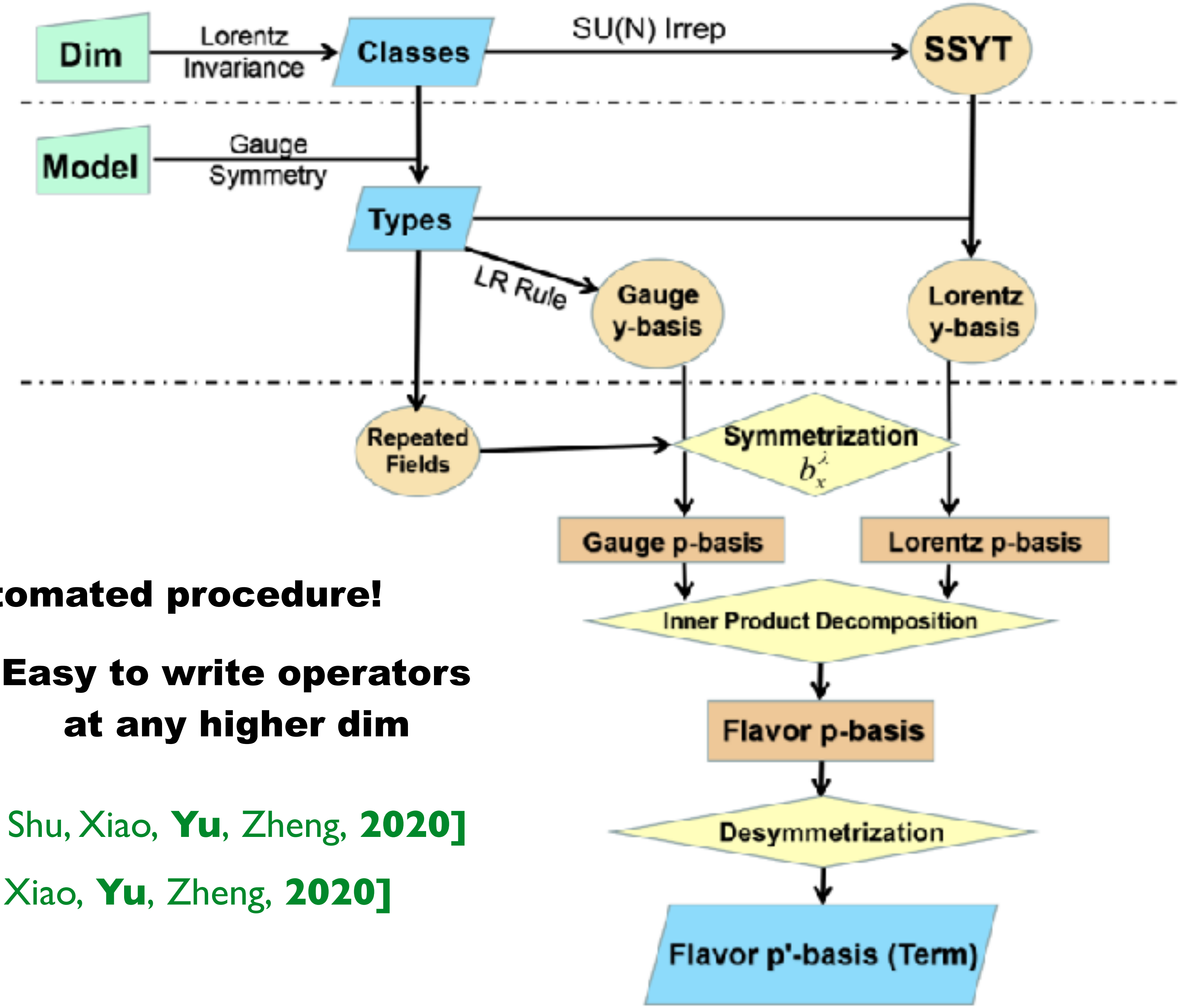

Total derivative terms!

$$\sum_i \epsilon^{\alpha_i\alpha_j}\tilde\epsilon_{\dot\alpha_i\dot\alpha_k} \to \sum_{m,n} \mathcal{U}^j_m \mathcal{U}^{\dagger n}_{\ k} \sum_i \epsilon^{\alpha_i\alpha_m}\tilde\epsilon_{\dot\alpha_i\dot\alpha_n}$$

# Flavor-specified Operators

Operators with repeated field: permutation symmetry among flavors

$$\Theta^{prst} = i\epsilon^{abc}\epsilon^{jk}\left((L_{pi}Q_{sbk}(Q_{raj}\sigma^{\mu}u^{\dagger}_{tc}) + (L_{pi}Q_{raj}(Q_{sbk}\sigma^{\mu}u^{\dagger}_{tc})\right) D_{\mu}H^{\dagger k}$$




**Automated procedure!**

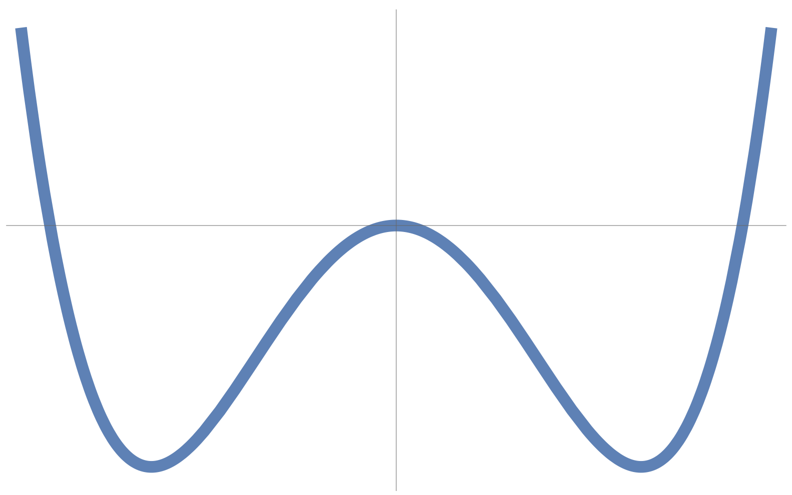
**Easy to write operators at any higher dim**

[ Li, Ren, Shu, Xiao, **Yu**, Zheng, **2020**]

[ Li, Ren, Xiao, **Yu**, Zheng, **2020**]

# Fundamental Higgs

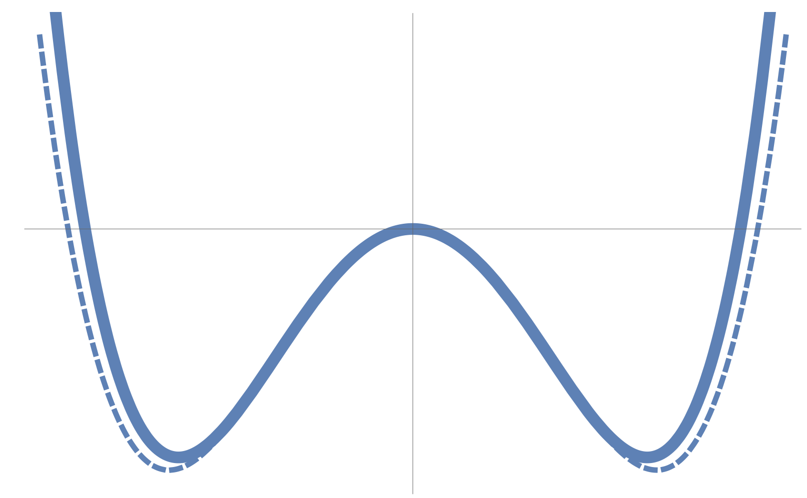
Higgs potential in SM



$$V = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

$$= \frac{1}{2} m_h^2 h^2 + d_3 \left(\frac{m_h^2}{2v}\right) h^3 + d_4 \left(\frac{m_h^2}{8v^2}\right) h^4 + \cdots$$

Higgs potential in SMEFT



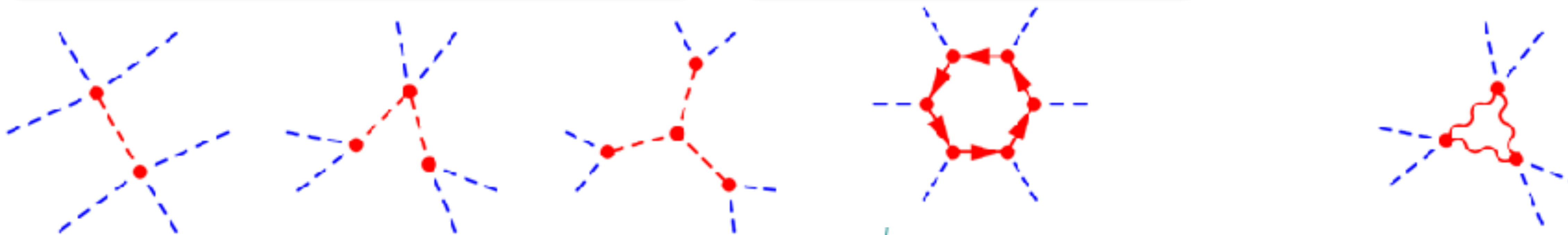
$$V = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6}{\Lambda^2} \lambda (H^\dagger H)^3 + \frac{c_8}{\Lambda^4} \left(H^\dagger H\right)^4$$

$$d_3 = 1 + c_6 \frac{v^2}{\Lambda^2} - c_H \frac{3v^2}{2\Lambda^2} + \mathcal{O}(\frac{1}{\Lambda^4}) ,$$
$$d_4 = 1 + c_6 \frac{6v^2}{\Lambda^2} - c_H \frac{25v^2}{3\Lambda^2} + \mathcal{O}(\frac{1}{\Lambda^4}) .$$

How to generate $(H^\dagger H)^3$ operator?

# New Physics Models

| Scalar Extension | Fermion Extension | Gauge Extension |
|---|---|---|



Tree level generate?

**Scalar Extension**

Group theory?

[Corbett, Joglekar, Li, **Yu, 2018**]

$H^\dagger H S,\ H^T H S$

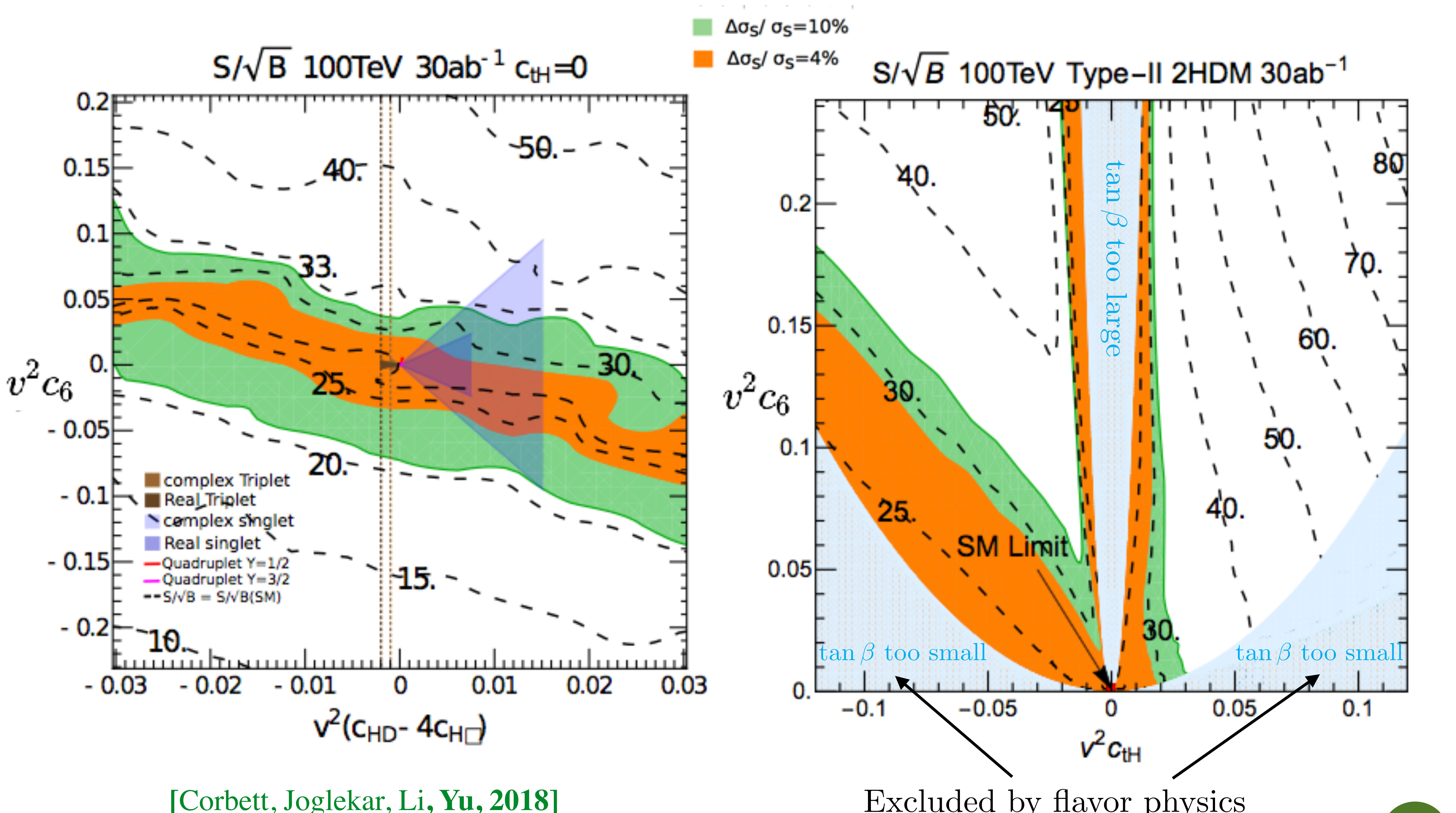
$$\begin{aligned} 2\otimes 2 &= 3_S + 1_A \\ 2\otimes 2\otimes 2 &= 4_S + 2 \end{aligned}$$

$H^\dagger H H^\dagger S$

| Scalar singlet | 2HDM | Triplet/Seesaw | Quadruplet |
|---|---|---|---|
| $S = s, \frac{1}{\sqrt{2}}(s+ia)$ | $\phi_2 = \begin{pmatrix} H_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + H_2^0 + iA_2^0) \end{pmatrix}$ | $\Sigma^a = \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{pmatrix}$ $\Delta = \begin{bmatrix} \frac{\Delta^+}{\sqrt{2}} & H^{++} \\ \frac{1}{\sqrt{2}}(\delta + v_\Delta + i\eta) & -\frac{\Delta^+}{\sqrt{2}} \end{bmatrix}$ | $\Delta \equiv \begin{pmatrix} \Delta^{+++} \\ \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{pmatrix}$ |

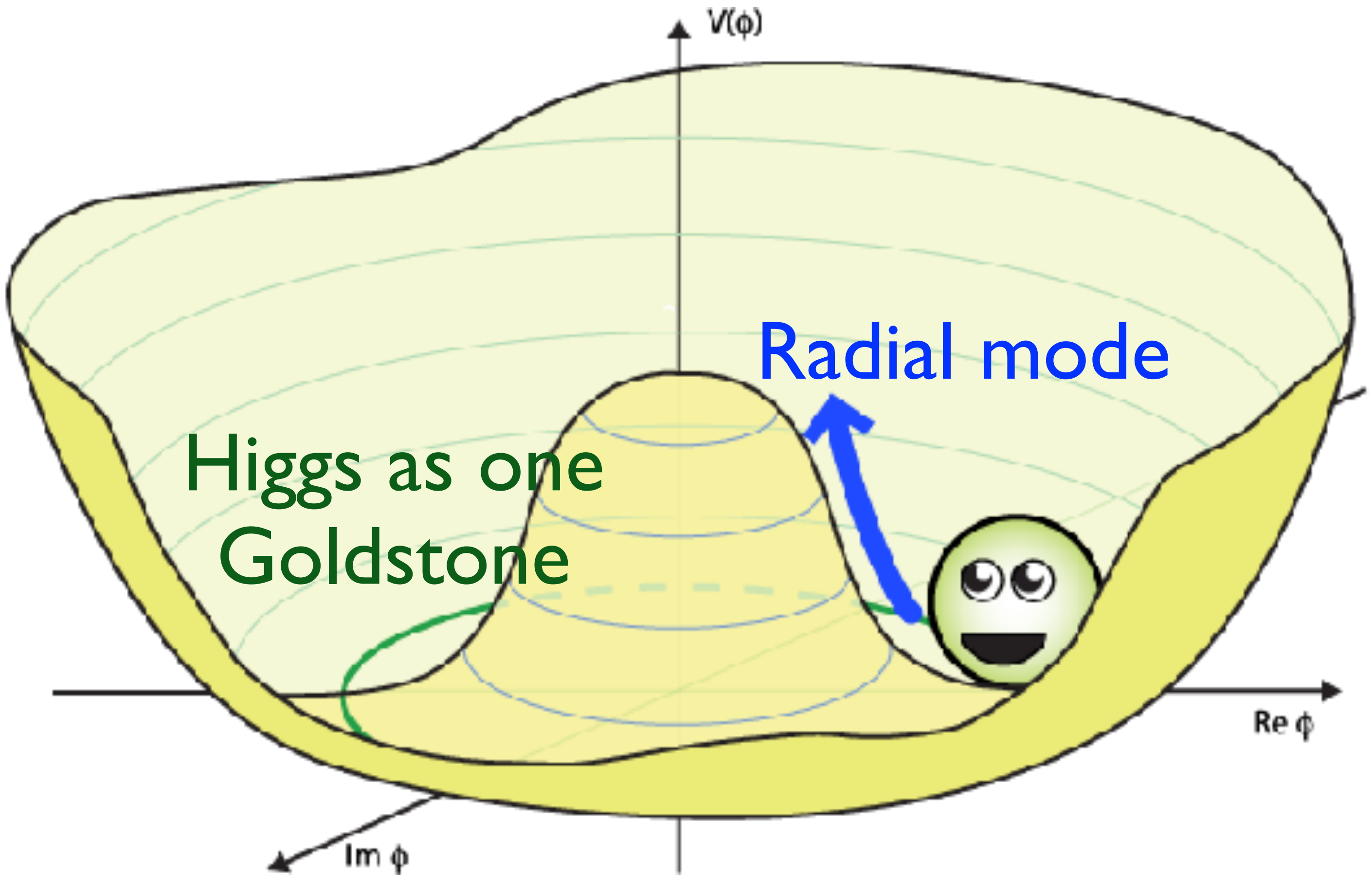
# Fundamental Higgs

Prediction on measurement of Higgs selfcoupling deviation based on UV models




[Corbett, Joglekar, Li, **Yu, 2018**]

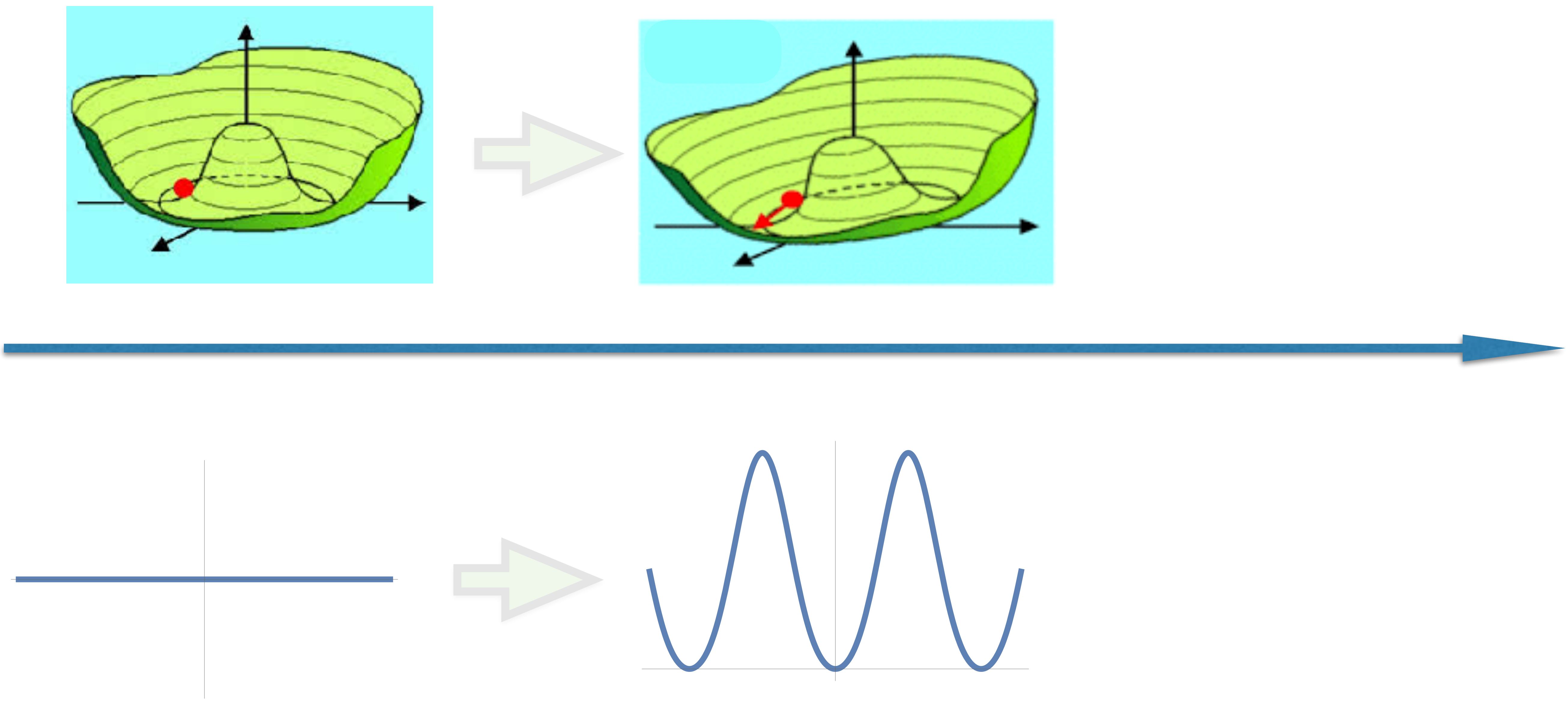
# (2) Pseudo-Goldstone Higgs




Little Higgs
Composite Higgs
Twin Higgs
…

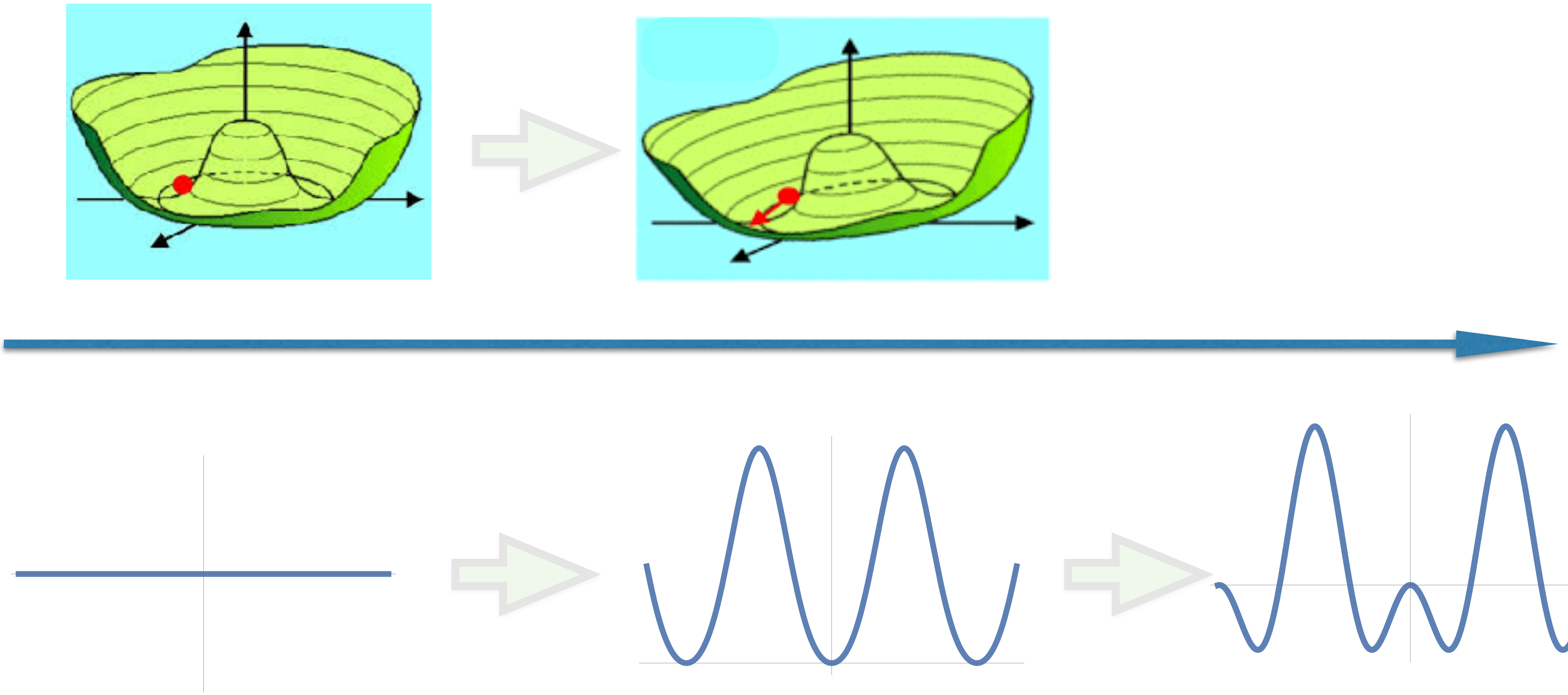
# Pseudo Nambu-Goldstone Higgs

Higgs boson as pseudo-Nambu Goldstone boson



# Pseudo Nambu-Goldstone Higgs

Higgs boson as pseudo-Nambu Goldstone boson



# PNGB Higgs Models

Chiral Lagrangian description

G → H

| $\mathcal{G}$ | $\mathcal{H}$ | $C$ | $N_G$ | $\mathbf{r}_{\mathcal{H}} = \mathbf{r}_{SU(2)\times SU(2)}\ (\mathbf{r}_{SU(2)\times U(1)})$ |
|---|---|---|---|---|
| SO(5) | SO(4) | ✓ | 4 | $\mathbf{4} = (\mathbf{2},\mathbf{2})$ |
| SO(6) | SO(5) | ✓ | 5 | $\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$ |
| SU(3) × U(1) | SU(2) × U(1) | | 5 | $\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$ |
| SU(4) | Sp(4) | ✓ | 5 | $\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$ |
| SO(7) | SO(6) | ✓ | 6 | $\mathbf{6} = 2\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$ |
| SO(8) | SO(7) | ✓ | 7 | $\mathbf{7} = 3\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$ |
| SU(4) × U(1) | SU(3) × U(1) | | 7 | $\mathbf{3}_{-1/3} + \bar{\mathbf{3}}_{+1/3} + \mathbf{1}_0 = 3\cdot\mathbf{1}_0 + \mathbf{2}_{\pm 1/2}$ |
| SO(7) | $G_2$ | ✓* | 7 | $\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$ |
| SO(9) | SO(8) | ✓ | 8 | $\mathbf{8} = 2\cdot(\mathbf{2},\mathbf{2})$ |
| SU(4) | $[SU(2)]^2 \times U(1)$ | ✓* | 8 | $(\mathbf{2},\mathbf{2})_{\pm 2} = 2\cdot(\mathbf{2},\mathbf{2})$ |
| $[SU(3)]^2$ | SU(3) | | 8 | $\mathbf{8} = \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0$ |
| Sp(6) | Sp(4) × SU(2) | ✓ | 8 | $(\mathbf{4},\mathbf{2}) = 2\cdot(\mathbf{2},\mathbf{2})$ |
| SU(5) | SU(4) × U(1) | ✓* | 8 | $\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2\cdot(\mathbf{2},\mathbf{2})$ |
| $[SO(5)]^2$ | SO(5) | ✓* | 10 | $\mathbf{10} = (\mathbf{1},\mathbf{3}) + (\mathbf{3},\mathbf{1}) + (\mathbf{2},\mathbf{2})$ |
| SO(7) | SO(5) × U(1) | ✓* | 10 | $\mathbf{10}_0 = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$ |
| SO(7) | $[SU(2)]^3$ | ✓* | 12 | $(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\cdot(\mathbf{2},\mathbf{2})$ |
| SU(5) | SO(5) | ✓* | 14 | $\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$ |
| SU(6) | Sp(6) | ✓* | 14 | $\mathbf{14} = 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{3}) + 3\cdot(\mathbf{1},\mathbf{1})$ |
| $[SO(6)]^2$ | SO(6) | ✓* | 15 | $\mathbf{15} = (\mathbf{1},\mathbf{1}) + 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3})$ |
| SO(9) | SO(5) × SO(4) | ✓* | 20 | $(\mathbf{5},\mathbf{4}) = (\mathbf{2},\mathbf{2}) + (\mathbf{1}+\mathbf{3},\mathbf{1}+\mathbf{3})$ |

[Csaki, et. al, 2015]

Composite Higgs
[Agashe, Contino, Pomarol 2004]

Minimal Neutral Naturalness
[Xu, **Yu**, Zhu, **2018**]

Twin Higgs
[Chacko, Goh, Harnik 2006]

Little Higgs
[Arkani-hamed, et.al. 2000]

# PNGB Higgs EFT

$m_\rho$

G/H with composite states

Integrate out heavy composite states

| $\mathcal{G}$ | $\mathcal{H}$ | $C$ | $N_G$ | $\mathbf{r}_{\mathcal{H}} = \mathbf{r}_{SU(2)\times SU(2)}$ $(\mathbf{r}_{SU(2)\times U(1)})$ |
|---|---|---|---|---|
| SO(5) | SO(4) | ✓ | 4 | $\mathbf{4} = (\mathbf{2}, \mathbf{2})$ |
| SO(6) | SO(5) | ✓ | 5 | $\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$ |
| SU(3) × U(1) | SU(2) × U(1) | | 5 | $\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$ |
| SU(4) | Sp(4) | ✓ | 5 | $\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$ |
| SO(7) | SO(6) | ✓ | 6 | $\mathbf{6} = 2 \cdot (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$ |
| SO(8) | SO(7) | ✓ | 7 | $\mathbf{7} = 3 \cdot (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$ |
| SU(4) × U(1) | SU(3) × U(1) | | 7 | $\mathbf{3}_{-1/3} + \bar{\mathbf{3}}_{+1/3} + \mathbf{1}_0 = 3 \cdot \mathbf{1}_0 + \mathbf{2}_{\pm 1/2}$ |
| SO(7) | $G_2$ | ✓* | 7 | $\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$ |
| SO(9) | SO(8) | ✓ | 8 | $\mathbf{8} = 2 \cdot (\mathbf{2}, \mathbf{2})$ |
| SU(4) | $[SU(2)]^2 \times U(1)$ | ✓* | 8 | $(\mathbf{2}, \mathbf{2})_{\pm 2} = 2 \cdot (\mathbf{2}, \mathbf{2})$ |
| $[SU(3)]^2$ | SU(3) | | 8 | $\mathbf{8} = \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0$ |
| Sp(6) | Sp(4) × SU(2) | ✓ | 8 | $(\mathbf{4}, \mathbf{2}) = 2 \cdot (\mathbf{2}, \mathbf{2})$ |
| SU(5) | SU(4) × U(1) | ✓* | 8 | $\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2 \cdot (\mathbf{2}, \mathbf{2})$ |
| $[SO(5)]^2$ | SO(5) | ✓* | 10 | $\mathbf{10} = (\mathbf{1}, \mathbf{3}) + (\mathbf{3}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$ |
| SO(7) | SO(5) × U(1) | ✓* | 10 | $\mathbf{10}_0 = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$ |
| SO(7) | $[SU(2)]^3$ | ✓* | 12 | $(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \cdot (\mathbf{2}, \mathbf{2})$ |
| SU(5) | SO(5) | ✓* | 14 | $\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$ |
| SU(6) | Sp(6) | ✓* | 14 | $\mathbf{14} = 2 \cdot (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{3}) + 3 \cdot (\mathbf{1}, \mathbf{1})$ |
| $[SO(6)]^2$ | SO(6) | ✓* | 15 | $\mathbf{15} = (\mathbf{1}, \mathbf{1}) + 2 \cdot (\mathbf{2}, \mathbf{2}) + (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3})$ |
| SO(9) | SO(5) × SO(4) | ✓* | 20 | $(\mathbf{5}, \mathbf{4}) = (\mathbf{2}, \mathbf{2}) + (\mathbf{1} + \mathbf{3}, \mathbf{1} + \mathbf{3})$ |

$f$

G/H

Integrate out heavy PNGB other than the Higgs

triplet, doublet
usually heavy

If all other PNGB heavy — **SO(5)/SO(4) EFT**

If one light PNGB (singlet) — **SO(6)/SO(5) EFT**

If one light PNGB (multiplet) — **….**

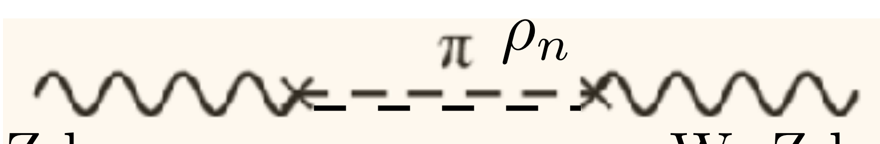
$v$

**EW chiral Lagrangian**

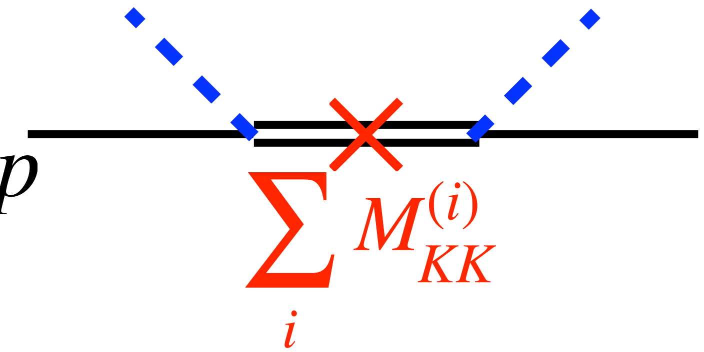
[Qi, **Yu**, Zhu, **2019**]

# EFT Description

Composite Higgs | Left-Right Z2 | Twin Higgs | Neutral Natural

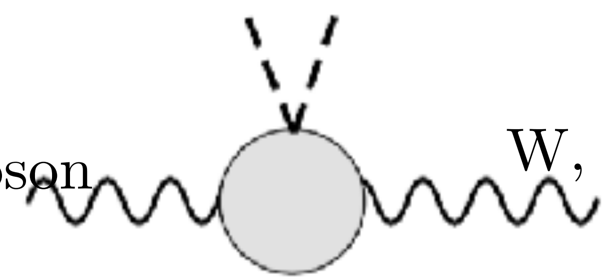


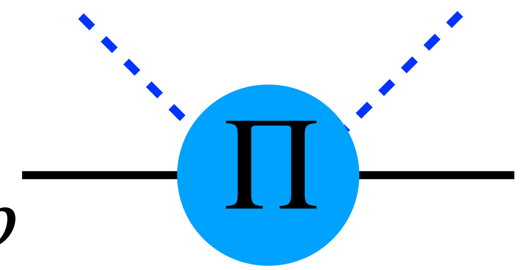

[Li, Xu, **Yu**, Zhu, **2019**]




Heavy composite states

[Heurtier, Li, Song, Su, Su, **Yu**, **2020**]




Generalized Effective Lagrangian

$$\mathcal{L} \supset \frac{1}{2}(P_T)^{\mu\nu}\left(\Pi_0(q^2)\mathrm{Tr}(A_\mu A_\nu) + \Pi_1(q^2)\Sigma A_\mu A_\nu \Sigma^T\right)$$

$$\mathcal{L}_{\rm eff} = \bar{t}_L \not{p}\,\Pi_{t_L}(p^2) t_L + \bar{t}_R \not{p}\,\Pi_{t_R}(p^2) t_R - \left(\bar{t}_L \Pi_{t_L t_R}(p^2) t_R + \mathrm{h.c.}\right)$$

# EW Chiral Lagrangian

Composite Higgs | Left-Right Z2 | Twin Higgs | Neutral Natural

$MCHM_{5+5,10+10,14+14}$ $5+1$

$MCHM_{14+14}$

$CTHM_{8+1,8+28,8+35}$

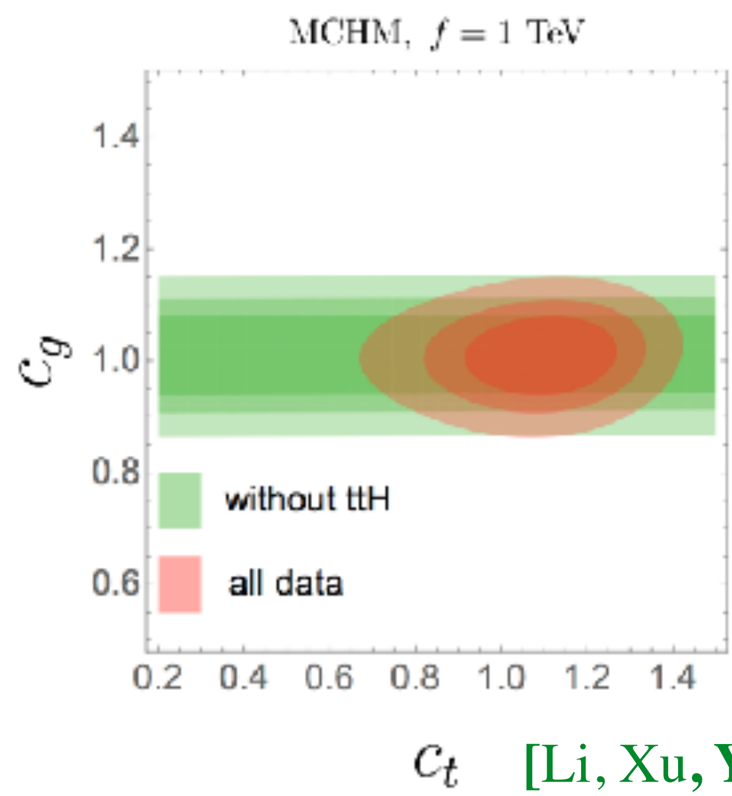
$CTHM_{8+35}$

EW Chiral Lagrangian

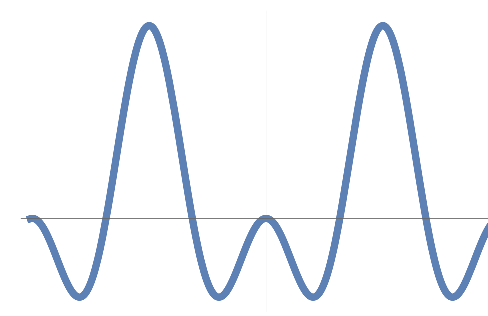
$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h)$$
$$+ \frac{v^2}{4}\mathrm{Tr}\left[(\partial_\mu U)^\dagger \partial^\mu U\right]\left(1 - 2a\frac{h}{v} - b\frac{h^2}{v^2} + \cdots\right)$$
$$- \frac{v}{\sqrt{2}}\left(\bar{t}_L, \bar{b}_L\right) U \left(1 + c_1\frac{h}{v} + c_2\frac{h^2}{v^2} + \cdots\right)\begin{pmatrix} y_t t_R \\ y_b b_R \end{pmatrix} + \mathrm{h.c.}$$

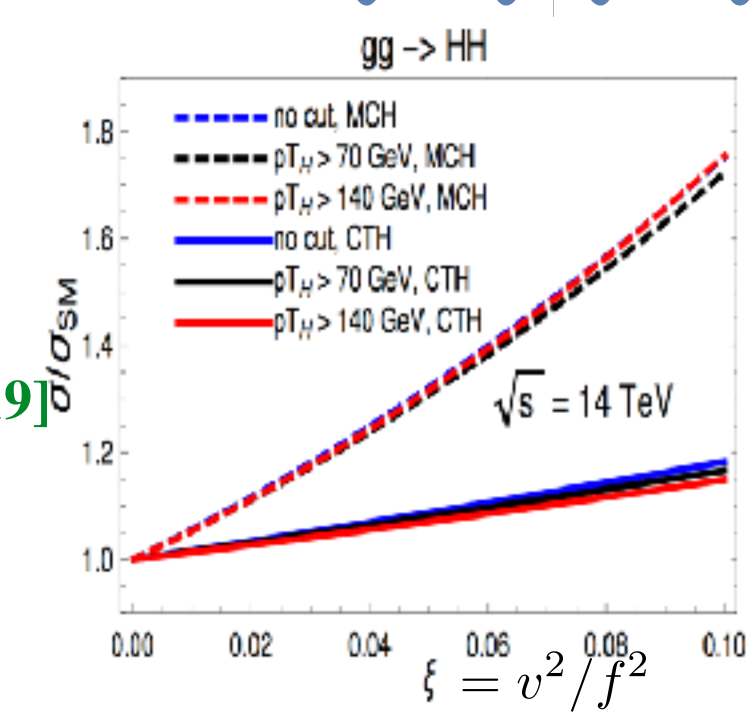
Higgs effective couplings

$(gg \to H)$ + Higgs global fit




[Li, Xu, **Yu**, Zhu, **2019**]






[Agrawal, Saha, Xu, **Yu**, Yuan, **2019**]

# Fundamental vs Composite?

PNGB Higgs EFT

SMEFT

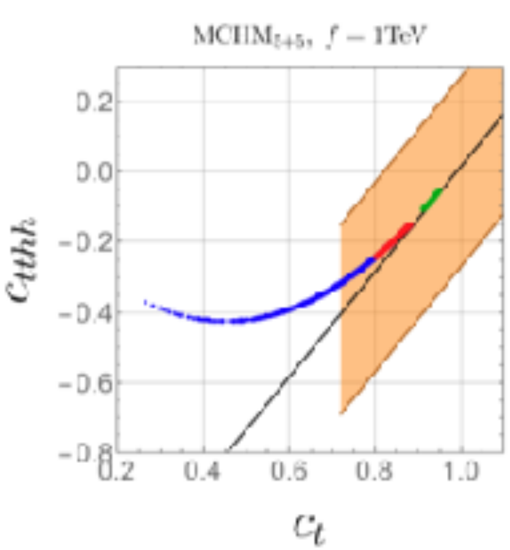
[Agrawal, Saha, Xu, **Yu**, Yuan, **2020**]

EW Chiral Lagrangian

$$
\begin{aligned}
\mathcal{L} = & \frac{1}{2}(\partial_\mu h)^2 - V(h) \\
& + \frac{v^2}{4}\mathrm{Tr}\left[(\partial_\mu U)^\dagger \partial^\mu U\right]\left(1 - 2a\frac{h}{v} - b\frac{h^2}{v^2} + \cdots\right) \\
& - \frac{v}{\sqrt{2}}\left(\bar{t}_L, \bar{b}_L\right) U \left(1 + c_1\frac{h}{v} + c_2\frac{h^2}{v^2} + \cdots\right)\begin{pmatrix} y_t t_R \\ y_b b_R \end{pmatrix} + \mathrm{h.c.}
\end{aligned}
$$

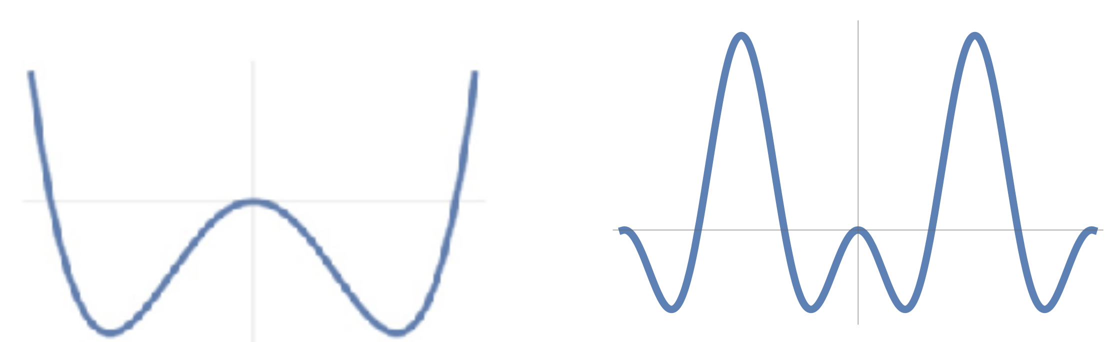
Higgs effective couplings

Higgs nonlinearity



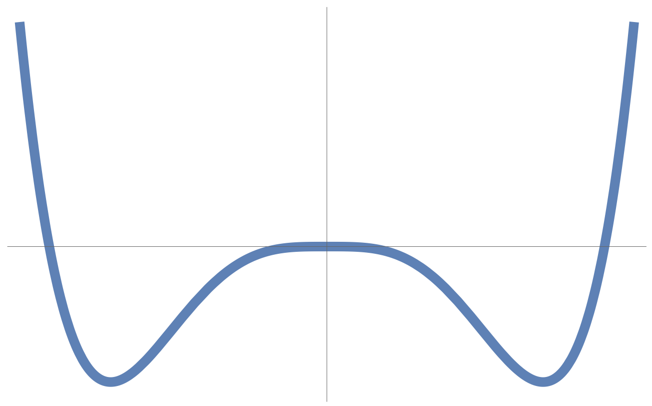

Non-flat metric in PNGB field space

Shape of Higgs potential



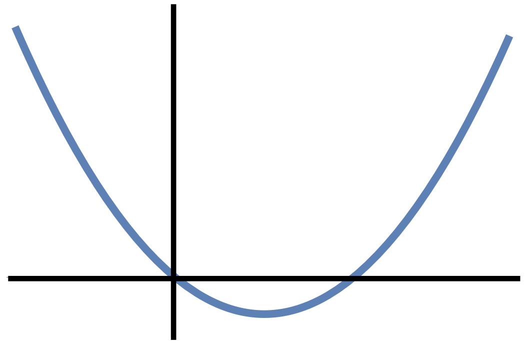
# (3) Other Kind of Higgs Potential?

Coleman Weinberg Higgs



$$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2 \log\frac{\phi^\dagger\phi}{\mu^2}$$

Tadpole-induced Higgs

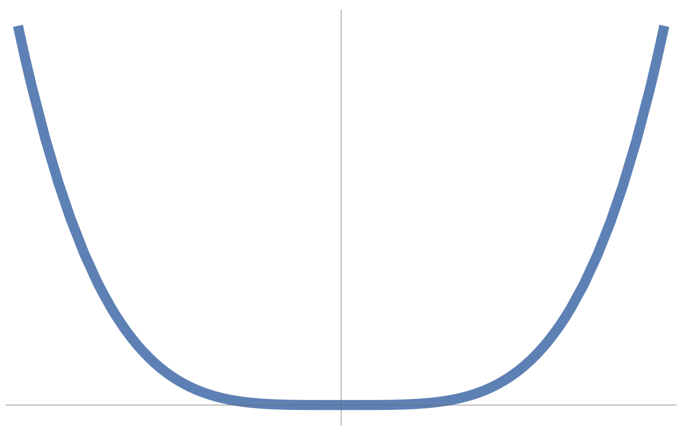


$$V(\phi) = -\mu^3\sqrt{\phi^\dagger\phi} + m^2\phi^\dagger\phi$$

# Coleman Weinberg Higgs

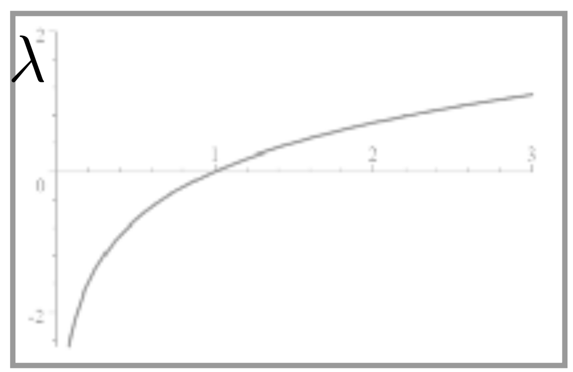
Classically scale invariant theory

Tree-level potential



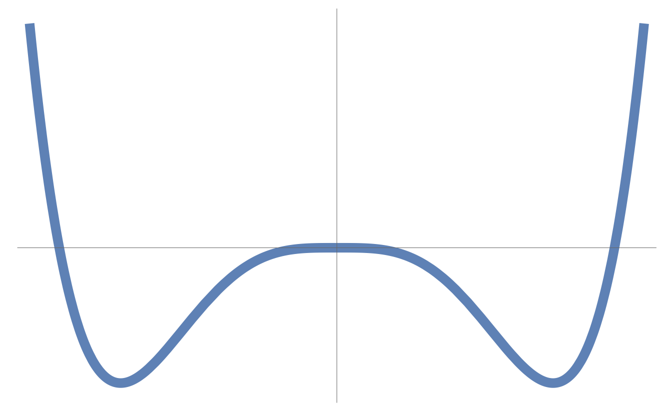
$$V(\phi) = \lambda(\phi^\dagger\phi)^2$$

[Coleman, Weinberg 73],
[Gildner, Weinberg 76] ,
...




Self-coupling running are opposite to SM case

Coleman Weinberg Higgs



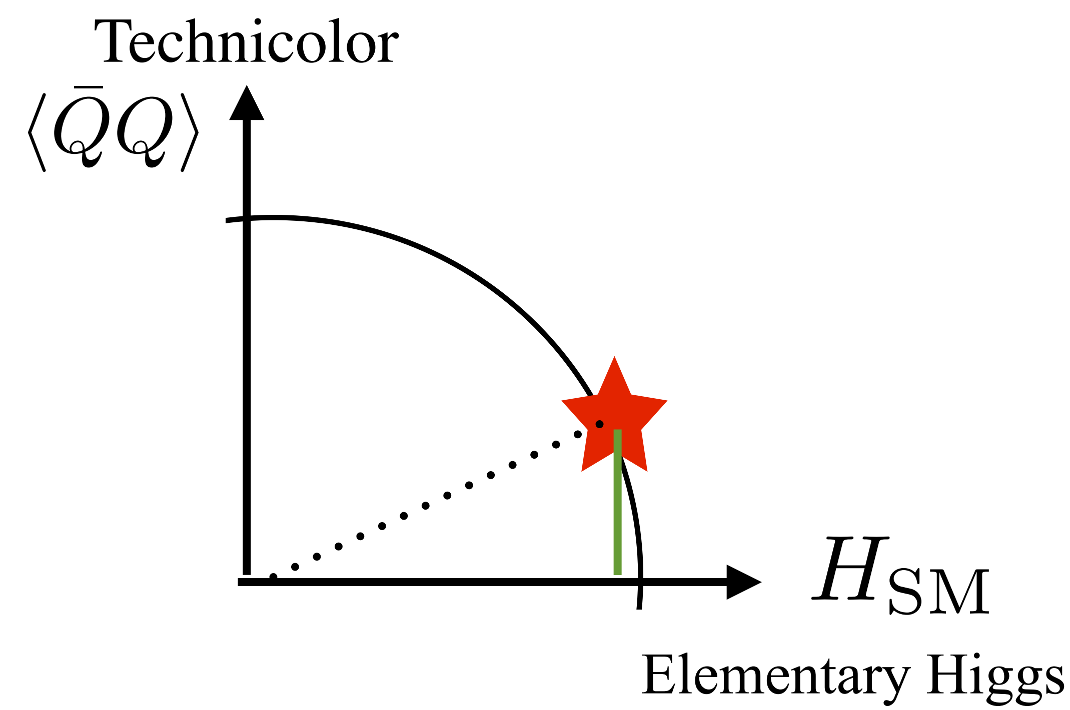
$$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2 \log\frac{\phi^\dagger\phi}{\mu^2}$$

Radiative correction triggers EWSB!

# Tadpole Induced Higgs

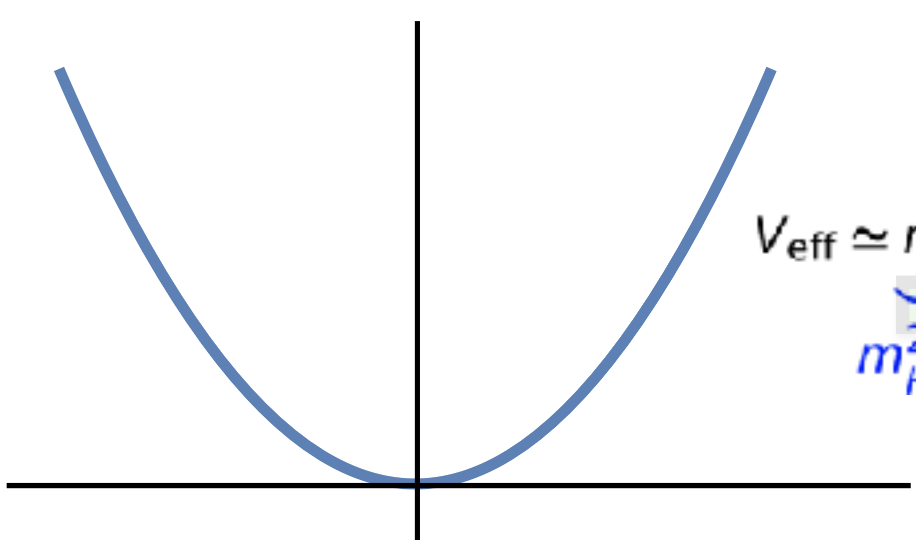
## Long-live technicolor: Bosonic technicolor


[Simmons 1989],
[Carone, Georgi 1994] ,
[Galloway, etc, 2013]
…




## Induced EWSB

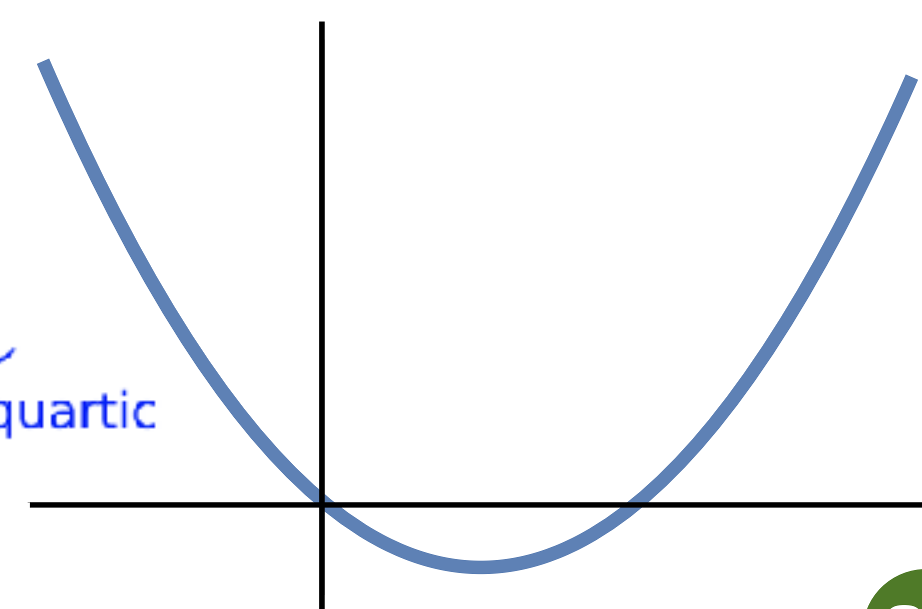
$$V(\phi) = -\mu^3 \sqrt{\phi^\dagger \phi} + m^2 \phi^\dagger \phi$$



$$V_{\rm eff} \simeq \underbrace{m_H^2}_{m_H^2 > 0} H^\dagger H + \epsilon(\Sigma^\dagger H + {\rm h.c.}) + \underbrace{\cdots}_{\text{neglect quartic}}$$

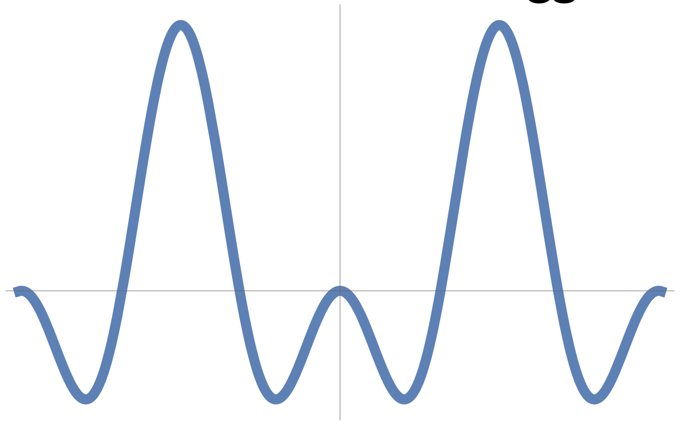
$\varepsilon < 0$

$\langle \Sigma \rangle \equiv \langle \bar{Q} Q \rangle$



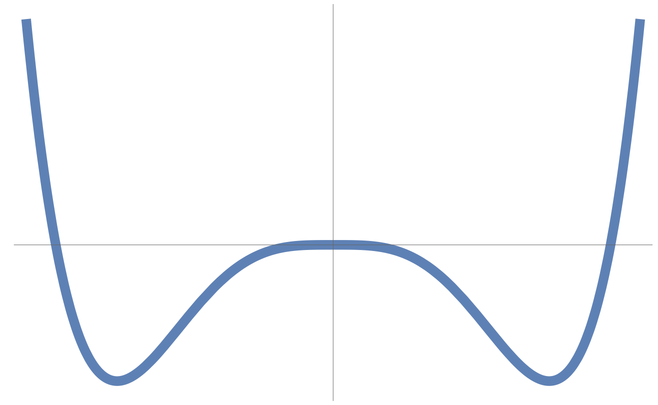
# Shape of Higgs Potential

Pseudo-Goldstone Higgs



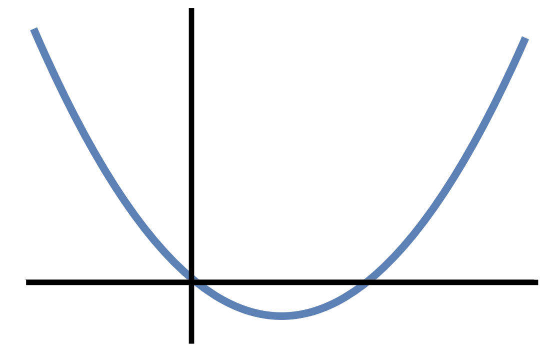
$$V(\phi) = -a \sin^2(\phi/f) + b \sin^4(\phi/f)$$

Coleman Weinberg Higgs



$$V(\phi) = \lambda(\phi^\dagger \phi)^2 + \epsilon(\phi^\dagger \phi)^2 \log \frac{\phi^\dagger \phi}{\mu^2}$$

Tadpole-induced Higgs



$$V(\phi) = -\mu^3 \sqrt{\phi^\dagger \phi} + m^2 \phi^\dagger \phi$$

Can we probe nature of Higgs other than the SM one?

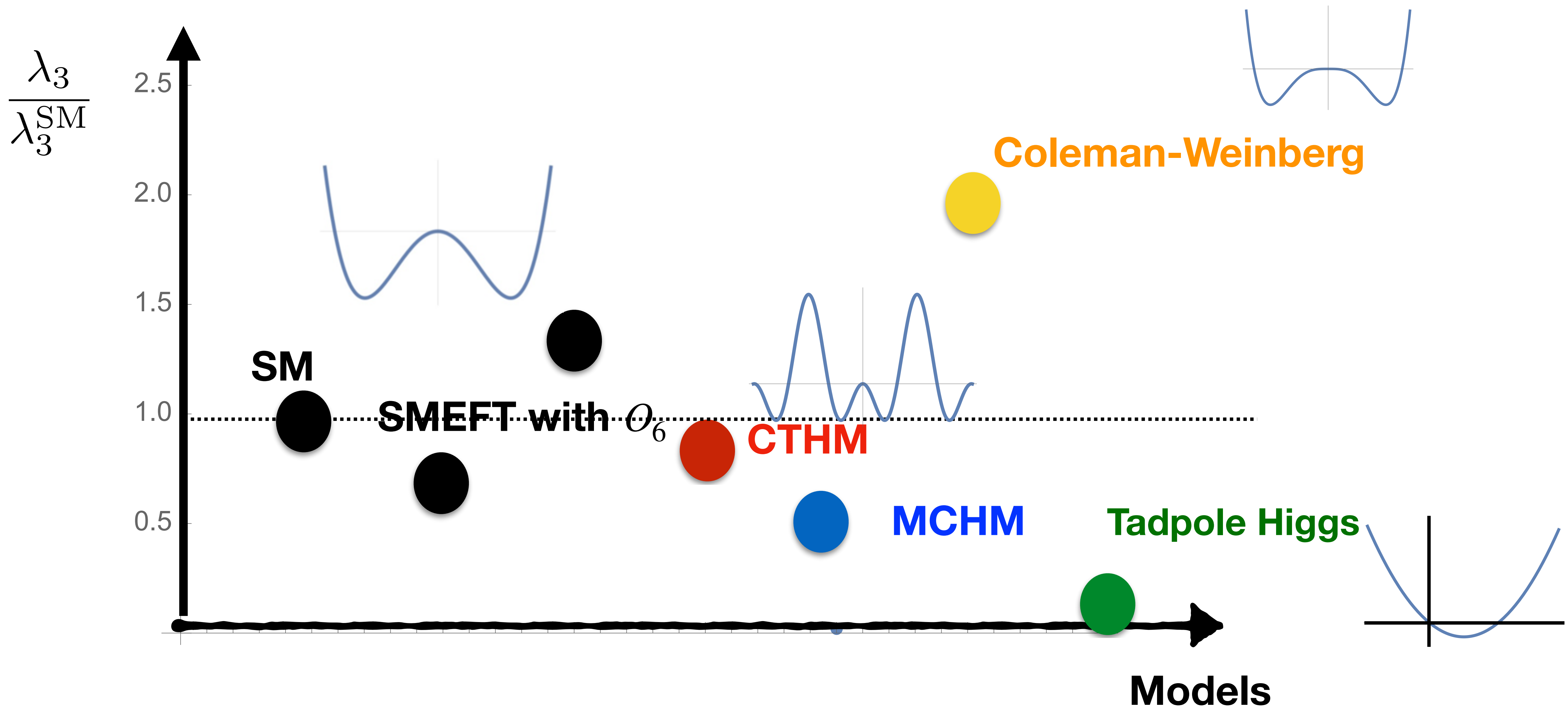
Landau-Ginzburg Higgs

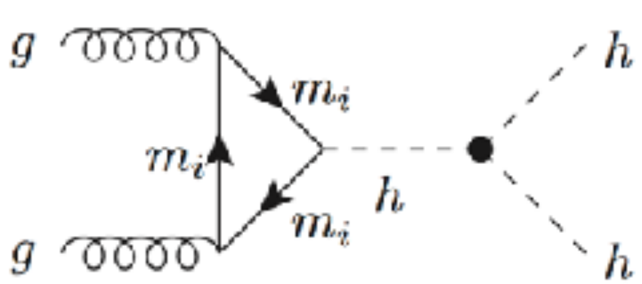
$$V(\phi) = -m^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

# Higgs Self Coupling

[Agrawal, Saha, Xu, **Yu**, Yuan, **2020**]

Make use of large difference in Higgs self coupling



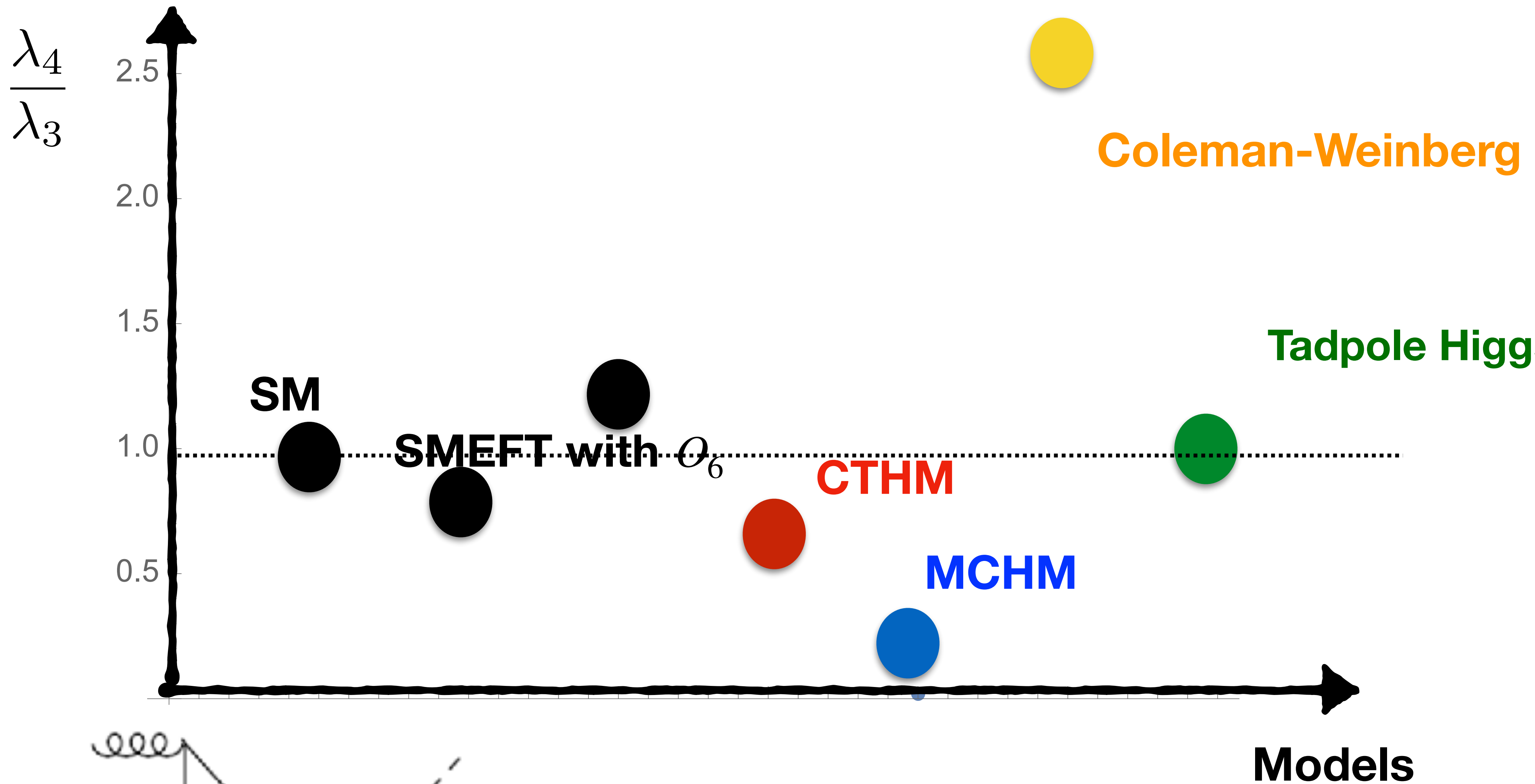

Di-Higgs production

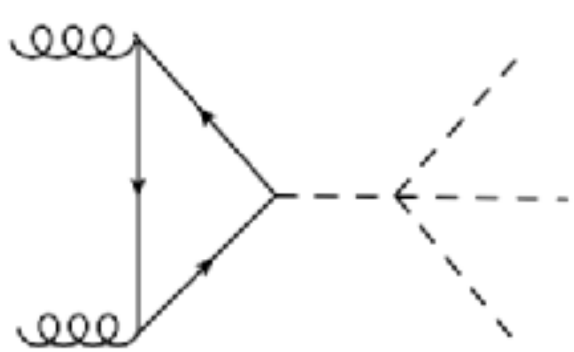
# Quartic Higgs Coupling

[Agrawal, Saha, Xu, **Yu**, Yuan, **2020**]

Confirm quartic coupling

Further determine shape of Higgs potential

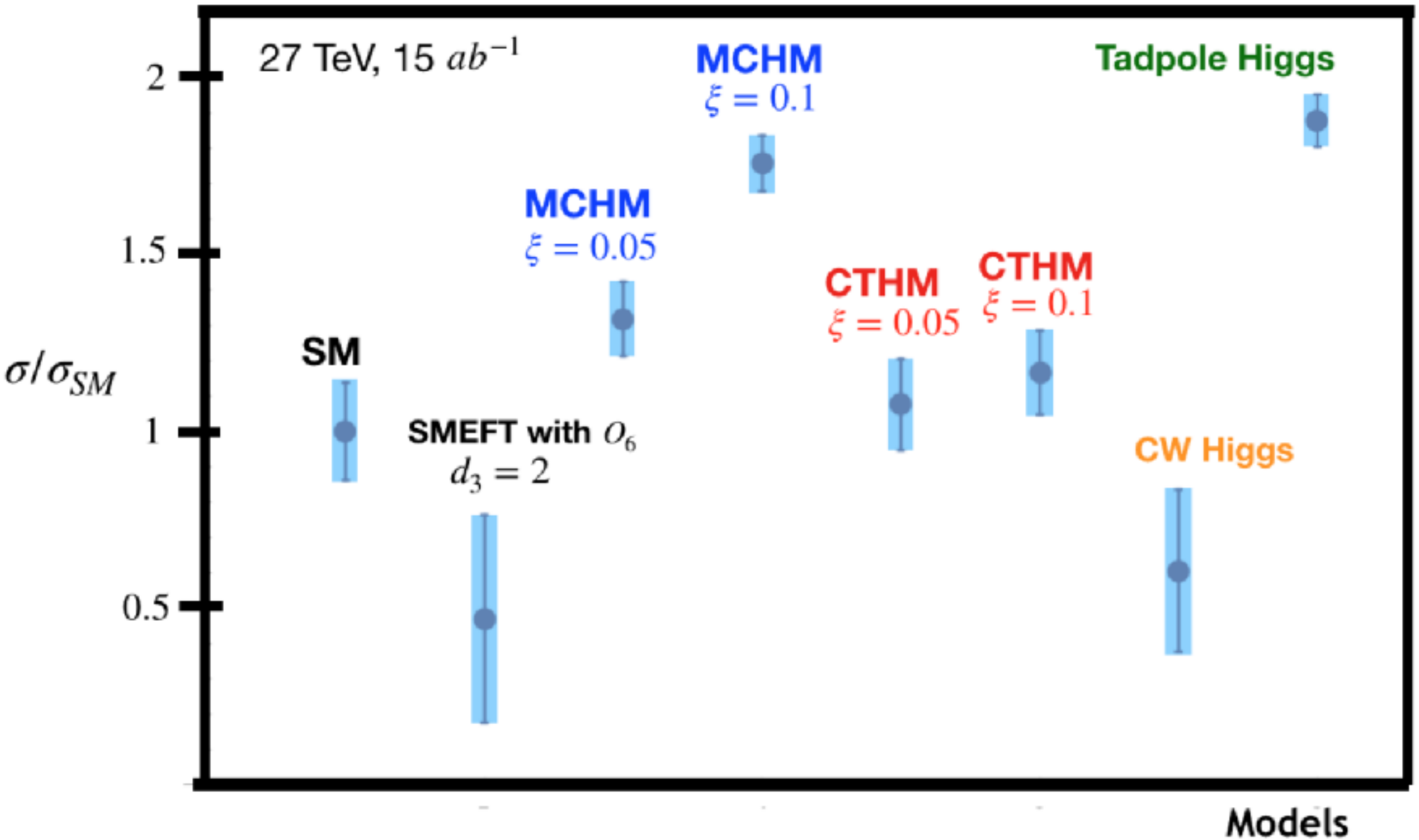


tri-Higgs production

# Higgs Self Coupling

[Agrawal, Saha, Xu, **Yu**, Yuan, **2020**]

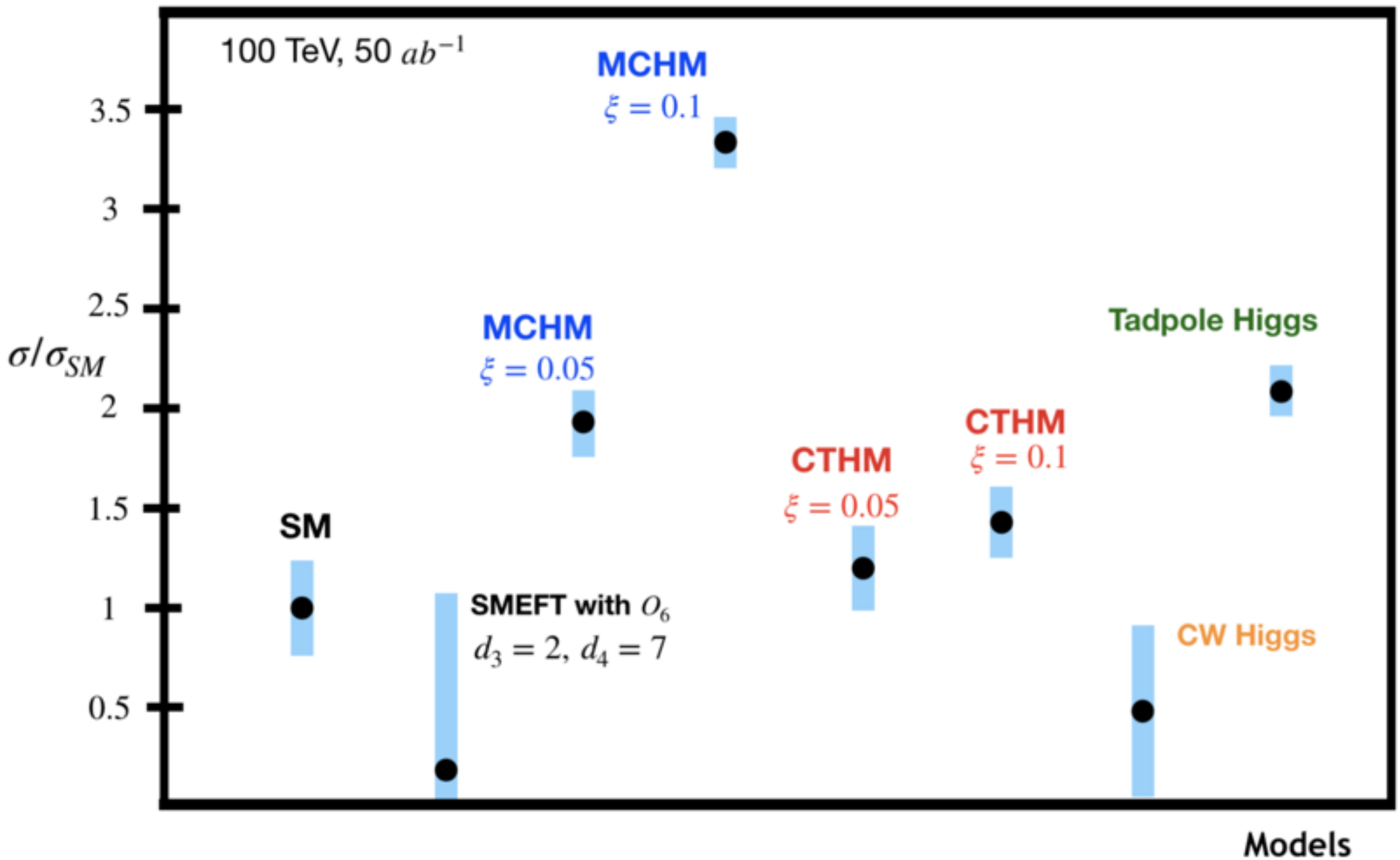



14% accuracy (1 sigma CL) for SM xsec at 27 TeV

[Goncalves, Han, Kling, Plehn, Takeuchi, 2018]

# Quartic Higgs Coupling

[Agrawal, Saha, Xu, **Yu**, Yuan, **2020**]



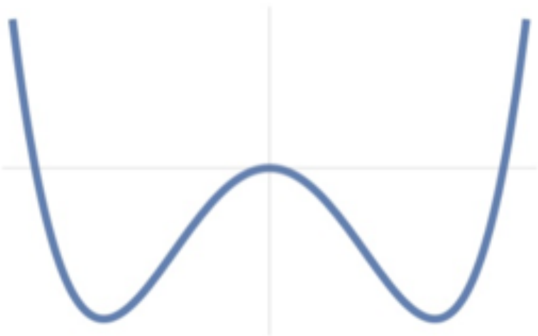

30% accuracy (1 sigma CL) for SM xsec at 100 TeV

[Fuks, Kim Lee, 2017]

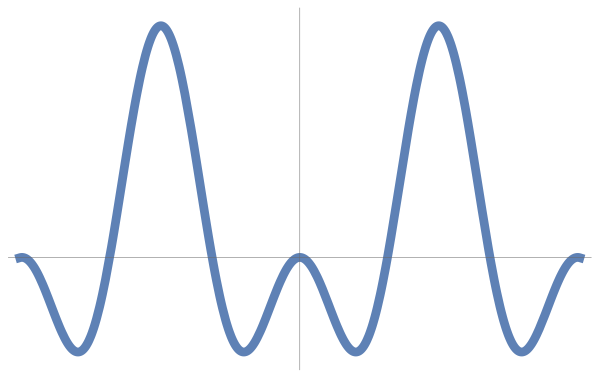
# Summary

Explore different Higgs potential by Nature of Higgs Boson

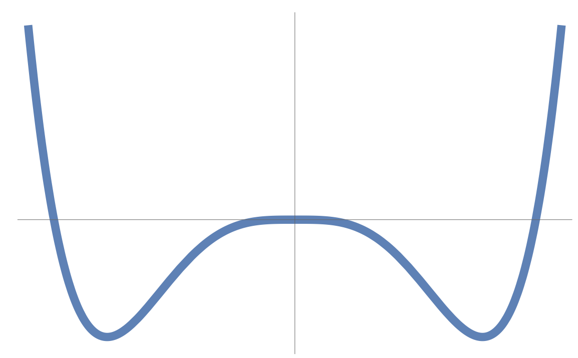
Landau-Ginzburg Higgs



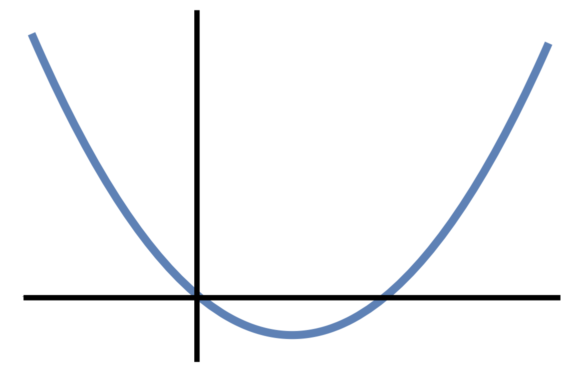
Pseudo-Goldstone Higgs



Coleman Weinberg Higgs

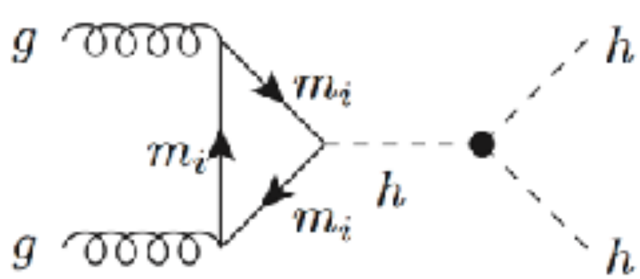


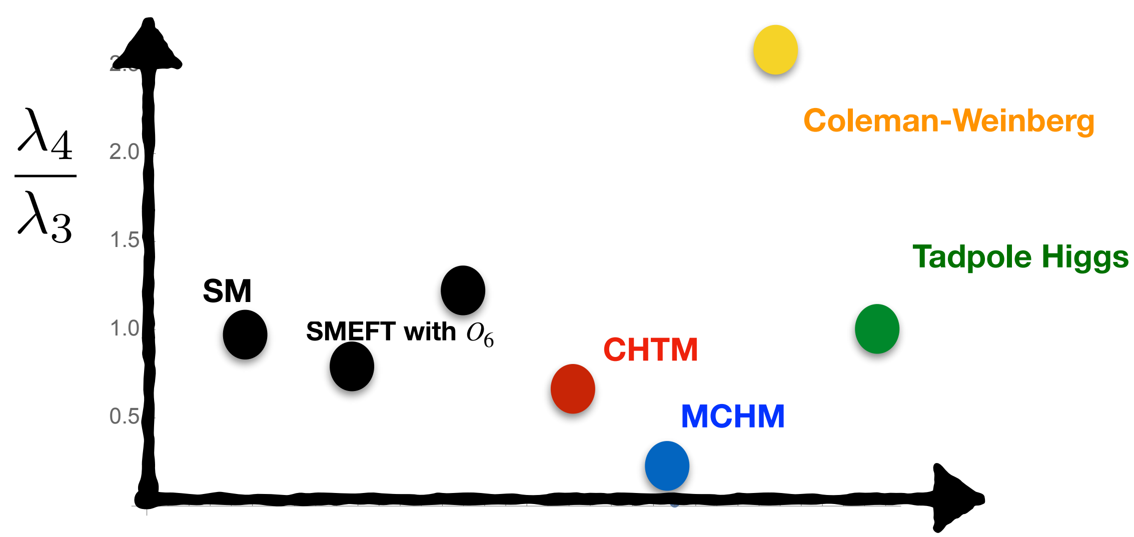
Tadpole-induced Higgs

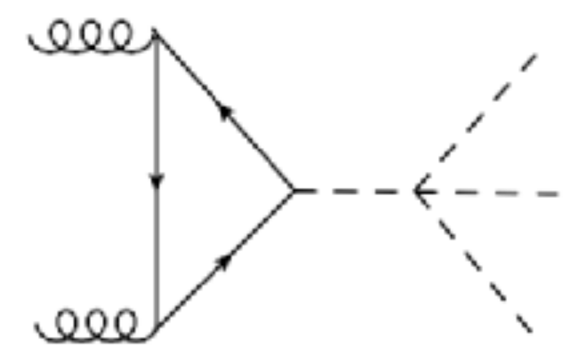


SMEFT is not enough to describe effective Lagrangian

Discriminate shape of Higgs potential via di/tri-Higgs production



**Thank you very much!**

# Backup Slides

# Why higher Dim Operators?

- Expect much smaller effects for dim > 7

$$
\begin{aligned}
|\mathcal{A}|^2 &\sim \left| A_{\mathrm{SM}} + \frac{A_{\mathrm{dim-6}}}{\Lambda^2} + \frac{A_{\mathrm{dim-8}}}{\Lambda^4} + \ldots \right|^2 \\
&\sim |A_{\mathrm{SM}}|^2 + \frac{2}{\Lambda^2} A_{\mathrm{dim-6}} A^*_{\mathrm{SM}} + \frac{1}{\Lambda^4} |A_{\mathrm{dim-6}}|^2 + \frac{2}{\Lambda^4} A_{\mathrm{dim-8}} A^*_{\mathrm{SM}}
\end{aligned}
$$

**New operators only appears at dim > 7**

Neutral triple gauge boson ZZZ, ZZA, ZAA couplings not appear at dim-6

$$
\mathcal{O}^{(1\sim6)}_{BWHH^\dagger D^2} \left| \begin{array}{ll}
(BW^I)(D^\nu H^\dagger \tau^I D_\mu H), & (B\tilde{W}^I)(D^\nu H^\dagger \tau^I D_\mu H), \\
iB^{[\mu}{}_\lambda W^{I\nu]\lambda}(D_\nu H^\dagger \tau^I D_\mu H), & iB^{[\mu}{}_\lambda \tilde{W}^{I\nu]\lambda}(D_\nu H^\dagger \tau^I D_\mu H), \\
B^{(\mu}{}_\lambda W^{I\nu)\lambda}(D_\nu H^\dagger \tau^I D_\mu H), & B^{(\mu}{}_\lambda \tilde{W}^{I\nu)\lambda}(D_\nu H^\dagger \tau^I D_\mu H)
\end{array} \right.
$$

**Higher dim operators not tightly constrained**

$$
\bar{e}_R (H^\dagger \sigma^a \ell)(\bar{\ell} \sigma^a H) e_R \to -\frac{1}{2} \langle H \rangle^2 (\bar{e} \gamma^\rho R e)(\bar{\nu} \gamma_\rho L \nu)
$$

Strong correlation among operators at dim-6 $\quad Q_{\substack{\ell e \\ prst}} = [\bar{\ell}_p \gamma^\mu \ell_r][\bar{e}_s \gamma_\mu e_t]$

**HL-LHC starts to probe the dim-8 effect**

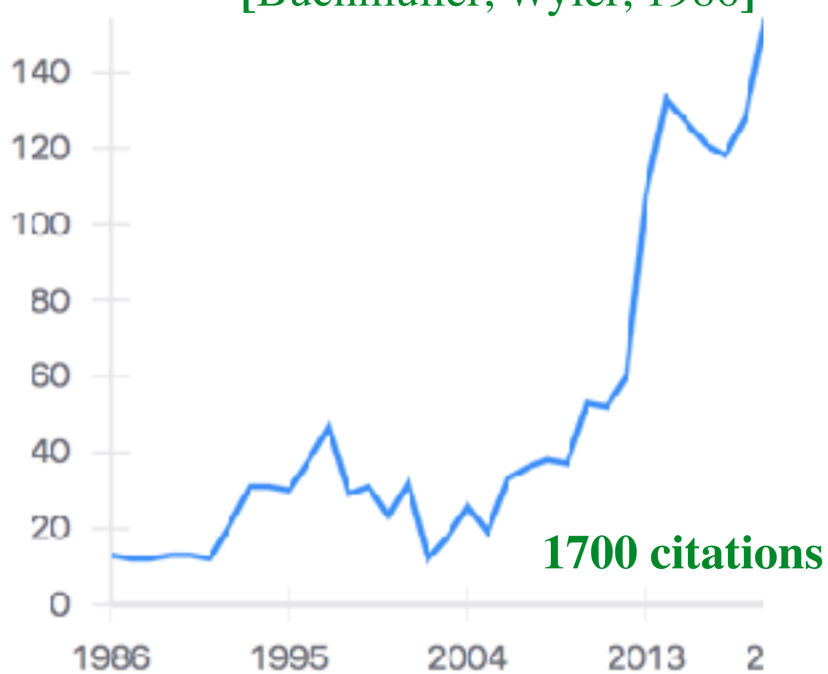
- 0vbb and proton decay start to probe dim-9 operators

# Redundancy Among Operators

- Often write over-complete set of operators

$$D^2\phi + J_\phi = 0, \quad i\not{D}\psi + J_\psi = 0, \quad D_\mu F^{\mu\nu} + J_A^\nu = 0, \quad [D_\mu, D_\nu] = -iF_{\mu\nu}. \quad X D_\mu Y \sim -D_\mu X Y.$$

[Buchmuller, Wyler, 1986]

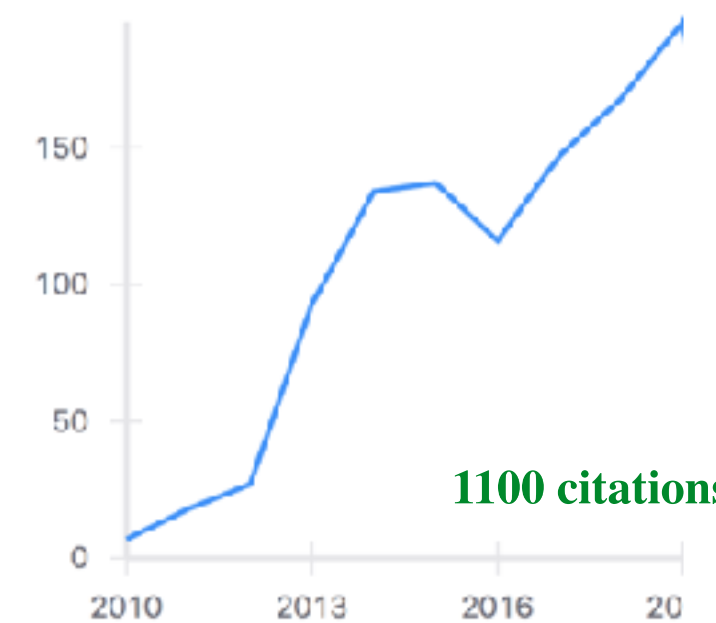



$$16 + 35 + 29 = 80$$

Over-complete operators

$$D^2\phi + J_\phi = 0,$$
$$i\not{D}\psi + J_\psi = 0,$$
$$D_\mu F^{\mu\nu} + J_A^\nu = 0,$$
$$[D_\mu, D_\nu] = -iF_{\mu\nu}.$$
$$X D_\mu Y \sim -D_\mu X Y.$$

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

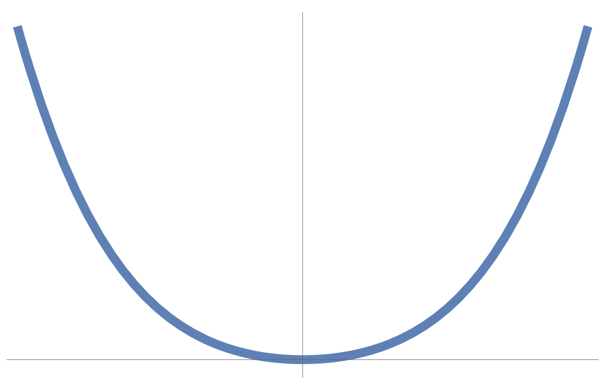


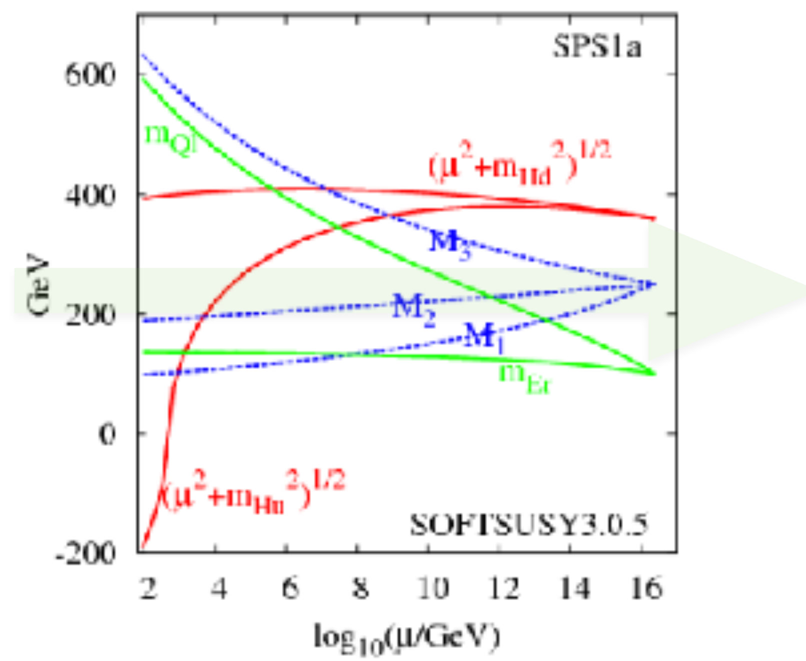

$$15 + 19 + 25 = 59$$

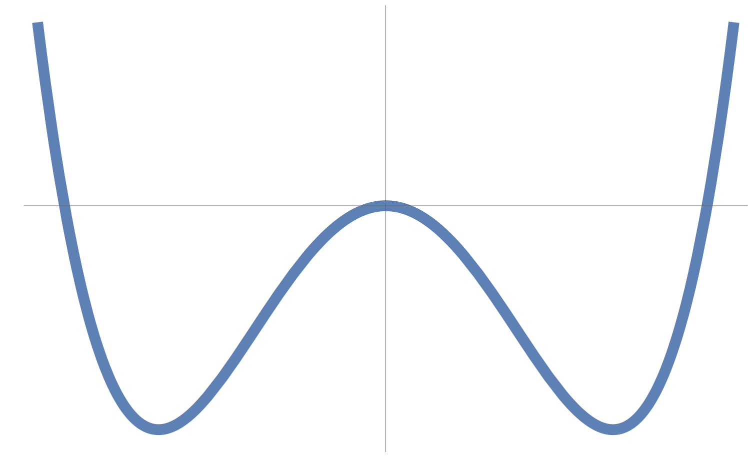
Independent operators

# Radiative Higgs Potential

Fundamental Higgs with supersymmetric top partner

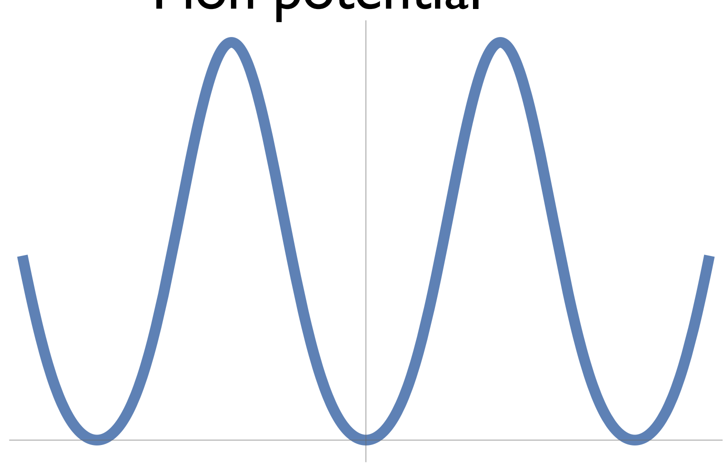


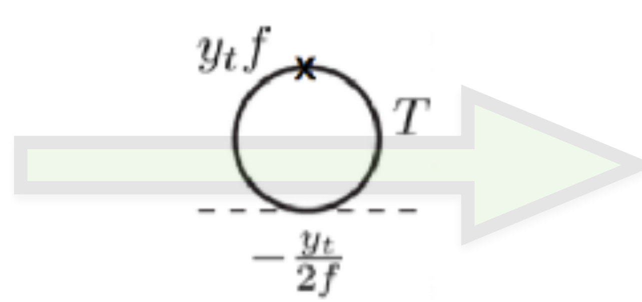


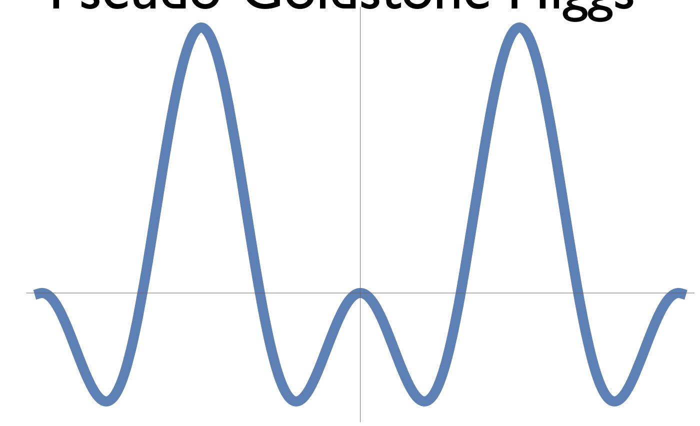
Composite Higgs with fermionic top partner

Pion potential






Pseudo-Goldstone Higgs



$$V(\phi) = -a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

# Matching Among EFTs