

Spontaneous CP Violation  
vs.  
Collective Symmetry Breaking

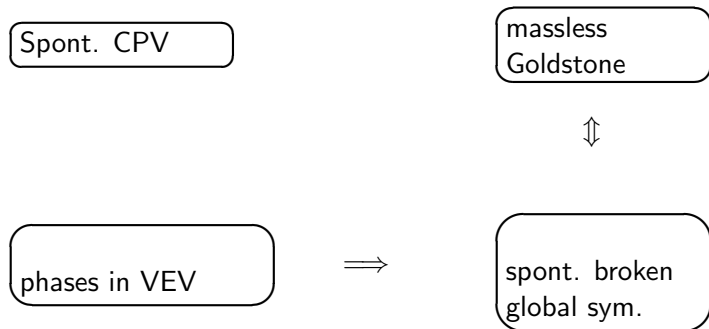
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arXiv:1003.4779 (with Patipan Uttayarat)

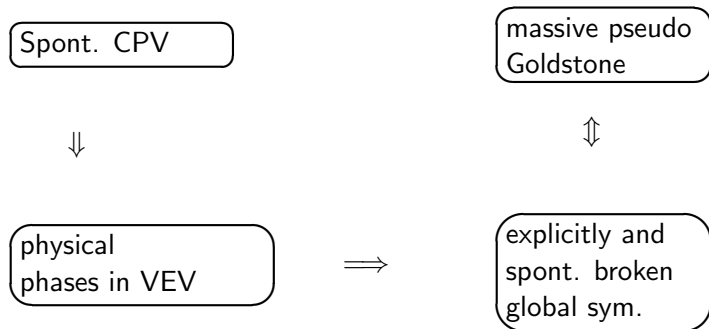
## Basic Idea:



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Little Higgs provides good laboratory for this

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# Outline

- ▶ Little Higgs Intro
- ▶ Conditions for spont. CPV
- ▶ Spont. CPV in  $SU(5)/SO(5)$  (suppressed effect)
- ▶ Spont. CPV in new  $SU(6)/SO(6)$

# Little Hierarchy

- ▶ SM Higgs sensitive to new scales  $\implies$  **(Big)** Hierarchy Problem

$$\implies \text{new physics at } \lesssim \text{TeV since } \frac{(1\text{TeV})^2}{16\pi^2} \sim v^2$$

- ▶ **But...**

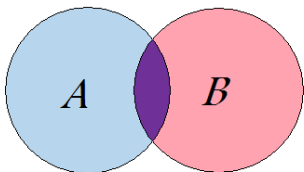
Precision tests forces  $\Lambda \gtrsim 10\text{TeV}$  (model & bound specific)

$\implies$  **Little** Hierarchy (**0.01** fine tuning)

- ▶ **Little** Hierarchy Problem *harder* than **Big** Hierarchy Problem

## Solution: Little Higgs

- ▶ Higgs is pseudo-Goldstone - gets mass through loops  
 $\implies$  Naively  $\delta m_H^2 \sim (\Lambda/4\pi)^2 \implies \Lambda \gtrsim 10\text{TeV}$
- ▶ Explicit Breaking is *Collective*
- ▶ Two terms, each breaking either  $A$  or  $B$
- ▶ Only diagrams involving both terms give  $\delta m_H \neq 0$
- ▶ more vertexes  $\implies$  No quadratic divergence at one-loop



# Littlest Higgs

- ▶ SU(5) Global Symmetry
- ▶ **Explicit breaking:** by gauging  $[SU(2) \times U(1)]^2 \supset SU(5)$ :

$$V = \begin{pmatrix} SU(2)_1 & & \\ & 1 & \\ & & SU(2)_2 \end{pmatrix}$$

$$Y_1 = \text{diag}(3, 3, -2, -2, -2), \quad Y_2 = \text{diag}(2, 2, 2, -3, -3)$$

- ▶ **Spont. Breaking:**  $\Sigma_0 = \begin{pmatrix} & & \mathbb{1} \\ & 1 & \\ \mathbb{1} & & \end{pmatrix}$
- ▶  $SU(5) \rightarrow SO(5)$ ,  $[SU(2) \times U(1)]^2 \rightarrow [SU(2) \times U(1)]_{\text{diag}}$

## Littlest Higgs (cont.)

- ▶ Goldstone bosons: 
$$\pi = \begin{pmatrix} \text{eaten} & H & \phi \\ H^\dagger & \text{eaten} & H^T \\ \phi^\dagger & H^* & \text{eaten} \end{pmatrix}$$
- ▶  $H$  shifts under:  $A = \text{SU}(3)_1$ ,  $B = \text{SU}(3)_2$
- ▶ gauge interactions break  $A, B$  *collectively*
- ▶  $\delta m_H^2 \sim \left(\frac{gf}{4\pi}\right)^2 \log \Lambda$  at 1-loop
- ▶ Collective breaking also with Yukawa terms...



# Mass Scales

↑ UV completion

—————  $\Lambda = 4\pi f$  (or lower)

↕ NLΣM

—————  $\sim \frac{\Lambda}{4\pi}$   $\phi, W', Z', t'$  get masses

Standard Model

—————  $\frac{f}{4\pi} \sim \frac{\Lambda}{(4\pi)^2}$   $m_H$

Standard Model

## Conditions for spont. CPV in LH

- ▶ There is a generator  $X$  which is:
  - ▶ spontaneously broken
  - ▶ explicitly broken
  
- ▶ But if  $X$  is spanned by both  $A$ +gauge and  $B$ +gauge, it must spoil Collective Symmetry Breaking

# The Hypercharge Model - Spont. CPV

- ▶ In Littlest Higgs: no SU(5)-related phase:  $\Sigma_0 = \begin{pmatrix} & & \mathbb{1} \\ & 1 & \\ \mathbb{1} & & \end{pmatrix}$
- ▶ ...if we don't gauge  $Y' \equiv Y_1 - Y_2 \sim \text{diag}(1, 1, -4, 1, 1)$  (Csáki et al., Perelstein et al.), we can break it explicitly by  $V = f(\Sigma_{33})$

- ▶ Physical phase:  $\Sigma_0 = \begin{pmatrix} & & e^{i\delta} \mathbb{1} \\ & e^{-4i\delta} & \\ e^{i\delta} \mathbb{1} & & \end{pmatrix}$

- ▶ New pseudo-Goldstone with EW-scale mass
- ▶ Problem: it breaks both SU(3)<sub>1,2</sub>
- ▶ ...has only suppressed effect on SM sector.

## SU(6)/SO(6) Model

- ▶ Explicit SU(6) breaking by gauging:

$$\left( \begin{array}{c|c|c} \text{SU}(2)_1 & & \\ \hline & 1 & \\ & & 1 \\ \hline & & \text{SU}(2)_2 \end{array} \right)$$

- ▶  $Y_1 \sim \text{diag}\{-2, -2, 1, 1, 1, 1\}$
- ▶  $Y_2 \sim \text{diag}\{-1, -1, -1, -1, 2, 2\}$
- ▶ Global sym.: SU(2)<sub>M</sub>

## SU(6)/SO(6) - cont.

► Vacuum:  $\Sigma_0 = \left( \begin{array}{c|cc|c} & & & \mathbb{1} \\ \hline & e^{i\alpha} \cos \theta & i \sin \theta & \\ & i \sin \theta & e^{-i\alpha} \cos \theta & \\ \hline \mathbb{1} & & & \end{array} \right)$

► Goldstone bosons:

$$\left( \begin{array}{c|cc|c} \mathbb{1} & H & K & \phi \\ \hline H^\dagger & \sigma & \rho & H^T \\ K^\dagger & \rho & -\sigma & K^T \\ \hline \phi^\dagger & H^* & K^* & \mathbb{1} \end{array} \right)$$

► Collective Symmetry Breaking:  $A = \text{SU}(4)_1$ ,  $B = \text{SU}(4)_2$

► Further explicit breaking by Yukawa...

# Summary

- ▶ Spontaneous CPV **requires** both **spontaneous** and **explicit** breaking of global symmetry.
- ▶  $SU(5)/SO(5)$  yields  $\mathcal{O}(1)$  phase but suppressed at low energy.
- ▶  $SU(6)/SO(6)$  model yields  $\mathcal{O}(1)$  phase,  $\mathcal{O}(1)$  low energy effect.

# Backup Slides

# NLSM (CWZ,CCWZ)

Goldstone Bosons:

▶  $\Sigma = e^{i\pi/f} \Sigma_0 e^{i\pi^T/f}, \quad \pi = \pi^a X^a$

▶  $X^a$  belongs to

SU(5)/SO(5)  $\pi = \begin{pmatrix} \text{eaten} & H & \phi \\ H^\dagger & \text{eaten} & H^T \\ \phi^\dagger & H^* & \text{eaten} \end{pmatrix}$



## Condition Violation in Hypercharge Model

- ▶  $Y' \sim \lambda_8^{\text{SU}(3)_1} + Y \sim \lambda_8^{\text{SU}(3)_2} + \#Y$
- ▶ Explicit Breaking of  $Y' \implies$  expl. breaking of both  $\text{SU}(3)_{1,2}$
- ▶ But can still be fine if non-collective breaking is small, e.g. :  
 $V \supset \frac{1}{16\pi^2} \Sigma_{33}$ 
  - ▶ keeps EW scale stable
  - ▶ Pseudo-Goldstone of  $Y'$  acquires weak scale mass
  - ▶ Spont. CPV phase generically  $\mathcal{O}(1)!$

## Yukawa Sector, SU(5)

- ▶ Add LH singlet  $\psi \Rightarrow Q^{i=1,2,3} \equiv \begin{pmatrix} Q^{a=1,2} \\ \psi \end{pmatrix}$
- ▶ Add RH singlet  $t'$

$$\mathcal{L}_Y = \lambda_1 f \bar{Q}_i \Omega_1^i u + \lambda' f \bar{\psi} t', \quad \Omega_1^i = \epsilon^{ijk} \epsilon^{xy} \Sigma_{jx} \Sigma_{ky}$$

- ▶  $\lambda_1$  :      SU(3)<sub>1</sub> exact      SU(3)<sub>2</sub> broken
- ▶  $\lambda'$  :      SU(3)<sub>1</sub> broken      SU(3)<sub>2</sub> exact

# Yukawas, SU(6)

- ▶  $SU(2)_M$  must be broken explicitly  
⇒ break  $SU(4)_{1,2} \rightarrow SU(3)_{1,2}$  explicitly:
- ▶  $\bar{Q}_i (\bar{\Sigma}^{i4} \Sigma_{44} + r \epsilon_{jkl} \epsilon_{xy} \bar{\Sigma}^{ij} \bar{\Sigma}^{kx} \bar{\Sigma}^{ly}) u + \lambda' \bar{\psi} t'$   
⇒ breaks collectively  $SU(3)_1$  and  $SU(4)_2$   
⇒  $H$  is light.  $K, \rho$  are heavy
- ▶  $\text{diag}(0, 0, 1, -1, 0, 0)$  spanned by  $\{T^8 \text{ of } SU(3)_1, Y, Y'\}$  and also by  $\{SU(4)_2\}$   
⇒ can't be broken without spoiling collective SB
- ▶ Spoil collective SB slightly by  $\epsilon f^4 \bar{\Sigma}^{33} \Sigma_{44}$   
⇒  $\sigma$  at EW scale
- ▶ stabilizes  $\theta \neq 0$  for generic  $r$
- ▶  $\sqrt{2} e^{-i\alpha} \cos \theta \left[ (2i - \sin \theta) + \frac{2i + \sin \theta}{3} H^\dagger H \right] \bar{Q} \tilde{H} u$

# BSM quark-Higgs Couplings

Low energy implications:

$$\frac{Z_{\alpha\beta}^u}{f^2} \bar{Q}_\alpha \tilde{H} u_\beta H^\dagger H + \frac{Z_{\alpha\beta}^d}{f^2} \bar{Q}_\alpha H d_\beta H^\dagger H + \frac{Z_{\alpha\beta}^\ell}{f^2} \bar{L}_\alpha H \ell_\beta H^\dagger H$$

- ▶ Can get  $Z_{\alpha\beta}$  from expanding  $\Sigma_{ij}$  in  $\lambda \bar{Q}_i \Omega^j u$
- ▶ But... No relative phase in  $H \leftrightarrow HH^\dagger H$  unless both  $SU(3)_{1,2}$  are broken  $\implies$  phase in  $Z_{\alpha\beta}$  is  $\varepsilon$ -suppressed