Institute of Theoretical Physics
Chinese Academy of Sciences

Shape of Higgs Potential at Future Colliders

Jiang-Hao Yu (于江浩)

Institute of Theoretical Physics, Chinese Academy of Science

Pankaj Agrawal, Debashis Saha, Ling-Xiao Xu, **JHY,** C.-P. Yuan, 1907.02078

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

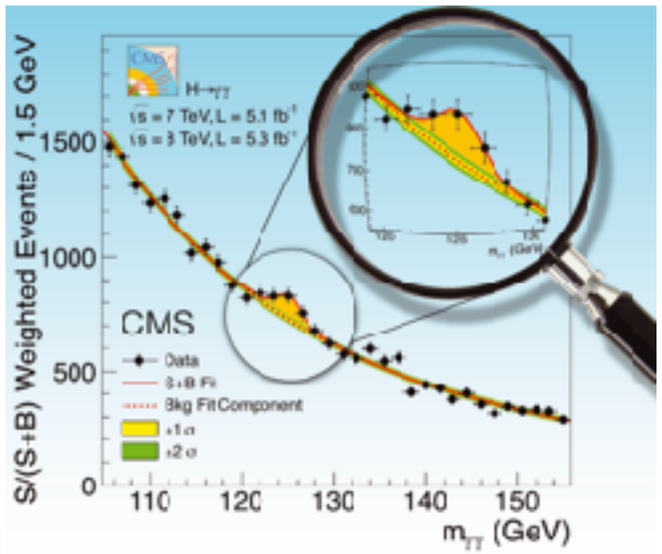
Tyler Corbett, Aniket Joglekar, Hao-Lin Li, **JHY**, JHEP 1805 (2018) 061

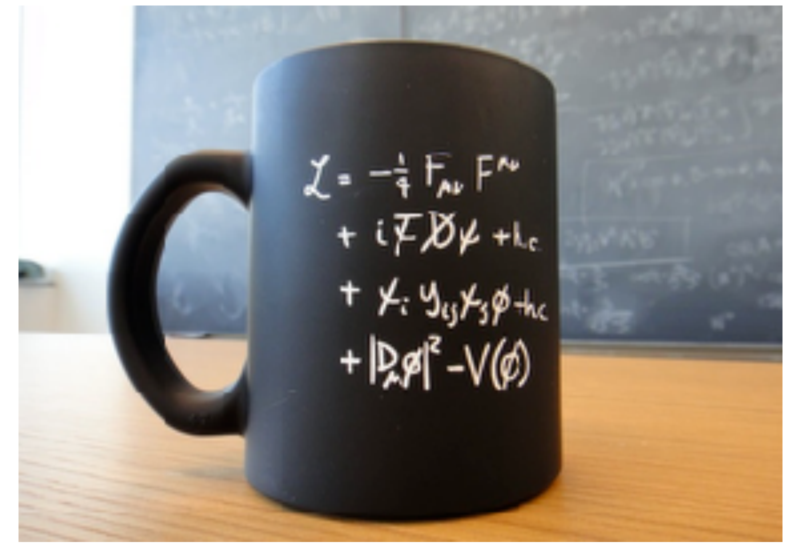
International Workshop on the High Energy CEPC

Nov. 18, 2019

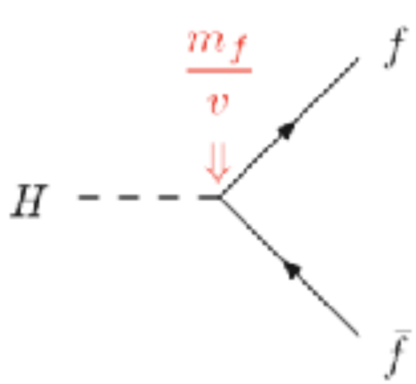
Higgs Boson

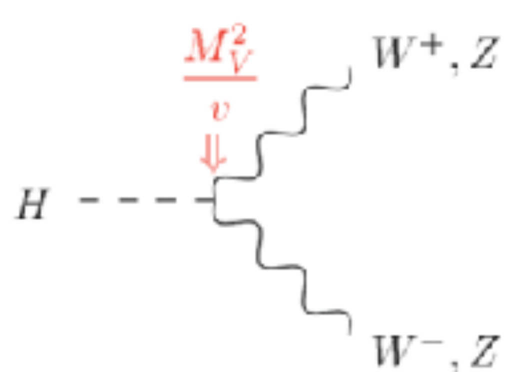
Higgs discovery completes the standard model spectrum

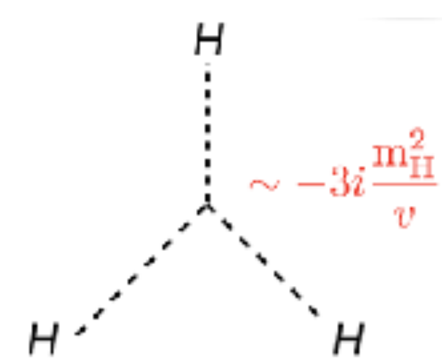




Given Higgs mass, all parameters in Higgs sector are predicted!

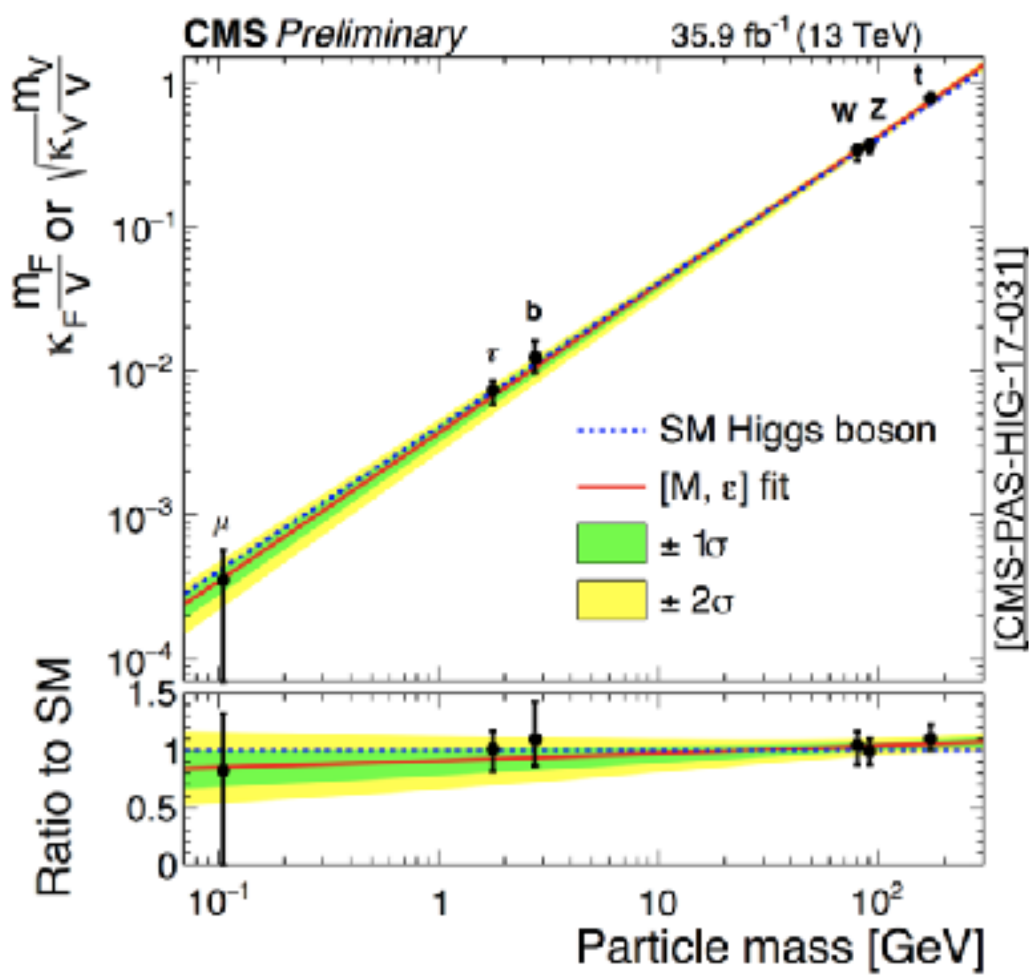


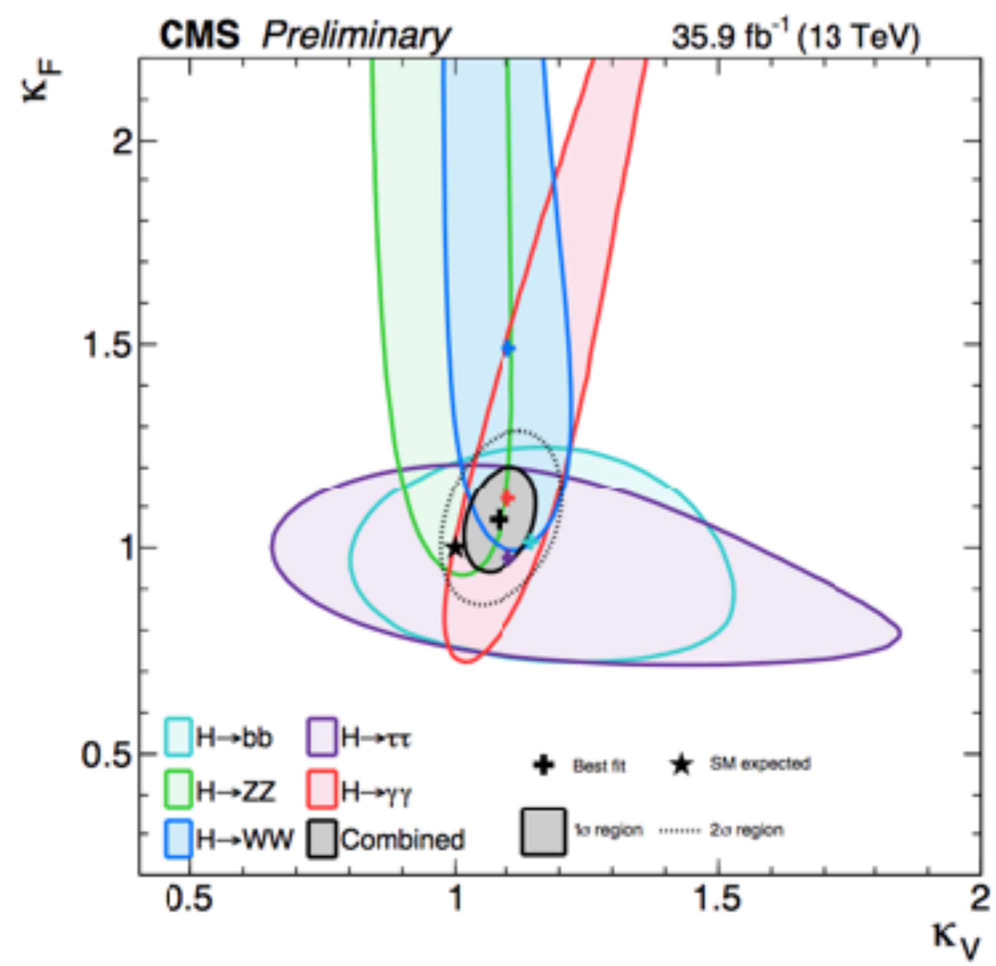




Known Known

Higgs couplings to gauge boson and fermion are measured



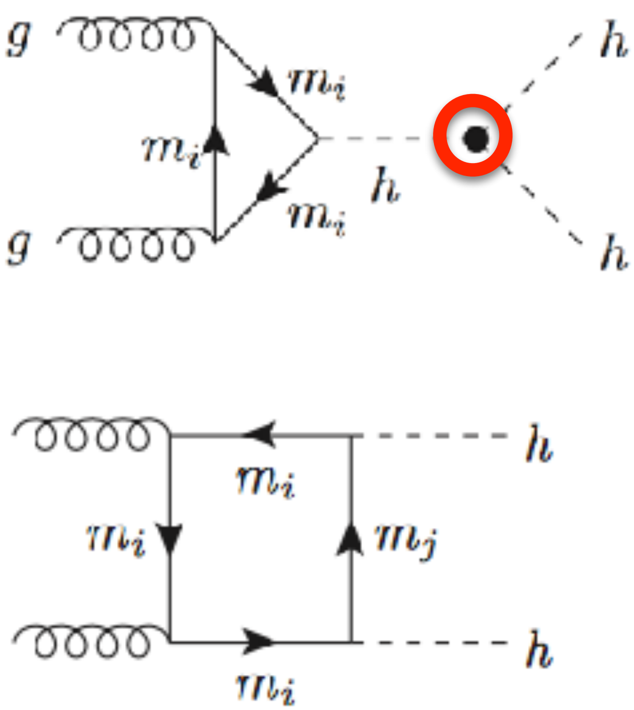


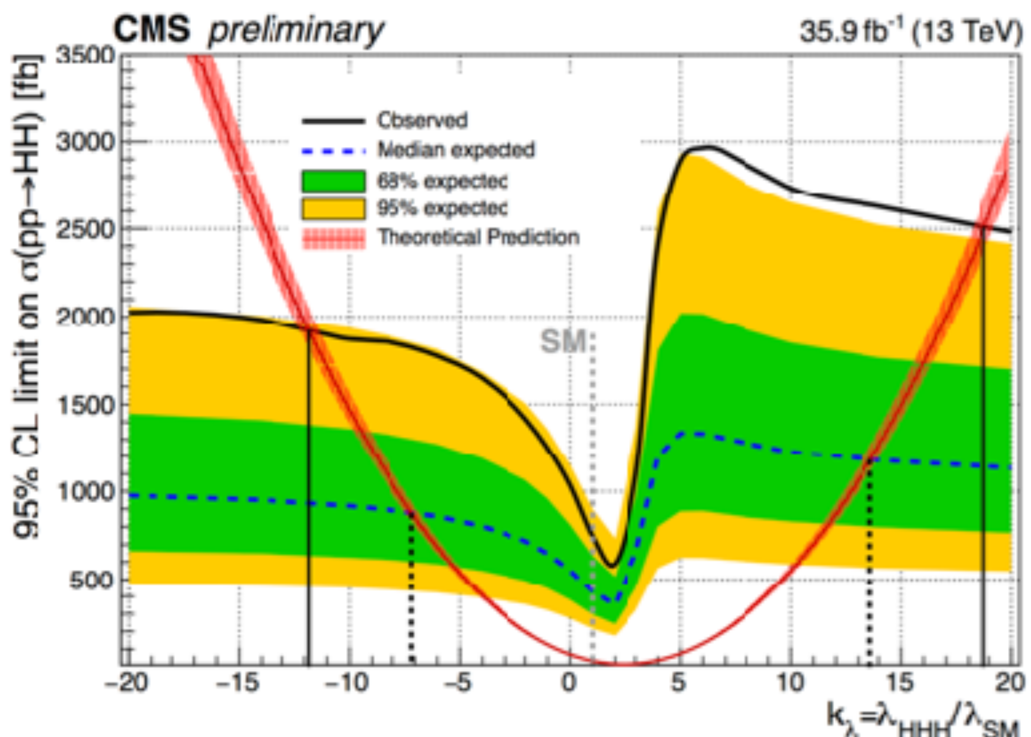
Any deviation from the SM in the Higgs sector is new physics!

Known Unknown

Higgs self coupling is not yet determined

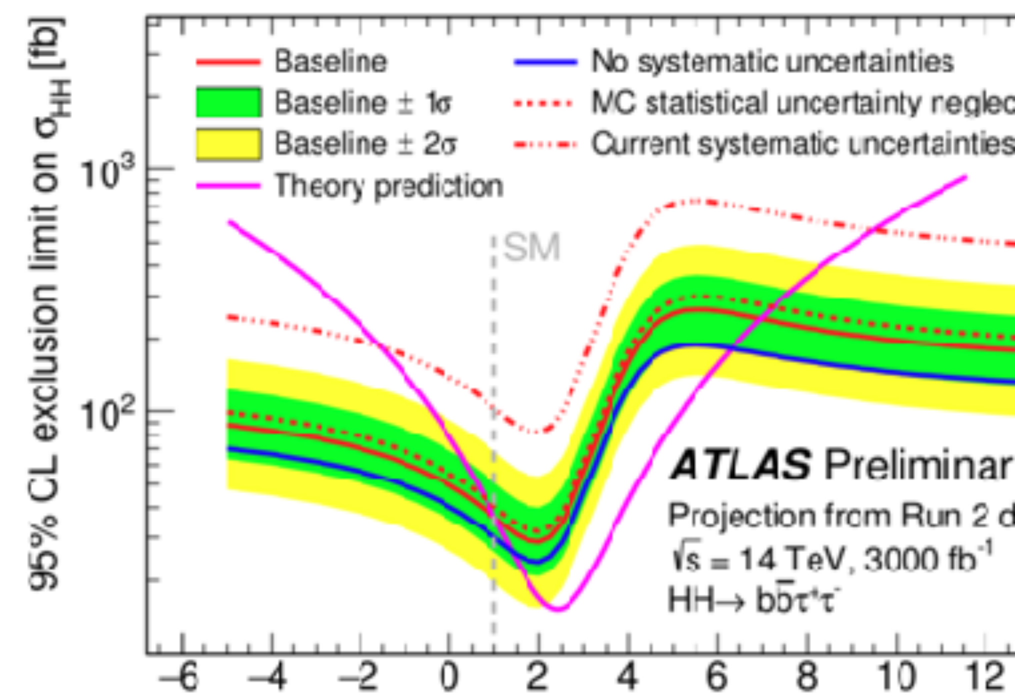
$$\lambda_{HHH}/\lambda_{HHH}^{SM} \sim 1.0^{+0.9}_{-0.8}$$





[CMS-PAS-HIG-17-030]

$$-11.8 < k_\lambda < 18.8$$



ATL-PHYS-PUB-2018-053

$$1.0 < \kappa_\lambda < 7.0$$

Shape of Higgs potential could be different from the SM!

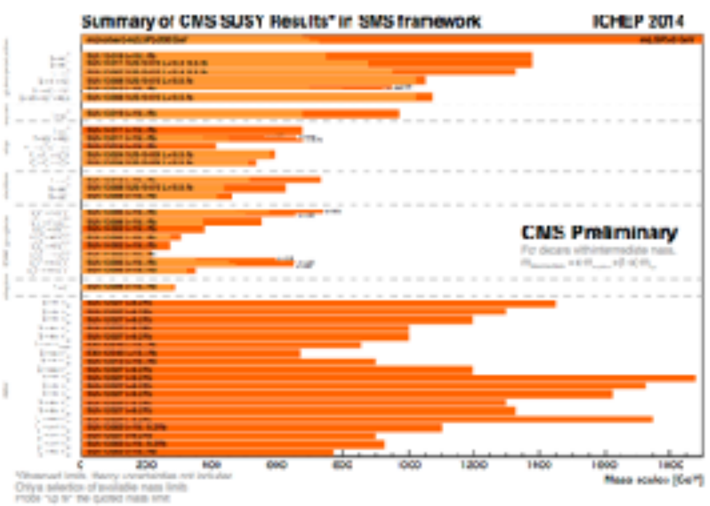
Higgs Portal to New Physics

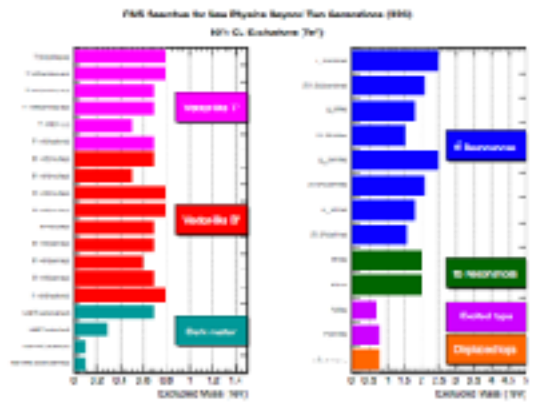
Top-down approach: new physics models

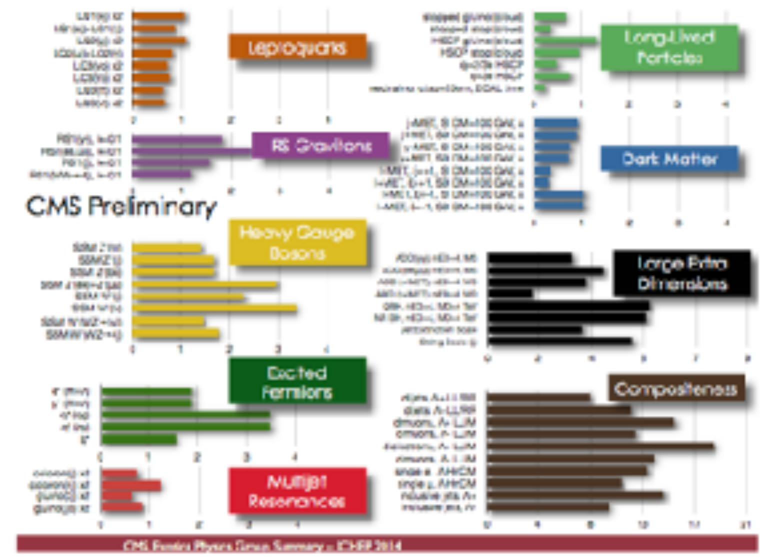
Simplified model

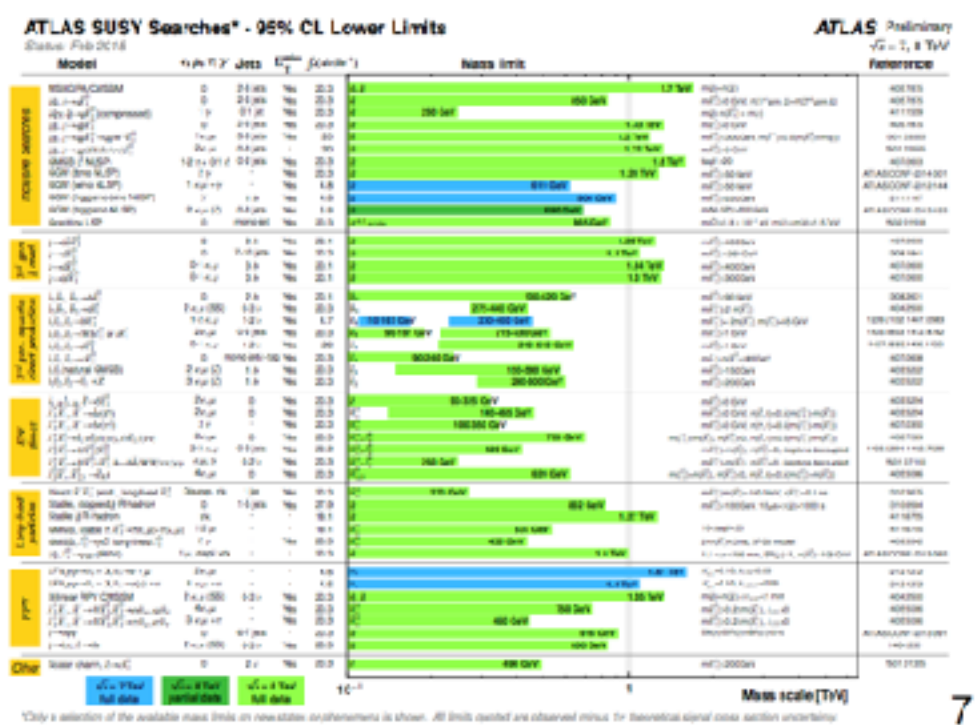
Bottom-up approach: Higgs effective field theory (HEFT)

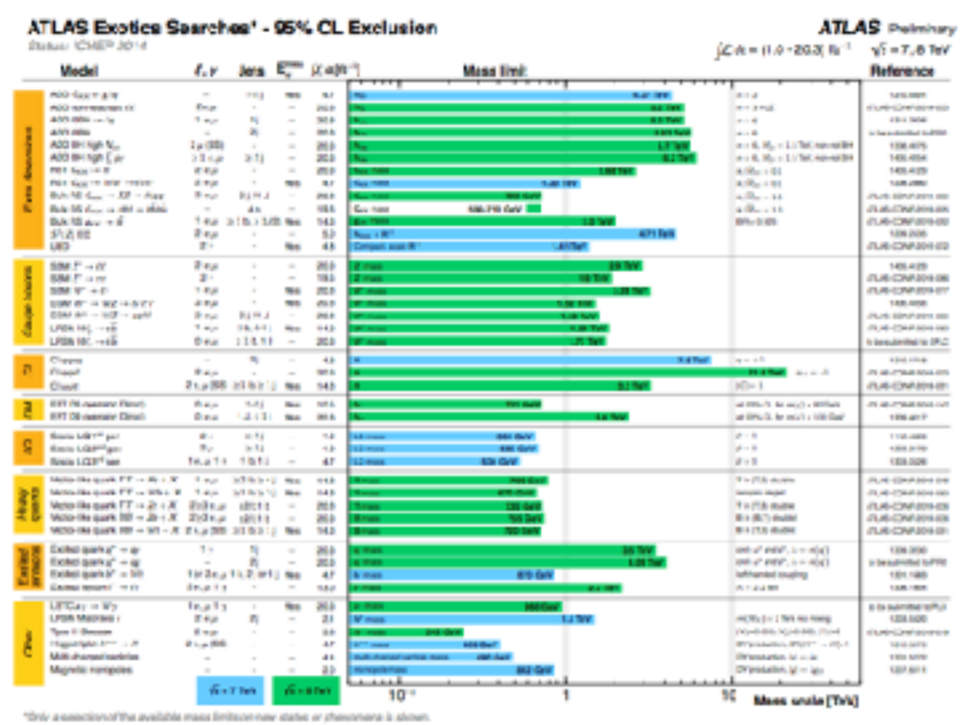
Scale of New Physics











SMEFT Framework

UV model

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

Integrate out TeV heavy states

Dim-6 SMEFT

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

$$Q_6 = (H^\dagger H)^3$$

$$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$

$$Q_{HD} = (D^\mu H)^\dagger H H^\dagger (D_\mu H)$$

$$Q_{eH} = (H^\dagger H)(\bar{L} e_R H)$$

$$Q_{uH} = (H^\dagger H)(\bar{Q} u_R \tilde{H})$$

$$Q_{dH} = (H^\dagger H)(\bar{Q} d_R H)$$

$$\frac{\alpha_s}{4\pi}\frac{c_g}{\Lambda^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

$$\frac{\alpha'}{4\pi}\frac{c_\gamma}{\Lambda^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

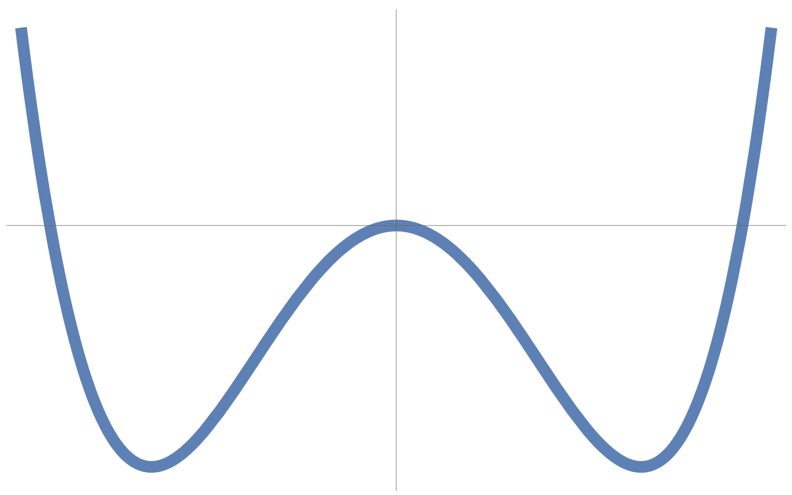
Electroweak symmetry breaking

Higgs EFT

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

Fundamental Higgs

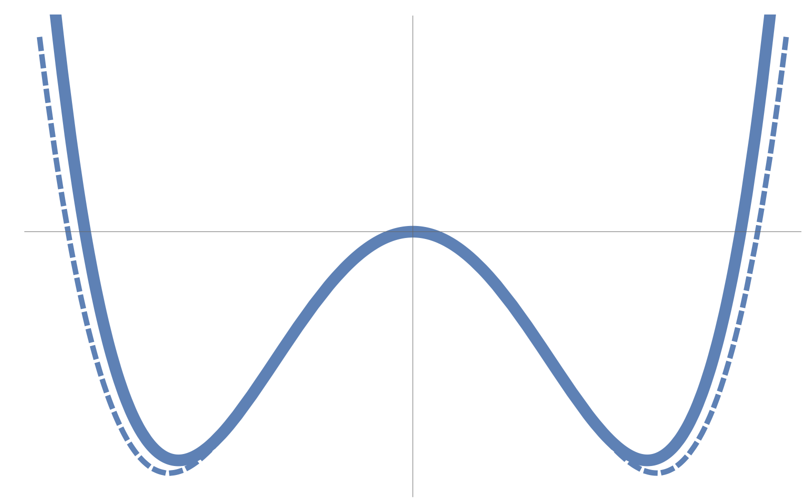
Higgs potential in SM



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

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

Higgs potential in SMEFT



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

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

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

UV Models

Scalar Extension

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

Fermion Extension

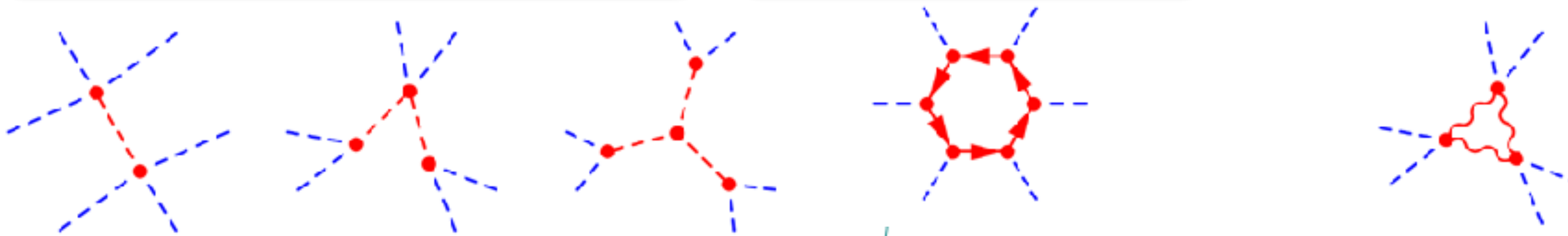
- Type-I seesaw
- Vectorlike fermion
- Heavy 4th gen.
- Vectorlike top
- Singlet-doublet dark matter
- …

Gauge Extension

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

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

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

Fundamental Higgs

Scalar singlet | 2HDM | Triplet/Seesaw | Quadruplet

Integrate out heavy scalars

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

Theory:	c_6	$c_{H\Box}$	c_{HD}	c_{eH}	c_{uH}	c_{dH}
$\mathbb{R}$ 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 $(Y=3/2)$	$\frac{\lvert\lambda_{H3\Phi}\rvert^2}{M^2}$	-	$\frac{6\lvert\lambda_{H3\Phi}\rvert^2 v^2}{2M^4}$	-	-	-

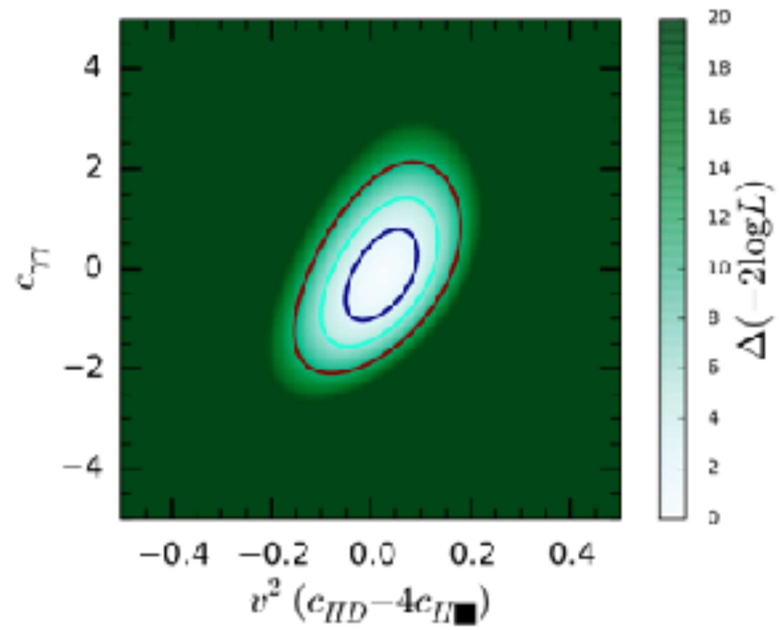
$g_{HS}H^\dagger HS$

$gH^T H\Delta$

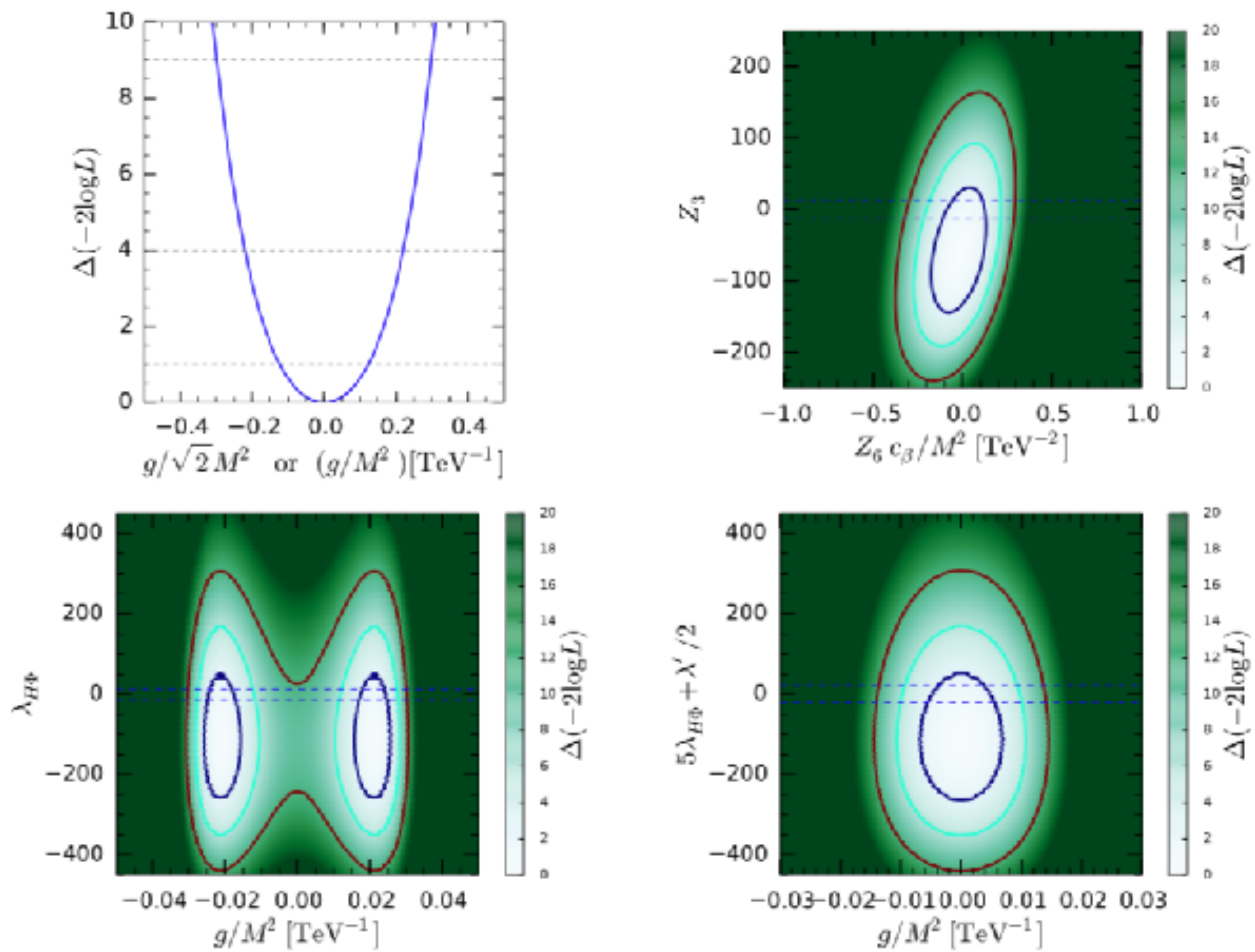
Di-Higgs EWPT and Single Higgs data

EWPT and Higgs Data

Constraints on EFT operators

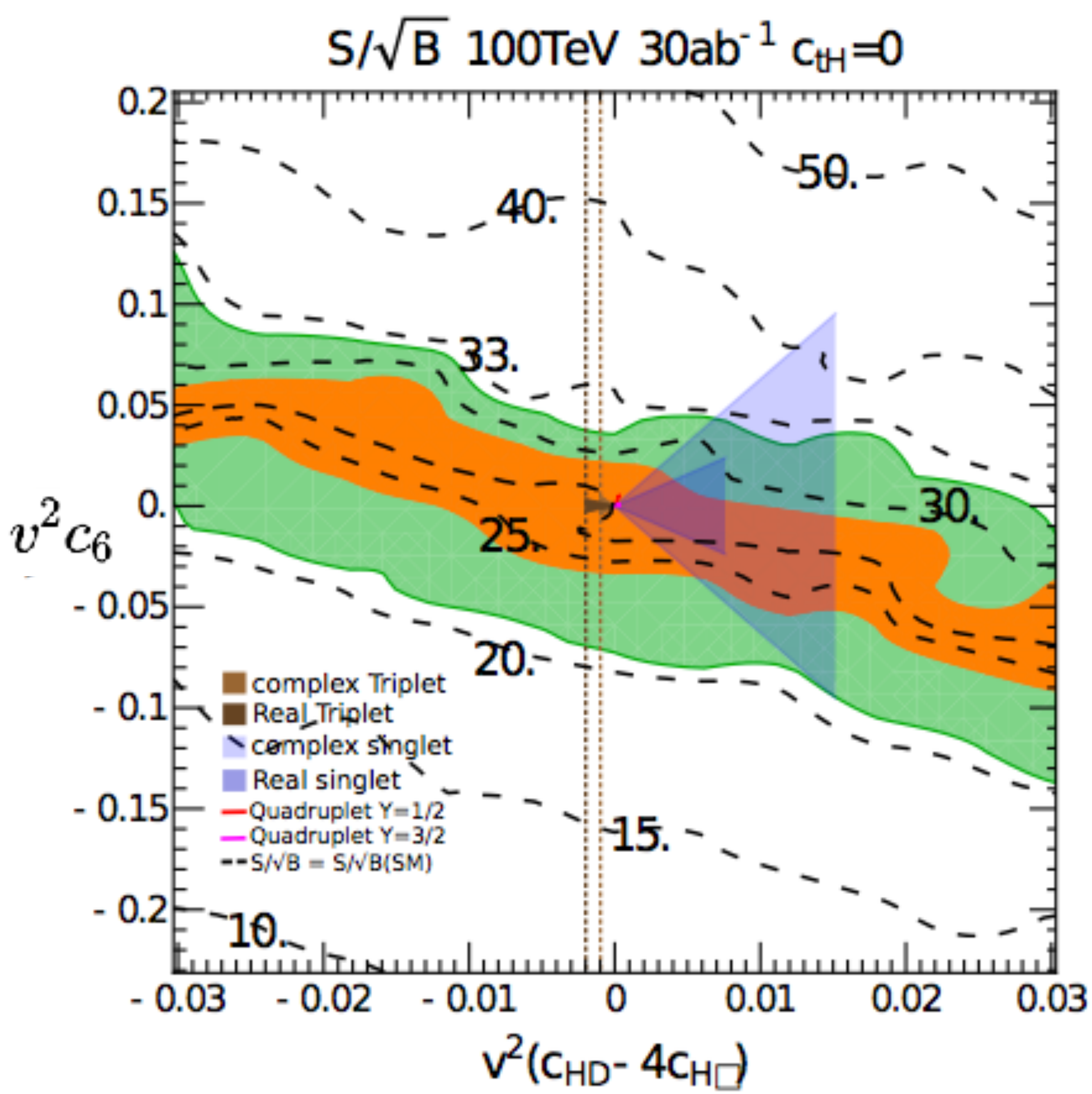


Model Parameters

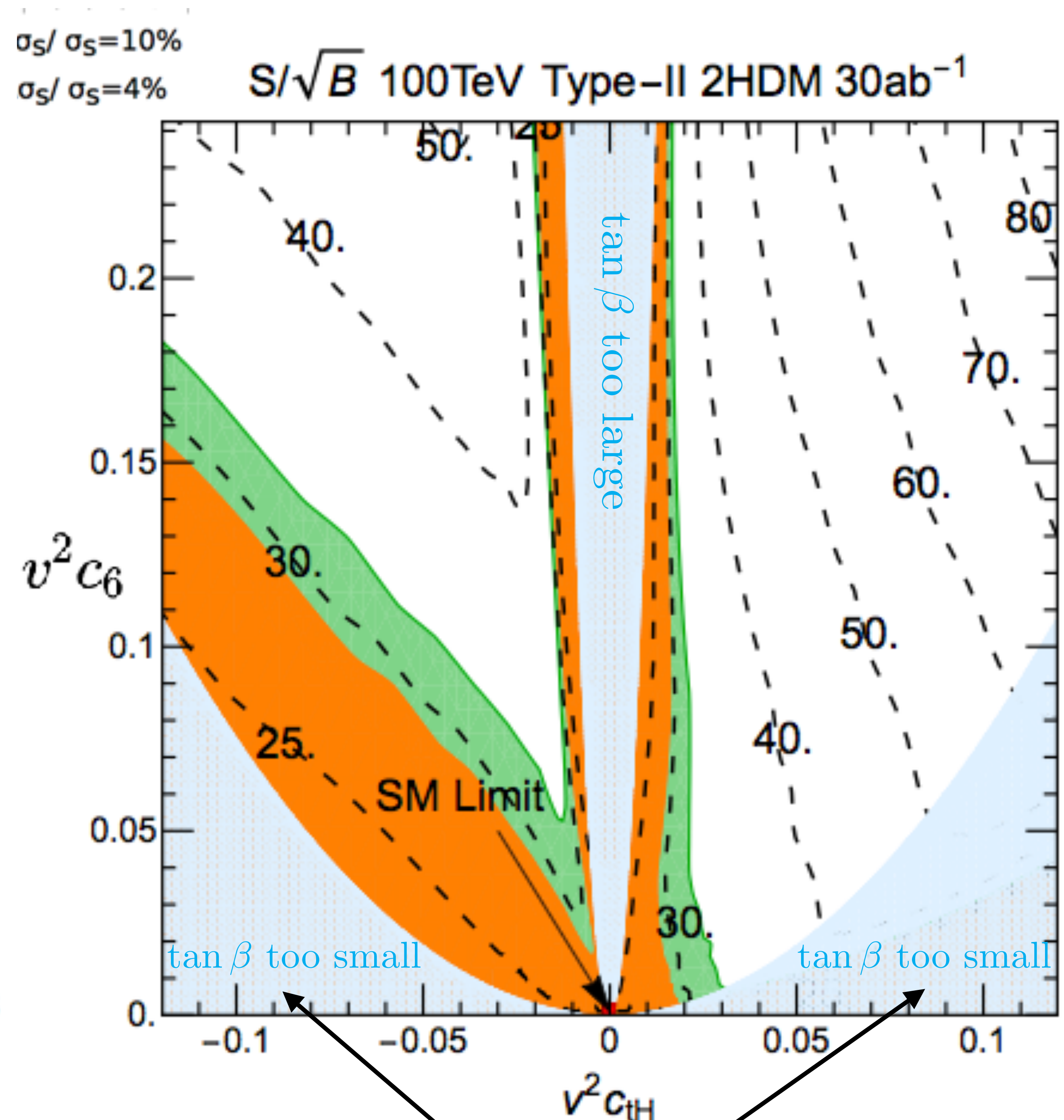


Fundamental Higgs

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



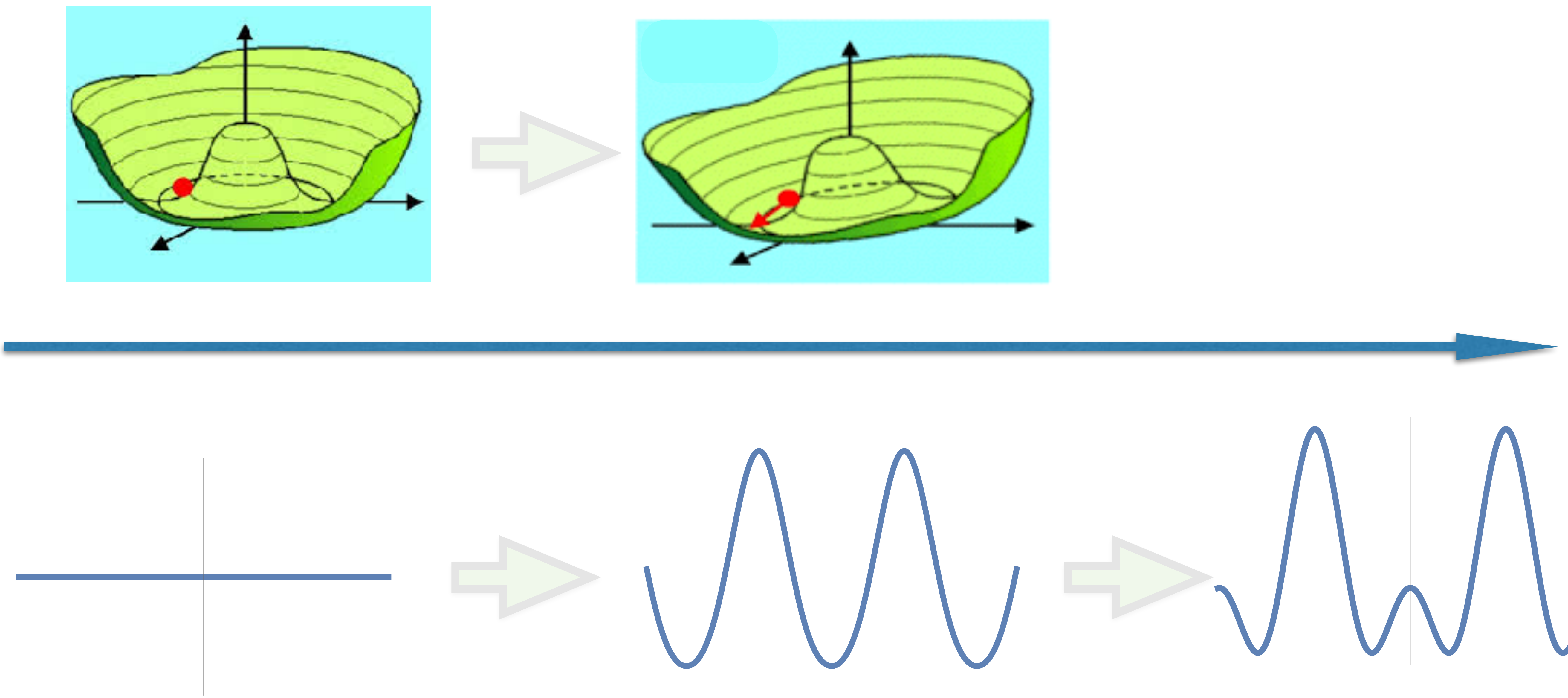
[Corbett, Joglekar, Li, **Yu, 2018**]



Excluded by flavor physics

Pseudo-Goldstone Higgs

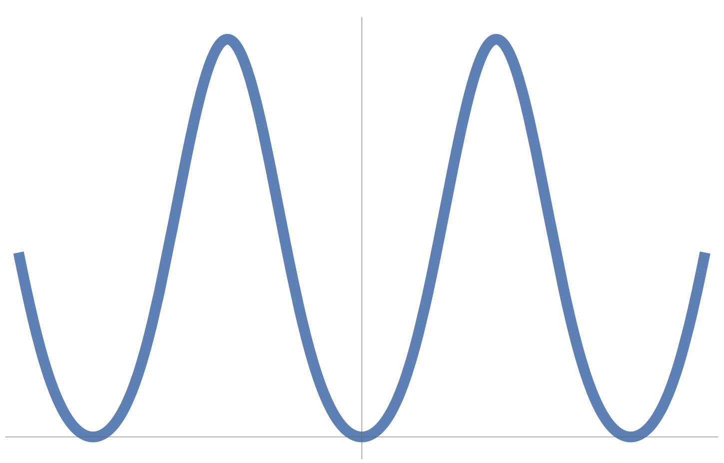
Higgs boson as pseudo-Nambu Goldstone boson

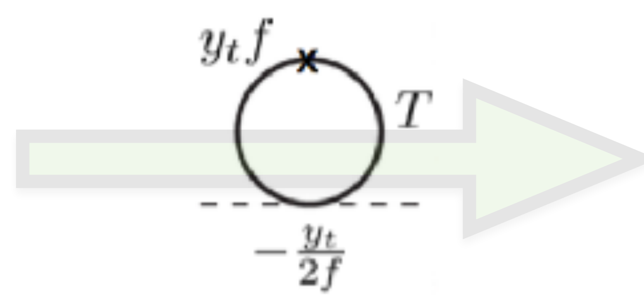


EW Symmetry Breaking!

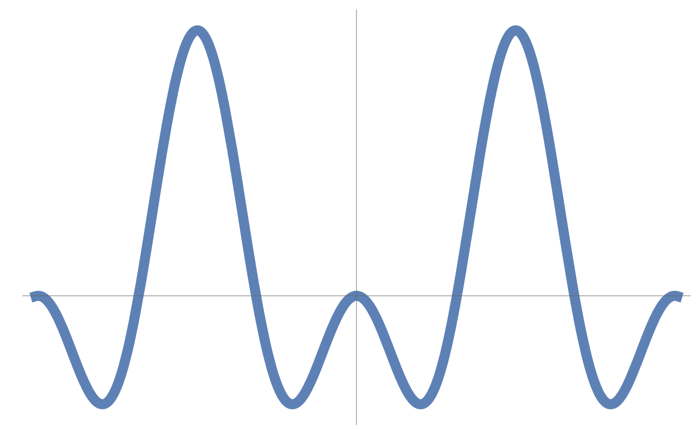
Incorporate the fermion sector

Higgs potential with only boson sector





EW symmetry breaking

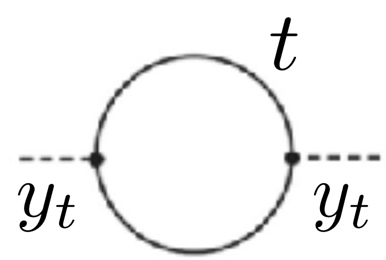


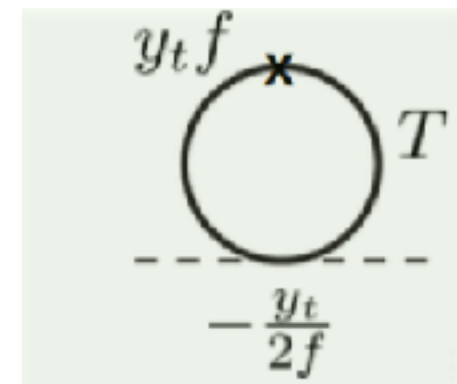
$$V(\phi) = -a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

The top partner triggers EWSB!

Top Partner

The top partner also protects the Higgs mass

$-(100\ \text{GeV})^2 =$  $+$ 

$+$ 

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

Solving hierarchy problem and realize EWSB

Usually need to introduce symmetry in fermion sector

PNGB Higgs Models

G/H cosets are universal, but fermion embedding quite different!

Little Higgs (2000) | Composite Higgs (2004) | Neutral Naturalness (2015)

[Craig, Knapen, Longhi 2015]

fundamental top partner | partial composite top partner | Colorless top partner

Littlest Higgs

[Arkani-hamed, et.al. 2000]

Minimal Composite Higgs

[Agashe, Contino, Pomarol 2004]

Collective symmetry breaking

[Foadi, Schmidt, **Yu, 2010**]

LR Z2 Higgs

[Chacko, Goh, Harnik 2006]

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

LR symmetry

[Chacko, Goh, Harnik 2006]

Mirror Twin Higgs

[Yu, **2016]**

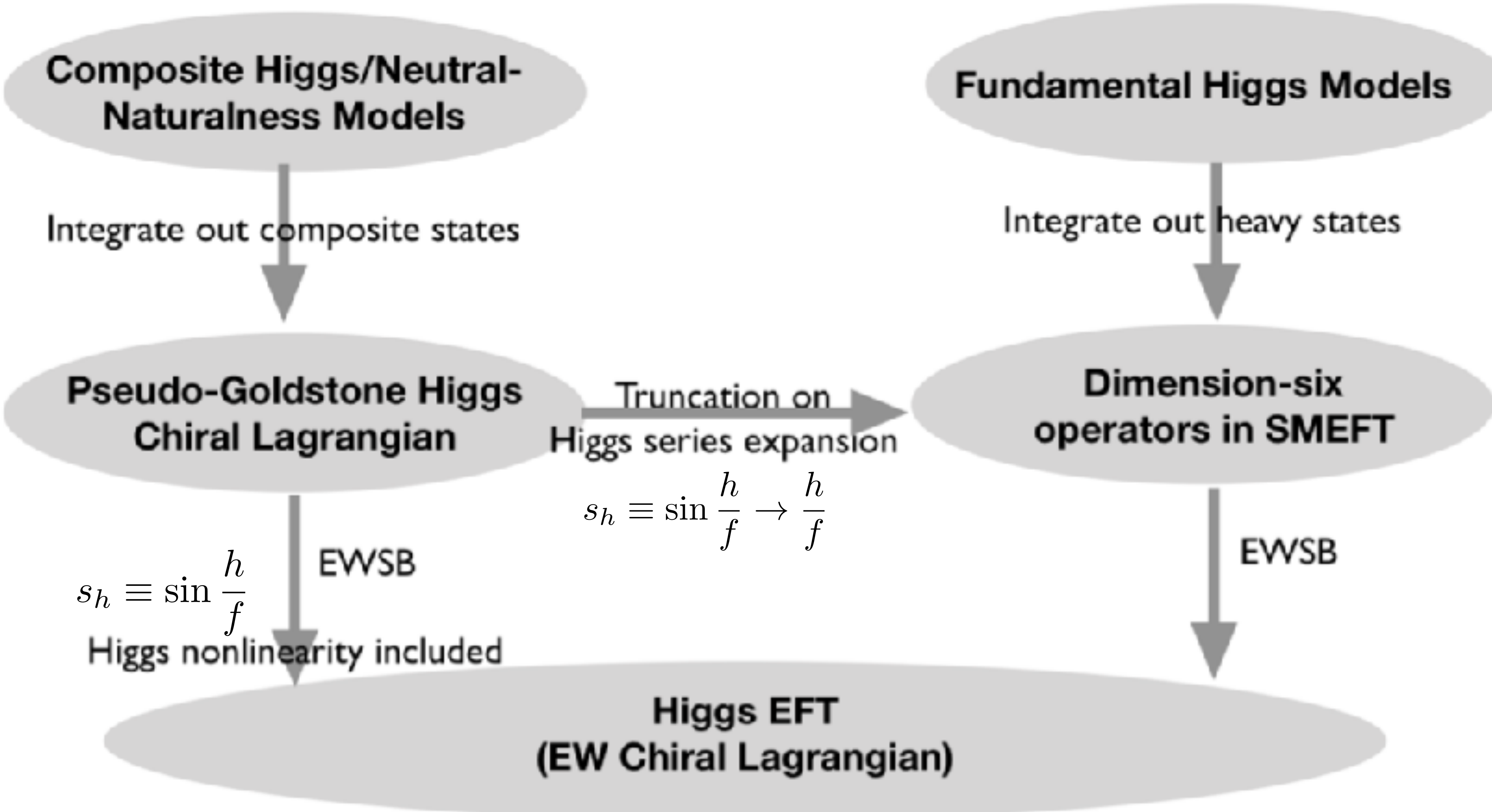
Minimal neutral naturalness

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

Z2/SU(6) symmetry

PNGB Chiral Lagrangian

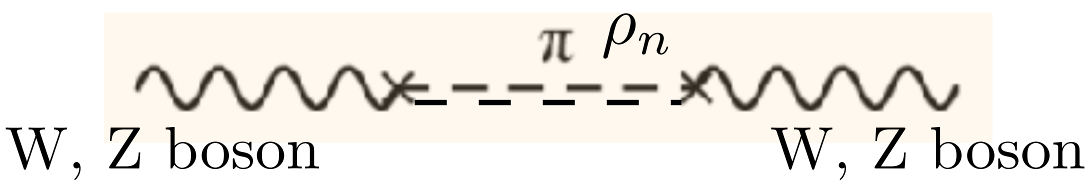
Higgs nonlinearity effect is not included in SMEFT

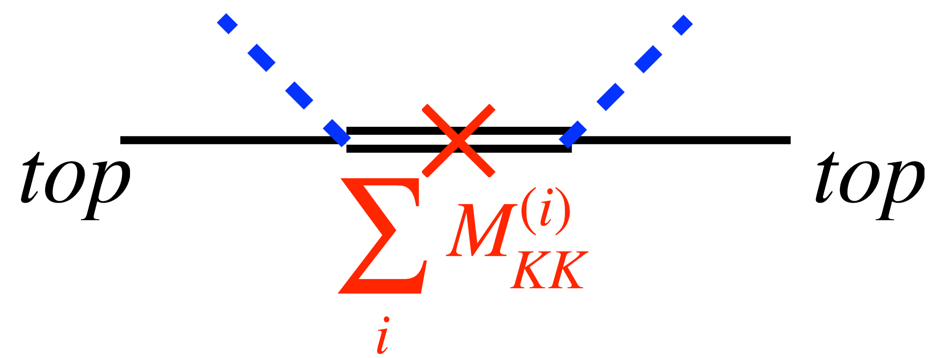


EFT Description

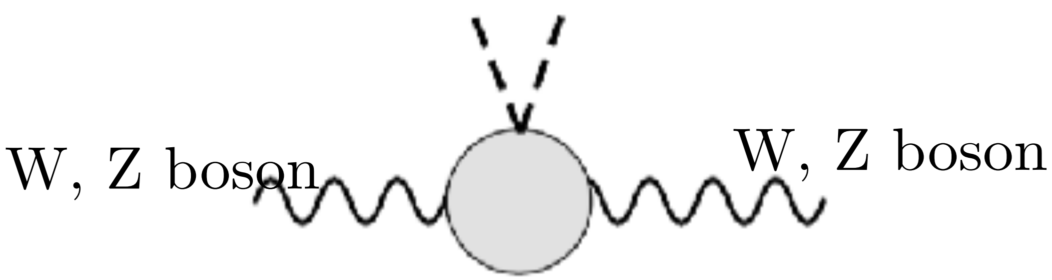
Composite Higgs | Left-Right Z2 | Twin Higgs | Minimal NN

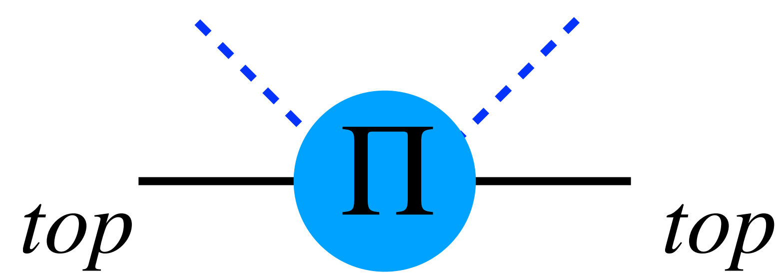
[Li, Xu, **Yu**, Zhu, **2019**]





Heavy composite states





Generalized Lagrangian

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

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

Low Energy Theorem

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

Top Higgs couplings

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

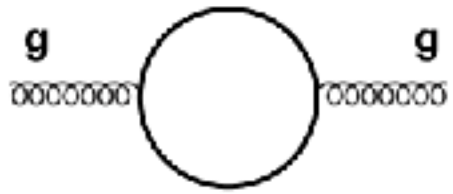
$$c_t = v \frac{\partial}{\partial \langle h \rangle} \log \Pi_{t_L t_R}(0)$$

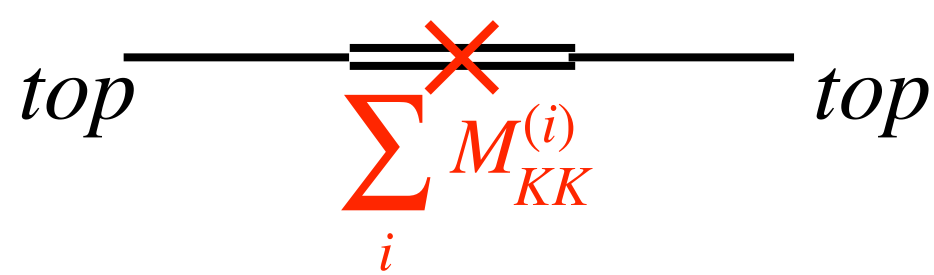
$$c_{tthh} = \frac{v^2}{2} \frac{1}{m_t} \frac{\partial^2 \Pi_{t_L t_R}(0)}{\partial \langle h \rangle^2}$$

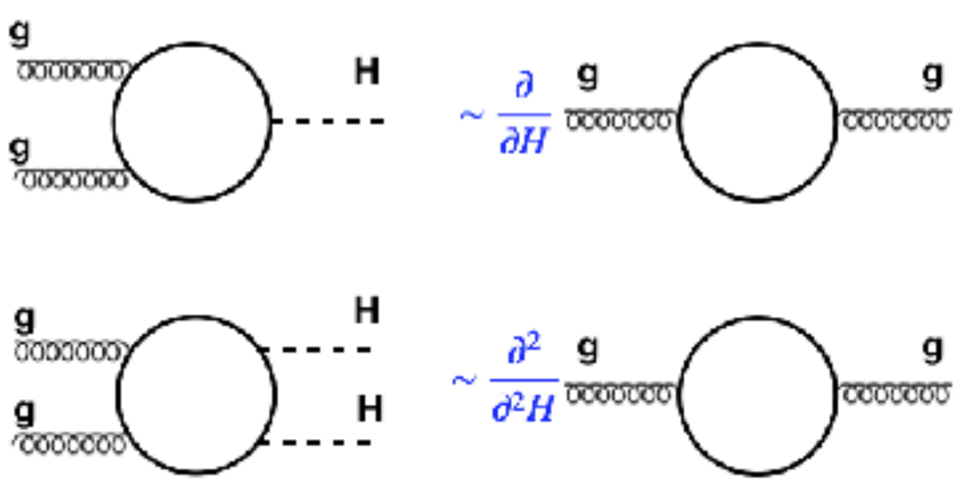
Top quark couplings to gluon gluon

$$\mathcal{L}^{(g)}_{eff} = \frac{\alpha_s}{24\pi} G^a_{\mu\nu} G^{a\mu\nu} \sum_i \log m_i^2(h)$$

$$\mathcal{L}^{(g)}_{eff} \equiv \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\mu\nu} \left(c_g \frac{h}{v} + \frac{1}{2} c_{gghh} \frac{h^2}{v^2} + \cdots \right)$$







$$c_g = v \frac{\partial}{\partial \langle h \rangle} \left[\frac{1}{2} \log \Pi_{t_L t_R}(0) \right]$$

$$c_{gghh} = -v^2 \frac{\partial^2}{\partial \langle h \rangle^2} \left[\frac{1}{2} \log \Pi_{t_L t_R}(0) \right]$$

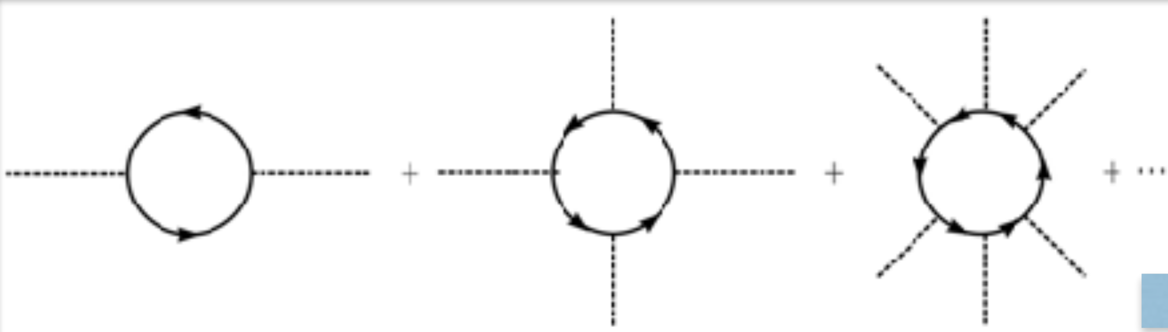
Radiative Higgs Potential!

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

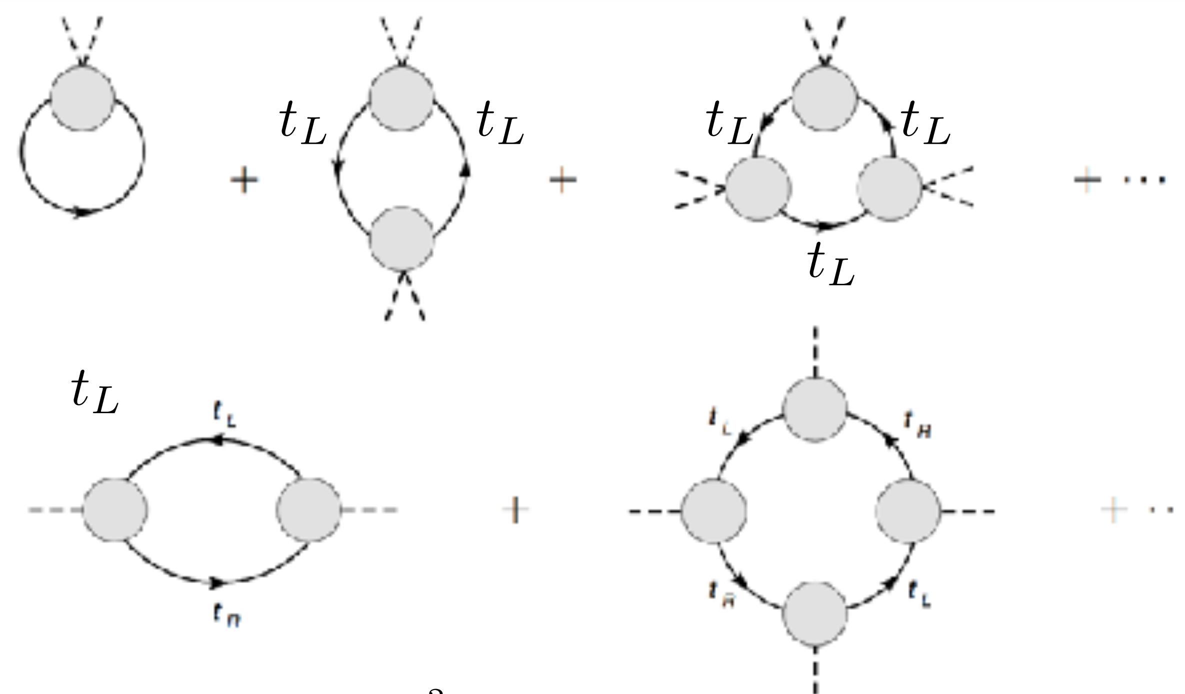
$$\Pi_{t_L}(-Q^2) = \Pi_{0t_L}(-Q^2) + \Pi_{1t_L}(-Q^2)\, s_h^2 + \Pi_{2t_L}(-Q^2)\, s_h^4 + \cdots$$

Coleman-Weinberg effective potential

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



$$V_1 = -2\lambda \frac{1}{2} Tr \int \frac{d^4p}{(2\pi)^4} \log\left[p^2 + M_f^2(\phi_c)\right]$$



$$V(h) = -\frac{2N_c}{16\pi^2} \int_0^{\Lambda^2} dQ^2 Q^2 \log[\Pi_{t_L}\Pi_{t_R} \cdot Q^2 + \Pi^2_{t_L t_R}]$$
$$= -\gamma_f s_h^2 + \beta_f s_h^4 + \cdots$$

Cutoff dependence

Complete Higgs Couplings

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

Obtain form factors

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

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

Low energy theorem

$$c_g = v \frac{\partial}{\partial \langle h \rangle}\left[\frac{1}{2}\log \Pi_{t_L t_R}(0)\right]$$

$$c_{gghh} = -v^2 \frac{\partial^2}{\partial \langle h \rangle^2}\left[\frac{1}{2}\log \Pi_{t_L t_R}(0)\right]$$

$$c_t = v \frac{\partial}{\partial \langle h \rangle}\log \Pi_{t_L t_R}(0)$$

$$c_{tthh} = \frac{v^2}{2}\frac{1}{m_t}\frac{\partial^2 \Pi_{t_L t_R}(0)}{\partial \langle h \rangle^2}$$

Radiative Higgs potential

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

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

$$c_{3h} = \frac{-\frac{1}{6}\frac{\partial^3 V(\langle h \rangle)}{\partial \langle h \rangle^3}}{-\frac{m_h^2}{2v}}$$

$$c_{4h} = \frac{-\frac{1}{24}\frac{\partial^4 V(\langle h \rangle)}{\partial \langle h \rangle^4}}{-\frac{m_h^2}{8v^2}}$$

EW Chiral Lagrangian

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

$\mathrm{MCHM}_{5+5,10+10,14+14}$ 5+1

MCHM_{14+14}

$\mathrm{CTHM}_{8+1,8+28,8+35}$

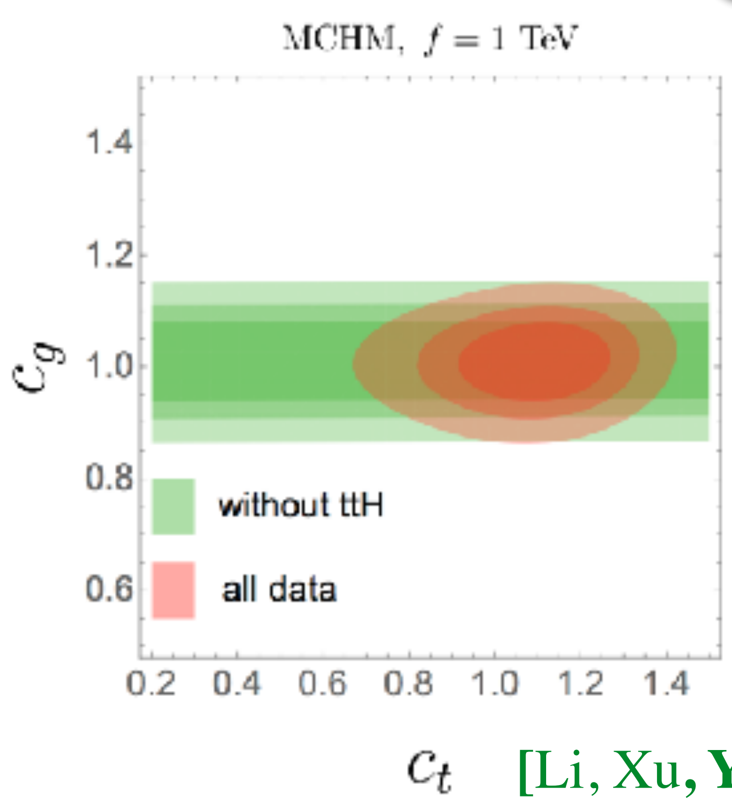
CTHM_{8+35}

EW Chiral Lagrangian

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

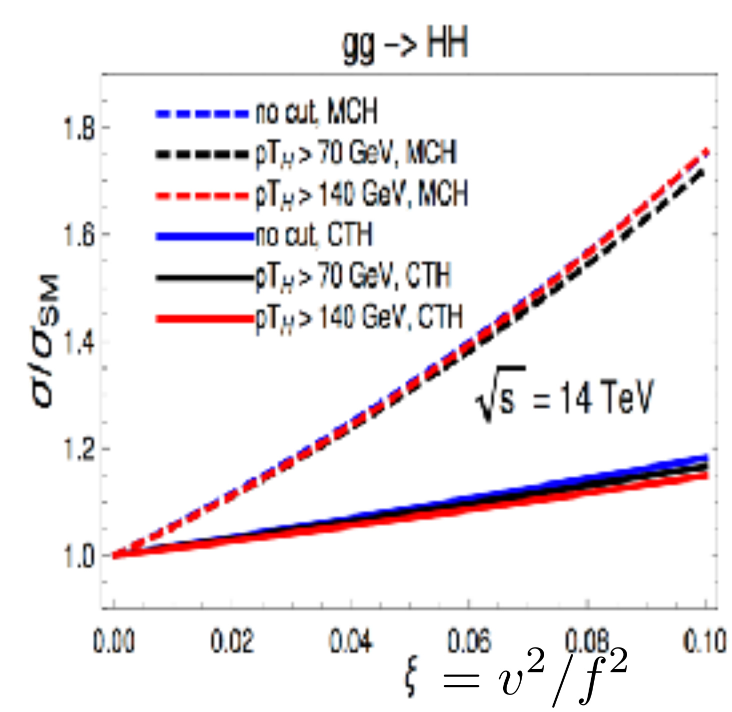
Higgs effective couplings

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



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

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



Fundamental vs Composite?

PNGB Higgs EFT

SMEFT

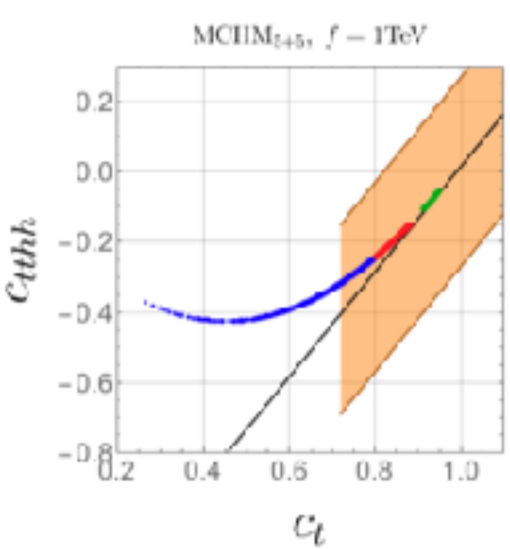
[Agrawal, Saha, Xu, **Yu**, Yuan, **2019**]

EW Chiral Lagrangian

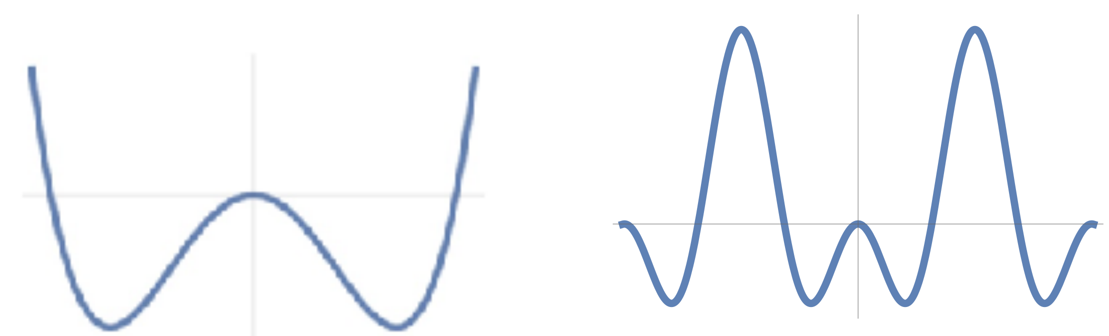
$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left[(\partial_\mu U)^\dagger \partial^\mu U\right]\left(1 - 2a\frac{h}{v} - b\frac{h^2}{v^2} + \cdots\right) - \frac{v}{\sqrt{2}}\left(\bar{t}_L, \bar{b}_L\right)U\left(1 + c_1\frac{h}{v} + c_2\frac{h^2}{v^2} + \cdots\right)\begin{pmatrix}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

Higgs effective couplings

Higgs nonlinearity



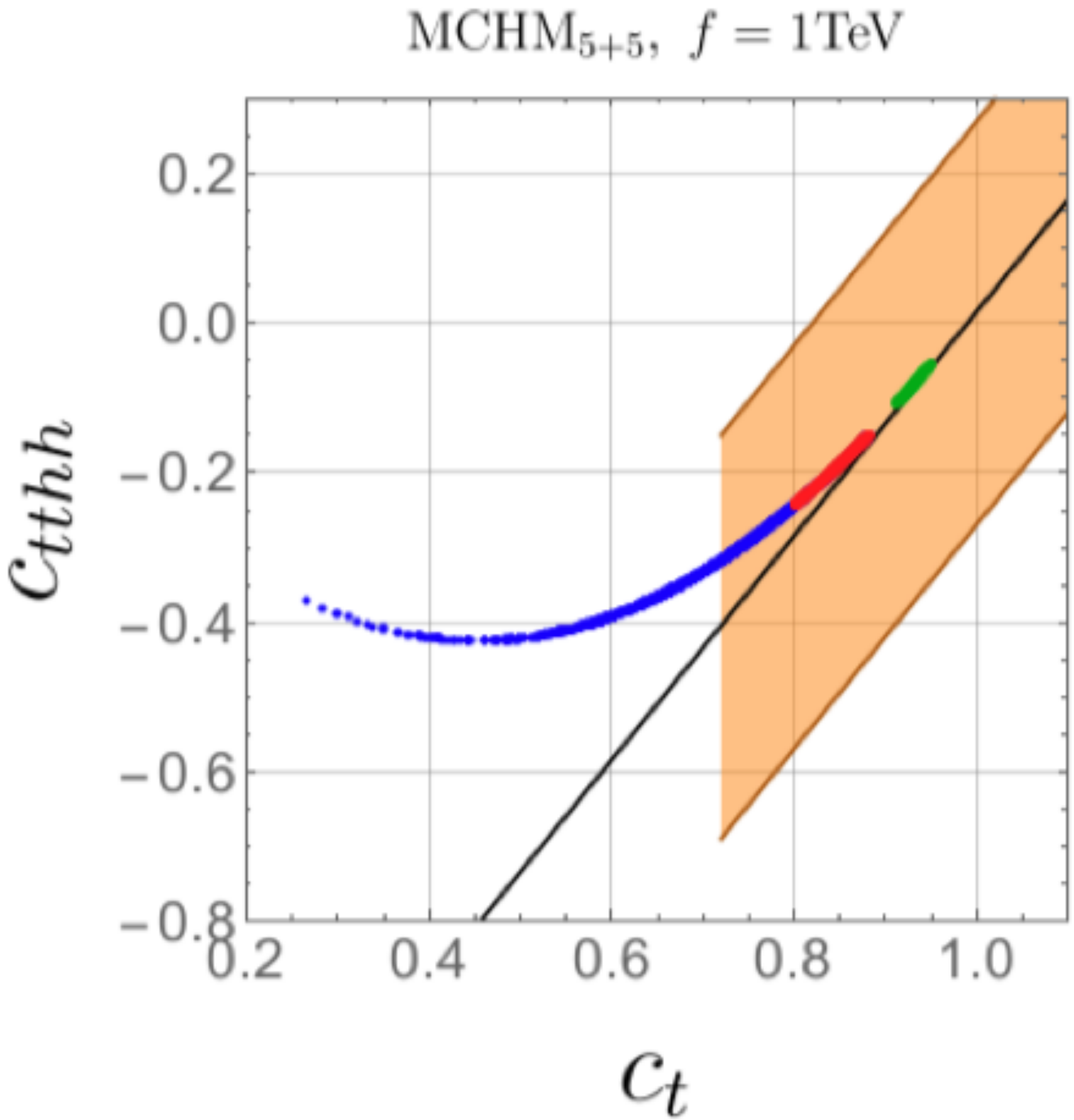
Shape of Higgs potential



Pseudo-Goldstone Higgs

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

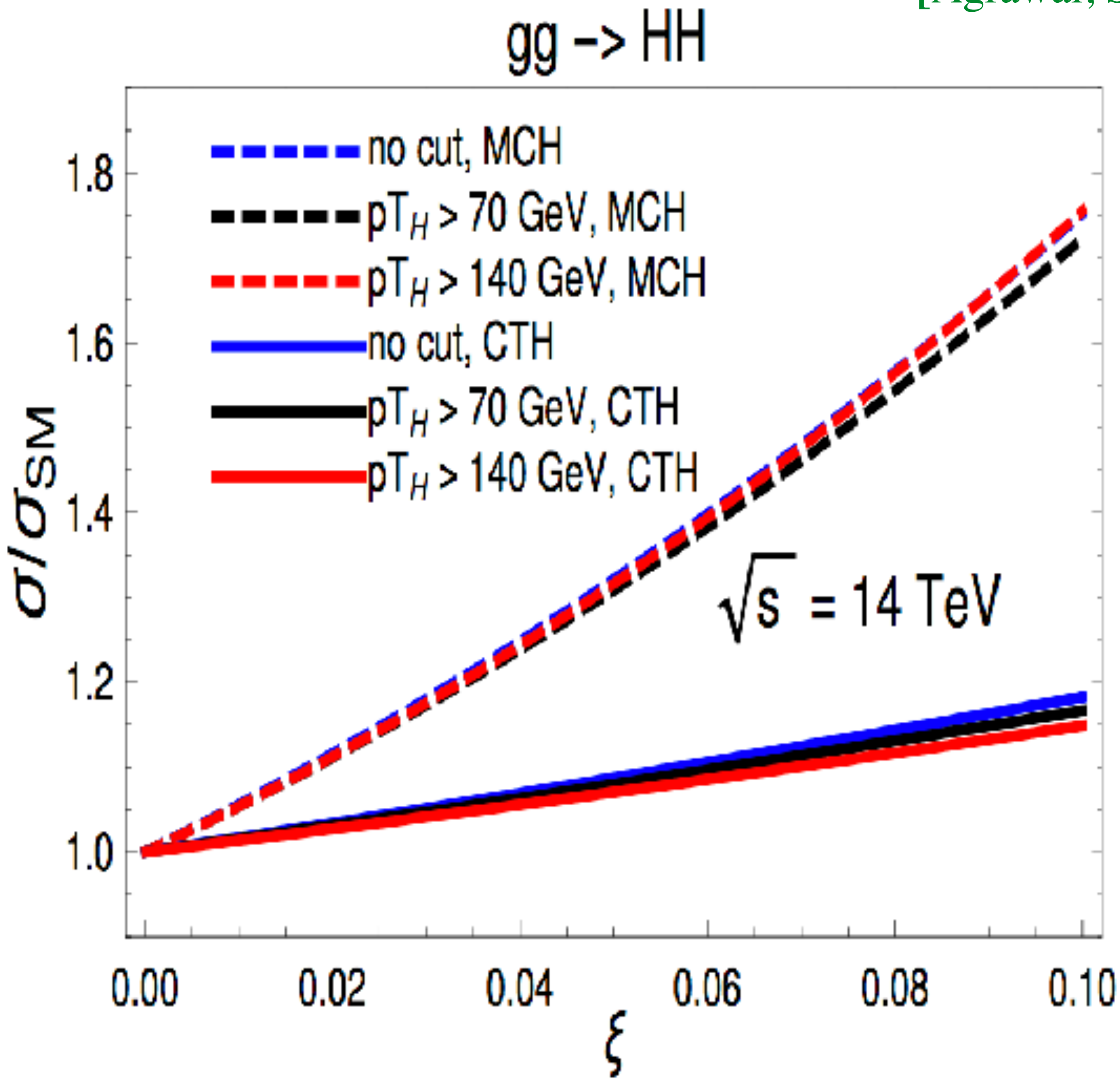
[Li, Xu, **Yu**, Zhu, **2019**]



Pseudo-Goldstone Higgs

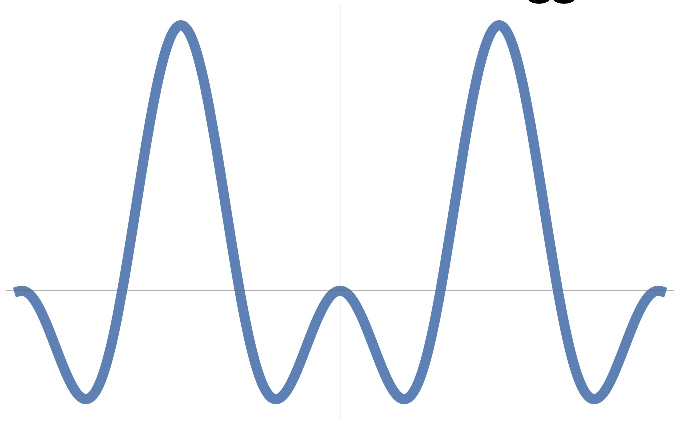
Similar to 2HDM, di-Higgs cross section is larger than SM one

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



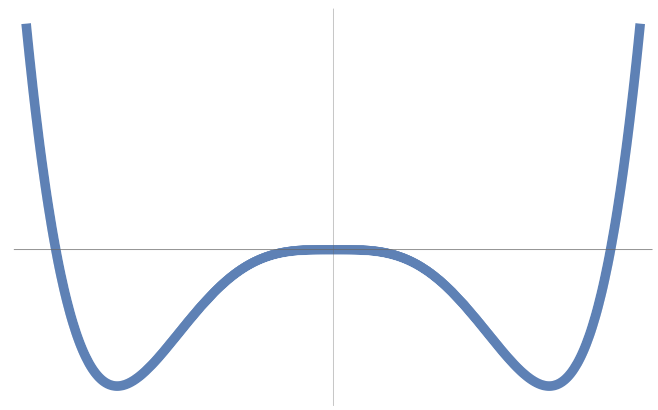
Shape of Higgs Potential

Pseudo-Goldstone Higgs



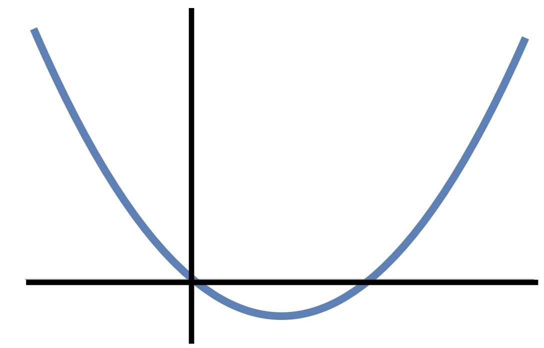
$$V(\phi) = -a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

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 from SM

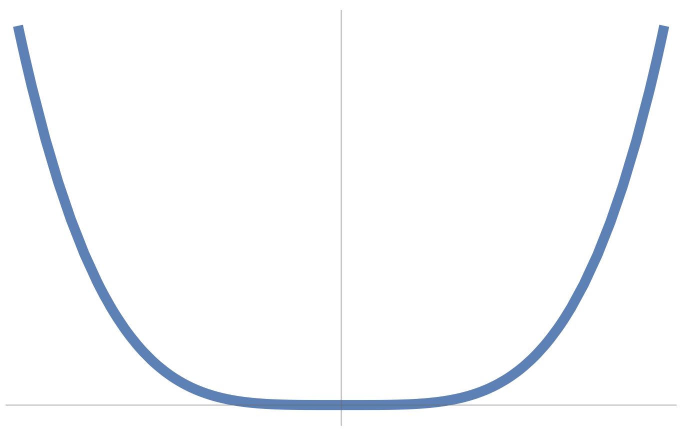
Landau-Ginzburg Higgs

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

Coleman Weinberg Higgs

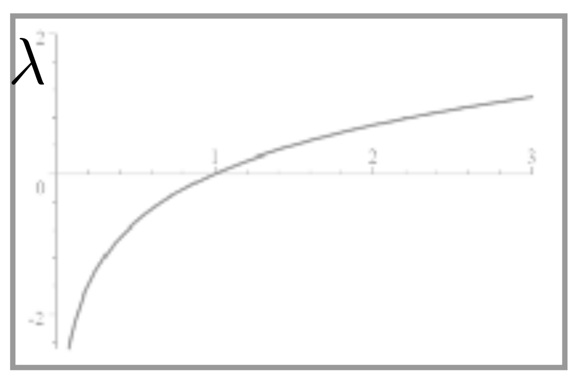
Classically scale invariant theory

Tree-level potential



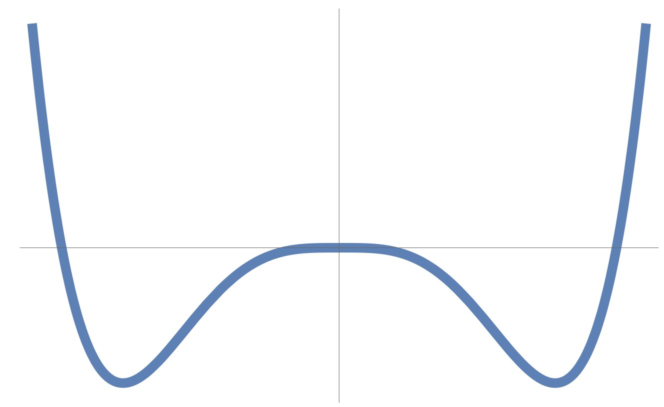
$$V(\phi) = \lambda(\phi^\dagger \phi)^2$$

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



Self-coupling runs to negative

Coleman Weinberg Higgs



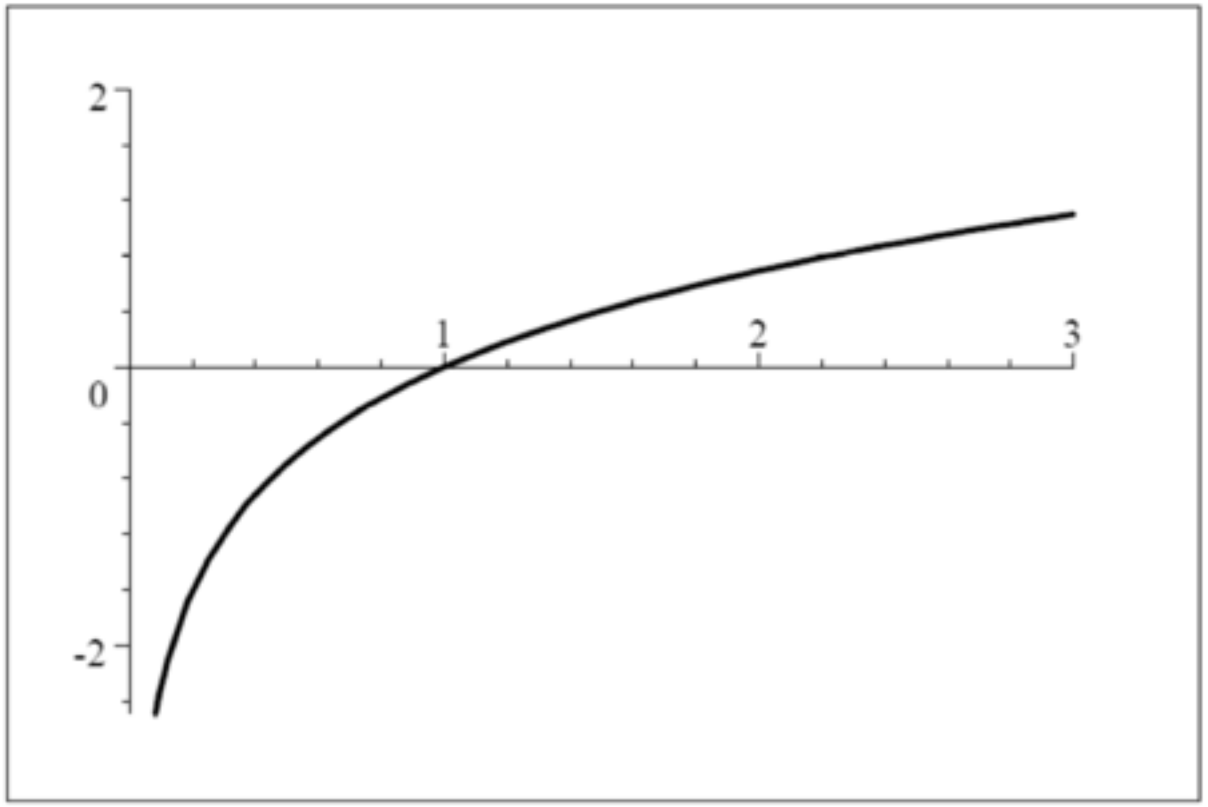
$$V(\phi) = \lambda(\phi^\dagger \phi)^2 + \epsilon(\phi^\dagger \phi)^2 \log \frac{\phi^\dagger \phi}{\mu^2}$$

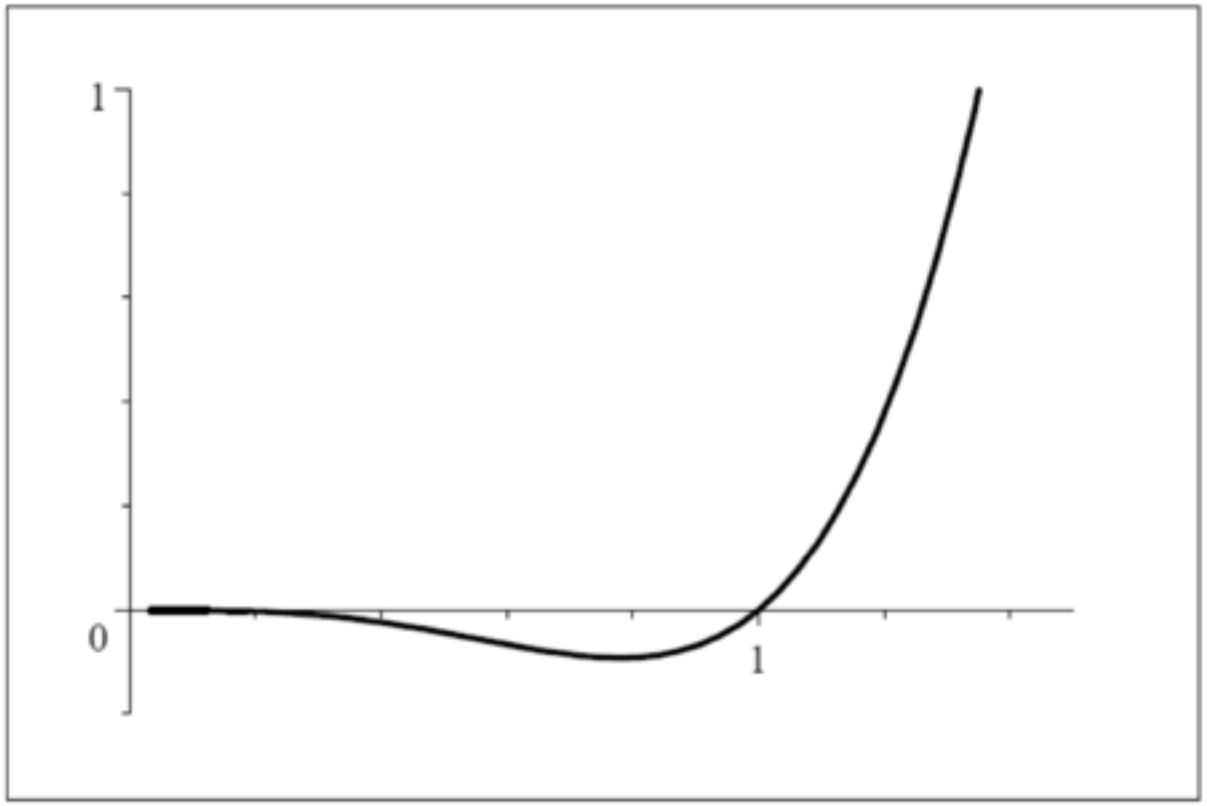
Radiative correction triggers EWSB!

Coleman Weinberg Higgs

Dimensional transmutation:

Running quartic coupling induces minimum.





$$\lambda(\mu) \approx \beta \ln(\mu/M)$$

$$V(h) \equiv \frac{\hat{\lambda}}{4} h^4 = \beta_\lambda \ln \frac{\mu}{M} h^4$$

$$\frac{v_0}{M'} \propto \exp\left(-\frac{\lambda(M')}{\beta}\right)$$

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

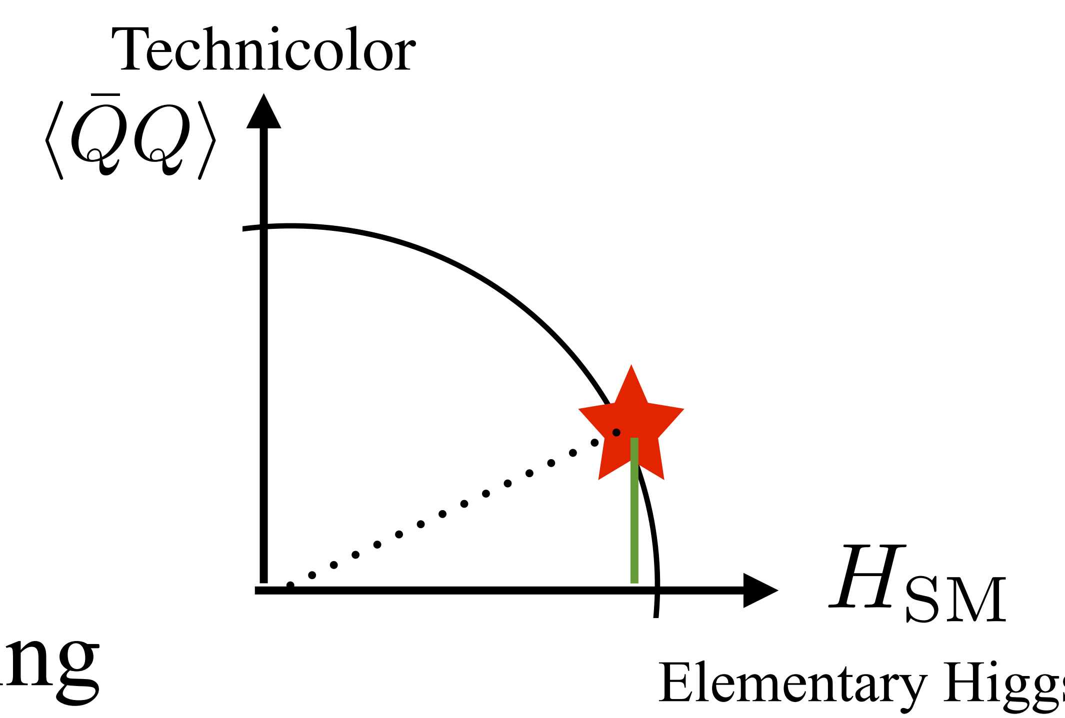
Tadpole Induced Higgs

Technicolor vs Higgs discovery

Predict no Higgs …

Long-live technicolor: Bosonic technicolor

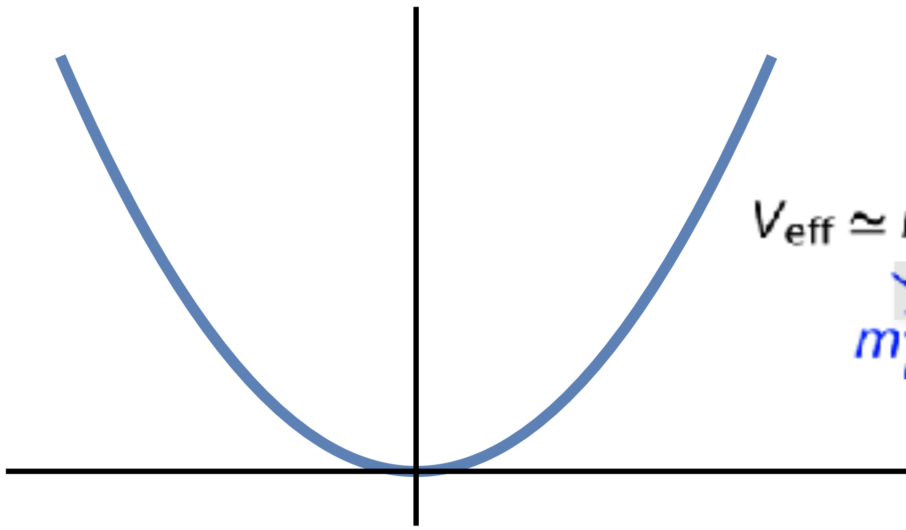
[Simmons 1989],
[Carone, Georgi 1994] ,
[Galloway, etc, 2013]
…



Violate unitary in W_L-W_L scattering

Tadpole Induced Higgs

Bosonic technicolor (Induced EWSB)

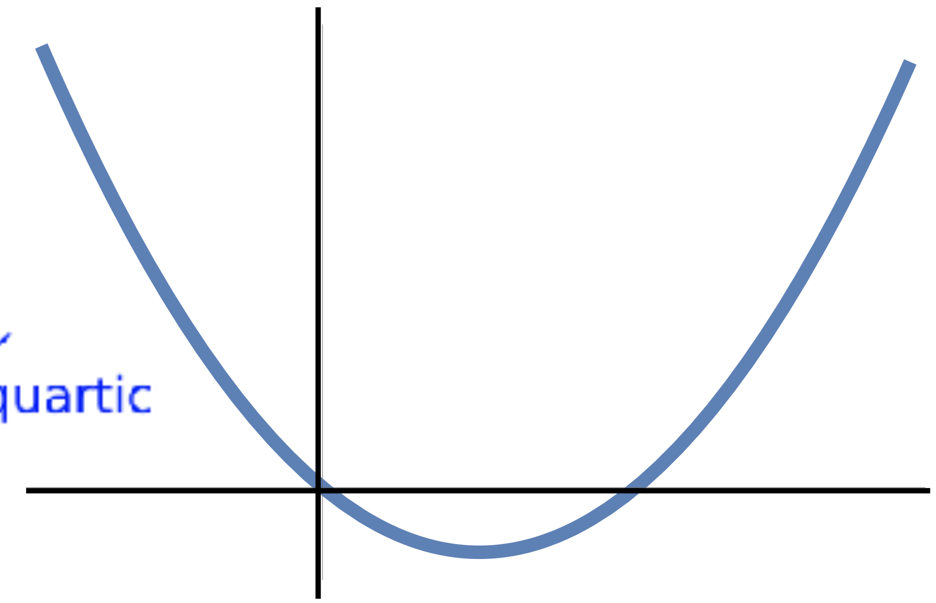


[Galloway, etc, 2013]

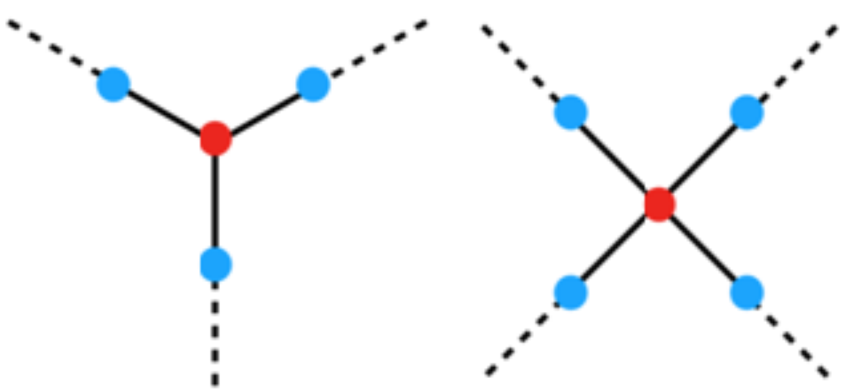
$$V_{\rm eff} \simeq \underbrace{m_H^2}_{m_H^2>0} H^\dagger H + \epsilon(\Sigma^\dagger H + \text{h.c.}) + \underbrace{\cdots}_{\text{neglect quartic}}$$

$\varepsilon < 0$

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



Higgs self couplings are induced by integrating out heavy states



$$\lambda_3 \sim \lambda_4 \sim 0$$

How to Distinguish Them?

SMEFT | PNGB Higgs | CW Higgs | Tadpole Higgs

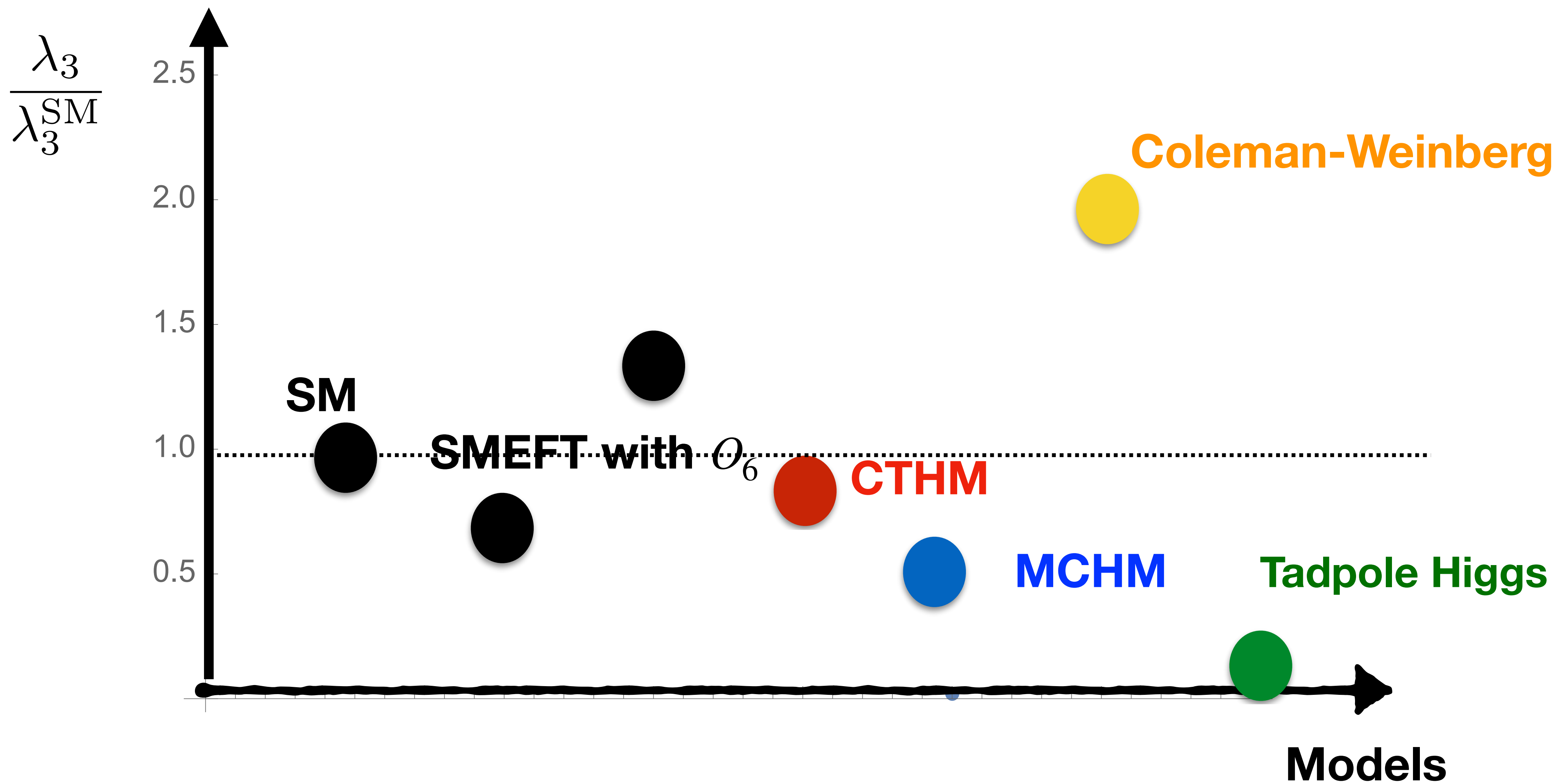
[Agrawal, Saha, Xu, **Yu**, Yuan, **2019**]

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

	a	b	c_1	c_2	c_3	d_3	d_4
SM	1	1	1	0	0	1	1
SMEFT (with non-vanishing O_6)	1	1	1	0	0	$1 + c_6 \frac{v^2}{\Lambda^2}$	$1 + c_6 \frac{6v^2}{\Lambda^2}$
MCH_{5+5}	$\simeq 1 - \frac{\xi}{2}$	$\simeq 1 - 2\xi$	$\simeq 1 - \frac{3}{2}\xi$	$\simeq -2\xi$	$\simeq -\frac{2}{3}\xi$	$\simeq 1 - \frac{3}{2}\xi$	$\simeq 1 - \frac{25}{3}\xi$
CTH_{8+1}	$\simeq 1 - \frac{\xi}{2}$	$\simeq 1 - 2\xi$	$\simeq 1 - \frac{1}{2}\xi$	$\simeq -\frac{1}{2}\xi$	$\simeq -\frac{1}{6}\xi$	$\simeq 1 - \frac{3}{2}\xi$	$\simeq 1 - \frac{25}{3}\xi$
pseudo dilaton: SM+ doublet	1	1	1	0	0	$\frac{5}{3}(1.75)$	$\frac{11}{3}(4.43)$
pseudo dilaton: SM+ 2 singlets	1	1	1	0	0	$\frac{5}{3}(1.91)$	$\frac{11}{3}(4.10)$
Induced EWSB:	$\simeq 1$	$\simeq 1$	$\simeq 1$	0	0	$\simeq 0$	$\simeq 0$

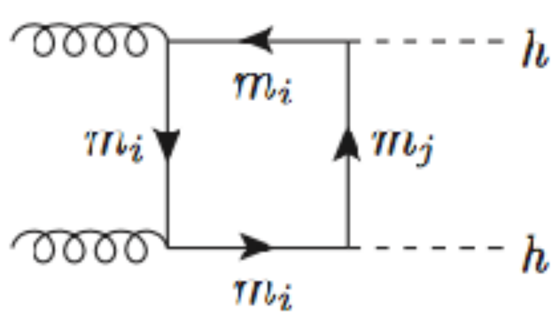
Higgs Self Coupling

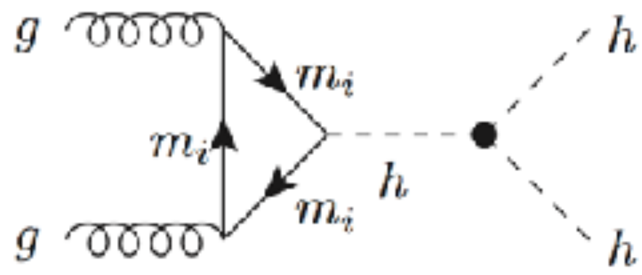
Make use of large difference in Higgs self coupling



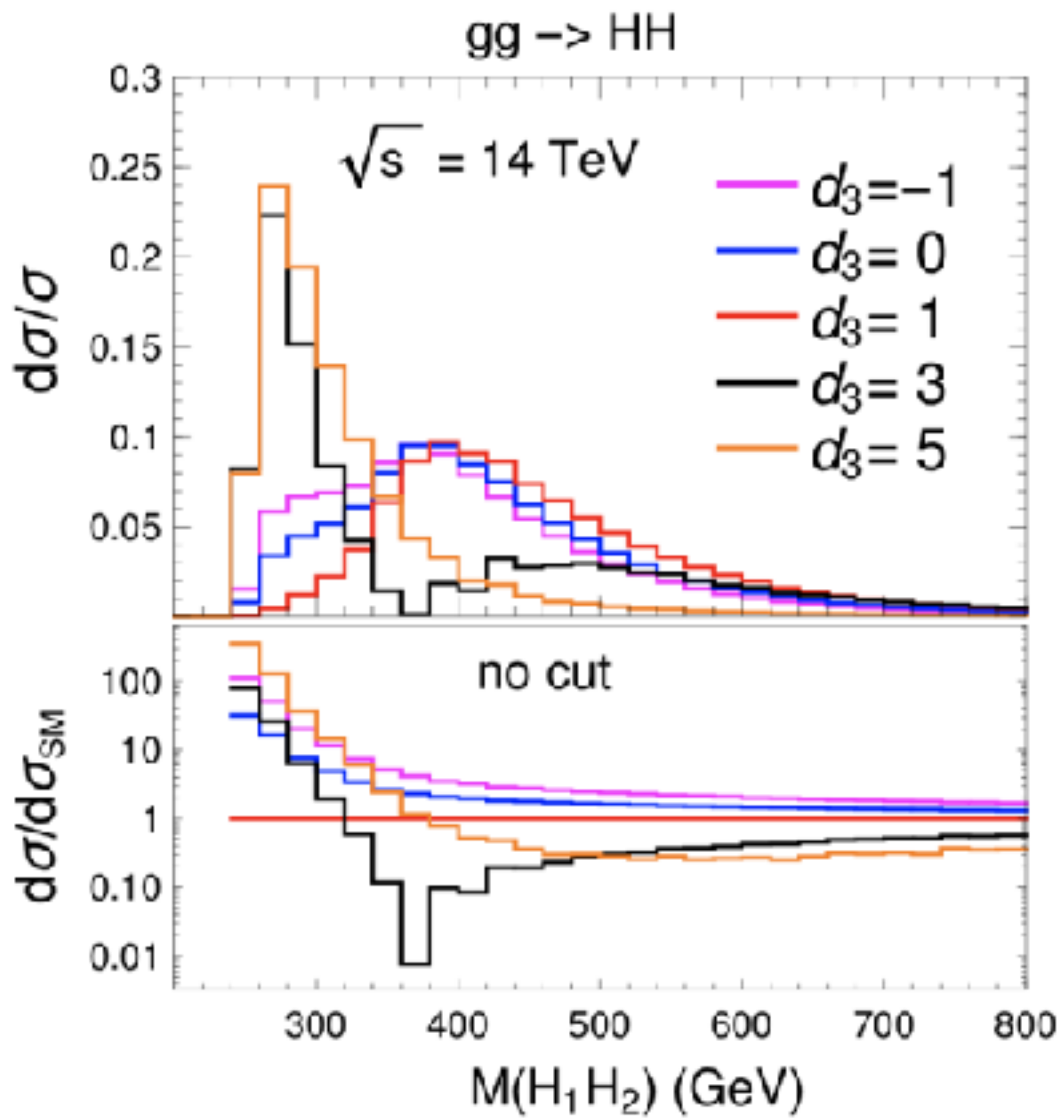
Di-Higgs production

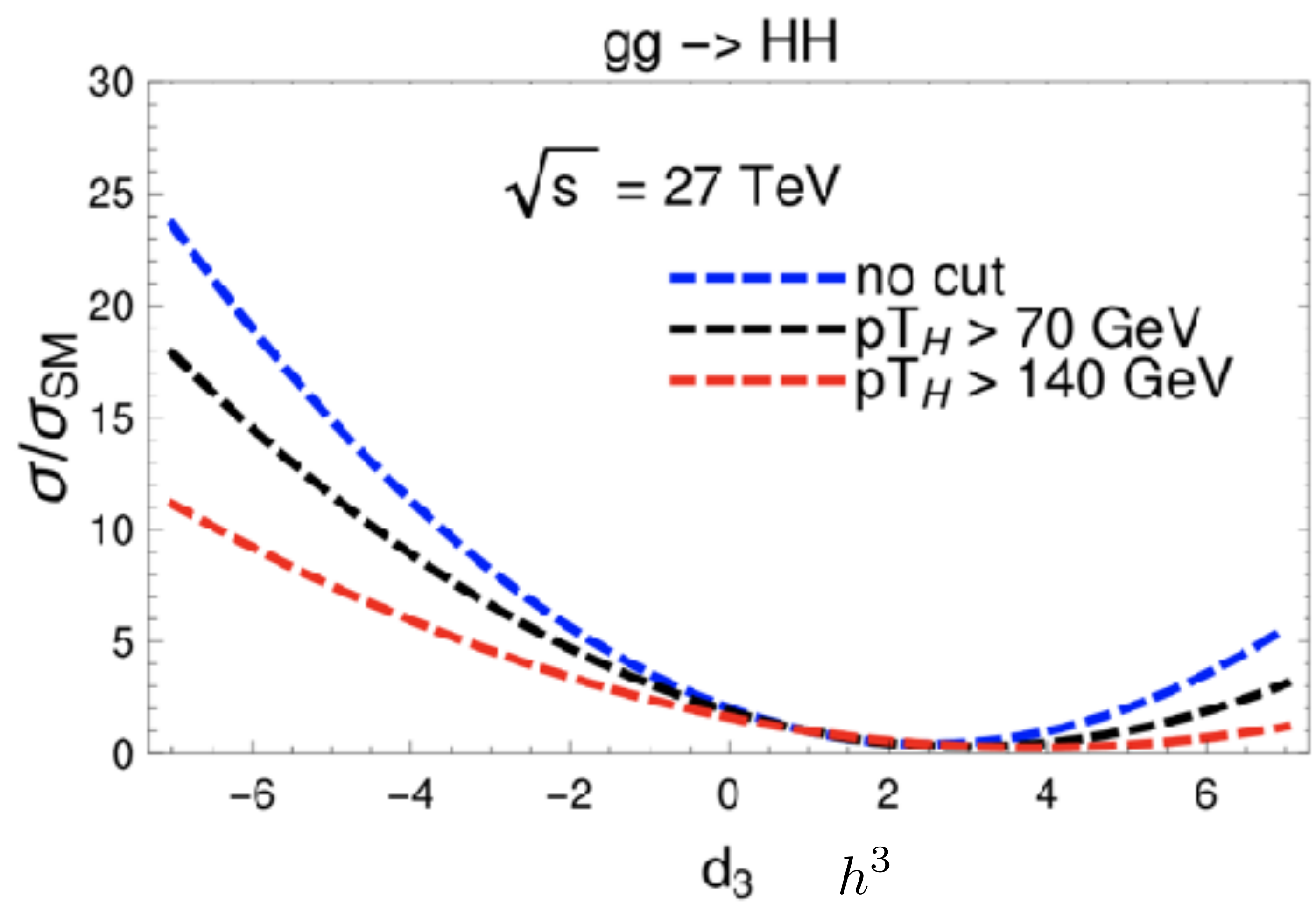
Di-Higgs Production



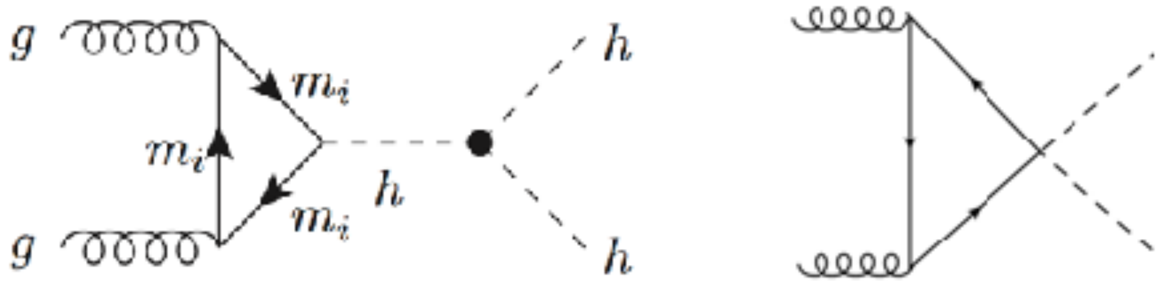


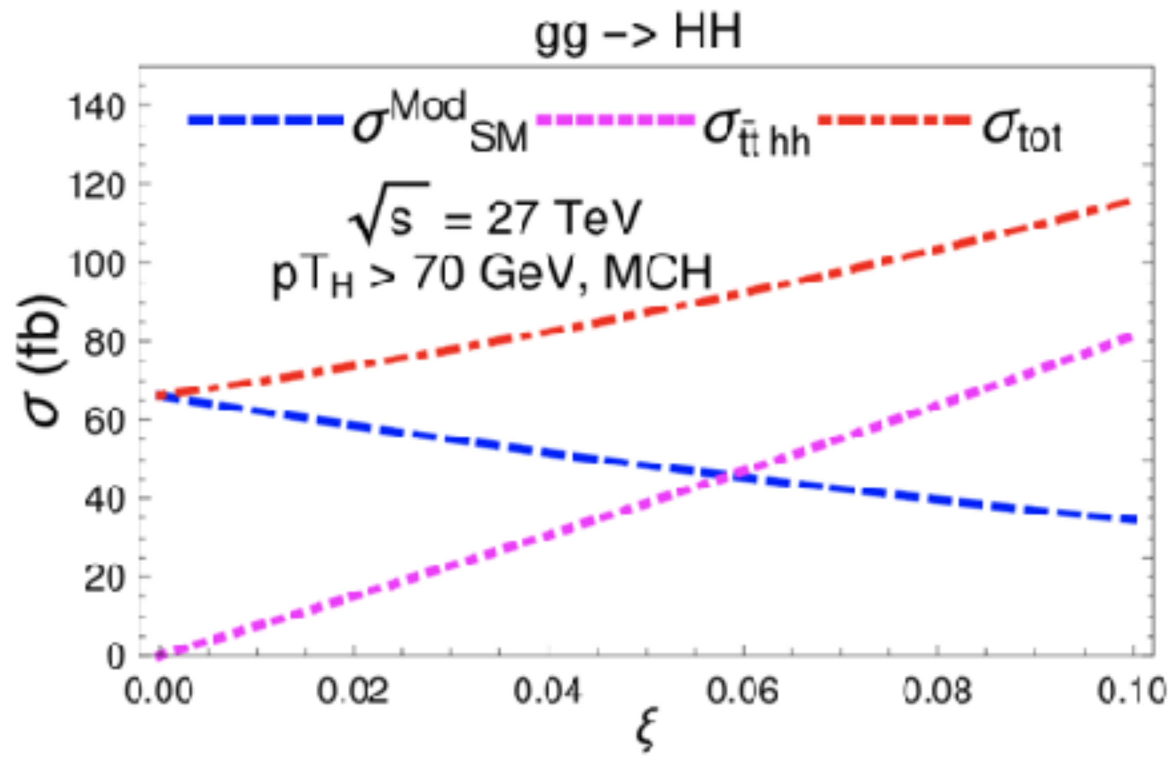
[Many references here …]

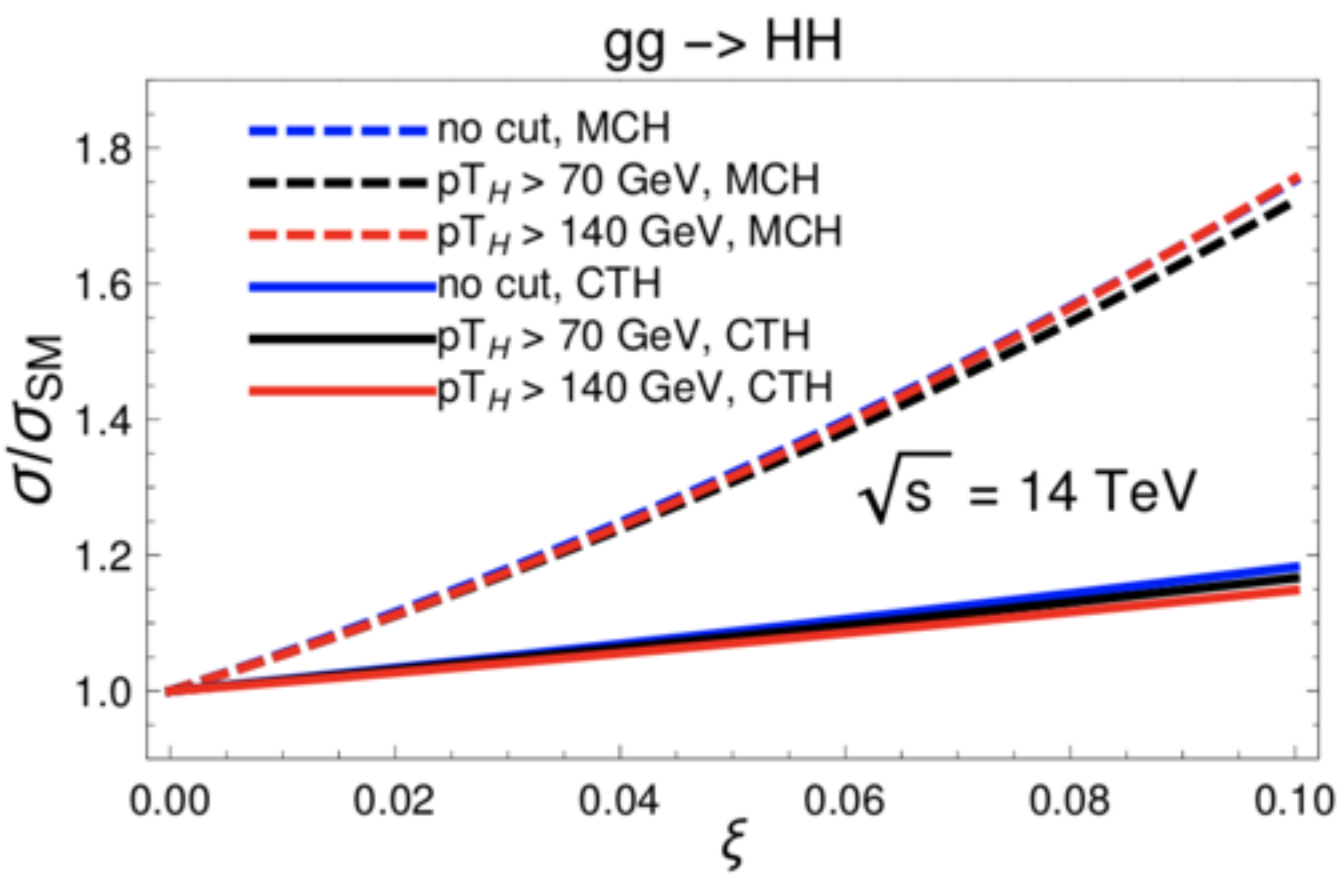


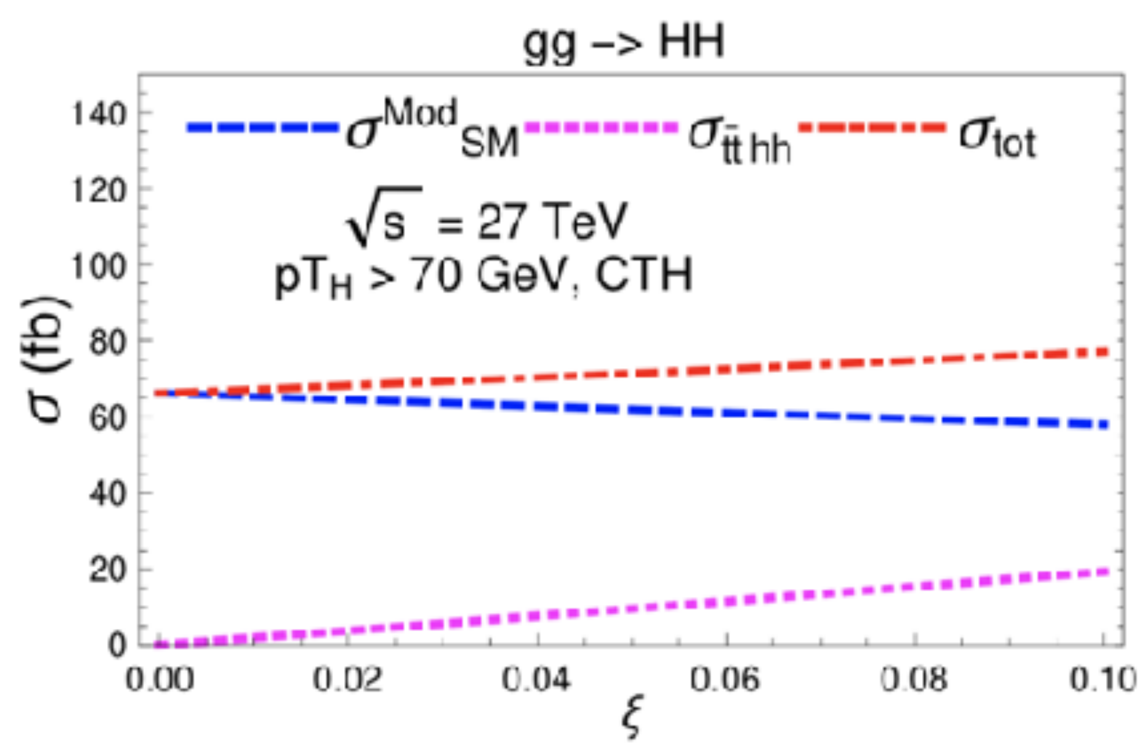


Di-Higgs Production







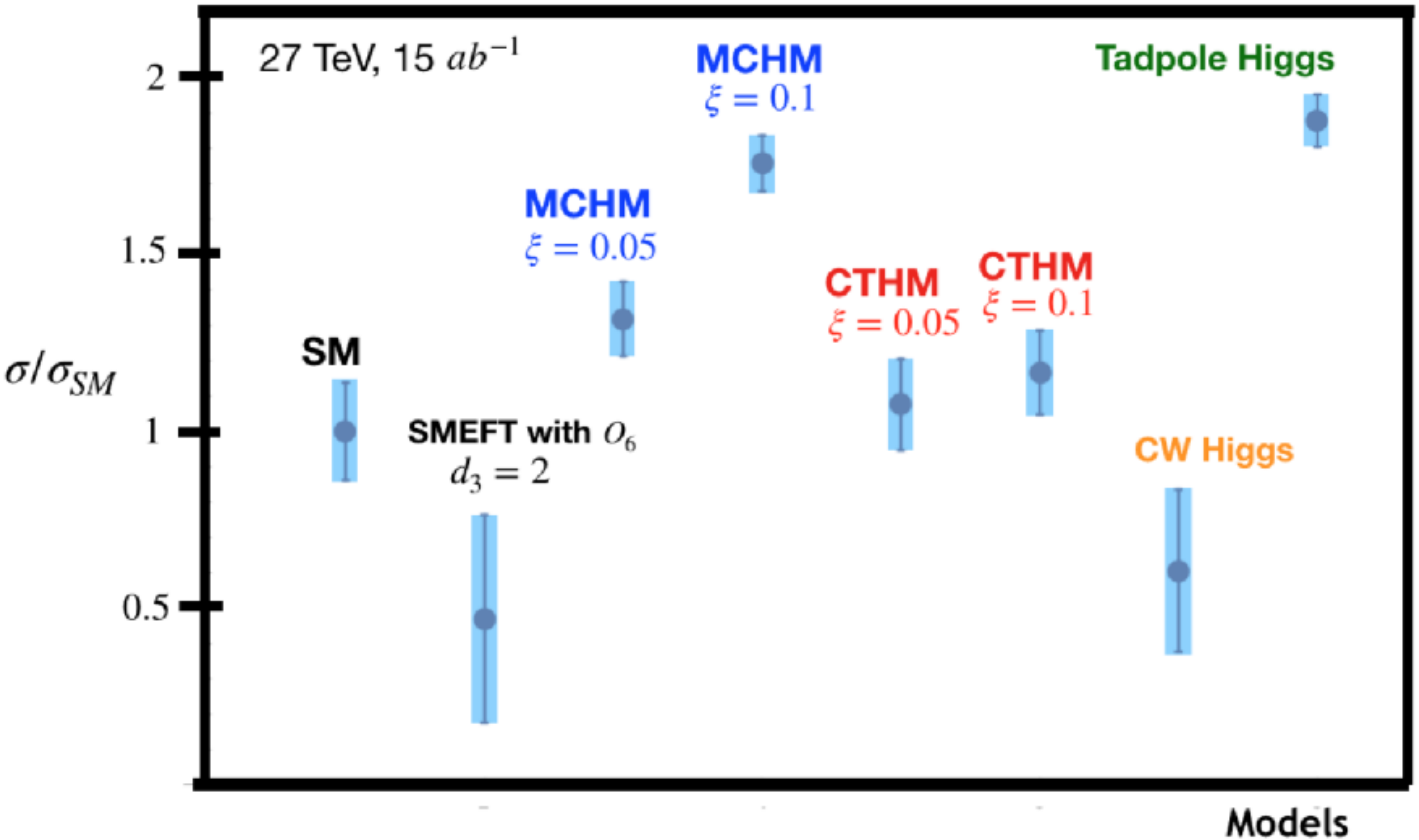


Take LO cross section
NLO K factor = 1.6
[Dawson, Dittmaier, Spira, 1998]

including tthh interference terms

Discriminating Models via HH Production

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

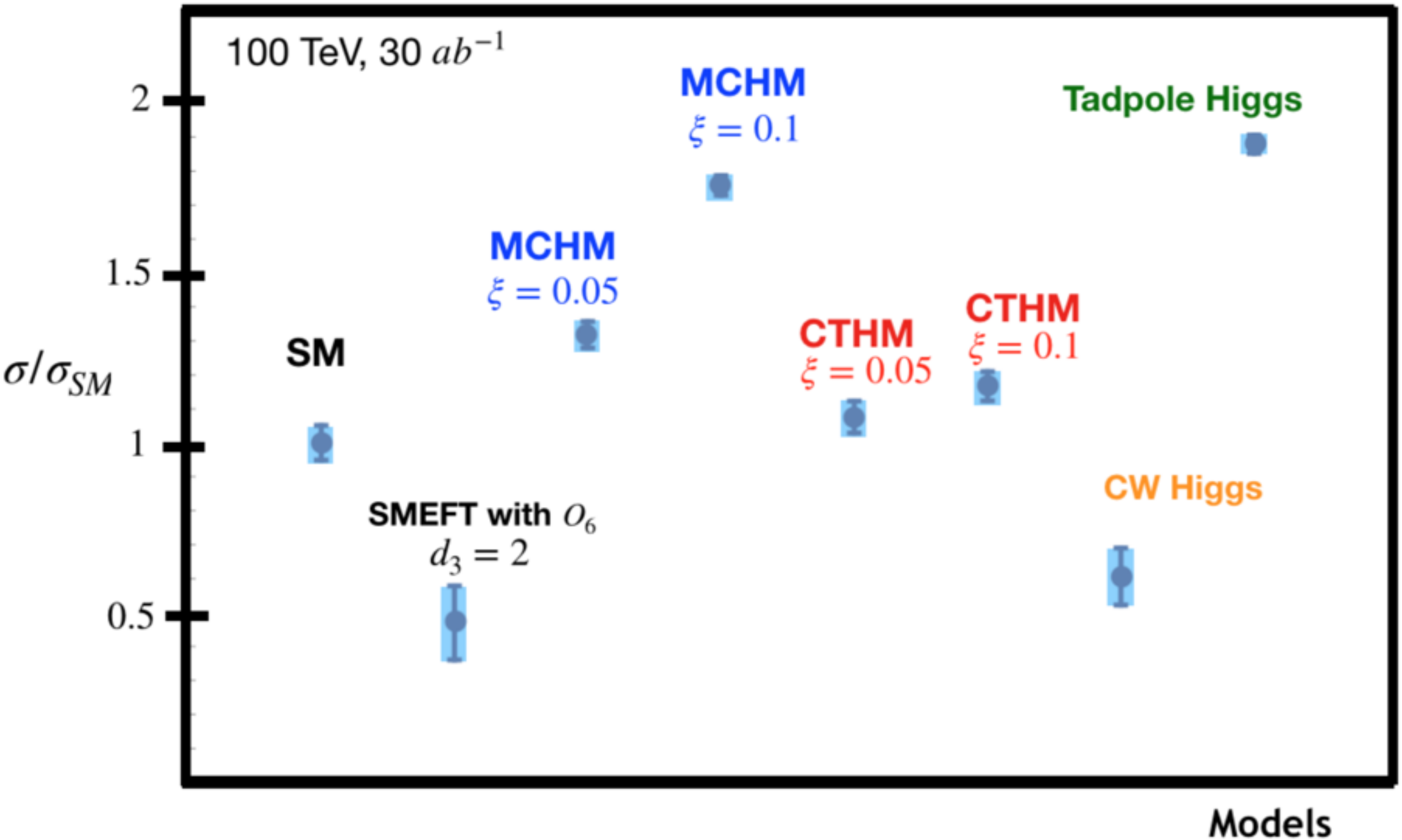


14% accuracy (1 sigma CL) for SM xsec at 27 TeV

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

Discriminating Models via HH Production

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



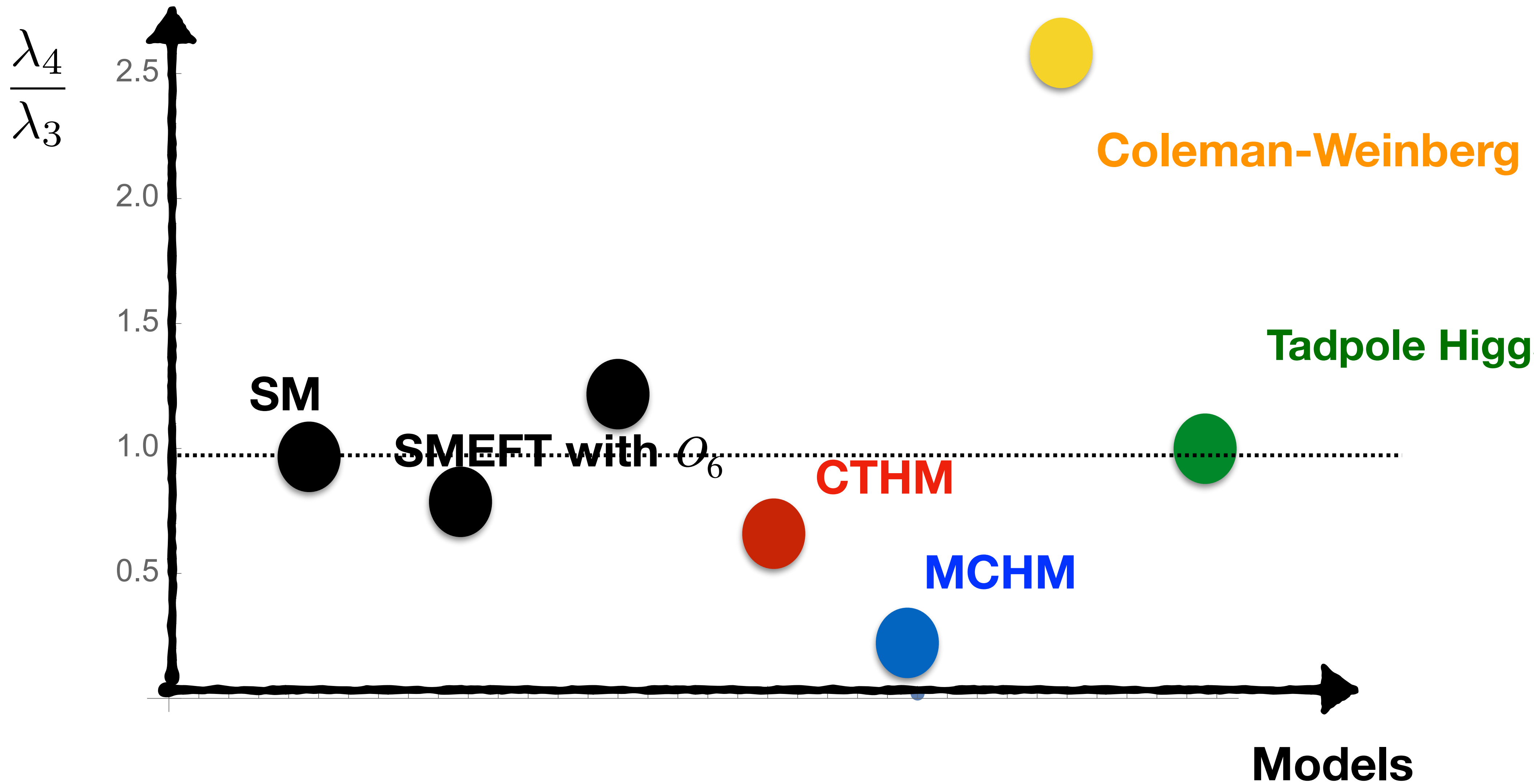
5% accuracy (1 sigma CL) for SM xsec at 100 TeV

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

Quartic Higgs Coupling

Confirm quartic coupling

Further determine shape of Higgs potential



tri-Higgs production

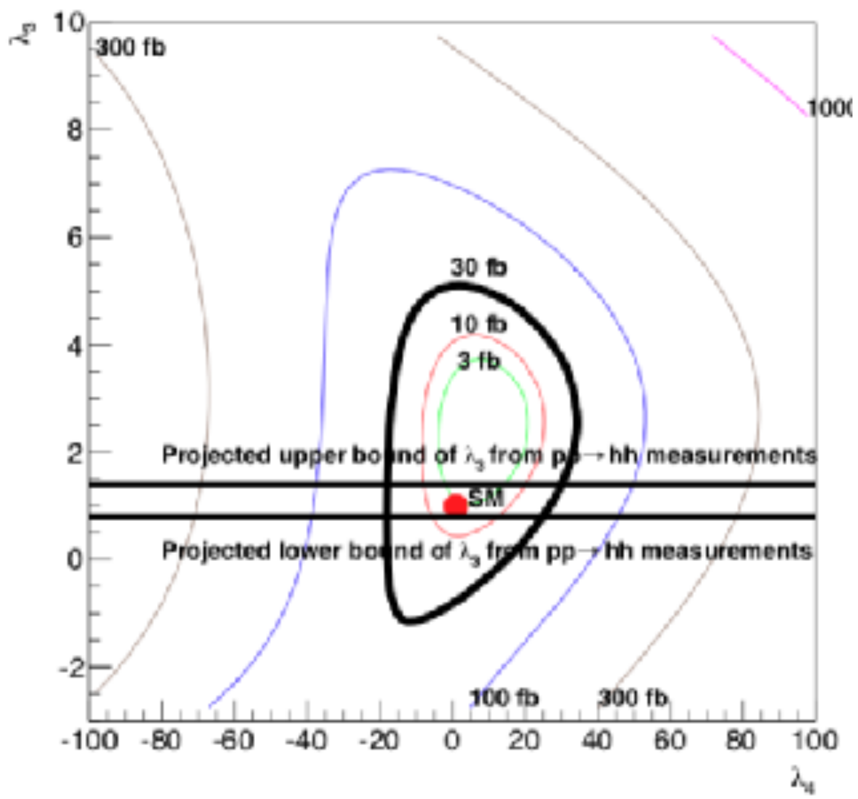
Quartic Higgs Coupling

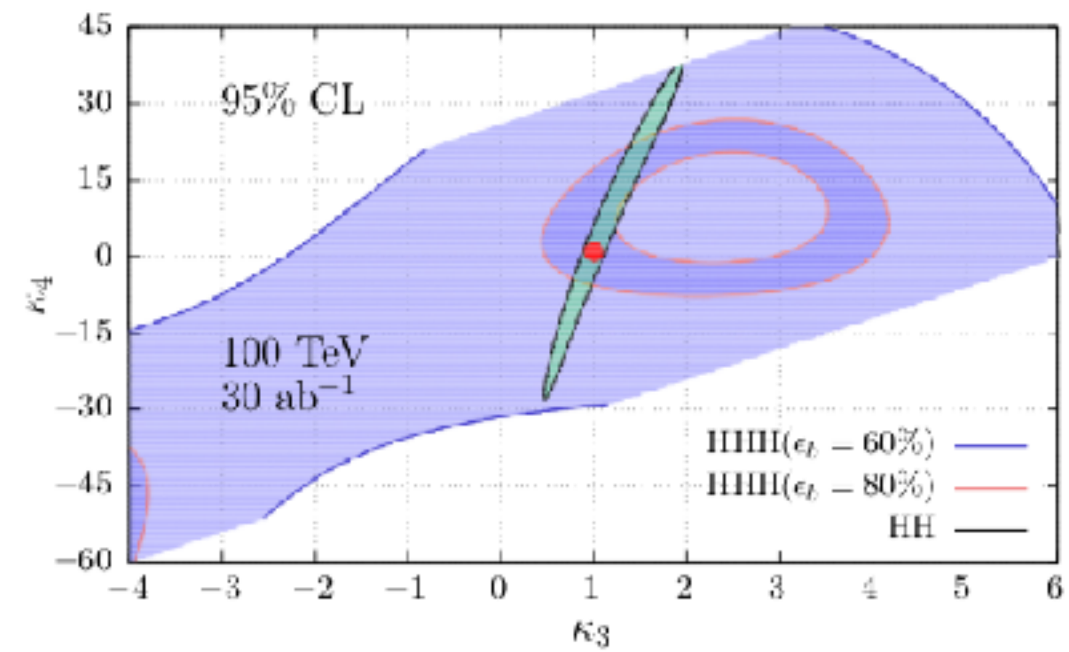
Three Higgs production at 10 TeV collider

[Papaefstathiou, Sakurai, 2016]

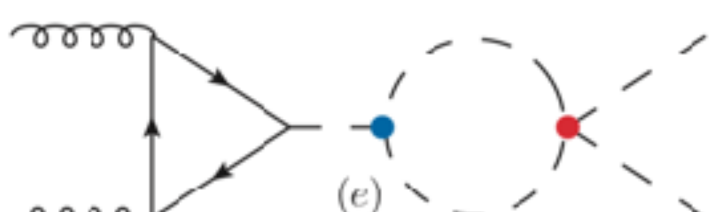
[Chen, Yan, Zhao, Zhong, Zhao, 2016]

[Borowka, Duhr, Maltoni, Pagani, Shivaji, Zhao, 2018]



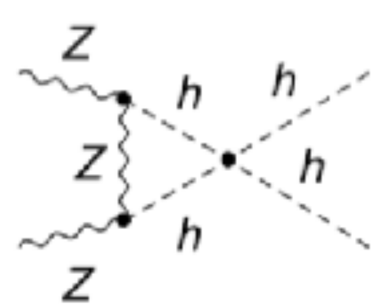


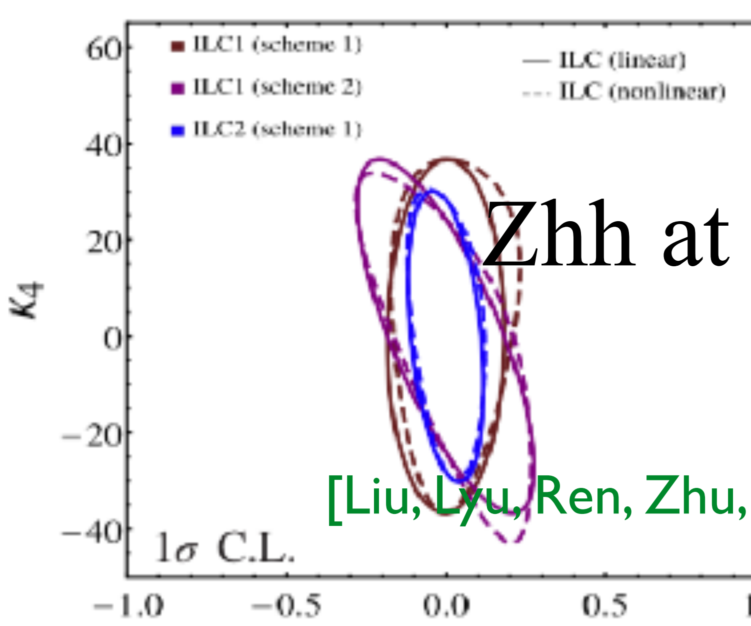
Indirect search via two-loop correction



Di-Higgs at HL-LHC and 100 TeV collider

[Borowka, Duhr, Maltoni, Pagani, Shivaji, Zhao, 2018]

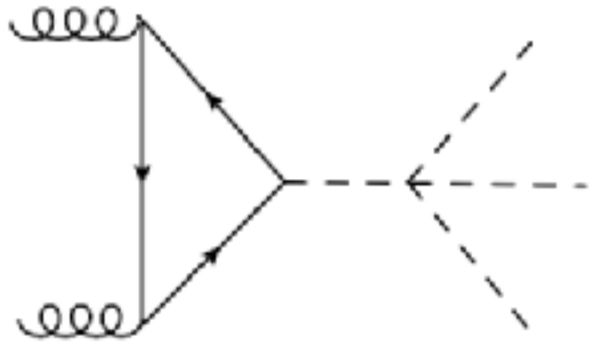


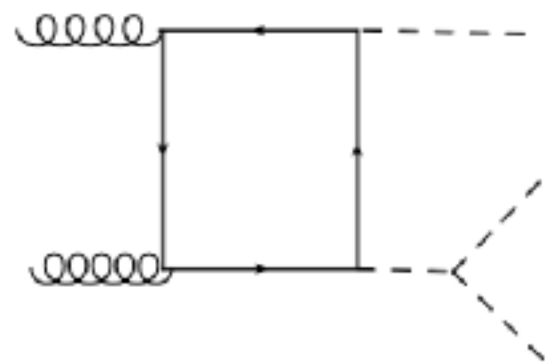


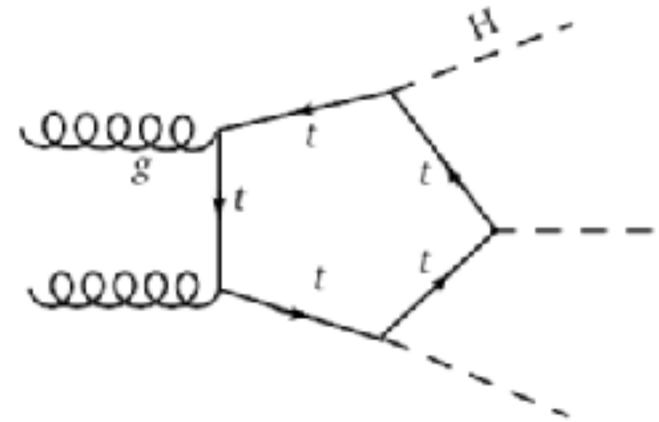
Zhh at ILC

[Liu, Lyu, Ren, Zhu, 2018]

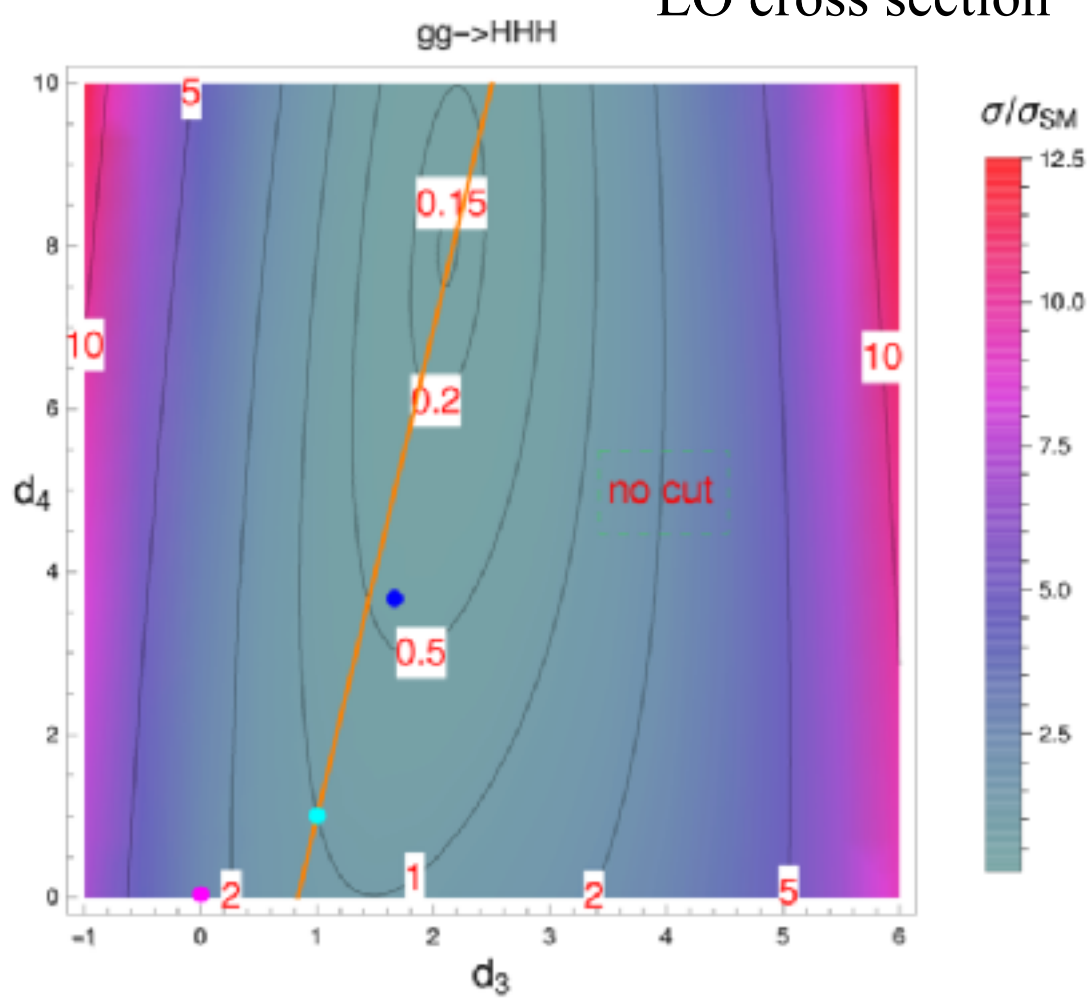
Tri-Higgs Production

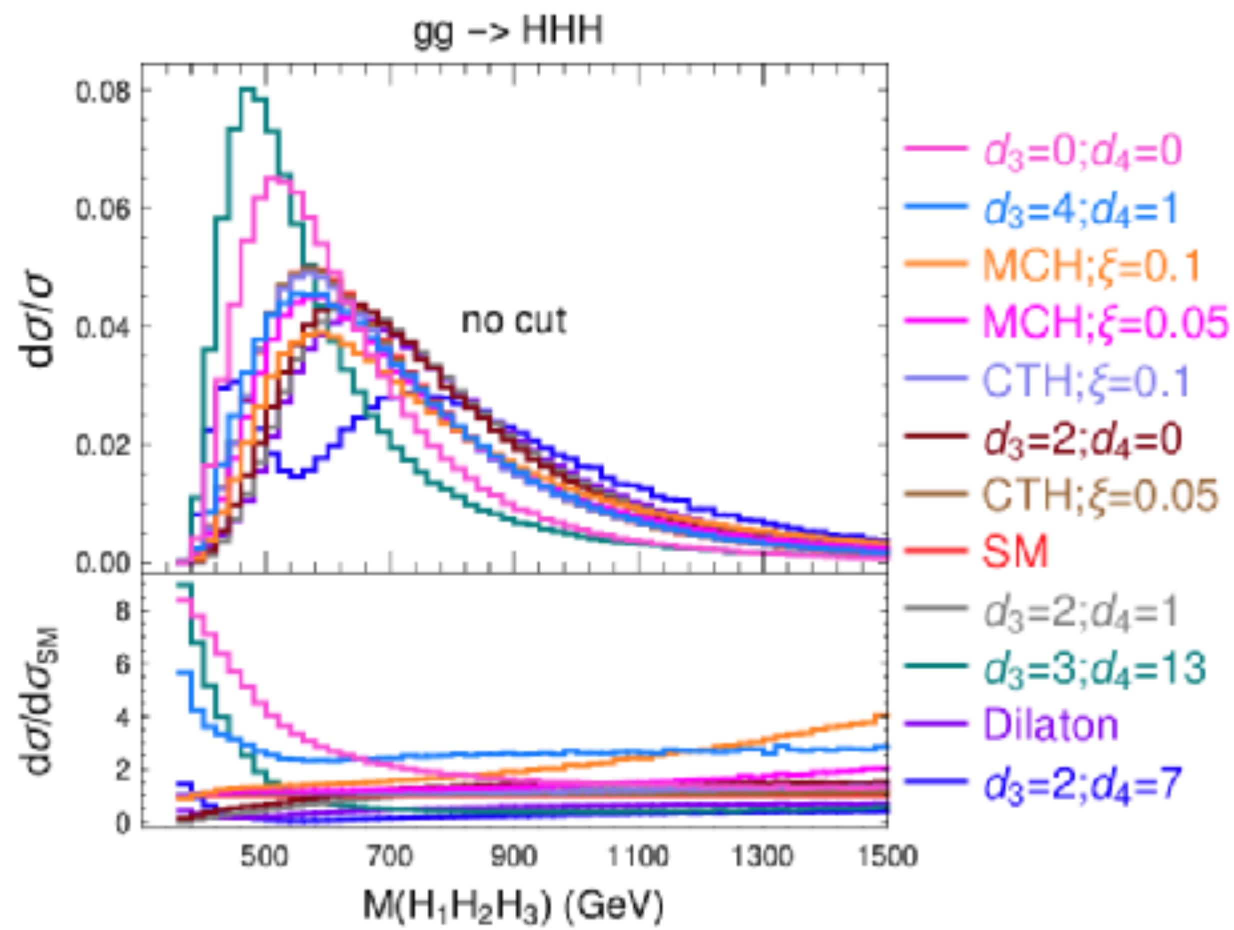






LO cross section

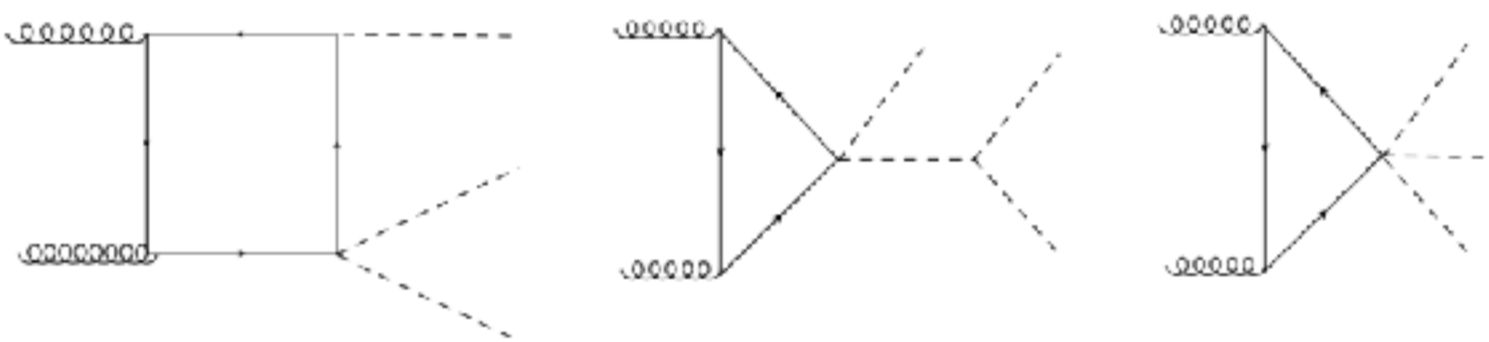


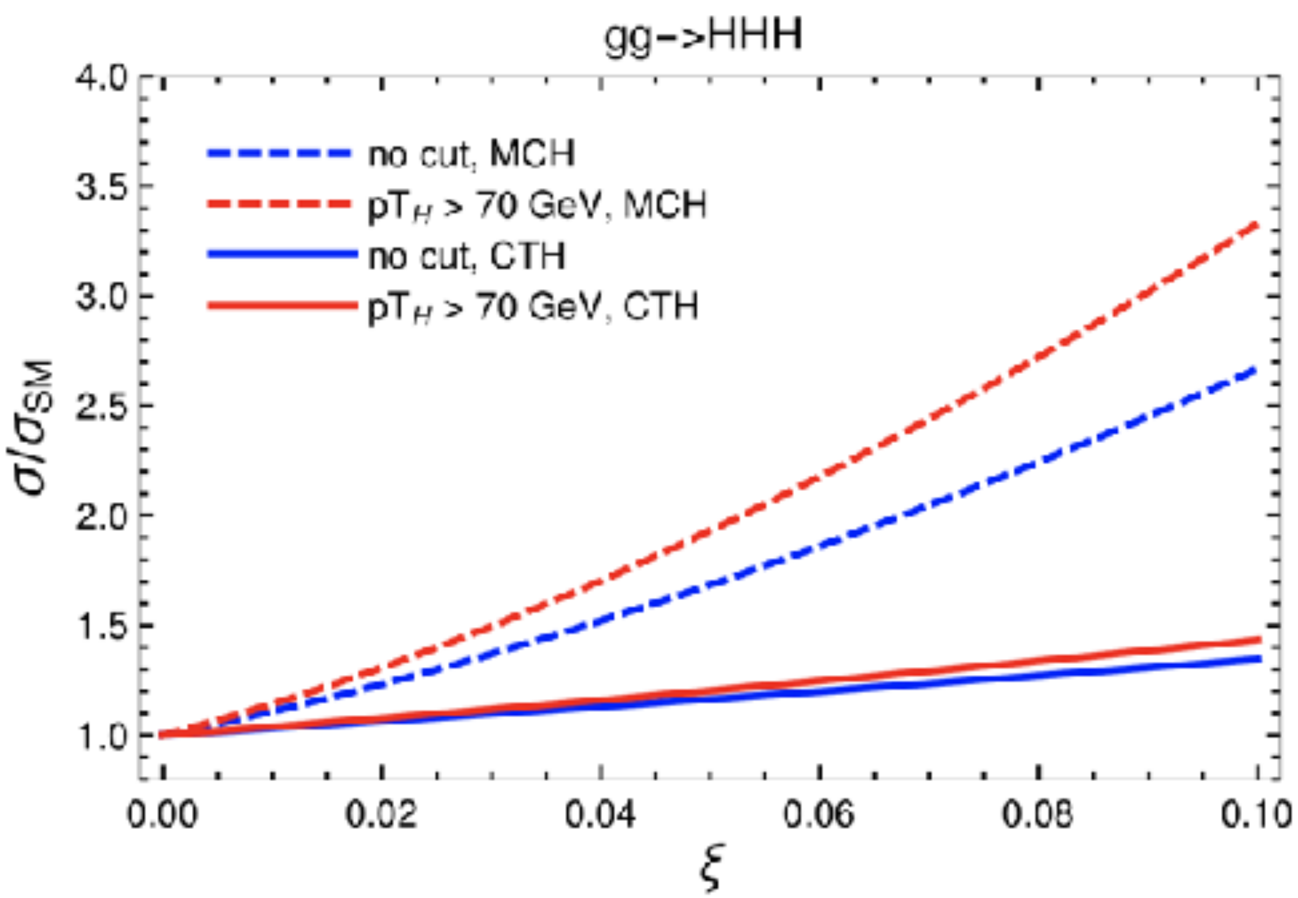


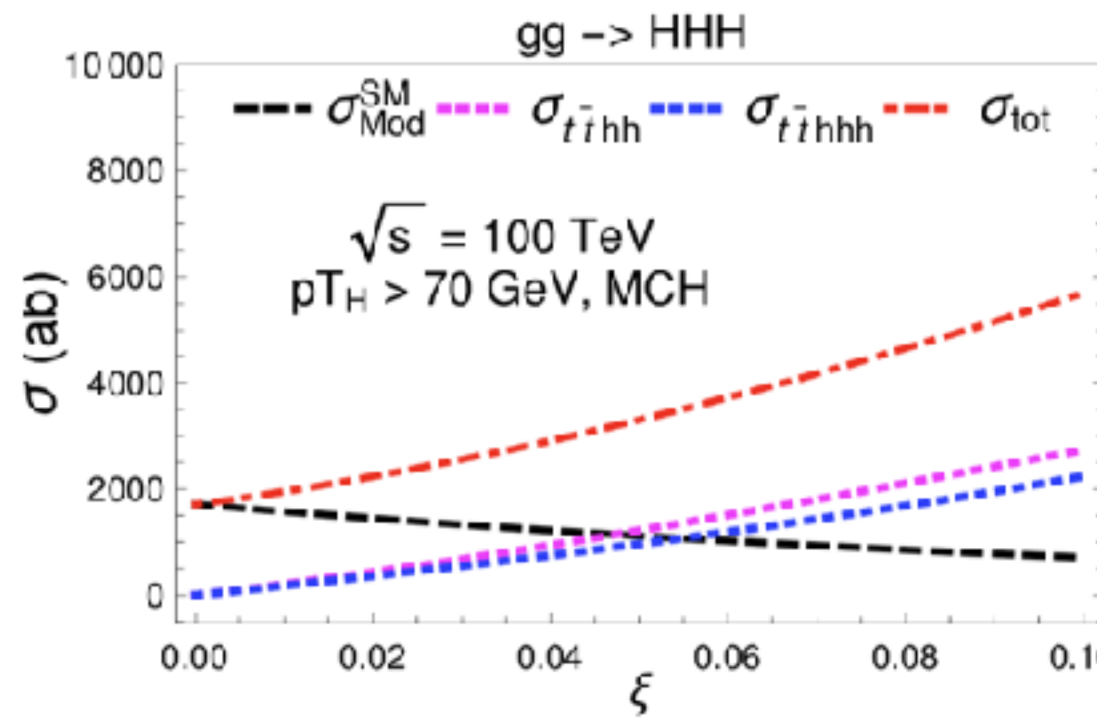
[Agrawal, Saha, Xu, **Yu**, Yuan, **2019**]

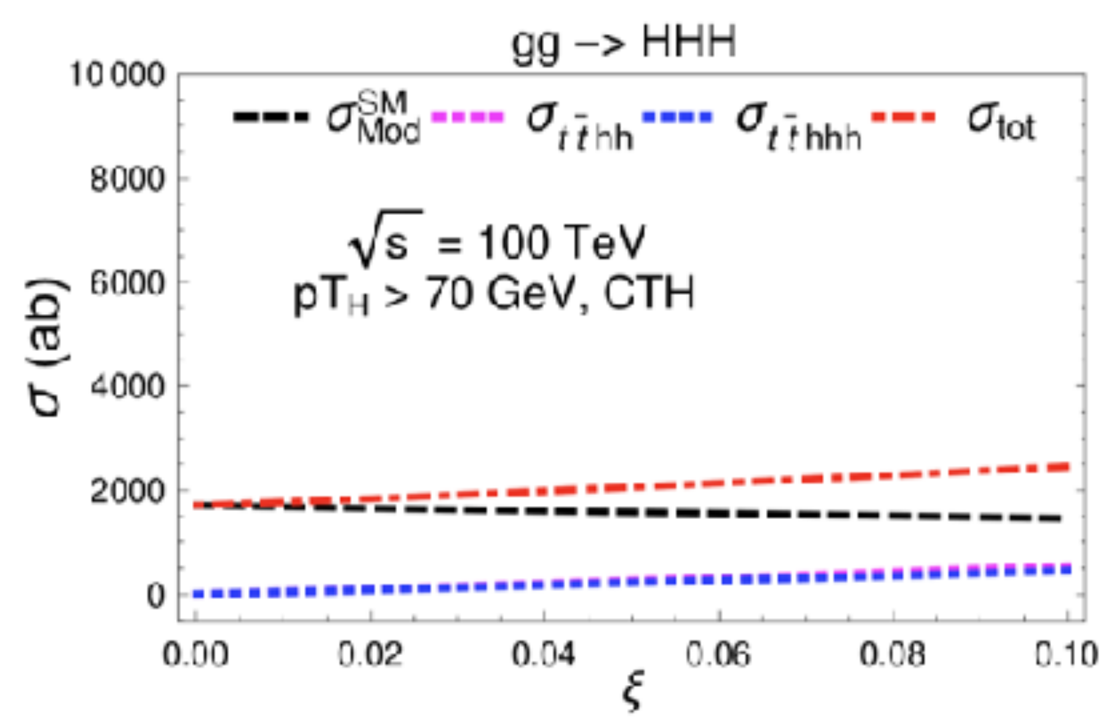
Tri-Higgs Production

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







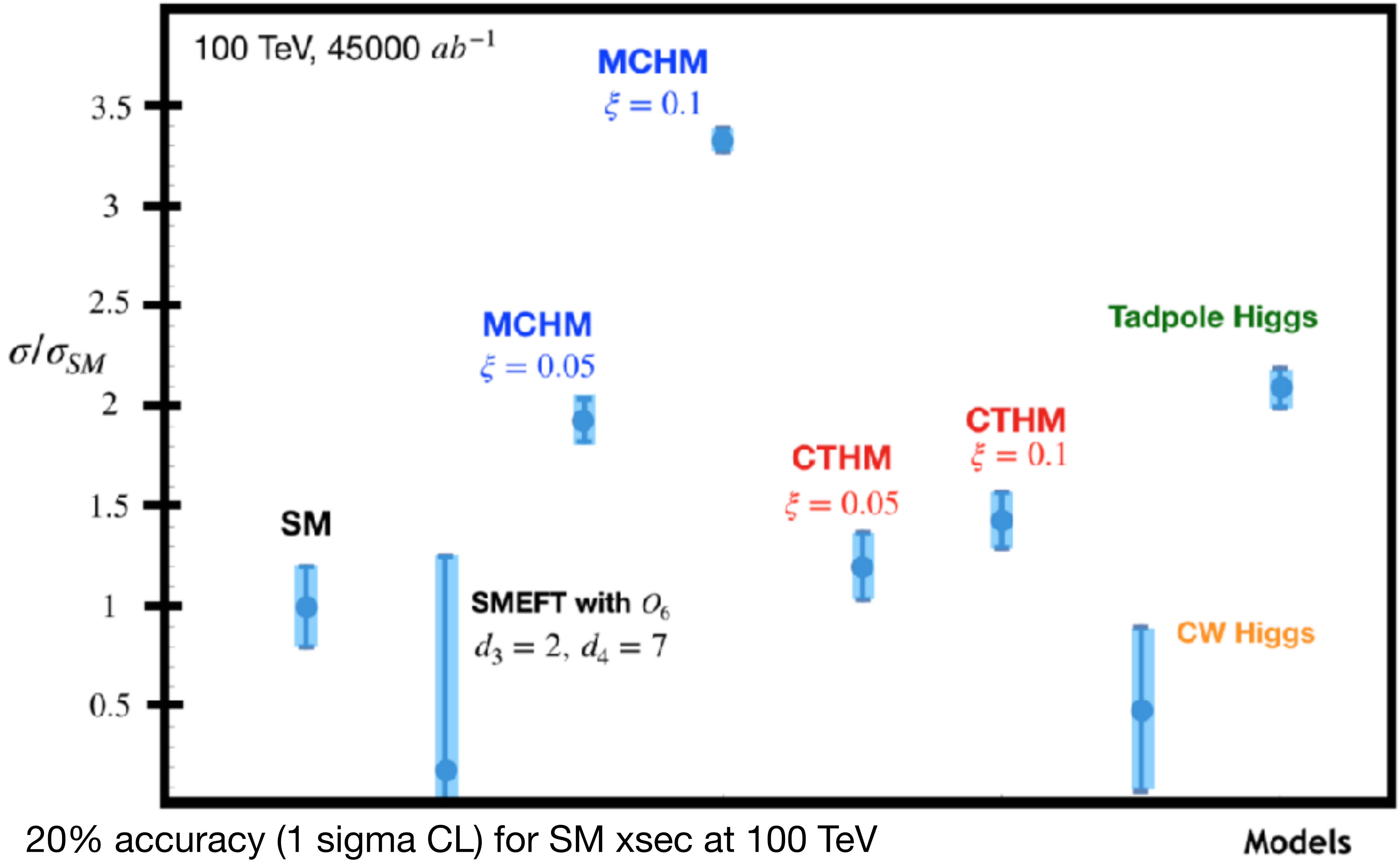


LO cross section, NLO K factor = 2

[Maltoni, Vryonidou, Zaro, 2014]

Tri-Higgs Production

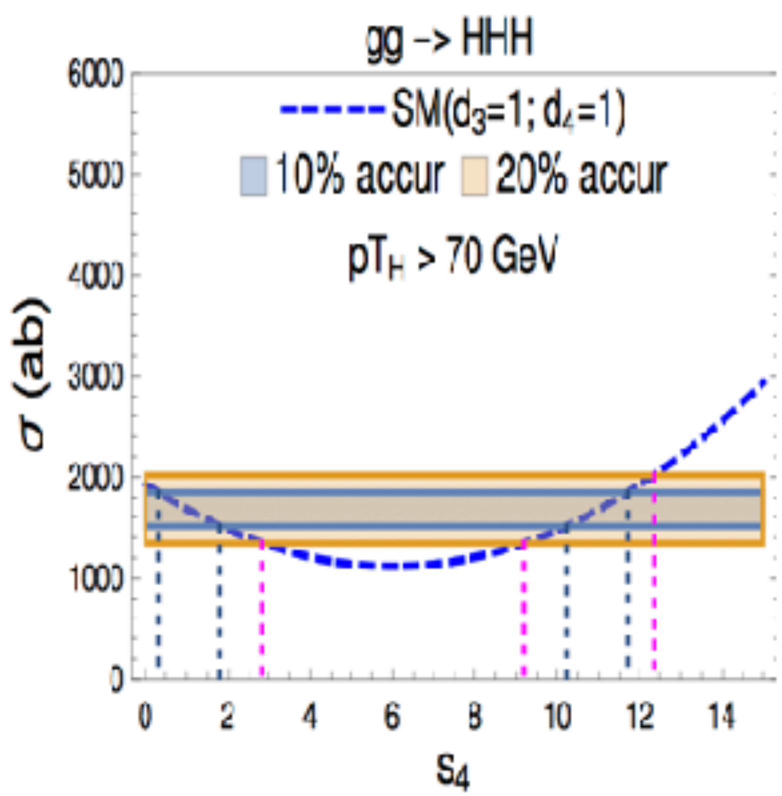
[Agrawal, Saha, Xu, **Yu**, Yuan, **2019**]



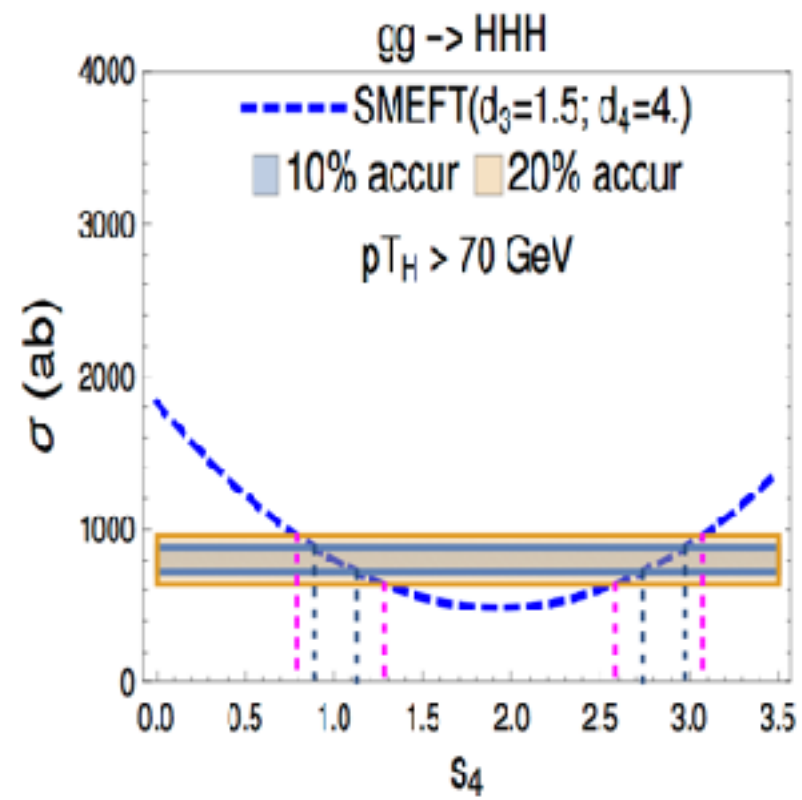
20% accuracy (1 sigma CL) for SM xsec at 100 TeV

[Chen, Yan, Zhao, Zhong, Zhao, 2016]

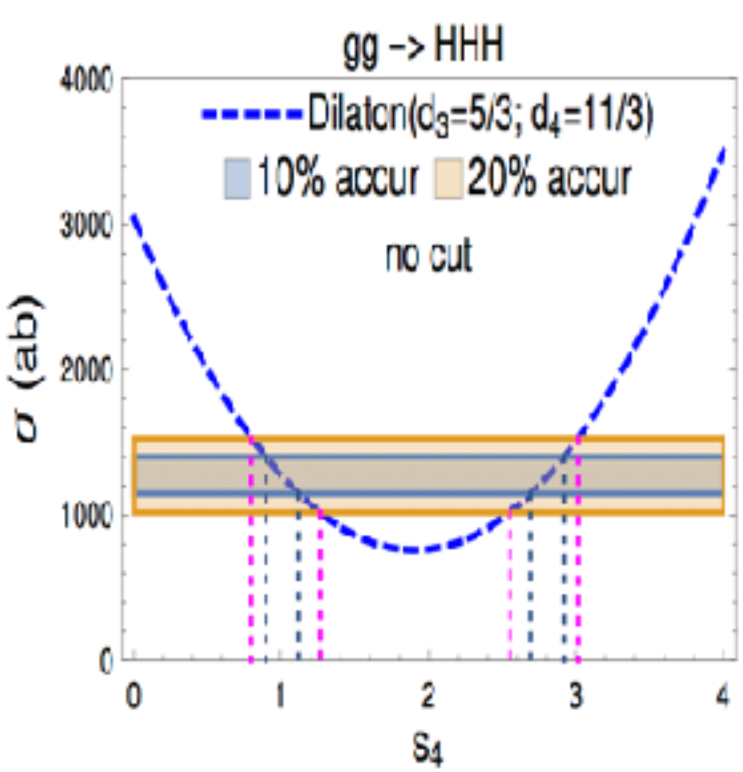
Determine Quartic Coupling



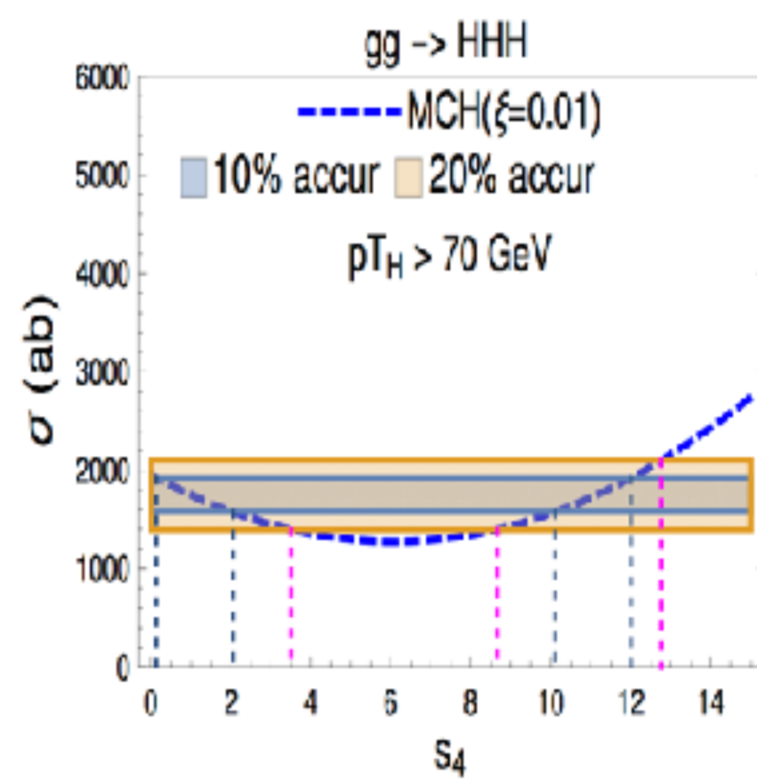
SM



SMEFT with O_6



MCHM

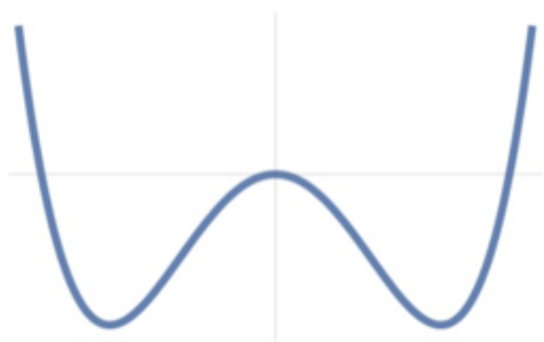


Coleman-Weinberg

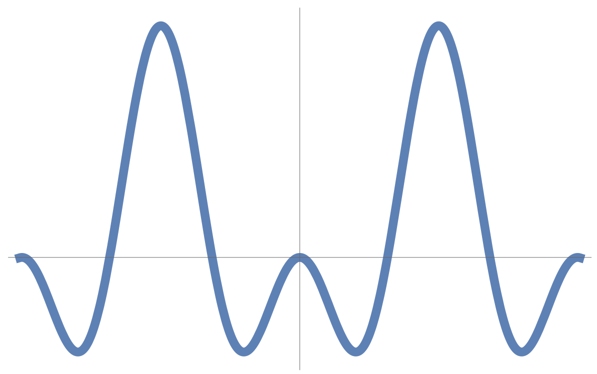
Summary

Explore Higgs potential beyond Landau-Ginzburg Higgs potential

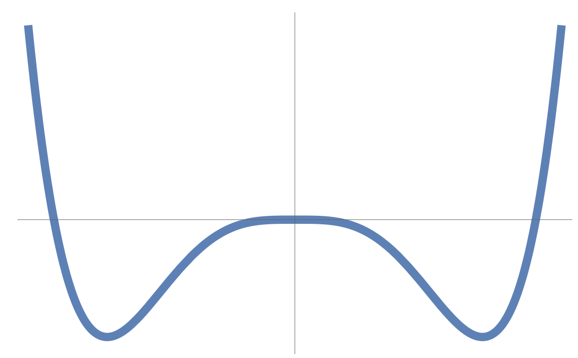
Landau-Ginzburg Higgs



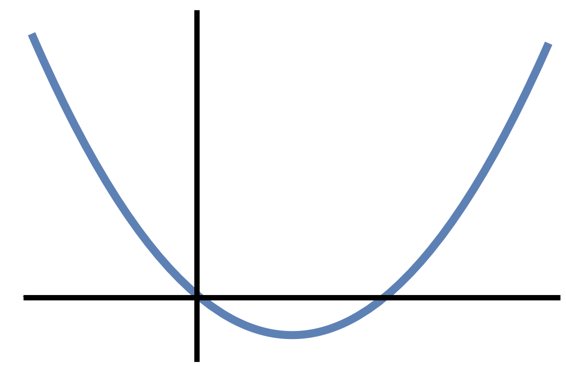
Pseudo-Goldstone Higgs



Coleman Weinberg Higgs

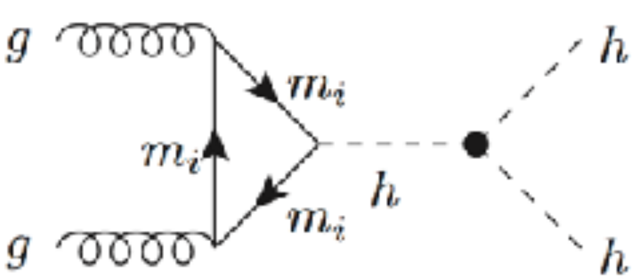


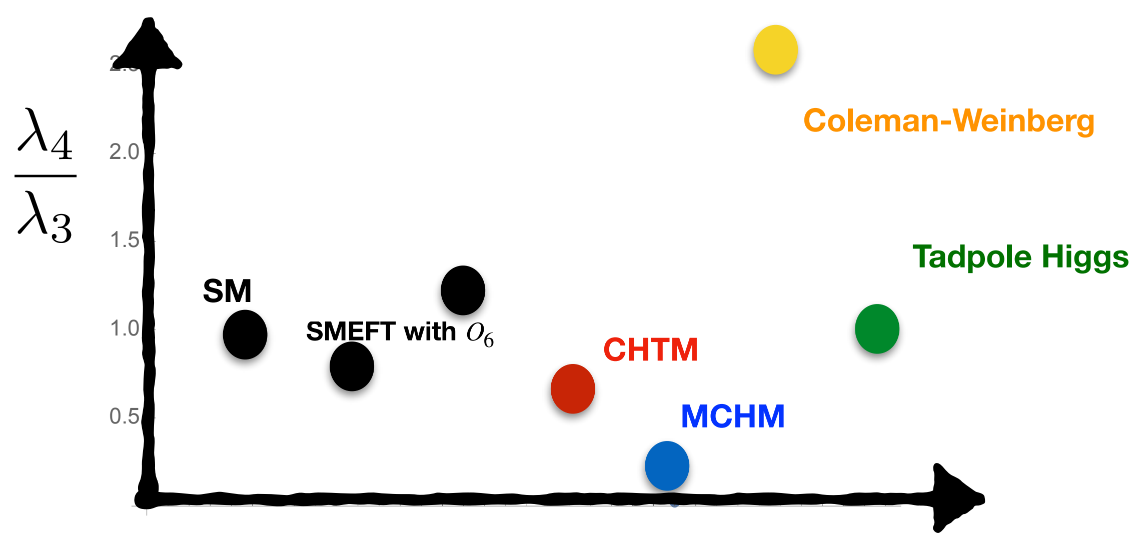
Tadpole-induced Higgs

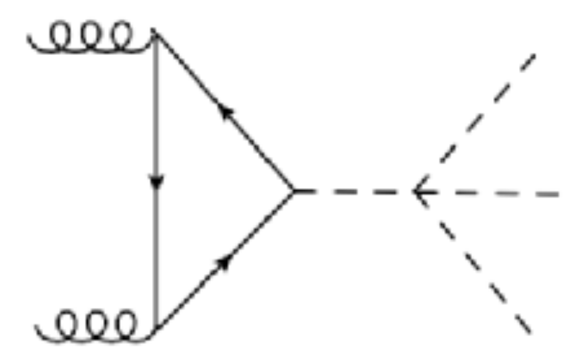


SMEFT is not enough to describe effective Lagrangian

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







Thanks very much!

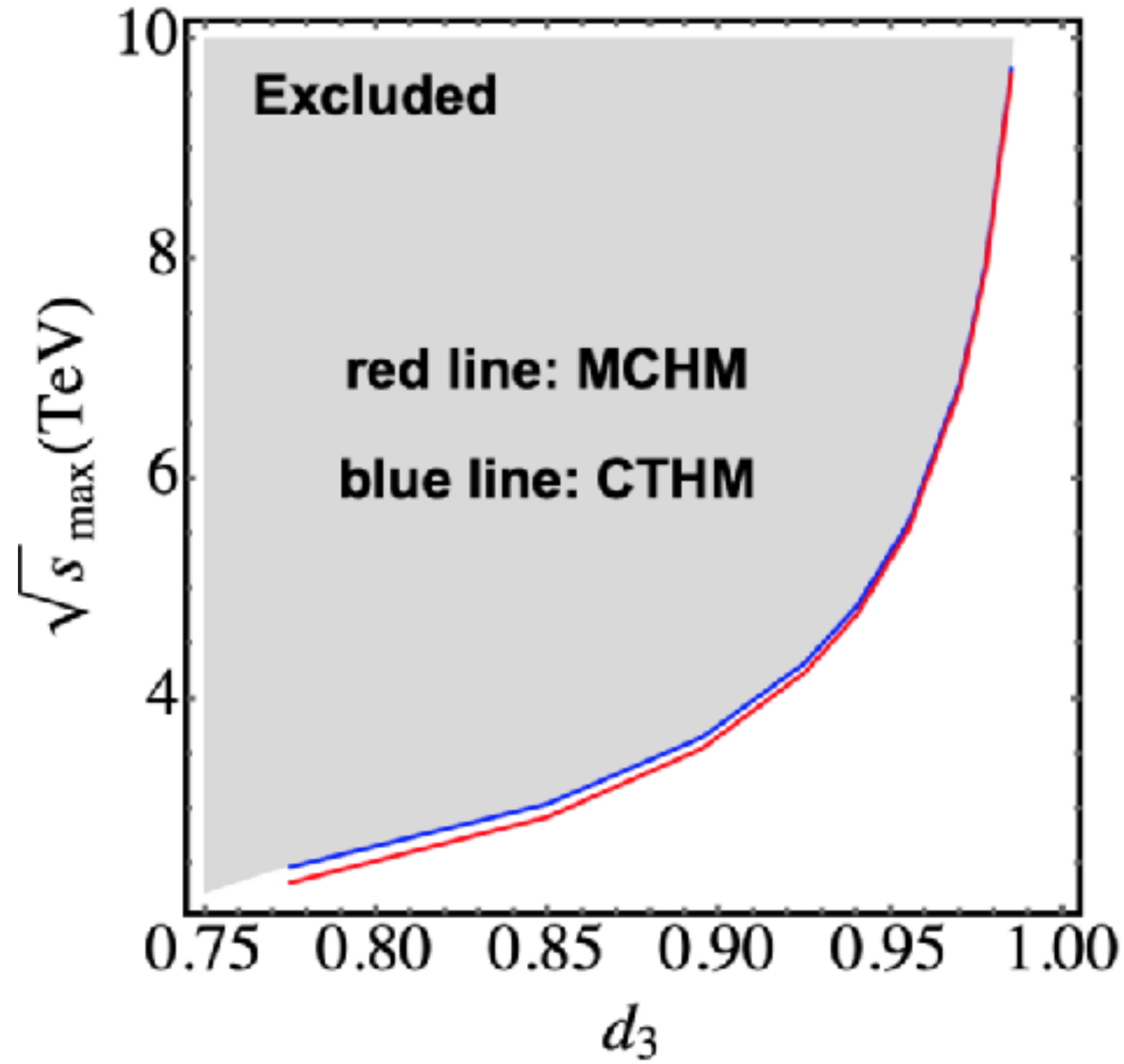
Theoretical Constraints

Perturbative tree-level unitarity constraint (s-wave)

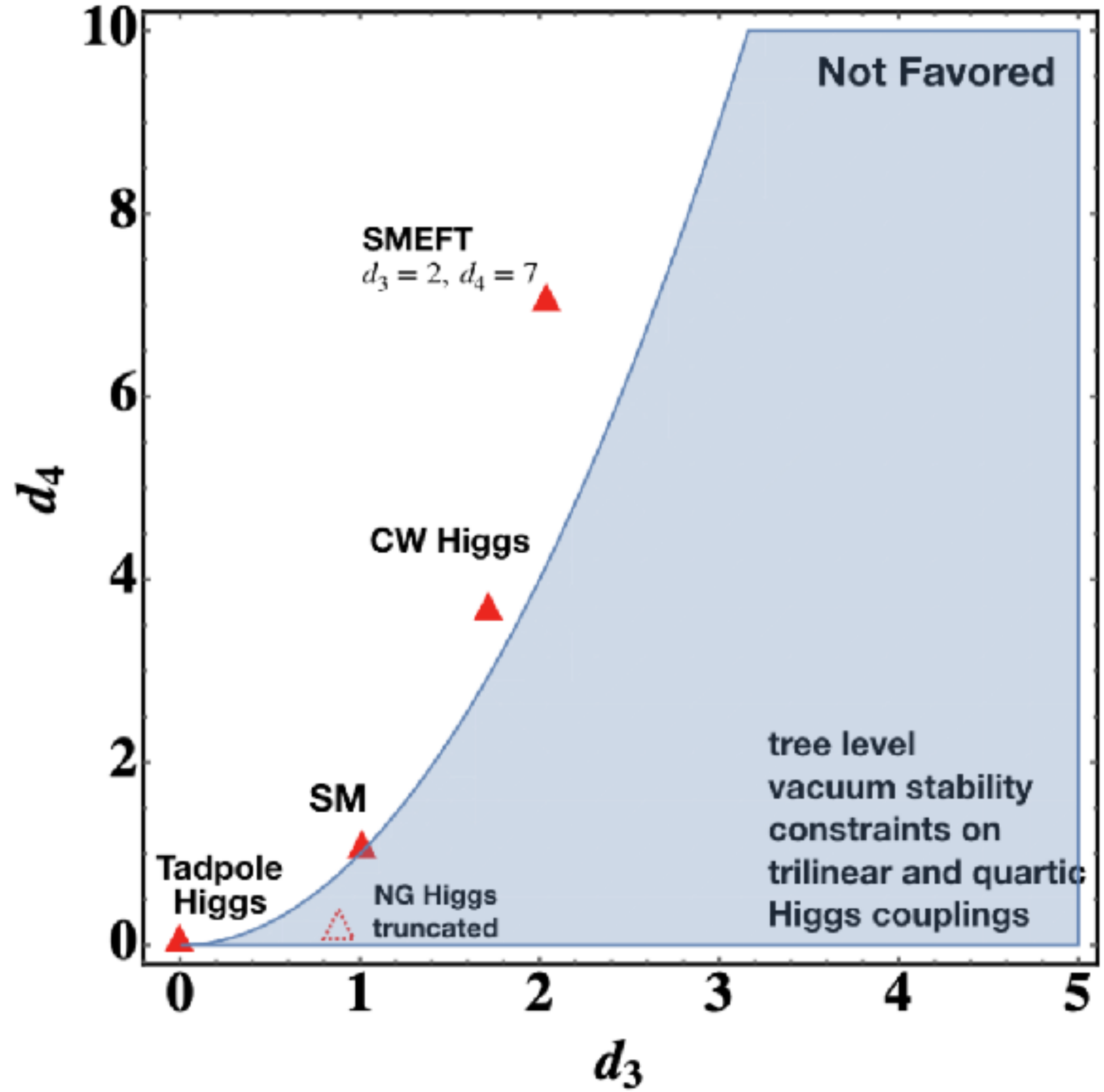
$$a_j(\sqrt{s}) = \frac{1}{32\pi}\int_0^{\pi} \mathrm{d}\theta \sin\theta \; P_j(\cos\theta)\; \mathcal{M}_{if}(\sqrt{s}, \cos\theta)$$

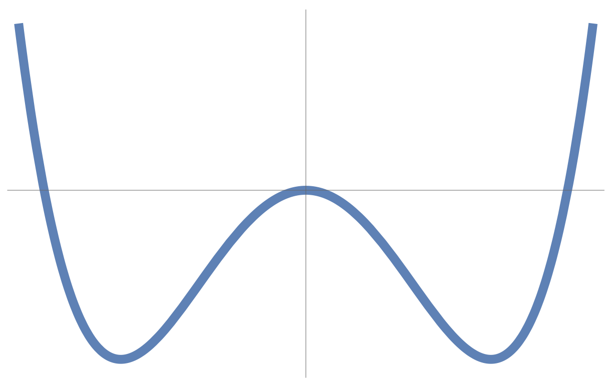
$$\left\{ t^+\bar{t}^+,\ t^-\bar{t}^-,\ \frac{1}{\sqrt{2}} w^a w^a,\ \frac{1}{\sqrt{2}} hh \right\}$$

$$\begin{pmatrix} -(c_1^2+1)m_t & 0 & (1-ac_1)\sqrt{\frac{s}{3}} & -2c_2\sqrt{\frac{s}{3}} \\ 0 & -(c_1^2+1)m_t & (-1+ac_1)\sqrt{\frac{s}{3}} & 2c_2\sqrt{\frac{s}{3}} \\ (1-ac_1)\sqrt{\frac{s}{3}} & (-1+ac_1)\sqrt{\frac{s}{3}} & \frac{s}{3m_t}(1-a^2) & -\frac{s}{3m_t}(b-a^2) \\ -2c_2\sqrt{\frac{s}{3}} & 2c_2\sqrt{\frac{s}{3}} & -\frac{s}{3m_t}(b-a^2) & -d_4\frac{m_h^2}{m_t} \end{pmatrix}$$

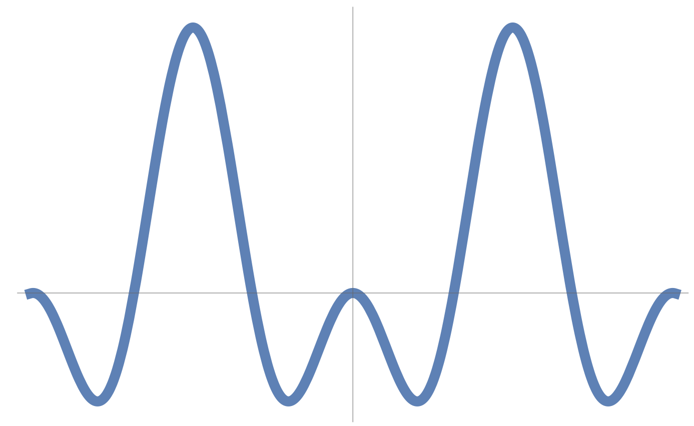


Tree-level Vacuum Stability

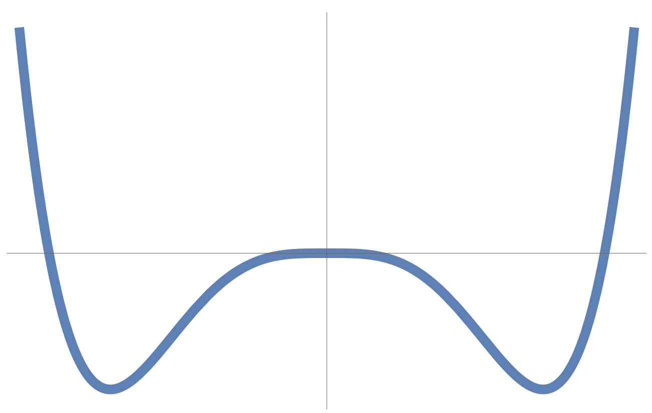




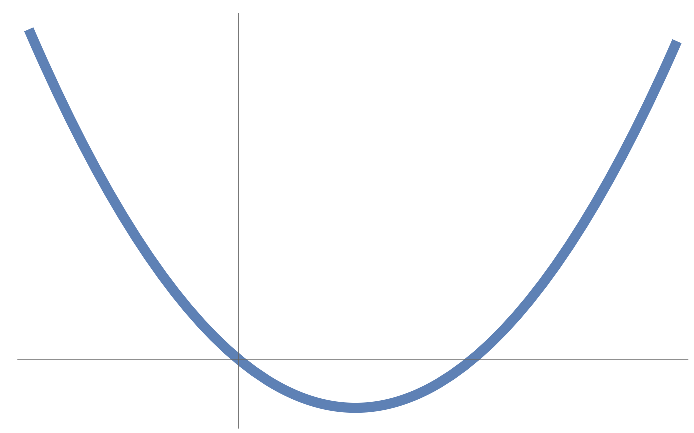
(a) Landau-Ginzburg Higgs



(b) Pseudo-Goldstone Higgs



(c) Coleman-Weinberg Higgs



(d) Tadpole-Induced Higgs