Little Higgs Theories and Dark Matter

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HC & I. Low, JHEP 0309:051,2003 (hep-ph/0308199)
JHEP 0408:061,2004 (hep-ph/0405243)

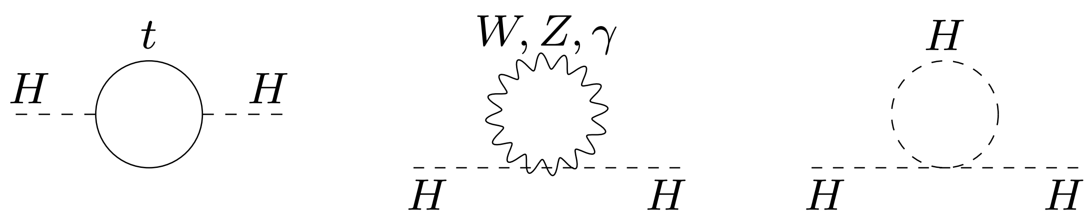
Tevatron ($E_{\text{CM}} = 2\text{TeV}$) is currently running,
LHC ($E_{\text{CM}} = 14\text{TeV}$) will start in 2007,
and numerous particle astrophysics experiments and observations are under way.
It's going to be an exciting time for particle and astroparticle physics.

Theoretically, there are good reasons to expect great discoveries at these experiments:

- The origin of electroweak symmetry breaking (EWSB),

- The composition of the dark matter in the universe.

The scalar Higgs field suffers from the hierarchy problem: the Higgs mass and VEV are very sensitive to Ultraviolet (UV) scale physics through quantum corrections.



$$\delta m_H^2 \sim \frac{1}{16\pi^2}\left\{\lambda_t^2,\ g^2,\ \lambda_H\right\}\Lambda_{\mathrm{UV}}^2$$

Naturalness requires these quadratically divergent contributions to be cut off by new physics at ~ 1 TeV.

Another hint of the TeV scale: dark matter

A weakly interacting stable neutral particle with a weak scale mass gives the right thermal relic abundance for the dark matter.

$$\Omega_{\text{wimp}} \sim \left(\frac{1}{10^2\alpha}\right)^2 \left(\frac{m_{\text{wimp}}}{1 \text{ TeV}}\right)^2$$

Therefore, we expect to discover not only the Higgs boson, but also exciting new physics at these TeV colliders.

Little Higgs theories

Higgs arises as a pseudo-Nambu-Goldstone boson (PNGB) of a spontaneously broken global symmetry, $G \to H$, with a special property that its mass is protected from one-loop quadratic divergences induced by the explicit symmetry breaking couplings.

The global symmetry is explicitly broken by 2 sets of interactions, with each set preserving a subset of the symmetry.

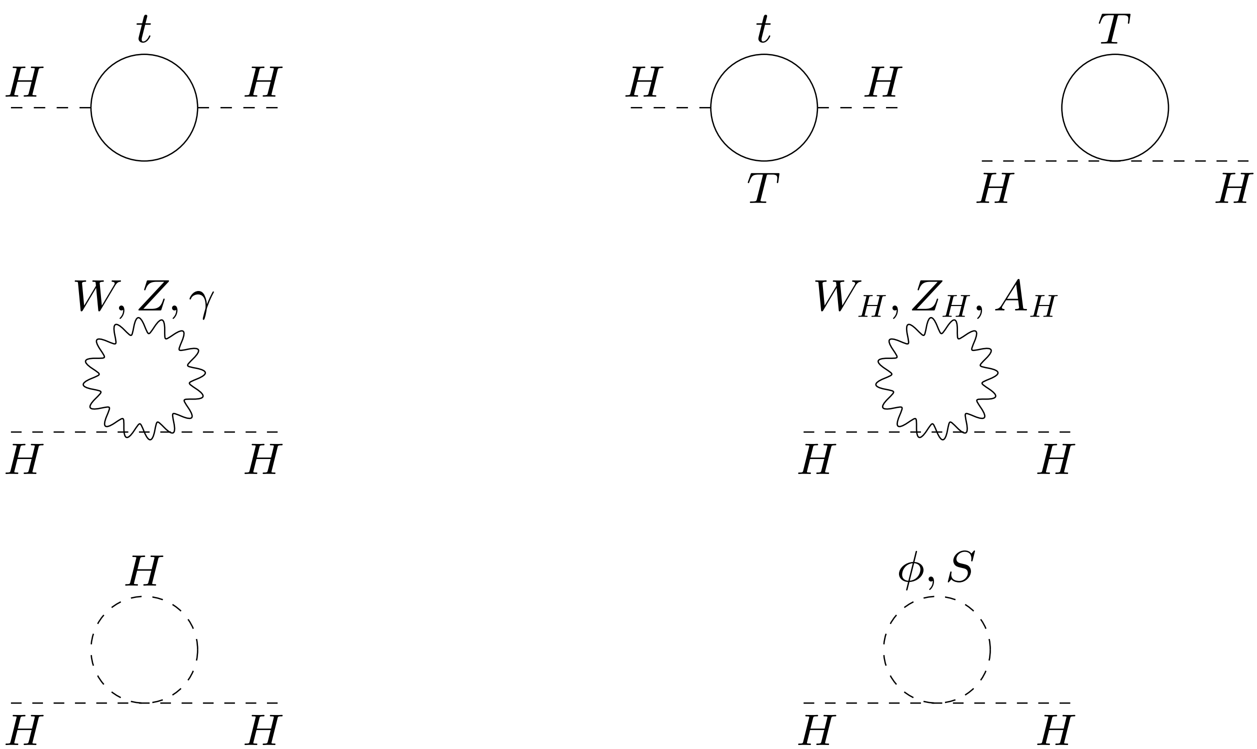
$$\mathcal{L} = \mathcal{L}_0 + \lambda_1 \mathcal{L}_1 + \lambda_2 \mathcal{L}_2$$

The Higgs is an exact NGB when either set of couplings is absent.

$$\delta m_H^2 \sim \left(\frac{\lambda_1^2}{16\pi^2}\right)\left(\frac{\lambda_2^2}{16\pi^2}\right)\Lambda^2$$

The cutoff Λ can be raised above 10 TeV, beyond the scale probed by the current electroweak data.

One-loop quadratic divergences are canceled by new particles at the TeV scale with the same spins as the corresponding SM particles.



$$m_{W_H} \sim gf,\ m_T \sim \lambda_t f, \ldots,\ f \sim 1\ \text{TeV},\ \Lambda \sim 4\pi f$$

Relations among couplings are ensured by non-linearly realized (approximate) global symmetry.

Generic spectrum for little Higgs theories:

UV completion

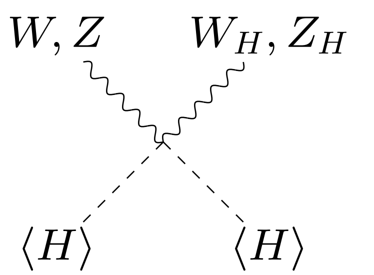
$\Uparrow$

$\Lambda \sim 4\pi f \sim 10$ TeV ——— UV cutoff

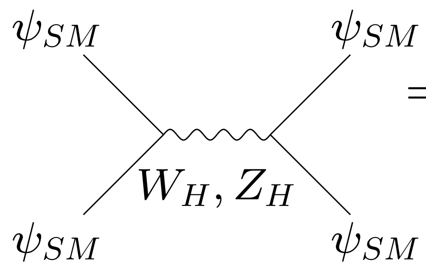
$f \sim 1$ TeV ——— T, W_H, Z_H, A_H, singlet/doublet/triplet scalars

100 GeV ——— SM with 1 or 2 Higgs Doublets

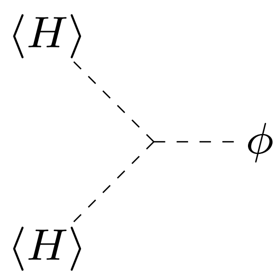
The new particles at $\sim$ 1 TeV can also contribute to EW observables.



$\Rightarrow$ Mass mixings between $W(Z)$, $W_H(Z_H)$. They shift the masses of W, Z and their couplings to fermions.



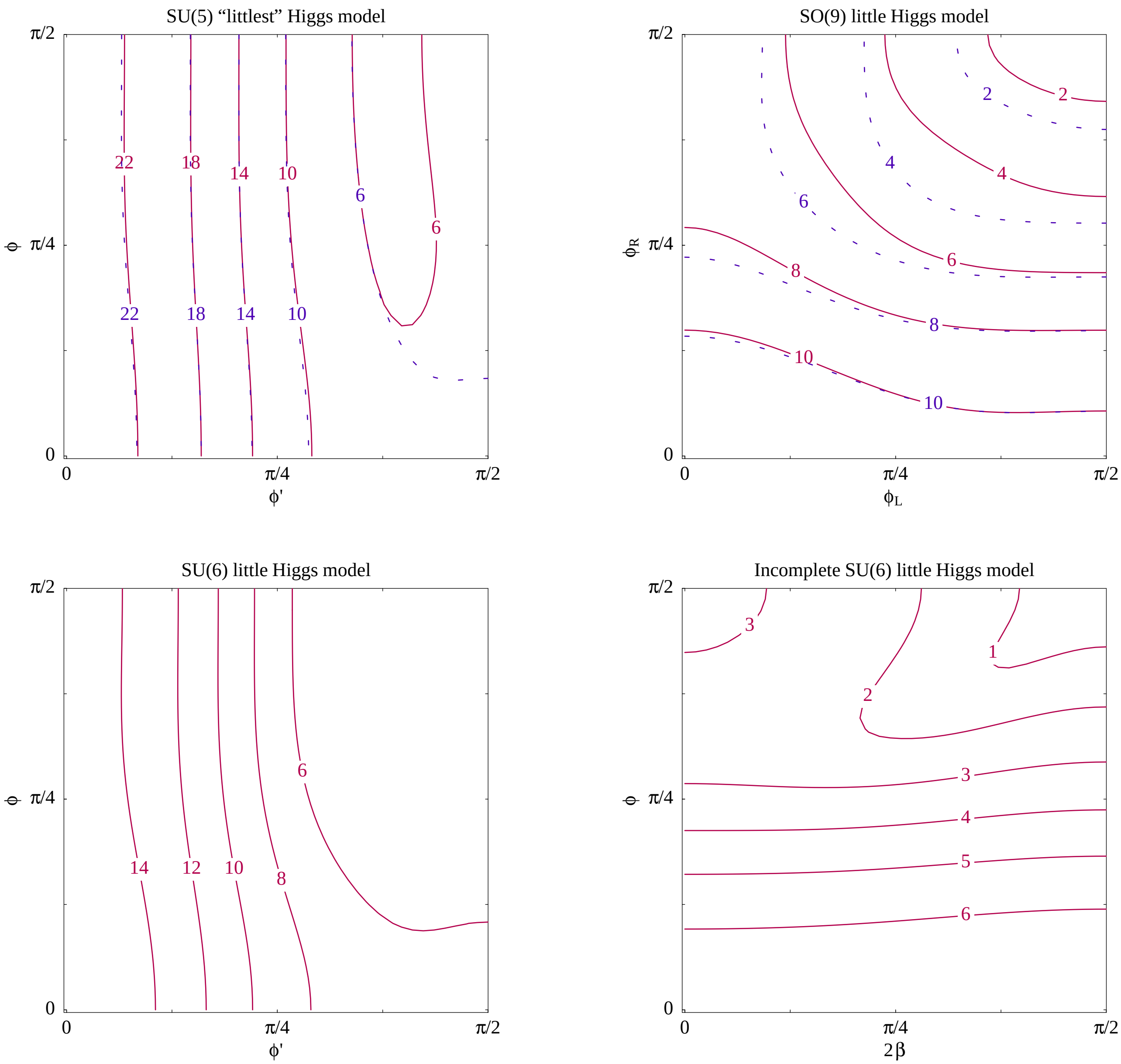
$\Rightarrow$ Induces 4-fermion interactions after integrating out W_H, Z_H.



$\Rightarrow$ Induces a triplet VEV $\langle \phi \rangle$ which shifts W, Z masses.

Generically f needs to be $\gtrsim$ a few TeV to avoid the constraints from EW data, potentially reintroducing the fine-tuning problem. (Csaki, Hubisz, Kribs, Meade, Terning, '02, Hewett, Petriello, Rizzo,'02,. . .)

Bounds on f (in TeV) for various models:



(Marandella, Schappacher, Strumia, '05)

T-parity (HC & Low, '03, '04)

The couplings which contribute to EW observables at tree level are not necessary for canceling the 1-loop quadratic divergence. They can be eliminated by a symmetry, T-parity:

$$\begin{aligned} SM &\rightarrow +SM \\ W_H, Z_H, A_H, \phi &\rightarrow -(W_H, Z_H, A_H, \phi) \end{aligned}$$

It is analogous to the R-parity in supersymmetric theories.

It can be imposed in many little Higgs models, in a similar way that Parity is conserved in QCD.

Phenomenology of little Higgs theories with T-parity:

- Contributions to EW observables are loop-suppressed. f can be $\lesssim$ 1TeV without violating EW precision data $\Rightarrow$ no fine tuning and new particles more accessible at colliders.

- Lightest T-odd particle (LTP) is stable. It can be a good dark matter candidate if it's neutral. (A likely candidate is the A_H gauge boson.)

- T-odd particles are pair-produced (traditional Z', W' searches don't apply), then they cascade decay down to LTP. Typical collider signals are $jets/leptons + \not{E}$, which mimic supersymmetry with R-parity.

Comparisons of the dark matter candidates in little Higgs theories and other theories

Comparisons with supersymmetry (SUSY):

- In SUSY, dark matter is likely to be the lightest neutralino, a Majorana fermion. Its annihilations to light fermions are helicity suppressed.

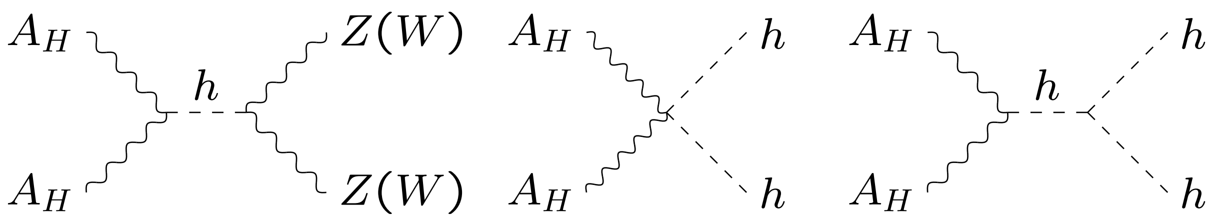
- A good dark matter candidate in little Higgs theories with T-parity is the heavy U(1) gauge boson, A_H. It is similar to the KK gauge boson in universal extra dimensions (UEDs). The annihilations can have significant branching fractions to light fermions $\Rightarrow$ good for indirect dark matter detections with e^+, ν, γ.

- Another possible dark matter candidate is a scalar pseudo-Nambu-Goldstone boson.

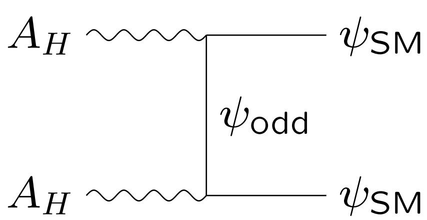
Lightest T-odd particle as the dark matter:

A_H is often the lightest T-odd particle.

Annihilation channels:



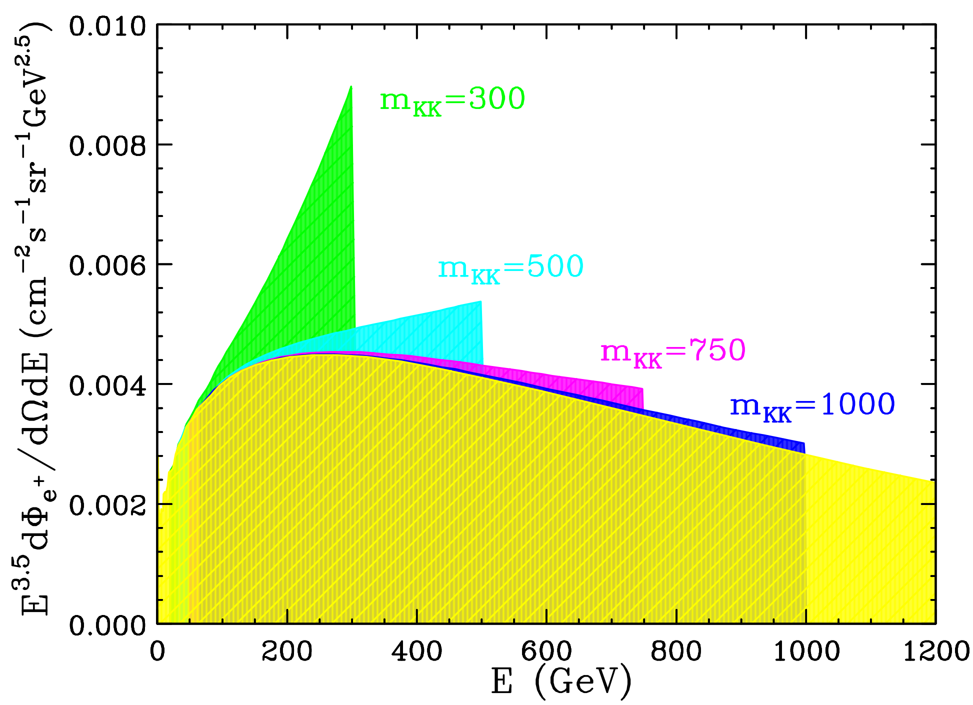
and in the presence of TeV T-odd fermions



It's somewhat similar to the Kaluza-Klein dark matter, (Servant, Tait, '02, HC, Feng, Matchev, '02) except that there is no reason for a degenerate spectrum.

Indirect detections of e^+, γ, and ν through dark matter annihilations may be distinctively promising.

(Positions from KK dark matter annihilations:)

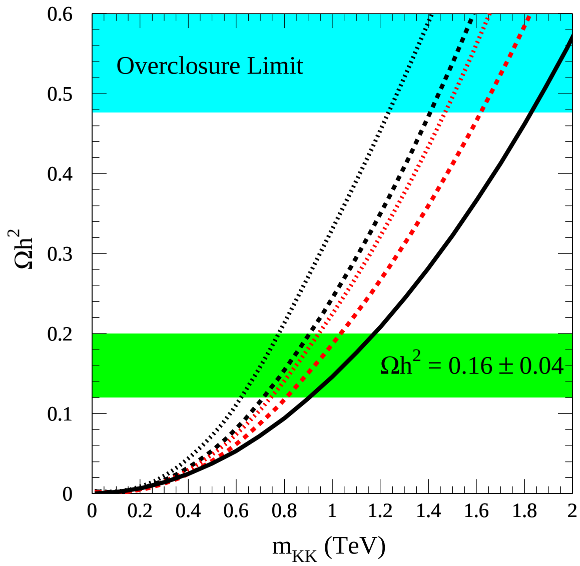


(HC, Feng, Matchev, '02)

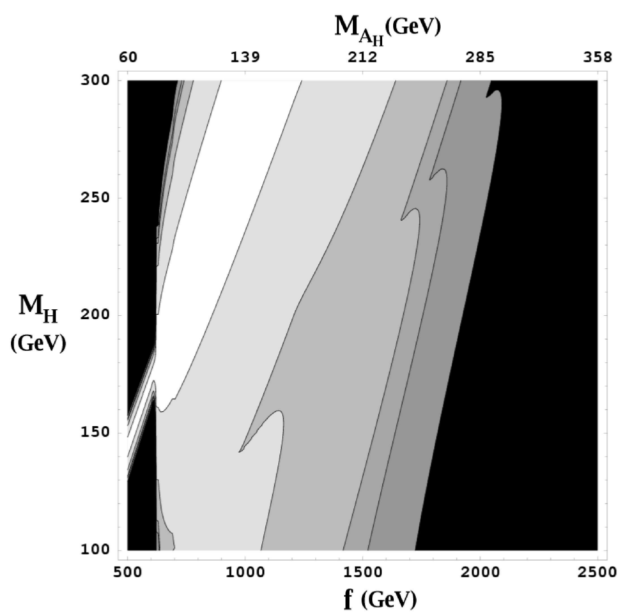
Comparisons with UEDs:

- The masses of various new particles in little Higgs theories are model-dependent and can be very different. They are not expected to be approximately degenerate as in UEDs. These affect the calculations of the relic density and detection rates.

- U(1) charge normalizations in little Higgs theories are also model-dependent. This affects the relative mass ratios of A_H and other particles. In particular, in models where only one U(1) is gauged, the dark matter candidate is the (would be eaten) pseudo-Nambu-Goldstone boson, a scalar particle rather than a vector particle.



KK dark matter relic density (Servant and Tait '02)



Littlest Higgs model with T-parity: from lightest to darkest, the A_H makes up ($0 - 10\%$, $10 - 50\%$, $50 - 70\%$, $70 - 100\%$, 100%, $> 100\%$) of the observed dark matter. (Hubisz and Meade '04)

Conclusions

1. Little Higgs theories provide a new mechanism to address the naturalness of the electroweak scale. With T-parity, the constraints from the electroweak precision data can be satisfied, and the lightest T-odd particle serves as a natural dark matter candidate. It provides a natural link between the TeV scale particle physics and cosmology.

2. LHC is expected to discover the new particles $\sim$ TeV which stabilize the EW scale. However, without the spin information, it's difficult to distinguish various theories (e.g., SUSY, UED, little Higgs) at a hadron collider. On the other hand, dark matter detections have different characteristics and can help to distinguish different theories before a linear collider with high enough energy is available.