Transverse Polarization in γZ and HZ production

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Outline

1. Introduction
   - Transverse beam polarization at linear collider
   - CP violation and polarization
2. The process $e^+e^- \to HZ$
   - Model-independent couplings for $e^+e^- \to HZ$
   - Angular distribution with transverse polarization
   - CP violating azimuthal asymmetry
   - Sensitivity
3. The process $e^+e^- \to \gamma Z$
   - Model-independent couplings for $e^+e^- \to \gamma Z$
   - Angular distribution with transverse polarization
   - Azimuthal asymmetries
   - Sensitivity

TRANSVERSE BEAM POLARIZATION

- Longitudinal polarization expected to be available at linear collider
- Electron polarization: 80–90%. Positron polarization: 60%
- Possible to convert linear polarization to transverse polarization with spin rotators
- Can transverse polarization be put to use?
  Triple gauge couplings (Diehl, Nachtmann), Extra dimensions (T. Rizzo), Contact interactions in $t\bar{t}$ production (B. Ananthanarayan, S.D.R.), Chargino/neutralino production/decay (A. Bartl et al.)

ROLE OF TRANSVERSE POLARIZATION

- Longitudinal beam polarization useful because it helps to
  - Reduce background
  - Increase sensitivity
- Transverse beam polarization provides azimuthal angle even for a two-particle final state
  - This could provide CP/T violating triple-product correlations
  - Even in CP conserving case, it provides additional observables through azimuthal distributions with a simpler final state
  - More information without measurement of final-state polarization
  - Hence improvement in statistics

CP-odd observables and beam polarization

- No CP-violating observables possible in $e^+e^- \to f\bar{f}$ without polarization (initial or final)
- Only scalar observable non-trivial observable:

$$(\hat{p}_{e^-} - \hat{p}_{e^+}) \cdot (\hat{p}_f - \hat{p}_{\bar{f}})$$

  which is CP even
- Without observing final-state polarization, CP-odd observables possible with longitudinal beam polarization:

$$(\vec{s}_{e^-} - \vec{s}_{e^+}) \cdot (\hat{p}_f - \hat{p}_{\bar{f}})$$

  This is CPT odd – requires non-zero absorptive part (or FSI)
- With transverse beam polarization, CP odd, CPT even observable possible:

$$(\hat{p}_{e^-} - \hat{p}_{e^+}) \times (\vec{s}_{e^-} - \vec{s}_{e^+}) \cdot (\hat{p}_f - \hat{p}_{\bar{f}})$$

CP-violating observables for neutral final state

- For $e^+e^- \to f + X$ where $f \equiv \bar{f}$
  CP-odd observable possible without polarization:
- This is $\cos\theta_f = (\hat{p}_{e^-} - \hat{p}_{e^+}).\hat{p}_f$
- It is odd under CP and CPT, hence measures absorptive part
- With transverse polarization another CP-odd observable possible which is CP odd but CPT even:

$$(\hat{p}_{e^-} - \hat{p}_{e^+}).\hat{p}_f\,[(\vec{s}_{e^-} \times \hat{p}_{e^+} \cdot \hat{p}_f)(\vec{s}_{e^+} \cdot \hat{p}_f) + (\vec{s}_{e^+} \times \hat{p}_{e^-} \cdot \hat{p}_f)(\vec{s}_{e^-} \cdot \hat{p}_f)]$$

- This is measured by $P_T \bar{P}_T \sin^2\theta_f \cos\theta_f \sin 2\phi$

The process $e^+e^- \to HZ$

Work done in collaboration with Kumar Rao

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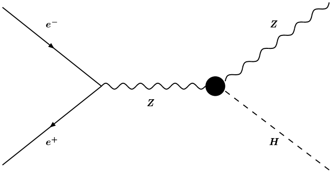

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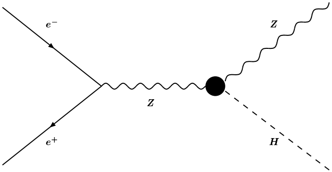
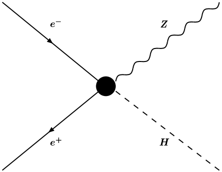


which includes SM and anomalous three-gauge boson coupling

We look at the general four-point coupling:



which includes the previous contribution, and additional contributions which may not have s-channel Z

Amplitude for $e^+e^- \to HZ$

The most general Lorentz-invariant chirality-conserving amplitude for

$$e^-(p_1) + e^+(p_2) \to Z(q,\varepsilon) + H(k)$$

is $\bar{v}(p2)\Gamma u(p1)$, where

$$\Gamma = \frac{i}{M}(V_1 + \gamma_5 A_1)\gamma\cdot\varepsilon - \frac{i}{M^3}(V_2 + \gamma_5 A_2) k\cdot\varepsilon - \frac{1}{M^3}\not{q}(V_3 + \gamma_5 A_3)(p_2 - p_1)\cdot\varepsilon$$

M is a scale put in to make the V_i and A_i dimensionless
V_i, A_i could be functions of s as well as t (i.e. cm energy, as well as scattering angle θ

Differential cross section

The SM differential cross section with transverse polarization $P_T, \bar{P}_T$ of e^-, e^+ is:

$$\frac{d\sigma_T^{\rm SM}}{d\Omega} = \frac{\lambda^{1/2}}{64\pi^2 s^2}\left\{F^2\left[(g_V^2+g_A^2)s\left[1+\frac{|\vec{q}|^2}{2m_Z^2}\sin^2\theta\right]\right.\right.$$
$$\left.\left. + P_T\overline{P}_T(g_V^2-g_A^2)\frac{s|\vec{q}|^2}{2m_Z^2}\sin^2\theta\cos 2\phi\right]\right\}$$

$$F = \frac{m_Z}{s-m_Z^2}\left(\frac{e}{2\sin\theta_W\cos\theta_W}\right)^2$$

Interference term with transverse polarization

We calculate the interference term between the SM contribution and the new physics contribution

$$\begin{aligned}
\frac{d\sigma_T^{\rm int}}{d\Omega} &= \frac{\lambda^{1/2}}{64\pi^2 s^2}\frac{2Fs}{M}\Bigg\{\Bigg[(g_V \mathrm{Re}V_1 - g_A \mathrm{Re}A_1) + \frac{|\vec{q}|^2}{m_Z^2}\sin^2\theta\,[(g_V \mathrm{Re}V_1 - g_A \mathrm{Re}A_1) \\
&+ P_T\overline{P}_T\,[(g_V \mathrm{Re}V_1 + g_A \mathrm{Re}A_1)\cos 2\phi - (g_V \mathrm{Im}A_1 + g_A \mathrm{Im}V_1)\sin 2\phi]]\Bigg] \\
&- \frac{s^{1/2} q_0 |\vec{q}|^2}{2M^2 m_Z^2}\sin^2\theta\,[(g_V \mathrm{Re}V_2 - g_A \mathrm{Re}A_2) \\
&+ P_T\overline{P}_T\,[(g_V \mathrm{Re}V_2 + g_A \mathrm{Re}A_2)\cos 2\phi - (g_V \mathrm{Im}A_2 + g_A \mathrm{Im}V_2)\sin 2\phi]] \\
&- \frac{s^{3/2}|\vec{q}|^3}{2M^2 m_Z^2}\cos\theta\sin^2\theta\,[(g_V \mathrm{Im}V_3 - g_A \mathrm{Im}A_3) \\
&+ P_T\overline{P}_T\,[(g_V \mathrm{Im}V_3 + g_A \mathrm{Im}A_3)\cos 2\phi + (g_V \mathrm{Re}A_3 + g_A \mathrm{Re}V_3)\sin 2\phi]\,]\Bigg\}
\end{aligned}$$

The last term (with ReV_3, ReA_3) violates CP, but not CPT

CP violating terms

- The term proportional to

$$P_T\overline{P}_T(g_V \mathrm{Re} A_3 + g_A \mathrm{Re} V_3)\cos\theta\sin^2\theta\sin 2\phi$$

is odd under CP, but even under CPT

- It is absent when only anomalous CP-violating *VVH* coupling

$$\tilde{b}_Z \varepsilon_{\alpha\beta\mu\nu} Z^{\alpha\beta} Z^{\mu\nu} H$$

is included (Hagiwara & Stong; Han & Jiang; Biswal et al.)

- It is the only CP-odd, CPT-even term, and hence the only term which does not require the presence of absorptive part

CP violating asymmetry

- It can be measured by means of the asymmetry

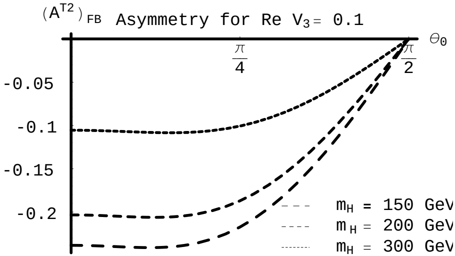
$$A = \frac{1}{\sigma}[\Delta\sigma_{\rm FB}(0 < \phi < \pi/2) - \Delta\sigma_{\rm FB}(\pi/2 < \phi < \pi) \\ + \Delta\sigma_{\rm FB}(\pi < \phi < 3\pi/2) - \Delta\sigma_{\rm FB}(3\pi/2 < \phi < 2\pi)]$$

- $\Delta\sigma_{\rm FB}(\phi)$ is the difference in the forward and backward differential cross sections of the Z for a given value of ϕ
- σ is the total cross section
- A can be evaluated to give

$$A = \frac{1}{\sigma}\frac{2Fs^{3/2}q^3}{M^3 m_Z^2}P_T\bar{P}_T(g_A{\rm Re}V_3 + g_V{\rm Re}A_3)$$

Limit on coupling from asymmetry A

The asymmetry A with a cut in forward and backward directions of θ_0 is shown as function of θ_0:



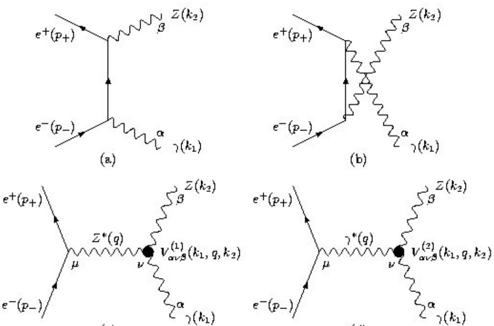
With $\sqrt{s} = 500$ GeV, $L = 500\ \mathrm{fb}^{-1}$, $P_T = 0.8$, $\bar{P}_T = 0.6$, $M = 500$ GeV, 90% CL limit on the coupling on Re V_3 is 6×10^{-3}

- This limit is dependent on the the scale parameter M chosen – it scales as M^3
- The limit is actually on the product of Re V_3 and the ZZH coupling (the latter is 1 for SM)

The process $e^+e^- \to \gamma Z$

Work done in collaboration with B. Ananthanarayan (Phys.Lett. B, JHEP)

- This process occurs in SM through t and u channel exchange of e
- New physics could produce an additional contribution from anomalous γZZ or $\gamma\gamma Z$ couplings



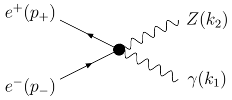
Triple-gauge couplings

- Triple-gauge couplings are given by

$$\begin{aligned}\mathscr{L} &= e\frac{\lambda_1}{2m_Z^2}F_{\mu\nu}\left(\partial^\mu Z^\lambda \partial_\lambda Z^\nu - \partial^\nu Z^\lambda \partial_\lambda Z^\mu\right) \\ &+ \frac{e}{16c_W s_W}\frac{\lambda_2}{m_Z^2}F_{\mu\nu}F^{\nu\lambda}\left(\partial^\mu Z_\lambda + \partial_\lambda Z^\mu\right),\end{aligned} \tag{1}$$

(D. Choudhury & SDR; B. Ananthanarayan, SDR, R. Singh, & A. Bartl)

- Or, through four-point $e^+e^-\gamma Z$ coupling (which includes the γZZ or $\gamma\gamma Z$ contributions)



Four-point coupling for $e^+e^- -> \gamma Z$

- Effective four-point coupling (chirality conserving) is

$$\Gamma^{CC}_{\alpha\beta} = \frac{ie^2}{4\sin\theta_W\cos\theta_W}\left\{\frac{1}{m_Z^4}\left((v_1+a_1\gamma_5)\gamma_\beta(2p_{-\alpha}(p_+\cdot k_1)-2p_{+\alpha}(p_-\cdot k_1))+\right.\right.$$
$$((v_2+a_2\gamma_5)p_{-\beta}+(v_3+a_3\gamma_5)p_{+\beta})(\gamma_\alpha 2p_-\cdot k_1-2p_{-\alpha}\not{k}_1)+$$
$$\left.((v_4+a_4\gamma_5)p_{-\beta}+(v_5+a_5\gamma_5)p_{+\beta})(\gamma_\alpha 2p_+\cdot k_1-2p_{+\alpha}\not{k}_1)\right)+$$
$$\left.\frac{1}{m_Z^2}(v_6+a_6\gamma_5)(\gamma_\alpha k_{1\beta}-\not{k}_1 g_{\alpha\beta})\right\} \tag{2}$$

- One can also write a general amplitude with chirality violating couplings
- We derive expressions for angular distributions arising from chirality conserving and chirality violating amplitudes interfering with the SM contribution
- We include longitudinal polarization or transverse polarization

Differential cross section with transverse polarization

The differential cross section for e^- and e^+ transverse polarization P_T and $\overline{P}_T$ comes out to be:

$$\left(\frac{d\sigma}{d\Omega}\right)_T = \mathscr{B}_T \left[\frac{1}{\sin^2\theta} \left(1 + \cos^2\theta + \frac{4\bar{s}}{(\bar{s}-1)^2} - P_T \overline{P}_T \frac{g_V^2 - g_A^2}{g_V^2 + g_A^2} \sin^2\theta \cos 2\phi \right) + C_T^{CC} + C_T^{CV} \right],$$

with

$$\mathscr{B}_T = \frac{\alpha^2}{16 \sin^2\theta_W m_W^2 \bar{s}} \left(1 - \frac{1}{\bar{s}}\right) (g_V^2 + g_A^2),$$

and

$$C_T^{CC} = \frac{1}{4(g_V^2 + g_A^2)} \left\{ \sum_{i=1}^{6} (g_V \mathrm{Im} v_i + g_A \mathrm{Im} a_i) X_i + P_T \overline{P}_T \sum_{i=1}^{6} ((g_V \mathrm{Im} v_i - g_A \mathrm{Im} a_i) \cos 2\phi + (g_A \mathrm{Re} v_i - g_V \mathrm{Re} a_i) \sin 2\phi) Y_i \right\},$$

Asymmetry

- We can use different azimuthal asymmetries to isolate different combinations of couplings.
- For the asymmetry A defined earlier,

$$\begin{aligned} A &= \frac{1}{\sigma}[\Delta\sigma_{\rm FB}(0<\phi<\pi/2) - \Delta\sigma_{\rm FB}(\pi/2<\phi<\pi) \\ &\quad + \Delta\sigma_{\rm FB}(\pi<\phi<3\pi/2) - \Delta\sigma_{\rm FB}(3\pi/2<\phi<2\pi)] \end{aligned}$$

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we get the expression:

$$A(\theta_0) = \mathscr{B}' P_T \bar{P}_T [g_A\{\bar{s}(\mathrm{Re}v_3 + \mathrm{Re}v_4) + 2\mathrm{Re}v_6\} - g_V\{\bar{s}(\mathrm{Re}a_3 + \mathrm{Re}a_4) + 2\mathrm{Re}a_6\}]$$

- It depends on the real parts of a combination of v_3, v_4, v_6 and a_3, a_4, a_6

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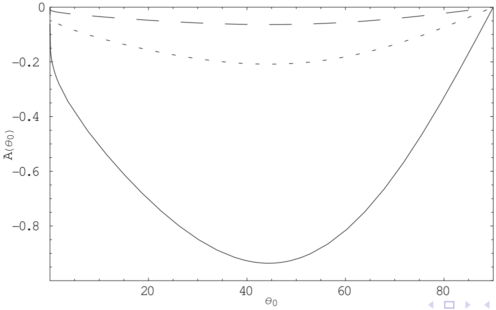

Sensitivity

We can evaluate the 90% CL limits on combinations of couplings corresponding to each asymmetry assuming the parameters

$$\sqrt{s} = 500\,\mathrm{GeV},\, P_T = 0.8,\, \bar{P}_T = 0.6,\, \int \mathscr{L} = 500\,\mathrm{fb}^{-1}$$

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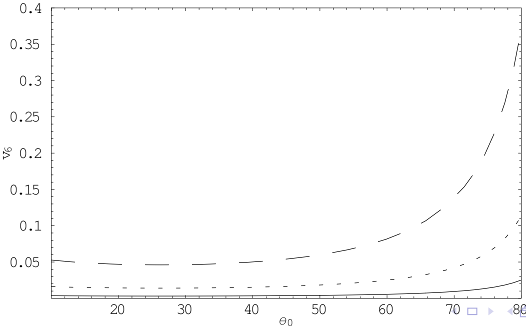
Example:



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A_1			A_2		
Re v_3	Re v_4	Re v_6	Im v_3	Im v_4	Im v_6
$2.1 \cdot 10^{-4}$	$2.1 \cdot 10^{-4}$	$3.1 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$	$4.6 \cdot 10^{-2}$
Re a_3	Re a_4	Re a_6	Im a_3	Im a_3	Im a_6
$3.1 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$	$4.6 \cdot 10^{-2}$	$2.1 \cdot 10^{-4}$	$2.1 \cdot 10^{-4}$	$3.1 \cdot 10^{-3}$

Table: Sensitivities for the asymmetries A_1 and A_2.

Summary

- General expressions using only Lorentz invariance were obtained for the processes $e^+e^- \to HZ$ and $e^+e^- \to \gamma Z$ (assuming chirality conserving and chirality violating couplings to e^+e^-)
- The corresponding angular dependences were obtained to linear order in new couplings for arbitrary longitudinal and transverse beam polarizations
- Asymmetries which isolate different θ and ϕ combinations in the diff.c.s. were calculated
- A CP-odd CPT-even asymmetry was found which needs e^+ and e^- transverse polarizations
- In the HZ case, this is present only when four-point e^+e^-HZ coupling is considered
- Limits of order 10^{-3} can be obtained on the dimensionless couplings at ILC