Top partners at the LHC: Mass and spin measurement

Matt Reece

Patrick Meade and MR, hep-ph/0601124

Institute for High-Energy Phenomenology
Newman Laboratory for Elementary-Particle Physics
Cornell University, Ithaca, NY 14853, USA

Motivation

Preparing for the LHC

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

- 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: $t\bar{t} + \not{E}_T$

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 $t' \to tN$ 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.

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`:

```
TT      TT~       S        D       FMASS FWIDTH  T    t'   8
N        N        F        S       NMASS NWIDTH  S    n   18
```

In `interactions.dat`:

```
g TT TT  GGS QCD
g g TT TT  GGS2 GGS2 QCD QCD
t N TT GTNR QED
N t TT  GTNL QED
```

Here `ggs= dcmplx(-G, Zero)` and `ggs2= dcmplx(G**2,Zero)`; `gtnr`, `gtnl` are "double complex(2)" as before.

MadGraph caveats

For reasonable accuracy we need to set renormalization and factorization scales of order $m_{t'}$. In `couplings.f` α_s is computed at the corresponding scale, but the default code only includes the five light quarks. Since we have a scale above m_{top}, we have to modify this running.

From the documentation it is not obvious how to ensure the correct handedness in all the couplings. To be absolutely sure we empirically worked this out from knowing that the implemented weak interaction couples only to left-handed things; thus we can construct decay chains that get zero cross section if we add the wrong coupling.

Signal vs. Backgrounds

Backgrounds

Our signal is $t\bar{t} + \not{E}_T$. 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 $\not{E}_T$ tail from the neutrino.

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

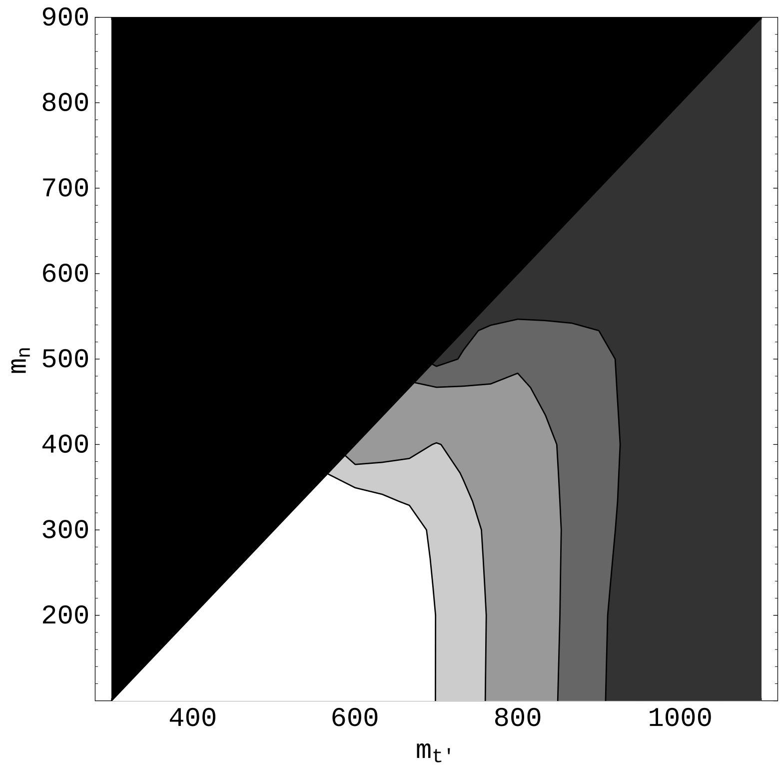
SM backgrounds have either $Z \to \nu\nu$ or $W \to \tau\nu$ with the hadronic tau decay faking a jet.

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

Cuts

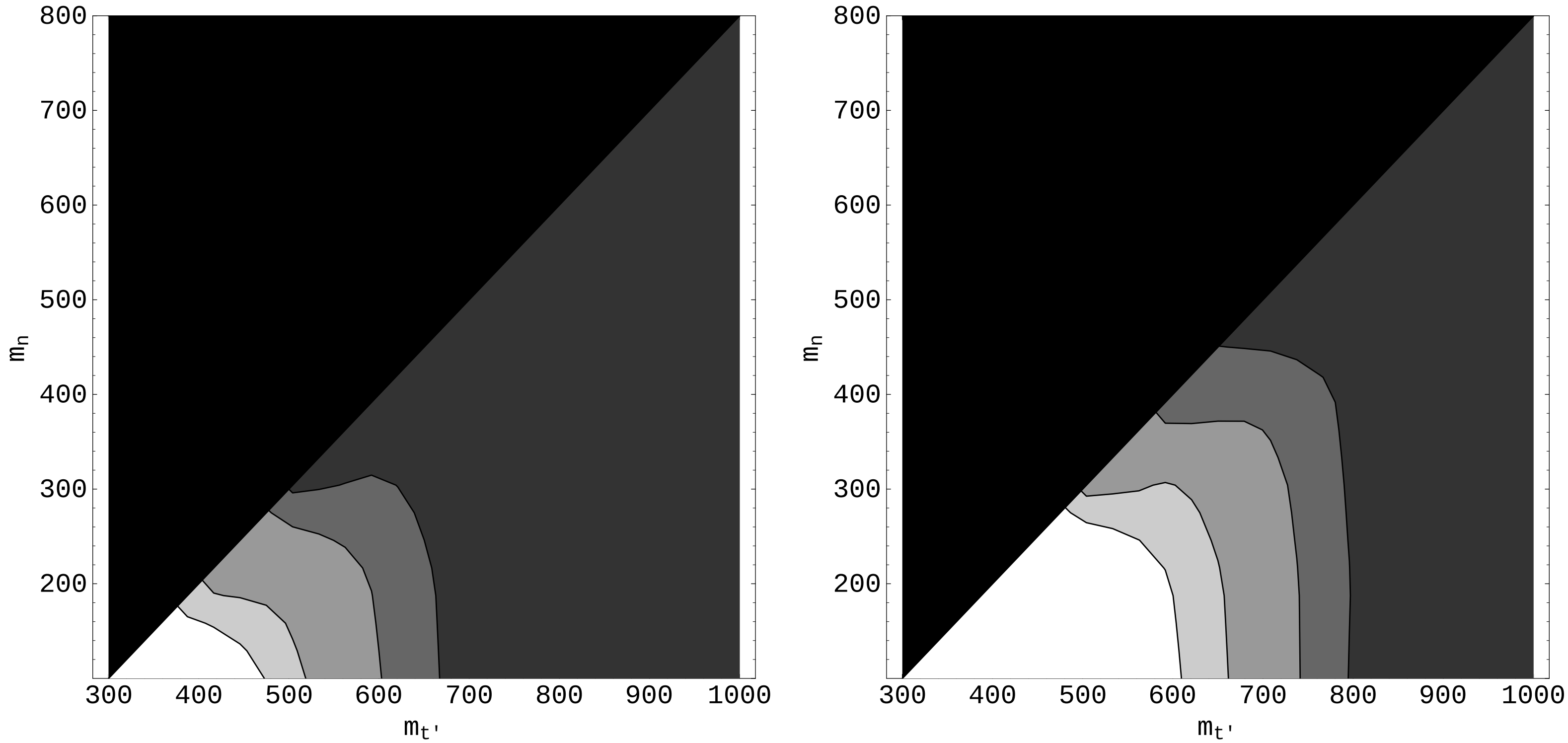
- Two b-tagged jets and four other jets.
- $E_T > 40$ GeV for all jets.
- At least one jet with $E_T > 100$ GeV.
- $\not{E}_T > 100$ GeV.
- $|\eta| < 2.5$ for all jets.
- $\Delta R > 0.4$ between any pair of jets.
- The four non-b jets split into two pairs reconstructing to a W: 60 GeV $< M_{jj} <$ 100 GeV.
- The two Ws pair up with the two b jets to reconstruct to a top: 150 GeV $< M_{jjb} <$ 190 GeV.
- $H_T > 500$ GeV, where $H_T = \not{E}_T + \sum_{jets} |\mathbf{p}_T|$.

Significance ($S/\sqrt{B}$)



Significance for the case t' fermion, N scalar, with $10 fb^{-1}$ luminosity. Contours are $> 15\sigma, > 10\sigma, > 5\sigma$, and $< 5\sigma$. We consider only $m_{t'} > m_N + 200$ GeV.

Significance ($S/\sqrt{B}$)



Significance for the case t' scalar, N fermion, with $10 fb^{-1}$ luminosity (left) and $100 fb^{-1}$ (right). Contours are $> 15\sigma, > 10\sigma, > 5\sigma$, and $< 5\sigma$. We consider only $m_{t'} > m_N + 200$ GeV.

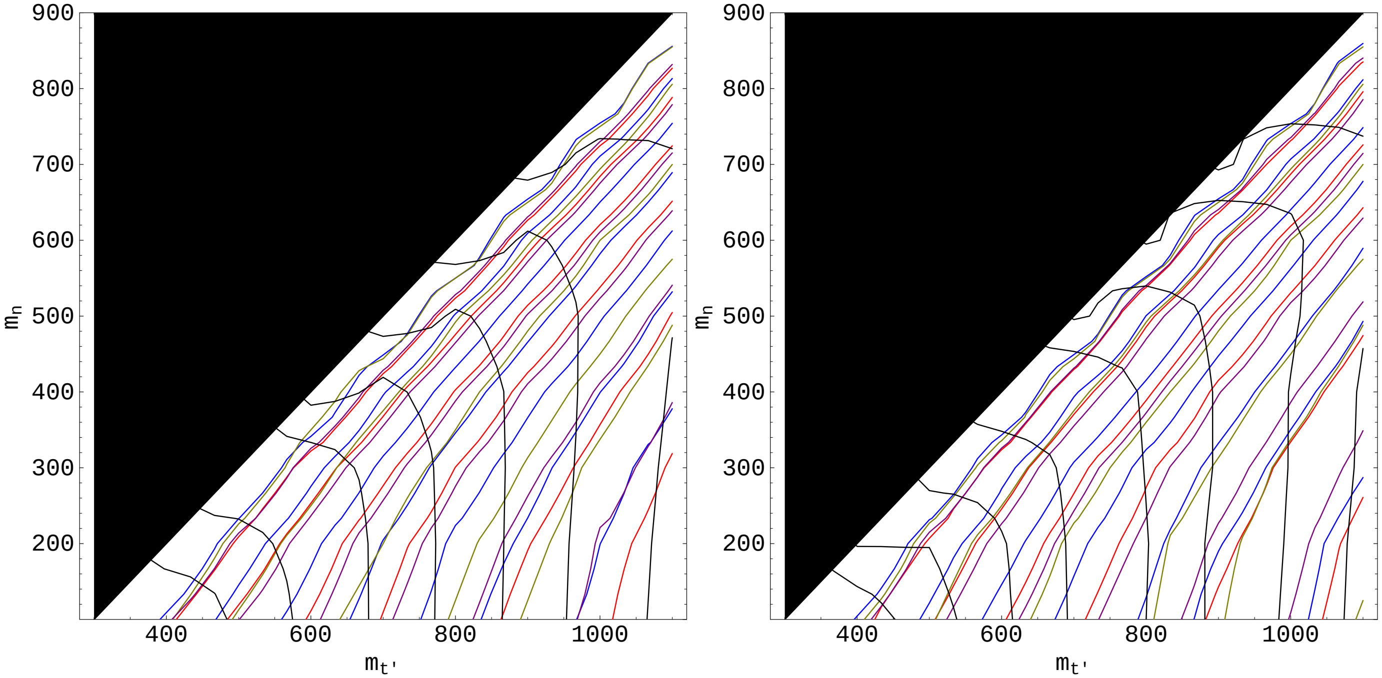
Mass Determination

Kinematic variables

It is often said that M_{eff}, defined as $\not{E}_T$ 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: $\langle \not{E}_T \rangle$, $\langle H_t \rangle$, M_{T2} (Cambridge group: Lester and Summers, hep-ph/9906349)

Our approach



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.**

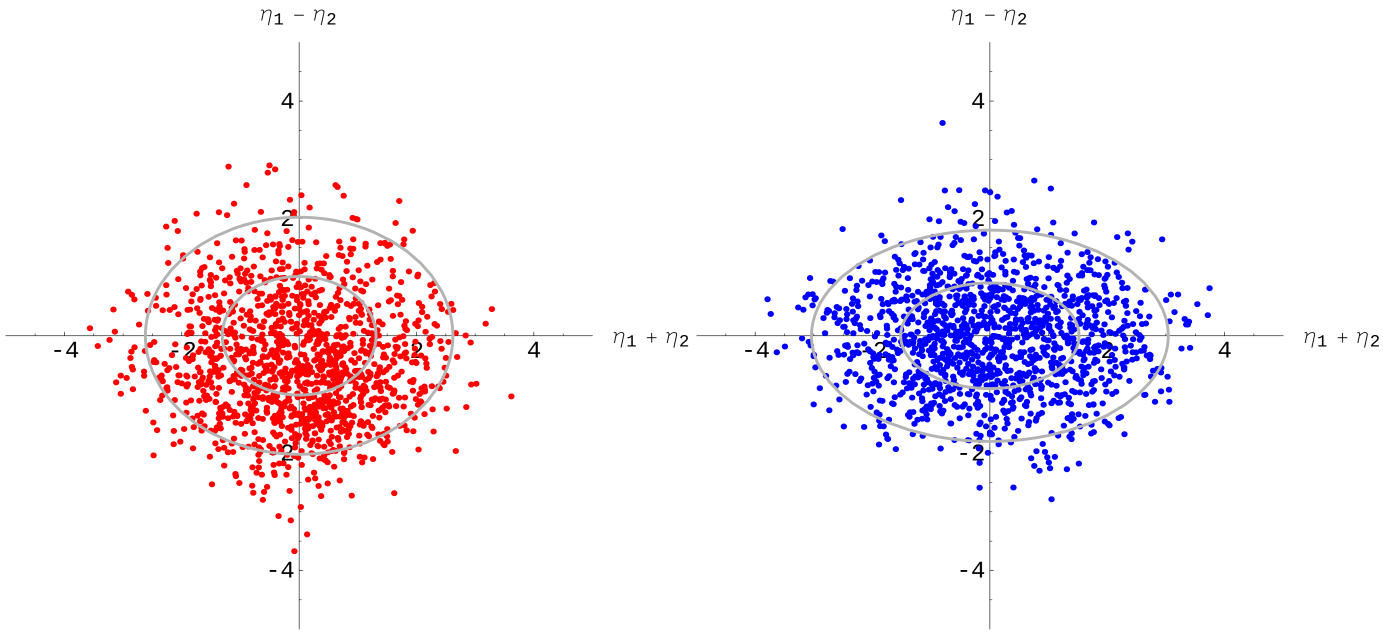
Spin determination

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 η's of the tops; vertical axis: difference of η'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.

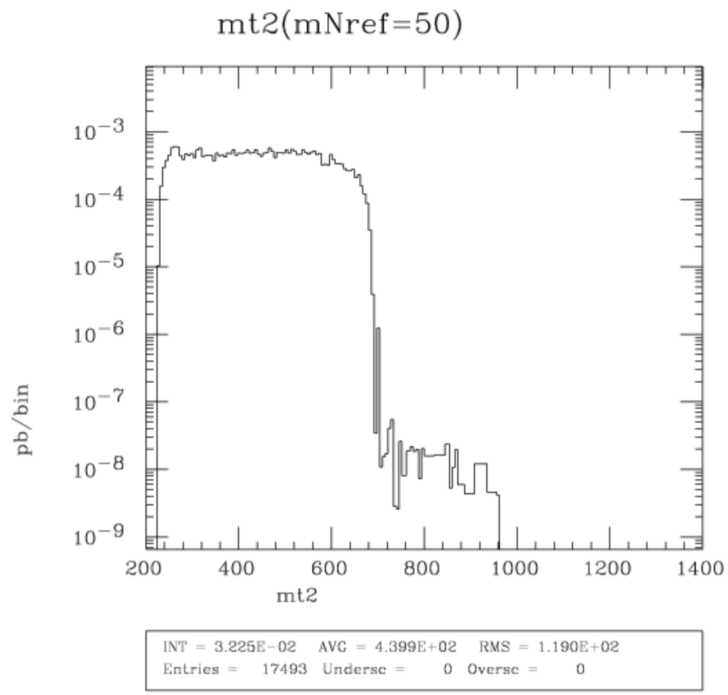
- Masses of t' and N can be found up to **discrete degeneracy from spin** of t'

- 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_z^{t1} and p_z^{t2} 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 $p_z^{t1}p_z^{t2} > 0$ and $p_z^{t1}p_z^{t2} < 0$, respectively.

$$BLA = \frac{N_+ - N_-}{N_+ + N_-} \tag{1}$$

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'.**