Top polarisation probes and top anomolous coupling

- ◊ Top polarisation: what physics can it probe
- ◊ Probes of the top polarisation and effects of anomalous coupling on them.

* based in part on JHEP 0612, 021 (2006), D. Choudhury, R. Godbole, S.D. Rindani, R. Singh and K. Wagh, in hep-ph/0602198 and work in progress with S.D. Rindani.

Fermion polarisation

Why study τ/t polarisation?

- Large mass of the third generation fermions means large coupling to a Higgs. Third generation fermions useful to probe Higgs physics.

- $f\bar{f}$ pair produced via gauge interactions will have opposite handedness, produced via Yukawa interactions will have the same handedness. A correlation between polarisation of f and $\bar{f}$ can be a probe of Higgs contribution.

- τ/t polarisation probes chirality structure of t production process, may it be Higgs physics, SUSY etc. For example, CP violation in the Higgs sector can reflect in the t polarisation produced in association with $t\bar{t}(\tau\tau)$ or $t(\tau)$ produced in decay of $\tilde{t}(\tilde{\tau})$ (say).

• Large mass of the top $\Rightarrow t$ decays before hadronisation. The decay l can retain the memory of the t polarisation. **This will be topic of the talk.**

• τ has hadronic decay modes. The energy distribution of the π produced in the decay, $\tau \to \nu_\tau \pi$ as well as those in $\tau \to \rho\nu_\tau, \tau \to A_1\nu_\tau$ depends on the handedness of the τ. Thus τ polarisation can be determined using decay π energy distribution. K. Hagiwara, A.D. Martin and D. Zeppenfeld, PLB **235** 198 (1990), B.K.Bullock, K.Hagiwara and A.D.Martin, PRL **67**, 3055 (1991), NPB **395**, 499 (1993) RG, M. Guchait, D.P. Roy PLB **618** 193 (2005)

• If $m_h < 2m_t$ then τ is the only fermion whose polarisation can be determined and into which a Higgs decays may be somewhat substantial.

♢ Thus t and τ polarisation are a very good probe for new and Higgs physics.

- 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.. Shelton : PRD 79, Nojiri et al JHEP, Perelstein. Produce t in cascade decays.

Polarisation measurement can provide model parameter information, mdoel descrimination, kinematic features due to polarisation effects can be used efffectively for searches.

- Non zero polarisation requires parity violation, and hence measures left-right mixing. R-parity violating SUSY can give rise to nonzero top polarisation (Hikasa PRD, 1999).

- It can give a clue to CP violation through dipole couplings.

When t and $\bar{t}$ are produced, a useful observable is top spin correlation:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_a d\cos\theta_b} = \frac{1}{4}(1 + B_1\cos\theta_a + B_2\cos\theta_b - C\cos\theta_a\cos\theta_b)$$

This has been very well studied theoretically (for example: $t\bar{t}H$, $t\bar{t}$ produced in RS Graviton decay etc.)

Needs reconstruction of both t and $\bar{t}$ rest frames.

It is conceivable that single top polarization can give better statistics.

Polarization can be measured by studying the decay distribution of a decay fermion f in the rest frame of the top:

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

θ_f is the angle between the f momentum and the top momentum, P_t is the degree of top polarization, κ_f is the "analyzing power" of the final-state particle f.

The analyzing power k_f for various channels is given by:

$$\kappa_b = -\frac{m_t^2 - 2m_W^2}{m_t^2 + 2m_W^2} \simeq -0.4$$

$$\kappa_W = -\kappa_b \simeq 0.4$$

$$\kappa_{\ell+} = \kappa_d = 1$$

The charged lepton or d quark has the best analysing power

- d-quark jet cannot be distinguished from the u-quark jet.

- In the top rest frame the down quark is on average less energetic than the up quark.

- Thus the less energetic of the two light quark jets can be used. Net spin analyzing power is $\kappa_j \simeq 0.5$

Leading QCD corrections to κ_b and κ_j are of order a few per cent. QCD corrections decrease $|\kappa|$ [Brandenburg,Si,Uwer 2002]

κ also affected by corrections to the form of the tbW coupling ("anomalous couplings")

It is useful to have a way of measuring polarization independent of such corrections.

Also useful is distribution in lab. frame, rather than in top rest frame.

Angular distribution of the decay lepton l in the rest frame of the top is the most efficient polarisation observable.

Which of the kinematic observables of the decay lepton as measured in the lab frame carry this polarisation information faithfully?

What are the speical issues here since LHC is a pp machine.

For highly boosted tops : what about rest frame reconstruction and angle measurements?

The angular distribution of charged leptons (down quarks) from top decay is not affected by anomalous tbW couplings (to linear order)

Rindani, Singh, Godbole

Checked earlier for $e^-e^+ \rightarrow t\bar{t}$ [Grzadkowski & Hioki, Rindani (2000)] and for $\gamma\gamma \rightarrow t\bar{t}$ [Grzadkowski & Hioki; Godbole, Rindani, Singh]

This is shown for any general process $A+B \rightarrow t+X$ in the c.m. frame [Godbole, Rindani, Singh (2006)]

Assumes narrow-width approximation for the top

This implies that charged-lepton angular distributions are more accurate probes of top polarization, rather than energy distributions or b or W angular distributions. How can these be best used?

Anomalous tbW couplings

General $\bar{t}bW$ vertex can be written as

$$\Gamma^\mu = \frac{g}{\sqrt{2}}\left[\gamma^\mu(f_{1L}P_L + f_{1R}P_R) - \frac{i\sigma^{\mu\nu}}{m_W}(p_t - p_b)_\nu \, (f_{2L}P_L + f_{2R}P_R)\right].$$

In SM, $f_{1L} = 1$, $f_{1R} = f_{2L} = f_{2R} = 0$.

Deviations from these values will denote "anomalous" couplings

Current liimits: Bernreuther, J. Phys. G., Nucl. Part. Phys. 35 (2008) Only f_{2R} can be nontrivial. $-0.57 < f_{2R} < 0.15$

Talk by Tony Liss at Top Workshop at CERN: $|f_{2R}|^2 < 0.20$

The above theorem depends on the factorization property of the decay density matrix in the rest frame of the top:

$$\langle \Gamma(\lambda, \lambda') \rangle = (m_t E_\ell^0)\ |\Delta(p_W^2)|^2\ A(\lambda, \lambda')\ F(E_\ell^0)$$

where

$$A(\pm, \pm) = (1 \pm \cos\theta_l), \qquad A(\pm, \mp) = \sin\theta_l e^{\pm i\phi_l} \tag{1}$$

For $A + B \to t + P_1 + ...P_n$, with $t \to b + W \to b + \ell + \nu_l$,

One can show:

$$d\sigma = \frac{1}{32\ \Gamma_t m_t (2\pi)^4} \left[\sum_{\lambda,\lambda'} d\sigma_{2\to n}(\lambda,\lambda') \ \times \ g^4 A(\lambda,\lambda') \right] dE_t \ d\cos\theta_t \ d\cos\theta_\ell$$
$$d\phi_\ell \times E_\ell \ F(E_\ell) \ dE_\ell \ dp_W^2 .$$

The only terms dependent on tbW anom. coupling are $F(E_\ell)$ and Γ_t and to leading order they cancel each other!

Lepton energy distribution and anomalous couplings:

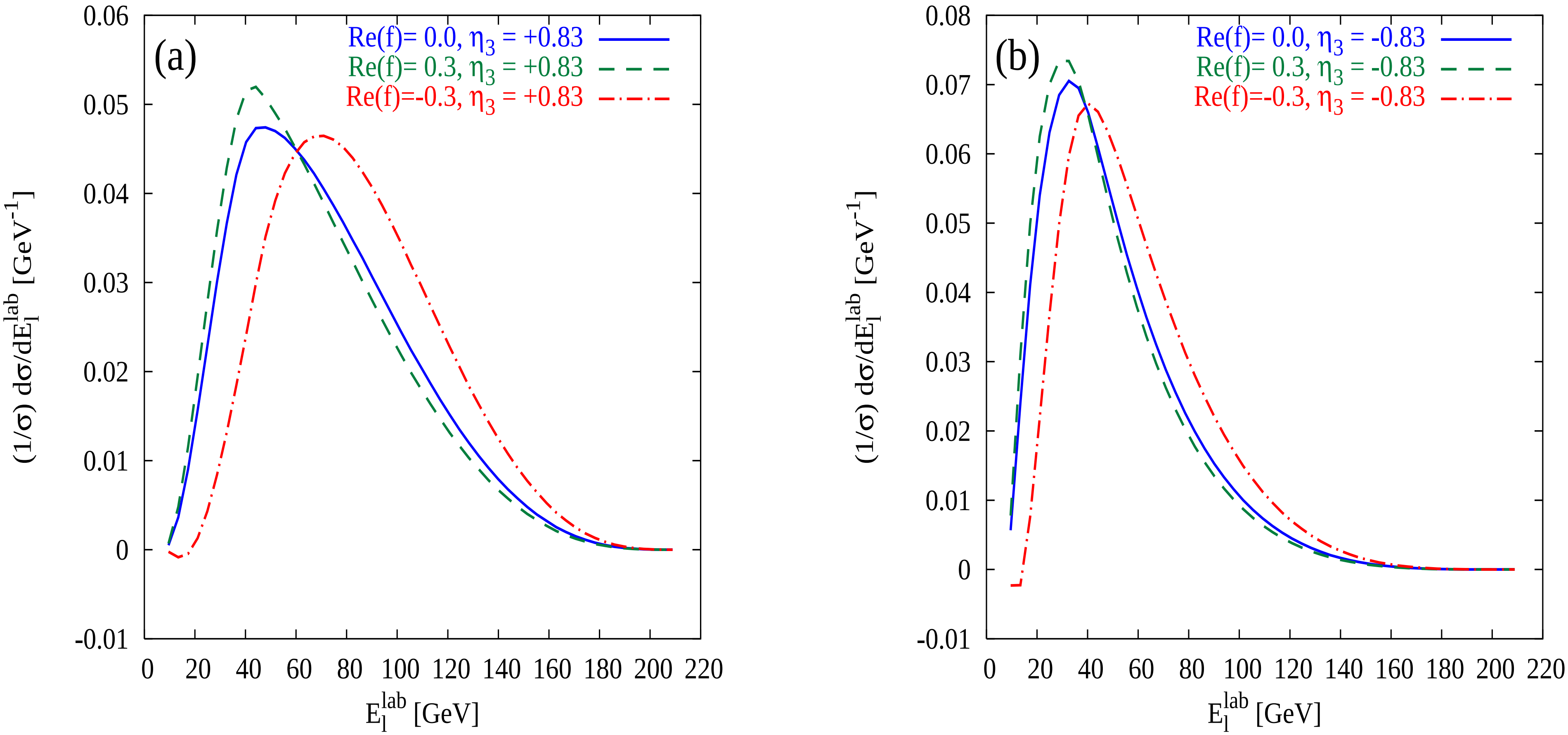
Various energy and angular distributions can be measured in top decay.

Energies of lepton, b jet, light jets, and their angular distributions can measure top polarization. However, they can be affected by anomalous couplings.

The angular distribution in the lab frame can be obtained from the one in the top rest frame.

Our calculations show that the normalised angular distributions of the decay lepton in the lab are not affected by the anomalous parts of the tbW vertex. I.e., there will be factors dependent on the top momentum etc. but nothing to do with the anomolous tbW vertex. Hence the correlation with top polarisation is faithfully reflected.

The decay lepton energy distributions in the laboratory contain some piece due to the anomalous couplings as well.


(a)
Re(f)= 0.0, η_3 = +0.83
Re(f)= 0.3, η_3 = +0.83
Re(f)=-0.3, η_3 = +0.83
(1/σ) dσ/dE$_l^{lab}$ [GeV^{-1}]
E$_l^{lab}$ [GeV]
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0 20 40 60 80 100 120 140 160 180 200 220
(b)
Re(f)= 0.0, η_3 = -0.83
Re(f)= 0.3, η_3 = -0.83
Re(f)=-0.3, η_3 = -0.83
(1/σ) dσ/dE$_l^{lab}$ [GeV^{-1}]
E$_l^{lab}$ [GeV]
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0 20 40 60 80 100 120 140 160 180 200 220

Use of lepton angular distributions in the LAB frame as a polarisation probe:

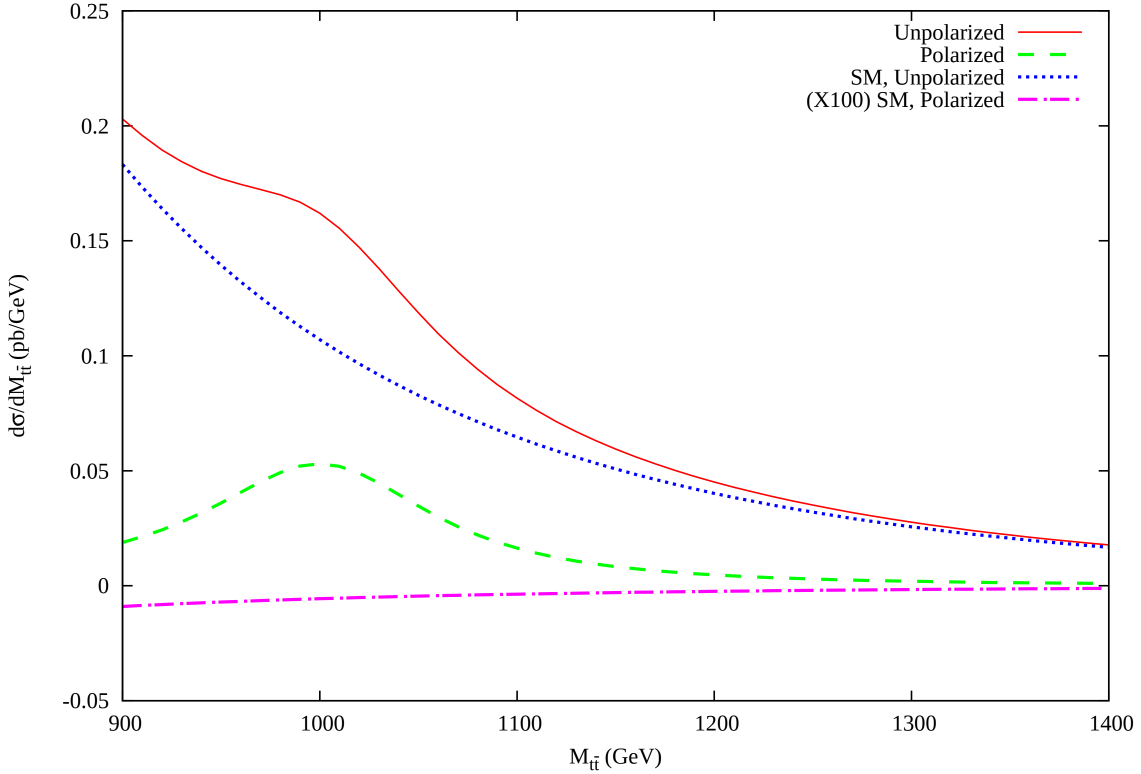
Take an example of a $t\bar{t}$ resonance with Parity violating couplings. Look for illustration at an extra Z model.

Little Higgs model has an extra massive gauge boson Z_H with right-handed couplings to fermions depending on one parameter (θ)

$$g_V^u = g_A^u = g \cot\theta$$

$$g_V^d = g_A^d = -g \cot\theta$$

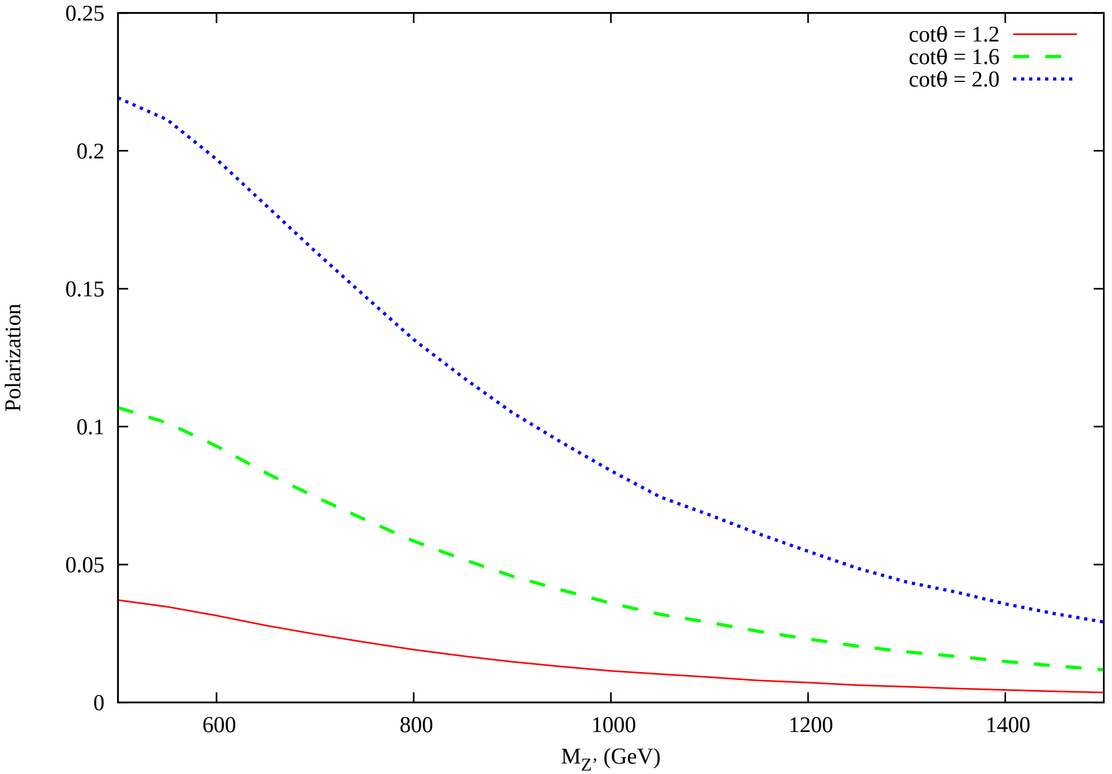
$t\bar{t}$ production and decay via γ, Z, Z' depends only on two new parameters: $m_{Z'}$ **and** $\cot\theta$.



The model can be tested using the $t\bar{t}$ invariant mass distribution
Polarization can be a further more sensitive test

$$P_t \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

Can be enhanced using cuts on $m_{t\bar{t}}$



Probes using angular distributions:

Different candidates:

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

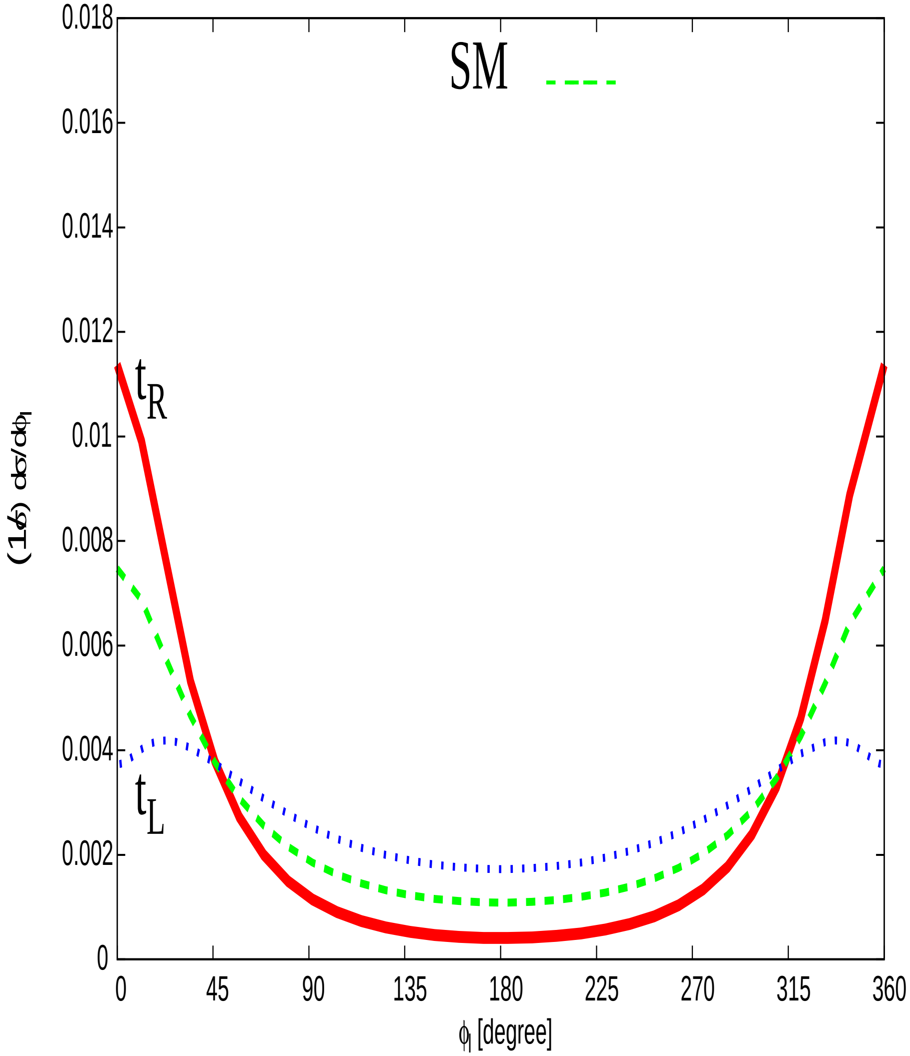
2) Angle between the decay lepton and the beam direction

If there is net Parity violation then there will be a nonzero net top polarisation.

This can then give rise to asymmetries in these distributions.

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.



Azimuthal distribution of the charged lepton in the lab.:

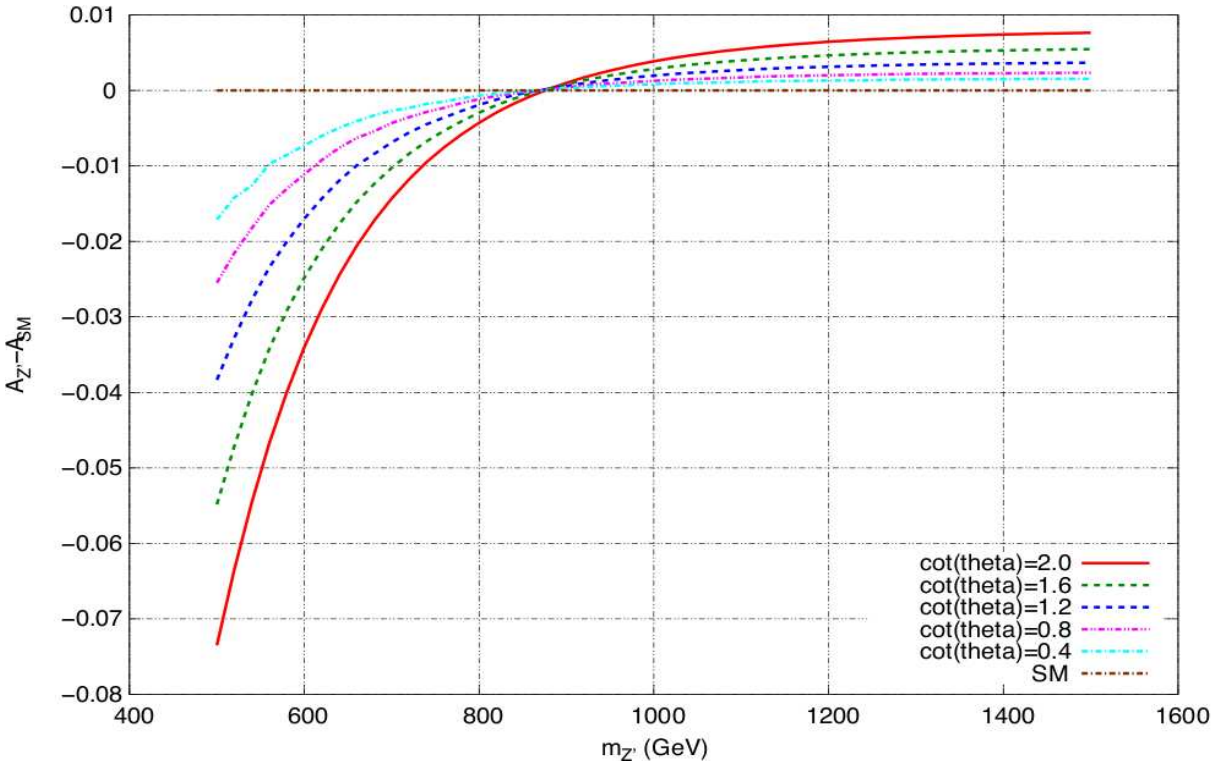
Distribution in ϕ_l, the azimuthal angle, defined with respect to the $t\bar{t}$ production plane, with beam direction as the z axis.

The two curves correspond to the top completely Left handed or right handed .

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

Azimuthal asymmetry

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



$\mathcal{O} = \mathcal{A} - \mathcal{A}_{SM}$ Optimisation with $m_{t\bar{t}}$ cuts etc. in progress.

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..

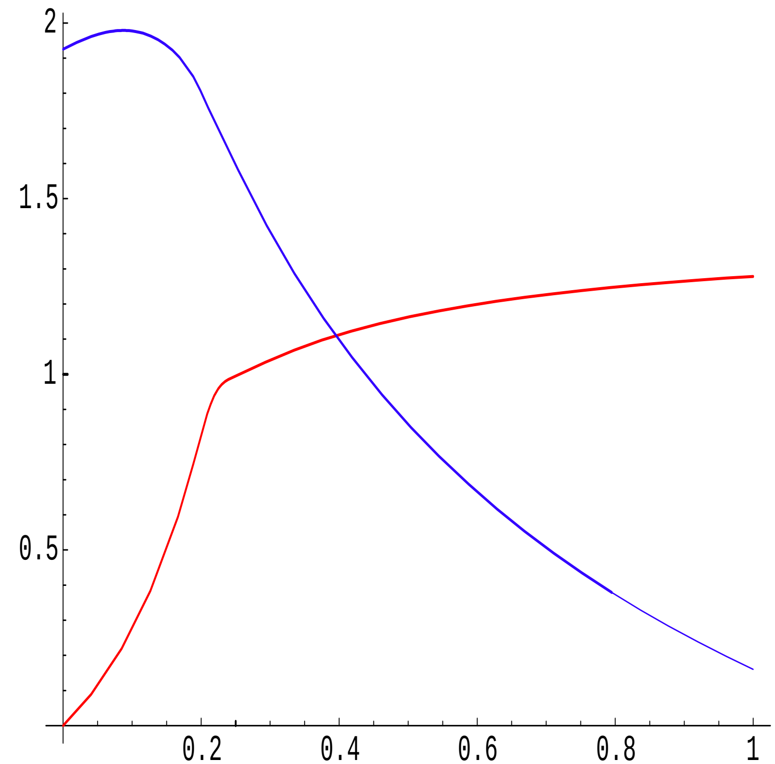
Collimated leptonic top quarks allow the energy of the lepton and the b-jet to be separately measured, but not the angular distributions.

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

$u = E_\ell/(E_\ell + E_b)$,

[J. Shelton arXiv:0811.0569]

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

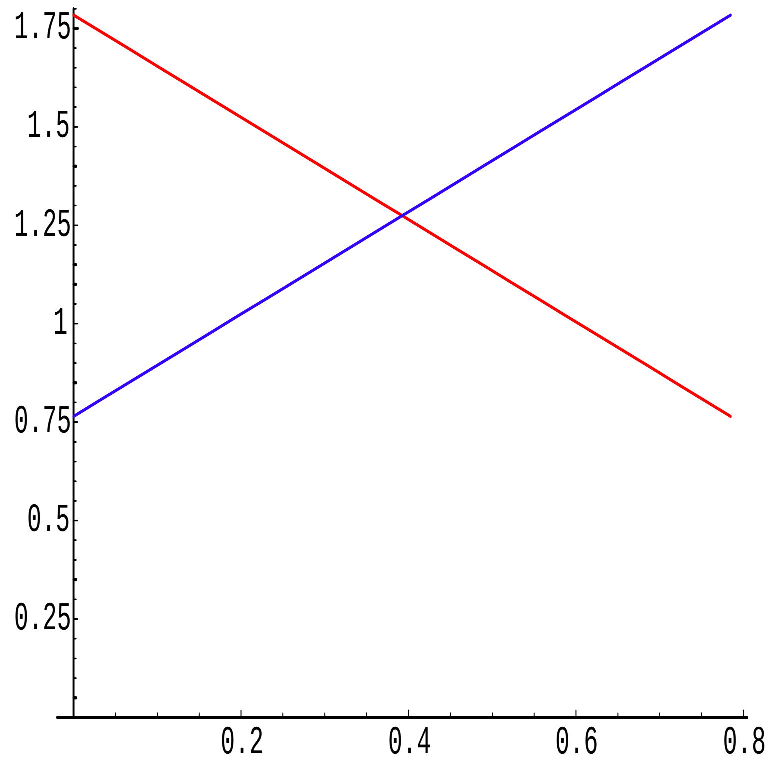


Blue line: Negative helcity top

Red line: positive helicity top

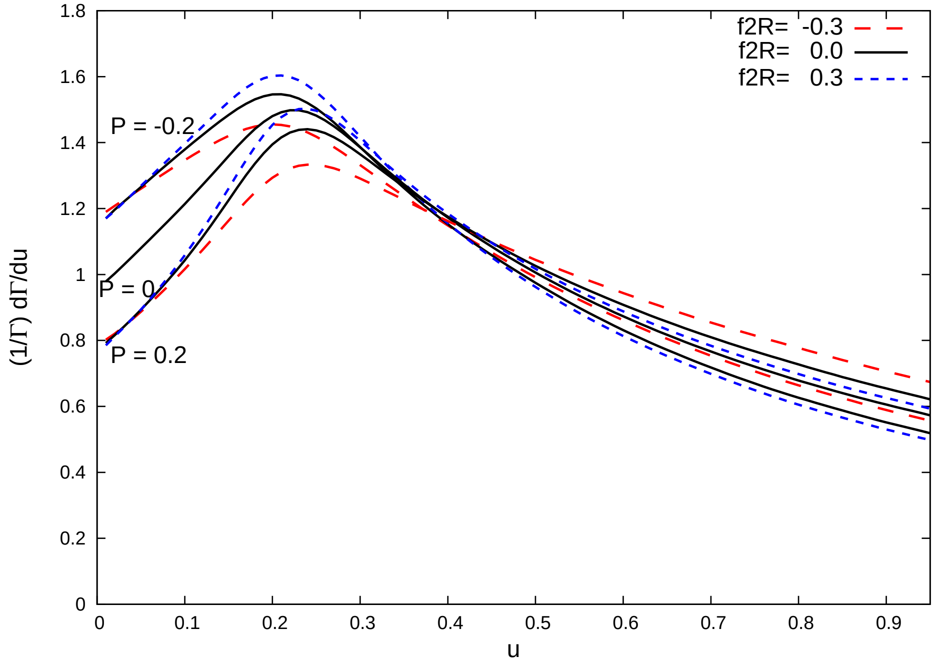
$\beta = 1$

For hadronically decaying tops she suggests:
$z = \frac{E_b}{E_t}$
(Almeida,Sung, Perez et al had also similarly suggested the distribution of the total p_T of b jet.)



Red line: positive helicity.
Blue line: negative helicity.

For top polarisation = 0.2:

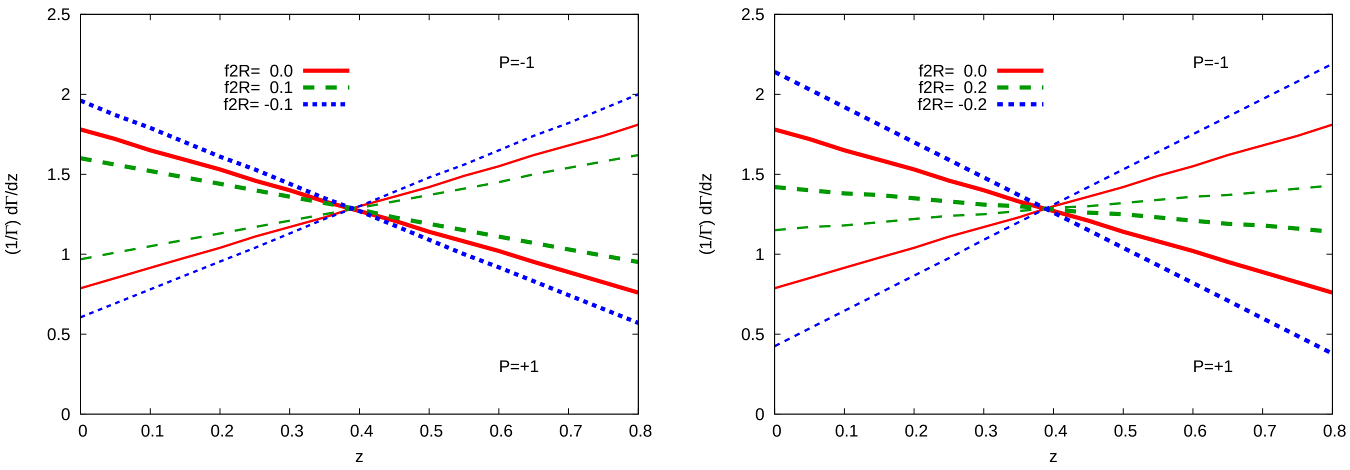


Restricted to $f_{2R} = 0.3$. Need to include quadratic terms for higher values?.

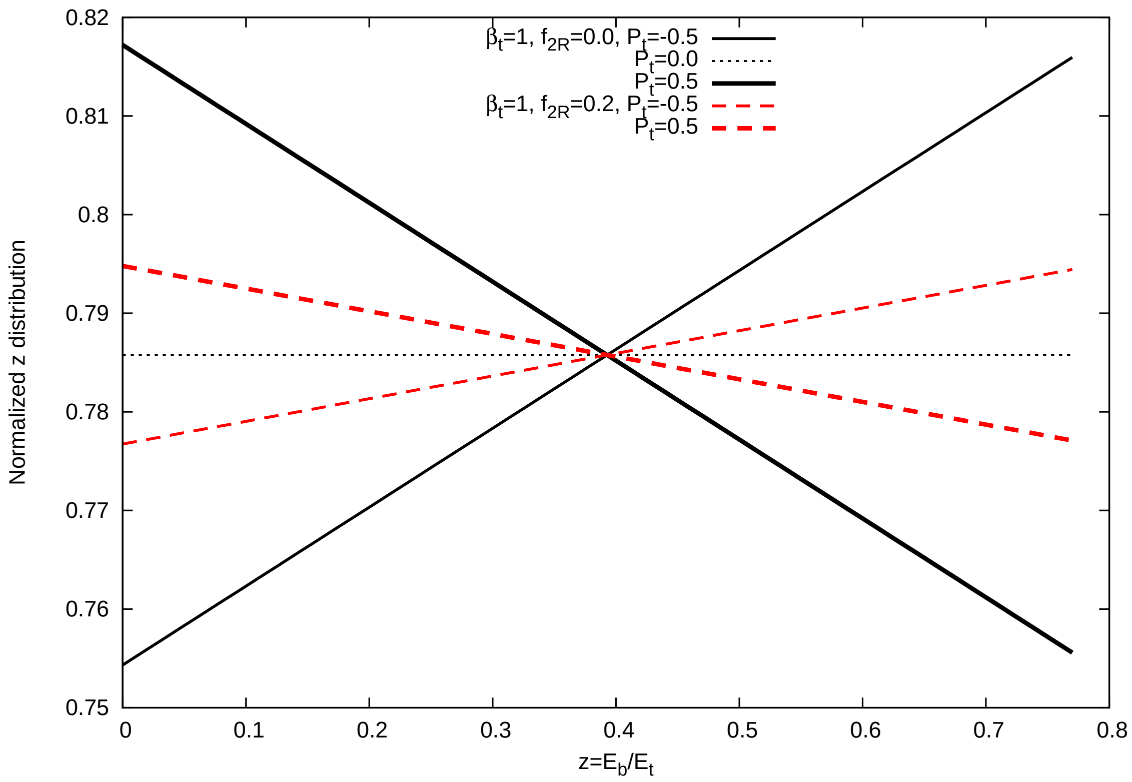
Aim: for the current limits on the anom. couplings what is the minimum value of expected polarisation where this probe can work?

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

with $\kappa_b = -0.406 + 1.43 f_{2R}$.

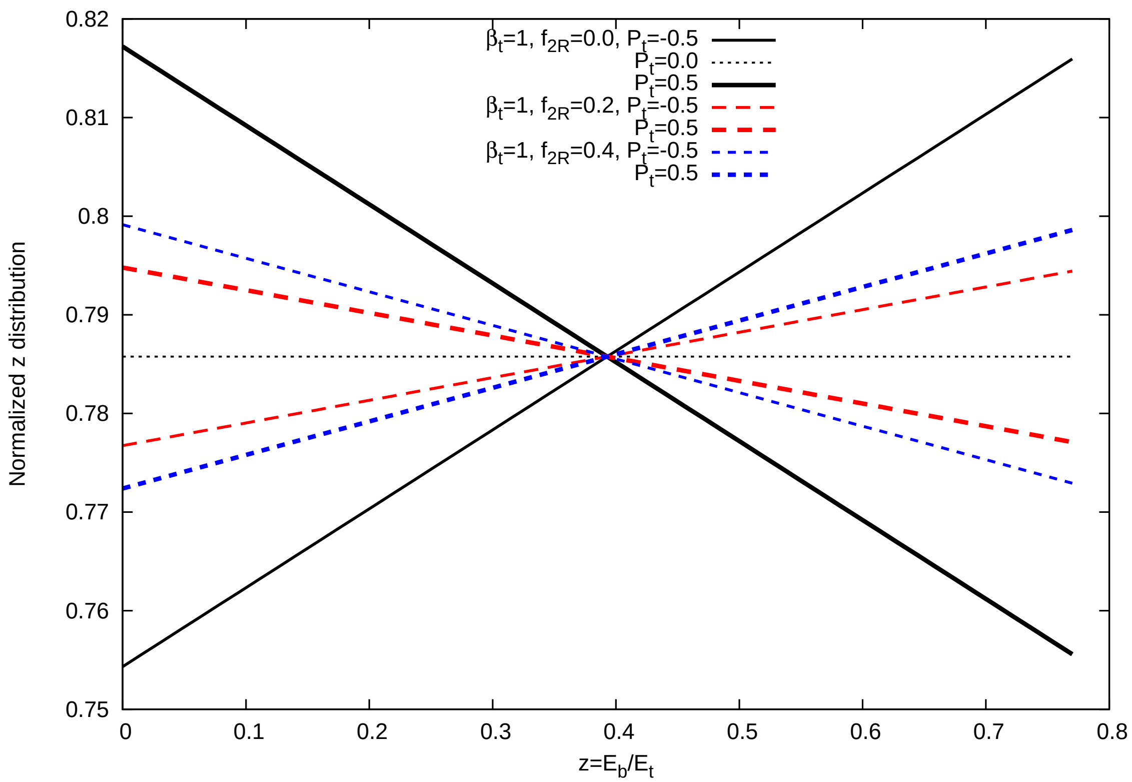


Effect for lower values of expected polarisation:



For the b–jet distributions the effect of anomalous couplings on the enerrgy fraction distribution in the lab is large.

Effect for lower values of expected polarisation:



With $f_2R = 0.4$ even the sign of the slope changes!

Conclusions

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

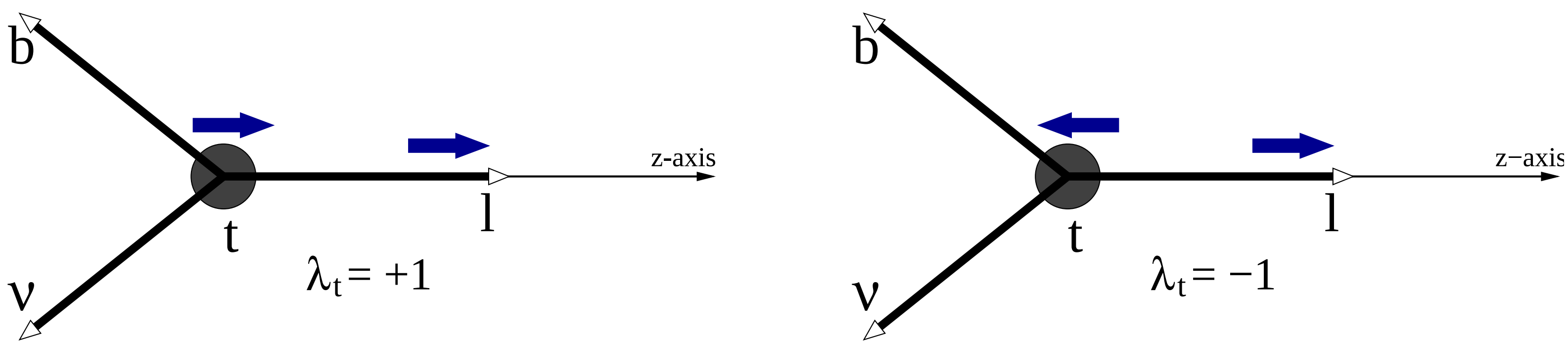
• Secondary decay lepton angular distributions are the most faithful polariometers, robust to effects of non standard tbW couplings as well as higher order corrections.

• 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 better probe.

• At the LHC showed that ϕ distibutions can be used to construct obeservables which directly probe the polarisation produced in the decay of a resnonance. An example of an extra Z' decaying into $t\bar{t}$ was presented.

A simple argument to understand the *independence of the angular distributions*

Thanks M. Peskin



The configuration with lepton momentum along the top quantization axis, the z axis.

All the other configurations can be obtained by simple rotations.‘

Note in the SM:

$$\mathcal{M}(t_\uparrow \to l^+_\uparrow \; b\nu_l; \phi_b = 0) = C_{SM} + \mathcal{O}(f_i)$$

$$\mathcal{M}(t_\downarrow \to l^+_\uparrow \; b\nu_l; \phi_b = 0) = 0 + \mathcal{O}(f_i).$$

The second amplitude is nonzero only for anom. couplings.

Can be then easily shown that the ϕ_b averaged decay density matrix is,

Neglecting the terms of $\mathcal{O}(f_i^2)$ we get

$$\langle \Gamma_t \rangle \propto (1 + \mathcal{O}(f_i)) \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix},$$

where $\mathcal{O}(f_i)$ term comes as normalization of the density matrix.

Matrix upon rotation becomes

$$\langle \Gamma_t \rangle \propto (1 + \mathcal{O}(f_i)) \left[\begin{array}{cc} 1 + \cos\theta_l & \sin\theta_l e^{i\phi_l} \\ \sin\theta_l e^{-i\phi_l} & 1 - \cos\theta_l \end{array} \right], \tag{2}$$

Similar to the result mentioned before; all the anomalous dependence occurs in the normalization factor $F(E_l)$ and the angular dependence is un-altered