複合2HDMにおけるCPの破れ

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arXiv: 2107.08201 (to be published in JHEP) に基づく

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今日のトーク

- 複合ヒッグス模型のレビュー
- 複合ヒッグス 2HDM

Hierarchy Problem

- SM はとても優れた有効理論

$$\Lambda_{\rm SM} \simeq M_{\rm Planck}$$

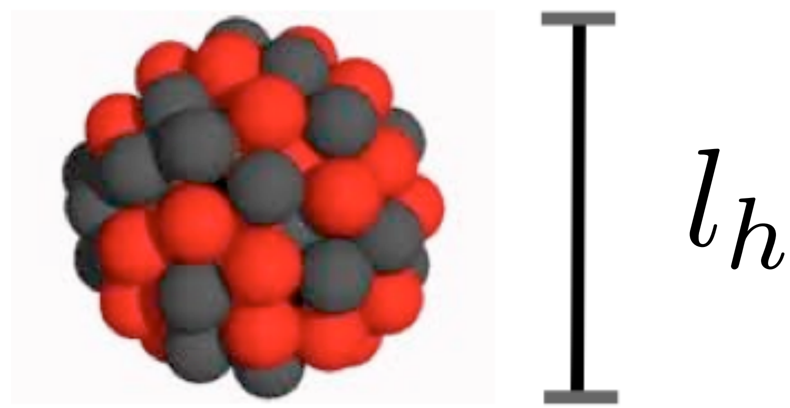
あるいは GUT scale ?

- とすると、なぜ $m_h \ll \Lambda_{\rm SM}$?

Composite Higgs

Kaplan, Georgi (86) +++

- Higgs は New strong dynamics から生じる **複合粒子**

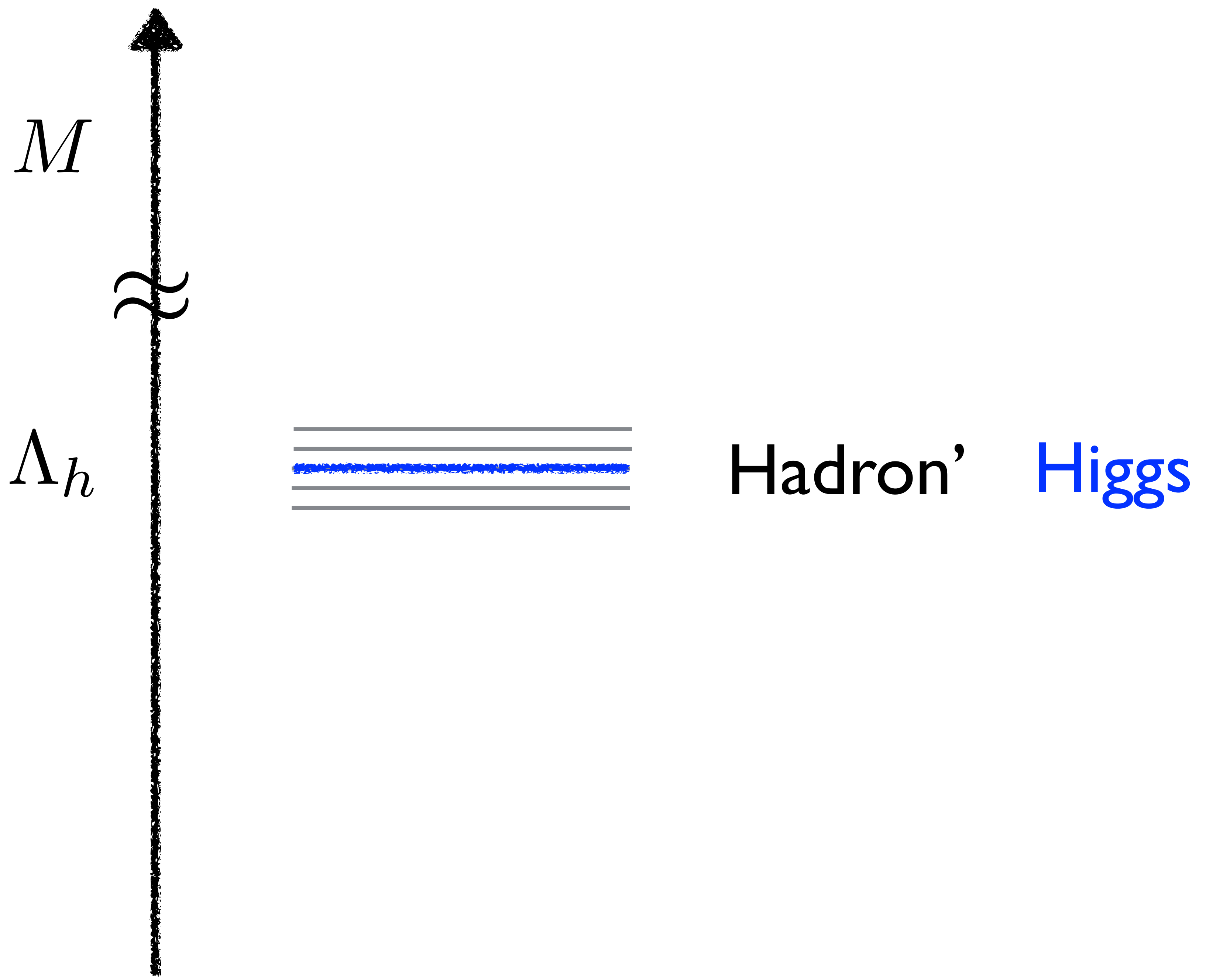


From Wikipedia

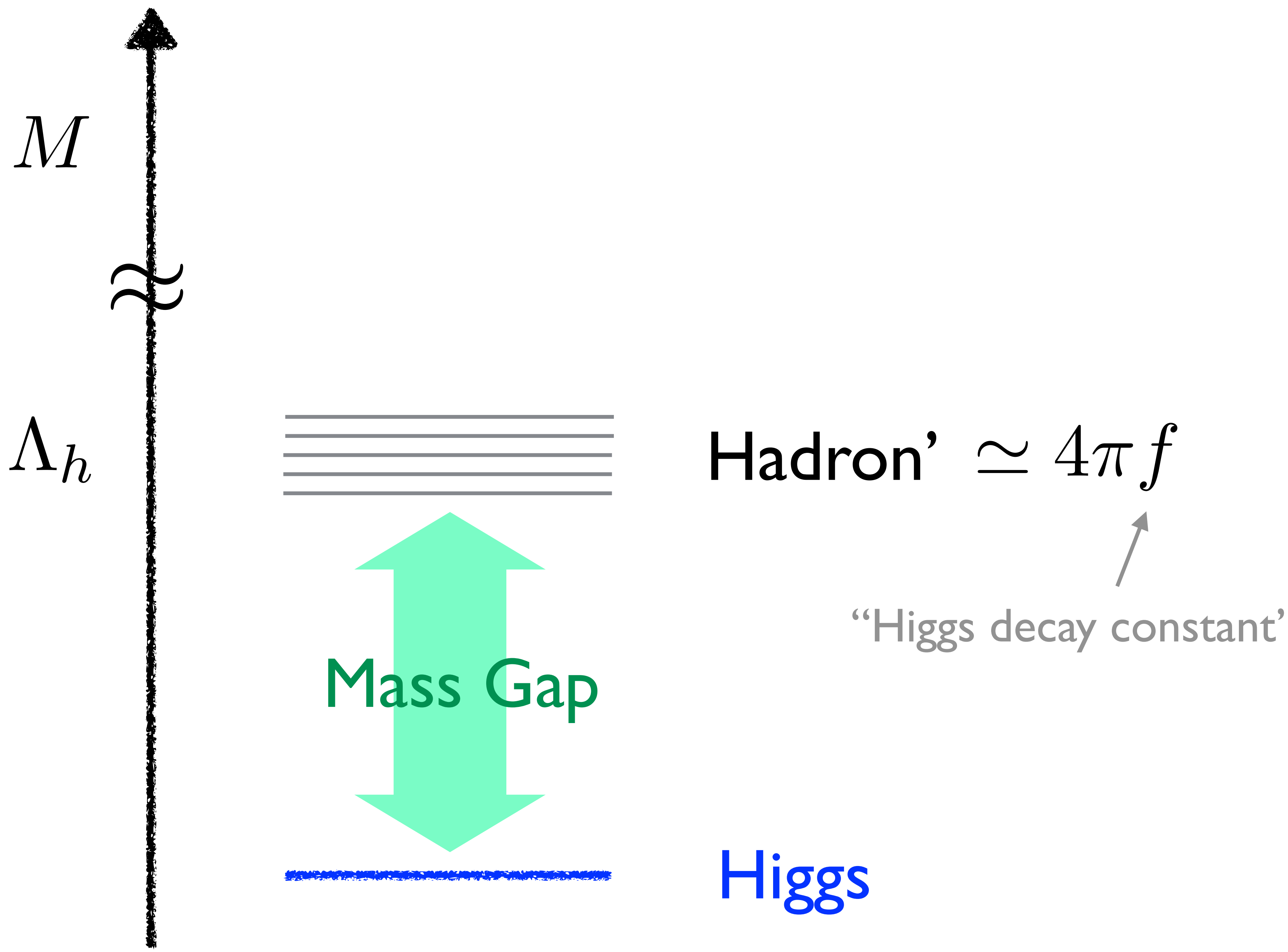
- $\Lambda_h \sim 1/l_h \ll \Lambda_{\rm SM} \simeq M_{\rm GUT}\,,\ M_{\rm Planck}$
- Λ_h 以上のスケールからくる補正は遮蔽される。

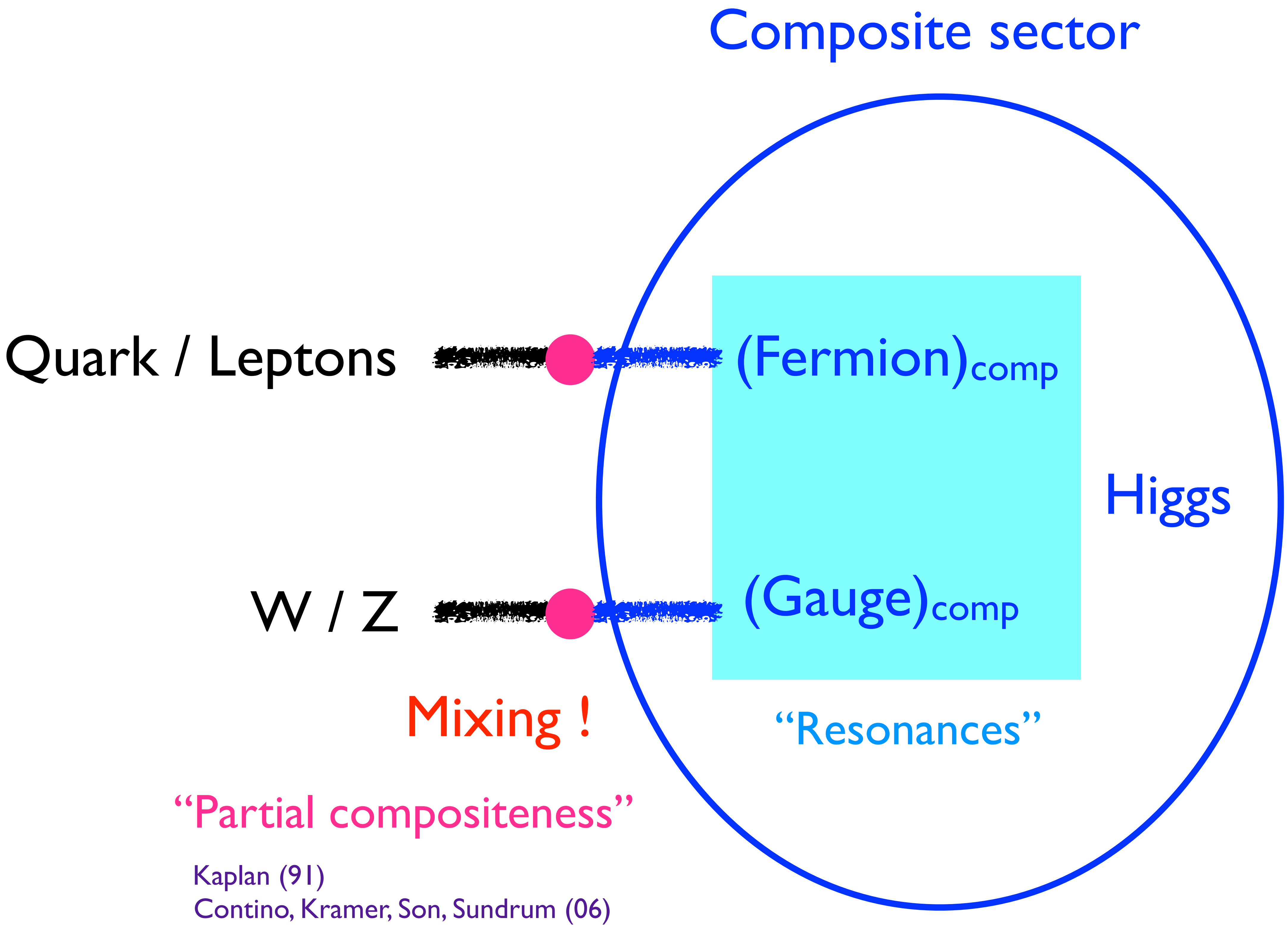
$\Longrightarrow$ m_h は UV insensitive

Higgs as “Hadron”



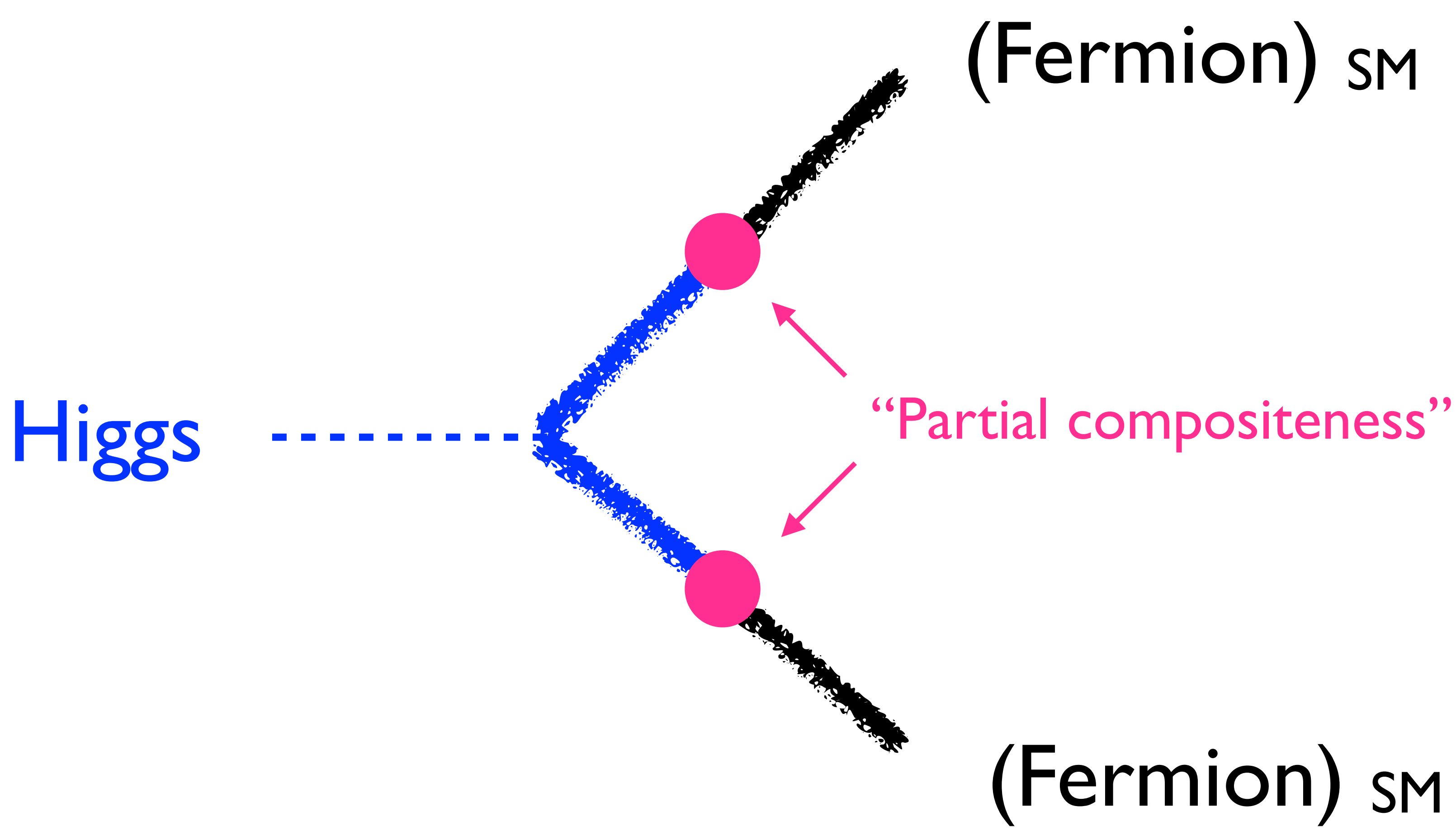
Higgs as “Pion”





Kaplan (91)
Contino, Kramer, Son, Sundrum (06)

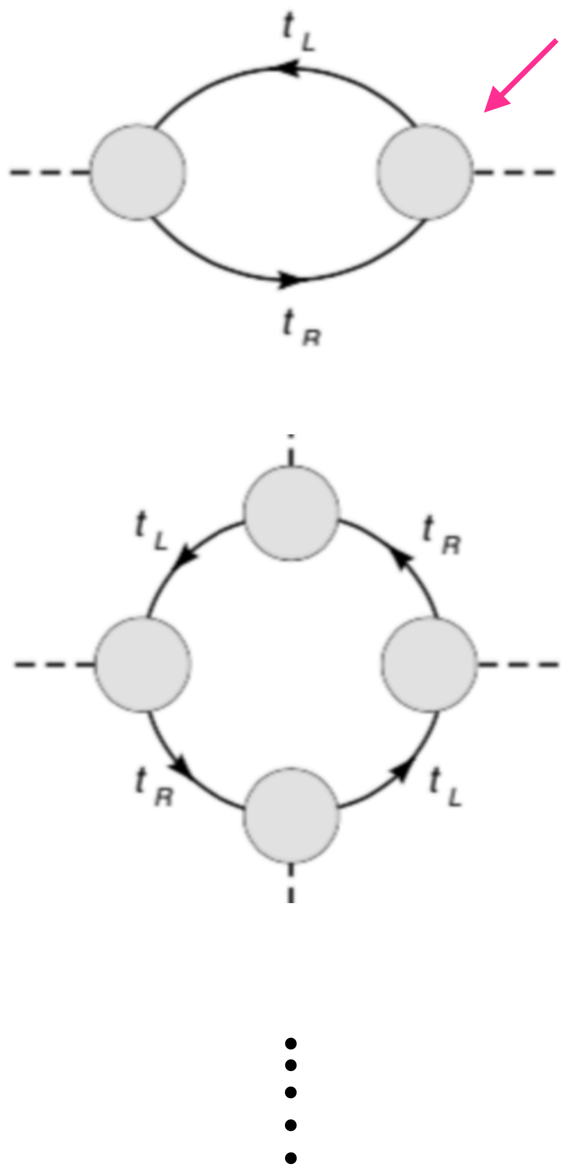
Yukawa



Large Mixing ⇆ Large Coupling

Higgs potential

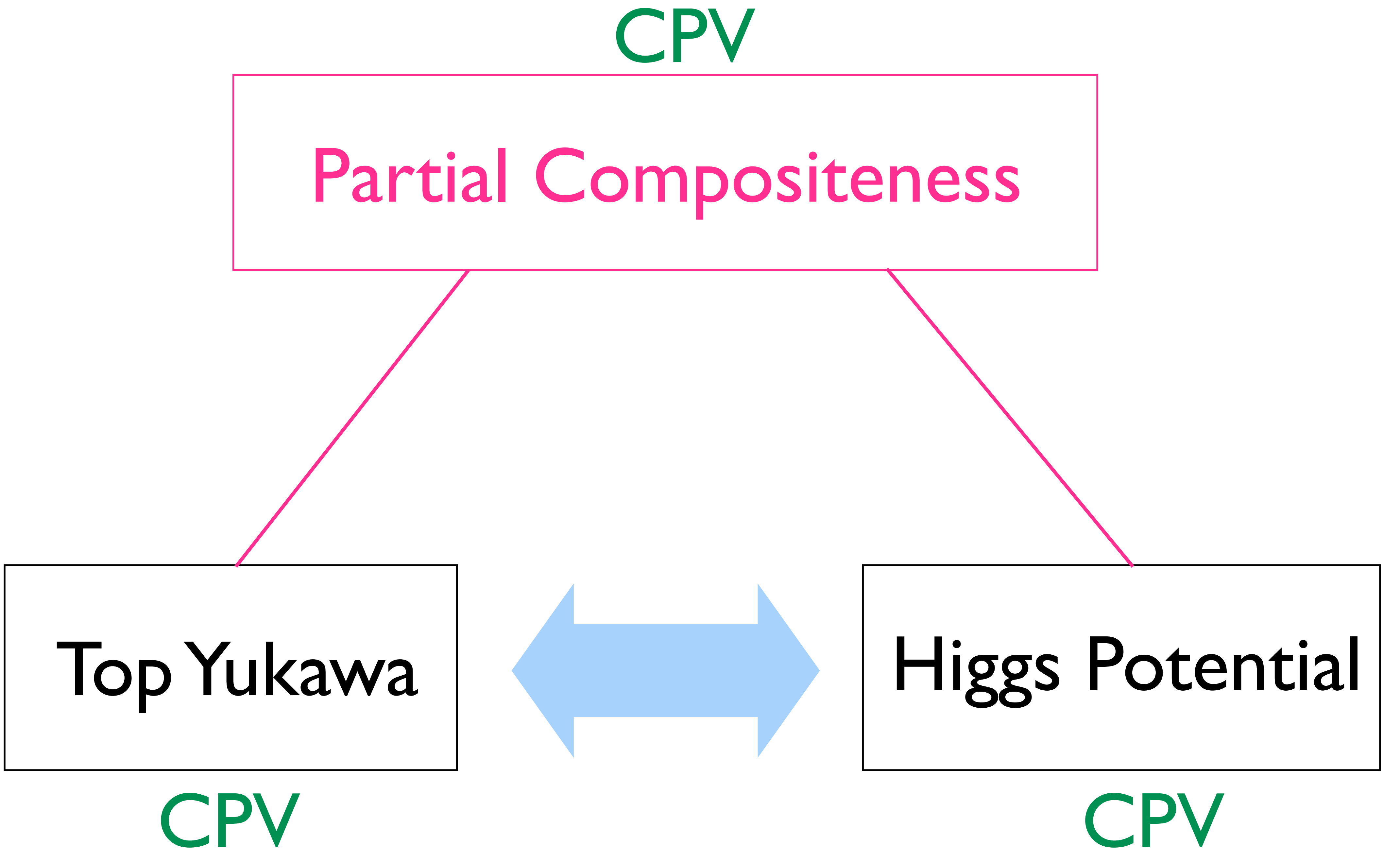
“Partial compositeness”



Higgs Potential

(CW potential)

Key point



CPV
Partial Compositeness
Top Yukawa
Higgs Potential
CPV
CPV

Benchmark

- Composite Two Higgs Doublet Model

- dim(G/H) = 8 = 4 + 4

- NGBs = Two Higgs Doublets

- G/H = SO(6) / SO(4) × SO(2)

Mrazek, Pomarol, Rattazzi, Redi, Wulzer (2011)
Bertuzzo, Ray, de Sandes, Savoy (2012)
DeCurtis, Moretti, Yagyu, Delle Rose (2018)

NGB (=Higgs) sector

- NGBs = Two Higgs Doublets

$$U = e^{i\frac{\Pi^{\hat{a}}}{f}X^{\hat{a}}} = \exp\left[\frac{i}{f}\begin{pmatrix} & -\vec{\phi}_1 & -\vec{\phi}_2 \\ \vec{\phi}_1^{\,T} & & \\ \vec{\phi}_2^{\,T} & & \end{pmatrix}\right]$$

G/H = SO(6)/[SO(4)×SO(2)]
の generator

$$\vec{\phi}_i = \begin{pmatrix} \phi_i^1 & \phi_i^2 & \phi_i^3 & \phi_i^4 \end{pmatrix}^T$$

$$\Phi_i = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_i^1 + i\phi_i^2 \\ \phi_i^3 + i\phi_i^4 \end{pmatrix}$$

NGB (=Higgs) sector

- NGBs = Two Higgs Doublets

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- 変換性 $U \xrightarrow{G} g\,U\,h^\dagger$ $\quad g \in G,\ h \in H$

- ラグランジアン $\mathcal{L} = \frac{f^2}{4}\mathrm{Tr}[\partial_\mu U^\dagger \partial^\mu U]$

Elementary sector

$$G_1 = SO(6)$$

f

A_μ

Composite sector

$$G_2 = SO(6)$$

U

(= Higgs)

Multi-site

Panico, Wulzer (11)
DeCurtis, Redi, Tesi (11)

- Multi-site 化

$$U = U_1 U_2$$

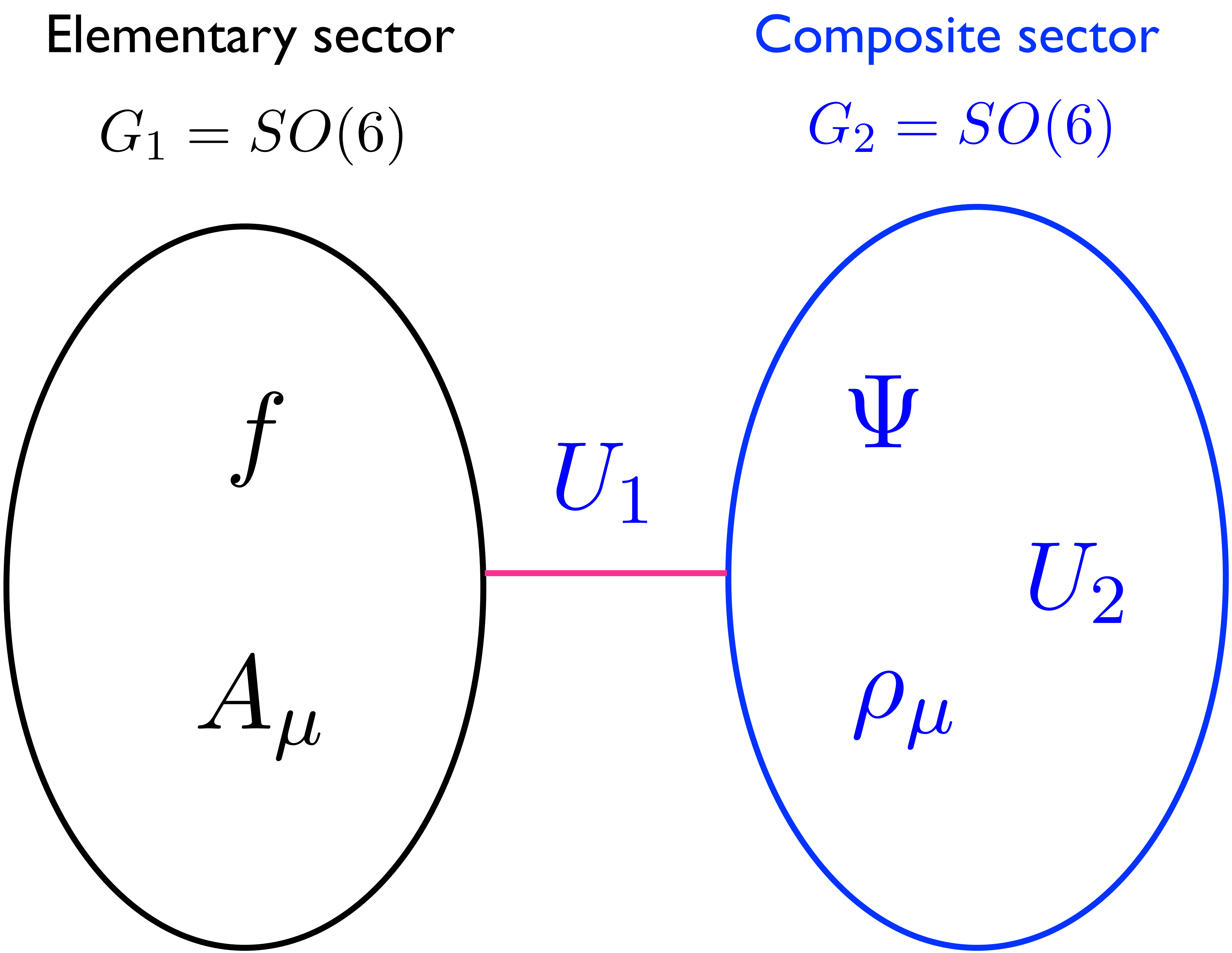
- Decay constant

$$\frac{1}{f^2} = \frac{1}{f_1^2} + \frac{1}{f_2^2}$$

- 変換性

$$\begin{aligned} U \to g\, U\, h^\dagger &= g_1\, U\, h^\dagger \\ &= g_1\, U_1 U_2\, h^\dagger \\ &= g_1\, U_1\, g_2^\dagger\, g_2\, U_2\, h^\dagger \end{aligned}$$

$$U_1 \to g_1\, U_1\, g_2^\dagger \qquad U_2 \to g_2\, U_2\, h^\dagger$$



Elementary sector
$G_1 = SO(6)$
f
A_μ
U_1
Composite sector
$G_2 = SO(6)$
Ψ
U_2
ρ_μ

Partial compositeness

Elementary

Composite

Fermion $\sim \quad \bar{f}\,\Delta_f\,U_1\Psi + h.c.$

Parameter

Partial compositeness

Fermion $\sim \quad \bar{f}\,\Delta_f\,U_1\Psi + h.c.$

Gauge $\sim \quad \frac{f_1^2}{4}\mathrm{Tr}[D_\mu U_1^\dagger D^\mu U_1]$

$D_\mu U_1 = \partial_\mu U_1 + iA_\mu U_1 - iU_1\rho_\mu$

Partial compositeness

Parameter $\in \mathbb{C}$ CPV !

Fermion $\sim \quad \bar{f}\,\Delta_f\,U_1\Psi + h.c.$

Gauge $\sim \quad \dfrac{f_1^2}{4}\mathrm{Tr}[D_\mu U_1^\dagger D^\mu U_1]$

$$D_\mu U_1 = \partial_\mu U_1 + iA_\mu U_1 - iU_1\rho_\mu$$

Fermion sector

$$\mathcal{L}_{\rm fermion} \sim \bar{f}_L \Delta_L U_1 \Psi_R + \bar{f}_R \Delta_R U_1 \Psi_L + \bar{\Psi}_L (M_\Psi + Y_1 \Sigma_2 + Y_2 \Sigma_2^2) \Psi_R$$

U_2 を線形化したもの (Adjoint Higgs)

- SM fermion は $f_{L,R}$ の中に埋め込まれている。

今日のトークでは

$$\mathcal{L}_{\rm fermion} \sim \bar{f}_L \Delta_L U_1 \Psi_R$$
$$+ \bar{f}_R \Delta_R U_1 \Psi_L$$
$$+ \bar{\Psi}_L (M_\Psi + Y_1 \Sigma_2 + Y_2 \Sigma_2^2) \Psi_R$$

U_2 を線形化したもの (Adjoint Higgs)

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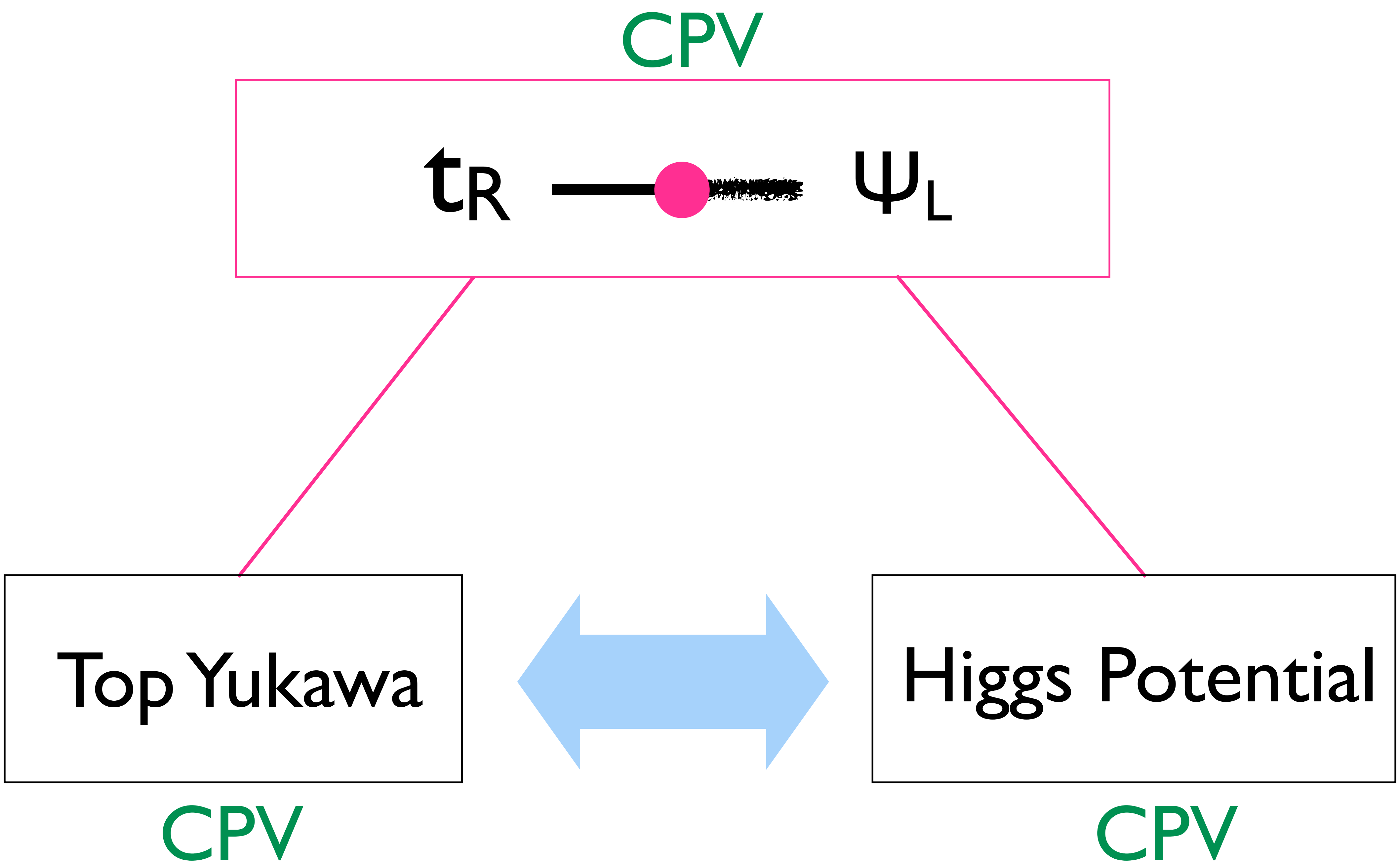
今日のトークでは



Higgs and Top

$$V(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - \left[m_3^2\Phi_1^\dagger\Phi_2 + h.c.\right]$$

$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$

$$+\left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + h.c.\right] \quad + \quad (\ldots.)$$

$$-\mathcal{L}_{\rm top} = \bar{q}_L\left(Y_{t,1}\widetilde{\Phi}_1 + Y_{t,2}\widetilde{\Phi}_2\right)t_R + h.c. \quad + \quad (\ldots.)$$

← 高次元演算子 (suppressed by f^{-2})

- m^2 , λ, Y_t は Partial compositeness で決まる

EWPTs

- (Higher dim.) $\supset \dfrac{1}{f^2}(\Phi_1^\dagger \overleftrightarrow{D}_\mu \Phi_2)^2$

- Vacuum $\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \quad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ v_2 e^{i\theta_v} \end{pmatrix}$

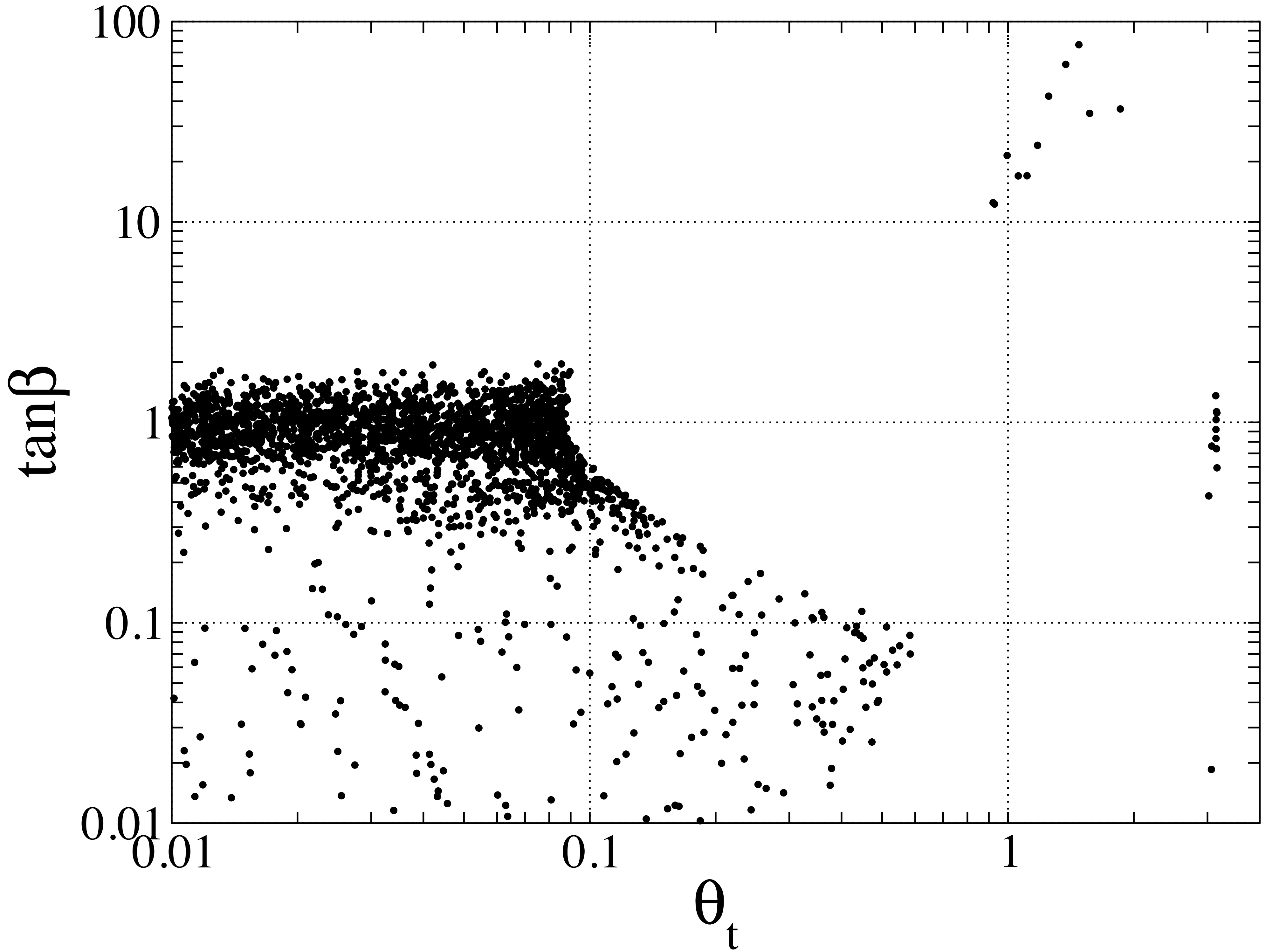
$\xi = \dfrac{v_{\rm EW}^2}{f^2}$

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

CPV !

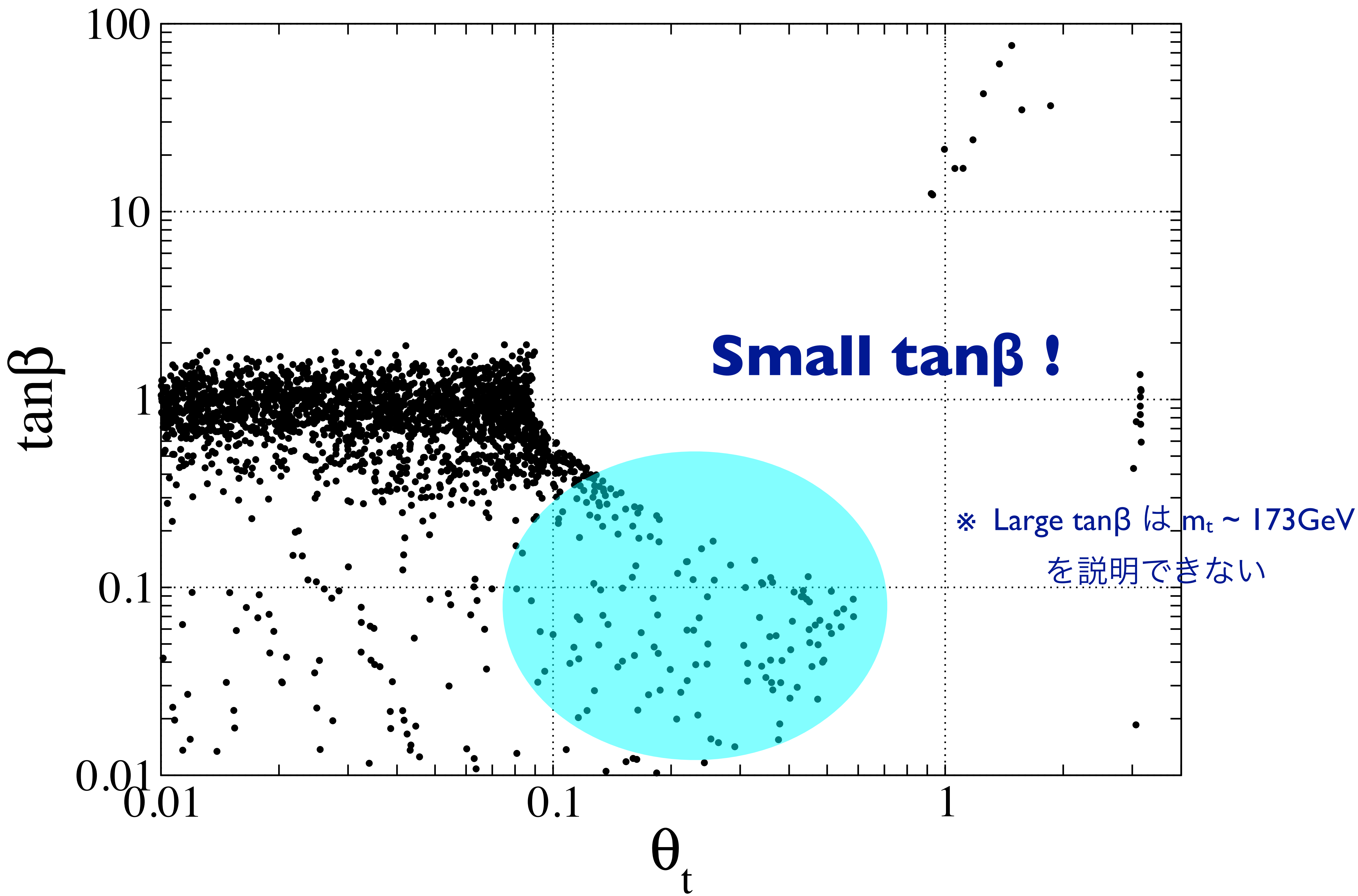
- CPV and $|\hat{T}| \lesssim 10^{-3}$ → $\tan\beta \begin{smallmatrix} \ll \\ \gg \end{smallmatrix} 1$

f = 1TeV



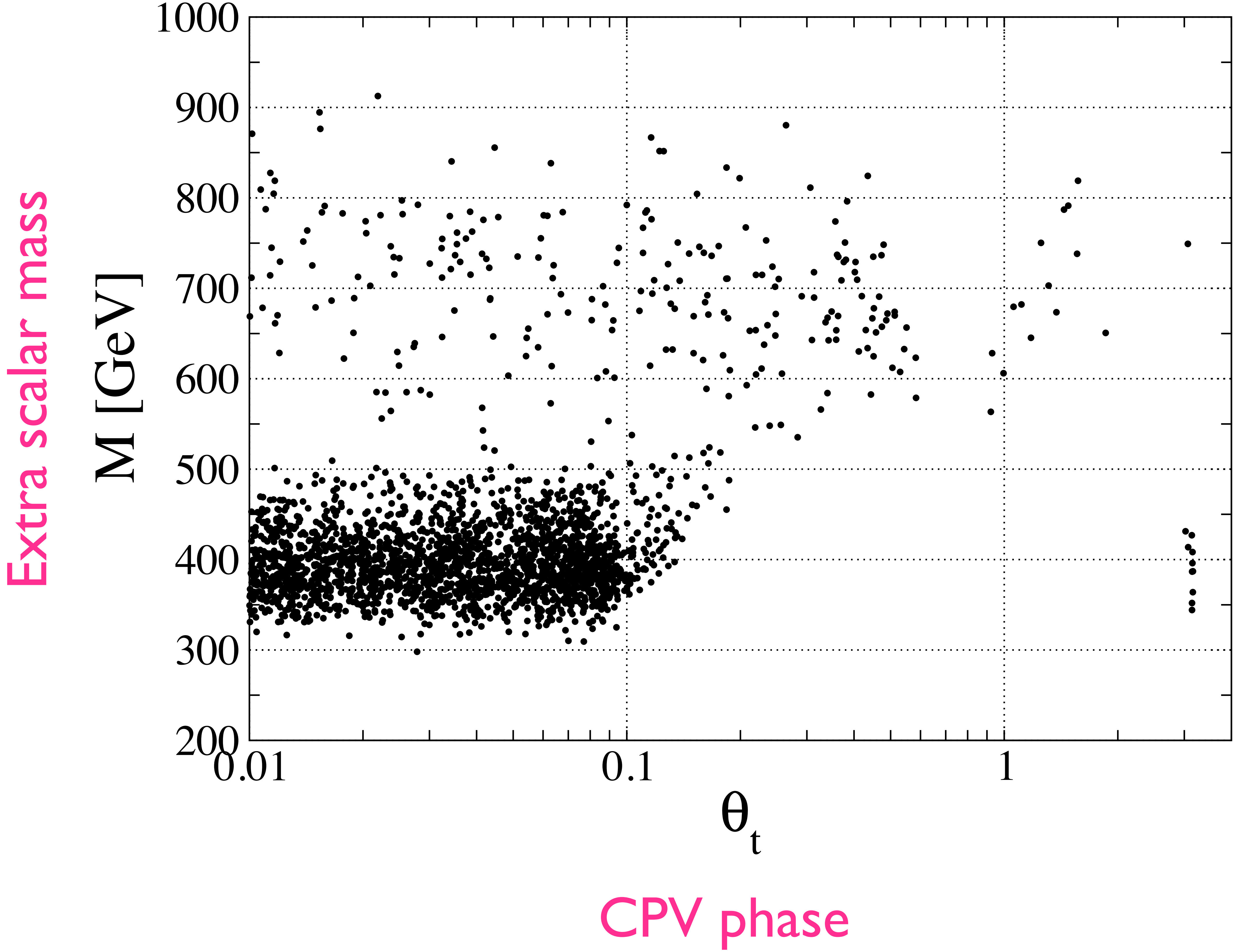
CPV phase

$f = 1\,\mathrm{TeV}$



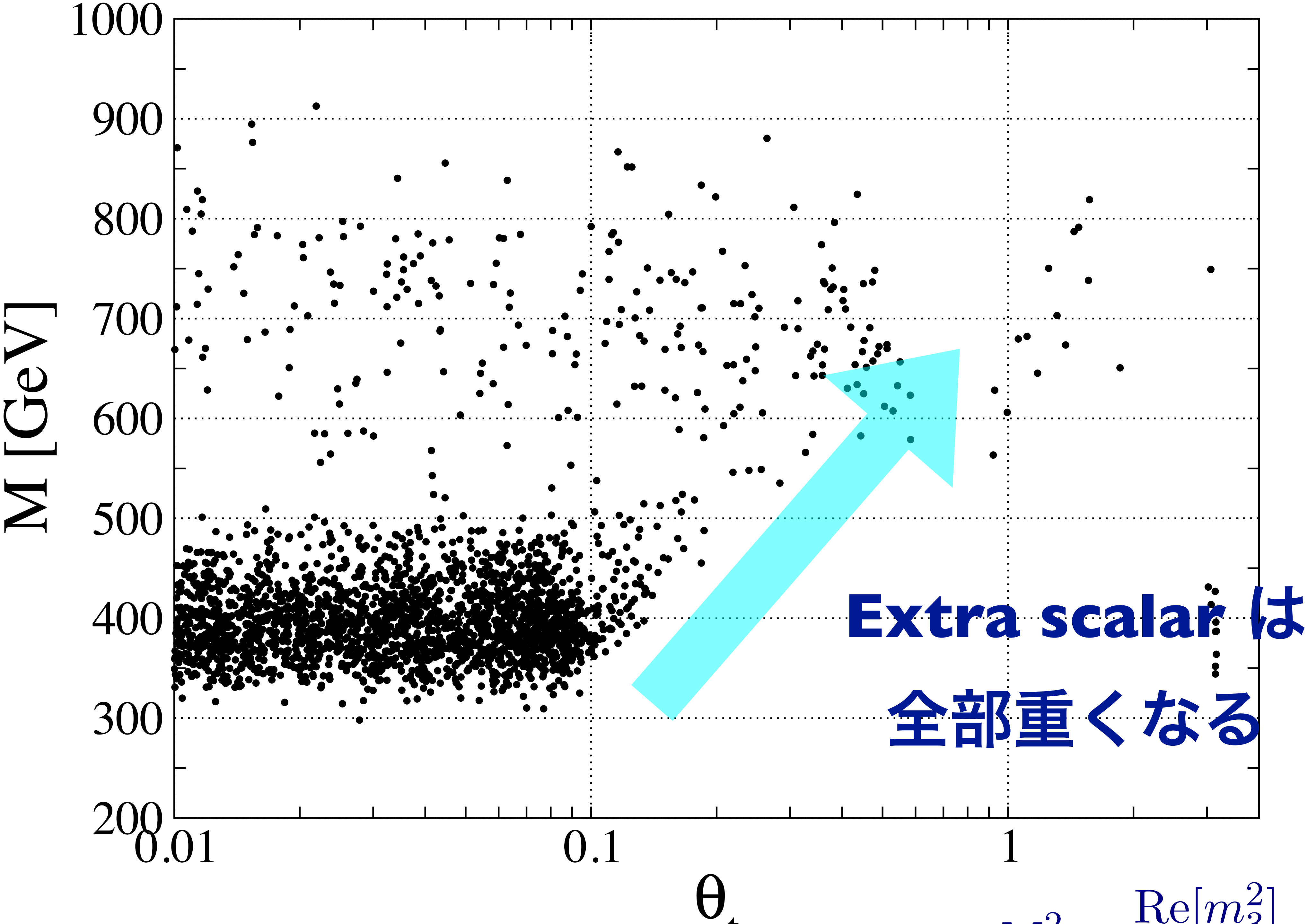
CPV phase

$m^2_{\rm scalar} \sim M^2 + \lambda v^2$



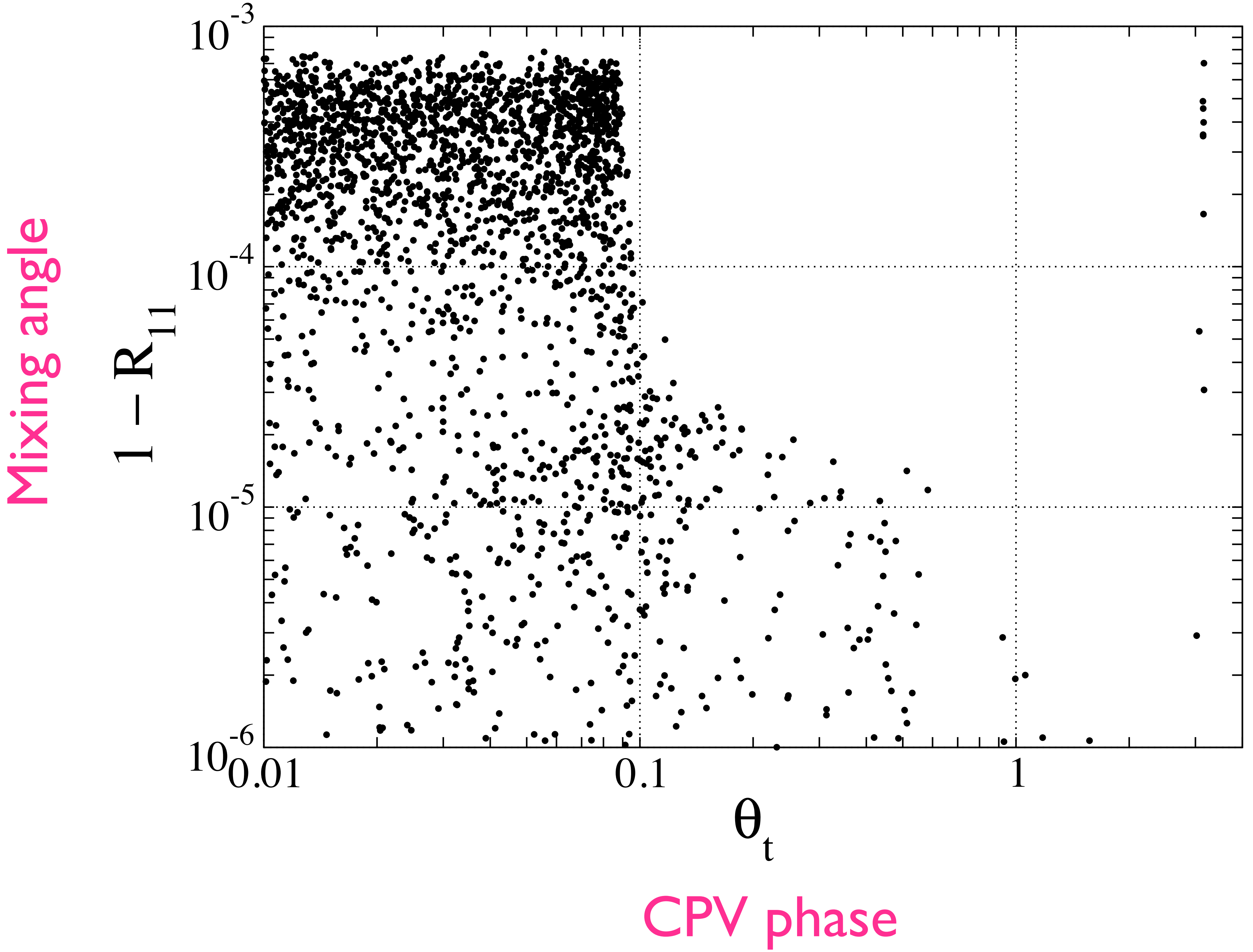
$m_{\rm scalar}^2 \sim M^2 + \lambda v^2$

Extra scalar mass

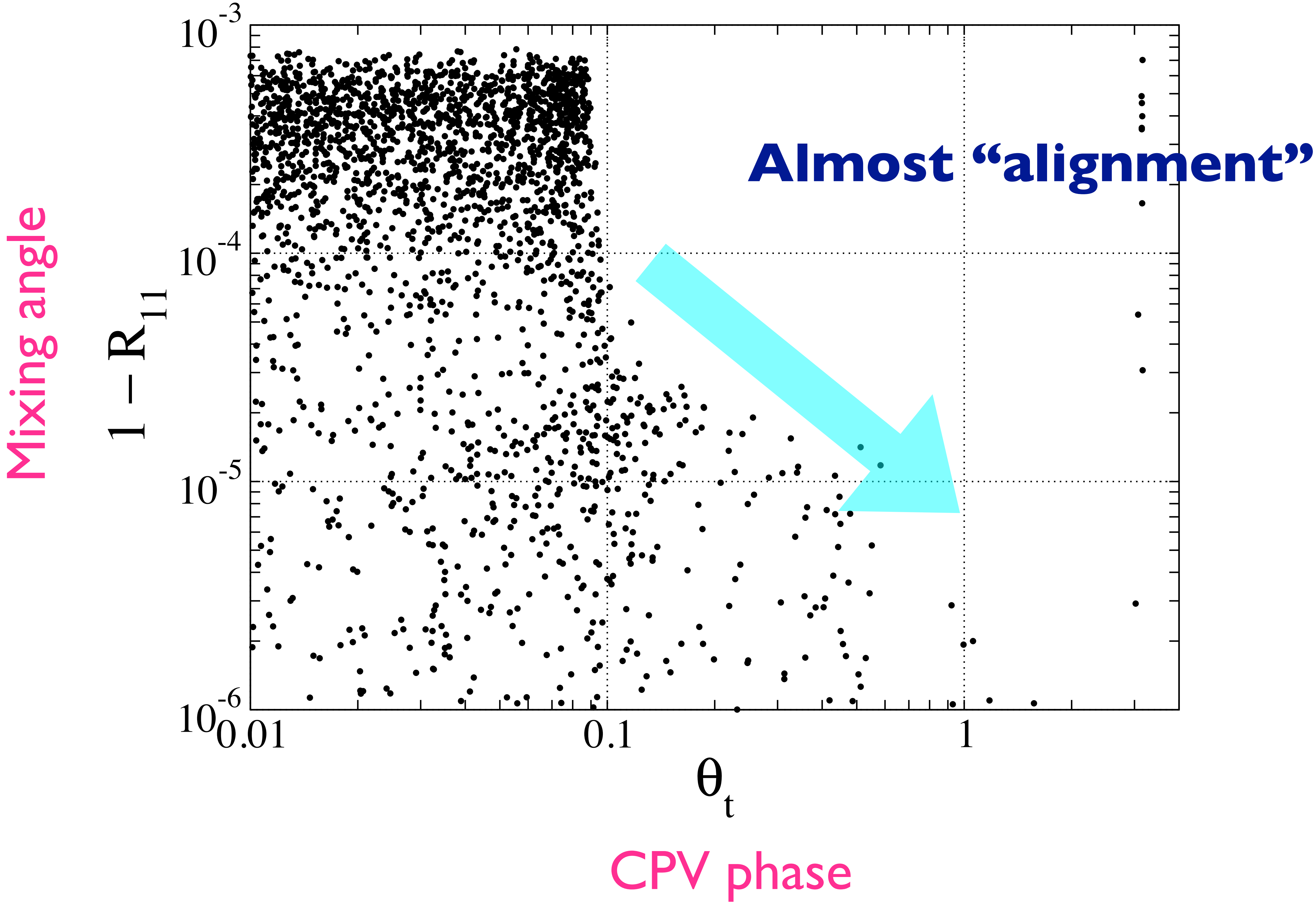


CPV phase

$M^2 \propto \frac{\mathrm{Re}[m_3^2]}{\tan\beta}$



Mixing angle
1 − R11
10-3
10-4
10-5
10-6
0.01
0.1
1
θt
CPV phase


Almost "alignment"
Mixing angle
1 − R11
CPV phase
θt
10^-3
10^-4
10^-5
10^-6
0.01
0.1
1

Higgs coupling

- Compositeness の影響で Higgs coupling がずれる。

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

$$\xi = \frac{v_{\rm EW}^2}{f^2}$$

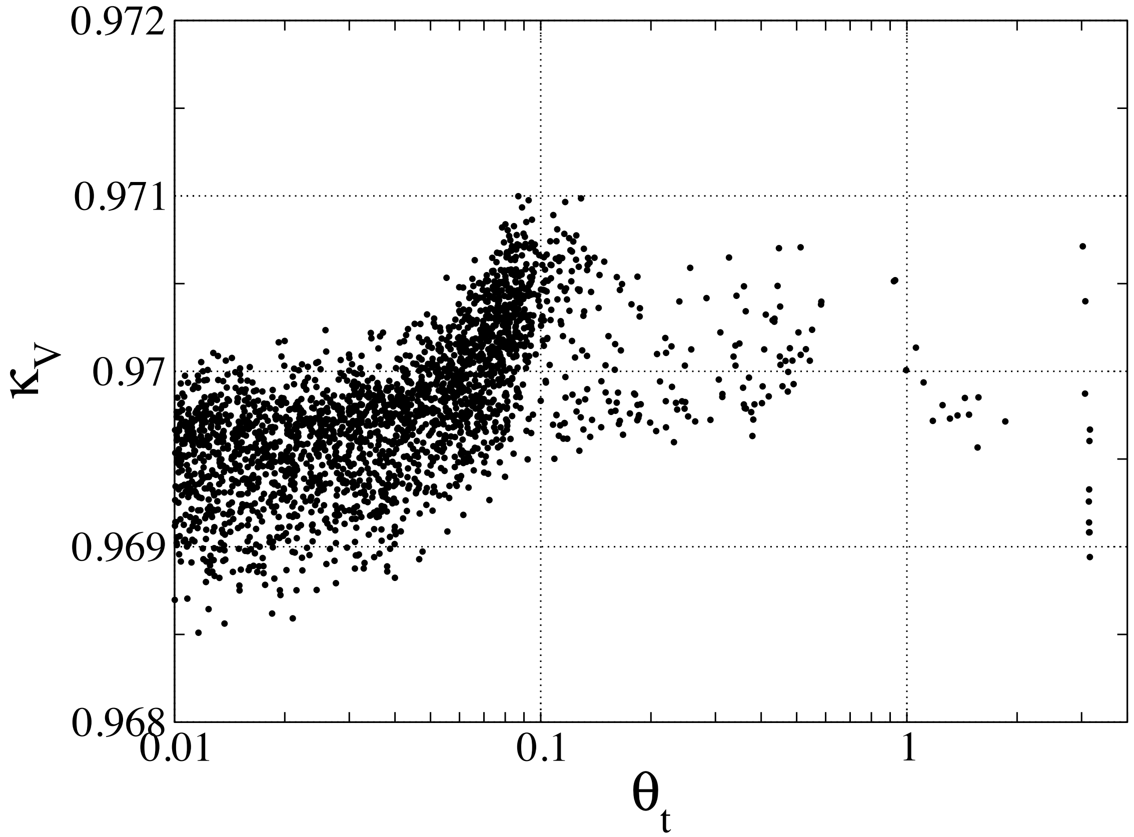
$$\mathrm{Re}[\kappa_t] \simeq 1 - \left(\frac{3}{2} + \frac{\zeta_t \tan\beta}{1 - \zeta_t \tan\beta}\right)\xi$$

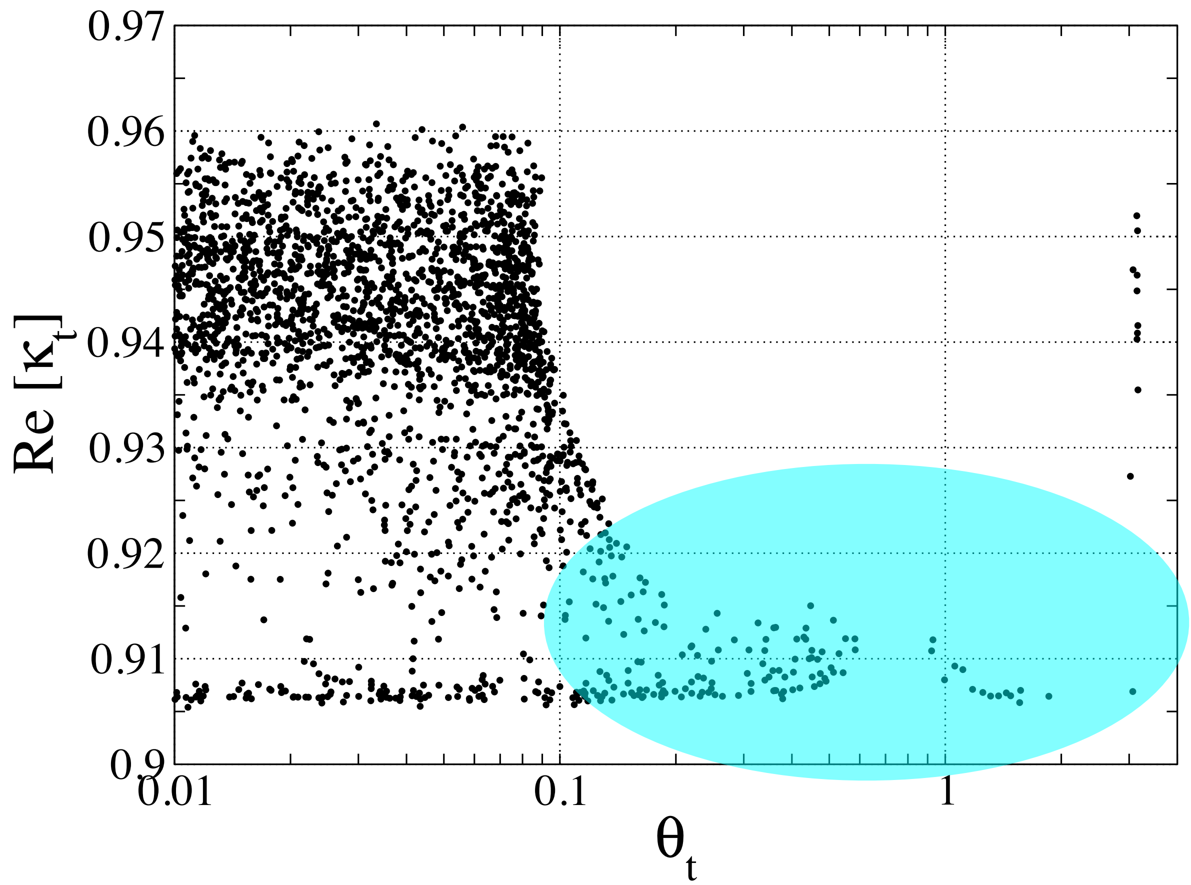
Ψ の Yukawa

$$\kappa_V = g_{hWW}^{\rm C2HDM}/g_{hWW}^{\rm SM} = g_{hZZ}^{\rm C2HDM}/g_{hZZ}^{\rm SM}$$

$$\mathcal{L} = -\frac{m_t}{v}\,\bar{t}\,(\mathrm{Re}[\kappa_t] + i\mathrm{Im}[\kappa_t])\,th$$

f = 1 TeV





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

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

Small tanβ

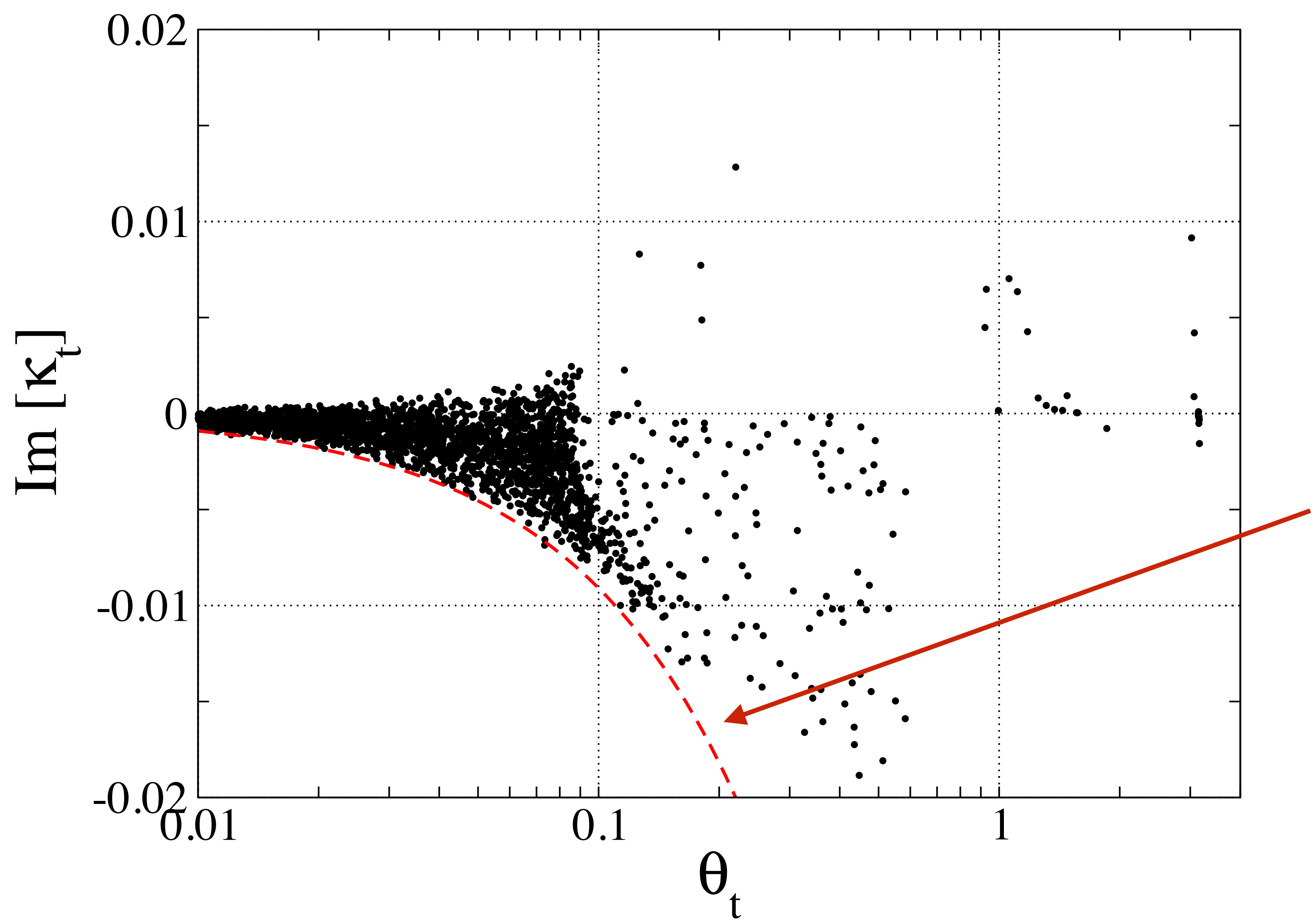
ここまでのまとめ

- SO(6) / SO(4)×SO(2) 模型 に注目
- Composite 2HDM
- T ~ 0 かつ CPV → Small tanβ
  - Decoupling and Alignment
  - $\kappa_V \simeq 1 - \frac{\xi}{2} \qquad \mathrm{Re}[\kappa_t] \simeq 1 - \frac{3}{2}\xi$

CPV signals

i) CPV top Yukawa coupling

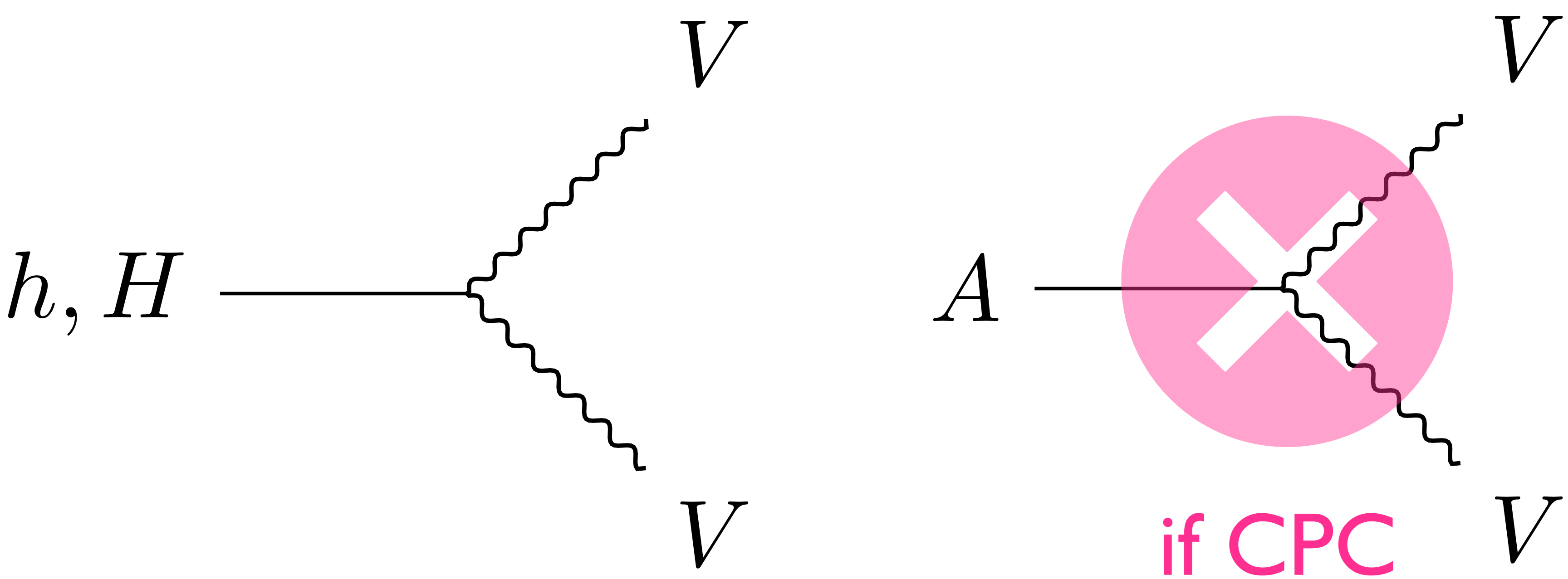
$$\mathcal{L} = -\frac{m_t}{v}\,\bar{t}\,(\mathrm{Re}[\kappa_t] + i\mathrm{Im}[\kappa_t])\,th$$



$\simeq \xi\,\theta_t\,\zeta_t$

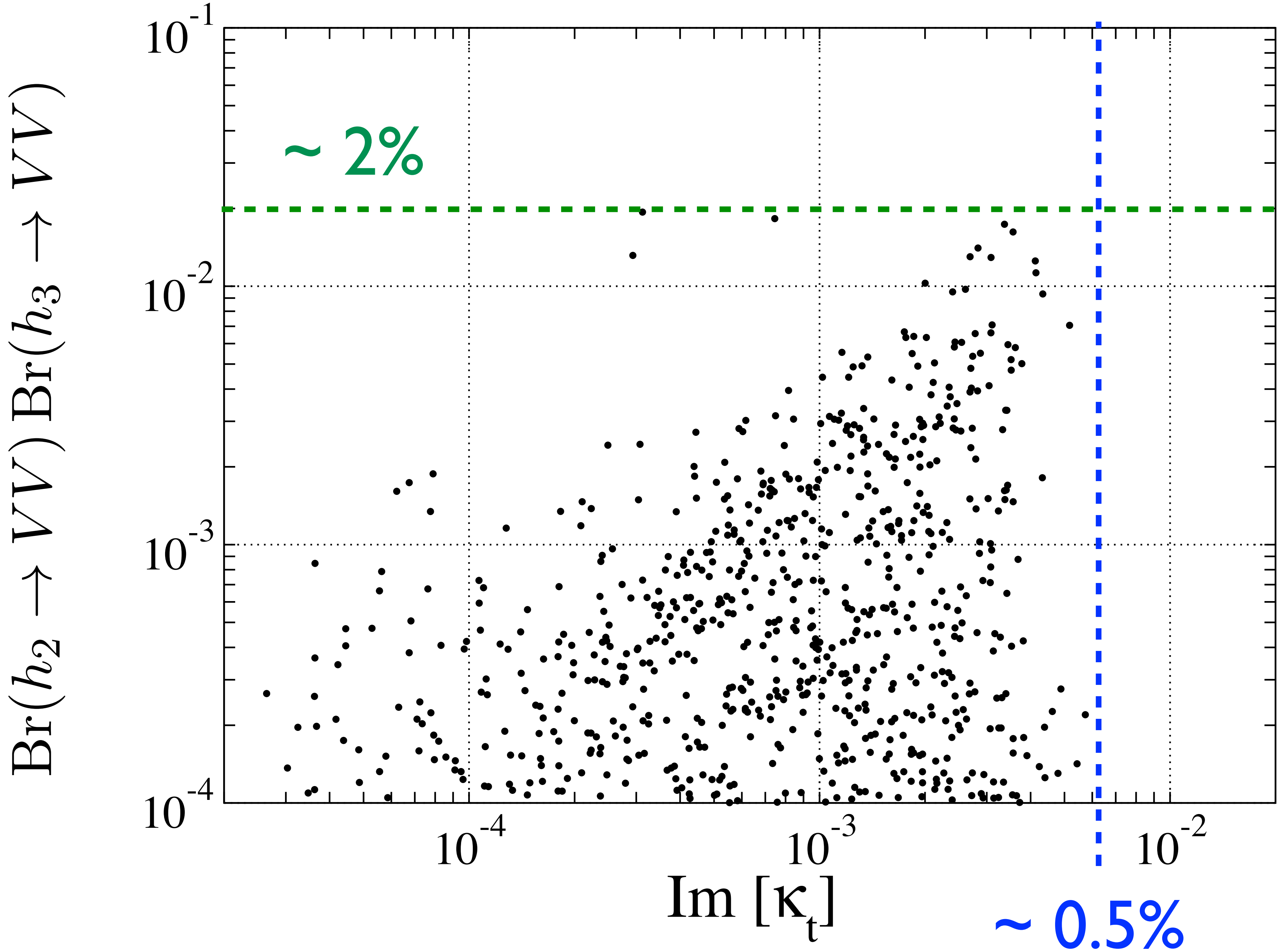
CPV signals

ii) <u>Three</u> neutral Higgs decay into WW/ZZ



CPV → $\prod_{i=1}^{3} \mathrm{Br}(h_i \to VV) \neq 0$

CPV signals



$\mathrm{Br}(h_2 \to VV)\,\mathrm{Br}(h_3 \to VV)$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
~ 2%
10^{-4}
10^{-3}
10^{-2}
Im [κ_t]
~ 0.5%

Summary

- 複合ヒッグス模型では、Partial compositeness を通じて、Higgs potential と Top-Yukawa が相関をもつ。

- CPV 複合2HDM [G/H = SO(6) / SO(4) × SO(2)] について調べた。

  - $\kappa_V \simeq 1 - \frac{\xi}{2}$ $\quad$ $\mathrm{Re}[\kappa_t] \simeq 1 - \frac{3}{2}\xi$

  - $\mathrm{Br}(h_2 \to VV)\mathrm{Br}(h_3 \to VV) \simeq 2\%$ for $\mathrm{Im}[\kappa_t] \simeq 0.5\%$