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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

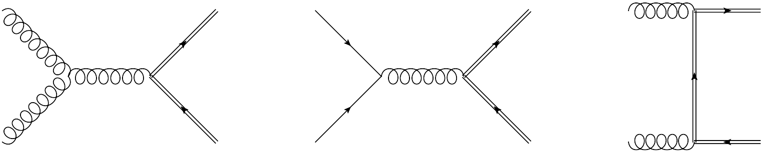
- Brief intro to top quark physics.
- Why look at polarisation?
- Lab frame observables for top polarisation.
- Results in $H^- t$ production.
- Wt vs. top pair production.
- Outlook.

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.

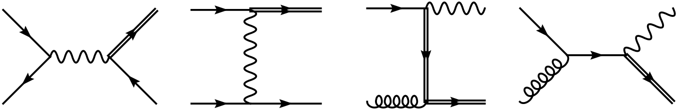
Top pair production

- 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...

Single Top Production



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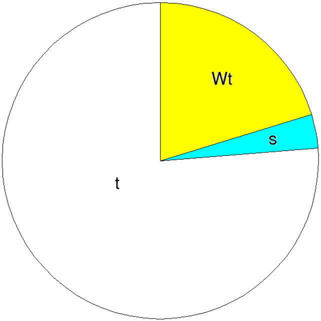
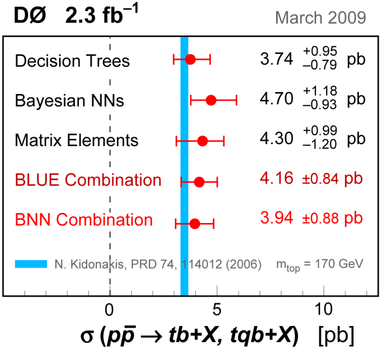
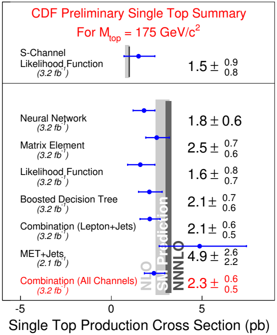
- Three modes of single top production at LO - s channel; t channel; Wt channel.

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



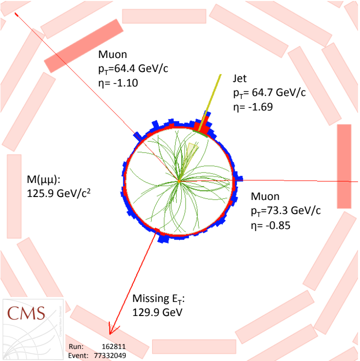
Tevatron Observation

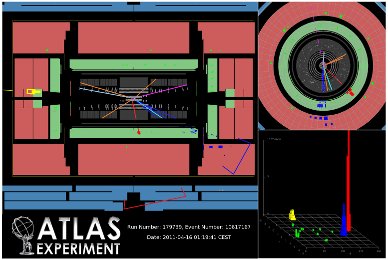




- Very recent observation (2009).
- Challenging analysis (neural networks, BDTs...).
- Direct measurements of V_{tb}: > 0.71 (CDF), > 0.78 (D0).

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...

Top polarisation

- 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

$$\sim \frac{1}{2}\left(1 + \kappa_f P_t \cos\theta_{f,\mathrm{rest}}\right).$$

Top polarisation

- Here $\theta_{f,\mathrm{rest}}$ 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* κ_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, κ_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

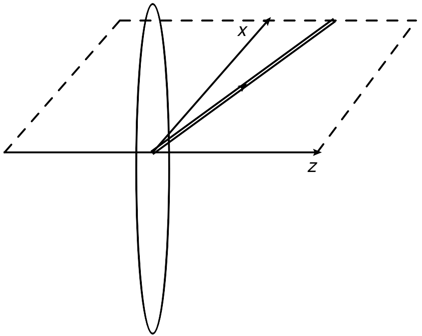
- Consider a top quark which is produced in association with some new physics particle X.
- This may affect the net polarisation of the top ($P_t \neq 0$).
- If the top decays leptonically, the angular distribution of the lepton is governed by P_t and κ_l.
- BSM corrections to the top quark decay are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

Lab frame observables

- 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 ϕ_l (azimuthal) and θ_l (polar) (Godbole, Rao, Rindani, Singh).
- Let's discuss each in turn...

Azimuthal angle ϕ_l

- 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, ϕ_l is the azimuthal angle between the decay lepton and the top in the (x, y) plane.

Polar angle θ_l

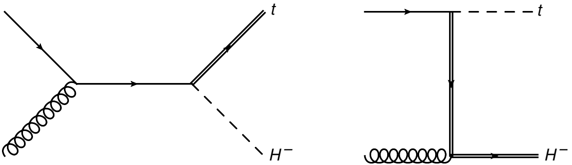
- The angle θ_l is more simply defined, as the polar angle of the decay lepton, using the top quark direction as the polar axis.
- In the rest frame, only the polar angle $\theta_{l,\mathrm{rest}}$ was relevant.
- However, after boosting to the lab frame, both ϕ_l and θ_l carry an imprint of the top 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

- The SM has only one Higgs doublet, giving rise to a single neutral scalar Higgs boson.
- Many extensions to the SM contain two Higgs doublets, each of which gains a vacuum expectation value.
- 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.
- For example, the MSSM is an example of a type II model.
- However, the notion of a two Higgs doublet model is much more general, and generically gives rise to extra Higgs bosons (scalar, pseudoscalar, charged).
- 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 analagous 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.

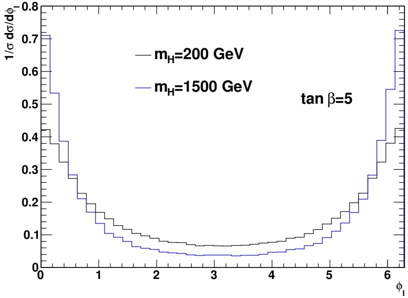
Comments

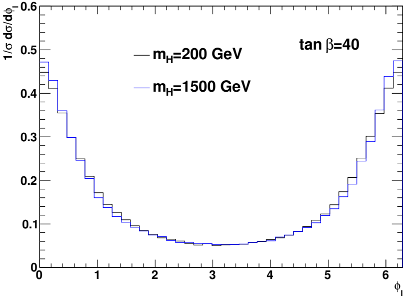
- The cross-section for $H^- t$ production is completely determined by the two BSM parameters m_{H^-}, $\tan\beta$ (plus SM inputs).
- Furthermore, the coupling of the H^- to the top quark has both a left-handed and a right-handed part.
- Thus, the top quark is only partially polarised in general if 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.

Calculational Details

- We calculated results for ϕ_l and θ_l, 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 - ϕ_l





- Peaked at $\phi_l = 0,\ 2\pi$, even for unpolarised tops, due to boost form rest frame.
- Polarisation dependent information modifies the overall shape.

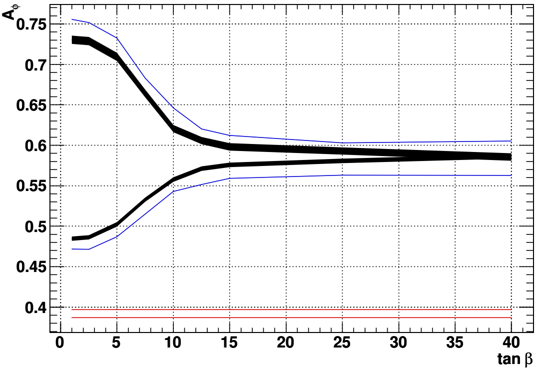
Azimuthal asymmetry parameter

- Note that ϕ_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_ϕ.
- A measurement of A_ϕ 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_ϕ

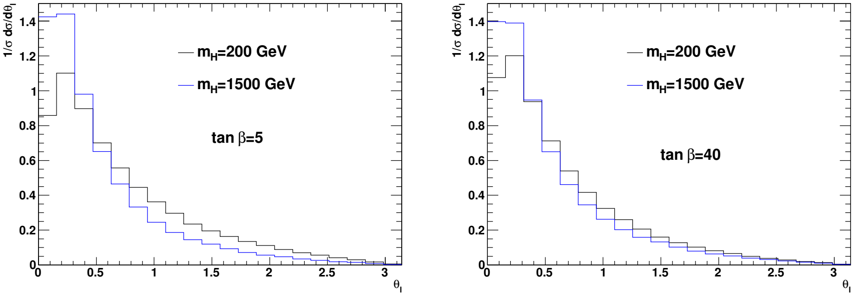


- Results are shown at LO (blue) and MC@NLO (red) level (statistical uncertainties shown), and for different Higgs masses (200-1500 GeV).

Comments

- A pronounced correlation is observed even at MC@NLO level: polarisation effects robust against higher order corrections.
- There is a wide spread of A_ϕ values, especially at lower $\tan\beta$: A_ϕ 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 - θ_l



- Peaked strongly at small θ_l.
- Crossing point for different points in parameter space.

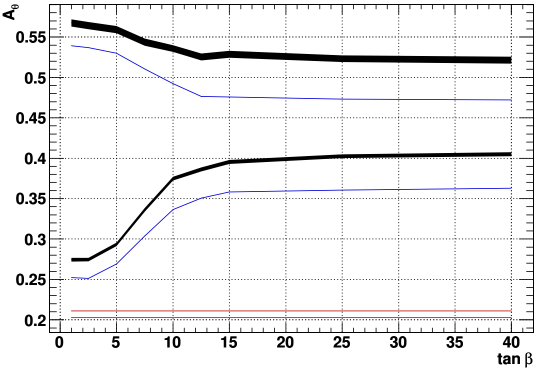
Polar asymmetry parameter

- This motivates the definition of a polar asymmetry parameter:

$$A_\theta = \frac{\sigma(\theta_l < \pi/4) - \sigma(\theta_l > \pi/4)}{\sigma(\theta_l < \pi/4) - \sigma(\theta_l > \pi/4)}.$$

- Analagous to the azimuthal parameter, but provides complementary information.
- In principle, combining A_ϕ and A_θ can give complete information on m_{H^-} and $\tan\beta$.

Results - A_θ



- Results are shown at LO (blue) and MC@NLO (red) level (statistical uncertainties shown), and for different Higgs masses (200-1500 GeV).

Comments

- As for the azimuthal parameter, A_θ 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_ϕ 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):

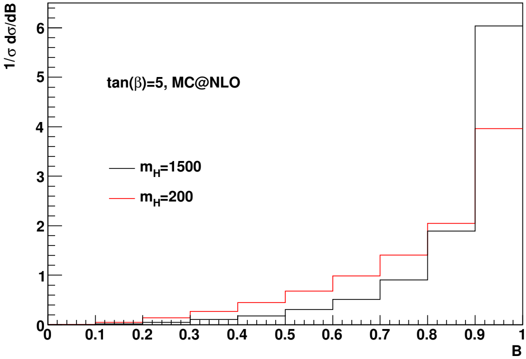
$$z = \frac{E_b}{E_t}, \quad u = \frac{E_l}{E_l + E_b},$$

  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.

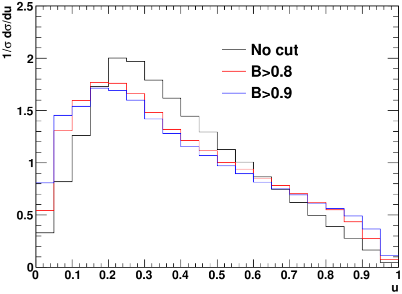
Boosted tops

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

$$B = \frac{|\mathbf{p}_{\mathrm{top}}|}{E_t}.$$

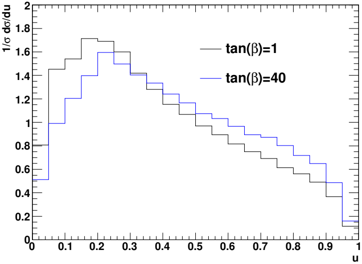


z and u parameters



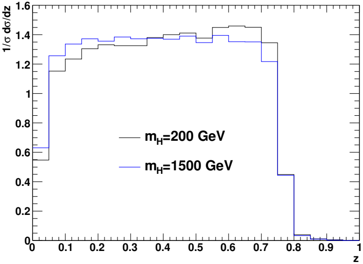
- Cutting on the boost parameter gives a well-defined shape which carries polarisation information (Shelton).
- Here shown for $\tan\beta = 1$, $m_{H^-} = 200$ GeV.

z and u parameters



- Shape varies around peak as parameters vary.

- For z parameter, slope carries polarisation information.



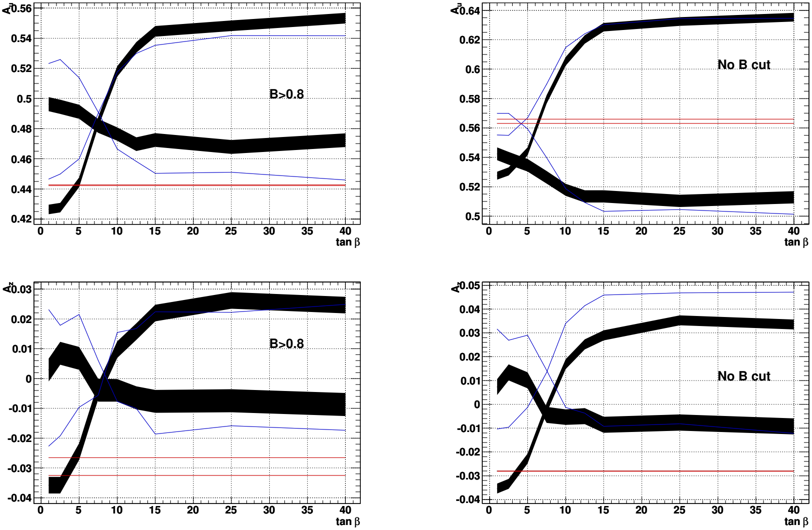
Energy asymmetry parameters

- 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



Comments

- 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 (ϕ_l, θ_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.

Wt production

- 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.

Wt production

- 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...

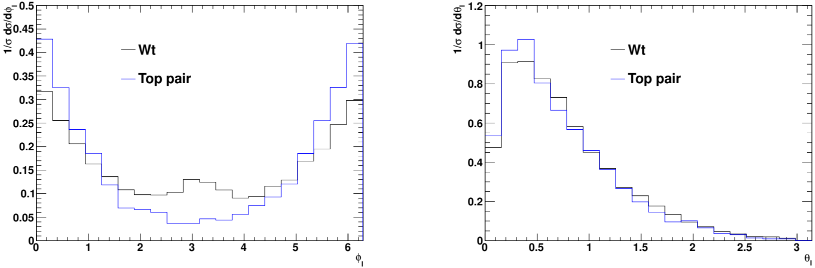
Wt signal cuts

1. The presence of exactly 1 b jet with $p_t^T > 50$ GeV and $|\eta| < 2.5$. No other b jets with $p_t^T > 25$ GeV and $|\eta| < 2.5$.
2. The presence of exactly 2 light flavor jets with $p_t^T > 25$ GeV and $|\eta| < 2.5$. In addition, their invariant mass should satisfy 55 GeV$< m_{j_1 j_2} < 85$ GeV.
3. Events are vetoed if the invariant mass of the b jet and light jet pair satisfies

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

4. The presence of exactly 1 isolated lepton with $p_t^T > 25$ 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 (η, ϕ) plane.
5. The missing transverse energy should satisfy E_T^{miss} >25 GeV.

Results for ϕ_l and θ_l



- Lepton used is isolated lepton from signal cuts...
- Notable difference between *Wt* and top pair production.

Asymmetry parameters

B_{cut}	Wt	Top pair
0	0.33 ± 0.01	0.63 ± 0.02
0.8	0.41 ± 0.02	0.70 ± 0.05
0.9	0.42 ± 0.03	0.70 ± 0.07
0.95	0.44 ± 0.04	0.68 ± 0.08

- A_ϕ is very different between Wt and top pair...

B_{cut}	Wt	Top pair
0	0.02 ± 0.01	0.26 ± 0.02
0.8	0.18 ± 0.02	0.38 ± 0.04
0.9	0.49 ± 0.03	0.75 ± 0.07
0.95	0.70 ± 0.05	0.97 ± 0.10

- ...as is A_θ.

Comments

- 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.