Z_2 Non-Restoration and Composite Higgs: Singlet-Assisted Baryogenesis w/o Topological Defects

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Based on 2112.12087 by Andrei Angelescu, Florian Goertz, AT

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- Baryon Asymmetry in the Universe (BAU): Why do we exist?
  - No antimatter in cosmic rays
  - No radiation from annihilation between matter and antimatter regions
- Initial preference for matter would be washed out by inflation
  $\Rightarrow$ need to create imbalance by Baryogenesis

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    1. Baryon number violation
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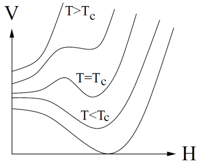
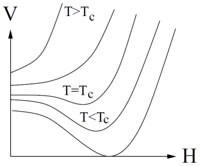


2nd order PT



Cline ph-0609145

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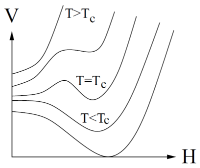

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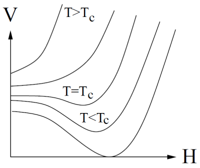

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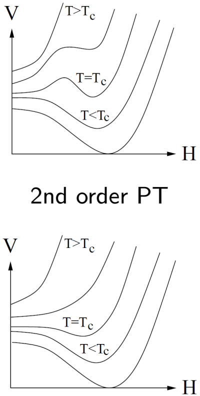

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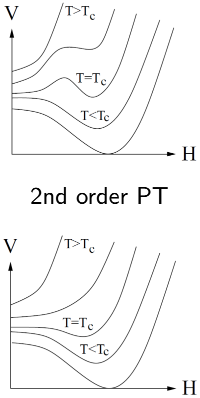

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  - start from broken phase

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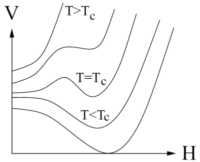

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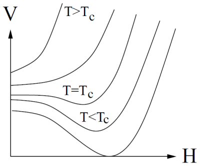

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Z_2 Non-Restoration: High T effective Potential

EFT considering $D \leq 4$ operators only: Z_2 SSB only

$$V_0(h,S) = \frac{\mu_h^2}{2}h^2 + \frac{\lambda_h}{4}h^4 + \frac{\mu_S^2}{2}S^2 + \frac{\lambda_S}{4}S^4 + \frac{\lambda_{hS}}{2}h^2S^2$$

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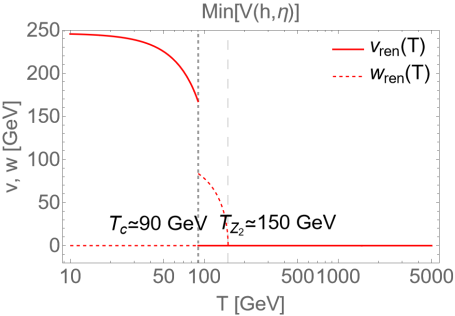

Spontaneous Z_2 breaking:
$(0,0) \to (w_{ren},0) \to (0,v_{ren})$

AA, FG, AT 2021
$\Lambda_{\text{NP}} = 1.5\,\text{TeV}, \lambda_S = -0.15,$
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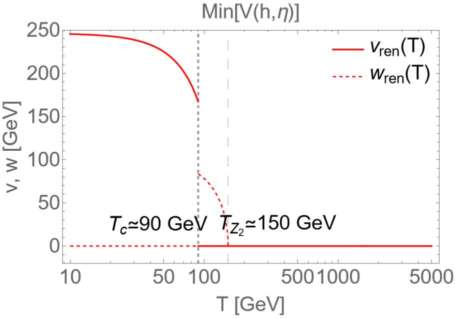

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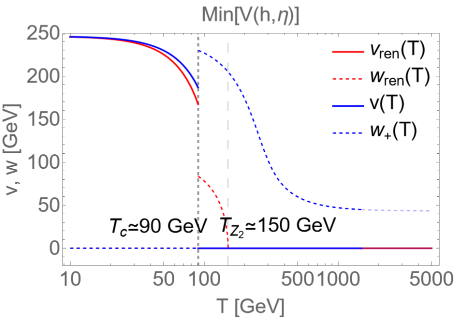

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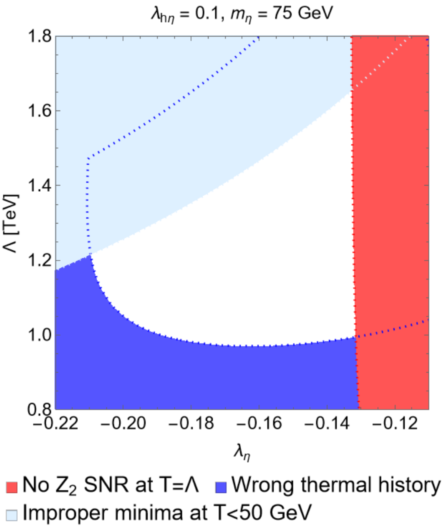
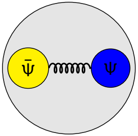
Z_2 SNR: Constraints

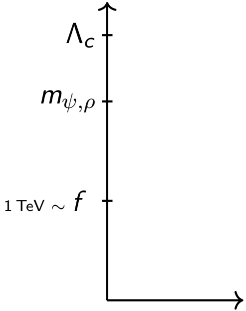


AA, FG, AT 2021

Composite Higgs in General

- Higgs h as composite of new confining force $\sim \pi$ in QCD





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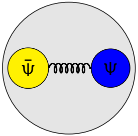

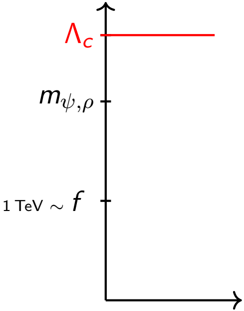

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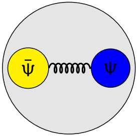

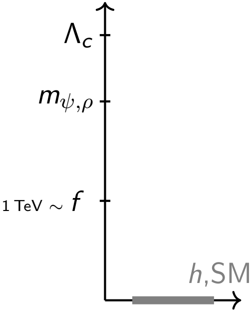

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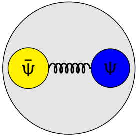
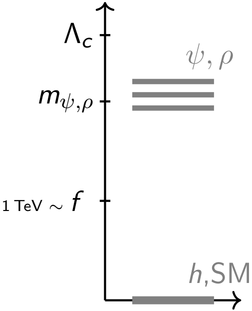
  - massive resonances ψ, ρ





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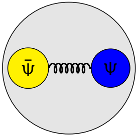

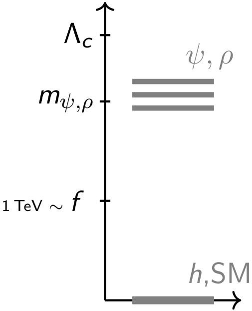

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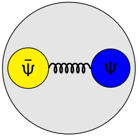

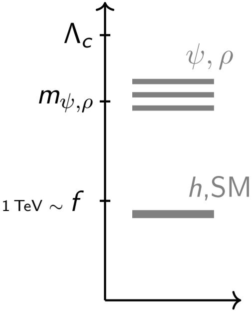

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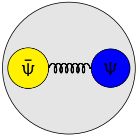

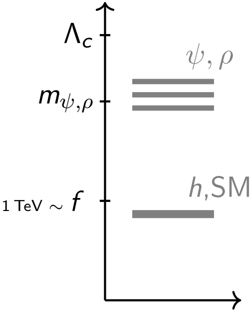

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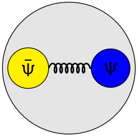

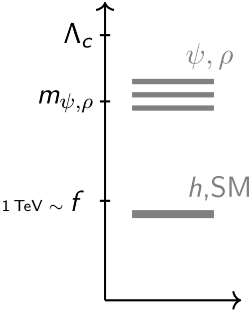

Solves Hierarchy Problem
& Higgs Potential is calculable!

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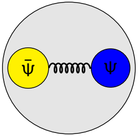
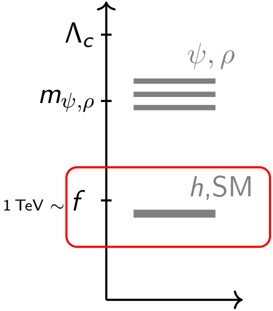
- $SO(6)/SO(5) \Rightarrow 4+1$ Goldstone dof
  - complex h doublet
  - scalar singlet S





Constructing $V(h, S)$ - Partial Compositeness

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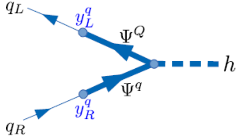

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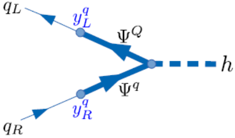

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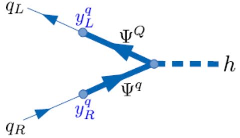

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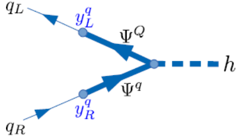

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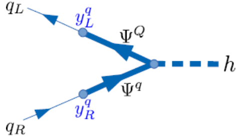

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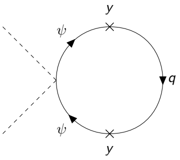
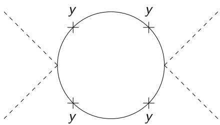
1-loop Coleman-Weinberg Potential:

$V(h, S) \supset$  $+$  $+ \dots$

$\sim y_{L,R}^2$ $\quad\quad$ $\sim y_{L,R}^4$

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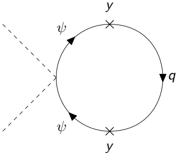
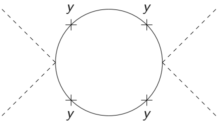
1-loop Coleman-Weinberg Potential:

$V(h, S) \supset$  $+$  $+ \dots$

$\sim y_{L,R}^2$ $\qquad$ $\sim y_{L,R}^4$

$\Rightarrow$ Sensitive to nature of ψ and strength of $y_{L,R}$

Choosing the Right Embedding

- V sensitive to what $SO(6)$ representation the composite resonances transform in
- analyzed $\psi_L(\psi_R)$ in $(\mathbf{1},)\,\mathbf{6},\mathbf{15},\mathbf{20}'$ of $SO(6)$
- considerations up to $D = 4$ terms: see e.g. DeCurtis2019, Bian2019, Xie2020,...

$$V = \underbrace{\frac{N_c m_\psi^4}{16\pi^2}}_{\text{dim factor}} \left(\frac{y_{L,R}}{g_{\text{UV}}}\right)^{\#2q} \underbrace{c_{nm}}_{\overset{!}{\sim}\mathcal{O}(1)} \left(\frac{h}{f}\right)^{2n} \left(\frac{S}{f}\right)^{2m}$$

$$\overset{!}{=} \frac{\mu_h^2}{2} h^2 + \frac{\lambda_h}{4} h^4 + \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \frac{\lambda_{hS}}{2} h^2 S^2 + \frac{S^6}{\Lambda_{\text{NP}}^2}$$

Comparison for different Fermion Embeddings

$V(h, S)$ terms of interest obtained to respective order $\mathcal{O}\left(\frac{y_{L,R}^2}{g_{\text{UV}}^2} \sim \frac{y_{L,R}^6}{g_{\text{UV}}^6}\right)$.

		$\mathbf{1}_R$	$\mathbf{6}_R$	$\mathbf{15}_R$	$\mathbf{20}'_R$
$\mathbf{6}_L$	h^2	No S-pot	2^{nd}	No S-pot	2^{nd}
	h^4		4^{th}		2^{nd}
	S^2		2^{nd}		2^{nd}
	S^4		4^{th}		2^{nd}
	S^6		6^{th}		4^{th}
	$h^2 S^2$		2^{nd}		2^{nd}
$\mathbf{15}_{\text{A}L}$	h^2	No top mass	No CPv	2^{nd}	2^{nd}
	h^4			4^{th}	2^{nd}
	S^2			2^{nd}	2^{nd}
	S^4			4^{th}	2^{nd}
	S^6			6^{th}	4^{th}
	$h^2 S^2$			4^{th}	2^{nd}
$\mathbf{20}'_L$	h^2	2^{nd}	2^{nd}	2^{nd}	2^{nd}
	h^4	2^{nd}	2^{nd}	2^{nd}	2^{nd}
	S^2	2^{nd}	2^{nd}	2^{nd}	2^{nd}
	S^4	4^{th}	4^{th}	4^{th}	2^{nd}
	S^6	6^{th}	6^{th}	6^{th}	4^{th}
	$h^2 S^2$	2^{nd}	2^{nd}	2^{nd}	2^{nd}

Comparison for different Fermion Embeddings

$V(h,S)$ terms of interest obtained to respective order $\mathcal{O}\left(\frac{y_{L,R}^2}{g_{\text{UV}}^2} \sim \frac{y_{L,R}^6}{g_{\text{UV}}^6}\right)$.

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	h^4		4th		2nd
	S^2		2nd		2nd
	S^4		4th		2nd
	S^6		6th		4th
	$h^2 S^2$		2nd		2nd
$\mathbf{15}_{AL}$	h^2	No top mass	No CPv	2nd	2nd
	h^4			4th	2nd
	S^2			2nd	2nd
	S^4			4th	2nd
	S^6			6th	4th
	$h^2 S^2$			4th	2nd
$\mathbf{20}'_L$	h^2	2nd	2nd	2nd	2nd
	h^4	2nd	2nd	2nd	2nd
	S^2	2nd	2nd	2nd	2nd
	S^4	4th	4th	4th	2nd
	S^6	6th	6th	6th	4th
	$h^2 S^2$	2nd	2nd	2nd	2nd

Comparison for different Fermion Embeddings

$V(h,S)$ terms of interest obtained to respective order $\mathcal{O}\left(\frac{y_{L,R}^2}{g_{\rm UV}^2} \sim \frac{y_{L,R}^6}{g_{\rm UV}^6}\right)$.

$\Rightarrow S^6$ term at $\mathcal{O}\left(\frac{y_{L,R}^4}{g_{\rm UV}^4}\right)$ & sizable CPv and top mass terms can be generated.

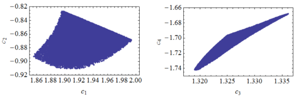
		$\mathbf{1}_R$	$\mathbf{6}_R$	$\mathbf{15}_R$	$\mathbf{20'}_R$
$\mathbf{6}_L$	h^2	No S-pot	2nd	No S-pot	2nd
	h^4		4th		2nd
	S^2		2nd		2nd
	S^4		4th		2nd
	S^6		6th		4th
	h^2S^2		2nd		2nd
$\mathbf{15}_{AL}$	h^2	No top mass	No CPv	2nd	2nd
	h^4			4th	2nd
	S^2			2nd	2nd
	S^4			4th	2nd
	S^6			6th	4th
	h^2S^2			4th	2nd
$\mathbf{20'}_L$	h^2	2nd	2nd	2nd	2nd
	h^4	2nd	2nd	2nd	2nd
	S^2	2nd	2nd	2nd	2nd
	S^4	4th	4th	4th	2nd
	S^6	6th	6th	6th	4th
	h^2S^2	2nd	2nd	2nd	2nd

Comparison for different Fermion Embeddings

$V(h,S)$ terms of interest obtained to respective order $\mathcal{O}\left(\frac{y_{L,R}^2}{g_{\rm UV}^2} \sim \frac{y_{L,R}^6}{g_{\rm UV}^6}\right)$.

$\Rightarrow$ S^6 term at $\mathcal{O}\left(\frac{y_{L,R}^4}{g_{\rm UV}^4}\right)$ & sizable CPv and top mass terms can be generated.

Can be matched to SNR EFT with $c_{nm} \sim \mathcal{O}(1)$, fulfilling all conditions for EWBG.



		$\mathbf{1}_R$	$\mathbf{6}_R$	$\mathbf{15}_R$	$\mathbf{20'}_R$
$\mathbf{6}_L$	h^2	No S-pot	2nd	No S-pot	2nd
	h^4		4th		2nd
	S^2		2nd		2nd
	S^4		4th		2nd
	S^6		6th		4th
	h^2S^2		2nd		2nd
$\mathbf{15}_{AL}$	h^2	No top mass	No CPv	2nd	2nd
	h^4			4th	2nd
	S^2			2nd	2nd
	S^4			4th	2nd
	S^6			6th	4th
	h^2S^2			4th	2nd
$\mathbf{20'}_L$	h^2	2nd	2nd	2nd	2nd
	h^4	2nd	2nd	2nd	2nd
	S^2	2nd	2nd	2nd	2nd
	S^4	4th	4th	4th	2nd
	S^6	6th	6th	6th	4th
	h^2S^2	2nd	2nd	2nd	2nd

Conclusion

- investigated thermal history of Higgs + S model with $D > 4$ terms
- starting from a Z_2-broken phase in the early universe avoids domain wall problem while allowing for a SFOEWPhT
- UV completion by $SO(6)/SO(5)$ composite Higgs model
  $\rightarrow$ accounts for HP and flavour hierarchies
- $V(h, S)$ structure calculated, including $D \geq 6$ terms
- models with t_R embedded in $\mathbf{20}'$ of $SO(6)$ yield large S^6 term
  $\rightarrow$ matched to the SNR scenario,
  may account for the correct baryon asymmetry in the universe.

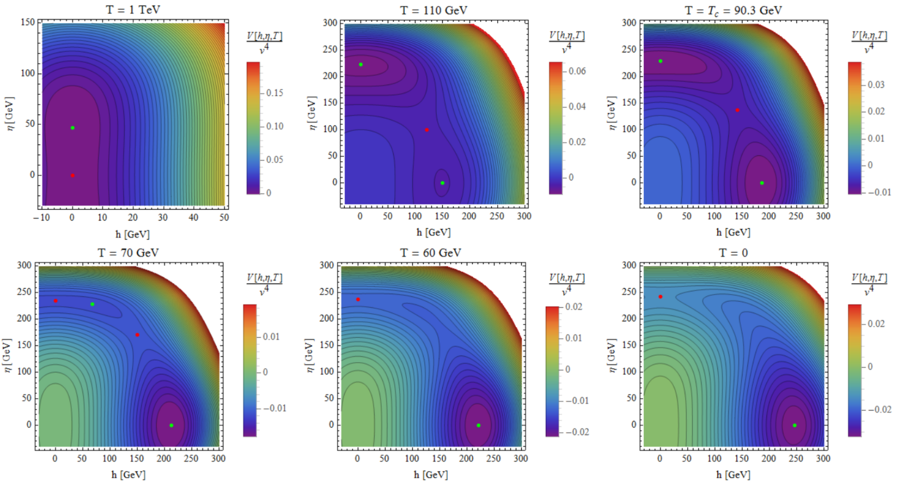
Outlook

- Could $SU(6)$ Gauge-Higgs Grand Unification include a EWBG Mechanism?
  - holographic to $SU(6)/SU(5)$ CH model
  - usual GUT BG suffers from sphaleron washout, low testability, high reheating temperature
  - unclear if usual GUT BG would even work $\rightarrow$ consider EWBG instead
- PNGB singlet as dark matter
- Cases with $V(S) = 0$ may have interesting implications

Thank you for Your Attention!

Feel free to contact me at aika.tada@mpi-hd.mpg.de

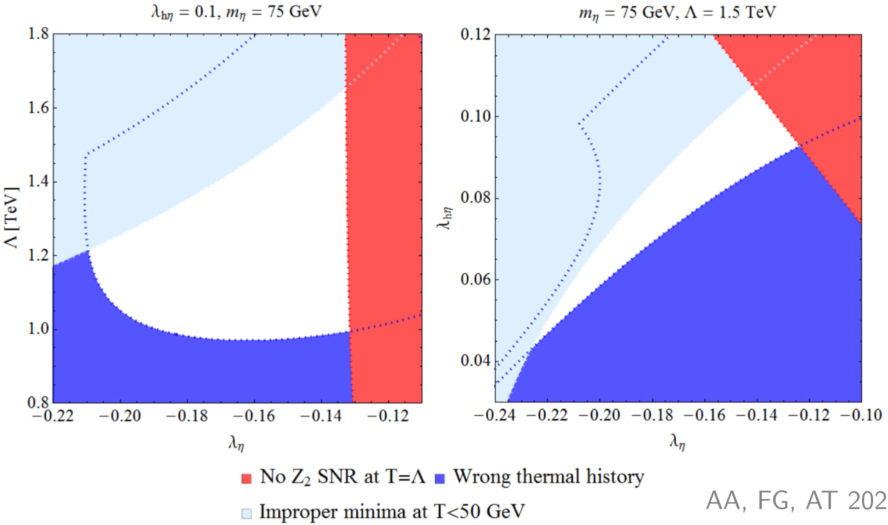
Z_2 Non-Restoration: Thermal Evolution



$$\Lambda_{\rm NP} = 1.5\,\text{TeV},\ \lambda_S = -0.15,\ \lambda_{hS} = 0.1,\ m_S = 75\,\text{GeV}$$

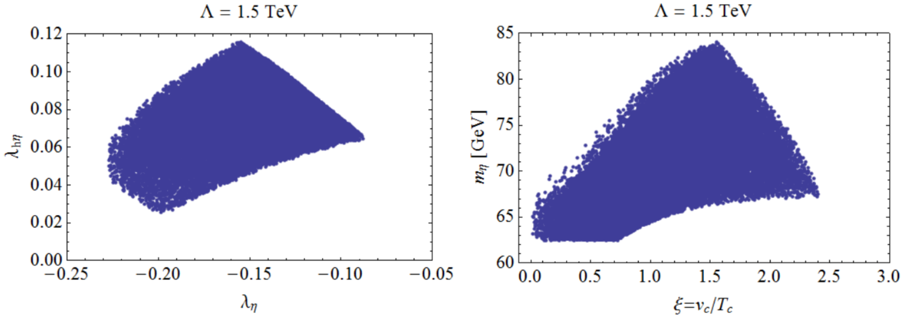
AA, FG, AT 2021

Z_2 SNR: Constraints



AA, FG, AT 2021

Z_2 SNR: Parameter Space

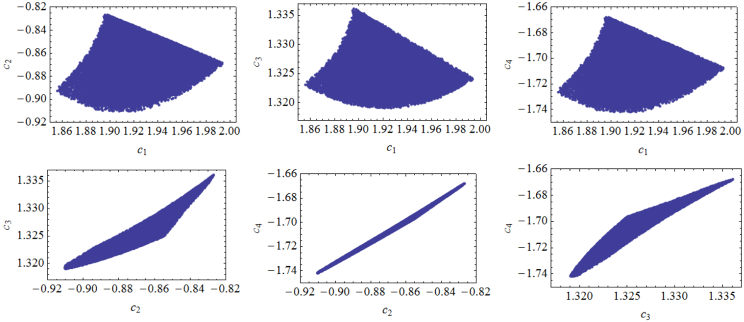


AA, FG, AT 2021

Matching to SNR Scenario

$$V = \frac{\mu_h^2}{2} h^2 + \frac{\lambda_h}{4} h^4 + \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \frac{\lambda_{hS}}{2} h^2 S^2 + \frac{S^6}{\Lambda_{\rm NP}^2}$$

$$\stackrel{!}{=} \frac{N_c m_\psi^4}{16\pi^2} \left(\frac{y_{L,R}}{g_{\rm UV}}\right)^{\#q} c_{nm} \left(\frac{h}{f}\right)^{2n} \left(\frac{S}{f}\right)^{2m}$$



Constructing the PNGB Potential

Embed q_L, t_R in full multiplets of $SO(6)$ via spurions:

$$Q_L = \Lambda_L^{\alpha} q_{L,\alpha}\,, \qquad Q_R = \Lambda_R t_R.$$

Dress the spurions with Goldstone matrix $U(h,S)$:

$$\begin{aligned}
(\Lambda')_{66} &= (U^T)_{6I}(U^T)_{6J}\Lambda^{IJ}\,, && I,J = 1,\dots,6,\\
(\Lambda')_{a6} &= (U^T)_{aI}(U^T)_{6J}\Lambda^{IJ}\,, && \\
(\Lambda')_{ab} &= (U^T)_{aI}(U^T)_{bJ}\Lambda^{IJ}\,, && a,b = 1,\dots,5
\end{aligned}$$

In 1-loop approximation to LO in Spurions via CCWZ formalism:

$$\begin{aligned}
V_{LO}(h,S) = \frac{N_c m_\psi^4}{16\pi^2}\Big(&\frac{y_L^2}{g_\psi^2} c_1 \left| \left(\Lambda_L^{\alpha\prime}\right)_{66} \right|^2 + \frac{y_L^2}{g_\psi^2} c_2 \left| \left(\Lambda_L^{\alpha\prime}\right)_{a6} \right|^2 \\
&+ \frac{y_R^2}{g_\psi^2} c_3 \left| \left(\Lambda_R'\right)_{66} \right|^2 + \frac{y_R^2}{g_\psi^2} c_4 \left| \left(\Lambda_R'\right)_{a6} \right|^2\Big)
\end{aligned}$$

Decomposition of $\mathbf{20}'$ of $SO(6)$ under SM gauge group

$$\begin{aligned}
\mathbf{20}'_{2/3} &\overset{SO(5)\times U(1)_X}{\longrightarrow} \mathbf{14}_{2/3} \oplus \mathbf{5}_{2/3} \oplus \mathbf{1}_{2/3} \\
&\overset{SO(4)\times U(1)_X}{\longrightarrow} \left[\mathbf{9}_{2/3} \oplus \mathbf{4}_{2/3} \oplus \mathbf{1}_{2/3}\right] \oplus \left[\mathbf{4}_{2/3} \oplus \mathbf{1}_{2/3}\right] \oplus \mathbf{1}_{2/3} \\
&\overset{SU(2)_L\times U(1)_Y}{\longrightarrow} \left[\left(\mathbf{3}_{5/3} \oplus \mathbf{3}_{2/3} \oplus \mathbf{3}_{-1/3}\right) \oplus \left(\mathbf{2}_{7/6} \oplus \mathbf{2}_{1/6}\right) \oplus \mathbf{1}_{2/3}\right] \\
&\qquad \oplus \left[\left(\mathbf{2}_{7/6} \oplus \mathbf{2}_{1/6}\right) \oplus \mathbf{1}_{2/3}\right] \oplus \mathbf{1}_{2/3}
\end{aligned}$$

$\rightarrow$ possible $\Lambda_L q_L$, $\Lambda_R t_R$ embeddings

- $Q_L = \Lambda_L q_L$ in $SO(5)$ $\mathbf{14}$ omits large $Zb\bar{b}$ couplings
- $Q_R = \Lambda_R t_R$ in $SO(5)$ $\mathbf{14_R} + \mathbf{5_R}$ ensures CPv and top mass

$$Q_L^{20'} = \cos\theta_{20L} e^{\imath\phi_{20L}} Q_L^{20'_A} + \sin\theta_{20L} Q_L^{20'_B}$$

$$Q_R^{20'} = \cos\theta_{20R1} e^{\imath\phi_{20R1}} t_R^{20'_A} + \sin\theta_{20R1} \cos\theta_{20R2} e^{\imath\phi_{20R2}} t_R^{20'_B} + \sin\theta_{20R1} \sin\theta_{20R2} t_R^{20'_C}$$

CPv and Mass terms from Spurion Analysis

$$Q_L^{20'} = \cos\theta_{20L} e^{\imath\phi_{20L}} Q_L^{20'_A} + \sin\theta_{20L} Q_L^{20'_B}$$

$$Q_R^{20'} = \cos\theta_{20R1} e^{\imath\phi_{20R1}} t_R^{20'_A} + \sin\theta_{20R1}\cos\theta_{20R2} e^{\imath\phi_{20R2}} t_R^{20'_B} + \sin\theta_{20R1}\sin\theta_{20R2} t_R^{20'_C}$$

$$\begin{aligned}
\mathcal{L}_{\text{Yukawa}}^{(20',20')} &= \frac{y_L y_R^*}{g_*} f \left[\left(\bar{Q}_L'^{20'}\right)_{66} \left(Q_R'^{20'}\right)_{66} M_1 + \left(\bar{Q}_L'^{20'}\right)_{6a} \left(Q_R'^{20'}\right)_{a6} M_5 \right] + \text{h.c.} \\
&\overset{(A,AB)}{=} \frac{y_L y_R^*}{g_* f^3} \bar{t}_L \Bigg[- f^2 h \sqrt{f^2 - h^2 - S^2} \frac{\sin\left(\theta_{20R1}\right) M_5}{2\sqrt{2}} \\
&\qquad - f^2 ihS \frac{3\cos\left(\theta_{20R1}\right) M_5}{4\sqrt{5}} \\
&\qquad - hS^2 \sqrt{f^2 - h^2 - S^2}\sqrt{2}\sin\left(\theta_{20R1}\right)\left(M_1 - M_5\right) \\
&\qquad + \frac{i}{2\sqrt{5}} \left(h^3 S - 4hS^3\right)\cos\left(\theta_{20R1}\right)\left(M_1 - M_5\right) \Bigg] t_R + \text{h.c.}
\end{aligned}$$

CCWZ: Effective Lagrangian for Spontaneously Broken Symmetries

Below condensation scale: Low energy description of SSB theory by CCWZ construction

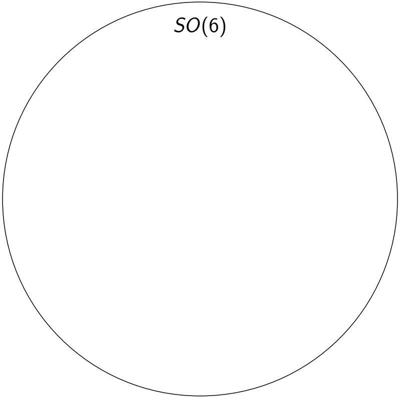
$$\langle \bar{\Psi}\Psi \rangle = \Sigma = U\Sigma_0, U = e^{i(\sqrt{2}/f)h_r \hat{T}_6^r}$$
$$\Sigma_0 = (0_{1\times 5}, 1)^T$$

$\hat{T}_6^r$: generators of broken symmetry $SO(6)/SO(5)$
Π_r: Goldstone bosons, transforming as fundamentals of $SO(5)$

$$U(\Pi) \overset{g\in SO(6)}{\longrightarrow} gU(\Pi)\, h^T(\Pi, g)$$
$$\text{with } h = \begin{pmatrix} h_5 & 0 \\ 0 & 1 \end{pmatrix}, h_5 \in SO(5)$$

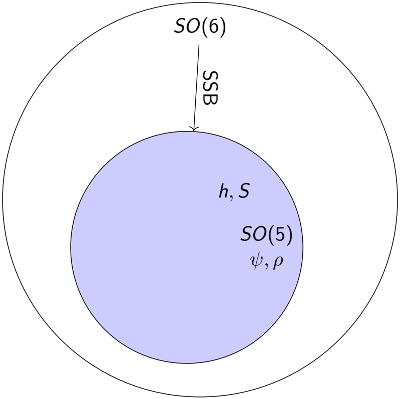
Decompose $SO(6)$ objects into $SO(5)$ objects using U
Construct $SO(5)$ invariant terms.
$\Rightarrow$ $SO(6)$ invariant Lagrangian with "broken" symmetry encoded in U for

$SO(6)/SO(5)$ Composite Higgs



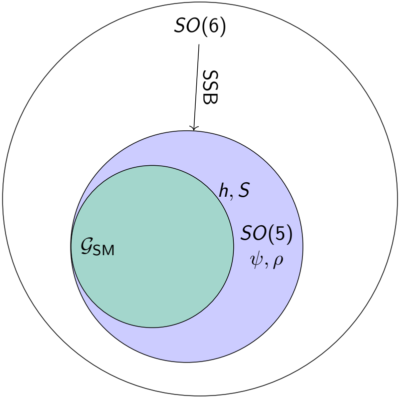
- Higgs as composite of new confining force (e.g. $SU(N)$)

$SO(6)/SO(5)$ Composite Higgs



- Higgs as composite of new confining force (e.g. $SU(N)$)
- Assume sponteneously broken global symmetry $\mathcal{G}/\mathcal{H}$ by condensation $\langle \bar{\Psi}\Psi \rangle \neq 0$
  $\rightarrow$ h as Nambu-Goldstone-Boson

$SO(6)/SO(5)$ Composite Higgs



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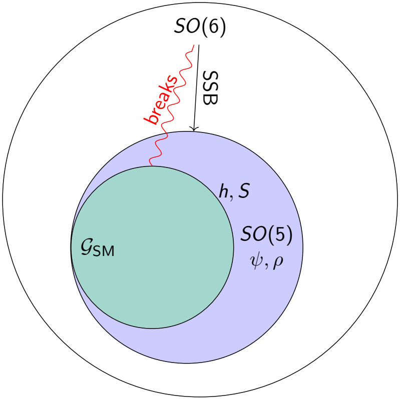

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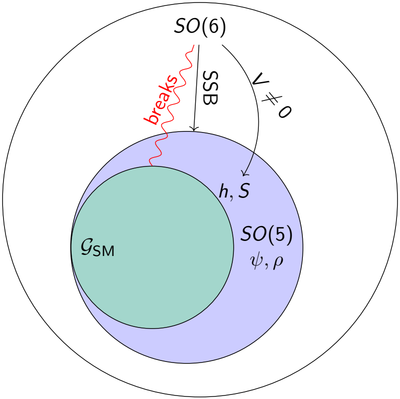
$SO(6)/SO(5)$ Composite Higgs



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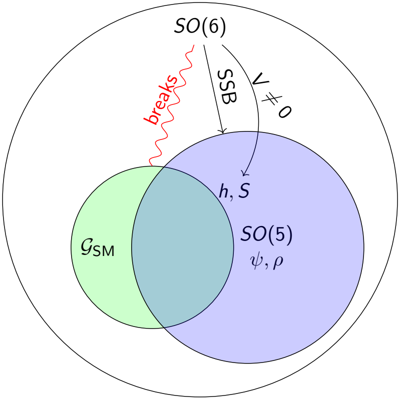
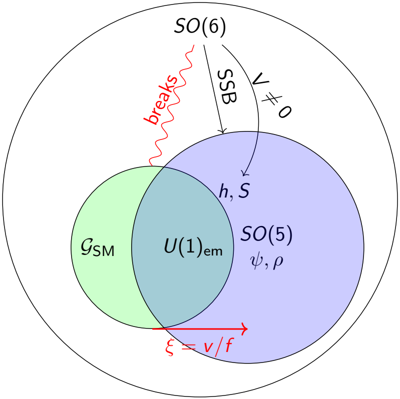
- Break $\mathcal{G}$ explicitly by interaction with Standard Model $\mathcal{G}_{SM}$

$SO(6)/SO(5)$ Composite Higgs



- Higgs as composite of new confining force (e.g. $SU(N)$)
- Assume sponteneously broken global symmetry $\mathcal{G}/\mathcal{H}$ by condensation $\langle\bar{\Psi}\Psi\rangle \neq 0$
  $\rightarrow h$ as Nambu-Goldstone-Boson
- Break $\mathcal{G}$ explicitly by interaction with Standard Model $\mathcal{G}_{\text{SM}}$
  $\rightarrow h$ as PNGB, $V(h) \neq 0$

$SO(6)/SO(5)$ Composite Higgs



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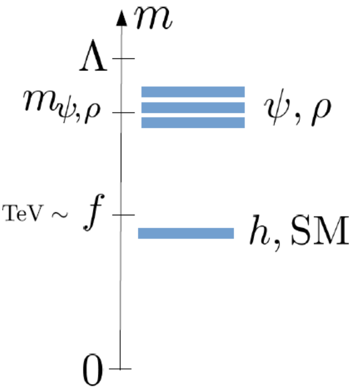
- Assume sponteneously broken global symmetry $\mathcal{G}/\mathcal{H}$ by condensation $\langle \bar{\Psi}\Psi \rangle \neq 0$
  $\rightarrow$ h as Nambu-Goldstone-Boson
- Break $\mathcal{G}$ explicitly by interaction with Standard Model $\mathcal{G}_{\mathrm{SM}}$
  $\rightarrow$ h as PNGB, $V(h) \neq 0$
- $\langle h \rangle = v$ induces EWSB

$SO(6)/SO(5)$ Composite Higgs



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