Alternative theories beyond the SM

(non SUSY, non ED, non ...)

Galileo Galilei Institute Workshop

September 2007

Per Osland
University of Bergen

overview from recent LCWS's


International Conference on Linear Colliders
Colloque international sur les collisionneurs linéaires
LCWS 2004
Paris, April 19-23, 2004
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recent LCWS's:

Paris 2004 ("old")

SLAC 2005

Bangalore 2006 (not there)

Hamburg 2007 ILC/LCWS

SLAC 2005 LCWS

Working groups/parallel streams:
Higgs and Electroweak Symmetry Breaking,
SUSY Particles,
New Physics at TeV Scales and Precision
Electroweak Studies,
...gg, cosmology

Hamburg 2007 ILC/LCWS

Forest of working groups/parallel streams:
TeV,
SUSY,
Higgs,
Loops,
gg,...

Non-SUSY (non-Higgs, non-...) BSM topics:

- Contact interactions
  - Polarization
- Anomalous vector boson couplings
- Extra dimensions (see also K. Sridhar)
- Non-standard Higgs sector
- Non-commutative geometry

Contact interactions

Notation (helicity amplitudes):

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

$$\eta_{ij} = \pm 1$$

- fermion pair final states: $\mu^+\mu^-, b\bar{b}, c\bar{c}$
- Bhabha

Λ_{ij} could represent s- or t-channel exchange

Examples: low-energy limit of Z', leptoquark

Aim: constrain Λ_{ij} (i: initial, j: final)

Contact interactions

Two approaches:

- Particular model (Riemann)
- Model-independent (Pankov et al)

Advantages vs LHC:
beam polarization, may disentangle
helicity amplitudes
clean environment
large reach (vs LHC)

Contact interactions

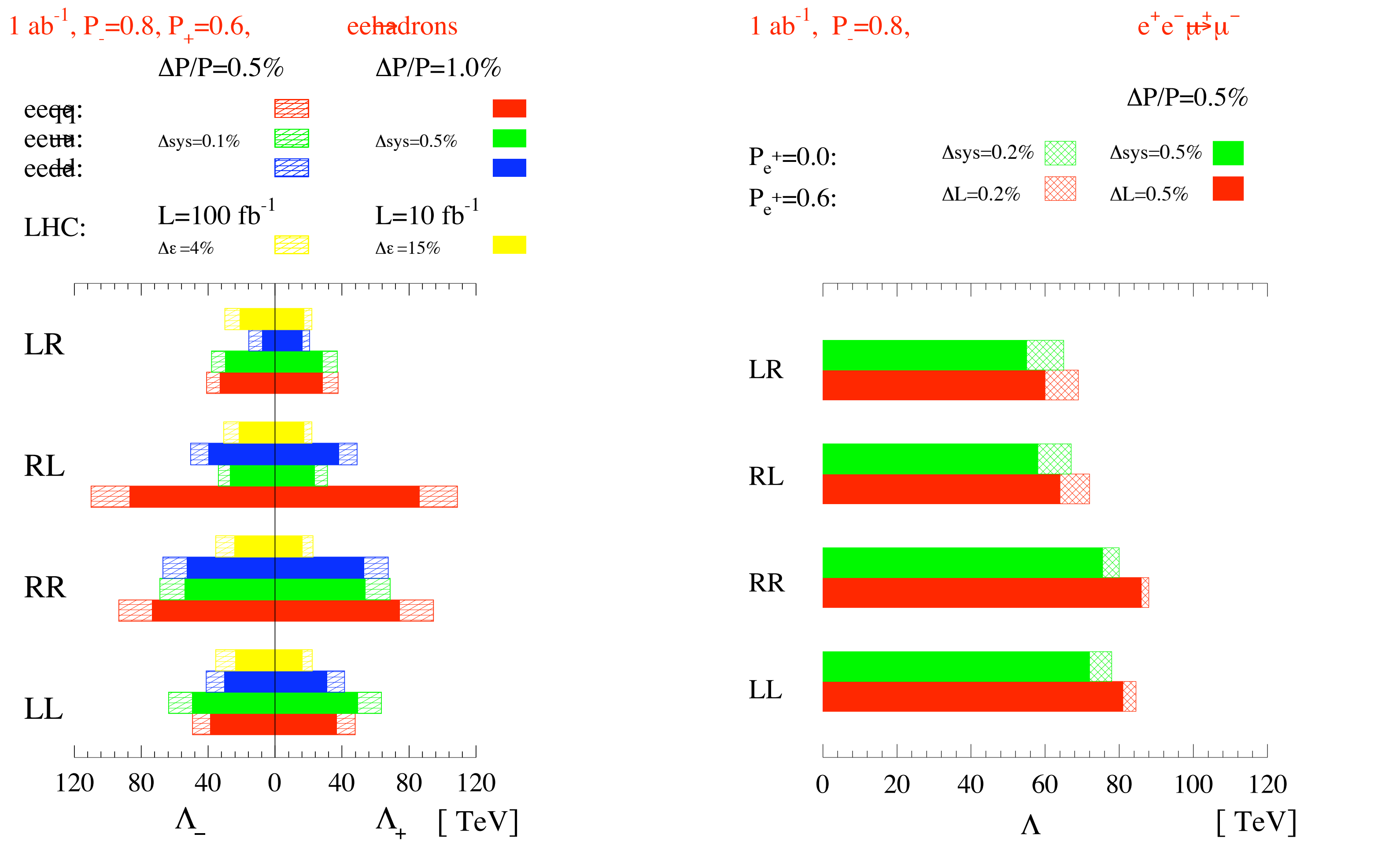


FIGURE 3.1-1. Sensitivities at the 95% CL of a $500\,\mathrm{GeV}$ ILC to contact interaction scales Λ for different helicities in $e^+e^- \to$ hadrons (left) and $e^+e^- \to \mu^+\mu^-$ (right) including beam polarization [122].

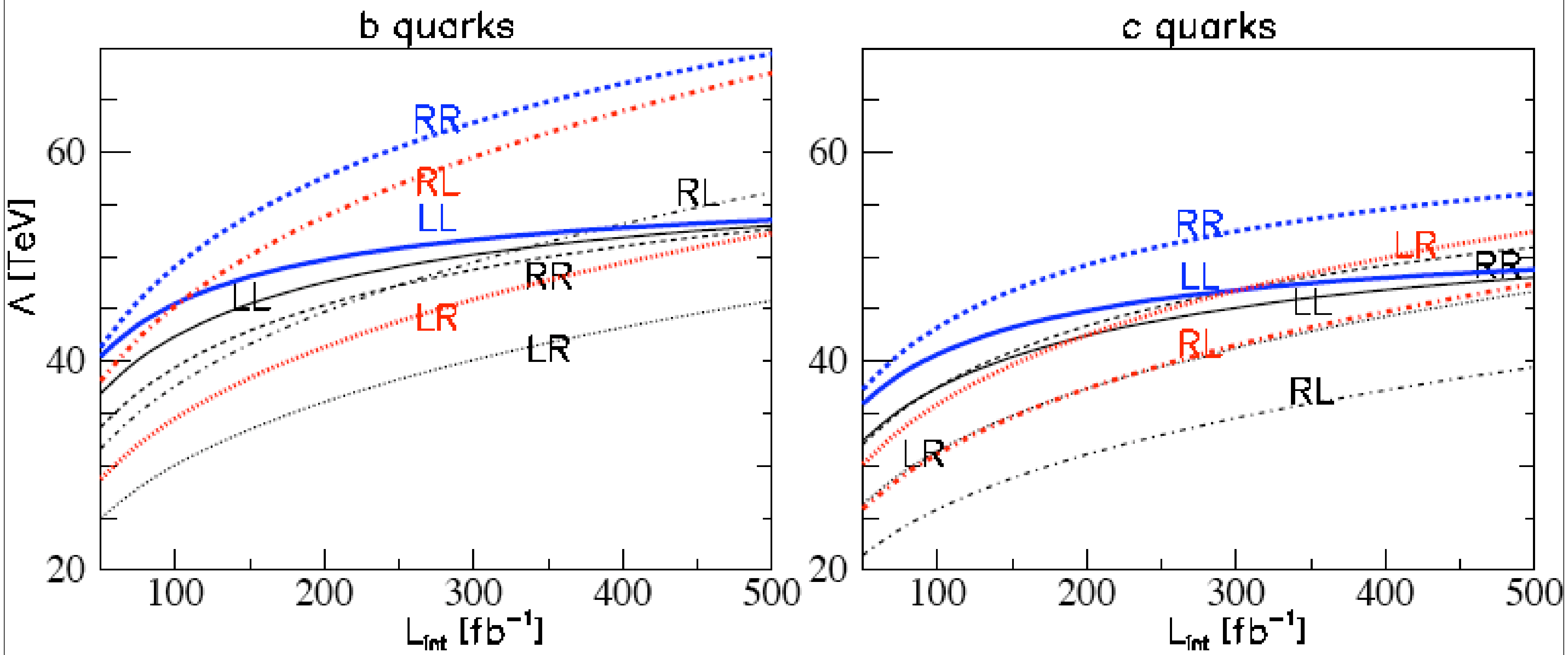
S. Riemann, LC-TH-2001-007.

Contact interactions

LCWS05

Importance of positron polarization!

Osland, Pankov, Paver (2005) Model independent



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

black: $(80\%, 0)$

500 GeV

LCWS06

Lorentz

Probing space-time structure of new physics with polarized beams at the ILC

Work done in collaboration with Saurabh D. Rindani

B. Ananthanarayan

Centre for High Energy Physics,
Indian Institute of Science, Bangalore

$\mathcal{L}^{4F}$ for $t\bar{t}$ production

- The Lagrangian takes the form

Scalar   Vector

$$\mathcal{L}^{4F} = \sum_{i,j=L,R} \Big[S_{ij}(\bar{e}P_i e)(\bar{t}P_j t) + V_{ij}(\bar{e}\gamma_\mu P_i e)(\bar{t}\gamma^\mu P_j t)$$

$$+T_{ij}(\bar{e}\frac{\sigma_{\mu\nu}}{\sqrt{2}}P_i e)(\bar{t}\frac{\sigma^{\mu\nu}}{\sqrt{2}}P_j t) \Big],$$

Tensor

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

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

$P_{L,R}$ are the left- and right-chirality projection.

$$\frac{d\sigma^{\pm\pm}}{d\Omega} = \frac{d\sigma^{\pm\pm}_{SM}}{d\Omega} \mp \frac{3\alpha\beta^2}{4\pi}\frac{m_t\sqrt{s}}{s-m_Z^2}\left(c_V^t c_A^e \mathrm{Re}S\right)\sin\theta\cos\phi,$$

$$\frac{d\sigma^{\pm\mp}}{d\Omega} = \frac{d\sigma^{\pm\mp}_{SM}}{d\Omega} \pm \frac{3\alpha\beta^2}{4\pi}\frac{m_t\sqrt{s}}{s-m_Z^2}\left(c_V^t c_A^e \mathrm{Im}S\right)\sin\theta\sin\phi,$$

CP odd

where

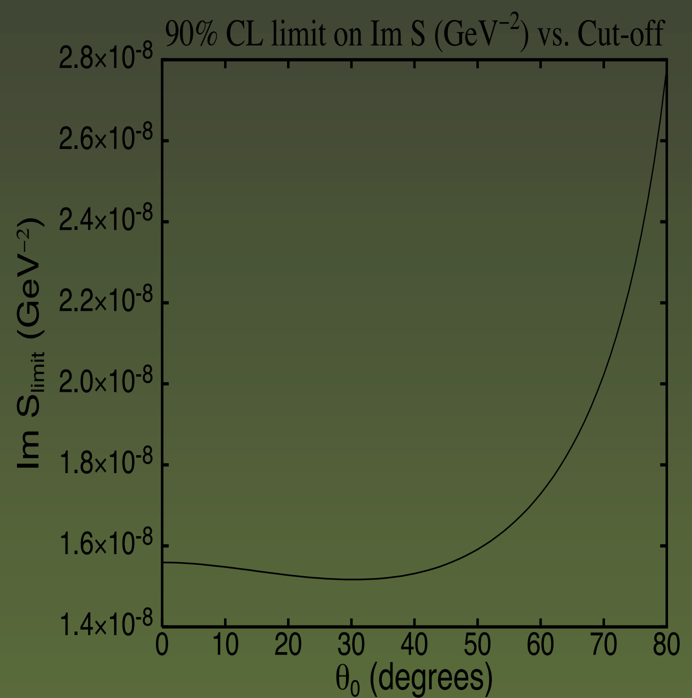
$$\frac{d\sigma^{\pm\pm}_{SM}}{d\Omega}$$

is the SM contribution to the cross-section that we do not spell out here, and

def

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

where c_V^i, c_A^i are the couplings of Z to e^-e^+ and $t\bar{t}$.



The 90% C.L. limit on Im S with $\mathcal{L}$=500 fb^{-1}

$\theta_0 < \theta < \pi - \theta_0$

$4\pi/\Lambda^2 \sim S \sim 10^{-8} \Rightarrow \Lambda \sim 30$ TeV

Trilinear (EW) gauge couplings $V = \gamma, Z$

$$\begin{aligned}\mathcal{L}_{WWV} \;\; = \;\; & g_{WWV}\Big[ig_1^V V_\mu \left(W_\nu^- W_{\mu\nu}^+ - W_{\mu\nu}^- W_\nu^+\right) + i\kappa_V W_\mu^- W_\nu^+ V_{\mu\nu} + i\frac{\lambda_V}{M_W^2} W_{\lambda\mu}^- W_{\mu\nu}^+ V_{\nu\lambda} \\ & + g_4^V W_\mu^- W_\nu^+ \left(\partial_\mu V_\nu + \partial_\nu V_\mu\right) + g_5^V \epsilon_{\mu\nu\lambda\rho}\left(W_\mu^- \partial_\lambda W_\nu^+ - \partial_\lambda W_\mu^- W_\nu^+\right) V_\rho \\ & + i\tilde{\kappa}_V W_\mu^- W_\nu^+ \tilde{V}_{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2} W_{\lambda\mu}^- W_{\mu\nu}^+ \tilde{V}_{\nu\lambda}\Big],\end{aligned} \quad \text{(iii}$$

SM: $g_1^V = 1 \quad \kappa_V = 1 \quad \lambda_V = 0$

RDR: Mönig, Sekaric

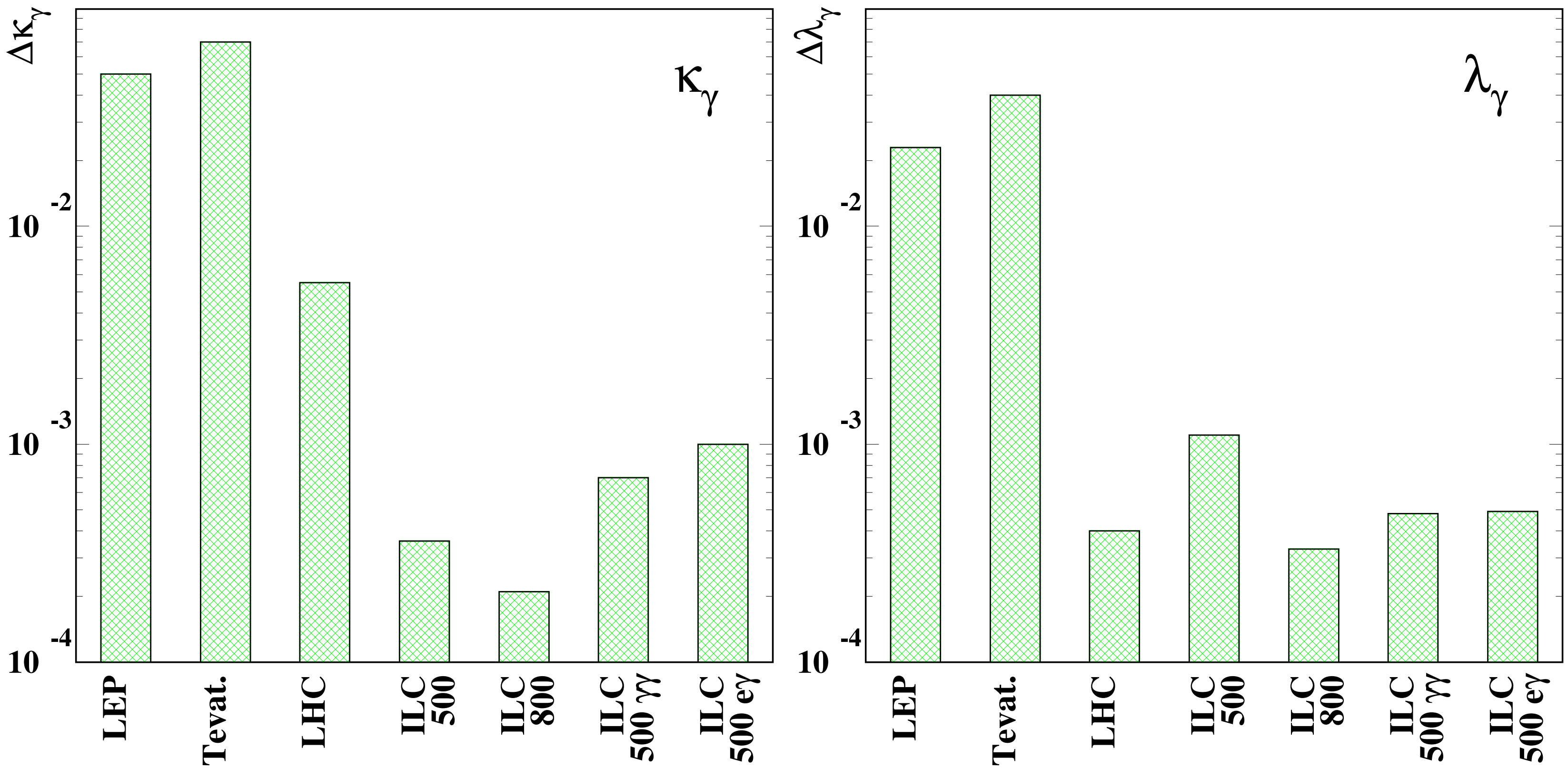


Figure 3.2.1: *Comparison of $\Delta\kappa_\gamma$ and $\Delta\lambda_\gamma$ at different machines. For LHC and ILC three years of running are assumed (LHC:* 300 fb^{-1}*, ILC* $\sqrt{s} = 500\,\mathrm{GeV}$*:* 900 fb^{-1}*, ILC* $\sqrt{s} = 800\,\mathrm{GeV}$*:* 1500 fb^{-1}*). If available the results from multi-parameter fits have been used.*

LCWS07

ILC sensitivity on Generic New Physics in Quartic Gauge Couplings

Jürgen Reuter

University of Freiburg

Beyer/Kilian/Krstonošić/Mönig/JR/Schmitt/Schröder, **EPJC 48** (2006), 353

DESY, June 1st, 2007

Parameterization of New Physics

- Higgs boson still not observed
- Aim: describe any physics beyond the SM as generically as possible
- Implement what we know about the SM
- Parameterize all the known physics (in the EW sector) by the **Chiral Electroweak Lagrangian**
- Implements $SU(2)_L \times U(1)_Y$ gauge invariance
- Building blocks (including longitudinal modes):

$$\psi(\text{SM fermions}), \quad W_\mu^a \ (a = 1, 2, 3), \quad B_\mu, \quad \Sigma = \exp\left[\frac{-i}{v} w^a \tau^a\right]$$

- Minimal Lagrangian including gauge interactions

$$\mathcal{L}_{\text{min}} = \sum_\psi \overline{\psi}(i\not{D})\psi - \frac{1}{2g^2}\,\text{tr}\,\{\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\} - \frac{1}{2g'^2}\,\text{tr}\,\{\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu}\} + \frac{v^2}{4}\,\text{tr}\,\{(vD_\mu\Sigma)(vD^\mu\Sigma)\}$$

Electroweak Chiral Lagrangian

$\mathbf{V} = \Sigma(\mathbf{D}\Sigma)^\dagger$ (longitudinal vectors), $\mathbf{T} = \Sigma\tau^3\Sigma^\dagger$ (neutral component)

Complete Lagrangian contains infinitely many parameters

small, $\Delta\rho$ constraint

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{min}} - \sum_\psi \overline{\psi}_L \Sigma M \psi_R + \beta_1 \mathcal{L}_0' + \sum_i \alpha_i \mathcal{L}_i + \frac{1}{v}\sum_i \alpha_i^{(5)} \mathcal{L}^{(5)} + \frac{1}{v^2}\sum_i \alpha_i^{(6)} \mathcal{L}^{(6)} + \dots$$

constrain these, i=5,7,10

$$\mathcal{L}_0' = \frac{v^2}{4}\,\text{tr}\,\{\mathbf{T}\mathbf{V}_\mu\}\,\text{tr}\,\{\mathbf{T}\mathbf{V}^\mu\}$$

$$\mathcal{L}_1 = \text{tr}\,\{\mathbf{B}_{\mu\nu}\mathbf{W}^{\mu\nu}\} \qquad \mathcal{L}_6 = \text{tr}\,\{\mathbf{V}_\mu\mathbf{V}_\nu\}\,\text{tr}\,\{\mathbf{T}\mathbf{V}^\mu\}\,\text{tr}\,\{\mathbf{T}\mathbf{V}^\nu\}$$

$$\mathcal{L}_2 = \text{i}\,\text{tr}\,\{\mathbf{B}_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]\} \qquad \mathcal{L}_7 = \text{tr}\,\{\mathbf{V}_\mu\mathbf{V}^\mu\}\,\text{tr}\,\{\mathbf{T}\mathbf{V}_\nu\}\,\text{tr}\,\{\mathbf{T}\mathbf{V}^\nu\}$$

$$\mathcal{L}_3 = \text{i}\,\text{tr}\,\{\mathbf{W}_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]\} \qquad \mathcal{L}_8 = \tfrac{1}{4}\,\text{tr}\,\{\mathbf{T}\mathbf{W}_{\mu\nu}\}\,\text{tr}\,\{\mathbf{T}\mathbf{W}^{\mu\nu}\}$$

$$\mathcal{L}_4 = \text{tr}\,\{\mathbf{V}_\mu\mathbf{V}_\nu\}\,\text{tr}\,\{\mathbf{V}^\mu\mathbf{V}^\nu\} \qquad \mathcal{L}_9 = \tfrac{\text{i}}{2}\,\text{tr}\,\{\mathbf{T}\mathbf{W}_{\mu\nu}\}\,\text{tr}\,\{\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]\}$$

$$\mathcal{L}_5 = \text{tr}\,\{\mathbf{V}_\mu\mathbf{V}^\mu\}\,\text{tr}\,\{\mathbf{V}_\nu\mathbf{V}^\nu\} \qquad \mathcal{L}_{10} = \tfrac{1}{2}\left(\text{tr}\,\{\mathbf{T}\mathbf{V}_\mu\}\,\text{tr}\,\{\mathbf{T}\mathbf{V}^\mu\}\right)^2$$

Flavor physics info contained in M (ignored here)

Indirect info on new physics in $\beta_1, \alpha_i, \dots$

Parameters and Scales, Resonances

α_i measurable at ILC

- $\alpha_i \ll 1$ (LEP)
- $\alpha_i \gtrsim 1/16\pi^2 \approx 0.006$ (renormalize divergencies, $16\pi^2\alpha_i \gtrsim 1$)

Translation of parameters into new physics scale Λ: $\alpha_i = v^2/\Lambda^2$

- Operator normalization is arbitrary
- Power counting can be intricate

To be specific: consider resonances that couple to EWSB sector
Resonance mass gives detectable shift in the α_i

- Narrow resonances $\Rightarrow$ particles
- Wide resonances $\Rightarrow$ continuum

$\beta_1 \ll 1 \Rightarrow SU(2)_c$ custodial symmetry (weak isospin, broken by hypercharge $g' \neq 0$ and fermion masses)

	$J = 0$	$J = 1$	$J = 2$
$I = 0$	σ^0 (Higgs ?)	ω^0 (γ'/Z' ?)	f^0 (Graviton ?)
$I = 1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ (W'/Z' ?)	$a^\pm, a^0$
$I = 2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$t^{\pm\pm}, t^\pm, t^0$

accounts for weakly and strongly interacting models

LCWS07

J. Reuter

Probing New Phyisics in Quartic Gauge Couplings

Encode New Physics in EW Chiral Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{min}} - \sum_{\psi} \overline{\psi}_L \Sigma M \psi_R + \beta_1 \mathcal{L}'_0 + \sum_i \alpha_i \mathcal{L}_i + \frac{1}{v} \sum_i \alpha_i^{(5)} \mathcal{L}^{(5)} + \frac{1}{v^2} \sum_i \alpha_i^{(6)} \mathcal{L}^{(6)} + \dots$$

$$\mathcal{L}'_0 = \frac{v^2}{4} \operatorname{tr}\{\mathbf{T}\mathbf{V}_\mu\} \operatorname{tr}\{\mathbf{T}\mathbf{V}^\mu\}$$

$$\mathcal{L}_1 = \operatorname{tr}\{\mathbf{B}_{\mu\nu}\mathbf{W}^{\mu\nu}\} \qquad \mathcal{L}_6 = \operatorname{tr}\{\mathbf{V}_\mu\mathbf{V}_\nu\} \operatorname{tr}\{\mathbf{T}\mathbf{V}^\mu\} \operatorname{tr}\{\mathbf{T}\mathbf{V}^\nu\}$$

$$\mathcal{L}_2 = \mathrm{i} \operatorname{tr}\{\mathbf{B}_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]\} \qquad \mathcal{L}_7 = \operatorname{tr}\{\mathbf{V}_\mu\mathbf{V}^\mu\} \operatorname{tr}\{\mathbf{T}\mathbf{V}_\nu\} \operatorname{tr}\{\mathbf{T}\mathbf{V}^\nu\}$$

$$\mathcal{L}_3 = \mathrm{i} \operatorname{tr}\{\mathbf{W}_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]\} \qquad \mathcal{L}_8 = \tfrac{1}{4} \operatorname{tr}\{\mathbf{T}\mathbf{W}_{\mu\nu}\} \operatorname{tr}\{\mathbf{T}\mathbf{W}^{\mu\nu}\}$$

$$\mathcal{L}_4 = \operatorname{tr}\{\mathbf{V}_\mu\mathbf{V}_\nu\} \operatorname{tr}\{\mathbf{V}^\mu\mathbf{V}^\nu\} \qquad \mathcal{L}_9 = \tfrac{\mathrm{i}}{2} \operatorname{tr}\{\mathbf{T}\mathbf{W}_{\mu\nu}\} \operatorname{tr}\{\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]\}$$

$$\mathcal{L}_5 = \operatorname{tr}\{\mathbf{V}_\mu\mathbf{V}^\mu\} \operatorname{tr}\{\mathbf{V}_\nu\mathbf{V}^\nu\} \qquad \mathcal{L}_{10} = \tfrac{1}{2} (\operatorname{tr}\{\mathbf{T}\mathbf{V}_\mu\} \operatorname{tr}\{\mathbf{T}\mathbf{V}^\mu\})^2$$

Measure deviations in quartic couplings:
- Triple gauge production
- Vector boson scattering

Interpret quartic couplings as new resonances

Integrating out resonances

- leads to anomalous quartic couplings

$$\alpha_5 = g_\sigma^2 \left(\frac{v^2}{8M_\sigma^2}\right) \qquad \alpha_7 = 2 g_\sigma h_\sigma \left(\frac{v^2}{8M_\sigma^2}\right) \qquad \alpha_{10} = 2 h_\sigma^2 \left(\frac{v^2}{8M_\sigma^2}\right)$$

Scale reach, TeV

Full signal & bckgrnd computed via WHIZARD

Final result:

Spin	$I=0$	$I=1$	$I=2$
0	1.55	–	1.95
1	–	2.49	–
2	3.29	–	4.30

SU(2)$_{\text{cust}}$ conserved

Spin	$I=0$	$I=1$	$I=2$
0	1.39	1.55	1.95
1	1.74	2.67	–
2	3.00	3.01	5.84

SU(2)$_{\text{cust}}$ violated

Effective Lagrangian before EWSB

- start from SM Lagrangian (incl. Higgs doublet φ)
- add all higher dim. operators which are
  - Lorentz-invariant
  - $SU(3) \times SU(2) \times U(1)$ invariant

$$\Rightarrow \quad \mathscr{L}_{eff} = \mathscr{L}_0 + \underbrace{\mathscr{L}_1}_{\text{dim 5 op.}} + \underbrace{\mathscr{L}_2}_{\text{dim 6 op.}} + \dots$$

- imposing
  - equation of motion
  - lepton and baryon number conservation

$\Rightarrow \quad \mathscr{L}_1$: none, $\mathscr{L}_2$: 80 operators

(Buchmüller, Wyler 1986)

Gauge and gauge-Higgs anomalous couplings

- pure gauge and gauge-Higgs part

dimensionless

$$\mathscr{L}_2 = \frac{1}{v^2}\Big(h_W O_W + h_{\tilde{W}} O_{\tilde{W}} + h_{\varphi W} O_{\varphi W} + h_{\varphi \tilde{W}} O_{\varphi \tilde{W}} + h_{\varphi B} O_{\varphi B} + h_{\varphi \tilde{B}} O_{\varphi \tilde{B}}$$
$$+ h_{WB} O_{WB} + h_{\tilde{W}B} O_{\tilde{W}B} + h_{\varphi}^{(1)} O_{\varphi}^{(1)} + h_{\varphi}^{(3)} O_{\varphi}^{(3)}\Big)\,,$$

$$O_W = \epsilon_{ijk}\, W_\mu^{i\,\nu} W_\nu^{j\,\lambda} W_\lambda^{k\,\mu}\,, \qquad O_{\tilde{W}} = \epsilon_{ijk}\, \tilde{W}_\mu^{i\,\nu} W_\nu^{j\,\lambda} W_\lambda^{k\,\mu}\,,$$

$$O_{\varphi W} = \frac{1}{2}\left(\varphi^\dagger \varphi\right) W_{\mu\nu}^i W^{i\,\mu\nu}\,, \qquad O_{\varphi \tilde{W}} = \left(\varphi^\dagger \varphi\right) \tilde{W}_{\mu\nu}^i W^{i\,\mu\nu}\,,$$

$$O_{\varphi B} = \frac{1}{2}\left(\varphi^\dagger \varphi\right) B_{\mu\nu} B^{\mu\nu}\,, \qquad O_{\varphi \tilde{B}} = \left(\varphi^\dagger \varphi\right) \tilde{B}_{\mu\nu} B^{\mu\nu}\,,$$

$$O_{WB} = \left(\varphi^\dagger \tau^i \varphi\right) W_{\mu\nu}^i B^{\mu\nu}\,, \qquad O_{\tilde{W}B} = \left(\varphi^\dagger \tau^i \varphi\right) \tilde{W}_{\mu\nu}^i B^{\mu\nu}\,,$$

$$O_\varphi^{(1)} = \left(\varphi^\dagger \varphi\right) \left(\mathcal{D}_\mu \varphi\right)^\dagger \left(\mathcal{D}^\mu \varphi\right)\,, \qquad O_\varphi^{(3)} = \left(\varphi^\dagger \mathcal{D}_\mu \varphi\right)^\dagger \left(\varphi^\dagger \mathcal{D}^\mu \varphi\right)\,.$$

- 10 dimensionless anomalous couplings h_i with

$$h_i \sim \mathcal{O}\left(v^2/\Lambda^2\right)\,,$$

where $v = 246$ GeV, $\Lambda =$ new physics scale

- 4 anomalous couplings CP violating

Processes at the ILC

- $e^+e^- \to Z$ (Giga Z) highly sensitive to (P_Z):

$$h_{WB}, h_{\varphi}^{(3)}$$

- $e^+e^- \to W^+W^-$ sensitive to (P_W):

$$h_W,\ h_{WB},\ h_{\varphi}^{(3)},\ h_{\tilde{W}},\ h_{\tilde{W}B}$$

  (3 CP conserving, 2 CP violating)

- $\gamma\gamma \to W^+W^-$ sensitive to (P_W):

$$h_W,\ h_{WB},\ h_{\tilde{W}},\ h_{\tilde{W}B}, (s_1^2 h_{\varphi W} + c_1^2 h_{\varphi B}),\ (s_1^2 h_{\varphi \tilde{W}} + c_1^2 h_{\varphi \tilde{B}})$$

  (3 CP conserving, 3 CP violating)

- only $\gamma\gamma$ process allows direct measurement of:

$$h_{\varphi WB} \equiv s_1^2\, h_{\varphi W} + c_1^2\, h_{\varphi B}$$
$$h_{\varphi \tilde{W}\tilde{B}} \equiv s_1^2\, h_{\varphi \tilde{W}} + c_1^2\, h_{\varphi \tilde{B}}$$

  where $s_1^2 \equiv \frac{e^2}{4\sqrt{2}G_F m_W^2}, \quad c_1^2 \equiv 1 - s_1^2$

- all processes together: 7 out of 10 indep. couplings observable

A. Manteuffel

Anomalous Couplings in $\gamma\gamma\to WW$

Gauge and gauge-Higgs anomalous couplings

$$\mathscr{L}_2 = \frac{1}{v^2}\left(h_W O_W + h_{\tilde{W}} O_{\tilde{W}} + h_{\varphi W} O_{\varphi W} + h_{\varphi \tilde{W}} O_{\varphi \tilde{W}} + h_{\varphi B} O_{\varphi B} + h_{\varphi \tilde{B}} O_{\varphi \tilde{B}} + h_{WB} O_{WB} + h_{\tilde{W}B} O_{\tilde{W}B} + h_\varphi^{(1)} O_\varphi^{(1)} + h_\varphi^{(3)} O_\varphi^{(3)}\right),$$

$$O_W = \epsilon_{ijk}\, W_\mu^{i\,\nu} W_\nu^{j\,\lambda} W_\lambda^{k\,\mu}, \qquad O_{\tilde{W}} = \epsilon_{ijk}\, \tilde{W}_\mu^{i\,\nu} W_\nu^{j\,\lambda} W_\lambda^{k\,\mu},$$

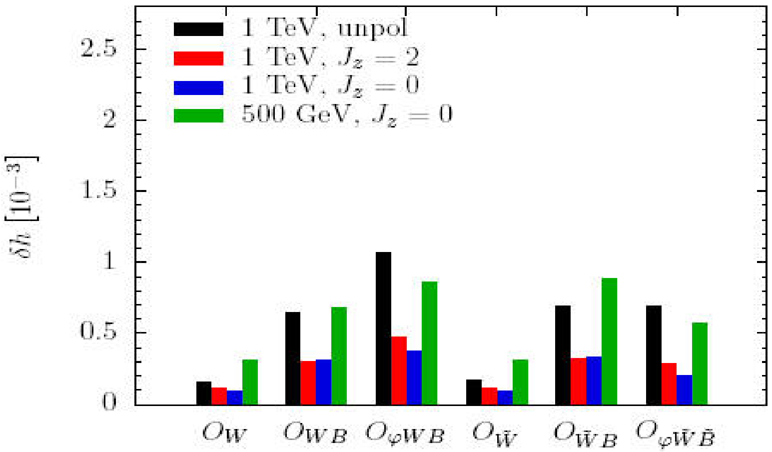
$$O_{\varphi W} = \frac{1}{2}\left(\varphi^\dagger \varphi\right) W^i_{\mu\nu} W^{i\,\mu\nu}, \qquad O_{\varphi \tilde{W}} = \left(\varphi^\dagger \varphi\right) \tilde{W}^i_{\mu\nu} W^{i\,\mu\nu},$$

$$O_{\varphi B} = \frac{1}{2}\left(\varphi^\dagger \varphi\right) B_{\mu\nu} B^{\mu\nu}, \qquad O_{\varphi \tilde{B}} = \left(\varphi^\dagger \varphi\right) \tilde{B}_{\mu\nu} B^{\mu\nu},$$

$$O_{WB} = \left(\varphi^\dagger \tau^i \varphi\right) W^i_{\mu\nu} B^{\mu\nu}, \qquad O_{\tilde{W}B} = \left(\varphi^\dagger \tau^i \varphi\right) \tilde{W}^i_{\mu\nu} B^{\mu\nu},$$

$$O_\varphi^{(1)} = \left(\varphi^\dagger \varphi\right) \left(\mathcal{D}_\mu \varphi\right)^\dagger \left(\mathcal{D}^\mu \varphi\right), \qquad O_\varphi^{(3)} = \left(\varphi^\dagger \mathcal{D}_\mu \varphi\right)^\dagger \left(\varphi^\dagger \mathcal{D}^\mu \varphi\right)$$

Sensitivity with polarized beams



Comparison of Sensitivities

	LEP & SLD (*) h_i [10^{-3}]	$ee \to WW$ (*) δh_i [10^{-3}]	$\gamma\gamma \to WW$ unpolarised δh_i [10^{-3}]	$\gamma\gamma \to WW$ $J_z = 0$ δh_i [10^{-3}]
h_W	-69 ± 39	0.3	0.6	0.3
h_{WB}	-0.06 ± 0.79	0.3	1.6	0.7
$h_{\varphi WB}$	×	×	2.2	0.9
$h_\varphi^{(3)}$	-1.15 ± 2.39	36.4	×	×
$h_{\tilde{W}}$	68 ± 81	0.3	0.7	0.3
$h_{\tilde{W}B}$	33 ± 84	2.2	2.0	0.9
$h_{\varphi \tilde{W}\tilde{B}}$	×	×	2.0	0.6

Physics Overview

Yasuhiro Okada (KEK)

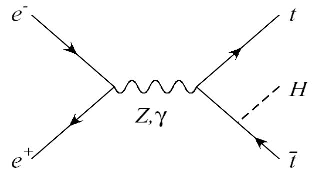
LCWS 06 & ILC GDE meeting, March 9, 2006

Indian Institute of Science, Bangalore, India

Coupling measurements at ILC

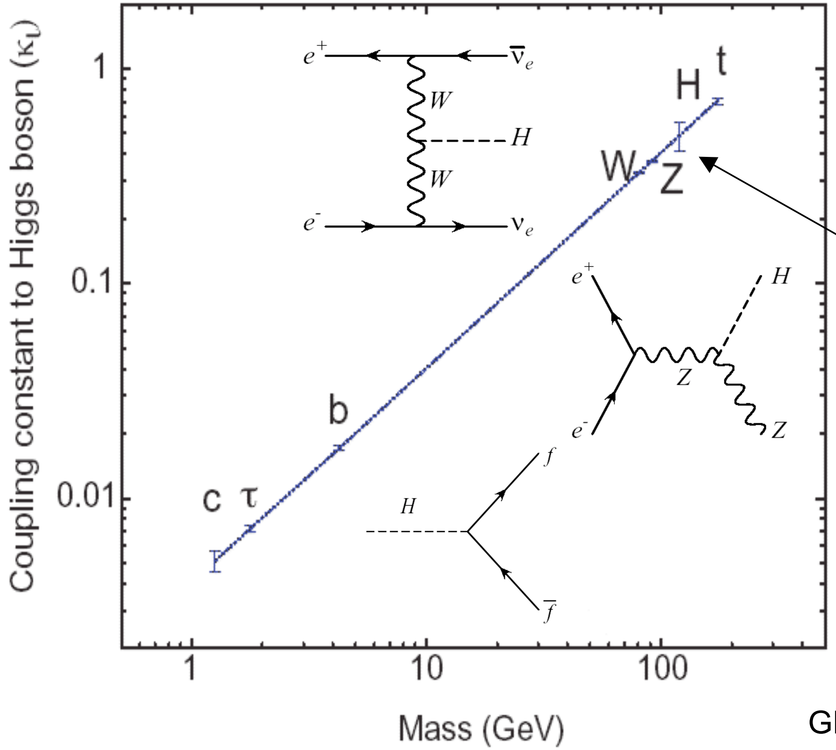
$$m_i = v \times \kappa_i$$

Coupling-Mass Relation

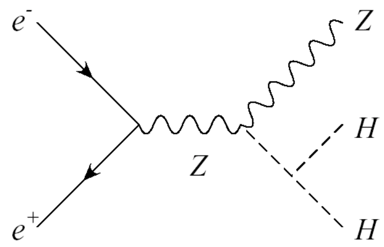


(Ecm>700 GeV)

LHC: (10)% for ratios of coupling constants
ILC: a few % determination



Higgs self-coupling



GLC Project

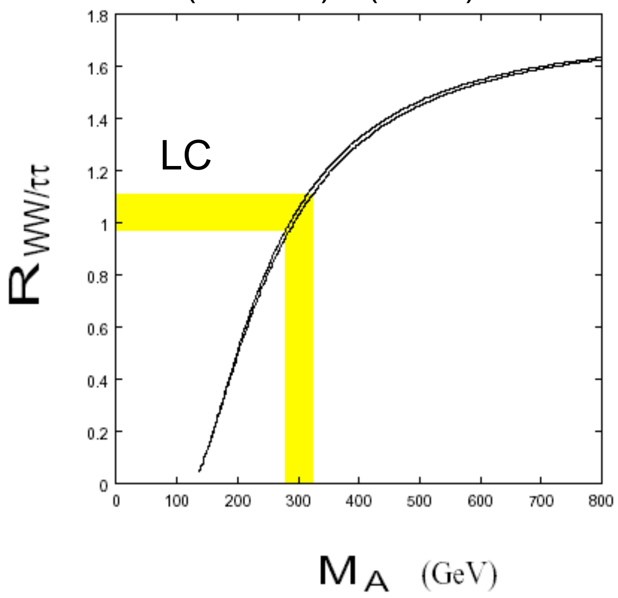
m_H=120 GeV, Ecm=300-500 GeV.L=500fb^{-1}

New physics effects in Higgs boson couplings

- In many new physics models, the Higgs sector is extended and /or involves new interactions. The Higgs boson coupling can have sizable deviation from the SM prediction.

The heavy Higgs boson mass in the MSSM

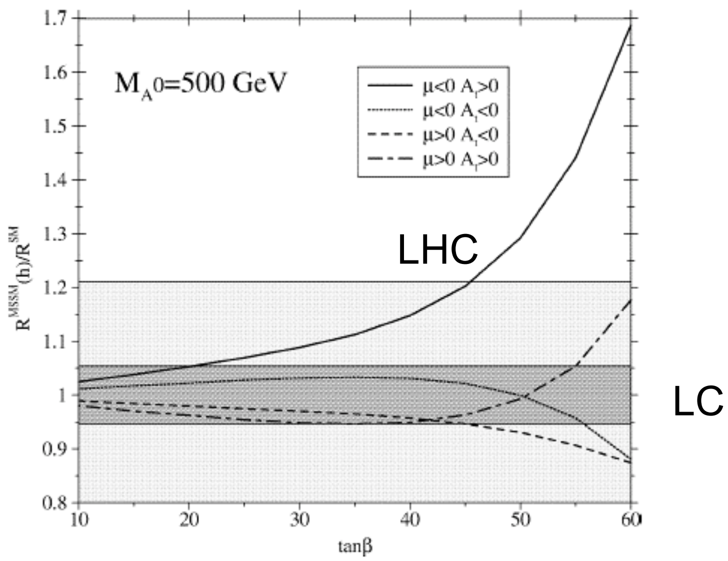
B(h->WW)/B(h->ττ)



ACFA report

SUSY correction to Yukawa couplings

B(h->bb)/B(h->ττ)

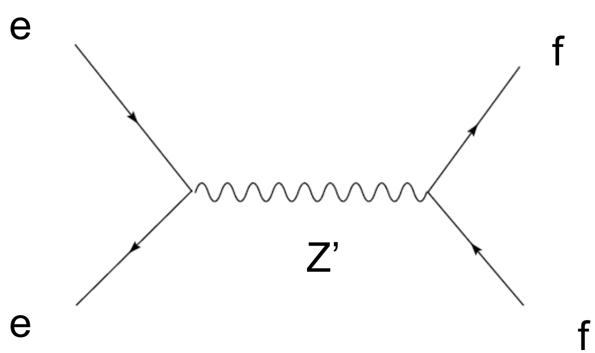


J.Guasch, W.Hollik,S.Penaranda

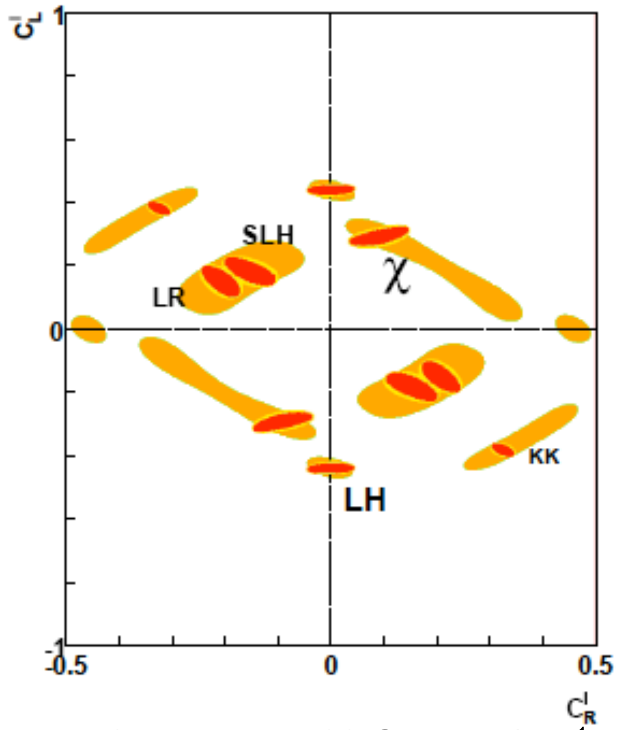
Z' and e^+e^-->ff processes

Even if ILC at 500 GeV cannot produce a new Z' particle kinematically,we can determine left-handed and right-handed couplings from ee-> ff processes.
This will give important information to identify the correct theory.

LHC=> mass
ILC => coupling



Z' coupling determination at ILC



$m_{Z'}$ =2TeV,Ecm=500 GeV, L=1ab^{-1}
with and w/o beam polarization

S.Godfrey, P.Kalyniak, A.Tomkins

RDR: Richard; Godfrey et al

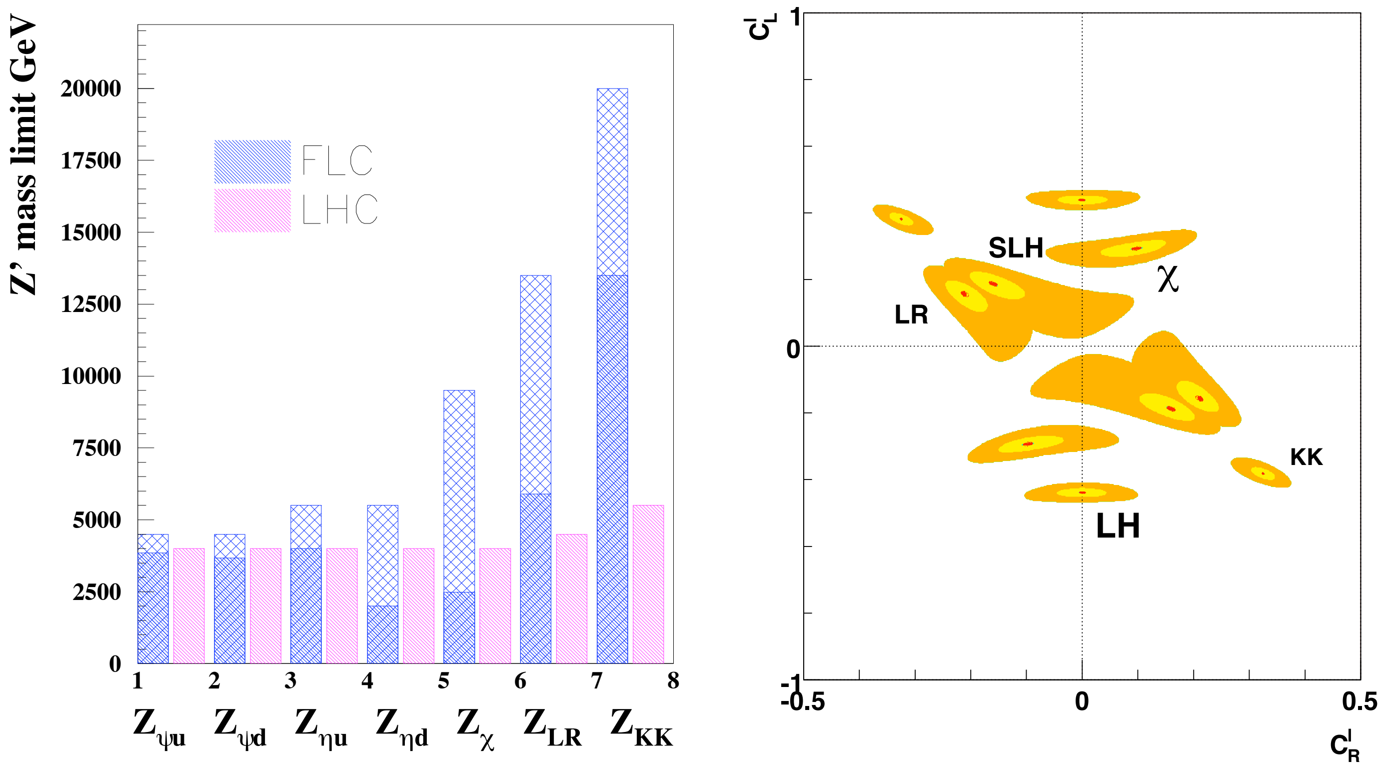


FIGURE 6.4-10. Left: the mass range covered by the LHC and the ILC (FLC) for a Z' boson in various scenarios; for the ILC the heavy hatched region is covered by exploiting the GigaZ option (sensitive to the Z–Z' mixing) and the high energy region (sensitive to the γ, Z–Z' interference) [15, 236]. Right: the ILC resolving power (95% CL) for $M_{Z'} = 1, 2$ and 3 TeV for left– and right–handed leptonic couplings (c^l_L and c^l_R) based on the leptonic observables $\sigma^{\mu}_{\text{pol}}$, A^{μ}_{LR} and A^{μ}_{FB}; the smallest (largest) regions correspond to $M_{Z'} = 1$ TeV (3 TeV) [237]. In both figures $\sqrt{s} = 500$ GeV and $\mathcal{L} = 1$ ab^{-1} are assumed.

Extra dimensions

	intermediate gravitons	free gravitons in final state
ADD	✔	✔
RS	✔	✔
UED	✔	✔

Final state

- two fermions
- two photon

Sridhar

- bremsstrahlung

P.O.

LCWS06

Distinguishing New Physics Scenarios at ILC with Polarized Beams

A.A. Pankov

Technical University of Gomel

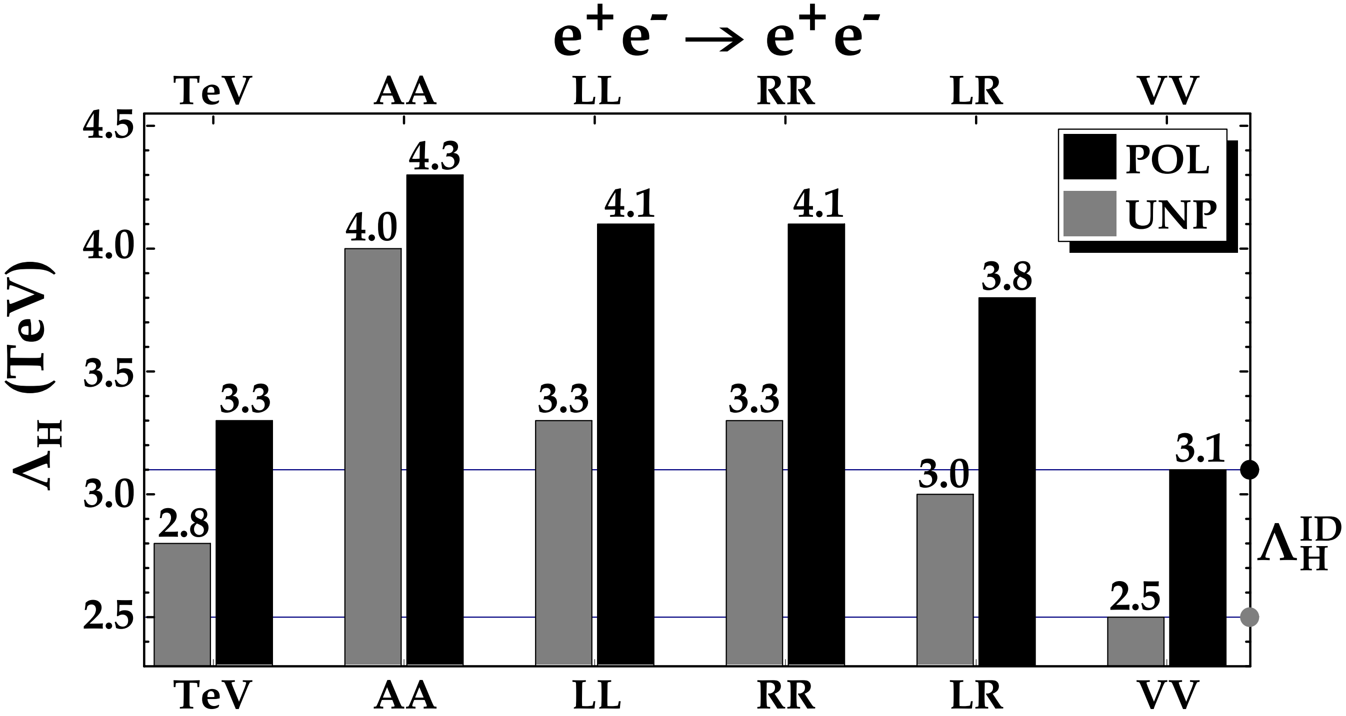
9 - 13 March, 2006, Bangalore

with *N.Paver* (INFN, Trieste) & *A.V.Tsytrinov* (Gomel)

Outline:

- Variety of New Physics Scenarios
- Fermion pair production:
  $e^+e^- \to l^+l^-$ $(l = e, \mu, \tau)$;
  $e^-e^- \to e^-e^-$
  $e^+e^- \to \bar{q}q$ $(q = c, b)$
- Observables: polarized differential distributions
- Discovery and identification reach
- Rôle of beam polarization in enhancing the identification reach

ID reach for ADD model



Exclusion reach: $\Lambda_H^{\rm VV}$, ...

Identification reach:

$$\Lambda_H^{\rm ID} = min\{\Lambda_H^{\rm VV}, \Lambda_H^{\rm AA}, \Lambda_H^{\rm RR}, \Lambda_H^{\rm LL}, \Lambda_H^{\rm LR}, \Lambda_H^{\rm TeV}\}$$

$\to \Lambda_H^{\rm ID} = 2.5(3.1)$ TeV.

Conclusions

- If New Physics effects are discovered, it is crucial to have good search strategies to determine its origin.
- We have considered the problem of how to distinguish the potential New Physics scenarios from each other at the ILC by using polarized differential distribution for fermion pair production processes.
- Identification reach (95% CL) at ILC:
  - ADD: $\Lambda_H = 3.1 - 6.9$ TeV depending on the ILC energy and luminosity
  - TeV^{-1}: $M_C = 15 - 35$ TeV
  - VV: $\Lambda_{VV} = 62 - 160$ TeV
  - AA: $\Lambda_{AA} = 70 - 170$ TeV
  - LL: $\Lambda_{LL} = 55 - 135$ TeV
  - RR, LR and RL: $\Lambda = 57 - 142$ TeV
- Polarization is quite important, in particular in case of CI models.

Event-shape of dileptons plus missing energy at a linear collider as a SUSY/ADD discriminant

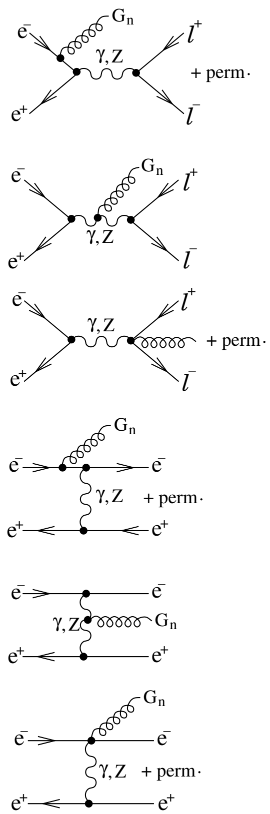
Probir Roy

Tata Institute of Fundamental Research, Mumbai, India

Based on work with Partha Konar, hep-ph/0509161, Phys. Lett. B634 (2006) 295

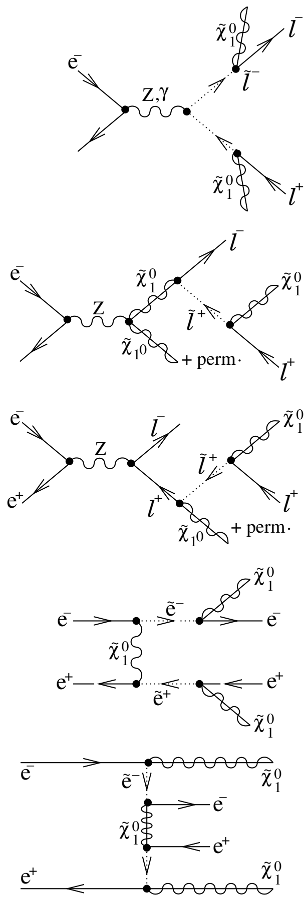
- Proposal
- Signal
- SM background and chosen cuts
- Cross-sections and event-shape variables
- Results
- Discussion

ADD



e^-
e^+
G_n
γ, Z
l^+
l^-
+ perm.

SUSY



e^-
e^+
Z,γ
Z
$\tilde{\chi}_1^0$
$\tilde{l}^-$
$\tilde{l}^+$
l^-
l^+
$\tilde{e}^-$
$\tilde{e}^+$
+ perm.

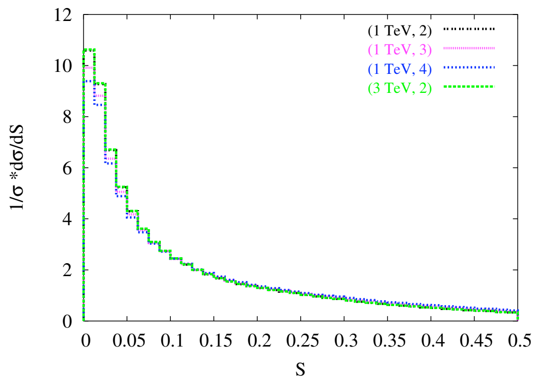
ADD

SUSY

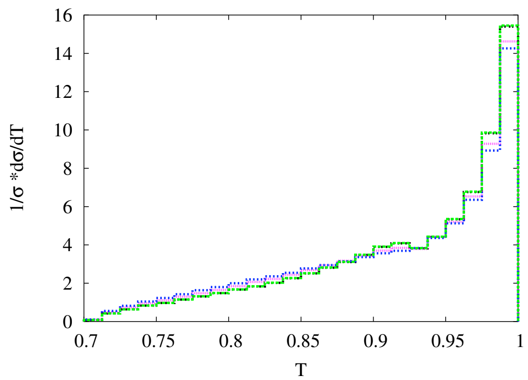
Results at $\sqrt{s} = 500$ GeV for ADD (M_s, d) and SUSY $(M_2, M_1, \mu, m_{\tilde{\ell}})$

ADD

Sphericity

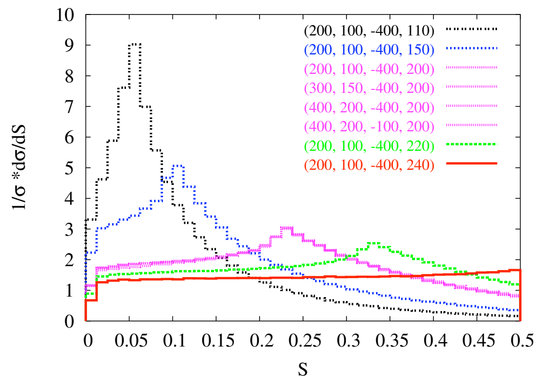


Thrust

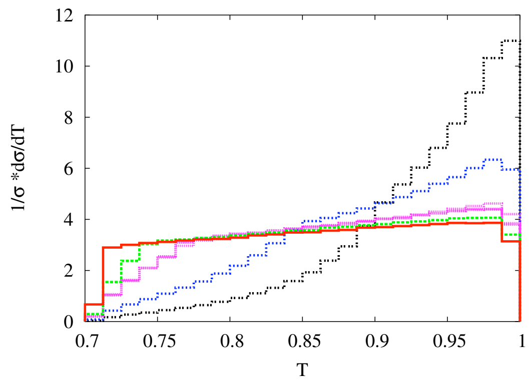


SUSY

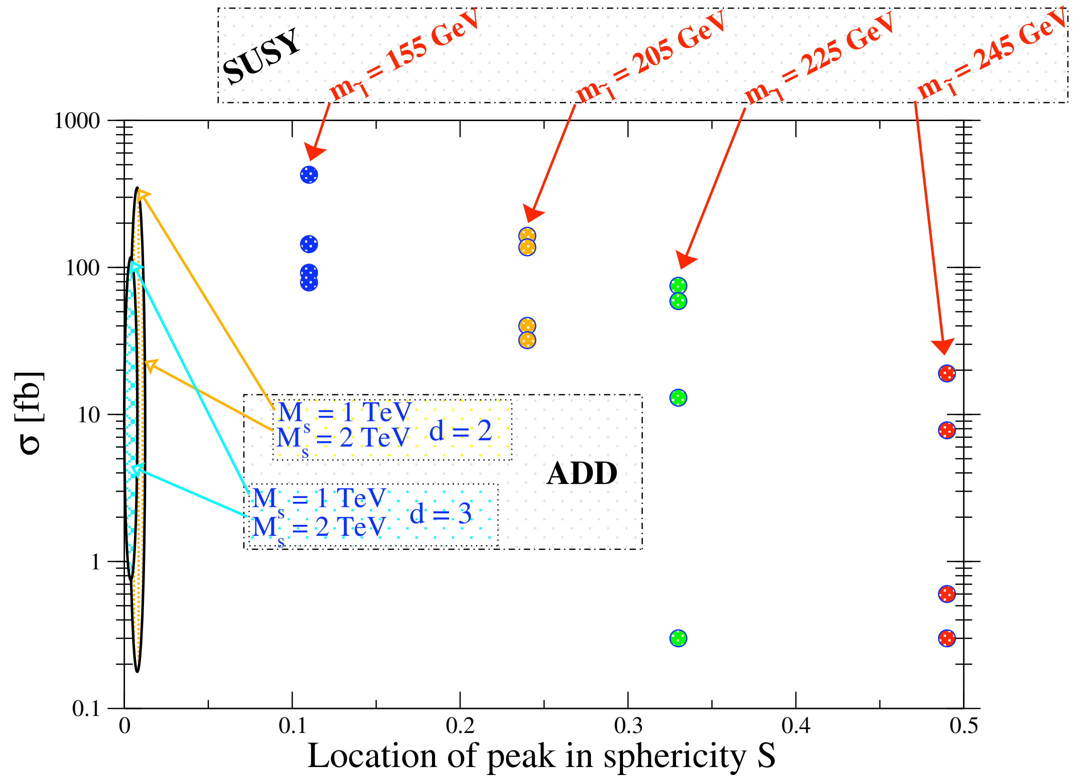
Sphericity



Thrust



ADD/SUSY discrimination via sphericity maximum at ILC



Graviton-induced Bremsstrahlung

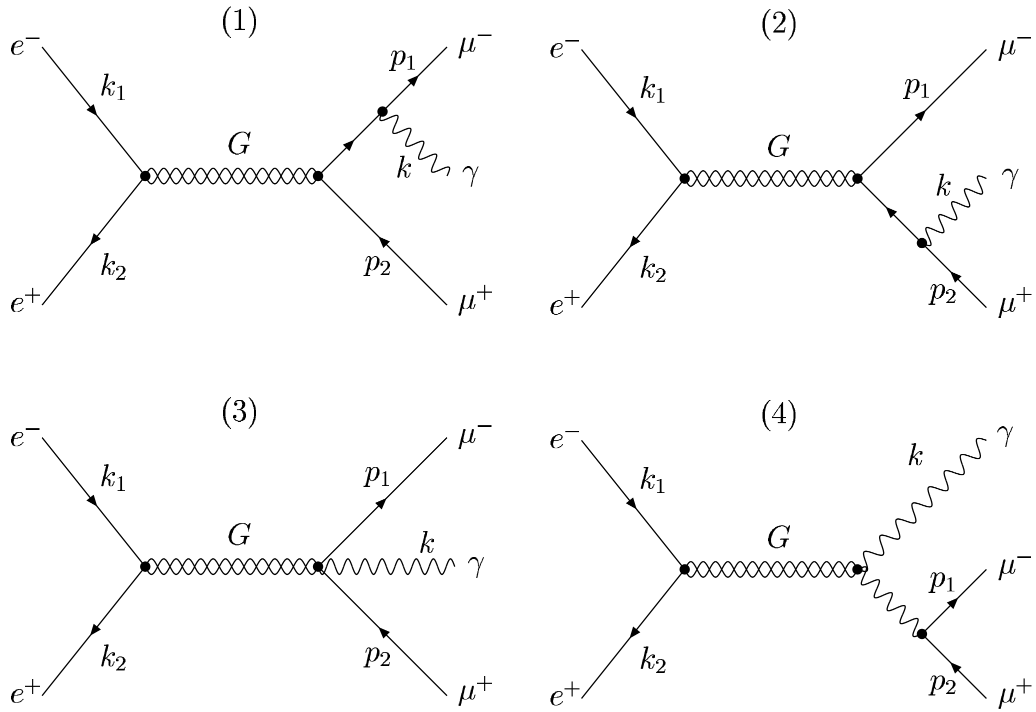
LCWS04

Per Osland, April, 2004

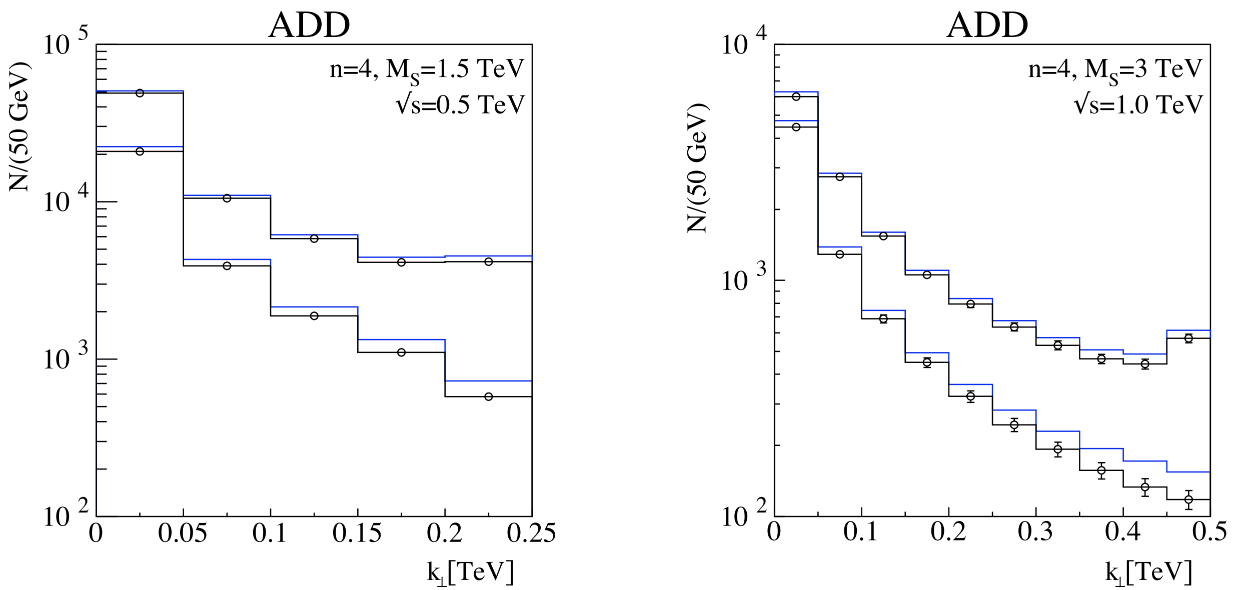
work with T. Buanes, E.W. Dvergsnes,
hep-ph/0403267, EPJC, in press

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

Final-state radiation (w.r.t. G)



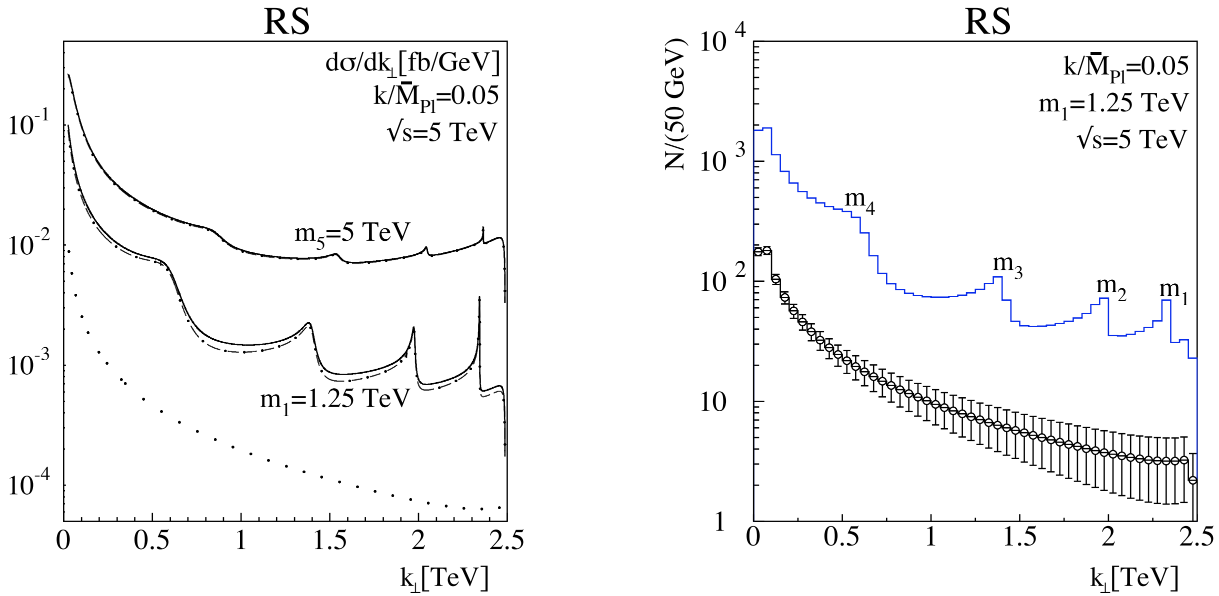
Photon $k_\perp$ distributions ($n = 4$):



With (upper) and without (lower set of curves) radiative return to Z.

The SM contribution is displayed with error bars (invisible in the left panel) corresponding to 300 fb^{-1}

Photon $k_\perp$ distributions: (cont)



Left: Lower curves, $m_1 = 1.25$ TeV, upper curve: $m_1 \simeq 1.16$ TeV ($m_5 = 5$ TeV). Graviton-related contributions: dash-dotted, SM contribution: dotted.

Right: bin-integrated $k_\perp$ distribution for $m_1 = 1.25$ TeV. Error bars (SM distribution) for $\mathcal{L}_{\text{int}} = 1000$ fb^{-1}

Probing Kaluza-Klein leptons at the International Linear Collider

Gautam Bhattacharyya

Saha Institute of Nuclear Physics, Kolkata

Work done with Paramita Dey, Anirban Kundu, and Amitava Raychaudhuri,

hep-ph/0502031, PLB 628 (2005) 141

A one-slide summary

- UED: all SM particles access the 5th dim.
- $R^{-1} \geq 250$ GeV ($g_\mu - 2$, FCNC, $Z \to b\bar{b}$, ρ)
- Compactification S^1/Z_2. Compactification breaks Lorentz symmetry. Also, translational invariance is lost along y, and $p_5 = n/R$ is not conserved.
- KK parity $= (-1)^n$ is conserved (similar to SUSY R_p) LKP (γ_1) is stable.
- $m_E = \sqrt{m_e^2 + 1/R^2} \simeq m_{\gamma_1}$
  Radiative corrections lift this degeneracy $\Rightarrow E_1 \stackrel{100\%}{\longrightarrow} e\gamma_1$
- $e^+e^- \to E_1^+ E_1^-$, Final state $e^+e^- +$ Missing energy
  Study based on $\sqrt{s} = 1$ TeV (upgraded ILC).

Non-standard Higgs

2HDM

Shinya Kanemura, Ilya Ginzburg, Maria Krawczyk, P.O.

- allows CP violation
- rich spectrum
- highly constrained by theory and data

Non-standard Higgs

J. van der Bij

M(inimal) N(on) M(inimal) S(tandard) M(odel)

with: T. Binoth

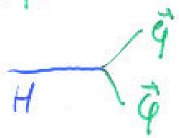
Stealth model

$$\mathcal{L} = -\partial_\mu \phi^+ \partial_\mu \phi - \lambda\left(\phi^+\phi - v^2/2\right)^2$$
$$-\frac{1}{2}\partial_\mu \vec{\varphi}\, \partial_\mu \vec{\varphi} - \frac{1}{2} m^2 \vec{\varphi}^{\,2} - \frac{\kappa}{8N}(\vec{\varphi})^2 - \frac{\omega}{2\sqrt{N}} \vec{\varphi}^{\,2} \phi^+\phi$$

$\vec{\varphi}$ N scalar real fields; singlets under $SU(3) \times SU(2) \times U(1)$

O(N)-symmetry, renormalizable, few extra parameters

$\langle \vec{\varphi} \rangle = 0 \quad \langle \phi \rangle = v \neq 0$



$\frac{\omega}{\sqrt{N}}$ invisible decay

$$\Gamma_H = \frac{\omega^2}{64\pi^2} \frac{v^2}{m_H}$$

ω can be large

$N \to \infty$ possibility non-perturbative $1/N$-expansion

Non-standard Higgs

Phenomenology

ω large $\rightarrow$ Γ_H large

Branching ratio ~ 100 % invisible

No signal at the LHC, only an enhancement over the background. One needs a very precise knowledge of the background, only possible at e^+e^- machines.

LCWS07 Ana Alboteanu

Quantum mechanics: position and momentum measurements complementary

$$[\hat{x}_i, \hat{p}_j] = \hat{x}_i \hat{p}_j - \hat{p}_j \hat{x}_i = i\hbar\delta_{ij} \quad \Rightarrow \quad \Delta x_i \cdot \Delta p_j \geqslant \frac{\hbar}{2}\delta_{ij}$$

Analog: postulation of noncommutative space-time

$$[\hat{x}_\mu, \hat{x}_\nu] = i\theta_{\mu\nu} = i\frac{C_{\mu\nu}}{\Lambda_{NC}{}^2} \quad \Rightarrow \quad \Delta\hat{x}_\mu \cdot \Delta\hat{x}_\nu \geqslant \frac{\theta_{\mu\nu}}{2}$$

- no experimental evidence yet
- possible, as long as the characteristic length scale $l_{NC} = \frac{1}{\Lambda_{NC}}$ small enough compared to the characteristic scales of present experiments
- introduces a minimal area / maximal energy:

$$A_{NC} = \frac{1}{\Lambda_{NC}^2}$$

Canonical noncommutativity: $\theta^{\mu\nu}$ constant 4×4-matrix:

$$[\hat{x}^\mu, \hat{x}^\nu] = i\theta^{\mu\nu} = i\frac{1}{{\Lambda_{NC}}^2} C^{\mu\nu} = i\frac{1}{{\Lambda_{NC}}^2} \begin{pmatrix} 0 & -E^1 & -E^2 & -E^3 \\ E^1 & 0 & -B^3 & B^2 \\ E^2 & B^3 & 0 & -B^1 \\ E^3 & -B^2 & B^1 & 0 \end{pmatrix}$$

Effective lagrangians

$$\mathcal{L}_{\text{eff.}} = \cdots + g\bar{\psi}(\hat{x})\gamma_\mu(1-\gamma_5)\psi(\hat{x})W^\mu(\hat{x}) + \cdots$$

with product of functions of noncommuting variables

$$(fg)(\hat{x}) = f(\hat{x})g(\hat{x})$$

realised by Moyal-Weyl $\star$-products of functions of commuting variables:

$$(f\star g)(x) = f(x)e^{\frac{i}{2}\overleftarrow{\partial^\mu}\theta_{\mu\nu}\overrightarrow{\partial^\nu}}g(x) = f(x)g(x) + \frac{i}{2}\theta_{\mu\nu}\frac{\partial f(x)}{\partial x_\mu}\frac{\partial g(x)}{\partial x_\nu} + \mathcal{O}(\theta^2)$$

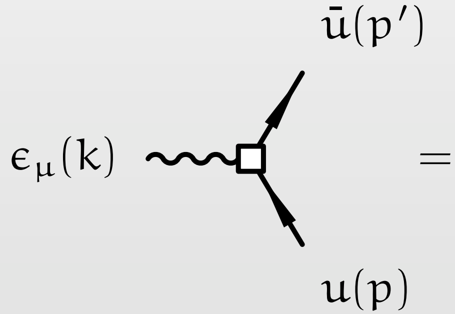
Note: $[x_\mu \overset{\star}{,} x_\nu](x) = (x_\mu \star x_\nu)(x) - (x_\nu \star x_\mu)(x) = i\theta_{\mu\nu} = [\hat{x}_\mu, \hat{x}_\nu]$

Noncommutative $SU(3)_C \times SU(2)_L \times U(1)_Y$ effective th. as expansion in $\mathcal{O}(\theta)$:

- replace usual "$\cdot$" products by "$\star$" products
- replace fields by their Seiberg-Witten maps

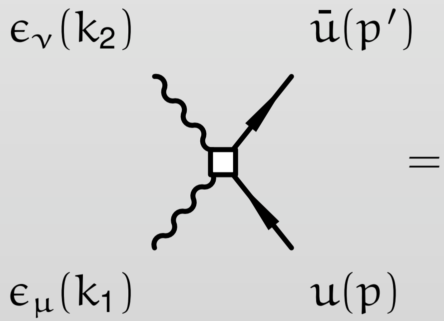
$$\text{e.g.} \quad S_{\text{fermions}} = \int d^4x \left(\sum_f \overline{\widehat{\Psi}}_{fL} \star i\widehat{\not{D}} \widehat{\Psi}_{fL} + \sum_f \overline{\widehat{\Psi}}_{fR} \star i\widehat{\not{D}} \widehat{\Psi}_{fR} \right)$$

$\Rightarrow$ NC-corrections to SM-interactions:



$$= \quad -\frac{g}{2}\left[k\theta^\mu \not{p} - p\theta^\mu \not{k} - (k\theta p)\gamma_\mu\right]$$

$\Rightarrow$ New interactions:



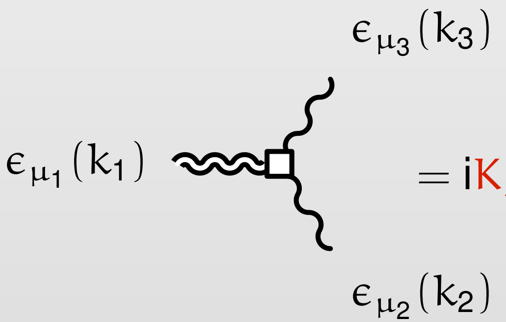
$$= \left\{ -\frac{g^2}{2}\left[k_2\theta^\mu\gamma^\nu - k_1\theta^\mu\gamma^\nu - \theta^{\mu\nu}\not{k}_1 + (\mu \leftrightarrow \nu, k_1 \leftrightarrow k_2)\right]\right.$$

In the enveloping algebra, the trace

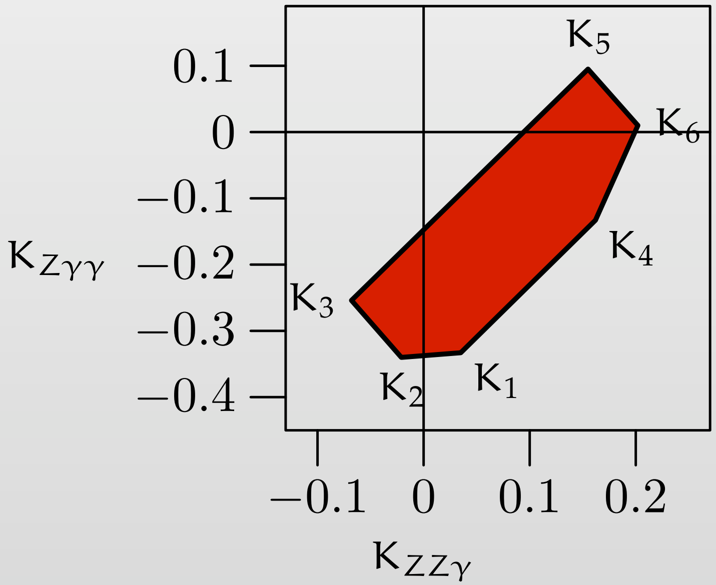
$$S_{\text{gauge}} = -\frac{1}{2}\int d^4x \ \mathrm{Tr}\left(\widehat{F}_{\mu\nu} \star \widehat{F}^{\mu\nu}\right)$$

depends on the representation:

- Minimal NCSM $\longrightarrow$ no triple neutral gauge boson interactions
- Nonminimal NCSM $\longrightarrow$ new interactions: $\gamma\gamma\gamma$, $Z\gamma\gamma$, $ZZ\gamma$, ...



$= iK_{Z\gamma\gamma} \cdot \ldots$



- coupling constants not unique, yet constrained from matching the SM at $\theta \longrightarrow 0$

A. Alboteanu

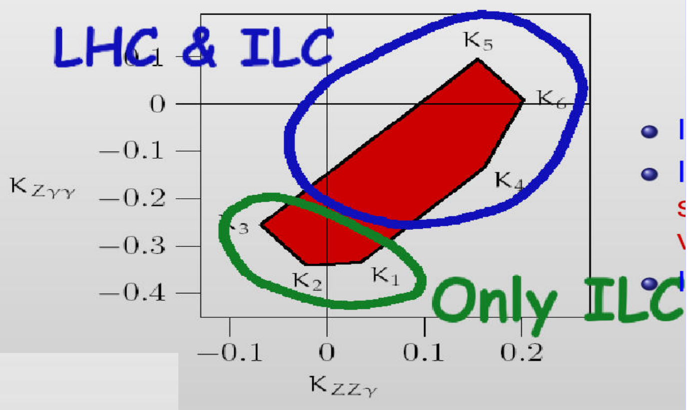
Non-Commutative Spacetime

- Postulate that spacetime coordinates do not commute
- Occurs in string theory in the presence of background fields

$$[\hat{x}_\mu, \hat{x}_\nu] = i\theta_{\mu\nu} = i\frac{C_{\mu\nu}}{\Lambda_{NC}{}^2} \quad \Rightarrow \quad \Delta\hat{x}_\mu \cdot \Delta\hat{x}_\nu \gtrsim \frac{\theta_{\mu\nu}}{2}$$

Characteristic NC scale

- Modifies SM interactions
- Induces new interactions among gauge fields



ILC sensitivity on Λ_{NC}:

$(K_{Z\gamma\gamma}, K_{ZZ\gamma})$	$\|\vec{E}\|^2 = 1, \vec{B} = 0$	$\vec{E} = 0, \|\vec{B}\|^2 = 1$
$K_0 \equiv (0, 0)$ (mNCSM)	$\Lambda_{NC} \gtrsim 2$ TeV	$\Lambda_{NC} \gtrsim 0.4$ TeV
$K_1 \equiv (-0.333, 0.035)$ (nmNCSM)	$\Lambda_{NC} \gtrsim 5.9$ TeV	$\Lambda_{NC} \gtrsim 0.9$ TeV
$K_5 \equiv (0.095, 0.155)$ (nmNCSM)	$\Lambda_{NC} \gtrsim 2.6$ TeV	$\Lambda_{NC} \gtrsim 0.25$ TeV
$K_3 \equiv (-0.254, -0.048)$(nmNCSM)	$\Lambda_{NC} \gtrsim 5.4$ TeV	$\Lambda_{NC} \gtrsim 0.9$ TeV

Studied $Z\gamma$ production @ ILC and LHC