Use of Polarisation at the ILC.

- ♢ Introduction.
- ♢ Three points

  i Use of beam polarisation :

  1. Longitudinal beam polarisation.
  2. Transverse beam polarisation.

  ii Measurement of longitudinal polarisation of final state particles.

Take some examples: How to probe open issues in the SM as well as to probe physics Beyond the SM Physics. (**influenced by current LHC results**)

1) TDR's: TESLA, JLC, NLC

2)G. Moortgat-Pick et al, Phys. Reports, 460 (2008) 131-243.

3) ILC : RDR, Physics at the ILC: A. Djouadi, J. lykken et al 0709.1893 [hep-ph].

The second reference specifically highlights that to get most advantage of an e^+e^- collider it is necessary to polarise **both** the beams.

In this talk I would like to focus

1)How positron beam polarisation helps.

2) How measurement of (longitudinal) polarisation of ferrmions produced in the final state can help probe Physics of the SM and Beyond.

3) Use of **Transverse** polarisation in model independent investigations.

When talking specifically I have stolen plots from the following people:

1) $t\bar{t}$ production J.G. Koerner and S.Groote et al., PRD 83, 054018 (2011).

2) $t\bar{t}H$: P.P.S. Bhupal Dev et al, PRL. 100, 051801 (2008), C. Hangst et al, EPJC 71:1681 (2011)

3) Model independent analysis of Contact Interactions involving $t\bar{t}$, Z, γ :

S. D. Rindani , Phys. Lett. B 602, 97 (2004), S.D. Rindani, B. Ananthnarayan, M. Patra, P. Sharma, Kumar in difft. combinations:. PLB 593, 95 (2004), PRD 70, 036005 (2004),PLB 606, 107 (2005),JHEP 0510, 077 (2005), Eur. Phys. J. C 46 705, (2006), PRD83, 016010 (2011).

4)Model independent analyses of ZZH/WWH coupling, contact interactions involving $eeZH$:

S. D. Rindani et al, PL B642, 85 (2006), PRD 77, 015009 (2008), PRD 79, 075007 (2009); Biswal et al, PRD 73, 035001 (2006), PRD 79, 035012 (2009), PLB 680 (2009) 81, PLB 693, 134 (2010); Hagiwara, Dutta PRD 78 115016 (2008),Rindani, Sumit Garg, Ananthanarayan et al, PRD85, 034006 (2012).

5)Specific BSM physics: SUSY: MSSM, R-parity violating and CP violating SUSY, TeV Scale Gravity, Z',strongly interacting W:

T. Rizzo JHEP 0302, 008 (2003), JHEP 0308, 051 (2003); S.D. Rindani et al, PLB 678 , 395, 2009; T. Gajdosik et al JHEP 0409, 051 (2004); L. Cabbibi et al, arXiv:0710.0726 [hep-ph], B.Ananthanarayan,M. Patra et al, JHEP 1102, 043 (2011), B. Ananthanarayan, M. Patra, P.Poulose, JHEP 1203 (2012) 060

6)A review T. Rizzo: SLAC-PUB/14280

Top studies: t polarisation (transverse and longitudinal) of the t and EW couplings: Calculation at NLO (QCD): J.G. Koerner and S.Groote et al.

If light higgs hints are confirmed:

Use of beam polarisation and measurement of t polarisation in study of $t\bar{t}H$ coupling (for a light higgs). A. Djouadi et al, Hangst et al

Use of longitudinal and transverse beam polarisation for determination of VVH vertex with $V = W/Z$ (for a light higgs) Biswal et al, Rindani et al

If the light SM Higgs signal is not confirmed:

Use of polarisation for strongly interacting WW sector. B. Ananthanarayan, M. Patra, P.Poulose

Apologies to Oscar Wilde!

Beam Polarisation:

SM: Chiral theory. Clear that beam polarisation can play an important role.

Recall:

Polarised DIS gave a measurement of $\sin^2\theta_W$ which was competitive with higher energy ν experiments.

SLC got a competitive measurement of $\sin^2\theta_W$ with LEP, but with much lower luminosity.

Recall from LEP/SLC days:

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4} A_e A_f$$

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \frac{1}{\langle |P_e| \rangle} = A_e$$

$$A_{LRFB} = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F - \sigma_B)_L + (\sigma_F - \sigma_B)_R} \frac{1}{\langle |P_e| \rangle} = \frac{3}{4} A_f$$

Here, $\langle |P_e| \rangle$ is the luminosity weighted electron beam polarisation.

In addition, one can also measure final state τ polarisation.

$$\langle P_\tau^0 \rangle = -A_\tau$$

SLC: 383500 Z's, $\sin^2\theta_W$ determined mainly from A_{LR}, A_{FB}^{LR}. Not affected by uncertainities in the Luminosities, efficiency etc, but affected by errors in knowledge of polarisation.

LEP: Millions of Z's. Much larger than SLC.

But SLC accuracy comparable to LEP for $\sin^2\theta_W$.

Thus one simple use of beam polarisation:

Increase the senstivity of a measurement with given luminosity OR decrease the luminosity required for a given level senstivity.

Questions:

What is the gain if the positron beam too is polarised?

What are the special advantages with transverse beam polarisation?

What extra does measurement of final state fermion (longitudinal) polarisation bring to the studies?

Two kinds of questions can be asked

1)How does polarisation help precision measurement of the SM vertices

2)How polarisation helps in probing a particular aspect of a specific type of BSM idea.

A common framework to analyse both in a model independent way now that we seem to **not** find any of our preferred BSM physics.

Anologous to the analysis of Ross,Dass Phys. Lett. B 57,173,1975; Nucl. Phys. B 118, 284 (1977), which was for probing the then undiscovered neutral currents.

Consider the process:

$$e^{+} + e^{-} \rightarrow X$$

Helicity amplitude $F(\lambda_{e^-}, \lambda_{e^+}) \propto v(p_{e^+}, \lambda_{e^+}) \Gamma_K u(p_{e^-}, \lambda_{e^-}) A_K$

Here $\Gamma_K = S, P, T, V$ and A_K is the transition amplitude which will depend on the particular final state X.

λ indicates the helicities. This describes all possible contributions (SM and beyond the SM).

In the high energy limit V,A couple opposite helicity states and S,T,P couple same helicity states.

Polarisation of the beams:

The general $\mathcal{M}^2$ can be written as a polynomial in $P^i_{e^\pm}$, the various coeffecients being combinations of different helicity amplitudes and cosine and sine of combinations of the azimuthal angle of the different polarisation vectors.

The $P^i_{e^\pm}$ are different components of the $e^\pm$ polarisation vectors. $P_{e^\pm} = P^3_{e^\pm}$ is the longitudinal degreee of polarisation, with positive (negative) values corresponding to right(left) handed polarisation;

$P^{1(2)}_{e^\pm}$ being transverse polarisation in and normal to the scattering plane.

Example: Terms bilinear in $P^T_{e^\pm}$:

$$-2P^{\mathrm{T}}_{e^-}P^{\mathrm{T}}_{e^+}[\cos(\phi_- - \phi_+)\Re(F_{\mathrm{RR}}F^*_{\mathrm{LL}}) + \cos(\phi_- + \phi_+ - 2\phi)\Re(F_{\mathrm{LR}}F^*_{\mathrm{RL}})]$$

etc.

Few facts:

The dynamics will decide F_{RL} etc. These contain dependence on scattering angles $\theta_i, \sqrt{s}$ etc.

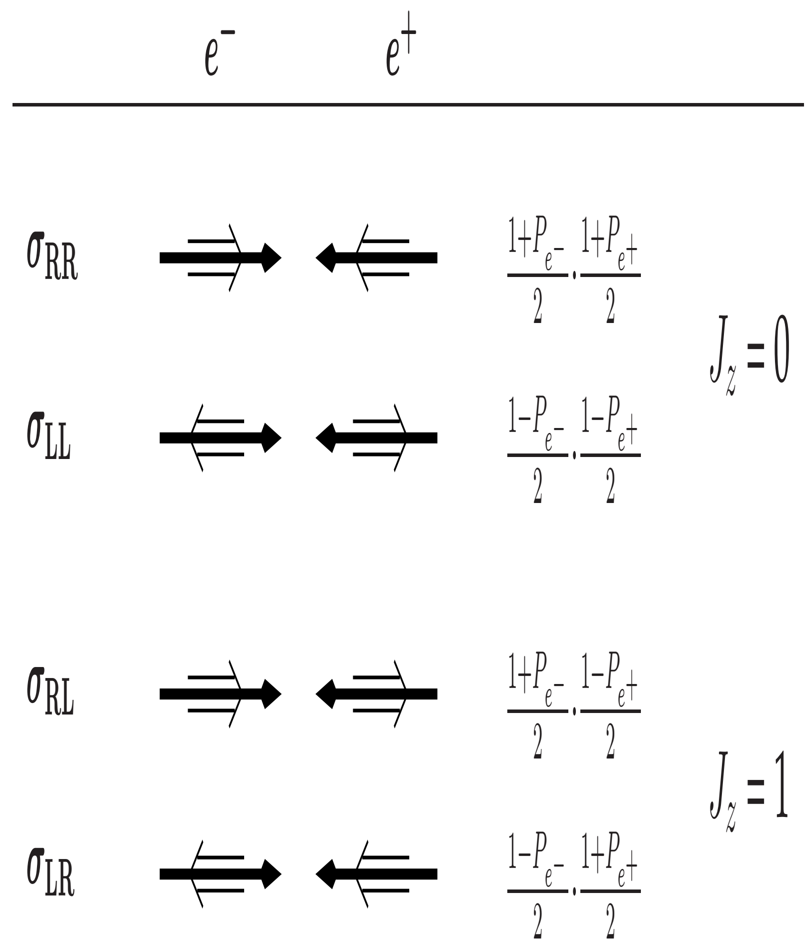
The contributions for different helicity configurations add up incoherently for longitudinally polarised beams.

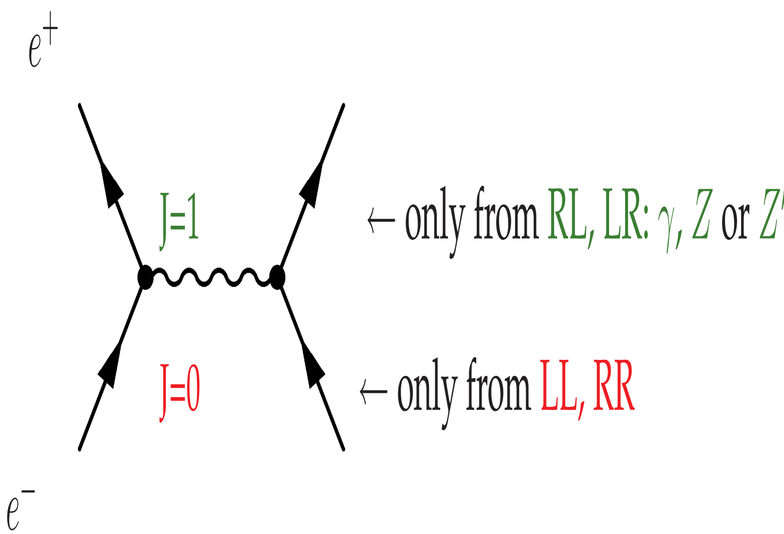
Transversely polarised beams generate interference terms between left and right helicity amplitudes.

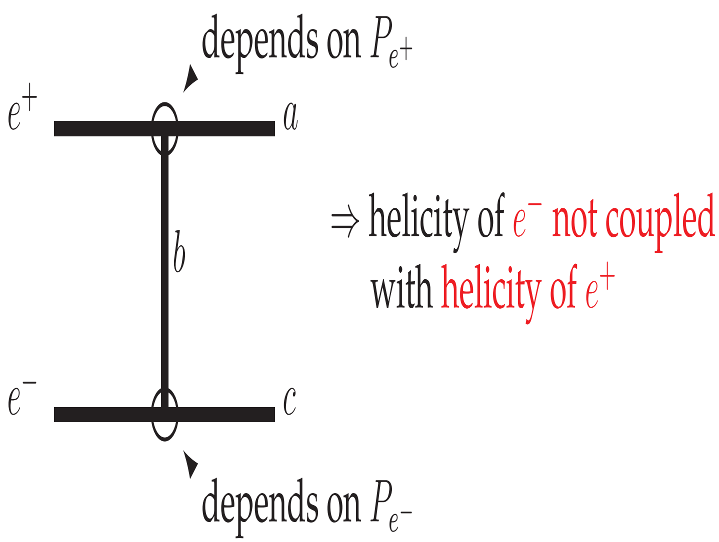
For longitudinally polarised beams alone:

$$\sigma(P_{e^-}P_{e^+}) = \frac{1}{4}[(1+P_{e^-})(1+P_{e^+})\sigma_{\mathrm{RR}} + (1-P_{e^-})(1-P_{e^+})\sigma_{\mathrm{LL}} + (1+P_{e^-})(1-P_{e^+})\sigma_{\mathrm{RL}} + (1-P_{e^-})(1+P_{e^+})\sigma_{\mathrm{LR}}],$$

where σ_{RR} etc. correspond to the completely polarised cross-sections and correspond to different configurations:







Whether polarisation of **both** beams will make any value addition will be decided by the dynamics we are trying to explore.

Different cases can be distinguished

For s-channel contribution the helcities of the two beams are coupled.

In the t channel case the helicities of the incoming beams are linked to the helicities of the final state particles.

These diagrams shows how by choosing the beam polarisations properly a particular background can be suppressed.

Also how final state particle polarisation can carry information on the dynamics

One can see from these expressions how (for example) the gain in sensitivity of probing a dynamics which will give rise to A_{LR}, with both beams polarised.

For an annihilation into a $J = 1$ particle only LR/RL will contribute

$$\sigma(P_{e^-} P_{e^+}) = \sigma_0 \left(1 - P_{e^+} P_{e^-}\right) \quad [1 - P_{\text{eff}}\, A_{\text{LR}}] \tag{1}$$

with $\sigma_0 = \frac{\sigma_{\text{RL}} + \sigma_{\text{LR}}}{4}$,A_{LR} the asymmetry, with $P_{\text{eff}} = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^+} P_{e^-}}$

Choose P_{e^-} and P_{e^+} with opposite signs. Cross-sections enhanced. Effective polarisation large, even if individual e^-/e^+ polarisations are small.

Hikasa: Phys. Lett. B 143 (1984) 266, PRD 33 (1986) 3203

For V/A couplings the amplitudes F_{RR} and F_{LL} are suppressed by m_e and thus zero.

Hence effect of transverse polarisation in this case vanishes after averaging over azimuthal angle.

Thus in this situation transverse polarisation can not give any extra information.

But if the new dynamics involves helicity changing amplitudes, then for arbitrary longitudinal polarisations there is no interference between the SM amplitudes (which conserve helicity) and the NP contribution which flip it.

In this case the new physics contributions are proportional to the square of the NP coupling.

With Transverse polarisation these interference terms are non zero and sensitivity to new couplings is then linear.

Clearly in such cases transverse polarisation can add to sensitivity of new physics, compared to the unpolarised and/or longitudinally polarised case.

Why study τ /(t) polarisation?

• Large mass of the top $\Rightarrow$ t decays before hadronisation. The decay l can retain the memory of the t polarisation and can be used as a polariometer.

I. Bigi and H. Krasemann, ZPC 7 (1981) 127 ; J. Kühn, Acta Phys. Austr. Suppl. XXIV (1982) 203; I. Bigi *et al.*, PLB 181 (1986) 157, for a recent review: S.D. Rindani, [hep-ph/0105318].

• The angular distribution of the decay l is unaffected by any non-standard contribution to the t decay vertex, to linear order in the anomalous coupling

B. Grzadkowski and Z. Hioki, PLB **476** (2000) 87; Z. Hioki, hep-ph/0104105,S.D. Rindani, Pramana **54** (2000) 791, K. Ohkuma, NP.Proc.Suppl. **111** (2002) 285, (hep-ph/0202126), R.G, S.D. Rindani and R. K. Singh, PRD **67** (2003) 095009

• τ has hadronic decay modes. The energy distribution of the π produced in the decay, $\tau \rightarrow \nu_\tau \pi$ as well as those in $\tau \rightarrow \rho\nu_\tau, \tau \rightarrow a_1\nu_\tau$ depends on the handedness of the τ. Thus τ polarisation can be determined using decay π energy distribution. K. Hagiwara, A.D. Martin and D. Zeppenfeld, PLB **235** 198 (1990), B.K.Bullock, K.Hagiwara and A.D.Martin, PRL **67**, 3055 (1991), NPB **395**, 499 (1993), D.P.Roy, PLB **277**, 183 (1992). D.P. Roy, RG, PLB **B 618** , 193, 2005.

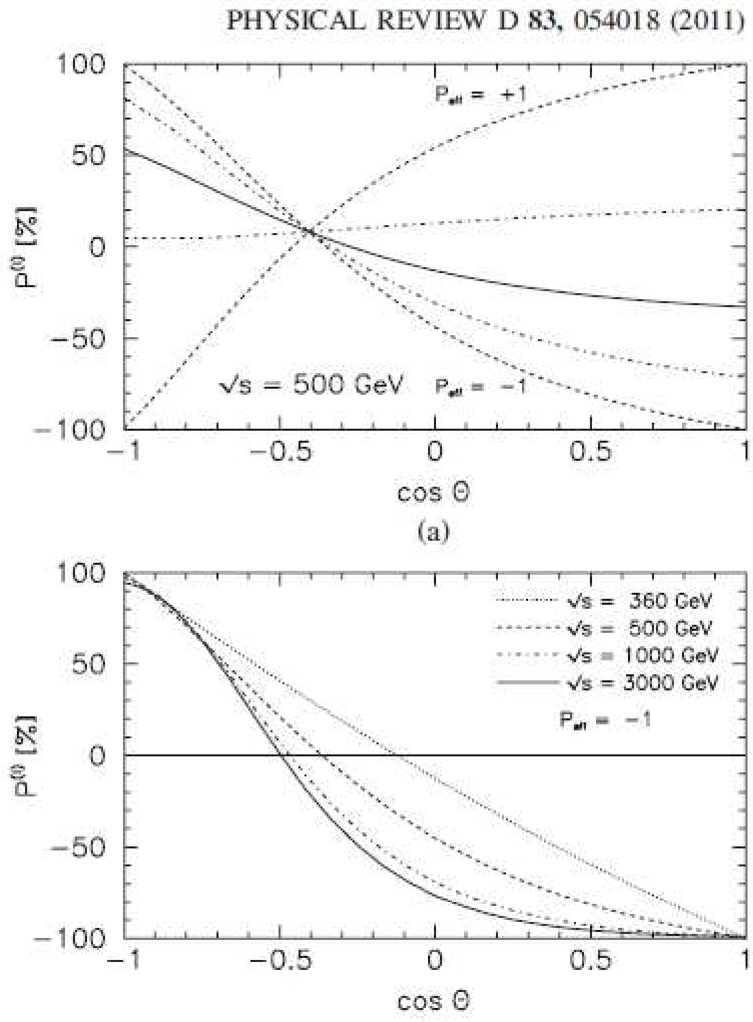
Why is it important to measure this polarisation?

• Third generation sfermions expected to be among the lightest. $\tilde{\tau}$ is even the NLSP in many situations. Polarisation of the decay fermions can carry information on SUSY model parameters, sfermion or chargino/neutralino composition, since the polarisation of decay fermion decided by the L–R mixing amoing the sfermions as well as the higgsino/gaugino mixing in the $\tilde{\chi}^0/\tilde{\chi}^{\pm}$ sector. Third generation sfermions ⇒ third generation fermions among the decay products. t, τ among them.

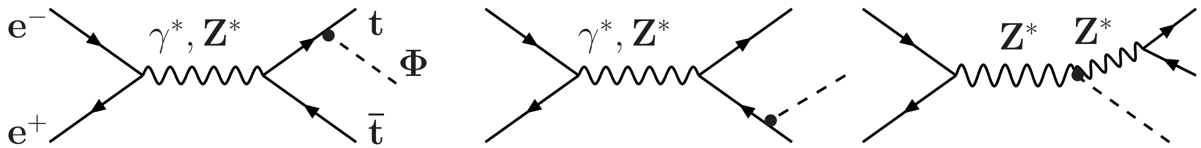
♢ Thus t and τ polarisation can carry important information on different types of new physics AND can also be measured.

Fermion polarisation measurement much easier at the leptonic colliders than at the hadronic colliders. Both the sensitivity to the effects giving rise to net polarisation and precision of the measurement is higher for the LC.

J.Koerner , D. Groote et al, PRD83, 2011 NLO QCD calculation of the top polarisation, its dependence on the initial beam poalrisation, energy and scattering angle



$t\bar{t}H$: P.P.S. Bhupal Dev et al, PRL 100, 051801 (2008), Hangst et al, EPJC71, 1681 (2011).



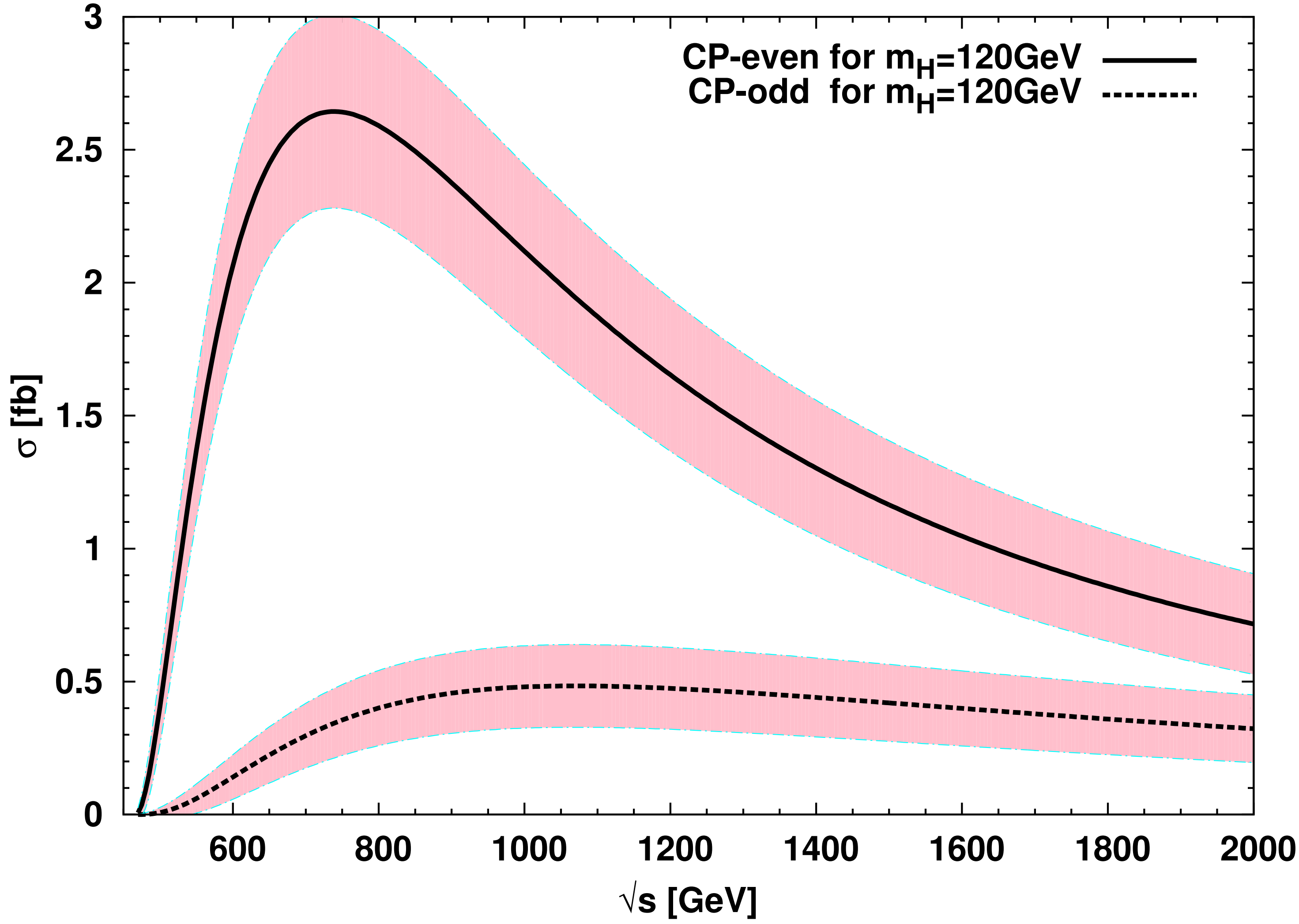
The parity violating nature of the Z coupling means $t/\bar{t}$ can have nonzero polarisation and it will be different from H/A.

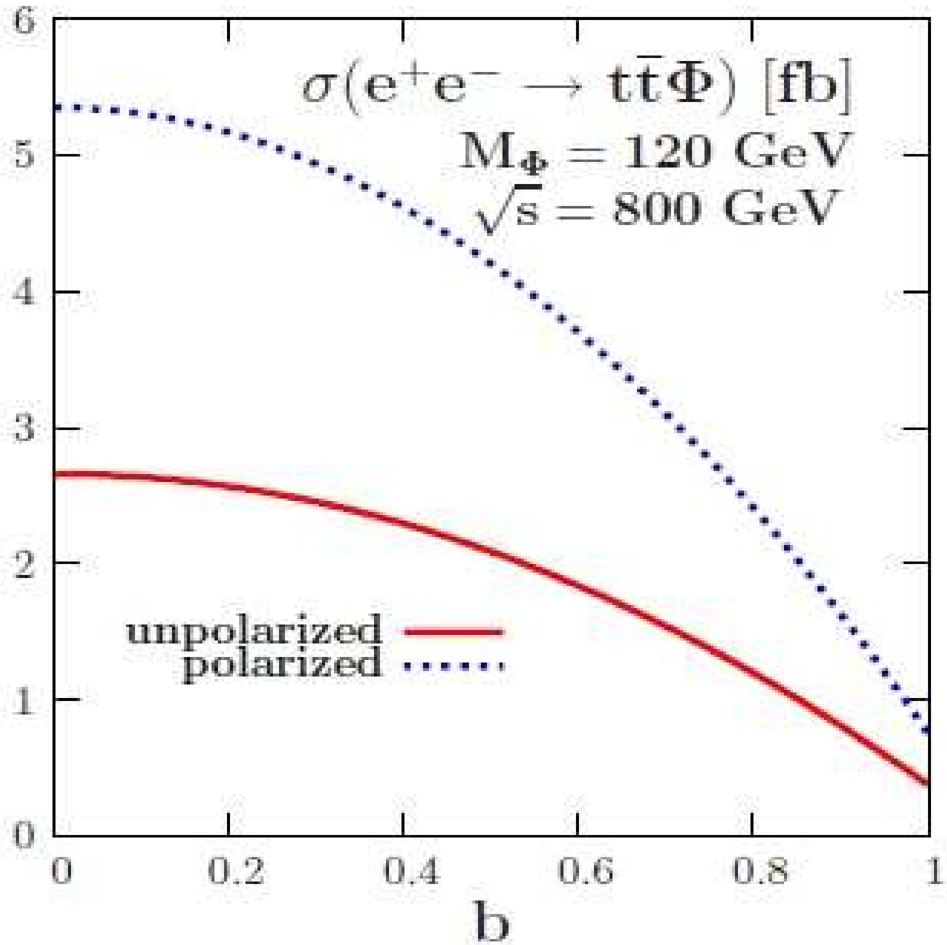
The cross-sections may also be enhanced by choosing e^+/e^- polarisation judiciously.

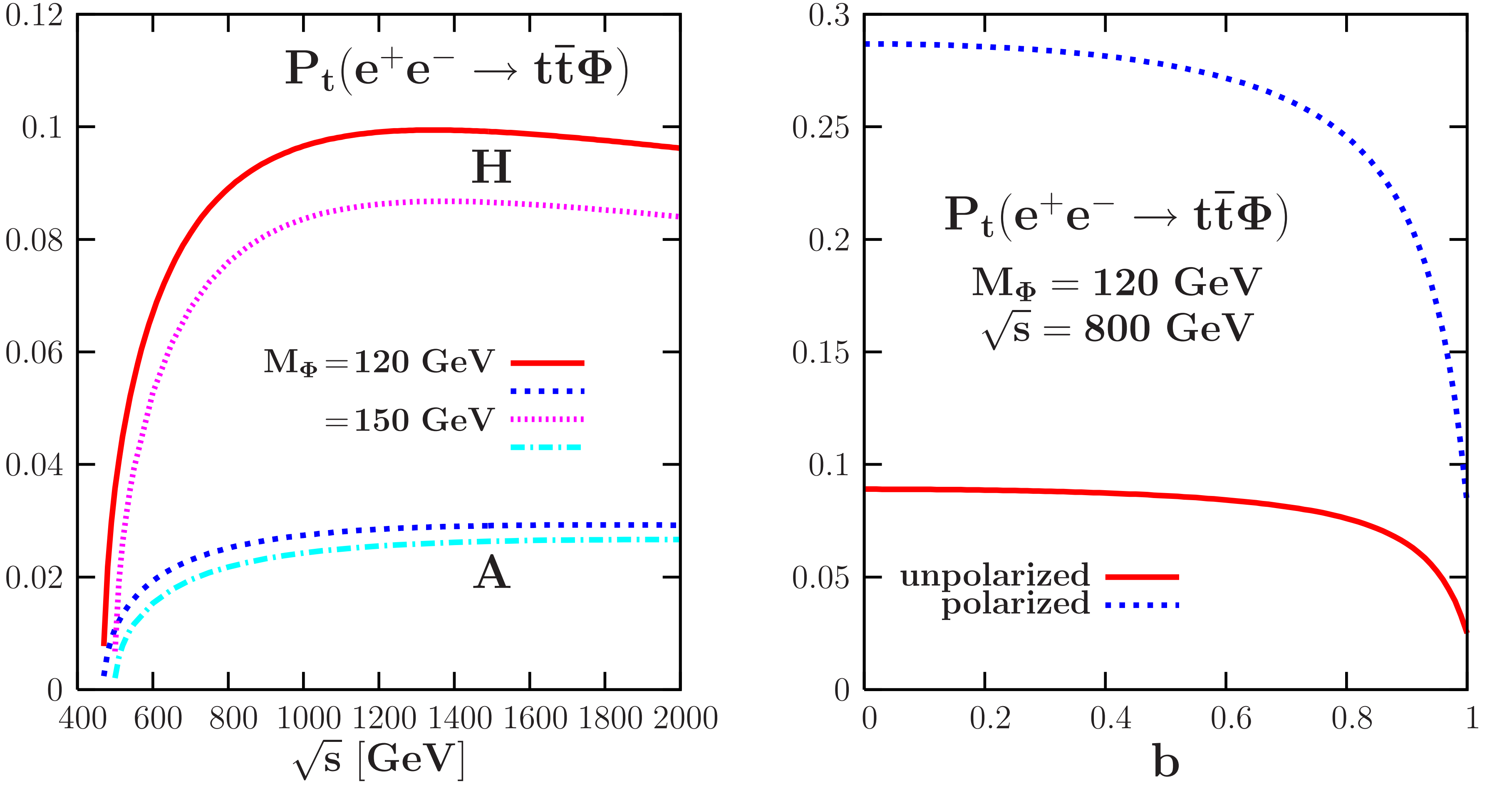
$$\phi_i t\bar{t} : -\bar{t}(a + ib\gamma_5) f \frac{g m_f}{2 m_W}$$

In the SM, $a = 1 = c$ and $b = 0$.

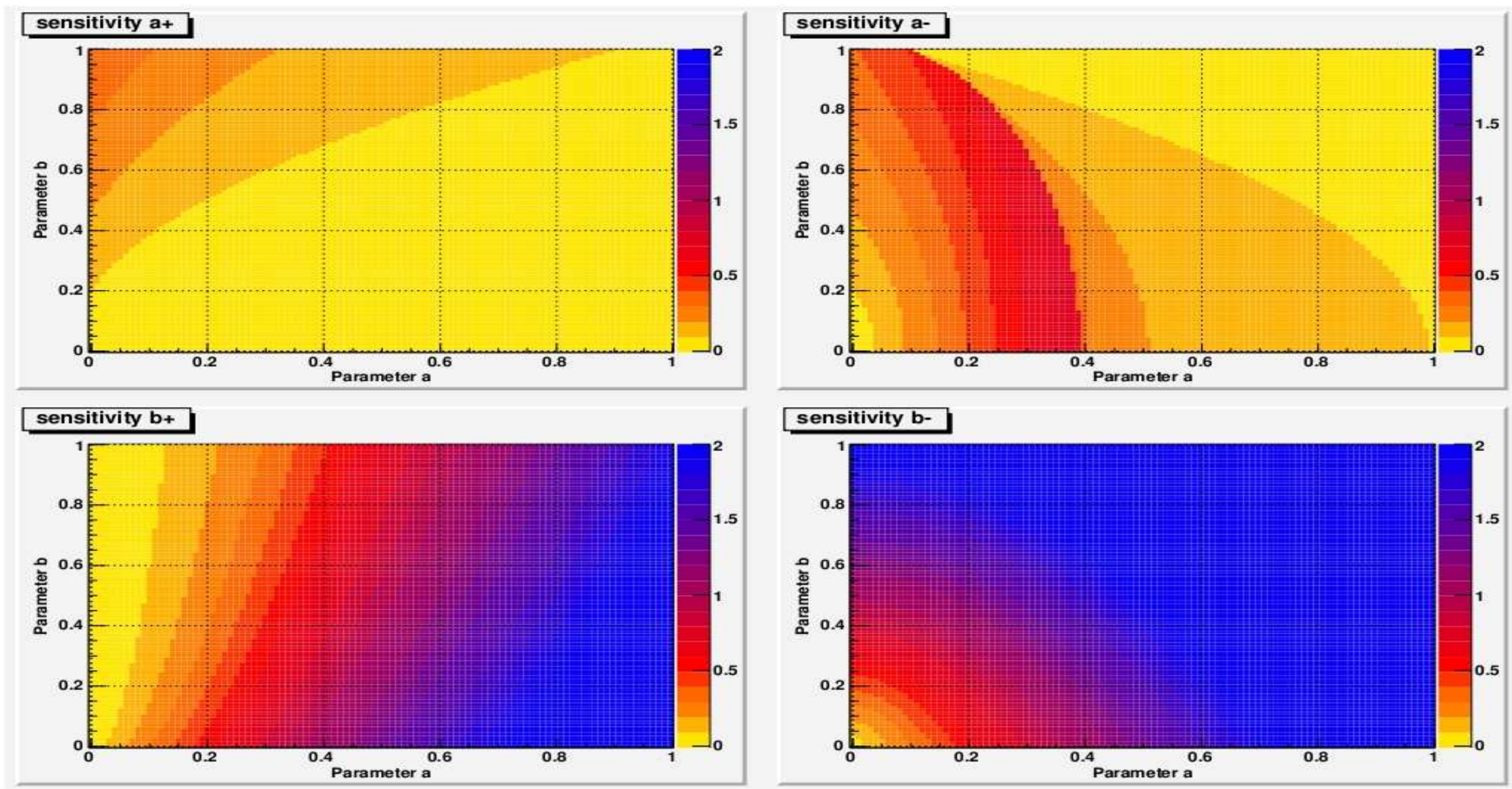
A model-independent way of parametrization can be $|a|^2 + |b|^2 = 1$.


CP-even for m_H=120GeV
CP-odd for m_H=120GeV
σ [fb]
√s [GeV]
0
0.5
1
1.5
2
2.5
3
600
800
1000
1200
1400
1600
1800
2000

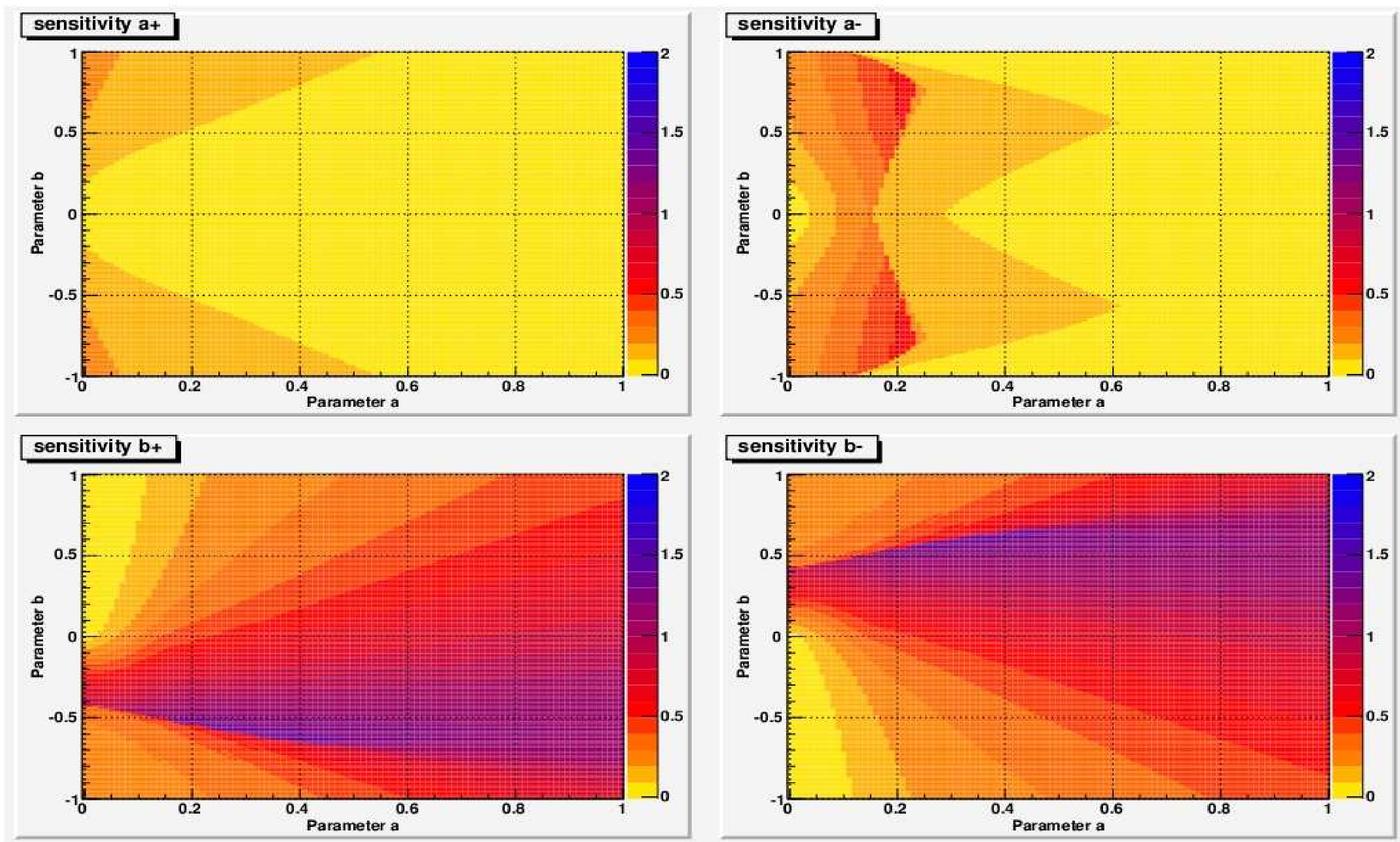

$\sigma(e^+e^- \to t\bar{t}\Phi)$ [fb]
$M_\Phi = 120$ GeV
$\sqrt{s} = 800$ GeV
unpolarized
polarized
b
0
1
2
3
4
5
6
0.2
0.4
0.6
0.8


Pt(e+e− → tt̄Φ)
H
A
MΦ = 120 GeV
= 150 GeV
0.12
0.1
0.08
0.06
0.04
0.02
0
400 600 800 1000 1200 1400 1600 1800 2000
√s [GeV]
Pt(e+e− → tt̄Φ)
MΦ = 120 GeV
√s = 800 GeV
unpolarized
polarized
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.2 0.4 0.6 0.8 1
b

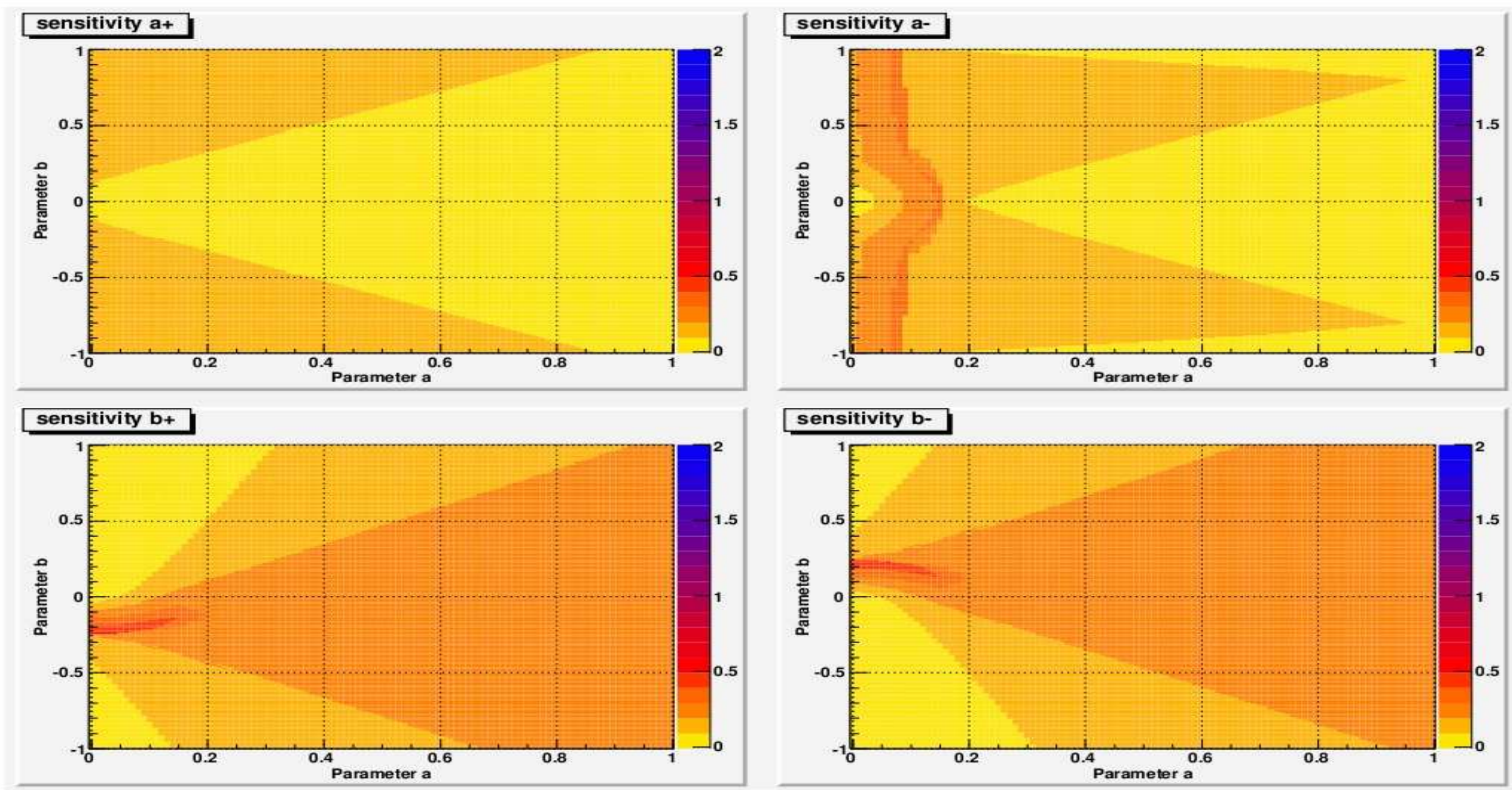
With just cross-section a is well restricted, b not very well. For $\sqrt{s} =$ 800 GeV with ILC TDR choice of polarisation, 1-σ.



Adding information on p_t helps. Polarisation crucial, interplay between σ and p_t helps decrease the error on a. At this energy up-down asymmetry does not do much.


sensitivity a+
sensitivity a-
sensitivity b+
sensitivity b-
Parameter a
Parameter b

All three and higher energy together work better.



Using both beams polarized in configuration b) instead of just the electron beam polarized in configuration a) can lead to a scaling factor between 0 and at most 2.

Suppression of WW backgrounds can always be done very effectively by choosing beam polarisation. $e^+e^- \to W^+W^- = 6.2pb$ (unpolarised)

$e^+e^- \to W^+W^- = 1.2pb$ (With only electron polarised 80%)

$e^+e^- \to W^+W^- = 0.6pb$ (With both e^- and e^+ polarised.)

Scale factor 0.5. S/B increases.

Even if both the signal and background increase similarly with polarisation and S/B does not change, $S/\sqrt{B}$ can change. I.e. the statistical significance can improve.

Earlier analyis : Optimal observable analysis:

Our new analysis Biswal, et al. Phys. Rev. D **73**, 035001 (2006); PRD **79**, 035012 (2009).

Most general VVH coupling structure:

$$\Gamma_{\mu\nu} = g_V \left[a_V \; g_{\mu\nu} + \frac{b_V}{M_V^2} \; (k^1_\nu k^2_\mu - g_{\mu\nu} k^1.k^2) + \frac{\tilde{b}_V}{M_V^2} \; \epsilon_{\mu\nu\alpha\beta} k^{1\alpha} k^{2\beta} \; \right]$$

• $\tilde{T}$: Naive time reversal operation.

• Cross-sections integrated over $CP\tilde{T}$ symmetric phase space will probe only the $CP-even$, $\tilde{T}$–even couplings. in the approximation that the anomalous couplings are small.

• Partially integrated cross-sections will be able to probe these. for example to probe a P-odd cpupling we construct Forward-Backward asymmetry.

• Constructed different observables out of the available momenta such that they have specific CP and $\tilde{T}$ transformation properties.

• Look at expectaion value of 'sign' of these observables.These asymmetries, are proportional to the part of the anomalous coupling which has the **same** CP and $\tilde{T}$ transformation properties as the observable, to leading order in the anomalous coupling.

Biswal et al:

Studied $e^+e^- \rightarrow f\bar{f}H$

We construct various asymmetries, using the mometa of particles. For some of the couplings these asymmetries are propotional to $(l_f^2 - r_f^2)$. For the Zee coupling this makes them small.

Hence by choosing either polarised beams and/or measuring the polarisation of the final state particles one can improve the sensitivity.

Using Polarized Beams				Unpolarized States	
Coupling		Limits	Observable used	Limits	Observable used
$\|\Re(\tilde{b}_Z\|$	$\leq$	0.067	$\mathcal{O}_{UD}(R2; e)$	0.067	$A_{UD}(R2; e)$
$\|\Re(\tilde{b}_Z)\|$	$\leq$	0.17	$\mathcal{O}_{UD}(R1; \mu)$	0.91	$A_{UD}(R1; \mu)$
$\|\Im(\tilde{b}_Z)\|$	$\leq$	0.011	$\mathcal{O}_{FB}(R1; \mu, q)$	0.064	$A_{FB}(R1; \mu, q)$

Han et al. have also observed the improvement for $\Im(\tilde{b}_z)$; T. Han and J. Jiang, Phys. Rev. D **63**, 096007 (2001).

Hagiwara and Stong: If one has real anomalous couplings no gain by transverse poalrisation.

Rindani et al: Noticed this is not true when some couplings are complex, i.e CP violation. But used only $e^+e^- \to ZH$ and not the l^+l^- coming from Z decay. Some of the couplings then not accessible.

Biswal et : We used $e^+e^- \to f\bar{f}H$. Already showed examples of improvement with Long. polarisation.

Next : What about trans. polarisation?

Biswal and Godbole, Phys. Lett. B **680**, 81 (2009) [arXiv:0906.5471 [hep-ph]].

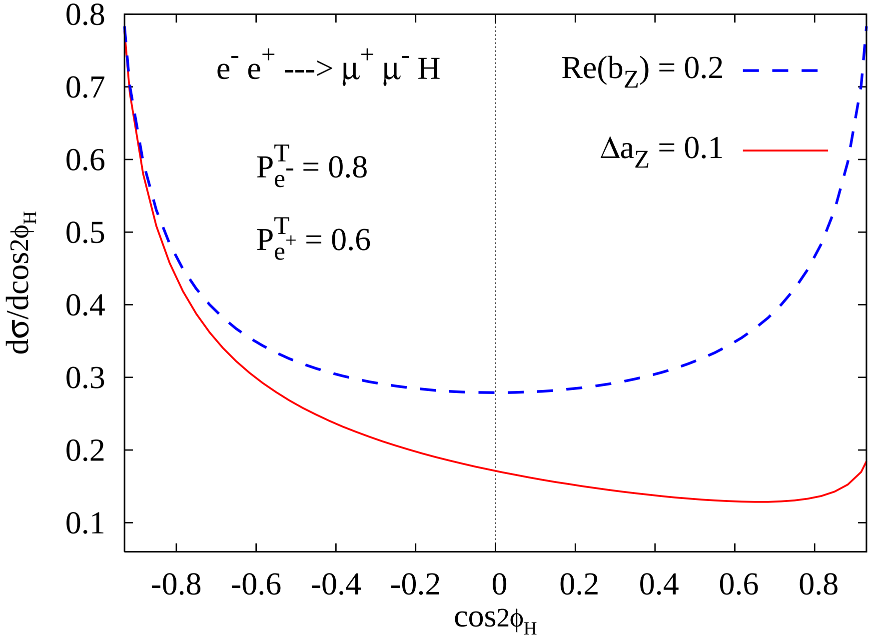
$\vec{P}_f \equiv \vec{p}_f - \vec{p}_{\bar{f}}$

ID	$\mathcal{C}_i^{\mathrm{T}}$	C	P	CP	$\tilde{T}$	$CP\tilde{T}$	Observable (O_i^{T})	Coupling
1	$(\vec{p}_{_H})_x^2 \; - \; (\vec{p}_{_H})_y^2$	$+$	$+$	$+$	$+$	$+$	O_1^{T}	$a_V,\ \Re(b_V)$
2	$(\vec{P}_f)_x * (\vec{P}_f)_y * (\vec{p}_{_H})_z$	$+$	$-$	$-$	$-$	$+$	O_2^{T}	$\Re(\tilde{b}_Z)$
3	$(\vec{p}_{_H})_x * (\vec{p}_{_H})_y * (\vec{P}_f)_z$	$-$	$-$	$+$	$-$	$-$	O_3^{T}	$\Im(b_Z)$

- For each combination, observable can be constructed as:

$$O_i^{\mathsf{T}} = \frac{1}{\sigma_{\mathsf{SM}}} \int [\mathsf{sign}(\mathcal{C}_i^{\mathsf{T}})] \frac{d\sigma}{d^3p_H d^3p_f} d^3p_H d^3p_f$$
$$= \frac{\sigma(\mathcal{C}_i^{\mathsf{T}} > 0) - \sigma(\mathcal{C}_i^{\mathsf{T}} < 0)}{\sigma_{\mathsf{SM}}}$$

Independent probes of CP- and $\tilde{T}$-even ZZH couplings. Biswal and Godbole, Phys. Lett. B **680**, 81 (2009) [arXiv:0906.5471 [hep-ph]].



$$O_1^{\mathsf{T}} \equiv O_1^{\mathsf{T}}(\Delta a_Z) \propto [\sigma(\cos 2\phi_H > 0) - \sigma(\cos 2\phi_H < 0)]$$

Probe of Δa_Z

Using $\mathcal{C}_1^{\mathsf{T}}$ we construct an azimuthal asymmetry:

$$\mathcal{A}_1^{\mathsf{T}} = \frac{\sigma(\cos 2\phi_H > 0) - \sigma(\cos 2\phi_H < 0)}{\sigma(\cos 2\phi_H > 0) + \sigma(\cos 2\phi_H < 0)}$$
$$\equiv \mathcal{A}_1^{\mathsf{T}}(\Re(b_Z)) : \text{Probe of } \Re(\mathrm{b_Z})$$

Both the CP- and $\tilde{T}$-even couplings, $\Re(b_Z)$ and Δa_Z, can be probed independently using $\mathcal{A}_1^{\mathsf{T}}$ and O_1^{T} respectively, which was not possible with unpolarized and/or linearly polarized beams.

S.D. Rindani et al, Phys. Lett. B 678 , 395, 2009

Considered $e^+e^- \to \mu^+\mu^-$

The modification of contact interactions by R-parity violating $S-$ channel or t-channel exchange

Due to transverse poalrisation indeed we can construct azimuthal asymmetries which were proportional linearly to the RPV couplings.

Current constraints obtained from rates.

With longitudinal polarisation (Rizzo) ILC sensitivity using angular distribution obtained

In our study the use of transverse polarisation increased the sensitivity.

Beam polarisation (longitudinal and transverse) together with measurement of polarisation of the fermions produced offer the possibilities of determining accurately the structure of the $t\bar{t}H$ and VVH coupling in all generality.