Polarization as a tool for studying new physics

Saurabh D. Rindani

Physical Research Laboratory
Ahmedabad

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Going beyond the standard model

- Standard model in good agreement with data from precision experiments
- Standard model yet has a number of unsatisfactory features
- Large number of parameters (fermion masses, mixings), CP violation, baryogenesis, ...
- Results on Higgs searches will shed light on mechanism of spontaneous symmetry breaking
- Clues from *WW* scattering

Physics at colliders

- Hadron colliders serve as discovery machines
- Can produce new particles and measure their properties
- Linear collider will make precision measurements of properties of SM particles and couplings
- For final states containing SM particles, new physics can be probed indirectly
- Deviations from SM cross section implies new physics
- Large variety of extensions of SM proposed: Extra scalars, fermions, superpartners, KK excitations, etc.

Polarization studies

- Basic measurement: Cross section
- More detailed tests through angular distributions, angular asymmetries
- Additional tool: polarization studies
- Particle polarization measurements, correlated with angle or with other spins, can give detailed information on interactions
- Additional information available through beam polarization at e^+e^- collider.

Plan

- Polarized beams at e^+e^- collider
  - General analysis
  - Longitudinal polarization
  - Transverse polarization
- Top polarization at colliders
  - Example from linear collider
  - How top polarization can be measured
  - Contamination from anomalous couplings
  - Example from LHC

Linear collider

- Linear e^+e^- collider operating at 500 GeV c.m. energy or higher in the planning phase (ILC, CLIC)
- Precision measurements of masses and couplings would be possible
- Longitudinal polarization of 80% for electrons and 60% for positrons considered feasible
- Transverse polarization to the same extent could also be achieved

Model-independent analysis

- A given model can be tested by making all possible predictions within the model and making a comparison with experiment
- This would have to be done for a number of models giving the same final state
- Another phenomenological approach is to parametrize experimental results in a model independent form using only kinematics
- These parameters may be determined from experiment and compared with predictions of models.

One-particle inclusive process

Single-particle distributions [B. Ananthanarayan, SDR]
Consider the inclusive process

$$e^+(p_+)e^-(p_-) \rightarrow h(p) + X$$

Look at SM contribution and interference term with new physics contribution (assumed small)

- h can be boson or fermion
- X can be a single particle ($\bar{h}$ or $\bar{h}'$)
- X can be more than one particle
- New physics could be anomalous ZhX vertex (as for example ZZH vertex)
- Could be other new particles exchanged (like Z')

Structure functions

- SM contribution through virtual γ and Z
- BSM contribution through scalar, pseudo scalar, vector, axial vector, tensor couplings
- New couplings to e^+e^- of the form

$$g_S + i\gamma_5 g_P, \quad g_V\gamma_\nu - g_A\gamma_\nu\gamma_5, \quad \text{or } g_T\sigma_{\alpha\beta}$$

- For spin-1 exchange, for example,

$$\Gamma_i \equiv (g_V\gamma_\nu - g_A\gamma_\nu\gamma_5)$$

- Tensor $H^{i\mu}$ appearing in the cross section can be written in terms of 3 structure functions:

$$H^V_{\mu\nu} = -g_{\mu\nu}W_1 + p_\mu p_\nu W_2 + \epsilon_{\mu\nu\alpha\beta}q^\alpha p^\beta W_3,$$

Angular distributions in $e^+e^- \to h + X$

Term	Correlation	P	C
$\mathrm{Re}\,(g_V W_1)$	$-4E^2(h_+h_- - 1)$	$+$	$+$
$\mathrm{Re}\,(g_A W_1)$	$4E^2(h_+ - h_-)$	$-$	$-$
$\mathrm{Re}\,(g_V W_2)$	$-2[2E^2\,\vec{p}\cdot\vec{s}_-\,\vec{p}\cdot\vec{s}_+ + (\vec{K}\cdot\vec{K}\,\vec{p}\cdot\vec{p}$ $-(\vec{p}\cdot\vec{K})^2)(h_+h_- - 1 - \vec{s}_+\cdot\vec{s}_-)]$	$+$	$+$
$\mathrm{Re}\,(g_A W_2)$	$2(\vec{K}\cdot\vec{K}\,\vec{p}\cdot\vec{p} - (\vec{p}\cdot\vec{K})^2)(h_+ - h_-)$	$-$	$-$
$\mathrm{Im}\,(g_V W_3)$	$8E^2(\vec{p}\cdot\vec{K})(h_+ - h_-)$	$-$	$+$
$\mathrm{Im}\,(g_A W_3)$	$-8E^2(\vec{p}\cdot\vec{K})(h_+h_- - 1)$	$+$	$-$
$\mathrm{Im}\,(g_A W_2)$	$2E(\vec{p}\cdot\vec{s}_+[\vec{K}\cdot\vec{s}_- \times \vec{p}] + \vec{p}\cdot\vec{s}_-[\vec{K}\cdot\vec{s}_+ \times \vec{p}])$	$-$	$-$

Table: List of VA correlations for g_V^e

Angular distributions

Term	Correlation	P	C
Re $(g_V W_1)$	$4E^2(h_+ - h_-)$	$-$	$-$
Re $(g_A W_1)$	$-4E^2(h_+h_- - 1)$	$+$	$+$
Re $(g_V W_2)$	$2(\vec{K}\cdot\vec{K}\,\vec{p}\cdot\vec{p} - (\vec{p}\cdot\vec{K})^2)(h_+ - h_-)$	$-$	$-$
Re $(g_A W_2)$	$-2[-2E^2\vec{p}\cdot\vec{s}_-\vec{p}\cdot\vec{s}_+ + (\vec{K}\cdot\vec{K}\,\vec{p}\cdot\vec{p}$ $-(\vec{p}\cdot\vec{K})^2)(h_+h_- - 1 + \vec{s}_+\cdot\vec{s}_-)]$	$+$	$+$
Im $(g_V W_3)$	$-8E^2(\vec{p}\cdot\vec{K})(h_+h_- - 1)$	$+$	$-$
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Some general conclusions

Some conclusions which are model and process independent

- Without polarization, the only correlations which survive are in the case of $\boldsymbol{V}$, $\boldsymbol{A}$ interactions.
- $\boldsymbol{S}$, $\boldsymbol{P}$, $\boldsymbol{T}$ interactions need transverse polarization
- In case of $\boldsymbol{V}$, $\boldsymbol{A}$, with transverse polarization, both beams have to be polarized
- In case of $\boldsymbol{V}$, $\boldsymbol{A}$ BSM interactions only at tree level, structure functions contributing with polarization and without polarization are the same.
- Hence no qualitatively new information is contained in the polarized distributions.
- Polarization can give information on absorptive parts of structure functions of BSM interactions, which cannot be obtained with only unpolarized beams

Some more general conclusions

- Absorptive part of one structure function $\mathbf{Im}\ W_2$ contributes only for transversely polarized beams
- This term vanishes unless two different vector particles are exchanged
- For example, for a neutral final state (no photon contribution), this term contributes only if there is an additional Z' exchange, with coupling different from those of Z
- For the case of a $H\overline{H}$ final state there are no CP-odd correlations for V, A interactions.
- This statement is true regardless of whether there is polarization or not.
- Thus, CP violation needs final-state polarization to be seen, or S, P, T interactions

Examples of form factor analysis

Analysis for more concrete final states may be done by writing the effective vertices (form factors) rather than structure functions.

- $e^+e^- \rightarrow \gamma Z$ with effective $\gamma\gamma Z$, γZZ vertices [D. Choudhury, SDR; B. Ananthanarayan, R. Singh, SDR, A. Bartl; B. Ananthanarayan, SDR]
- $e^+e^- \rightarrow HZ$, $e^+e^- \rightarrow He^+e^-$ with effective ZZH vertices, $e^+e^- \rightarrow H\nu\bar{\nu}$ with effective WWH vertices [B. Biswal, D. Choudhury, R. Godbole, Mamta, PRD 2007]
- $e^+e^- \rightarrow HZ$, $e^+e^- \rightarrow H\mu^+\mu^-$ with effective $eeHZ$ vertices [K. Rao, SDR, PLB 2007, PRD 2008; P. Sharma, SDR, PRD 2009]
- $e^+e^- \rightarrow f\bar{f}$ in R-parity violating MSSM [R. Godbole, S. Rai, SDR, PLB 2009]

Analysis is done of the sensitivity of measurement of couplings for a given energy and luminosity.

Top quark production at LHC

- Copious production of $t\bar{t}$ pairs at LHC (SM c.s. $\approx$ 800 pb)
- Also large single top production (seen at Tevatron)
- Top quarks can also arise in the decays of new particles – resonances, new gauge bosons, Higgs bosons, squarks, gluinos . . .

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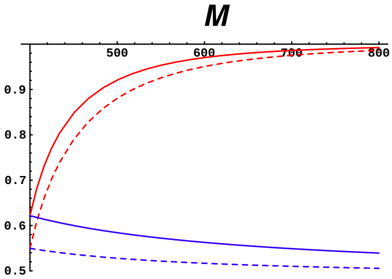
  - Or vice versa
- In SM, $\bar{t}bW^+$ vertex is left-handed
- It can receive modifications beyond SM from loops
- Also, other channels possible e.g., $t \longrightarrow bH^+$

Production mechanisms and top polarization

- Top polarization can give more information about the production mechanism than just the cross section
- It can thus allow measurements of the parameters of the theory
- It requires parity violation, and hence measures left-right mixing
- It can give a clue to CP violation through dipole couplings
- It can give information on the theory in cascade decays

Example of polarization in cascade decay

Top quark polarization vs. parent particle mass M in GeV
Purely chiral couplings.



Solid curves: Stop decaying into top and neutralino

The red (upper) curve has a fixed neutralino mass of **200** GeV. The blue (lower) curves have neutralino mass of $M - 200$ GeV.

Dashed curves: Spin-1/2 heavy quark T decaying into top and spin-1 particle.

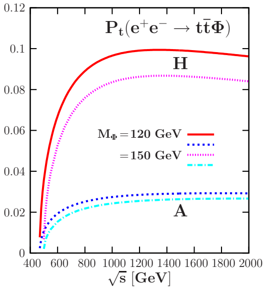
Scalar vs. pseudoscalar Higgs

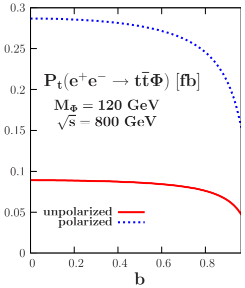
Top polarization in the process

$$e^+e^- \to t\bar{t}H$$

can be used to discriminate between CP even and CP odd Higgs

[P. Bhupal Dev, A. Djouadi, R. Godbole, M. Muhlleitner, SDR, PRL 100, 2008]





Top spin correlation vs. single top polarization

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

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

- This has been very well studied theoretically
- Also seems experimentally feasible
- Needs reconstruction of both t and $\bar{t}$ rest frames
- It is conceivable that single top polarization can give better statistics
- At Tevatron or LHC, single top polarization implies new physics

Measuring polarization

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

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

where
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.

Analyzing power for various channels

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 $\kappa_j \simeq 0.5$

Corrections to the analyzing power

- 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
- The formula shown above does not take into account spin correlations – that needs a spin density matrix formalism

Spin density matrix

At amplitude level

$$M(A{+}B \to t{+}X \to f{+}X'{+}X) = M(A{+}B \to t(\lambda)X) \;\; M(t(\lambda) \to fX$$

At transition probability level

$$|M(AB \to tX \to fX'X)|^2 = \;\; M(AB \to t(\lambda)X)\, M(AB \to t(\lambda')X)^* \\ \times M(t(\lambda) \to fX')\, M(t(\lambda') \to fX')^*$$

OR

$$|M(A+B \to t+X \to f+X'+X)|^2 = \rho(\lambda,\lambda')\; \Gamma(\lambda,\lambda')$$

ρ: production density matrix
Γ: decay density matrix

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

A "theorem"

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

Factorization property

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

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

Spin density matrix for production

Production density matrix defines polarization matrix:

$$\rho(\lambda, \lambda') = \sigma_{tot} \, P_t(\lambda, \lambda')$$

$$P_t = \frac{1}{2} \begin{pmatrix} 1 + \eta_3 & \eta_1 - i\eta_2 \\ \eta_1 + i\eta_2 & 1 - \eta_3 \end{pmatrix},$$

Longitudinal polarization is

$$\eta_3 = \left[\sigma(+) - \sigma(-)\right] / \sigma_{tot}$$

Transverse polarization in the plane of production:

$$\eta_1 = \left[\rho(+,-) + \rho(-,+)\right] / \sigma_{tot}$$

Transverse polarization perpendicular to the plane of production:

$$i\,\eta_2 = \left[\rho(+,-) - \rho(-,+)\right] / \sigma_{tot}$$

Angular distribution

The angular distribution of leptons in terms of polarizations:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_l\, d\phi_l} = C\ [1 + \eta_3\ \cos\theta_l + \eta_1\ \sin\theta_l \cos\phi_l + \eta_2\ \sin\theta_l\ s$$

$$\frac{\eta_3}{2} = \frac{1}{4\pi\ C\ \sigma}\left[\int_0^1 d\cos\theta_l \int_0^{2\pi} d\phi_l \frac{d\sigma}{d\cos\theta_l\ d\phi_l} - \int_{-1}^0 d\cos\theta_l \int_0^{2\pi} d\phi_l \frac{d\sigma}{d\cos\theta_l\ d\right.$$

$$\frac{\eta_2}{2} = \frac{1}{4\pi\ C\ \sigma}\int_{-1}^1 d\cos\theta_l \left[\int_0^{\pi} d\phi_l \frac{d\sigma}{d\cos\theta_l\ d\phi_l} - \int_{\pi}^{2\pi} d\phi_l \frac{d\sigma}{d\cos\theta_l\ d\phi_l}\right]$$

$$\frac{\eta_1}{2} = \frac{1}{4\pi\ C\ \sigma}\int_{-1}^1 d\cos\theta_l \left[\int_{-\pi/2}^{\pi/2} d\phi_l \frac{d\sigma}{d\cos\theta_l\ d\phi_l} - \int_{\pi/2}^{3\pi/2} d\phi_l \frac{d\sigma}{d\cos\theta_l\ d\phi_l}\right]$$

Here $C = \frac{1}{4\pi} BR(t \to bl\nu)$

Little Higgs Model

- We choose for illustration and extra Z model
- Litle Higgs model has an extra massive gauge boson Z_H with left-handed couplings to fermions depending on one parameter (θ):

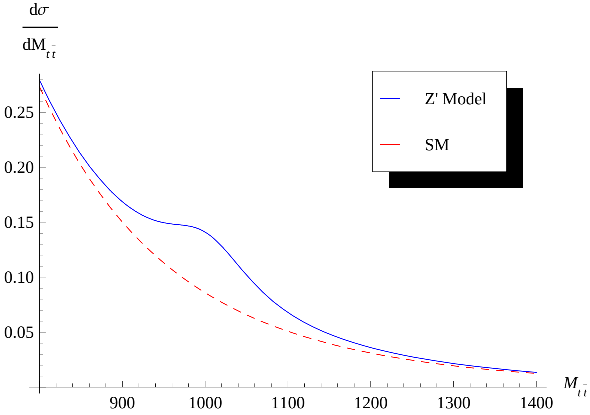
$$g_V^u = g_A^u = g \cot\theta$$

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

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

$t\bar{t}$ invariant mass distribution

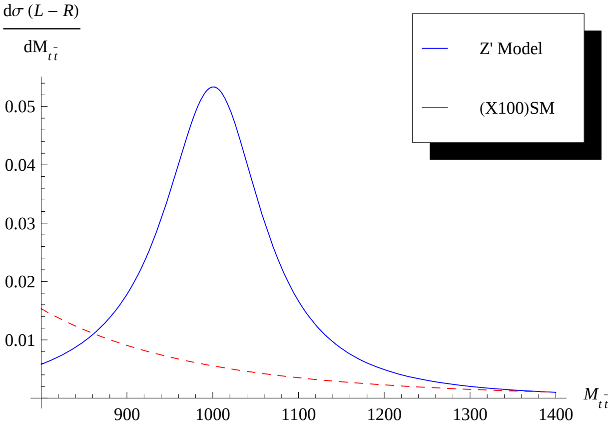
The model can be tested using the $t\bar{t}$ invariant mass distribution



Polarization can be a further more sensitive test

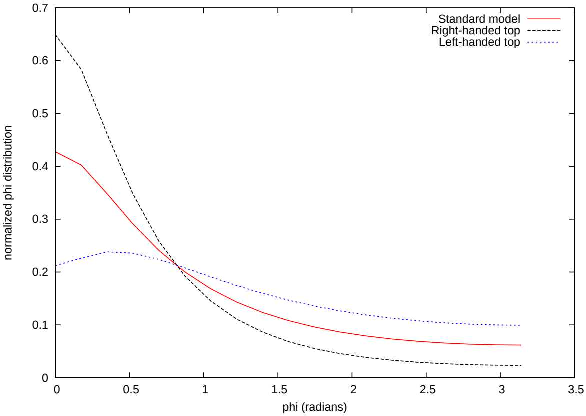
Top longitudinal polarization

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



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



[R. Godbole, K. Rao, SDR, R.K. Singh]

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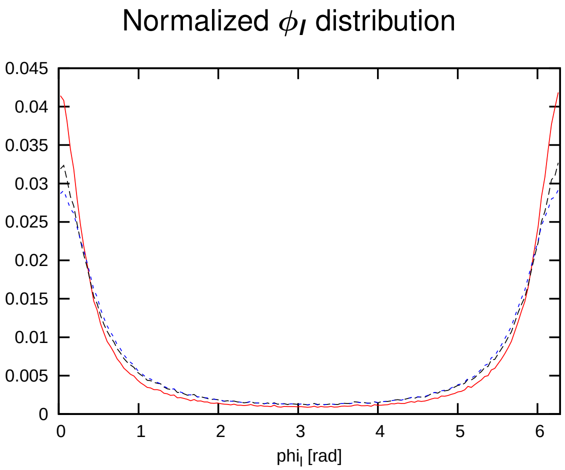
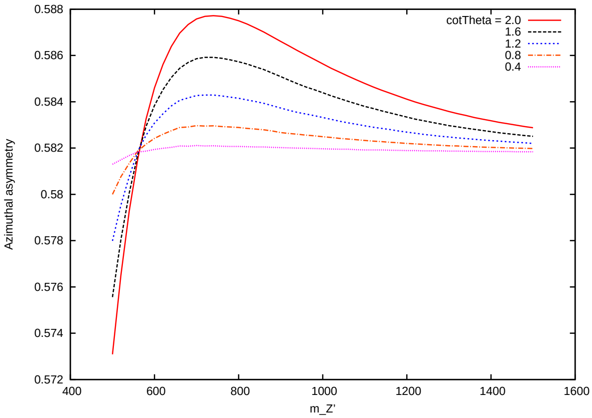


Azimuthal asymmetry of charged lepton

Azimuthal asymmetry

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

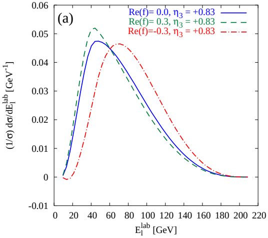


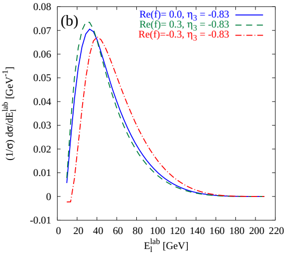
Lepton energy distribution and anomalous couplings

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





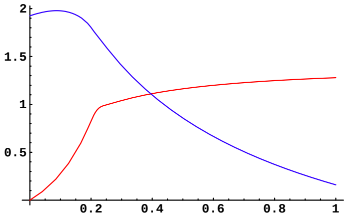
Collimated top quarks

Systems with large invariant mass of $t\bar{t}$ can produce highly boosted tops – with collimated decay products

- 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 PRD 79, 014032 (2009)]



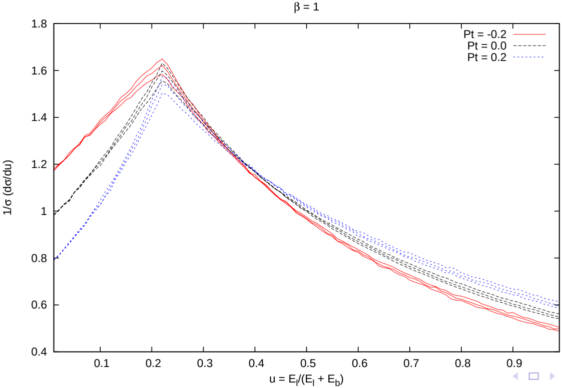
Blue: right-handed; Red

Top polarization for large β_t

Anomalous $\bar{t}bW^+$ vertex can be written as

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

Effect of anomalous coupling may not be distinguishable from effect of polarization



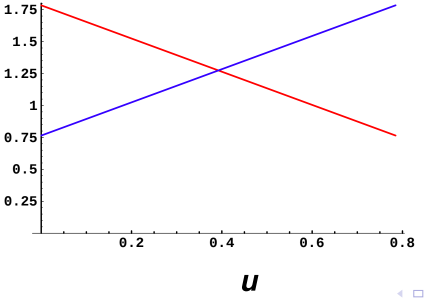
Collimated top quarks

Another variable: fraction of the visible energy carried by the b quark

$$z = \frac{E_b}{E_\ell + E_b},$$

[J. Shelton PRD 79, 014032 (2009)]

Red: positive helicity top; Blue: Negative helicity top



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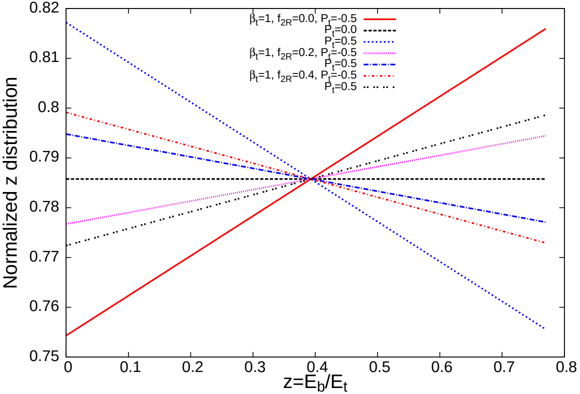

Another suggestion: D. Krohn, J. Shelton, L-T. Wang, arXiv:0909.3855

Summary

- Beam polarization at e^+e^- linear colliders can help to separate out different kinds of interactions (space-time properties, CP, etc)
- Top polarization could be useful in many different theoretical scenarios where top is one of the particles produced at LHC
- A relatively clean signature of top polarization is the secondary lepton angular distribution
- Azimuthal distribution seem to be particularly sensitive tests in case of extra Z' scenarios