2 Higgs doublets as pseudo Nambu-Goldstone bosons

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Collaboration with

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Introduction

From LHC results

- At least 1 Higgs boson exists.
- It shows $SU(2)_L$ doublet nature.
- Its mass is 125 GeV.

Questions

- Why the Higgs boson mass is such small with respect to NP scale?
- What is the true shape of the Higgs sector?

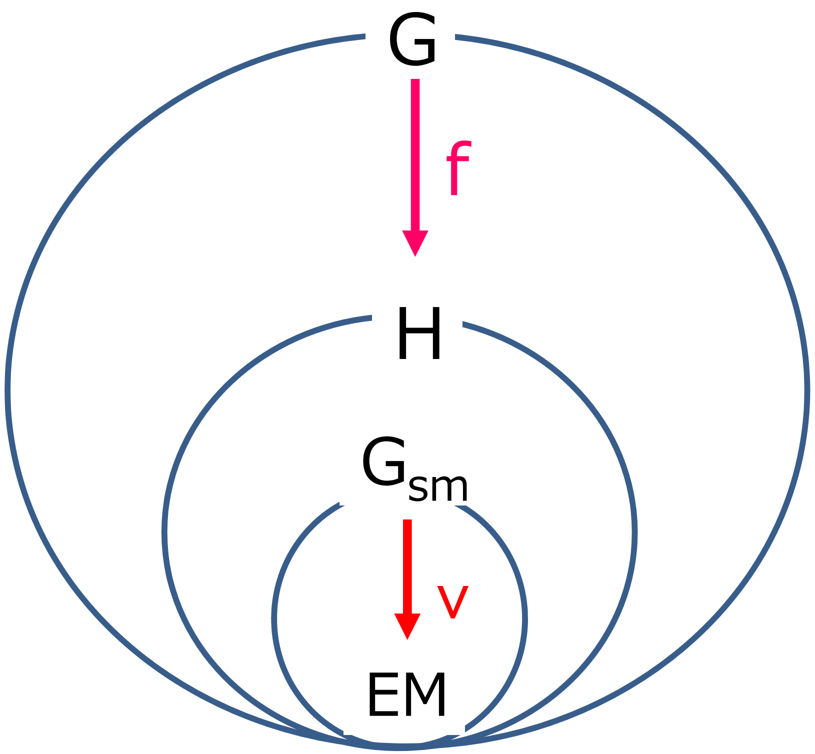
(Possible) answer

- Higgs is a pseudo Nambu-Goldstone boson (pNGB).
- Higgs sector has a multi-doublet structure (many motivations).

Let’s combine **pNGB Higgs** and **multi-Higgs structure**!

Introduction to pNGB 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) should be 4 or lager.



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SO(6)	SO(5)	5	$\mathbf{5}=(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+2}+\bar{\mathbf{4}}_{-2}=2\times(\mathbf{2},\mathbf{2})$
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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Agashe, Contino, Pomarol (2005)

1 Doublet: Minimal Composite Higgs Model

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1 Doublet + 1 Singlet

Gripaios, Pomarol, Riva, Serra (2009)

Redi, Tesi (2012)

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2 Doublets

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

Bertuzzo, Ray, Sandes, Savoy (2013)

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We consider 2 Higgs doublets as pNGB from 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, $\hat{a}$=1-4)

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$$\Phi \equiv (\phi_1^{\hat{a}}, \phi_2^{\hat{a}})$$

- pNGB matrix: $U(\phi_1^{\hat{a}}, \phi_2^{\hat{a}}) \equiv \exp\left[\sqrt{2}i\left(T_1^{\hat{a}}\frac{\phi_1^{\hat{a}}}{f} + T_2^{\hat{a}}\frac{\phi_2^{\hat{a}}}{f}\right)\right] = \exp\left[\begin{pmatrix} 0_{4\times4} & \Phi \\ -\Phi^T & 0_{2\times2}\end{pmatrix}\right]$

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

$$\Sigma = U\Sigma_0 U^T = \begin{pmatrix} \Sigma(6,1) & \Sigma(4,2) \\ -\Sigma^T(4,2) & \Sigma(1,1)\end{pmatrix} \qquad \Sigma_0 = i\sqrt{2}T_S = \begin{pmatrix} 0_{4\times4} & 0_{4\times2} \\ 0_{2\times4} & i\sigma_2\end{pmatrix}$$

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

Higgs Potential

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- We need to introduce the explicit breaking of G.

Elementary Sector

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

$\psi_{\rm ele} \in W^a_\mu,\ q_L,\ t_R, \dots$

Mixing

Strong Sector

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

$\mathcal{O}_{\rm str} \in \rho^A_\mu,\ \Psi^r, \dots$

$$\mathcal{L}_{\rm mix} = (\Delta_\psi)^{\alpha I}\, \psi^\alpha_{\rm ele}\, \mathcal{O}^I_{\rm str}$$

α: $SU(2)_L \times U(1)_Y$ index

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- Non-zero potential appears at 1-loop level via the CW mechanism.

Mrazek, Pomarol, Rattazi, Redi, Serra, Wulzer

(1) Spurion method, (2) Explicit model

Explicit Model

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

Elementary Sector

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

$$g_W,\ y_L,\ y_R$$

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$$\mathcal{L}_{\rm ele} = -\frac{1}{4g_W^2} W^a_{\mu\nu} W^{a\,\mu\nu} + \frac{1}{y_L^2}\bar{q}_L i \not{D} q_L + \frac{1}{y_R^2}\bar{t}_R i \not{D} t_R$$

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

$$-\frac{1}{4}\,{\rm tr}\rho^A_{\mu\nu}\rho^{A\,\mu\nu} + \frac{m_\rho^2}{2}(\rho^A)_\mu(\rho^A)^\mu$$ + Σ-(ρ, W) interaction

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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

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Embeddings into SO(6) multiplets :

$$W_\mu^a \in W_\mu^A \qquad t_R^6 = (\Delta_{t_R})^I \, t_R \quad q_L^6 = (\Delta_{q_L})^{\alpha I} \, q_L^\alpha$$

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

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$$\mathcal{L}_{\rm mix} = m_\rho^2 W_\mu^A \rho^{A\mu} + \Delta(\bar{q}_L^6 \Psi^6 + \bar{t}_R^6 \Psi^6)$$

Effective Lagrangian

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

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

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$$K_{LL} = I_{2\times 2} + \sum_{i,j}^{1,2} K_{LL}^{ij} \Phi_i^c \Phi_j^{c\dagger} (\cdots)$$

$(\cdots)$: function of SU(2) invariants e.g., $\Phi_1^\dagger \Phi_1,\ (\Phi_1^\dagger \Phi_1)^2, \ldots$

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- The Higgs potential can be straightforwardly calculated as

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

- After int. and expansion by $\Phi_{1,2}$, we can extract the potential parameters.

Effective Lagrangian

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

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

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Matching Conditions

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

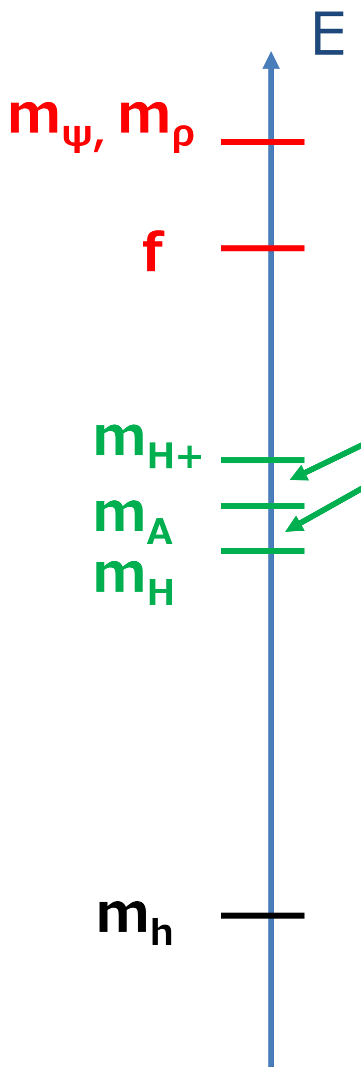
$$m_W^2 = \langle G_{LL} \rangle_{q^2 \to 0} = \frac{1}{4} \underbrace{\frac{g_W^2 g_\rho^2}{g_W^2 + g_\rho^2}}_{g^2} \underbrace{f^2 \sin^2 \frac{v}{f}}_{v_{sm}^2 = [\mathrm{sqrt}(2)\, G_F]^{-1}}$$

$$m_t = \langle K_{LR} \rangle_{q^2 \to 0} \sim \frac{v}{\sqrt{2}} \underbrace{\frac{m_\Psi \Delta_L \Delta_R}{Y \sqrt{\Delta_L^2 + m_\Psi^2} \sqrt{\Delta_R^2 + Y^2}} \frac{Y_1 s_\beta + Y_2 c_\beta}{f}}_{Y_t}$$

$$v^2 = v_1^2 + v_2^2 \qquad \tan\beta = v_2 / v_1$$

$$\Delta_{L,R} = y_{L,R} \Delta \qquad Y = \sqrt{Y_1^2 + Y_2^2}$$

Typical Prediction of Mass Spectrum



$$\mathcal{O}(M^2 \times \frac{v^2}{f^2})$$

$$M^2 \equiv \frac{m_3^2}{s_\beta c_\beta} \sim \frac{1}{16\pi^2} Y_1 Y_2 \sim \frac{f^2}{16\pi^2}$$

Y_1: C_2 breaking term

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$$m_h^2 = \lambda_i v^2$$

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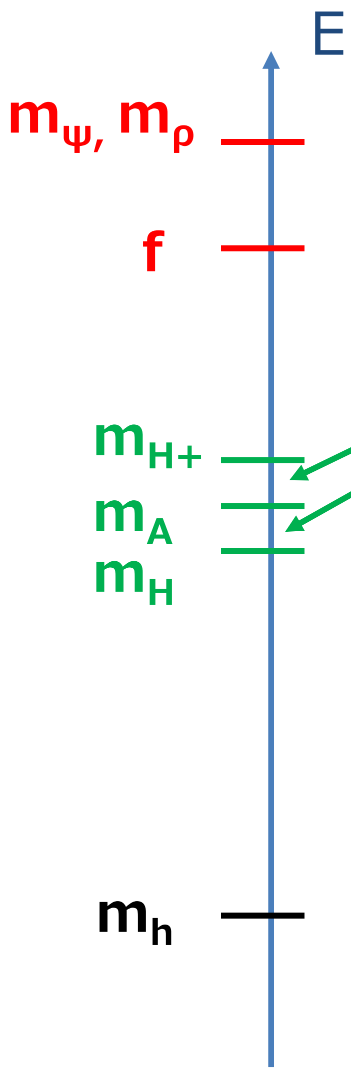

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★f → ∞ : All extra Higgses are decoupled

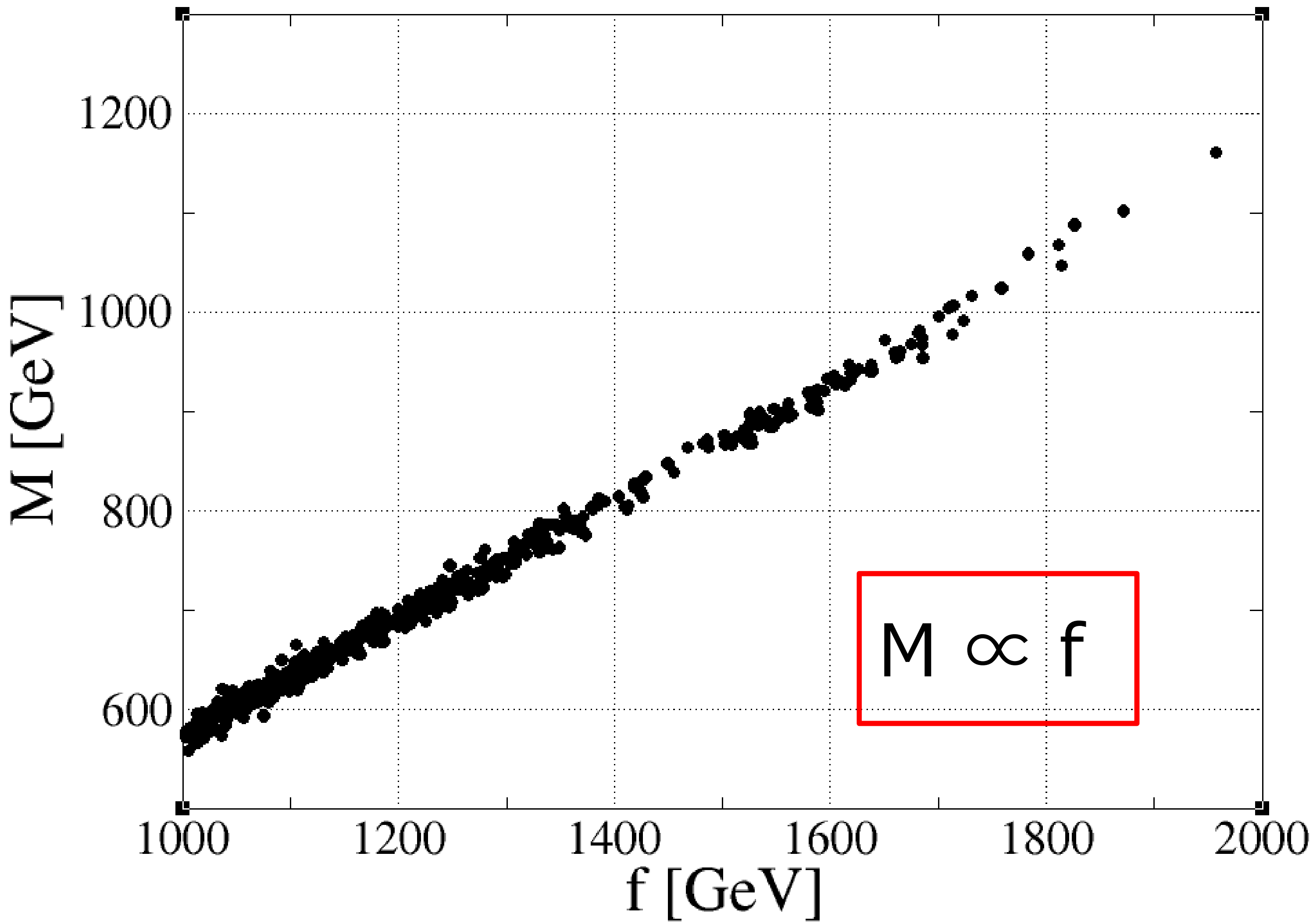
→ (elementary) SM limit

★To get M≠0, we need C_2 breaking

(Yukawa alignment is required).

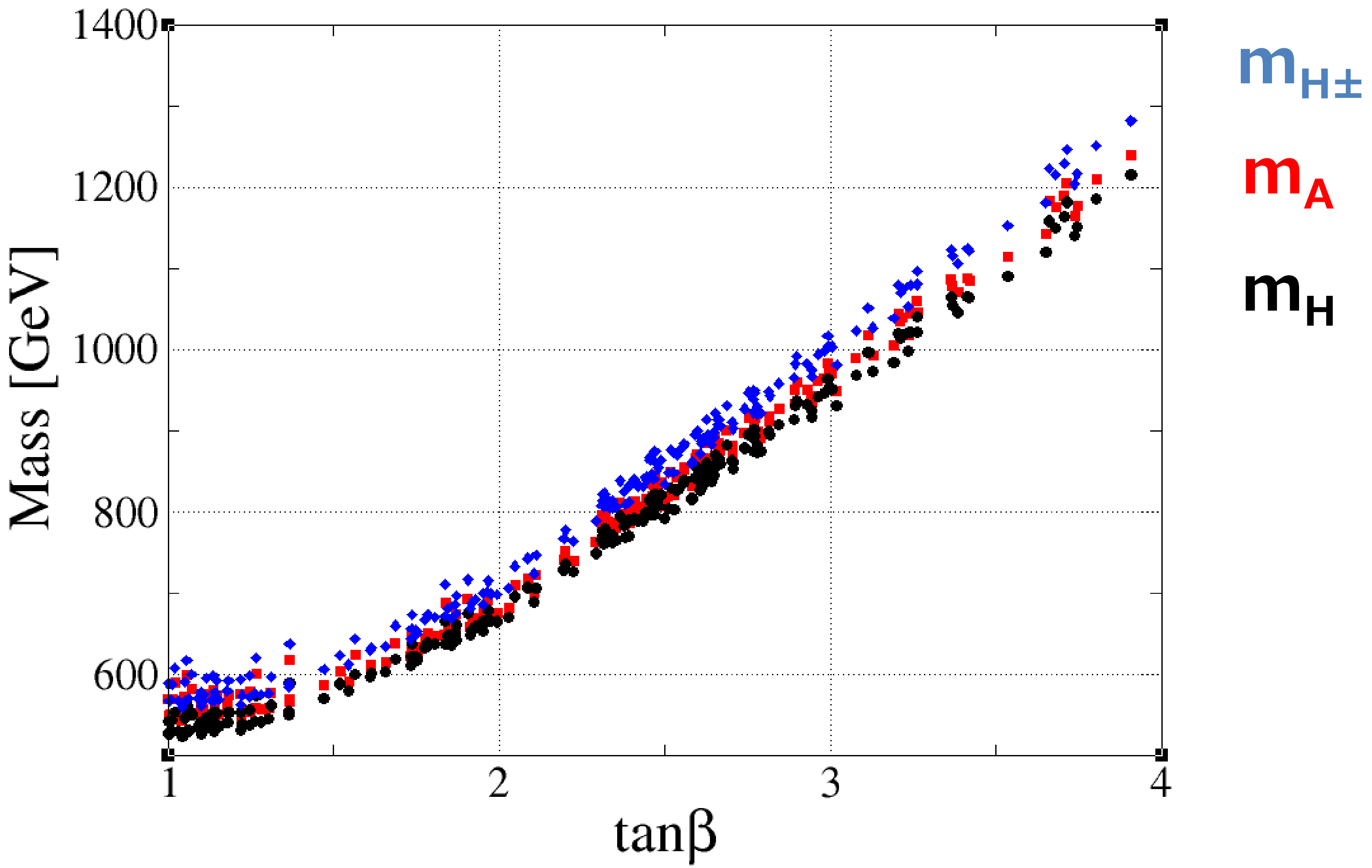
Correlation b/w f and M

tanβ = 2, m_ρ = f, mt = 173 GeV, 124 < m_h < 126 GeV



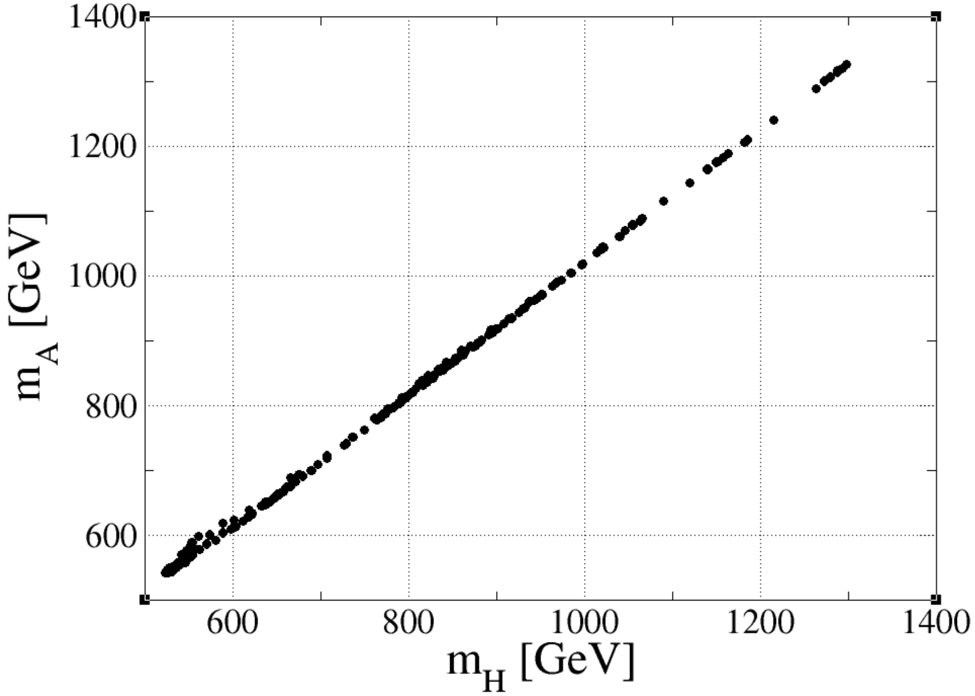
Correlation b/w tanβ and m(extra)

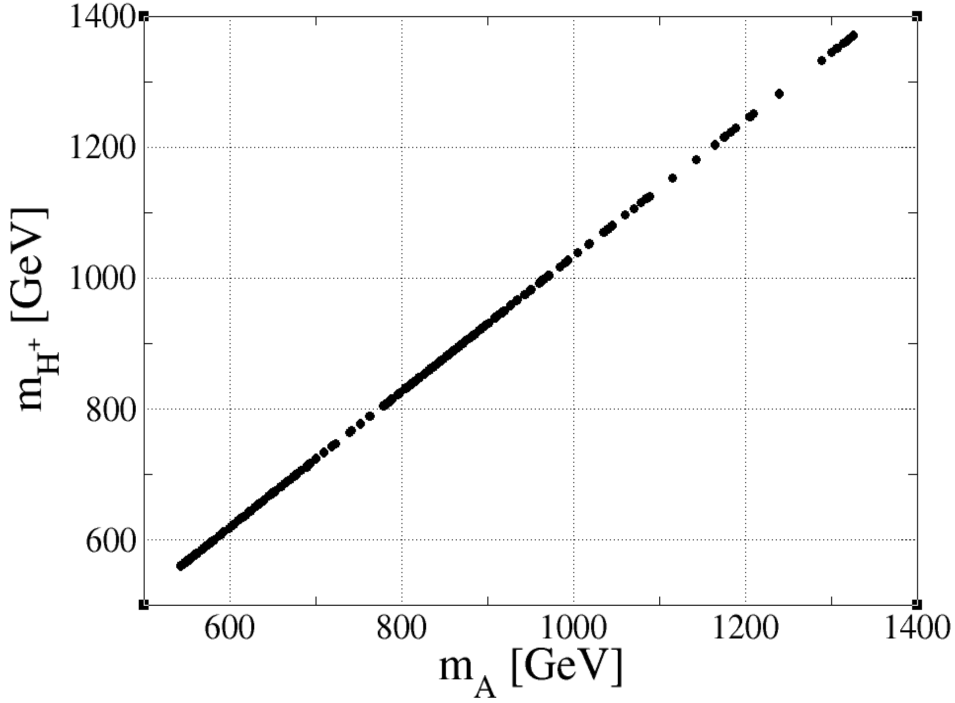
f = 1.2 TeV, m_ρ = f, mt = 173 GeV, 124 < m_h < 126 GeV



Correlation b/w extra Higgs masses

f = 1.2 TeV, $m_\rho = f$, mt = 173 GeV, 124 < m_h < 126 GeV

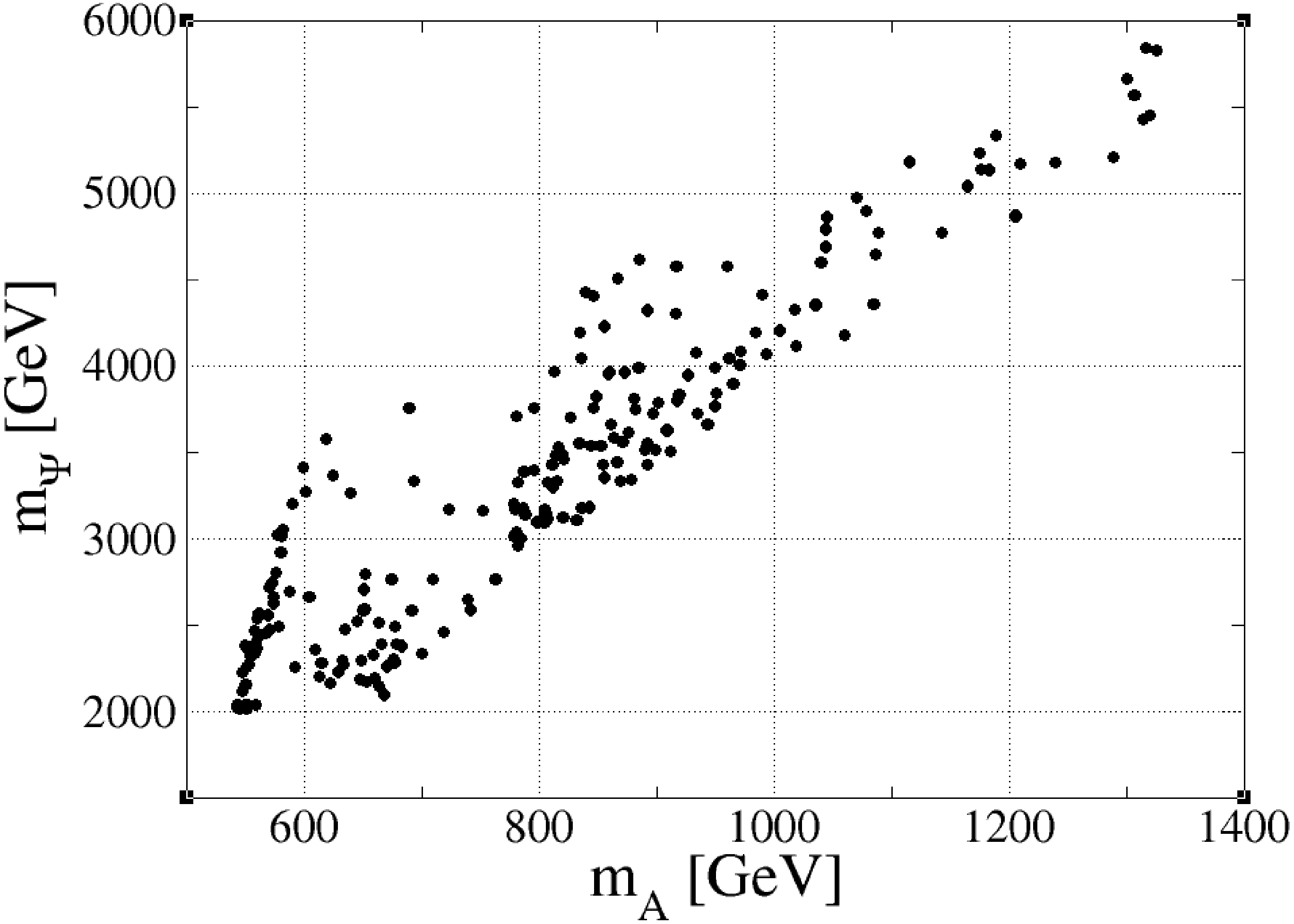




$$m_{H+} \gtrsim m_A \gtrsim m_H$$

Correlation b/w m_A and m_ψ

f = 1.2 TeV, m_ρ = f, mt = 173 GeV, 124 < m_h < 126 GeV



Summary

- Higgs as pNGB scenario gives natural explanation for a light Higgs.

  Taking a lager global sym., we obtain a multi-Higgs structure.

- Giving the strong sector Lagrangian, we can explicitly calculate all the potential parameters in terms of the strong parameters.

- We found a strong/characteristic prediction for the Higgs mass spectrum and a correlation to the mass of heavy fermion resonance.

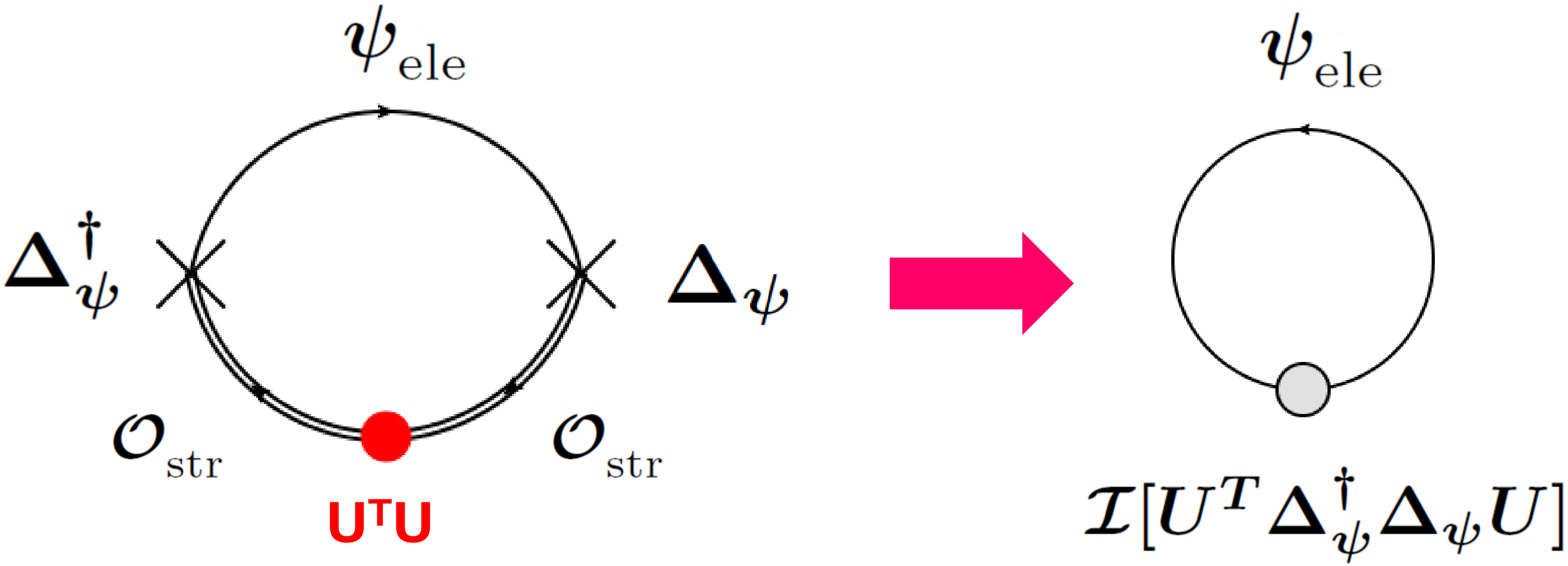
Spurion Method

- The Higgs potential is calculated only by using the spurion VEV Δ_ψ and U.

$$\mathcal{L}_{\rm mix} = (\boldsymbol{\Delta}_\psi)^{\alpha I}\, \psi^{\alpha}_{\rm ele}\, \mathcal{O}^{I}_{\rm str}$$

Merit: Quite General (but still we need to assume fermion rep.)

Demerit: Losing the correlation, O(1) uncertainties in pot. parameters.



Spurion Method

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

- Fermionic contribution assuming **r** = **6**-plet of SO(6).

Operator	$\mathcal{I}^1_{(0,1)}$	$\mathcal{I}^1_{(1,0)}$	$\mathcal{I}^1_{(2,0)}$	$\mathcal{I}^4_{(2,0)}$	$\mathcal{I}^5_{(2,0)}$	$\mathcal{I}^1_{(1,1)}$	$\mathcal{I}^5_{(1,1)}$	$\mathcal{I}^6_{(1,1)}$	$\mathcal{I}^1_{(0,2)}$	$\mathcal{I}^4_{(0,2)}$
$\frac{1}{16\pi^2}\times$	$-\frac{y_L^2 g_\rho^2}{2}$	$y_R^2 g_\rho^2$	$\frac{y_R^4}{4}$	$\frac{y_R^4}{4}(\frac{g_\rho}{4\pi})^2$	$\frac{y_R^4}{4}(\frac{g_\rho}{4\pi})^2$	$\frac{y_R^2 y_L^2}{4}$	$y_R^2 y_L^2(\frac{g_\rho}{4\pi})^2$	$-y_R^2 y_L^2(\frac{g_\rho}{4\pi})^2$	$-\frac{y_L^4}{2}$	$-y_L^4(\frac{g_\rho}{4\pi})^2$
m_{11}^2/f^2	1	$\cos^2\theta$	0	0	0	$\cos^2\theta$	$\cos^2\theta$	0	1	1
m_{22}^2/f^2	1	$\sin^2\theta$	0	0	0	$\sin^2\theta$	$\sin^2\theta$	0	1	1
m_{12}^2/f^2	0	0	0	0	$\sin 4\theta$	0	0	0	0	0
$\tilde{m}_{12}^2/f^2$	0	0	0	0	0	$-\sin 2\theta$	0	$\frac{1}{2}\sin 2\theta$	0	0
λ_1	$-\frac{1}{3}$	$-\frac{1}{3}\cos^2\theta$	$2\cos^4\theta$	$2\cos^4\theta$	0	$-\frac{4}{3}\cos^2\theta$	$-\frac{7}{12}\cos^2\theta$	0	$-\frac{7}{12}$	$-\frac{11}{24}$
λ_2	$-\frac{1}{3}$	$-\frac{1}{3}\sin^2\theta$	$2\sin^4\theta$	$2\sin^4\theta$	0	$-\frac{4}{3}\sin^2\theta$	$-\frac{7}{12}\sin^2\theta$	0	$-\frac{7}{12}$	$-\frac{11}{24}$
λ_3	0	0	$\sin^2\theta$	$-\sin^2\theta$	0	0	$-\frac{1}{4}$	0	0	$-\frac{1}{4}$
λ_4	$-\frac{2}{3}$	$-\frac{1}{3}$	0	$2\sin^2 2\theta$	0	$-\frac{4}{3}$	$-\frac{1}{3}$	0	$-\frac{7}{6}$	$-\frac{2}{3}$
$\tilde{\lambda}_4$	0	0	0	0	0	0	0	0	$\frac{1}{2}$	0
λ_5	0	0	0	0	0	0	0	0	0	0
λ_6	0	0	0	0	$-\frac{1}{3}\sin 4\theta$	0	0	0	0	0
$\tilde{\lambda}_6$	0	0	0	0	0	$\frac{2}{3}\sin 2\theta$	0	$-\frac{1}{12}\sin 2\theta$	0	0
λ_7	0	0	0	0	$-\frac{1}{3}\sin 4\theta$	0	0	0	0	0
$\tilde{\lambda}_7$	0	0	0	0	0	$\frac{2}{3}\sin 2\theta$	0	$-\frac{1}{12}\sin 2\theta$	0	0

- Arbitral O(1) parameters appear in front of each operator.

tanβ = 1.5, f = 800 GeV, m_ρ = f,

mt = 173 GeV, 124 < m_h < 126 GeV