A little Higgs model with exact dark matter parity

Pedro Schwaller

Institute for Theoretical Physics
University of Zurich

The New, the Rare and the Beautiful Workshop
Zurich, Switzerland
January 6, 2010

Outline

Based on arxiv:0906.1816 and arXiv:0912.3647
with A. Freitas and D. Wyler

Hierarchies and Goldstone bosons

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

Little Hierarchy Problem

Possible Solution: Higgs as Goldstone boson Georgi, Kaplan 1985

- Global symmetry group G broken to subgroup H by strong dynamics
- Yields massless Goldstone boson for each broken generator
- Higgs doublet realized as part of these bosons

Little Higgs models

However:

- Higgs couplings to gauge bosons and fermions break global symmetry
- generate Higgs mass terms at one loop: $\delta m_h \sim g\frac{\Lambda}{4\pi}$, $\lambda_{top}\frac{\Lambda}{4\pi}$
- again too large for $\Lambda \sim 10$ TeV

Issue adressed some 20 years later:

Collective Symmetry Breaking Arkani-Hamed et. al. 2001/2002

- Enlarge G such that two separate global symmetries protect the Higgs
- Only collective breaking of both global symmetries lead to a Higgs mass

Little Higgs Models

The minimal Moose

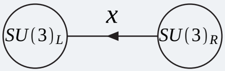
Example: Arkani-Hamed et. al. 2002

- 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:

$$X \rightarrow L X R^\dagger$$

Represented as “link” fields between global groups



The minimal Moose

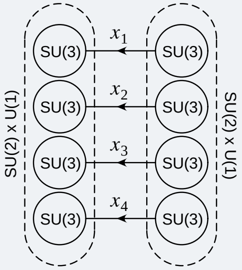
- For realistic model, need four link fields

$$X_i = e^{2ix_i/f}$$

- Higgs quartic interaction obtained from

$$\mathcal{L}_P = \kappa f^4 \mathrm{tr}[X_1 X_2^\dagger X_3 X_4^\dagger] + \kappa' f^4 \mathrm{tr}[X_1 X_4^\dagger X_3 X_2^\dagger] + \text{h.c.}$$

- Respects collective symmetry breaking



Scalar particle content:

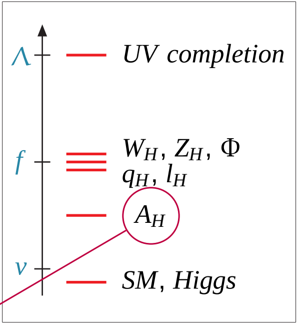
$$x_i = \begin{pmatrix} \phi_i + \frac{1}{\sqrt{3}}\eta_i & h_i \\ h_i^\dagger & -\frac{2}{\sqrt{3}}\eta_i \end{pmatrix}$$

- Each link field yields a real electroweak singlet, a complex doublet and a real triplet

Little Higgs models and T-parity

T-parity: Cheng, Low 2003, 2004

- Z_2 (parity) symmetry of scalar and gauge lagrangian
- Extended to symmetry of full model by adding mirror fermions: heavy partners for the SM quarks and leptons
- All new (heavy) particles are parity-odd
- Lightest T-odd particle stable: dark matter candidate!



Particle Spectrum, with $f \sim 1$ TeV and $\Lambda = 4\pi f$

T-parity forbids exchange of new particles at tree-level
$\longrightarrow$ Low masses (sub-TeV) for new particles possible

But T-parity is broken

Little Higgs models are effective theories of some strong dynamics
$\rightarrow$ should include WZW term Γ_{WZW} into effective Lagrangian Hill, Hill, 2007

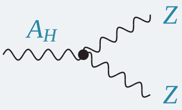
Problem:

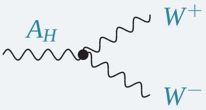
- T-parity implemented as $X_i \rightarrow X_i^\dagger$, $A_L \leftrightarrow A_R$
- The WZW term is odd under this operation:

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

and therefore leads to T-parity violating interactions.

The leading effect is the decay of A_H into pairs of W- or Z-bosons:



,


$$\sim \frac{N}{48\pi^2} \frac{v^2}{f^2}$$

Can we find a model with an exact dark matter parity?

An exchange symmetry

Remember: The problem is that $X \to X^\dagger$ is not a symmetry of Γ_{WZW}

Alternative possibility:

- Consider two link fields X_1 and X_2 with opposite link direction:

$$X_1 \to L_1 X_1 R_1^\dagger \qquad X_2 \to R_2 X_2 L_2^\dagger$$

- 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

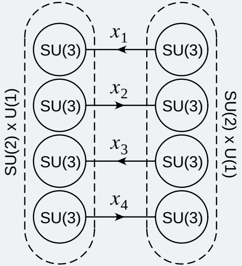
$$X_1 \leftrightarrow X_2 \qquad A_L \leftrightarrow A_R$$

$\to$ New parity symmetry: X-Parity

A little Higgs model with X-parity

- 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 X-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

- Forbids vacuum expectation values for X-even singlets and triplets at the tree level, removes unwanted couplings
- Only the two X-even doublets h_a, h_b may aquire a vev

$\longrightarrow$ effective Two Higgs Doublet model

Fermion couplings

Want fermion sector that realizes X-parity linearly

- Introduce two lefthanded fermion doublets for each flavor:

$$Q_a = (d_a, u_a, 0)^T \qquad Q_b = (d_b, u_b, 0)^T$$

- X-parity acts as $Q_a \leftrightarrow Q_b$

- Large mass for T-odd combination $Q_H = 1/\sqrt{2}(Q_a - Q_b)$ from

$$\mathcal{L}_c = -\frac{\lambda_c}{\sqrt{2}} f \left(Q_a \xi_1 - Q_b \Omega \xi_1^\dagger - Q_b \xi_2 \Omega + Q_a \Omega \xi_2^\dagger \Omega \right) Q_c^c + \text{h.c.}$$

- where $Q_c^c = (d_c^c, u_c^c, 0)^T$ Dirac partner for Q_H, $Q_c^c \to -\Omega Q_c^c$ under X-parity
- $\xi_i = \sqrt{X_i} = e^{i x_i / f}$

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 X-parity, need

$$Q_{3a} = (d_{3a}, u_{3a}, U_a)^T,\ Q_{3b} = (d_{3b}, u_{3b}, U_b)^T,\ Q^c_{3c} = (d^c_{3c}, u^c_{3c}, U^c_c)^T$$

- Corresponding righthanded partners U^c_a, U^c_b

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

- Parameters λ, λ_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 X-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 X-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:

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

Scalar masses

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

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

Resulting spectrum:

- All X-odd scalars receive $\mathcal{O}(f)$ masses $\rightarrow$ the gauge boson A_H is the lightest parity odd particle
- Most X-even scalars receive $\mathcal{O}(f)$ masses, except:
  - one Higgs doublet h_a
  - one scalar triplet ϕ_a

Electroweak Symmetry Breaking

- Higgs quartic potential V_4 from Plaquette terms, MSSM like
- quadratic potential generated radiatively:

$$V_2 = \frac{1}{2}\left[m_a^2|h_a|^2 + M_b^2|h_b|^2 + (m_{ab}^2 h_a^\dagger h_b + \text{h.c.})\right]$$
$$M_b \sim \mathcal{O}(f), \qquad m_a, m_{ab} \sim \mathcal{O}(v)$$

- Electroweak symmetry breaking works if $|m_{ab}|^4 > m_a^2 M_b^2$
- Nonzero m_{ab} requires imaginary parameter in the scalar self interactions $\longrightarrow$ CP-violation
- h_a, h_b aquire vev with $|\langle h_a \rangle|^2 + |\langle h_b \rangle|^2 = (246\ \text{GeV})^2$ for natural parameter choices

Physical Higgs states:

- Light ("little") Higgs h_0 (mostly from h_a)
- H^0, A^0, $H^\pm$ with masses $\sim M_b$
- CP violating mixings suppressed by $m_{ab}/M_b \ll 1$

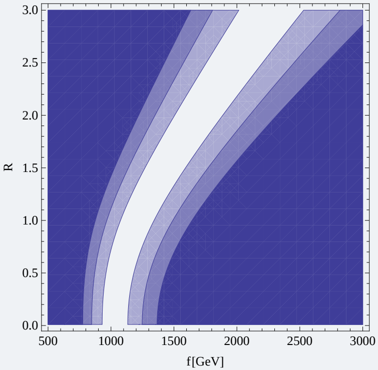
Phenomenology

Electroweak precision tests

Main contributions to T-parameter from

- Moderate custodial symmetry breaking in scalar sector
- Mixing in the top sector, depends on f and mixing parameter R
- Mass splitting of $W_H^\pm$, W_H^0 and of H^0, A^0, $H^\pm$

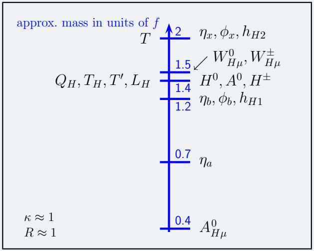
Allowed region in f-R plane, for fixed values of the mass splittings in the Higgs sector:



Note:
New particle masses around $1\ \mathrm{TeV}$ allowed! $\rightarrow$ model can be tested at LHC

Particle Content

Particles		X-Parity
Heavy gauge bosons	$A_H, Z_H, W_H^{\pm}$	-
Mirror quarks	Q_H	-
Mirror leptons	L_H	-
Top partners	T	+
	T_H, T'	-
Triplets	ϕ_x	-
	ϕ_a, ϕ_b	+
Singlets	η_x	-
	η_a, η_b	+
X-even doublets	h_0, $H^{0,\pm}$, A^0	+
X-odd dublets	h_{H1}, h_{H2}	-

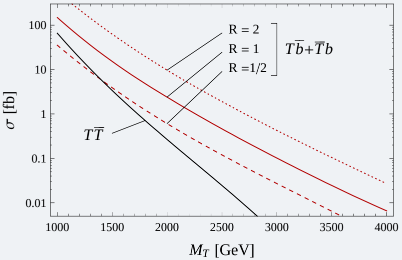


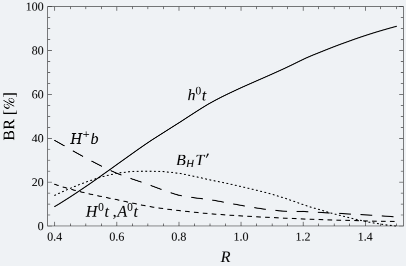
Scalar masses depend on ultraviolet physics, cannot be computed precicely in the effective theory

- X-odd particles produced in pairs
  $\longrightarrow$ missing energy signals since A_H escapes from the detector
- Not easy to find or discriminate from other models

LHC Signatures

- X-even T quark can be single and pair produced
- Sizeable production cross section if $M_T \lesssim 2$ TeV
- Complicated decay signatures into Higgs sector





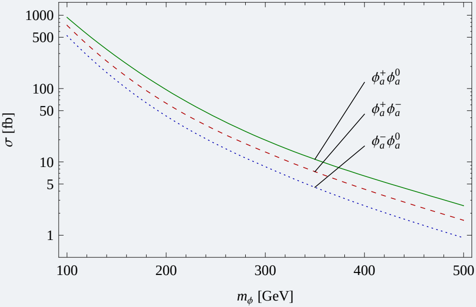
- Large cross section also possible for pair production of T'
- Top quark sector accessible at LHC

LHC Signatures

A smoking gun:

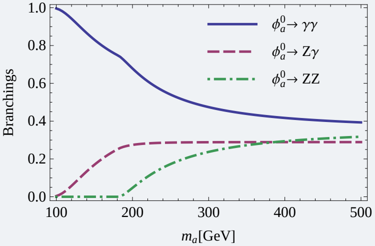
- Small mass of ϕ_a allows a large pair production cross section
- Protected by approximate T-parity, only decays into electroweak gauge bosons allowed (similar to $\pi^0 \to \gamma\gamma$)

Pair production at LHC ($\sqrt{s} = 14$ TeV):



LHC Signatures

- Large branching of ϕ_a^0 into decay modes with one or two photons
- $\mathcal{O}(\text{ GeV})$ mass splitting opens $\phi_a^{\pm} \to \phi_a^0 W^{\pm,*}$ channel for charged triplet fields



LHC Signatures

Multi-lepton signal rates ($m_a = 300$ GeV):

$\Delta m_a = 5$ GeV	10 TeV	14 TeV	$\Delta m_a = 20$ GeV	10 TeV	14 TeV
$l^+\gamma\gamma\gamma \not{E}$	1.04 fb	1.86 fb	$l^+\gamma\gamma\gamma\gamma \not{E}$	0.47 fb	0.84 fb
$l^+l^+l^-\gamma\gamma \not{E}$	0.049 fb	0.087 fb	$l^+l^+l^-\gamma\gamma\gamma \not{E}$	0.038 fb	0.068 fb
$l^+l^-\gamma\gamma \not{E}$	0.27 fb	0.51 fb	$l^+l^-\gamma\gamma\gamma\gamma \not{E}$	0.053 fb	0.10 fb

Multi-photon signal rates ($m_a = 300$ GeV):

$\Delta m_a = 5$ GeV	10 TeV	14 TeV	$\Delta m_a = 20$ GeV	10 TeV	14 TeV
$\gamma\gamma + X$	17.5 fb	32.5 fb	$\gamma\gamma + X$	15.1 fb	28.2 fb
$\gamma\gamma\gamma + X$	6.82 fb	12.6 fb	$\gamma\gamma\gamma + X$	9.31 fb	17.4 fb
			$\gamma\gamma\gamma\gamma + X$	4.20 fb	7.87 fb

Conclusions

- Little Higgs models are an interesting solution to the hierarchy problem
- The Little Higgs model with X-Parity is viable and has a stable dark matter candidate
- Anomalous decays of light scalars make an early discovery at LHC possible

HAPPY BIRTHDAY DANIEL