# Composite 2HDMs and their CPV phenomena

Kei Yagyu（Osaka U.）

*S. D. Curtis, L. D. Rose, S. Moretti and KY, 1810.06465 [hep-ph] (JHEP)*

*S. D. Curtis, S. Moretti, R. Nagai and KY, 2107.08201 [hep-ph] (JHEP)*

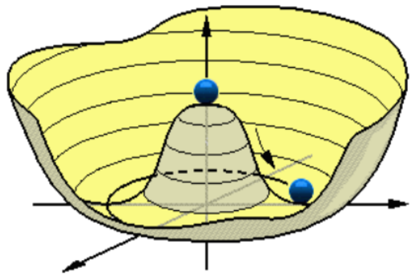
LHC Higgs WG3 Subgroup: Extended Higgs Sector

2021, Nov. 5th, Online

# Higgs Problems

- So far, the SM Higgs sector can successfully describe current experimental data.

$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$



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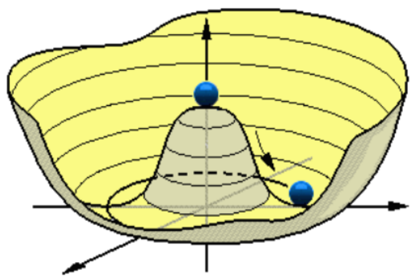

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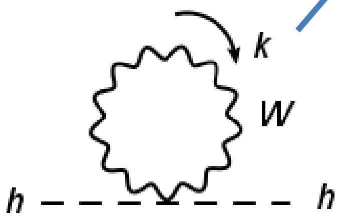


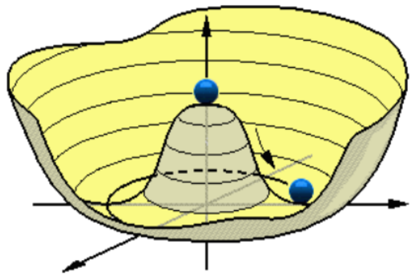

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Any other representations?

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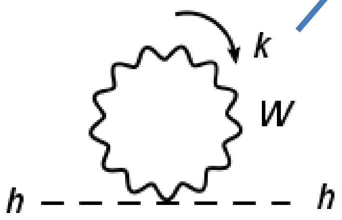


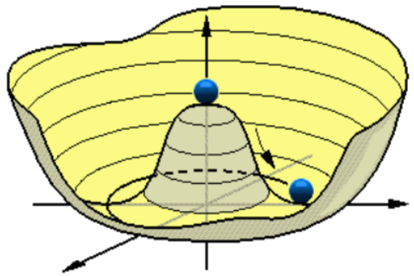

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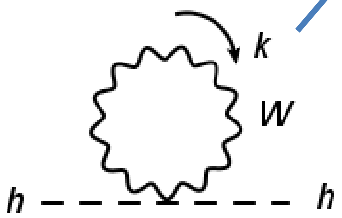


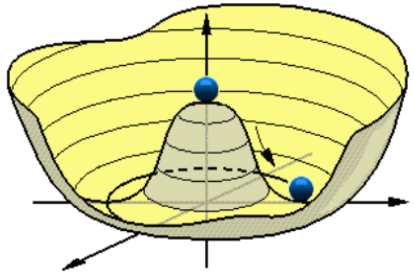

Yukawa coupling? $\frac{y_e}{y_t} \sim 10^{-5}$

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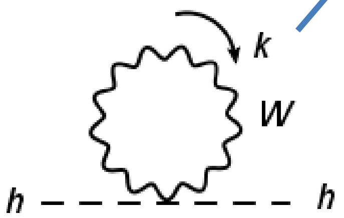


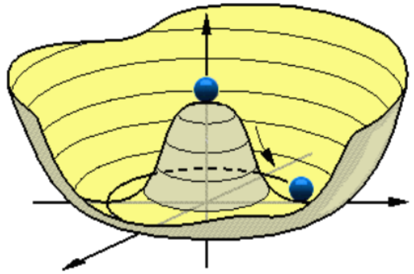

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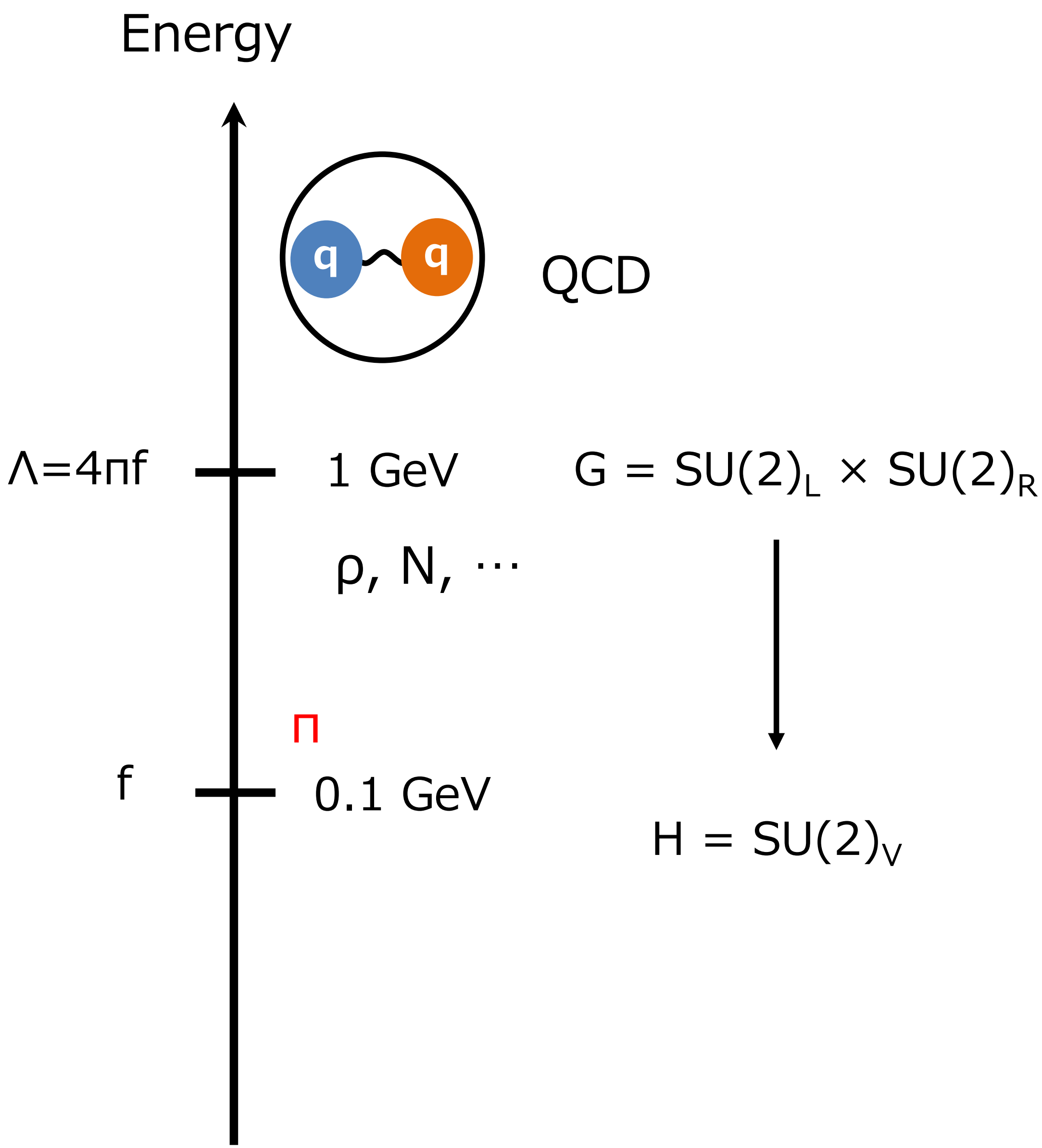
The Higgs sector is the center of the problem in the SM.

Composite Higgs scenario can explain the origin of EWSB.

# Higgs as a pseudo Nambu-Goldstone

*Georgi, Kaplan (1984)*



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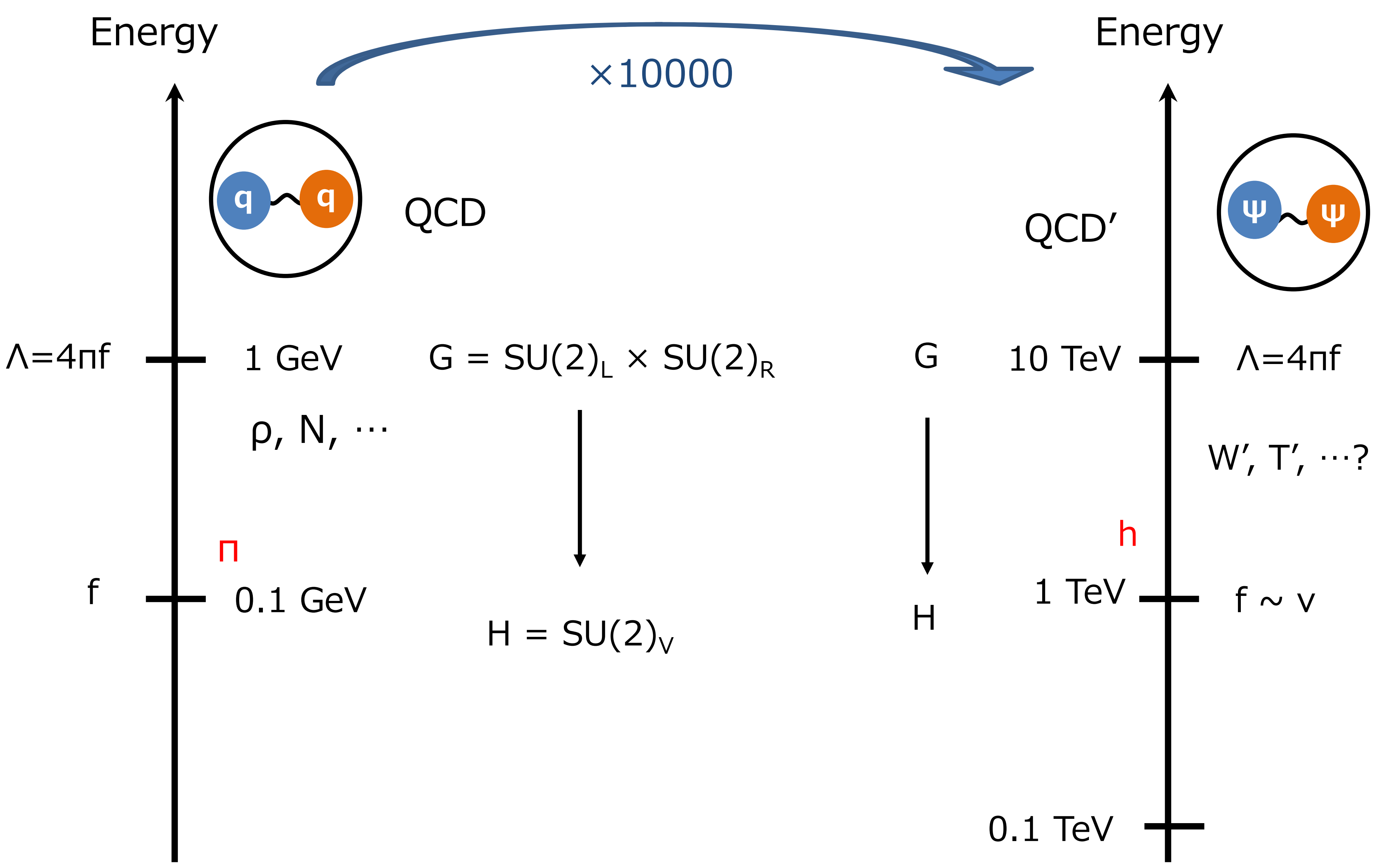

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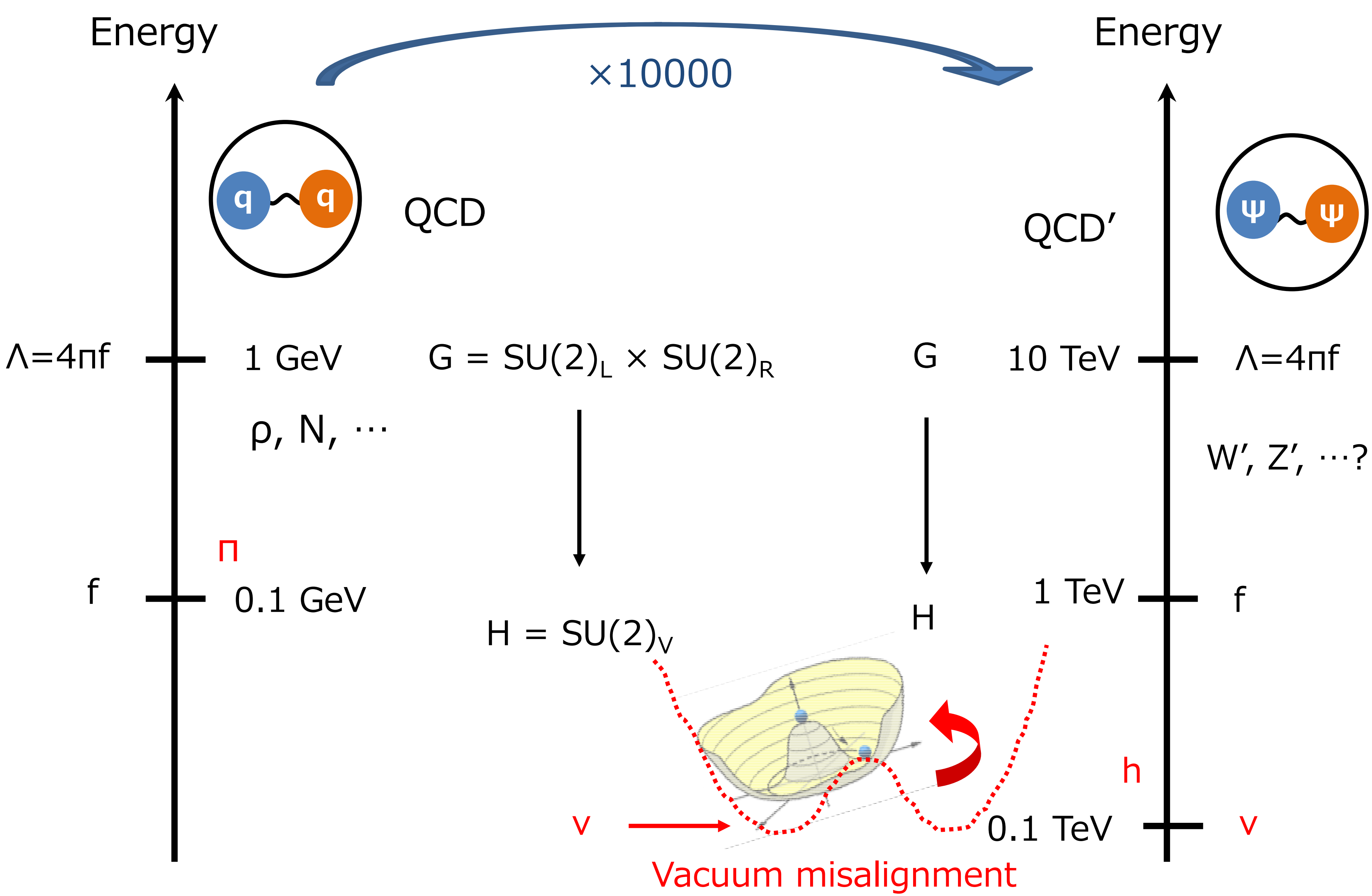


# Composite Higgs Models

*Mrazek et al, NPB 853 (2011) 1-48*

| G [dim] | H [dim] | Higgs sector |
|---|---|---|
| SO(5) [10] | SO(4) [6] | Φ *(Agashe, Contino, Pomarol (2005))* |
| SO(6) [15] | SO(5) [10] | Φ + S |
| SO(6) [15] | SO(4)×SO(2) [7] | Φ + Φ′ |
| SU(5) [24] | SU(4)×U(1) [16] | |
| Sp(6) [21] | Sp(4)×SU(2) [13] | |
| SU(5) [24] | SO(5) [10] | Φ + Δ + S |
| | | etc. |

# Composite 2HDMs（C2HDMs）

*Mrazek et al (2011)*

*De Curtis, Delle Rose, Moretti, KY (2018)*

- G/H: SO(6) × U(1)$_X$ / SO(4) × SO(2) × U(1)$_X$

- SO(6) generators (15): $T^A = \{\underline{T^a_{L,R}},\ \underline{T_S},\ \underline{T^{\hat{a}}_{1,2}}\}$ (A=1-15, a=1-3, $\hat{a}$=1-4)

  6 SO(4)  1 SO(2)  8 Broken

- NGB Mat.: $U = \exp\sqrt{2}i\left[T_1^{\hat{a}}\frac{\phi_1^{\hat{a}}}{f} + T_2^{\hat{a}}\frac{\phi_2^{\hat{a}}}{f}\right] = \exp\frac{-i}{f}\begin{pmatrix} 0 & 0 & 0 & 0 & \phi_1^1 & \phi_2^1 \\ 0 & 0 & 0 & 0 & \phi_1^2 & \phi_2^2 \\ 0 & 0 & 0 & 0 & \phi_1^3 & \phi_2^3 \\ 0 & 0 & 0 & 0 & \phi_1^4 & \phi_2^4 \\ -\phi_1^1 & -\phi_1^2 & -\phi_1^3 & -\phi_1^4 & 0 & 0 \\ -\phi_2^1 & -\phi_2^2 & -\phi_2^3 & -\phi_2^4 & 0 & 0 \end{pmatrix}$

  2 Higgs Doublets

- **15**-plet : $\Sigma = U\Sigma_0 U^T$

$$\Sigma_0 = i\sqrt{2}T_S = \begin{pmatrix} 0_{4\times4} & 0_{4\times2} \\ 0_{2\times4} & i\sigma_2 \end{pmatrix}$$

$$\Sigma \underset{g}{\rightarrow} \Sigma' = g\,\Sigma\,g^{-1}$$

# Structure of C2HDM

*Mrazek et al (2011)*

*De Curtis, Delle Rose, Moretti, KY (2018)*

**Elementary Sector**

$SO(6) \times U(1)_X$

$A_\mu^A, \quad q_L^r, \quad t_R^r$

$G_{sm} = SU(2)_L \times U(1)_Y$

SM particles embedded

Kinetic term only

**Mixing**

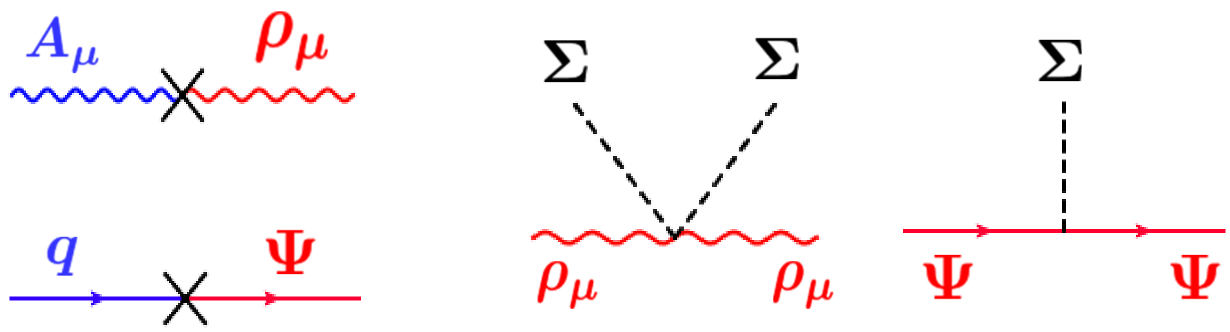
Partial Compositeness

**Strong Sector**

$SO(6) \times U(1)_X \to$

$SO(4) \times SO(2) \times U(1)_X$

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



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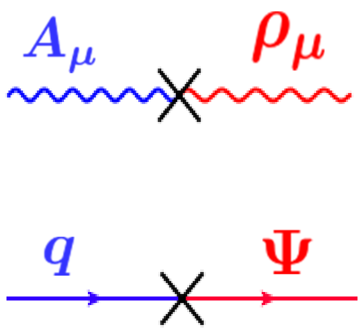
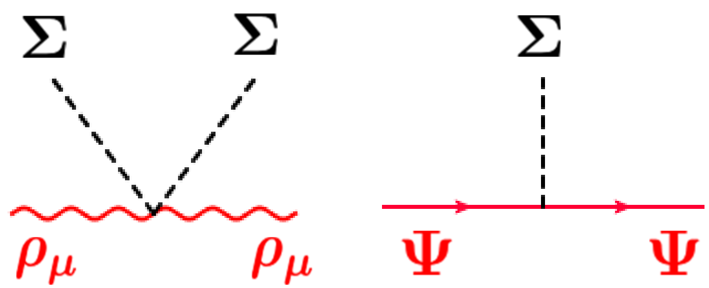
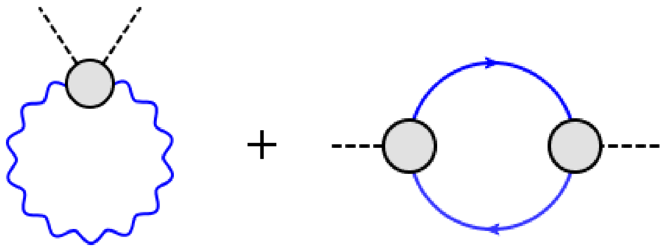



Integrate ρ & ψ out

$V_{eff} =$  $+ \cdots$ ⇒ Vacuum misalignment

# Explicit Model (Fermion Sector)

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

$$\mathcal{L}_{\rm str} = \bar{\Psi}^6 (i\not{D} - m_\Psi)\Psi^6 - \bar{\Psi}^6_L (Y_1 \Sigma + Y_2 \Sigma^2)\Psi^6_R + \text{h.c.}$$

$$+\Delta_L \bar{q}^6_L \Psi^6_R + \Delta_R \bar{t}^6_R \Psi^6_L + \text{h.c.}$$

where $$(q_L^{\mathbf{6}})_t = (\Upsilon^t_L)^T q_L \,, \quad t_R^{\mathbf{6}} = (\Upsilon^t_R)^T t_R$$

$$\Upsilon^t_L = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & i & 0 & 0 \\ 1 & -i & 0 & 0 & 0 & 0 \end{pmatrix} \qquad \Upsilon^t_R = \begin{pmatrix} 0 & 0 & 0 & 0 & \cos\theta_t & i\sin\theta_t \end{pmatrix}$$

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- CPV sources can be introduced in the strong sector parameters.

For simplicity, we consider a non-zero $\theta_t$ as a CPV source (others → real).

# Higgs potential & Yukawa interactions

## Higgs potential

$$V_{\rm eff}(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - \left[m_3^2\Phi_1^\dagger\Phi_2 + {\rm h.c.}\right]$$
$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + {\rm h.c.} \quad + \mathcal{O}(\Phi_{1,2}^6)$$

$$\mathrm{Im}\,[\lambda_6] = \mathrm{Im}\,[\lambda_7] = \frac{4}{3}\frac{\mathrm{Im}[m_3^2]}{f^2} \propto \sin 2\theta_t, \quad \mathrm{Im}[\lambda_5] \sim 0$$

## Yukawa interactions

$$\zeta_t = \frac{Y_1}{Y_2}$$

$$\mathcal{L}_{\rm eff}^Y \propto -\bar{q}_L\left[(\cos\theta_t + i\zeta_t\sin\theta_t)\tilde{\Phi}_1 + (\zeta_t\cos\theta_t + i\sin\theta_t)\tilde{\Phi}_2\right]t_R + {\rm h.c.} + \mathcal{O}(\Phi_{1,2}^3)$$

- All the potential & Yukawa sector parameters are determined by the strong sector.
- Both potential & Yukawa sector contain the CPV phase from the common origin.

# EWSB

- Higgs Kinetic Term

$$\mathcal{L}_{\text{kin}} = \frac{f^2}{4}\mathrm{Tr}(D_\mu\Sigma)^T(D_\mu\Sigma) \quad \supset \frac{1}{f^2}(\Phi_1^\dagger \overleftrightarrow{D}_\mu \Phi_2)^2$$

- Higgs VEVs

$$\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}, \quad \langle\Phi_2\rangle = \begin{pmatrix} 0 \\ \frac{v_2 e^{i\theta_v}}{\sqrt{2}} \end{pmatrix}$$

- T parameter

$$\xi = \frac{v^2}{f^2}$$

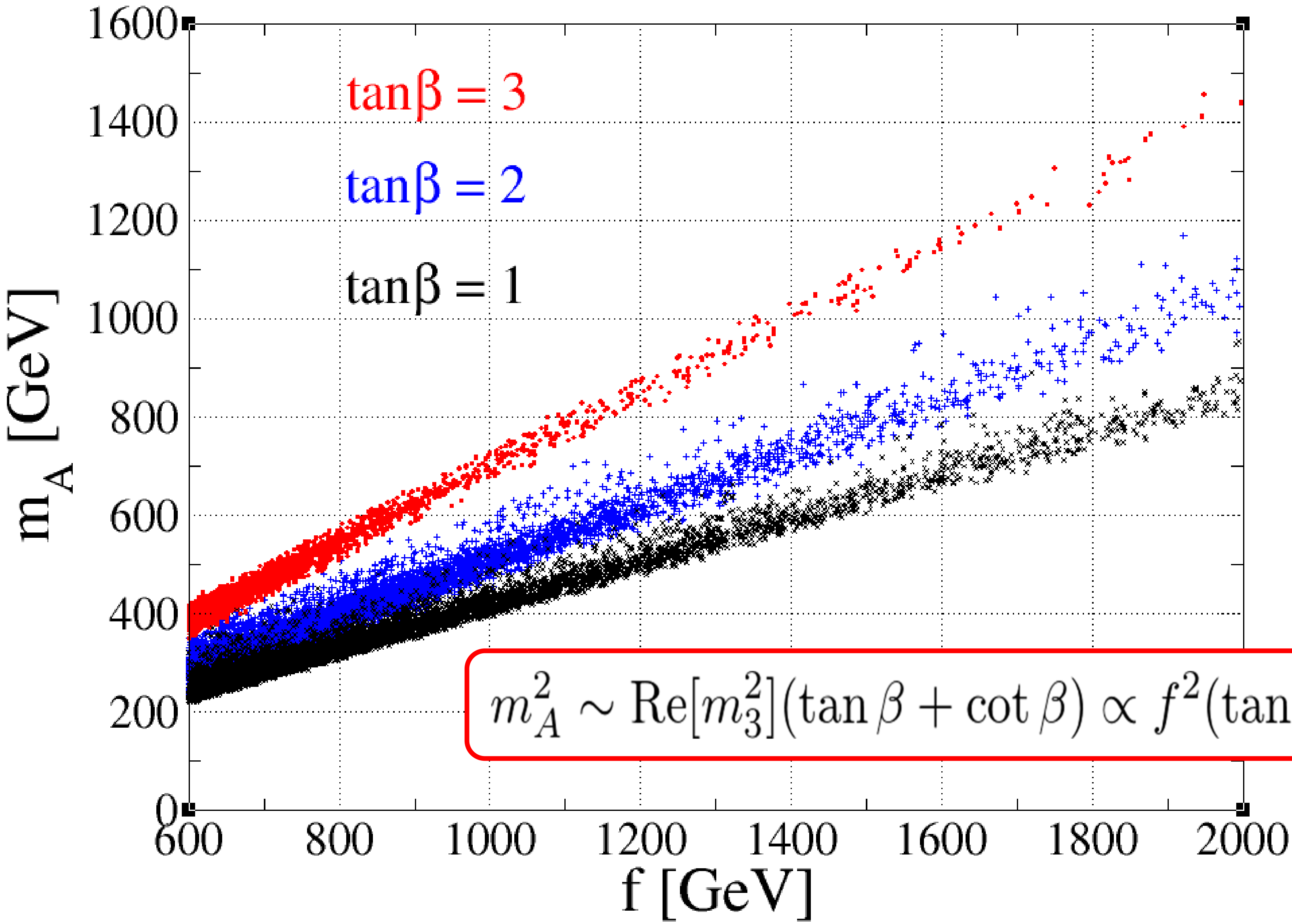
$$\hat{T} \simeq \xi \frac{\mathrm{Im}[\langle\Phi_1^\dagger\rangle\langle\Phi_2\rangle]^2}{(|\langle\Phi_1\rangle|^2 + |\langle\Phi_2\rangle|^2)^2} \simeq \xi \frac{\tan^2\beta}{(1+\tan^2\beta)^2}\sin^2\theta_v$$

$\theta_v \sim 2\theta_t$

$$|\hat{T}| < 10^{-3} \quad \Rightarrow \quad \tan\beta \gg 1 \ \text{ or } \ \tan\beta \ll 1$$

# CPC Case: f VS $M_A$

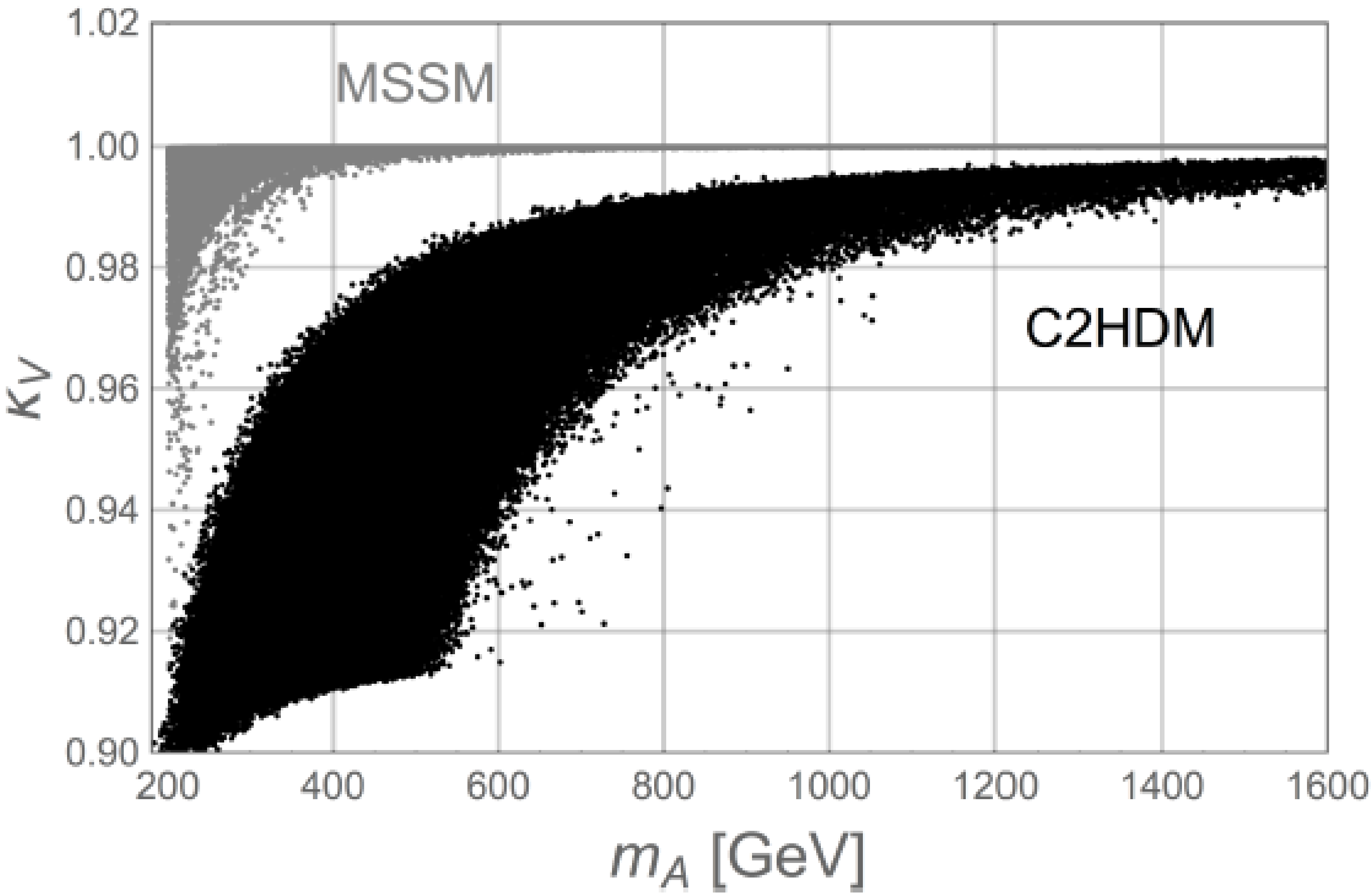
*De Curtis, Delle Rose, Moretti, KY (2018)*




$$m_A^2 \sim \mathrm{Re}[m_3^2](\tan\beta + \cot\beta) \propto f^2(\tan\beta + \cot\beta)$$

# CPC Case: $M_A$ VS $\kappa_V$ ($= g_{hVV}/g_{hVV}^{SM}$)

*De Curtis, Delle Rose, Moretti, KY (2018)*



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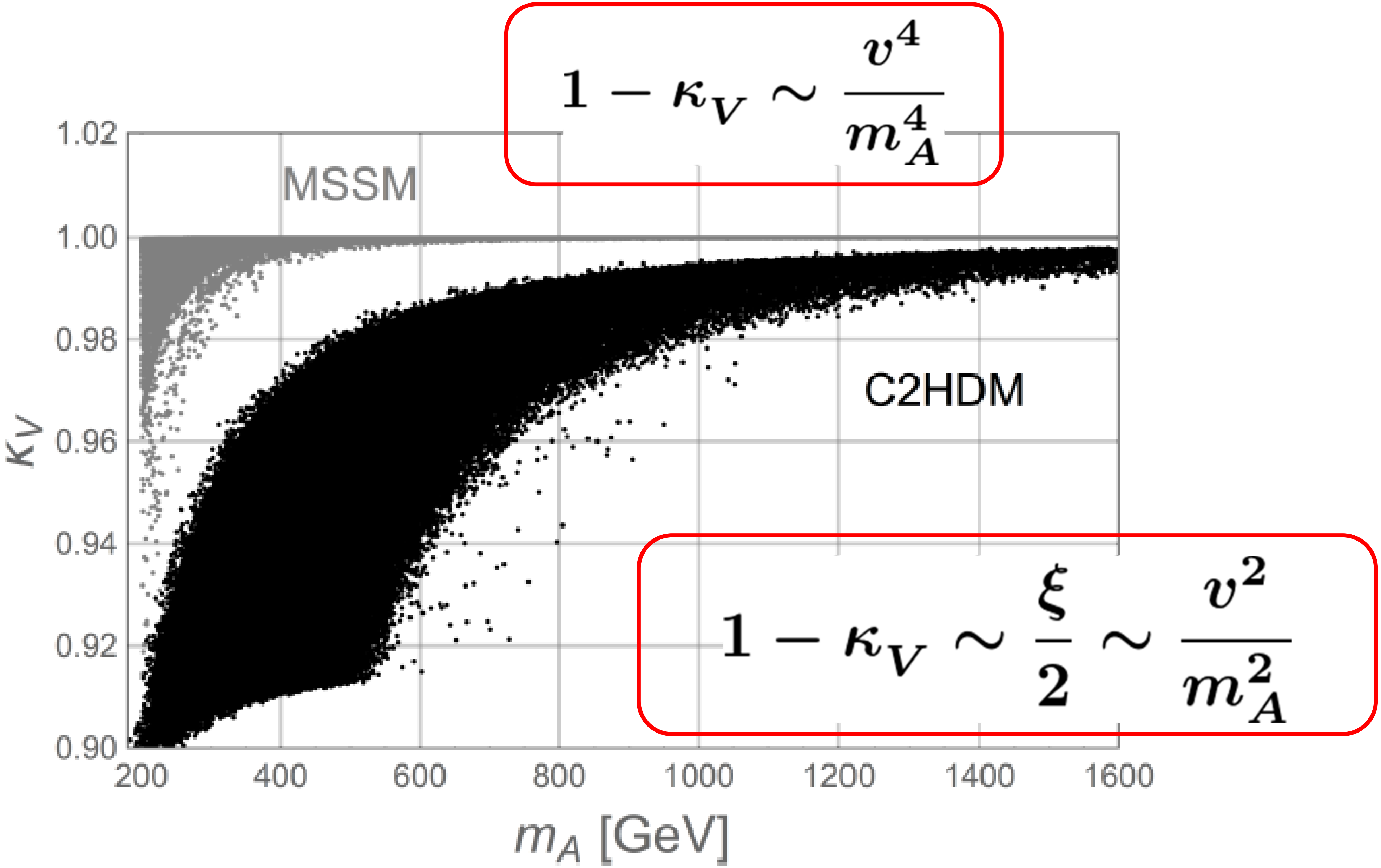
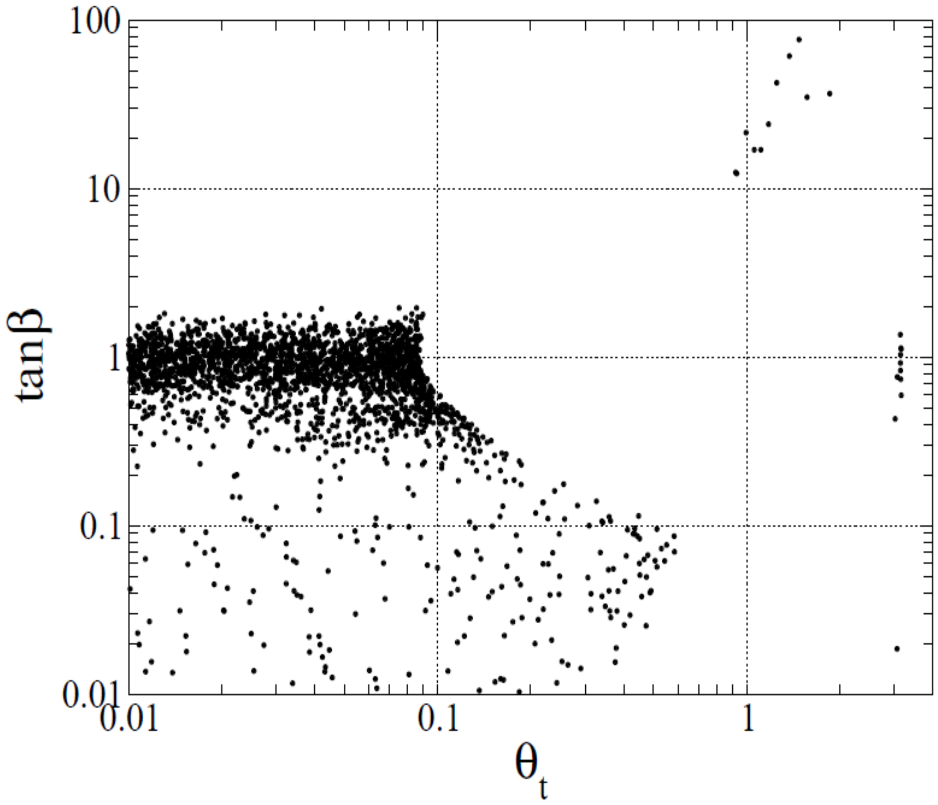
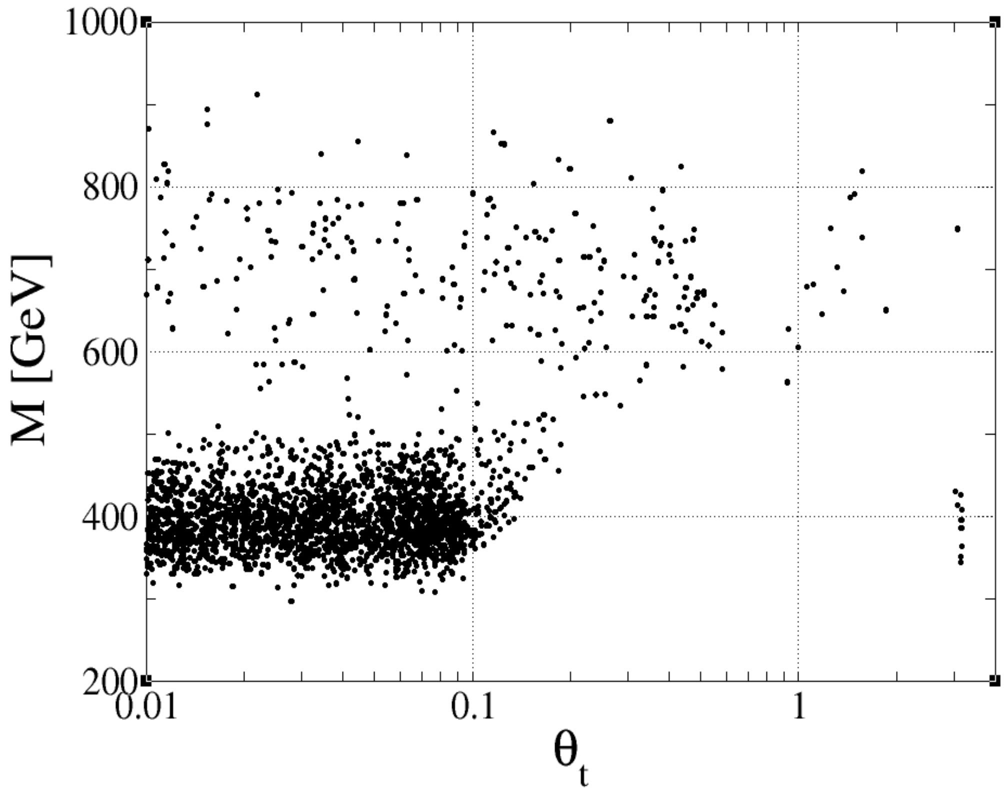


# CPV Case: tanβ and M

*De Curtis, Moretti, Nagai, KY (2021)*

- f = 1 TeV




$$M^2 \simeq \mathrm{Re}[m_3^2](\tan\beta + \cot\beta)$$ ≃ (Extra Higgs Mass)$^2$

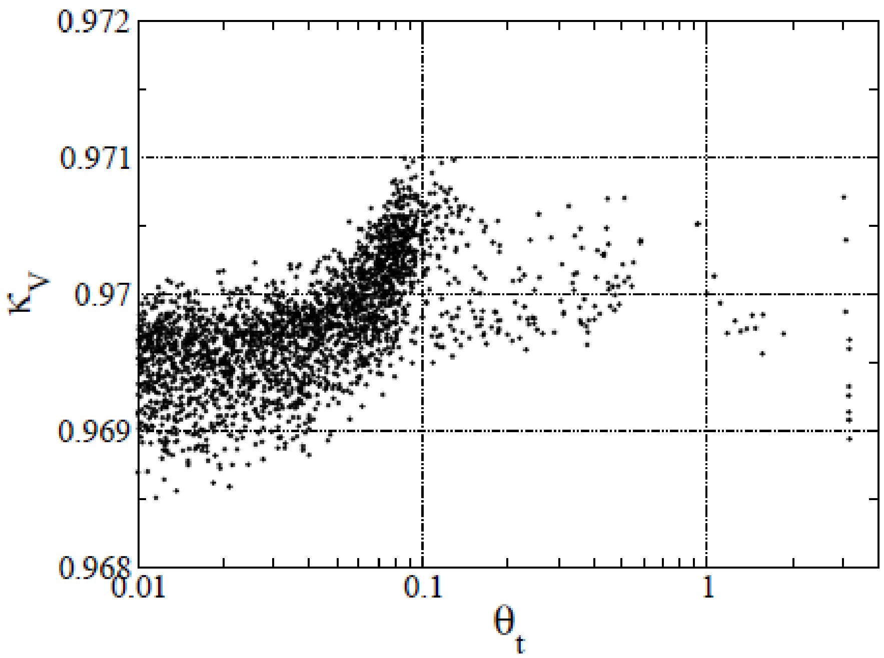
# CPV Case: h(125) Couplings

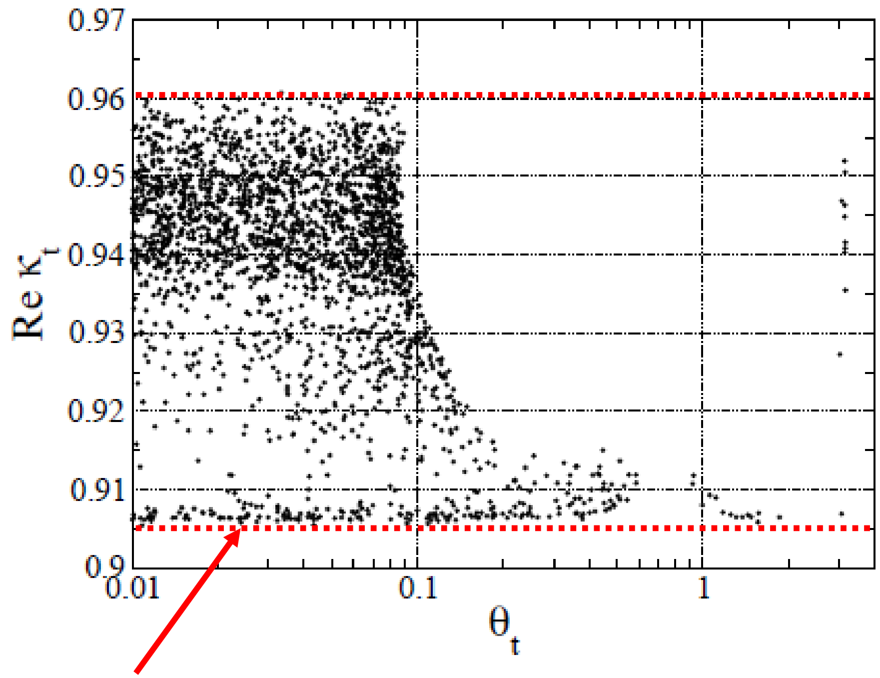
De Curtis, Moretti, Nagai, KY (2021)

- f = 1 TeV

$$\kappa_V \simeq 1 - \frac{\xi}{2}\left(1 - \frac{1}{2}\sin^2 2\beta \sin^2 2\theta_t\right)$$

$$\mathrm{Re}\,\kappa_t \simeq 1 - \xi\left(\frac{3}{2} + \frac{\zeta_t \tan\beta}{1 - \zeta_t \tan\beta}\right)$$



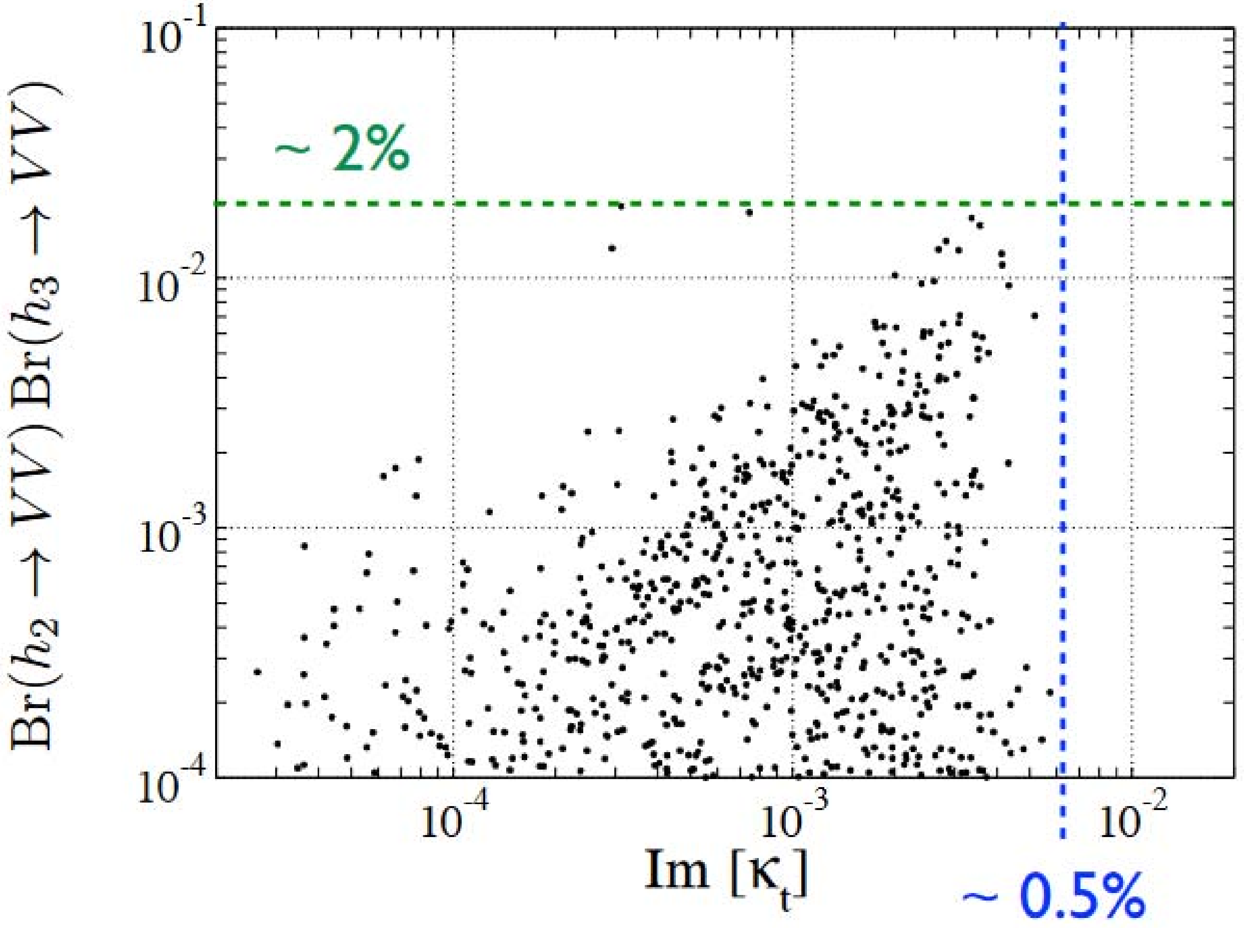



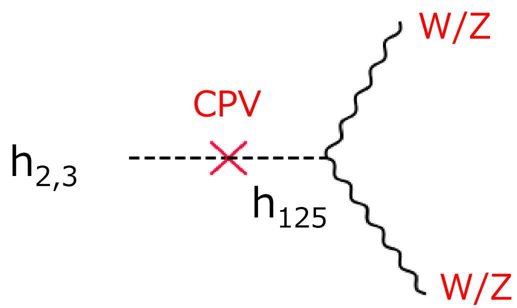

$$\sim 1 - \frac{3}{2}\xi$$

# CPV in Potential VS CPV in Yukawa

*De Curtis, Moretti, Nagai, KY (2021)*

*Keus, King, Moretti, KY (2015)*




- Both heavier neutral Higgs boson can decay into diboson.
- Correlation b/w Im$[\kappa_t]$ and product of BRs can be important to test the CPV C2HDM!

# Summary

- Composite Higgs scenario can explain the origin of the EWSB.
- 2HDM itself provides phenomenologically attractive scenarios e.g., EWBG.

  We construct the composite version of the 2HDM with CPV.
- SUSY or composite Higgs can be distinguished by looking at

  the decoupling behavior ($\kappa_V$ and $m_A$).
- CPV C2HDM can indirectly be tested by measuring

  the correlation b/w Im [$\kappa_t$] and diboson decays of heavy Higgs bosons.