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Polarisation Studies in $H^- t$ and $Wt$ Production

Work done with Godbole, Hartgring, Niessen (arXiv:1111.0759)

UCL HEP Seminar
Overview

- Brief intro to top quark physics.
- Why look at polarisation?
- Lab frame observables for top polarisation.
- Results in $H^- t$ production.
- $Wt$ vs. top pair production.
- Outlook.
Top quark physics

- Top quark is the heaviest known fundamental particle.
- Mass is close to the energy scale of electroweak symmetry breaking.
- Top sector is thus a potential window through which to look for new physics!
- Top can be produced in pairs or singly.
Top pair production

► Most existing studies have focussed on top pair production.

► Cross-section known to NLO + NNLL level.
► Allows precision measurement of SM inputs (e.g. $m_t$, PDFs).
► Potential BSM effects (e.g. new resonances).
► Single top production has appeared only relatively recently...
Three modes of single top production at LO - $s$ channel; $t$ channel; $Wt$ channel.

- Clean test of the EW sector.
- Total LHC cross-section $\sim 320\text{pb}$ (c.f. $\sigma_{t\bar{t}} \sim 830\text{pb}$) at 14TeV:
### Tevatron Observation

<table>
<thead>
<tr>
<th>Method</th>
<th>March 2009</th>
<th>( \sigma (p\bar{p} \rightarrow tb+X, tqb+X) ) [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision Trees</td>
<td></td>
<td>3.74 (\pm 0.95) (-0.79) pb</td>
</tr>
<tr>
<td>Bayesian NNs</td>
<td></td>
<td>4.70 (\pm 1.18) (-0.93) pb</td>
</tr>
<tr>
<td>Matrix Elements</td>
<td></td>
<td>4.30 (\pm 0.99) (-1.20) pb</td>
</tr>
<tr>
<td>BLUE Combination</td>
<td></td>
<td>4.16 \pm 0.84 pb</td>
</tr>
<tr>
<td>BNN Combination</td>
<td></td>
<td>3.94 (\pm 0.88) pb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N. Kidonakis, PRD 74, 114012 (2006) (m_{top} = 170) GeV</td>
</tr>
</tbody>
</table>

- **Very recent observation (2009).**
- **Challenging analysis (neural networks, BDTs...).**
- **Direct measurements of** \(V_{tb}\): > 0.71 (CDF), > 0.78 (D0).
LHC Measurements

- Both ATLAS and CMS now closing in on SM single top.
- Shown are candidate $Wt$ and $t$-channel events.
Single vs. pair production

- We have seen that pair production is mainly QCD-based, whereas single top production is purely EW in the SM.
- This explains the difference in cross-sections.
- There is another important difference: in pair production, the top quark is *unpolarised* on average.
- By contrast, in $Wt$ production, the top quark gets completely polarised.
- If the top quark is singly produced in association with a new physics particle, the polarisation can be somewhere in between.
- Let us look at polarisation in more detail...
In a given production process, the degree of polarisation of the top quark is defined by

\[ P_t = \frac{\sigma(+,+) - \sigma(-,-)}{\sigma(+,+) + \sigma(-,-)}, \]

where \( \sigma(\pm, \pm) \) is the cross-section for a positively or negatively polarised top.

If the top quark decays according to

\[ t \to Wb \to ff'b, \]

the decay product \( f \) is distributed in the top quark rest frame according to

\[ \sim \frac{1}{2} \left( 1 + \kappa_f P_t \cos \theta_{f,\text{rest}} \right). \]
Top polarisation

- Here $\theta_{f,\text{rest}}$ is the (rest frame) angle between the decay product $f$ and the top quark spin vector.

- The strength of the correlation is governed by the analysing power $\kappa_f$.

- This depends on the decay product $f$, and receives higher order corrections from SM or BSM diagrams.

- For a lepton ($f = l$), $\kappa_l \simeq 1$ at leading order.

- Furthermore, $\kappa_l$ is insensitive to BSM corrections to the decay of the top quark, to a first approximation (Godbole, Rao, Rindani, Singh).
Leptons as new physics probes

- Consider a top quark which is produced in association with some new physics particle $X$.
- This may affect the net polarisation of the top ($P_t \neq 0$).
- If the top decays leptonically, the angular distribution of the lepton is governed by $P_t$ and $\kappa_\ell$.
- BSM corrections to the top quark decay are irrelevant, as they do not change $\kappa_\ell$.
- It follows that lepton angular distributions can be used to infer the coupling of $X$ to the top quark!
The preceding argument is based on an angular distribution in the top quark rest frame.

It is easier more useful to construct observables in the lab frame.

We assume that the (lab frame) top quark direction can be accurately reconstructed.

Then one can consider two angles, which we call $\phi_I$ (azimuthal) and $\theta_I$ (polar) (Godbole, Rao, Rindani, Singh).

Let’s discuss each in turn...
Azimuthal angle $\phi_I$

- Choose the beam direction to define the $z$ axis.
- Then choose the top quark direction to lie in the $(x, z)$ plane, such that the top quark has positive $x$ component.

Upon constructing a right-handed coordinate system, $\phi_I$ is the azimuthal angle between the decay lepton and the top in the $(x, y)$ plane.
Polar angle $\theta_l$

- The angle $\theta_l$ is more simply defined, as the polar angle of the decay lepton, using the top quark direction as the polar axis.
- In the rest frame, only the polar angle $\theta_{l,\text{rest}}$ was relevant.
- However, after boosting to the lab frame, both $\phi_l$ and $\theta_l$ carry an imprint of the top polarisation.
- They were first considered in the context of top pair production (Godbole, Rao, Rindani, Singh), but have subsequently been examined in $H^-t$ and $Wt$ production (Huitu et. al., Godbole et. al.).
- Here we will consider $H^-t$ production, in a general two Higgs doublet model.
Two Higgs doublet models

巨型的，The SM has only one Higgs doublet, giving rise to a single neutral scalar Higgs boson.巨型的，

巨型的，Many extensions to the SM contain two Higgs doublets, each of which gains a vacuum expectation value.巨型的，

巨型的，Such theories are divided into so-called type I or type II theories, depending on how the doublets couple to the various up and down-type fermions.巨型的，

巨型的，For example, the MSSM is an example of a type II model.巨型的，

巨型的，However, the notion of a two Higgs doublet model is much more general, and generically gives rise to extra Higgs bosons (scalar, pseudoscalar, charged).巨型的，

巨型的，In particular, there are charged particle $H^\pm$, that can couple to the top quark.
$H^- t$ production

- The leading order diagrams for $H^- t$ production are analogous to $Wt$ production.

- We assume the general type II coupling:

$$G_{H^- t \bar{b}} = -\frac{i}{v \sqrt{2}} V_{tb} \left[ m_b \tan \beta (1 - \gamma_5) + m_t \cot \beta (1 + \gamma_5) \right],$$

where $\tan \beta$ is the ratio of VEVs for the two doublets.
The cross-section for $H^-t$ production is completely determined by the two BSM parameters $m_{H^-}$, $\tan \beta$ (plus SM inputs).

Furthermore, the coupling of the $H^-$ to the top quark has both a left-handed and a right-handed part.

Thus, the top quark is only partially polarised in general if produced with a charged Higgs.

Furthermore, the amount of polarisation depends on $\tan \beta$ and $m_{H^-}$.

By studying the polarisation of the top, we can in principle determine the new physics parameters!

Polarisation observables can also be used to reduce backgrounds.
Calcutational Details

- We calculated results for $\phi_I$ and $\theta_I$, we used the recently developed MC@NLO software for $H^-t$ production (Weydert et. al.).
- This includes NLO matrix elements interfaced with a parton shower algorithm, with spin correlations included according to the algorithm of Frixione, Laenen, Motylinski, Webber.
- I will also occasionally show LO parton level results for comparison, obtained with MadGraph.
- Parameters used throughout are as follows: $m_t = 172.5$ GeV, $\Gamma_t = 1.4$ GeV, $m_b = 4.95$ GeV, $\mu_r = \mu_f = m_t$.
- Partons are MSTW 2008 LO and NLO for the MadGraph and MC@NLO results.
Results - $\phi_I$

- Peaked at $\phi_I = 0, 2\pi$, even for unpolarised tops, due to boost form rest frame.

- Polarisation dependent information modifies the overall shape.
Azimuthal asymmetry parameter

- Note that $\phi_l$ distributions for different parameter values cross at $\phi_l = \pi/2, 3\pi/2$.
- This allows us to define a single asymmetry parameter

\[
A_\phi = \frac{\sigma(\cos \phi_l > 0) - \sigma(\cos \phi_l < 0)}{\sigma(\cos \phi_l > 0) + \sigma(\cos \phi_l < 0)}.
\]

- Each point in parameter space (tan $\beta$, $m_{H^-}$) gives a different value of $A_\phi$.
- A measurement of $A_\phi$ can then be used to determine the parameters of the $H^-$ boson, if discovered.
- Can also be used to distinguish $H^-t$ production from backgrounds.
Results - $A_\phi$

- Results are shown at LO (blue) and MC@NLO (red) level (statistical uncertainties shown), and for different Higgs masses (200-1500 GeV).
A pronounced correlation is observed even at MC@NLO level: polarisation effects robust against higher order corrections.

There is a wide spread of $A_\phi$ values, especially at lower $\tan \beta$: $A_\phi$ is a sensitive probe of parameter space.

The $Wt$ and $Ht$ results can be very different - this can be used to reduce the $Wt$ background.

Next, can consider the polar angle...
Results - $\theta_l$

- Peaked strongly at small $\theta_l$.
- Crossing point for different points in parameter space.
Polar asymmetry parameter

- This motivates the definition of a polar asymmetry parameter:

\[
A_\theta = \frac{\sigma(\theta_1 < \pi/4) - \sigma(\theta_1 > \pi/4)}{\sigma(\theta_1 < \pi/4) - \sigma(\theta_1 > \pi/4)}.
\]

- Analogous to the azimuthal parameter, but provides complementary information.

- In principle, combining \( A_\phi \) and \( A_\theta \) can give complete information on \( m_{H^-} \) and \( \tan \beta \).
Results - $A_\theta$

- Results are shown at LO (blue) and MC@NLO (red) level (statistical uncertainties shown), and for different Higgs masses (200-1500 GeV).
As for the azimuthal parameter, $A_\theta$ is robust against higher order corrections.

It provides useful complementary information - in particular, it is sensitive to different Higgs masses at large $\tan\beta$, whereas $A_\phi$ is not.

Again very different to the $Wt$ result, and thus useful for background reduction.

As well as angular observables, additional observables have been recently proposed involving the energy of the top quark and its decay products...
Energy observables

- **Shelton** has recently proposed the following observables (at parton level):

\[
z = \frac{E_b}{E_t}, \quad u = \frac{E_l}{E_l + E_b},
\]

where \( E_l, E_b \) are the energies of the lepton and \( b \) quark (or jet) from the top decay, and \( E_t \) the top energy.

- These are sensitive to new physics corrections to both the top quark production and decay, and carry top polarisation information.

- They were originally proposed only for *boosted* tops.
Boosted tops

- There are many choices one can make to define how boosted a given top quark is.
- I will use

\[ B = \frac{|p_{\text{top}}|}{E_t}. \]
Cutting on the boost parameter gives a well-defined shape which carries polarisation information (Shelton).

Here shown for $\tan \beta = 1$, $m_{H^-} = 200$ GeV.
**z and u parameters**

- Shape varies around peak as parameters vary.

- For z parameter, slope carries polarisation information.

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- $\frac{1}{\sigma} \cdot \frac{dz}{du}$

- $\tan(\beta) = 1$

- $\tan(\beta) = 40$

---

- $m_H = 200$ GeV

- $m_H = 1500$ GeV
Energy asymmetry parameters

The features of the $z$ and $u$ parameters suggest the following asymmetry parameters:

\[
A_u = \frac{\sigma(u > 0.215) - \sigma(u < 0.215)}{\sigma(u > 0.215) + \sigma(u < 0.215)},
\]

\[
A_z = \frac{\sigma(0.1 \leq z \leq 0.4) - \sigma(0.4 \leq z \leq 0.7)}{\sigma(0.1 \leq z \leq 0.4) + \sigma(0.4 \leq z \leq 0.7)}.
\]

These provide complementary information to the angular asymmetries.

In particular, they are sensitive to the decay of the top, as well as the production.
$A_z$ and $A_u$
Differences in $A_z$ and $A_u$ parameters can be smaller than for angular asymmetries, thus are less sensitive to polarisation effects in general.

Also seem to be more sensitive to higher order corrections.

Nevertheless, recent work in a different new physics context has shown that the $z$ and $u$ distributions remain useful, even when detector effects etc. are included (Papaefstathiou, Sakurai).

In some regions of parameter space, $A_z$ is of opposite sign in $H^- t$ and $Wt$ production.
Summary of $H^- t$ Production

- Top polarisation effects can be used to measure the coupling of the top to associated particles (e.g. a charged Higgs boson).
- Lab frame angular distributions ($\phi_l, \theta_l$) are sensitive to top polarisation.
- Asymmetry parameters can be defined which maximise the differences throughout parameter space ($\tan \beta, m_{H^-}$).
- Energy ratio distributions are also useful, but require boosted tops.
- Get complementary information from all these parameters: angular asymmetries are insensitive to corrections to top decay.
Earlier we saw three modes of SM single top production ($s-$, $t-$ and $Wt-$channel).

Throughout the talk, $Wt$ production has been considered as a background to $H^-t$ production.

However, it is also of interest in itself.

In particular, it is sensitive only to new physics corrections to the $Wtb$ vertex, and not to four-fermion operators.

Thus, $Wt$ production cleanly isolates possible new physics contributions.
The main background to $Wt$ production is top pair production.

Indeed, there are subtleties in how one separates $Wt$ and $t\bar{t}$ production beyond LO * CONTROVERSY WARNING *.

See White, Frixione, Laenen, Maltoni for a full discussion (also Kauer, Zeppenfeld).

Assuming we can indeed talk about $Wt$, are any of the observables we have talked about useful when $Wt$ is the signal?

After all, the top quark is completely polarised in $Wt$ production, but unpolarised on average in top pair production...

To investigate, have used MC@NLO for $Wt$ and $t\bar{t}$ with (semi)-realistic signal cuts...
Wt signal cuts

1. The presence of exactly 1 $b$ jet with $p_T > 50$ GeV and $|\eta| < 2.5$. No other $b$ jets with $p_T > 25$ GeV and $|\eta| < 2.5$.
2. The presence of exactly 2 light flavor jets with $p_T > 25$ GeV and $|\eta| < 2.5$. In addition, their invariant mass should satisfy $55$ GeV $< m_{j_1j_2} < 85$ GeV.
3. Events are vetoed if the invariant mass of the $b$ jet and light jet pair satisfies

$$150 \text{ GeV} < \sqrt{(p_{j_1} + p_{j_2} + p_b)^2} < 190 \text{ GeV}.$$ 

4. The presence of exactly 1 isolated lepton with $p_T > 25$ GeV and $|\eta| < 2.5$. The lepton should satisfy $\Delta R > 0.4$ with respect to the two light jets and the $b$ jet, where $R$ is the distance in the ($\eta, \phi$) plane.
5. The missing transverse energy should satisfy $E^\text{miss}_T > 25$ GeV.
Lepton used is isolated lepton from signal cuts...

Notable difference between $Wt$ and top pair production.
Asymmetry parameters

<table>
<thead>
<tr>
<th>$B_{cut}$</th>
<th>$Wt$</th>
<th>Top pair</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.33 ± 0.01</td>
<td>0.63 ± 0.02</td>
</tr>
<tr>
<td>0.8</td>
<td>0.41 ± 0.02</td>
<td>0.70 ± 0.05</td>
</tr>
<tr>
<td>0.9</td>
<td>0.42 ± 0.03</td>
<td>0.70 ± 0.07</td>
</tr>
<tr>
<td>0.95</td>
<td>0.44 ± 0.04</td>
<td>0.68 ± 0.08</td>
</tr>
</tbody>
</table>

- $A_\phi$ is very different between $Wt$ and top pair...

- ...as is $A_\theta$.

<table>
<thead>
<tr>
<th>$B_{cut}$</th>
<th>$Wt$</th>
<th>Top pair</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.02 ± 0.01</td>
<td>0.26 ± 0.02</td>
</tr>
<tr>
<td>0.8</td>
<td>0.18 ± 0.02</td>
<td>0.38 ± 0.04</td>
</tr>
<tr>
<td>0.9</td>
<td>0.49 ± 0.03</td>
<td>0.75 ± 0.07</td>
</tr>
<tr>
<td>0.95</td>
<td>0.70 ± 0.05</td>
<td>0.97 ± 0.10</td>
</tr>
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</table>
Angular observables indeed seem to be useful for reducing top pair backgrounds to $Wt$.

Energy observables ($z, u$) were also considered in arXiv:1111.0759, but not as useful.

This is principally because the top is not very boosted in $Wt$ production.

This was only a very basic study, but deserves further investigation.
Conclusions

- Top polarisation is an effective tool for probing new physics models.
- Lab frame observables can be defined which carry polarisation information.
- We focussed on angular and energy observables in $H^- t$ production.
- Asymmetry parameters can be used to pin down the parameter space of a charged Higgs boson, and to potentially reduce backgrounds.
- Angular observables also seem to be useful in $Wt$ production.
- The observables are robust against higher order corrections.