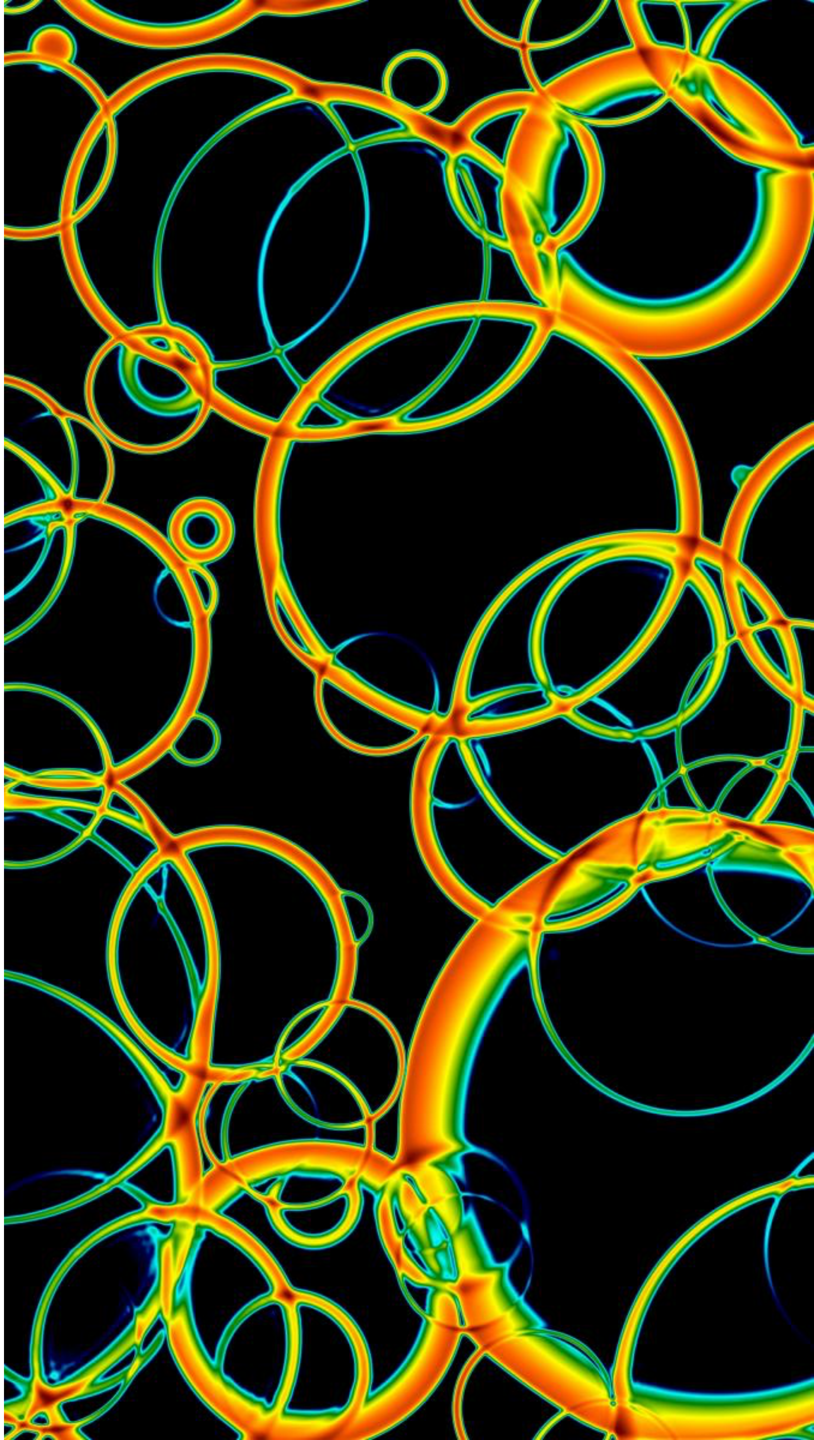
Strong 1st order EW phase transition in composite Higgs models

Ke-Pan Xie (Seoul National University)

2019.12.5 IBS-Busan workshop

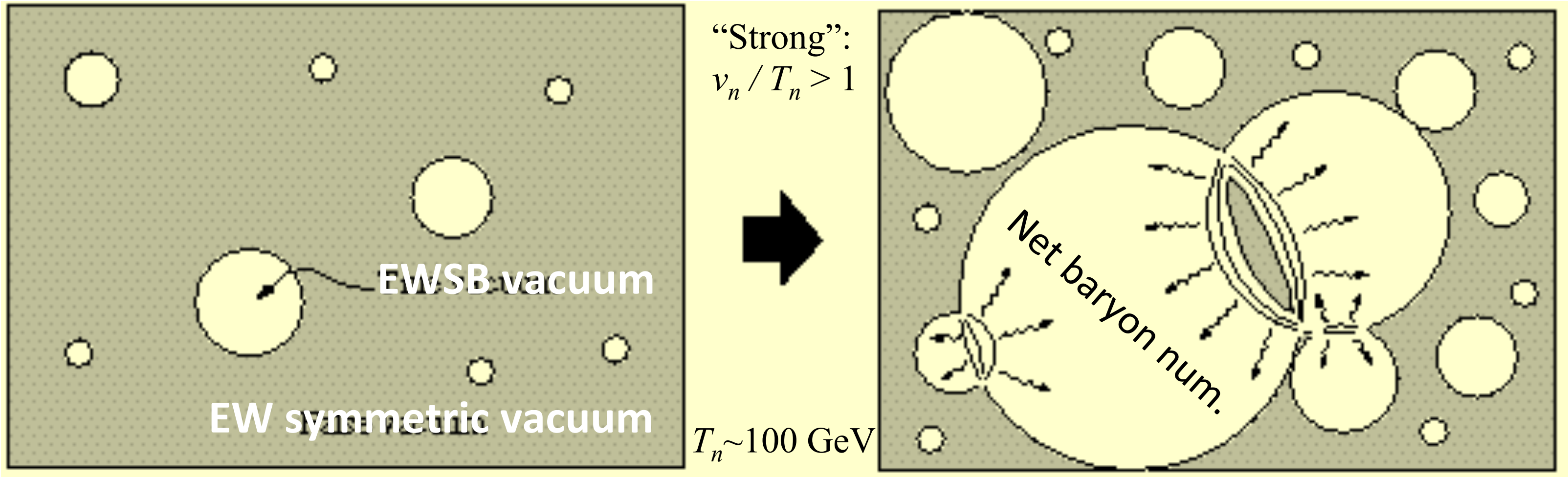
Ligong Bian, Yongcheng Wu and **Ke-Pan Xie**,
arXiv:1909.02014 (Accepted by JHEP)



Explaining the baryon-antibaryon asymmetry

- The EW baryogenesis mechanism

The asymmetry is generated during the strong 1st order EW phase transition in the early universe.



However, the SM fails to realize this mehcanism: EW phase transition is NOT 1st order; the CP phase is too tiny.

- Realizing EW baryogensis by adding a real singlet

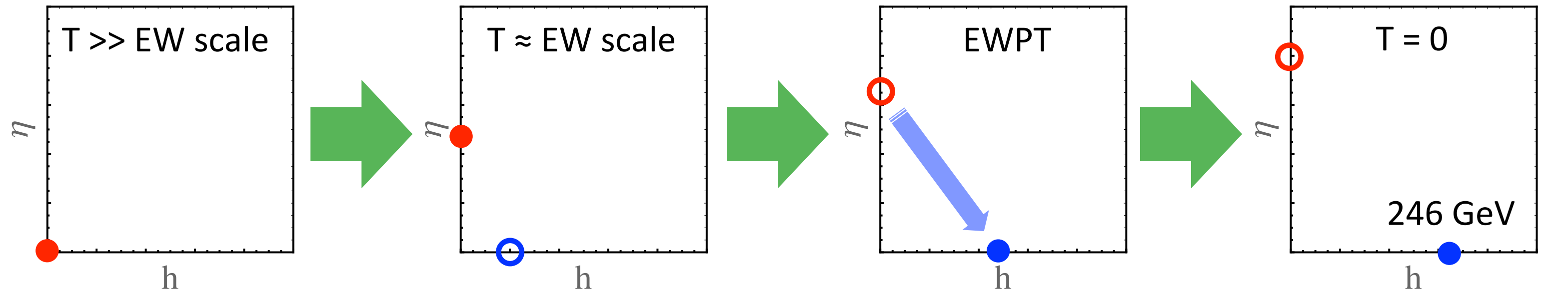
The scalar potential becomes:

$$V(h,\eta) = \frac{\mu_h^2}{2}h^2 + \frac{\lambda_h}{4}h^4 + \frac{\mu_\eta^2}{2}\eta^2 + \frac{\lambda_\eta}{4}\eta^4 + \frac{\lambda_{h\eta}}{2}h^2\eta^2.$$

At finite temperature:

$$V_T(h,\eta) = \frac{\mu_h^2 + c_h T^2}{2}h^2 + \frac{\lambda_h}{4}h^4 + \frac{\mu_\eta^2 + c_\eta T^2}{2}\eta^2 + \frac{\lambda_\eta}{4}\eta^4 + \frac{\lambda_{h\eta}}{2}h^2\eta^2$$

Strong 1st order EWPT can be achieved by

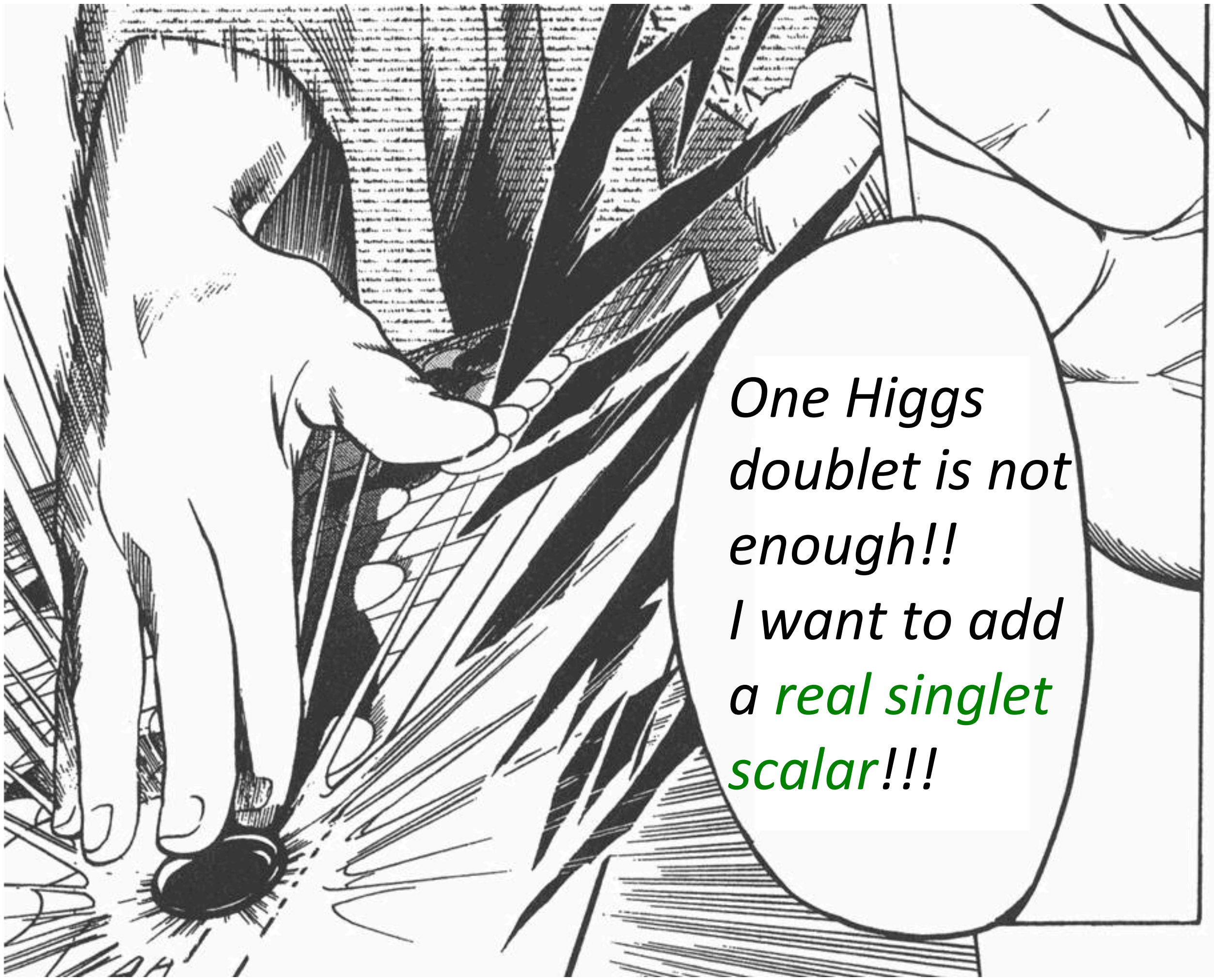


in SOME suitable parameter space.

CP violating phase comes from the *η-relevant* interaction.

- How to get such a real singlet?

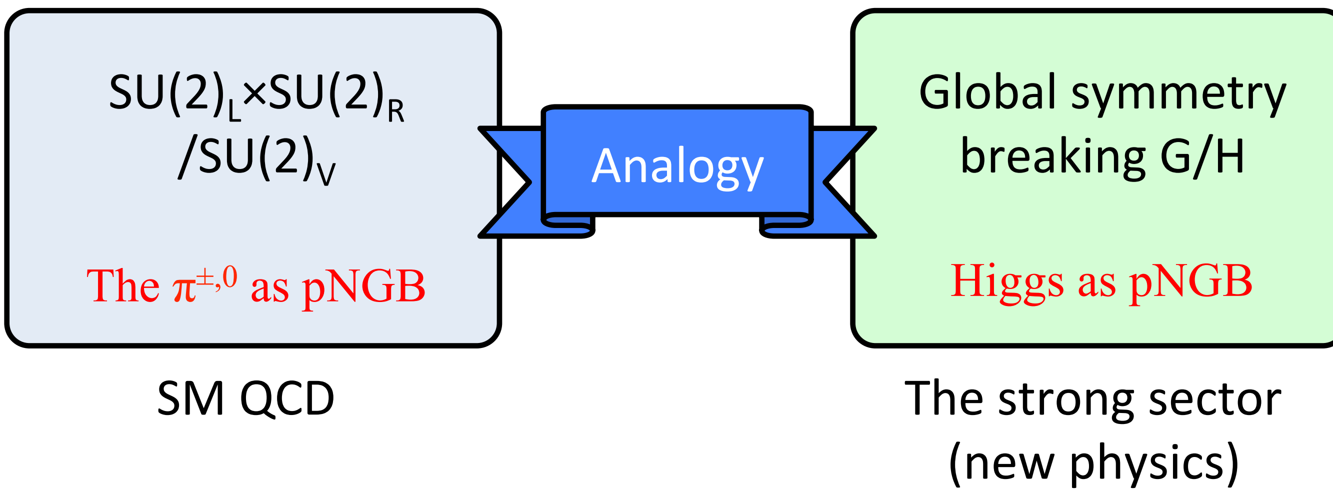
Of course it can be added just by hand.



- How to get such a real singlet?

But it can also exist naturally in the composite Higgs models, in which the Higgs boson is a pseudo-NGB from a spontaneous global symmetry breaking G/H.

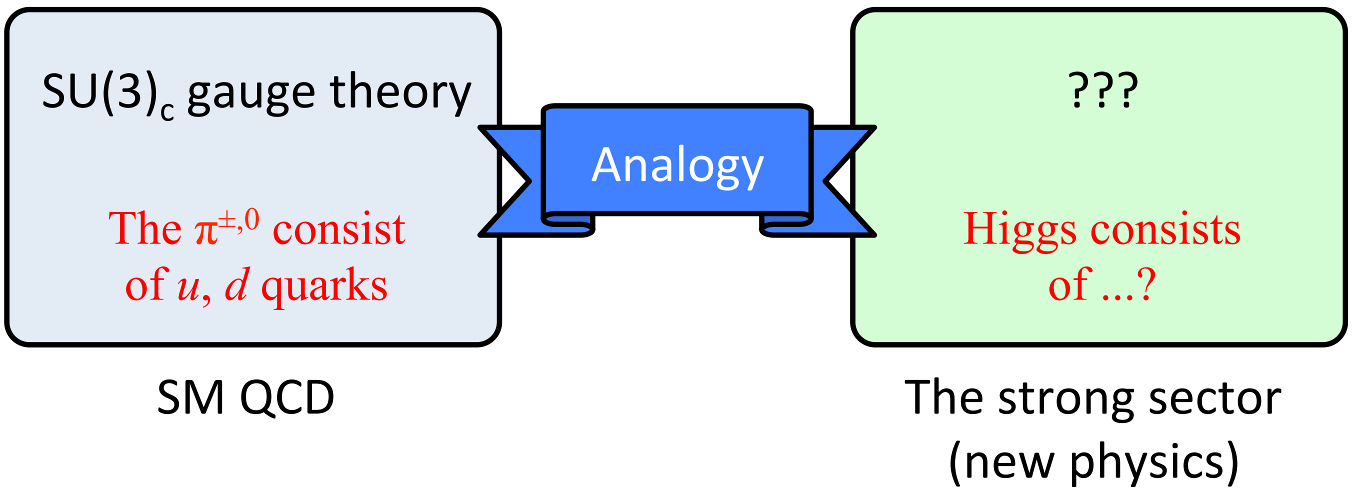
Kaplan *et al* (1984) and Agashe *et al* (2005)



The top-down description (chiral perturbation theory):
minimal setup: G/H = SO(5)/SO(4),
10 - 6 = 4 pNGBs: exactly one Higgs doublet.
However...

- How to get such a real singlet?

But it can also exist naturally in the composite Higgs models, in which the Higgs boson is a pseudo-NGB from a spontaneous global symmetry breaking G/H.

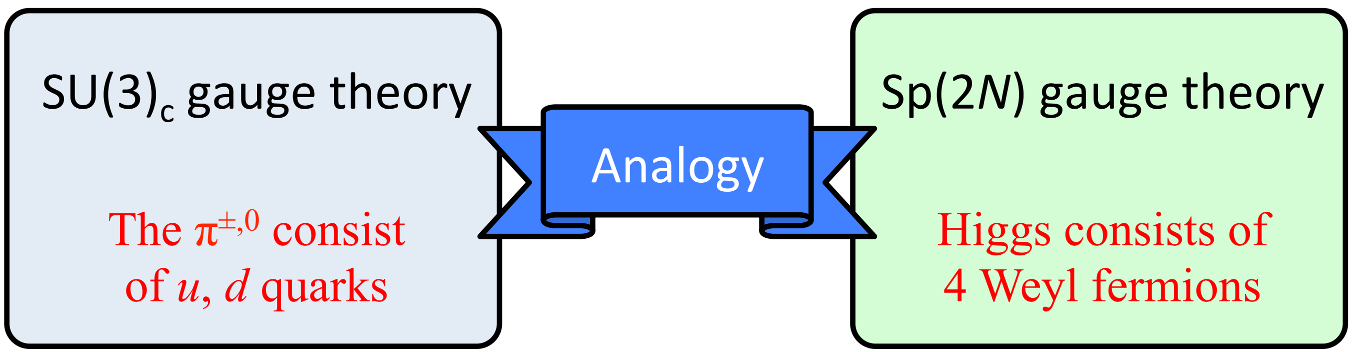


The bottom-up approach (UV completion):
minimal setup: G/H = SO(5)/SO(4)? NO!

- How to get such a real singlet?

But it can also exist naturally in the composite Higgs models, in which the Higgs boson is a pseudo-NGB from a spontaneous global symmetry breaking G/H.

G. Cacciapaglia *et al*, JHEP 04 (2014) 111.



SM QCD

The strong sector (new physics)

The bottom-up approach (UV completion):
minimal setup: G/H = SO(6)/SO(5) = SU(4)/Sp(4) .
Four-flavor Weyl fermions under a Sp(2N) gauge group.
15 - 10 = 5 pNGBs: one Higgs doublet + one real singlet!

- How to get such a real singlet?

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ia *et al*, JHEP 04 (2014) 111.

All ingredients of are given...

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

arXiv:1110.2876

Electroweak baryogenesis in non-minimal composite Higgs models

José R. Espinosa,[a,b] Ben Gripaios,[c] Thomas Konstandin[d] and Francesco Riva[b,e]

Estimates the EW phase transition and calculates the EW baryogenesis.

gauge theory

s consists of
yl fermions

rong sector
v physics)

The bottom-up approach (UV completion):

minimal setup: G/H = SO(6)/SO(5) = SU(4)/Sp(4) .

Four-flavor Weyl fermions under a Sp(2*N*) gauge group.

15 - 10 = 5 pNGBs: one Higgs doublet + one real singlet!

New!!

A detailed study about $V(h,\eta)$ and EWPT

Y.Wu, L.Bian and K.-P.Xie, 1909.02014 (This talk)

- Sketch of the model Gripaios *et al*, JHEP 0904 (2009) 070

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm strong} + \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\mu} B^\mu + y_L \bar{q}_L \mathcal{O}_R + y_R \bar{t}_R \mathcal{O}_L$$

$W^{a_L}_\mu$; B_μ;

$q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix}$; t_R; b_R; $\cdots$

$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$; e_R; $\cdots$

The elementary sector (SM particles)

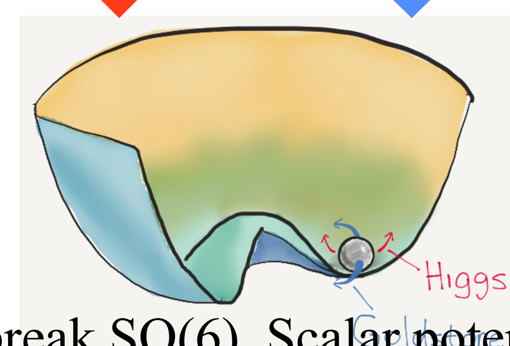
Subgroup $SU(2)_L \times U(1)_Y$ gauged

SM fermions embedded in incomplete SO(6) rep.

Global symmetry breaking SO(6)/SO(5)

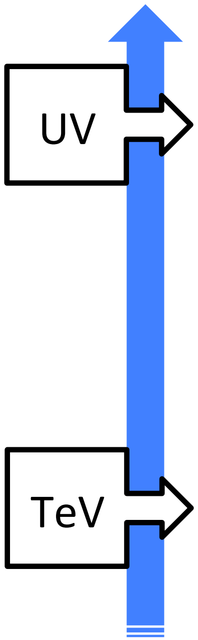
Higgs + singlet

The strong sector (new physics)



Interactions **Explicitly** break SO(6). Scalar potential generated; EWSB!

• Describing strong dynamics at different scales



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm strong} + \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\,\mu} B^\mu + y_L \bar{q}_L \mathcal{O}_R + y_R \bar{t}_R \mathcal{O}_L$$

Confinement of the strong sector

pseudo-NGBs: $H,\ \eta$

Vector resonances: $\langle 0|\mathcal{J}_\mu|\rho_n\rangle = \epsilon_\mu m_{\rho_n} f_n;$

Fermion resonances: $\langle 0|\mathcal{O}|\Psi_n\rangle = \Delta_n$

CCWZ description

1. SO(6) is non-linearly realized via the Goldstone matrix

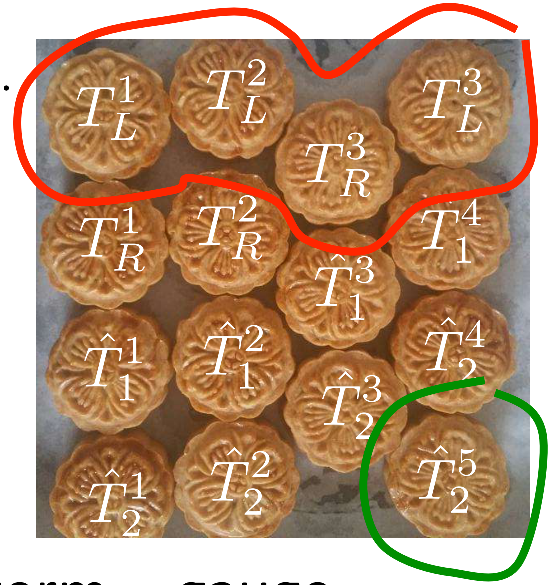
$$U = \exp\left\{ i\frac{\sqrt{2}}{f} T^i h_i \right\},$$

2. SM particles are embedded in the incomplete SO(6) reps;
3. Composite resonances are in SO(5) reps.

- Interactions: gauge part

* Hypercharge: $Y = T_R^3$.

Subgroup $SU(2)_L \times U(1)_Y$ gauged:



$$SO(6) \xrightarrow[\text{breaking}]{\text{explicit}} \underline{SU(2)_L \times U(1)_Y} \times \underline{U(1)_\eta},$$

T_2^5 : associated with η.

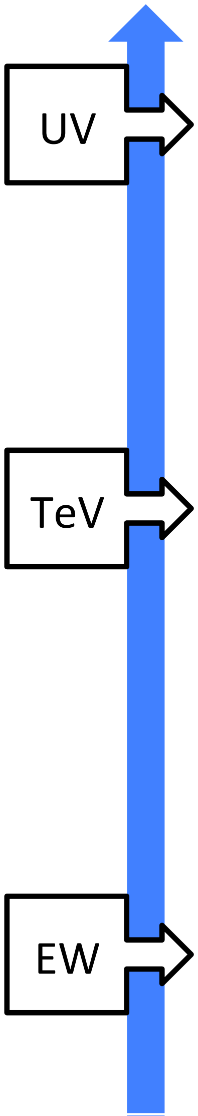
Potential generated via explicit breaking term -- gauge interactions only generate $V(h)$!!

Elementary EW gauge bosons: W and B;

Composite resonances: ρ and a, in 10 and 5 rep. of SO(5).

$\mathbf{10} \to \mathbf{3}_0 \oplus \mathbf{1}_1 \oplus \mathbf{1}_0 \oplus \mathbf{1}_{-1} \oplus \mathbf{2}_{1/2} \oplus \mathbf{2}_{-1/2}$: $\rho^{\bar{A}} \to \rho_L \oplus \rho_R^+ \oplus \rho_R^0 \oplus \rho_R^{-1} \oplus \rho_D \oplus \tilde{\rho}_D$;	$\mathbf{5} \to \mathbf{2}_{1/2} \oplus \mathbf{2}_{-1/2} \oplus \mathbf{1}_0$: $a^r \to a_D \oplus \tilde{a}_D \oplus a_S$

- The gauge contributions to potential



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm strong} + \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\mu} B^\mu + y_L \bar{q}_L \mathcal{O}_R + y_R \bar{t}_R \mathcal{O}_L + \text{h.c.}$$

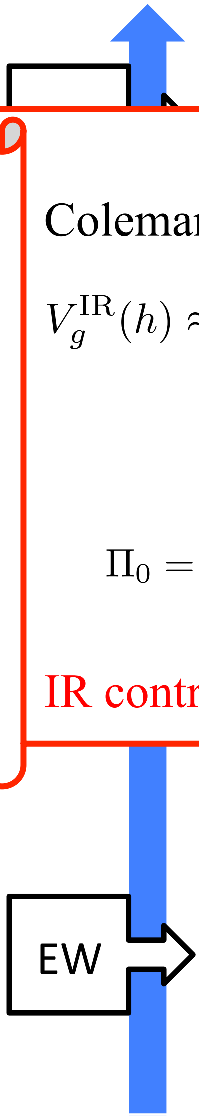
Confinement of the strong sector

$$\mathcal{L}_\rho = -\frac{1}{4}\text{tr}\left[\rho_{\mu\nu}\rho^{\mu\nu}\right] + \frac{M_\rho^2}{2g_\rho^2}\text{tr}\left[(g_\rho \rho_\mu - e_\mu)^2\right] - \frac{1}{4}\text{tr}[a_{\mu\nu}a^{\mu\nu}] + \frac{M_a^2}{2}\text{tr}\left[a_\mu a^\mu\right]$$
$$+ \text{Higher order operators.}$$

Integrating out the heavy resonances

$$\mathcal{L}_{\rm EW} \supset \frac{1}{2} P_T^{\mu\nu} \Bigg\{ \left(-p^2 + \frac{g_0'^2}{g_0^2}\Pi_0(p^2)\right) B_\mu B_\nu + \left(-p^2 + \Pi_0(p^2)\right) W^a_\mu W^a_\nu$$
$$+ \frac{\Pi_1(p^2)}{4}\frac{h^2}{f^2}\left[W^1_\mu W^1_\nu + W^2_\mu W^2_\nu + \left(W^3_\mu - \frac{g_0'}{g_0}B_\mu\right)\left(W^3_\nu - \frac{g_0'}{g_0}B_\nu\right)\right] \Bigg\}$$
$$+ \text{Higher order operators,}$$

• The gauge contributions to potential



Agashe *et al*, Nucl.Phys. B719 (2005) 165-187

Coleman-Weinberg potential from the leading operators.

$$V_g^{\rm IR}(h) \approx \frac{6}{2}\int \frac{d^4Q}{(2\pi)^4} \ln\left(1+\frac{\Pi_1}{4\Pi_W}\frac{h^2}{f^2}\right) + \frac{3}{2}\int \frac{d^4Q}{(2\pi)^4} \ln\left[1+\left(\frac{g_0'^2}{g_0^2}\frac{\Pi_1}{4\Pi_B}+\frac{\Pi_1}{4\Pi_W}\right)\frac{h^2}{f^2}\right],$$

$$\Pi_W = Q^2 + \Pi_0, \quad \Pi_B = Q^2 + (g_0'^2/g_0^2)\Pi_0$$

$$\Pi_0 = \sum_{n=1}^{N_\rho} g_0^2 \frac{Q^2 f_{\rho(n)}^2}{Q^2 + M_{\rho(n)}^2}, \quad \Pi_1 = g_0^2 f^2 + 2g_0^2\left(\sum_{n=1}^{N_a}\frac{Q^2 f_{a(n)}^2}{Q^2+M_{a(n)}^2} - \sum_{n=1}^{N_\rho}\frac{Q^2 f_{\rho(n)}^2}{Q^2+M_{\rho(n)}^2}\right),$$

IR contributions: calculable. *Expressed* in terms of masses and interactions.

IR

$$\mathcal{L}_{\rm EW} \supset \frac{1}{2}P_T^{\mu\nu}\Big\{\left(-p^2+\frac{g_0'^2}{g_0^2}\Pi_0(p^2)\right)B_\mu B_\nu + \left(-p^2+\Pi_0(p^2)\right)W_\mu^a W_\nu^a$$
$$+\frac{\Pi_1(p^2)}{4}\frac{h^2}{f^2}\left[W_\mu^1 W_\nu^1 + W_\mu^2 W_\nu^2 + \left(W_\mu^3 - \frac{g_0'}{g_0}B_\mu\right)\left(W_\nu^3-\frac{g_0'}{g_0}B_\nu\right)\right]\Big\}$$
$$+ \text{Higher order operators},$$

- The gauge contributions to potential

Marzocca *et al*, JHEP 1208 (2012) 013

Higher order operators generating scalar potential.

Gauge spurtion: $gA_\mu = gT_L^a W_\mu^a + g' T_R^3 B_\mu \equiv \mathcal{G}_{\bar{A}a} T^{\bar{A}} W_\mu^a + \mathcal{G}'_{\bar{A}} T^{\bar{A}} B_\mu,$

$$c_g f^4 \Sigma^\dagger \mathcal{G}_a \mathcal{G}_a \Sigma \to c_g \frac{3}{4} g^2 f^2 h^2, \quad \frac{d_g}{16\pi^2} f^4 \left(\Sigma^\dagger \mathcal{G}_a \mathcal{G}_a \Sigma\right)^2 \to d_g \frac{9g^4}{256\pi^2} h^4, \quad \cdots,$$

$c_g, d_g \sim \mathcal{O}(1).$

UV contributions: incalculable. *Estimated* by Naïve Dimensional Analysis.

EW

$$\mathcal{L}_{\rm EW} \supset \frac{1}{2} P_T^{\mu\nu} \Big\{ \left(-p^2 + \frac{g_0'^2}{g_0^2} \Pi_0(p^2)\right) B_\mu B_\nu + \left(-p^2 + \Pi_0(p^2)\right) W_\mu^a W_\nu^a + \frac{\Pi_1(p^2)}{4} \frac{h^2}{f^2} \left[W_\mu^1 W_\nu^1 + W_\mu^2 W_\nu^2 + \left(W_\mu^3 - \frac{g_0'}{g_0} B_\mu\right)\left(W_\nu^3 - \frac{g_0'}{g_0} B_\nu\right)\right] \Big\}$$

+ Higher order operators, UV

- ## Interactions: fermion part

* U(1)$_X$ is introduced: $Y = X + T_R^3$.

Elementary quarks: incomplete rep. of SO(6)

$$\mathbf{6}_{2/3} \to \mathbf{2}_{7/6} \oplus \mathbf{2}_{1/6} \oplus \mathbf{1}_{2/3} \oplus \mathbf{1}_{2/3},$$

$$q_L^{\mathbf{6}} = \frac{1}{\sqrt{2}}\begin{pmatrix} ib_L & b_L & it_L & -t_L & 0 & 0 \end{pmatrix}^T,$$

$$t_R^{\mathbf{6}} = \begin{pmatrix} 0 & 0 & 0 & 0 & it_R c_\theta & t_R s_\theta \end{pmatrix}^T,$$

$$\mathbf{1}_{2/3} : t_R$$

$$\mathbf{15}_{2/3} \to \mathbf{3}_{2/3} \oplus \mathbf{1}_{5/3} \oplus \mathbf{1}_{2/3} \oplus \mathbf{1}_{-1/3} \oplus \mathbf{2}_{7/6} \oplus \mathbf{2}_{1/6} \oplus \mathbf{2}_{7/6} \oplus \mathbf{2}_{1/6} \oplus \mathbf{1}_{2/3},$$

$$q_L^{\mathbf{15}} = (q_L^{\mathbf{6}})_j \hat{T}_1^j,\ t_R^{\mathbf{15}} = T_R^3 t_R c_\theta + \hat{T}_2^5 t_R e^{I\phi} s_\theta.$$

Composite top parnters: complete rep. of SO(5)

$$\mathbf{1}_{2/3} : \Psi_{\mathbf{1}}$$

$$\mathbf{5}_{2/3} \to \mathbf{2}_{7/6} \oplus \mathbf{2}_{1/6} \oplus \mathbf{1}_{2/3} :$$

$$\Psi_{\mathbf{5}} \to Q_X \oplus Q \oplus \widetilde{T}$$

$$\mathbf{10}_{2/3} \to \mathbf{3}_{2/3} \oplus \mathbf{1}_{5/3} \oplus \mathbf{1}_{2/3} \oplus \mathbf{1}_{-1/3} \oplus \mathbf{2}_{7/6} \oplus \mathbf{2}_{1/6} :$$

$$\Psi_{\mathbf{10}} \to Y \oplus K_{5/3} \oplus K_{2/3} \oplus K_{-1/3} \oplus J_X \oplus J_Q,$$

Partial compositeness:

$$SO(6) \times U(1)_X \xrightarrow[\text{breaking}]{\text{explicit}} SU(2)_L \times U(1)_Y$$

contributes to $V(h,\eta)$ generally. Combine q_L and t_R embeddings: 2 × 3 = 6 models.

- Benchmark models (q_L embedding + t_R embedding)

$$\mathcal{L}_{\mathbf{6+1}} \supset y_L^{\mathbf{5}} f(\bar{q}_L^{\mathbf{6}})_I U_{Ir} \Psi_{\mathbf{5}}^r + y_L^{\mathbf{1}} f(\bar{q}_L^{\mathbf{6}})_I U_{I6} \Psi_{\mathbf{1}} + y_R^{\mathbf{1}} f \bar{t}_R^{\mathbf{1}} \Psi_{\mathbf{1}} + \text{h.c.}\ ;$$

No η potential

✔
$$\mathcal{L}_{\mathbf{6+6}} \supset y_L^{\mathbf{5}} f(\bar{q}_L^{\mathbf{6}})_I U_{Ir} \Psi_{\mathbf{5}}^r + y_L^{\mathbf{1}} f(\bar{q}_L^{\mathbf{6}})_I U_{I6} \Psi_{\mathbf{1}} + y_R^{\mathbf{5}} f(\bar{t}_R^{\mathbf{6}})_I U_{Ir} \Psi_{\mathbf{5}}^r + y_R^{\mathbf{1}} f(\bar{t}_R^{\mathbf{6}})_I U_{I6} \Psi_{\mathbf{1}} + \text{h.c.}\ ;$$

$$\mathcal{L}_{\mathbf{6+15}} \supset y_L^{\mathbf{5}} f(\bar{q}_L^{\mathbf{6}})_I U_{Ir} \Psi_{\mathbf{5}}^r + y_L^{\mathbf{1}} f(\bar{q}_L^{\mathbf{6}})_I U_{I6} \Psi_{\mathbf{1}} + y_R^{\mathbf{10}} f(\bar{t}_R^{\mathbf{15}})_{IJ} U_{Jr} \Psi_{\mathbf{10}}^{rs} [U^\dagger]_{sI} + y_R^{\mathbf{5}} f \Sigma_I^\dagger (\bar{t}_R^{\mathbf{15}})_{IJ} U_{Jr} \Psi_{\mathbf{5}}^r + \text{h.c.}\ ;$$

No η potential

$$\mathcal{L}_{\mathbf{15+1}} \supset y_L^{\mathbf{10}} f(\bar{q}_L^{\mathbf{15}})_{IJ} U_{Jr} \Psi_{\mathbf{10}}^{rs} [U^\dagger]_{sI} + y_L^{\mathbf{5}} f \Sigma_I^\dagger (\bar{q}_L^{\mathbf{15}})_{IJ} U_{Jr} \Psi_{\mathbf{5}}^r + y_R^{\mathbf{1}} f \bar{t}_R^{\mathbf{1}} \Psi_{\mathbf{1}} + \text{h.c.}\ ;$$

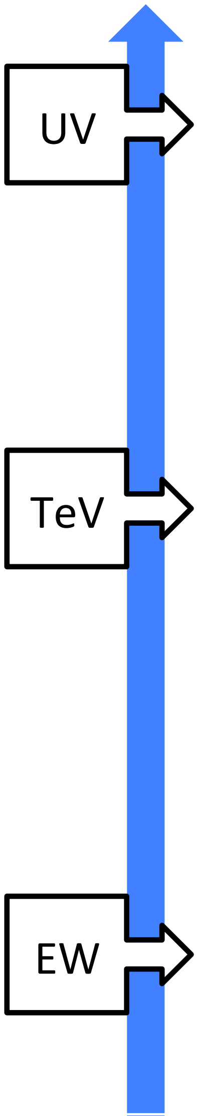
No top mass

✔
$$\mathcal{L}_{\mathbf{15+6}} \supset y_L^{\mathbf{10}} f(\bar{q}_L^{\mathbf{15}})_{IJ} U_{Jr} \Psi_{\mathbf{10}}^{rs} [U^\dagger]_{sI} + y_L^{\mathbf{5}} f \Sigma_I^\dagger (\bar{q}_L^{\mathbf{15}})_{IJ} U_{Jr} \Psi_{\mathbf{5}}^r + y_R^{\mathbf{5}} f(\bar{t}_R^{\mathbf{6}})_I U_{Ir} \Psi_{\mathbf{5}}^r + y_R^{\mathbf{1}} f(\bar{t}_R^{\mathbf{6}})_I U_{I6} \Psi_{\mathbf{1}} + \text{h.c.}\ ;$$

✔
$$\mathcal{L}_{\mathbf{15+15}} \supset y_L^{\mathbf{10}} f(\bar{q}_L^{\mathbf{15}})_{IJ} U_{Jr} \Psi_{\mathbf{10}}^{rs} [U^\dagger]_{sI} + y_L^{\mathbf{5}} f \Sigma_I^\dagger (\bar{q}_L^{\mathbf{15}})_{IJ} U_{Jr} \Psi_{\mathbf{5}}^r + y_R^{\mathbf{10}} f(\bar{t}_R^{\mathbf{15}})_{IJ} U_{Jr} \Psi_{\mathbf{10}}^{rs} [U^\dagger]_{sI} + y_R^{\mathbf{5}} f \Sigma_I^\dagger (\bar{t}_R^{\mathbf{15}})_{IJ} U_{Jr} \Psi_{\mathbf{5}}^r + \text{h.c.}\ .$$

• The fermion contribution to potential

(6+6 as an illustration)



UV:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm strong} + \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\mu} B^\mu + y_L \bar{q}_L \mathcal{O}_R + y_R \bar{t}_R \mathcal{O}_L + {\rm h.c.}$$

Confinement of the strong sector

TeV:

$$\mathcal{L}_{\mathbf{6+6}} \supset y_L^{\mathbf{5}} f (\bar{q}_L^{\mathbf{6}})_I U_{Ir} \Psi^r_{\mathbf{5}} + y_L^{\mathbf{1}} f (\bar{q}_L^{\mathbf{6}})_I U_{I6} \Psi_{\mathbf{1}} + y_R^{\mathbf{5}} f (\bar{t}_R^{\mathbf{6}})_I U_{Ir} \Psi^r_{\mathbf{5}} + y_R^{\mathbf{1}} f (\bar{t}_R^{\mathbf{6}})_I U_{I6} \Psi_{\mathbf{1}} + {\rm h.c.} + \text{Higher order operators;}$$

Integrating out the heavy resonances

EW:

$$\mathcal{L}_{\mathbf{6+6}} \supset \bar{t}_L \not{p} \left(\Pi_0^q + \frac{\Pi_1^q}{2} \frac{h^2}{f^2} \right) t_L + \bar{t}_R \not{p} \left[\Pi_0^t + \Pi_1^t \left(c_\theta^2 \frac{\eta^2}{f^2} + s_\theta^2 \left(1 - \frac{h^2 + \eta^2}{f^2} \right) \right) \right] t_R$$

$$- \frac{M_1^t}{\sqrt{2}} \frac{h}{f} \left(s_\theta \sqrt{1 - \frac{h^2 + \eta^2}{f^2}} + i c_\theta \frac{\eta}{f} \right) \bar{t}_L t_R + {\rm h.c.}$$

$$+ \text{Higher order operators}$$

• The fermion contribution to potential

(6+6 as an illustration)

Coleman-Weinberg potential from the leading operators.

$$V_f^{\mathrm{IR}}(h,\eta) \approx -2N_c \int \frac{d^4Q}{(2\pi)^4} \Big\{ \ln\left(1+\frac{\Pi_1^q}{2\Pi_0^q}\frac{h^2}{f^2}\right) + \ln\left[1+\frac{\Pi_1^t}{\Pi_0^t}\left(s_\theta^2\left(1-\frac{h^2}{f^2}\right)+c_{2\theta}\frac{\eta^2}{f^2}\right)\right] + \ln\left[1+\frac{1}{Q^2}\frac{|M_1^t|^2}{2\Pi_0^q\Pi_0^t}\frac{h^2}{f^2}\left(s_\theta^2\left(1-\frac{h^2}{f^2}\right)+c_{2\theta}\frac{\eta^2}{f^2}\right)\right]\Big\},$$

$$\Pi_0^{q,t} = 1+\sum_{n=1}^{N_{\mathbf{5}}}\frac{|y_{L,R}^{\mathbf{5}(n)}|^2 f^2}{Q^2+M_{\mathbf{5}(n)}^2}, \quad \Pi_1^{q,t} = -\sum_{n=1}^{N_{\mathbf{5}}}\frac{|y_{L,R}^{\mathbf{5}(n)}|^2 f^2}{Q^2+M_{\mathbf{5}(n)}^2}+\sum_{n=1}^{N_{\mathbf{1}}}\frac{|y_{L,R}^{\mathbf{1}(n)}|^2 f^2}{Q^2+M_{\mathbf{1}(n)}^2},$$

$$M_0^t = \sum_{n=1}^{N_{\mathbf{5}}}\frac{y_L^{\mathbf{5}(n)}(y_R^{\mathbf{5}(n)})^* f^2 M_{\mathbf{5}(n)}}{Q^2+M_{\mathbf{5}(n)}^2}, \quad M_1^t = -\sum_{n=1}^{N_{\mathbf{5}}}\frac{y_L^{\mathbf{5}(n)}(y_R^{\mathbf{5}(n)})^* f^2 M_{\mathbf{5}(n)}}{Q^2+M_{\mathbf{5}(n)}^2}+\sum_{n=1}^{N_{\mathbf{1}}}\frac{y_L^{\mathbf{1}(n)}(y_R^{\mathbf{1}(n)})^* f^2 M_{\mathbf{1}(n)}}{Q^2+M_{\mathbf{1}(n)}^2}.$$

IR contributions: calculable. *Expressed* in terms of masses and interactions.

EW

$$\mathcal{L}_{\mathbf{6+6}} \supset \bar{t}_L \not{p}\left(\Pi_0^q+\frac{\Pi_1^q}{2}\frac{h^2}{f^2}\right)t_L + \bar{t}_R \not{p}\left[\Pi_0^t+\Pi_1^t\left(c_\theta^2\frac{\eta^2}{f^2}+s_\theta^2\left(1-\frac{h^2+\eta^2}{f^2}\right)\right)\right]t_R - \frac{M_1^t}{\sqrt{2}}\frac{h}{f}\left(s_\theta\sqrt{1-\frac{h^2+\eta^2}{f^2}}+ic_\theta\frac{\eta}{f}\right)\bar{t}_L t_R + \mathrm{h.c.}$$

IR

$+$ Higher order operators

- # The fermion contribution to potential

(6+6 as an illustration)

Higher order operators generating scalar potential.

Fermion spurtion: $q_L^{\mathbf{6}} = \mathcal{Q}^{\mathbf{6}} q_L, \quad t_R^{\mathbf{6}} = \mathcal{T}^{\mathbf{6}} t_R,$

$$c_f^L \Lambda^2 f^2 \frac{|y_L|^2}{16\pi^2} \Sigma^\dagger \mathcal{Q}^{\mathbf{6}} \mathcal{Q}^{\mathbf{6}\dagger} \Sigma \to c_f^L \frac{|y_L|^2}{2} f^2 h^2, \quad \cdots$$

$$c_f^R \Lambda^2 f^2 \frac{|y_R|^2}{16\pi^2} \Sigma^\dagger \mathcal{T}^{\mathbf{6}} \mathcal{T}^{\mathbf{6}\dagger} \Sigma \to c_f^R |y_R|^2 f^2 \left(\eta^2 c_{2\theta} + (f^2 - h^2) s_\theta^2\right), \quad \cdots$$

$$c_f^{L,R} \sim \mathcal{O}(1)$$

UV contributions: incalculable. *Estimated* by Naïve Dimensional Analysis.

EW

$$\mathcal{L}_{\mathbf{6+6}} \supset \bar{t}_L \not{p} \left(\Pi_0^q + \frac{\Pi_1^q}{2} \frac{h^2}{f^2}\right) t_L + \bar{t}_R \not{p} \left[\Pi_0^t + \Pi_1^t \left(c_\theta^2 \frac{\eta^2}{f^2} + s_\theta^2 \left(1 - \frac{h^2 + \eta^2}{f^2}\right)\right)\right] t_R$$

$$- \frac{M_1^t}{\sqrt{2}} \frac{h}{f} \left(s_\theta \sqrt{1 - \frac{h^2 + \eta^2}{f^2}} + i c_\theta \frac{\eta}{f}\right) \bar{t}_L t_R + \text{h.c.}$$

$+$ Higher order operators UV

- ## The minimal Higgs potential hypothesis (MHP)

A summary: sources of the potential

	Gauge-induced	Fermion-induced
IR contributions (calculable)	Form factors of vector bosons $\Pi_{0,1}(p^2)$	Form factors of fermions $\Pi_0^{q,t}(p^2)$, $\Pi_1^{q,t}(p^2)$ and $M_{0,1}^t(p^2)$
UV contributions (estimated by NDA)	Local operators involved $g^{(\prime)}$	Local operators involved $y_{L,R}$

* NDA: Naïve Dimentional Analysis

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MHP: assume the UV contributions to be zero due to some unknown mechanism.
Then the potential is calculable!!

Information | References (63) | Citations (235) | Files | Plots

General Composite Higgs Models

David Marzocca (INFN, Trieste & SISSA, Trieste), Marco Serone (INFN, Trieste & SISSA, Trieste & ICTP, Trieste), Jing Shu (INFN, Trieste & SISSA, Trieste)

May 2012 - 51 pages

JHEP 1208 (2012) 013
DOI: 10.1007/JHEP08(2012)013

First proposed by Ref. and then generally adopted by other studies [1205.6434, 1404.7419, 1703.08011, etc].

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MHP: assume the UV contributions to be zero due to some unknown mechanism.

Question: is MHP compatible with strong 1st order EWPT?

Y.Wu, L.Bian and K.-P.Xie, 1909.02014 (This talk)

s Models

rieste & SISSA, Trieste & ICTP, Trieste), Jing Shu (INFN, Trieste & SISSA, Trieste)

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- The 6+6 and 15+15 models

Mathing the potential via IR contributions

$$V_f^{\rm IR}(h,\eta) \approx -2N_c \int \frac{d^4Q}{(2\pi)^4} \Big\{ \ln\left(1+\frac{\Pi_1^q}{2\Pi_0^q}\frac{h^2}{f^2}\right) + \ln\left[1+\frac{\Pi_1^t}{\Pi_0^t}\left(s_\theta^2\left(1-\frac{h^2}{f^2}\right)+c_{2\theta}\frac{\eta^2}{f^2}\right)\right] + \ln\left[1+\frac{1}{Q^2}\frac{|M_1^t|^2}{2\Pi_0^q\Pi_0^t}\frac{h^2}{f^2}\left(s_\theta^2\left(1-\frac{h^2}{f^2}\right)+c_{2\theta}\frac{\eta^2}{f^2}\right)\right]\Big\},$$

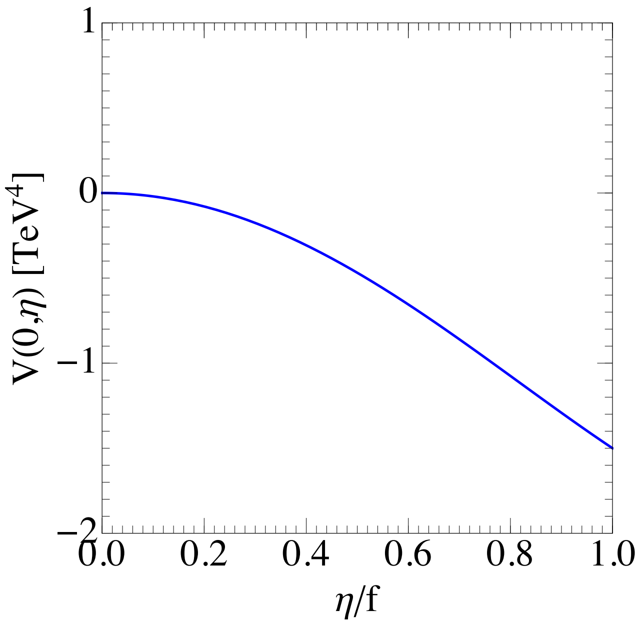
into

$$V_f(h,\eta) = \frac{\mu_f^2}{2}h^2 + \frac{\lambda_f}{4}h^4 + \frac{\mu_\eta^2}{2}\eta^2 + \frac{\lambda_\eta}{4}\eta^4 + \frac{\lambda_{h\eta}}{2}h^2\eta^2$$

gives

$$\langle\eta\rangle_{\rm local} = \sqrt{-\mu_\eta^2/\lambda_\eta} \gg f,$$

which is inconsistent with the chiral perturbation theory.



- The 15+6 model

Cannot generate a strong enough potential barrier: $\lambda_{h\eta}^2 - \lambda_h\lambda_\eta < 0$,

- # A summary

All three models fail to trigger strong 1st order EWPT via IR contributions alone!
The *minimal Higgs potential* hyperthesis is incompatible with EW baryogenesis for the models we consider.

- # What if we really want to trigger the EWPT?

If the UV contributions are non-negligible, then...

$$(\mu_h^2)^{\rm UV} = c_g \frac{3g^2}{2} f^2 + c_{g'} \frac{g'^2}{2} f^2 + c_f^L |y_L|^2 f^2 - 2c_f^R |y_R|^2 f^2 s_\theta^2 - \frac{d_f^R}{4\pi^2} |y_R|^4 f^2 s_\theta^4,$$

$$(\mu_\eta^2)^{\rm UV} = 2c_f^R |y_R|^2 f^2 c_{2\theta} + \frac{d_f^R}{4\pi^2} |y_R|^4 f^2 s_\theta^2 c_{2\theta},$$

$$\ldots$$

$\mathbf{6}+\mathbf{6}$	Gauge-induced	Fermion-induced
	$c_g f^4 \Sigma^\dagger \mathcal{G}_a \mathcal{G}_a \Sigma$	$c_f^L \|y_L\|^2 f^4 \Sigma^\dagger \mathcal{Q}^{\mathbf{6}} \mathcal{Q}^{\mathbf{6}\dagger} \Sigma$
UV contributions	$c_{g'} f^4 \Sigma^\dagger \mathcal{G}' \mathcal{G}' \Sigma$	$c_f^R \|y_R\|^2 f^4 \Sigma^\dagger \mathcal{T}^{\mathbf{6}} \mathcal{T}^{\mathbf{6}\dagger} \Sigma$
Estimated by NDA	$\frac{d_g}{16\pi^2} f^4 \left(\Sigma^\dagger \mathcal{G}_a \mathcal{G}_a \Sigma\right)^2$	$\frac{d_f^L}{16\pi^2} \|y_L\|^4 f^4 \left(\Sigma^\dagger \mathcal{Q}^{\mathbf{6}} \mathcal{Q}^{\mathbf{6}\dagger} \Sigma\right)^2$
	$\frac{d_{g'}}{16\pi^2} f^4 \left(\Sigma^\dagger \mathcal{G}' \mathcal{G}' \Sigma\right)^2$	$\frac{d_f^R}{16\pi^2} \|y_R\|^4 f^4 \left(\Sigma^\dagger \mathcal{T}^{\mathbf{6}} \mathcal{T}^{\mathbf{6}\dagger} \Sigma\right)^2$

- Combining IR and UV contributions

IR contributions: controlled by resonances mass, coupling constants:

Higgs decay const. Top partner mass t_R embedding param.

$$\{M_\rho, M_a, f, M_{\mathbf{1}}, M_{\mathbf{5}}, M_{\mathbf{1}'}, y_L^{\mathbf{5}}, y_R^{\mathbf{5}}, \theta\},$$

Vector resonances mass Fermion couplings

UV contributions: determined by Wilson coefficients:

$$\{c_g, g_{g'}, c_f^L, c_f^R, d_f^L, d_f^R\},$$

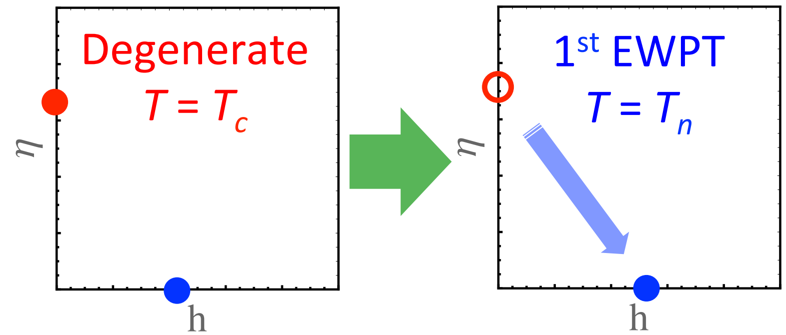
Combination:
We use Monte Carlo Markov Chain to find the allowed parameter space consistent with current EW & Higgs measurements and strong 1st order EW phase transition.

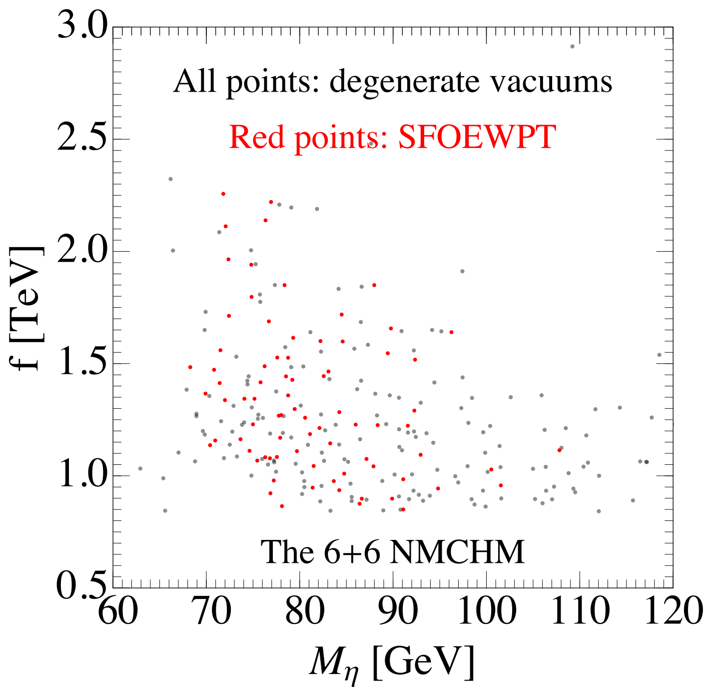
- Combining IR and UV contributions

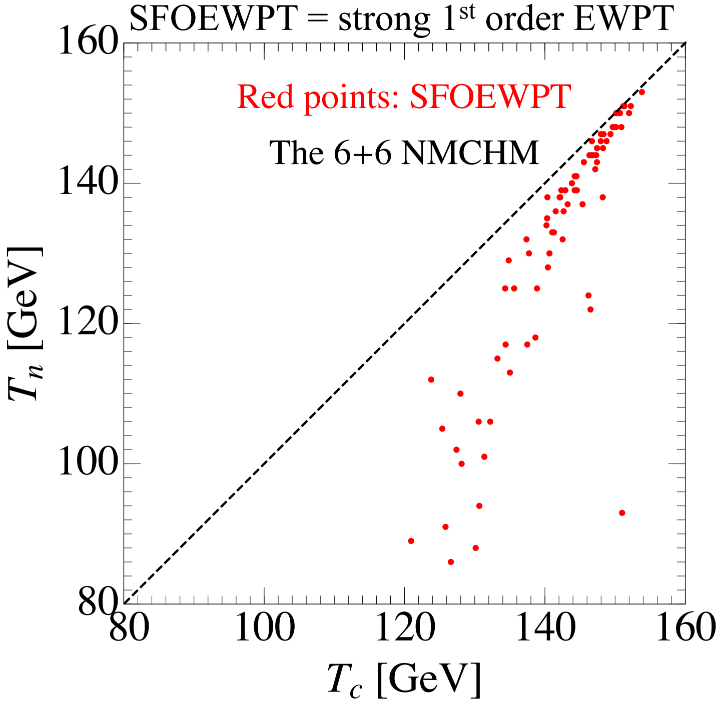
We get strong 1st order EWPT!
Bubble nucleation:

$$\Gamma/V \approx T^4 \left(\frac{S_3}{2\pi T}\right)^{3/2} e^{-S_3(T)/T},$$

EWPT finishes if Γ > Hubble const.

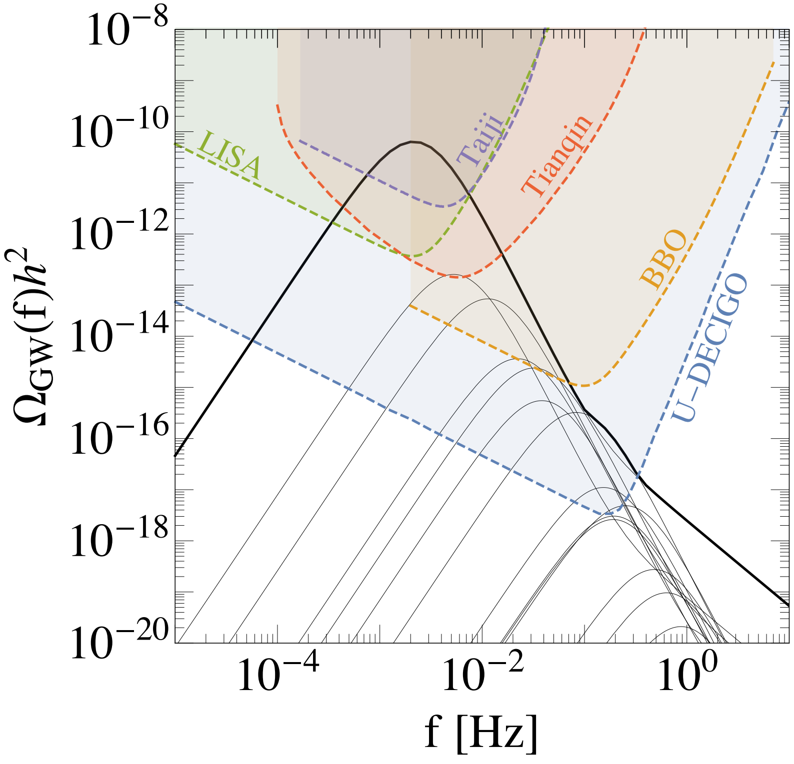


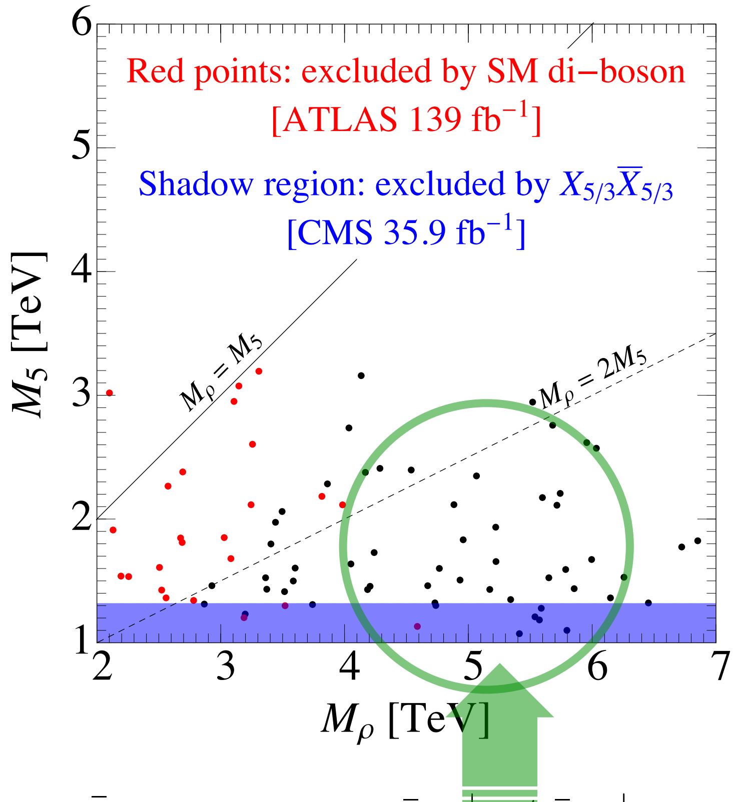




- Pheno: gravitational waves and collider searches

Strength of GWs can be derived using the numerical formulae in [C. Caprini *et al*. JCAP 1604 (2016) 001].





Hopeful channels
$$pp \to \rho_L^\pm \to X_{5/3}\bar{X}_{2/3} + T\bar{B} + \text{c.c.} + \cdots \to t\bar{t}W^\pm Z/t\bar{t}W^\pm h,$$
$$pp \to \rho_{L,R}^0 \to X_{5/3}\bar{X}_{5/3} + X_{2/3}\bar{X}_{2/3} + T\bar{T} + \cdots \to t\bar{t}W^+W^-/t\bar{t}Zh,$$

Conclusion

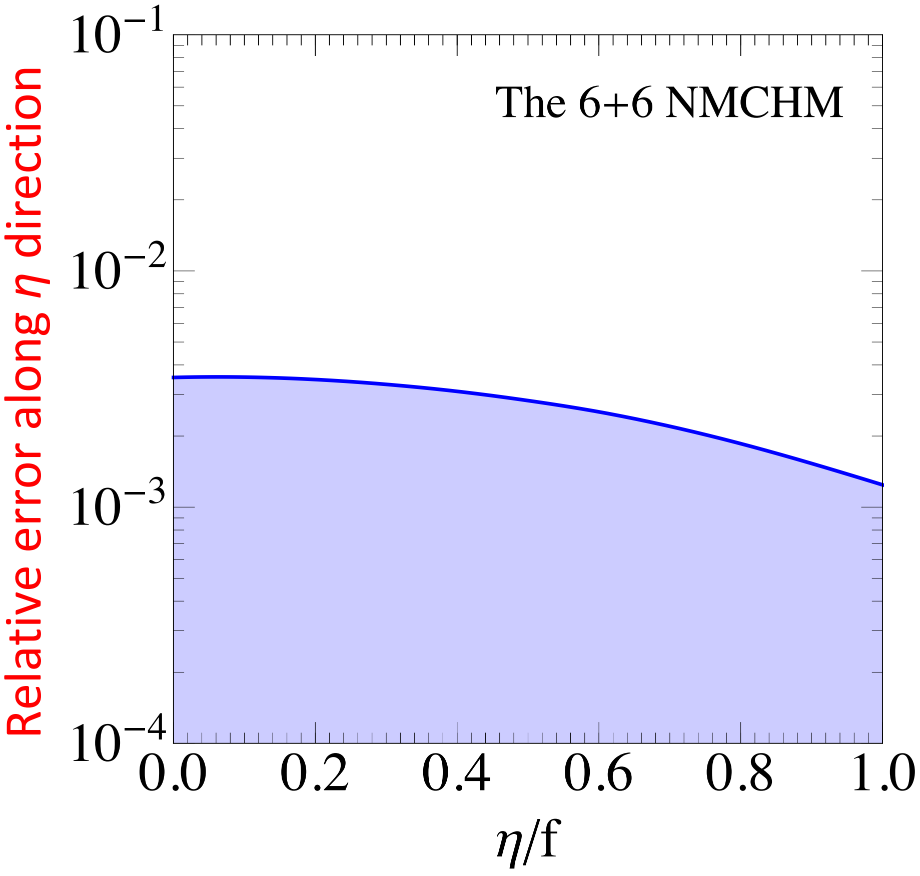
- Qualitative analysis shows that the SO(6)/SO(5) composite Higgs model provides all necessary ingredients for EW baryogenesis;

- For concrete models with fermion embedding up to 15 of SO(6), quantitative calculation shows that strong 1st order EWPT can be realized only when the higher order incalculable contributions are taken into account.

Thank you!

Backup

- The validity of polynomial expansion at $\eta \sim f$



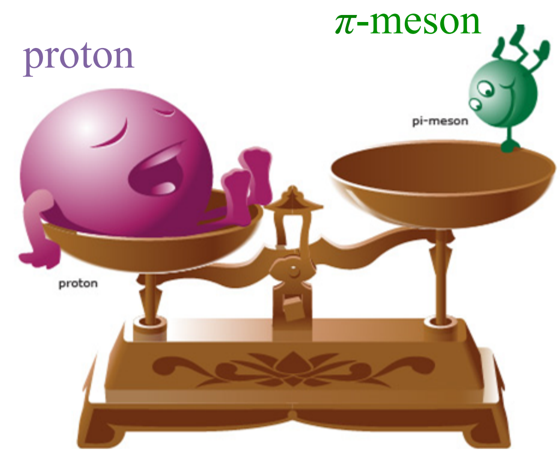
- How to get such a real singlet?

But it can also emerge naturally in the composite Higgs models.

An elementary Higgs boson's mass is sensitive to the quantum correction from high scale physics: $M_h \approx M_{\text{Planck}}$! Hierarchy problem.

But a composite Higgs boson can be naturally light: $M_h << M_{\text{planck}}$, like the $\pi^{\pm,0}$ in low energy QCD: $M_\pi << M_{\text{QCD}}$.

A top-down perspective: light scalars as pseudo-NGBs from spontaneous global symmetry breaking.



- # Top-down description of a composite Higgs

The (small) $\pi^{\pm,0}$ mass is generated by $SU(2)_L \times SU(2)_R$ explicit breaking term. Similarly, the composite Higgs potential is --

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm strong}$$
$$+ \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\mu} B^\mu + y_L \bar{q}_L \mathcal{O}_R + y_R \bar{t}_R \mathcal{O}_L$$

$W^{a_L}_\mu;\ B_\mu;$

$q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix};\ t_R;\ b_R;\ \cdots$

$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix};\ e_R;\ \cdots$

The elementary sector (SM particles)

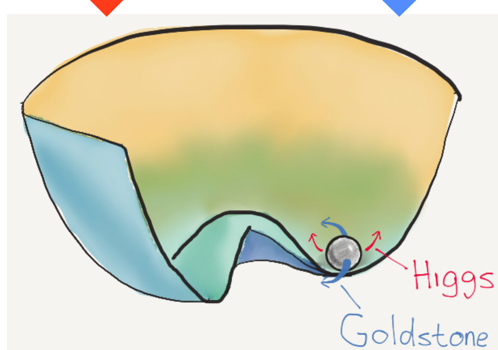
Subgroup $SU(2)_L \times U(1)_Y$ gauged

Fermions embedded in incomplete *G* rep.

Global symmetry breaking G/H

Higgs as pNGB

The strong sector (new physics)



Interactions **Explicitly** break *G*. Scalar potential generated: EWSB!

- Top-down description of a composite Higgs

The minimal setup: Contino *et al*, Phys. Rev. D75, 055014 (2007)

1. G/H = SO(5)/SO(4); 10 - 6 = 4 pNGBs: one Higgs doublet.
2. 3rd generation quarks embedded the 5 rep. of SO(5).

Known as the Minimal Composite Higgs Model. However...

- Bottom-up perspective

The $\pi^{\pm,0}$ consist of *u*, *d* quarks, which interact under a $SU(3)_c$ gauge theory: QCD.
What about the constituents of the composite Higgs?

G. Cacciapaglia *et al*, JHEP 04 (2014) 111.

The minimal solution of this question is G/H = SU(4)/Sp(4):
Four-flavor Weyl fermions under a Sp(2*N*) gauge group.

The scalar sector: 15 - 10 = 5 pNGBs: Higgs + one real singlet!