

# Positron Polarization at the International Linear Collider

Nello Paver / Per Osland

# Overview

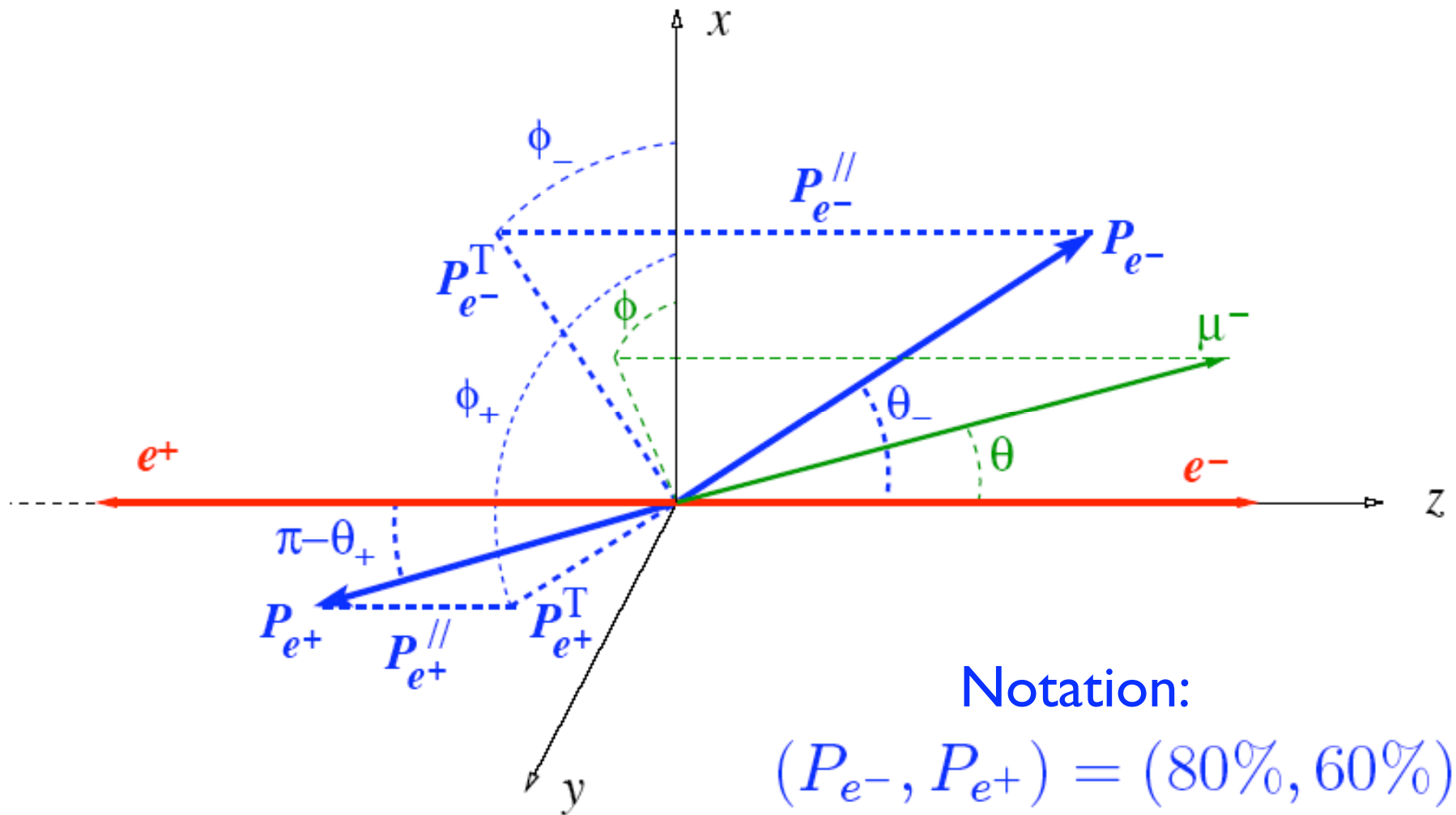
## SM studies

- top couplings
- SM Higgs searches (see report)
- triple gauge couplings
- precision measurements at Giga Z

## New Physics

- suppression of SM background
- SUSY studies (Nauenberg)
- fermion-pair production
- CP sensitive observables

Allow general (long. & transv.) polarizations




# t-quark flavour-changing neutral couplings $t \rightarrow Vq$

Aguilar-Saavedra, T. Riemann, hep-ph/0102197

Glover, hep-ph/0410110

Couplings [ $10^{-4}$ ]     $300 \text{ fb}^{-1}$



		E=500 GeV unpol	E=500 GeV (80%,0)	E=500 GeV (80%,45%)	E=800 GeV (80%,60%)	
$\Upsilon_\mu$	BR( $t \rightarrow Zq$ )	6.1	3.9	2.2	1.9	LEP: 70
$\sigma_{\mu\nu}$	BR( $t \rightarrow Zq$ )	0.48	0.31	0.17	0.07	
$\Upsilon_\mu$	BR( $t \rightarrow \Upsilon q$ )	0.30	0.17	0.093	0.038	Tevatron: 32

$3\sigma$  discovery limits

LHC in  $10^{-5}$  range

# Suppression of SM background in new-physics search

Polarization of both beams decisive in suppressing background

Smuon mass measurement above threshold [Nauenberg et al](#)

$$e^+ e^- \rightarrow \tilde{\mu}^+ \tilde{\mu}^+ \quad \tilde{\mu}^\pm \rightarrow \mu^\pm \text{LSP}$$

Production (smuons) via s-channel  $\gamma, Z$  exchange, RL and LR configurations

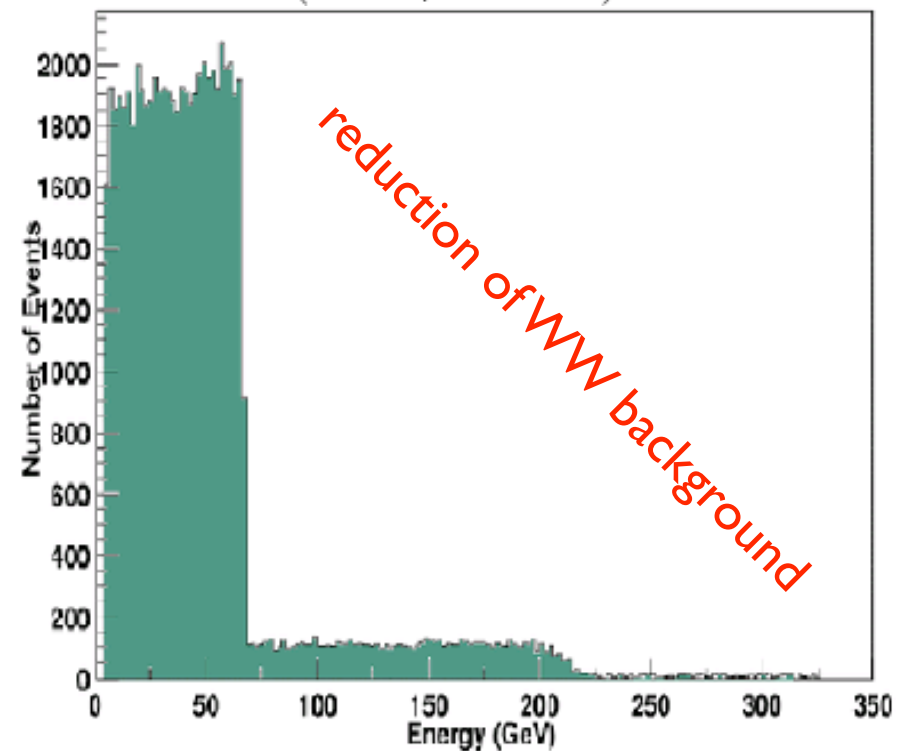
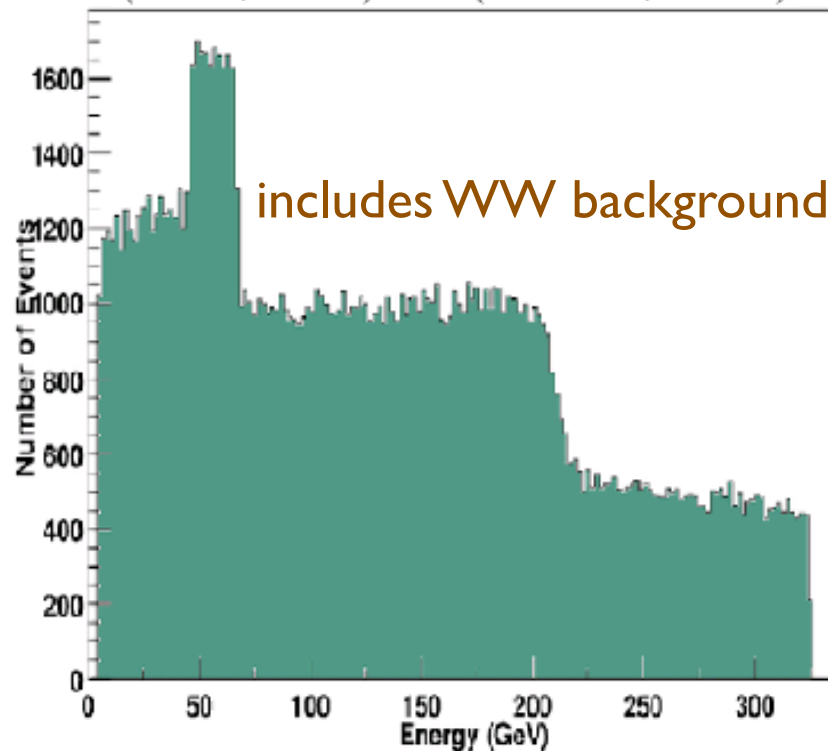
Background: WW pairs

750 GeV

$$\mathcal{L}_{\text{int}} = 500 \text{ fb}^{-1}$$

$$(P_{e^-}, P_{e^+}) = (-80\%, 80\%)$$

$$(80\%, -80\%)$$

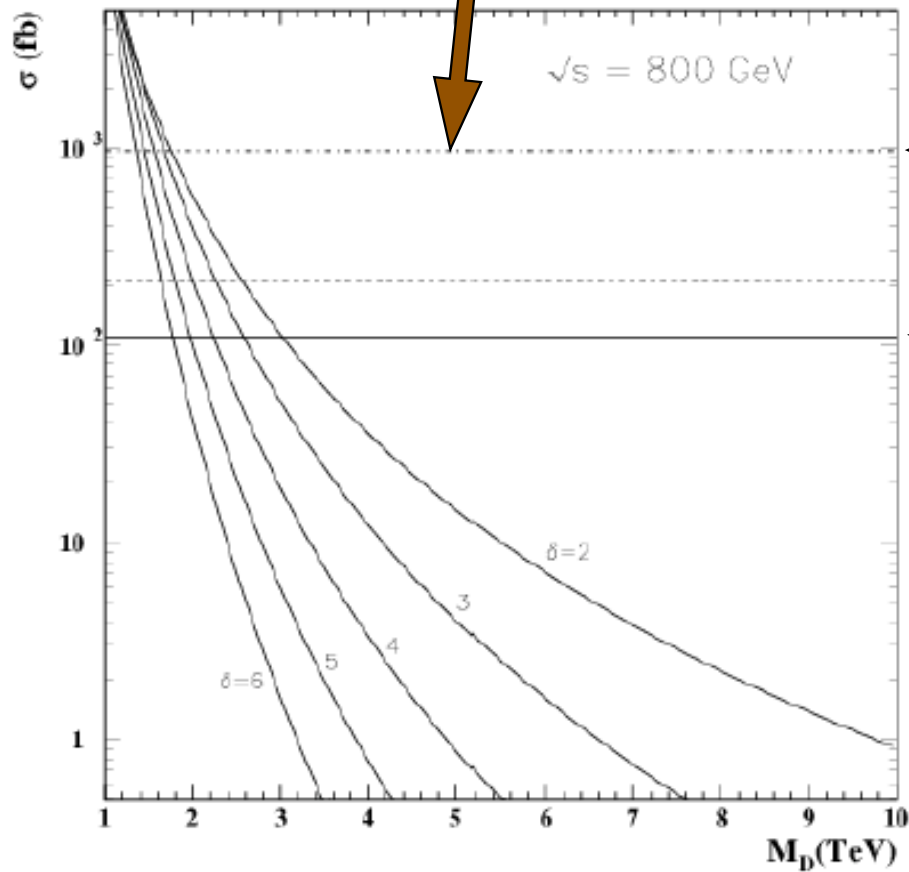


# Gravity in extra dimensions (ADD) Wilson

$$e^+ e^- \rightarrow \gamma G$$

$$\text{Background: } e^+ e^- \rightarrow \nu \bar{\nu} \gamma$$

$\nu$  couples Left



← unpolarized

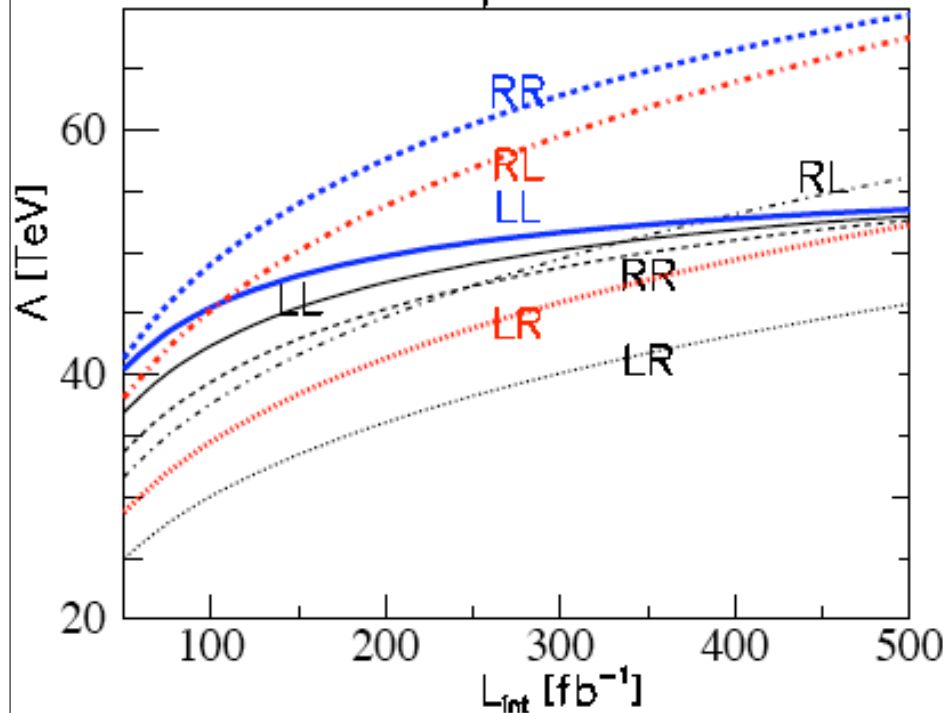
←  $(P_{e^-}, P_{e^+}) = (80\%, 60\%)$

# Contact interaction searches (model independent)

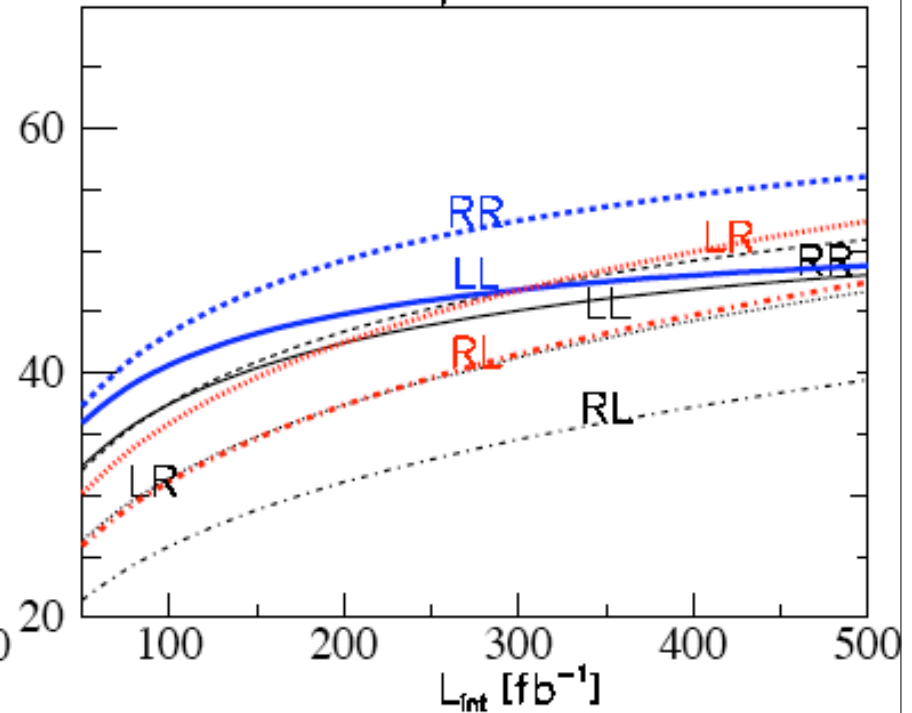
Osland, Pankov, Paver

$$\mathcal{L}_{\text{CI}} = \frac{1}{1 + \delta_{ef}} \sum_{i,j} \frac{4\pi \eta_{ij}}{\Lambda_{ij}^2} (\bar{e}_i \gamma_\mu e_i) (\bar{f}_j \gamma^\mu f_j) \quad i, j = R, L$$

b quarks



c quarks



blue / red:  $(P_{e^-}, P_{e^+}) = (80\%, 60\%)$   
 black:  $(80\%, 0)$

500 GeV

Related model-dependent work by S. Riemann

# CP violation in $Z \rightarrow b\bar{b}g, b\bar{b}gg$

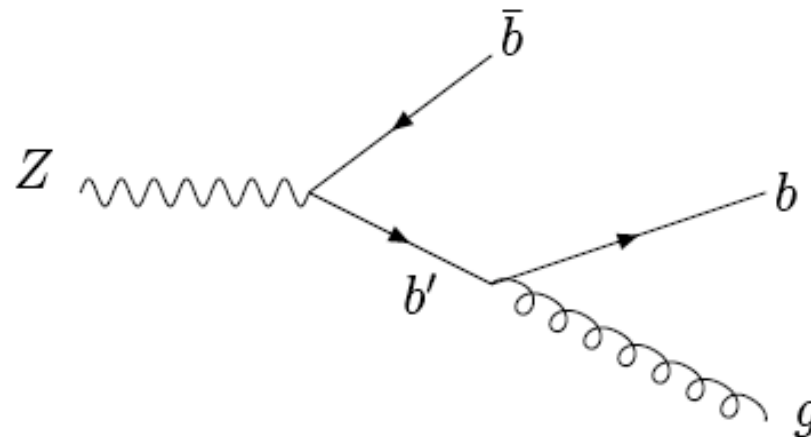
Nachtmann and Schwanenberger

$$\mathcal{L}_{CP}(x) = [ h_{Vb} \bar{b}(x) T^a \gamma^\nu b(x) + h_{Ab} \bar{b}(x) T^a \gamma^\nu \gamma_5 b(x) ] Z^\mu(x) G_{\mu\nu}^a(x)$$

Quark-substructure-like scenario:

$$\begin{aligned} \mathcal{L}'(x) = & - \frac{e}{2 \sin \theta_W \cos \theta_W} Z_\mu(x) \bar{b}'(x) \gamma^\mu (g'_V - g'_A \gamma_5) b(x) \\ & - i \frac{g_s}{2m_{b'}} \hat{d}_c \bar{b}'(x) \sigma^{\mu\nu} \gamma_5 T^a b(x) G_{\mu\nu}^a(x) + \text{h.c.} \end{aligned}$$

$h_{Vb}$   $h_{Ab}$  determined by virtual  $b'$  exchange





CP-odd observables:

$$T_{33} = (\hat{\mathbf{k}}_{\bar{b}} - \hat{\mathbf{k}}_b)_3 (\hat{\mathbf{k}}_{\bar{b}} \times \hat{\mathbf{k}}_b)_3 \quad V_3 = (\hat{\mathbf{k}}_{\bar{b}} \times \hat{\mathbf{k}}_b)_3$$

$T_{33}$  sensitive to combination of constants  $h_b$ , insensitive to polarization

$V_3$  sensitive to combination of constants  $\tilde{h}_b$ , requires  $b$ - $\bar{b}$  distinction

$V_3$	$y_{cut}$	$(P_{e-}, P_{e+})$				
		(0, 0)	(+80%, 0)	(-80%, 0)	(+80%, -60%)	(-80%, +60%)
$\tilde{h}_b [10^{-3}]$	0.01	8.5	2.5	1.9	1.8	1.4
	0.1	9.5	3.0	2.1	2.0	1.5
$m_{b'}$ [TeV]	0.01	0.9	1.6	1.9	2.0	2.2
	0.1	0.9	1.5	1.8	1.9	2.1

no limits yet on  $b$  excitation  $b'$

# Transverse polarization and CP violation

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

Momenta:  $e^- : \mathbf{p}$     $f : \mathbf{k}$

$$\begin{aligned} d\sigma_{\text{pol}} = & A_1 [\mathbf{P}_{e^+}^T \cdot \mathbf{k} + \mathbf{P}_{e^-}^T \cdot \mathbf{k}] + A_2 [\mathbf{P}_{e^+}^T \cdot \mathbf{k} - \mathbf{P}_{e^-}^T \cdot \mathbf{k}] \\ & + B (\mathbf{P}_{e^+}^T \cdot \mathbf{P}_{e^-}^T) + C (\mathbf{P}_{e^+}^T \cdot \mathbf{k}) (\mathbf{P}_{e^-}^T \cdot \mathbf{k}) + D (\mathbf{P}_{e^+}^T \times \mathbf{P}_{e^-}^T) \cdot \mathbf{p} \\ & + E_1 [(\mathbf{P}_{e^+}^T \times \mathbf{k}) \cdot \mathbf{p}] (\mathbf{P}_{e^-}^T \cdot \mathbf{k}) + E_2 [(\mathbf{P}_{e^-}^T \times \mathbf{k}) \cdot \mathbf{p}] (\mathbf{P}_{e^+}^T \cdot \mathbf{k}) \end{aligned}$$

*A, D and E terms violate P*

*B and C terms combine to give familiar*

$$|\mathbf{P}_{e^-}^T| |\mathbf{P}_{e^+}^T| \sin^2 \theta \cos(2\phi - \phi_- - \phi_+)$$

*E terms give*

$$|\mathbf{P}_{e^-}^T| |\mathbf{P}_{e^+}^T| \sin^2 \theta \sin(2\phi - \phi_- - \phi_+)$$

# Transverse polarization and CP violation, cont

$$\begin{aligned} d\sigma_{\text{pol}} = & A_1[\mathbf{P}_{e^+}^T \cdot \mathbf{k} + \mathbf{P}_{e^-}^T \cdot \mathbf{k}] + A_2[\mathbf{P}_{e^+}^T \cdot \mathbf{k} - \mathbf{P}_{e^-}^T \cdot \mathbf{k}] \\ & + B(\mathbf{P}_{e^+}^T \cdot \mathbf{P}_{e^-}^T) + C(\mathbf{P}_{e^+}^T \cdot \mathbf{k})(\mathbf{P}_{e^-}^T \cdot \mathbf{k}) + D(\mathbf{P}_{e^+}^T \times \mathbf{P}_{e^-}^T) \cdot \mathbf{p} \\ & + E_1[(\mathbf{P}_{e^+}^T \times \mathbf{k}) \cdot \mathbf{p}](\mathbf{P}_{e^-}^T \cdot \mathbf{k}) + E_2[(\mathbf{P}_{e^-}^T \times \mathbf{k}) \cdot \mathbf{p}](\mathbf{P}_{e^+}^T \cdot \mathbf{k}) \end{aligned}$$

$\mathbf{P}_{e^+}^T$  or  $\mathbf{P}_{e^-}^T$  provides new direction

Allows measuring CP violation without final-state spin analysis

Dass and Ross, 1975, 1977:

With only  $(V, A)$  couplings, and  $m_e \rightarrow 0$ ,  $A$  terms (linear) vanish

Ananthanarayan, Rindani, hep-ph/0309260:

Consider scalar and tensor couplings in  $e^+e^- \rightarrow t\bar{t}$

four-fermi NP interaction:

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

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



scalar



(vector)



tensor

$P_i$  are helicity projection operators



$$S_{RR} = S_{LL}^*, \quad S_{LR} = S_{RL} = 0, \quad V_{ij} = V_{ij}^*$$

$$T_{RR} = T_{LL}^*, \quad T_{LR} = T_{RL} = 0$$

## *Dass and Ross theorem does not apply*

Cross section depends on combination:

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

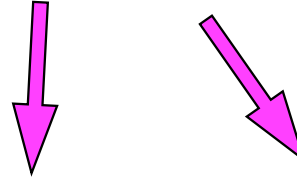
scalar   tensor  
SM couplings

Interference between  $S$  and SM amplitude gives terms **linear** in transverse polarization,  $\sim \cos(\phi), \sin(\phi)$

**A certain combination of such terms violates CP**

Note that new vector coupling does not contribute to **linear** terms

Project out CP violating up-down asymmetry:

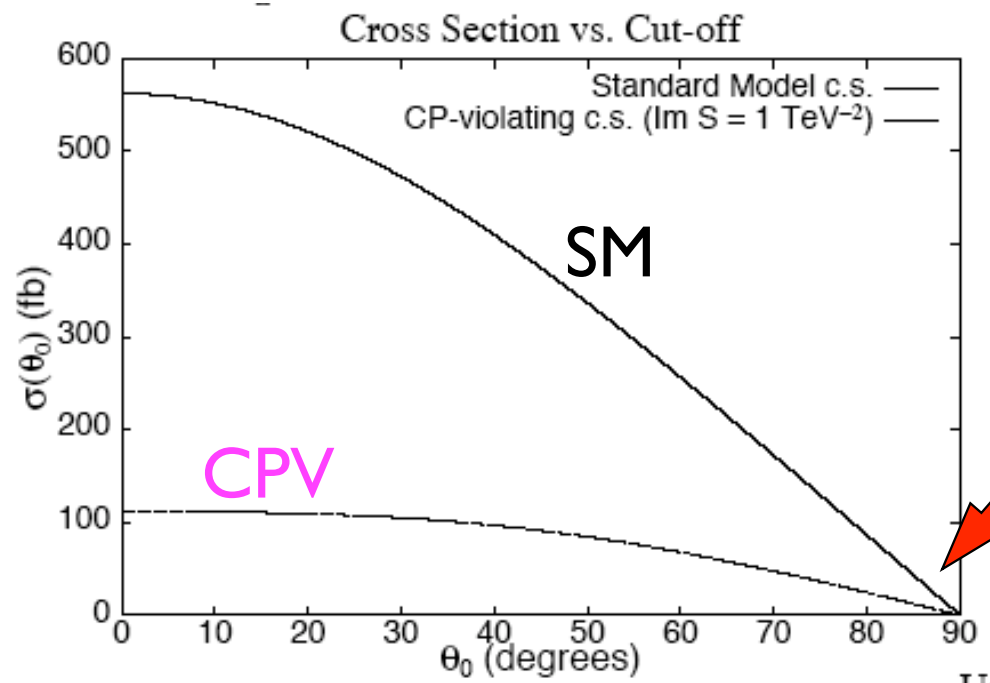


$\theta$ -integrated version:

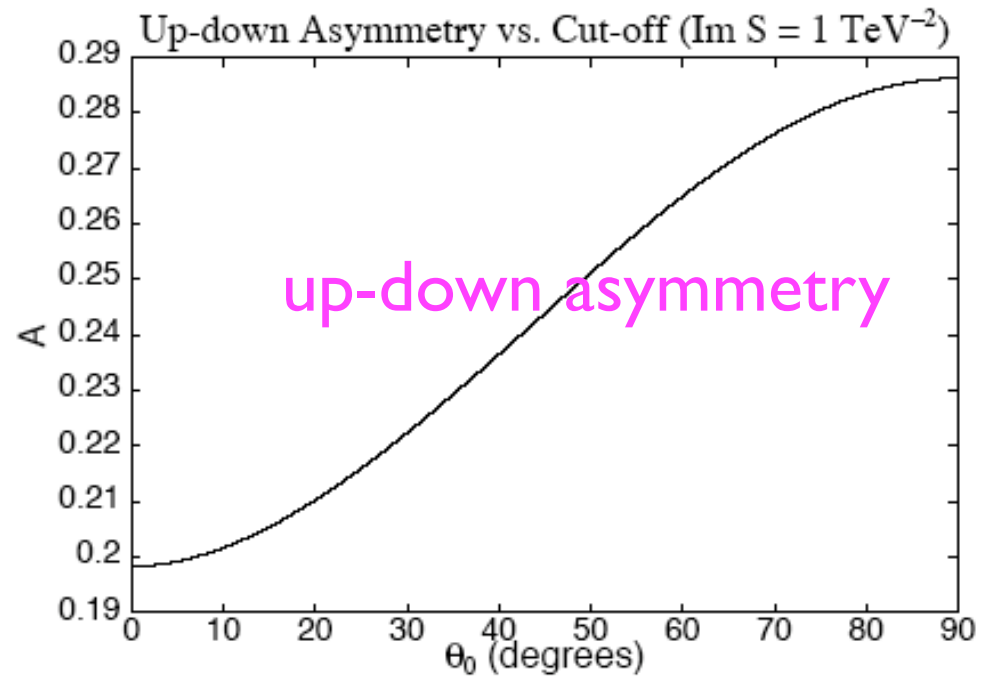
$$A(\theta_0) = \frac{\int_{-\cos\theta_0}^{\cos\theta_0} d\cos\theta \left[ \int_0^\pi \frac{d\sigma^{+-}}{d\Omega} d\phi - \int_\pi^{2\pi} \frac{d\sigma^{+-}}{d\Omega} d\phi \right]}{\text{sum}}$$

Note:

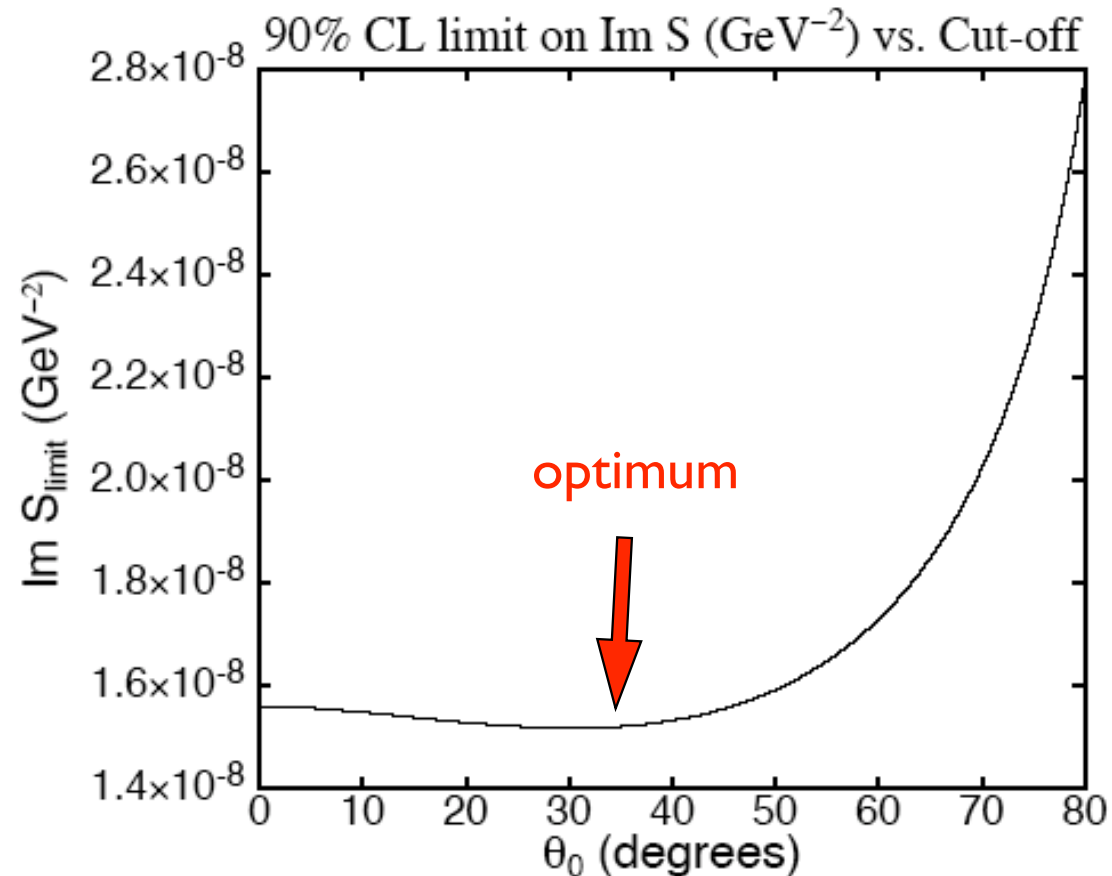
- these terms (linear in transverse polarization) can not be seen unless both beams are transversely polarized
- sensitive only to imaginary part of  $S$



no rate



# Bound on $\text{Im } S$ [ $\text{GeV}^{-2}$ ]



Corresponds to bound on  $\Lambda$  of order 8-10 TeV  
(assuming perfect polarization)

with  $\alpha_i = \mathcal{O}(1)$

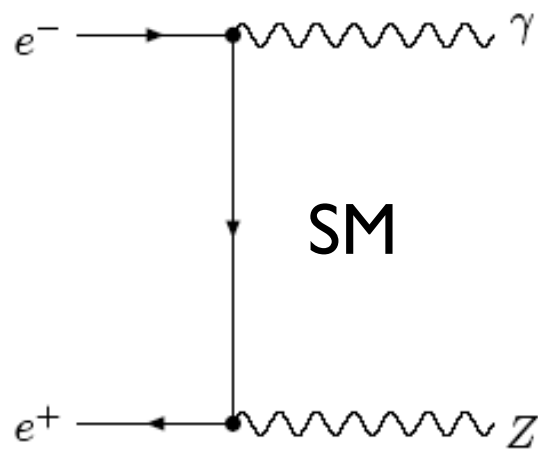
remember  $\mathcal{L} = \mathcal{L}^{SM} + \frac{1}{\Lambda^2} \sum_i (\alpha_i \mathcal{O}_i + \text{h.c.})$



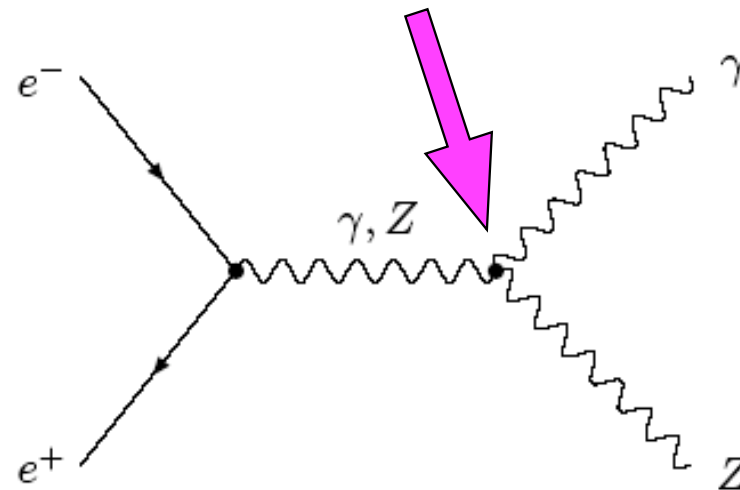
# Transverse polarization and CP violation, $\Upsilon$ Z production

Most general effective CP-violating Lagrangian for  $\Upsilon\Upsilon Z$  and  $\Upsilon ZZ$  interactions:

$$\mathcal{L} = e \frac{\lambda_1}{2m_Z^2} F_{\mu\nu} (\partial^\mu Z^\lambda \partial_\lambda Z^\nu - \partial^\nu Z^\lambda \partial_\lambda Z^\mu) + \frac{e}{16c_W s_W} \frac{\lambda_2}{m_Z^2} F_{\mu\nu} F^{\nu\lambda} (\partial^\mu Z_\lambda + \partial_\lambda Z^\mu)$$



CP violation



FB asymmetry CP-odd but "naive" T even

Define **CP-odd asymmetries**, combining forward-backward asymmetry with azimuthal asymmetry:

$$A_1 = \frac{1}{\sigma_0} \sum_{n=0}^3 (-1)^n \int_{\pi n/2}^{\pi(n+1)/2} d\phi \left( \int_0^{\cos \theta_0} d \cos \theta - \int_{-\cos \theta_0}^0 d \cos \theta \right) \frac{d\sigma}{d\Omega}$$

$$A_2 = \frac{1}{\sigma_0} \sum_{n=0}^3 (-1)^n \int_{\pi(2n-1)/4}^{\pi(2n+1)/4} d\phi \left( \int_0^{\cos \theta_0} d \cos \theta - \int_{-\cos \theta_0}^0 d \cos \theta \right) \frac{d\sigma}{d\Omega}$$

$$A_3 = \frac{2}{\sigma_0} \left\{ \int_0^{\cos \theta_0} d \cos \theta \left( \int_{-\pi/4}^{\pi/4} d\phi + \int_{3\pi/4}^{5\pi/4} d\phi \right) \frac{d\sigma}{d\Omega} - \int_{-\cos \theta_0}^0 d \cos \theta \left( \int_{-\pi/4}^{\pi/4} d\phi + \int_{3\pi/4}^{5\pi/4} d\phi \right) \frac{d\sigma}{d\Omega} \right\}$$

$$A_1 \sim \text{Re } \lambda_2$$

$$A_2, A_3 \sim \text{Im } \lambda_1, \text{Im } \lambda_2$$

## Integrated asymmetries:

$$A_1(\theta_0) \sim -\mathbf{P}_{e^-}^T \mathbf{P}_{e^+}^T g_A \operatorname{Re} \lambda_2$$

$$A_2(\theta_0) \sim \mathbf{P}_{e^-}^T \mathbf{P}_{e^+}^T [(g_V^2 - g_A^2) \operatorname{Im} \lambda_1 - g_V \operatorname{Im} \lambda_2]$$

$$A_3(\theta_0) \sim \left[ \frac{\pi}{2} [(g_V^2 + g_A^2) \operatorname{Im} \lambda_1 - g_V \operatorname{Im} \lambda_2] \right. \\ \left. + \mathbf{P}_{e^-}^T \mathbf{P}_{e^+}^T [(g_V^2 - g_A^2) \operatorname{Im} \lambda_1 - g_V \operatorname{Im} \lambda_2] \right]$$

## Results, direct limits:

Coupling	Individual limit from			Simultaneous limits
	$A_1$	$A_2$	$A_3$	
$\operatorname{Re} \lambda_2$	$1.4 \times 10^{-2}$			
$\operatorname{Im} \lambda_1$		$6.2 \times 10^{-3}$	$3.8 \times 10^{-3}$	$7.1 \times 10^{-3}$
$\operatorname{Im} \lambda_2$		$9.1 \times 10^{-2}$	$3.0 \times 10^{-2}$	$6.7 \times 10^{-2}$

90% C.L. limits for a cut-off angle of  $\theta_0 = 26^\circ$ ,  $\sqrt{s} = 500$  GeV,  
 $\mathcal{L}_{\text{int}} = 500 \text{ fb}^{-1}$  and  $(\mathbf{P}_{e^-}^T, \mathbf{P}_{e^+}^T) = (80\%, 60\%)$

## Extra-dimensional gravity

**ADD:** Arkani-Hamed, Dimopoulos, Dvali: hep-ph/9803315,  
Antoniadis et al: hep-ph/9804398

Effective interaction (Hewett):

$$\mathcal{L}^{\text{ADD}} = i \frac{4\lambda}{M_H^4} T_{\mu\nu} T^{\mu\nu}$$

parametrize strength by:

$$f_g = \frac{\lambda s^2}{4\pi\alpha_{\text{e.m.}} M_H^4}$$

**RS:** Randall, Sundrum: hep-ph/9905221

$$\frac{\lambda}{M_H^4} \rightarrow \frac{-1}{8\Lambda_\pi^2} \sum_n \frac{1}{s - m_n^2 + im_n\Gamma_n}$$

Identification reaches make use of angular analysis

Osland, Pankov, Paver: hep-ph/0304123

$M_H$ [TeV]	$\mathcal{L}_{\text{int}} [\text{fb}^{-1}]$		
	100	300	500
$\sqrt{s} = 0.5$ TeV (long. pol.)			
unpolarised beams	2.3	2.6	2.9
$(\mathbf{P}_{e^-}, \mathbf{P}_{e^+}) = (+80\%, 0)$	2.5	2.8	3.05
$(\mathbf{P}_{e^-}, \mathbf{P}_{e^+}) = (+80\%, -60\%)$	2.45	3.0	3.25

$5\sigma$  identification reach on the mass scale  $M_H$  vs.  $\mathcal{L}_{\text{int}}$  from  $e^+e^- \rightarrow f\bar{f}$ , combining  $f = \mu, \tau, b, c$ , energy 0.5 TeV

From azimuthal asymmetry [ $\cos(2\varphi)$  pos vs neg]:

with

$$(\mathbf{P}_{e^-}^T, \mathbf{P}_{e^+}^T) = (80\%, 60\%)$$

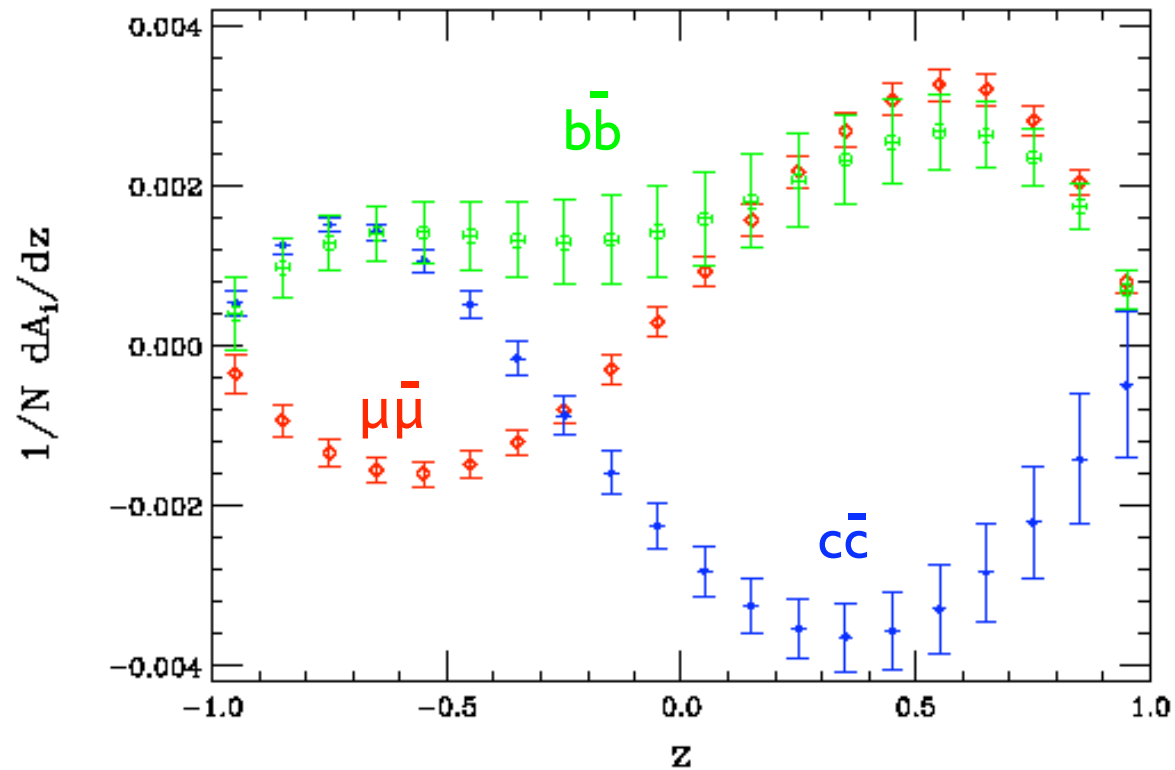
Rizzo: hep-ph/0211374

$M_H$ [TeV]	$\mathcal{L}_{\text{int}} [\text{fb}^{-1}]$			
	100	300	500	1000
(transv. pol.)				
$\sqrt{s} = 0.5$ TeV	1.6	1.9	2.0	2.2
$\sqrt{s} = 0.8$ TeV	2.4	2.6	2.8	3.1
$\sqrt{s} = 1.0$ TeV	2.8	3.2	3.4	3.8

Rizzo: hep-ph/0211374

From azimuthal asymmetry [ $\sin(2\phi)$  pos vs neg]:

$$\frac{1}{N} \frac{dA_i^T}{d \cos \theta} = \frac{1}{\sigma} \left[ \int_+ - \int_- \right] d\phi \frac{d\sigma}{d \cos \theta d\phi}$$



## Separation between ADD and RS

$$(\mathbf{P}_{e^-}^T, \mathbf{P}_{e^+}^T) = (80\%, 60\%)$$

5 $\sigma$ disc. reach $M_H$ [TeV]	$\mathcal{L}_{\text{int}} [\text{fb}^{-1}]$			
	100	300	500	1000
$\sqrt{s} = 0.5$ TeV	1.2	1.3	1.4	1.6
$\sqrt{s} = 0.8$ TeV	1.8	2.0	2.2	2.4
$\sqrt{s} = 1.0$ TeV	2.2	2.4	2.6	2.8

5 $\sigma$  reach for the discovery of nonzero azimuthal asymmetry  
 $N^{-1}dA_i^T/dz$  vs  $\mathcal{L}_{\text{int}}$  for  $d = 3$

# Summary

Polarized positron beam (in addition to electron beam)

- allows for decisive suppression of SM background for New Physics searches
- provides more independent observables, allows identification of New-Physics effects
- provides clues to new CP-violation sources