OPTIMAL POLARIZED OBSERVABLES FOR MODEL-INDEPENDENT NEW PHYSICS SEARCHES AT THE LINEAR COLLIDER

N. Paver

Dept. of Theoretical Physics and INFN, Trieste (Italy)

(with A.A. Babich, P. Osland and A.A. Pankov)

Abstract

For the process of fermion-pair production at a future electron-positron Linear Collider with $E_{CM} = 0.5$ TeV and longitudinally polarized electron beam, we discuss the sensitivity of helicity cross sections to four-fermion contact interactions.

The analysis is based on polarized, integrated cross sections, hopefully convenient in order to disentangle helicity cross sections from the data and derive model-independent constraints.

Optimal kinematical cuts are applied in order to increase the sensitivity of such integrated cross sections to the new interactions and improve the constraints, in particular as regards their chiral structure.

1 Introduction

Contact interaction: a convenient parameterization of deviations from the SM that may be caused by some new physics at a very large scale Λ.

We study such manifestations in high-energy

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

Lowest-dimensional, contact four-fermion $eeff$ interaction Lagrangian with helicity conserving, flavor-diagonal fermion currents (Eichten et al.; Rückl; Schildknecht; Burges et al.; Cashmore):

$$\mathcal{L} = \frac{g_{eff}^2}{\Lambda^2}\left[\eta_{LL}\left(\bar{e}_L\gamma_\mu e_L\right)\left(\bar{f}_L\gamma^\mu f_L\right) + \eta_{LR}\left(\bar{e}_L\gamma_\mu e_L\right)\left(\bar{f}_R\gamma^\mu f_R\right)\right.$$
$$\left. + \eta_{RL}\left(\bar{e}_R\gamma_\mu e_R\right)\left(\bar{f}_L\gamma^\mu f_L\right) + \eta_{RR}\left(\bar{e}_R\gamma_\mu e_R\right)\left(\bar{f}_R\gamma^\mu f_R\right)\right]$$

- Models: typical $\eta_{\alpha\beta} = \pm 1,\ 0\ (\alpha, \beta = R, L)$
- Conventionally: $g_{eff}^2 = 4\pi$ (strong at $E_{CM} \sim \Lambda$)
- Defines $\Lambda_{\alpha\beta}$: standard for comparing the power of different new-physics searches

Example: very heavy $M_{Z'} \sim \sqrt{\alpha}\,\Lambda$

Constraints on $\mathcal{L}$: look from deviations from SM predictions in the relevant experimental data.

In principle, deviations of observables (cross sections, etc.) can depend on *all* four-fermion effective coupling constants.

Current analyses usually assume non-zero value for only *one* parameter at a time, and *all* the remaining ones equal to *zero*.

Global analysis (Berger, Cheung, Hagiwara, Zeppenfeld): $\Lambda \sim \mathcal{O}(10)$ TeV

• Procedure to disentangle individual effective couplings *highly desirable*: avoid *potential cancellations* that may *weaken* the bounds

• **Polarized observables**: directly distinguish *helicity cross* sections (dependent on *individual* couplings)

• **Integrated cross sections**: advantage for limited statistics

$\Rightarrow$ Minimal set of free independent parameters in a χ^2 analysis

$\Rightarrow$ derivation of general constraints on *eell*, *eecc* and *eebb* couplings, etc.

• Optimization: choice of kinematical region $\Rightarrow$ improved sensitivity

Earlier references: Schrempp's, Wermes, Zeppenfeld; Cheung, Godfrey, Hewett; S. Riemann, talk in Oxford (no polarization)

2 Polarized integrated observables

$$e^+ + e^- \to \bar{f} + f, \qquad (f \neq e, t;\, m_f \ll \sqrt{s})$$

- s-channel $\gamma, Z + \mathcal{L}$:

$$\frac{d\sigma}{d\cos\theta} = \frac{3}{8}\left[(1+\cos\theta)^2\,\tilde{\sigma}_+ + (1-\cos\theta)^2\,\tilde{\sigma}_-\right]$$

Helicity cross sections:

$$\tilde{\sigma}_+ = \frac{1}{4}\,[(1+P_e)(1-P_{\bar{e}})\,\sigma_{RR} + (1-P_e)(1+P_{\bar{e}})\,\sigma_{LL}]$$

$$\tilde{\sigma}_- = \frac{1}{4}\,[(1+P_e)(1-P_{\bar{e}})\,\sigma_{RL} + (1-P_e)(1+P_{\bar{e}})\,\sigma_{LR}]$$

Helicity amplitudes ($\alpha, \beta = L, R$):

$$\sigma_{\alpha\beta} = [N_C]\,\frac{4\pi\alpha_{em}^2}{3s}\,|A_{\alpha\beta}|^2$$

$$A_{\alpha\beta} = (Q_e)_\alpha (Q_f)_\beta + g_\alpha^e\, g_\beta^f\, \chi_Z + \frac{s\eta_{\alpha\beta}}{\alpha_{em}\Lambda^2},$$

- SM values:

$$g_L^f = (I_{3L}^f - Q_f s_W^2)/s_W c_W; \quad g_R^f = Q_f s_W^2/s_W c_W$$

$$\chi_Z = s/(s - M_Z^2 + is\Gamma_Z/M_Z)$$

Total cross section:

$$\begin{aligned}\sigma &= \int_{-1}^{1} \frac{d\sigma}{d\cos\theta} d\cos\theta \equiv \sigma_{\rm F} + \sigma_{\rm B} \\ &= \frac{1}{4}\left[(1+P_e)(1-P_{\bar e})(\sigma_{RR}+\sigma_{RL})\right. \\ &+ \left.(1-P_e)(1+P_{\bar e})(\sigma_{LL}+\sigma_{LR})\right]\end{aligned}$$

Forward-backward asymmetry:

$$\begin{aligned}\sigma\, A_{\rm FB} &= (\sigma_{\rm F} - \sigma_{\rm B}) \\ &= \frac{3}{4}\left[(1+P_e)\,(1-P_{\bar e})\,(\sigma_{RR}-\sigma_{RL})\right. \\ &+ \left.(1-P_e)\,(1+P_{\bar e})\,(\sigma_{LL}-\sigma_{LR})\right]\end{aligned}$$

- depend on *all* helicity cross sections ⇒ do not allow separation by themselves (even with polarization)
- Combinations of σ and A_{FB} are needed (4 measmts)

More general integration range:

- more convenient for discussion of expected uncertainties and corresponding sensitivities to parameters in $\mathcal{L}$
- maximal sensitivity & significance of the resulting bounds

3 Separation of the helicity cross sections

'Direct' projection of $\tilde{\sigma}_\pm$ as differences of integrated polarized observables (Frere, Novikov, Vysotsky):

- Define $z^*_\pm \equiv \cos\theta^*_\pm$:

$$\left(\int_{z^*_\pm}^{1} - \int_{-1}^{z^*_\pm}\right)(1 \mp \cos\theta)^2\, d\cos\theta = 0$$

- $z^*_\pm = \mp(2^{2/3} - 1) = \mp 0.59 \Rightarrow \theta^*_+ = 126^\circ,\ \theta^*_- = 54^\circ$

$(|\cos\theta| < c \Rightarrow |z^*_\pm| = (1 + 3c^2)^{1/3} - 1)$

- Integrated observables:

$$\sigma_{1+} - \sigma_{2+} \equiv \left(\int_{z^*_+}^{1} - \int_{-1}^{z^*_+}\right)\frac{d\sigma}{d\cos\theta}\, d\cos\theta$$

$$\sigma_{1-} - \sigma_{2-} \equiv \left(\int_{-1}^{z^*_-} - \int_{z^*_-}^{1}\right)\frac{d\sigma}{d\cos\theta}\, d\cos\theta$$

Numerically:

$$\tilde{\sigma}_+ = \gamma\,(\sigma_{1+} - \sigma_{2+})$$

$$\tilde{\sigma}_- = \gamma\,(\sigma_{2-} - \sigma_{1-})$$

with

$$\gamma = \left[3\left(2^{2/3} - 2^{1/3}\right)\right]^{-1} = 1.018$$

Corresponding to the different electron beam longitudinal polarizations:

$$P_e = \pm 1,\ P_{\bar{e}} = 0\ : \qquad \tilde{\sigma}_+ \propto \sigma_{RR},\ \sigma_{LL}$$

$$P_e = \pm 1,\ P_{\bar{e}} = 0\ : \qquad \tilde{\sigma}_- \propto \sigma_{RL},\ \sigma_{LR}$$

In practice, polarization will not be exact, i.e., $|P_e| < 1$

- assume $P_e = \pm P$, $P_{\bar{e}} = 0$

$$\sigma_{RR} = \frac{1+P}{P}\tilde{\sigma}_+(P) - \frac{1-P}{P}\tilde{\sigma}_+(-P)$$

$$\sigma_{LL} = \frac{1+P}{P}\tilde{\sigma}_+(-P) - \frac{1-P}{P}\tilde{\sigma}_+(P)$$

- analogous for $\tilde{\sigma}_{RL}$, $\tilde{\sigma}_{LR}$: $\sigma_+(\pm P) \Rightarrow \sigma_-(\pm P)$

4 Optimization

More generally:

$$
\begin{aligned}
\sigma_1(z^*) &\equiv \int_{z^*}^{1} \frac{d\sigma}{d\cos\theta} d\cos\theta \\
&= \frac{1}{8}\left\{\left[8-(1+z^*)^3\right]\tilde{\sigma}_+ + (1-z^*)^3\,\tilde{\sigma}_-\right\}
\end{aligned}
$$

$$
\begin{aligned}
\sigma_2(z^*) &\equiv \int_{-1}^{z^*} \frac{d\sigma}{d\cos\theta} d\cos\theta \\
&= \frac{1}{8}\left\{(1+z^*)^3\,\tilde{\sigma}_+ + \left[8-(1-z^*)^3\right]\tilde{\sigma}_-\right\}
\end{aligned}
$$

$$
\begin{aligned}
\tilde{\sigma}_+ &= \frac{1}{6(1-z^{*2})}\left[\left(8-(1-z^*)^3\right)\sigma_1(z^*) - (1-z^*)^3\,\sigma_2(z^*)\right] \\
\tilde{\sigma}_- &= \frac{1}{6(1-z^{*2})}\left[-(1+z^*)^3\,\sigma_1(z^*) + \left(8-(1+z^*)^3\right)\sigma_2(z^*)\right]
\end{aligned}
$$

Specific cases:

(i) $z^* = 0$: $\sigma_1 = \sigma_F,\ \sigma_2 = \sigma_B \Rightarrow \tilde{\sigma}_\pm = \frac{1}{2}\sigma\left(1 \pm \frac{4}{3}A_{FB}\right)$

(ii) $z^* = z^*_+ = -0.59$: $\Rightarrow \tilde{\sigma}_+ = \gamma\left(\sigma_{1+} - \sigma_{2+}\right)$ •

(iii) $z^* = z^*_- = 0.59$: $\Rightarrow \tilde{\sigma}_- = \gamma\left(\sigma_{2-} - \sigma_{1-}\right)$ •

- Might be tuned for maximum sensitivity to Λ's

5 Radiative corrections

Including SM one-loop SM electroweak radiative corrections:

- improved Born approximation
- best known SM parameters: G_F, M_Z and $\alpha(M_Z^2)$
- replacements:

$$\alpha_{em} \Rightarrow \alpha_{e.m.}(M_Z^2)$$

$$g_L^f \Rightarrow \frac{1}{\sqrt{\kappa}}\left(I_{3L}^f - Q_f \sin^2\theta_W^{\mathrm{eff}}\right), \qquad g_R^f \Rightarrow -\frac{Q_f}{\sqrt{\kappa}}\sin^2\theta_W^{\mathrm{eff}}$$

$$\sin^2\theta_W \Rightarrow \sin^2\theta_W^{\mathrm{eff}}, \qquad \sin^2(2\theta_W^{\mathrm{eff}}) \equiv \kappa = \frac{4\pi\alpha(M_Z^2)}{\sqrt{2}G_\mathrm{F}\, M_Z^2\rho}$$

$$\rho \approx 1 + \frac{3G_\mathrm{F}m_{top}^2}{8\pi^2\sqrt{2}}$$

Initial/final state radiation

- radiative return to the Z peak:

$$\frac{s'}{s} = \left(1 - \frac{E_\gamma}{E_{beam}}\right) > \frac{M_Z^2}{s}$$

$\Delta \equiv \frac{E_\gamma}{E_{beam}} = 0.9$

- numerical analysis: program ZEFIT & ZFITTER (Riemann; Bardin), input $m_{top} = 175$ GeV and $m_H = 300$ GeV

6 Numerical analysis and bounds on Λ

For $\sqrt{s} \ll \Lambda$: contact interaction contributes *via* interference term:

$$\begin{aligned} \Delta\sigma_{\alpha\beta} &\equiv \sigma_{\alpha\beta} - \sigma_{\alpha\beta}^{SM} \\ &= N_C\,\sigma_{\rm pt}\,2\left(Q_e\,Q_f + g_\alpha^e\,g_\beta^f\,\chi_Z\right)\cdot\frac{s\eta_{\alpha\beta}}{\alpha_{em}\Lambda^2} \end{aligned}$$

$(\alpha, \beta = L, R)$

- independent individual couplings disentangled

$\Rightarrow$ no possibility of accidental cancellations in interference terms

χ^2 analysis of 'experimental data' for $\sigma_{\alpha\beta}$:

- Suppose *no deviation* is observed within the expected experimental uncertainty:
- assessment of sensitivity $\Rightarrow$ constraints on contact interaction couplings
- $\chi^2 = \left(\frac{\Delta\sigma_{\alpha\beta}}{\delta\sigma_{\alpha\beta}}\right)^2$
- $\delta\sigma_{\alpha\beta}$ combines statistical and systematic uncertainties
- criterion: $\chi^2 < \chi^2_{\rm crit}$
- $\chi^2_{\rm crit}$ specifies the desired 'confidence' level:
- typical $\chi^2_{crit} = 3.84$ for 95% C.L. with a one-parameter fit.

Inputs

Identification efficiencies ϵ and systematic uncertainties δ^{sys}:

- $\epsilon = 100\%$ and $\delta^{sys} = 0.5\%$ for leptons
- $\epsilon = 60\%$ and $\delta^{sys} = 1\%$ for b quarks
- $\epsilon = 35\%$ and $\delta^{sys} = 1.5\%$ for c quarks

Luminosity:

- $\sqrt{s} = 0.5\,\text{TeV}$: $L_{int} = 50\,\text{fb}^{-1}$, and $\frac{1}{2}L_{int}$ for each polarizations $P_e = \pm P$
- $\sqrt{s} = 0.5\,\text{TeV}$: $L_{int} = 500\,\text{fb}^{-1}$, and $\frac{1}{2}L_{int}$ for each polarizations $P_e = \pm P$

Qualitatively, bounds on Λ:

$$\Lambda^{-2}_{(\alpha\beta)} < \sqrt{\chi^2_{crit}}\,\frac{\alpha_{e.m.}}{s}\,\frac{\delta\sigma_{\alpha\beta}}{N_C\sigma_{pt}\,|A^{SM}_{\alpha\beta}|}. \qquad (\alpha,\beta = L,R)$$

with $\sigma_{pt} = \dfrac{4\pi\alpha^2_{em}}{3s}$

- Sensitivity of $\sigma_{\alpha\beta}$ to Λ:

$$S = \frac{(\Delta\sigma_{\alpha\beta}/\sigma_{\alpha\beta})}{\underbrace{(\delta\sigma_{\alpha\beta}/\sigma_{\alpha\beta})}_{\sigma_{1,2}(z^*)}} \quad \begin{matrix}\leftarrow \text{deviation} \\ \leftarrow \text{expected uncertainty}\end{matrix}$$

Table 1: Contact-interaction reach (in TeV) at an e^+e^- linear collider with $E_{\rm c.m.} = 0.5$ TeV and $\mathcal{L}_{\rm int} = 50\,{\rm fb}^{-1}$, at 95% C.L. Radiative corrections are included, with a cut on the energy of photons emitted in the initial state. The arrows indicate the increase of sensitivity of the observables obtained by the optimization.

process	P	$\Lambda_{\rm LL}$	$\Lambda_{\rm RR}$	$\Lambda_{\rm LR}$	$\Lambda_{\rm RL}$
$\mu^+\mu^-$	1.0	$40 \to 41$	$39 \to 40$	$26 \to 40$	$28 \to 41$
	0.8	$37 \to 38$	$37 \to 38$	$25 \to 37$	$26 \to 37$
	0.5	$32 \to 32$	$31 \to 32$	$21 \to 30$	$21 \to 30$
$\bar{b}b$	1.0	$41 \to 42$	$45 \to 47$	$17 \to 31$	$34 \to 42$
	0.8	$40 \to 41$	$38 \to 39$	$17 \to 29$	$29 \to 38$
	0.5	$36 \to 37$	$29 \to 29$	$13 \to 25$	$22 \to 31$
$\bar{c}c$	1.0	$32 \to 33$	$36 \to 37$	$21 \to 32$	$20 \to 30$
	0.8	$31 \to 32$	$32 \to 33$	$20 \to 31$	$18 \to 27$
	0.5	$27 \to 28$	$26 \to 27$	$18 \to 27$	$15 \to 22$

Table 2: Same as Table 1, but at $\mathcal{L}_{\rm int} = 500\,{\rm fb}^{-1}$. Radiative corrections are included.

process	P	$\Lambda_{\rm LL}$	$\Lambda_{\rm RR}$	$\Lambda_{\rm LR}$	$\Lambda_{\rm RL}$
$\mu^+\mu^-$	1.0	$54 \to 55$	$55 \to 56$	$37 \to 57$	$40 \to 59$
	0.8	$51 \to 52$	$51 \to 53$	$35 \to 54$	$38 \to 55$
	0.5	$44 \to 45$	$43 \to 44$	$31 \to 46$	$31 \to 47$
$\bar{b}b$	1.0	$48 \to 49$	$64 \to 67$	$26 \to 50$	$50 \to 66$
	0.8	$47 \to 48$	$51 \to 53$	$25 \to 48$	$41 \to 61$
	0.5	$43 \to 44$	$36 \to 37$	$23 \to 43$	$30 \to 47$
$\bar{c}c$	1.0	$35 \to 37$	$42 \to 43$	$24 \to 44$	$24 \to 47$
	0.8	$34 \to 35$	$38 \to 39$	$23 \to 43$	$22 \to 41$
	0.5	$30 \to 32$	$29 \to 30$	$21 \to 39$	$18 \to 32$

95% CL

Left entries: $z^* = z^*_\pm \Rightarrow \sigma_{1\pm}\,;\ \sigma_{2\pm}$

- best sensitivity to Λ: $b\bar{b}$ (worst for $c\bar{c}$)
- dependence on P
- with $\delta^{\rm stat}$ only: Λ scales as $\Lambda \sim (s\,\mathcal{L}_{\rm int})^{1/4}$
- Λ_{RL} and Λ_{LR}: dominates $\delta^{\rm stat}$
- Λ_{RR} and Λ_{LL}: dominates $\delta^{\rm sys}$
- Generally: higher sensitivity if also $P_{e^+} \neq 0$ (provided same level of luminosity)
- Sensitivity of σ_{RL}, σ_{LR} considerably smaller than σ_{LL}, σ_{RR}

Table 1 ($\mathcal{L}_{int} = 50\ fb^{-1}$; 95% CL)

process	P	Λ_{LL}	Λ_{RR}	Λ_{LR}	Λ_{RL}
$\mu^+\mu^-$	1.0	$40 \to 41$	$39 \to 40$	$26 \to 40$	$28 \to 41$
	0.8	$37 \to 38$	$37 \to 38$	$25 \to 37$	$26 \to 37$
	0.5	$32 \to 32$	$31 \to 32$	$21 \to 30$	$21 \to 30$
$\bar{b}b$	1.0	$41 \to 42$	$45 \to 47$	$17 \to 31$	$34 \to 42$
	0.8	$40 \to 41$	$38 \to 39$	$17 \to 29$	$29 \to 38$
	0.5	$36 \to 37$	$29 \to 29$	$13 \to 25$	$22 \to 31$
$\bar{c}c$	1.0	$32 \to 33$	$36 \to 37$	$21 \to 32$	$20 \to 30$
	0.8	$31 \to 32$	$32 \to 33$	$20 \to 31$	$18 \to 27$
	0.5	$27 \to 28$	$26 \to 27$	$18 \to 27$	$15 \to 22$

Table 2 ($\mathcal{L}_{int} = 500\ fb^{-1}$; 95% CL)

process	P	Λ_{LL}	Λ_{RR}	Λ_{LR}	Λ_{RL}
$\mu^+\mu^-$	1.0	$54 \to 55$	$55 \to 56$	$37 \to 57$	$40 \to 59$
	0.8	$51 \to 52$	$51 \to 53$	$35 \to 54$	$38 \to 55$
	0.5	$44 \to 45$	$43 \to 44$	$31 \to 46$	$31 \to 47$
$\bar{b}b$	1.0	$48 \to 49$	$64 \to 67$	$26 \to 50$	$50 \to 66$
	0.8	$47 \to 48$	$51 \to 53$	$25 \to 48$	$41 \to 61$
	0.5	$43 \to 44$	$36 \to 37$	$23 \to 43$	$30 \to 47$
$\bar{c}c$	1.0	$35 \to 37$	$42 \to 43$	$24 \to 44$	$24 \to 47$
	0.8	$34 \to 35$	$38 \to 39$	$23 \to 43$	$22 \to 41$
	0.5	$30 \to 32$	$29 \to 30$	$21 \to 39$	$18 \to 32$

- Improved sensitivity : $\delta\sigma_{\alpha\beta}$ minimum $\Rightarrow z^*_{opt}$ ⊙
- No improvement on Λ_{RR} and Λ_{LL}

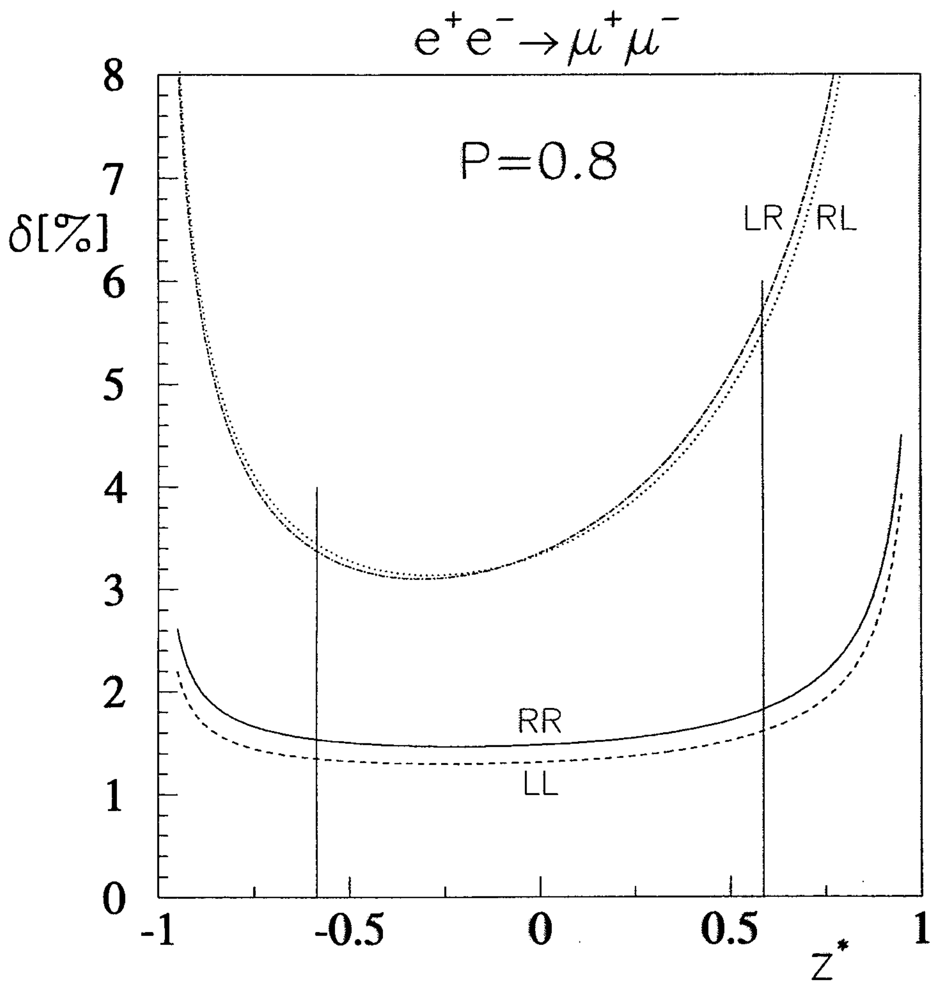
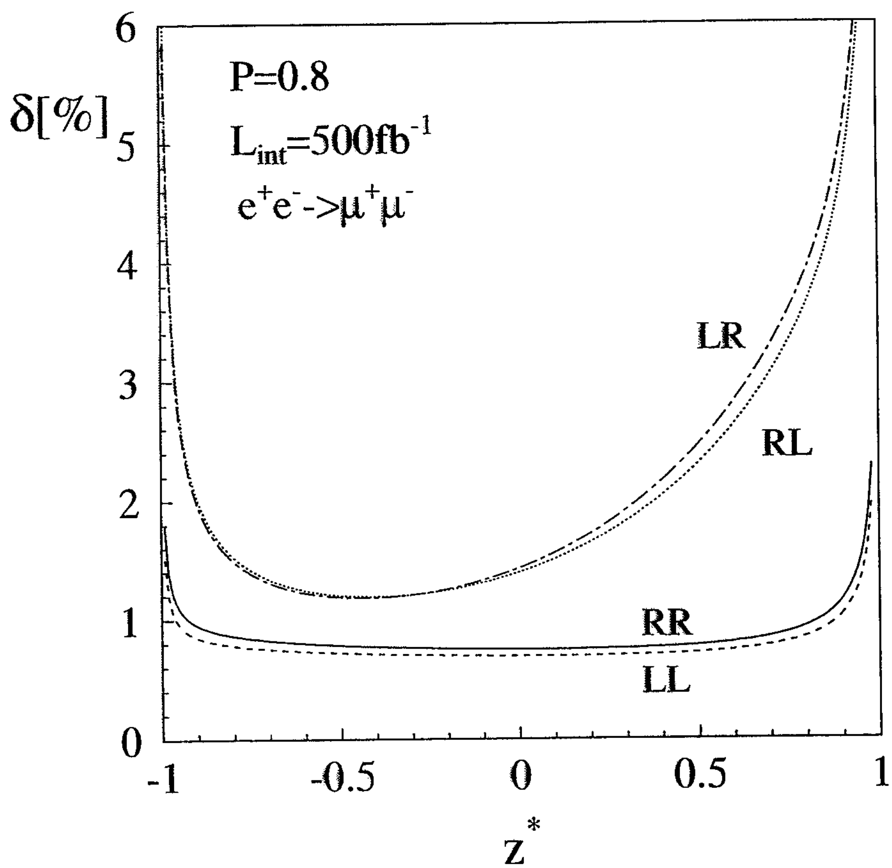


Figure 1: The uncertainty on the helicity cross sections $\sigma_{\alpha\beta}$ in the SM as a function of z^* for the process $e^+e^- \to \mu^+\mu^-$ at $\sqrt{s} = 0.5$ TeV, $\mathcal{L}_{\rm int} = 50$ fb^{-1}, $P = 0.8$, $\epsilon = 100\%$ and $\delta^{\rm sys} = 0.5\%$. Radiative corrections are included.


P=0.8
L_int=500fb^-1
e+e- -> μ+μ-
δ[%]
LR
RL
RR
LL
z*
0
1
2
3
4
5
6
-1
-0.5
0
0.5
1

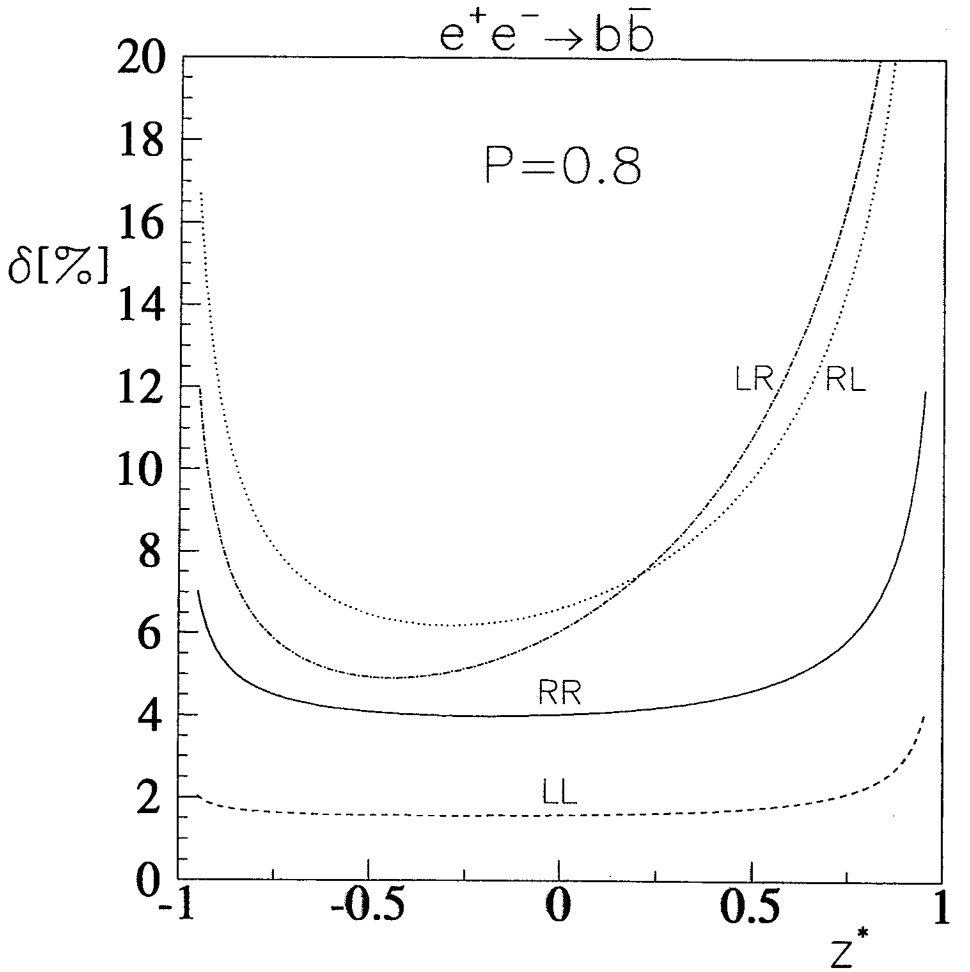
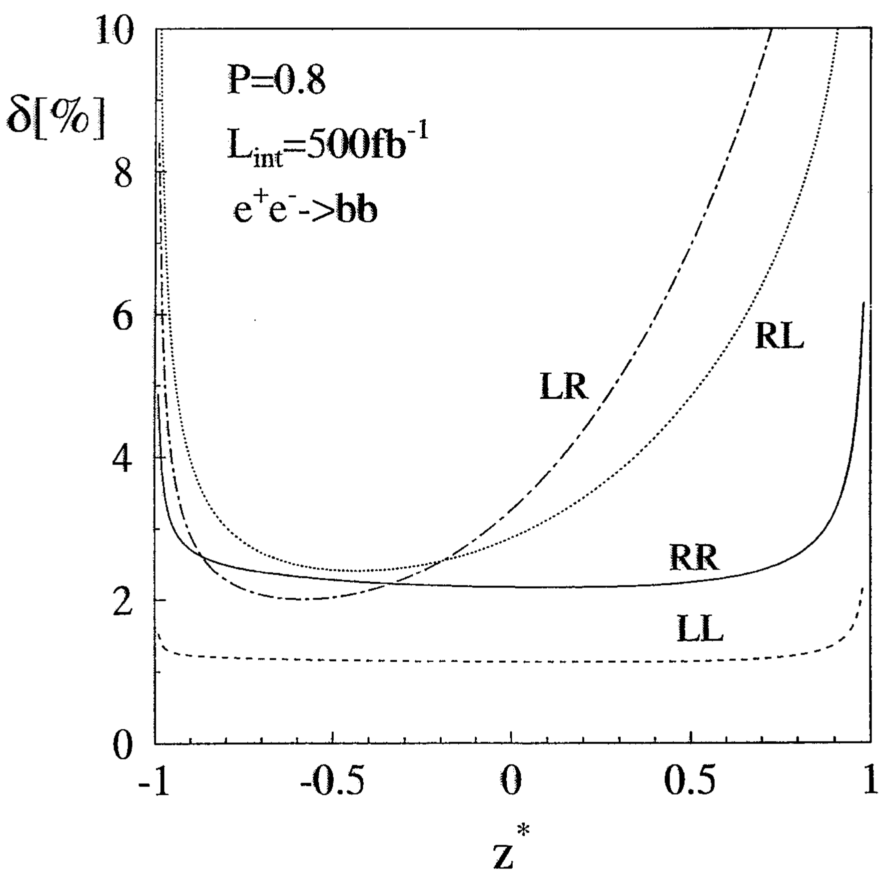


Figure 2: Same as in Fig. 1, but for the process $e^+e^- \to \bar{b}b$ at $\epsilon = 60\%$ and $\delta^{sys} = 1.0\%$.



P=0.8
L_int=500fb^-1
e+e- ->bb
δ[%]
LR
RL
RR
LL
z*
10
8
6
4
2
0
-1
-0.5
0
0.5
1

CONCLUSIONS

- analysis disentangles the four effective couplings of C.I. Lagrangian via separate measmt. of individual helicity cross sections from polarized integrated observables
- With suitable kinematical bins: optimal sensitivity (in principle)
- C.I. can be probed up to Λ's of order 40-100 times E_{CM} (dep. on initial helicity and final flavor)