The Minimal Moose with Exact T-Parity

Pedro Schwaller

Institute for Theoretical Physics
University of Zurich

SUSY 2009
Northeastern University, Boston
June 6, 2009
Outline

1. Little Higgs Models and T-parity
2. A model with exact T-parity
3. Particle Spectrum and EWPO

Based on work done in collaboration with A. Freitas and D. Wyler
Hierarchies and the Higgs

- The Standard Model perfectly describes physics up to a few 100 GeV
- Naturalness requires new physics at the 1 TeV scale to stabilize the Higgs mass
- Experiment: Generic new physics only allowed at $\sim 10$ TeV

Little Hierarchy Problem


- Higgs is Goldstone boson, protected by two or more global symmetries
- Only collective breaking of all global symmetries gives the Higgs boson a mass!

$\rightarrow$ Little Higgs Models
The minimal Moose

Example:

- Global symmetry $G = SU(3)_L \times SU(3)_R$ broken to $H = SU(3)_V$
- Gauge $[SU(2) \times U(1)]_L \times [SU(2) \times U(1)]_R$ subgroups, broken to $[SU(2) \times U(1)]_{SM}$
- Taken separately, each gauge group preserves enough global symmetries to leave some Goldstone bosons massless
- Any contribution to the Higgs mass must involve both gauge groups, can only occur at the two loop level
- $\delta m_h \sim g_L g_R \frac{\Lambda}{(4\pi)^2}$, allows $\Lambda \sim 10$ TeV

Goldstones $X = e^{2ix/f}$ transform under $G$ as:

$X \rightarrow LXR^†$

Represented as “link” fields between global groups
The minimal Moose

- For realistic model, need **four** link fields
  \[ X_i = e^{2 \pi i x_i / f} \]

- Higgs quartic interaction obtained from
  \[ \mathcal{L}_P = \kappa f^4 \text{tr}[X_1 X_2^\dagger X_3 X_4^\dagger] + \kappa' f^4 \text{tr}[X_1 X_4^\dagger X_3 X_2^\dagger] + \text{h.c.} \]

- Respects collective symmetry breaking

**T-Parity** Cheng, Low, 2003/4

- Original model strongly constrained by EWPO Kilic, Mahbubani, 2003

- Can be resolved by adding a discrete \( \mathbb{Z}_2 \) symmetry under which new particles are odd

- Requires introduction of “mirror” fermions \( Q_H \) and \( L_H \)

- Yields a dark matter candidate
The problems with T-parity

Little Higgs models are effective theories of some strong dynamics → should include WZW term $\Gamma_{WZW}$ into effective Lagrangian

Problem:

- T-parity typically implemented as $X_i \rightarrow X_i^\dagger$, $A_L \leftrightarrow A_R$
- The WZW term is odd under this action

$$\Gamma_{WZW}(X_i, A_L, A_R) \rightarrow -\Gamma_{WZW}(X_i, A_L, A_R)$$

- Breaks T-parity, leads to decay of dark matter candidate

Barger, Gao, Kong, 2007; Freitas, Schwaller, Wyler, 2008

Moreover:

- Other T-violating operators introduced by radiative corrections
- T-parity challenged already at the conceptual level
T-parity as exchange symmetry

A “simple” way out  Krohn, Yavin, 2008

Consider two link fields $X_1$ and $X_2$ with opposite link direction, e.g.

$$X_1 \rightarrow L_1 X_1 R_1^\dagger \quad X_2 \rightarrow R_2 X_2 L_2^\dagger$$

WZW term then given by

$$\Gamma_{WZW} = \Gamma(X_1, A_L, A_R) + \Gamma(X_2, A_R, A_L)$$

Even under the exchange symmetry

$$X_1 \leftrightarrow X_2 \quad A_L \leftrightarrow A_R$$

$\rightarrow$ new T-Parity
A new little Higgs model

- Take \([SU(3)_L \times SU(3)_R]^4 \rightarrow SU(3)^4\) breaking pattern (Minimal Moose), but with modified link field directions.
- Gauge \([SU(2) \times U(1)]_L \times [SU(2) \times U(1)]_R\) subgroups with identical couplings.
- Define T-parity as:
  \[X_1 \leftrightarrow X_2, \quad X_3 \leftrightarrow X_4, \quad A_L \leftrightarrow A_R\]

Remnant of original T-parity remains as approximate symmetry:
- Acts as \(X_i \rightarrow \Omega X_i \Omega, A_L \leftrightarrow A_R\).
- Forbids vacuum expectation values for T-even singlets and triplets, removes unwanted couplings.
- T'-parity, weakly broken by \(\Gamma_{WZW}\).
 Scalars

Under the SM gauge group, the Goldstone fields $x_i$ decompose as

$$x_i = \begin{pmatrix} \phi_i + \frac{1}{\sqrt{3}} \eta_i & h_i \\ h_i^\dagger & -\frac{2}{\sqrt{3}} \eta_i \end{pmatrix}$$

- Each link field yields a real electroweak singlet, a complex doublet and a real triplet
- One T-odd triplet and singlet eaten by heavy gauge bosons
- $\Omega = \text{diag}(1, 1, -1)$ ensures that remaining singlets and triplets are T’-odd
- Only the two T-even doublets $h_a, h_b$ may acquire a vev

$\rightarrow$ effective Two Higgs Doublet model
Fermion couplings

Want fermion sector that realizes T-parity linearly

- Introduce two left-handed fermion doublets for each flavor:
  \[ Q_a = (d_a, u_a, 0)^T \quad Q_b = (d_b, u_b, 0)^T \]

- T-parity acts as \( Q_a \leftrightarrow Q_b \)
- Large mass for T-odd combination \( Q_H = \frac{1}{\sqrt{2}}(Q_a - Q_b) \) from
  \[
  \mathcal{L}_c = -\frac{\lambda_c}{\sqrt{2}} f \left( Q_a \xi_1 - Q_b \Omega \xi_1^\dagger - Q_b \xi_2 \Omega + Q_a \Omega \xi_2^\dagger \right) Q_c^c + \text{h.c.}
  \]
- where \( Q_c^c = (d_c^c, u_c^c, 0)^T \) Dirac partner for \( Q_H \), \( Q_c^c \rightarrow -\Omega Q_c^c \) under T-parity
- \( \xi_i = \sqrt{X_i} = e^{ix_i/f} \)
Top Yukawa coupling

- Yukawa couplings for fermion doublets break global $SU(3)$ symmetries
- Large Higgs mass from top Yukawa $\rightarrow$ need to make top sector $SU(3)$ symmetric
- with T-parity, need

$$Q_{3a} = (d_{3a}, u_{3a}, U_a)^T, \quad Q_{3b} = (d_{3b}, u_{3b}, U_b)^T, \quad Q_{3c}^c = (d_{3c}^c, u_{3c}^c, U_c^c)^T$$

- Corresponding righthanded partners $U_a^c, U_b^c$

$$\mathcal{L}_{top} = -\lambda_f Q_{3a} \left( X_3 + \Omega X_4^\dagger \Omega \right) \begin{pmatrix} 0 \\ 0 \\ U_b^c \end{pmatrix} - \lambda_f Q_{3b} \left( \Omega X_3^\dagger \Omega + X_4 \right) \begin{pmatrix} 0 \\ 0 \\ U_a^c \end{pmatrix} + \text{h.c.}$$

- Parameters $\lambda, \lambda_c$ constrained by $\lambda_{top} = 1/\sqrt{2}$, free parameter $R = \lambda/\lambda_c$ controls top mixing
Top quark sector

Linearizing $\mathcal{L}_c$ and $\mathcal{L}_{top}$ we obtain

- Two T-odd top partners $T_H = \frac{1}{\sqrt{2}}(u_{3a} - u_{3b})$ and $T' = \frac{1}{\sqrt{2}}(U_a - U_b)$
- Masses $M_{T_H} = 2\lambda_c f$ and $M_{T'} = 2\lambda f$

the T-even top quarks mix and yield

- Massive $T$ quark with $M_T = 2\sqrt{\lambda^2 + \lambda_c^2 f}$
- Massless top quark $t$ with Yukawa coupling to $h_a$ doublet:

$$\lambda_{top} = \frac{\sqrt{2}\lambda\lambda_c}{\sqrt{\lambda^2 + \lambda_c^2}}$$

Note:

- $T$ quark can be decoupled by increasing $\lambda_c$, without affecting the Higgs mass
- Quadratic divergence cancelled by parity-odd $T'$ quark
Scalar masses and EWSB

Goldstone bosons receive $\mathcal{O}(f)$ masses from several sources:

- Explicit mass terms from Plaquette operators $\mathcal{L}_p$
- One-loop masses from mirror fermion mass and kinetic terms
- One-loop masses from top Yukawa couplings

Adding all contributions, only one Higgs doublet $h_a$ and a scalar triplet $\phi_a$ remain light

EWSB via two Higgs doublet model with heavy second doublet $h_b$

$h_a, h_b$ acquire vevs with $\langle h_a \rangle^2 + \langle h_b \rangle^2 = v^2 = (246 \text{ GeV})^2$ for natural parameter choices

Yields light SM like neutral Higgs and heavy $H^0, A^0$ and $H^\pm$
Electroweak precision tests

Main contributions to T-parameter from
- mixing in the top sector, depends on $R, f$
- Mass splitting of $W^\pm_H, W^0_H$, suppressed for large $f$
- Mass splitting of heavy Higgs fields $H^0, A^0, H^\pm$

Allowed region in $f-R$ plane, for
- $M^2_{H^\pm} - M^2_{A^0} = (200 \text{ GeV})^2$
- $M^2_{H^0} - M^2_{A^0} = -(200 \text{ GeV})^2$

Note:
Constraints from $S$-parameter in general weaker
Other constraints could be important → more detailed analysis required
Conclusions

Main Messages:

- Exchange symmetry yields a more robust implementation of T-parity for little Higgs models

- Minimal Moose model with exact T-parity successfully reproduces the standard model at low energies

- Pass electroweak precision tests even for low new physics scales $\rightarrow$ in reach of LHC