Search for the Top Partner at the LHC using Multi-b-jet channel

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Consider the vector-like quark $T$ which mixes with top quark (Top partner)

Decay mode is possible

Using multi-b channel, how is the LHC’s sensitivity
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3. LHC prospect with multi-b-jet channel
1. Models including top partner

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<tr>
<td>MSSM+extra matter</td>
<td>Okada, Moroi (1992)</td>
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<tr>
<td></td>
<td>Kurosawa, Maru, Yanagida (2001)</td>
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<tr>
<td></td>
<td>Endo-san</td>
</tr>
</tbody>
</table>
Little Higgs model

Arkani-Hamed, Cohen, Georgi (2001)
Why the EWSB scale $\ll M_{\text{pl}}$?

How about introducing a dynamical SSB mechanism? Higgs is pNGB!

Effective theory with cut-off at scale $\Lambda$

Generally, any operators should be generated

Note: operators like

$$\frac{1}{\Lambda^2} |H^\dagger D_\mu H|^2 \quad \frac{1}{\Lambda^2} (H^\dagger \sigma^i H) W_{\mu\nu} W^{i\mu\nu}$$

conflict with the electroweak precise measurement

$$\rightarrow \quad \Lambda > 9 \, \text{TeV}$$

Han, Skiba (2007)
Little hierarchy

To avoid fine-tuning, \( \Lambda \sim 4\pi m_Z \sim \text{TeV} \)

But \( \Lambda > 9\ \text{TeV} \)  

Little Hierarchy problem
Solution: symmetry

Due to some symmetry, (depends on model)

\[ = 0 \times \Lambda^2 + c_1 \times m_T^2 \ln\left(\frac{\Lambda^2}{m_T^2}\right) \]

(So do gauge sector)
MSSM+extra matter

Endo-san

Okada, Moroi (1992)
Kurosawa, Maru, Yanagida (2001)
MSSM

Super symmetric extension of 2HD Standard model

(later discovered) problem: Higgs is heavier than we thought!

\[ m_{h^0} > 114.4 \text{ GeV} > m_Z \quad (\text{LEP}) \]

Quantum correction can raise higgs mass.

Raise SUSY breaking scale?

cf. \[ m_h = 125 \text{ GeV} \]
Possible solution: extra matter

Some models contain extra vector-like matter at low energy

\[ U(3, 2, \frac{1}{6}), Q(\bar{3}, 1, -\frac{2}{3}), \ldots \]

\[ W \supset yUQH_u \]

Enhance Higgs mass!

Big bonus: possible solution to muon $g - 2$ even for $m_{h^0} = 125$ GeV

Endo, Hamaguchi, Iwamoto, Yokozaki (2011)
2. Current status of the top partner search
Constraints from CDF result

Assuming pair creation and

\[ T \rightarrow bW \]

1-lepton, b-jet search

Picture: KH, Matsumoto, Nojiri, Tobioka(2012)
Constraints from CMS result

Assuming pair creation and $T \rightarrow bW$ di-lepton

Picture: KH, Matsumoto, Nojiri, Tobioka(2012)
Constraints from CMS result

Assuming pair creation and

\[ T \rightarrow tZ \]

\[ Z \rightarrow l^+l^- , \]

1 isolated lepton

\[ Br(T \rightarrow tZ) \]

1.1 fb^{-1}
95% CL limit

\[ m_{tp} \text{ (GeV)} \]

Picture: KH, Matsumoto, Nojiri, Tobioka(2012)
3. LHC prospect with multi-b-jet channel

Concentrate on $bW$, $th$
Tools and assumptions

- Madgraph5
- Pythia
- Delphes
- ATLAS’s object reconstruction method

For b-tagging, SVO50 method
b-tag efficiency ~ 0.6
mis-tag rate ~ 0.01
at high-pt

\[ m_h = 120 \text{ GeV}, \quad \sqrt{s} = 8 \text{ TeV} \]
1-lepton + 1,2 b-jet

Imitating and modifying CMS’s search

- Aim at
  
  \[ T \bar{T} \rightarrow bW^+ \bar{b}W^- \]

- Expect very hard b-jet

- W decay -> lepton, missing, jets

- Try to reconstruct the mass
  
  \[ M_{bl\nu} \]
Event selection

- Exactly 1 isolated lepton with $p_T > 30$ GeV
- $E_T > 20$ GeV
- $\geq 4$ isolated jets and 1 or 2 of them are b-jets
- The jets have $p_T > 80, 50, 30$ GeV
- The leading b-jet has $p_T > 260$ GeV
- $M_{blv} > 400$ GeV
- $M_{eff} > 1000$ GeV
## Cut flow

15 fb\(^{-1}\) data, \(m_{\tilde{t}p} = 500\) GeV, \(p_T\)-jet > 70, 40 GeV, leptonic decay

<table>
<thead>
<tr>
<th></th>
<th>(\tilde{t}\tilde{t} +\text{jets})</th>
<th>(W + \text{jets})</th>
<th>(t_p\tilde{t}_p \rightarrow bWbW)</th>
<th>(t_p\tilde{t}_p \rightarrow bWth)</th>
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<td>0.000033</td>
<td>0.031</td>
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<td>0.0099</td>
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</table>

KH, Matsumoto, Nojiri, Tobioka(2012)
LHC’s sensitivity

Expected 95% CL excluded region if no excess

\[(\text{cross section}) \times (\text{acceptance}) > 4.4 \text{ fb}\]

Assuming 20% uncertainty in the background estimation.
1-lepton + $\geq 3$ b-jet

- Aim at $\bar{T}T \rightarrow bWth$ or $thth$

- Expect many hard b-jet

- W decay -> lepton, missing, jets
Event selection

- Exactly 1 isolated lepton with pt > 30 GeV
- $E_T > 20$ GeV
- $\geq 5$ isolated jets and more than 2 of them are b-jets
- The b-jets have pt > 140, 80, 80 GeV
- $M_{blv} > 250$ GeV
- $M_{eff} > 1200$ GeV
**Cut flow**

15 fb$^{-1}$ data, $m_{t\bar{t}} = 500$ GeV, ptb-jet > 20 GeV

<table>
<thead>
<tr>
<th></th>
<th>$t\bar{t}$ +jets</th>
<th>$t\bar{t}b\bar{b}$</th>
<th>$t_{\bar{t}}t_{\bar{t}} \rightarrow bWb\bar{W}$</th>
<th>$t_{\bar{t}}t_{\bar{t}} \rightarrow bWth$</th>
<th>$t_{\bar{t}}t_{\bar{t}} \rightarrow th\bar{t}h$</th>
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<td>lepton, missing, 5jets, b-jets</td>
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<td>0.0014</td>
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<td>0.0059</td>
</tr>
</tbody>
</table>

$W$ +jets, $Wb\bar{b}$ +jets: negligible

KH, Matsumoto, Nojiri, Tobioka(2012)
LHC’s sensitivity
Expected 95% CL excluded region if no excess

(cross section) × (acceptance) > 0.92 fb

Assuming 20% uncertainty in the background estimation
LHC’s discovery potential

Expected 5σ discovered region

\[(\text{cross section}) \times (\text{acceptance})\] > 2.3 fb

Assuming 20% uncertainty in
The background estimation

\[\int \mathcal{L} \, dt = 15 \, \text{fb}^{-1}\]

\[m_{h} = 120 \, \text{GeV}\]

\[\sqrt{s} = 8 \, \text{TeV}\]
Summary

- Some models contain vector-like quark which mixes with top quark (top partner)
- Multi b- jet channel have grate sensitivity to the top partner, especially for decay into top and higgs
Electro weak observables

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
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</thead>
<tbody>
<tr>
<td>$\alpha^{-1}$</td>
<td>137.035999679(94)</td>
</tr>
<tr>
<td>$G_F$ (GeV$^{-2}$)</td>
<td>$1.16637(1)\times10^{-5}$</td>
</tr>
<tr>
<td>$m_Z$ (GeV)</td>
<td>91.1876(21)</td>
</tr>
<tr>
<td>$\Delta\alpha_{lep}(m_Z^2)$</td>
<td>0.03150</td>
</tr>
<tr>
<td>$\Delta\alpha_{h}(m_Z^2)$</td>
<td>0.027626(138)</td>
</tr>
<tr>
<td>$\Delta\alpha_{top}(m_Z^2)$</td>
<td>-0.00007</td>
</tr>
<tr>
<td>$m_W$ (GeV)</td>
<td>80.399(23)</td>
</tr>
<tr>
<td>$m_t$ (GeV)</td>
<td>173.2(9)</td>
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<tr>
<td>$s_t^2$</td>
<td>0.23153(16)</td>
</tr>
<tr>
<td>$\Gamma_{Z\rightarrow\ell^+\ell^-}$ (MeV)</td>
<td>83.984(86)</td>
</tr>
<tr>
<td>$\alpha_s(m_Z^2)$</td>
<td>0.1184(7)</td>
</tr>
</tbody>
</table>
Little Higgs model

Suppose EWSB is generated by some mechanism

\[ \text{Cutoff} \quad \Lambda > 10 \text{ TeV} \quad \text{(Han, Skiba (2007))} \]

Even if Higgs were pNGB, to avoid little hierarchy,

\[
\frac{1}{\Lambda^2} (H^\dagger \sigma^i H) W^i_{\mu\nu} B^{\mu\nu}
\]

\[
= 0 \times \Lambda^2 + c_1 \times m_T^2 \ln\left( \frac{\Lambda^2}{m_T^2} \right)
\]

due to some symmetry. (depends on model)
Top see saw

Chivukula, Dobrescu, Georgi, Hill (1999)
Top quark condensate

\[ H \leftrightarrow t_L^\dagger t_R \quad : \text{same quantum number} \]

How about top quark condensation like BCS theory?

Intrinsic energy scale provide dynamical scale

top quark Yukawa coupling is naturally large

Problem: top quark should be heavier

\[ m_t \approx \frac{4\pi v}{\sqrt{N_c \ln \frac{\Lambda}{v}}} \quad \Lambda : \text{cut off (=intrinsic energy scale)} \]

\[ N_c : \text{Number of color} \]
Solution: seesaw mechanism

Introduce vector-like quark $T$

\[ m_t \approx \frac{4\pi v}{\sqrt{N_c \ln \frac{\Lambda}{\nu}}} \sin \theta \]

Suppressed by mixing angle
MSSM+extra matter

\[ m_{h^0} > 114.4 \text{ GeV} > m_Z \]  \quad (\text{LEP})

Raise stop mass and allow little hierarchy?

Possible solution: utilize vector-like extra matter

\[ U(3, 2, \frac{1}{6}), Q(\bar{3}, 1, -\frac{2}{3}), \ldots \]

\[ W \supset yUQH_u \]

Enhance Higgs mass!

cf. \[ m_h = 124 - 126 \text{ GeV} \]?

...
Coupling with 1\textsuperscript{st}, 2\textsuperscript{nd} generations

ex. $K\bar{K}$

\[ \theta_{L1,2} \leq 10^{-3} \]
Systematic errors

- $t\bar{t}$ cross section: $166 \pm 11$ pb  \hspace{1cm} (CMS, 2011)

- Integrated luminosity: 3.7%  \hspace{1cm} (ATLAS, 2011)

- b-tag efficiency and mis-tag rate
  : not accurately included

  (results with taking into the effect with rough estimate are also shown)
Uncertainties in b-tagging

With 35 pb\(^{-1}\) data, for SVO50 method, (ATLAS-CONF-2011-089)

- b-tagging efficiency: \(~5\%\) (sys) \(10\%\) (stat)
- mis-tag rate for light jets: \(~10\%\) (stat)
- mis-tag rate for c-jets: not calibrated. \(~0.14\) (ATLAS TDR)
1 lepton + 1,2b-jets
1 lepton + 1,2b-jets
1 lepton + 1,2b-jets
1 lepton + 1,2b-jets

After hard b-jet cut,

\[ m_{t\bar{t}} = 500 \text{ GeV}, \sin\theta_L = 0.1, \sin\theta_R = 0.03 \]
1 lepton + $\geq 3$ b-jets

![Graphs showing distributions of $p_T$ for the 1st, 2nd, and 3rd b-jets for different decay modes: tt, TT->bwbw, TT->bwth, TT->thth.](image)
1 lepton + $\geqslant 3$ b-jets
### Possible terms

<table>
<thead>
<tr>
<th></th>
<th>SU(3)\textsubscript{c}</th>
<th>SU(2)\textsubscript{L}</th>
<th>U(1)\textsubscript{Y}</th>
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<td>Q\textsuperscript{3}</td>
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<td>3</td>
<td>1</td>
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<td>2/3</td>
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<td>U\textsubscript{R}</td>
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<td>2/3</td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>2</td>
<td>1/2</td>
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</table>

\[-m_U U_L^\dagger U_R + h.c.
\]

\[-y_3 Q^3 H^c u^3_R - y_U Q^3 U^c H^c U_R + h.c.
\]

\[-\frac{\lambda}{m_U} U_L^\dagger u_3 R |H|^2 + h.c.
\]
Parameterization

To diagonalize mass,

\[
\begin{pmatrix}
t_L \\ T_L
\end{pmatrix} = \begin{pmatrix}
\cos\theta_L & -\sin\theta_L \\
\sin\theta_L & \cos\theta_L
\end{pmatrix} \begin{pmatrix}
u_L^3 \\ U_L
\end{pmatrix}
\]

\[
\begin{pmatrix}
t_R \\ T_R
\end{pmatrix} = \begin{pmatrix}
\cos\theta_R & -\sin\theta_R \\
\sin\theta_R & \cos\theta_R
\end{pmatrix} \begin{pmatrix}
u_R^3 \\ U_R
\end{pmatrix}
\]

\[m_{tp}, \theta_L, \theta_R\]
Let's look at $\sin \theta_R$ dependence

- $m_{tp} = 500$ GeV
- $\sin \theta_L = 0.1$
- $\lambda = -1$
- $\lambda = 1$

KH (2012)
Constraint from EWPM

\[ m_h = 120 \text{ GeV} \]

S, T, U method with
\[ \sin^2 \theta_{\text{lep}}^{\text{eff}}, \Gamma_{Z \to l^+ l^-}, m_W \]

\( m_{t\bar{t}} \) allowed region

KH, Matsumoto, Nojiri, Tobioka (2012)
Constraints from CMS result

Assuming pair creation and

\[ T \rightarrow bW \]

1-lepton, b-jet search

\[ Br(T \rightarrow bW) \]

95% CL limit

\[ m_{tp} \text{ (GeV)} \]

Picture: KH, Matsumoto, Nojiri, Tobioka(2012)