Top polarisation at the LHC.

- ♢ Top polarisation: what is it good for?.
- ♢ Probes of the top polarisation and effects of anomalous coupling on them.
- ♢ Example of its use for a $t\bar{t}$ resonance.

* 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/R.K. Singh.

Top quarks at the LHC:

• Copious production of $t\bar{t}$ pairs at LHC **(SM c.s. $\approx$ 800 pb at** 14 **TeV)**

• Large single top production (seen at Tevatron)

• 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 SM from BSM tops!

• Polarisation can be one important handle.

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

- 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.

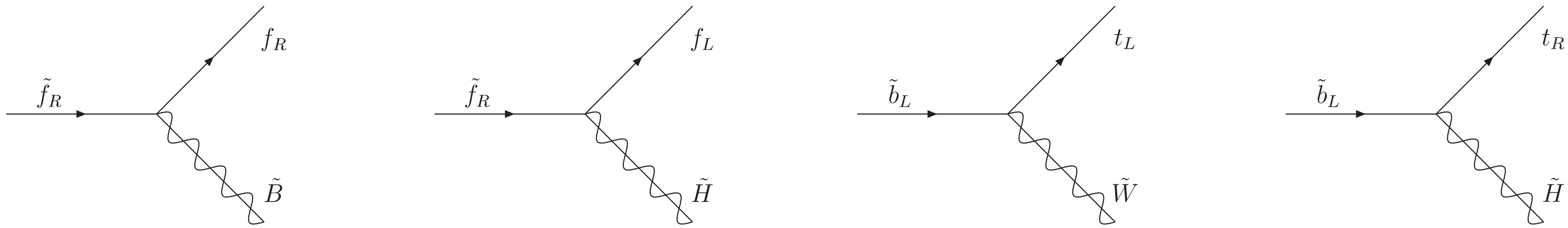
Polarisation measurement can provide model parameter information, mdoel descrimination, kinematic features due to polarisation effects can be used efffectively for searches.

- 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.

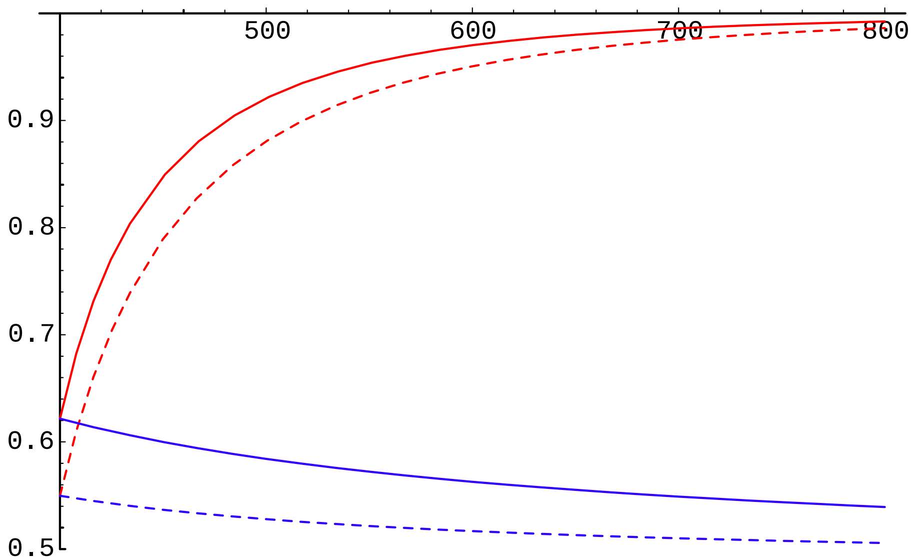
t produced in stop decay. M. Nojiri, PRD **51** (1995) 6281 [hep-ph/9412374] for τ

$f = t/\tau$



- In MSSM mass eigenstates of $\tilde{f}$ (sleptons/squarks) $\tilde{f}_1, \tilde{f}_2$, are mixtures of $\tilde{f}_L$ and $\tilde{f}_R$, $f = t, \tau$.
- Mixing affects gauge couplings of $\tilde{f}_i, i = 1, 2$ and hence the production rates.
- The $\tilde{\chi}_j^{\pm}, j = 1, 2$, $\tilde{\chi}_j^0, j = 1, 4$ are mixtures of higgsinos and gauginos.
- Couplings of sfermions with higgsinos flip chirality whereas those with gauginos do not.

- Net helicity of produced f in the decay $\tilde{f}_i \to \tilde{\chi}_j^0 f$ AND $\tilde{f}_i \to \tilde{\chi}_j^{\pm} f'$ depends on the L–R mixing in the sfermion sector and on the gaugino-higgsino mixing.



Shelton: 0811.0569, Phys. Rev. D 79, 014032, 2009.

For purely chiral couplings.

Solid lines for opposite spin partners (SUSY)

Dashed lines for same spin partner (little Higgs/UED..)

Blue lines for a fixed mass difference between decaying particle and the χ_0/heavy boson partner , red for a fixed mass of the boson partner.

Top polarisation for the same spin cascade is less than that for the opposite spin cascade.

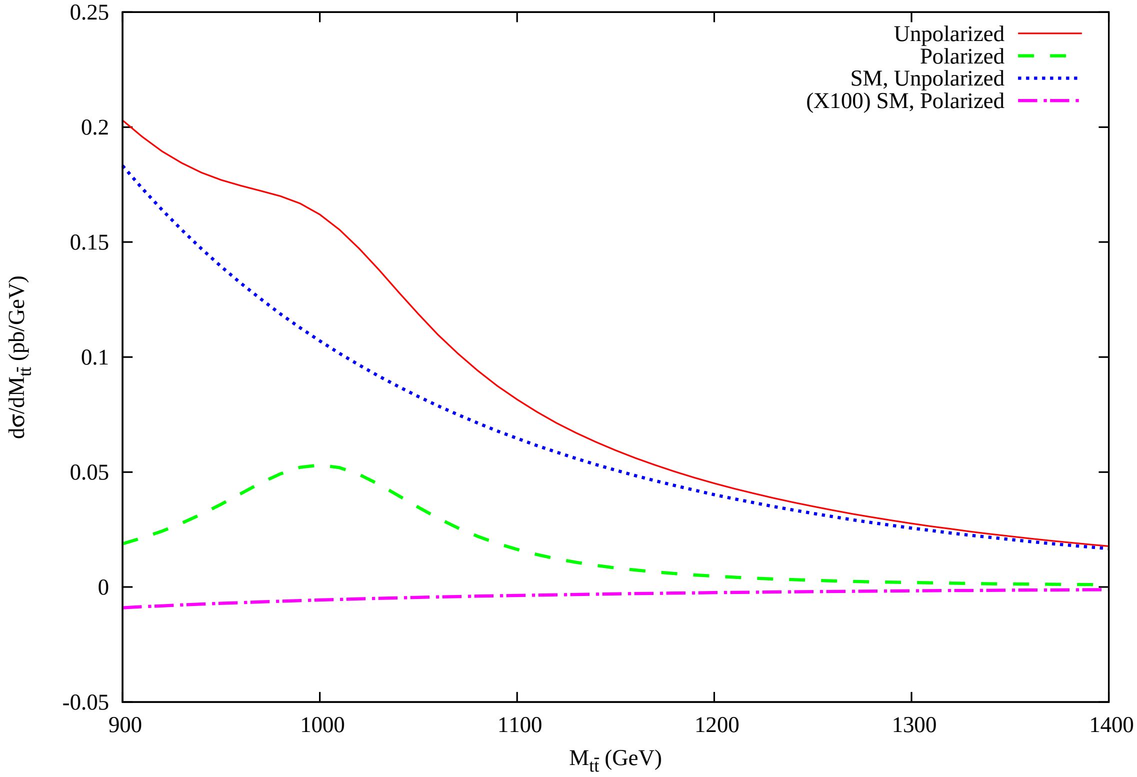
Another example is $t\bar{t}$ resonance with Parity violating couplings. Look for illustration at an extra Z model.

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

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

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

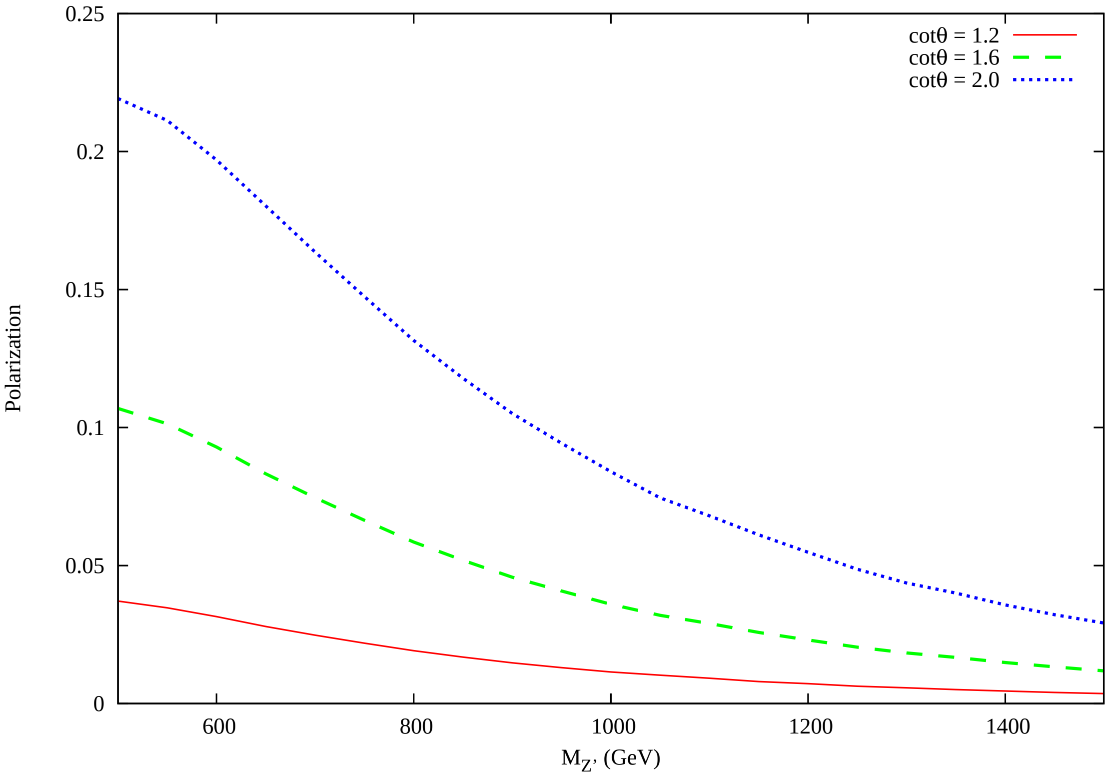
$t\bar{t}$ production and decay via γ, Z, Z' depends only on two new parameters: $m_{Z'}$ **and** $\cot\theta$.



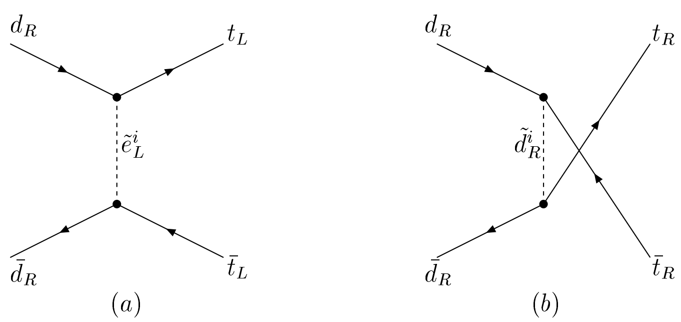
The model can be tested using the $t\bar{t}$ invariant mass distribution
Polarization can be a further more sensitive test

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

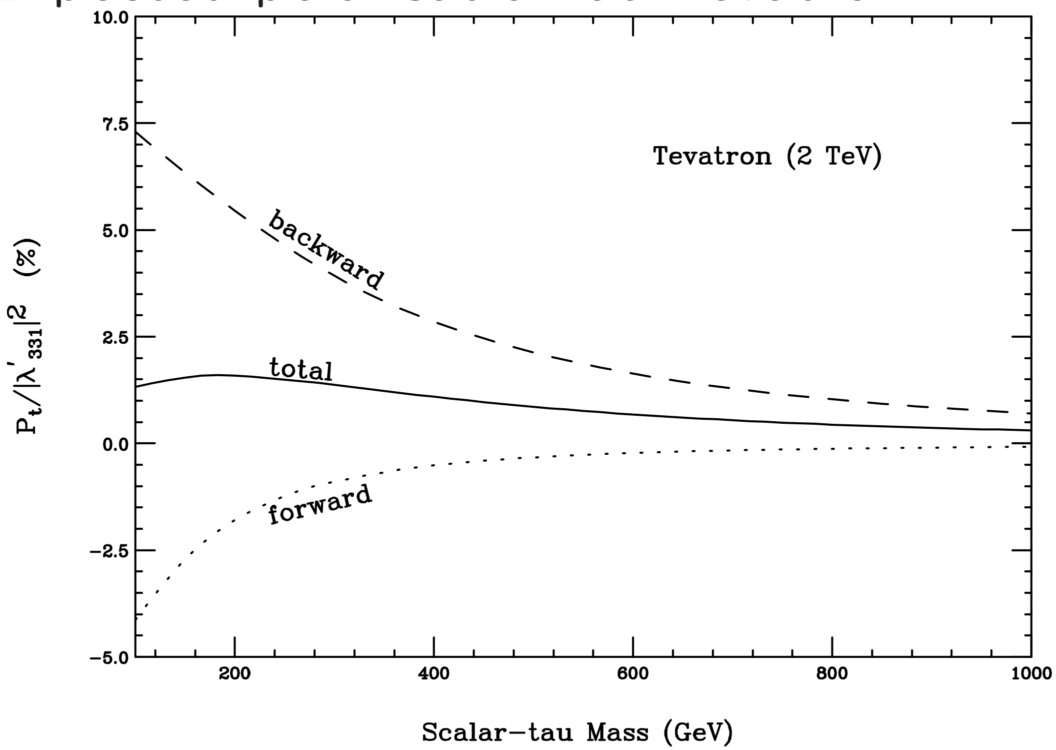
Can be enhanced using cuts on $m_{t\bar{t}}$



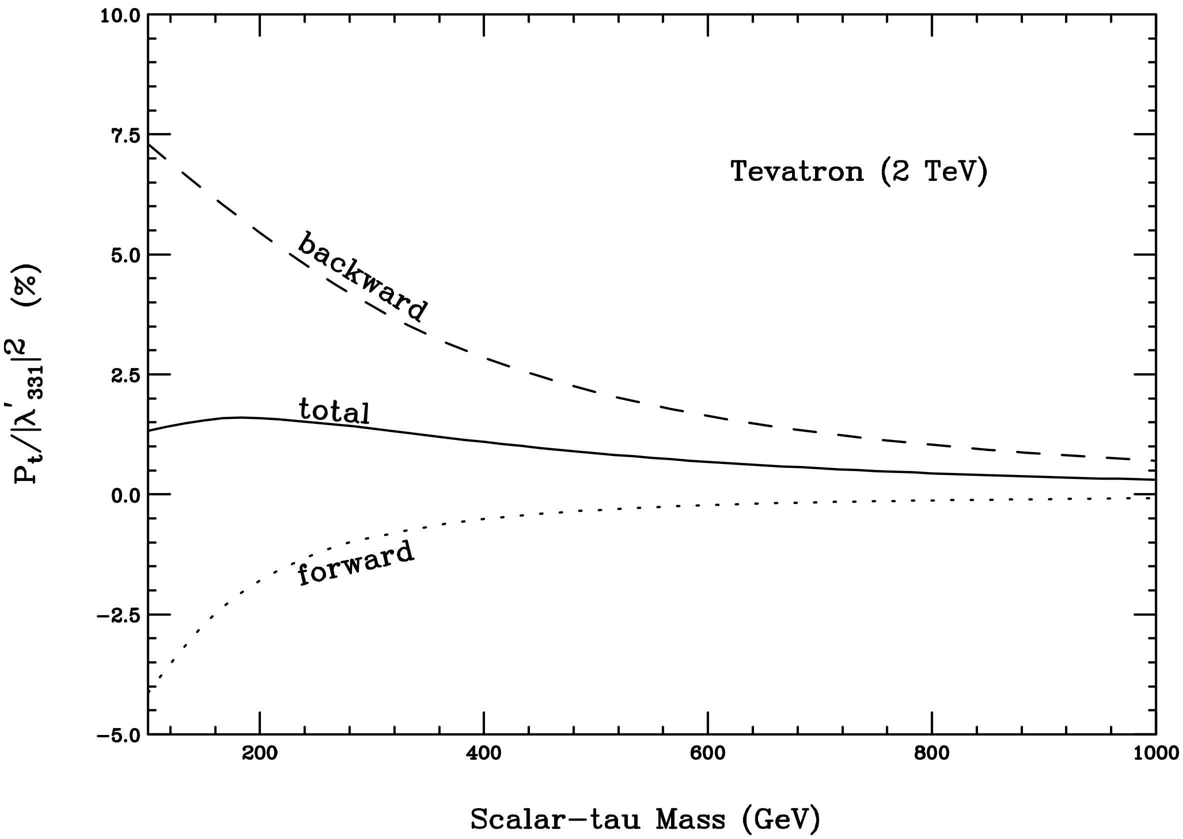
Hikasa PRD 60, 114041, 99



Expected polarisation at Tevatron:



Expected poalrisation at the Tevatron:



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) (Talk by Ritesh Singh)

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

This is shown for any general process $A + B \to t + X$ 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

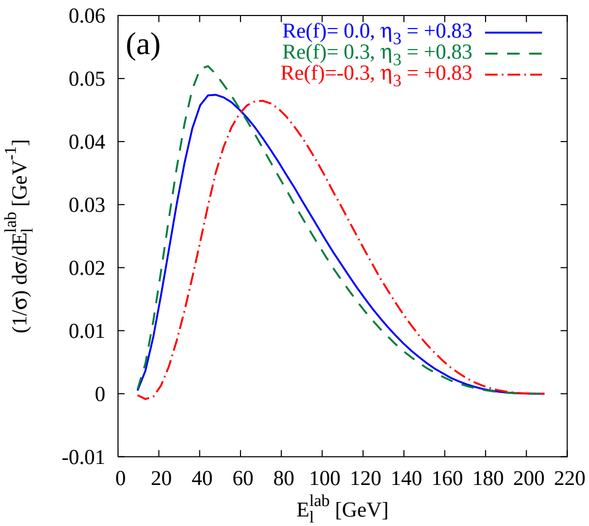
Current liimits: Bernreuther, J. Phys. G., Nucl. Part. Phys. 35 (2008) $-0.57 < f_{2R} < 0.15$ Take $f_{1L} = 1$.

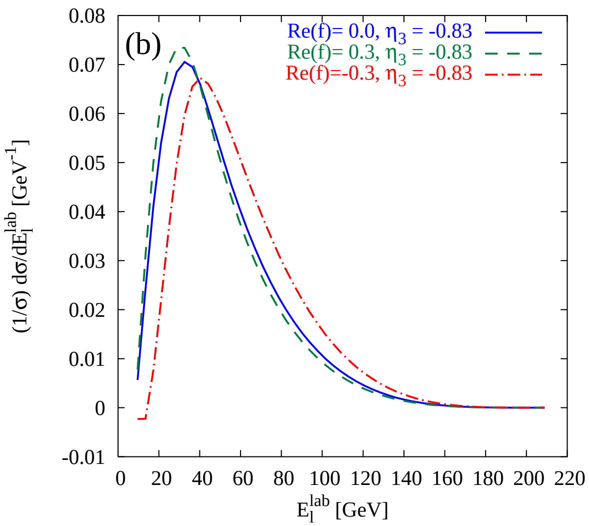
Talk by Tony Liss: $|f_{2R}|^2 < 0.20$

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.





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..

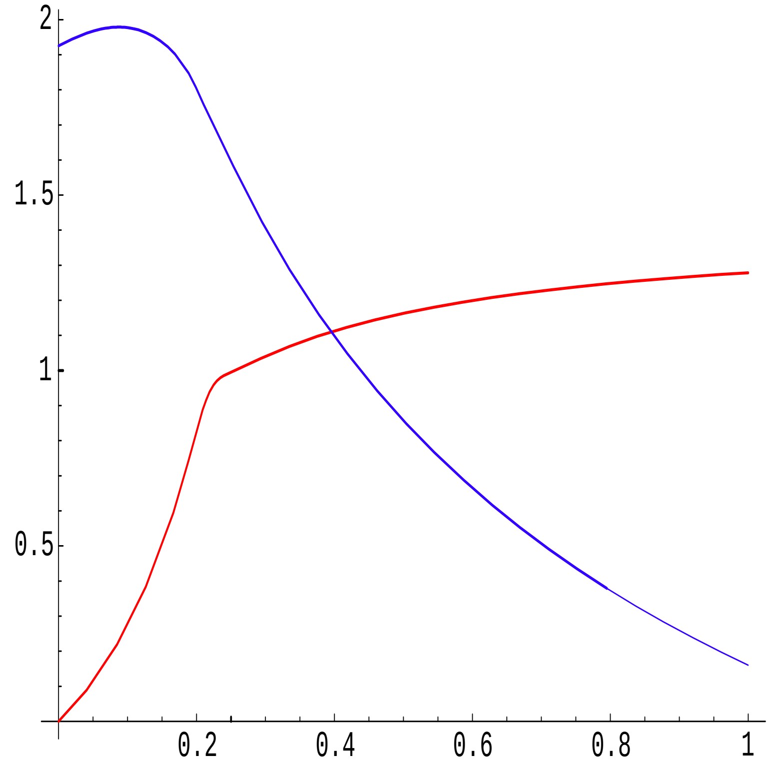
Collimated leptonic top quarks allow the energy of the lepton and the b-jet to be separately measured, but not the angular distributions.

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]

$\frac{1}{\Gamma}\frac{d\Gamma}{du}$ as a function of u.

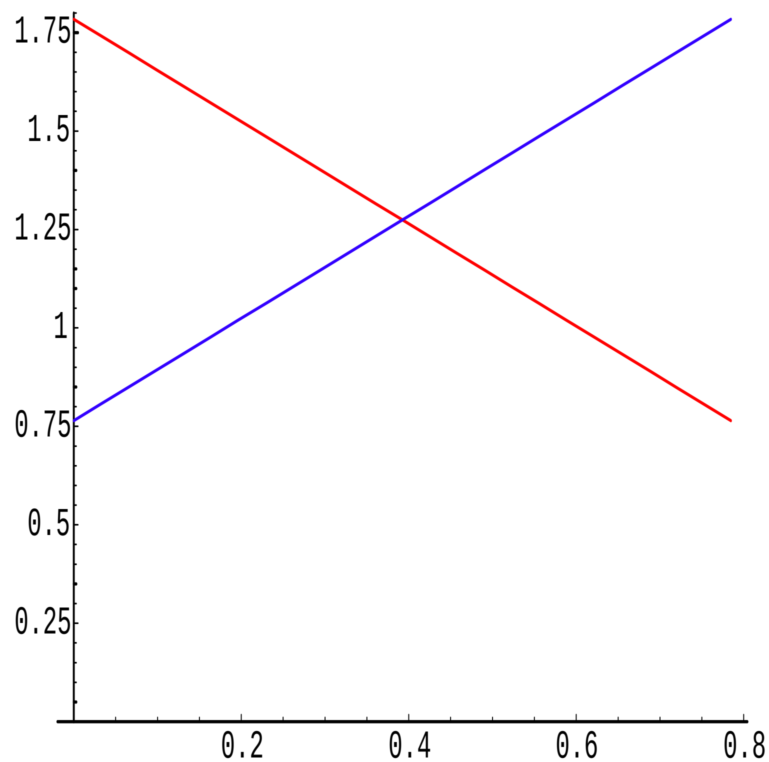


Blue line: Negative helcity top

Red line: positive helicity top

$\beta = 1$

For hadronically decaying tops she suggests:
$z = \frac{E_b}{E_t}$
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.)



1) Discuss one possible way of tracking the polarisation through angular distribution

2)Effect of anomalous couplings on u, z distribution as probes of top polarisation for Boosted tops.

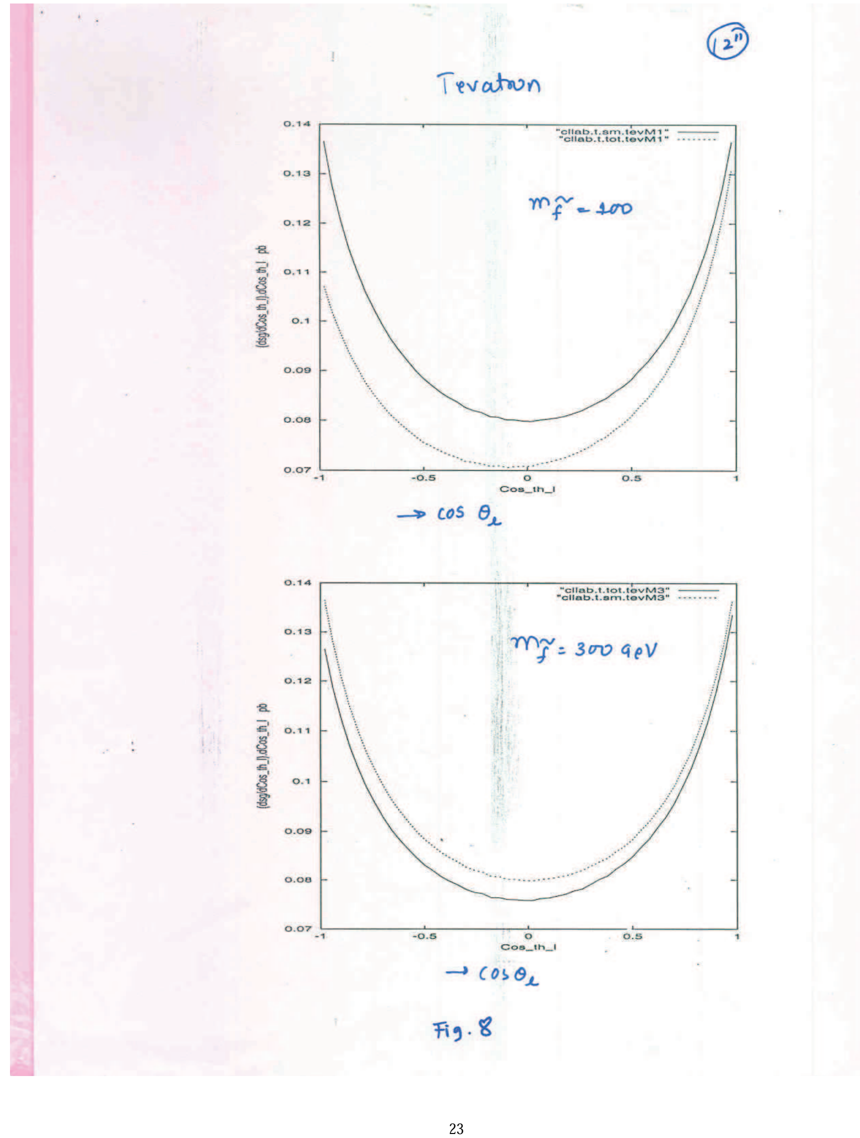
Different candidates:

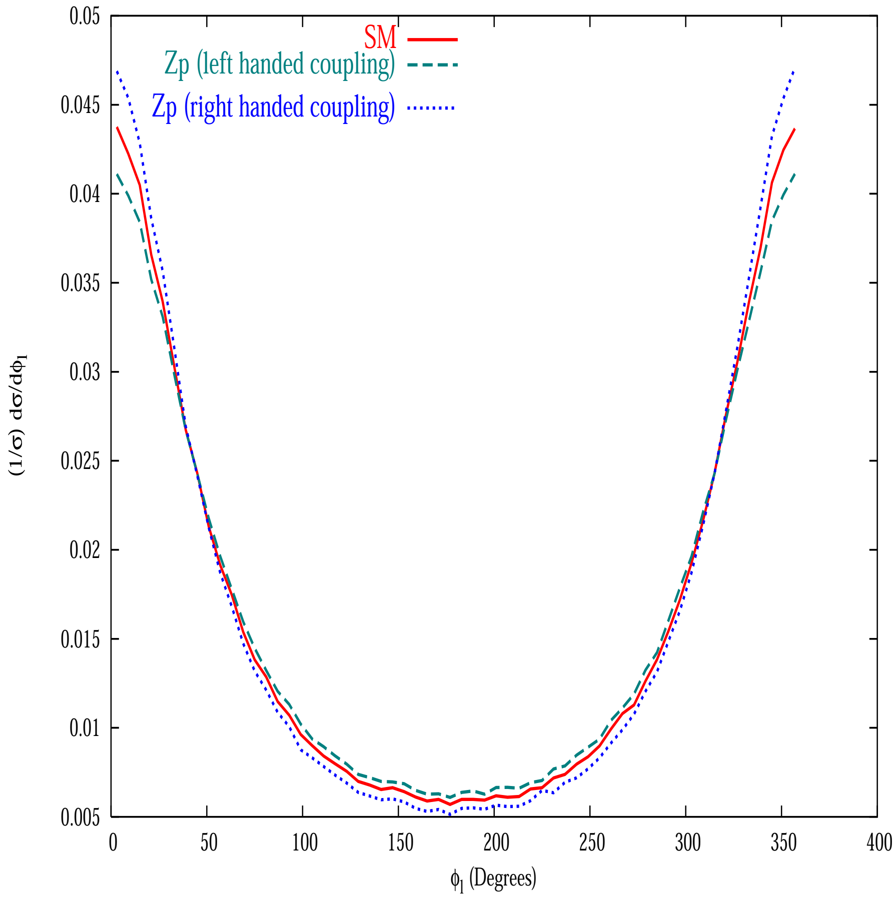
1) Angle between top and the decay lepton in the lab:

2) Angle between the decay lepton and the beam direction

For the Tevatron energies, R-parity violating case, effect can be seen.

The distribution for LHC shows only very minor sensitivity to value and sign of polarisation for larger masses of the Z_H. Many things responsible, boost among them.





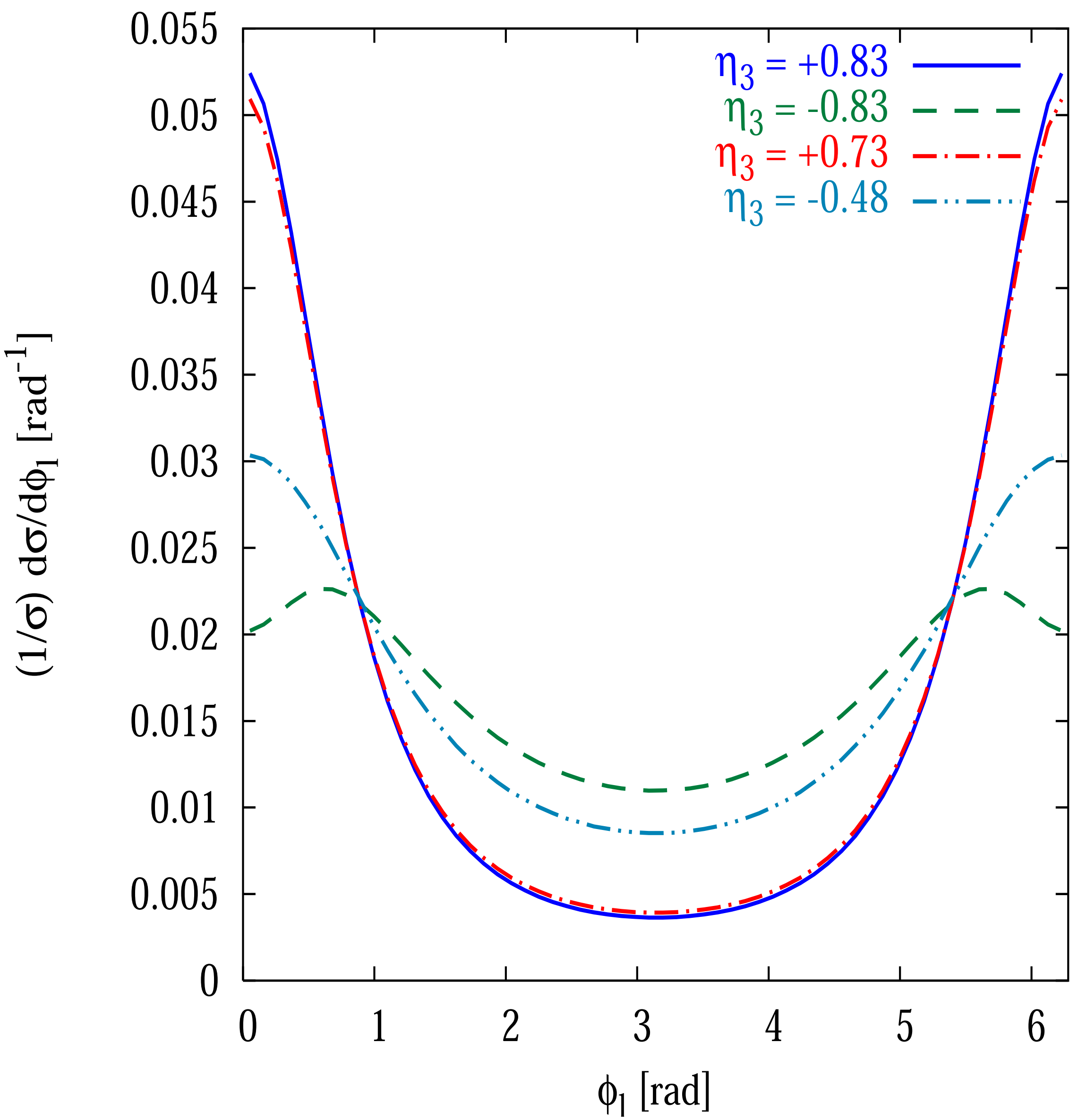
Azimuthal distribution of the charged lepton:

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

The two curves correspond to Z' completely Left handed or right handed couplings.

The choice of beam direction is not relevant as the distribution symmetric for ϕ_l to $2\pi - \phi_l$.

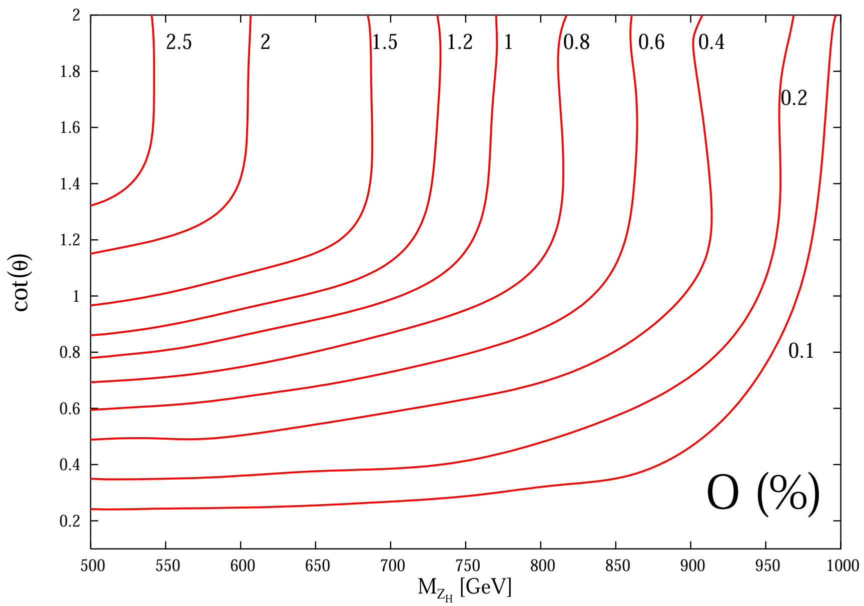
For lower centre of mass energies, effects are much more sizable. Example from $\gamma\gamma \rightarrow t\bar{t}$



Azimuthal asymmetry

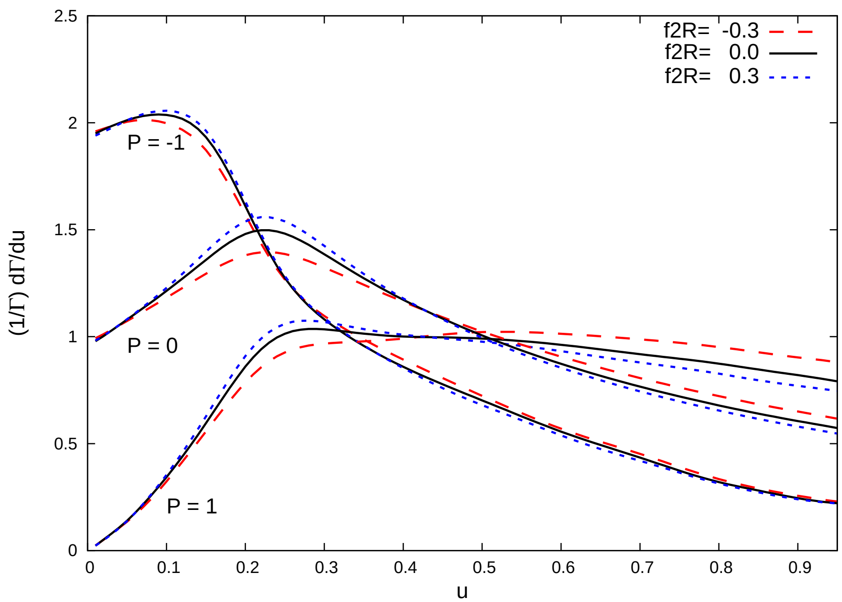
$$\mathcal{A} = \frac{1}{\sigma}\left[\sigma(\phi_l < \pi/2) + \sigma(\phi_l > 3\pi/2) - \sigma(\pi/2 < \phi_l < 3\pi/2)\right]$$

$$\mathcal{O} = \mathcal{A} - \mathcal{A}_{SM}$$



Optimisation with $m_{t\bar{t}}$ cuts etc. in progress.

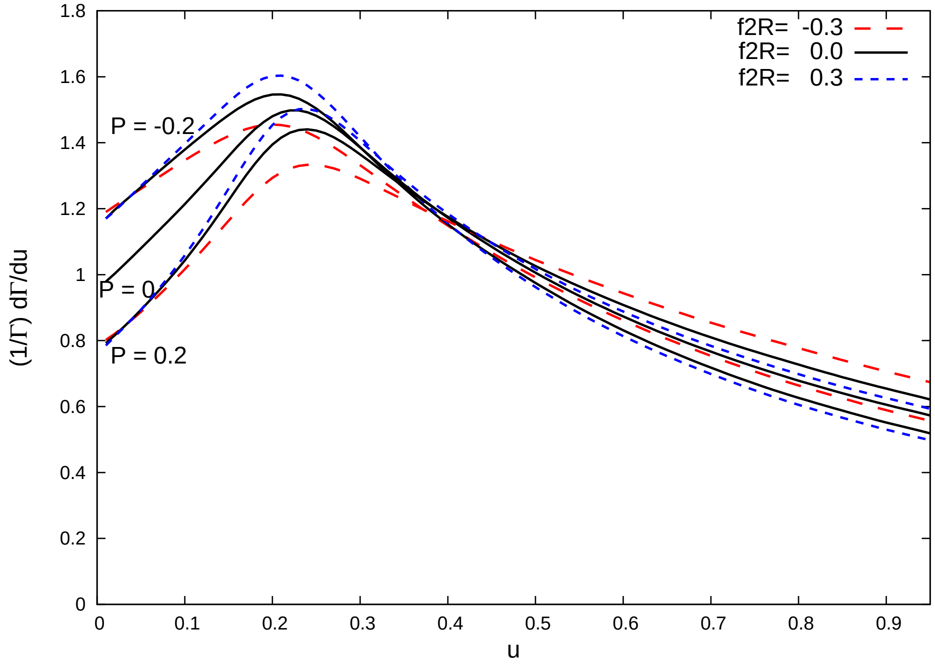
Can one use the u variable? Need to study Effect of anomalous couplings on the u distribution:



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:

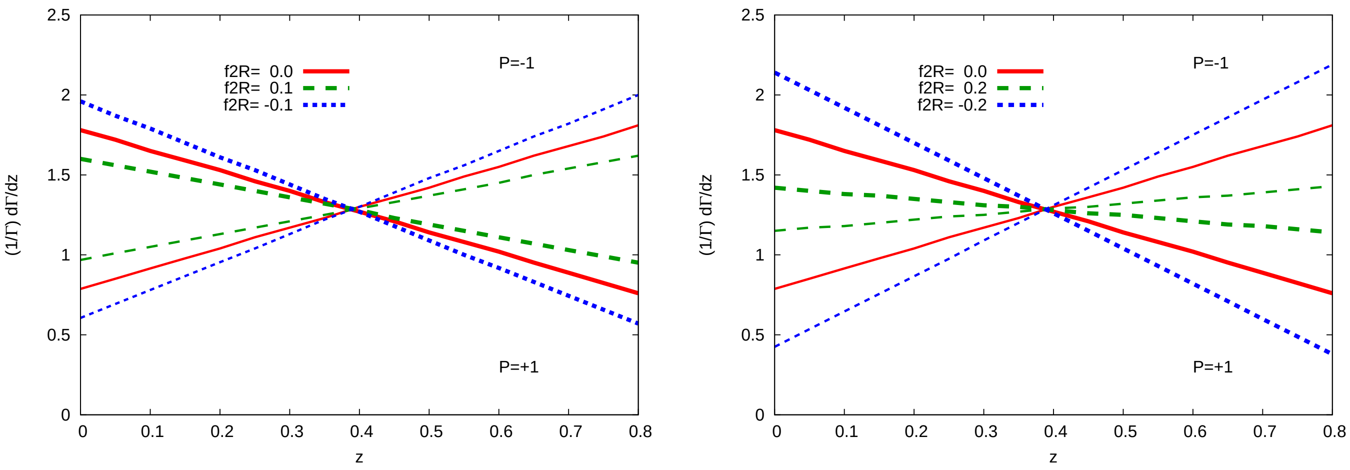


Restricted to $f_{2R} = 0.3$. Need to include quadratic terms for higher values. (Under progress)

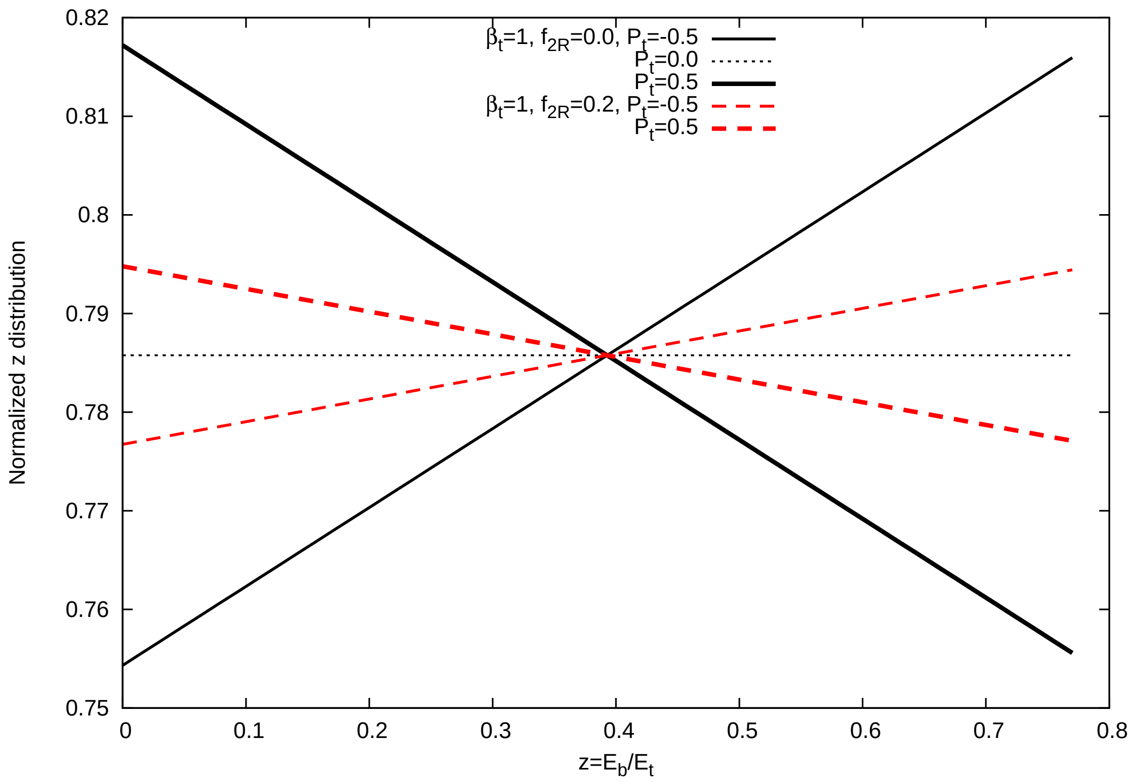
Aim: for the current limits on the anom. couplings what is the minimum value of expected polarisation where this probe can work?

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

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

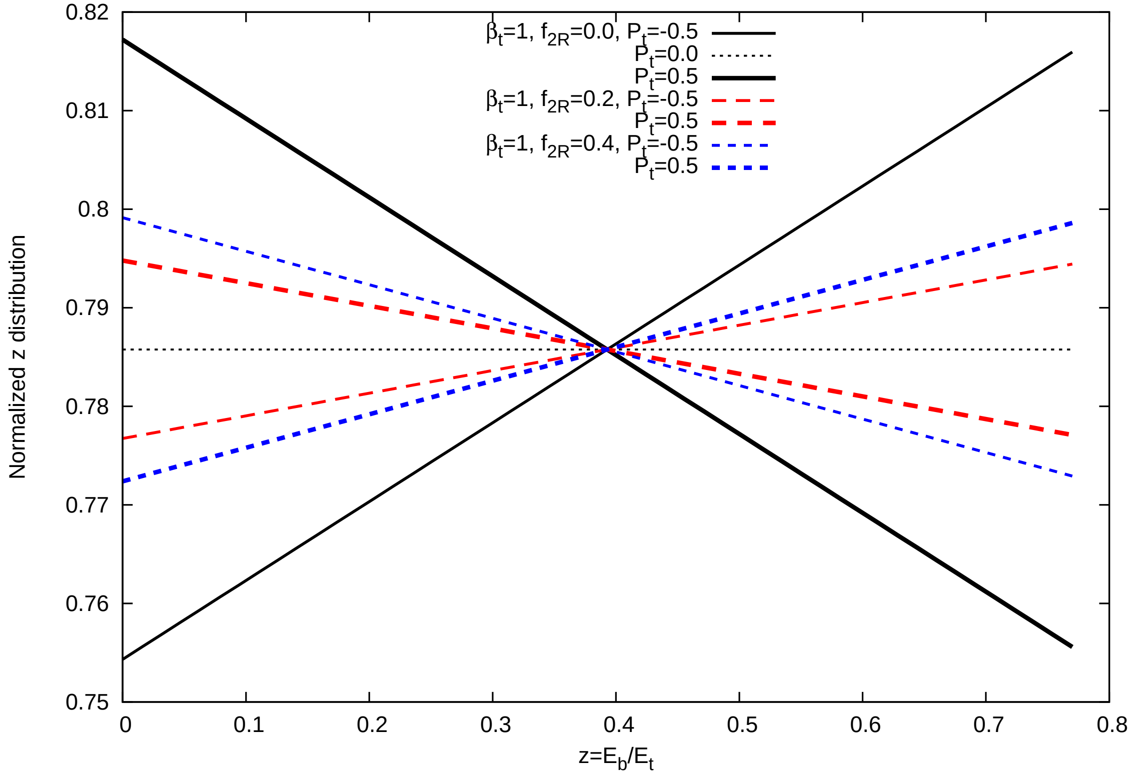


Effect for lower values of expected polarisation:



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 $f_2 R = 0.4$ 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.