Resonances and Electroweak Observables

at the ILC

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WK, P. Krstonošić, K. Mönig, J. Reuter, work in progress

New Physics and Weak Interactions

This session is about new physics at the TeV scale; in particular, new physics connected to EWSB.

We expect *direct* signals of new physics: new particles, new symmetries, extra dimensions, and more. However, any new physics that is visible at all will also have an *indirect effect* of the interactions of the known quarks, leptons, massless gauge bosons and massive vector bosons at lower energies.

This talk: look just at indirect effects,

and try to be generic.

(The most generic description is trivial: write down a Lagrangian with all possible interactions that are consistent with (QED and QCD) gauge invariance. We also may assume Lorentz and, for simplicity, CP invariance. All (but one) parameters in such a Lagrangian are observables, in principle. There are infinitely many. This is completely generic, and almost completely useless.)

A reasonable description should make use of the facts that we already know about weak interactions.

Back to the Roots

Any model of massive vector bosons can be written as a gauge theory, spontaneously broken. Here: $SU(2)_L \times U(1)_Y \to U(1)_{\rm QED}$. The Lagrangian (in general gauge) contains three scalars that are related to the longitudinal helicity component of the massive vector bosons.

We need:

$$\psi\text{(quarks and leptons)}, \quad W_\mu^a \ (a = 1,2,3), \qquad B_\mu, \qquad \Sigma = \exp\frac{-i}{v} w^a \tau^a$$

These are propagating fields and thus have kinetic energies:

$$\mathcal{L}_{\rm kin} = \sum_\psi \bar\psi (i\partial\!\!\!/)\psi - \frac{1}{4g^2} W_{\mu\nu}^a W^{\mu\nu,a} - \frac{1}{4g'^2} B_{\mu\nu} B^{\mu\nu} + \frac{v^2}{4}\,\mathrm{tr}\,\{(\partial_\mu\Sigma)(\partial^\mu\Sigma)\}$$

Now, the dynamics: try *minimal coupling*, i.e., replace ordinary by covariant derivatives.

$$\mathcal{L}_{\rm min} = \sum_\psi \bar\psi (iD\!\!\!\!/\,)\psi - \frac{1}{2g^2}\,\mathrm{tr}\,\{\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}\} - \frac{1}{2g'^2}\,\mathrm{tr}\,\{\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu}\} + \frac{v^2}{4}\,\mathrm{tr}\,\{(\mathbf{D}_\mu\Sigma)(\mathbf{D}^\mu\Sigma)\}$$

This model contains only three parameters: g, g', and the scale v.

Electroweak Parameters

The complete Lagrangian has infinitely many parameters:

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

With $\mathbf{V} = \Sigma(\mathbf{D}\Sigma)^\dagger$ (longitudinal vector boson), and $\mathbf{T} = \Sigma\tau^3\Sigma^\dagger$ (projects out neutral component):

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

$$\mathcal{L}_1 = \operatorname{tr}\{\mathbf{B}_{\mu\nu}\mathbf{W}^{\mu\nu}\} \qquad \mathcal{L}_2 = \mathrm{i}\operatorname{tr}\{\mathbf{B}_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu]\} \qquad \mathcal{L}_3 = \mathrm{i}\operatorname{tr}\{\mathbf{W}_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu]\}$$

$$\mathcal{L}_4 = (\operatorname{tr}\{\mathbf{V}_\mu\mathbf{V}_\nu\})^2 \qquad \mathcal{L}_5 = (\operatorname{tr}\{\mathbf{V}_\mu\mathbf{V}^\mu\})^2$$

$$\mathcal{L}_6 = \operatorname{tr}\{\mathbf{V}_\mu\mathbf{V}_\nu\}\operatorname{tr}\{\mathbf{T}\mathbf{V}^\mu\}\operatorname{tr}\{\mathbf{T}\mathbf{V}^\nu\} \qquad \mathcal{L}_7 = \operatorname{tr}\{\mathbf{V}_\mu\mathbf{V}^\mu\}(\operatorname{tr}\{\mathbf{T}\mathbf{V}_\nu\})^2$$

$$\mathcal{L}_8 = \frac{1}{4}(\operatorname{tr}\{\mathbf{T}\mathbf{W}_{\mu\nu}\})^2 \qquad \mathcal{L}_9 = \frac{\mathrm{i}}{2}\operatorname{tr}\{\mathbf{T}\mathbf{W}_{\mu\nu}\}\operatorname{tr}\{\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu]\} \qquad \mathcal{L}_{10} = \frac{1}{2}(\operatorname{tr}\{\mathbf{T}\mathbf{V}_\mu\})^2(\operatorname{tr}\{\mathbf{T}\mathbf{V}_\nu\})^2$$

To explain all electroweak precision data, we need the matrix M (flavor physics), but apparently the remaining parameters are small, no larger than required for the renormalization of radiative corrections with cutoff $\Lambda \sim 4\pi v$.

Therefore, the gauge-covariant approach makes sense for a phenomenological description.

All indirect information on new physics is encoded in the values of β_1, α_i, ...

Parameters and Scales

The α_i parameters can be measured at the ILC. (See, e.g., Predrag's and Jadranka's talks.)

What do we expect?

- The α_i parameters should be $\ll 1$. For many of them, this has been established by LEP.
- The α_i parameters should be $\gtrsim 1/16\pi^2 = 0.006$. This is required by consistency since many of them renormalize divergences.

  (In plots, we often show $16\pi^2\alpha_i$ instead of α_i. These numbers are expected $\gtrsim 1$.)

Traditionally, to get a feeling of experimental sensitivity,

one translates α values into a new-physics scale Λ, according to

$$\alpha_i = v^2/\Lambda^2 \qquad \Rightarrow \qquad \Lambda = v/\sqrt{\alpha_i}$$

However, this is misleading since the operator normalization is arbitrary.

Even worse: *we will see that, in many cases, the power-counting is also misleading.*

Resonances

More meaningful: investigate concrete new-physics contributions to the α_i. Therefore, we look at

resonances that couple to the EWSB sector,

The new-physics reach is characterized by the resonance mass that gives a detectable α_i shift.

Narrow resonances = particles. Wide resonances = continuum.

Symmetry: Because $\beta_1 \ll 1$, vector boson scattering exhibits a *custodial* $SU(2)_c$ symmetry (weak isospin). This symmetry is broken by the hypercharge coupling ($g' \neq 0$) and by fermion masses, but may be used as a guideline.

We catalog the possible resonance multiplets by spin and isospin, but allow for isospin violation.

	$J = 0$	$J = 1$	$J = 2$
$I = 0$	σ^0 (Higgs?)	ω^0 (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?)	$\cdots$	$t^{\pm\pm}, t^\pm, t^0$

This accounts for both weakly and strongly-interacting models.

Integrating Out

Let's look at the tree-level effects of resonances on electroweak interactions.

Recipe: For each resonance Φ, write a generic Lagrangian

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

Example: Scalar singlet

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

Effective Lagrangian:

$$\mathcal{L}_\sigma^{\rm eff} = \frac{v^2}{8M_\sigma^2}\left[g_\sigma\,\mathrm{tr}\left\{\mathbf{V}_\mu \mathbf{V}^\mu\right\} + h_\sigma\left(\mathrm{tr}\left\{\mathbf{T}\mathbf{V}_\mu\right\}\right)^2\right]^2 + O(M_\sigma^{-4})$$

Result: Anomalous quartic gauge 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 $h_\sigma = 0$

Coupling Strength and Anomalous Coupling

All indirect effects are proportional to $(\text{coupling})^2$. *How large can that be?*

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

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

If this is to make sense, we should require $\Gamma \leq M$. The largest allowed coupling of the resonance to the EWSB sector corresponds to $\Gamma = M$ (broad continuum) and $\Gamma(\text{non-}WW, ZZ) = 0$.

Simplified: Assume isospin ($h_\sigma = 0$):

$$g_\sigma^2 \leq \frac{32\pi}{3}\left(\frac{v^2}{M_\sigma^2}\right)\left(\frac{\Gamma_\sigma}{M_\sigma}\right) \leq \frac{32\pi}{3}\left(\frac{v^2}{M_\sigma^2}\right)$$

Apply this bound to the effective Lagrangian:

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

Insert numbers:

$$M_\sigma = 1\ \text{TeV} \quad \Rightarrow \quad 16\pi^2\alpha_5 \leq 2.4 \qquad\qquad M_\sigma = 1.5\ \text{TeV} \quad \Rightarrow \quad 16\pi^2\alpha_5 \leq 0.5$$

Scalars, Vectors, and Tensors

So, the sensitivity decreases like $1/M^4$. *Is this generic?*

- Scalar: $\Gamma \sim g^2 M^3$ and $\alpha \sim g^2/M^2 \Rightarrow \alpha_{\mathsf{sat}} \sim 1/M^4$
- Vector: $\Gamma \sim g^2 M$ and $\alpha \sim g^2/M^2 \Rightarrow \alpha_{\mathsf{sat}} \sim 1/M^2$?
- Tensor: like scalar

Let's look more closely at a vector resonance (isospin triplet, simplified):

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

The leading term ($1/M^2$):

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

...but this term just renormalizes the kinetic energy (i.e., v) and is thus unobservable.

$\Rightarrow$ The observable effect decreases like $1/M^4$.

Vector Resonances

The full Lagrangian (vector triplet resonance, fermions omitted):

$$
\begin{aligned}
\mathcal{L}_\rho = & -\frac{1}{8}\operatorname{tr}\{\boldsymbol{\rho}_{\mu\nu}\boldsymbol{\rho}^{\mu\nu}\} + \frac{M_\rho^2}{4}\operatorname{tr}\{\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu\} + \frac{\Delta M_\rho^2}{8}\left(\operatorname{tr}\{\mathbf{T}\boldsymbol{\rho}_\mu\}\right)^2 \\
& + \frac{\mu_\rho}{4} g \operatorname{tr}\{\boldsymbol{\rho}_\mu \mathbf{W}^{\mu\nu}\boldsymbol{\rho}_\nu\} + \frac{\mu'_\rho}{4} g' \operatorname{tr}\{\boldsymbol{\rho}_\mu \mathbf{B}^{\mu\nu}\boldsymbol{\rho}_\nu\} \\
& + \mathrm{i}\frac{g_\rho v^2}{2}\operatorname{tr}\{\boldsymbol{\rho}_\mu \mathbf{V}^\mu\} + \mathrm{i}\frac{h_\rho v^2}{2}\operatorname{tr}\{\boldsymbol{\rho}_\mu \mathbf{T}\}\operatorname{tr}\{\mathbf{T}\mathbf{V}^\mu\} \\
& + \mathrm{i}\frac{\ell_\rho}{2M_\rho^2}\operatorname{tr}\{\boldsymbol{\rho}_{\mu\nu}\mathbf{W}^\nu{}_\rho \mathbf{W}^{\rho\mu}\} + \mathrm{i}\frac{\ell'_\rho}{2M_\rho^2}\operatorname{tr}\{\boldsymbol{\rho}_{\mu\nu}\mathbf{B}^\nu{}_\rho \mathbf{W}^{\rho\mu}\} + \mathrm{i}\frac{\ell''_\rho}{2M_\rho^2}\operatorname{tr}\{\boldsymbol{\rho}_{\mu\nu}\mathbf{T}\}\operatorname{tr}\{\mathbf{T}\mathbf{W}^\nu{}_\rho \mathbf{W}^{\rho\mu}\} \\
& + \cdots
\end{aligned}
$$

Effective Lagrangian:

- All α_i parameters $\sim 1/M_\rho^4$
- except for β_1 (i.e., $\Delta\rho$ or T parameter): contribution $\sim h_\rho/M_\rho^2$

$\Rightarrow$ Limit on T parameter constrains h_ρ.

More on Vector Resonances

But there are fermions: couple ρ to fermion current(s) j_μ

$\Rightarrow$ 4-fermion contact interaction(s) $j_\mu j^\mu$ proportional to $1/M_\rho^2$ (effective T and U parameters)

$\Rightarrow$ Vector coupling $j_\mu V^\mu$ proportional to $1/M_\rho^2$

- $\longrightarrow$ Effective S parameter
- $\longrightarrow$ Mismatch between measured fermionic and bosonic gauge coupling g

Effect on triple gauge vertices:

- Order $1/M^2$: Renormalization of ZWW coupling (present simultaneously with 4-fermion contact interaction)
- Order $1/M^4$:
  - Shifts in Δg_1^Z, $\Delta\kappa^\gamma$, $\Delta\kappa^Z$ depend on couplings and magnetic moments
  - Isospin conservation implies $\Delta\kappa^\gamma + \frac{c_w^2}{s_w^2}(\Delta\kappa^Z - \Delta g_1^Z) = 0$
  - Shifts in λ^γ and λ^Z, generically $\lambda^\gamma \neq \lambda^Z$ even if isospin is conserved

Effect on quartic gauge vertices:

- Order $1/M^4$, orthogonal to scalar (in $\alpha_4 - \alpha_5$ space)

Conclusions (preliminary)

Model-independent description of new-physics effects in electroweak data: measure all electroweak parameters (anomalous couplings) at the ILC.

For a model-independent estimate of the ILC reach, translate this into the achievable limits on resonances. Consider all reasonable quantum numbers and all independent couplings.

First results: don't expect too much ...

$\Rightarrow$ 4-fermion contact interactions are most sensitive $(1/M^2)$

$\Rightarrow$ Leading bosonic terms generically suppressed by $1/M^4$ (for maximal coupling)

If we reach the necessary sensitivity, there are many things that complement LHC data:

$\Rightarrow$ Triple gauge couplings sensitive to vector resonances, nontrivial effects (magnetic moments)

$\Rightarrow$ Quartic gauge couplings sensitive to all types of resonances

$\Rightarrow$ GigaZ data (improved S, T, U) would greatly increase overall significance

(t.b.c.)