Top polarisation: what physics can it probe: specific example of BSM explanations of $A_{FB}^t$ of Tevatron.

A measure of polarisation using angular distribution of decay leptons.

Observables using top polarisation for probing CP property of Higgs and CP violation at $e^+e^-$ colliders.

If possible:
- Polarisation measures using energies for highly boosted tops.
Based in part on


3) D. Choudhury, RG, Pratishruti Saha, S.D.Rindani arXiv: 1012.4750

Top quarks:

- **Copious production of** $t\bar{t}$ **pairs at LHC** (SM c.s. $\approx 160$ pb at 7 TeV)

- **Important role in new physics signatures:** Top quarks can also arise in the decays of new particles – resonances, new gauge bosons, Higgs bosons, squarks, gluinos . . .

- **Template for issues in new physics:** example of determination of spin and mass!

- **Most important background to a lot of new physics.** What features can be used effectively to de-lineate the SM tops from BSM tops!

- **Polarisation can be one important handle.**
Top polarisation and BSM.

- Top polarization can give more information about the production mechanism than just the cross section does.

- Top partners with the different spin (SUSY) or same spin UED/Little Higgs, associated $tH^+$ production...


Top polarisation can carry information on the model parameters. Use kinematic features due to polarisation effect to isolate signal from background in searches (Agashe et al. ...)

- Non zero top polarisation requires parity violation and hence measures left-right mixing. One example: R-parity violating SUSY (Hikasa PRD, 1999).

- It can give a clue to CP violation through dipole couplings: Soni, Bar Shalom,..
Top polarisation and BSM.

BSM characterisation using top polarisation

Example: BSM explanations of the Forward-Backward asymmetry seen at the Tevatron.

CDF and D0 reported FB asymmetry in $t\bar{t}$ production \textit{D0: PRL 100, 142002 (2008), CDF: PRL 101, 202001 (2008)}.

$$A_{FB}^t = 0.193 \pm 0.0065 \pm 0.024$$

CDF published result, newer value somewhat lower

Now CDF result $m_{t\bar{t}}$ dependent $A_{FB}$.

SM expectation (NLO : Rodrigo/Kuehn) : 0.051

Presented at La Thuille a result using the dilepton channel (where both $t$ and $\bar{t}$ decay leptonically) as well.
Hikasa PRD 60, 114041, 99

RPV SUSY contributions

Expected FB asymmetry at Tevatron:

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Chiral colour models: axigluons, $pp \rightarrow \text{Axigluon} + X \rightarrow t\bar{t} + X$ can also give rise to a FB asymmetry.


Corrected in D. Choudhury, RG, Singh and Wagh, PLB 657 (2007) 69

Wrong sign (alas!)
A host of BSM explanations:

**Examples** of some which explain most of the observed features 'satisfactorily'

1) *t*-channel colour triplet (sextet) scalar object:


2) *t*-channel colour singlet vector exchange: 


3) *t* channel + *s* channel vector exchange: 


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4) \textit{s-channel strongly interacting vector exchange:}


\textbf{(Axigluons: (pre)dicted)}: D. Choudhury, RG, Singh and Wagh, PLB 657 (2007) 69; alas wrong sign!

\textbf{Generalisation: flavour non-universal axigluon}


\textbf{Many more. Some of the latest:}

1101.5203 Y. Bai et al, 1103.2297 Cedric Delaunay et al, 1103.2757 Zoltan Ligeti et al, 1103.2765
J. A. AguilarSaavedra et al.

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The Forward backward top asymmetry originates due to different reasons in different model explanations.

The chirality structure is also different.

Expected top polarisation can be different.

\[ A_p = \frac{\sigma^{pol}}{\sigma^{tot}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \]
Top polarisation and BSM.

In all the three different models expected top polarisation quite different for different physics explanations. Correlation between top polarisation and FB asymmetry quite different.

Exploring Measurement of top polarisation a useful tool to get information on production mechanism.

Φ : Tait et al colour triplet/sextet scalar $Z'$: Murayama, Wells $t$–channel vector $A$: Flavour nonuniversal axigluons.
There are two recent analyses which are have looked at the polarisation:

1) J. Cao, L. Wu, J. M. Yang, arXiv:1011.5564 [hep-ph] (three specific models). Only for LHC, also correlation with $\sigma_{tt}$ is not implemented.

2) D.-W. Jung, P. Ko, J. S. Lee, arXiv:1011.5976 [hep-ph], model independent analysis. Masses not large enough. Direct contact of the models with this analysis?
Some more discrimination possible. Use $R_A = \frac{A(|\Delta y|<1)}{A(|\Delta y|\geq1)}$
Included statistical errors.
Top polarisation and BSM.

Realism:

At 7 TeV:

![Graph showing polarisation and cross-section](image-url)
Polarisation can be measured by studying the decay distribution of a decay fermion $f$ in the rest frame of the top:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_f} = \frac{1}{2} \left( 1 + P_t \kappa_f \cos \theta_f \right),$$

$\theta_f$ is the angle between the $f$ momentum and the top momentum, $P_t$ is the degree of top polarization, $\kappa_f$ is the “analyzing power” of the final-state particle $f$.

$\kappa_f = 1$ for $f = \ell$. 
The angular distribution of charged leptons (down quarks) from top decay in the rest frame not affected by anomalous $tbW$ couplings (to linear order) is:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_l} = \frac{1}{2} (1 + P_t \cos \theta_l) ,$$

Energy integrated angular distributions of the decay lepton in the lab are also not affected by the anomalous parts of the $tbW$ vertex. (Observed before: Hioki et al, Rindani, Ohkuma, R. Singh et al) Shown for general case: RG, S. Rindani and R. Singh. Now a general argument: R.G., M. Peskin, S. Rindani, R. Singh

Hence the correlation with top polarisation is faithfully reflected.

On the other hand the decay lepton energy distributions in the laboratory contain some piece due to the anomalous couplings as well.
Angular distribution of the decay lepton $l$ in the rest frame of the top is the most efficient polarisation observable.

The angular distributions of the decay leptons in the lab frame can carry this polarisation information faithfully.

For highly boosted tops: what about rest frame reconstruction and angle measurements? If we use something other than angles? How robust wrt anomalous top couplings?
Top polarisation and BSM. Probe polarisation using lepton angular distributions?

Different candidates:

1) Angle between top and the decay lepton in the lab:

2) Angle between the decay lepton and the beam direction

For the Tevatron energies, we (RG, Poulse, Rindani) had showed that in R-parity violating case, effect can be seen as FB asymmetry of the lepton. (results for the $A_{FB}$ models in progress.)

The distributions for the LHC case will show no sensitivity.

This can work ONLY for an asymmetric collider: i.e there is a preferred direction. (Tevatron)

This can not happen at LHC: $x_1 - x_2$ symmetrisation will wipe it out.

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Top polarisation and BSM. Probe polarisation using lepton angular distributions?

LHC 14 TeV

$\frac{1}{\sigma} \frac{d\sigma}{d\phi_l}$ [rad$^{-1}$]

$\phi_l$ [rad]

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Distribution in $\phi_l$, the azimuthal angle, defined with respect to the $t\bar{t}$ production plane, with beam direction as the $z$ axis.

The two curves correspond to the top being completely Left handed or right handed, dropping all other effects on phi distributions.

The choice of beam direction (ie. +ve or -ve) is not relevant as the distribution symmetric for $\phi_l$ to $2\pi - \phi_l$.

In practice effects of finite polarization and/or spin coherence effects from off diagonal elements need to be included.

Construct an asymmetry which will reflect polarisation.

$$A = \frac{1}{\sigma} \left[ \sigma(\phi_l < \pi/2) + \sigma(\phi_l > 3\pi/2) - \sigma(\pi/2 < \phi_l < 3\pi/2) \right]$$
Top polarisation and BSM.

\[ P_t \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \]

\[ \cot(\theta) = 0.5 \quad \cot(\theta) = 1.0 \quad \cot(\theta) = 1.5 \quad \cot(\theta) = 2.0 \]

LHC 7 TeV

Tevatron 1.96 TeV

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Top polarisation and BSM. 

Sensitivity at 7 TeV and at the Tevatron:

Adaptive cut: $p_t^{T} \in \left[ \beta(M_{Z'}^2)(M_{Z'} - 2\Gamma_{Z'})/2, \beta(M_{Z'}^2)(M_{Z'} + 2\Gamma_{Z'})/2 \right]$. 

For Tevatron: $15fb^{-1}$, For 7TeV for $1fb^{-1}$ sensitivity a little worse than 14 TeV option.
To study $\mathcal{CP}$ in a model independent way:

\[
\phi_i f \bar{f} : -\bar{f}(a_f + i b_f \gamma_5) f \frac{g m_f}{2 m_W},
\]

\[
VV \phi_i : c_V \frac{g m_V^2}{m_W} g_{\mu \nu} (V = W/Z \text{ tree})
\]

\[
= \eta\epsilon^{\mu \nu \rho \sigma} p_\rho k_\sigma / m_Z^2 (\text{loop level})
\]
The probes which use $\phi ZZ$ coupling to determine CP and/or CP mixing for production of Higgs are ambiguous. Reasons: for a pseudoscalar the strength is necessarily small as loops are involved. For a state of mixed CP, only the CP-even part gets projected out in production.

$t\bar{t}\phi$ production treats $H/A$ democratically.

Gunion and collaborators studied optimal observable technique to study CP property of the Higgs and concluded that with a high luminosity it should be possible to measure even a mixing of a few degrees. Slice the phase space region and use the kinematical distributions of the particles expected for the signal in an optimal way. However, the physics contained in the optimal observable technique used is not so obvious.
• RG, A. Djouadi et al. (PRL 100, 051801 (2008)) pointed out a simple way to discriminate CP even and CP odd case.

• The energy dependence of cross-section and polarisation of top carries information on CP character of the Higgs boson.
Top polarisation and BSM. Some results.

\[ \sqrt{s} \text{ [GeV]} \]

- CP-even for \( m_H = 120 \text{GeV} \)
- CP-odd for \( m_H = 120 \text{GeV} \)

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Threshold dependence very different for scalar and pseudoscalar. Steep dependence (S vs P wave).

Define \( \rho = 1 - 2m_t/\sqrt{s} - M_\Phi/\sqrt{s} \)

\[
F_1^H = -F_2^H \simeq 12 \left( \frac{m_t^2}{M_H \sqrt{s}} \right)^{3/2} \rho^2 \quad F_1^A = -F_2^A \simeq 4 \left( \frac{m_t^4}{M_A s \sqrt{s}} \right)^{1/2} \rho^3.
\]

May be just two measurements, at 500 and (say) 800, would see the difference. For \( M_\Phi = 120 \) GeV, the ratios for \( H \) and \( A \) are 7.5 and 63, as \( \sqrt{s} \) changes from 500 to 800 GeV.

Recall: radiative corrections are also substantial. So taking ratios is a good idea. Polarisation shows similar energy dependence and is again different for \( H(b=0,a=1) \) and \( A(b=1,a=0) \).
Top polarisation and BSM.

- CP-even for $M_\Phi = 120\,\text{GeV}$
- CP-odd for $M_\Phi = 120\,\text{GeV}$
- CP-even for $M_\Phi = 150\,\text{GeV}$
- CP-odd for $M_\Phi = 150\,\text{GeV}$

$\sqrt{s}$ [GeV]
Define a CP violating asymmetry (Bar Shalom et al)
Azimuthal angle of the anti-top with respect to the top-electron plane:

\[
\sin \varphi = \frac{\vec{p}_2 (\vec{q}_a \times \vec{p}_1)}{|\vec{p}_2| |\vec{q}_a \times \vec{p}_1|} \sim \epsilon p_1 p_2 q_a q_b .
\]

The up-down asymmetry of the $t\bar{t}\Phi$ cross section $\sigma$ is defined as

\[
A_\varphi = \frac{\sigma(\text{up}) - \sigma(\text{down})}{\sigma(\text{up}) + \sigma(\text{down})},
\]

\[
\text{unpolarised}
\quad \text{polarised with } P_e^+ = 0.6, P_e^- = -0.8
\quad \text{polarised with } P_e^+ = -0.6, P_e^- = 0.8
\]
Top polarisation and BSM.  

Model independent analysis?

Take

\[ C_{tt\Phi} = -i \frac{e}{\sin \theta_W} \frac{m_t}{2M_W} (a + ib\gamma_5) \equiv -ig_{ttH} (a + ib\gamma_5) \]

See how well can these observables alone constrain \( a, b \).

Calculate limits of region in \( a, b \) plane around \( a_0, b_0 \) such that

\[ |O(a, b) - O(a_0, b_0)| = f \Delta O(a_0, b_0) \]

\( \Delta O(a_0, b_0) \) is the fluctuation and \( f \) level of significance.

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With just cross-section $a$ is well restricted, $b$ not very well. For $\sqrt{s} = 800$ GeV with ILC TDR choice of polarisation, 1-$\sigma$. 
Top polarisation and BSM.
Adding information on $p_t$ helps. Polarisation crucial, interplay between $\sigma$ and $p_t$ helps decrease the error on $a$. At this energy up-down asymmetry does not do much.
Top polarisation and BSM.

Add polarisation, asymm.
All three and higher energy together work better.
Can these observables reject against a possible hypothesis that the particle produced in association is a vector?

Choose a $Z'$ with $g_V, g_A$ such that predicted is $\sigma_{t\bar{t}Z'}$ within 10% of $\sigma(t\bar{t}H_0)$, $H_0$ the SM Higgs.

Calculate $P_t$ and ratios of cross-sections at different energies $1000/800$, $1300/800$ and $1300/1000$.

Values expected for a SM Higgs 0.11, 0.85, 0.61 and 0.72
Top polarisation and BSM.

Comparisons
Characteristic shape of the distribution in the invariant mass of $t\bar{t}\phi$ system.

The $pp \rightarrow t\bar{t}\phi$:

Idea: can one use this feature along with the azimuthal angle distributions to control the bkgd? The $b\bar{b}$ in the $t\bar{t}b\bar{b}$ QCD background is produced from a spin 1 gluon.

1) Clean variable to decide the CP at large luminosity
2) Perhaps use this feature to help clean up the signal?
Top polarisation and BSM. Anom coupling, $P_l$ and lepton energy distns.

Dependence on anom. $tbW$ couplings. Careful if one constructs measures of polarisation using energies of decay products as we do for boosted tops.

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Conclusions

- Measurement of Top polarization can be a very good probe of some types of BSM physics

- Secondary decay lepton angular distributions are the most faithful polariometers, robust to effects of non standard $tbW$ couplings as well as higher order corrections.

- At the LHC $\phi$ distribution can be used to construct observables which directly probe the polarisation produced in the decay of a resonance. An example of an extra $Z'$ decaying into $t\bar{t}$ was presented.
• Use of energy dependence of the total $t\bar{t}\Phi$ cross-section, along with $p_t$ and up-dpwn asymmetry affords establishing CP of the scalar state should it be a CP eigenstate

• Even more importantly, it also affords a model independent analysis of a possible CP violation as well. Higher energy helps, due to an increased up-down asymmetry, even if the cross-section decreases

• The energy distributions of the decay leptons are sensitive to anomalous $tbW$ couplings.

• Energy fraction of the lepton and $b$–jet can be used for the boosted tops. Lepton distribution less sensitive to the anom. coupling and hence a more robust probe.
Collimated top quarks and polarisation
Systems with large invariant mass of $t\bar{t}$ can produce highly boosted tops – with collimated decay products Lian-Tao wang, Thaler; G. Perez, Sterman.

Collimated leptonic top quarks allow the energy of the lepton and the $b$-jet to be separately measured, but not the angular distributions.

The momentum fraction of the visible energy carried by the lepton provides a natural polarimeter.

$$u = \frac{E_\ell}{(E_\ell + E_b)},$$

[J. Shelton arXiv:0811.0569]

$$(1/\Gamma)(d\Gamma/du)$$ as a function of $u$. 

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Can one use the $u$ variable? Need to study Effect of anomalous couplings on the $u$ distribution:

If the expected polarisation is large then contamination by the anom. couplings seems small.

Recall that shape of lepton energy distn. did not change too much with anomalous coupling. Position of the peak shifted.
For top polarisation = 0.2:

Aim: for the current limits on the anom. couplings what is the minimum value of expected polarisation where this probe can work?
For hadronically decaying tops she suggests:

\[ z = \frac{E_b}{E_t} \]

**Blue line: negative helicity.**

**Red line: positive helicity.**

(Almeida, Sung, Perez et al had also similarly suggested the distribution of the total \( p_T \) of \( b \) jet.)
Top polarisation and BSM.

\[
\frac{1}{\Gamma} \frac{d\Gamma}{dz} = \frac{m_t^2}{\beta(m_t^2 - m_w^2)} \left(1 + P_t \kappa_b \left(-\frac{1}{\beta} + \frac{2m_t^2z}{\beta(m_t^2 - m_w^2)}\right)\right)
\]

with \( \kappa_b = -0.406 + 1.43f_{2R} \).
Top polarisation and BSM.

Effect for lower values of expected polarisation:

For the $b$-jet distributions the effect of anomalous couplings on the energy fraction distribution in the lab is large.

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Top polarisation and BSM.

Effect for lower values of expected polarisation:

With $f_2 R = 0.4$ even the sign of the slope changes!

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Top polarisation and BSM.

BACKUP SLIDES
Top polarisation and BSM.

Phi distribution and $P_T^T$

LHC 14 TeV

$M_{Z'} = 750$ GeV

(b)
1) Contribution to $t\bar{t}$ production, jet production.

2) Production of light states exchanged in t-channels which gives rise to $A_{FB}$

3) $Z'$: Like sign top pairs, $Z'Z'$, $Z' + t$

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Top polarisation and BSM.

Azimuthal distribution

This is the distribution in the azimuthal angle between lepton from the decay of the $t$ and the $b$-quark from the decay of the $\bar{t}$ (or vice versa).

Different for the $ttH$ signal and $ttjj$ background!

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Top polarisation and BSM. Inv. mass and Azimuthal distribution

The shapes of the signal and background are quite different.

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Top polarisation and BSM. Combine the two

Can the differences in shape be utilized effectively to distinguish signal from the background?