

Testing Composite Higgs Models at the Higgs Factory

Kei Yagyu (Osaka U.)

Collaboration with

S. De Curtis, L. Delle Rose (Florence U.)

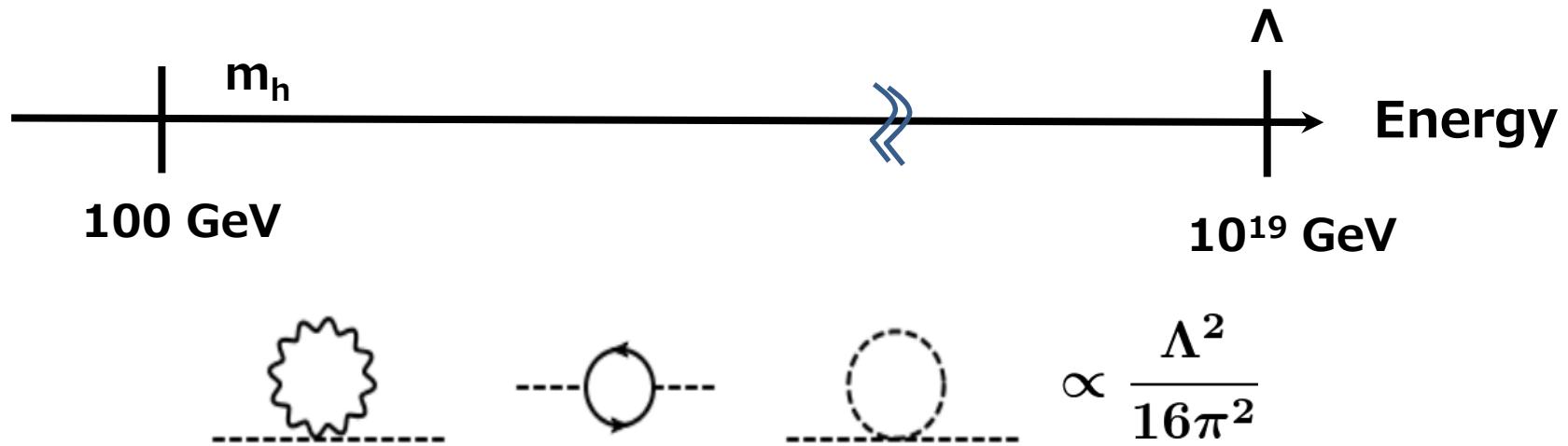
and S. Moretti (Southampton U.)

1810.06465 (JHEP), 1803.01865 (PLB)

LCWS2019, Oct. 30th, Sendai

What/Where is New Physics?

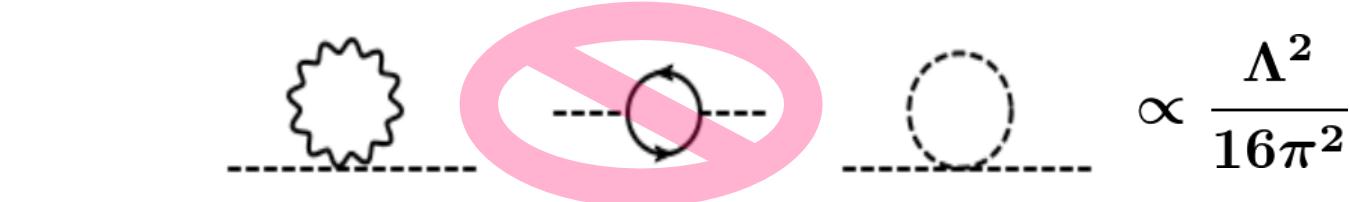
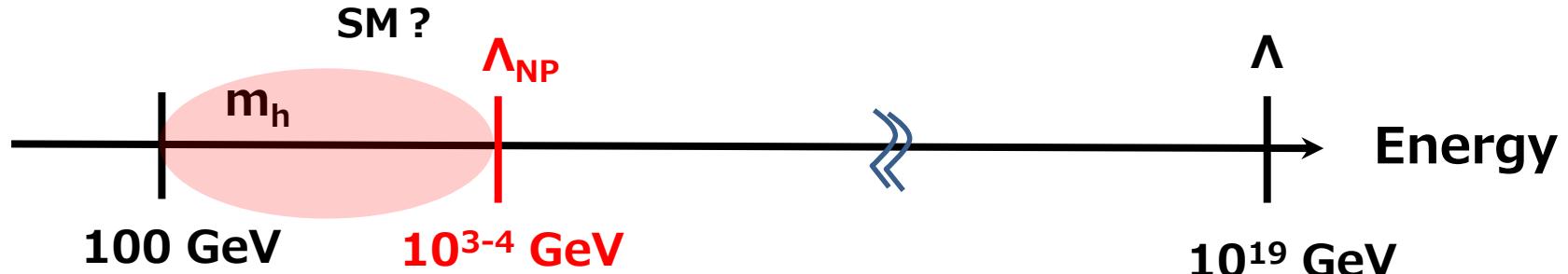
- At least now, we know



- This picture causes a huge fine-tuning in the Higgs boson mass.

What/Where is New Physics?

- At least now, we know



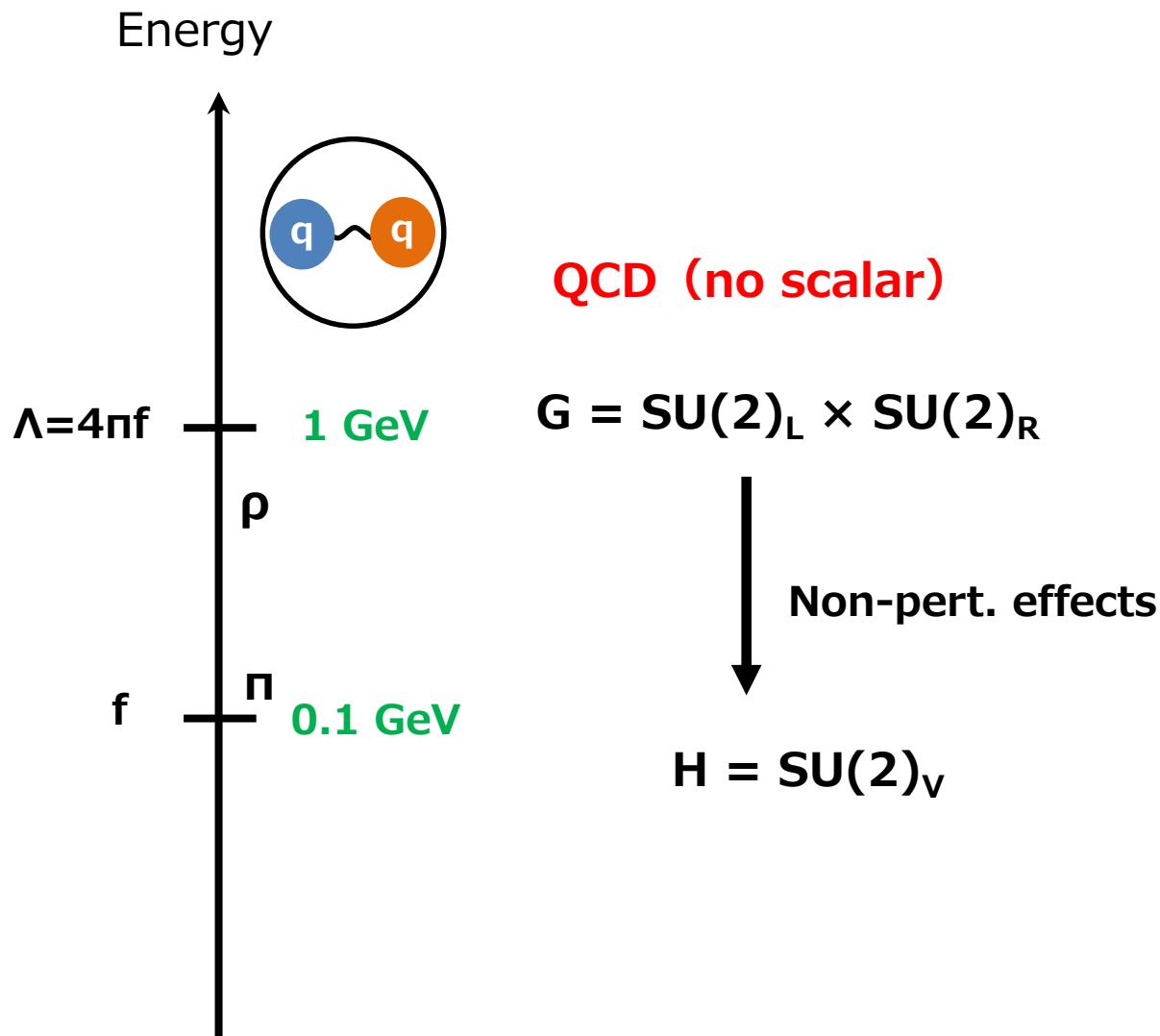
Higgs is a

- Scalar (SUSY) : Chiral symmetry
- Fermion (Composite Higgs) : Chiral symmetry
- Gauge boson (Gauge-Higgs unification): Gauge symmetry

Pion and Composite Higgs

Georgi, Kaplan (1984)

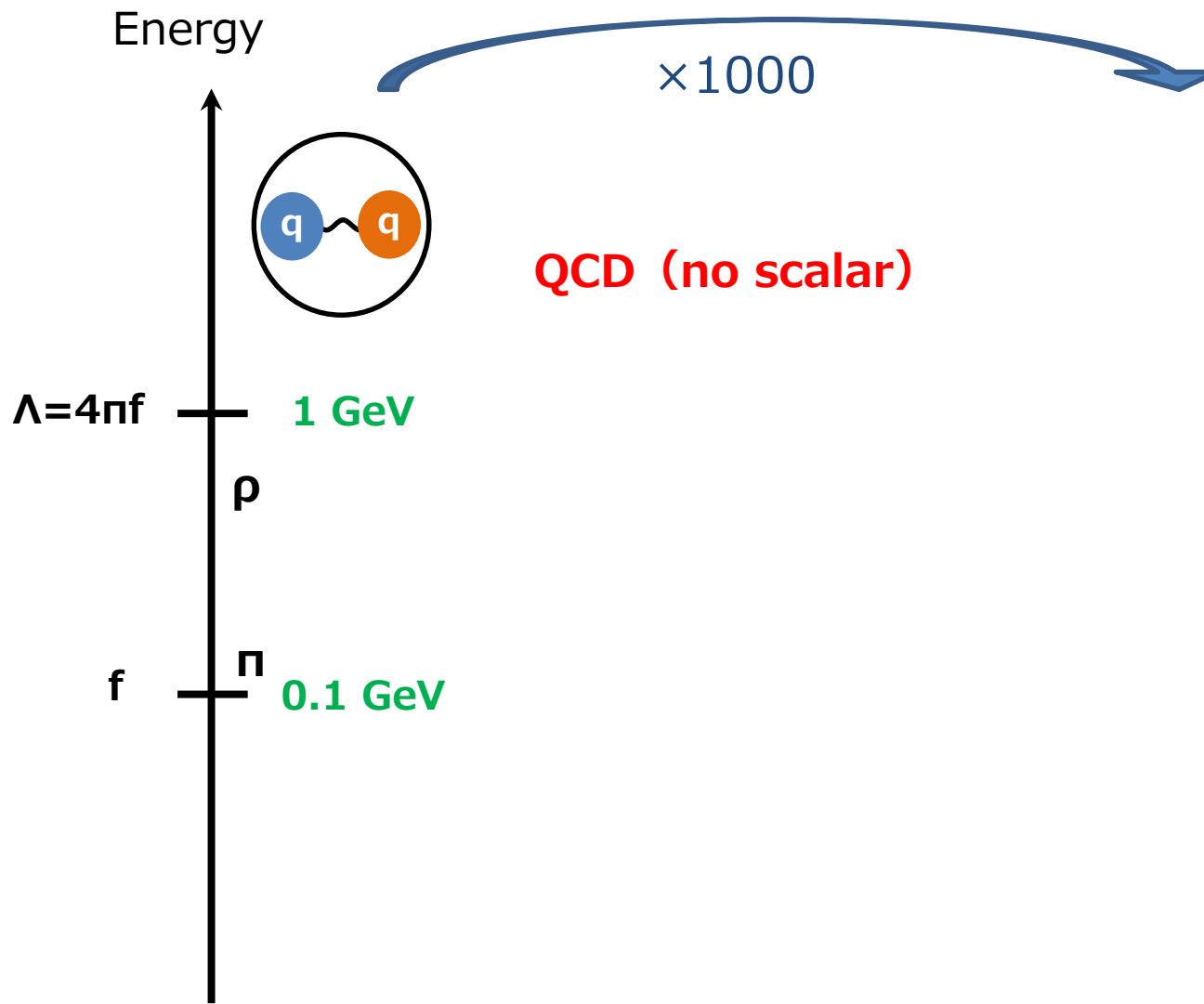
Contino, Nomura, Pomarol (2003)



Pion and Composite Higgs

Georgi, Kaplan (1984)

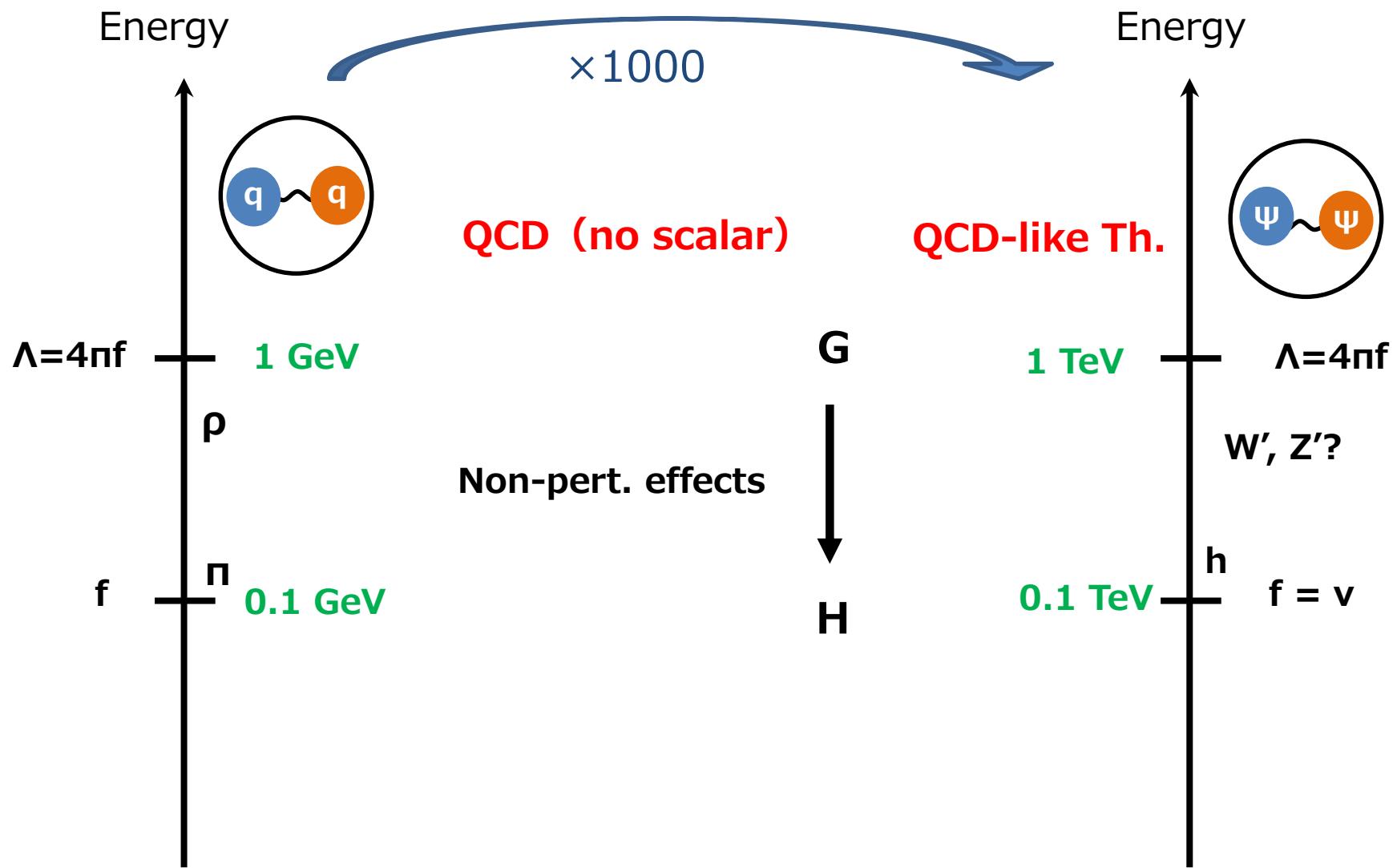
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Pion and Composite Higgs

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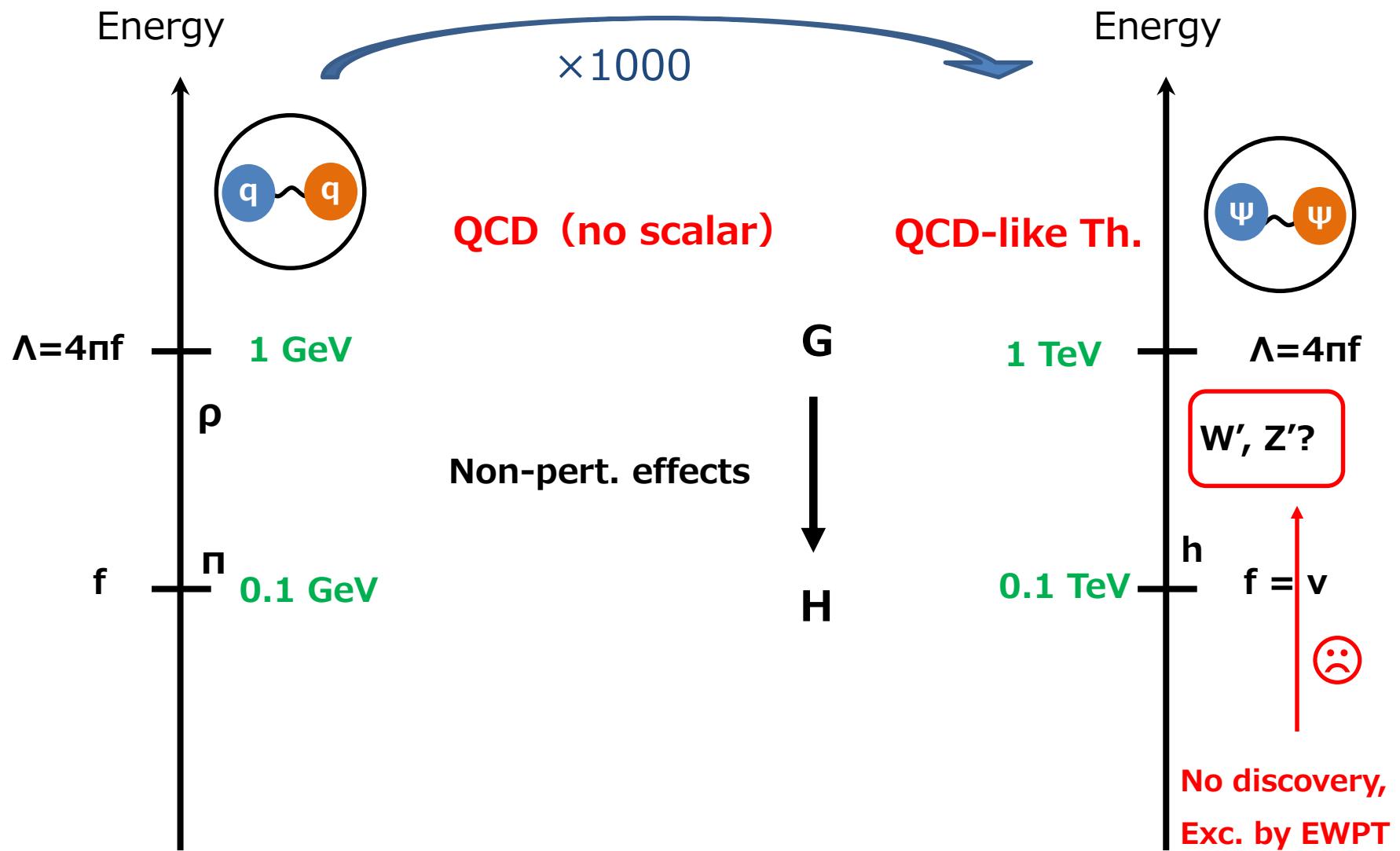
Contino, Nomura, Pomarol (2003)



Pion and Composite Higgs

Georgi, Kaplan (1984)

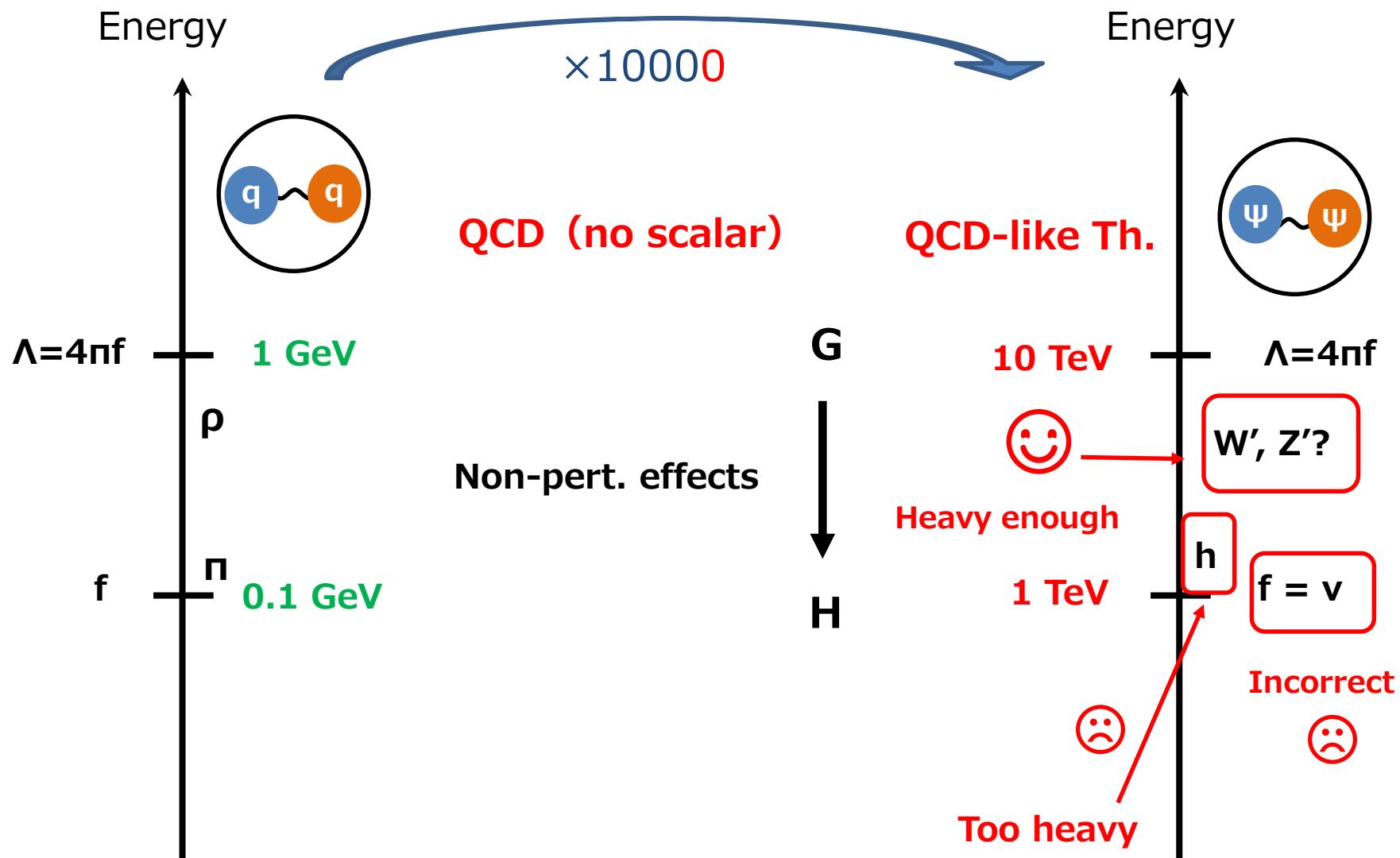
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Pion and Composite Higgs

Georgi, Kaplan (1984)

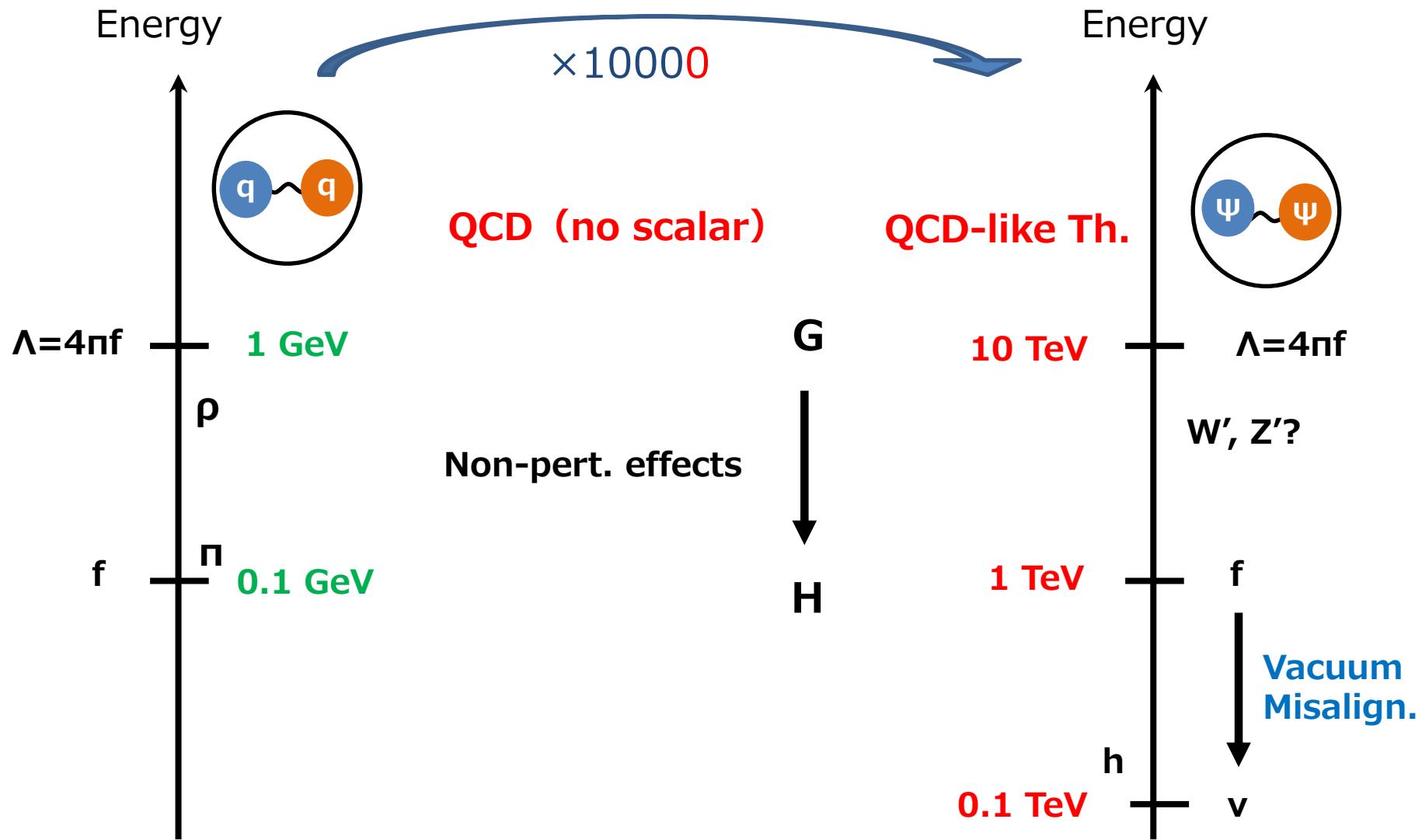
Contino, Nomura, Pomarol (2003)



Pion and Composite Higgs

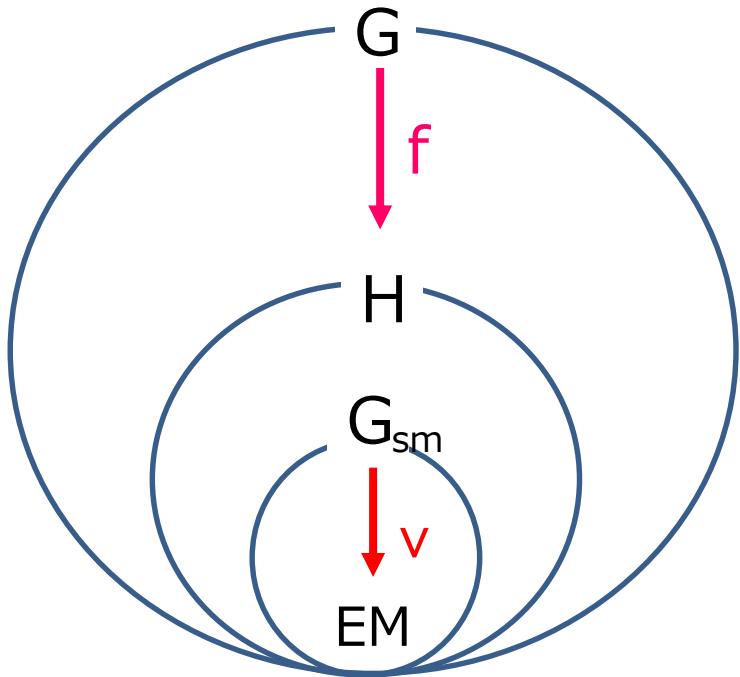
Georgi, Kaplan (1984)

Contino, Nomura, Pomarol (2003)



Basic Rules for the Construction

- The structure of the Higgs sector is determined by the **coset G/H** .
- H should contain the custodial $SO(4) \simeq SU(2)_L \times SU(2)_R$ symmetry.
- The number of NGBs ($\dim G - \dim H$) must be 4 or larger.
- Explicit breaking of G must be introduced. *Mrazek et al, NPB 853 (2011) 1-48*



G [dim]	H [dim]	Higgs sector
$SO(5)$ [10]	$SO(4)$ [6]	<i>Agashe, Contino, Pomarol (2005)</i> Φ
$SO(6)$ [15]	$SO(5)$ [10]	$\Phi + S$
$SO(6)$ [15]	$SO(4) \times SO(2)$ [7]	
$SU(5)$ [24]	$SU(4) \times U(1)$ [16]	$\Phi + \Phi'$
$Sp(6)$ [21]	$Sp(4) \times SU(2)$ [13]	
$SU(5)$ [24]	$SO(5)$ [10]	$\Phi + \Delta + S$ etc

Structure of CHMs

Elementary Sector

$$W_\mu^a, q_L, t_R$$

- Explicit G breaking
- No Higgs
- No potential & Yukawa

Mixing

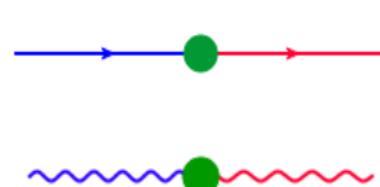
Strong Sector

$$\rho_\mu^A, \Psi^r, \Sigma$$

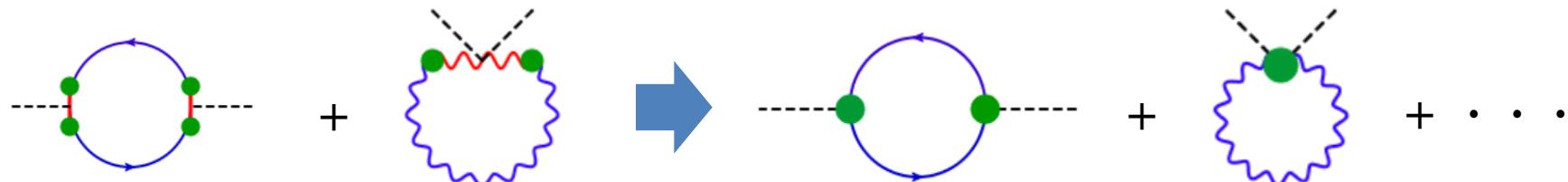
- Exact G symmetry
- $G/H \ni \Sigma$ (pNGBs)

Partial Compositeness

Only kinetic terms



Potential =



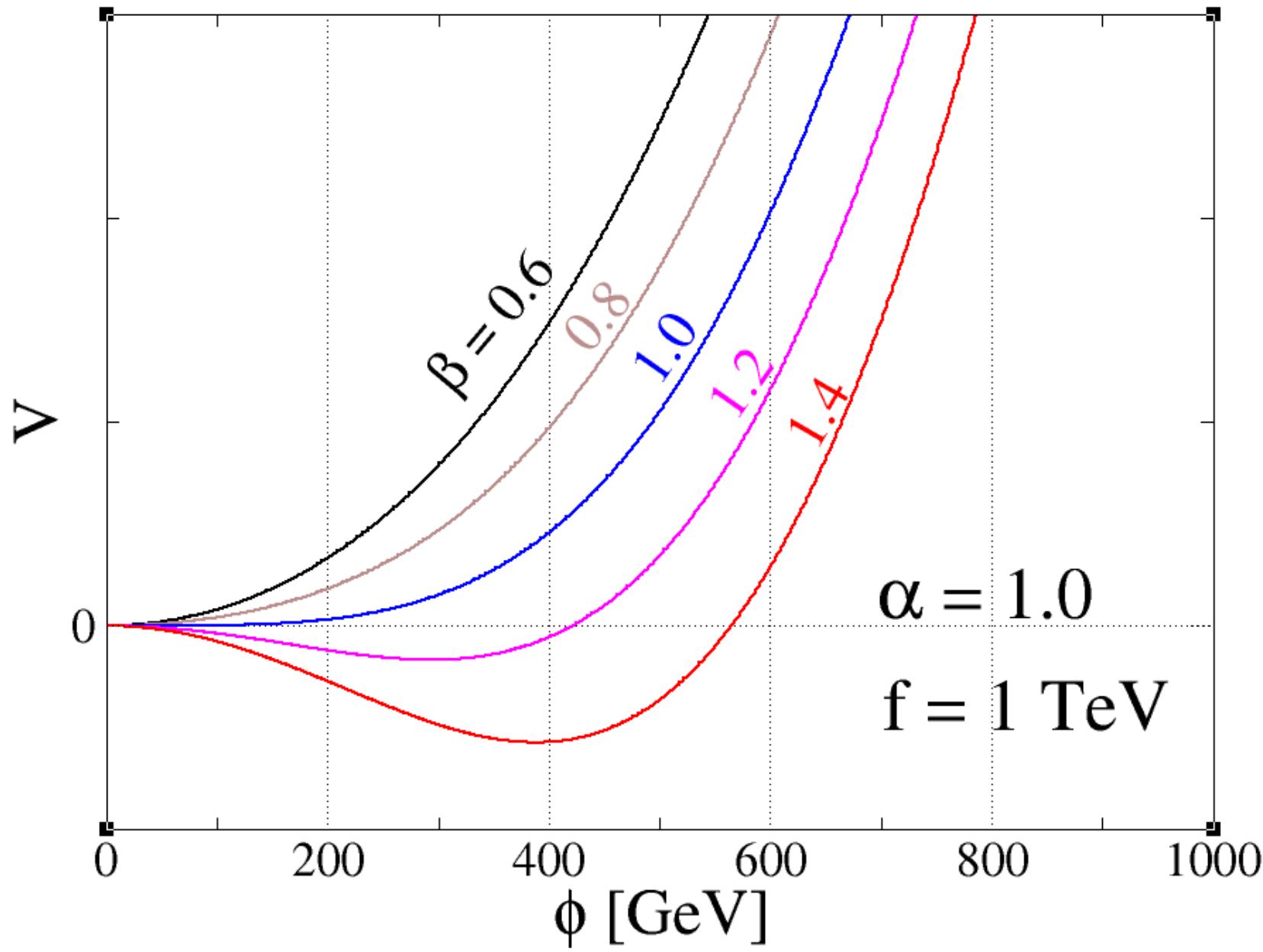
Vacuum misalignment

- The Higgs potential is written as

$$V \sim \frac{1}{16\pi^2} \left[\alpha \sin^2 \frac{\phi}{f} - \beta \sin^2 \frac{\phi}{f} \cos^2 \frac{\phi}{f} \right]$$


$$\frac{v_{\text{sm}}}{f} = \sin \frac{\langle \phi \rangle}{f} = \sqrt{\frac{\beta - \alpha}{\beta}}$$

Stationary condition ($V' = 0$)



Vacuum misalignment

- The Higgs potential is written as

$$V \sim \frac{f^4}{16\pi^2} \left[\alpha \sin^2 \frac{\phi}{f} - \beta \sin^2 \frac{\phi}{f} \cos^2 \frac{\phi}{f} \right]$$

➡ $\frac{v_{\text{sm}}}{f} = \sin \frac{\langle \phi \rangle}{f} = \sqrt{\frac{\beta - \alpha}{\beta}}$

Stationary condition ($V' = 0$)

➡ $m_h^2 = \frac{1}{16\pi^2} 8v^2 \beta \sim (125 \text{ GeV})^2 \times \left(\frac{\beta}{5}\right)$

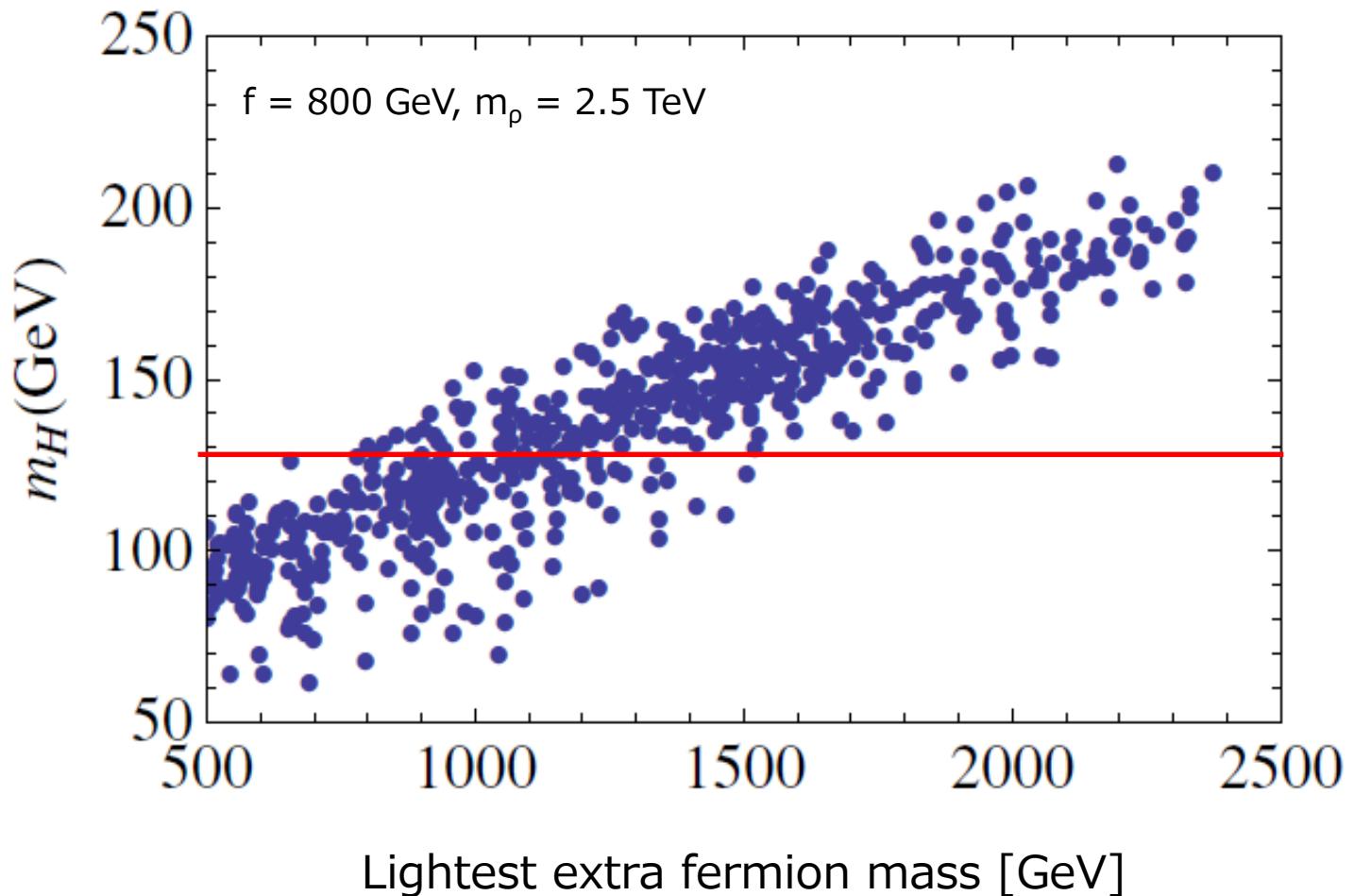
Higgs Mass (V'')

The light Higgs boson is naturally explained by an O(1) coefficient.

α and β can be predicted from strong dynamics.

Higgs boson mass (Minimal CHM)

De Curtis, Redi, Tesi, JHEP04 (2012) 042



Structure of CHMs

Elementary Sector

$$W_\mu^a, q_L, t_R$$

- Explicit G breaking
- No Higgs
- No potential & Yukawa

Mixing

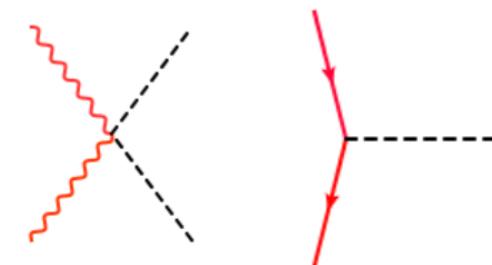
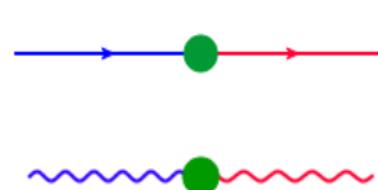
Partial Compositeness

Strong Sector

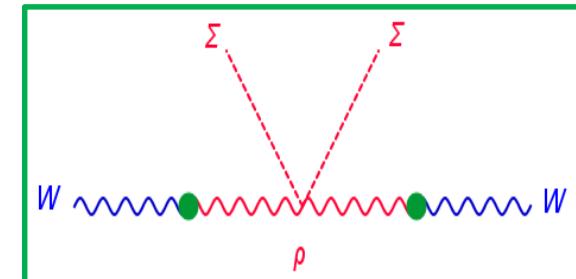
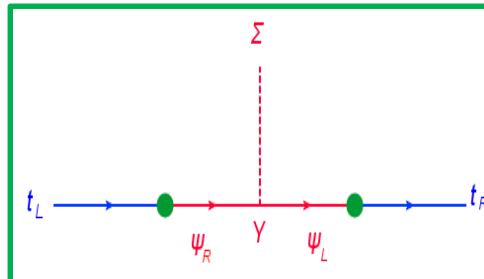
$$\rho_\mu^A, \Psi^r, \Sigma$$

- Exact G symmetry
- $G/H \ni \Phi$ (pNGBs)

Only kinetic terms



Higgs boson couplings:



Higgs boson couplings

Kanemura, Kaneta, Machida, Shindou, PRD91 (2014) 115016

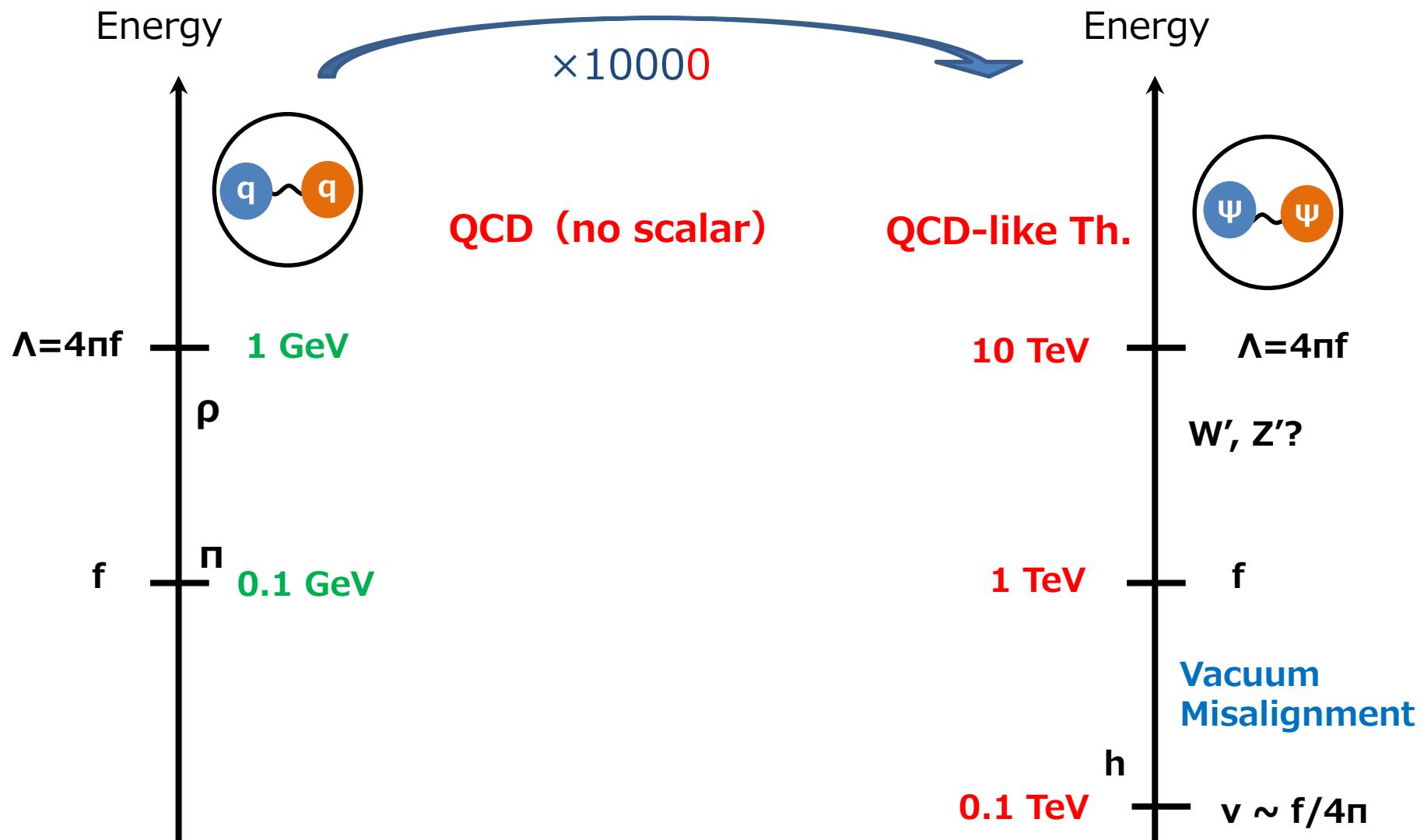
Model	κ_V	c_{hhVV}	κ_{hhh}	c_{hhhh}	κ_t	κ_b	c_{hhtt}	c_{hhbb}
MCHM ₄	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$	$1-\frac{7}{3}\xi$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
MCHM ₅	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
MCHM ₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
MCHM ₁₄	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_3	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_6	-4ξ
MCHM ₅₋₅₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\sqrt{1-\xi}$	-4ξ	$-\xi$
MCHM ₅₋₁₀₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\xi$	$-\xi$
MCHM ₅₋₁₄₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_5	$\sqrt{1-\xi}$	F_8	$-\xi$
MCHM ₁₀₋₅₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$-\xi$	-4ξ
MCHM ₁₀₋₁₄₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
MCHM ₁₄₋₁₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-28\xi/3+28\xi^2/3}{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-4ξ	-4ξ
MCHM ₁₄₋₅₋₁₀	$\sqrt{1-\xi}$	$1-2\xi$	H_1	H_2	F_4	$\frac{1-2\xi}{\sqrt{1-\xi}}$	F_7	-4ξ

Fingerprinting is possible among various MCHMs!

Pion and Composite Higgs

Georgi, Kaplan (1984)

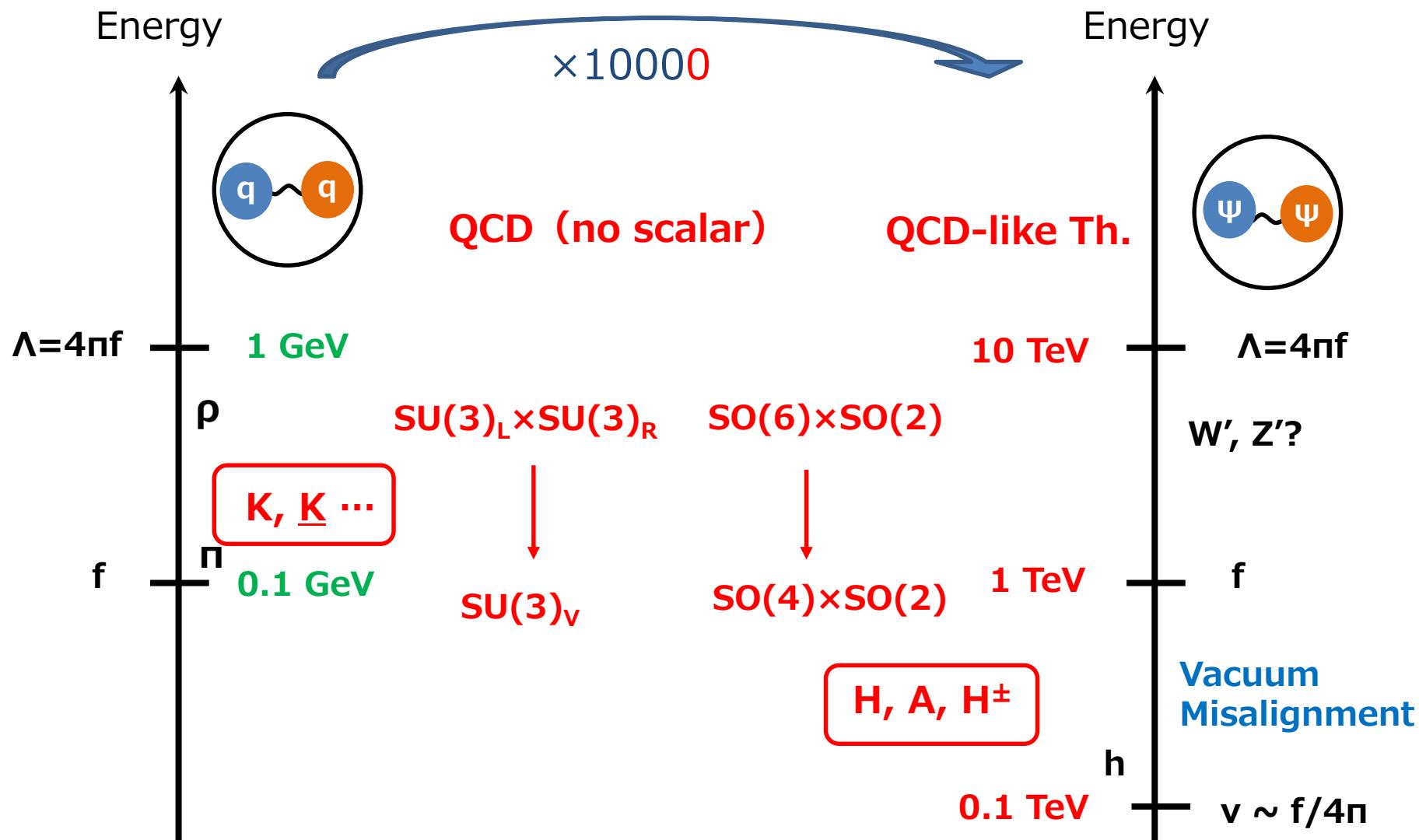
Contino, Nomura, Pomarol (2003)



Pion and Composite Higgs

Georgi, Kaplan (1984)

Contino, Nomura, Pomarol (2003)



Effective Potential

$$\begin{aligned} V(\Phi_1, \Phi_2) = & m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - [m_3^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] \\ & + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \text{h.c.} + \mathcal{O}(\Phi^6) \end{aligned}$$

All the potential parameters \mathbf{m}_i^2 and λ_i are given as a function of strong parameters:

$$m_i^2 = m_i^2(g_\rho, f, \dots) \quad \lambda_i = \lambda_i(g_\rho, f, \dots)$$

Effective Potential

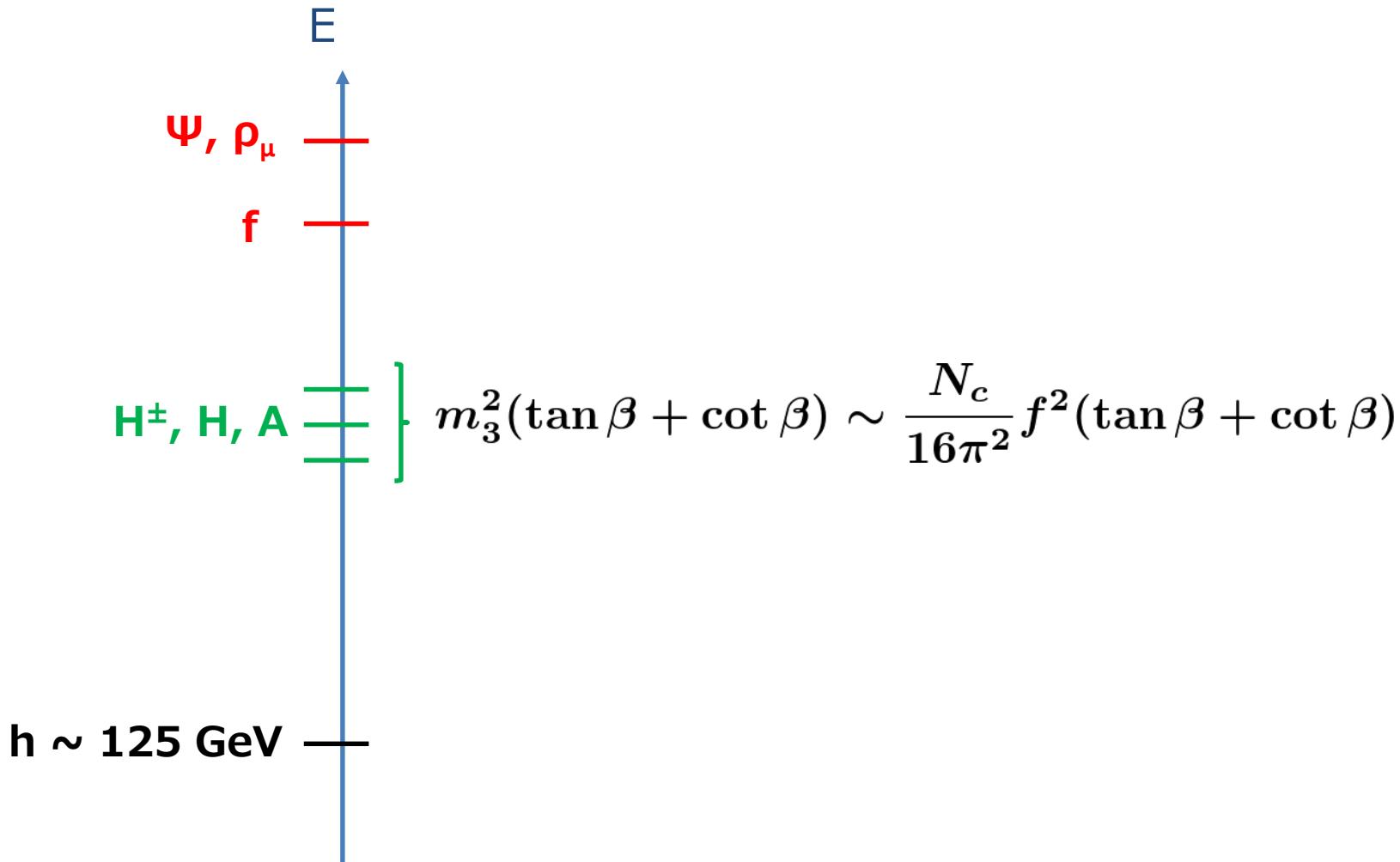
$$\begin{aligned} V(\Phi_1, \Phi_2) = & m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - \left[m_3^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] \\ & + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \text{h.c.} + \mathcal{O}(\Phi^6) \end{aligned}$$

□ Fermion loop contributions

$$\frac{5m_3^2}{3f^2} = \lambda_6 = \lambda_7$$

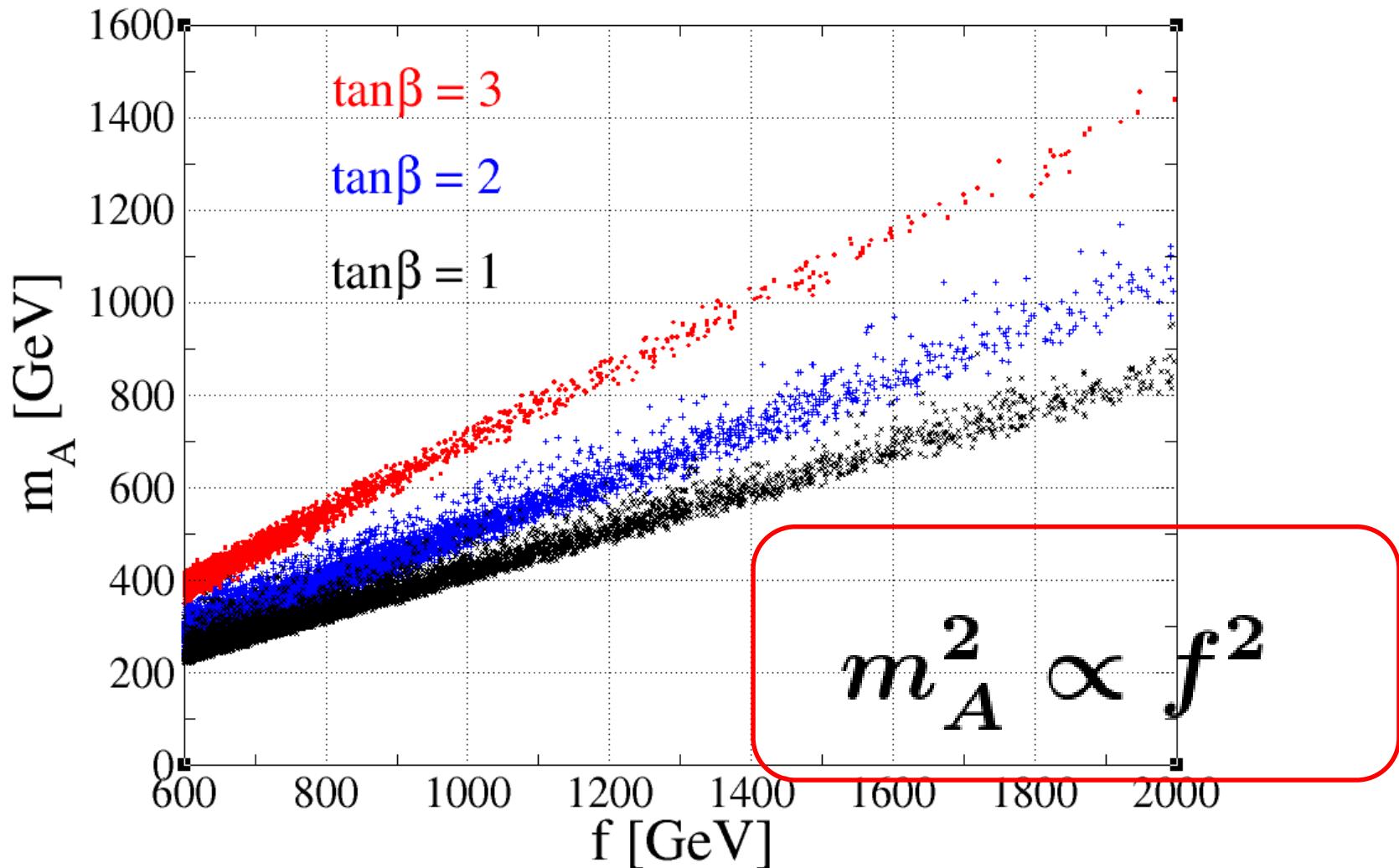
→ { Hardly-broken Z_2 symmetry
Unbroken Z_2 symmetry (Inert 2HDM)

Typical Prediction of Mass Spectrum



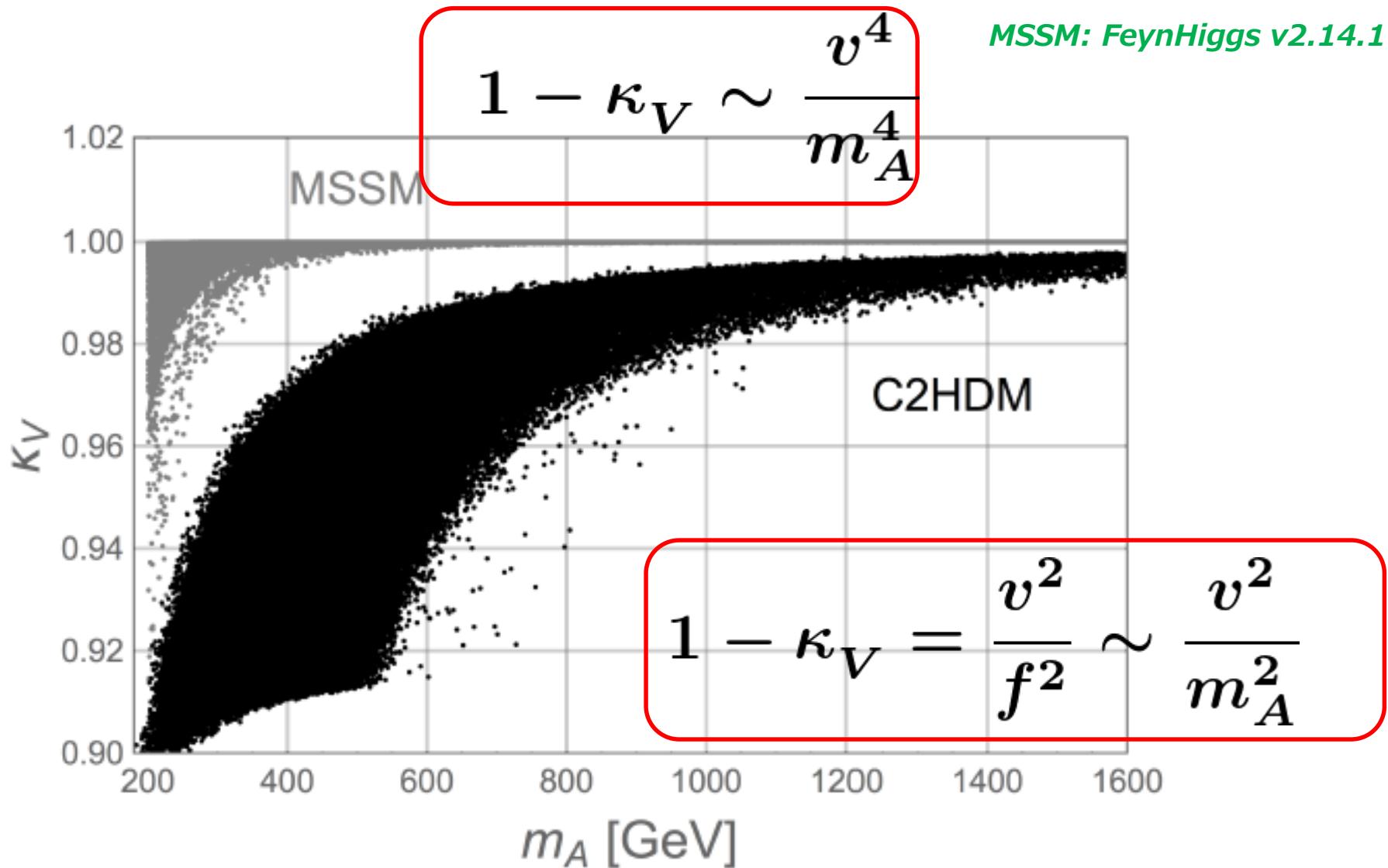
Correlation b/w f and m_A

De Curtis, Delle Rose, Moretti, KY, arXiv: 1803.01865 [hep-ph]



Correlation b/w m_A and κ_V ($= g_{hVV}/g_{hVV}^{\text{SM}}$)

De Curtis, Delle Rose, Moretti, KY, arXiv: 1803.01865 [hep-ph]

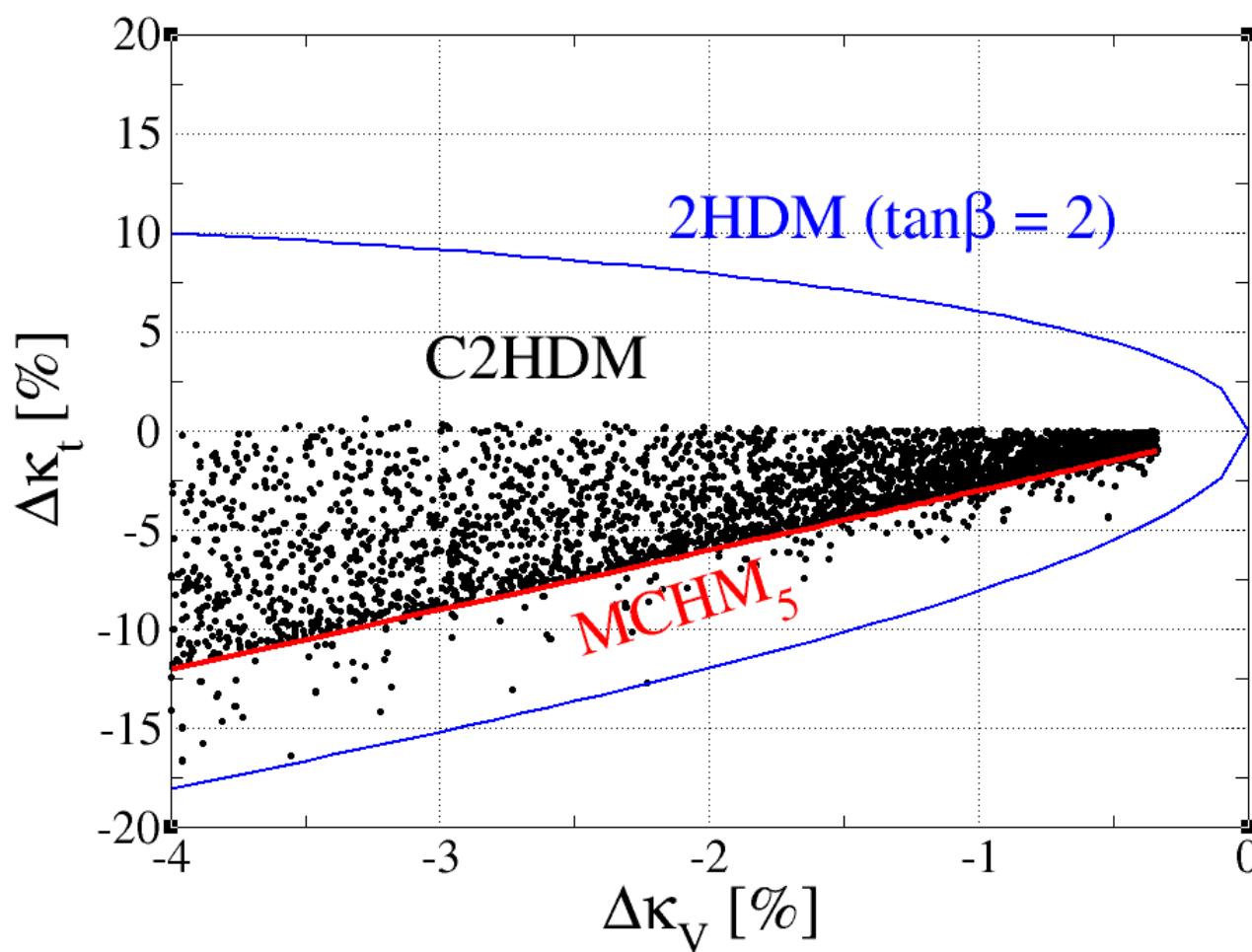


Correlation b/w κ_V and κ_t

$800 < f < 3000 \text{ GeV}$

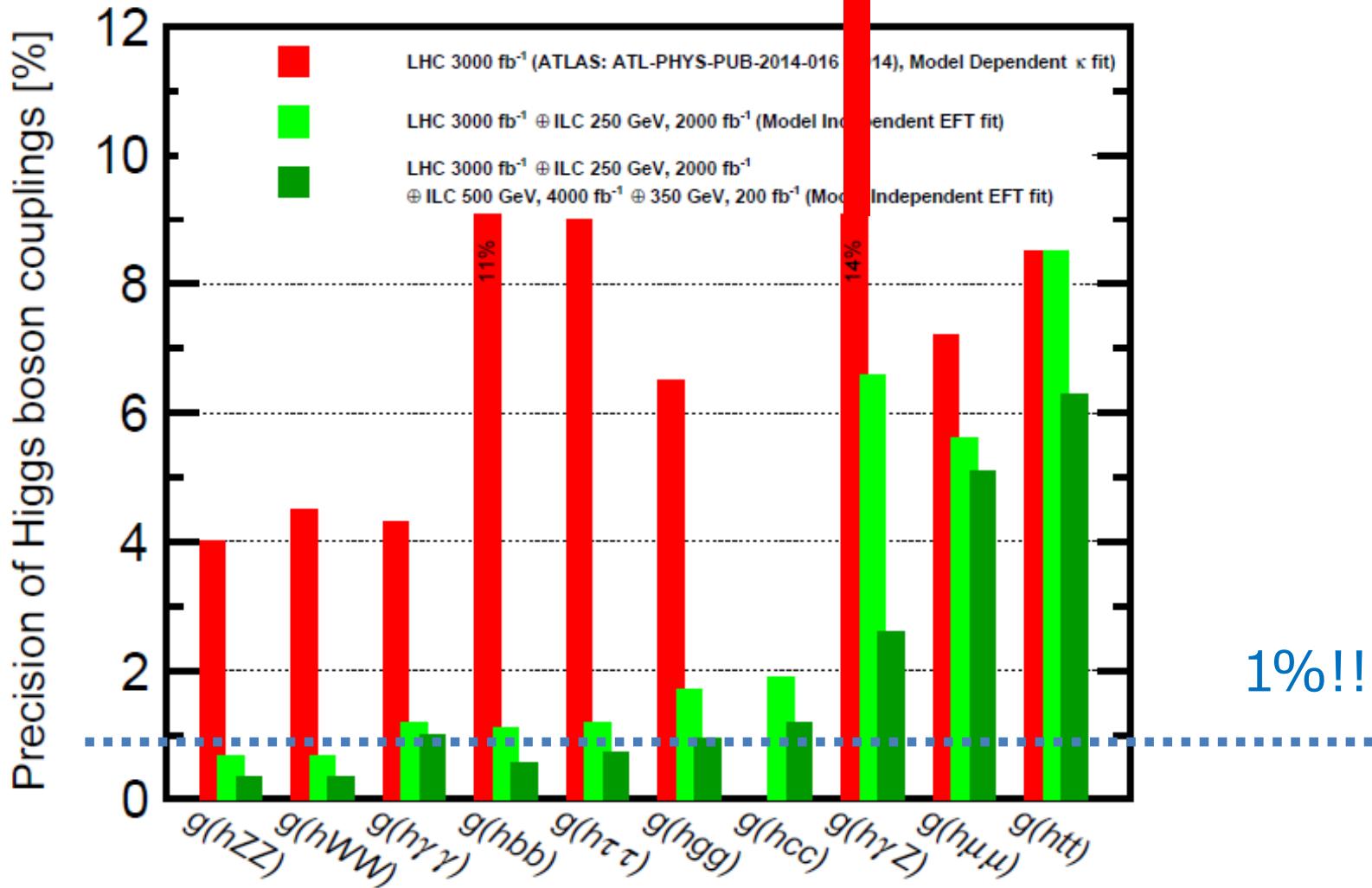
$$\Delta\kappa_t \simeq \Delta\kappa_V(3 - 2X)$$

$$0 \lesssim X \lesssim 1$$



Summary

- CHMs (Higgs = pNGB) can naturally explain the light Higgs boson.
- The Higgs potential is predictable from strong dynamics.
- Non-minimal Higgs sectors can also be constructed by taking larger cosets.
- C2HDMs have **slower decoupling property** (c.f. MSSM).
- Correlation b/w κ_V and κ_t can be significantly different
in the MCHM₅, C2HDM and 2HDM.



Setup for C2HDM

- We introduce SO(6) 6-plet fermions for the explicit Lagrangian:

$$\mathcal{L}_{\text{str}} = \bar{\Psi}^6 (i \not{D} - m_{\Psi}) \Psi^6 - \bar{\Psi}_L^6 (\cancel{Y_1 \Sigma} + Y_2 \Sigma^2) \Psi_R^6 + \text{h.c.}$$
$$+ \Delta_L \bar{q}_L^6 \Psi_R^6 + \Delta_R \bar{t}_R^6 \Psi_L^6 + \text{h.c.}$$

- Z_2 -like symmetry in the strong sector can be introduced.

C_2 symmetry

(to avoid FCNCs)

$$U(\phi_1^{\hat{a}}, \phi_2^{\hat{a}}) \rightarrow C_2 U(\phi_1^{\hat{a}}, \phi_2^{\hat{a}}) C_2 = U(\phi_1^{\hat{a}}, -\phi_2^{\hat{a}})$$

$$\Sigma \rightarrow -C_2 \Sigma C_2$$

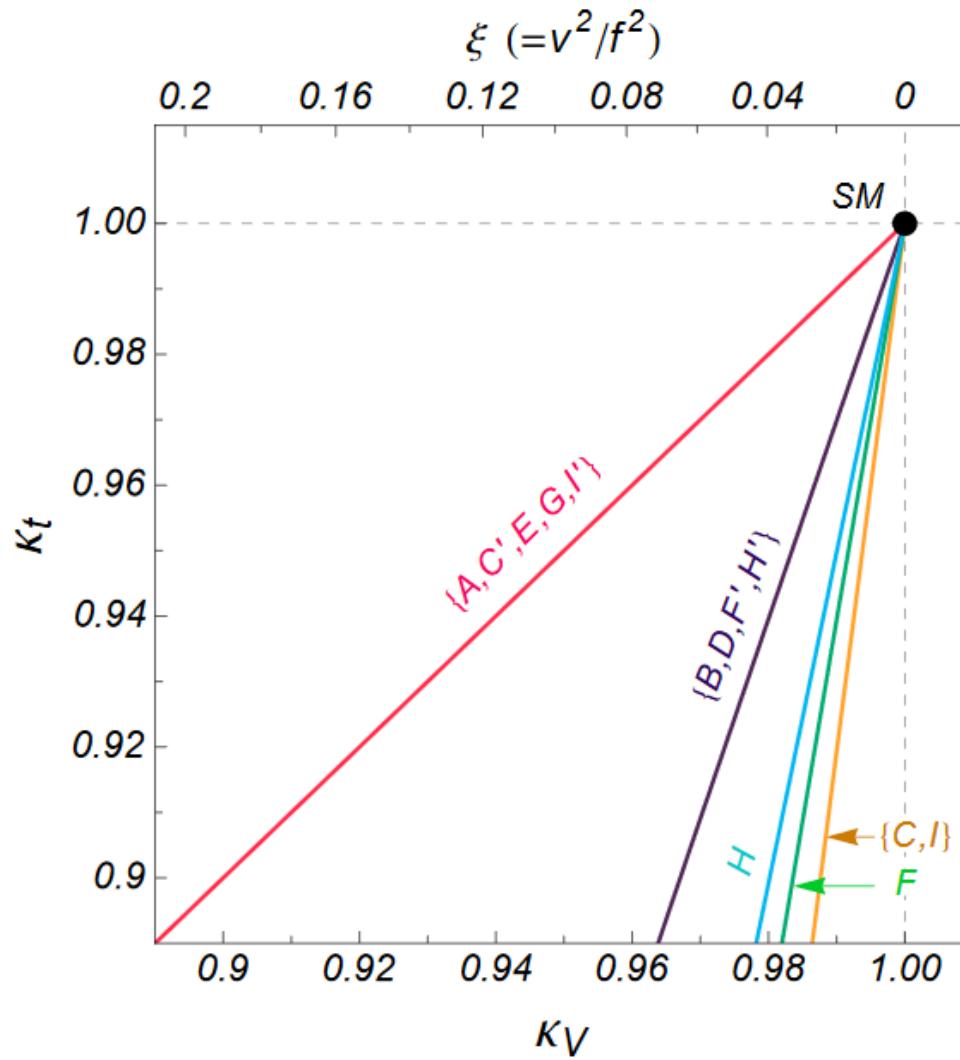
$$\Psi^6 \rightarrow C_2 \Psi^6$$

$$C_2 = \text{diag}(1, 1, 1, 1, 1, -1)$$

1. Unbroken case, 2. Spontaneously broken case and
3. Hardly broken case
(there is no option for the softly-breaking)

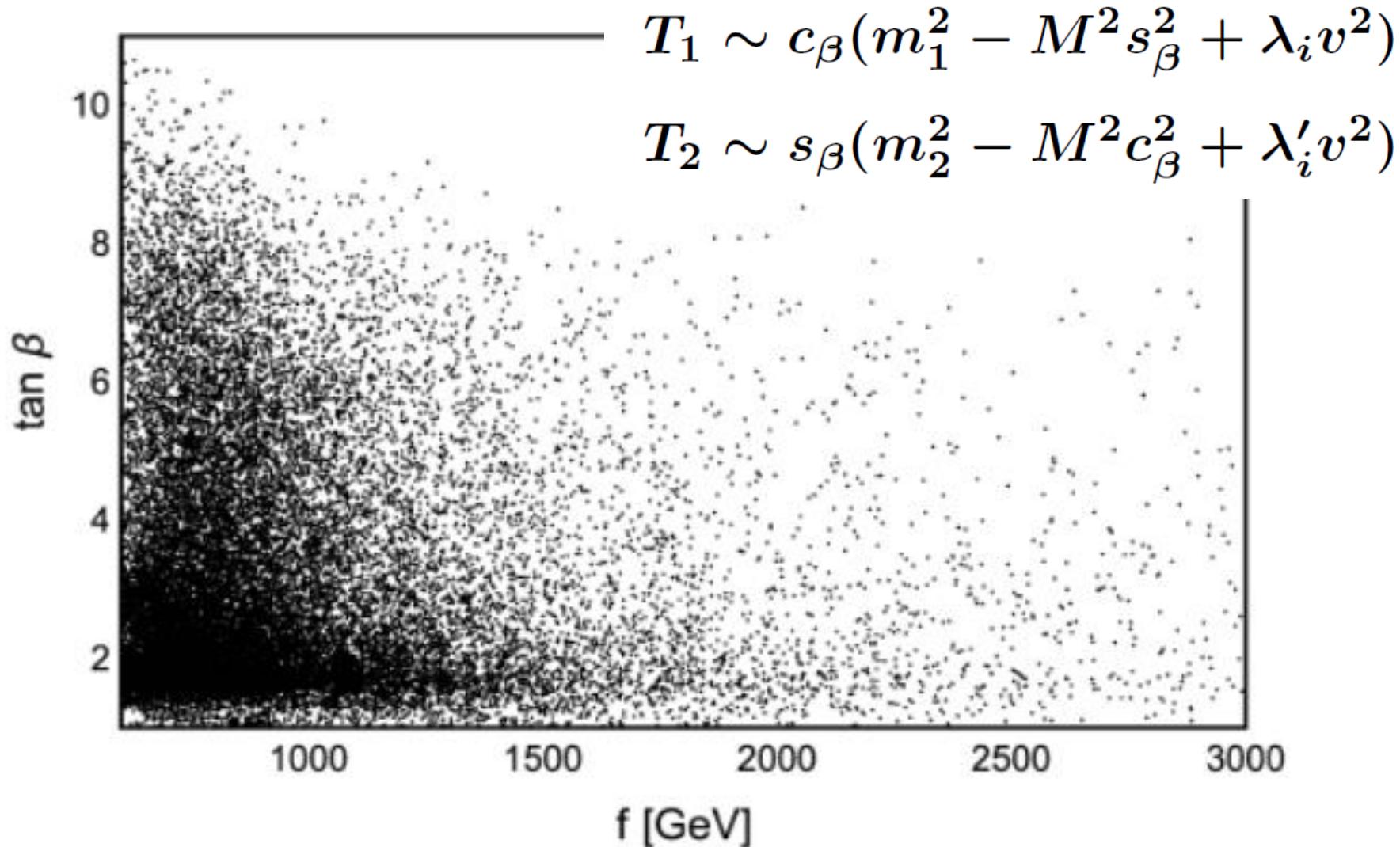
Higgs boson couplings

Kanemura, Kaneta, Machida, Shindou, PRD91 (2014) 115016

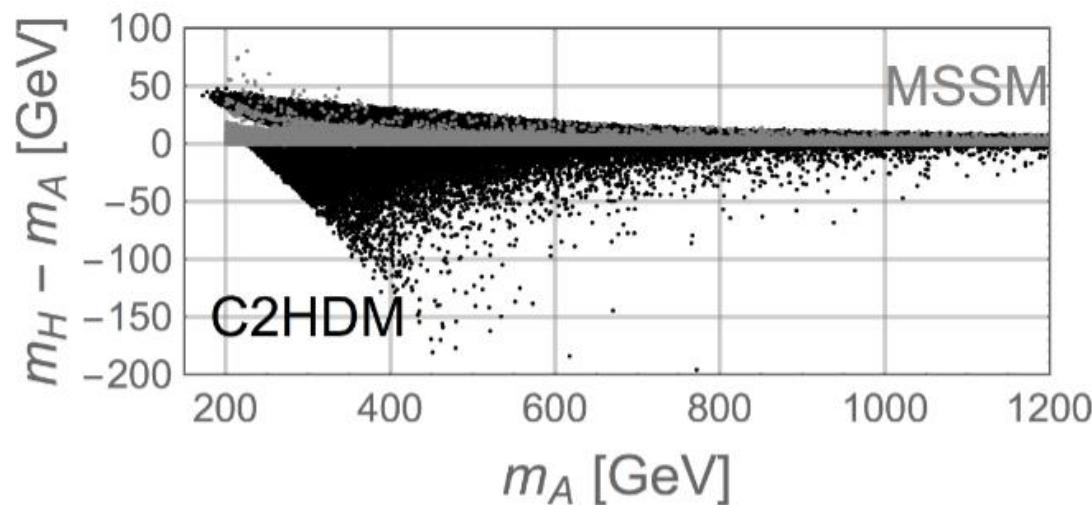
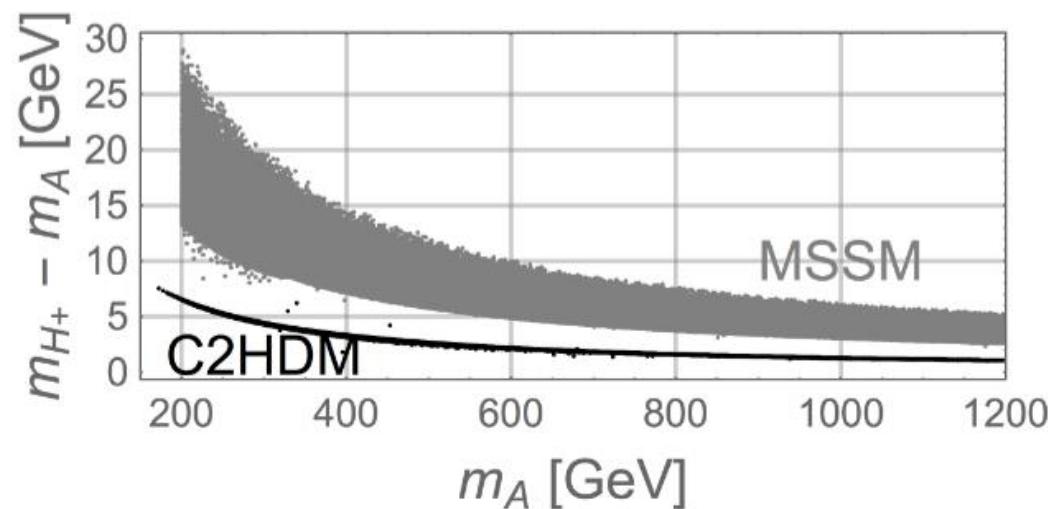


f VS tan β

De Curtis, Delle Rose, Moretti, KY, arXiv: 1803.01865 [hep-ph]



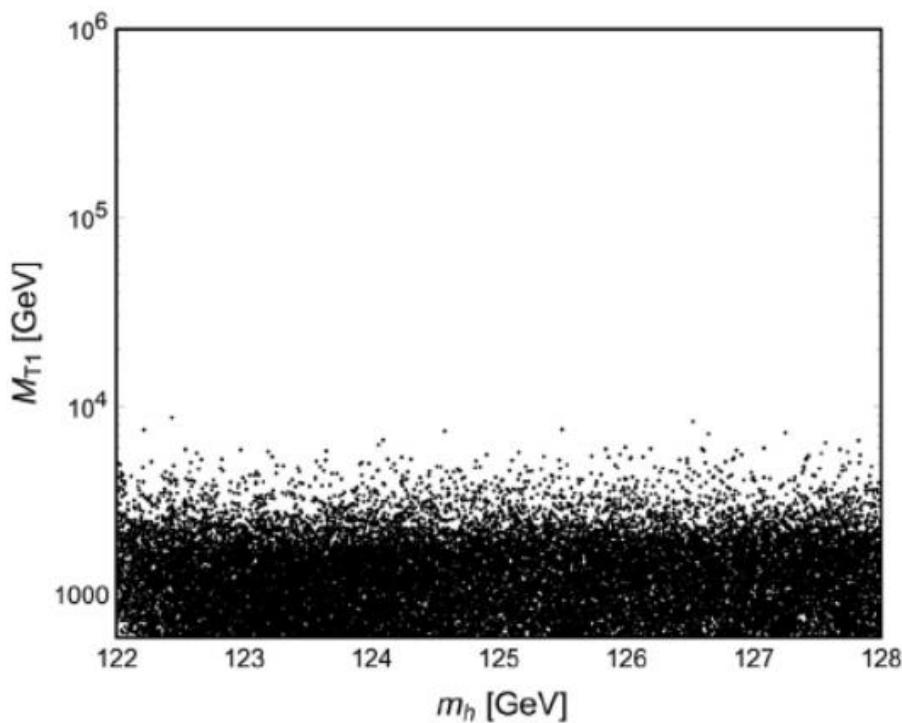
Correlation b/w m_A and mass differences



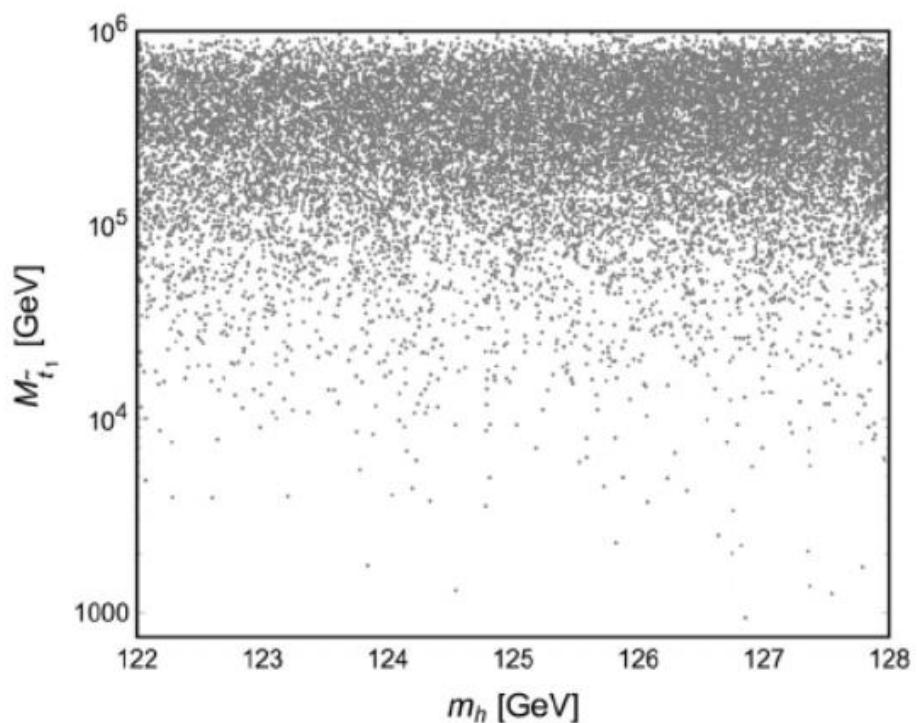
Masses of heavy top partners

De Curtis, Delle Rose, Moretti, KY, arXiv: 1803.01865 [hep-ph]

C2HDM



MSSM

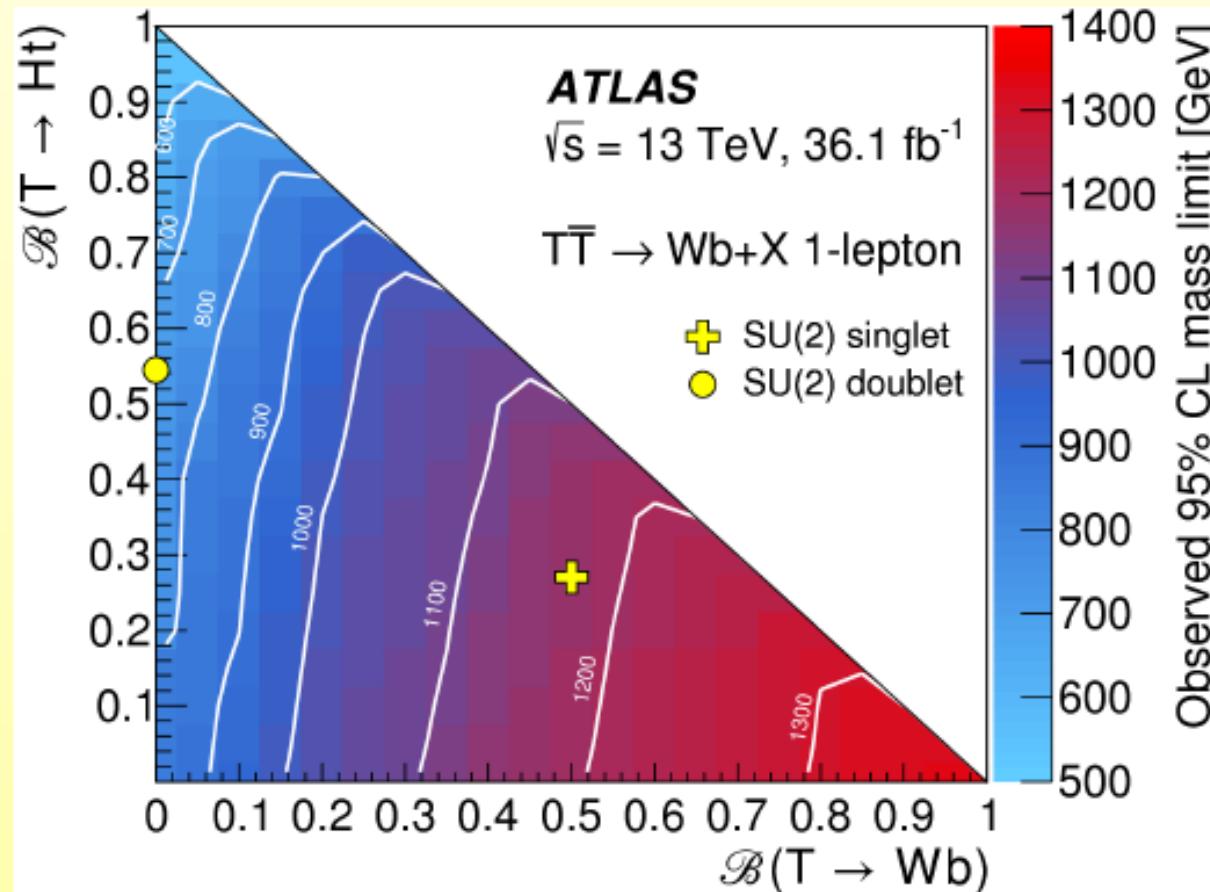


- Direct bounds

Slide from Csaba Csaki

Spin 1/2 top partners

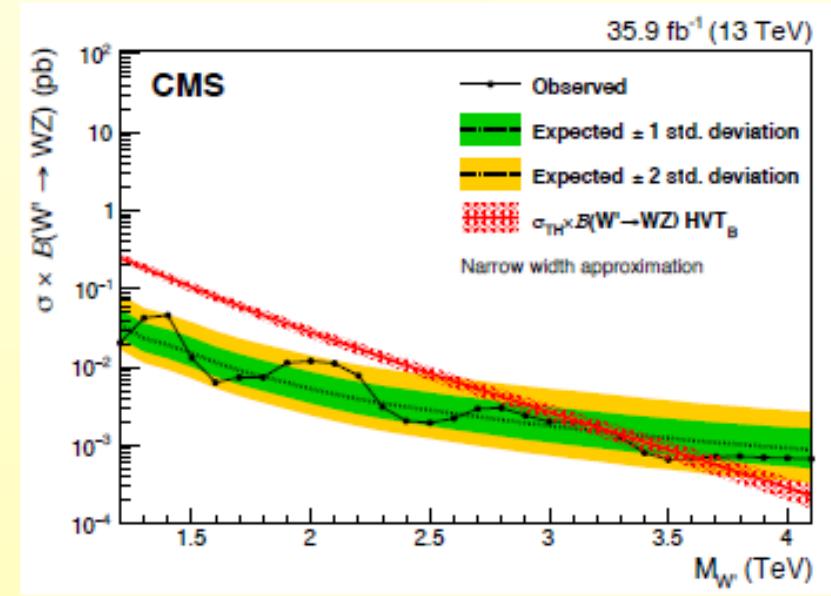
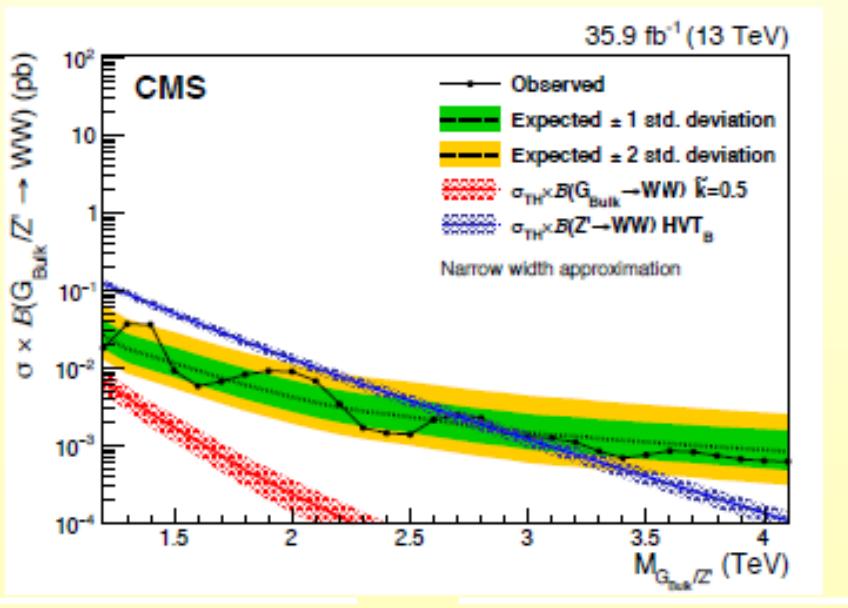
Recent CMS bound > 1.3 TeV



- Direct bounds

Spin 1 partners W' , Z'

Slide from Csaba Csaki



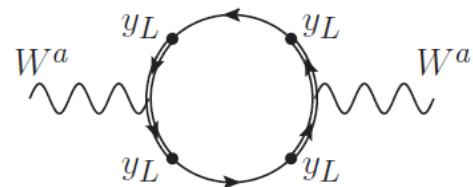
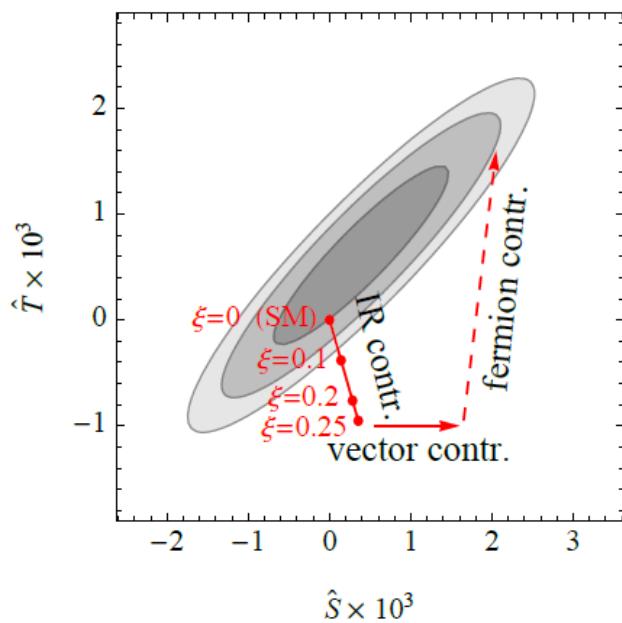
S, T parameter

Panico, Wulzer, arXiv:1506.01961

□ Contribution from heavy resonances



$$\Delta \hat{S} = \frac{g_0^2}{2\tilde{g}_\rho^2} \xi \simeq \frac{m_W^2}{m_\rho^2}$$



$$\Delta \hat{T} \simeq \frac{N_c}{16\pi^2} \frac{y_L^4 f^2}{m^2} \xi$$

$$y_L = \Delta_L/f, m : \text{lightest fermion partner mass}$$