第十四届TeV物理工作组学术研讨会 (14th workshop on TeV Physics)

Shape of Higgs Potential at Future Colliders

Jiang-Hao Yu (于江浩)

ITP, CAS (中国科学院理论物理研究所)

Pankaj Agrawal, Debashis Saha, Ling-Xiao Xu, **JHY,** C.-P. Yuan, 1905.xxxxx

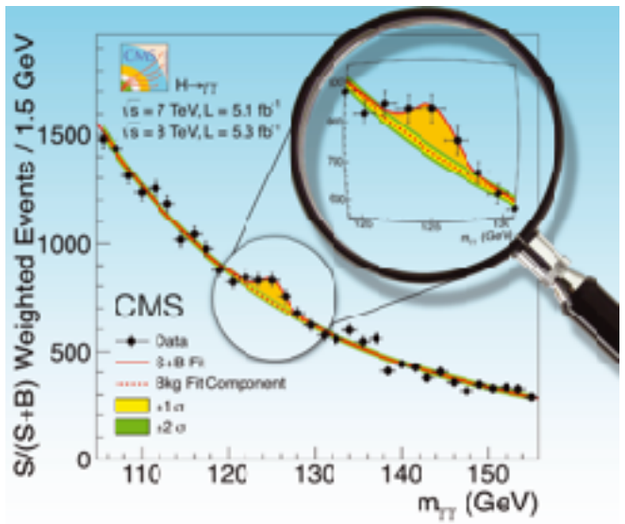
Hao-Lin Li, Ling-Xiao Xu, **JHY,** Shouhua Zhu, 1904.05359

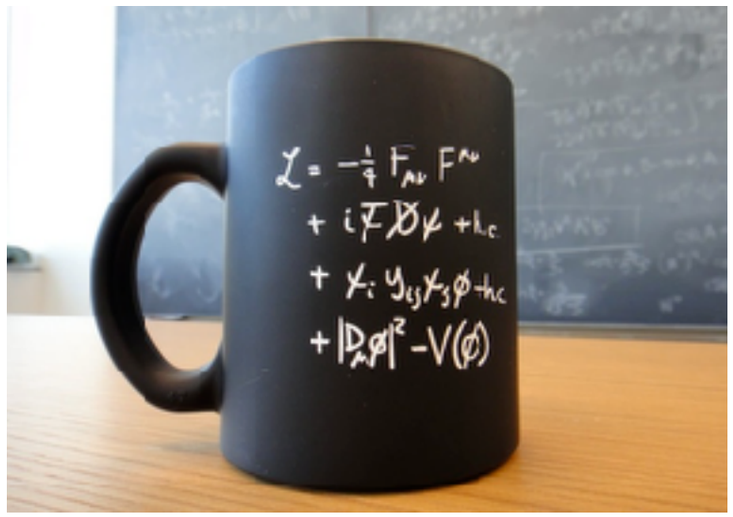
Tyler Corbett, Aniket Joglekar, Hao-Lin Li, **JHY**, JHEP 1805 (2018) 061

April 20, 2019

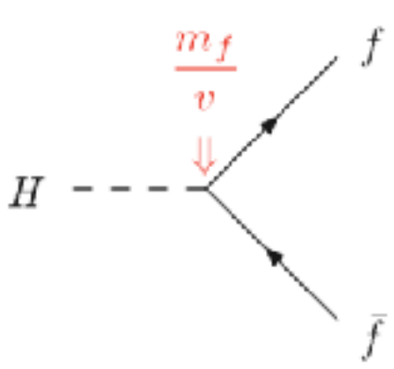
Higgs Boson

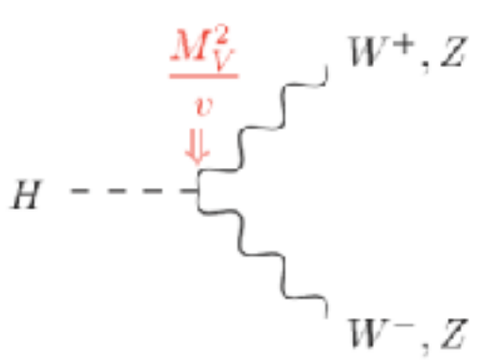
Higgs discovery completes the standard model spectrum

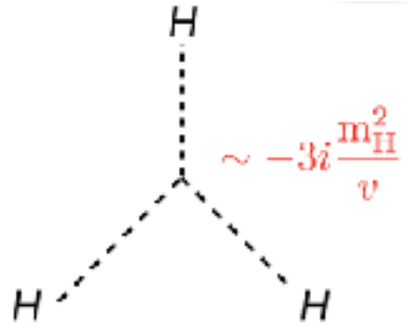




Given Higgs mass, all parameters in Higgs sector are predicted!

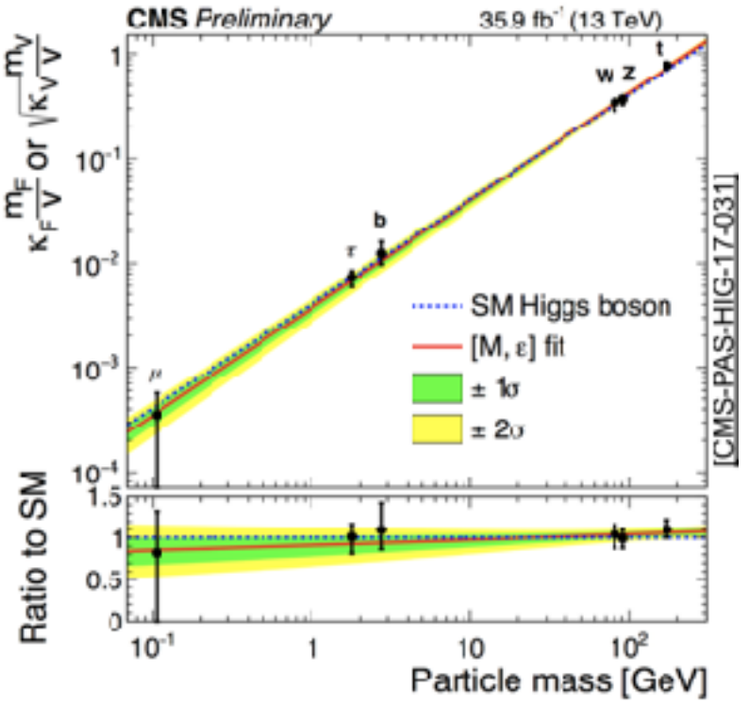


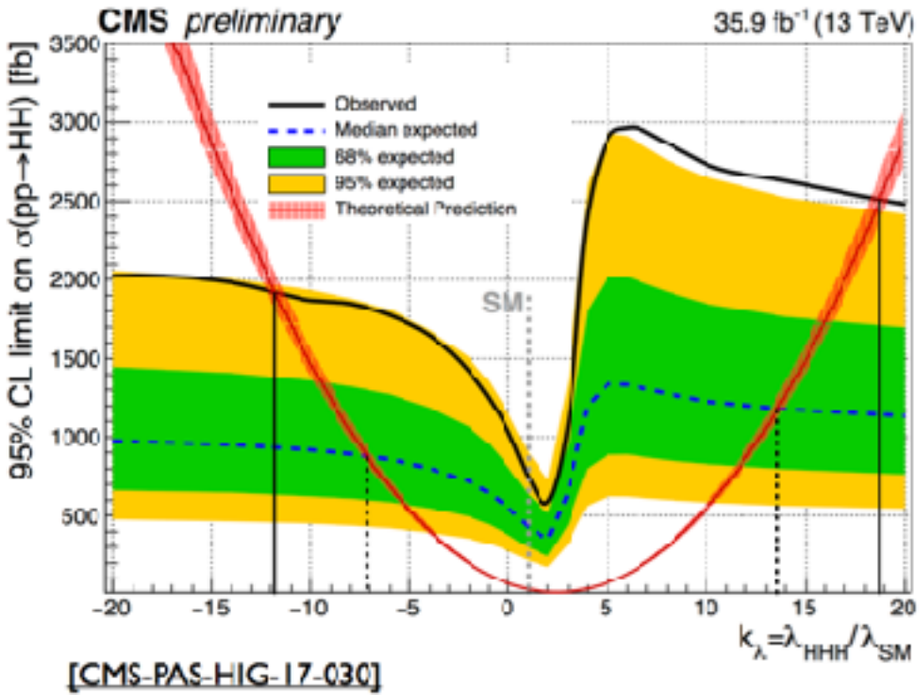




Higgs and New Physics

Any deviation from the SM in the Higgs sector is new physics!

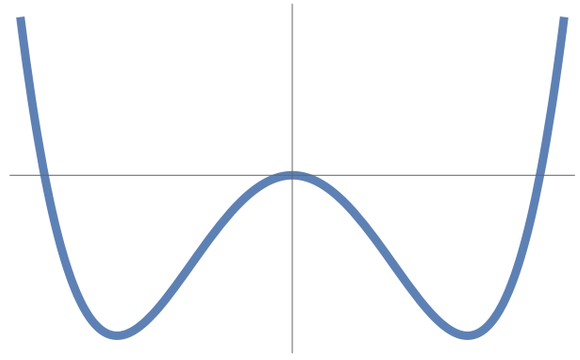




Deviation

from gauge/fermion Higgs couplings

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



Different Potential

than Landau-Ginzburg potential

New Physics in Higgs Sector

Parametrize new physics effects using SMEFT

$m_{\rm NP} \sim$ TeV

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

New Physics Model

shape of Higgs potential

$$Q_H = (H^\dagger H)^3\,,$$
$$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)\,,$$
$$Q_{HD} = (D^\mu H)^\dagger H H^\dagger (D_\mu H)\,,$$
$$Q_{uH} = (H^\dagger H)(\bar{Q} u_R \tilde{H})\,,$$

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

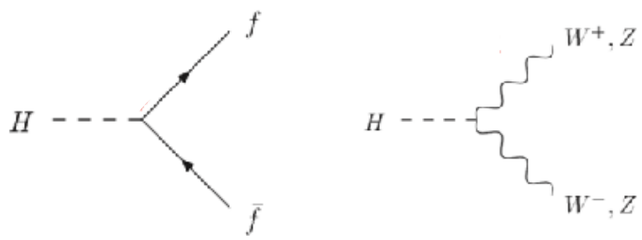
$v \sim 246$ GeV

$$\frac{\alpha_s}{4\pi}\frac{c_g}{\Lambda^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} \qquad \frac{\alpha'}{4\pi}\frac{c_\gamma}{\Lambda^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

Higgs EFT

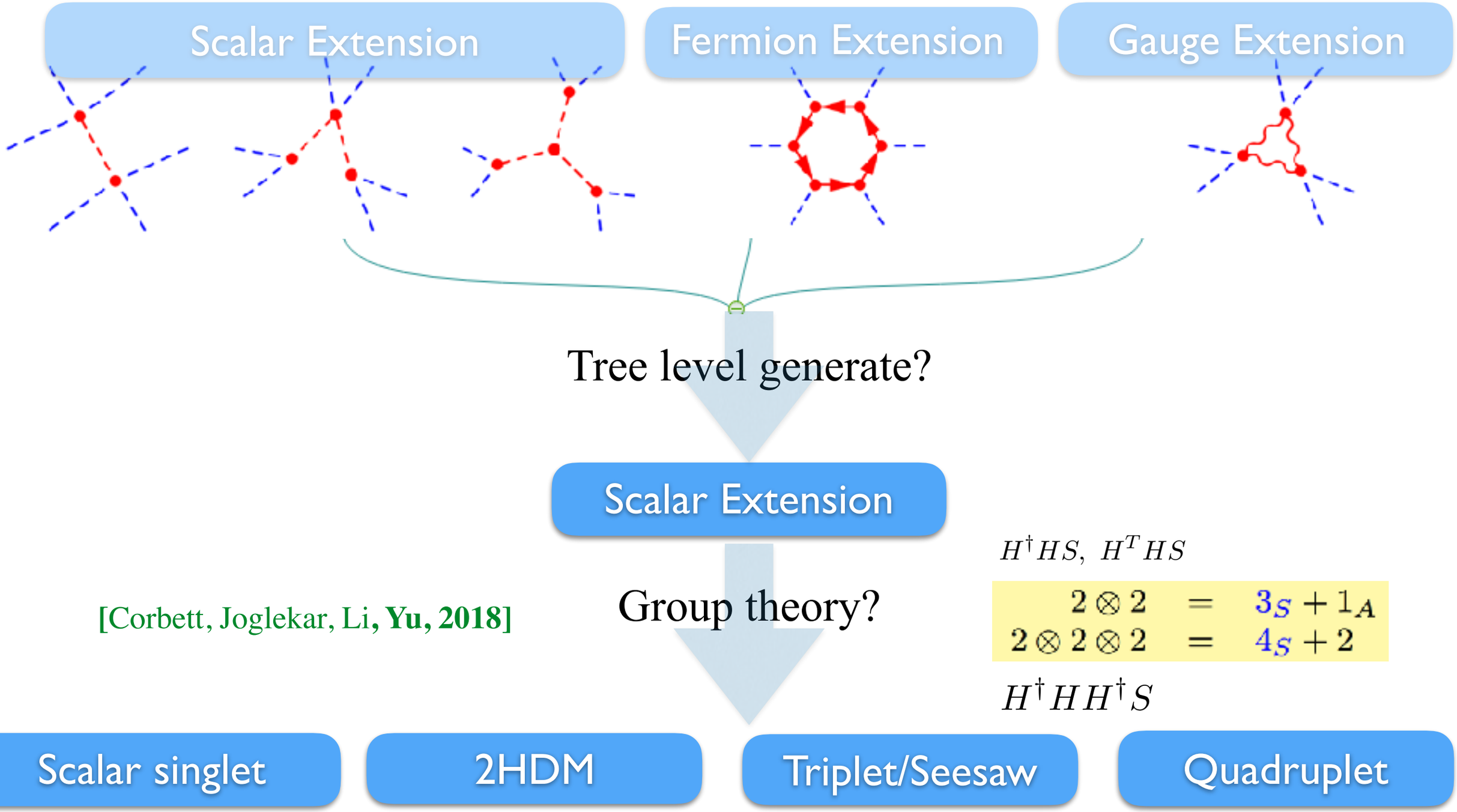
$$\begin{aligned}\mathcal{L} = {} & \tfrac{1}{2}(\partial_\mu h)^2 - V(h) \\ & + \tfrac{v^2}{4}\mathrm{Tr}\left[(\partial_\mu U)^\dagger \partial^\mu U\right]\left(1 + 2a\tfrac{h}{v} - b\tfrac{h^2}{v^2} + \cdots\right) \\ & - \tfrac{v}{\sqrt{2}}\left(\bar{t}_L, \bar{b}_L\right) U \left(1 + c_1\tfrac{h}{v}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

Effective Coupling Strength



New Physics Models

How to generate H^6 operator?



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

Fundamental Higgs

Scalar singlet | 2HDM | Triplet/Seesaw | Quadruplet

Integrate out heavy scalars

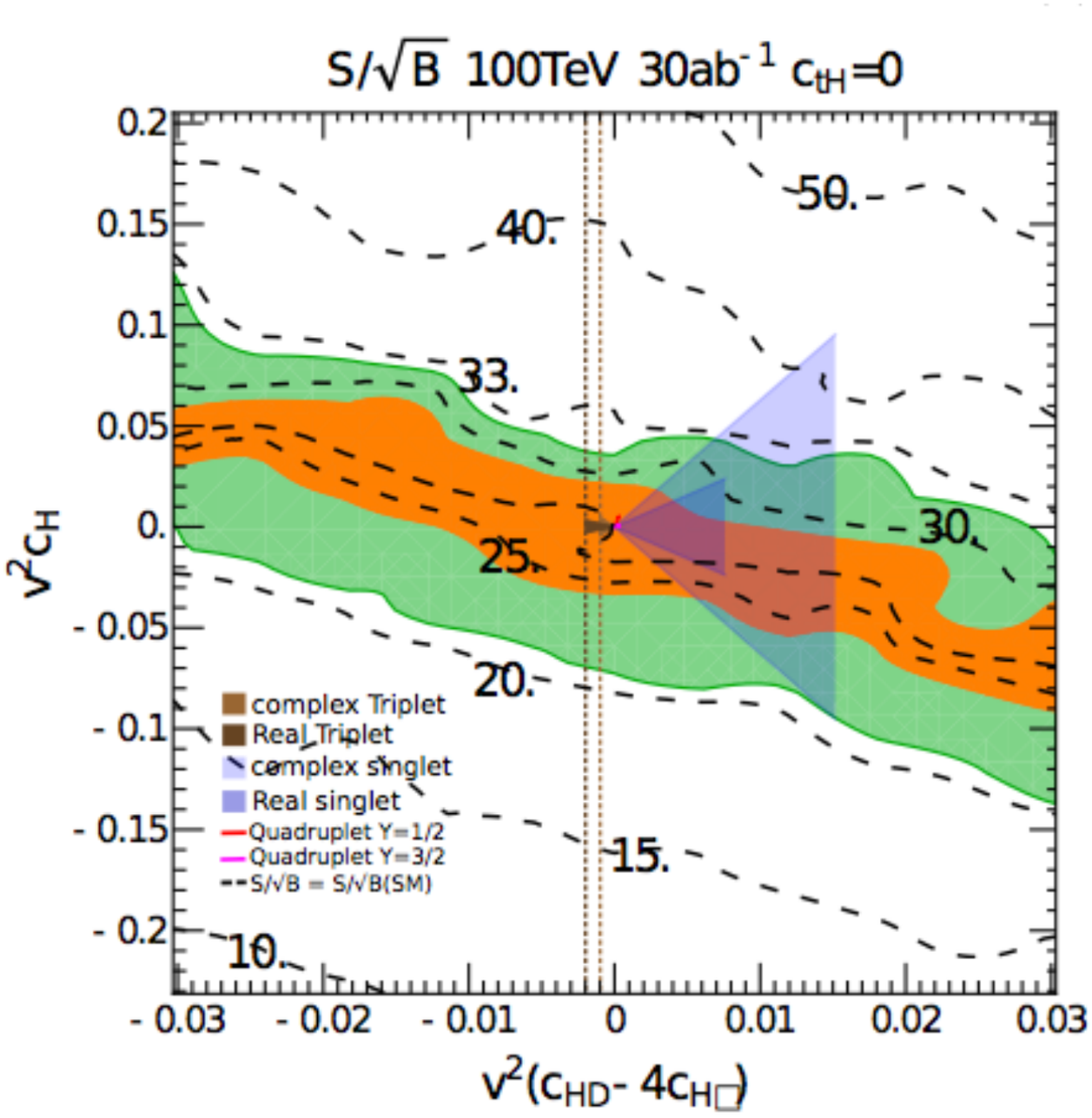
[Corbett, Joglekar, Li, **Yu, 2018**]

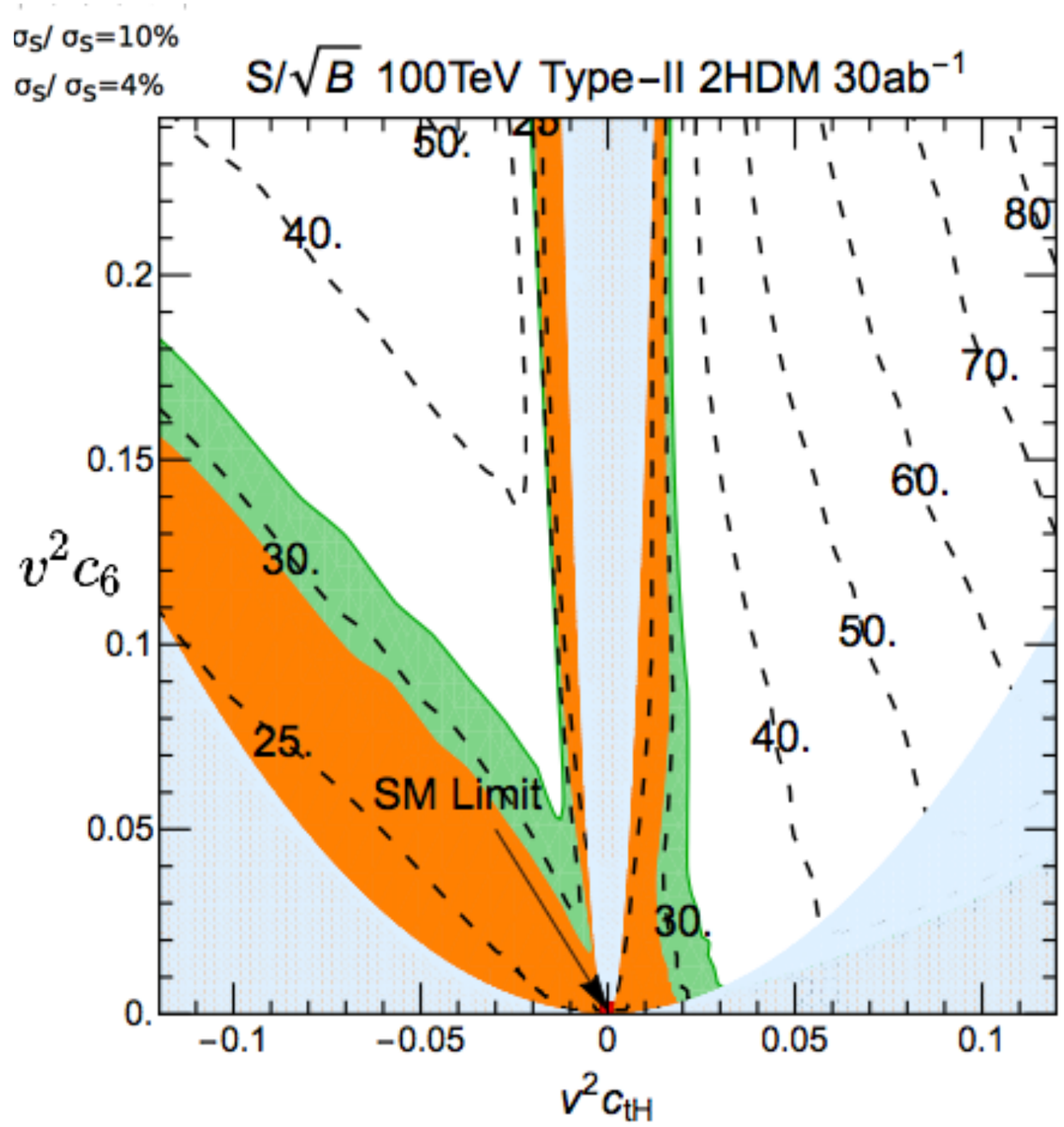
Theory:	C_6	$c_{\Phi\Box}$	$c_{\Phi D}$	$c_{e\Phi}$	$c_{u\Phi}$	$c_{d\Phi}$
$\mathbb{R}$ Singlet	$-\frac{\lambda_{HS}}{2}\frac{g_{HS}^2}{M^4}$	$-\frac{g_{HS}^2}{2M^4}$	-	-	-	-
$\mathbb{C}$ Singlet	$-\left(\frac{\lvert g_{HS}\rvert^2\lambda'_{H\Phi}}{2M^4}+\frac{\mathrm{Re}[g_{HS}^2\lambda_{H\Phi}]}{M^4}\right)$	$-\frac{\lvert g_{HS}\rvert^2}{M^4}$	-	-	-	-
2HDM, Type I	$\frac{\lvert Z_6\rvert^2}{M^2}$	-	-	$\frac{Z_6}{M^2}Y_l c_\beta$	$\frac{Z_6}{M^2}Y_u c_\beta$	$\frac{Z_6}{M^2}Y_d c_\beta$
Type II:	$\frac{\lvert Z_6\rvert^2}{M^2}$	-	-	$-\frac{Z_6}{M^2}Y_l s_\beta$	$\frac{Z_6}{M^2}Y_u c_\beta$	$-\frac{Z_6}{M^2}Y_d s_\beta$
Lepton-Specific:	$\frac{\lvert Z_6\rvert^2}{M^2}$	-	-	$-\frac{Z_6}{M^2}Y_l s_\beta$	$\frac{Z_6}{M^2}Y_u c_\beta$	$\frac{Z_6}{M^2}Y_d c_\beta$
Flipped:	$\frac{\lvert Z_6\rvert^2}{M^2}$	-	-	$\frac{Z_6}{M^2}Y_l c_\beta$	$\frac{Z_6}{M^2}Y_u c_\beta$	$-\frac{Z_6}{M^2}Y_d s_\beta$
$\mathbb{R}$ Triplet ($Y=0$)	$-\frac{g^2}{M^4}\left(\frac{\lambda_{H\Phi}}{8}-\lambda\right)$	$\frac{g^2}{8M^4}$	$-\frac{g^2}{2M^4}$	$\frac{g^2}{4M^4}Y_l$	$\frac{g^2}{4M^4}Y_u$	$\frac{g^2}{4M^4}Y_d$
$\mathbb{C}$ Triplet ($Y=-1$)	$-\frac{\lvert g\rvert^2}{M^4}\left(\frac{\lambda_{H\Phi}}{4}+\frac{\lambda'}{8}-2\lambda\right)$	$\frac{\lvert g\rvert^2}{2M^4}$	$\frac{\lvert g\rvert^2}{M^4}$	$\frac{\lvert g\rvert^2}{2M^4}Y_l$	$\frac{\lvert g\rvert^2}{2M^4}Y_u$	$\frac{\lvert g\rvert^2}{2M^4}Y_d$
$\mathbb{C}$ Quadruplet ($Y=1/2$)	$\frac{\lvert\lambda_{H3\Phi}\rvert^2}{M^2}$	-	$\frac{2\lvert\lambda_{H3\Phi}\rvert^2 v^2}{2M^4}$	-	-	-
$\mathbb{C}$ Quadruplet ($Y=3/2$)	$\frac{\lvert\lambda_{H3\Phi}\rvert^2}{M^2}$	-	$\frac{6\lvert\lambda_{H3\Phi}\rvert^2 v^2}{2M^4}$	-	-	-

EWPT and Single Higgs data

Fundamental Higgs

EWPT and Single Higgs data put constraints on di-Higgs cross section



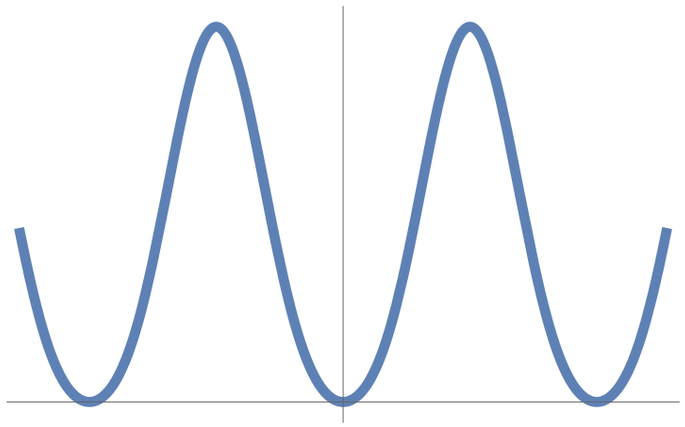


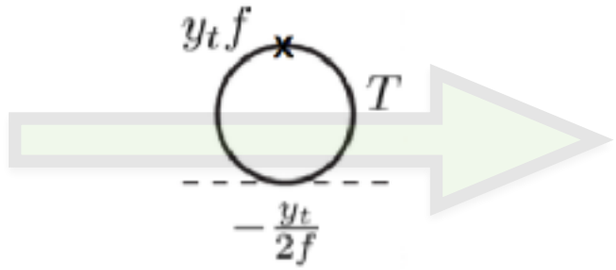
[Corbett, Joglekar, Li, **Yu, 2018]**

Pseudo-Goldstone Higgs

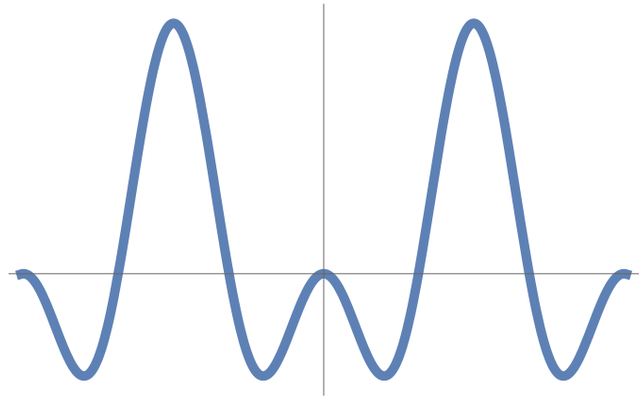
Higgs as pseudo-goldstone Boson

Pion potential





Pseudo-Goldstone Higgs

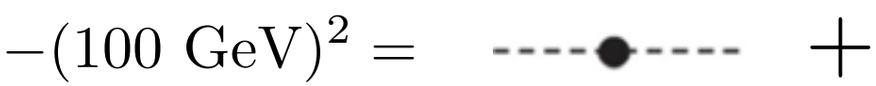


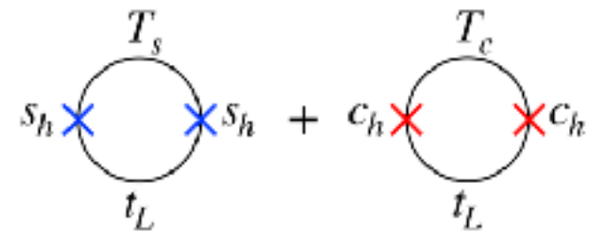
$$V(\phi) = -a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

(Composite) fermion states trigger EWSB!

PNGB Higgs Models

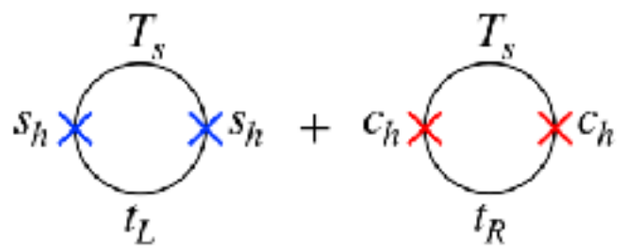
Composite fermion states also solve little hierarchy problem





Composite Higgs

[Agashe, Contino, Pomarol 2004]

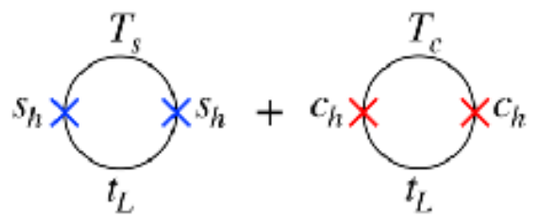


Left-Right Z2

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

Twin Higgs

[Chacko, Goh, Harnik 2006]



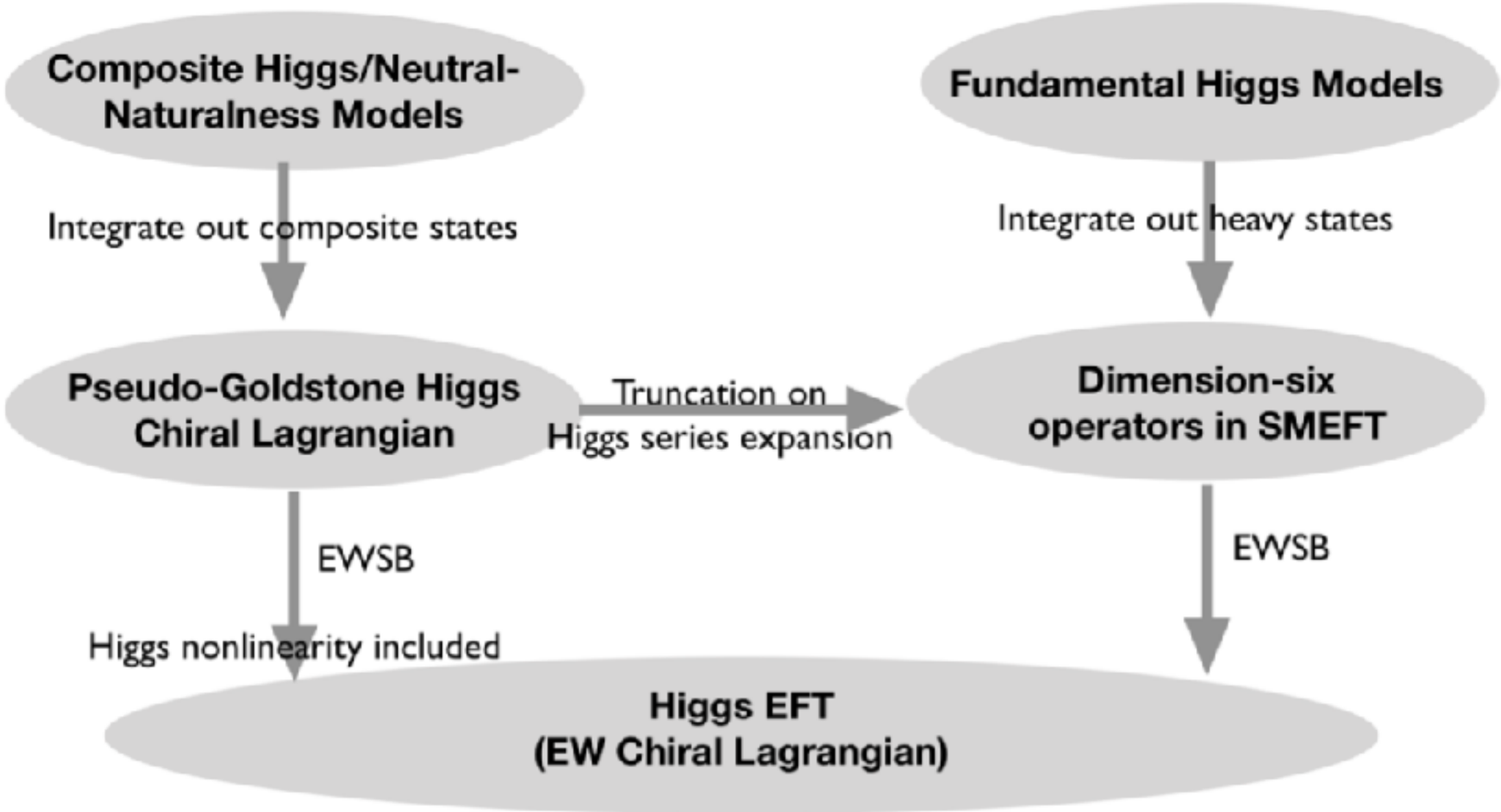
Minimal NN

[Xu, **Yu**, Zhu, 2018]

$$= \quad (m^0)^2 \quad + \quad \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + 6y_t^2\right) \quad + \quad \frac{6y_t^2}{16\pi^2} m_{\mathrm{t}'}^2 \log\frac{\Lambda^2}{m_{\mathrm{t}'}^2}$$

PNGB Chiral Lagrangian

Higgs nonlinearity effect is not included in SMEFT



Integrate Out by Form Factors

Composite Higgs | Left-Right Z2 | Twin Higgs | Minimal NN

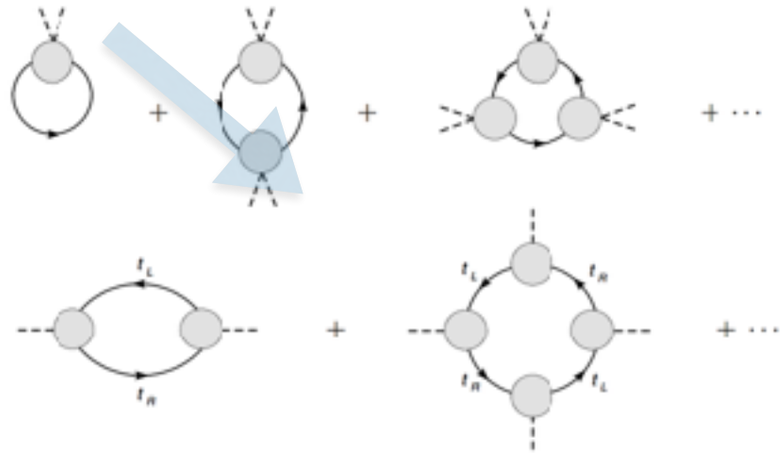
Form factor method [Li, Xu, **Yu**, Zhu, **2019**]

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

Low energy theorem

$$c_g = v \frac{\partial}{\partial \langle h \rangle} \left[\frac{1}{2} \sum_i \log m_i^2(h) \right],$$

$$c_{ggh} = -v^2 \frac{\partial^2}{\partial \langle h \rangle^2} \left[\frac{1}{2} \sum_i \log m_i^2(h) \right],$$



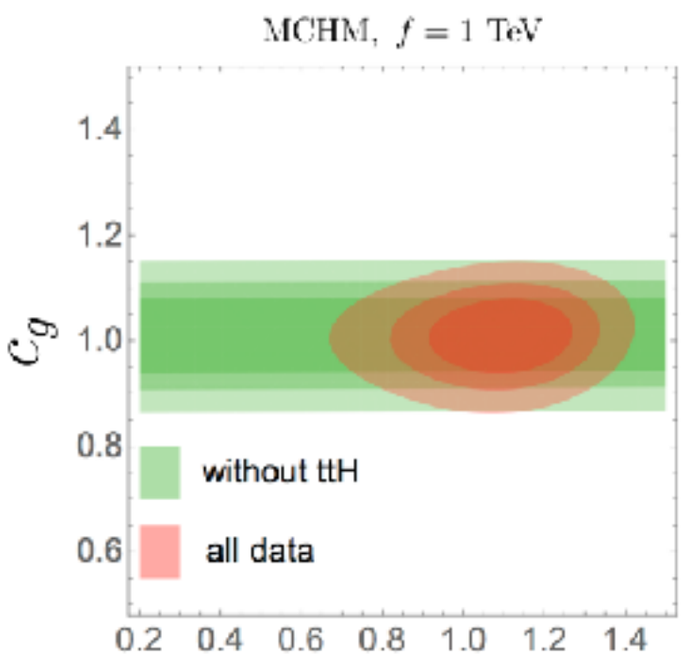
$$V(h) = -\frac{2N_c}{16\pi^2} \int_0^{\Lambda^2} \mathrm{d}Q^2 Q^2 \log[\Pi_{t_L} \Pi_{t_R} \cdot Q^2 + \Pi_{t_L t_R}^2]$$

$$= -\gamma_f s_h^2 + \beta_f s_h^4 + \cdots$$

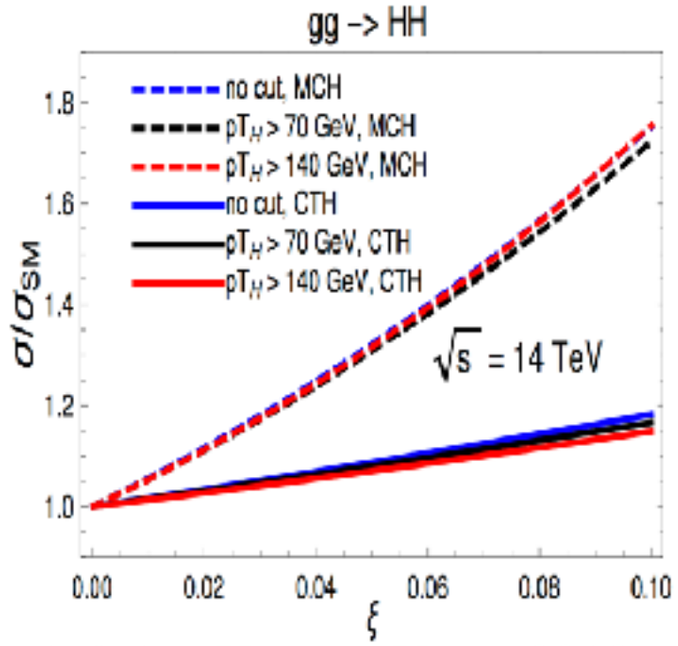
EW Chiral Lagrangian

Composite Higgs | Left-Right Z2 | Twin Higgs | Minimal NN

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



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

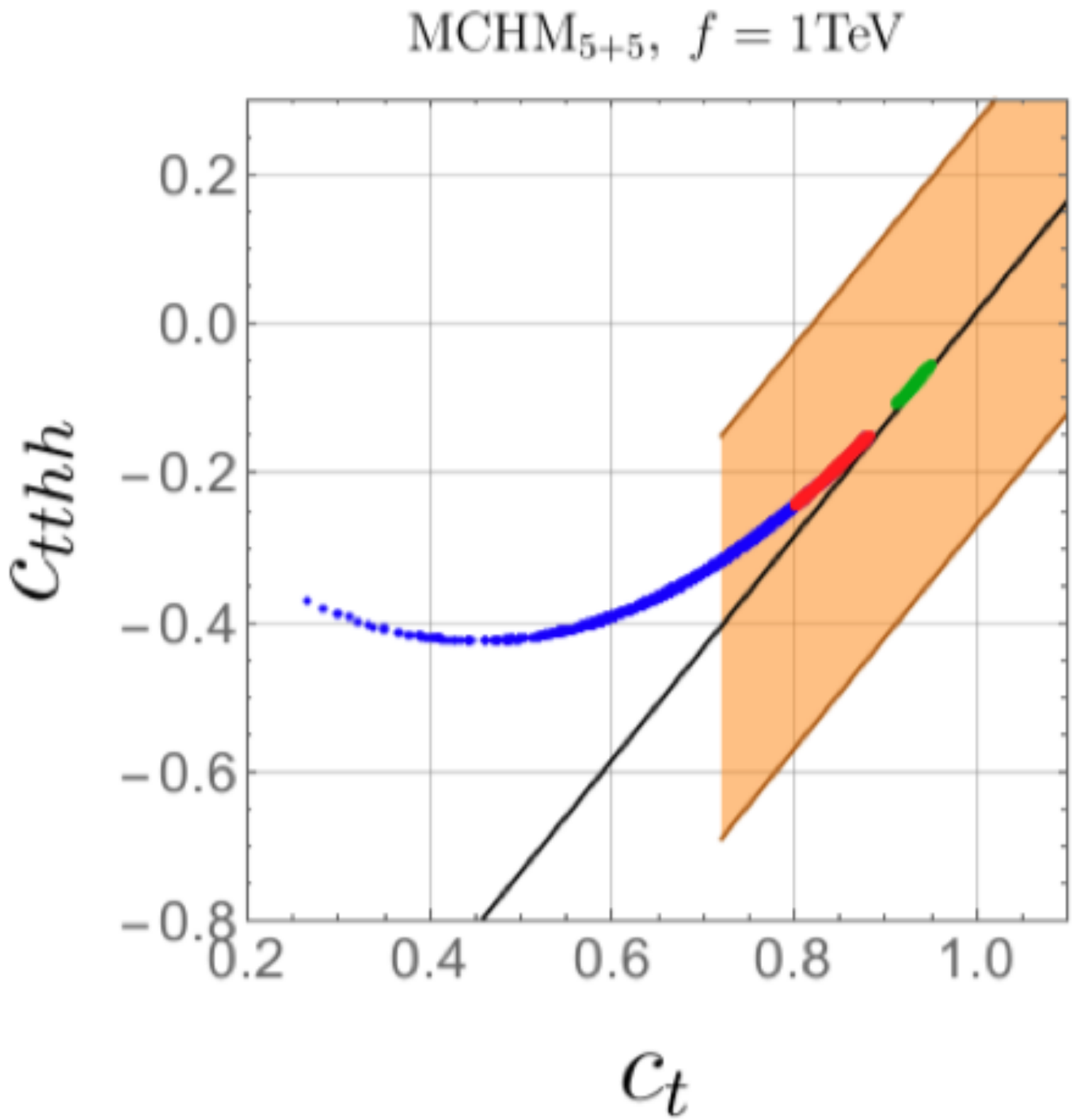


[Agrawal, Saha, Xu, **Yu**, Yuan, **2019**]

Pseudo-Goldstone Higgs

Dim-6 SMEFT (SILH) does not encode Higgs nonlinearity

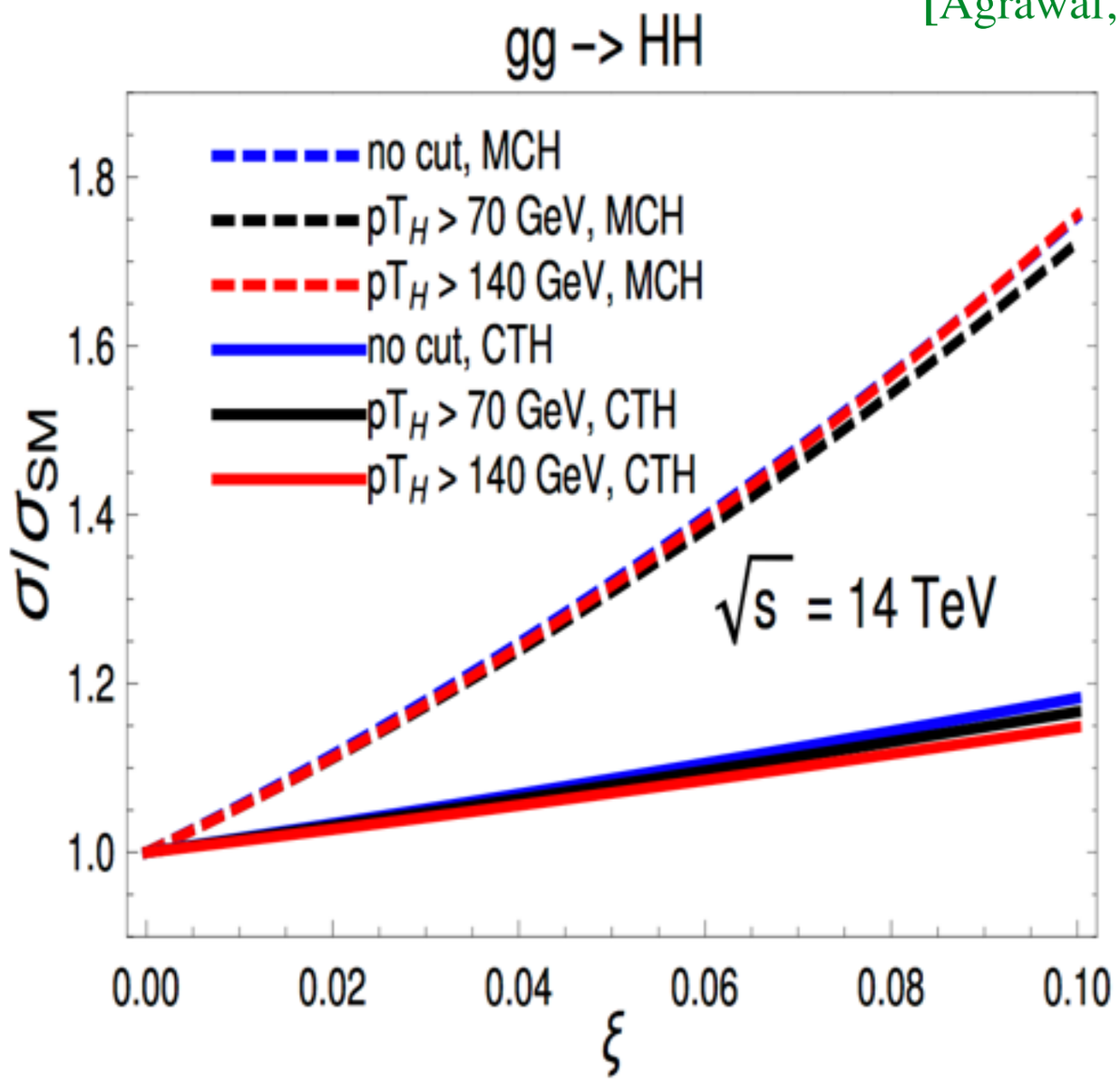
[Li, Xu, **Yu**, Zhu, **2019**]



Pseudo-Goldstone Higgs

Similar to 2HDM, di-Higgs cross section is larger than SM one

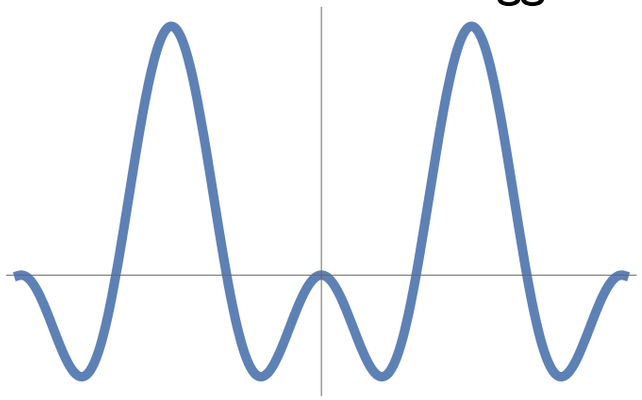
[Agrawal, Saha, Xu, **Yu**, Yuan, **2019**]



Difference: strong correlation among Wilson coefficients

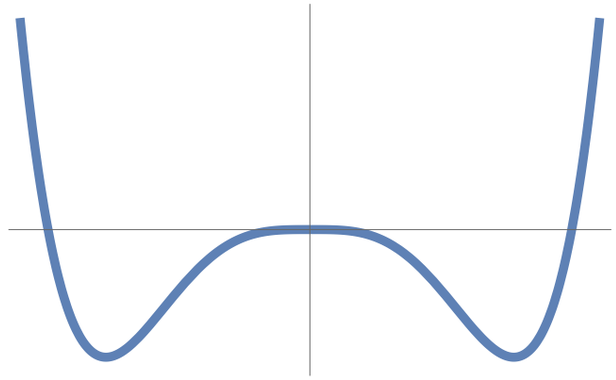
Shape of Higgs Potential

Pseudo-Goldstone Higgs



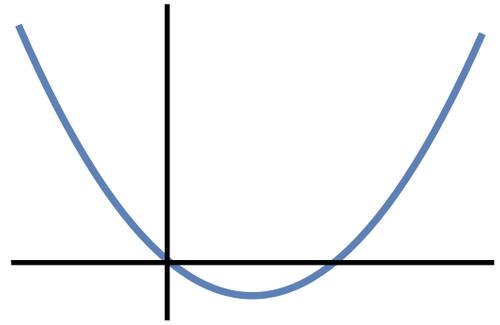
$$V(\phi) = a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

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



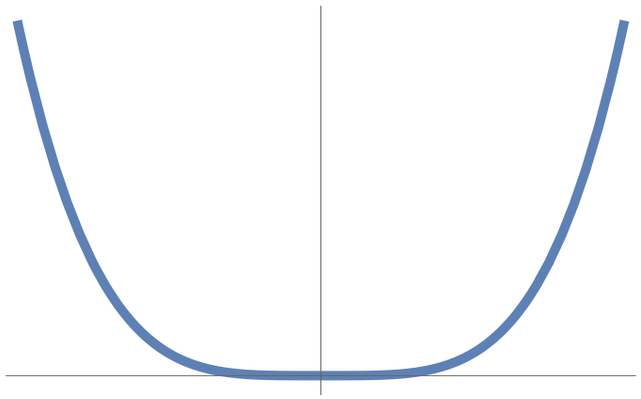
$$V(\phi) = -\mu^3\sqrt{\phi^\dagger\phi} + m^2\phi^\dagger\phi$$

Very different analytic Higgs behavior

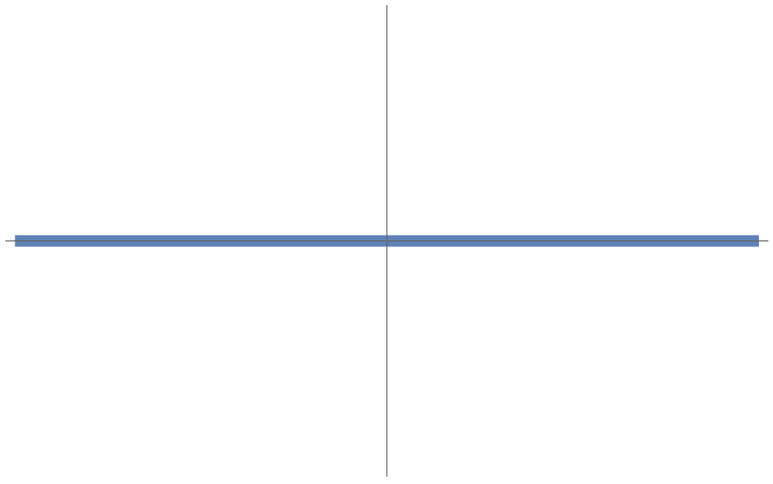
Coleman Weinberg Higgs

Radiative correction triggers electroweak symmetry breaking

Tree-level potential



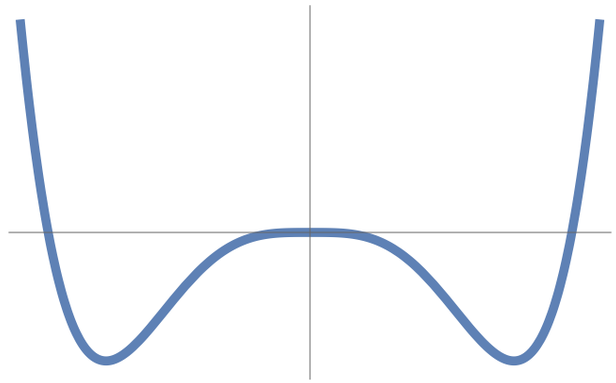
Or flat direction



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

Dimensional Transmutation

Coleman Weinberg Higgs



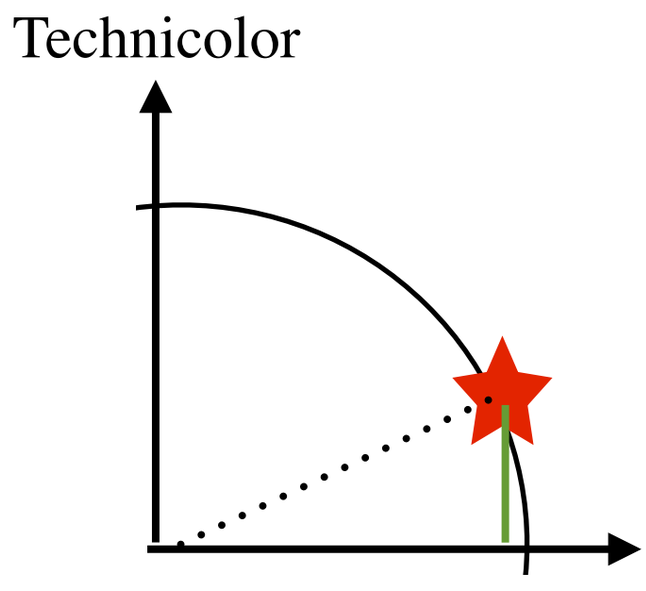
$$V_1(\varphi \mathbf{n}) = \frac{1}{64\pi^2}\frac{\mathrm{Tr}M^4}{v_\varphi^4}\varphi^4\left(\ln\frac{\varphi^2}{v_\varphi^2} - \frac{1}{2}\right)$$

$$\simeq \frac{1}{64\pi^2}\frac{\mathrm{Tr}M^4}{v_\varphi^4}\left(4\langle h\rangle^2 h^2 + \frac{20}{3}\langle h\rangle h^3 + \frac{11}{3}h^4\right)$$

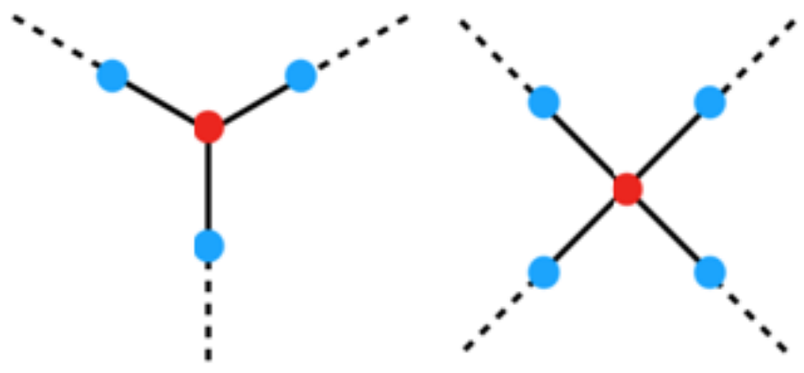
$$\frac{\lambda_3}{\lambda_3^{\mathrm{SM}}} = \frac{5}{3}, \quad \frac{\lambda_4}{\lambda_4^{\mathrm{SM}}} = \frac{11}{3}$$

Tadpole Induced Higgs

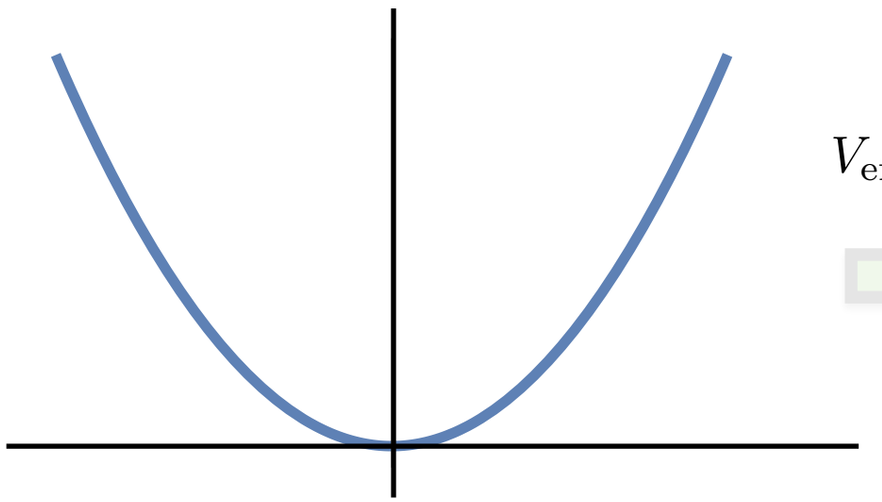
Bosonic technicolor (Induced EWSB)



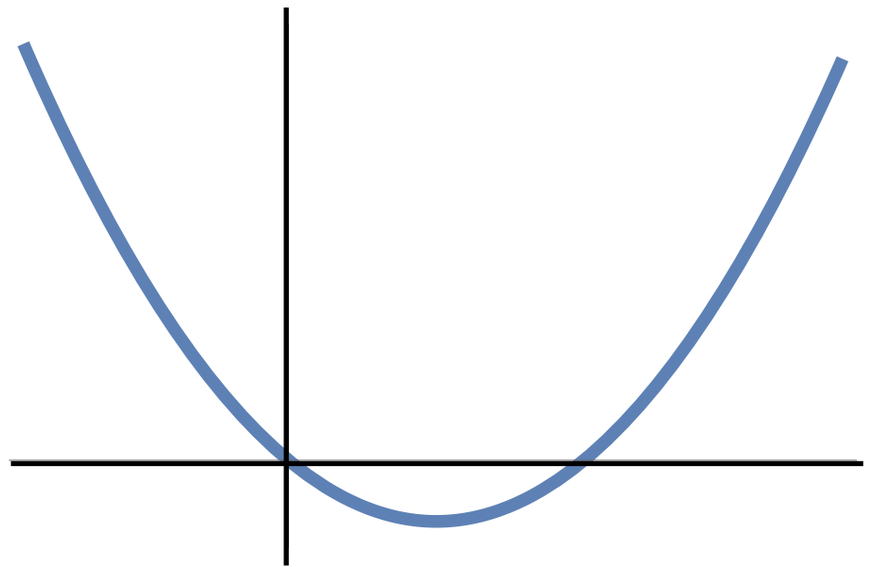
[Simmons 1989],
[Carone, Georgi 1994] ,
[Galloway, etc, 2013]
...



$\lambda_3 \sim \lambda_4 \sim 0$



$V_{\rm eff} \simeq m_H^2 H^\dagger H + f^3 (H + \text{h.c.})$



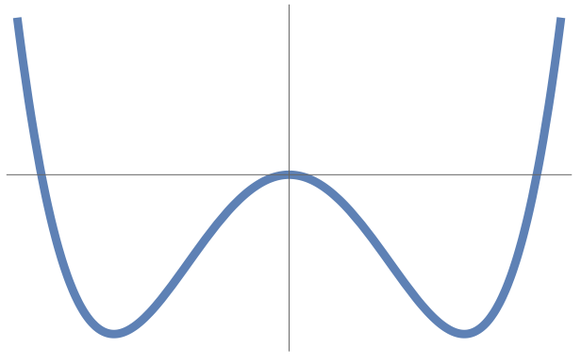
non-decoupling

How to Distinguish Them?

SMEFT | PNGB Higgs | CW Higgs | Tadpole Higgs

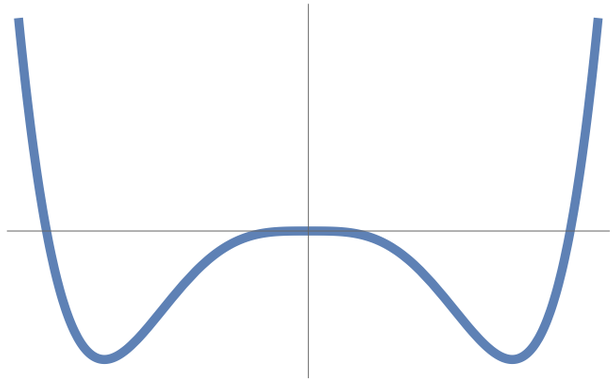
[Agrawal, Saha, Xu, **Yu**, Yuan, **2019**]

Landau-Ginzburg Higgs



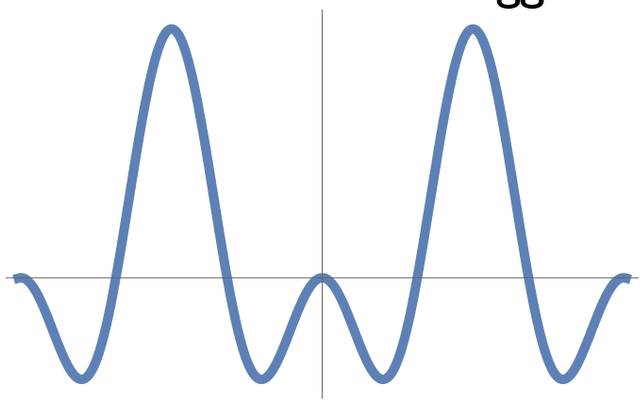
$$V(\phi) = -m^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$

Coleman Weinberg Higgs



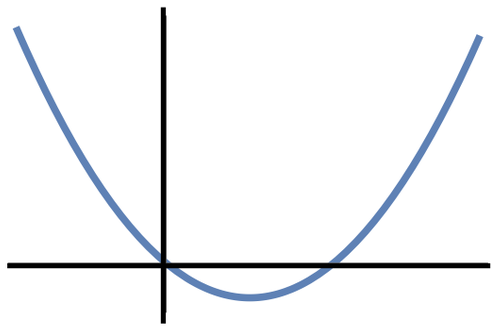
$$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2\log\frac{\phi^\dagger\phi}{\mu^2}$$

Pseudo-Goldstone Higgs



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

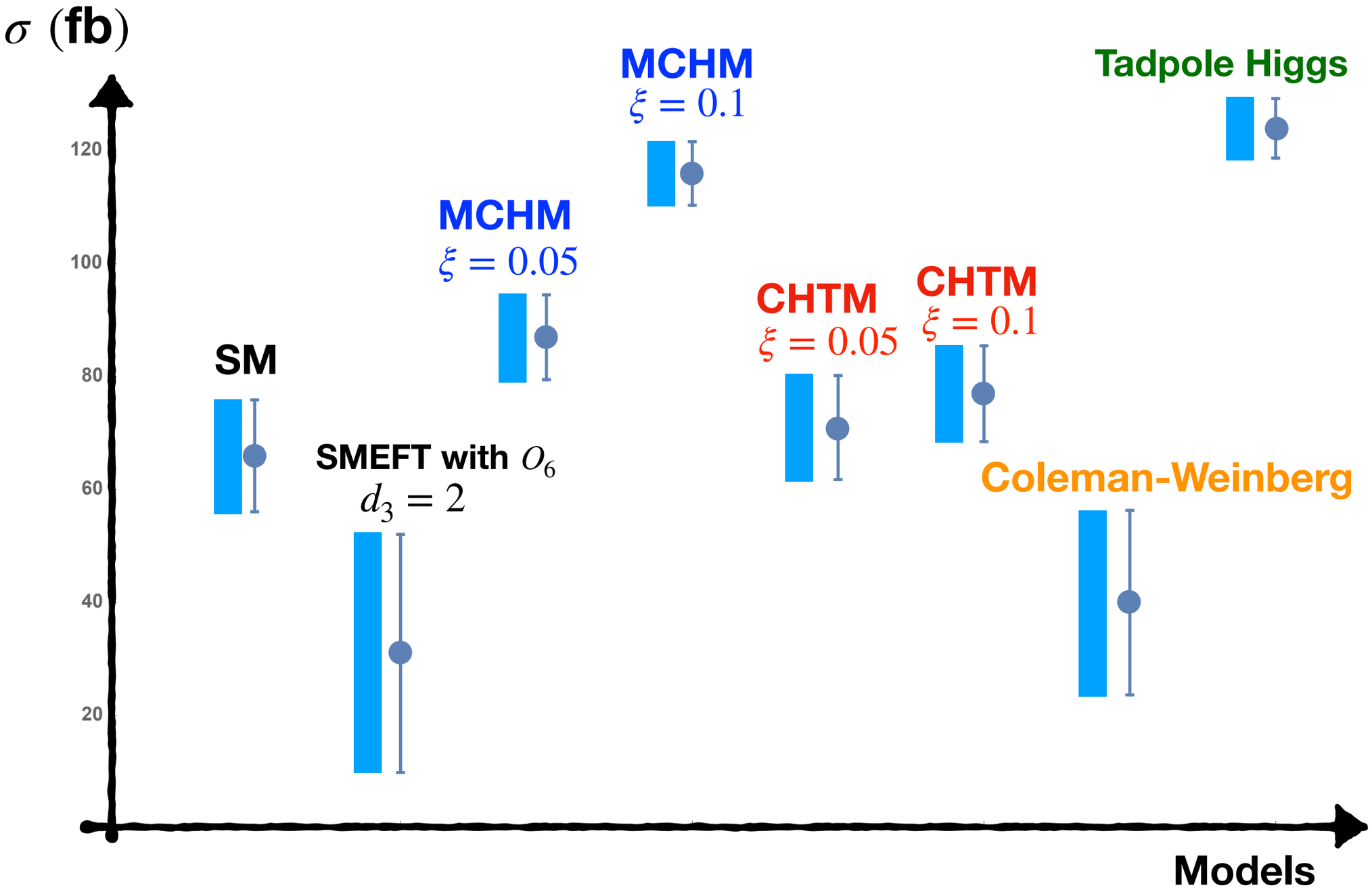
Tadpole-induced Higgs



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

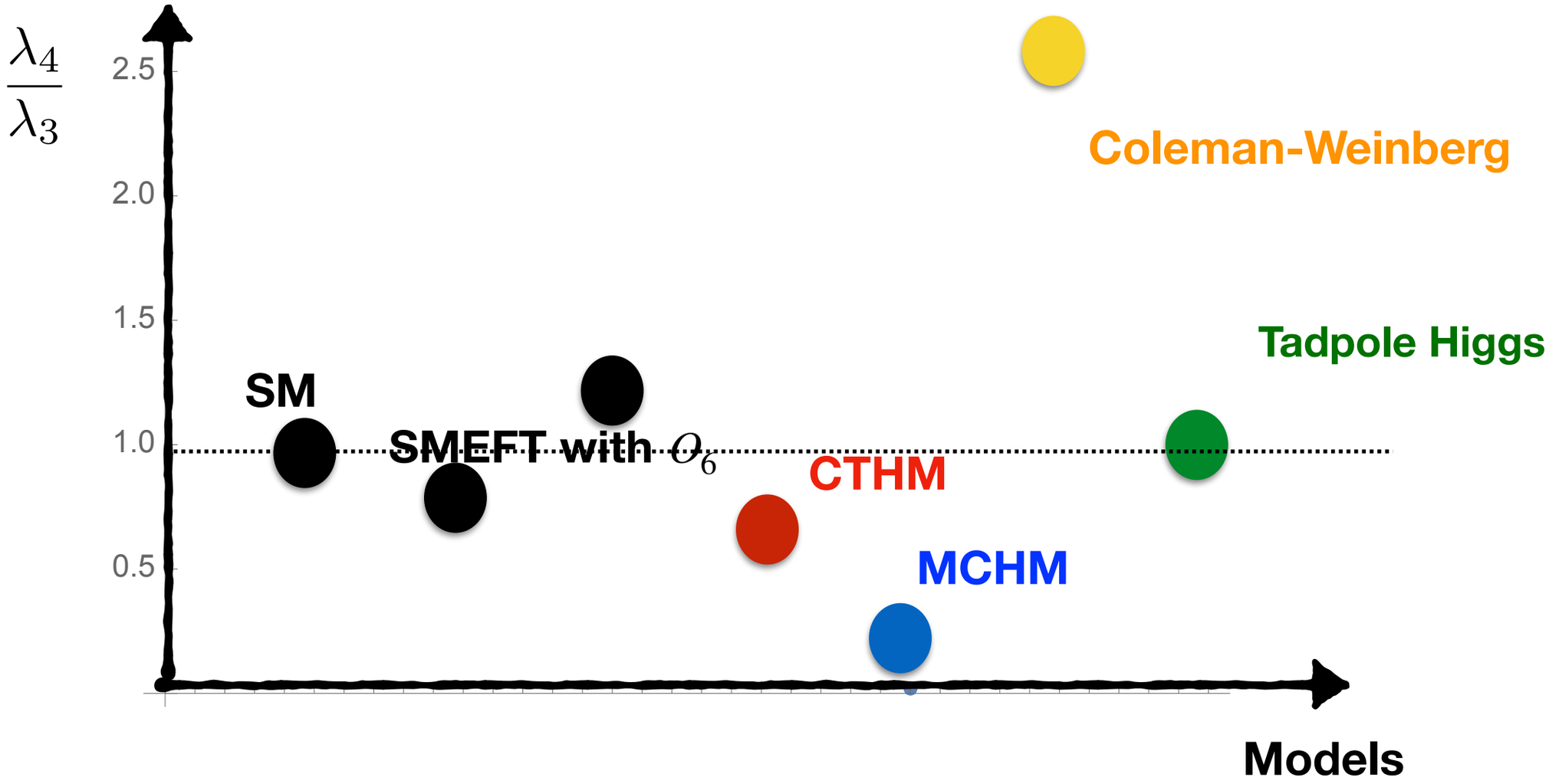
Model Discrimination

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



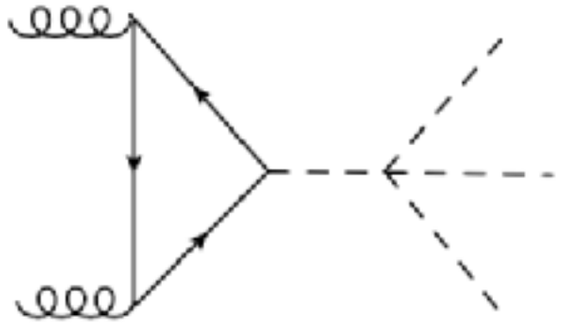
Quartic Higgs Coupling

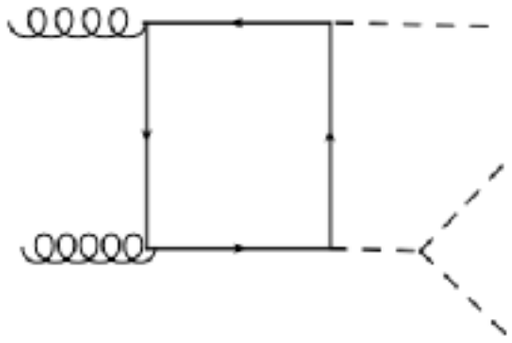
Determine the shape of Higgs potential

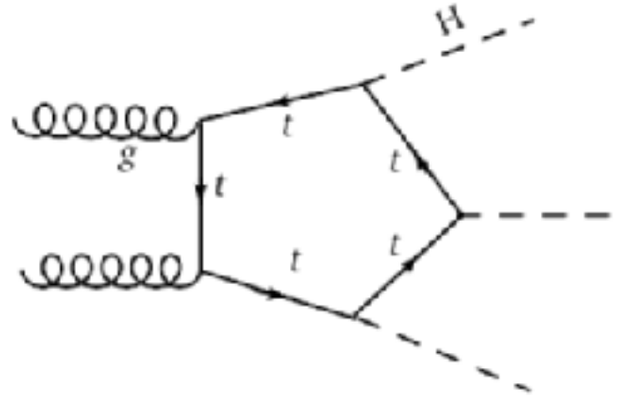


tri-Higgs production

Tri-Higgs Production

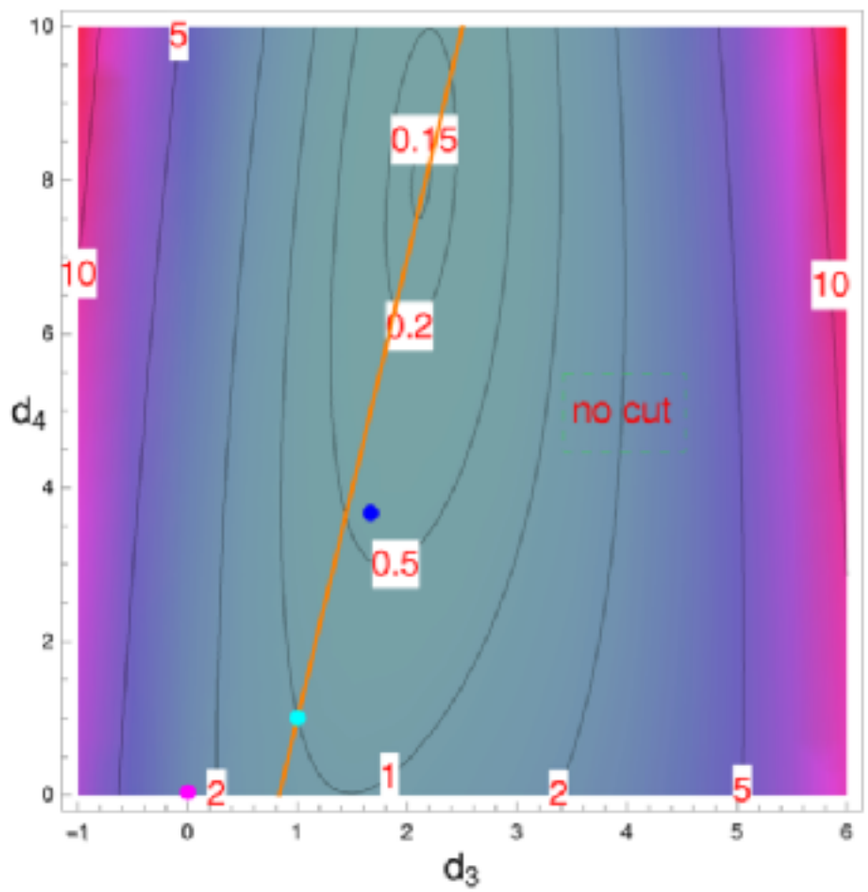


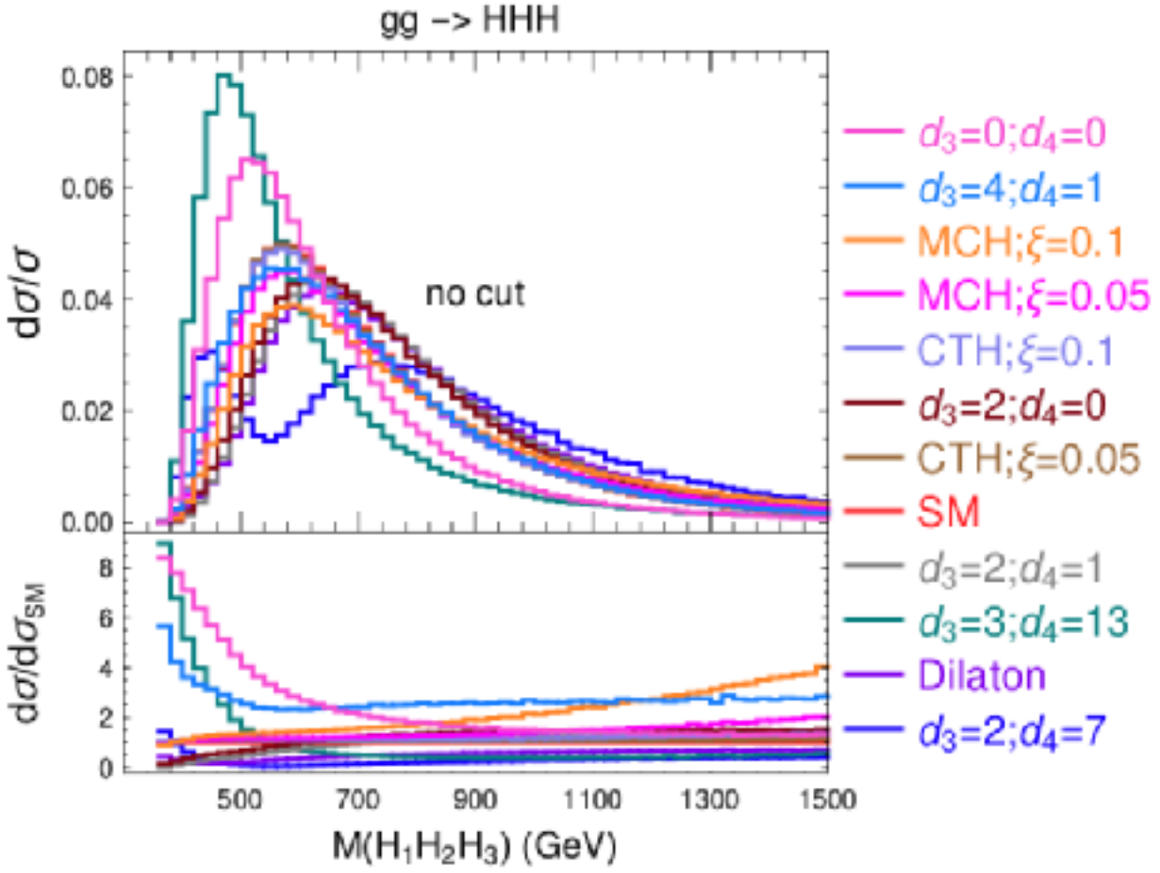




Many references

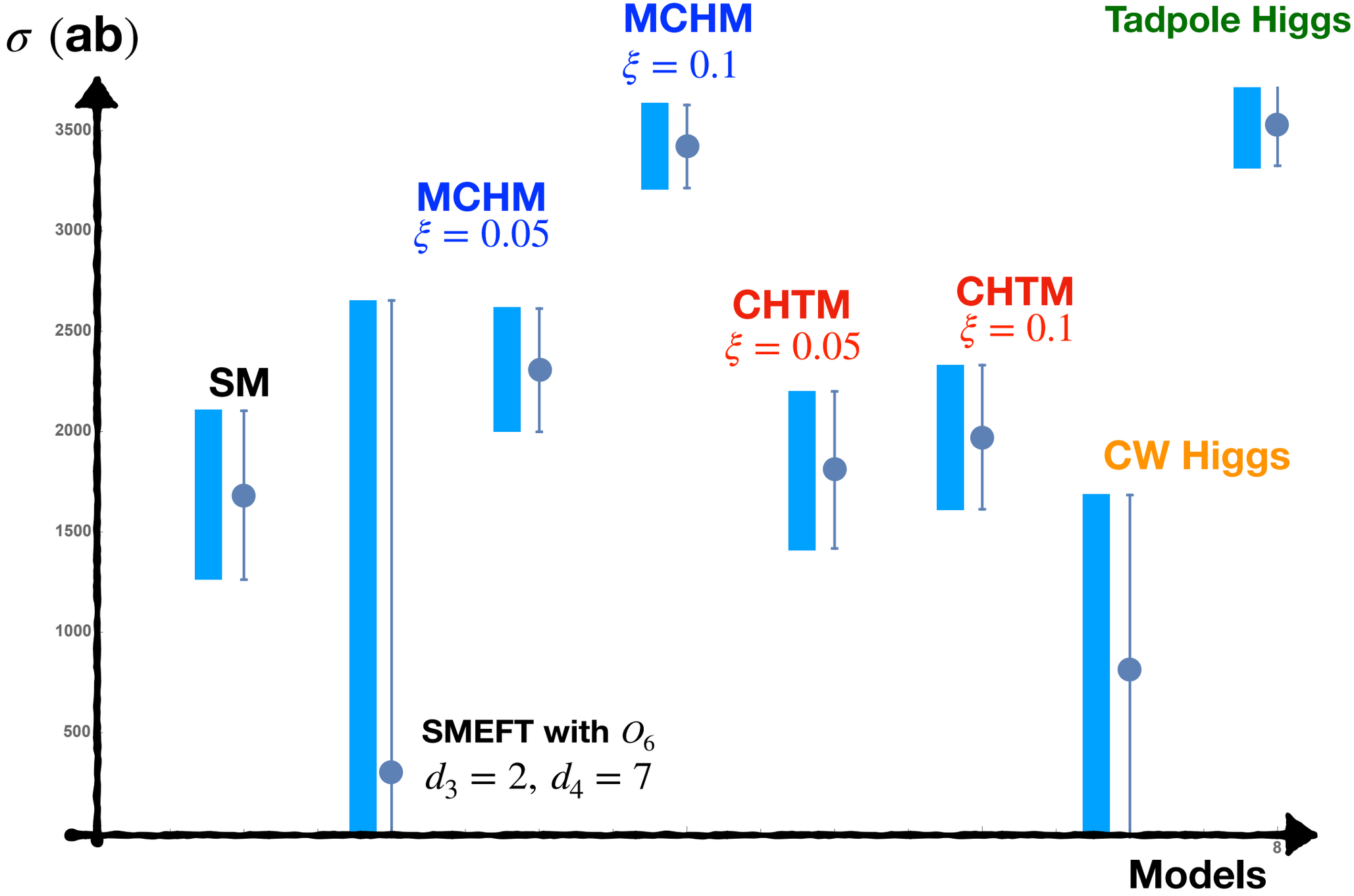
…





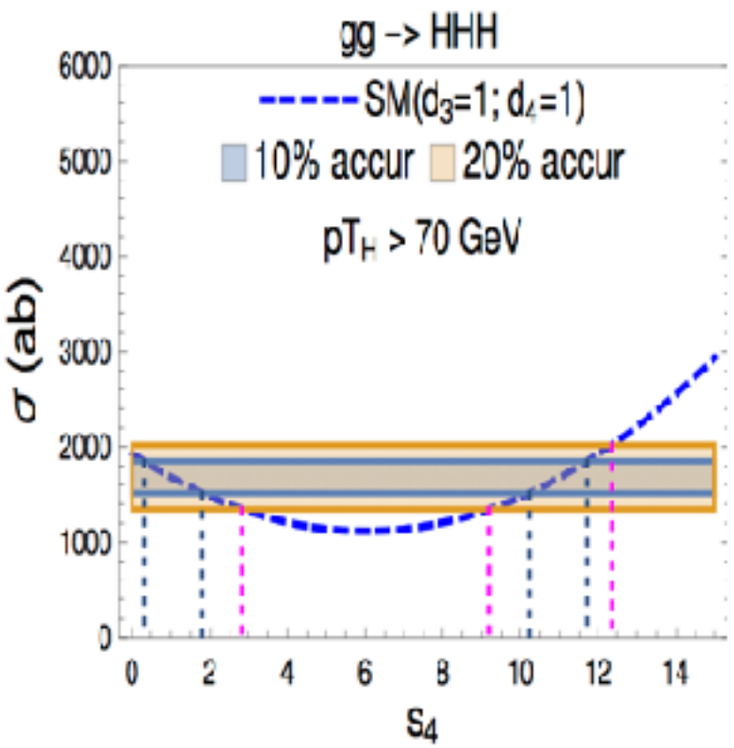
[Agrawal, Saha, Xu, **Yu**, Yuan, **2019**]

Tri-Higgs Production

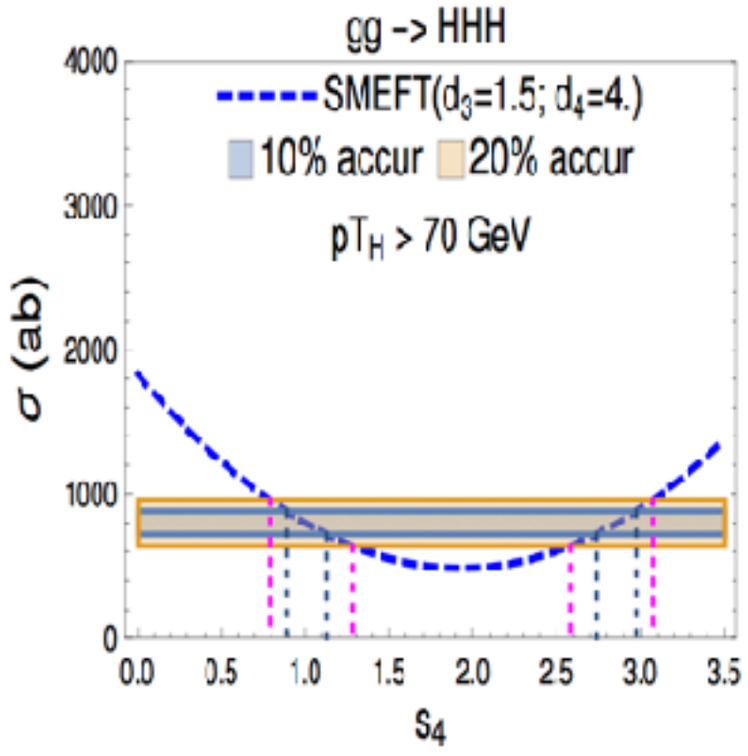


[Agrawal, Saha, Xu, **Yu**, Yuan, **2019**]

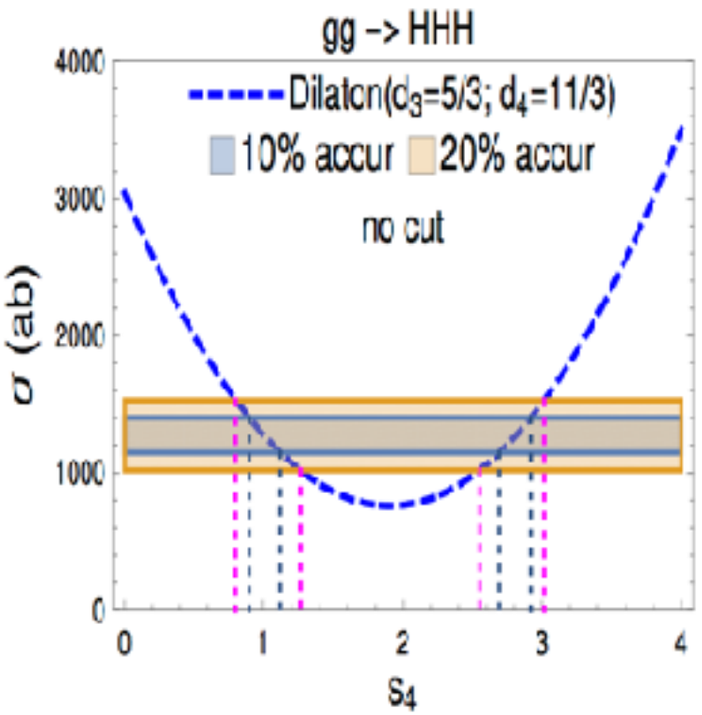
Determine Quartic Coupling



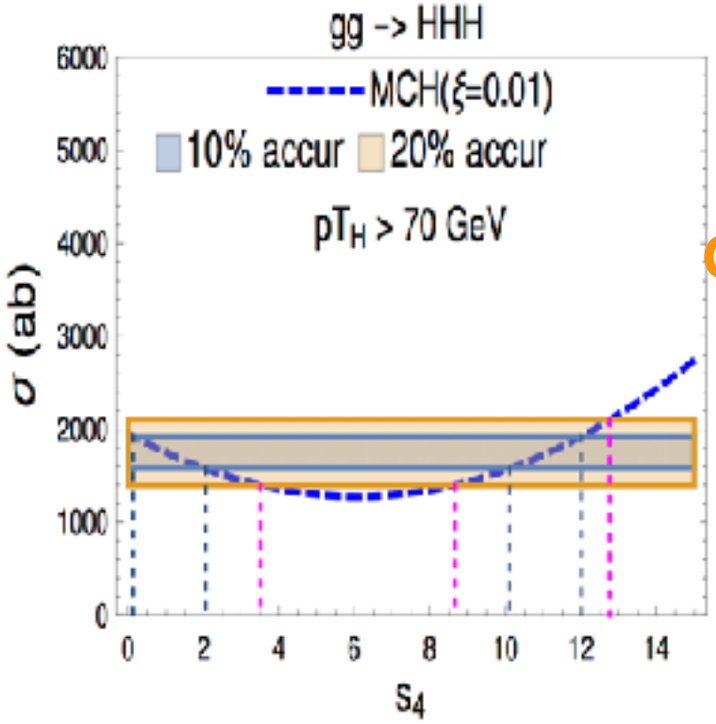
SM



SMEFT with O_6



MCHM

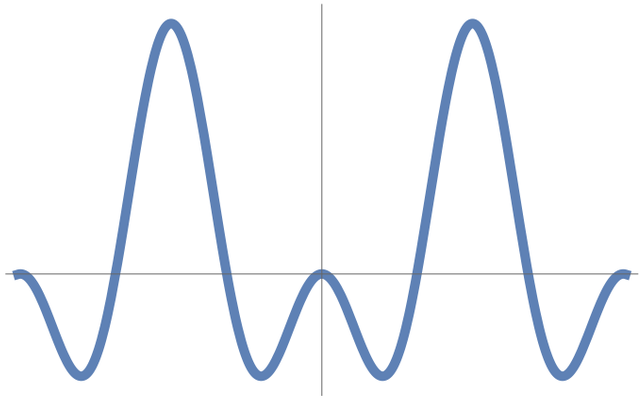


Coleman-Weinberg

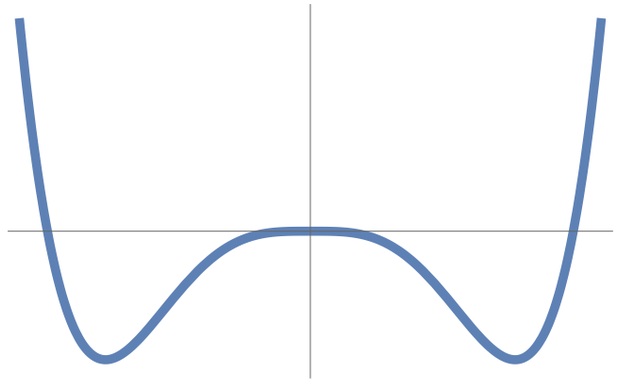
Summary

Explore Higgs potential beyond Landau-Ginzburg Higgs potential

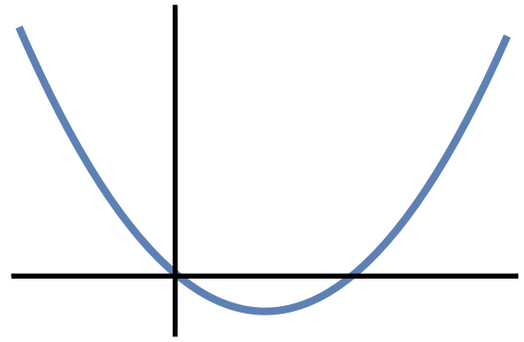
Pseudo-Goldstone Higgs



Coleman Weinberg Higgs

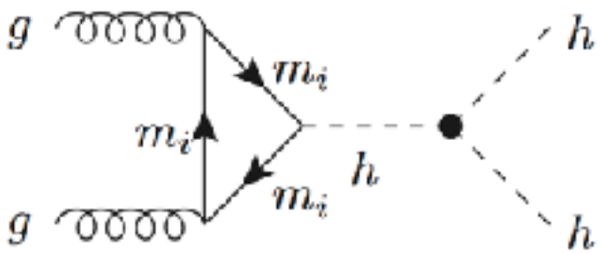


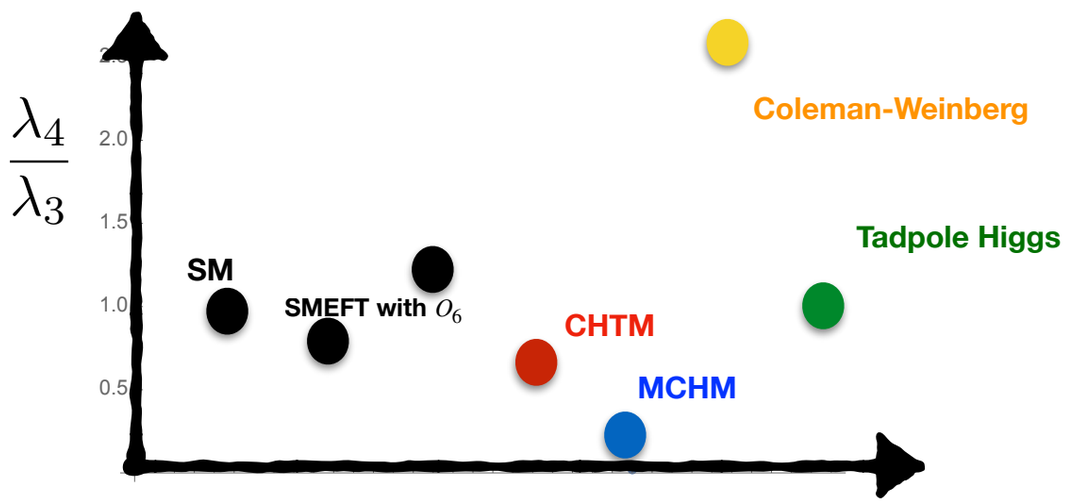
Tadpole-induced Higgs

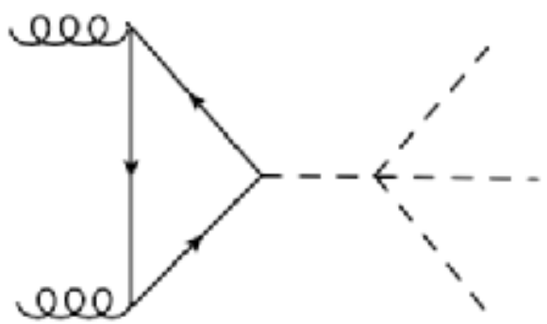


SMEFT is not enough to describe effective Lagrangian

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







Thanks very much!