CP violation at a linear collider with transverse polarization

December 16, 2003

Saurabh D. Rindani

Physical Research Laboratory
Ahmedabad

Introduction

- Longitudinal polarized beams expected to be available at linear collider

Introduction

- Longitudinal polarized beams expected to be available at linear collider
- Likely degrees of polarization: 80% for e^- and 60% for e^+

Introduction

- Longitudinal polarized beams expected to be available at linear collider
- Likely degrees of polarization: 80% for e^- and 60% for e^+
- Spin rotators can convert longitudinal polarization to transverse polarization

Introduction

- Longitudinal polarized beams expected to be available at linear collider
- Likely degrees of polarization: 80% for e^- and 60% for e^+
- Spin rotators can convert longitudinal polarization to transverse polarization
- Can transverse polarization be used to get different information as compared to longitudinal polarization?

Work done in collaboration with B. Ananthanarayan

Transverse polarization

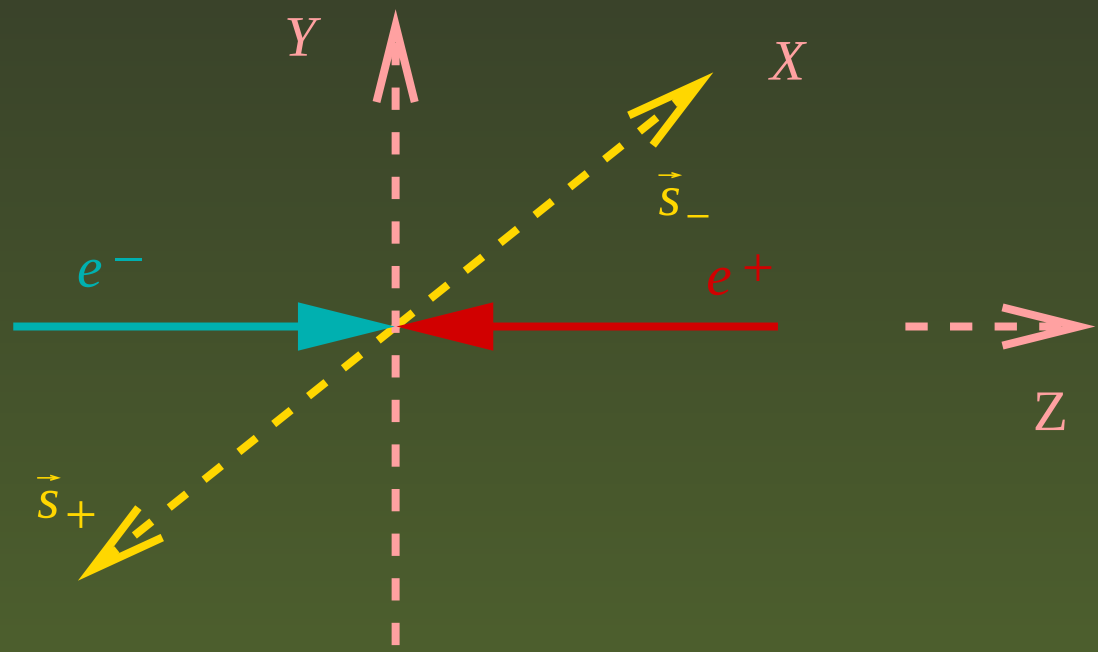
- Transverse polarization breaks rotational symmetry of the initial state

Transverse polarization

- Transverse polarization breaks rotational symmetry of the initial state
- It thus permits the definition of an azimuthal angle

Transverse polarization

- Transverse polarization breaks rotational symmetry of the initial state
- It thus permits the definition of an azimuthal angle



CP violation

- Studying CP violation in $e^+e^- \to f\bar{f}$ needs

CP violation

- Studying CP violation in $e^+e^- \to f\bar{f}$ needs
  - either polarized e^+ and/or e^- beams

CP violation

- Studying CP violation in $e^+e^- \longrightarrow f\bar{f}$ needs
  - either polarized e^+ and/or e^- beams
  - or measurement of polarization of f and/or $\bar{f}$

CP violation

- Studying CP violation in $e^+e^- \longrightarrow f\bar{f}$ needs
  - either polarized e^+ and/or e^- beams
  - or measurement of polarization of f and/or $\bar{f}$
- Without final-state spin measurement, only scalar is $\vec{p_e} \cdot \vec{p_f}$, which is CP even

CP violation

- Studying CP violation in $e^+e^- \longrightarrow f\bar{f}$ needs
  - either polarized e^+ and/or e^- beams
  - or measurement of polarization of f and/or $\bar{f}$
- Without final-state spin measurement, only scalar is $\vec{p}_e \cdot \vec{p}_f$, which is CP even
- With transverse polarization, one can construct CP-odd triple products like $\vec{p}_e \times \vec{s}_e \cdot \vec{p}_f$

ϕ distribution and chiral invariance

For e^- and e^+ transverse polarizations parallel or antiparallel, Hikasa (1986) obtained the azimuthal distribution:

$$
\begin{aligned}
|\overline{\mathcal{M}}|^2 &= \frac{1}{4}(|T_{++}|^2 + |T_{--}|^2 + |T_{+-}|^2 + |T_{-+}|^2) \\
&+ (2P_T P_T')[\mathrm{Re}\left(e^{-2i\phi} T_{+-} T_{-+}^* + T_{++}^* T_{--}\right)] \\
&+ P_T\,\mathrm{Re}\left(e^{-i\phi}[T_{+-}^* T_{--} + T_{++}^* T_{-+}]\right) \\
&+ P_T'\,\mathrm{Re}\left(e^{-i\phi}[T_{+-}^* T_{++} + T_{--}^* T_{-+}]\right)
\end{aligned}
$$

- $T_{++} = 0, T_{--} = 0 \implies$ chiral invariance
- No $\sin\phi$ and $\cos\phi$ terms (only $\sin 2\phi$ and $\cos 2\phi$)
- Asymmetry under $\phi \to \pi + \phi$ will reveal chirality violation

Transverse polarization for chirality violation

- Azimuthal asymmetry of $\sin\phi$ and $\cos\phi$ terms can be used to study interference between chiral invariant and non-invariant terms

Transverse polarization for chirality violation

- Azimuthal asymmetry of $\sin\phi$ and $\cos\phi$ terms can be used to study interference between chiral invariant and non-invariant terms
- In particular, we can study interference terms between SM amplitude and amplitude with new chirality violating interactions

Transverse polarization for chirality violation

- Azimuthal asymmetry of $\sin\phi$ and $\cos\phi$ terms can be used to study interference between chiral invariant and non-invariant terms
- In particular, we can study interference terms between SM amplitude and amplitude with new chirality violating interactions
- These interference terms are absent with longitudinal polarization (or no polarization) – This is where transverse polarization helps!

Transverse polarization for chirality violation

- Azimuthal asymmetry of $\sin\phi$ and $\cos\phi$ terms can be used to study interference between chiral invariant and non-invariant terms
- In particular, we can study interference terms between SM amplitude and amplitude with new chirality violating interactions
- These interference terms are absent with longitudinal polarization (or no polarization) – This is where transverse polarization helps!
- Polarization of both e^- and e^+ not necessary

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

- Top quark interesting because it is heavy
- Top polarization can be measured because it decays before hadronization
- Model independent Lagrangian for new physics:

$$\mathcal{L} = \mathcal{L}^{SM} + \frac{1}{\Lambda^2}\sum_i (\ \alpha_i \mathcal{O}_i + \text{h.c.}\ ),$$

The second term can be rewritten using Fierz transf.:

$$\begin{aligned}
\mathcal{L}^{4F} &= \sum_{i,j=L,R}\Big[S_{ij}(\bar{e}P_i e)(\bar{t}P_j t) \\
&+ V_{ij}(\bar{e}\gamma_\mu P_i e)(\bar{t}\gamma^\mu P_j t) \\
&+ \frac{1}{2}T_{ij}(\bar{e}\sigma_{\mu\nu}P_i e)(\bar{t}\sigma^{\mu\nu}P_j t)\Big]
\end{aligned}$$

Top angular distribution

- S and T terms do not interfere with SM contribution

Top angular distribution

- S and T terms do not interfere with SM contribution
- V term does not contribute to CP violation

Top angular distribution

- S and T terms do not interfere with SM contribution
- V term does not contribute to CP violation
- Differential cross section including S and T terms:

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

Top angular distribution

- S and T terms do not interfere with SM contribution
- V term does not contribute to CP violation
- Differential cross section including S and T terms:

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

- The extra term above is even under CP

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

Top angular distribution

- S and T terms do not interfere with SM contribution
- V term does not contribute to CP violation
- Differential cross section including S and T terms:

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

- The extra term above is even under CP

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

- The extra term above is odd under CP, because

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

CP-odd asymmetry

- We can define a CP-odd asymmetry:

$$A(\theta) = \frac{\displaystyle\int_0^{\pi} \frac{d\sigma^{+-}}{d\Omega} d\phi - \int_{\pi}^{2\pi} \frac{d\sigma^{+-}}{d\Omega} d\phi}{\displaystyle\int_0^{\pi} \frac{d\sigma^{+-}}{d\Omega} d\phi + \int_{\pi}^{2\pi} \frac{d\sigma^{+-}}{d\Omega} d\phi}$$

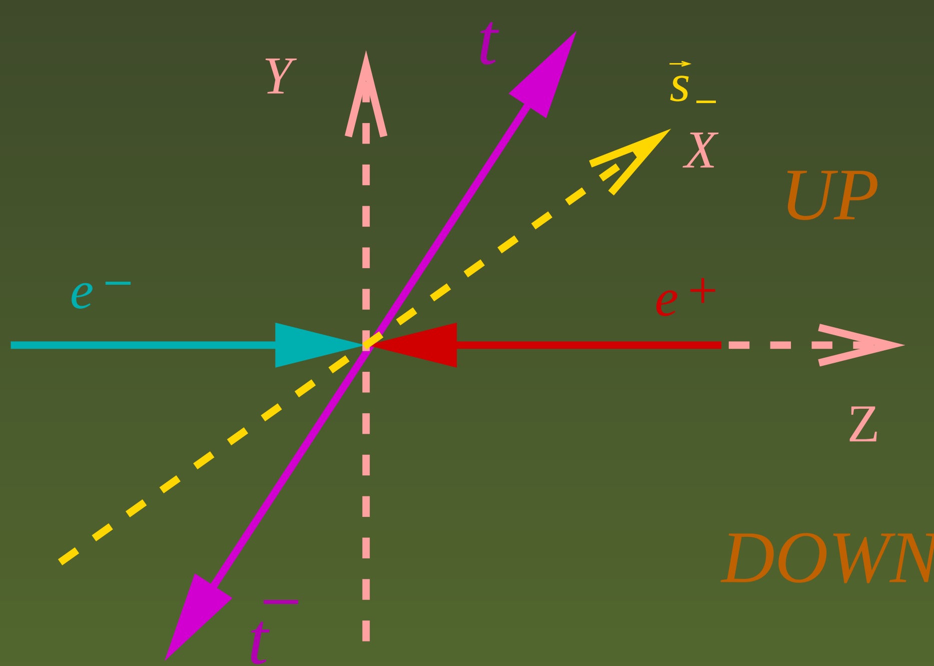
- The corresponding integrated version is:

$$A(\theta_0) = \frac{\displaystyle\int_{-\cos\theta_0}^{\cos\theta_0} d\cos\theta \left(\int_0^{\pi} \frac{d\sigma^{+-}}{d\Omega} d\phi - \int_{\pi}^{2\pi} \frac{d\sigma^{+-}}{d\Omega} d\phi \right)}{\displaystyle\int_{-\cos\theta_0}^{\cos\theta_0} d\cos\theta \left(\int_0^{\pi} \frac{d\sigma^{+-}}{d\Omega} d\phi + \int_{\pi}^{2\pi} \frac{d\sigma^{+-}}{d\Omega} d\phi \right)}$$

Up-down asymmetry

The CP-odd asymmetry can be thought of as an UP-DOWN asymmetry.

UP: Top quark produced above the xz plane
DOWN: Top quark produced below the xz plane

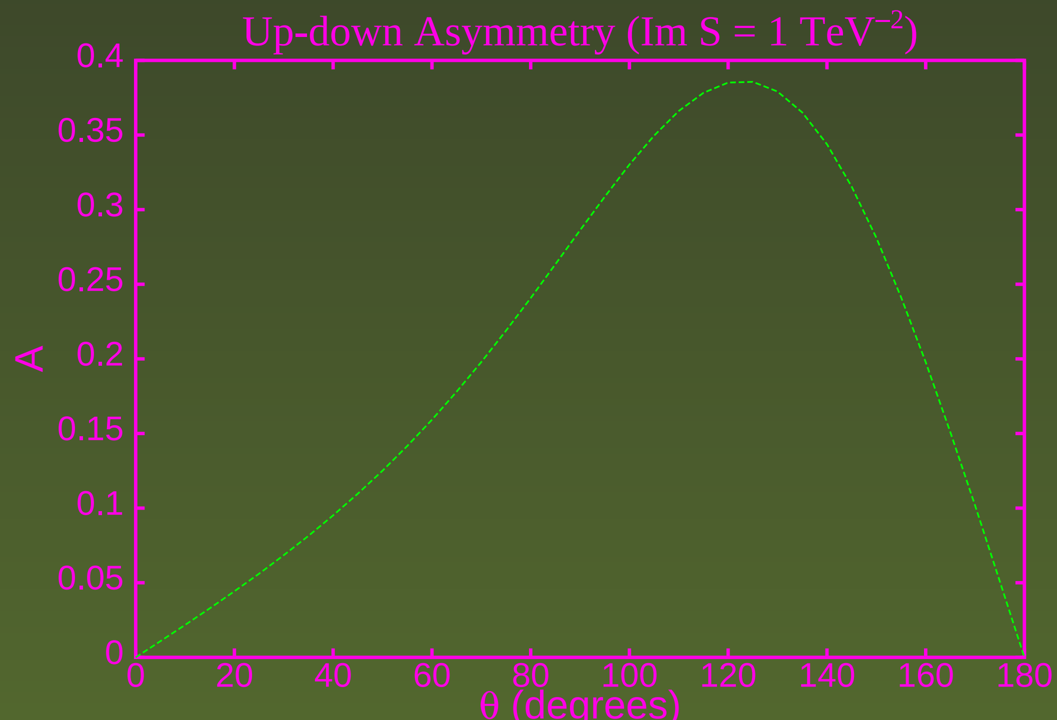


Asymmetry – Numerical values

- The asymmetry is proportional to the imaginary part of the combination:

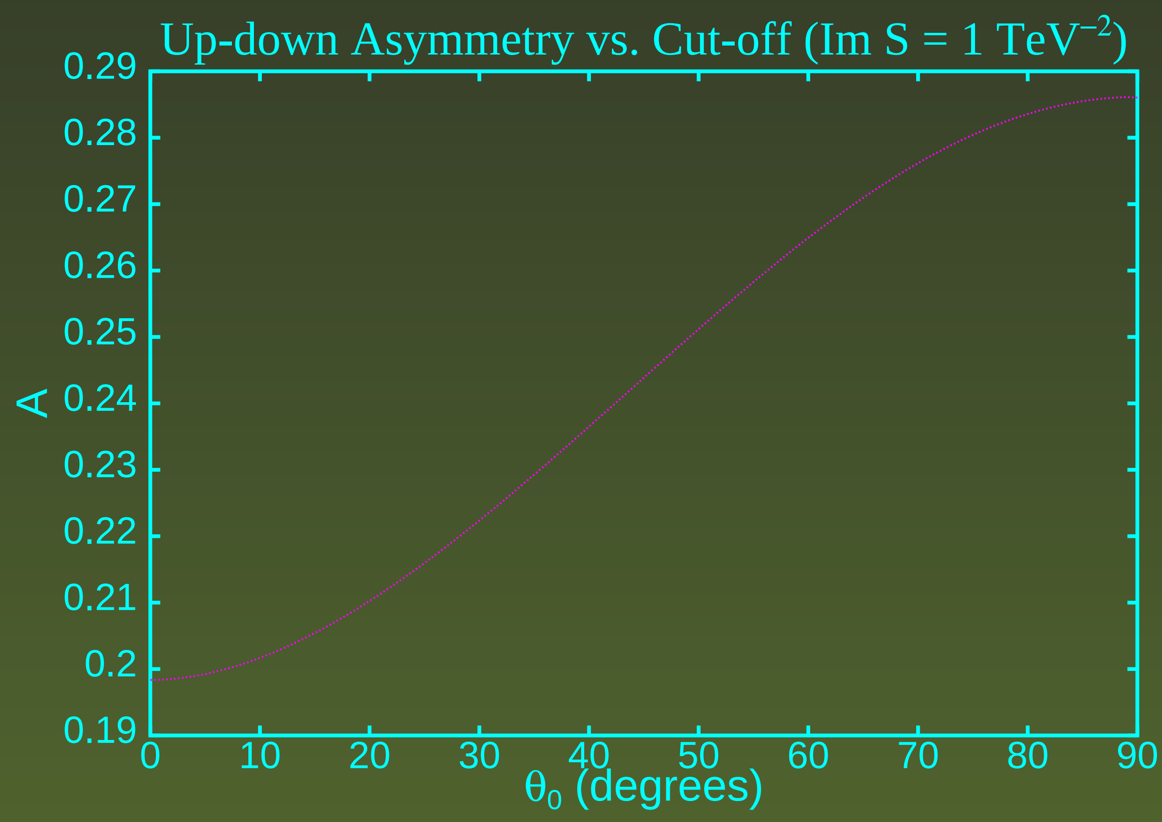
$$S \equiv S_{RR} + \frac{2c_A^t c_V^e}{c_V^t c_A^e} T_{RR},$$

We show results for $\mathrm{Im}S = 1\ \mathrm{TeV}^{-2}$



Integrated asymmetry – Numerical values

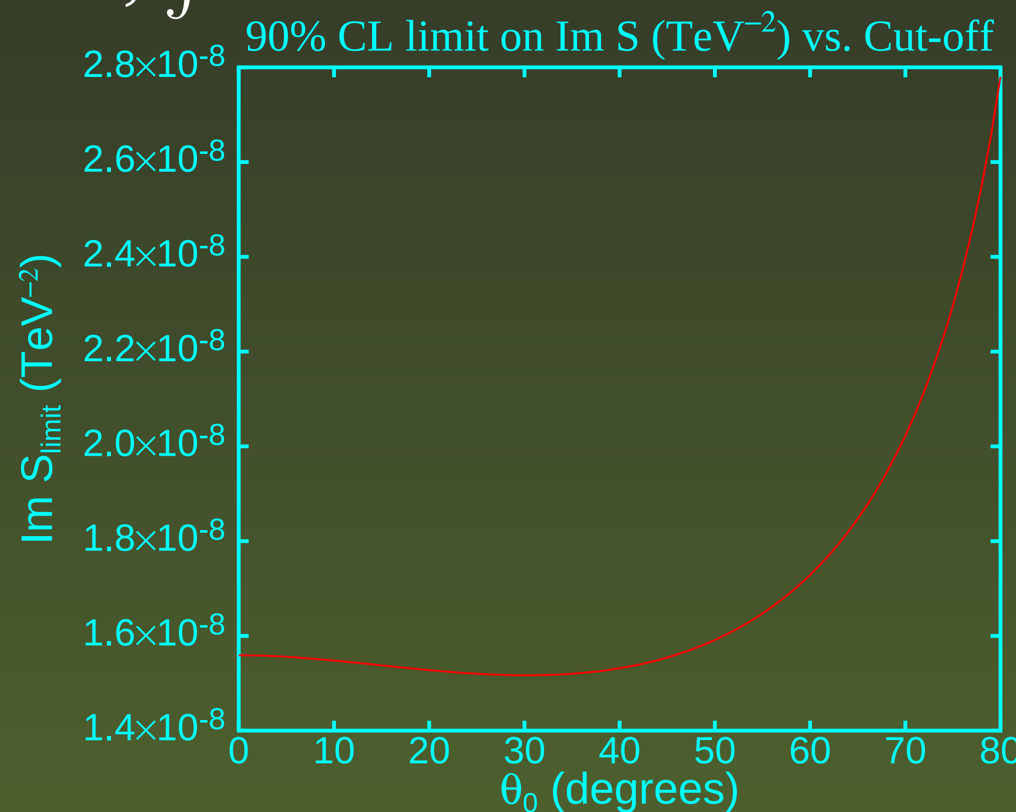
- The integrated asymmetry $A(\theta_0)$ as a function of the cut-off angle θ_0:



Limits on Im S

The 90% C.L. limit on ImS is shown for the choice:

- $\sqrt{s} = 500$ GeV, $\int \mathcal{L}dt = 500$ fb^{-1}



- Assuming couplings $\mathcal{O}(1)$, limit is $\Lambda \approx 8$ TeV

Realistic polarization

So far both e^- and e^+ assumed to have 100% polarization.

- More realistic: 80% for e^- and 60% for e^+

Realistic polarization

So far both e^- and e^+ assumed to have 100% polarization.

- More realistic: 80% for e^- and 60% for e^+
- Our asymmetry gets multiplied by a factor

$$\frac{1}{2}(P_{e^-} - P_{e^+})$$

for realistic polarizations

Realistic polarization

So far both e^- and e^+ assumed to have 100% polarization.

- More realistic: 80% for e^- and 60% for e^+
- Our asymmetry gets multiplied by a factor

$$\frac{1}{2}(P_{e^-} - P_{e^+})$$

  for realistic polarizations
- Asymmetry reduces by a factor 0.7

Realistic polarization

So far both e^- and e^+ assumed to have 100% polarization.

- More realistic: 80% for e^- and 60% for e^+
- Our asymmetry gets multiplied by a factor
$$\frac{1}{2}(P_{e^-} - P_{e^+})$$
for realistic polarizations
- Asymmetry reduces by a factor 0.7
- Limit on Λ decreases to about 6.7 TeV

Realistic polarization

So far both e^- and e^+ assumed to have 100% polarization.

- More realistic: 80% for e^- and 60% for e^+
- Our asymmetry gets multiplied by a factor
$$\frac{1}{2}(P_{e^-} - P_{e^+})$$
for realistic polarizations
- Asymmetry reduces by a factor 0.7
- Limit on Λ decreases to about 6.7 TeV
- For $P_{e^-} = .8$ and $P_{e^+} = 0$, the limit decreases to about 5 TeV

Summary

- Transverse polarization can be used to study interference of (S, P) or T type couplings with SM contribution
  (Not possible with longitudinal polarization)

Summary

- Transverse polarization can be used to study interference of (S, P) or T type couplings with SM contribution
(Not possible with longitudinal polarization)
- Transverse polarization cannot give CP-odd asymmetries when e^+e^-Z' vertex is (V, A), even if $Z't\bar{t}$ vertex is CP violating

Summary

- Transverse polarization can be used to study interference of (S, P) or T type couplings with SM contribution
(Not possible with longitudinal polarization)
- Transverse polarization cannot give CP-odd asymmetries when e^+e^-Z' vertex is (V, A), even if $Z't\bar{t}$ vertex is CP violating
- For the case of transverse polarization

$$\vec{s}_{e^-} = -\vec{s}_{e^+},$$

CP-odd asymmetry $\sin\phi \longrightarrow -\sin\phi$ can be used to limit new (S, P) or T interactions.

Summary (continued)

- In case of (S, P) intereactions, limits that can be put are:

$$|\text{Im } S| < 1.3 \times 10^{-8} \text{ GeV}^{-1}$$

$$\Lambda < 8 \text{ TeV}$$

for $\sqrt{s} = 500$ GeV and $\int \mathcal{L} dt = 500 \text{fb}^{-1}$, assuming 100% polarization.

Summary (continued)

- In case of (S, P) intereactions, limits that can be put are:

$$|\mathrm{Im}\ S| < 1.3 \times 10^{-8}\ \mathrm{GeV}^{-1}$$

$$\Lambda < 8\ \mathrm{TeV}$$

for $\sqrt{s} = 500$ GeV and $\int \mathcal{L}dt = 500\mathrm{fb}^{-1}$, assuming 100% polarization.

- The limits are fairly insensitive to the cut-off θ_0

Summary (continued)

- In case of (S, P) intereactions, limits that can be put are:

$$|\mathrm{Im}\ S| < 1.3 \times 10^{-8}\ \mathrm{GeV}^{-1}$$

$$\Lambda < 8\ \mathrm{TeV}$$

  for $\sqrt{s} = 500$ GeV and $\int \mathcal{L} dt = 500 \mathrm{fb}^{-1}$, assuming 100% polarization.
- The limits are fairly insensitive to the cut-off θ_0
- The limit improves for larger $\sqrt{s}$

Summary (continued)

- In case of (S, P) intereactions, limits that can be put are:

$$|\mathrm{Im}\ S| < 1.3 \times 10^{-8}\ \mathrm{GeV}^{-1}$$

$$\Lambda < 8\ \mathrm{TeV}$$

  for $\sqrt{s} = 500$ GeV and $\int \mathcal{L} dt = 500 \mathrm{fb}^{-1}$, assuming 100% polarization.
- The limits are fairly insensitive to the cut-off θ_0
- The limit improves for larger $\sqrt{s}$
- Such CP violation could arise in many models like 2HDM, SUSY, etc. However, comparison not easy, as effective Lagrangians not available.