A. Belyaev "New Phenomenology of Littlest Higgs models with T-parity", UW-Madison, December 7, 2006
OUTLINE

+ Motivation
+ Little Higgs model: the idea
+ Littlest Higgs model with T-parity (LHT)
+ Phenomenology of LHT model
+ Conclusions
The present status of the SM

- Based on SU(3)xSU(2)xU(1) symmetry spontaneously broken down to SU(3)xU(1):
- Matter: 3 generations of quarks and leptons
- One of the central role is played by Higgs field
  - One complex Higgs doublet
  - 3 degrees of freedom got eaten by massless W and Z, which acquire mass
  - 1 DOF becomes the massive scalar, Higgs boson

Higgs boson is still unobserved, it is the most wanted particle!
The present Higgs mass limit is 114.4 GeV from LEP2 $e^+e^-$ collider
SM: Experimental/Theoretical problems

- **Theoretical problems**
  - **naturalness and gauge hierarchy problem**

\[ M_H^2 = M_{H_0}^2 + \Delta M_H, \quad SM: \Delta M_H \sim \Lambda_{UV}^2 \]

\[ \delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2} [-2\Lambda_{UV}^2 + ...] \]
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  - Does not explain Dark Matter
    (WMAP results, galactic rotation curves, gravitational lensing)
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- Baryogenesis: the amount of CP violation is not enough because it predicts baryon asymmetry 10 orders of magnitude below the observed one
Consequences of SUSY

- Local SUSY transformations introduce spin-2 graviton
  \[ \text{spin}2 \rightarrow \text{spin}3/2 \rightarrow \text{spin}1 \rightarrow \text{spin}1/2 \rightarrow \text{spin}0 \]

- Provides connection to superstring models: crucial ingredient - allows to include fermions

- Solves fine-tuning problem of SM

- Provides unification of gauge couplings

- EW symmetry is broken radiatively via RGE running \( H_u \) and \( H_D \)

- Provides perfect DM candidate: stable LSP

- Potentially solves baryogenesis problem
“Little” Fine Tuning in MSSM

Tree-level lightest Higgs boson mass is below Z-boson mass

\[ M_{h}^{2} = \frac{1}{2} \left[ m_{A}^{2} + M_{Z}^{2} - \sqrt{\left( M_{A}^{2} + M_{Z}^{2} \right)^{2} - 4 m_{A}^{2} M_{Z}^{2} \cos^{2} 2\beta} \right] \Rightarrow M_{h} \simeq M_{Z} |\cos 2\beta| \text{ for } M_{a} \gg M_{Z} \]

Top-stop Radiative corrections to the light Higgs mass drive its mass up!

\[ \delta M_{h} = \frac{3 g^{2} m_{t}^{4}}{8\pi^{2} m_{W}^{2}} \left[ \ln \left( \frac{M_{S}^{2}}{m_{t}^{2}} \right) + x_{t}^{2} \left( 1 - \frac{x_{t}^{2}}{12} \right) \right] \]

SUSY scale >1 TeV is required to satisfy LEP2 \( M_{h} > 114.4 \text{ GeV} \) constraint. This leads to \( \sim 1\% \) of tuning to get Z-mass right

\[ m_{Z}^{2} = \frac{|m_{H_{d}}^{2} - m_{H_{u}}^{2}|}{\sqrt{1 - \sin^{2}(2\beta)}} - m_{H_{u}}^{2} - m_{H_{d}}^{2} - 2|\mu|^{2} \]
**Little Higgs model as an alternative to SUSY**

Arkani-Hamed, Cohen, Georgi hep-ph/0105239

- "Little Higgs" is a pseudo-Nambu-Goldstone boson of spontaneously broken global symmetry.
- This symmetry is also explicitly broken but only "collectively": when two or more couplings in the Lagrangian are non-vanishing: \( \mathcal{L} = \mathcal{L}_0 + \lambda_1 \mathcal{L}_1 + \lambda_2 \mathcal{L}_2 \)
- Setting any of these couplings to zero restores the symmetry and therefore the masslessness of the "little Higgs"
- Thus, little Higgs acquires its mass at second loop

\[
\delta m_H^2 \sim \left( \frac{\lambda_1^2}{16\pi^2} \right) \left( \frac{\lambda_2^2}{16\pi^2} \right) \Lambda^2 \\
m_H \sim O(100) \text{ GeV for } \Lambda \sim 10 \text{ TeV}
\]
Littlest Higgs: a minimal realization of Little Higgs


**SU(5) global symmetry is spontaneously broken to SO(5) by the VEV of**

\[
\Sigma_0 = \begin{pmatrix}
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0
\end{pmatrix}
\]

**at the scale** \( f \)

\[A_H, \ Z_H, \ W_H^{\pm}\]

**SU(5) ⊃ [SU(2) × U(1)]_1 × [SU(2) × U(1)]_2**

\[\lambda_1 \mathcal{L}_1 \quad \lambda_2 \mathcal{L}_2\]

**VEV = \( f \) ~ O(1) TeV**

**SO(5) ⊃ SU(2) × U(1)**

\[(N^2-1) [24] - N(N-1)/2 [10] = 14 \text{ goldstone bosons}\]

\[1_0 \oplus 3_0 \oplus 2_{\pm 1/2} \oplus 3_{\pm 1}\]

**Goldstone boson matrix parameterization in non-linear sigma model**

\[
\Pi = \begin{pmatrix}
0 & H/\sqrt{2} & \Phi \\
H^\dagger/\sqrt{2} & 0 & H^\dagger/\sqrt{2} \\
\Phi^\dagger/\sqrt{2} & H^*/\sqrt{2} & 0
\end{pmatrix}
\]

\[\Sigma = \exp(i\Pi/f)\Sigma_0\]

**Higgs is exact NG boson under either global SU(3)**

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Collective Symmetry Breaking

\[[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2\] are embedded in global SU(5)

\[Q^a_{SU(2)_1} = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad Y_1 = \frac{1}{10} \begin{pmatrix} 3 \\ 3 \\ -2 \\ -2 \end{pmatrix}\]

\[Q^a_{SU(2)_2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -\sigma^{a*}/2 \end{pmatrix}, \quad Y_2 = \frac{1}{10} \begin{pmatrix} 2 \\ 2 \\ 2 \\ -3 \end{pmatrix}\]

Either SU(3) is enough to keep Higgs massless. Sum of all gauge interactions break both SU(3)s and generate the Higgs mass.

\[\Lambda^2 \text{ corrections are canceled.}\]
Littlest Higgs: scalar kinetic term

\[ \mathcal{L}_\Sigma = \frac{1}{2} \frac{f^2}{4} \text{Tr} |\mathcal{D}_\mu \Sigma|^2 \]

with covariant derivative given by

\[ \mathcal{D}_\mu \Sigma = \partial_\mu \Sigma - i \sum_{j=1}^{2} \left( g_j (W_j \Sigma + \Sigma W_j^T) + g'_j (B_j \Sigma + \Sigma B_j^T) \right) \]

where \( \Sigma \) expanded around its vacuum expectation value

\[ \Sigma = \Sigma_0 + \frac{2i}{f} \left( \begin{array}{cc} \phi^\dagger & \frac{h^\dagger}{\sqrt{2}} \\ \frac{h^*}{\sqrt{2}} & 0 \\ 0_{2\times2} & \frac{h}{\sqrt{2}} \end{array} \right) + \mathcal{O}\left(\frac{1}{f^2}\right), \]

Lagrangian contains non-renormalizable interactions:
can be only low energy effective description of physics.

The loop contribution becomes as important as tree-level diagram
at the scale \( \Lambda \lesssim 4\pi f \) : theory becomes strongly coupled
LH Model industry: model building and phenomenology

Martin Schmaltz; Burdman, Perelstein, Pierce;

Han, Logan, McElrath, Wang;

Dib, Rosenfeld, Zerwekh;

Csaki, Hubisz, Kribs, Meade, Terning;

Huo, Zhu; Chang; Park, Song; Sullivan;

Perelstein, Peskin, Pierce; ...
**Little Higgs Model with T-parity (LHT)**

- Large tree-level corrections e.g. due to the exchange of additional heavy gauge bosons and non-vanishing VEV of triplet higgs: $f > 5 \text{ TeV}$, fine-tuning again!

- T-parity ($Z_2$ symmetry) (Cheng, Low 2003) forbids mixing with SM

$$SU(2)_1 \times U(1)_1 \leftrightarrow SU(2)_2 \times U(1)_2$$

- SM particles $\rightarrow$ + SM particles

$$(W_H, Z_H, A_H, \Phi, Q) \rightarrow -(W_H, Z_H, A_H, \Phi, Q)$$

- $g_1 = g_2 = \sqrt{2}g$ and $g'_1 = g'_2 = \sqrt{2}g'$

- **No tree-level to EW observables**

- **The lightest T-odd particle is a good DM candidate**

- **New scale $f$ can be lower then 1 TeV**

interesting phenomenology! (Hubisz et al., 2004)
LHT Model

Hsin-Chia Cheng, Ian Low,
Jay Hubisz, Patrick Meade,
Andrew Noble, Maxim Perelstein,
Claudio O. Dib, Rogerio Rosenfeld,
Alfonso Zerwekh, Seung J. Lee, Gil Paz,
Chuan-Ren Chen, Kazuhiro Tobe,
C.-P. Yuan, Andreas Birkedal, ...
LHT: new particles

Gauge sector

\[ A_H \quad (m \sim g' f / \sqrt{5}) \]
\[ Z_H, \ W_H^\pm \quad (m \sim g f) \]

Higgs sector

\[ \Phi : \ \phi^{++}, \ \phi^+, \ \phi^0, \ \phi^P \quad (m \sim \sqrt{2}m_h f / v) \]

\[ SU(2)_L \text{ doublets} \]

Fermion sector

\[ t'_+ \quad (m \sim \sqrt{\lambda_1^2 + \lambda_2^2} f) \]
\[ t'_- \quad (m \sim \lambda_2 f) \]

\[ Q_L^{(-)}, \ L_L^{(-)}, \ m \sim \sqrt{2\kappa} f \]

\[ SU(2)_L \text{ doublets} - \text{crucial component:} \]

provides gauge invariance and unitarity, solves the problem of 4-fermion contact interactions. Missed in the previous studies! Fermions do not decouple!

Pointed by Rattazzi
Cancellation of quadratic divergences

New heavy particles *bosons, top-quarks, scalars* cancel the respective SM one-loop quadratic divergences.
LHT Model: Yukawa interactions

\[-\frac{\lambda_1}{2\sqrt{2}} f \epsilon_{ijk} \epsilon_{xy} \left[ (\bar{Q}_1)_i \Sigma_{jx} \Sigma_{ky} - (\bar{Q}_2 \Sigma_0)_i \tilde{\Sigma}_{jx} \tilde{\Sigma}_{ky} \right] u_{R+} \]

\[-\lambda_2 f (\bar{U}_L U_{R_1} + \bar{U}_L U_{R_2}) + \text{h.c.}, \]

with \( Q_1 = (q_1, U_{L_1}, 0_2)^T \) and \( Q_2 = (0_2, U_{L_2}, q_2)^T \)

giving \( t, \ t_+, \ t_- \) with \( \sin \alpha = \frac{\lambda_1}{\sqrt{\lambda_1^2 + \lambda_2^2}} \)

\( M_t \sim (\lambda_2 \sin \alpha) v, \ M_{t-} \sim \lambda_2 f, \ M_{t+} \sim (\lambda_2 / \cos \alpha) f \)

\[-\kappa f (\bar{\Psi}_2 \xi \Psi_c + \bar{\Psi}_1 \Sigma_0 \Omega \xi^\dagger \Omega \Psi_c) + \text{h.c.} \]

fermion \( SU(2) \) doublets \( q_1 \) and \( q_2 \):

\( \Psi_1 = (q_1, 0, 0_2)^T \) and \( \Psi_1 = (0_2, 0, q_2)^T \)

giving \( U_-, \ D_- \), with \( M_Q_- = \sqrt{2} \kappa f \)
$A_H, \ m \sim g^2 f / \sqrt{2}$

$Z_H, \ W^\pm_H, \ m \sim g f$

$\phi^{++}, \ \phi^+, \ \phi^0, \ \phi^P$; 

$m \sim \sqrt{2} m_h f / \nu$

$\sin \alpha = \lambda_1 / \sqrt{\lambda_1^2 + \lambda_2^2}$

$M_t \simeq (\lambda_2 \sin \alpha) \nu,$

$M_{t-} \simeq \lambda_2 f,$

$M_{t+} \simeq (\lambda_2 / \cos \alpha) f$

$Q_L^{(-)}, \ L_L^{(-)},$

$m \sim \sqrt{2} \kappa f$

**Model parameters:**

$f, \ M_h, \ \sin \alpha, \ \kappa$
LHT: particle interactions

\[ V_H \]

\[ F_- \to f \]

\[ V \]

\[ F_- \to F_- \]

\[ V_H \]

\[ V \]

\[ F_- \to F_- \]

\[ \Phi \]

\[ H \]

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Phenomenology of LHT model

Model implementation: Lanhep → CalcHEP

Lanhep (A. Semenov) is the package for automatic generation of Feynman rules (model) for CalcHEP (A. Pukhov)

It lowers down a lot the possibility of human mistake

Previously, the essential part of the model has been implemented by J. Hubisz and P. Meade in hep-ph/0411264

Our study aims

- to implement the complete model
- to check the previous studies
- to systematise all possible phenomenology
- to apply CalcHEP-PYTHIA for multibody final states
- To calculate DM relic density within the complete model using MicroMEGAs 2.0 (A. Pukhov et al)
LHT implementation using LanHEP(1)

**Model:** Littlest Higgs-T

**Abstract**

CalcHEP package is created for calculation of decay and high energy collision processes of elementary particles in the lowest order (tree) approximation. The main idea put into the CalcHEP was to make available passing from the lagrangian to the final distributions effectively with the high level of automatization.

Use F2 key to get information about interface facilities and F1 - as online help.
LHT implementation using LanHEP(2)
LHT implementation using LanHEP(3)
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<td>Z</td>
<td></td>
<td>EE^2<em>vh/(2</em>CW^2*SW^2)</td>
</tr>
</tbody>
</table>

\[ \text{Lagrangian} \]

\[ \langle > d\text{Lagrangian} / \ dA(p1) \ dA(p2) \ dA(p3) \]

\[ G(m3) * (1-G5) \]

\[ -SW^2*G(m3) * (1-G5) + 5*del^2*CW*xh*(1-G5)*G(m3) \]

\[ 5*CW^2*G(m3) * (1-G5) + del^2*SW*xh*(1-G5)*G(m3) \]

\[ G(m3) * (1-G5) \]

\[ G(m3) \]

\[ (1-2*SW^2)*G(m3) * (1-G5) - 2*SW^2*G(m3) * (1+G5) \]

\[ G(m3) * (1-G5) \]

\[ G(m3) \]

\[ 1 \]

\[ (1-2*SW^2)*G(m3) * (1-G5) - 2*SW^2*G(m3) * (1+G5) \]

\[ G(m3) * (1-G5) \]

\[ G(m3) \]

\[ 1 \]

\[ (1-2*SW^2)*G(m3) * (1-G5) - 2*SW^2*G(m3) * (1+G5) \]

\[ G(m3) * (1-G5) \]

\[ m2.p3*m1.m3-m1.p3*m2.m3+m3.p1*m1.m2-m2.p1*m1.m3-m3.m3.p2 \]

\[ 1 \]

\[ m2.m3 \]

\[ m2.m3 \]

\[ SW^2*m2.m3+(zero0*CW^2*xh^2*m2.m3+2*del^2*SW*CW*xh \]
LHT implementation using LanHEP(6)

<table>
<thead>
<tr>
<th>Model: Littlest Higgs-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of particles (antiparticles)</td>
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</table>

<table>
<thead>
<tr>
<th>Particle</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>W⁺(W⁻)</td>
<td>W boson</td>
</tr>
<tr>
<td>Z(0)</td>
<td>Z boson</td>
</tr>
<tr>
<td>G(G)</td>
<td>gluon</td>
</tr>
<tr>
<td>n₁(N₁)</td>
<td>neutrino</td>
</tr>
<tr>
<td>e₂(E₂)</td>
<td>muon</td>
</tr>
<tr>
<td>u(U)</td>
<td>u-quark</td>
</tr>
<tr>
<td>s(S)</td>
<td>s-quark</td>
</tr>
<tr>
<td>t₁(T₁)</td>
<td>t-quark</td>
</tr>
<tr>
<td>t₂(T₂)</td>
<td>T2-todd</td>
</tr>
<tr>
<td>~W⁺(~W⁻)</td>
<td>W heavy</td>
</tr>
<tr>
<td>~A(~A)</td>
<td>photon heavy</td>
</tr>
<tr>
<td>H(H)</td>
<td>H higgs</td>
</tr>
<tr>
<td>~P⁺(~P⁻)</td>
<td>p⁺ higgs</td>
</tr>
<tr>
<td>e₁(E₁)</td>
<td>electron</td>
</tr>
<tr>
<td>n₃(N₃)</td>
<td>tau-neutrino</td>
</tr>
<tr>
<td>d(D)</td>
<td>d-quark</td>
</tr>
<tr>
<td>t(T)</td>
<td>t-quark</td>
</tr>
<tr>
<td>~u(~U)</td>
<td>u-todd</td>
</tr>
<tr>
<td>~s(~S)</td>
<td>s-todd</td>
</tr>
<tr>
<td>~t₁(~T₁)</td>
<td>T1-todd</td>
</tr>
</tbody>
</table>

Enter process: \( u, u \rightarrow \sim u, \sim u \)
LHT implementation using LanHEP(7)
(sub)Process: u, u -> ~u, ~u
Monte Carlo session: 1(continue)

<table>
<thead>
<tr>
<th>#IT</th>
<th>Cross section [pb]</th>
<th>Error %</th>
<th>nCall</th>
<th>chi**2</th>
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<tr>
<td>4</td>
<td>5.1794E-02</td>
<td>2.34E-01</td>
<td>9826</td>
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<tr>
<td>5</td>
<td>5.1761E-02</td>
<td>2.37E-01</td>
<td>9826</td>
<td></td>
</tr>
<tr>
<td>&lt; &gt;</td>
<td>5.1961E-02</td>
<td>1.23E-01</td>
<td>49130</td>
<td>3</td>
</tr>
</tbody>
</table>

Constraints

Display dependence

Sqrt2= 1.4142
CW= 0.88197
MW= 80.425
v= 246.22

del= 0.24622
g= 0.65327
gp= 0.34909
xh= 0.14168
MAH= 150.2
MZH= 648.32
Muo= 1403.5
LHT: relic density abundance results

$0.094 < \Omega h^2 < 0.129$

Asano, Matsumoto, Okada, Okada, hep-ph/0602157

$m_{A_H}(\text{GeV})$

Model parameters:

$f, \ M_h, \ \sin \alpha, \ \kappa$
Production and decay

like-sign leptons!
T-odd fermion non-decoupling effect: heavy vector boson pair production

was previously neglected, but there is no decoupling of T-odd fermions: crucial for gauge invariance and unitarity

$$A^\gamma (-+)= -\frac{s_W^2 \sin \theta}{3f^2} s,$$

$$A^Z (-+)= -\left(1 - \frac{4}{3}s_W^2\right) \frac{\sin \theta}{4f^2} s,$$

$$A^{d-} (-+) = \frac{\sin \theta}{4f^2} s$$

rates were overestimated by factor 2-5
Heavy quarks production rates and signatures

\[ \sin \alpha = \frac{1}{\sqrt{2}} \ (\lambda_1 = \lambda_2), \ \kappa = 1 \]

EW production due to the initial double valence quarks leads to like sign lepton signature (LSL), it is comparable to strong production and becomes even more important for heavier masses due to parton luminosity behavior!
Heavy quarks production rates and signatures

Like-sign lepton signature (LSL)

\[ \sigma (\text{fb}) \]

\[ pp \rightarrow Q\bar{Q} \text{ signatures} \]

- \[ \hat{t}^\pm E_T^\pm + j \]
- \[ \overline{t}^\pm E_T^\pm + j \]
- \[ \overline{t}^\pm E_T^\pm \]
- \[ \overline{t}^\pm q\bar{q} + j \]

Opposite sign leptons (OSL) and 1-lepton signature (1L)

\[ q\bar{q} \rightarrow Q\bar{Q} \]
\[ (Q \rightarrow W_H^+ q') \rightarrow W_H^+ W_H^+ q' q' \]

\[ q\bar{q} (gg) \rightarrow Q\bar{Q} \rightarrow W_H^+ W_H^- q' \bar{q}' \]
Heavy top/bottom production rates and signatures

\[ f = 1 \text{ TeV}, \quad \kappa = 1 \]
\[ \text{Br}(T \rightarrow W_H b) = 0.62 \]
\[ \text{Br}(B \rightarrow W_H t) = 0.62 \]
\[ \text{Br}(t_- \rightarrow A_H t) = 1 \]
\[ \text{Br}(t_+ \rightarrow W b) = 0.44 \]
\[ \text{Br}(t_+ \rightarrow H t) = 0.19 \]
\[ \text{Br}(t_+ \rightarrow Z t) = 0.21 \]
\[ \text{Br}(t_+ \rightarrow A_H t_-) = 0.16 \]

**OSL + 2b (2t) signature**

\[ q\bar{q}(gg) \rightarrow T\bar{T} \rightarrow W^+_H W^-_H b\bar{b} \]

\[ q\bar{q}(gg) \rightarrow B\bar{B} \rightarrow W^+_H W^-_H tt \]

**Single top 1L + 1b signature**

\[ bq \rightarrow t_+ q \rightarrow W_H b q \]
Heavy quark-vector boson associate production

\[ f = 1 \text{ TeV}, \quad \kappa = 1 \]

\[ Br(Q \rightarrow W_H q') = 0.62 \]

\[ Br(W_H \rightarrow A_H W) = 1.0 \]

\[ Br(Z_H \rightarrow A_H H) = 1.0 \]

**OSL, 1L signatures**

\[ qg \rightarrow Q^- W_H \rightarrow W_H W_H q' \]

**Indirect Higgs production as a result of cascade decays**

\[ qg \rightarrow Q^- Z_H \rightarrow W_H Z_H q' \]

\[ \rightarrow W q' A_H A_H H \]

\[ M_H = 120 \text{ GeV} \]
Heavy vector boson pair production

\[ f = 1 \text{ TeV}, \quad \kappa = 1 \]
\[ \text{Br}(Q \rightarrow W_H q') = 0.62 \]
\[ \text{Br}(W_H \rightarrow A_H W) = 1.0 \]
\[ \text{Br}(Z_H \rightarrow A_H H) = 1.0 \]

OSL, 1L signatures

\[ W_H^+ W_H^- \rightarrow W^+ A_H W^- A_H \]

Associate Higgs production

\[ Z_H W_H \rightarrow HW A_H A_H \]

Higgs pair production

\[ Z_H Z_H \rightarrow HH A_H A_H \]
Heavy scalar boson pair production

**Study of 3-body tree-level decays for Heavy Higgs bosons is needed!**

$$Br(H^+ \rightarrow A_H W^+) = 1$$

$$q\bar{q} \rightarrow H^{++} H^{--}$$

$$q\bar{q}' \rightarrow H^{++} H^-$$
The signal observability

- CalcHEP – PYTHIA interface is crucial for further analysis beyond the parton level
- PYTHIA allows now to include new particles and their decay in easy fashion
  (thanks to Peter Skands and Sasha Pukhov)

```
BLOCK QNUMBERS 90024 # WH+
  1  3  # 3 times electric charge
  2  3  # number of spin states (2S+1)
  3  1  # colour rep (1: singlet, 3: triplet, 8: octet)
  4  1  # Particle/Antiparticle distinction (0=own anti)

BLOCK MASS  # Mass Spectrum
  90024  5.000000E+02  # WH+

DECAY  90024   1.000000E+00  # WH+ width
       1.0000E-00   2  24   90022  # Br(WH -> W+ AH)
```
Let's look at LHT vs SUSY cascade decays

Both, SUSY and LHT could give the same signature pattern

One should look closely: various decay channels, spin correlations, couplings
Gluon has no partner in LHT model!

Study of spins and couplings is quite a challenge at the LHC
Before Identifying SUSY in the LHC Olympics ...

**SUSY LHwTP dictionary**

<table>
<thead>
<tr>
<th>Squarks, sleptons</th>
<th>Mirror fermions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauginos</td>
<td>Heavy gauge bosons</td>
</tr>
<tr>
<td>2 Higgs</td>
<td>Scalar triplet</td>
</tr>
<tr>
<td>Gluino</td>
<td>NONE</td>
</tr>
<tr>
<td>NONE</td>
<td>Singlet quarks</td>
</tr>
</tbody>
</table>

 *(Slide from Jay Hubisz)*
Conclusions

- LHT model is well motivated (hierarchy, EW observables, DM) and leads to an exciting phenomenology at the LHC.
- The complete LHT model has been implemented into CalcHEP, independent implementation was important!

New results

- All relevant LHC signatures has been systematized.
- $\kappa$-term $t$-odd quark [SU(2) SM partners] production has been suggested: the most interesting phenomenology.
- New signatures: LSL, OSL, 1L, ... has been pointed out.
- Importance of non-decoupling effects: especially for heavy vector boson pair and higgs boson production.

CalcHEP-PYTHIA interface: understanding the signal observability and including spin correlations is crucial.
\[ -\frac{\lambda_1}{2\sqrt{2}} f \epsilon_{ijk} \epsilon_{xy} \left[ (\bar{Q}_1)_i \Sigma_{jx} \Sigma_{ky} - (\bar{Q}_2 \Sigma_0)_i \tilde{\Sigma}_{jx} \tilde{\Sigma}_{ky} \right] u_{R+} \]

\[ -\lambda_2 f (\bar{U}_{L1} U_{R1} + \bar{U}_{L2} U_{R2}) + \text{h.c.,} \]

with \( Q_1 = (q_1, U_{L1}, 0_2)^T \) and \( Q_2 = (0_2, U_{L2}, q_2)^T \)

giving \( t, t_+, t_- \) with \( \sin \alpha = \frac{\lambda_1}{\sqrt{\lambda_1^2 + \lambda_2^2}} \)

\( M_t \sim (\lambda_2 \sin \alpha) v, \quad M_{t-} \sim \lambda_2 f, \quad M_{t+} \sim \left( \frac{\lambda_2}{\cos \alpha} \right) f \)

\[ -\kappa f (\bar{\Psi}_2 \xi \Psi_c + \bar{\Psi}_1 \Sigma_0 \Omega \xi^{\dagger} \Omega \Psi_c) + \text{h.c.} \]

fermion \( SU(2) \) doublets \( q_1 \) and \( q_2 \):

\( \Psi_1 = (q_1, 0, 0_2)^T \) and \( \Psi_1 = (0_2, 0, q_2)^T \)

giving \( U_-, D_- \), with \( M_{Q_-} = \sqrt{2}\kappa f \)
SUSY LHWTP dictionary

- squarks, sleptons $\leftrightarrow$ mirror fermions
- gauginos $\leftrightarrow$ heavy gauge bosons
- 2 Higgs $\leftrightarrow$ scalar triplet
- gluino $\leftrightarrow$ NONE
- NONE $\leftrightarrow$ Singlet quarks