

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....
- 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: $t\bar{t} + \cancel{E}_T$

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 $t'\bar{t}' \rightarrow t\bar{t} + 2N$.

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 α_s to take account of m_t threshold.

Signal vs. Backgrounds

Backgrounds

Our signal is $t\bar{t} + \cancel{E}_T$. 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 \cancel{E}_T tail from the neutrino.

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

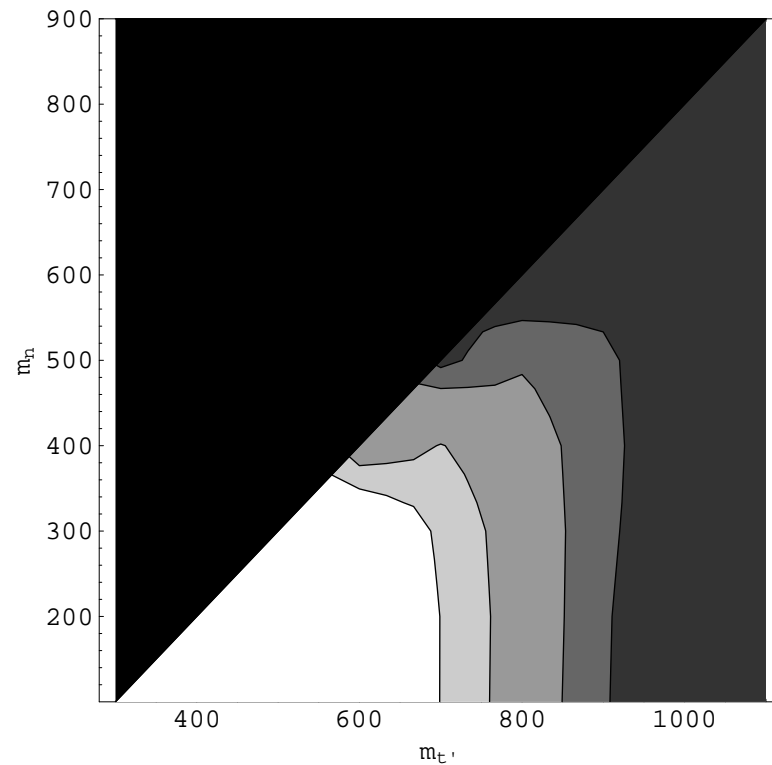
SM backgrounds have either $Z \rightarrow \nu\nu$ or $W \rightarrow \tau\nu$ with the hadronic tau decay faking a jet.

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

Cuts

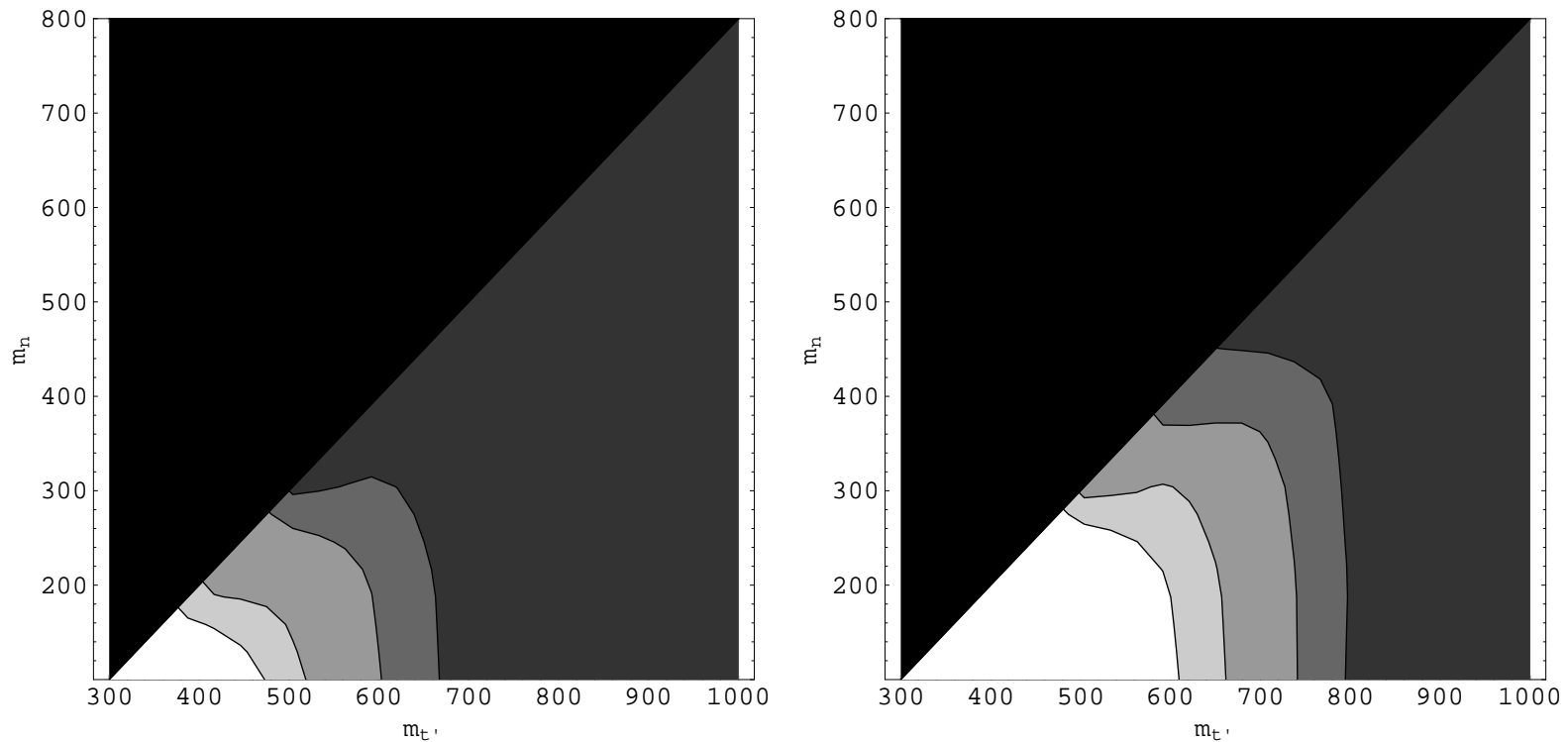
- Two b -tagged jets and four other jets.
- $E_T > 40$ GeV for all jets.
- At least one jet with $E_T > 100$ GeV.
- $\cancel{E}_T > 100$ GeV.
- $|\eta| < 2.5$ for all jets.
- $\Delta R > 0.4$ between any pair of jets.
- The four non- b jets split into two pairs reconstructing to a W : $60 \text{ GeV} < M_{jj} < 100 \text{ GeV}$.
- The two W s pair up with the two b jets to reconstruct to a top: $150 \text{ GeV} < M_{jjb} < 190 \text{ GeV}$.
- $H_T > 500$ GeV, where $H_T = \cancel{E}_T + \sum_{jets} |\mathbf{p}_T|$.

Significance (S/\sqrt{B})



Significance for the case t' fermion, N scalar, with $10fb^{-1}$ luminosity. Contours are $> 15\sigma$, $> 10\sigma$, $> 5\sigma$, $> 3\sigma$, and $< 3\sigma$. We consider only $m_{t'} > m_N + 200$ GeV.

Significance (S/\sqrt{B})



Significance for the case t' scalar, N fermion, with 10 fb^{-1} luminosity (left) and 100 fb^{-1} (right). Contours are $> 15\sigma$, $> 10\sigma$, $> 5\sigma$, $> 3\sigma$, and $< 3\sigma$. We consider only $m_{t'} > m_N + 200$ GeV.

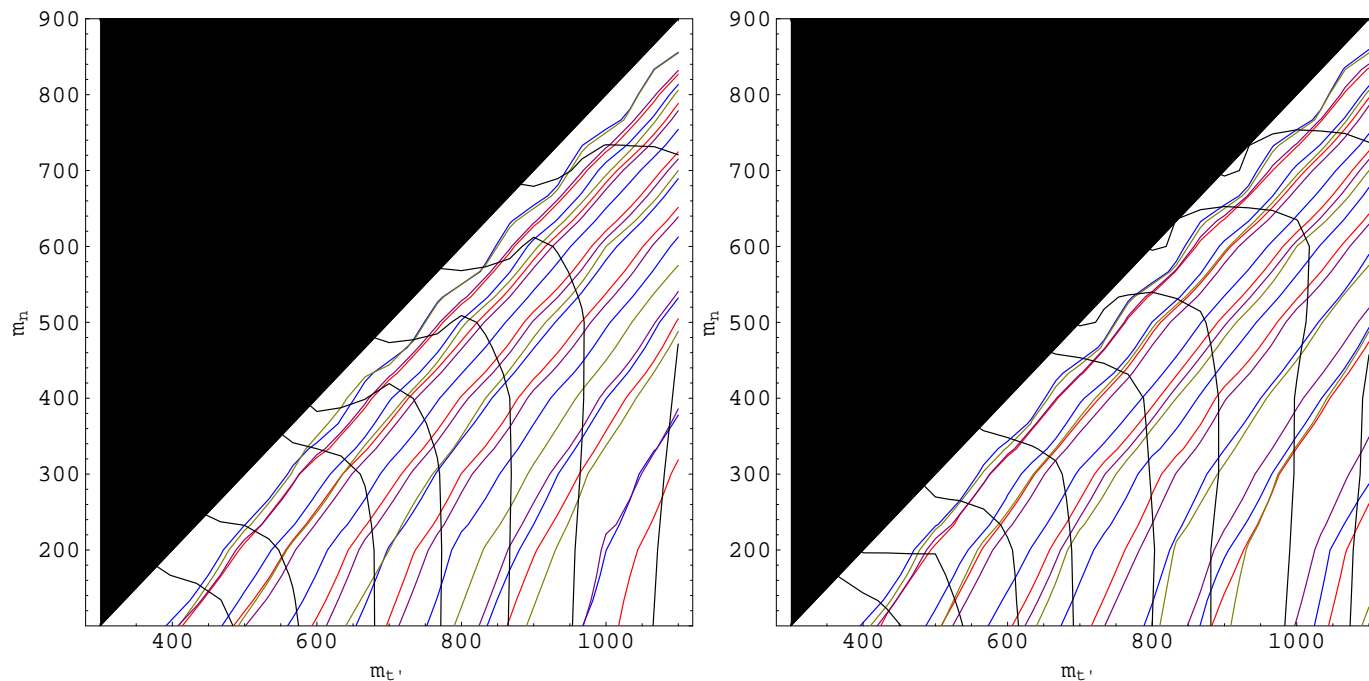
Mass Determination

Kinematic variables

It is often said that M_{eff} , defined as \cancel{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: $\langle \cancel{E}_T \rangle$, $\langle H_t \rangle$, 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.**

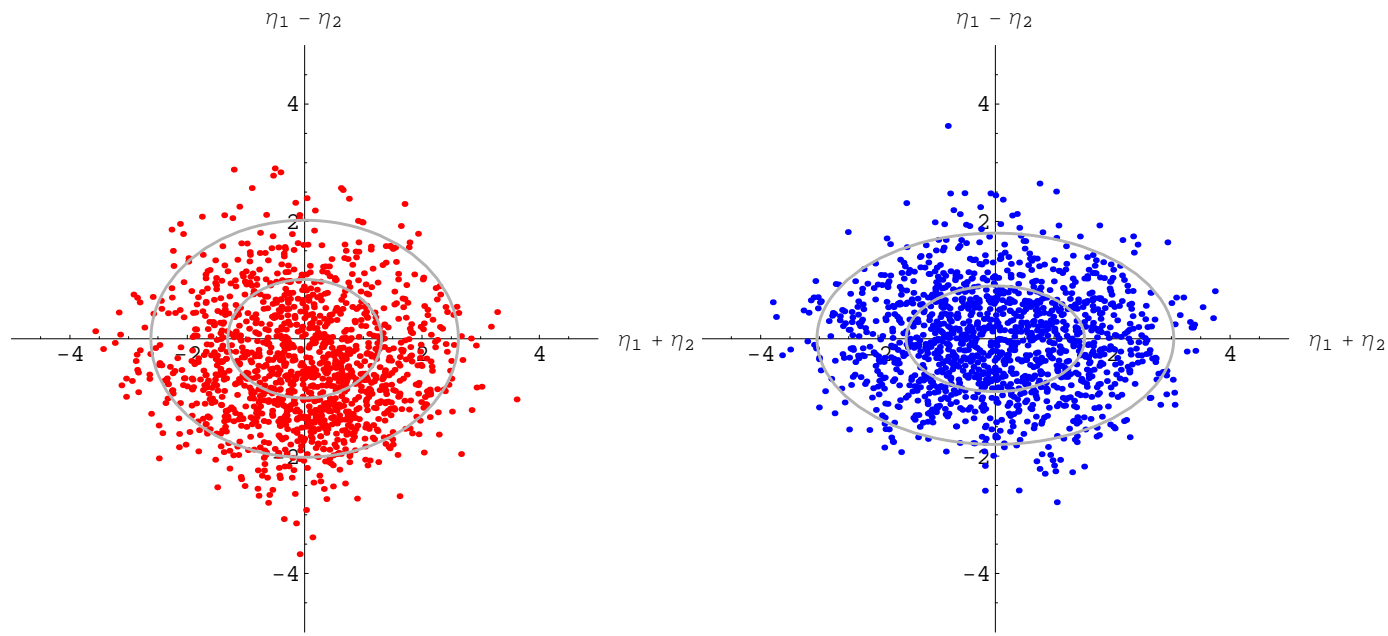
Spin determination

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}



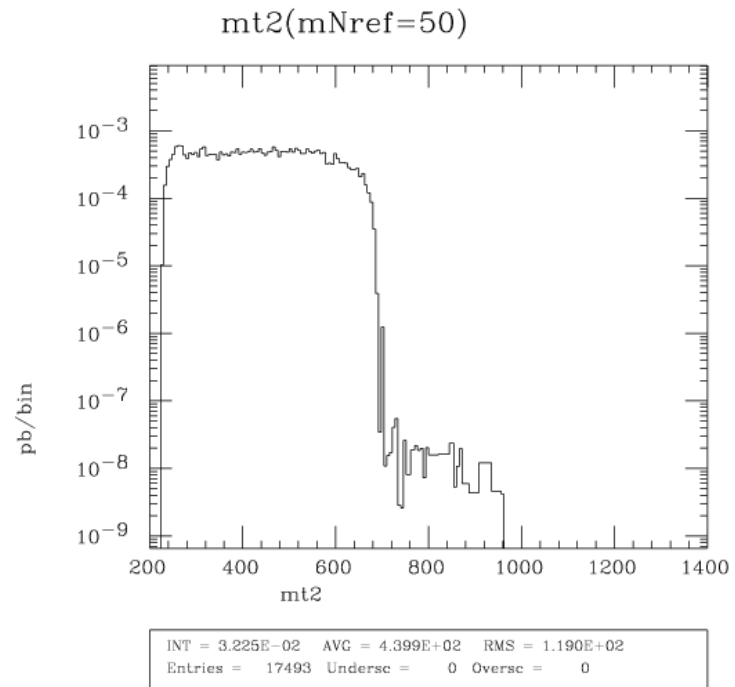
Horizontal axis: sum of η 's of the tops; vertical axis: difference of η 's (the boost-invariant quantity). The scalar case, for equal cross section and $\langle H_t \rangle$, is *lighter*, as manifested in a more horizontally stretched ellipse. (Alternative: make asymmetries.)

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.

$$BLA = \frac{N_+ - N_-}{N_+ + N_-} \quad (1)$$

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' .**

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.