Reconstructing dileptonic $t\bar{t}$ events (and doing stuff with them)

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Why are $t\bar{t}$ studies interesting in general?

- The LHC is the first machine where we can study top interactions with decent statistics
  - First opportunity to really stress the Standard Model in this sector
- Well-motivated BSM probe which can provide constraints on and/or discover a wide range of models

Some basic top 'pheno' background: A top decays to either a b jet + a lepton + a neutrino or a b jet + two light jets, so $t\bar{t}$ events decay either

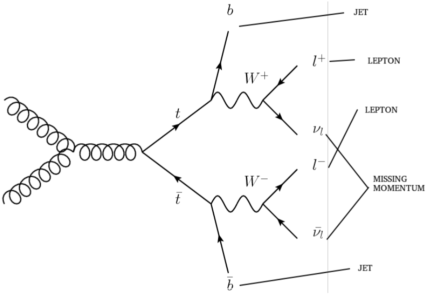
1. hadronically (2 b jets, 4 light jets)
2. semi-leptonically (2 b jets, 2 light jets, 1 lepton, 1 neutrino)
3. dileptonically (2 b jets, 2 leptons, 2 neutrinos)

Why is the dileptonic channel interesting?

- Clean signature, low backgrounds
- Leptons are easy to measure precisely

$\Rightarrow$ good channel for measuring spin correlations using the leptons, what about top polarisation observables?

There's an obvious problem if we want to reconstruct the individual top momenta:



How do you reconstruct two neutrinos from a single missing energy vector?

hep-ph/0603011 and 1305.1878: Assuming both tops and Ws are on-shell we can go through a lot of algebra to find the analytic solution(s).

- Attractive for its conceptual simplicity (elegance)
- Gives up to 4 different solutions since it's based on finding the roots of a fourth-order polynomial
- Used by CMS (together with some 'magic'[1] to determine which of the solutions is the most likely)

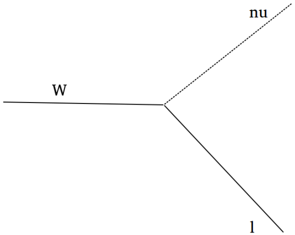
[1] Think 'evaluate parton level matrix element at each phase space point'.

Neutrino weighting: Scan over the solution space for the two neutrinos and weigh each solution based on how well it reproduces kinematic constraints.

- Attractive for its conceptual simplicity (brute force)
- Gives as many solutions as you want in a well-defined manner but is computationally expensive (need to recalculate any quantity which depends on the neutrino momenta every time)
- Used by ATLAS

Before introducing MAOS neutrino reconstruction, let's take a step back and discuss what M_{T2} is.

Back in the 80s, the UA1 experiment at the SPS invented the 'transverse mass' M_T in order to measure the W mass in the leptonic channel



$$M_T^2 = 2\left(E_T^{lep} \not{E}_T - \mathbf{p}_T^{lep} \cdot \not{\mathbf{p}}_T\right) \leq m_W^2$$

(The equality holds if the lepton and neutrino have the same rapidity.)

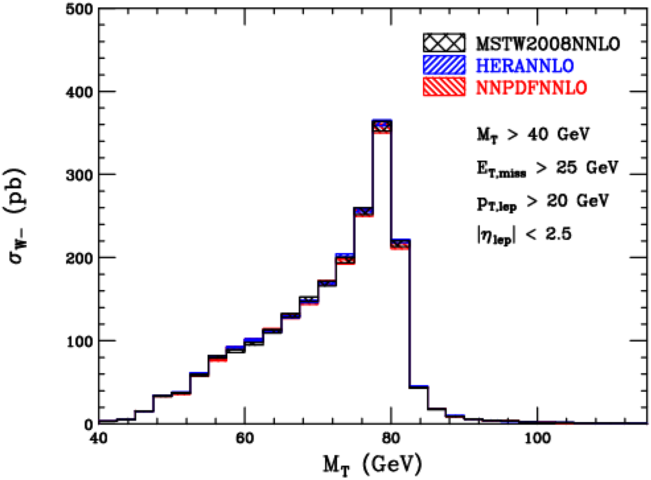
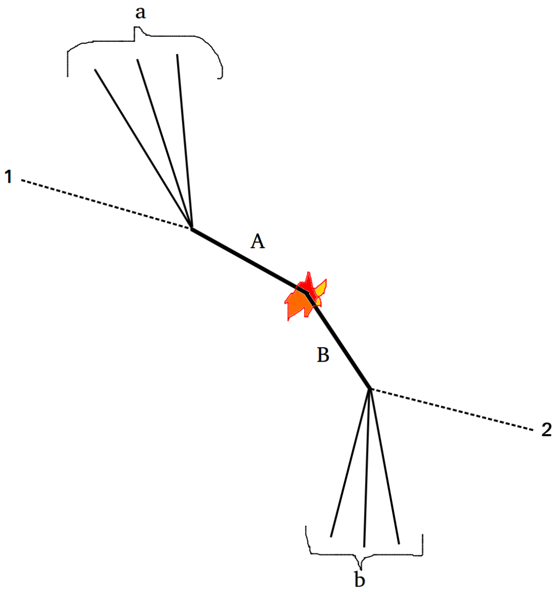


Figure: Taken from 1201.5896.

In the late 90s Lester and Summers (hep-ph/9906349) realised it would be useful to extend M_T to situations where two particles have decayed semi-invisibly. They found the 'obvious' generalisation is:

$$M_{T2}^2 = \min_{\mathbf{p}_{T,1}+\mathbf{p}_{T,2}=\not{p}_T} \left(\max\left[M_T^2(\mathbf{p}^{\text{vis}}_{T,a}, \mathbf{p}_{T,1}), M_T^2(\mathbf{p}^{\text{vis}}_{T,b}, \mathbf{p}_{T,2})\right]\right) \quad (1)$$

Since they intended it for use in SUSY searches it was dubbed the 'stransverse mass'.


a
1
A
B
2
b

Initially M_{T2} was calculated using numerical minimisation algorithms, but in 2008 Cheng and Han (0810.5178) invented a very clever way of performing the calculation:

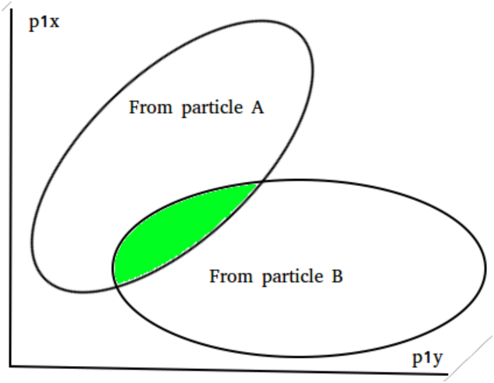
Denote the visible decay products of particle A p_a and the invisible decay product p_1. Assuming A was produced on-shell the invisible particle energy is:

$$E_1 = \frac{p_{a,x}}{E_a} p_{1,x} + \frac{p_{a,y}}{E_a} p_{1,y} + \frac{m_A^2 - m_1^2 - m_a^2}{2E_a} \tag{2}$$

We can also write down the inequality that must be fulfilled for $p_{1,z}$ to be physical (real):

$$p_{1,z}^2 = E_1^2 - p_{1,x}^2 - p_{1,y}^2 - m_1^2 \geq 0 \quad (3)$$

Insert (2) into (3) and you end up with an elliptic region of 'allowed' values for $p_{1,x}$ and $p_{1,y}$. We can do the same thing for particle B and since $\mathbf{p}_{T,1} + \mathbf{p}_{T,2} = \not{\mathbf{p}}_T$ we can put everything onto the $p_{1,x}$ vs $p_{1,y}$ plane.


p1x
From particle A
From particle B
p1y

If we allow the mass of the parent particles A and B to be a floating variable, we can use it to determine the size of the ellipses.

From definition (1) M_{T2} is given by the smallest value of $m_{A/B}$ which still allows for a solution for the invisible momenta.

$\Rightarrow$ Problem of calculating M_{T2} has been turned into a problem of finding overlap between two ellipses!

(1411.4312: problem of overlapping ellipses was elegantly solved in a more-or-less obscure maths paper from 2006 by Etayo, Gonzalez-Vega, and del Rio $\Rightarrow$ forms the basis for the safest and fastest M_{T2} calculating algorithm available today.)

Suggests another way to perform the neutrino reconstruction: the so-called 'M_{T2} Assisted On-Shell' or MAOS method:

- $p_{1,x}$, $p_{1,y}$, $p_{2,x}$, $p_{2,y}$ are uniquely determined in the M_{T2} calculation.
- $p_{1,z}$ and $p_{2,z}$ can be found by solving the quadratic equation (3) for each, giving us 4 permutations.

Note the permutational ambiguity only affects the longitudinal part of the invisible momenta. But why would these values be good approximations to the real invisible momenta?

1. For events close to the kinematic end-point (when $M_{T2} = M_T(A) = M_T(B) = m_{A/B}$) the MAOS momenta should be close to the true invisible momenta.
2. The number of events with real solutions to the invisible momenta is maximised (0810.4853).

Point 2 applies more to BSM searches where the masses are unknown but point 1 is a motivation for using this to reconstruct the neutrinos in dileptonic $t\bar{t}$.

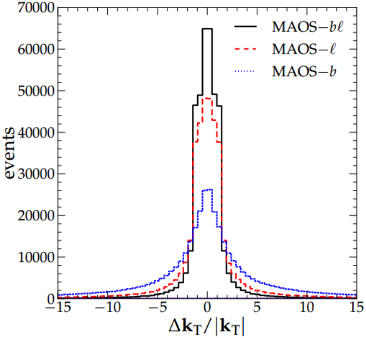
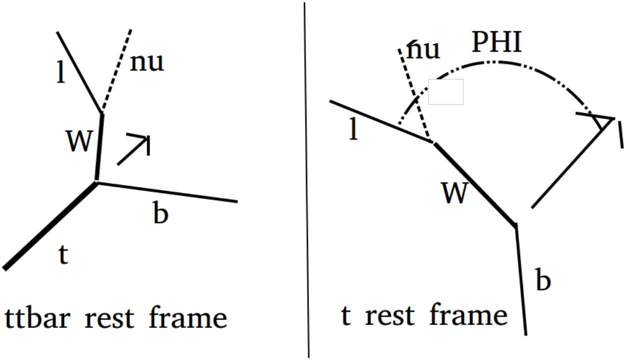


Figure: Taken from 1308.2226.

With neutrinos fully reconstructed, can investigate quantities in dileptonic $t\bar{t}$ production which require the individual top momenta information, such as polarisation observables.

These typically involve lepton angles in the 'helicity frames', the rest frames of the individual tops with the spin quantisation axis used as a reference direction.



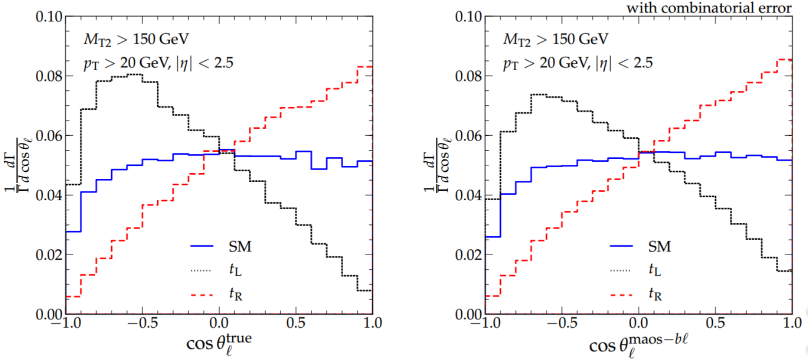
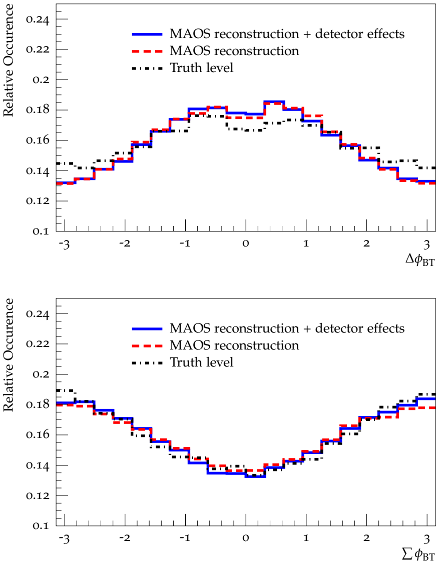


Figure: Taken from 1308.2226.

Baumgart-Tweedie angles from 1212.4888.

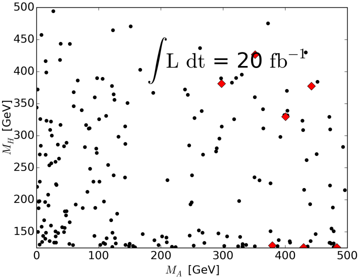


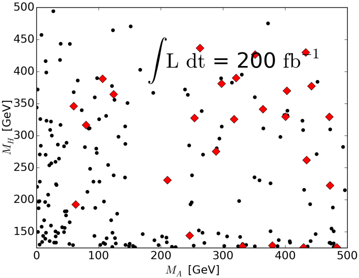
$t\bar{t}$ spin correlations and top polarisations are often modified by BSM physics $\Rightarrow$ offer an alternative to mass spectrum resonances for discovering and constraining new physics.

Consider a Type II 2HDM where the light CP-even Higgs is the LHC 125 GeV scalar, $\tan\beta \approx 1$ and $m_{H^\pm} \approx m_t$[2]

- Since the charged scalars are almost mass-degenerate with the top they are very difficult to find in resonance searches
- Light scalar looks a lot like the SM Higgs
- This part of parameter space is largely unconstrained

[2] We have generated allowed parameter points in this neighbourhood using 2HDMC (0902.0851)


$\int L\ dt = 20\ \text{fb}^{-1}$
M_H [GeV]
M_A [GeV]
500
450
400
350
300
250
200
150
0
100
200
300
400
500


$\int L\ dt = 200\ \text{fb}^{-1}$
M_H [GeV]
M_A [GeV]
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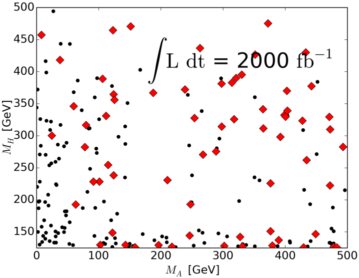
$\int L\ dt = 2000\ \text{fb}^{-1}$
M_H [GeV]
M_A [GeV]
500
450
400
350
300
250
200
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0
100
200
300
400
500

- The dileptonic $t\bar{t}$ channel is useful for angular observables (clean leptons)
- Reconstructing neutrinos challenge for finding individual top momenta
- MAOS method competitive alternative to other reconstruction techniques
- Shows promise for constraining/discovering BSM physics which 'hides' from resonance searches