Electroweak baryogenesis from a composite Higgs

A novel model with high dimensional fermion representations

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In collaboration with Ligong Bian and Yongcheng Wu, JHEP 12 (2020) 047

Two long standing puzzles in the Standard Model

1. The **hierarchy problem**

"Naturally"
$M_h \approx M_{\mathrm{Pl}} \approx 10^{19}$ GeV

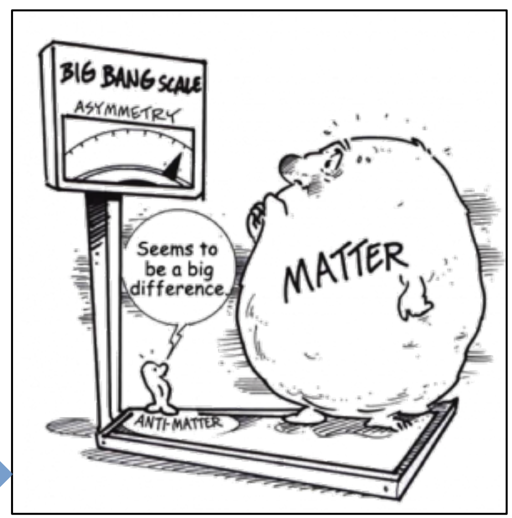
2. The **matter-antimatter asymmetry** of the Universe

N(matter): $1 + 10^{-9}$

N(antimatter): 1

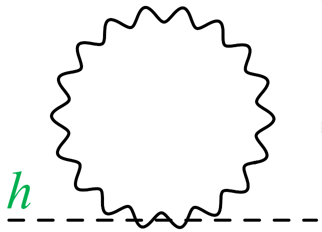
Annihilation

N(matter): 10^{-9}



- ... Solved by a composite Higgs!

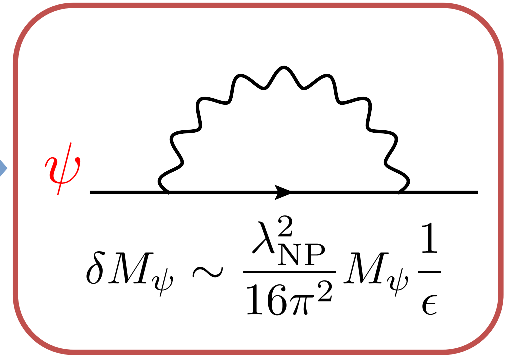
1. The **hierarchy problem**



"Naturally"
$M_h \approx M_{\rm Pl} \approx 10^{19}$ GeV

$h \sim \langle \psi\bar\psi \rangle$

A light Higgs!



Kaplan *et al*, NPB1991
Agashe *et al*, NPB2005

2. The **matter-antimatter asymmetry** of the Universe

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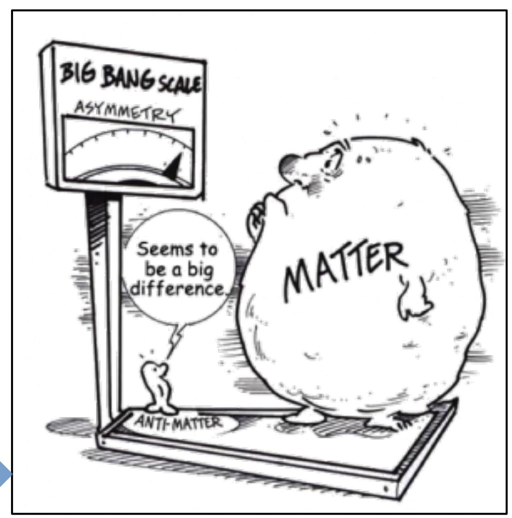
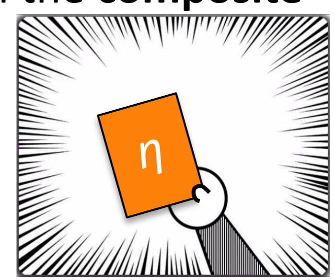


New scalar(s) in the **composite Higgs model**!

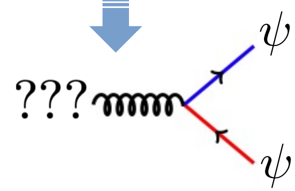


Higgs + new scalar
= EW baryogenesis

- # Minimal UV completed composite Higgs model

UV scale: 4-flavor Weyl fermions with a Sp(2*N*) gauge theory;
[Cacciapaglia *et al*, JHEP2014]

$$h \sim \langle \psi\bar{\psi} \rangle$$



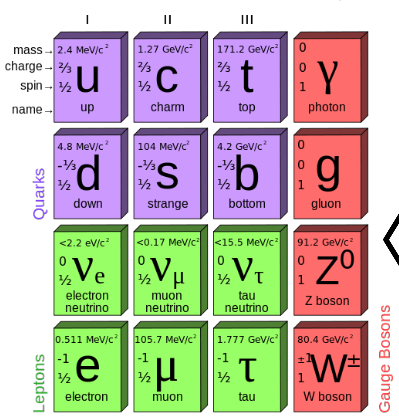
TeV scale (below confinement): <u>CCWZ EFT</u>;

Global SU(4)/Sp(4) = SO(6)/SO(5)[Gripaios *et al*, JHEP2009]

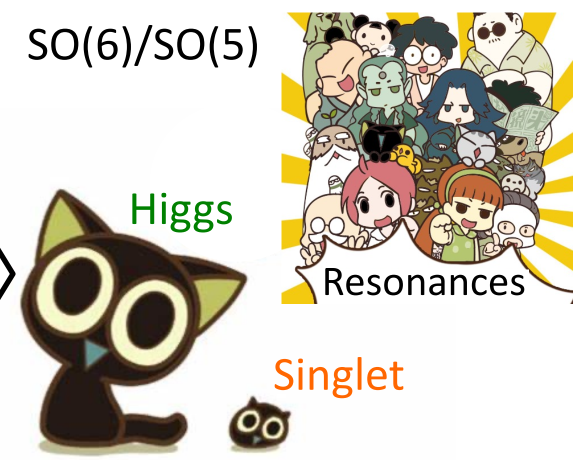
✓ 15 – 10 = 5 pNGBs: Higgs doublet (4) + real singlet (1)

✓ Composite resonances: spin-1, spin-1/2, etc;

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



SO(6)-breaking Interactions:
Source of potential



The elementary sector
(SM without Higgs)

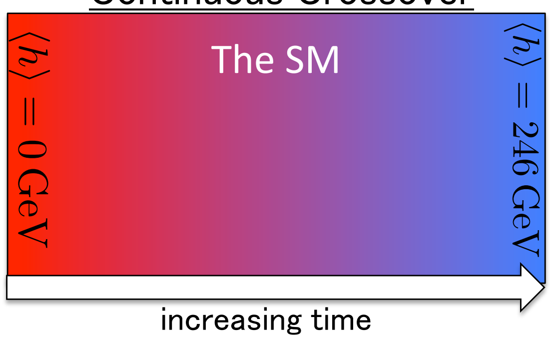
The composite sector
(New strong dynamics)

• Why an additional real singlet is enough?

3 conditions to generate the asymmetry:[Sakharov,1967]

(1)	Baryon number violation;	[For the SM: EW sphaleron ☑]
(2)	C/CP violation;	[For the SM: CKM phase too small ☒]
(3)	Departure from equilibrium.	[For SM: NOT satisfied ☒]

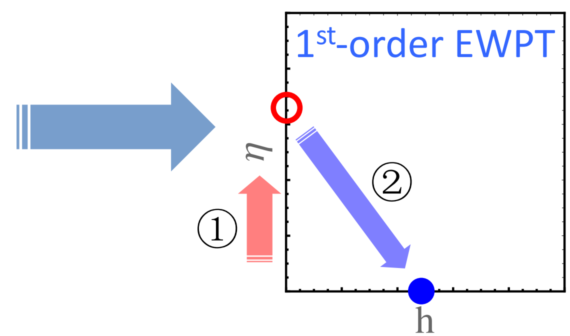
Continuous Crossover



First Order Phase Transition

But adding a **real singlet** is sufficient!

- **Departure from equilibrium** can be realized by
- **CP violating phase** comes from the *η-relevant* interactions.



The SO(6)/SO(5) composite Higgs model is a candidate!

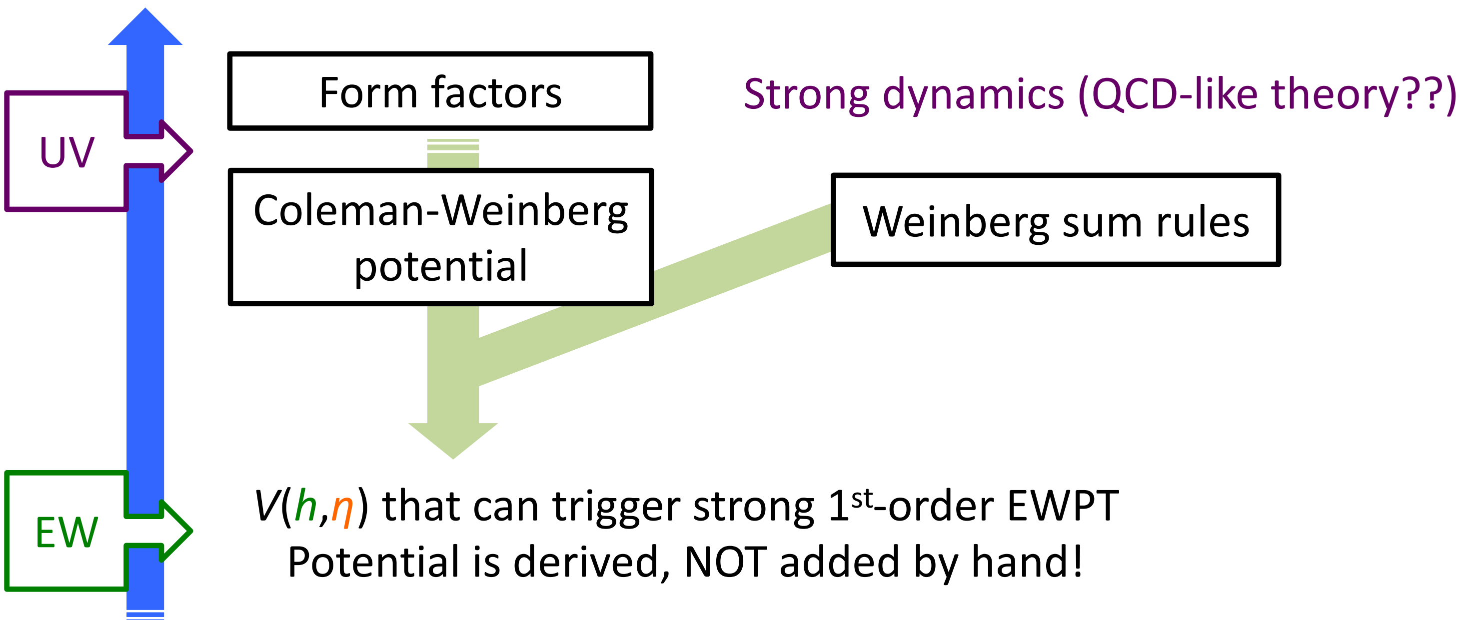
- Composite Higgs model, *not just* Higgs + singlet…

The scalar potential

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

is derived by the form factors of the strong dynamics!!

Question: can we build a composite Higgs model with appropriate potential that can satisfy the Sakharov conditions?



• Generating the scalar potential

Potential source 1: gauge interactions

$$\mathcal{L}_{\rm int} \supset \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\mu} B^\mu$$

SM gauge bosons: W^μ_a, B^μ

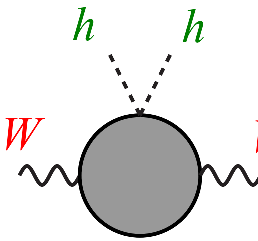
Strong currents: $\mathcal{J}^a_\mu$, $\mathcal{J}_{Y\mu}$

Gauging a subgroup of SO(6) --

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

Higgs potential *V*(*h*) is generated !!

W & Z mass



$$\langle \mathcal{J}\mathcal{J}\rangle \sim g^2 f^2 \sin^2\frac{h}{f}$$

Potential source 2: fermion interactions

$$\mathcal{L}_{\rm int} \supset \bar{q}_L \mathcal{O}_R + \bar{t}_R \mathcal{O}_L + \text{h.c.}$$

SM quarks embedded to reps of SO(6): $\bar{q}_L$, $\bar{t}_R$

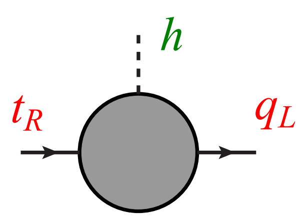
Strong operators: $\mathcal{O}_R$, $\mathcal{O}_L$

Symmetry breaking –

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

Joint potential *V*(*h*,*η*) is generated !!

Top mass



$$\langle \mathcal{O}_L\mathcal{O}_R\rangle \sim \frac{y_L y_R}{g_\rho} f \sin\frac{h}{f}$$

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

- Fermion sector

Elementary quarks: **20'** of SO(6)

$$\mathbf{6}\otimes\mathbf{6}=\mathbf{1}\oplus\mathbf{15}\oplus\mathbf{20}'$$

$$SO(6)\times U(1)_X \to SO(5)\times U(1)_X \to SO(4)\times U(1)_X \to SU(2)_L\times U(1)_Y \quad (Y=X+T_R^3)$$

$$\begin{aligned}\mathbf{20}'_{2/3} &\to \mathbf{14}_{2/3}\oplus\mathbf{5}_{2/3}\oplus\mathbf{1}_{2/3}\\ &\to (\mathbf{9}_{2/3}\oplus\mathbf{4}_{2/3}\oplus\mathbf{1}_{2/3})\oplus(\mathbf{4}_{2/3}\oplus\mathbf{1}_{2/3})\oplus\mathbf{1}_{2/3}\\ &\to \left[(\mathbf{3}_{5/3}\oplus\mathbf{3}_{2/3}\oplus\mathbf{3}_{-1/3})\oplus(\mathbf{2}_{7/6}\oplus\underline{\mathbf{2}_{1/6}})\oplus\underline{\mathbf{1}_{2/3}}\right]\oplus\left[(\mathbf{2}_{7/6}\oplus\underline{\mathbf{2}_{1/6}})\oplus\underline{\mathbf{1}_{2/3}}\right]\oplus\underline{\mathbf{1}_{2/3}}.\end{aligned}$$

Two/three ways to embed q_L/t_R, respectively;

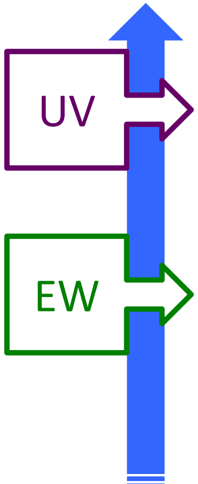
Top partners: reps of SO(5)

$$SO(5)\times U(1)_X \to SO(4)\times U(1)_X \to SU(2)_L\times U(1)_Y \quad (Y=X+T_R^3)$$

$$\begin{aligned}\mathbf{14}_{2/3} &\to (\mathbf{9}_{2/3}\oplus\mathbf{4}_{2/3}\oplus\mathbf{1}_{2/3})\\ &\to \left[(\mathbf{3}_{5/3}\oplus\mathbf{3}_{2/3}\oplus\mathbf{3}_{-1/3})\oplus(\mathbf{2}_{7/6}\oplus\mathbf{2}_{1/6})\oplus\mathbf{1}_{2/3}\right]\\ \mathbf{5}_{2/3} &\to (\mathbf{4}_{2/3}\oplus\mathbf{1}_{2/3})\to\left[(\mathbf{2}_{7/6}\oplus\mathbf{2}_{1/6})\oplus\mathbf{1}_{2/3}\right]\end{aligned}$$

The top partners in **14**, **5** or **1** of SO(5).

• Fermion-induced scalar potential



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm strong} + \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\mu} B^\mu + \bar{q}_L^{\mathbf{20}'} \mathcal{O}_R^{\mathbf{20}'} + \bar{t}_R^{\mathbf{20}'} \mathcal{O}_L^{\mathbf{20}'} + \text{h.c.}$$

------ Integrating out the strong dynamics ------

Form factors

$$\Sigma \sim \left(0, 0, 0, \frac{h}{f}, \frac{\eta}{f}, \sqrt{1 - \frac{h^2+\eta^2}{f^2}}\right)^T$$

$$\begin{aligned}\mathcal{L}_\Psi \to\ & \text{tr}\left[\bar{q}_L^{\mathbf{20}'} \gamma^\mu p_\mu q_L^{\mathbf{20}'}\right] \Pi_0^q + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} \gamma^\mu p_\mu q_L^{\mathbf{20}'} \Sigma\right) \Pi_1^q + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} \Sigma\right) \gamma^\mu p_\mu \left(\Sigma^T q_L^{\mathbf{20}'} \Sigma\right) \Pi_2^q \\ & + \text{tr}\left[\bar{t}_R^{\mathbf{20}'} \gamma^\mu p_\mu t_R^{\mathbf{20}'}\right] \Pi_0^t + \left(\Sigma^T \bar{t}_R^{\mathbf{20}'} \gamma^\mu p_\mu t_R^{\mathbf{20}'} \Sigma\right) \Pi_1^t + \left(\Sigma^T \bar{t}_R^{\mathbf{20}'} \Sigma\right) \gamma^\mu p_\mu \left(\Sigma^T t_R^{\mathbf{20}'} \Sigma\right) \Pi_2^t \\ & + \text{tr}\left[\bar{q}_L^{\mathbf{20}'} t_R^{\mathbf{20}'}\right] M_0^t + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} t_R^{\mathbf{20}'} \Sigma\right) M_1^t + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} \Sigma\right) \left(\Sigma^T t_R^{\mathbf{20}'} \Sigma\right) M_2^t + \text{h.c.},\end{aligned}$$

------ Coleman-Weinberg potential ------

$$\begin{aligned}V_f(h,\eta) \approx & -2N_c \int \frac{d^4Q}{(2\pi)^4} \left[\ln\left(1 + \frac{\Pi_1^q}{2\Pi_0^q} \frac{\eta^2}{f^2}\right) + \ln\left(1 + \frac{\Pi_1^q}{4\Pi_0^q} \frac{h^2 + 2\eta^2}{f^2} + \frac{\Pi_2^q}{\Pi_0^q} \frac{h^2\eta^2}{f^4}\right)\right] \\ & -2N_c \int \frac{d^4Q}{(2\pi)^4} \ln\left[1 + \frac{\Pi_1^t}{2\Pi_0^t}\left(1 - \frac{h^2}{f^2}\right) + \frac{2\Pi_2^t}{\Pi_0^t} \frac{\eta^2}{f^2}\left(1 - \frac{h^2+\eta^2}{f^2}\right)\right] \\ & -2N_c \int \frac{d^4Q}{(2\pi)^4} \ln\left[1 + \frac{1}{8Q^2\Pi_0^q\Pi_0^t} \frac{h^2}{f^2}\left(1 - \frac{h^2+\eta^2}{f^2}\right)\left|M_1^t + 4M_2^t \frac{\eta^2}{f^2}\right|^2\right],\end{aligned}$$

Matching!
(f > 1 TeV)

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

- # What are the form factors?

Functions of Q^2 (Euclidean momentum), top partner masses & couplings

$$\Pi_0^{q,t}=1+\sum_{n=1}^{N_{\mathbf{14}}}\frac{|y_{L,R}^{\mathbf{14}(n)}|^2f^2}{Q^2+M_{\mathbf{14}(n)}^2},\quad \Pi_1^{q,t}=2\left(\sum_{n=1}^{N_{\mathbf{5}}}\frac{|y_{L,R}^{\mathbf{5}(n)}|^2f^2}{Q^2+M_{\mathbf{5}(n)}^2}-\sum_{n=1}^{N_{\mathbf{14}}}\frac{|y_{L,R}^{\mathbf{14}(n)}|^2f^2}{Q^2+M_{\mathbf{14}(n)}^2}\right),$$

$$\Pi_2^{q,t}=\frac{6}{5}\sum_{n=1}^{N_{\mathbf{1}}}\frac{|y_{L,R}^{\mathbf{1}(n)}|^2f^2}{Q^2+M_{\mathbf{1}(n)}^2}-2\sum_{n=1}^{N_{\mathbf{5}}}\frac{|y_{L,R}^{\mathbf{5}(n)}|^2f^2}{Q^2+M_{\mathbf{5}(n)}^2}+\frac{4}{5}\sum_{n=1}^{N_{\mathbf{14}}}\frac{|y_{L,R}^{\mathbf{14}(n)}|^2f^2}{Q^2+M_{\mathbf{14}(n)}^2},$$

$$M_0^t=\sum_{n=1}^{N_{\mathbf{14}}}\frac{y_L^{\mathbf{14}(n)}y_R^{\mathbf{14}(n)*}f^2M_{\mathbf{14}(n)}}{Q^2+M_{\mathbf{14}(n)}^2},$$

$$M_1^t=2\left(\sum_{n=1}^{N_{\mathbf{5}}}\frac{y_L^{\mathbf{5}(n)}y_R^{\mathbf{5}(n)*}f^2M_{\mathbf{5}(n)}}{Q^2+M_{\mathbf{5}(n)}^2}-\sum_{n=1}^{N_{\mathbf{14}}}\frac{y_L^{\mathbf{14}(n)}y_R^{\mathbf{14}(n)*}f^2M_{\mathbf{14}(n)}}{Q^2+M_{\mathbf{14}(n)}^2}\right),$$

$$M_2^t=\frac{6}{5}\sum_{n=1}^{N_{\mathbf{1}}}\frac{y_L^{\mathbf{1}(n)}y_R^{\mathbf{1}(n)*}f^2M_{\mathbf{1}(n)}}{Q^2+M_{\mathbf{1}(n)}^2}-2\sum_{n=1}^{N_{\mathbf{5}}}\frac{y_L^{\mathbf{5}(n)}y_R^{\mathbf{5}(n)*}f^2M_{\mathbf{5}(n)}}{Q^2+M_{\mathbf{5}(n)}^2}+\frac{4}{5}\sum_{n=1}^{N_{\mathbf{14}}}\frac{y_L^{\mathbf{14}(n)}y_R^{\mathbf{14}(n)*}f^2M_{\mathbf{14}(n)}}{Q^2+M_{\mathbf{14}(n)}^2},$$

The integral converges if $\Pi_{1,2}^{q,t}/\Pi_0^{q,t}\sim Q^{-6}$ by **Weinberg sum rules** --

$$\sum_{n=1}^{N_{\mathbf{14}}}|y_{L,R}^{\mathbf{14}(n)}|^2=\sum_{n=1}^{N_{\mathbf{5}}}|y_{L,R}^{\mathbf{5}(n)}|^2=\sum_{n=1}^{N_{\mathbf{1}}}|y_{L,R}^{\mathbf{1}(n)}|^2,$$

$$\sum_{n=1}^{N_{\mathbf{14}}}|y_{L,R}^{\mathbf{14}(n)}|^2M_{\mathbf{14}(n)}^2=\sum_{n=1}^{N_{\mathbf{5}}}|y_{L,R}^{\mathbf{5}(n)}|^2M_{\mathbf{5}(n)}^2=\sum_{n=1}^{N_{\mathbf{1}}}|y_{L,R}^{\mathbf{1}(n)}|^2M_{\mathbf{1}(n)}^2.$$

And then the integral is calculable!

- # Back to cosmology

The scalar potential

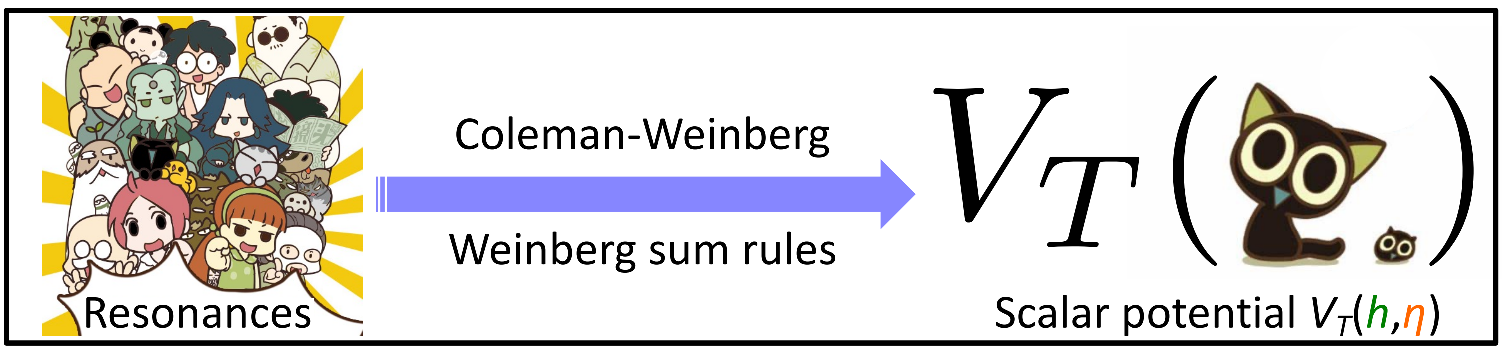
$$V(h,\eta)=\frac{\mu_h^2}{2}h^2+\frac{\lambda_h}{4}h^4+\frac{\mu_\eta^2}{2}\eta^2+\frac{\lambda_\eta}{4}\eta^4+\frac{\lambda_{h\eta}}{2}h^2\eta^2.$$

is <u>determined</u> by the *resonance mass and couplings*.

At finite temperature

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

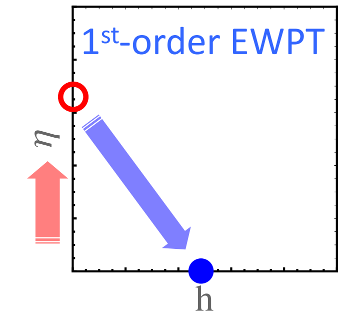
$$c_h=\frac{3g^2+g'^2}{16}+\frac{y_t^2}{4}+\frac{\lambda_h}{2}+\frac{\lambda_{h\eta}}{12},\quad c_\eta=\frac{\lambda_\eta}{4}+\frac{\lambda_{h\eta}}{3},$$

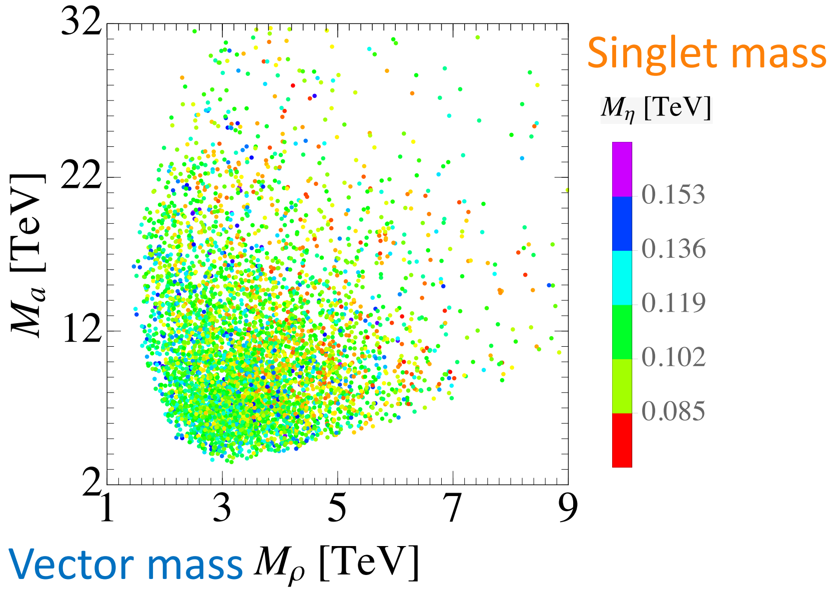


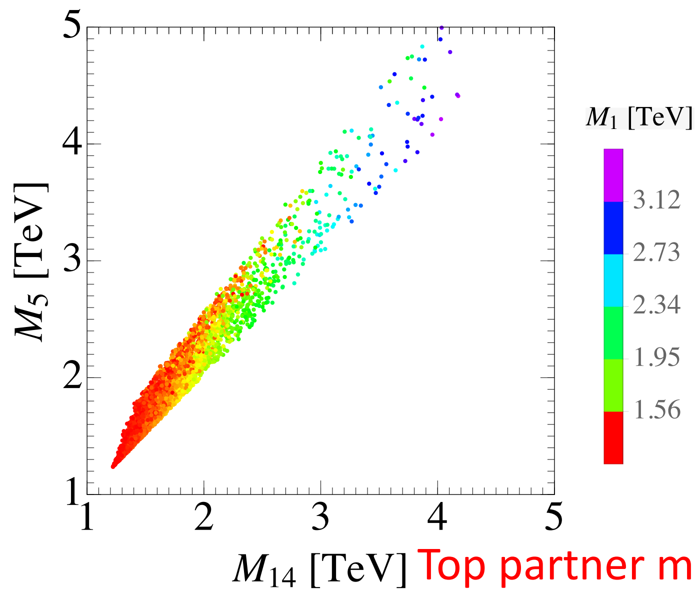
Question: can we find appropriate resonance spectrum to realize the 1st-order EW phase transition?

- # Back to cosmology

Yes! We find the parameter space allowed by the Higgs & EW measurements and the 1st-order EW phase transition. [**K.-P.Xie**, Y.Wu and L.Bian, JHEP2020 This talk]







The quartic couplings of η^4 and $h^2\eta^2$ are enhanced for **20'** rep; lower reps cannot provide large enough Coleman-Weinberg potential to trigger the 1st-order EWPT.

- Phase transition is OK, then next...

CP violating phase

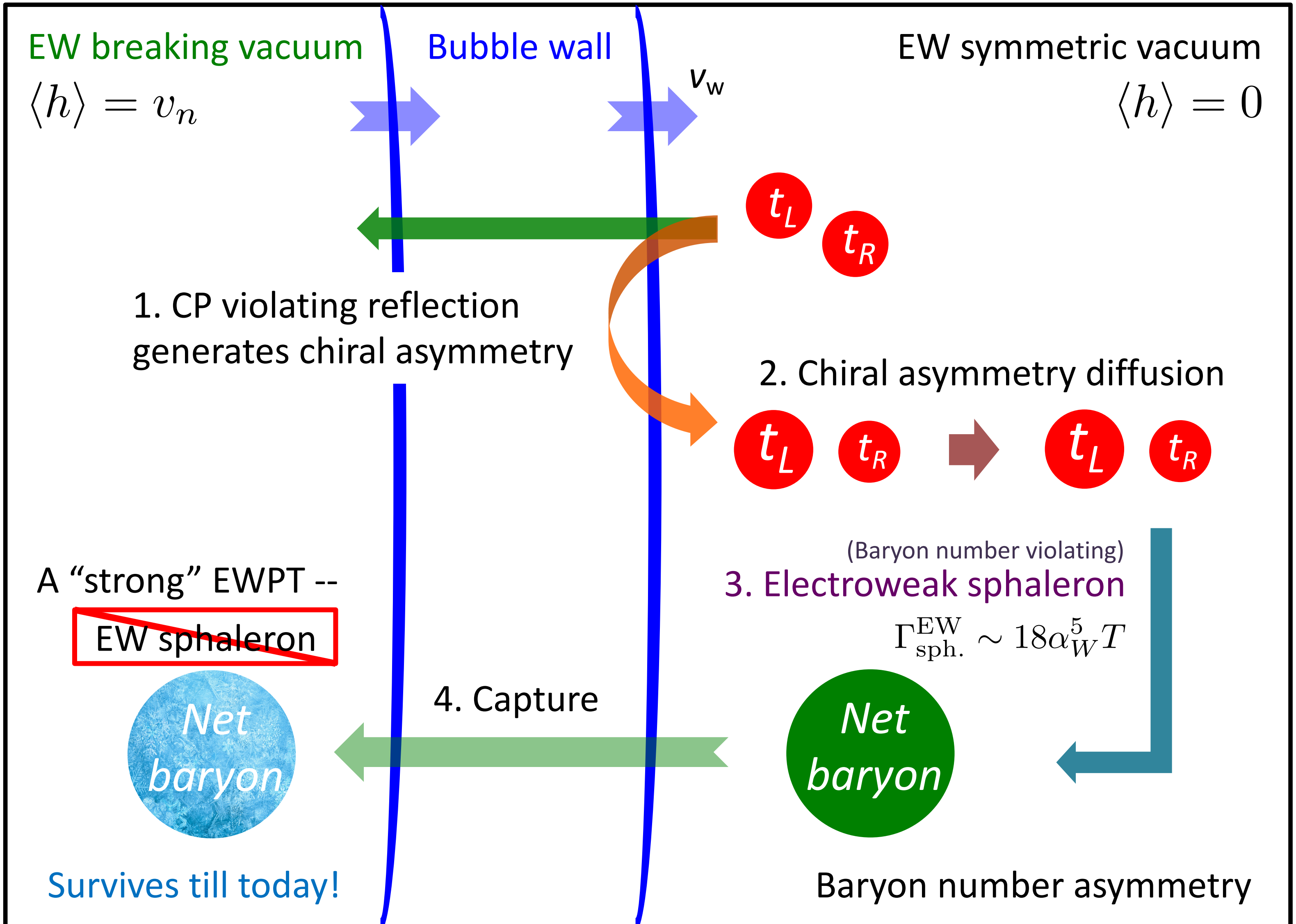
$$\mathcal{L}_\Psi \to \text{tr}\left[\bar{q}_L^{\mathbf{20}'}\gamma^\mu p_\mu q_L^{\mathbf{20}'}\right]\Pi_0^q + \left(\Sigma^T\bar{q}_L^{\mathbf{20}'}\gamma^\mu p_\mu q_L^{\mathbf{20}'}\Sigma\right)\Pi_1^q + \left(\Sigma^T\bar{q}_L^{\mathbf{20}'}\Sigma\right)\gamma^\mu p_\mu\left(\Sigma^T q_L^{\mathbf{20}'}\Sigma\right)\Pi_2^q$$
$$+\,\text{tr}\left[\bar{t}_R^{\mathbf{20}'}\gamma^\mu p_\mu t_R^{\mathbf{20}'}\right]\Pi_0^t + \left(\Sigma^T\bar{t}_R^{\mathbf{20}'}\gamma^\mu p_\mu t_R^{\mathbf{20}'}\Sigma\right)\Pi_1^t + \left(\Sigma^T\bar{t}_R^{\mathbf{20}'}\Sigma\right)\gamma^\mu p_\mu\left(\Sigma^T t_R^{\mathbf{20}'}\Sigma\right)\Pi_2^t$$
$$+\,\text{tr}\left[\bar{q}_L^{\mathbf{20}'}t_R^{\mathbf{20}'}\right]M_0^t + \left(\Sigma^T\bar{q}_L^{\mathbf{20}'}t_R^{\mathbf{20}'}\Sigma\right)M_1^t + \left(\Sigma^T\bar{q}_L^{\mathbf{20}'}\Sigma\right)\left(\Sigma^T t_R^{\mathbf{20}'}\Sigma\right)M_2^t + \text{h.c.},$$

$$M_0^t = \sum_{n=1}^{N_{\mathbf{14}}}\frac{y_L^{\mathbf{14}(n)}y_R^{\mathbf{14}(n)*}f^2M_{\mathbf{14}(n)}}{Q^2+M_{\mathbf{14}(n)}^2},$$
$$M_1^t = 2\left(\sum_{n=1}^{N_{\mathbf{5}}}\frac{y_L^{\mathbf{5}(n)}y_R^{\mathbf{5}(n)*}f^2M_{\mathbf{5}(n)}}{Q^2+M_{\mathbf{5}(n)}^2} - \sum_{n=1}^{N_{\mathbf{14}}}\frac{y_L^{\mathbf{14}(n)}y_R^{\mathbf{14}(n)*}f^2M_{\mathbf{14}(n)}}{Q^2+M_{\mathbf{14}(n)}^2}\right),$$
$$M_2^t = \frac{6}{5}\sum_{n=1}^{N_{\mathbf{1}}}\frac{y_L^{\mathbf{1}(n)}y_R^{\mathbf{1}(n)*}f^2M_{\mathbf{1}(n)}}{Q^2+M_{\mathbf{1}(n)}^2} - 2\sum_{n=1}^{N_{\mathbf{5}}}\frac{y_L^{\mathbf{5}(n)}y_R^{\mathbf{5}(n)*}f^2M_{\mathbf{5}(n)}}{Q^2+M_{\mathbf{5}(n)}^2} + \frac{4}{5}\sum_{n=1}^{N_{\mathbf{14}}}\frac{y_L^{\mathbf{14}(n)}y_R^{\mathbf{14}(n)*}f^2M_{\mathbf{14}(n)}}{Q^2+M_{\mathbf{14}(n)}^2},$$

$$\mathcal{L}_\Psi \supset -\frac{y_t}{\sqrt{2}}\bar{t}_L t_R h\left[\frac{M_{1,0}^t}{|M_{1,0}^t|}\left(1-\frac{h^2-v^2}{2f^2}\right)+\frac{\eta^2}{2f^2}\left(\frac{8M_{2,0}^t}{|M_{1,0}^t|}-\frac{M_{1,0}^t}{|M_{1,0}^t|}\right)\right]+\text{h.c.}$$
$$\supset -\frac{y_t}{\sqrt{2}}\bar{t}_L t_R h\left[e^{i\phi_1}\left(1-\frac{h^2+\eta^2-v^2}{2f^2}\right)+\rho_t e^{i\phi_2}\frac{\eta^2}{2f^2}\right]+\text{h.c.}$$

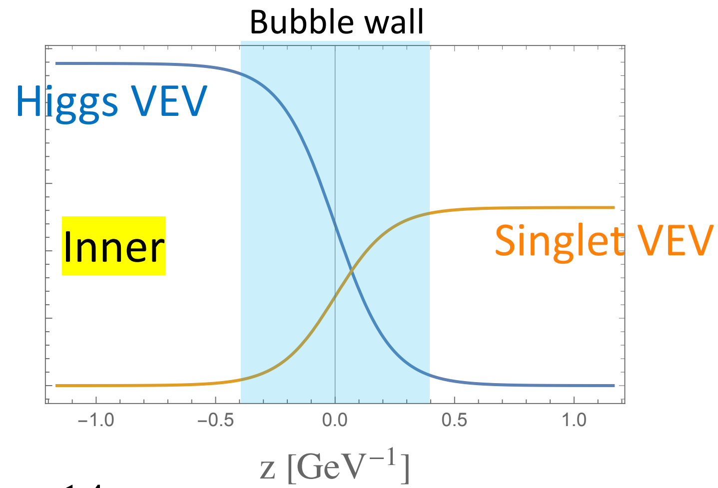
Novelty: CPV from dimension-6 operator $ih\eta^2 t\gamma^5 t$!

- 1st-order EWPT + CP phase = EW baryogenesis

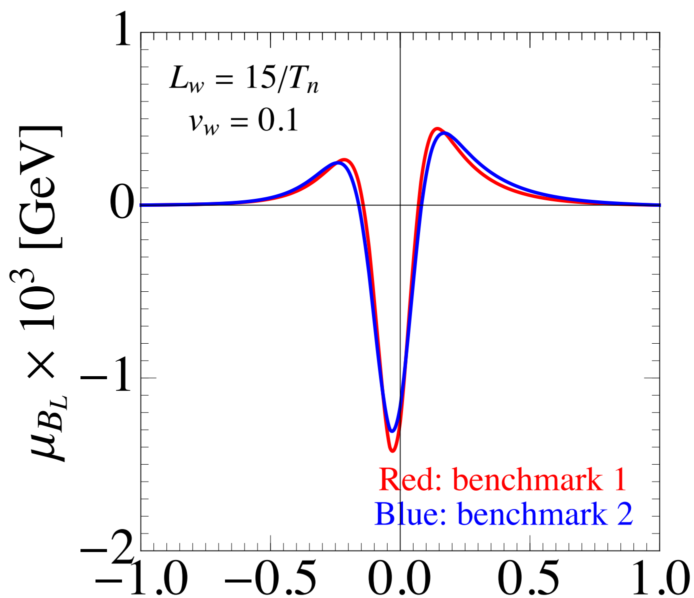


- # EW baryogenesis

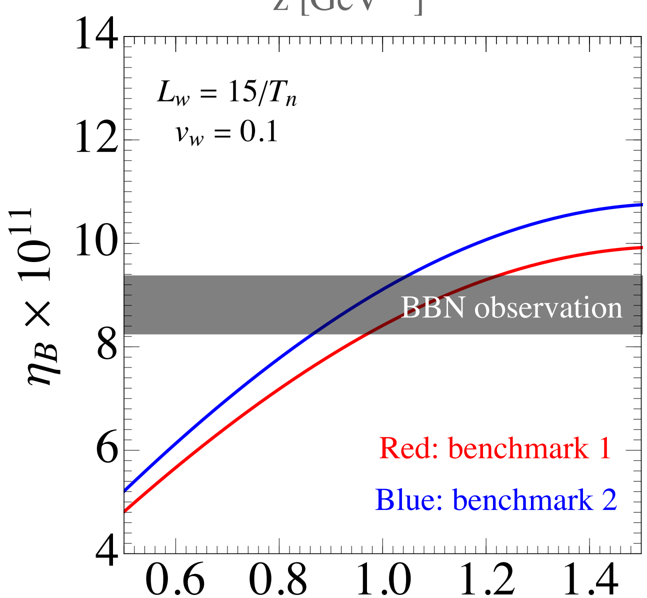
Mechanism proposed in [Joyce *et al*, PRL1995]. Technically we adopt [Fromme *et al*, JHEP2007] to calculate.



Two benchmarks for illustration:



Spatial distance from bubble center



CP phase

The baryon asymmetry of the universe can be explained.

- # Conclusion

We build a composite Higgs model:

- ❑ SO(6)/SO(5), scalar sector: Higgs + singlet;
- ❑ q_L and t_R are both embedded in **20'**;

- ❑ The first composite Higgs model that succeeds to trigger the strong 1st-order EWPT via Coleman-Weinberg potential;
- ❑ CP violation is from the dim-6 operator $ih\eta^2 t\gamma^5 t$;
- ❑ EW baryogenesis is realized.

- ❑ Resonances at O(TeV), accessible at colliders; EWPT gravitational waves detectable.

Thank you!

- Backup: Embedding q_L, t_R into 20'

$$Zf\bar{f} = \frac{g}{c_W}\left(T_L^3 - s_W^2 Q\right),$$

$$\mathcal{L} \supset -\frac{1}{\sqrt{2}} h y_L^{\mathbf{14}} \left(\frac{\eta e^{-i\phi_L}\cos\theta_L}{f + \sqrt{f^2 - h^2 - \eta^2}} + \sin\theta_L \right) \left(\bar{b}_L N_{-1/3} + \bar{b}_L Y_{-1/3} \right)$$

$$q_L^{\mathbf{20}'} = q_L^{\mathbf{20}'_A} e^{i\phi_L}\cos\theta_L + q_L^{\mathbf{20}'_B}\sin\theta_L$$

$$\begin{bmatrix} \mathbf{14}_{2/3} & \rightarrow & \mathbf{3}_{5/3} & \oplus & \mathbf{3}_{2/3} & \oplus & \mathbf{3}_{-1/3} & \oplus & \mathbf{2}_{7/6} & \oplus & \mathbf{2}_{1/6} & \oplus & \mathbf{1}_{2/3} \\ \Psi_{\mathbf{14}} & \rightarrow & K & \oplus & N & \oplus & Y & \oplus & J_X & \oplus & J_Q & \oplus & T' \end{bmatrix},$$

ϑ_L = 0 and η = 0 at zero temeprature can protect Zb_Lb_L ;

$$t_R^{\mathbf{20}'_A} : \Pi_{LR}^t = -\frac{1}{2\sqrt{5}} \frac{h\eta}{f^2} \left(\frac{3M_1^t}{2} - M_2^t \frac{h^2 - 4\eta^2}{f^2} \right),$$

$$t_R^{\mathbf{20}'_B} : \Pi_{LR}^t = -\frac{1}{2\sqrt{2}} \frac{h}{f} \sqrt{1 - \frac{h^2+\eta^2}{f^2}} \left(M_1^t + 4M_2^t \frac{\eta^2}{f^2} \right),$$

$$t_R^{\mathbf{20}'_C} : \Pi_{LR}^t = \frac{1}{\sqrt{30}} \frac{h\eta}{f^2} \left[M_1^t - M_2^t \left(5 - 6\frac{h^2+\eta^2}{f^2} \right) \right].$$

Only the second embedding provides a massive top when the VEV η = 0 at zero temperature.

- Back to cosmology

The 1st-order EWPT needs large quartic couplings.

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

For the high dimensional rep 20', $\lambda_{\eta,h\eta}$ is enhanced!

$$\begin{aligned}\mathcal{L}_\Psi \to\ & \mathrm{tr}\left[\bar{q}_L^{\mathbf{20}'}\gamma^\mu p_\mu q_L^{\mathbf{20}'}\right]\Pi_0^q + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'}\gamma^\mu p_\mu q_L^{\mathbf{20}'}\Sigma\right)\Pi_1^q + \boxed{\left(\Sigma^T \bar{q}_L^{\mathbf{20}'}\Sigma\right)\gamma^\mu p_\mu \left(\Sigma^T q_L^{\mathbf{20}'}\Sigma\right)\Pi_2^q} \\ & + \mathrm{tr}\left[\bar{t}_R^{\mathbf{20}'}\gamma^\mu p_\mu t_R^{\mathbf{20}'}\right]\Pi_0^t + \left(\Sigma^T \bar{t}_R^{\mathbf{20}'}\gamma^\mu p_\mu t_R^{\mathbf{20}'}\Sigma\right)\Pi_1^t + \boxed{\left(\Sigma^T \bar{t}_R^{\mathbf{20}'}\Sigma\right)\gamma^\mu p_\mu \left(\Sigma^T t_R^{\mathbf{20}'}\Sigma\right)\Pi_2^t} \\ & + \mathrm{tr}\left[\bar{q}_L^{\mathbf{20}'} t_R^{\mathbf{20}'}\right] M_0^t + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} t_R^{\mathbf{20}'}\Sigma\right) M_1^t + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'}\Sigma\right)\left(\Sigma^T t_R^{\mathbf{20}'}\Sigma\right) M_2^t + \mathrm{h.c.},\end{aligned}$$

Composite Higgs model with reps lower than 20' cannot trigger a 1st-order EWPT via the Coleman-Weinberg potential along.

Our work: the first composite Higgs model that succeeds to trigger the strong 1st-order EWPT via Coleman-Weinberg potential.

- EW baryogenesis benchmarks

Details of the parameters

	f [TeV]	M_ρ [TeV]	M_a [TeV]	$M_{\mathbf{14}}$ [TeV]	$M_{\mathbf{5}}$ [TeV]	$M_{\mathbf{1}}$ [TeV]	$M_{\mathbf{14}'}$ [TeV]	$M_{\mathbf{1}'}$ [TeV]
B1	2.17	4.57	6.49	1.61	1.89	1.05	8.57	13.9
B2	1.88	3.41	9.02	1.68	1.77	1.37	8.47	18.7

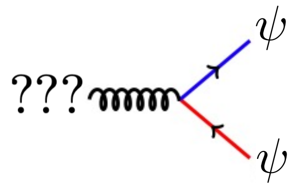
	$y_L^{\mathbf{14}}$	$y_R^{\mathbf{14}}$	$y_L^{\mathbf{5}}$	$y_R^{\mathbf{5}}$	$y_L^{\mathbf{1}}$	$y_R^{\mathbf{1}}$	$y_L^{\mathbf{14}'}$	$y_R^{\mathbf{14}'}$	$y_L^{\mathbf{1}'}$	$y_R^{\mathbf{1}'}$	M_η [GeV]
B1	1.90	0.676	-1.91	0.681	1.90	0.676	0.224	0.0798	0.216	0.0769	91.8
B2	2.11	0.574	2.12	-0.575	2.11	0.574	0.141	0.0383	0.126	0.0342	99.9

Table 1: The benchmarks used to evaluate the BAU. The T_n for B1 and B2 are respectively 59.2 GeV and 76.4 GeV; while v_n for B1 and B2 are respectively 222 GeV and 205 GeV.

• Why extra scalar(s) in composite Higgs models?

Composite Higgs ----- UV scale ----- SM QCD

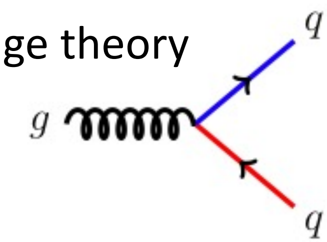
$h \sim \langle \psi\bar{\psi} \rangle$ ➡



Strong dynamics: unknown
Sp(2*N*) or SU(*N*) gauge theory?

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} + \sum_j \bar{q}_j i\gamma^\mu (\partial_\mu - i g_s G^a_\mu T^a) q_j$$

$SU(3)_c$ gauge theory



------- confinement scale -------

$\mathcal{G}/\mathcal{H}$ [Coleman-Callan-Wess-Zumino]

- Minimal setup: SU(4)/Sp(4) -- 4-flavor Weyl fermions with a Sp(2*N*) gauge theory; [Cacciapaglia *et al*, JHEP2014]
- 4 + 1 pNGBs (Higgs doublet + singlet)

$$U(\vec{\pi}) = \exp\left\{ i\frac{\sqrt{2}}{f} \hat{T}_2^r \pi^r \right\},$$

- Vector & Fermion resonances (top partners);

$SU(2)_L \times SU(2)_R / SU(2)_V$ [ChPT]

- For (*u*,*d*) 2-flavor quarks;
- 3 pNGBs ($\pi^{0,\pm}$)

$$U(\vec{\pi}) = \exp\left\{ \frac{i}{\sqrt{2} f} \tau^i \pi^i \right\},$$

- Vector (*ρ*-mesons, etc) & fermion resonaces (protons, etc);