Composite 2 Higgs doublet models

Kei Yagyu

Seikei U

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Collaboration with

Stefania De Curtis, Luigi Delle Rose, Andrea Tesi (U of Florence),

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2018, 31st May, ALCW18, Fukuoka

Introduction

Higgs boson was found at **125 GeV** at the LHC, but ···

The Higgs sector is still mystery···. In fact, we do not know

- The **Nature** of the Higgs boson.
- The **true shape** of the Higgs sector.
- The reason for the **small Higgs mass** with respect to a NP scale.

2 important paradigms (dynamics)

- **Supersymmetry** (weak) and **Compositeness** (strong)

Both scenarios can provide a **2HDM** as a low energy EFT.

Can we distinguish these scenarios from the 2HDM property?

Plan of the talk

- Introduction to composite (pNGB) Higgs
- Composite 2HDM (C2HDM)
- Results
- Summary

Pion Physics ↔ Higgs Physics

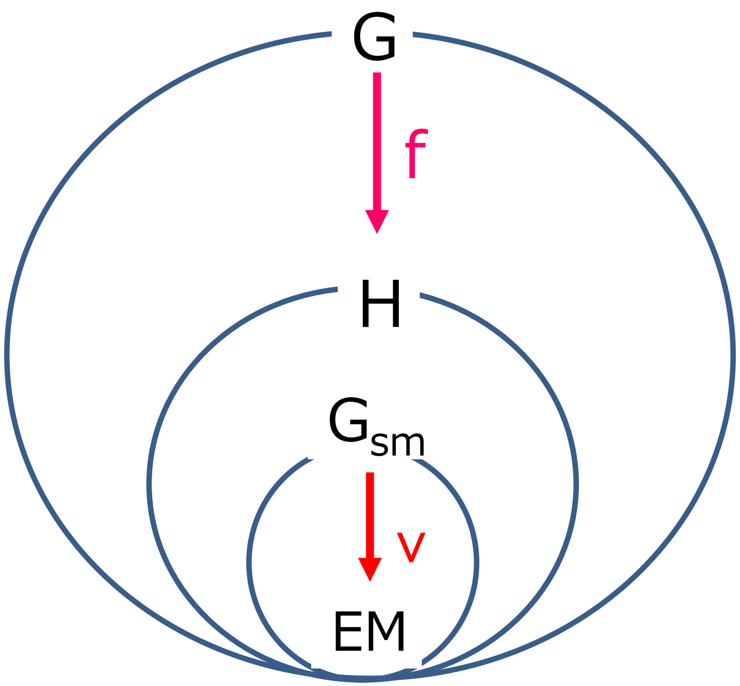
Georgi, Kaplan 80's

- From now on, let me say "**Composite Higgs**" as **pNGB Higgs**.
- This scenario can be understood by analogy of the pion physics.

	Pion Physics	Higgs Physics
Fundamental Theory	QCD	QCD-like theory
Spontaneous sym. breaking	$SU(2)_L \times SU(2)_R \to SU(2)_V$	$G \to H$
pNGB modes	$(\pi^0, \pi^\pm) \sim 135$ MeV	$h \sim 125$ GeV
Other resonances	$\rho \sim 770$ MeV, $\cdots$	New spin 1 and ½ states ~ Multi-TeV

Basic Rules for Composite Higgs

- Suppose there is a global symmetry G at scale above f (~TeV), which is spontaneously broken down into a subgroup H.
- 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 (dimG-dimH) must be 4 or lager.



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G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4}=(\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5}=(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+\mathbf{2}}+\bar{\mathbf{4}}_{-\mathbf{2}}=2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6}=2\times(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7}=(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10}_{\mathbf{0}}=(\mathbf{3},\mathbf{1})+(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3})=3\times(\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2})=2\times(\mathbf{2},\mathbf{2}),(\mathbf{2},\mathbf{2})+2\times(\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5}+\bar{\mathbf{4}}_{+\mathbf{5}}=2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14}=(\mathbf{3},\mathbf{3})+(\mathbf{2},\mathbf{2})+(\mathbf{1},\mathbf{1})$

Table from Mrazek, Pomarol, Rattazi, Redi, Serra, Wulzer NPB 853 (2011) 1-48

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1 Doublet: Minimal Composite Higgs Model

Agashe, Contino, Pomarol (2005)

Kanemura, Kaneta, Machida, Shindou (2014)

Table from Mrazek, Pomarol, Rattazi, Redi, Serra, Wulzer NPB 853 (2011) 1-48

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SO(6)	SO(4) × SO(2)	[illegible]	[illegible]
SO(7)	[illegible]	[illegible]	[illegible]
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1 Doublet + 1 Singlet

Gripaios, Pomarol, Riva, Serra (2009)

Redi, Tesi (2012)

Table from Mrazek, Pomarol, Rattazi, Redi, Serra, Wulzer NPB 853 (2011) 1-48

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2 Doublets

Mrazek, Pomarol, Rattazi, Redi, Serra, Wulzer (2011)

Bertuzzo, Ray, Sandes, Savoy (2013)

Table from Mrazek, Pomarol, Rattazi, Redi, Serra, Wulzer NPB 853 (2011) 1-48

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In this talk, I take SO(6) → SO(4)×SO(2).

Construction of 2 pNGB Doublets

- 15 SO(6) generators: $T^A = \{\underbrace{T^a_{L,R}}_{\text{6 SO(4)}},\ \underbrace{T_S}_{\text{1 SO(2)}},\ \underbrace{T^{\hat a}_{1,2}}_{\text{8 Broken}}\}$ (A=1-15, a=1-3, â=1-4)

$$\Phi \equiv (\phi^{\hat a}_1, \phi^{\hat a}_2)$$

- pNGB matrix: $U(\phi^{\hat a}_1, \phi^{\hat a}_2) \equiv \exp\left[\sqrt{2}i\left(T^{\hat a}_1 \frac{\phi^{\hat a}_1}{f} + T^{\hat a}_2 \frac{\phi^{\hat a}_2}{f}\right)\right] = \exp\left[\begin{pmatrix} 0_{4\times 4} & \Phi \\ -\Phi^T & 0_{2\times 2} \end{pmatrix}\right]$

  U is transformed non-linearly under SO(6): $U \to g\, U h^{-1}(g, \phi^{\hat a}_{1,2})$

- Linear rep. **Σ(15): 15** = (**6**,**1**) ⊕ (**4**,**2**) ⊕ (**1**,**1**) under SO(4)×SO(2)

$$\Sigma = U \Sigma_0 U^T = \begin{pmatrix} \Sigma(6,1) & \Sigma(4,2) \\ -\Sigma^T(4,2) & \Sigma(1,1) \end{pmatrix} \qquad \Sigma_0 = i\sqrt{2}T_S = \begin{pmatrix} 0_{4\times 4} & 0_{4\times 2} \\ 0_{2\times 4} & i\sigma_2 \end{pmatrix}$$

  Σ is transformed linearly under SO(6): $\Sigma \to g\, \Sigma\, g^{-1}$ and $\Sigma_0 \to h\, \Sigma_0\, h^{-1}$

Higgs Potential

- The potential becomes 0 because of the shift symmetry of the NGB.

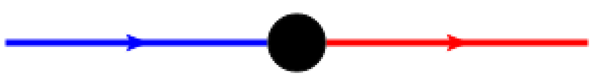
  → the Higgs mass also becomes 0.

- We need to introduce the explicit breaking of G.

  → NGB Higgs becomes **p**NGB with a finite mass.

Kaplan, PLB365, 259 (1991)

- Explicit breaking can be realized by partial compositeness



Linear mixing

a Particle in elementary sector

a Particle in strong sector

Strategy

Explicit Model

SO(6) invariant Lagrangian
with partial compositeness

Integrating out
heavy DOFs

Effective Lagrangian

SU(2)×U(1) invariant Lag.
with form factors

Coleman-Weinberg
mechanism

Effective Potential

2HDM potential with
predicted parameters

Phenomenology

Higgs mass spectrum
Higgs couplings, decays, etc…

Explicit Model

Based on the 4DCHM, De Curtis, Redi, Tesi, JHEP04 (2012) 042

$$\mathcal{L} = \mathcal{L}_{\rm elem} + \mathcal{L}_{\rm str} + \mathcal{L}_{\rm mix}$$

Elementary Sector

$SU(2)_L \times U(1)_Y$

$$\boldsymbol{W^a_\mu,\ q_L,\ t_R}$$

Mixing

Partial Compositeness

Strong Sector

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

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

$$\boldsymbol{\rho^A_\mu,\ \Psi^6,\ \Sigma}$$

Explicit Model

Based on the 4DCHM, De Curtis, Redi, Tesi, JHEP04 (2012) 042

Embeddings into SO(6) multiplets :

$$W_\mu^a \in W_\mu^A \qquad q_L \in q_L^6 \qquad t_R \in t_R^6$$

Elementary Sector

SU(2)$_L$×U(1)$_Y$

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

Mixing

Partial Compositeness

Strong Sector

SO(6)×U(1)$_X$

→ SO(4)× SO(2)×U(1)$_X$

$$\rho_\mu^A, \; \Psi^6, \; \Sigma$$

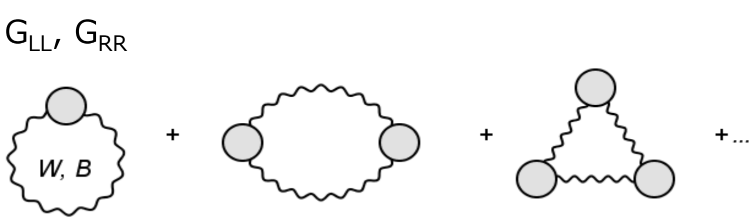
$$\mathcal{L}_{\rm mix} = (f^2 g_\rho g_W) W_\mu^A \rho^{A\mu} + (\Delta_L \bar{q}_L^6 \Psi_R^6 + \Delta_R \bar{t}_R^6 \Psi_L^6 + \text{h.c.})$$

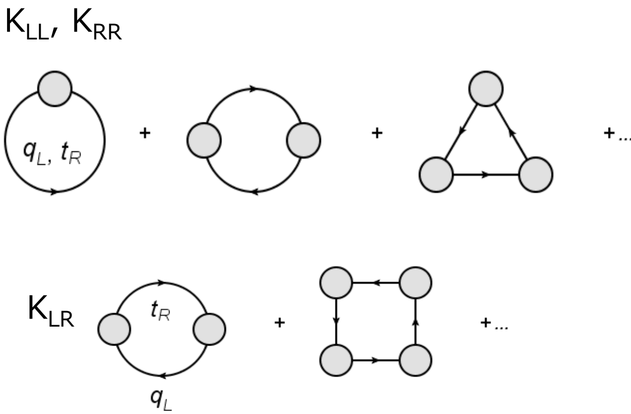
Effective Lagrangian

- All the strong sector information are encoded into the form factors:

$$\mathcal{L}_{\rm eff} = (W_\mu, B_\mu) \begin{pmatrix} G_{LL} & G_{LR} \\ G_{LR} & G_{RR} \end{pmatrix} \begin{pmatrix} W^\mu \\ B^\mu \end{pmatrix} + (\bar{q}_L, \bar{t}_R) \begin{pmatrix} \not{q}\, K_{LL} & K_{LR} \\ K_{LR} & \not{q}\, K_{RR} \end{pmatrix} \begin{pmatrix} q_L \\ t_R \end{pmatrix}$$

- We then calculate the 1-loop CW potential.





$$V = \frac{1}{f^4} \int \frac{d^4k}{(2\pi)^4} \left(\frac{3}{2} \ln \det G - 2N_c \ln \det K \right)$$

Effective Potential

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

All the potential parameters $\mathbf{m_i^2}$ and $\boldsymbol{\lambda_i}$ are given as a function of strong parameters:

$$m_i^2 = m_i^2(g_\rho, f, \ldots) \qquad \lambda_i = \lambda_i(g_\rho, f, \ldots)$$

Matching Conditions

- We need to reproduce the top mass and the weak boson mass.

$$m_W^2 = \langle G_{LL} \rangle_{q^2 \to 0} = \frac{1}{4} \boxed{\frac{g_W^2 g_\rho^2}{g_W^2 + g_\rho^2}} \boxed{f^2 \sin^2 \frac{v}{f}}$$

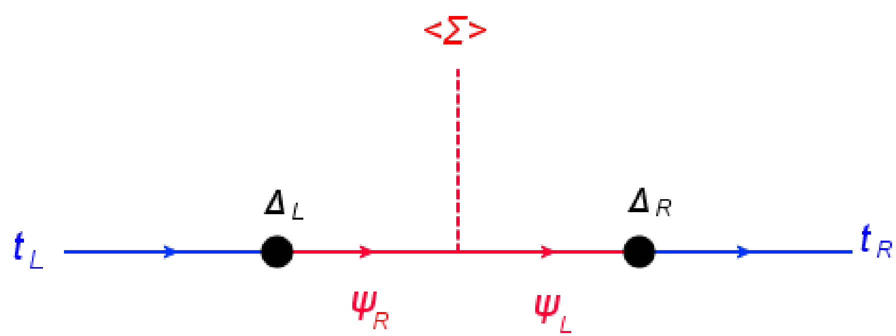
$$v^2 = v_1^2 + v_2^2$$

$$\tan\beta = v_2 / v_1$$

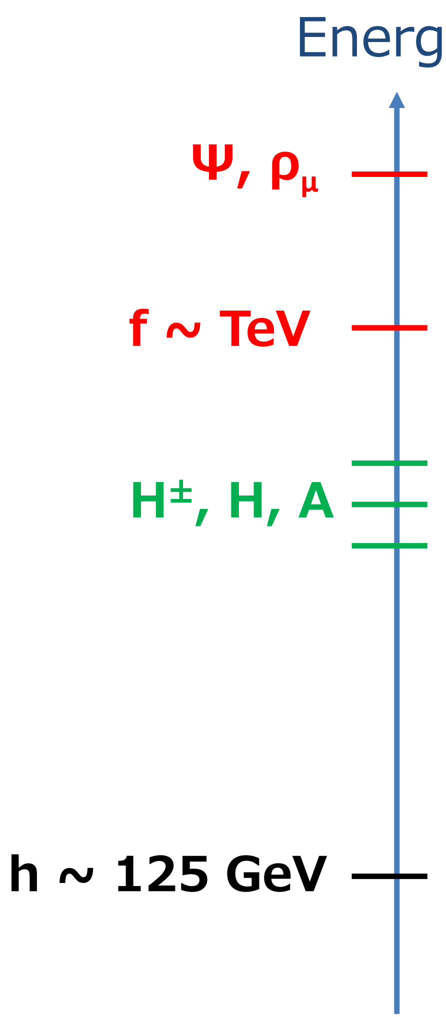
g^2 $\quad$ $V_{sm}^2 \sim (246\ \mathrm{GeV})^2$

$$m_t \sim \langle K_{LR} \rangle_{q^2 \to 0} \sim \frac{v}{\sqrt{2}} \boxed{\frac{\Delta_L \Delta_R}{m_\Psi^2}}$$

Y_t



Typical Prediction of Mass Spectrum



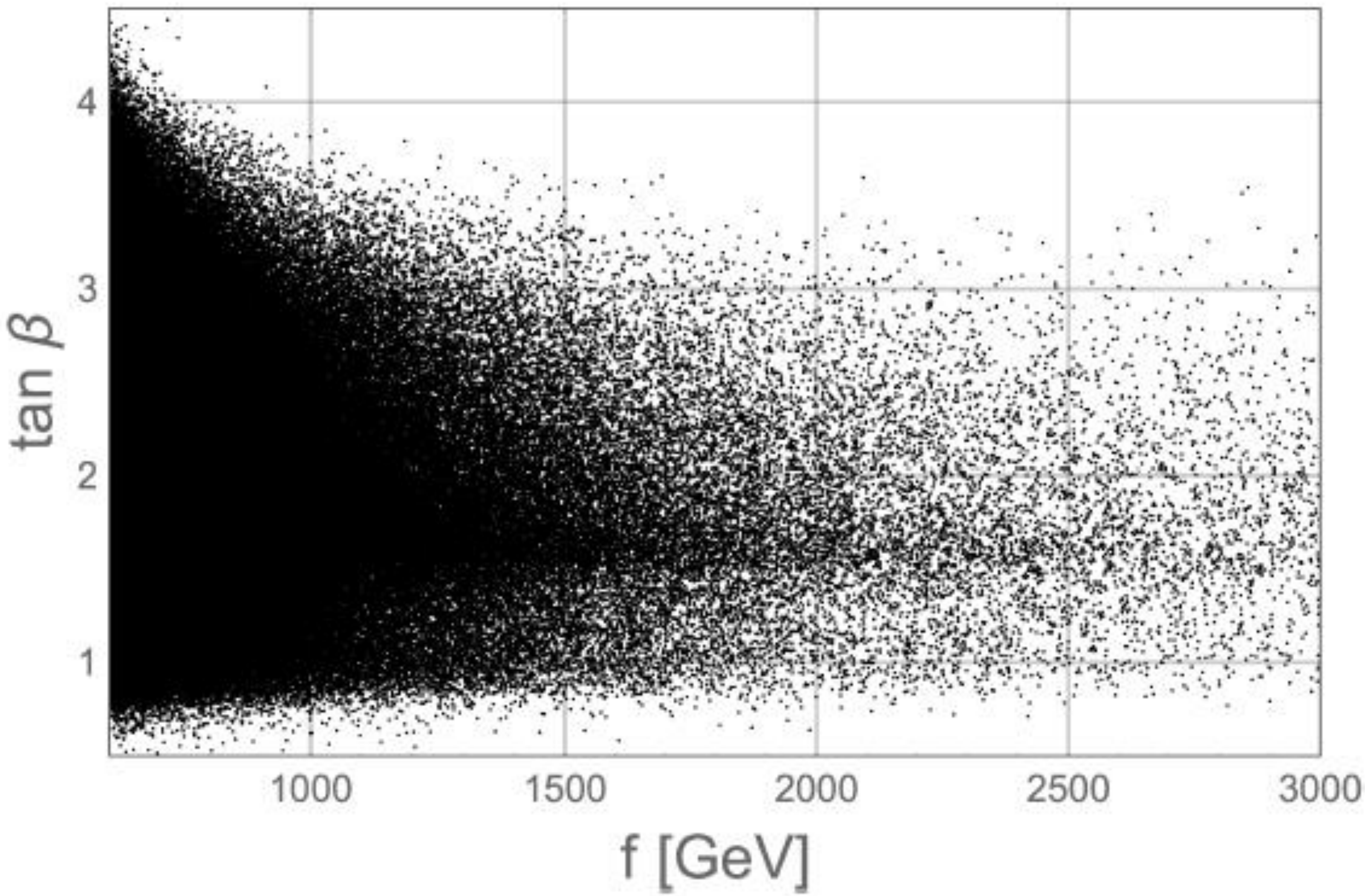
$$M^2 \sim \frac{f^2}{16\pi^2}$$

$$m_h^2 \sim \frac{N_c}{16\pi^2} g_\rho^2 m_t^2$$

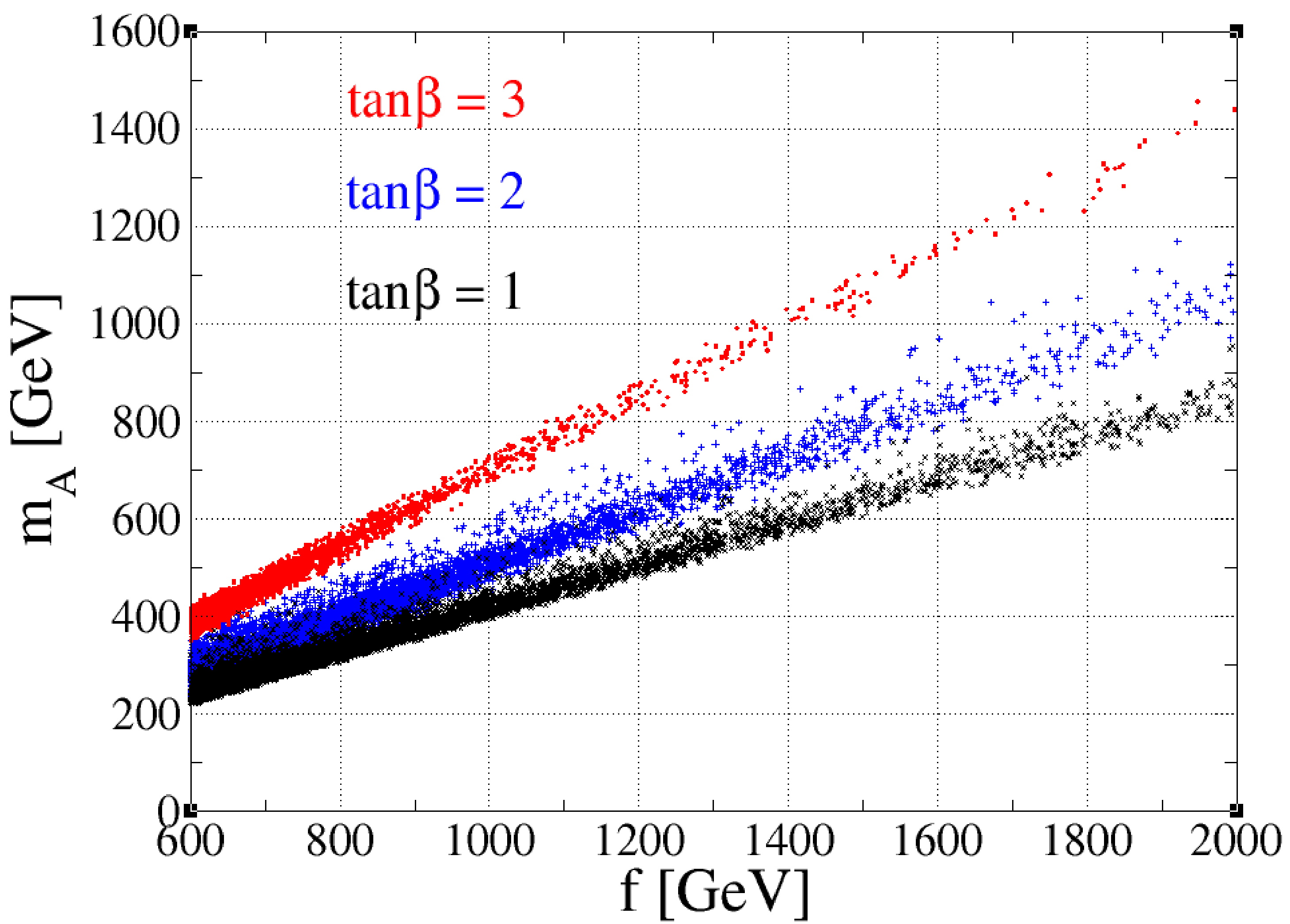
★ The Higgs mass m_h is naturally explained by $g_\rho \sim 5$.

★ f → ∞ : All extra Higgs bosons are decoupled.
→ (elementary) SM limit.

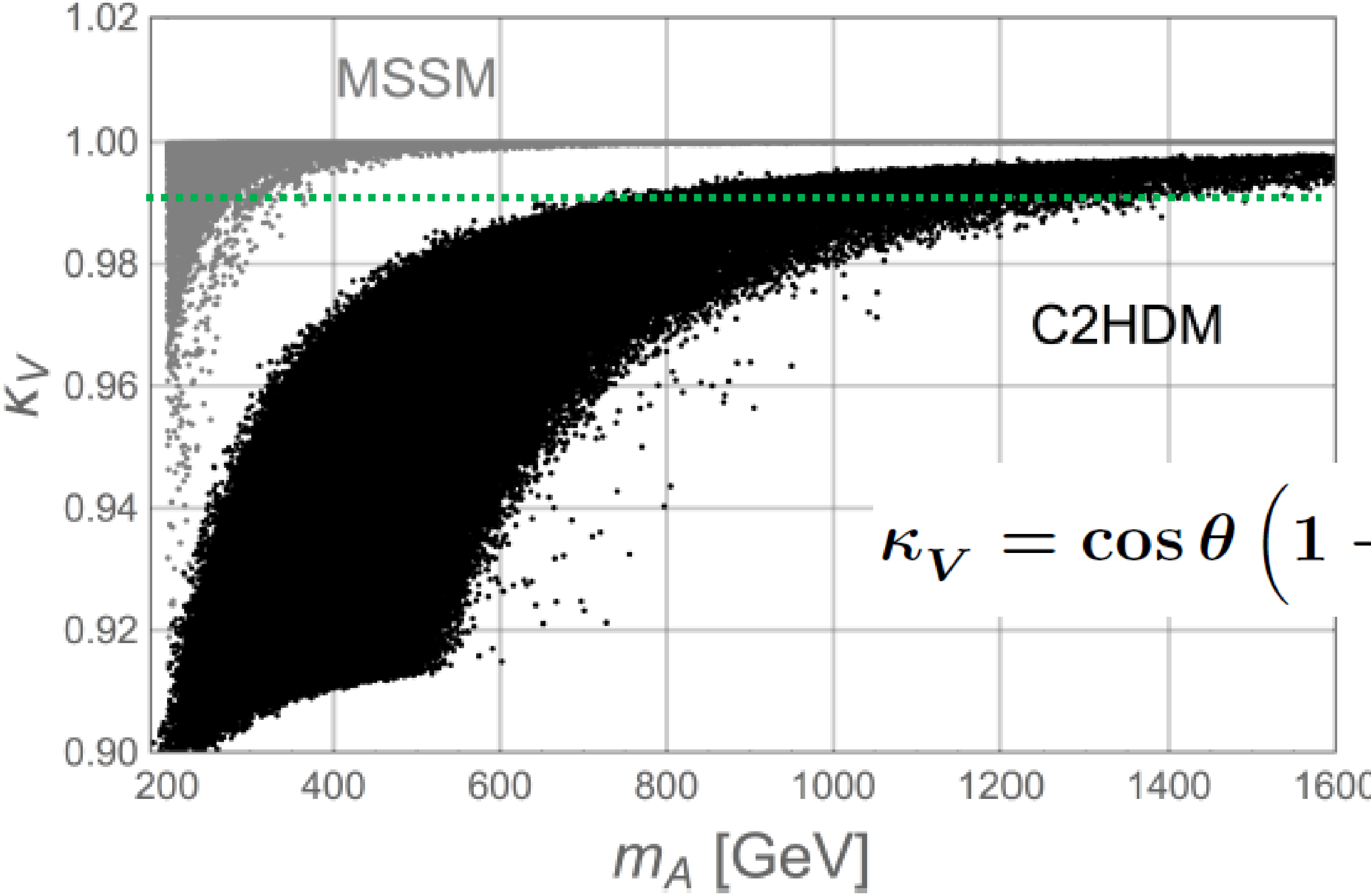
f VS tanβ



Correlation b/w f and m_A

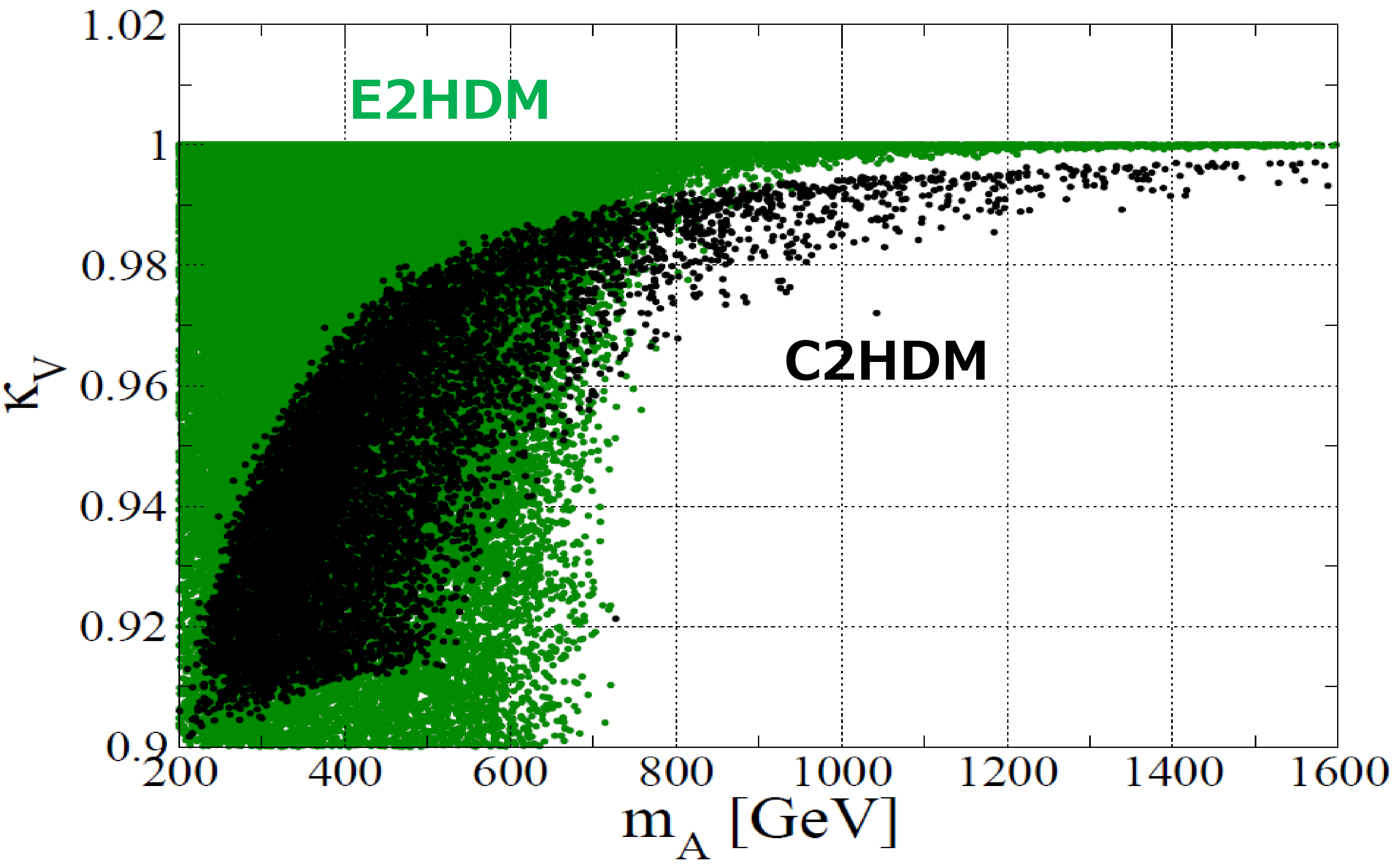


Correlation b/w m_A and κ_V (= g_{hVV}/g_{hVV}^{SM})



$$\kappa_V = \cos\theta\left(1 - \frac{1}{2}\frac{v^2}{f^2}\right)$$

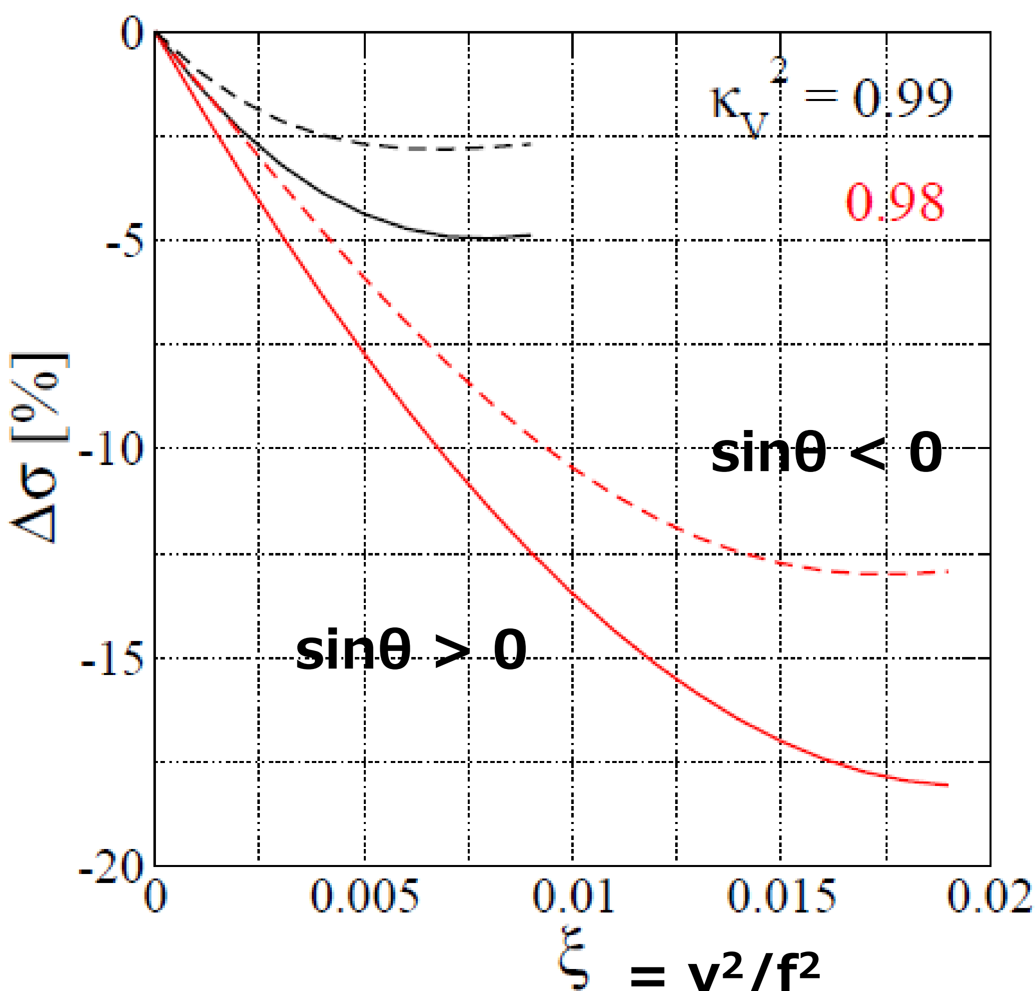
Correlation b/w m_A and κ_V (= g_{hVV}/g_{hVV}^{SM})



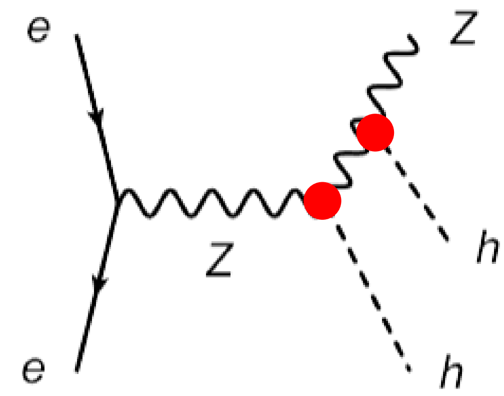
Ratio of σ($e^+e^- \rightarrow Zhh$) @ $\sqrt{s}$ = 1 TeV

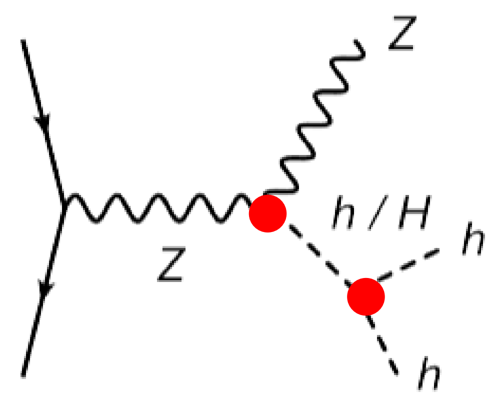
De Curtis, Moretti, KY, Yildirim, PRD95 095026

$\Delta\sigma = \sigma(\text{C2HDM})/\sigma(\text{E2HDM}) - 1$



= v^2/f^2





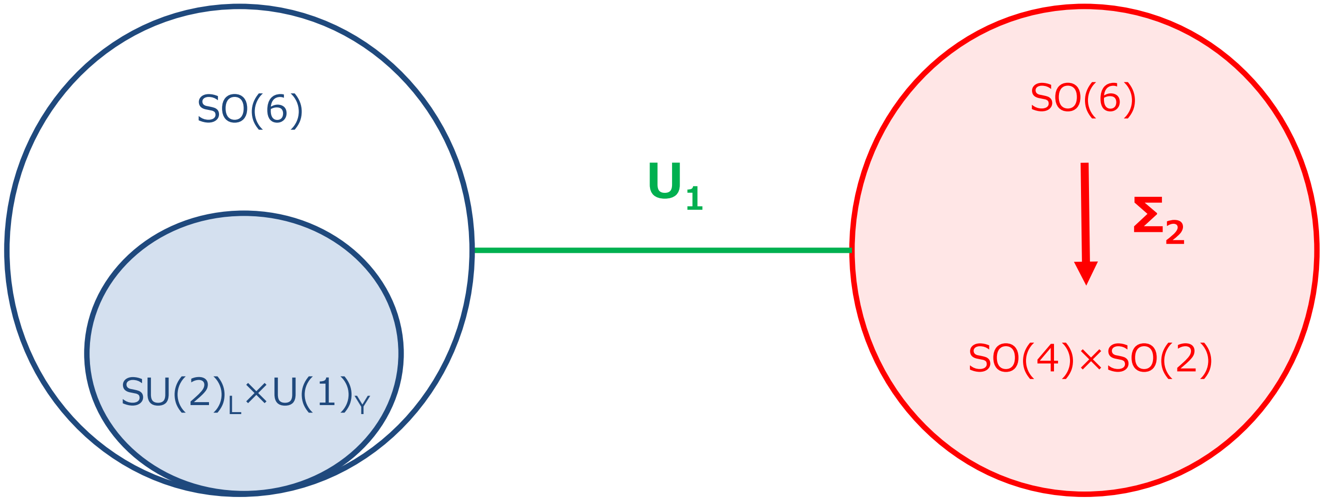
Summary

- Composite (=pNGB) Higgs can naturally explain the **light Higgs .**
- Taking the SO(6)/SO(4)*SO(2) coset, we obtain C2HDMs as a low energy EFT, where 2HDM parameters can be **predicted** by the **strong dynamics**.
- The MSSM and C2HDM can be distinguished by looking at the **decoupling behavior (κV-mA) .**
- The C2HDM can be further distinguished from E2HDMs from the decoupling behaviour or by looking at **$e^+e^- \to$ Zhh** process.

Gauge Sector Lagrangian (in unitary gauge)

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

Elementary Sector (g_W, W_μ) **Strong Sector (g_ρ, ρ_μ)**



$$U_1 = U(1/f \to f/f_1^2)$$

$$\Sigma_2 = \Sigma(1/f \to f/f_2^2)$$

$$1/f^2 = 1/f_1^2 + 1/f_2^2$$

$$\mathcal{L}_{\rm str} = \frac{f_1^2}{4}\mathrm{tr}(D_\mu U_1)^\dagger(D^\mu U_1) + \frac{f_2^2}{4}\mathrm{tr}(D_\mu \Sigma_2)^T(D^\mu \Sigma_2) - \frac{1}{4}\mathrm{tr}\rho^A_{\mu\nu}\rho^{A\mu\nu}$$

$$D_\mu U_1 = \partial_\mu U_1 - i g_W W_\mu U_1 + i g_\rho U_1 \rho_\mu \qquad D_\mu \Sigma_2 = \partial_\mu \Sigma_2 - i g_\rho [\rho_\mu, \Sigma_2]$$

Explicit Model

Based on the 4DCHM, De Curtis, Redi, Tesi, JHEP04 (2012) 042

$$\mathcal{L}_{\text{elem}} = -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} + \bar{q}_L \, i\not{D} \, q_L + \bar{t}_R \, i\not{D} \, t_R$$

Elementary Sector

$SU(2)_L \times U(1)_Y$

$$W^a_\mu, \; q_L, \; t_R$$

Mixing

Partial Compositeness

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

$$-\frac{1}{4} \text{tr} \rho^A_{\mu\nu} \rho^{A\,\mu\nu} + \frac{m_\rho^2}{2} (\rho^A)_\mu (\rho^A)^\mu \quad + (\Sigma\text{-}\rho) \text{ interactions}$$

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Based on the 4DCHM, De Curtis, Redi, Tesi, JHEP04 (2012) 042

C_2 symmetry

(to avoid FCNCs)

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

$$\Sigma \to -C_2 \Sigma C_2$$

$$\Psi^6 \to C_2 \Psi^6$$

C_2 = diag(1,1,1,1,1,-1)

Elementary Sector

$SU(2)_L \times U(1)_Y$

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

Mixing

Partial Compositeness

Strong Sector

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

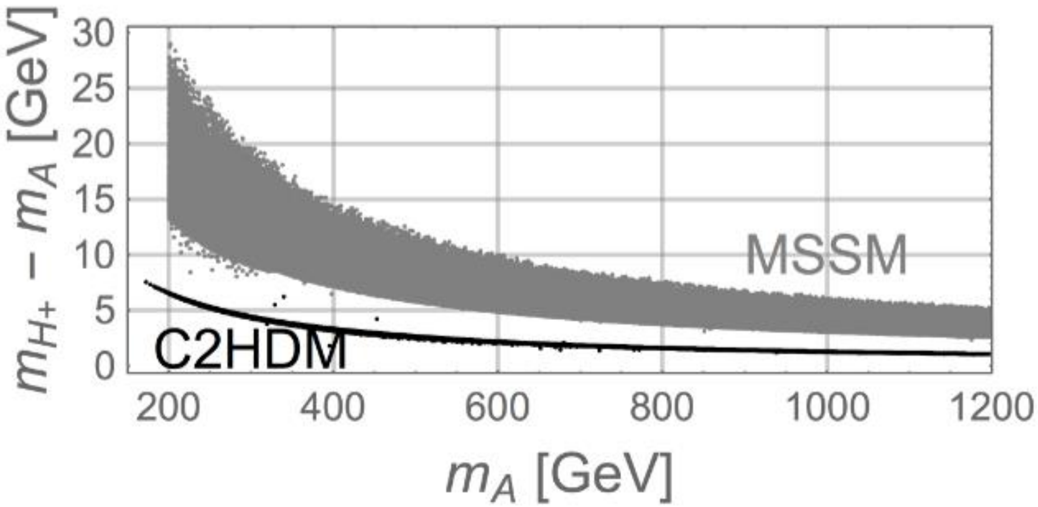
$\to SO(4) \times SO(2) \times U(1)_X$

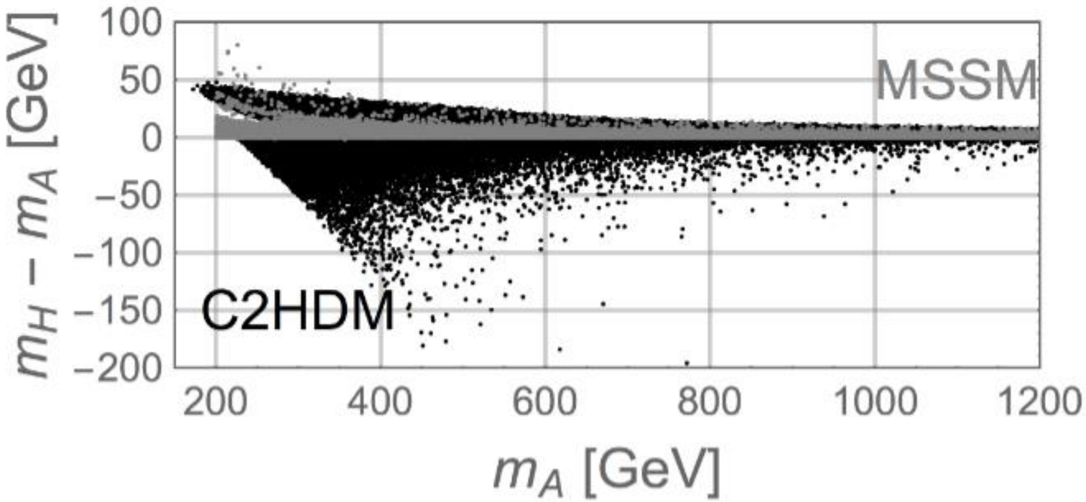
$$\rho_\mu^A,\ \Psi^6,\ \Sigma$$

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

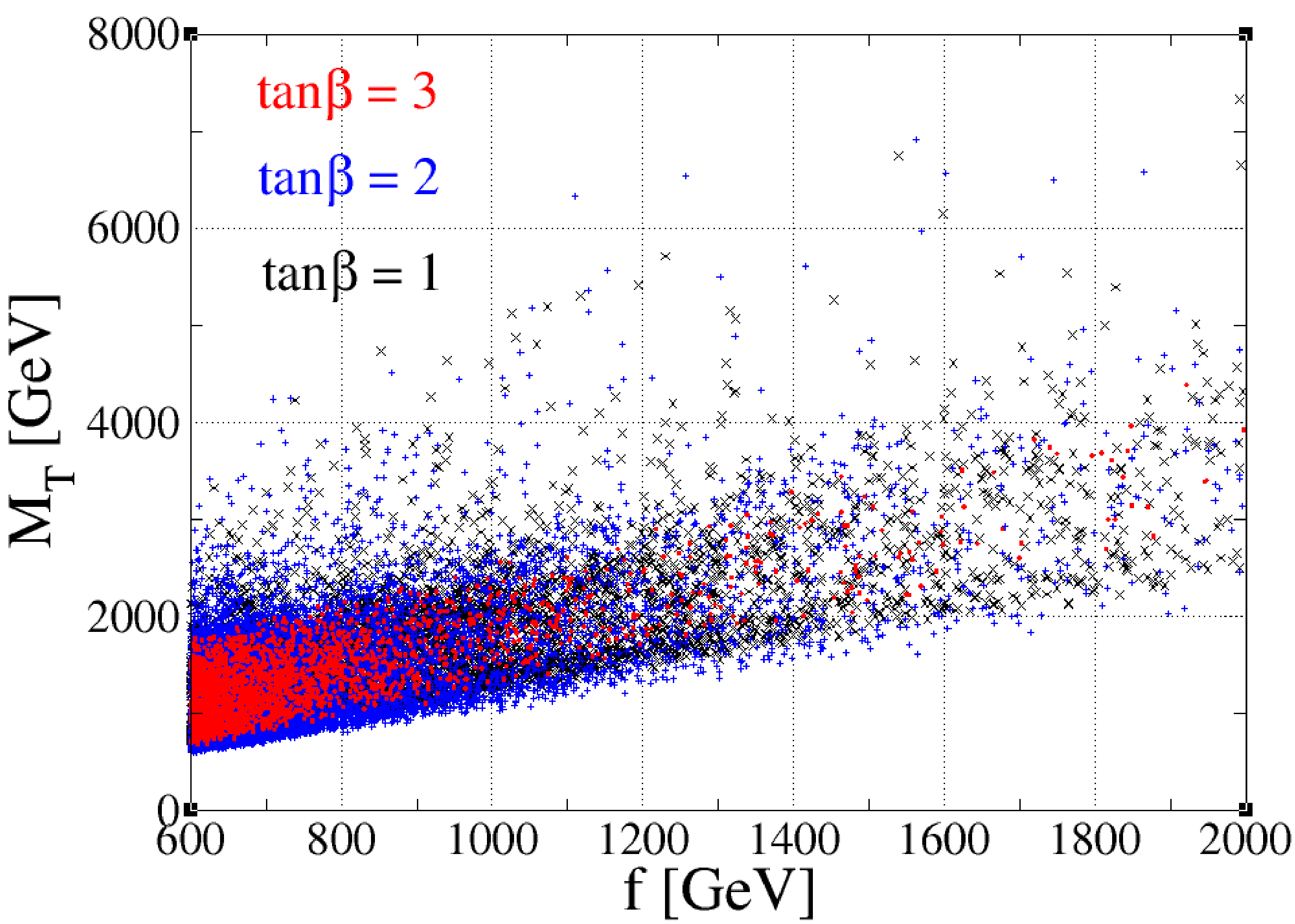
$$-\frac{1}{4}\,\mathrm{tr}\rho_{\mu\nu}^A \rho^{A\,\mu\nu} + \frac{m_\rho^2}{2} (\rho^A)_\mu (\rho^A)^\mu$$ + (Σ-ρ) interactions

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



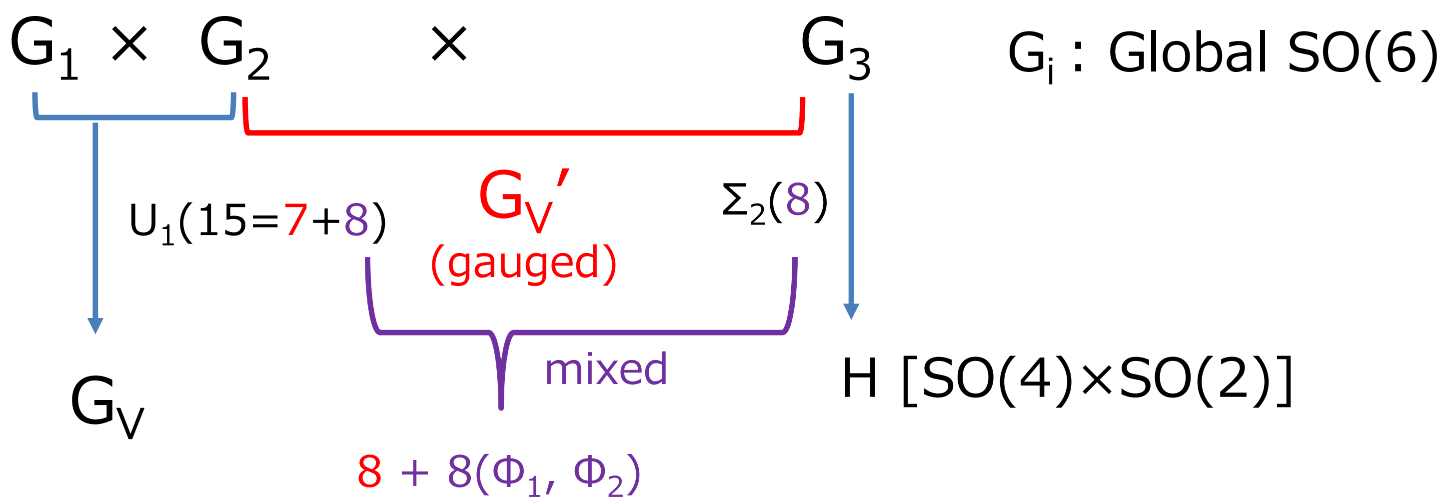


Correlation b/w f and M_T



Gauge Sector Lagrangian

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



7 + 8 NGBs are absorbed into the longitudinal components of gauge bosons of adj[SO(6)].

Effective Lagrangian

- Integrating out the heavy degrees of freedom (ρ^A and ψ^6), we obtain the effective low energy Lagrangian

$$\mathcal{L}_{\rm eff} = (W_\mu, B_\mu) \underbrace{\begin{pmatrix} G_{LL} & G_{LR} \\ G_{LR} & G_{RR} \end{pmatrix}}_{\coloneqq G} \begin{pmatrix} W^\mu \\ B^\mu \end{pmatrix} + (\bar{q}_L, \bar{t}_R) \underbrace{\begin{pmatrix} \not{q}\, K_{LL} & K_{LR} \\ K_{LR} & \not{q}\, K_{RR} \end{pmatrix}}_{\coloneqq K} \begin{pmatrix} q_L \\ t_R \end{pmatrix}$$

$$K_{LL} = I_{2\times 2} + K_{LL}^{11} \Phi_1^c \Phi_1^{c\dagger} + K_{LL}^{22} \Phi_2^c \Phi_2^{c\dagger} + (K_{LL}^{12} \Phi_1^c \Phi_2^{c\dagger} + \mathrm{h.c.})$$

$$K_{LR} = \Phi_1^c K_{LR}^1 + \Phi_2^c K_{LR}^2$$

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These coefficients can be expanded as $1 + c_1^{ij}\, \Phi_i^\dagger \Phi_j + c_2^{ij}\, (\Phi_i^\dagger \Phi_j)^2 + \cdots$

c_1, c_2, ⋯ are determined by strong parameters.

Numerical Analysis

Input parameters (to be scanned):

$f,\ g_\rho,\ Y_1\ ,\ Y_2\ ,\ \Delta_L,\ \Delta_R,\ M_\Psi,\ M_\Psi^{12}$

$\downarrow$

Tadpole conditions: $T_1 = T_2 = 0$

$\downarrow$

165 GeV < m_t < 175 GeV

$\downarrow$

120 GeV < m_h < 130 GeV

Yukawa Interactions

- The structure of the Yukawa interaction is that in the Aligned 2HDM.

$$\mathcal{L}_{\text{eff}} = \frac{\sqrt{2} m_t}{v} \bar{q}_L (\Phi^c + \zeta_t \Psi^c) t_R + \text{h.c.} + \mathcal{O}(\xi^{3/2})$$

$$\zeta_t \equiv \frac{\bar{\zeta}_t - \tan\beta}{1 + \bar{\zeta}_t \tan\beta} \quad \text{with} \quad \bar{\zeta}_t = \frac{M_1^t}{M_2^t}.$$

- All M_1^t, M_2^t and $\tan\beta$ can be predicted by strong dynamics, so the ζ_t factor is also predicted.

Yukawa Interactions