

Little Higgs Models

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Outline

- 1 Introduction to Little Higgs Models
- 2 Collider Signals of T-parity Violation
- 3 A Model with Exact Dark Matter Parity

The Hierarchy Problem

Standard model hierarchy problem:

$$\Delta m_H^2 = \text{---} \circlearrowleft \text{---} \sim \lambda_t^2 \Lambda^2$$

large new scale,
e.g. M_{GUT} , M_{planck}

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equal couplings due to SUSY

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Global symmetry:

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Little Higgs

Little Higgs models

How to build a little Higgs model? Arkani-Hamed et al 2001, 2002

- Make Higgs boson the Goldstone boson of a global symmetry group G
- Ensure that all couplings (e.g. gauge couplings, Yukawa couplings) preserve at least a subgroup of G
- Coupling relations (previous slide) will automatically be fulfilled

To achieve this we have to

- Add a partner T for the top quark
- Add partners for the electroweak gauge bosons, W_H , Z_H and A_H
- Add scalar triplet ϕ in the Higgs sector

The model is characterized by the scale $f \sim 1 \text{ TeV}$ where G is spontaneously broken!

Most new particles get $\mathcal{O}(f)$ masses

Little Higgs models and T-parity

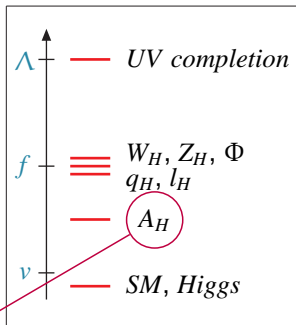
T-parity: Cheng, Low 2003, 2004

- 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!

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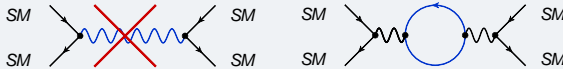
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Particle Spectrum, with $f \sim 1$ TeV and $\Lambda = 4\pi f$

Pheno Overview

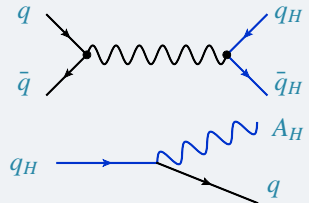
T-parity forbids exchange of new particles at tree-level:



⇒ Small contributions of new particles to electroweak precision observables:
Low masses (sub-TeV) for new particles possible!

At colliders:

- Pair production of T-odd particles via standard processes
- Decay to lightest T-odd particle: Jets (leptons) + missing energy signals



But T-parity is broken

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

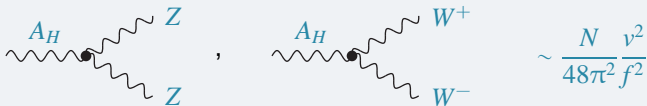
Problem:

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

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

and therefore leads to T-parity violating interactions.

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

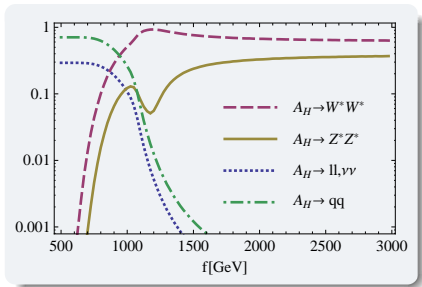
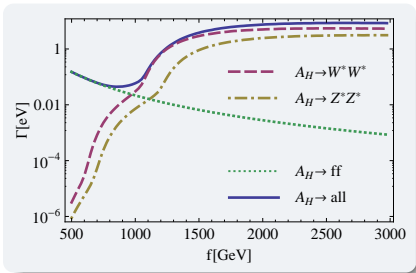


A_H Z Z , A_H W^+ W^- $\sim \frac{N}{48\pi^2} \frac{v^2}{f^2}$

Decays of A_H

Total width, including:

- Real $A_H \rightarrow W^+ W^-, ZZ$ decays
- Virtual $A_H \rightarrow VV^*, V^* V^*$ decays
- One-loop contributions
 $A_H \rightarrow f\bar{f}$

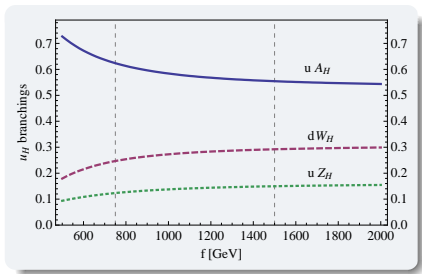
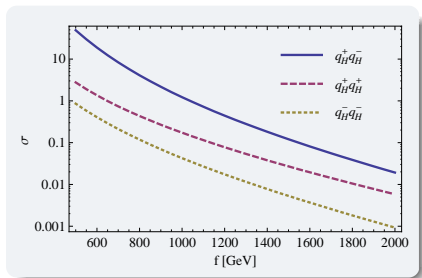


Branching Fractions:

- Below $f \sim 1000$ GeV
fermionic decays dominate
- Of fermionic decay modes:
~ 10% charged leptons
~ 20% neutrinos

Collider (LHC) Phenomenology

Production cross section of mirror quark pairs at LHC, in picobarn:



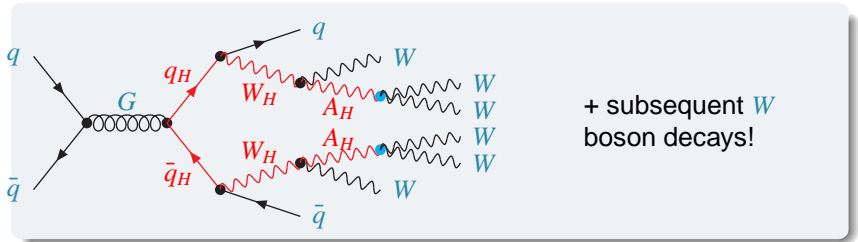
Branching Fractions for the decay $u_H \rightarrow u V_H$, with

- $m_{q_H} = \sqrt{2} \kappa f$
- $\kappa = 0.5$

For larger κ , W_H and Z_H channels more important

Collider (LHC) Phenomenology

A sample process ($f > 1 \text{ TeV}$, $m_{qH} > M_{W_H}$):



- events with **10 or more final states** are generic
- look for many jets, a few leptons, and some \cancel{E}_T
- rare channels like $e^+e^+\mu^-\mu^- + n \text{ jets}$ may help discriminate from other models

Collider (LHC) Phenomenology

Signal rates (before cuts) for the most probable final states:

| $f = 750 \text{ GeV}$ | | $f = 1500 \text{ GeV}$ | |
|---------------------------|---------------------|-------------------------------|---------------------|
| Final state | $\sigma[\text{fb}]$ | Final state | $\sigma[\text{fb}]$ |
| $6j$ | 994 | $10j$ | 8.2 |
| $4j + \cancel{E}$ | 568 | $8j + l + \cancel{E}$ | 8.4 |
| $6j + h$ | 306 | $6j + ll + \cancel{E}$ | 5.2 |
| $6j + l_*^- + \cancel{E}$ | 124 | $8j + l_*^- + l + \cancel{E}$ | 1.40 |

Hard leptons (denoted by l_*) arise from chains containing

$$q_H \rightarrow qW_H \rightarrow qWA_H \rightarrow ql\nu_l A_H$$

- For f larger than 1500 GeV : Hard to separate from background
- Same sign hard lepton signals might help, but have $\sigma < 1\text{fb}$

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

An exchange symmetry

Remember: The problem was that $\Sigma \rightarrow \Sigma^\dagger$ is not compatible with Γ_{WZW}

Alternative possibility:

- Assume we have two Goldstone fields, Σ_1 and Σ_2
- The WZW term then given by the sum of both contributions:

$$\Gamma_{WZW} = \Gamma(\Sigma_1, A_L, A_R) + \Gamma(\Sigma_2, A_R, A_L)$$

- This term is **even** under the eXchange symmetry

$$\Sigma_1 \leftrightarrow \Sigma_2 \quad A_L \leftrightarrow A_R$$

→ New parity symmetry: **X-Parity**

Features of the new model

Particle content:

- Gauge boson and fermion content (almost) unchanged
- Second Goldstone field Σ_2 introduced in the scalar sector
- Introduces additional scalar singlets and triplets and a **second Higgs doublet**

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

- Explicit mass terms
- One-loop masses from mirror fermion mass and kinetic terms
- One-loop masses from top Yukawa couplings

One Higgs doublet h_1 and a scalar triplet ϕ_a remain light

- EWSB via two Higgs doublet model with heavy second doublet h_2
- h_1, h_2 acquire vevs with $\langle h_1 \rangle^2 + \langle h_2 \rangle^2 = v^2 = (246 \text{ GeV})^2$
- Yields light SM like neutral Higgs and heavy H^0, A^0 and H^\pm

Electroweak precision tests

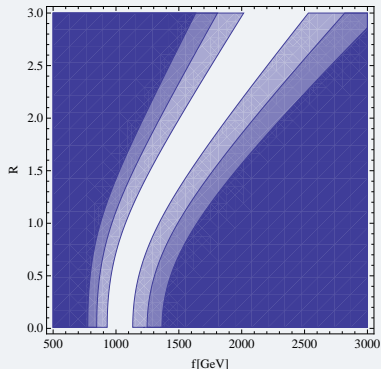
Main contributions to T-parameter from

- 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 TeV allowed! \rightarrow model can be tested at LHC

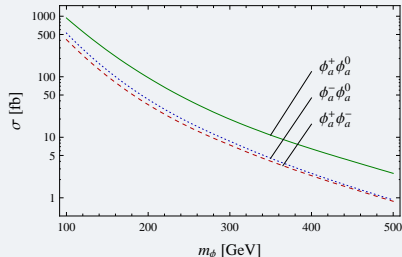


Signatures

- A_H is the lightest parity odd particle and a good dark matter candidate
- Pair production and jets + missing energy signals dominate again

One new distinct signature:

- Light ϕ_a produced copiously at LHC
- Main decay modes into SM gauge bosons, in particular $\phi_a^0 \rightarrow \gamma\gamma$
- Distinct $4\gamma + l^\pm$ signals possible, small \cancel{E}



Currently under investigation!

Conclusions

- Little Higgs models are an provide an interesting solution to the hierarchy problem
- T-parity is broken in the original models, resulting in interesting phenomenological signatures
- Using exchange symmetries, we built a working little Higgs model with stable dark matter and promising new signals