Little Higgs Models

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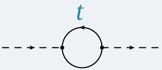
Outline

The Hierarchy Problem

Standard model hierarchy problem:

$\Delta m_H^2 =$ 

$\sim \lambda_t^2 \Lambda^2$

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

The Hierarchy Problem

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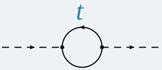

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Supersymmetry:

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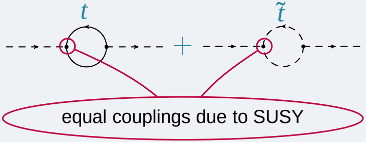

$$\sim \lambda_t^2 m_{susy}^2$$

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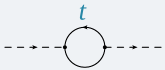

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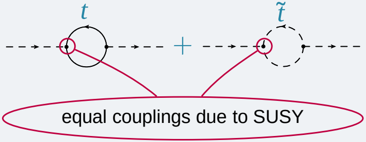

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Global symmetry:

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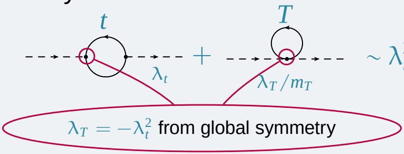

$\sim \lambda_t^2 m_T^2$

The Hierarchy Problem

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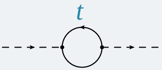
$\Delta m_H^2 =$ 

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

Supersymmetry:

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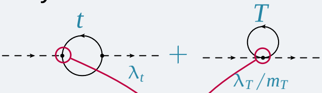
equal couplings due to SUSY

Global symmetry:

$\Delta m_H^2 =$ 

$\sim \lambda_t^2 m_T^2$

$\lambda_T = -\lambda_t^2$ from global symmetry

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 $f \sim 1\ \mathrm{TeV}$ 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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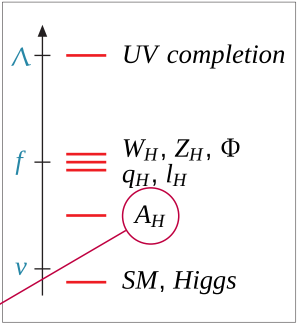
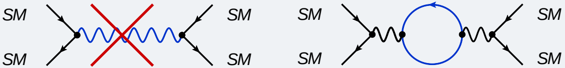


Particle Spectrum, with $f \sim 1$ TeV and $\Lambda = 4\pi f$

Pheno Overview

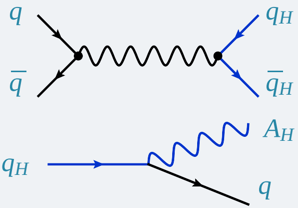
T-parity forbids exchange of new particles at tree-level:



$\Longrightarrow$ 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
$\rightarrow$ should include WZW term Γ_{WZW} into effective Lagrangian Hill, Hill, 2007

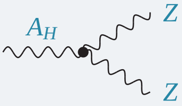
Problem:

- 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:



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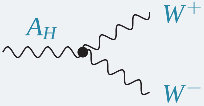
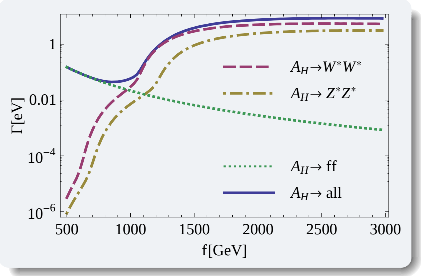


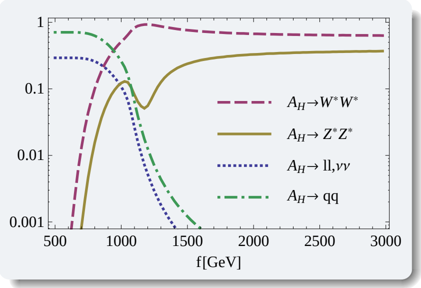
$$\sim \frac{N}{48\pi^2} \frac{v^2}{f^2}$$

Decays of A_H

Total width, including:

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



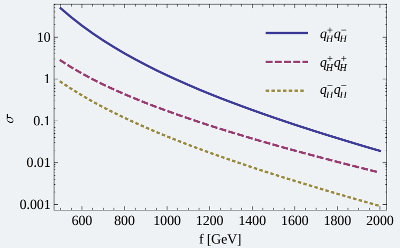


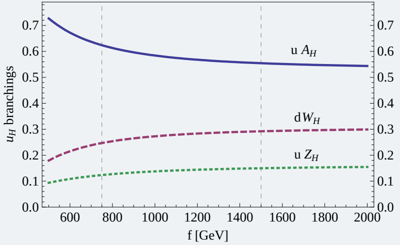
Branching Fractions:

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

Collider (LHC) Phenomenology

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





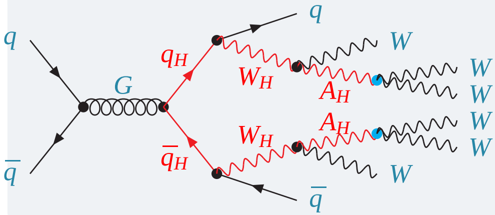
Branching Fractions for the decay $u_H \to uV_H$, with

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

For larger κ, W_H and Z_H channels more important

Collider (LHC) Phenomenology

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



+ subsequent W boson decays!

- events with 10 or more final states are generic
- look for many jets, a few leptons, and some $\not{E}_T$
- rare channels like $e^+ e^+ \mu^- \mu^- + \text{n jets}$ may help discriminate from other models

Collider (LHC) Phenomenology

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

$f = 750$ GeV		$f = 1500$ GeV	
Final state	$\sigma[fb]$	Final state	$\sigma[fb]$
$6j$	994	$10j$	8.2
$4j + \not{E}$	568	$8j + l + \not{E}$	8.4
$6j + h$	306	$6j + ll + \not{E}$	5.2
$6j + l_*^- + \not{E}$	124	$8j + l_*^- + l + \not{E}$	1.40

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

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

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

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

$$\Sigma_1 \leftrightarrow \Sigma_2 \qquad A_L \leftrightarrow A_R$$

$\rightarrow$ 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

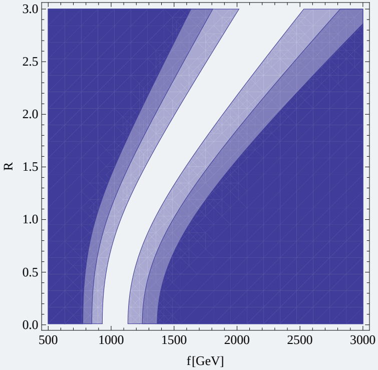
- EWSB via two Higgs doublet model with heavy second doublet h_2
- h_1, h_2 aquire vevs with $\langle h_2\rangle^2 + \langle h_2\rangle^2 = v^2 = (246\ \mathrm{GeV})^2$
- Yields light SM like neutral Higgs and heavy H^0, A^0 and $H^\pm$

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:



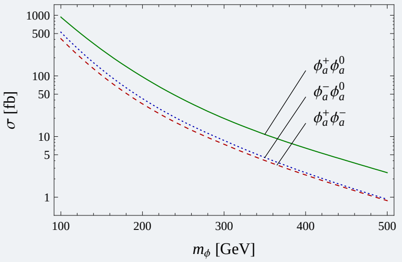
Note:
New particle masses around $1\ \mathrm{TeV}$ allowed! $\longrightarrow$ model can be tested at LHC

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 $\phi_a^0 \to \gamma\gamma$
- Distinct $4\gamma + l^{\pm}$ signals possible, small $\not{E}$



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