Positron Polarization at the International Linear Collider

Nello Paver / Per Osland

Overview

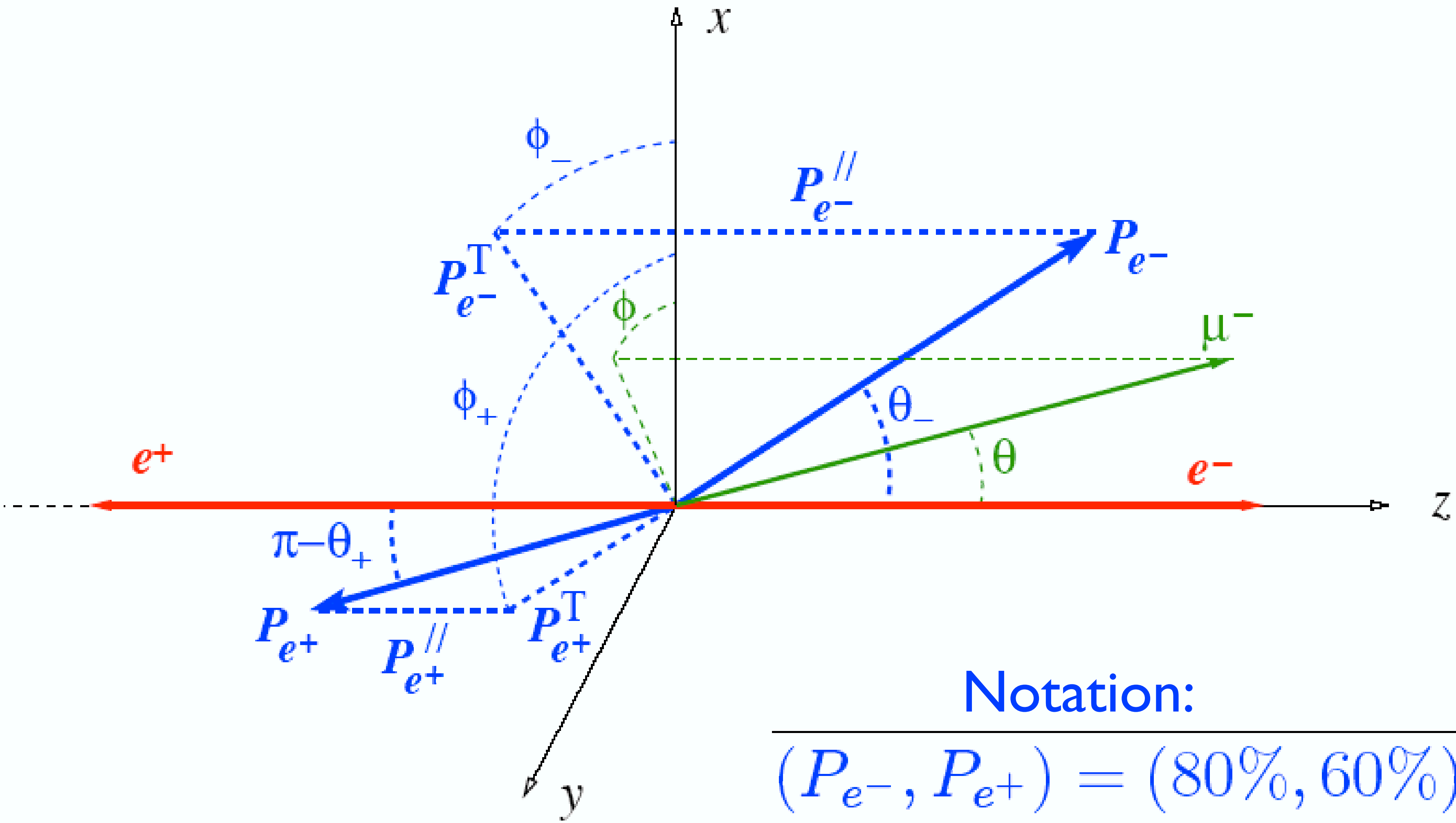
SM studies

- 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



Notation:

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

t-quark flavour-changing neutral couplings $\overline{t \rightarrow Vq}$

Aguilar-Saavedra, T. Riemann, hep-ph/0102197
Glover, hep-ph/0410110

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

		E=500 GeV unpol	E=500 GeV (80%,0)	E=500 GeV (80%,45%)	E=800 GeV (80%,60%)	
γ_μ	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	
γ_μ	BR($t\rightarrow \gamma q$)	0.30	0.17	0.093	0.038	Tevatron: 32

3σ 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

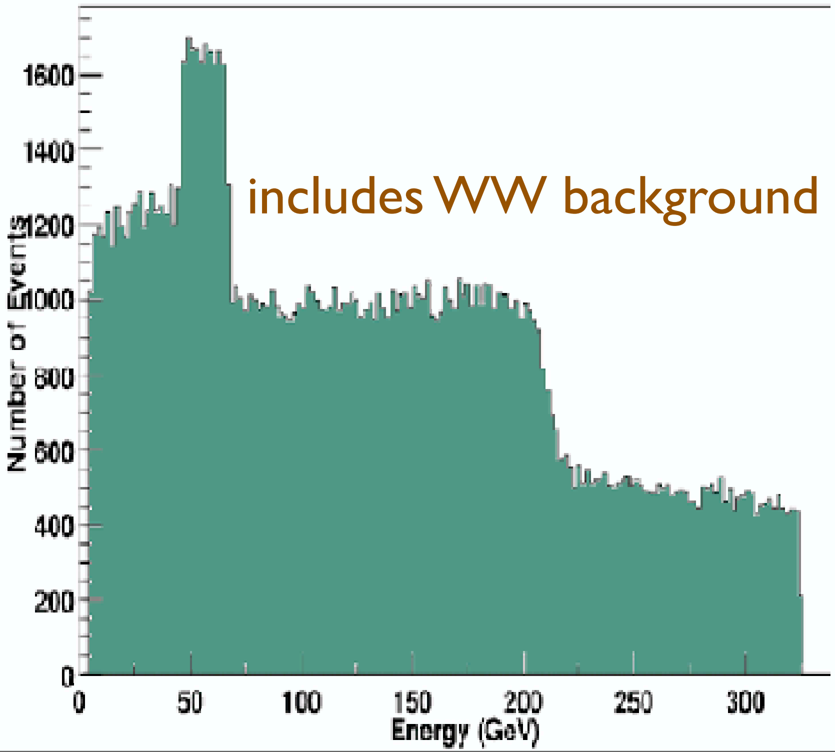
$\overline{e^+ \, e^- \; \rightarrow \tilde{\mu}^+ \, \tilde{\mu}^+}$ $\tilde{\mu}^\pm \rightarrow \mu^\pm \, \mathrm{LSP}$

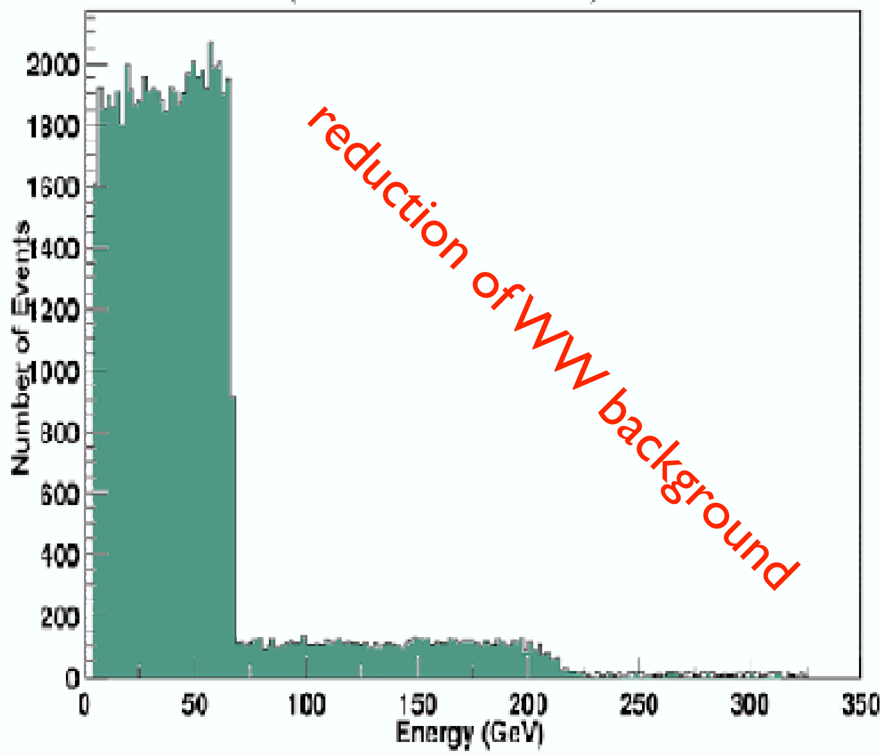
Production (smuons) via s-channel γ,Z exchange, RL and LR configurations

Background: WW pairs

$750 \, \mathrm{GeV}$ $\mathcal{L}_{\mathrm{int}} = 500 \, \mathrm{fb}^{-1}$

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



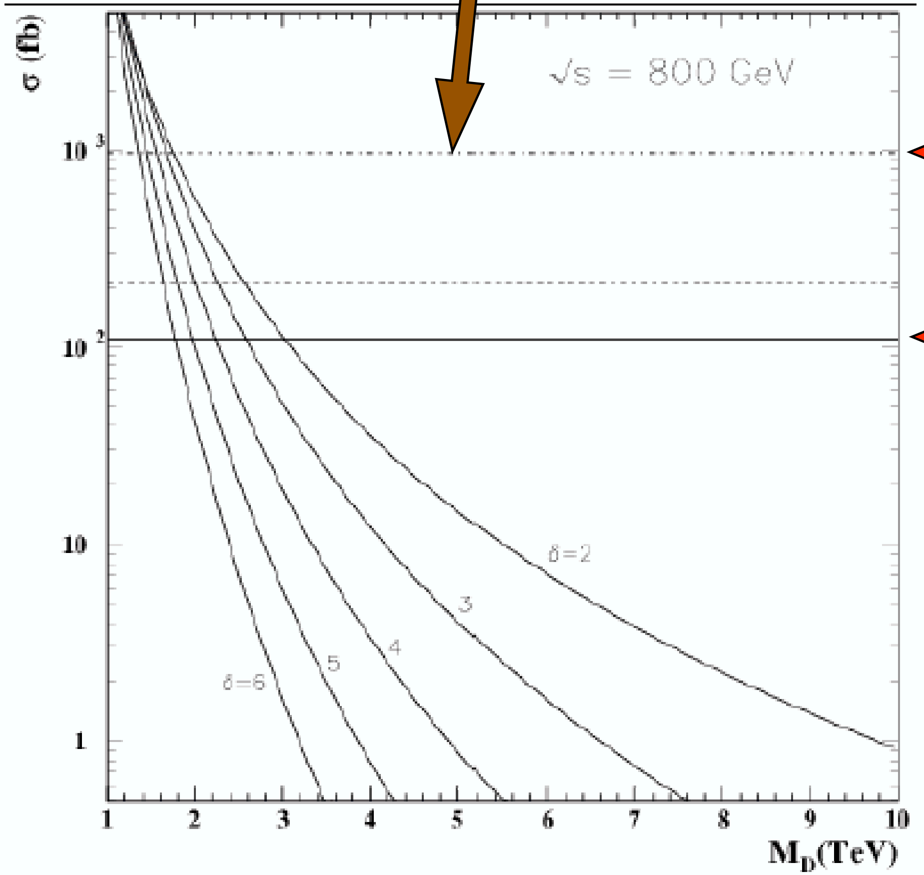


Gravity in extra dimensions (ADD) Wilson

$\overline{e^+ e^- \longrightarrow \gamma G}$

Background: $\overline{e^+ e^- \longrightarrow \nu\bar{\nu}\gamma}$

ν couples Left



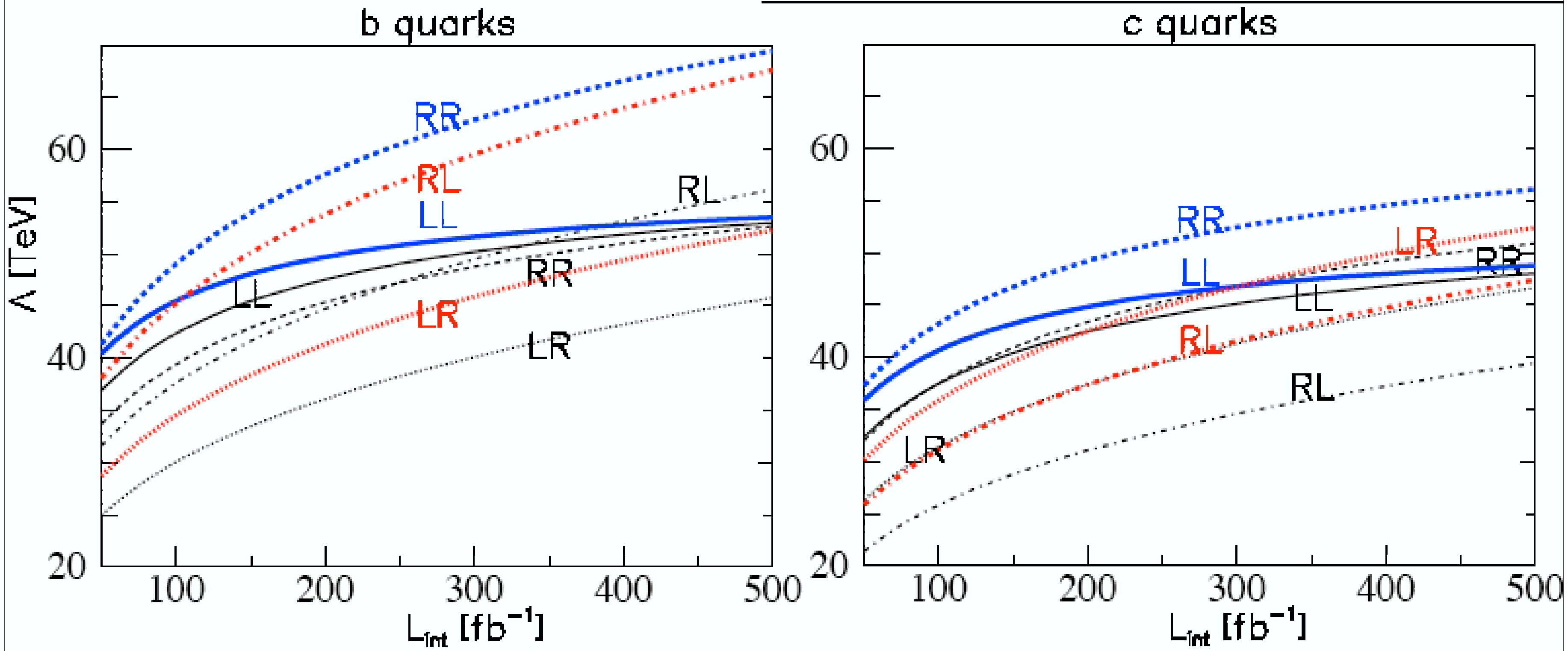
unpolarized

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

Contact interaction searches (model independent)

Osland, Pankov, Paver

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



blue / red: $(\mathbf{P}_{e^-}, \mathbf{P}_{e^+}) = (80\%, 60\%)$

black: $(80\%, 0)$

500 GeV

Related model-dependent work by S. Riemann

CP violation in Z → b$\bar{\text{b}}$g, b$\bar{\text{b}}$gg

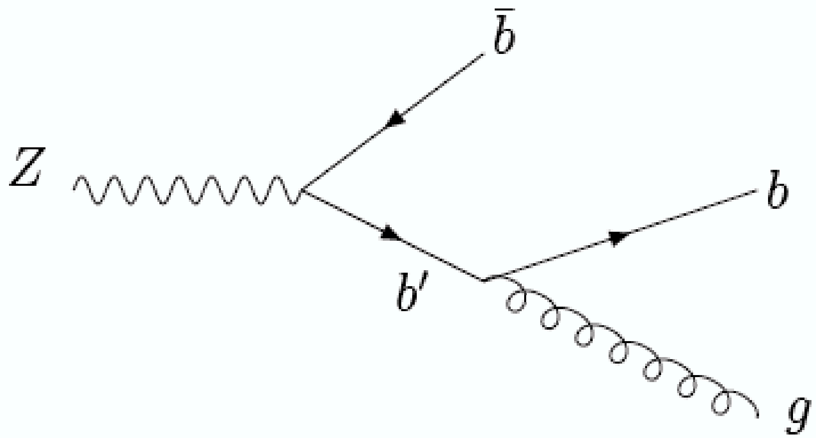
Nachtmann and Schwanenberger

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

Quark-substructure-like scenario:

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

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



CP-odd observables:

$$\overline{T_{33} = (\widehat{\mathbf{k}}_{\bar{b}} - \widehat{\mathbf{k}}_b)_3 \, (\widehat{\mathbf{k}}_{\bar{b}} \times \widehat{\mathbf{k}}_b)_3} \qquad V_3 = (\widehat{\mathbf{k}}_{\bar{b}} \times \widehat{\mathbf{k}}_b)_3$$

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

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

$$\overline{e^+e^- \to f\bar{f}}$$

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

$$d\sigma_{\rm pol} = A_1[\mathbf{P}^T_{e+} \cdot \mathbf{k} + \mathbf{P}^T_{e-} \cdot \mathbf{k}] + A_2[\mathbf{P}^T_{e+} \cdot \mathbf{k} - \mathbf{P}^T_{e-} \cdot \mathbf{k}]$$
$$+ B(\mathbf{P}^T_{e+} \cdot \mathbf{P}^T_{e-}) + C(\mathbf{P}^T_{e+} \cdot \mathbf{k})(\mathbf{P}^T_{e-} \cdot \mathbf{k}) + D(\mathbf{P}^T_{e+} \times \mathbf{P}^T_{e-}) \cdot \mathbf{p}$$
$$+ E_1[(\mathbf{P}^T_{e+} \times \mathbf{k}) \cdot \mathbf{p}](\mathbf{P}^T_{e-} \cdot \mathbf{k}) + E_2[(\mathbf{P}^T_{e-} \times \mathbf{k}) \cdot \mathbf{p}](\mathbf{P}^T_{e+} \cdot \mathbf{k})$$

$\overline{A,\ D \text{ and } E \text{ terms violate } P}$

B and C terms combine to give familiar

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

E terms give

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

Transverse polarization and CP violation, cont

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

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

Allows measuring CP violation without final-state spin analysis

Dass and Ross, 1975, 1977:

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

Ananthanarayan, Rindani, hep-ph/0309260:

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

four-fermi NP interaction:

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

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

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:

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

scalar

SM couplings

tensor

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

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:

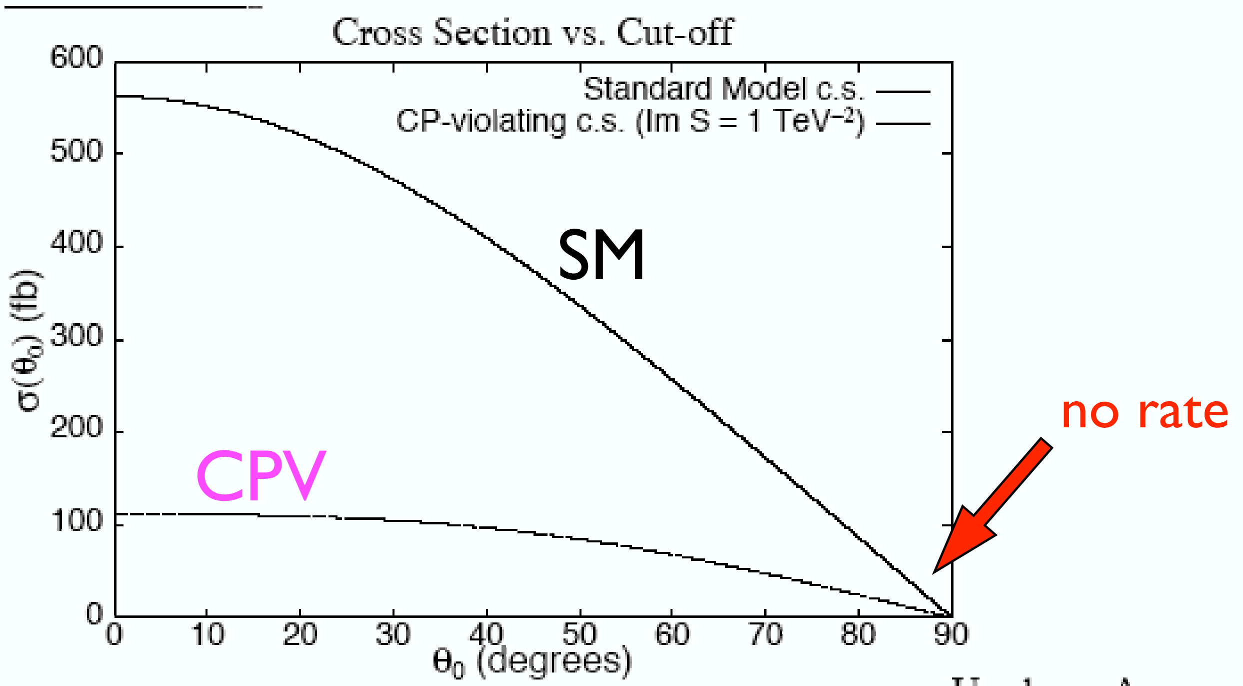
θ-integrated version:

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

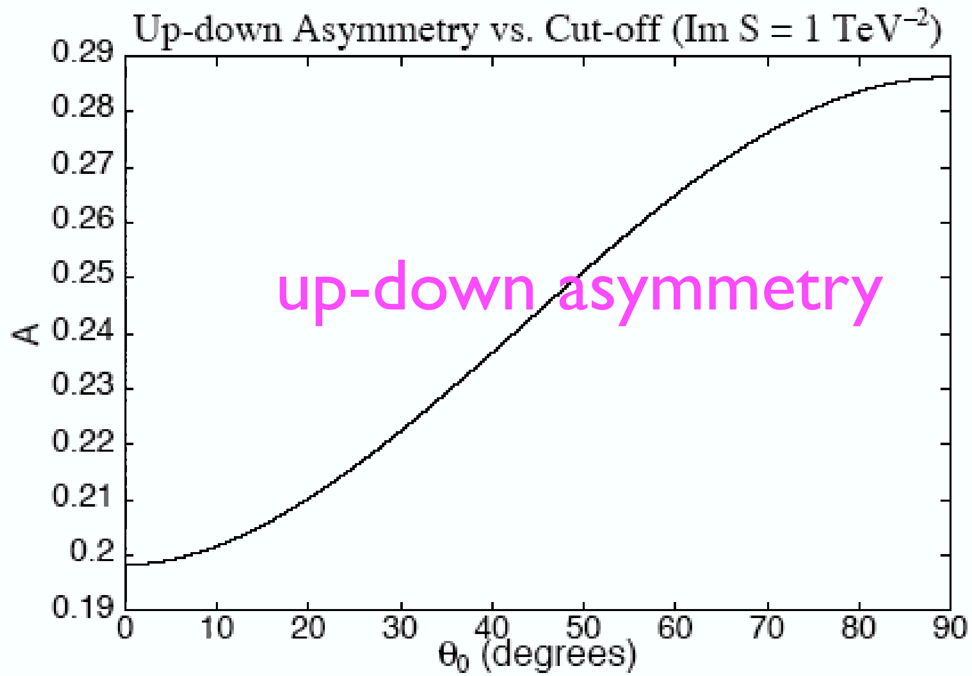
Note:

- these terms (linear in transverse polarization) can not be seen unless both beams are transversely polarized

- sensitive only to imaginary part of *S*

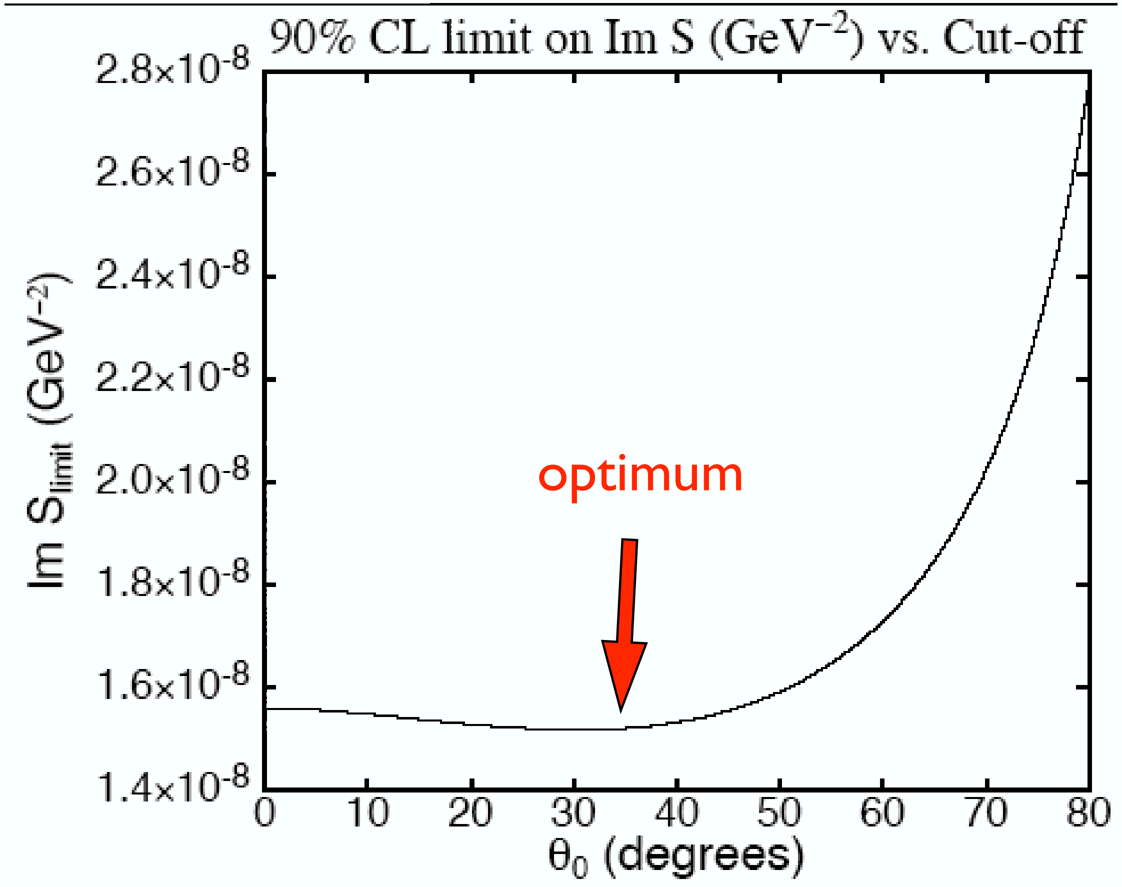


Cross Section vs. Cut-off
Standard Model c.s.
CP-violating c.s. (Im S = 1 TeV^{-2})
SM
CPV
no rate
$\sigma(\theta_0)$ (fb)
θ_0 (degrees)



Up-down Asymmetry vs. Cut-off (Im S = 1 TeV^{-2})
up-down asymmetry
A
θ_0 (degrees)

Bound on $\mathrm{Im}\, S\ [\mathrm{GeV}^{-2}]$



Corresponds to bound on Λ of order 8-10 TeV

(assuming perfect polarization)

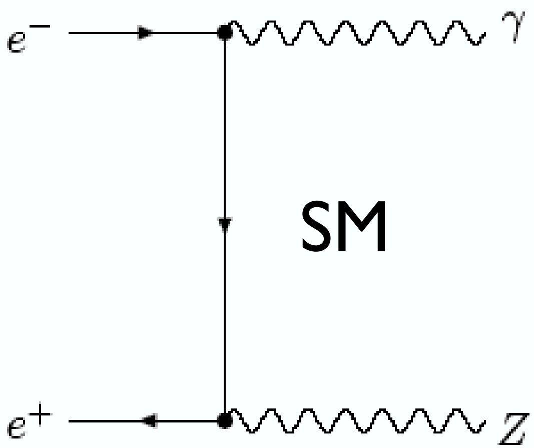
with $\alpha_i = \mathcal{O}(1)$

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

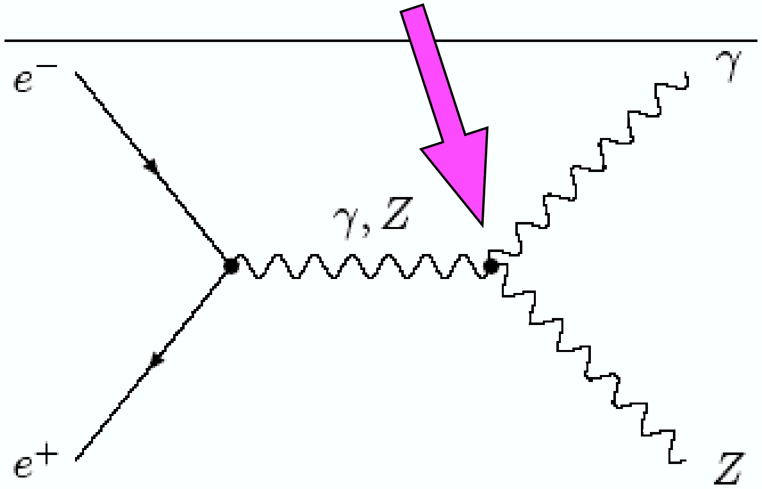
Transverse polarization and CP violation, ϒ Z production

Most general effective CP-violating Lagrangian
for ϒϒZ and ϒZZ interactions:

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



CP violation



FB asymmetry CP-odd but "naive" T even

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

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

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

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

$A_1 \sim \mathrm{Re}\,\lambda_2$ $\qquad$ $A_2,\ A_3 \sim \mathrm{Im}\,\lambda_1, \mathrm{Im}\,\lambda_2$

Integrated asymmetries:

$$A_1(\theta_0) \sim -\mathbf{P}^T_{e^-}\mathbf{P}^T_{e^+}\, g_A\, \mathrm{Re}\,\lambda_2$$

$$A_2(\theta_0) \sim \mathbf{P}^T_{e^-}\mathbf{P}^T_{e^+}\, [(g_V^2 - g_A^2)\,\mathrm{Im}\,\lambda_1 - g_V\,\mathrm{Im}\,\lambda_2]$$

$$A_3(\theta_0) \sim \Big[\frac{\pi}{2}[(g_V^2 + g_A^2)\,\mathrm{Im}\,\lambda_1 - g_V\,\mathrm{Im}\,\lambda_2] + \mathbf{P}^T_{e^-}\mathbf{P}^T_{e^+}[(g_V^2 - g_A^2)\mathrm{Im}\,\lambda_1 - g_V\,\mathrm{Im}\,\lambda_2]\Big]$$

Results, direct limits:

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

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

Extra-dimensional gravity

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

Effective interaction (Hewett):

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

parametrize strength by:

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

RS: Randall, Sundrum: hep-ph/9905221

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

Identification reaches make use of angular analysis

Osland, Pankov, Paver: hep-ph/0304123

M_H [TeV] $\sqrt{s} = 0.5$ TeV (long. pol.)	$\mathcal{L}_{\rm int}$ [fb^{-1}] 100	300	500
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

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

From azimuthal asymmetry [cos(2φ) pos vs neg]:

with

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

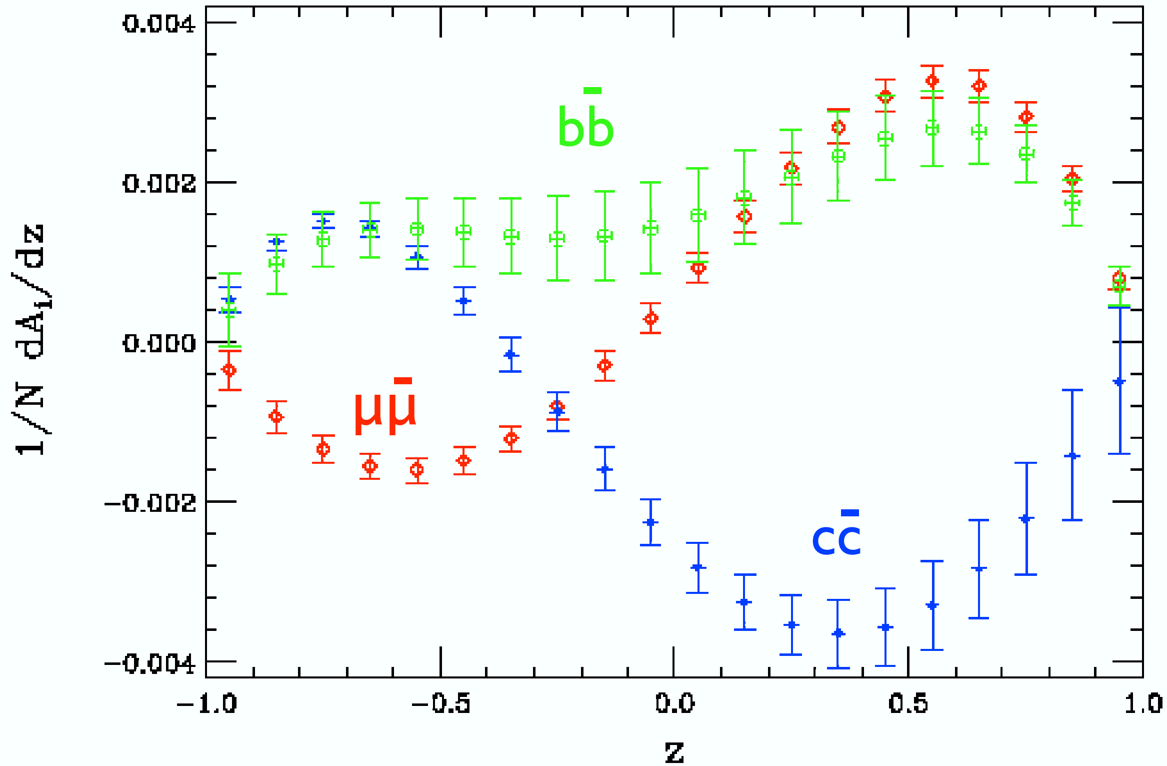
Rizzo: hep-ph/0211374

M_H [TeV] (transv. pol.)	$\mathcal{L}_{\rm int}$ [fb^{-1}] 100	300	500	1000
$\sqrt{s} = 0.5$ 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(2ϕ) 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

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

5 σ disc. reach M_H [TeV]	$\mathcal{L}_{\text{int}}$ [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

5σ 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