Indications of New physics in Fermion Pair Production

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Outline:

- Sensitivity w/o e^+ polarization
- New Physics:
  - Contact interaction, extra dimensions
  - Z'
  - Exchange of leptoquarks
  - Comparison LC and LHC

e$^+$e$^-$ $\to f\bar{f}$ at LC:

interference of virtual γ and Z exchange with NP

$$\frac{d\sigma}{d\cos\theta} \sim \frac{d\sigma(\mathrm{SM})}{d\cos\theta} + \frac{d\sigma(\gamma \otimes NP, Z \otimes NP)}{d\cos\theta} + \frac{d\sigma(NP)}{d\cos\theta}$$

$\sigma(\gamma \otimes NP, Z \otimes NP)$: main contribution to potential deviations from SM expectations

Already studied:

- Z$'$: sensitivity, resolution power
- CI, Extra Dimensions
- LQ, $\tilde{q}$: sensitivity above kin. limit
- details see DESY 123/A...E, Talks & proceeedings at workshops and conferences and ref. therein

HERE:

- gain with polarization of positrons
- 'realistic' error scenarios
- Comparison with LHC

Four-fermion contact interaction

general framework to describe interactions beyond the SM

$$\mathcal{L}_{eff} \sim \sum_{i,k=L,R} \eta_{ik} \frac{g^2}{\Lambda_{ik}^2} (\bar{\mathrm{e}}_i \gamma^\mu \mathrm{e}_i)(\bar{f}_k \gamma^\mu f_k)$$

C.I. models

Model	η_{LL}	η_{RR}	η_{LR}	η_{RL}
LL	± 1	0	0	0
RR	0	± 1	0	0
LR	0	0	± 1	0
RL	0	0	0	± 1
VV	± 1	± 1	± 1	± 1
AA	± 1	± 1	∓ 1	∓ 1
V0	± 1	± 1	0	0
A0	0	0	± 1	± 1

$\Lambda \approx \lambda / m_X$

$$\frac{d\sigma_{L,R}}{d\cos\theta} = \sum_{i,j=\mathsf{L},\mathsf{R}} \rho_{i,j} |\mathcal{A}_{i,j}|^2$$

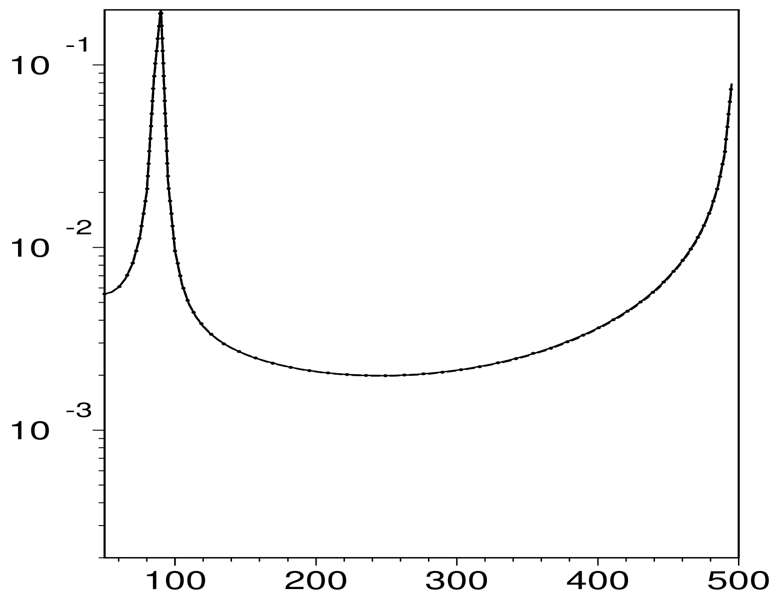
with helicity amplitudes

$$\begin{aligned}
\mathcal{A}^{ef}_{i,k} &= \left(Q_e Q_f + C^e_i C^f_k \chi + \eta_{i,k} \frac{s}{\alpha} \frac{1}{\Lambda^2} \right) \frac{t}{s}; \\
& i,k = \mathsf{L},\mathsf{R}; \quad i \neq k, \\
\mathcal{A}^{ef}_{i,i} &= \left(Q_e Q_f + C^e_i C^f_i \chi + \eta_{i,i} \frac{s}{\alpha} \frac{1}{\Lambda^2} \right) \frac{u}{s}; \\
& i = \mathsf{L},\mathsf{R}.
\end{aligned}$$

$$\begin{aligned}
\chi(s) &= \frac{s}{s - m_{\mathsf{Z}}^2 + i s \Gamma_{\mathsf{Z}}/m_{\mathsf{Z}}}; \quad \chi(t) = \frac{t}{t - m_{\mathsf{Z}}^2}, \\
C^f_{\mathsf{L}} &= v_f + a_f \\
C^f_{\mathsf{R}} &= v_f - a_f.
\end{aligned}$$

Sensitivity to New Physics Effects

- ISR $\rightarrow$ acollinear events, return to the Z peak



- non–radiative events: sensitive to NP
- $s'/s = (1 - E_\gamma/E_{beam}) > m_Z^2/s$
- LC at 500 GeV: $\sqrt{s'} > 0.6\sqrt{s}$

LEP2:

- errors of σ, A_{FB} statistically dominated
- $ee \to \mu\mu$: $\Lambda > 7.2...20$ TeV
  $ee \to uu$: $\Lambda > 2.2...16$ TeV
  $ee \to dd$: $\Lambda > 2.2...16$ TeV
  $ee \to qq$: $\Lambda > 3.4....8$ TeV

Extrapolation to higher energies:

$$\Lambda \sim \frac{m_X}{g} \sim (\mathcal{L}_{int} \times s)^{1/4}$$

Expect at LC improvement at least by factor ≈7–8!

BUT:

Limitation by syst. errors

$$\Lambda \sim (\mathcal{L}_{int} \times s)^{1/4} \times \left[1 + (\Delta sys/\Delta stat)^2\right]^{-1/4}$$

With e^+ polarization: $P_{e^-},\ P_{e^+} \Rightarrow P$;

$$P = \frac{-P_{e^-} + P_{e^+}}{1 - P_{e^-} P_{e^+}}$$

$P_{e^+} = 0.8,\ P_{e^+} = 0.6$: P=0.95
$P_{e^+} = 0.8,\ P_{e^+} = 0.4$: P=0.91

- Assume: ΔP is the dominating syst. error in A_{LR} measurement;

$$\Delta A_{LR} = \sqrt{(\Delta_{stat} A_{LR})^2 + (\Delta_{syst} A_{LR})^2}$$

$$= \sqrt{\frac{1 - P^2 A_{LR}^2}{N P^2} + A_{LR}^2 (\frac{\Delta P}{P})^2}$$

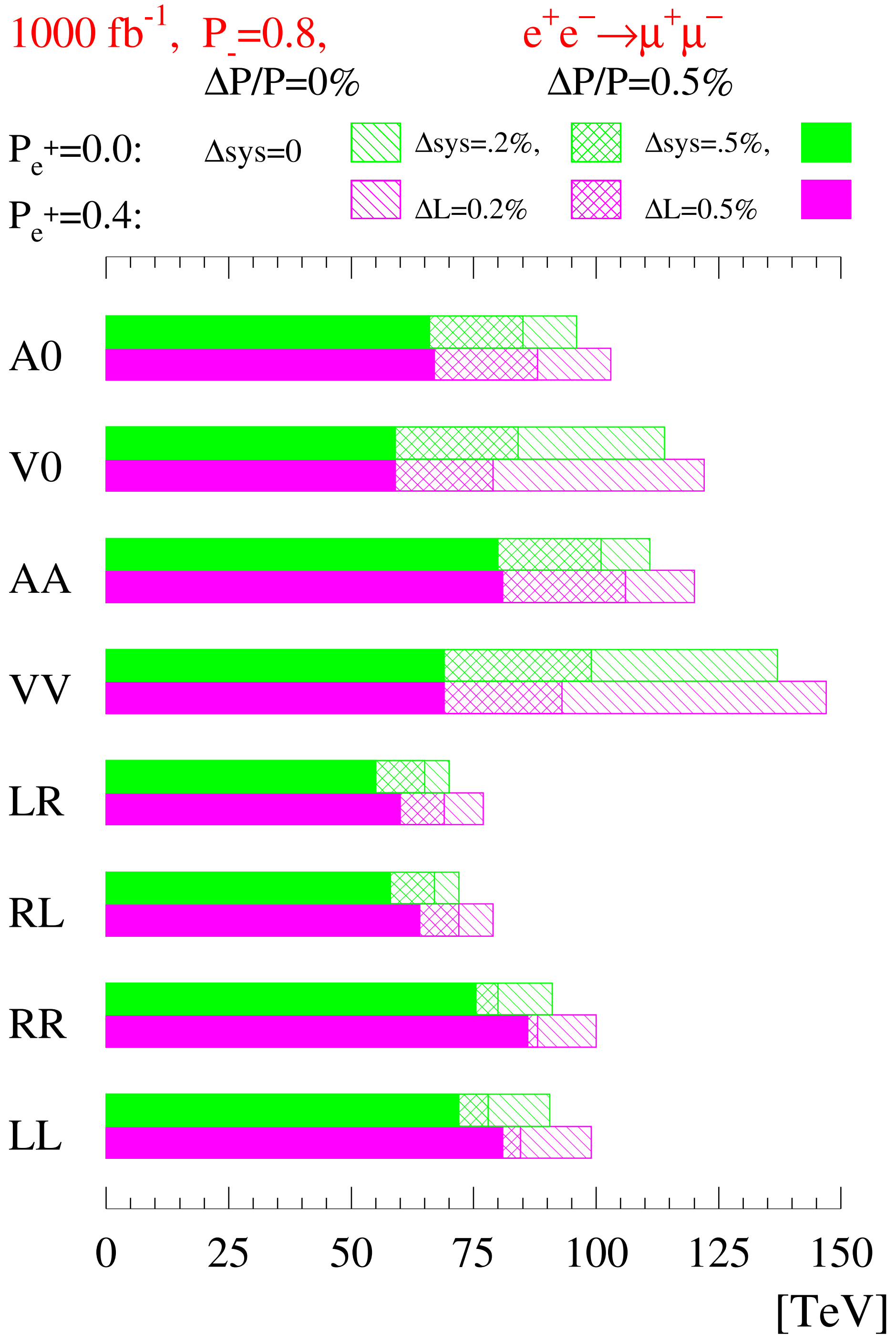
- $A_{LR}^{\mu\mu} \approx$ 6%, $\Delta_{stat} A^{\mu\mu}$ ≈0.2%
  $A_{LR}^{q\bar{q}} \approx$ 45%, $\Delta_{stat} A_{LR}^{q\bar{q}}$ ≈0.1%

- $\Delta P_{e^-},\ \Delta P_{e^+}$ should be smaller than 1% !!

'Experimental' Input

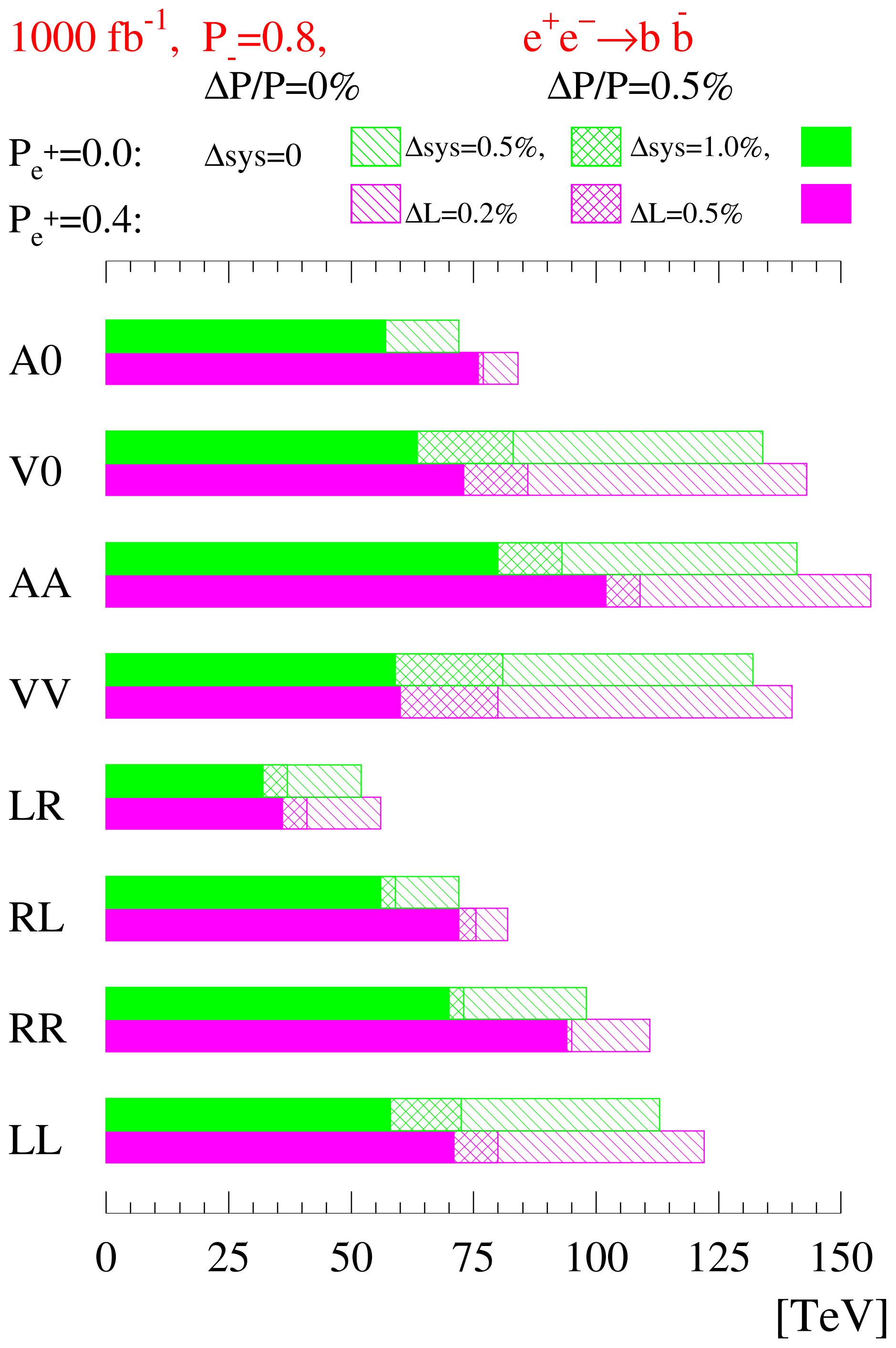
- $\sqrt{s}$ = 0.5 TeV
- $\mathcal{L}_{int}$ =1000 fb^{-1}, $\Delta\mathcal{L}$ = 0.5%, 0.2%
- experimental errors:
  - ee $\rightarrow$ $\mu\mu$:
    $\epsilon = 0.95$
    Δsys = 0.5%, 0.2%
  - ee $\rightarrow$ $hadrons$:
    $\epsilon = 0.90$
    Δsys = 0.5%; 0.02% (0.1%)
  - ee $\rightarrow$ bb:
    $\epsilon = 0.6$
    Δsys = 1.0%; 0.5%
  - ee $\rightarrow$ cc:
    $\epsilon = 0.4$
    Δsys = 1.5%; 1%
  - flavour tagging: $\cos\theta < 0.9$
- Polarization:
  P$_{e^-}$ = 80%; P$_{e^+}$ = 40%, 0%
  $\Delta P_\pm / P_\pm$ = 0.5%, 1.0% !
- Observables: σ, A_{FB}, A_{LR} and R$_b$, R$_c$

Expected Sensitivity from $ee \to \mu\mu$

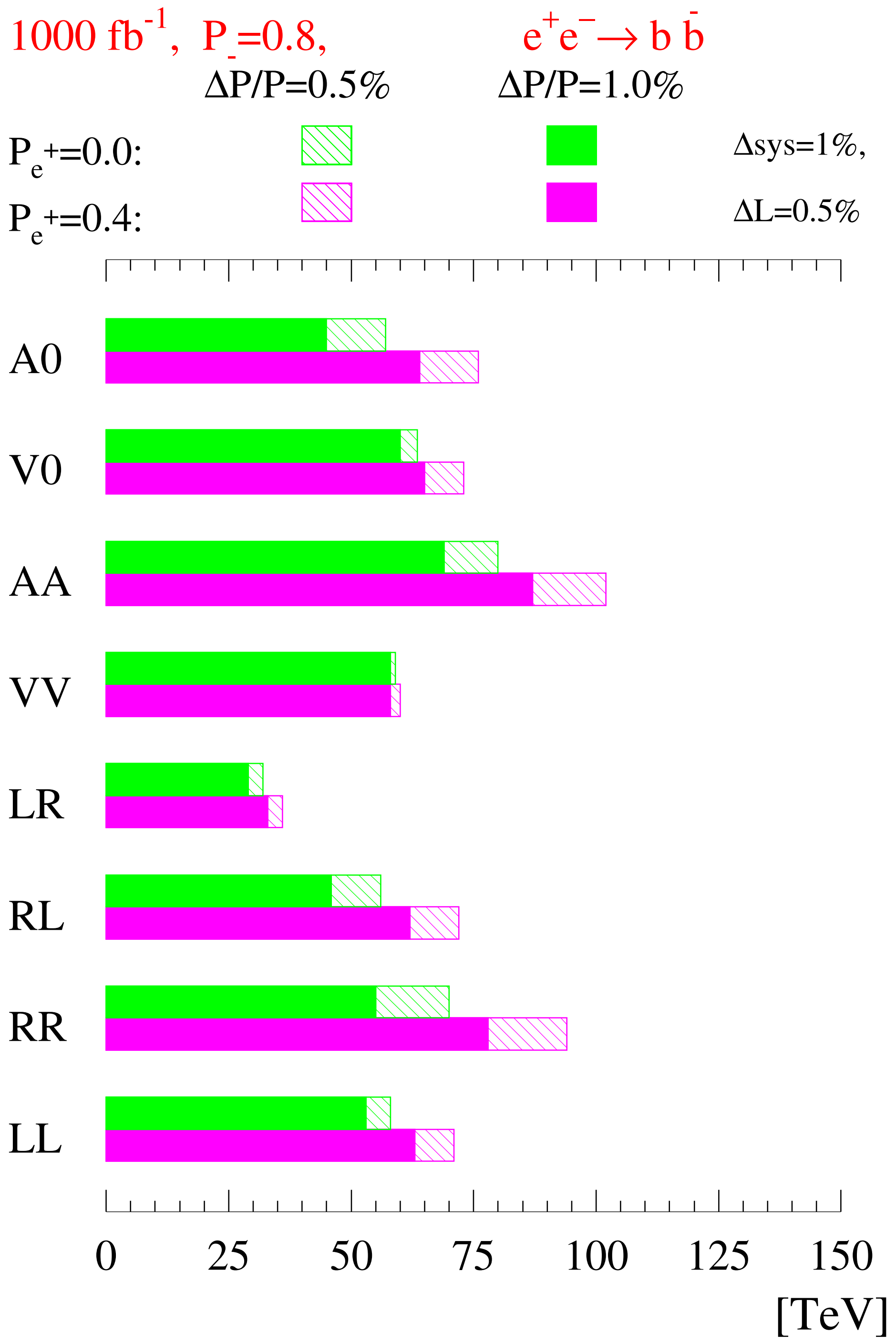


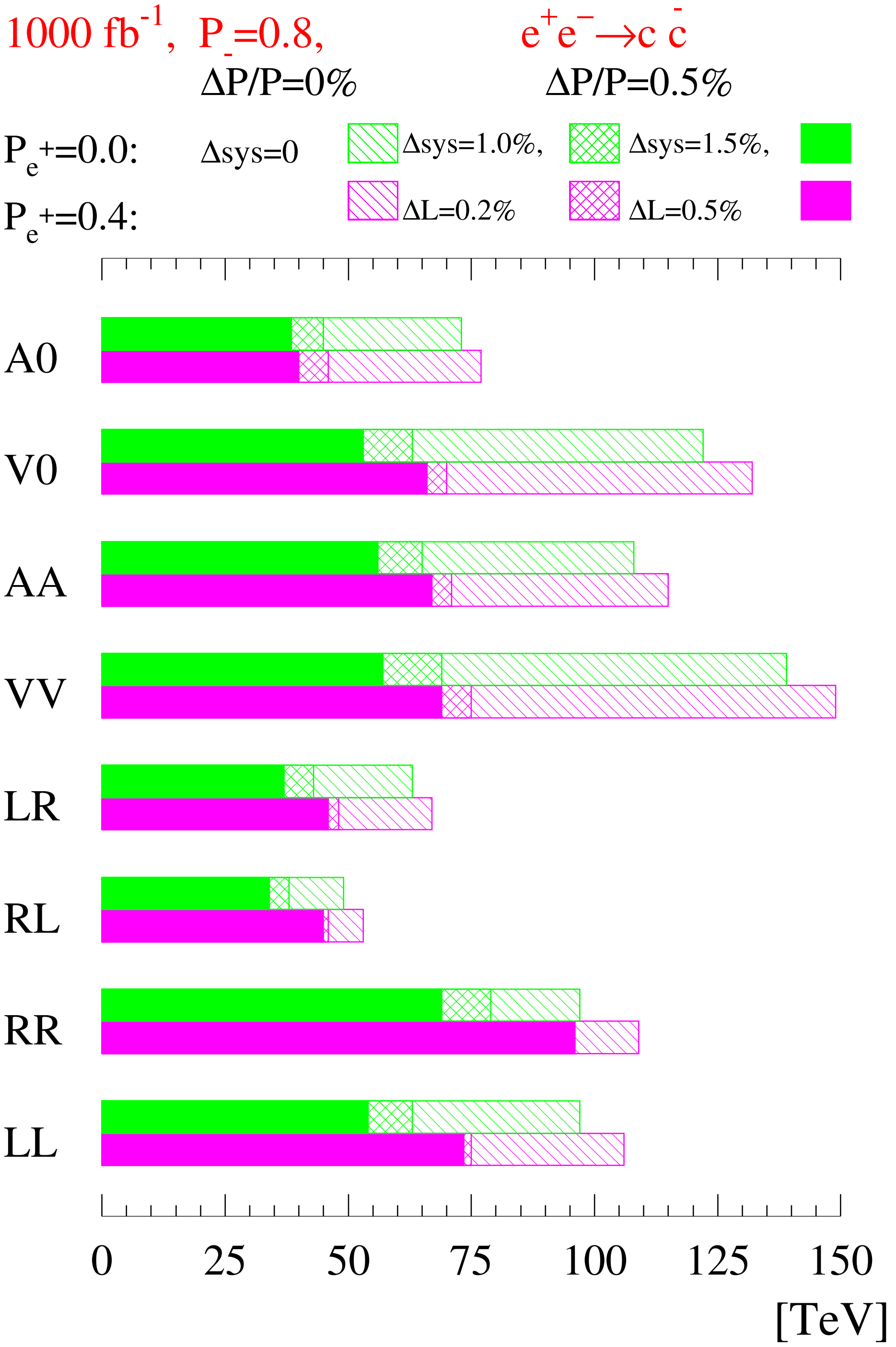
LHC is not sensitive to $ee\mu\mu$ contact interction
$\Delta P/P = 1\%$ or 0.5% is not important

Expected Sensitivity from $ee \to bb$

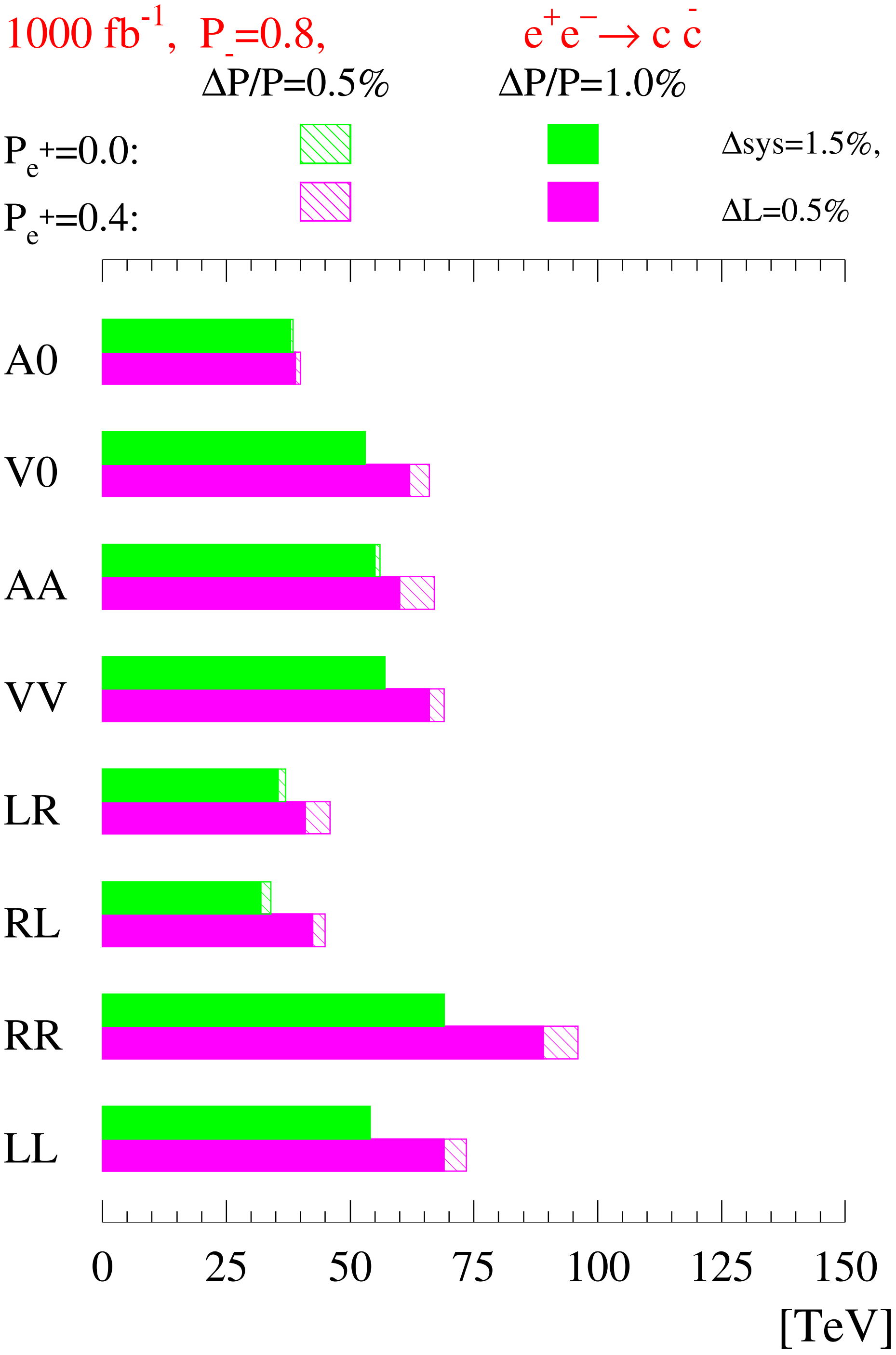


Influence of $\Delta P/P$

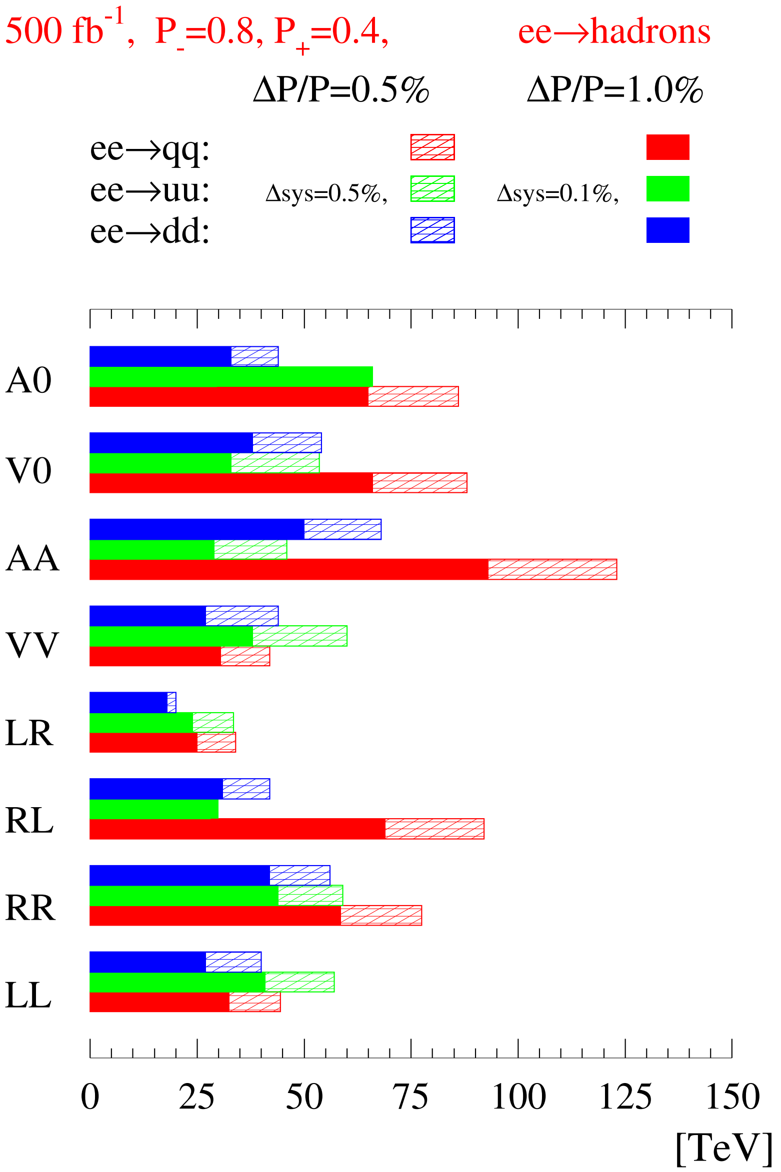



1000 fb^-1, P_-=0.8,
e+e−→c c̄
ΔP/P=0%
ΔP/P=0.5%
P_e+=0.0:
Δsys=0
Δsys=1.0%,
Δsys=1.5%,
P_e+=0.4:
ΔL=0.2%
ΔL=0.5%
A0
V0
AA
VV
LR
RL
RR
LL
0
25
50
75
100
125
150
[TeV]

Influence of $\Delta P/P$



Expected Sensitivity from $ee \to qq$



- Details in CMS NOTE 1999/075, Gupta, Jain, Mondal
- Study of deviations from SM predictions in dielectron data
- Assumptions:
  $\delta\epsilon = 4\%$; 15%
  L $=$ 10 fb^{-1}; 100 fb^{-1}, ΔL $=$ 5%
- $\Lambda_{eeqq} >$ 16... 36 TeV

	$\eta_{ij} = -1$	$\eta_{ij} = +1$	$\eta_{ij} = -1$	$\eta_{ij} = +1$
$\delta\epsilon = 4\%$	10 fb^{-1}		100 fb^{-1}	
LL	25.2	16.4	35.4	22.3
RR	25.2	16.5	35.4	22.6
LR	22.0	17.6	30.0	22.0
RL	22.4	17.4	30.7	21.9
$\delta\epsilon = 15\%$	10 fb^{-1}		100 fb^{-1}	
LL	24.0	16.4	33.8	20.1
RR	24.3	16.4	33.8	20.2
LR	21.3	17.5	29.2	22.0
RL	21.7	17.4	29.7	21.8

Direct observation: see further talks at this workshop

Indirect limits: (see also J. Hewett)
for $\sqrt{s}$ =500 GeV, L_{int} =1000 fb^{-1}, $ee \rightarrow ff$:

$$M_S \geq 5.3TeV$$

Specifics:

- angular distribution: charge identification of bb, cc final states reduces statistics
- polarisation error is not important; P_{e^+} improves the limits slightly

	M_S [TeV]	
	$P_{e^+} = 0.4$	$P_{e^+} = 0.0$
ee$\rightarrow \mu\mu$	4.05	3.78
ee$\rightarrow$ bb	4.74	4.42
ee$\rightarrow$ cc	4.73	4.38
combined	5.34	4.96

$\sqrt{s}$=800 GeV: $m_S > $ 7.6 TeV

Exchange of Leptoquarks

- LQ pair production: $m_{LQ} < \sqrt{s}/2$
- single LQ production: $m_{LQ} < \sqrt{s}$
- LQ searches at LHC:
  - max. mass reach (L=100 fb^{-1}):
    ≈ 1.47 TeV for B(LQ→lq)=100%
    ≈ 1.20 TeV for B(LQ→lq)= 50%
    (see CMS NOTE 1999/027, Abdullin, Charles, Luckel)
- indirect searches at LC: $m_{LQ} > \sqrt{s}$
  LQ's could be exchanged in ee→hadrons in u-channel ($F = L + 3B = 2$) and in t-channel ($F = 0$):

  Consider:
  - S_o, S_1, $\tilde{\mathrm{S}}_o$, $\mathrm{S}_{1/2}$, $\tilde{\mathrm{S}}_{1/2}$
  - V_o, V_1, $\tilde{\mathrm{V}}_o$, $\mathrm{V}_{1/2}$, $\tilde{\mathrm{V}}_{1/2}$
- LEP2:

  For LQ with Yukawa coupl. of el.magn. strength:
  Sensitivity up to $m_{LQ} \approx 3 \times \sqrt{s}$

Assume: $g_{L,R} = \sqrt{4\pi\alpha}$, P_{e^-}=0.8; P_{e^-}=0.4

LQ type	$m_{\rm LQ}^{min}$[TeV]		
	$\Delta P/P = 1.0\%$ $\Delta L = 0.5\%$ $\Delta_{sys}^{had} = 0.5\%$	$\Delta P/P = 0.5\%$ $\Delta L = 0.5\%$ $\Delta_{sys}^{had} = 0.5\%$	$\Delta P/P = 0.5\%$ $\Delta L = 0.2\%$ $\Delta_{sys}^{had} = 0.1\%$
$S_0(\mathrm{L}) \to \mathrm{eu}$	2.44	3.20	3.40
$S_0(\mathrm{R}) \to \mathrm{eu}$	2.63	3.49	3.57
$\tilde{S}_0(\mathrm{R}) \to \mathrm{ed}$	2.55	3.40	3.42
$S_1(\mathrm{L}) \to \mathrm{eu},\ \mathrm{ed}$	1.47	1.82	2.23
$S_{1/2}(\mathrm{L}) \to \mathrm{e\bar{u}}$	1.45	1.89	2.02
$S_{1/2}(\mathrm{R}) \to \mathrm{e\bar{u}},\ \mathrm{e\bar{d}}$	2.29	3.04	3.07
$\tilde{S}_{1/2}(\mathrm{L}) \to \mathrm{e\bar{d}}$	0.23	0.26	0.28
$V_{1/2}(\mathrm{L}) \to \mathrm{ed}$	1.23	1.45	1.72
$V_{1/2}(\mathrm{R}) \to \mathrm{eu},\ \mathrm{ed}$	0.68	0.69	0.69
$\tilde{V}_{1/2}(\mathrm{L}) \to \mathrm{eu}$	0.47	0.48	0.48
$V_0(\mathrm{L}) \to \mathrm{e\bar{d}}$	2.25	2.80	3.42
$V_0(\mathrm{R}) \to \mathrm{e\bar{d}}$	3.59	4.79	4.82
$\tilde{V}_0(\mathrm{R}) \to \mathrm{e\bar{u}}$	3.78	4.98	5.10
$V_1(\mathrm{L}) \to \mathrm{e\bar{u}},\ \mathrm{e\bar{d}}$	4.47	5.86	6.06

- case A:
  $\Delta P_{e^\pm} = 1.0\%$, $\Delta\mathcal{L} = 0.5\%$,
  $\Delta^{sys}\epsilon_{lepton} = 0.5\%$, $\Delta^{sys}\epsilon_{hadron} = 0.5\%$;

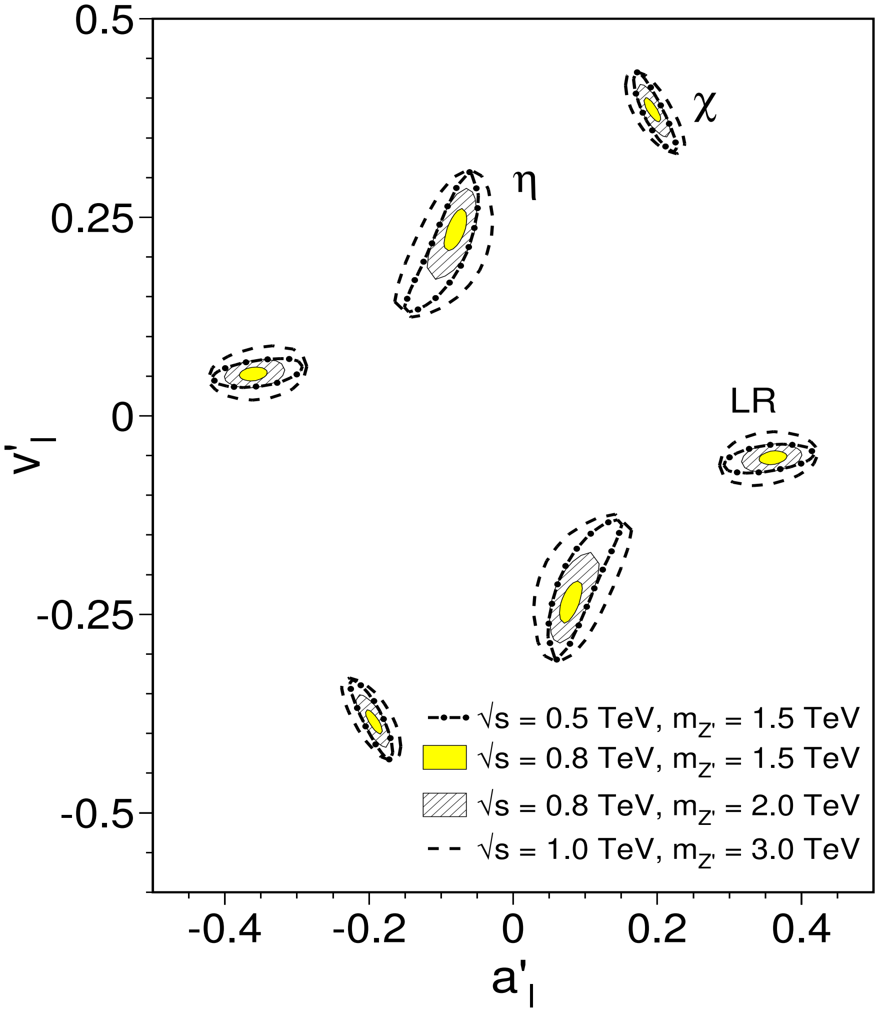
- case B:
  $\Delta P_{e^\pm} = 0.5\%$, $\Delta\mathcal{L} = 0.2\%$,
  $\Delta^{sys}\epsilon_{lepton} = 0.1\%$, $\Delta^{sys}\epsilon_{hadron} = 0.1\%$;

$\mathcal{L}_{int} = 1000\ \mathrm{fb}^{-1}$; $P_{e^-} = 80\%$; $P_{e^+} = 40\%$

$\sqrt{s}[TeV]$	errors	χ	ψ	η	LR
0.5	A	6.12	2.67	3.73	7.12
0.5	B	7.03	3.80	4.36	9.04
0.8	A	9.10	4.69	5.29	10.50
0.8	B	9.59	4.85	5.69	12.48
$P_{e^+}=0$					
0.5	A	5.47	2.41	3.26	5.21
0.5	B	6.74	3.66	4.06	7.01

$e^+ e^- \to l^+ l^-$

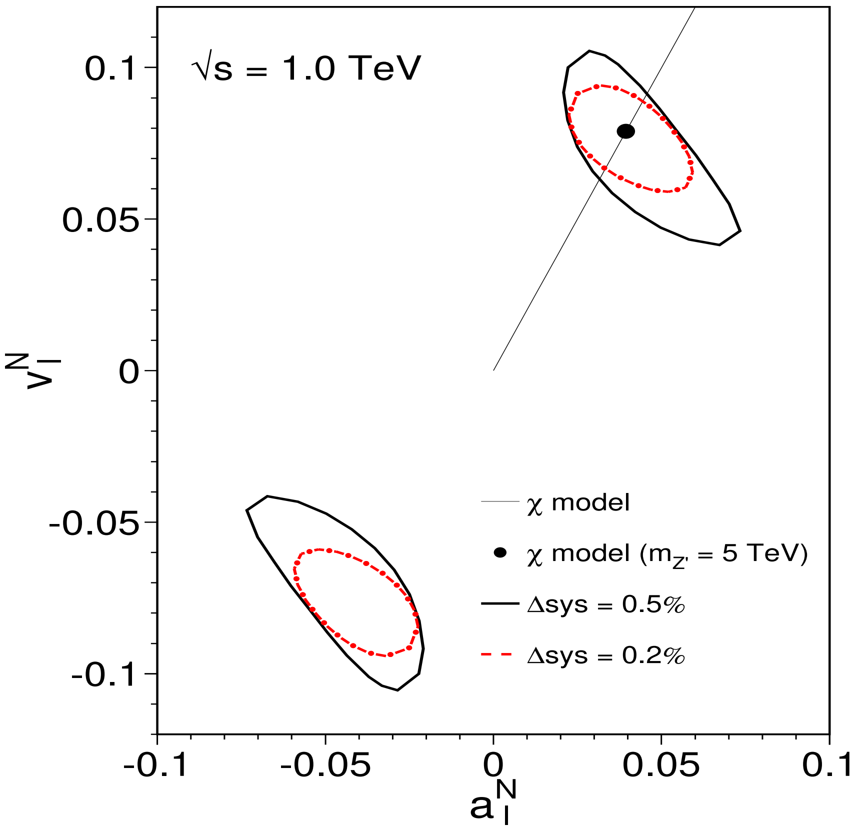
- lepton universality
- $m_{Z'}$ is known from LHC: $m_{Z'} \leq 4$ TeV
- $\mathcal{L}_{int} = 1000$ fb^{-1}, P_{e^-}=0.8; P_{e^-}=0.6
- $\Delta P_{e^\pm} = 0.5\%$, $\Delta\mathcal{L} = 0.5\%$,
  $\Delta^{sys}\epsilon_{lepton} = 0.5\%$,



$m_{Z'} > 4.5$ TeV

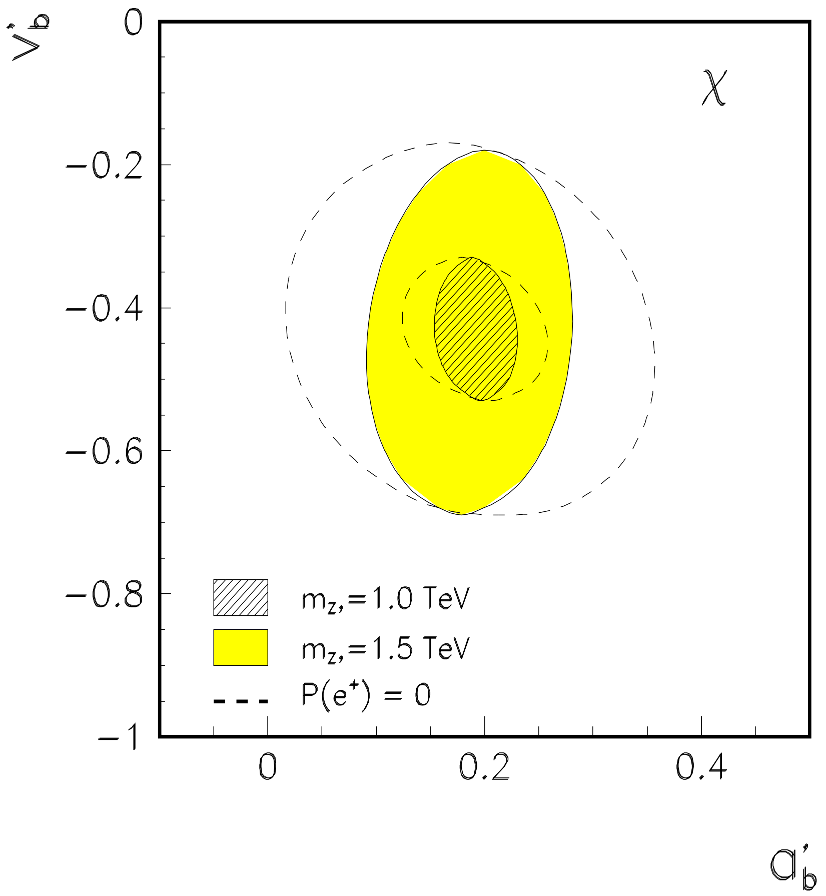
$$a_f^N = a'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}; \qquad v_f^N = v'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}.$$

- $\sqrt{s} = 1$ TeV
- $\mathcal{L}_{int} = 1000$ fb^{-1}, P_{e^-}=0.8; P_{e^-}=0.6
- $\Delta P_{e^\pm} = 0.5\%$, $\Delta\mathcal{L} = 0.5\%$,
  $\Delta^{sys}\epsilon_{lepton} = 0.5\%$, 0.2%



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

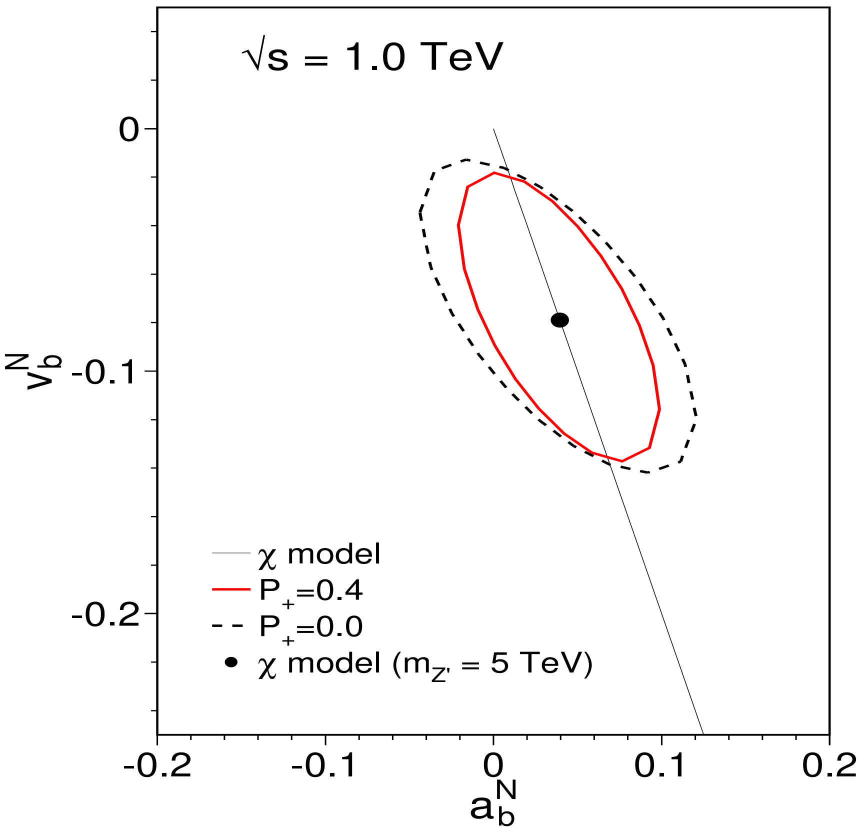
- $m_{Z'}$ is known from LHC
- $\mathcal{L}_{int} = 500$ fb^{-1}, P_{e^-}=0.8; P_{e^-}=0.6
- $\Delta P_{e^\pm} = 0.5\%$, $\Delta\mathcal{L} = 0.5\%$,



$m_{Z'} > 4.5$ TeV

$$a_f^N = a'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}; \qquad v_f^N = v'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}.$$

- $\sqrt{s} = 1$ TeV
- $\mathcal{L}_{int} = 1000\ \mathrm{fb}^{-1}$, P_{e^-}=0.8; P_{e^-}=0.4
- $\Delta P_{e^\pm} = 0.5\%$, $\Delta\mathcal{L} = 0.2\%$, $\Delta^{sys}\epsilon_b = 0.5\%$



Interpretation of deviations from SM ecpectations

- Identification of models needs:
  - polarization
  - small syst. errors
  - comb. analyses
- sensitivity to $g/m_X \Rightarrow$ measurement of couplings, if X is discovered with LHC
- if no hint to mass m_X from LHC identification possible for some models of NP

- FPP is good tool to search for new phenomena above their production threshold
- e^+ polarization increases sensitivity to NP,
- polarization error influences sensitivity to NP, depending on model of NP

- Sensitivity reach ($\sqrt{s} = 500$ GeV):
  - C.I.: $\Lambda >$ 25 ... 130 TeV for 500 fb^{-1}; depending on fin. state and model
  - LQ: With $g = \sqrt{4\pi\alpha}$ sensitivity up to $m_{LQ} \approx$ 6 TeV seems possible

- $m_{Z'}$: 2...12 TeV;
- good model discrimination (Z′) should be possible up to $m_{Z'} = 3...5\sqrt{s}$ – even if $m_{Z'}$ is unknown
- LHC and LC are complementary - not competing !!