Four-Dimensional UV Completion of Composite Higgs Models Up to Planck Scale

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Based on 1911.05454 and 2001.xxxxx

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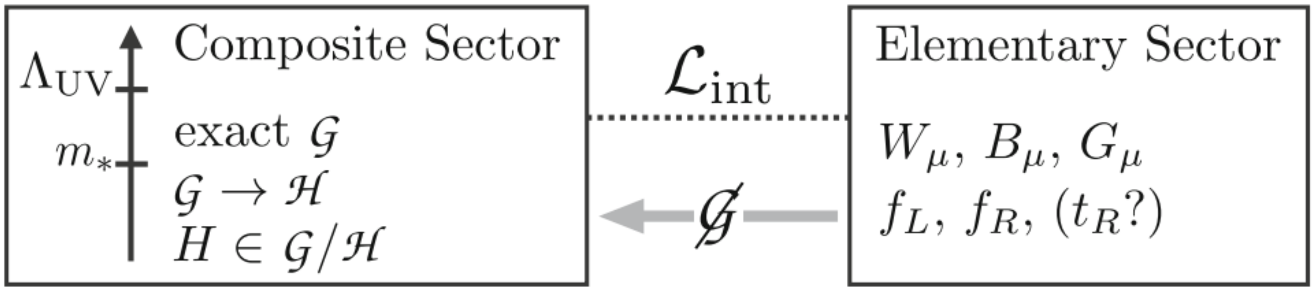
Composite Higgs: A Recap

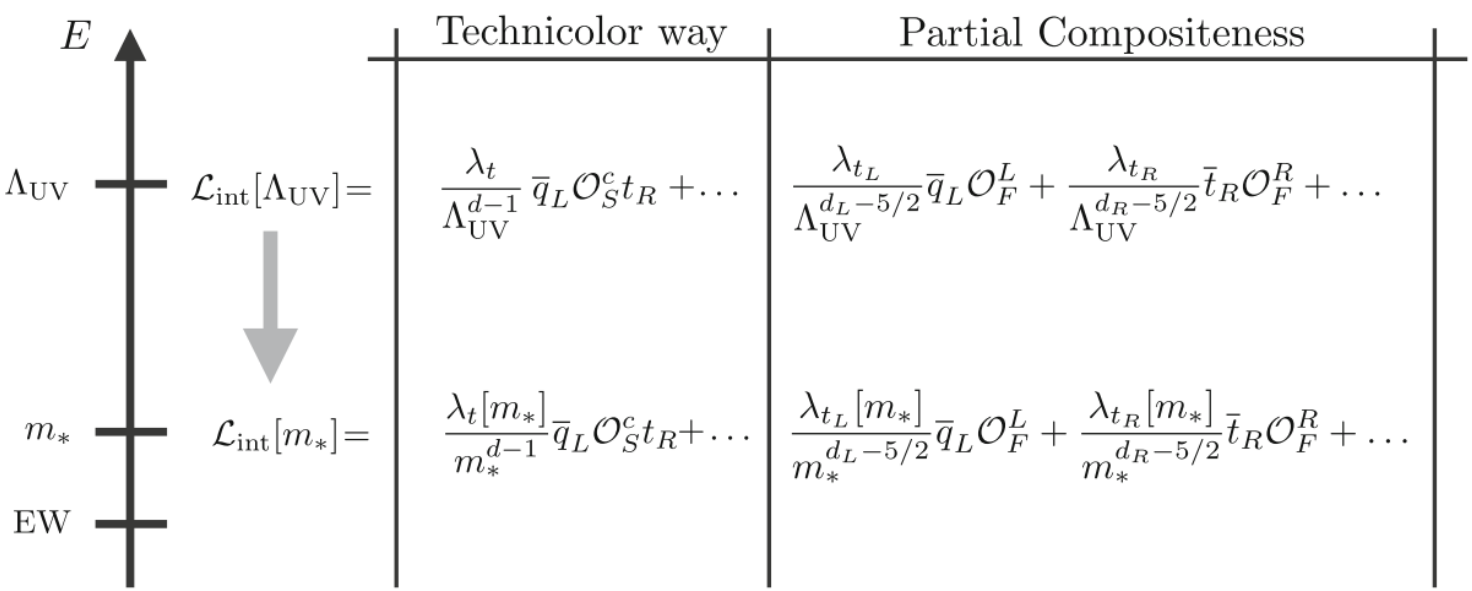
- pNGB Higgs

G. Panico and A. Wulzer, 1506.01961

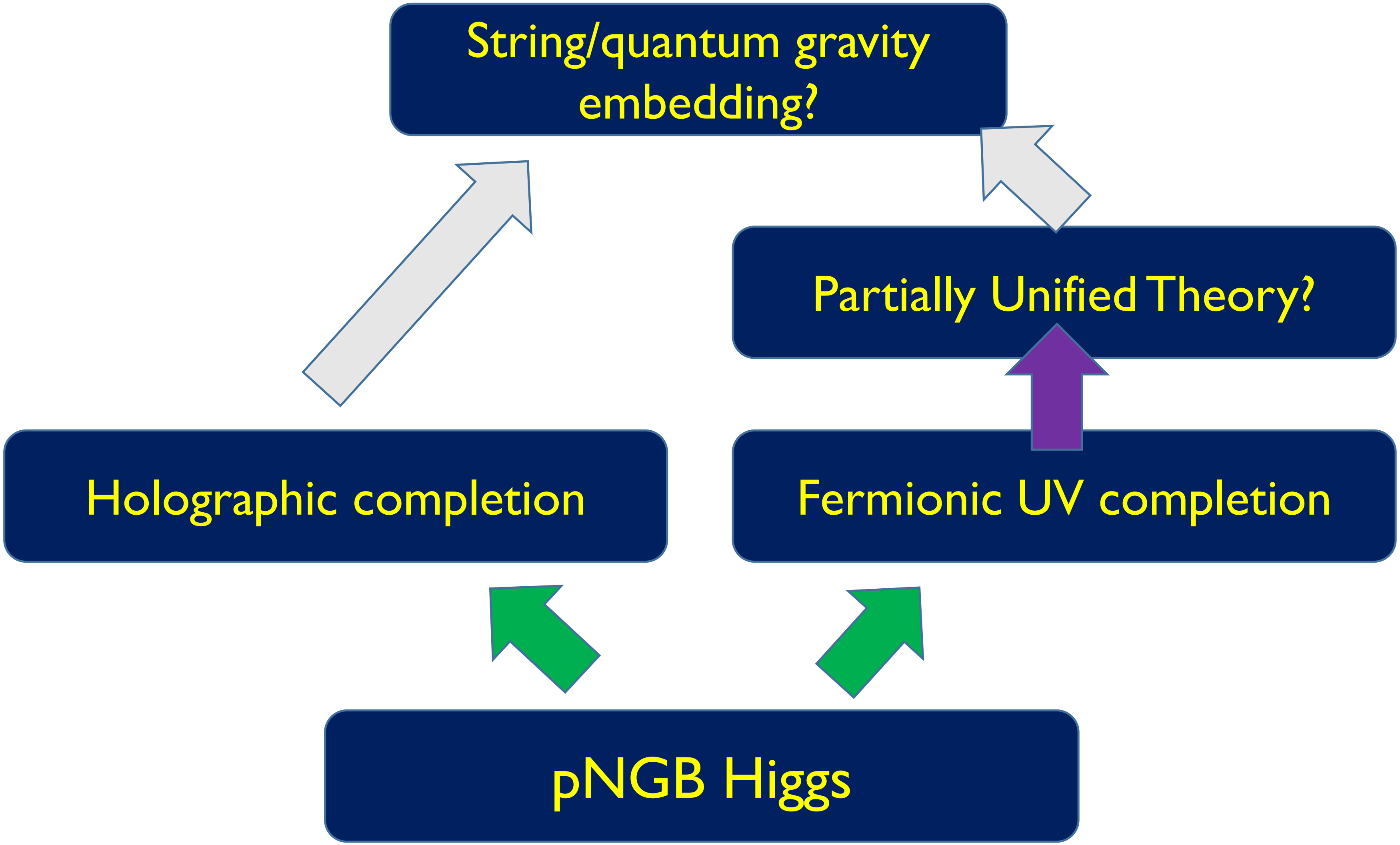


- Partial compositeness

G. Panico and A. Wulzer, 1506.01961



Effective Field Theory and UV Completion

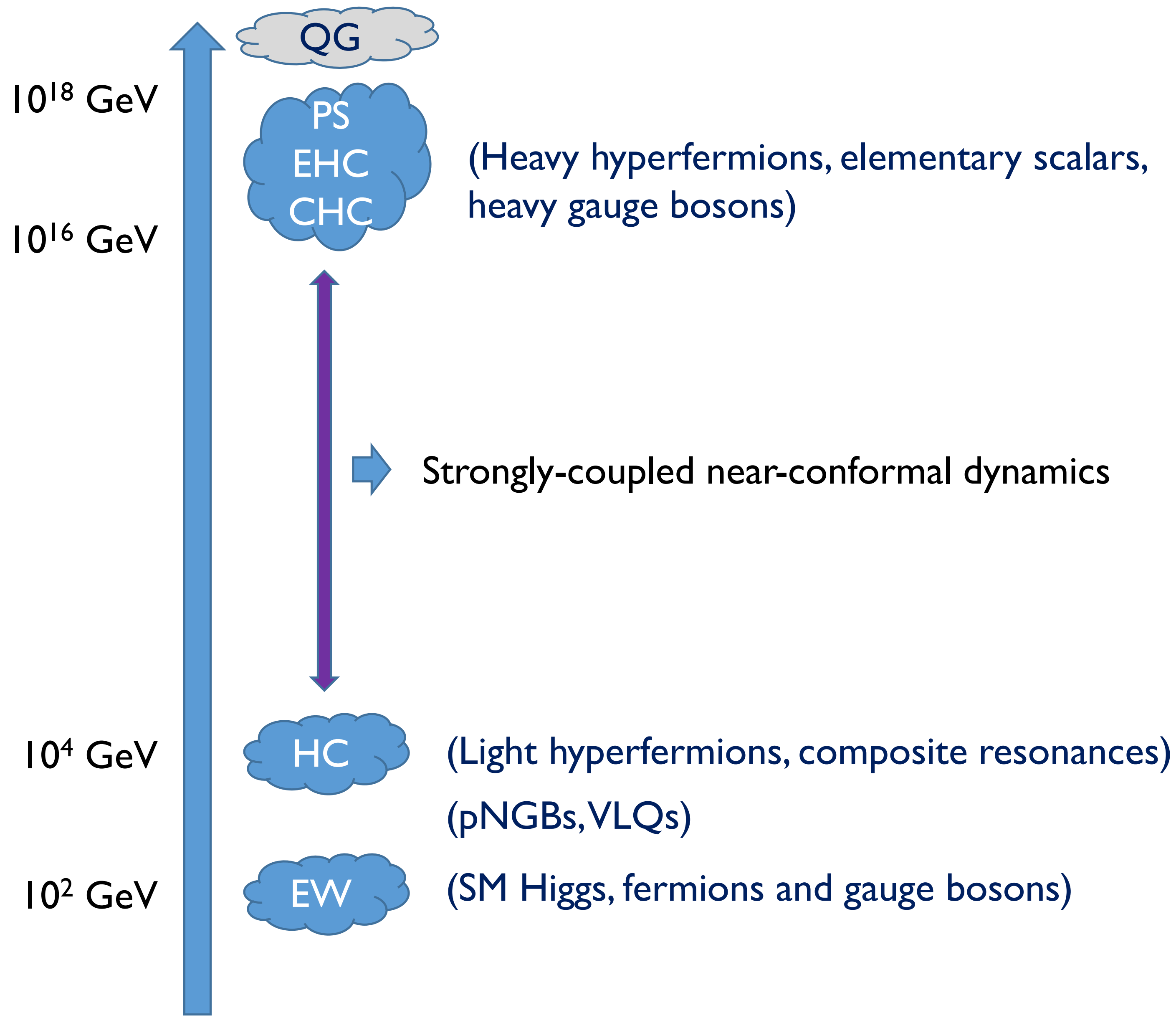


Minimal Ferretti's Models

$G_{\rm HC}$	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Real	Real	$SU(5)/SO(5) \times SU(6)/SO(6)$				
$SO(N_{\rm HC})$	$5 \times \mathbf{S}_2$	$6 \times \mathbf{F}$	$N_{\rm HC} \geq 55$	$\frac{5(N_{\rm HC}+2)}{6}$	$1/3$	/	
$SO(N_{\rm HC})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$N_{\rm HC} \geq 15$	$\frac{5(N_{\rm HC}-2)}{6}$	$1/3$	/	
$SO(N_{\rm HC})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{\rm HC} = 7, 9$	$\frac{5}{6}, \frac{5}{12}$	$1/3$	$N_{\rm HC} = 7, 9$	M1, M2
$SO(N_{\rm HC})$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{\rm HC} = 7, 9$	$\frac{5}{6}, \frac{5}{3}$	$2/3$	$N_{\rm HC} = 7, 9$	M3, M4
	Real	Pseudo-Real	$SU(5)/SO(5) \times SU(6)/Sp(6)$				
$Sp(2N_{\rm HC})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$2N_{\rm HC} \geq 12$	$\frac{5(N_{\rm HC}+1)}{3}$	$1/3$	/	
$Sp(2N_{\rm HC})$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$2N_{\rm HC} \geq 4$	$\frac{5(N_{\rm HC}-1)}{3}$	$1/3$	$2N_{\rm HC} = 4$	M5
$SO(N_{\rm HC})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{\rm HC} = 11, 13$	$\frac{5}{24}, \frac{5}{48}$	$1/3$	/	
	Real	Complex	$SU(5)/SO(5) \times SU(3)^2/SU(3)$				
$SU(N_{\rm HC})$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{\rm HC} = 4$	$\frac{5}{3}$	$1/3$	$N_{\rm HC} = 4$	M6
$SO(N_{\rm HC})$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$N_{\rm HC} = 10, 14$	$\frac{5}{12}, \frac{5}{48}$	$1/3$	$N_{\rm HC} = 10$	M7
	Pseudo-Real	Real	$SU(4)/Sp(4) \times SU(6)/SO(6)$				
$Sp(2N_{\rm HC})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$2N_{\rm HC} \leq 36$	$\frac{1}{3(N_{\rm HC}-1)}$	$2/3$	$2N_{\rm HC} = 4$	M8
$SO(N_{\rm HC})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{\rm HC} = 11, 13$	$\frac{8}{3}, \frac{16}{3}$	$2/3$	$N_{\rm HC} = 11$	M9
	Complex	Real	$SU(4)^2/SU(4) \times SU(6)/SO(6)$				
$SO(N_{\rm HC})$	$4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$6 \times \mathbf{F}$	$N_{\rm HC} = 10$	$\frac{8}{3}$	$2/3$	$N_{\rm HC} = 10$	M10
$SU(N_{\rm HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A}_2$	$N_{\rm HC} = 4$	$\frac{2}{3}$	$2/3$	$N_{\rm HC} = 4$	M11
	Complex	Complex	$SU(4)^2/SU(4) \times SU(3)^2/SU(3)$				
$SU(N_{\rm HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \overline{\mathbf{A}}_2)$	$N_{\rm HC} \geq 5$	$\frac{4}{3(N_{\rm HC}-2)}$	$2/3$	$N_{\rm HC} = 5$	M12
$SU(N_{\rm HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{S}_2, \overline{\mathbf{S}}_2)$	$N_{\rm HC} \geq 5$	$\frac{4}{3(N_{\rm HC}+2)}$	$2/3$	/	
$SU(N_{\rm HC})$	$4 \times (\mathbf{A}_2, \overline{\mathbf{A}}_2)$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{\rm HC} = 5$	4	$2/3$	/	

 A. Belyaev et al., JHEP 01 (2017) 094

Summary of the Model Structure



Partial Unification: Techni-Pati-Salam

A. Belyaev et al., JHEP 01 (2017) 094

	Pseudo-Real	Real	SU(4)/Sp(4) $\times$ SU(6)/SO(6)				
$\mathrm{Sp}(2N_{\mathrm{HC}})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$2N_{\mathrm{HC}} \leq 36$	$\frac{1}{3(N_{\mathrm{HC}}-1)}$	$2/3$	$2N_{\mathrm{HC}} = 4$	M8

- M8 as the starting point => Simple embedding and model building
- Examination of quantum numbers suggest the simplest unification option is to unify Sp(4) hypercolor and SU(3) color gauge groups (with hypercharge) into $SU(7)_{EHC} \times U(1)_E$. Miraculously, by carefully choosing quantum numbers, the whole theory can be made anomaly-free, with top PC mediated by a massive vector from EHC breaking.
- Two hints at a higher-level unification to $SU(8)_{PS} \times SU(2)_R$ (TPS)
  - Lepton masses left unexplained at the EHC level.
  - The miraculous anomaly cancellation might be better understood.

TPS: Fermion Field Content for the 3rd Family

Table 7: Fermionic Field Contents for the 3rd Generation

Fields	Embedding	$SU(8)_{PS}$	$SU(2)_L$	$SU(2)_R$
Ω_{PS}	$\left(\begin{pmatrix} L_t \\ t_L \\ \nu_{\tau L} \end{pmatrix} \begin{pmatrix} L_b \\ b_L \\ \tau_L \end{pmatrix}\right)$	$\mathbf{8}$	$\mathbf{2}$	$\mathbf{1}$
Υ_{PS}	$\left(\begin{pmatrix} U_b \\ b_R^c \\ \tau_R^c \end{pmatrix} \begin{pmatrix} D_t \\ t_R^c \\ \nu_{\tau R}^c \end{pmatrix}\right)$	$\overline{\mathbf{8}}$	$\mathbf{1}$	$\mathbf{2}$
Ξ_{PS}	$\left(\begin{pmatrix} U_t \\ \chi \\ B \end{pmatrix} \begin{pmatrix} D_b \\ \tilde{\chi} \\ \tilde{B} \end{pmatrix}\right)$	$\mathbf{70}$	$\mathbf{1}$	$\mathbf{1}$
N_{PS}	N	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$

Note when $B, \tilde{B}$ are decomposed under $Sp(4)\times SU(3)\times U(1)_I$, they look like

$$B = \underbrace{(\mathbf{1},\mathbf{1})(-12)}_{\rho} + \underbrace{(\mathbf{4},\overline{\mathbf{3}})(-5)}_{\eta} + \underbrace{(\mathbf{1},\mathbf{3})(2)}_{\omega}, \quad \tilde{B} = \underbrace{(\mathbf{1},\mathbf{1})(12)}_{\tilde{\rho}} + \underbrace{(\mathbf{4},\mathbf{3})(5)}_{\tilde{\eta}} + \underbrace{(\mathbf{1},\overline{\mathbf{3}})(-2)}_{\tilde{\omega}} \quad (1)$$

TPS: Inclusion of Scalars

Field	Spin	$SU(8)_{\rm PS}$	$SU(2)_L$	$SU(2)_R$	Q_G
Φ	0	$\mathbf{8}$	$\mathbf{1}$	$\mathbf{2}$	q
Θ	0	$\mathbf{28}(=\mathbf{A}_2)$	$\mathbf{1}$	$\mathbf{1}$	$2q$
Δ	0	$\mathbf{56}(=\mathbf{A}_3)$	$\mathbf{1}$	$\mathbf{2}$	q
Ψ	0	$\mathbf{63}(=\mathbf{Adj})$	$\mathbf{1}$	$\mathbf{1}$	0
N	1/2	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0
Ω	1/2	$\mathbf{8}$	$\mathbf{2}$	$\mathbf{1}$	q
Υ	1/2	$\bar{\mathbf{8}}$	$\mathbf{1}$	$\mathbf{2}$	$-q$
Ξ	1/2	$\mathbf{70}(=\mathbf{A}_4)$	$\mathbf{1}$	$\mathbf{1}$	0

$$\mathcal{L} = \mathcal{L}_G + \mathcal{L}_F + \mathcal{L}_S + \mathcal{L}_Y + \mathcal{L}_V$$

$$\begin{aligned}\mathcal{L}_Y = & -\mu_N N N - \lambda_\Phi \Upsilon \Phi N - \mu_\Xi \Xi\Xi - \lambda_\Psi \Xi \Psi \Xi \\ & - \lambda_{\Theta L} \Omega \Theta^* \Omega - \lambda_{\Theta R} \Upsilon \Theta \Upsilon - \lambda_\Delta \Upsilon \Delta \Xi + \text{c.c.}\end{aligned}$$

Role of scalars	
Yukawa couplings	VEVs
Scalar-mediated PC4F operators	Φ : PS breaking
	Ψ : EHC breaking
	Θ : CHC breaking
	Δ : EHC and/or CHC breaking
Hyperfermion masses/mixing, Neutrino masses, accidental mixing (e.g. $b_R^c - \tilde{\omega}$)	

TPS: Vector-Mediated PC4F Operators

- Quantum number notation

$$\{\mathbf{56},\mathbf{2}\} \Rightarrow \{SU(8)_{PS}, SU(2)_R)\}, \quad \mathbf{21}_{1/7} \Rightarrow SU(7)_{EHC,U(1)_E}$$
$$[\mathbf{1},\bar{\mathbf{3}}]_{1/3} \Rightarrow [SU(4)_{CHC}, SU(3)_C]_{U(1)_Y}, \quad (\mathbf{4},\mathbf{3})_{1/6} \Rightarrow (Sp(4)_{HC}, SU(3)_C)_{U(1)_Y}$$

- Mediator $(\mathbf{4},\bar{\mathbf{3}})_{-1/6}+(\mathbf{4},\mathbf{3})_{1/6}$ => Quark partial compositeness

$$\mathcal{O}^t_{\chi\eta}=(\bar{D}_t\bar{\sigma}^\mu t^c_R)(\bar{\chi}\bar{\sigma}_\mu\eta) \qquad \mathcal{O}^b_{\chi\eta}=(\bar{U}_b\bar{\sigma}^\mu b^c_R)(\bar{\chi}\bar{\sigma}_\mu\eta) \qquad \mathcal{O}^L_{\eta\chi}=(\bar{L}\bar{\sigma}^\mu q_L)(\bar{\eta}\bar{\sigma}_\mu\chi)$$
$$\mathcal{O}^t_{U\chi}=(\bar{D}_t\bar{\sigma}^\mu t^c_R)(\bar{U}_t\bar{\sigma}_\mu\chi) \qquad \mathcal{O}^b_{U\chi}=(\bar{U}_b\bar{\sigma}^\mu b^c_R)(\bar{U}_t\bar{\sigma}_\mu\chi) \qquad \mathcal{O}^L_{\chi U}=(\bar{L}\bar{\sigma}^\mu q_L)(\bar{\chi}\bar{\sigma}_\mu U_t)$$
$$\mathcal{O}^t_{\chi D}=(\bar{D}_t\bar{\sigma}^\mu t^c_R)(\bar{\tilde{\chi}}\bar{\sigma}_\mu D_b) \qquad \mathcal{O}^b_{\chi D}=(\bar{U}_b\bar{\sigma}^\mu b^c_R)(\bar{\tilde{\chi}}\bar{\sigma}_\mu D_b) \qquad \mathcal{O}^L_{D\chi}=(\bar{L}\bar{\sigma}^\mu q_L)(\bar{D}_b\bar{\sigma}_\mu\tilde{\chi})$$
$$\mathcal{O}^t_{\eta\chi}=(\bar{D}_t\bar{\sigma}^\mu t^c_R)(\bar{\tilde{\eta}}\bar{\sigma}_\mu\tilde{\chi}) \qquad \mathcal{O}^b_{\eta\chi}=(\bar{U}_b\bar{\sigma}^\mu b^c_R)(\bar{\tilde{\eta}}\bar{\sigma}_\mu\tilde{\chi}) \qquad \mathcal{O}^L_{\chi\eta}=(\bar{L}\bar{\sigma}^\mu q_L)(\bar{\tilde{\chi}}\bar{\sigma}_\mu\tilde{\eta})$$

- Mediator $(\mathbf{4},\mathbf{1})_{1/2}+(\mathbf{4},\mathbf{1})_{-1/2}$ => Lepton partial compositeness

$$\mathcal{O}^\nu_{\eta\chi}=(\bar{D}_t\bar{\sigma}^\mu \nu^c_{\tau R})(\bar{\tilde{\eta}}\bar{\sigma}_\mu\chi) \qquad \mathcal{O}^\tau_{\eta\chi}=(\bar{U}_b\bar{\sigma}^\mu \tau^c_R)(\bar{\tilde{\eta}}\bar{\sigma}_\mu\chi) \qquad \mathcal{O}^l_{\chi\eta}=(\bar{L}\bar{\sigma}^\mu l_L)(\bar{\chi}\bar{\sigma}_\mu\tilde{\eta})$$
$$\mathcal{O}^\nu_{\chi\eta}=(\bar{D}_t\bar{\sigma}^\mu \nu^c_{\tau R})(\bar{\tilde{\chi}}\bar{\sigma}_\mu\eta) \qquad \mathcal{O}^\tau_{\chi\eta}=(\bar{U}_b\bar{\sigma}^\mu \tau^c_R)(\bar{\tilde{\chi}}\bar{\sigma}_\mu\eta) \qquad \mathcal{O}^l_{\eta\chi}=(\bar{L}\bar{\sigma}^\mu l_L)(\bar{\eta}\bar{\sigma}_\mu\tilde{\chi})$$

Note: all the vector and scalar-mediated PC4F operators are generated automatically, instead of being put in by hand.

TPS: Scenario for Three Families

Table 2: Explicit Fermion Field Contents for Three Generations		
1st Generation	2nd Generation	3rd Generation
N^1	N^2	N^3
$\Omega^1 = \left(\begin{pmatrix} L_u^1 \\ u_L^1 \\ \nu_L^1 \end{pmatrix} \begin{pmatrix} L_d^1 \\ d_L^1 \\ e_L^1 \end{pmatrix} \right)$	$\Omega^2 = \left(\begin{pmatrix} L_u^2 \\ u_L^2 \\ \nu_L^2 \end{pmatrix} \begin{pmatrix} L_d^2 \\ d_L^2 \\ e_L^2 \end{pmatrix} \right)$	$\Omega^3 = \left(\begin{pmatrix} L_u^3 \\ u_L^3 \\ \nu_L^3 \end{pmatrix} \begin{pmatrix} L_d^3 \\ d_L^3 \\ e_L^3 \end{pmatrix} \right)$
$\Upsilon^1 = \left(\begin{pmatrix} U_d^1 \\ d_R^{1c} \\ e_R^{1c} \end{pmatrix} \begin{pmatrix} D_u^1 \\ u_R^{1c} \\ \nu_R^{1c} \end{pmatrix} \right)$	$\Upsilon^2 = \left(\begin{pmatrix} U_d^2 \\ d_R^{2c} \\ e_R^{2c} \end{pmatrix} \begin{pmatrix} D_u^2 \\ u_R^{2c} \\ \nu_R^{2c} \end{pmatrix} \right)$	$\Upsilon^3 = \left(\begin{pmatrix} U_d^3 \\ d_R^{3c} \\ e_R^{3c} \end{pmatrix} \begin{pmatrix} D_u^3 \\ u_R^{3c} \\ \nu_R^{3c} \end{pmatrix} \right)$
	$\Xi = \left(\begin{bmatrix} U_u \\ \chi \\ B \end{bmatrix} \begin{bmatrix} D_d \\ \tilde{\chi} \\ \tilde{B} \end{bmatrix} \right)$	
$B = \underbrace{(\mathbf{1},\mathbf{1})(-12)}_{\rho} + \underbrace{(\mathbf{4},\bar{\mathbf{3}})(-5)}_{\eta} + \underbrace{(\mathbf{1},\mathbf{3})(2)}_{\omega}$,	$\tilde{B} = \underbrace{(\mathbf{1},\mathbf{1})(12)}_{\tilde{\rho}} + \underbrace{(\mathbf{4},\mathbf{3})(5)}_{\tilde{\eta}} + \underbrace{(\mathbf{1},\bar{\mathbf{3}})(-2)}_{\tilde{\omega}}$	

Heavy

Mixing?

TPS: Symmetry and Decoupling Considerations

- Question: In pure QCD, does there exist nonvanishing flavor-changing condensate, say

$$< t\bar{c} + \bar{t}c > \neq 0 \,?$$

- Answer: No. According to a theorem by Vafa and Witten, non-chiral global symmetry cannot be spontaneously broken in a vector-like gauge theory.
- Question: what about the situation in full SM?
- Answer: Probably no. Otherwise we will have very exotic dyanamics, that is, violation of the 't Hooft decoupling condition that is not justifiable by an EFT analysis.

TPS: Symmetry and Decoupling Considerations

- Taking the 2nd family as an example, a mass term for the 2nd family SM fermion breaks both

$$Z_{L2} \text{ and } SU(2)_{L2}$$

	Definition
Z_{Lp}	All components of Ω^p are odd, all other fields are even.
$SU(2)_{Lp}$	The simultaneous $SU(2)_L$ rotation of all components in Ω^p.

	$SU(8)_{PS} \times SU(2)_R$ Gauge	$SU(2)_L$ Gauge	Family-Conserving Yukawa	Family-Changing Yukawa
Z_{Lp}	Y	Y	Y	N
$SU(2)_{Lp}$	Y	N	Y	N

- Without family-changing Yukawa, Z_{L2} can only be spontaneously broken, which also leads to spontaneous breaking of $SU(2)_{L2}$, violating 't Hooft decoupling condition in the current scenario. Our conclusion here is family-changing Yukawa (a second Θ) is needed.

TPS: Summary and Open Issues

- Recap of minimal scalar and fermion field content

Field	Spin	$SU(8)_{\rm PS}$	$SU(2)_L$	$SU(2)_R$	#
Φ	0	$\mathbf{8}$	$\mathbf{1}$	$\mathbf{2}$	1
Θ	0	$\mathbf{28}(=\mathbf{A}_2)$	$\mathbf{1}$	$\mathbf{1}$	2
Δ	0	$\mathbf{56}(=\mathbf{A}_3)$	$\mathbf{1}$	$\mathbf{2}$	1
Δ_L	0	$\mathbf{56}(=\mathbf{A}_3)$	$\mathbf{2}$	$\mathbf{1}$	1
Ψ	0	$\mathbf{63}(=\mathbf{Adj})$	$\mathbf{1}$	$\mathbf{1}$	2
N	1/2	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	3
Ω	1/2	$\mathbf{8}$	$\mathbf{2}$	$\mathbf{1}$	3
Υ	1/2	$\bar{\mathbf{8}}$	$\mathbf{1}$	$\mathbf{2}$	3
Ξ	1/2	$\mathbf{70}(=\mathbf{A}_4)$	$\mathbf{1}$	$\mathbf{1}$	1

- Open issues: Suppression of unwanted flavor and CP violation. Although the flavor scale is around 10^{16} GeV, flavor and CP violation are incorporated into local PC4F operators whose effects are preserved down to ~10 TeV. The most stringent bound comes from electron EDM. G. Panico, A. Pomarol and M. Riembau, 1810.09413

You might have questions about

- Types and structure of scalar-mediated PC4F operators?
- Top-bottom mass splitting?
- Prospects for strongly-coupled near-conformal dynamics?
- Evolution of gauge couplings, coupling unification issues, Landau poles?
- Rank of the mass matrix, mass generation of the 1^{st} family?
- Fate of accidental symmetries, baryon number violation?
- Cosmologically stable charged/colored relics?
- Dark matter candidate?
- Neutrino mass generation?
- Features of low-energy model, coset and fermion partner representations?
- Novel collider signatures?
- …

Summary and Outlook

- We made an attempt to build UV completion of a class of composite Higgs models based on partial compositeness in four-dimensional spacetime.
- Starting from a composite Higgs model based on Sp(4) hypercolor group, we are able to build an anomaly-free and renormalizable UV completion based on the Techni-Pati-Salam group $SU(8)_{PS} \times SU(2)_L \times SU(2)_R$.
- The main open issue is the suppression of unwanted flavor and CP violation, while generating realistic fermion mass and mixing at the same time, which will be the subject of future study.
- Lattice calculation is expected to play an important role in testing the validity of the models.

Back up

TPS: Scalar-Mediated PC4F Operators

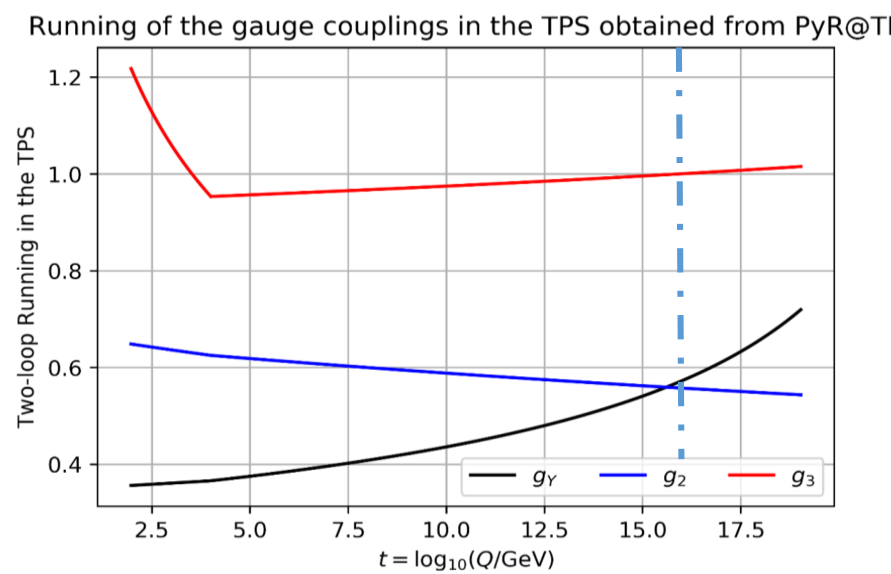
Table 3: Quantum Numbers of Fermion Bilinears (Simplified)

Term	1 SM Field	0 SM Field
$\Xi\Psi\Xi$	None	$\chi\eta \Rightarrow (\mathbf{4},\mathbf{1})_{-1/2}$ $\tilde{\chi}\tilde{\eta} \Rightarrow (\mathbf{4},\mathbf{1})_{1/2}$ $U_t D_b \Rightarrow (\mathbf{5},\mathbf{1})_0$, $\chi\tilde{\eta} \Rightarrow (\mathbf{4},\bar{\mathbf{3}})_{-1/6}$, $U_t\tilde{\chi} \Rightarrow (\mathbf{4},\bar{\mathbf{3}})_{-1/6}$, $\eta\tilde{\chi} \Rightarrow (\mathbf{4},\mathbf{3})_{1/6}$, $\chi D_b \Rightarrow (\mathbf{4},\mathbf{3})_{1/6}$. $\eta\tilde{\eta} \Rightarrow (\mathbf{5},\mathbf{1})_0$.
$\Omega\Theta\Omega$	$Lq_L \Rightarrow (\mathbf{4},\mathbf{3})_{1/6}$, $Ll_L \Rightarrow (\mathbf{4},\mathbf{1})_{-1/2}$.	$LL \Rightarrow (\mathbf{5},\mathbf{1})_0$
$\Upsilon\Theta\Upsilon$	$U_b t_R^c \Rightarrow (\mathbf{4},\bar{\mathbf{3}})_{-1/6}$, $U_b \nu_{\tau R}^c \Rightarrow (\mathbf{4},\mathbf{1})_{1/2}$, $D_t b_R^c \Rightarrow (\mathbf{4},\bar{\mathbf{3}})_{-1/6}$. $D_t \tau_R^c \Rightarrow (\mathbf{4},\mathbf{1})_{1/2}$.	$U_b D_t \Rightarrow (\mathbf{5},\mathbf{1})_0$
$\Upsilon\Delta\Xi$	$\chi b_R^c \Rightarrow (\mathbf{5},\mathbf{1})_0$, $\chi t_R^c \Rightarrow (\mathbf{5},\mathbf{1})_{-1}$, $\eta b_R^c \Rightarrow (\mathbf{4},\mathbf{3})_{1/6}$, $\eta t_R^c \Rightarrow (\mathbf{4},\mathbf{3})_{-5/6}$, $D_b b_R^c \Rightarrow (\mathbf{4},\bar{\mathbf{3}})_{5/6}$, $D_b t_R^c \Rightarrow (\mathbf{4},\bar{\mathbf{3}})_{-1/6}$, $\tilde{\chi} b_R^c \Rightarrow (\mathbf{5},\mathbf{3})_{2/3}$, $\tilde{\chi} t_R^c \Rightarrow (\mathbf{5},\mathbf{3})_{-1/3}$, $\tilde{\eta} b_R^c \Rightarrow (\mathbf{4},\mathbf{1})_{1/2}$. $\tilde{\eta} t_R^c \Rightarrow (\mathbf{4},\mathbf{1})_{-1/2}$. $U_t \tau_R^c \Rightarrow (\mathbf{4},\mathbf{1})_{1/2}$, $U_t \nu_{\tau R}^c \Rightarrow (\mathbf{4},\mathbf{1})_{-1/2}$, $\chi \tau_R^c \Rightarrow (\mathbf{5},\mathbf{3})_{2/3}$, $\chi \nu_{\tau R}^c \Rightarrow (\mathbf{5},\mathbf{3})_{-1/3}$, $\eta \tau_R^c \Rightarrow (\mathbf{4},\bar{\mathbf{3}})_{5/6}$. $\eta \nu_{\tau R}^c \Rightarrow (\mathbf{4},\bar{\mathbf{3}})_{-1/6}$.	$U_t U_b \Rightarrow (\mathbf{5},\mathbf{1})_0$, $U_t D_t \Rightarrow (\mathbf{5},\mathbf{1})_{-1}$, $\chi U_b \Rightarrow (\mathbf{4},\mathbf{3})_{1/6}$, $\chi D_t \Rightarrow (\mathbf{4},\mathbf{3})_{-5/6}$, $\tilde{\chi} U_b \Rightarrow (\mathbf{4},\bar{\mathbf{3}})_{5/6}$, $\tilde{\chi} D_t \Rightarrow (\mathbf{4},\bar{\mathbf{3}})_{-1/6}$, $\tilde{\eta} U_b \Rightarrow (\mathbf{5},\mathbf{3})_{2/3}$. $\tilde{\eta} D_t \Rightarrow (\mathbf{5},\mathbf{3})_{-1/3}$.

TPS: Evolution of Gauge Couplings

- For Sp(4) gauge theory with N_1 Weyl hyperfermions in the fundamental, and N_2=6 Weyl hyperfermions in the two-index antisymmetric representation:
  - Maximum N_1 to be asymptotically free: 20
  - Maximum N_1 to be confining: 10 (SDE) or 4 (Pica-Sannino beta function)

    C. Pica and F. Sannino, 1011.3832
  - N_1=10 or 12 => Good prospect to enter strongly-coupled near-conformal (SCNC) regime between condensation and flavor scale
- Evolution of SM gauge couplings:



TPS: Rank of the Mass Matrix

- The mass matrix for three families is given as a correlator matrix

$$M = \begin{pmatrix} < O_{L1} O_{R1} > & < O_{L1} O_{R2} > & < O_{L1} O_{R3} > \\ < O_{L2} O_{R1} > & < O_{L2} O_{R2} > & < O_{L2} O_{R3} > \\ < O_{L3} O_{R1} > & < O_{L3} O_{R2} > & < O_{L3} O_{R3} > \end{pmatrix}$$

- Note the elementary property of the correlator is that it is linear with respect to the participating operators. Reduction of the rank of the mass matrix may result due to a too universal operator structure, e.g.

$$O_{Li} = y_{Li} O_L, \quad O_{Ri} = y_{Ri} O_R$$

- In the current scenario, from the table of scalar-mediated PC4F operators, the situation is like (for leptons)

$$O_{Li} = y_{LAi} O_{LA}, i = 1, 2, \quad O_{L3} = y_{LA3} O_{LA} + y_{LB3} O_{LB}$$

which means the rank of the mass matrix is at most 2 for leptons.

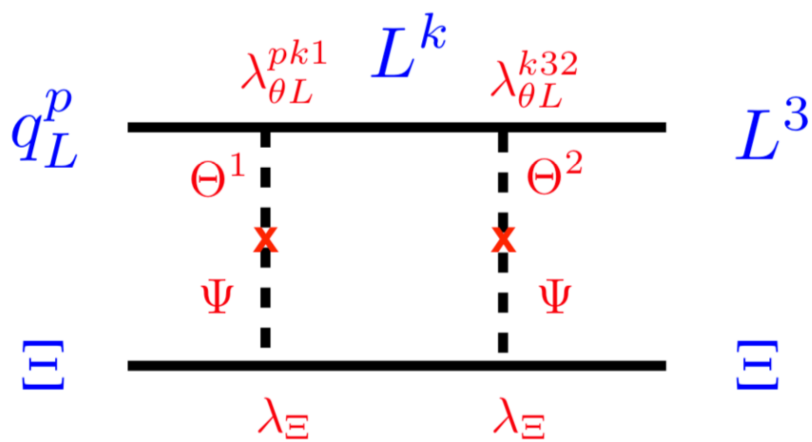
TPS: Mass Generation for the 1st Family

- Method 1: Introduce a Δ_L scalar field, which transforms as 56 under SU(8), doublet under $SU(2)_L$, and singlet under $SU(2)_R$. A new type of Yukawa coupling is allowed

$$\lambda^p_{\Delta L}\ \Omega^p \Delta_L \Xi$$

which gives rise to a new set of scalar-mediated PC4F operators.

- Method 2: Even without new scalar fields, new PC4F operators might be formed at loop-level, e.g.



TPS: Accidental U(1) Symmetries

- We may introduce three accidental U(1) symmetries: hyperbaryon number (H), baryon number (B), and lepton number (L).
  - SM fermions are assigned baryon and lepton numbers as in the SM, and zero hyperbaryon number. For hyperfermions we assign

$$L_u^p, L_d^p \text{ satisfy } L = B = 0, H = \frac{1}{2}$$

- It turns out we may assign consistent H, B, L quantum numbers to all scalar, fermion, vector field components, which are preserved by the Lagrangian except for some terms in the scalar potential.
- In fact, two linear combinations of H, B, L, say B-L and H-2L, are gauged, while the remaining combination can be chosen as $U(1)_G$, defined by

$$G = 2H + 3B + L$$

which commutes with all gauge symmetries but is not gauged.

TPS: Accidental U(1) Symmetries

- Existence of scalar leptoquarks which can mediate proton decay

$$[\Theta]\{28,1\} = [1,3]_{-1/3} + [4,1]_{-1/2} + [1,3]_{1/3} + [4,3]_{1/6} + [6,1]_0$$

Explicit baryon number violating term

$$\mathcal{L}_{GB}^{4\Theta} = \lambda_{GB}^{4\Theta} \epsilon_{ijklmnop} \Theta^{ij*} \Theta^{kl*} \Theta^{mn*} \Theta^{op*} + \text{c.c.}$$

- Spontaneous baryon number violation may occur through VEV of Δ.
- Although the unification scale is high, baryon number violating effects are dangerous since they could be preserved down to a much lower scale due to the large anomalous dimensions of some hyperbaryon operators.
- The simplest way to solve this problem is to forbid VEV of Δ, and turn off all the explicit baryon number violating terms in the scalar potential.
- Baryon number is violated by quantum anomaly, which is of no worry because it is a very small effect.

TPS: Accidental U(1) Symmetries

- Even spontaneous baryon number violation is turned off, $U(1)_G$ is still spontaneously broken. However, this does not give rise to physical Goldstone bosons, because

$$G = 2(H - 2L) - 5(B - L) + 8B$$

- Implication of baryon number conservation for long-lived neutral and charged particles:

$$\text{B:}\begin{cases} \rho = D = \frac{1}{2}, \\ \eta = \tilde{\chi} = \frac{1}{6}, \\ \chi = \tilde{\eta} = -\frac{1}{6}, \\ U = \tilde{\rho} = -\frac{1}{2}. \end{cases} \quad \text{L:}\begin{cases} \rho = \eta = \chi = U = \frac{1}{2}, \\ \tilde{\rho} = \tilde{\eta} = \tilde{\chi} = D = -\frac{1}{2}. \end{cases}$$

$$\omega \to \tilde{\rho} + t + \tau^-$$

DM candidate