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

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

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

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

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

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

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

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

Flavor physics info contained in M (ignored here)

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

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 $(\gamma'/Z'$?)	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

Integrating out resonances

Consider leading order effects of resonances on EW sector:

$$\mathcal{L}_\Phi = z\left[\Phi\left(M_\Phi^2 + DD\right)\Phi + 2\Phi J\right] \qquad \Rightarrow \qquad \mathcal{L}_\Phi^{\text{eff}} = -\frac{z}{M^2}JJ + \frac{z}{M^4}J(DD)J + \mathcal{O}(M^{-6})$$

- Simplest example: scalar singlet σ:

$$\mathcal{L}_\sigma = -\frac{1}{2}\left[\sigma(M_\sigma^2 + \partial^2)\sigma - g_\sigma v\sigma\,\text{tr}\left\{\mathbf{V}_\mu\mathbf{V}^\mu\right\} - h_\sigma\,\text{tr}\left\{\mathbf{T}\mathbf{V}_\mu\right\}\text{tr}\left\{\mathbf{T}\mathbf{V}^\mu\right\}\right]$$

- Effective Lagrangian

$$\mathcal{L}_\sigma^{\text{eff}} = \frac{v^2}{8M_\sigma^2}\left[g_\sigma\,\text{tr}\left\{\mathbf{V}_\mu\mathbf{V}^\mu\right\} + h_\sigma\,\text{tr}\left\{\mathbf{T}\mathbf{V}_\mu\right\}\text{tr}\left\{\mathbf{T}\mathbf{V}^\mu\right\}\right]^2$$

- leads to anomalous quartic couplings

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

- Special case: SM Higgs with $g_\sigma = 1$ and $h_\sigma = 0$

Coupl. strengths, Anomal. Couplings, Power Counting

Scalar resonance width ($M_\sigma \gg M_W, M_Z$):

$$\Gamma_\sigma = \frac{g_\sigma^2 + \frac{1}{2}(g_\sigma^2 + 2h_\sigma^2)^2}{16\pi} \left(\frac{M_\sigma^3}{v^2}\right) + \Gamma(\text{non} - WW, ZZ)$$

Largest allowed coupling for a broad continuum: $\Gamma \sim M \gg \Gamma(\text{non} - WW, ZZ) \sim 0$ translates to bounds for effective Lagrangian (e.g. scalar with no isospin violation):

$$\alpha_5 \leq \frac{4\pi}{3}\left(\frac{v^4}{M_\sigma^4}\right) \approx \frac{0.015}{(M_\sigma \text{ in TeV})^4} \quad \Rightarrow \quad 16\pi^2\alpha_5 \leq \frac{2.42}{(M_\sigma \text{ in TeV})^4}$$

Scalar:	$\Gamma \sim g^2 M^3,\ \alpha \sim g^2/M^2$	$\Rightarrow$	$\alpha_{\text{max}} \sim 1/M^4$
Vector:	$\Gamma \sim g^2 M,\ \alpha \sim g^2/M^2$	$\Rightarrow$	$\alpha_{\text{max}} \sim 1/M^2$
Tensor:	$\Gamma \sim g^2 M^3,\ \alpha \sim g^2/M^2$	$\Rightarrow$	$\alpha_{\text{max}} \sim 1/M^4$

Vector triplet (simplified)

$$\mathcal{L}_\rho = -\frac{1}{8}\,\text{tr}\left\{\boldsymbol{\rho}_{\mu\nu}\boldsymbol{\rho}^{\mu\nu}\right\} + \frac{M_\rho^2}{4}\,\text{tr}\left\{\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu\right\} + \frac{\mathrm{i}g_\rho v^2}{2}\,\text{tr}\left\{\boldsymbol{\rho}_\mu\mathbf{V}^\mu\right\}$$

$1/M^2$ term renormalizes kinetic energy (i.e. v), hence unobservable:

$$\mathcal{L}_\rho^{\text{eff}} = \frac{g_\rho^2 v^4}{4M_\rho^2}\,\text{tr}\left\{(\mathbf{D}_\mu\Sigma)(\mathbf{D}^\mu\Sigma)\right\} + \mathcal{O}(1/M_\rho^4)$$

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Vector Resonances

$$\mathcal{L}_\rho = -\frac{1}{8}\,\mathrm{tr}\left\{\boldsymbol{\rho}_{\mu\nu}\boldsymbol{\rho}^{\mu\nu}\right\} + \frac{M_\rho^2}{4}\,\mathrm{tr}\left\{\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu\right\} + \frac{\Delta M_\rho^2}{8}\left(\mathrm{tr}\left\{\mathbf{T}\boldsymbol{\rho}_\mu\right\}\right)^2 + \mathrm{i}\frac{\mu_\rho}{2}g\,\mathrm{tr}\left\{\boldsymbol{\rho}_\mu\mathbf{W}^{\mu\nu}\boldsymbol{\rho}_\nu\right\}$$
$$+\,\mathrm{i}\frac{\mu_\rho'}{2}g'\,\mathrm{tr}\left\{\boldsymbol{\rho}_\mu\mathbf{B}^{\mu\nu}\boldsymbol{\rho}_\nu\right\} + \mathrm{i}\frac{g_\rho v^2}{2}\,\mathrm{tr}\left\{\boldsymbol{\rho}_\mu\mathbf{V}^\mu\right\} + \mathrm{i}\frac{h_\rho v^2}{2}\,\mathrm{tr}\left\{\boldsymbol{\rho}_\mu\mathbf{T}\right\}\mathrm{tr}\left\{\mathbf{T}\mathbf{V}^\mu\right\}$$
$$+\,\frac{g' v^2 k_\rho}{2M_\rho^2}\,\mathrm{tr}\left\{\boldsymbol{\rho}_\mu[\mathbf{B}^{\nu\mu},\mathbf{V}_\nu]\right\} + \frac{g v^2 k_\rho'}{4M_\rho^2}\,\mathrm{tr}\left\{\boldsymbol{\rho}_\mu[\mathbf{T},\mathbf{V}_\nu]\right\}\mathrm{tr}\left\{\mathbf{T}\mathbf{W}^{\nu\mu}\right\}$$
$$+\,\frac{g v^2 k_\rho''}{4M_\rho^2}\,\mathrm{tr}\left\{\mathbf{T}\boldsymbol{\rho}_\mu\right\}\mathrm{tr}\left\{[\mathbf{T},\mathbf{V}_\nu]\mathbf{W}^{\nu\mu}\right\} + \mathrm{i}\frac{\ell_\rho}{M_\rho^2}\,\mathrm{tr}\left\{\boldsymbol{\rho}_{\mu\nu}\mathbf{W}^\nu{}_\rho\mathbf{W}^{\rho\mu}\right\}$$
$$+\,\mathrm{i}\frac{\ell_\rho'}{M_\rho^2}\,\mathrm{tr}\left\{\boldsymbol{\rho}_{\mu\nu}\mathbf{B}^\nu{}_\rho\mathbf{W}^{\rho\mu}\right\} + \mathrm{i}\frac{\ell_\rho''}{M_\rho^2}\,\mathrm{tr}\left\{\boldsymbol{\rho}_{\mu\nu}\mathbf{T}\right\}\mathrm{tr}\left\{\mathbf{T}\mathbf{W}^\nu{}_\rho\mathbf{W}^{\rho\mu}\right\}$$

all $\alpha_i \sim 1/M_\rho^4$, except for $\beta_1 \sim \Delta\rho \sim T \sim h_\rho^2/M_\rho^2$

4-fermion contact interaction $j_\mu j^\mu \sim 1/M_\rho^2$ (eff. T and U parameter)

vector coupling $j_\mu V^\mu \sim 1/M_\rho^2$ (eff. S parameter)
Mismatch: measured fermionic vs. bosonic coupling g Nyffeler/Schenk, 2000; Kilian/JR, 2003

Effects on Triple Gauge Couplings

- $\mathcal{O}(1/M^2)$: Renormalization of ZWW coupling
- $\mathcal{O}(1/M^4)$: shifts in Δg_1^Z, $\Delta\kappa^\gamma$, $\Delta\kappa^Z$, λ^γ, λ^Z

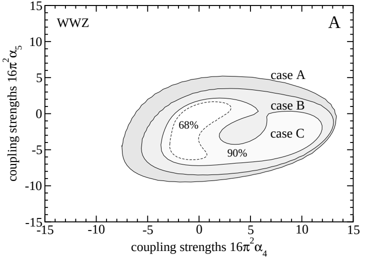
Effects on Quartic Gauge Couplings

- $\mathcal{O}(1/M^4)$, orthogonal (in α_4–α_5 space) to scalar case

Results: Triboson production

$e^+e^- \to WWZ/ZZZ$, dep. on $(\alpha_4+\alpha_6)$, $(\alpha_5+\alpha_7)$, $\alpha_4+\alpha_5+2(\alpha_6+\alpha_7+\alpha_{10})$

Polarization populates longitudinal modes, suppresses SM bkgd.



Simulation with WHIZARD Kilian/Ohl/JR

1 TeV, 1 ab^{-1}, full 6-fermion final states, SIMDET fast simulation

Observables: M^2_{WW}, M^2_{WZ}, $\sphericalangle(e^-, Z)$

A) unpol., B) 80% e^-_R, C) 80% e^-_R, 60% e^+_L

$16\pi^2\times$	WWZ no pol.	WWZ e^- pol.	WWZ both pol.	ZZZ no pol.	best
$\Delta\alpha_4^+$	9.79	4.21	1.90	3.94	1.78
$\Delta\alpha_4^-$	−4.40	−3.34	−1.71	−3.53	−1.48
$\Delta\alpha_5^+$	3.05	2.69	1.17	3.94	1.14
$\Delta\alpha_5^-$	−7.10	−6.40	−2.19	−3.53	−1.64

32 % hadronic decays

Durham jet algorithm

Bkgd. $t\bar{t} \to 6$ jets

Veto against $E^2_{\text{mis}} + p^2_{\perp,\text{mis}}$

No angular correlations yet

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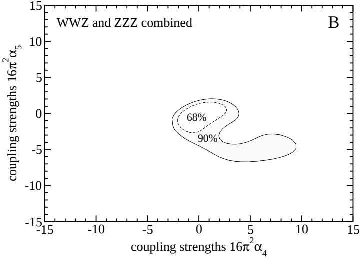

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Vector Boson Scattering

1 TeV, 1 ab^{-1}, full 6f final states, 80 % e_R^-, 60 % e_L^+ polarization, binned likelihood

Contributing channels: $WW \to WW$, $WW \to ZZ$, $WZ \to WZ$, $ZZ \to ZZ$

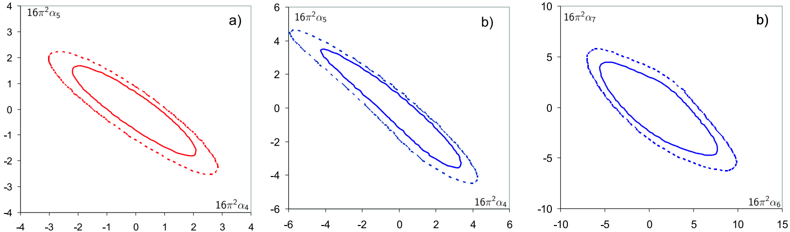
Process	Subprocess	σ [fb]
$e^+e^- \to \nu_e\bar\nu_e q\bar q q\bar q$	$WW \to WW$	23.19
$e^+e^- \to \nu_e\bar\nu_e q\bar q q\bar q$	$WW \to ZZ$	7.624
$e^+e^- \to \nu\bar\nu q\bar q q\bar q$	$V \to VVV$	9.344
$e^+e^- \to \nu e q\bar q q\bar q$	$WZ \to WZ$	132.3
$e^+e^- \to e^+e^- q\bar q q\bar q$	$ZZ \to ZZ$	2.09
$e^+e^- \to e^+e^- q\bar q q\bar q$	$ZZ \to W^+W^-$	414.
$e^+e^- \to b\bar b X$	$e^+e^- \to t\bar t$	331.768
$e^+e^- \to q\bar q q\bar q$	$e^+e^- \to W^+W^-$	3560.108
$e^+e^- \to q\bar q q\bar q$	$e^+e^- \to ZZ$	173.221
$e^+e^- \to e\nu q\bar q$	$e^+e^- \to e\nu W$	279.588
$e^+e^- \to e^+e^- q\bar q$	$e^+e^- \to e^+e^- Z$	134.935
$e^+e^- \to X$	$e^+e^- \to q\bar q$	1637.405

$SU(2)_c$ conserved case, all channels

coupling	$\sigma-$	$\sigma+$
α_4	-1.41	1.38
α_5	-1.16	1.09

$SU(2)_c$ broken case, all channels

coupling	$\sigma-$	$\sigma+$
α_4	-2.72	2.37
α_5	-2.46	2.35
α_6	-3.93	5.53
α_7	-3.22	3.31
α_{10}	-5.55	4.55

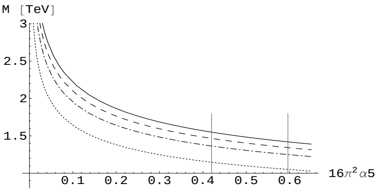


Interpretation as limits on resonances

Consider the width to mass ratio, $f_\sigma = \Gamma_\sigma / M_\sigma$

$SU(2)$ conserving scalar singlet

$$M_\sigma = v \left(\frac{4\pi f_\sigma}{3\alpha_5} \right)^{\frac{1}{4}}$$

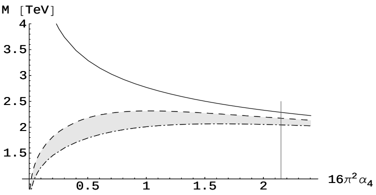


$f = 1.0$ (full), 0.8 (dash), 0.6 (dot-dash), 0.3 (dot)

$SU(2)$ broken vector triplet

needs input from TGC covariance matrix

$$M_{\rho^\pm} = v \left(\frac{12\pi\alpha_4 f_{\rho^\pm}}{\alpha_4^2 + 2(\alpha_2^\lambda)^2 + s_w^2(\alpha_4^\lambda)^2/(2c_w^2)} \right)^{\frac{1}{4}}$$



upper/lower limit from λ_Z, grey area: magnetic moments

Final result:

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

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

Summary

New Physics generically encoded in EW Chiral Lagrangian

ILC can measure deviations in quartic gauge couplings

- either via triple boson production
- or via vector boson scattering

interpreted as resonances coupled to EW bosons

Sensitivity rises with number of intermediate states: $1.5 - 6$ TeV

Full analysis including all channels/backgrounds with WHIZARD

Power counting for vector resonances might be intricate:
only $\Delta\rho$ scales like $1/M^2$

ILC allows to detect also (very) broad resonances