Mirror Color Symmetry Breaking in Twin Higgs model

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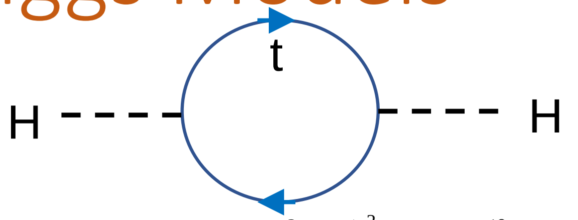
"*Breaking Mirror Twin Color*" Brian Batell, Wei Hu, and Christopher B. Verhaaren, 2004.10761

Outline

- Spontaneous Symmetry Breaking in Twin Higgs Models.
  - 1. Motivation: Evade LHC Bound
  - 2. Twin Higgs Model (Z2, global)
  - 3. Spontaneous breaking of twin color.
- *Triplet example (Φ, $V(\Phi)$, $< \Phi >$)*
  - 1. β-function, Confinement.
  - 2. coupling of Φ to matter
  - 3. mass terms for twin fermion.
  - 4. Indirect, precision tests
    - Baryon, Lepton # violation, flavor, CP violation, current unversality
  - 5. Collider Phenomenology
    - Colored scalar production,
    - ggH production and Hγγ radiative decay
- Summary

Spontaneous Symmetry Breaking in Twin Higgs Models

1. Motivation: Evade LHC Bound on top partner



$$\delta_{SM} m_H^2 = -\frac{3y_t^2}{4\pi^2}\Lambda_{SM}^2 + \ldots \qquad \Delta \sim \frac{\delta_{SM} m_H^2}{m_H^2} \sim \frac{\Lambda_{Planck}^2}{m_H^2} \sim \frac{(10^{19}GeV)^2}{(100GeV)^2} \sim 10^{34}$$

- Neutral top partners, evade the constraint below ~ 1TeV:
- Twin Higgs is the first example of neutral naturalness

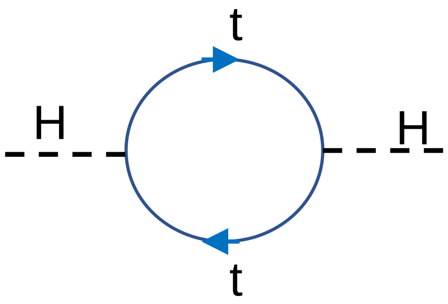
- Add a copy of the SM sector but singlet under SM, may also serve as dark sector.
- When the global symmetry spontaneously breaks, the goldstones will contain Higgs doublet.

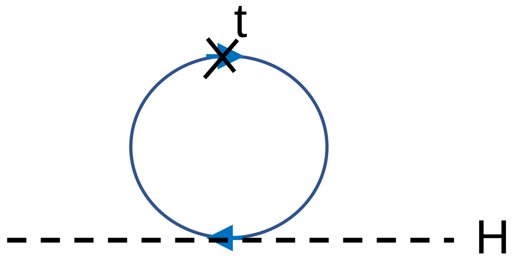
2. Twin Higgs Model

(Z2, global)

- Copy the SM sector by Z2 symmetry, remove quadratic divergence.
- Enlarge Higgs global symmetry to SU(4), broken spontaneously

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \qquad \lambda_A H_A q_A t_A + \lambda_B H_B q_B t_B$$





$$\Delta V = \frac{3\lambda^2}{8\pi^2}\Lambda^2 \left(H_A^\dagger H_A + H_B^\dagger H_B\right) = \frac{3\lambda^2}{8\pi^2}\Lambda^2 H^\dagger H$$

$$i\lambda_t \boldsymbol{h} q_A t_A + \lambda_t \left(f - \frac{1}{2f}\boldsymbol{h}^\dagger \boldsymbol{h}\right) q_B t_B$$

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} = \exp\left(\frac{i}{f}\Pi\right)\begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix} \qquad \Pi = \left(\begin{array}{ccc|c} 0 & 0 & 0 & h_1 \\ 0 & 0 & 0 & h_2 \\ 0 & 0 & 0 & 0 \\ \hline h_1^* & h_2^* & 0 & 0 \end{array}\right)$$

Chacko, 2005, 0506256

3. Spontaneous breaking of twin color

- Introduce a heavy scalar with color triplet, sextet, octet for two sectors.

$$\begin{pmatrix} \Phi_A \\ \Phi_B \end{pmatrix}$$

$$\Phi_B \in (\mathbf{3},\mathbf{1},Y_\Phi), \quad (\mathbf{6},\mathbf{1},Y_\Phi), \quad (\mathbf{8},\mathbf{1},0)$$

- Most general Z2 symmetric scalar potential

$$V_\Phi = -\mu^2 \left|\Phi\right|^2 + \lambda \left|\Phi\right|^4 + \delta \left(\left|\Phi_A\right|^4 + \left|\Phi_B\right|^4\right)$$

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- δ >0, two equal vevs in each sector, discarded.
- δ <0, two global minima, vev only in one sector:

$$\Phi_A = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}, \qquad \Phi_B = \begin{pmatrix} 0 \\ 0 \\ f_\Phi \end{pmatrix}$$

- Colored triplet scalar, spontaneous breaking to SU(2):
- Bound states of SU(2):
  - Mesons $u\bar{u}$, baryons uu, gluballs

$\mathbf{I}:$	$(\mathbf{3},\mathbf{1},Y_\Phi)$	$[SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(2)_c \times U(1)'_{\rm EM}]_B$
$\mathbf{II}:$	$(\mathbf{6},\mathbf{1},Y_\Phi)$	$[SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(2)_c \times U(1)'_{\rm EM}]_B$
$\mathbf{III}:$	$(\mathbf{6},\mathbf{1},Y_\Phi)$	$[SU(3)_c \times SU(2)_L \times U(1)_Y \to SO(3)_c]_B$
$\mathbf{IV}:$	$(\mathbf{8},\mathbf{1},0)$	$[SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(2)_c \times U(1)_c \times U(1)_{\rm EM}]_B$
$\mathbf{V}:$	$(\mathbf{8},\mathbf{1},0)$	$[SU(3)_c \times SU(2)_L \times U(1)_Y \to U(1)_c \times U(1)'_c \times U(1)_{\rm EM}]_B$

L. F. Li, Phys. Rev. D 9, 1723 (1974)

Triplet example (Φ, V(Φ), < Φ >)

- Colored triplet scalar: $\Phi_B (\equiv \Phi_1) = \begin{pmatrix} 0 \\ 0 \\ f_\Phi \end{pmatrix}$
- Full potential:

$$V = -M_H^2 |H|^2 + \lambda_H |H|^4 - M_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \lambda_{H\Phi} |H|^2 |\Phi|^2$$
$$+ \delta_H \left(|H_A|^4 + |H_B|^4\right) + \delta_\Phi \left(|\Phi_A|^4 + |\Phi_B|^4\right) + \delta_{H\Phi} \left(|H_A|^2 - |H_B|^2\right)\left(|\Phi_A|^2 - |\Phi_B|^2\right)$$

- 1st line respects U(4) x U(6) symmetry, 2nd line breaks it, preserving Z2
- -> pseudo Goldstones as Higgs boson and scalar.
- $\delta_H > 0$, symmetric vev, $\delta_{H\Phi}$ term breaks Z2 by Φ vev.

. 1. β-function, Confinement.

$\mathbf{I}: \quad (\mathbf{3}, \mathbf{1}, Y_\Phi)$

$\mathbf{II}: \quad (\mathbf{6}, \mathbf{1}, Y_\Phi)$

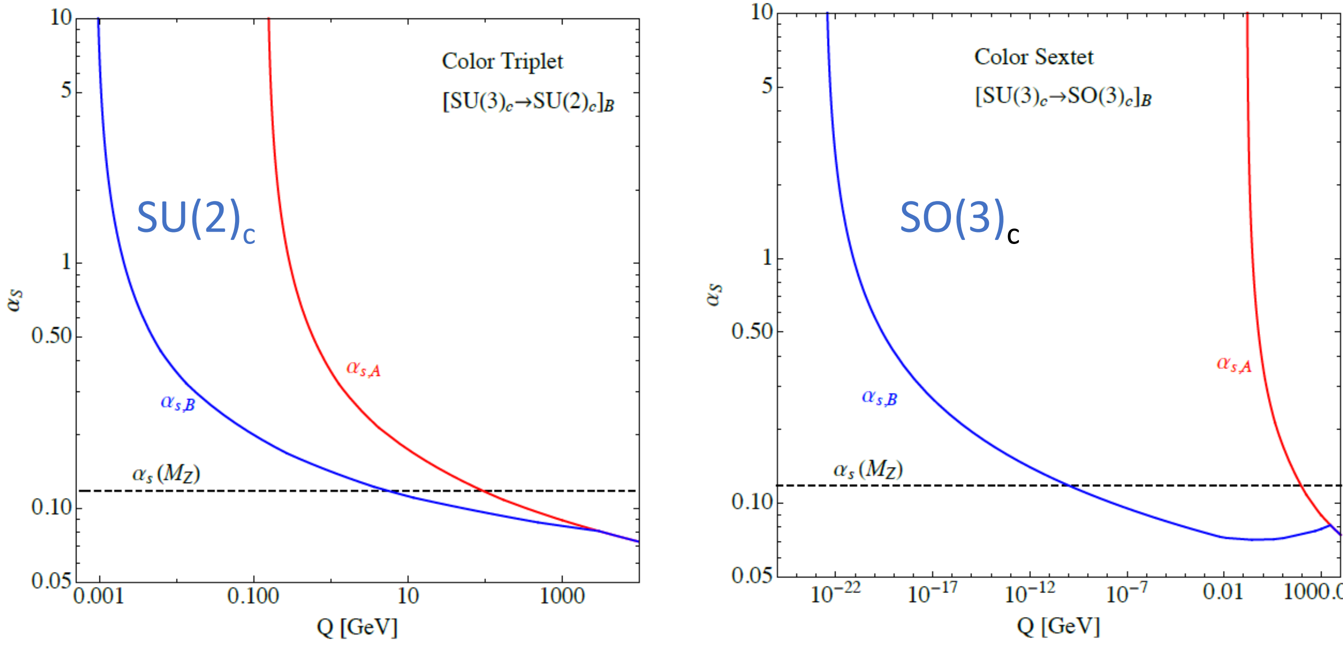
$\mathbf{III}: \quad (\mathbf{6}, \mathbf{1}, Y_\Phi)$

$\mathbf{IV}: \quad (\mathbf{8}, \mathbf{1}, 0)$

$$d\alpha_s^{-1}/d\ln\mu = b/2\pi$$

$$b = \frac{11}{3}C_{\rm Ad} - \frac{2}{3}\sum_f c_f T_f - \frac{1}{6}\sum_s c_s T_s$$

- Low QCD confinement scale ~ MeV, 10^{-23}GeV
- Baryon: sum of quark masses, like quirks.



$$m_\phi = 1\ \text{TeV},\ f_\Phi = 3\ \text{TeV}$$

Kang, Luty 2009, 0805.4642

2. Coupling of Φ to matter

- Allow scalar Φ to decay
- Adjust/raise the mass spectrum of fermions

Φ	Coupling to fermion bilinear	ϕ_A decay	Twin fermion mass terms
			$[SU(2)_c \times U(1)'_{\rm EM}]_B$
$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	$\Phi\,(Q\,Q)$	$\phi_A \to \bar{u}\,\bar{d}$	$\hat{u}_B\,\hat{d}_B$
	$\Phi^\dagger\,(Q\,L)$	$\phi_A \to u\,e, d\,\nu$	$\hat{u}_{B3}\,e_B,\;\hat{d}_{B3}\,\nu_B$
	$\Phi^\dagger\,\bar{u}\,\bar{d}$	$\phi_A \to \bar{u}\,\bar{d}$	$\hat{\bar{u}}_B\,\hat{\bar{d}}_B$
	$\Phi\,\bar{u}\,\bar{e}$	$\phi_A \to u\,e$	$\hat{\bar{u}}_{B3}\,\bar{e}_B$
	$\Phi\,\bar{d}\,(L\,H)$	$\phi_A \to d\,\nu$	$\hat{\bar{d}}_{B3}\,\nu_B$
	$\Phi\,(H^\dagger Q)(Q\,H)$	$\phi_A \to \bar{u}\,\bar{d}$	$\hat{u}_B\hat{d}_B$
	$\Phi^\dagger\,(H^\dagger Q)(L\,H)$	$\phi_A \to d\nu$	$\hat{d}_{B3}\,\nu_B$
	$\Phi^\dagger\,(Q\,H)(H^\dagger L)$	$\phi_A \to u\,e$	$\hat{u}_{B3}\,e_B$

3. mass terms for twin fermions.

- Triplet (3, 1, 2/3), $\lambda_{\bar{d}\bar{d}}\, \Phi_B^\dagger\, \bar{d}_B\, \bar{d}_B$
- λ antisymmetric in generation space
- Lagrangian:

$$-\mathcal{L} \supset \overline{M}_d\, \hat{\bar{d}}_B\, \hat{\bar{s}}_B + m_{d_B}\, \hat{\bar{d}}_B\, \hat{d}_B + m_{s_B}\, \hat{\bar{s}}_B\, \hat{s}_B + \mathrm{H.c.}$$

$$(\hat{\bar{d}},\quad \hat{\bar{s}},\quad \hat{d},\quad \hat{s})$$

$$\begin{pmatrix} 0 & \lambda_{12} f_\Phi & \frac{y_d v_B}{2\sqrt{2}} & 0 \\ -\lambda_{12} f_\Phi & 0 & 0 & \frac{y_s v_B}{2\sqrt{2}} \\ -\frac{y_d v_B}{2\sqrt{2}} & 0 & 0 & 0 \\ 0 & -\frac{y_s v_B}{2\sqrt{2}} & 0 & 0 \end{pmatrix}$$

- Seesaw eigenstates, assume λ ~ O(1):

$\overline{M}_d$ $\quad m_{s_B} m_{d_B}/\overline{M}_d$ $\quad$ 5 TeV and 100 eV

- Remove Seesaw

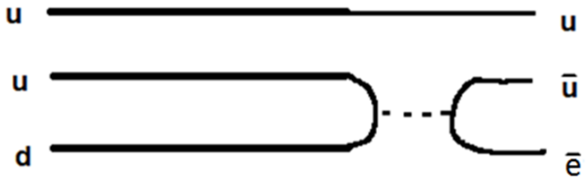
$$\frac{c_{QQ}}{2\Lambda^2}\, \Phi_B\, (H_B^\dagger Q_B)(H_B^\dagger Q_B)$$

4. Indirect, precision tests

- Baryon, Lepton # violation, flavor, CP violation, EDM , Charged current processes, *Typical examples* for illustration:

- A. Baryon #: Proton decay: $p^+ \to e^+ \pi^0$

$\Phi_d^\dagger \bar{u}\bar{d}$ $\quad \Phi_d^\dagger Q L$



$$\Gamma(p^+ \to e^+\pi^0) =$$

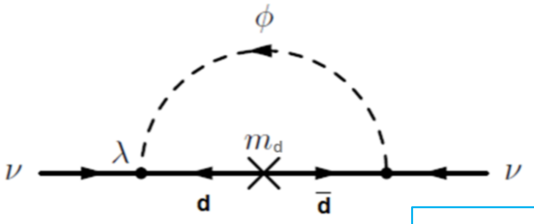
$$\frac{|\lambda_{QL}^{11}\,\lambda_{\bar{u}\bar{d}}^{11}|^2}{m_{\phi_A}^4}\frac{|\alpha|^2(1+F+D)^2 m_p}{64\pi f^2}\left(1-\frac{m_\pi^2}{m_p^2}\right)^2$$

$$\simeq (10^{34}\,\mathrm{yr})^{-1}\left(\frac{\sqrt{|\lambda_{QL}^{11}\,\lambda_{\bar{u}\bar{d}}^{11}|}}{4\times 10^{-13}}\right)^4\left(\frac{\mathrm{TeV}}{m_{\phi_A}}\right)^4$$

Super-Kamiokande 2017 1610.03597

- Lepton #: neutrino

$\Phi_d^\dagger Q L$ $\quad \frac{1}{\Lambda}\Phi_d \bar{d} L H$



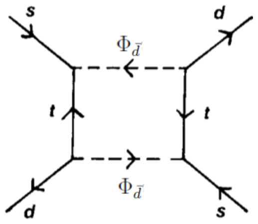
$$m_\nu \sim \frac{\lambda_{QL}\,c_{\bar{d}L}\,m_d\,v_A}{16\sqrt{2}\pi^2\Lambda}\log\left(\frac{\Lambda}{m_{\phi_A}}\right) \approx 0.1\,\mathrm{eV}\left(\frac{\lambda_{QL}\,c_{\bar{d}L}}{10^{-7}}\right)\left(\frac{5\,\mathrm{TeV}}{\Lambda}\right)$$

4. Indirect precision tests

- B. Quark and lepton FCNC: $K^0 - \bar{K}^0$ mixing,
  - tree level $\Phi \sim (\mathbf{6}, \mathbf{1}, -\frac{2}{3})$ $\quad \Phi_{dd}\bar{d}\bar{d}$ $\quad C^{sd}_{V,RR}(\bar{s}_A\gamma^\mu P_R d_A)(\bar{s}_A\gamma^\mu P_R d_A)$

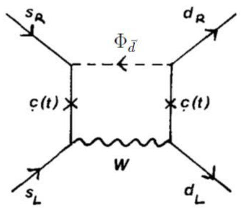
$$C^{sd}_{V,RR} = \frac{\lambda^{11}_{dd}\lambda^{22*}_{dd}}{8m^2_{\phi_A}} \approx \left(\frac{1}{10^4\,\mathrm{TeV}}\right)^2\left(\frac{\mathrm{TeV}}{m_{\phi_A}}\right)^2\left(\frac{\lambda^{11}_{dd}\lambda^{22*}_{dd}}{10^{-7}}\right)$$

  - Loop level $\Phi \sim (\mathbf{3}, \mathbf{1}, -\frac{1}{3})$ $\quad \Phi^\dagger_d \bar{u}\bar{d}$



$$C^{sd}_{V,RR}(\bar{s}_A\gamma^\mu P_R d_A)(\bar{s}_A\gamma^\mu P_R d_A)$$

$$C^{sd}_{V,RR} = \frac{\left(\sum_I \lambda^{I2}_{\bar{u}\bar{d}}\lambda^{I1*}_{\bar{u}\bar{d}}\right)^2}{64\pi^2 m^2_{\phi_A}} \approx \left(\frac{1}{10^4\,\mathrm{TeV}}\right)^2\left(\frac{\mathrm{TeV}}{m_{\phi_A}}\right)^2\left(\frac{\sum_I \lambda^{I2}_{\bar{u}\bar{d}}\lambda^{I1*}_{\bar{u}\bar{d}}}{3\times 10^{-3}}\right)^2$$



$$C^{sd}_{S,RL}\left[(\bar{s}^i_A P_R d_{Ai})(\bar{s}^j_A P_L d_{Aj}) - (\bar{s}^i_A P_R d_{Aj})(\bar{s}^j_A P_L d_{Ai})\right]$$

$$C^{sd}_{S,RL} = \frac{G_F}{8\sqrt{2}\pi^2} V_{td}V^*_{ts}\lambda^{32}_{\bar{u}\bar{d}}\lambda^{31*}_{\bar{u}\bar{d}}\frac{m_t^2}{m_\phi^2}\log\left(\frac{m_\phi^2}{m_W^2}\right) \approx \left(\frac{1}{10^4\,\mathrm{TeV}}\right)^2\left(\frac{\mathrm{TeV}}{m_{\phi_A}}\right)^2\left(\frac{\lambda^{32}_{\bar{u}\bar{d}}\lambda^{31*}_{\bar{u}\bar{d}}}{2\times 10^{-3}}\right)$$

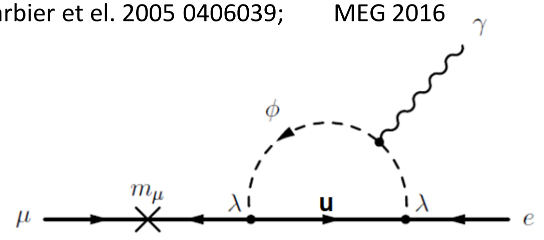
Barbieri, Nucl. Phys. B (1986); Slavich, Nucl. Phys. B (2001) 0008270

UTfit 2008 0707.0636

4. Indirect precision tests

- FCNC: Lepton flavor violation, $\mu \to e\,\gamma$

Barbier et el. 2005 0406039; MEG 2016



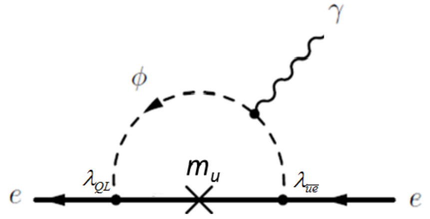
$\Phi \sim (\mathbf{3}, \mathbf{1}, -\frac{1}{3})$ $\Phi_d^\dagger Q L$

$$\mathrm{Br}(\mu \to e\gamma) = \tau_\mu \frac{\alpha\,|\sum_I \lambda_{QL}^{I1*}\lambda_{QL}^{I2}|^2\, m_\mu^5}{2^{14}\,\pi^4\, m_\phi^4} \simeq 4\times 10^{-13} \left(\frac{1\,\mathrm{TeV}}{m_\phi}\right)^4 \left(\frac{|\sum_I \lambda_{QL}^{I1*}\lambda_{QL}^{I2}|^2}{2\times 10^{-6}}\right)$$

- C. electron EDM

ACME 2018

$\lambda_{QL}\lambda_{\overline{u}\overline{e}}$



$\Phi \sim (\mathbf{3}, \mathbf{1}, -\frac{1}{3})$ $\Phi_d^\dagger Q L$ $\Phi_d \bar{u}\bar{e}$ $\mathcal{L} \supset -\frac{i}{2}\, d_e\, \bar{e}_A\, \sigma_{\mu\nu}\gamma^5 e_A\, F_A^{\mu\nu}$

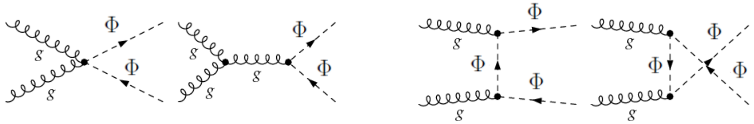
$$d_e \simeq \frac{e\, m_t}{32\pi^2 m_\phi^2}\left[7 + 4\log\left(\frac{m_t^2}{m_\phi^2}\right)\right] \mathrm{Im}[\lambda_{QL}^{31}\,\lambda_{\bar{u}\bar{e}}^{31}] \approx 10^{-29}\, e\,\mathrm{cm} \left(\frac{1\,\mathrm{TeV}}{m_{\phi_A}}\right)^2 \left(\frac{\mathrm{Im}[\lambda_{QL}^{31}\,\lambda_{\bar{u}\bar{e}}^{31}]}{10^{-10}}\right)$$

- D. Charged current processes: $\Phi \sim (\mathbf{3}, \mathbf{1}, -\frac{1}{3})$ $\Phi_d^\dagger Q L$

PiENu 2015, 1506.05845

$$R_\pi \equiv \frac{\Gamma(\pi^- \to e^-\bar{\nu}_e)}{\Gamma(\pi^- \to \mu^-\bar{\nu}_\mu)} \simeq R_\pi^{\mathrm{SM}} \left(1 + \frac{|\lambda_{QL}^{11}|^2 - |\lambda_{QL}^{12}|^2}{2\sqrt{2}\,G_F\,|V_{ud}|\, m_{\phi_A}^2}\right) \qquad \sqrt{|\lambda_{QL}^{11}|^2 - |\lambda_{QL}^{12}|^2} < 0.4\left(\frac{m_{\phi_A}}{1\,\mathrm{TeV}}\right)$$

5. Collider Phenomenology



- A. Direct searches for colored scalar
- Pair production pp -> $\phi_A \phi^*_A$: most robust probe

- Squark searches ϕ_A -> q ν: excludes 1.2 TeV for squark, stop, sbottoms by CMS ATLAS, 13 TeV, 137 fb^{-1} .
  - 1.6TeV at HL-LHC (14 TeV, 3 ab^{-1}) and 10 TeV at 100TeV collider

- Leptoquark searches ϕ_A -> q l:
  - 1st and 2nd gens *lljj*, excludes 1.4-1.6 TeV by ATLAS CMS, 13 TeV, 35.9 fb^{-1} .
    - 2-3 TeV at HL-LHC and 10 TeV at 100 TeV collider

5. Collider Phenomenology

- A. Direct searches for colored scalar

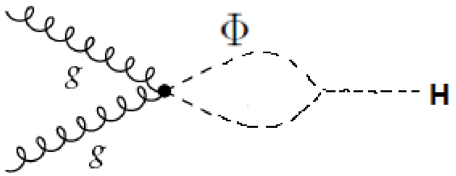
  - 3rd gen (τ, b, t), $\tau\tau$ ($b\tau$): 900GeV (1TeV) by ATLAS and CMS,
    $t\mu$: 1.4 TeV, *te*: *900*GeV recast of CMS SUSY, be and $b\mu$: 1.5 TeV

- Diquark searches: ϕ_A -> qq($q$bar): 500(600) GeV for triplet *jj* (*bj*) by ATLAS CMS, 800 GeV for Octet, expect similar limits for sextet
  - 2 or more times for HL-LHC (14 TeV, 3 ab^{-1})

  - *tttt, 1TeV for octet by recast of CMS, to 1.3 TeV at HL-LHC*

5. Collider Phenomenology

- B. Higgs coupling modifications
- ggH, γγH production
- change the production cross section of Higgs
- Probe light scalars and low f_Φ ~ 300(500) GeV for triplet (sextet, octet)



$$V \supset A_{h\phi_A^\dagger \phi_A}\, h\, |\phi_A|^2 \qquad A_{h\phi_A^\dagger \phi_A} = -\frac{m_h^2\, v_A}{f_\Phi^2}\frac{\cot(2\vartheta)}{\sin\vartheta}$$

$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{\rm SM}} \simeq \left|\cos\vartheta - c_\Phi\, d_\Phi\, Y_\Phi^2\, \frac{A_{h\phi_A\phi_A^*}\, v_A}{6\, m_\phi^2\, A_{\gamma\gamma}^{\rm SM}}\right|^2$$

$$\sin\theta \sim 1/3, \qquad \frac{\Gamma(h\to gg)}{\Gamma(h\to gg)_{\rm SM}} \simeq \left|\cos\vartheta + c_\Phi\, T_\Phi\, \frac{A_{h\phi_A\phi_A^*}\, v_A}{3\, m_\phi^2\, A_{gg}^{\rm SM}}\right|^2, \qquad A_{\gamma\gamma}^{\rm SM} \approx 6.5,\ A_{gg}^{\rm SM} \approx 1.4$$

. Summary

- MTH provides an elegant symmetry-based understanding of little hierarchy problem
- Z2 breaking is spontaneous,
- leads to big difference between two sectors: residual symmetry, confinement, particle spectrum.
- Dynamical mass terms generated by scalar fermion couplings, and tied to the precision tests in the visible sector,
- Colored scalars may be probed at colliders like LHC

- OUTLOOK: Cosmological histories within our models:
  - role of scalar in baryogenesis
  - Twin baryons and bound states may serve as dark candidate or as dark radiation, featuring new long range forces and/or low confinement scales,
  - Sextet broken to $SO(3)_c$ is interesting for its rather low confinement and long range forces ~ earth size. Kang, Luty 2009, 0805.4642

- Thank you!

Backup

Φ	Coupling to fermion bilinear	ϕ_A decay	Twin fermion mass terms	
			$[SU(2)_c \times U(1)'_{\rm EM}]_B$	
$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	$\Phi\,(Q\,Q)$	$\phi_A \to \bar u\,\bar d$	$\hat u_B\,\hat d_B$	
	$\Phi^\dagger\,(Q\,L)$	$\phi_A \to u\,e, d\,\nu$	$\hat u_{B3}\,e_B,\ \hat d_{B3}\,\nu_B$	
	$\Phi^\dagger\,\bar u\,\bar d$	$\phi_A \to \bar u\,\bar d$	$\hat{\bar u}_B\,\hat{\bar d}_B$	
	$\Phi\,\bar u\,\bar e$	$\phi_A \to u\,e$	$\hat{\bar u}_{B3}\,\bar e_B$	
	$\Phi\,\bar d\,(L\,H)$	$\phi_A \to d\,\nu$	$\hat{\bar d}_{B3}\,\nu_B$	
	$\Phi\,(H^\dagger Q)(Q\,H)$	$\phi_A \to \bar u\,\bar d$	$\hat u_B \hat d_B$	
	$\Phi^\dagger\,(H^\dagger Q)(L\,H)$	$\phi_A \to d\,\nu$	$\hat d_{B3}\,\nu_B$	
	$\Phi^\dagger\,(Q\,H)(H^\dagger L)$	$\phi_A \to u\,e$	$\hat u_{B3}\,e_B$	
$(\mathbf{3},\mathbf{1},\frac{2}{3})$	$\Phi^\dagger\,\bar d\,\bar d$	$\phi_A \to \bar d\,\bar d$	$\hat{\bar d}_B\,\hat{\bar d}_B$	
	$\Phi\,\bar u\,(L\,H)$	$\phi_A \to u\,\nu$	$\hat{\bar u}_{B3}\,\nu_B$	
	$\Phi\,\bar d\,(H^\dagger L)$	$\phi_A \to d\,\bar e$	$\hat{\bar d}_{B3}\,e_B$	
	$\Phi^\dagger\,(H^\dagger Q)\,\bar e$	$\phi_A \to d\,\bar e$	$\hat d_{B3}\,\bar e_B$	
	$\Phi\,(H^\dagger Q)(H^\dagger Q)$	$\phi_A \to \bar d\,\bar d$	$\hat d_B\,\hat d_B$	
	$\Phi^\dagger\,(Q\,H)(L\,H)$	$\phi_A \to u\,\nu$	$\hat u_{B3}\,\nu_B$	
$(\mathbf{3},\mathbf{1},-\frac{4}{3})$	$\Phi^\dagger\,\bar u\,\bar u$	$\phi_A \to \bar u\,\bar u$	$\hat{\bar u}_B\,\hat{\bar u}_B$	
	$\Phi\,\bar d\,\bar e$	$\phi_A \to d\,e$	$\hat{\bar d}_{B3}\,\bar e_B$	
	$\Phi\,(Q\,H)\,(Q\,H)$	$\phi_A \to \bar u\,\bar u$	$\hat u_B\,\hat u_B$	
	$\Phi^\dagger\,(H^\dagger Q)(H^\dagger L)$	$\phi_A \to d\,e$	$\hat d_{B3}\,e_B$	
$(\mathbf{3},\mathbf{1},\frac{5}{3})$	$\Phi^\dagger\,(Q\,H)\,\bar e$	$\phi_A \to u\,\bar e$	$\hat u_{B3}\,\bar e_B$	
	$\Phi\,\bar u\,(H^\dagger L)$	$\phi_A \to u\,\bar e$	$\hat{\bar u}_{B3}\,e_B$	
			$[SU(2)_c \times U(1)'_{\rm EM}]_B$	$[SO(3)_c]_B$
$(\mathbf{6},\mathbf{1},\frac{1}{3})$	$\Phi^\dagger\,(Q\,Q)$	$\phi_A \to u\,d$	$\hat u_{B3}\,\hat d_{B3}$	$u_B\,d_B$
	$\Phi\,\bar u\,\bar d$	$\phi_A \to u\,d$	$\hat{\bar u}_{B3}\,\hat{\bar d}_{B3}$	$\bar u_B\,\bar d_B$
	$\Phi^\dagger\,(Q\,H)(H^\dagger Q)$	$\phi_A \to u\,d$	$\hat u_{B3}\,\hat d_{B3}$	$u_B\,d_B$
$(\mathbf{6},\mathbf{1},-\frac{2}{3})$	$\Phi\,\bar d\,\bar d$	$\phi_A \to d\,d$	$\hat{\bar d}_{B3}\,\hat{\bar d}_{B3}$	$\bar d_B\,\bar d_B$
	$\Phi^\dagger(H^\dagger Q)(H^\dagger Q)$	$\phi_A \to d\,d$	$\hat d_{B3}\,\hat d_{B3}$	$d_B\,d_B$
$(\mathbf{6},\mathbf{1},\frac{4}{3})$	$\Phi\,\bar u\,\bar u$	$\phi_A \to u\,u$	$\hat{\bar u}_{B3}\,\hat{\bar u}_{B3}$	$\bar u_B\,\bar u_B$
	$\Phi^\dagger(Q\,H)(Q\,H)$	$\phi_A \to u\,u$	$\hat u_{B3}\,\hat u_{B3}$	$u_B\,u_B$
			$[SU(2)_c \times U(1)_c \times U(1)_{\rm EM}]_B$	$[U(1)_c \times U(1)'_c \times U(1)_{\rm EM}]_B$
$(\mathbf{8},\mathbf{1},0)$	$\Phi\,(Q\,H)\bar u$	$\phi_A \to u\,\bar u$	$\hat u_B\,\hat{\bar u}_B - 2\hat u_{B3}\,\hat{\bar u}_{B3}$	$\hat u_{B1}\,\hat{\bar u}_{B1} - \hat u_{B2}\,\hat{\bar u}_{B2}$
	$\Phi\,(H^\dagger Q)\bar d$	$\phi_A \to d\,\bar d$	$\hat d_B\,\hat{\bar d}_B - 2\hat d_{B3}\,\hat{\bar d}_{B3}$	$\hat d_{B1}\,\hat{\bar d}_{B1} - \hat d_{B2}\,\hat{\bar d}_{B2}$

- New EM Charges

$$\mathbf{I}: \quad (\mathbf{3},\mathbf{1},Y_\Phi) \quad Q_B^{\rm EM} = \tau^3 + Y + \sqrt{3}\, Y_\Phi\, T^8$$

$$\mathbf{II}: \quad (\mathbf{6},\mathbf{1},Y_\Phi) \quad Q_B^{\rm EM} = \tau^3 + Y + \frac{\sqrt{3}}{2}\, Y_\Phi\, T^8$$

$$\mathbf{IV}: \quad (\mathbf{8},\mathbf{1},0) \quad Q_B^{\rm EM} = \tau^3 + Y\ .$$

I $(\mathbf{3},\mathbf{1},Y_\Phi)$				
$\hat\psi$ \ Y_Φ	$5/3$	$2/3$	$-1/3$	$-4/3$
$Q_B^{\rm EM}[\hat u_{B\,\hat\imath}] = -Q_B^{\rm EM}[\hat{\bar u}_B^{\,\hat\imath}]$	$3/2$	1	$1/2$	0
$Q_B^{\rm EM}[\hat d_{B\,\hat\imath}] = -Q_B^{\rm EM}[\hat{\bar d}_B^{\,\hat\imath}]$	$1/2$	0	$-1/2$	-1
$Q_B^{\rm EM}[\hat u_{B3}] = -Q_B^{\rm EM}[\hat{\bar u}_B^{\,3}]$	-1	0	1	2
$Q_B^{\rm EM}[\hat d_{B3}] = -Q_B^{\rm EM}[\hat{\bar d}_B^{\,3}]$	-2	-1	0	1

II $(\mathbf{6},\mathbf{1},Y_\Phi)$			
$\hat\psi$ \ Y_Φ	$4/3$	$1/3$	$-2/3$
$Q_B^{\rm EM}[\hat u_{B\,\hat\imath}] = -Q_B^{\rm EM}[\hat{\bar u}_B^{\,\hat\imath}]$	1	$3/4$	$1/2$
$Q_B^{\rm EM}[\hat d_{B\,\hat\imath}] = -Q_B^{\rm EM}[\hat{\bar d}_B^{\,\hat\imath}]$	0	$-1/4$	$-1/2$
$Q_B^{\rm EM}[\hat u_{B3}] = -Q_B^{\rm EM}[\hat{\bar u}_B^{\,3}]$	0	$1/2$	1
$Q_B^{\rm EM}[\hat d_{B3}] = -Q_B^{\rm EM}[\hat{\bar d}_B^{\,3}]$	-1	$-1/2$	0