Probing space-time structure of new physics with polarized beams at the ILC

Work done in collaboration with Saurabh D. Rindani

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- Use the work of Dass and Ross as a guide (only γ^*), for the process $e^+e^- \longrightarrow hX$ (see G. V. Dass and G. G. Ross, Phys. Lett. B57 (1975) 173; Nucl.Phys.B118 (1977) 284)

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- Generalization to processes of the type $e^+e^- \to h(S)X, h_1h_2X$ (work in progress)

$\mathcal{L}^{4F}$ for $t\bar{t}$ production

- The Lagrangian takes the form

$$\mathcal{L}^{4F} = \sum_{i,j=L,R} \Big[S_{ij}(\bar{e}P_i e)(\bar{t}P_j t) + V_{ij}(\bar{e}\gamma_\mu P_i e)(\bar{t}\gamma^\mu P_j t) + T_{ij}(\bar{e}\frac{\sigma_{\mu\nu}}{\sqrt{2}}P_i e)(\bar{t}\frac{\sigma^{\mu\nu}}{\sqrt{2}}P_j t) \Big],$$

$$S_{RR} = S^*_{LL},\ S_{LR} = S_{RL} = 0, V_{ij} = V^*_{ij},$$
$$T_{RR} = T^*_{LL}, T_{LR} = T_{RL} = 0$$

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- Taking e^--TP to be 100% and along the positive or negative x axis, e^+-TP to be 100%, parallel or anti-parallel to e^- polarization. z-axis along the direction of the e^-, the crosssection for $e^+e^- \to t\bar{t}$, (superscripts denoting the respective signs of the e^- and e^+ TP)

$$\frac{d\sigma^{\pm\pm}}{d\Omega} = \frac{d\sigma^{\pm\pm}_{SM}}{d\Omega} \mp \frac{3\alpha\beta^2}{4\pi}\frac{m_t\sqrt{s}}{s-m_Z^2}\left(c_V^t c_A^e \mathrm{Re}S\right)\sin\theta\cos\phi,$$

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where

$$\frac{d\sigma^{+\pm}_{SM}}{d\Omega}$$

is the SM contribution to the cross-section that we do not spell out here, and

$$S \equiv S_{RR} + \frac{2c_A^t c_V^e}{c_V^t c_A^e} T_{RR},$$

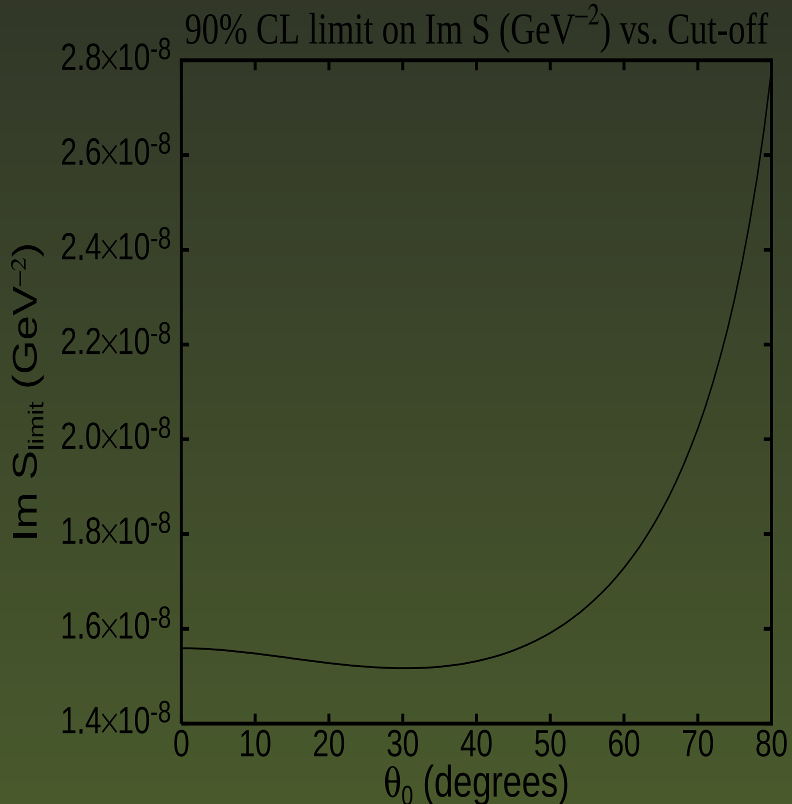
where c_V^i, c_A^i are the couplings of Z to e^-e^+ and $t\bar{t}$.

The differential cross section corresponding to anti-parallel e^- and e^+ polarizations, has the CP-odd quantity

$$\sin\theta\sin\phi \equiv \frac{(\vec{p}_{e^-} - \vec{p}_{e^+}) \times (\vec{s}_{e^-} - \vec{s}_{e^+}) \cdot (\vec{p}_t - \vec{p}_{\bar{t}})}{|\vec{p}_{e^-} - \vec{p}_{e^+}||\vec{s}_{e^-} - \vec{s}_{e^+}||\vec{p}_t - \vec{p}_{\bar{t}}|},$$

while the interference term in the case with parallel e^- and e^+ polarizations, has the CP-even quantity

$$\sin\theta\cos\phi \equiv \frac{(\vec{p}_t - \vec{p}_{\bar{t}}) \cdot (\vec{s}_{e^-} + \vec{s}_{e^+})}{2|\vec{p}_t - \vec{p}_{\bar{t}}|}$$



The 90% C.L. limit on Im S with $\mathcal{L}$=500 fb^{-1}

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- We calculate the relevant factor in

$$\mathrm{Tr}\left[(1 - \gamma 5 h_+ + \gamma 5 \not{s}_+)\not{p}_+ \right.$$
$$\left. \gamma_\mu (g_V^e - g_A^e \gamma_5)(1 + \gamma 5 h_- + \gamma 5 \not{s}_-)\not{p}_- \Gamma_i\right] H^{i\mu}.$$

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- Γ_i is the corresponding coupling to the new physics current, $p_\pm$ are the four-momenta of $e^\pm$, $h_\pm$ are the helicities and $s_\pm$ are respectively their TPs.

1. Scalar and Pseudoscalar case:

$$\Gamma = g_S + i g_P \gamma_5 .$$

The tensor $H^{i\mu}$ for this case has only one index, viz., μ. Hence the most general form for H is

$$H^S_\mu = F(q^2, p \cdot q) p_\mu ,$$

where F is a function of the Lorentz-invariant quantities q^2 and $p \cdot q$.

2. Vector and Axial-Vector case:

$$\Gamma_\mu = \gamma_\mu (g_V - g_A \gamma_5).$$

The tensor H for this case has two indices, and can be written as

$$H^V_{\mu\nu} = -g_{\mu\nu} W_1(q^2, p \cdot q)$$
$$+ p_\mu p_\nu W_2(q^2, p \cdot q) + \epsilon_{\mu\nu\alpha\beta} q^\alpha p^\beta W_3(q^2, p \cdot q),$$

where now there are three invariant functions, W_1, W_2, W_3.

3. Tensor case:
In the tensor case, the leptonic coupling is

$$\Gamma_{\mu\nu} = g_T \sigma_{\mu\nu}.$$

The tensor H for this case can be written in terms of the four invariant functions F_1, F_2, PF_1, PF_2 as

$$\begin{aligned} H^T_{\mu\rho\tau} &= (q_\rho p_\tau - q_\tau p_\rho) p_\mu F_1(q^2, p\cdot q) \\ &+ (g_{\rho\mu} p_\tau - g_{\tau\mu} p_\rho) F_2(q^2, p\cdot q) \\ &+ \epsilon_{\rho\tau\alpha\beta} p^\alpha q^\beta p_\mu PF_1(q^2, p\cdot q) \\ &+ \epsilon_{\rho\tau\mu\alpha} p^\alpha PF_2(q^2, p\cdot q). \end{aligned}$$

Term	Correlation	P	C
$\mathrm{Im}\,(g_P F)$	$-2E^2\,(\vec{s}_+ - \vec{s}_-)\cdot\vec{p}$	$-$	$-$
$\mathrm{Im}\,(g_S F)$	$2E\,[\vec{K}\cdot(\vec{s}_+ + \vec{s}_-)\times\vec{p}]$	$+$	$-$
$\mathrm{Re}\,(g_S F)$	$2E^2\,\vec{p}\cdot(h_+\vec{s}_- - h_-\vec{s}_+)$	$+$	$-$
$\mathrm{Re}\,(g_P F)$	$-2E\,[\vec{K}\cdot(h_+\vec{s}_- + h_-\vec{s}_+]\times\vec{p})$	$-$	$-$

List of S, P correlations for g_V^e

$\vec{K} \equiv (\vec{p}_- - \vec{p}_+)/2 = E\hat{z}$, where $\hat{z}$ is a unit vector in the z-direction, E is the beam energy, and $\vec{s}_\pm$ lie in the x-y plane.

Term	Correlation	P	C
$\text{Im}\,(g_P F)$	$2E^2\,(h_+\vec{s}_- + h_-\vec{s}_+)\cdot\vec{p}$	$+$	$+$
$\text{Im}\,(g_S F)$	$2E\,[\vec{K}\cdot(h_+\vec{s}_- - h_-\vec{s}_+)\times\vec{p}]$	$-$	$+$
$\text{Re}\,(g_S F)$	$2E^2\,\vec{p}\cdot(\vec{s}_+ + \vec{s}_-)$	$-$	$+$
$\text{Re}\,(g_P F)$	$2E\,[\vec{K}\cdot(\vec{s}_+ - \vec{s}_-)\times\vec{p}]$	$+$	$+$

List of S, P correlations for g_A^e

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

List of V, A correlations for g_A^e

Term	Correlation	P	C
$\text{Im}(g_T F_1)$	$-8E^2\vec{p}\cdot\vec{K}[\vec{p}\cdot(\vec{s}_+ + \vec{s}_-)]$	$-$	$-$
$\text{Im}(g_T F_2)$	$-4E^2\vec{p}\cdot(\vec{s}_+ - \vec{s}_-)$	$-$	$-$
$\text{Im}(g_T P F_1)$	$-8E\vec{p}\cdot\vec{K}[\vec{K}\cdot(\vec{s}_+ - \vec{s}_-)\times\vec{p}]$	$+$	$-$
$\text{Im}(g_T P F_2)$	$4E[\vec{K}\cdot(\vec{s}_+ + \vec{s}_-)\times\vec{p}]$	$+$	$-$
$\text{Re}(g_T F_1)$	$8E\vec{p}\cdot\vec{K}[\vec{K}\cdot(h_+\vec{s}_- - h_-\vec{s}_+)\times\vec{p}]$	$-$	$-$
$\text{Re}(g_T F_2)$	$-4E[\vec{K}\cdot(h_+\vec{s}_- + h_-\vec{s}_+)\times\vec{p}]$	$-$	$-$
$\text{Re}(g_T P F_1)$	$8E^2\vec{p}\cdot\vec{K}[\vec{p}\cdot(h_+\vec{s}_- + h_-\vec{s}_+)]$	$+$	$-$
$\text{Re}(g_T P F_2)$	$4E^2\vec{p}\cdot(h_+\vec{s}_- - h_-\vec{s}_+)$	$+$	$-$

List of T correlations for g_A^e

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Applications

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- t- and u-channel exchange processes
  Matrix element for $e^-(p_-) + e^+(p_+) \rightarrow \gamma_\alpha(k_1) + Z_\beta(k_2)$ can be written as

$$M = e\bar{v}(p_+)\left[\frac{1}{t}\gamma^\beta(g_V^e - g_A^e\gamma_5)\right.$$

$$\left.(\not{p}_- - \not{k}_1)\gamma^\alpha + \frac{1}{u}\gamma^\alpha(\not{p}_- - \not{k}_2)\gamma^\beta(g_V^e - g_A^e\gamma_5)\right]u(p_-),$$

where $t = (p_- - k_1)^2$ and $u = (p_- - k_2)^2$.

Can be rewritten as

$$M = e\bar{v}(p_+)\left[\gamma_\mu(g_V^e - g_A^e\gamma_5)T_1^{\mu\alpha\beta} + \gamma_\mu(g_A^e - g_V^e\gamma_5)T_2^{\mu\alpha\beta}\right]u(p_-), \qquad (-15)$$

where

$$T_1^{\mu\alpha\beta} = g^{\mu\beta}\left(\frac{2p_-^\alpha}{t} - \frac{2p_+^\alpha}{u}\right) + (-g^{\mu\alpha}k_1^\beta + g^{\alpha\beta}k_1^\mu)\left(\frac{1}{t} - \frac{1}{u}\right), \qquad (-15)$$

and

$$T_2^{\mu\alpha\beta} = -i\epsilon^{\mu\alpha\beta\lambda}k_{1\lambda}\left(\frac{1}{t} + \frac{1}{u}\right). \qquad (-15)$$

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- There is an apparent problem: the “hadronic" tensor will involve leptonic momenta. On summing over final state polarizations, the leptonic momenta will be contracted appropriately to give Lorentz scalars like $p_-.k_1$, $p_-.k_2$, etc., which can be rewritten in terms of s, t and u.

Applications continued

- The same CP-odd correlation arises in a different context of supersymmetry in the process $e^+e^- \to \tilde{\chi}_i \tilde{\chi}_j$, $i \neq j$, where $\tilde{\chi}_i$ are neutralinos in the theory, which are self-conjugate. Here the CP-odd terms arise in the cross terms between the s-channel and the t- and u-channel production diagrams (see S.Y. Choi, J. Kalinowski, G. Moortgat-Pick and P.M. Zerwas Eur.Phys.J.C22 (2001) 563, Addendum-ibid.C23 (2002) 769; A. Bartl et al., JHEP 0601 (2006) 170.)

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- Rizzo has considered probing extra-dimensional models using transverse polarization. The key observation is that an azimuthal angle dependence of the form $\cos 2\phi$ and $\sin 2\phi$ when the s-channel exchange of a tower of massive gravitons is introduced.

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  (see T. G. Rizzo, JHEP 0302 (2003) 008.)
- We then find that it is possible to have a CP-odd correlation given by a product of the correlation in the last line of either Table 3 or 4 and the factor $\vec{p} \cdot \vec{K}$, where p is the momentum of a neutralino. This has been discussed and a numerical study of a corresponding CP-odd asymmetry has been carried out

- The other example from MSSM is that of chargino pair production. We find that for the process $e^+e^- \longrightarrow \tilde{\chi}_i^+ \tilde{\chi}_j^-$, where $\tilde{\chi}_i^\pm$ denote charginos, no CP-odd correlation exists at tree level However, it is found in that the corresponding coefficient vanishes at tree level. (see

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- Another example from the MSSM which would fall in the category of case 2b of Sec. 4 is the neutralino pair-production process mentioned above, but when the energy and momentum that is measured is of a lepton arising in the decay chain of a neutralino. In this case, it is possible to construct a CP-odd correlation using leptons of opposite charges, and the effect is non-vanishing. See forthcoming. (see A. Bartl, K. Hohenwarter-Sodek, T. Kernreiter and H. Rud Eur.Phys.J.C36 (2004) 515-522).

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- Non-commutative geometry

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- Measurement of spin of h through decay products

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- BA and SDR, work in progress