Top partners at the LHC: Mass and spin measurement

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Motivation
Preparing for the LHC

- There are *many* possible (classes of) models, some better motivated than others: SUSY, Little Higgs, UED, etc.

- It’s easy to get bogged down in theoretical studies of particular models and choices of parameters.

- We want to advocate **model-independent** study of new physics at the LHC. We should try to develop some general tools and diagnostics for discriminating different scenarios. But where to start?

- Let’s begin with naturalness: top partner $t'$ is (usually) the first expectation
The signal: \( t\bar{t} + E_T \)

The signal we consider is production of a heavy partner of the top quark, which we call the \( t' \). If it decays (eventually) to all SM particles, it should be relatively easy to find (much like finding the real top quark).

On the other hand if – as in SUSY with R-parity – the \( t' \) decay involves a stable neutral particle that is invisible, things are more difficult. So we posit that there is some stable lightest parity-odd particle (LPOP), which we denote \( N \). (Motivations: dark matter, precision constraints.)

The signal we want to study is the decay \( t'\bar{t}' \to t\bar{t} + 2N \).
Properties of the $t'$, $N$

For our study we have essentially two parameters, the masses of the $t'$ and the $N$, as well as one discrete choice of spin. The $t'$ can be a scalar as in SUSY (in which case the $N$ must be a fermion), or a fermion as in e.g. Little Higgs with T-parity in which case the $N$ can be a vector or scalar.

The coupling for the $t'Nt$ vertex is another parameter, but has little effect on our study. We assume the $t' \rightarrow tN$ branching ratio is 1. *Our results should apply when there are other decay modes*, provided the branching ratio is order 1 and can be estimated.
Implementation in MadGraph

Thanks to F. Maltoni, T. Stelzer for assistance.
Why MadGraph?

- Can generate all diagrams for $t\bar{t} + 2N$, including interference (for $gg \rightarrow t\bar{t} + 2N$, about 30 diagrams).

- Helicity amplitude calculation: $2 \rightarrow 4$ is fast.

- Spin correlation in decay $t' \rightarrow tN$ is kept, so we can trust angular distributions if we reconstruct the full top momentum.

- We had difficulty getting $2 \rightarrow 4$ integration to converge in CompHEP for this process, even after trying to regularize the poles appropriately.
MadGraph usage notes

• Width entered by hand.

• Set factorization and renormalization scales to $m_t'$.

• Change running of $\alpha_s$ to take account of $m_t$ threshold.
Signal vs. Backgrounds
Backgrounds

Our signal is $t\bar{t} + E_T$. One usually likes to look for $t\bar{t}$ in the “lepton+jets” channel. But SM $t\bar{t}$ has a huge rate, and the leptonic decays have a long $E_T$ tail from the neutrino.

So we propose something a little surprising: **the all-hadronic channel is in fact the easiest!**

SM backgrounds have either $Z \to \nu\nu$ or $W \to \tau\nu$ with the hadronic tau decay faking a jet.

$t\bar{t}Z$, $t\bar{t}j$ with one top decaying through $\tau$ are the biggest backgrounds. Smaller: $Zb\bar{b} + 4j$, $Z + 6j$, $Wb\bar{b} + 3j$, etc. (Alpgen)
Cuts

- Two $b$-tagged jets and four other jets.
- $E_T > 40$ GeV for all jets.
- At least one jet with $E_T > 100$ GeV.
- $E_T > 100$ GeV.
- $|\eta| < 2.5$ for all jets.
- $\Delta R > 0.4$ between any pair of jets.
- The four non-$b$ jets split into two pairs reconstructing to a $W$: $60$ GeV < $M_{jj} < 100$ GeV.
- The two $W$s pair up with the two $b$ jets to reconstruct to a top: $150$ GeV < $M_{jjb} < 190$ GeV.
- $H_T > 500$ GeV, where $H_T = E_T + \sum_{jets} |p_T|$.
Significance for the case $t'$ fermion, $N$ scalar, with $10 fb^{-1}$ luminosity. Contours are $> 15 \sigma$, $> 10 \sigma$, $> 5 \sigma$, $> 3 \sigma$, and $< 3 \sigma$. We consider only $m_{t'} > m_N + 200$ GeV.
Significance for the case $t'$ scalar, $N$ fermion, with $10 fb^{-1}$ luminosity (left) and $100 fb^{-1}$ (right). Contours are $> 15\sigma$, $> 10\sigma$, $> 5\sigma$, $> 3\sigma$, and $< 3\sigma$. We consider only $m_{t'} > m_N + 200$ GeV.
Mass Determination
Kinematic variables

It is often said that $M_{eff}$, defined as $E_T$ plus the $p_T$’s of the four hardest jets, measures the mass of a strongly interacting particle.

However (see also Cheng, Low, Wang hep-ph/0510225) we find it really measures something more like the mass difference between the strongly interacting particle and the LPOP. So do other kinematic variables: $\langle E_T \rangle$, $\langle H_t \rangle$, $M_{T2}$ (Cambridge group: Lester and Summers, hep-ph/9906349)
For a given spin, cross section tells us the $t'$ mass, kinematic variables tell us the mass splitting. There is in general a degeneracy – for any given point with a scalar $t'$, there is a corresponding point with a fermion $t'$ and the same observables. **We need some other observable.**
Spin determination
Using the Cross-Section Difference

We know that, at the same $m_{t'}$, the fermion $t'$ has a bigger cross section than a scalar $t'$. But we can’t use this directly, since we need cross-section together with another kinematic variable to measure ($m_{t'}, m_N$) for a given spin.

But there should be other properties of the events that are sensitive to the overall mass scale. Thus we propose that instead of measuring spin correlations, one should determine the spin by measuring the overall mass scale, as determined by boosts.
Pseudorapidity Correlations of $t$ and $\bar{t}$

Horizontal axis: sum of $\eta$'s of the tops; vertical axis: difference of $\eta$'s (the boost-invariant quantity). The scalar case, for equal cross section and $\langle H_t \rangle$, is lighter, as manifested in a more horizontally stretched ellipse. (Alternative: make asymmetries.)
Conclusions

• The signal can be found in the **hadronic** channel up to high masses.

• Masses of $t'$ and $N$ can be found up to **discrete degeneracy from spin** of $t'$

• The spin of the $t'$ can be determined (with very high luminosity) from an **asymmetry** or **pseudorapidity correlations** sensitive to **overall boost**

• $N$ spin and couplings are harder: try other asymmetries, spin correlations....
Additional slides
Cambridge MT2 Observable

Lester, Summers hep-ph/9906349
Barr, Lester, Stephens hep-ph/0304226
Beam-Line Asymmetry

We define a variable called the **beam-line asymmetry** ("BLA") as follows.

$p_{z1}^t$ and $p_{z2}^t$ are the $z$-components of the momenta of the top quarks in the lab frame. Let $N_+$ and $N_-$ count the number of events where $p_{z1}^t p_{z2}^t > 0$ and $p_{z1}^t p_{z2}^t < 0$, respectively.

\[
BLA = \frac{N_+ - N_-}{N_+ + N_-}
\]
Beam-Line Asymmetry: Examples

BLA is sensitive to the overall boost of the $t\bar{t}$ system. It includes some spin correlations, but mostly the difference we want comes from the boost.

Examples: $t'$ fermion with mass 800 GeV, $N$ scalar with mass 450 GeV vs. $t'$ scalar with mass 550 GeV, $N$ fermion with mass 100 GeV. Both have $\langle H_T \rangle \approx 865$ GeV and $\sigma \approx 42$ fb (after cuts). **BLA is 0.11 for the fermion $t'$ and 0.21 for the scalar $t'$**.

$t'$ fermion with mass 550 GeV, $N$ scalar with mass 300 GeV vs. $t'$ scalar with mass 350 GeV, $N$ fermion with mass 100 GeV. Both have $\langle H_T \rangle \approx 650$ GeV and $\sigma \approx 220$ fb (after cuts). **BLA is 0.22 for the fermion $t'$ and 0.38 for the scalar $t'$**.
MadGraph Implementation: $t'$ fermion, $N$ scalar

In particles.dat:

```
f       f~        F        S        FMASS FWIDTH T    f  99
n       n         S        D        NMASS NWIDTH S    n  18
```

In interactions.dat:

```
f       f       g        GG       QCD
f       t       n        GFNL      QED
t       f       n        GFNR      QED
```

In couplings.f (declared in coupl.inc, type "double complex (2)"):

```
gfnr(1) = dcmplx( Zero, Zero )
gfnr(2) = dcmplx( ee, Zero )
gfnl(1) = dcmplx( ee, Zero )
gfnl(2) = dcmplx( Zero, Zero )
```
Madgraph: \( t' \) scalar, \( N \) fermion

In particles.dat:

\[
\begin{array}{cccccc}
TT & TT & S & D & \text{FMASS} & \text{FWIDTH} & T & t' & 8 \\
N & N & F & S & \text{NMASS} & \text{NWIDTH} & S & n & 18 \\
\end{array}
\]

In interactions.dat:

\[
\begin{array}{cccccc}
g & TT & TT & \text{GGS} & \text{QCD} \\
g & g & TT & TT & \text{GGS2} & \text{GGS2} & \text{QCD} & \text{QCD} \\
t & N & TT & \text{GTNR} & \text{QED} \\
N & t & TT & \text{GTNL} & \text{QED} \\
\end{array}
\]

Here \( ggs = \text{dcmplx}(-G, \text{Zero}) \) and \( ggs2 = \text{dcmplx}(G**2,\text{Zero}) \); \( gt\), \( gt\) are "double complex(2)" as before.