Resonances and Unitarity in Weak Boson Scattering at the LHC

Jürgen Reuter

DESY Hamburg

Alboteanu/Kilian/JR, arXiv:0806.4145 (JHEP); M. Mertens, 2005;
Kilian/Kobel/Mader/JR/Schumacher, work in progress;
Beyer/Kilian/Krstonošić/Mönig/JR/Schmitt/Schröder, EPJC 48 (2006), 353 [ILC version]

Seminar, BNL, N.Y., Nov. 1st, 2012
Doubts on the Standard Model

- describes microcosm (too good?)
- 28 free parameters

Hierarchy Problem

chiral symmetry: \( \delta m_f \propto v \ln(\Lambda^2/v^2) \)

no symmetry for quantum corrections to Higgs mass

\[
\delta M_H^2 \propto \Lambda^2 \sim M_{\text{Planck}}^2 = (10^{19})^2 \text{GeV}^2
\]

20000 GeV^2 = (10000000000000000000000000) GeV^2
Open Questions

– Unification of all interactions (?)

– Baryon asymmetry $\Delta N_B - \Delta N_{\bar{B}} \sim 10^{-9}$
  missing CP violation

– Flavour: three generations

– Tiny neutrino masses: $m_\nu \sim \frac{\nu^2}{M}$

– Dark Matter:
  ▶ stable
  ▶ only weakly interacting
  ▶ $m_{DM} \sim 100$ GeV

– Quantum theory of gravity

– Cosmic inflation

– Cosmological constant
Ideas for New Physics since 1970
Model-Independent Description of the EW sector

- The "IT" boson is observed ... Higgs ?
- Aim: describe any physics beyond the SM as generically as possible
- Implement what we know about the SM
- Implements $SU(2)_L \times U(1)_Y$ gauge invariance
- Building blocks (including longitudinal modes):

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

- Minimal Lagrangian including gauge interactions

\[ \mathcal{L}_{\text{min}} = \sum_\psi \overline{\psi}(i\gamma^\mu)\psi - \frac{1}{2g^2} \text{tr} [W_{\mu\nu} W^{\mu\nu}] - \frac{1}{2g'2} \text{tr} [B_{\mu\nu} B^{\mu\nu}] + \frac{v^2}{4} \text{tr} [(D_\mu \Sigma)(D^\mu \Sigma)] \]
The Fundamental Building Blocks

- \( V = \Sigma (D \Sigma)^\dagger \) (longitudinal vectors), \( T = \Sigma \tau^3 \Sigma^\dagger \) (neutral component)

- **Unitary gauge** (no Goldstones): \( w \equiv 0 \), i.e., \( \Sigma \equiv 1 \).

\[
V \rightarrow -\frac{ig}{2} \left[ \sqrt{2}(W^+ \tau^+ + W^- \tau^-) + \frac{1}{c_w} Z \tau^3 \right]
\]

\[
T \rightarrow \tau^3
\]

- **Gaugeless limit** (only Goldstones) \((g, g' \rightarrow 0)\):

\[
V \rightarrow \frac{i}{v} \left\{ \sqrt{2} \partial w^+ \tau^+ + \sqrt{2} \partial w^- \tau^- + \partial z \tau^3 \right\} + O(v^{-2})
\]

\[
T \rightarrow \tau^3 + 2\sqrt{2} \frac{i}{v} (w^+ \tau^+ - w^- \tau^-) + O(v^{-2})
\]

So \( T \) projects out the neutral part:

\[
\text{tr} [TV] = \frac{2i}{v} \left[ \partial z + \frac{i}{v} (w^+ \partial w^- - w^- \partial w^+) \right] + O(v^{-3})
\]
**Electroweak Chiral Lagrangian**

Complete Lagrangian contains infinitely many parameters

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{min}} - \sum_{\psi} \overline{\psi} L \Sigma M \psi + \beta_1 L' + \sum_i \alpha_i L_i + \frac{1}{v} \sum_i \alpha_i^{(5)} L^{(5)} + \frac{1}{v^2} \sum_i \alpha_i^{(6)} L^{(6)} + \ldots \]

\[ L' = \frac{v^2}{4} \text{tr} [T V_{\mu}] \text{tr} [T V^\mu] \]

\[ L_1 = \text{tr} [B_{\mu\nu} W^{\mu\nu}] \quad L_6 = \text{tr} [V_{\mu} V_{\nu}] \text{tr} [T V^\mu] \text{tr} [T V^\nu] \]

\[ L_2 = \text{itr} [B_{\mu\nu} [V^{\mu}, V^{\nu}]] \quad L_7 = \text{tr} [V_{\mu} V^{\mu}] \text{tr} [T V_{\nu}] \text{tr} [T V^\nu] \]

\[ L_3 = \text{itr} [V_{\mu\nu} V^{\mu \nu}] \quad L_8 = \frac{1}{4} \text{tr} [T W_{\mu\nu}] \text{tr} [T W^{\mu\nu}] \]

\[ L_4 = \text{tr} [V_{\mu} V_{\nu}] \text{tr} [V^{\mu} V^{\nu}] \quad L_9 = \frac{1}{2} \text{tr} [T W_{\mu\nu}] \text{tr} [T [V^{\mu}, V^{\nu}]] \]

\[ L_5 = \text{tr} [V_{\mu} V^{\mu}] \text{tr} [V_{\nu} V^{\nu}] \quad L_{10} = \frac{1}{2} (\text{tr} [T V_{\mu}] \text{tr} [T V^{\mu}])^2 \]

Indirect info on new physics in \( \beta_1, \alpha_i, \ldots \) (Flavor physics only in \( M \))

**Electroweak precision observables (LEP I/II, SLC):**

\[ \Delta S = -16\pi \alpha_1 \quad \alpha_1 = 0.0026 \pm 0.0020 \]

\[ \Delta T = 2\beta_1 / \alpha_{\text{QED}} \quad \beta_1 = -0.00062 \pm 0.00043 \]

\[ \Delta U = -16\pi \alpha_8 \quad \alpha_8 = -0.0044 \pm 0.0026 \]
Anomalous triple and quartic gauge couplings

\[ \mathcal{L}_{TGC} = i e \left[ g_1^\gamma A_\mu \left( W^- W^{+\mu\nu} - W^+ W^{-\mu\nu} \right) + \kappa^\gamma W^- W^+ A^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2} W^- W^+ W^{\mu\nu} A^\rho A^\mu \right] \\
+ i e \frac{c_w}{s_w} \left[ g_1^Z Z_\mu \left( W^- W^{+\mu\nu} - W^+ W^{-\mu\nu} \right) + \kappa^Z W^- W^+ Z^{\mu\nu} + \frac{\lambda^Z}{M_W^2} W^- W^+ W^{\mu\nu} Z^\rho A^\mu \right] \]

SM values: \( g_1^{\gamma,Z} = \kappa^{\gamma,Z} = 1, \lambda^{\gamma,Z} = 0 \) and \( \delta Z = \frac{\beta_1 + g'^2 \alpha_1}{c_w^2 - s_w^2} \)

\( g_{1/2}^{VV'} = 1, h^{ZZ} = 0 \)

\( \Delta g_1^{\gamma} = 0 \)

\( \Delta g_1^{Z} = \delta Z + \frac{g^2}{c_w^2} \alpha_3 \)

\( \Delta g_2^{\gamma} = \frac{g^2}{c_w^2} \alpha_3 \)

\( \Delta g_2^{Z} = \frac{g^2}{c_w^2} \alpha_3 \)

\( \Delta g_1^{ZZ} = \Delta g_2^{ZZ} = 0 \)

\( \Delta g_1^{WZ} = \Delta g_2^{WZ} = \delta Z + \frac{g^2}{c_w^2} \alpha_3 \)

\( \Delta g_1^{W^Z} = \Delta g_2^{W^Z} = \delta Z + \frac{g^2}{c_w^2} \alpha_3 \)

\( \Delta g_1^{ZZ} = 2 \Delta g_2^{ZZ} - \frac{g^2}{c_w^2} (\alpha_5 + \alpha_7) \)

\( \Delta g_1^{W^W} = 2 c_w^2 \Delta g_1^{\gamma Z} + 2 g^2 (\alpha_9 - \alpha_8) + g^2 \alpha_4 \)

\( \Delta g_2^{W^W} = 2 c_w^2 \Delta g_1^{\gamma Z} + 2 g^2 (\alpha_9 - \alpha_8) - g^2 (\alpha_4 + 2 \alpha_5) \)

\( h^{ZZ} = g^2 [\alpha_4 + \alpha_5 + 2 (\alpha_6 + \alpha_7 + \alpha_{10})] \)
Anomalous triple and quartic gauge couplings

\[ \mathcal{L}_{QGC} = e^2 \left[ g_1^{\gamma\gamma} A^{\mu} A^{\nu} W_{\mu}^- W_{\nu}^+ - g_2^{\gamma\gamma} A^{\mu} A^{\nu} W_{\mu}^- W_{\nu}^+ \right] + e^2 \frac{c_w}{s_w} \left[ g_1^{\gamma Z} A^{\mu} Z^{\nu} (W_{\mu}^- W_{\nu}^+ + W_{\mu}^+ W_{\nu}^-) - 2g_2^{\gamma Z} A^{\mu} Z_{\mu} W_{\nu}^- W_{\nu}^+ \right] + e^2 \frac{c_w^2}{s_w^2} \left[ g_1^{ZZ} Z^{\mu} Z^{\nu} W_{\mu}^- W_{\nu}^+ - g_2^{ZZ} Z^{\mu} Z_{\mu} W_{\nu}^- W_{\nu}^+ \right] + \frac{e^2}{2s_w^2} \left[ g_1^{WW} W^{-\mu} W^{+\nu} W_{\mu}^- W_{\nu}^+ - g_2^{WW} (W^{-\mu} W_{\mu}^+)^2 \right] + \frac{e^2}{4s_w^2 c_w^4} h^{ZZ} (Z^{\mu} Z_{\mu})^2 \]

SM values: \( g_1^{\gamma,Z} = \kappa^{\gamma,Z} = 1 \), \( \lambda^{\gamma,Z} = 0 \) and \( \delta Z = \frac{\beta_1 + g' \alpha_1}{c_w^2 - s_w^2} \) \( g_{1/2}' = 1 \), \( h^{ZZ} = 0 \)

\[ \Delta g_1^{\gamma} = 0 \quad \Delta \kappa^{\gamma} = g^2 (\alpha_2 - \alpha_1) + g^2 \alpha_3 + g^2 (\alpha_9 - \alpha_8) \]

\[ \Delta g_1^{Z} = \delta Z + \frac{g^2}{c_w^2} \alpha_3 \quad \Delta \kappa^{Z} = \delta Z - g' (\alpha_2 - \alpha_1) + g^2 \alpha_3 + g^2 (\alpha_9 - \alpha_8) \]

\[ \Delta g_{1/2}^{\gamma} = 0 \quad \Delta g_{1/2}^{ZZ} = 2\Delta g_1^{\gamma} - \frac{g^2}{c_w^2} (\alpha_4 + \alpha_7) \]

\[ \Delta g_1^{\gamma Z} = \Delta g_2^{\gamma Z} = \delta Z + \frac{g^2}{c_w^2} \alpha_3 \]

\[ \Delta g_1^{ZZ} = 2\Delta g_1^{\gamma Z} + \frac{g^2}{c_w^2} (\alpha_4 + \alpha_6) \quad \Delta g_1^{WW} = 2c_w^2 \Delta g_1^{\gamma Z} + 2g^2 (\alpha_9 - \alpha_8) + g^2 \alpha_4 \]

\[ \Delta g_1^{WW} = 2c_w^2 \Delta g_1^{\gamma Z} + 2g^2 (\alpha_9 - \alpha_8) - g^2 (\alpha_4 + 2\alpha_5) \]

\[ h^{ZZ} = g^2 [\alpha_4 + \alpha_5 + 2 (\alpha_6 + \alpha_7 + \alpha_{10})] \]
Parameters and Scales, Resonances

\( \alpha_i \) 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 \( \Lambda \): \( \alpha_i = v^2/\Lambda^2 \)

- 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 \( \alpha_i \)

- 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)

| \( I \) | \( J = 0 \) | \( J = 1 \) | \( J = 2 \) |
|-----|-----|-----|-----|
| 0   | \( \sigma^0 \) (Higgs ?) | \( \omega^0 \) (\( \gamma'/Z' \) ?) | \( f^0 \) (Graviton ?) |
| 1   | \( \pi^\pm, \pi^0 \) (2HDM ?) | \( \rho^\pm, \rho^0 \) (\( W'/Z' \) ?) | \( a^\pm, a^0 \) |
| 2   | \( \phi^{\pm\pm}, \phi^\pm, \phi^0 \) (Higgs triplet ?) | — | \( t^{\pm\pm}, t^\pm, t^0 \) |

accounts for weakly and strongly interacting models
Model-Independent Way – Effective Field Theories

How to clearly separate effects of heavy degrees of freedom?

Toy model: Two interacting scalar fields $\varphi$, $\Phi$

$$Z[j, J] = \int \mathcal{D}[\Phi] \mathcal{D}[\varphi] \exp \left[ i \int dx \left( \frac{1}{2} (\partial \varphi)^2 - \frac{1}{2} \Phi (\Box + M^2) \Phi - \lambda \varphi^2 \Phi - \ldots + J \Phi + j \varphi \right) \right]$$

Low-energy effective theory $\Rightarrow$ integrating out heavy degrees of freedom (DOF) in path integrals, set up Power Counting

Completing the square:

$$\Phi' = \Phi + \frac{\lambda}{M^2} \left( 1 + \frac{\partial^2}{M^2} \right)^{-1} \varphi^2 \Rightarrow \quad \rightarrow$$

$$\frac{1}{2} (\partial \Phi)^2 - \frac{1}{2} M^2 \Phi^2 - \lambda \varphi^2 \Phi = -\frac{1}{2} \Phi' (M^2 + \partial^2) \Phi' + \frac{\lambda^2}{2M^2} \varphi^2 \left( 1 + \frac{\partial^2}{M^2} \right)^{-1} \varphi^2.$$
Effective Dim. 6 Operators

\[ O_{JJ}^{(I)} = \frac{1}{F^2} \text{tr} [J^{(I)} \cdot J^{(I)}] \]

\[ O'_{h,1} = \frac{1}{F^2} ((Dh)^\dagger h) \cdot (h^\dagger (D^h)) - \frac{v^2}{2} |Dh|^2 \]

\[ O'_{hh} = \frac{1}{F^2} (h^\dagger h - v^2/2) (Dh)^\dagger \cdot (Dh) \]

\[ O'_{h,3} = \frac{1}{F^2} \frac{1}{3} (h^\dagger h - v^2/2)^3 \]
\[ O'_{WW} = -\frac{1}{F^2} \frac{1}{2} (h^\dagger h - v^2/2) \text{tr} [W_{\mu\nu} W^{\mu\nu}] \]
\[ O_B = \frac{1}{F^2} \frac{i}{2} (D_{\mu} h)^\dagger (D_{\nu} h) B^{\mu\nu} \]
\[ O'_{BB} = -\frac{1}{F^2} \frac{1}{4} (h^\dagger h - v^2/2) B_{\mu\nu} B^{\mu\nu} \]

\[ O_{Vq} = \frac{1}{F^2} \bar{q} h (\bar{\Psi} h) q \]
Oblique Corrections: $S$, $T$, $U$

$Z_L \rightarrow Z_L \Delta T \sim \Delta \rho \sim \Delta M_Z^2 Z \cdot Z$

$Z_T \rightarrow Z_T \Delta S \sim W^0_{\mu \nu} B^{\mu \nu}$, $\Delta U \sim W^0_{\mu \nu} W^0_{\mu \nu}$

- All low-energy effects order $v^2/F^2$ (Wilson coefficients)
- Low-energy observables with low-energy input $G_F$, $\alpha$, $M_Z$ affected by non-oblique contributions:

\[ G_F = \frac{1}{v} \longrightarrow \frac{1}{v} \left( 1 - \alpha \Delta T + \delta \right) , \]

\[ \delta \equiv -\frac{v^2}{4} f_J^{(3)} \]

$S_{\text{eff}} = \Delta S$

$T_{\text{eff}} = \Delta T - \frac{1}{\alpha} \delta$

$U_{\text{eff}} = [\Delta U = 0] + \frac{4s_w^2}{\alpha} \delta$

- non-oblique flavour-dependent corrections $\Rightarrow$ enforce flavour-dependent EW fit
Integrating out resonances

Consider leading order effects of resonances on EW sector:

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

- Simplest example: scalar singlet \( \sigma \):

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

- Effective Lagrangian

\[
\mathcal{L}_\sigma^{\text{eff}} = \frac{v^2}{8 M_\sigma^2} \left[ g_\sigma \text{tr} \left[ V_\mu V^\mu \right] + h_\sigma \text{tr} \left[ TV_\mu \right] \text{tr} \left[ TV^\mu \right] \right]^2
\]

- leads to anomalous quartic couplings

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

- 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):

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

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

**Vector:** $\Gamma \sim g^2 M$, $\alpha \sim g^2 / M^2$ \quad $\Rightarrow$ \quad $\alpha_{\text{max}} \sim 1 / M^2$

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

Vector triplet (simplified)

$$L_\rho = -\frac{1}{8} \text{tr} [\rho_{\mu\nu} \rho^{\mu\nu}] + \frac{M_\rho^2}{4} \text{tr} [\rho_{\mu} \rho^{\mu}] + \frac{ig_\rho v^2}{2} \text{tr} [\rho_{\mu} V^{\mu}]$$

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

$$L_{\rho}^{\text{eff}} = \frac{g_\rho^2 v^4}{4M_\rho^2} \text{tr} [(D_\mu \Sigma)(D^\mu \Sigma)] + O(1/M_\rho^4)$$
Vector Resonances

\[\mathcal{L}_\rho = -\frac{1}{8} \text{tr} \left[ \rho_{\mu\nu} \rho^{\mu\nu} \right] + \frac{M_\rho^2}{4} \text{tr} \left[ \rho_{\mu} \rho^{\mu} \right] + \frac{\Delta M_\rho^2}{8} \left( \text{tr} \left[ T \rho_{\mu} \right] \right)^2 + i \frac{\mu_\rho}{2} g \text{tr} \left[ \rho_{\mu} W^{\mu\nu} \rho_{\nu} \right] \]

\[+ i \frac{\mu_\rho}{2} g' \text{tr} \left[ \rho_{\mu} B^{\mu\nu} \rho_{\nu} \right] + i g_\rho v^2 \frac{1}{2} \text{tr} \left[ \rho_{\mu} V^{\mu} \right] + i h_\rho v^2 \frac{1}{2} \text{tr} \left[ \rho_{\mu} T \right] \text{tr} \left[ TV^{\mu} \right] \]

\[+ \frac{g' v^2 k'_\rho}{2 M_\rho^2} \text{tr} \left[ \rho_{\mu} \left[ B^{\nu\mu}, V_{\nu} \right] \right] + \frac{g v^2 k'_\rho}{4 M_\rho^2} \text{tr} \left[ \rho_{\mu} \left[ T, V_{\nu} \right] \right] \text{tr} \left[ TV^{\nu\mu} \right] \]

\[+ \frac{g v^2 k''_\rho}{4 M_\rho^2} \text{tr} \left[ T \rho_{\mu} \right] \text{tr} \left[ \left[ T, V_{\nu} \right] W^{\nu\mu} \right] + i \frac{\ell_\rho}{M_\rho^2} \text{tr} \left[ \rho_{\mu\nu} W^{\nu\rho} W^{\rho\mu} \right] \]

\[+ i \frac{\ell'_\rho}{M_\rho^2} \text{tr} \left[ \rho_{\mu\nu} B^{\nu\rho} W^{\rho\mu} \right] + i \frac{\ell''_\rho}{M_\rho^2} \text{tr} \left[ \rho_{\mu\nu} T \right] \text{tr} \left[ TW^{\nu\rho} W^{\rho\mu} \right] \]

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 \( g \) \( \text{Nyffeler/Schenk, 2000; Kilian/JR, 2003} \)

Effects on Triple Gauge Couplings

- \( \mathcal{O}(1/M^2) \): Renormalization of \( ZWW \) coupling
- \( \mathcal{O}(1/M^4) \): shifts in \( \Delta g_1^Z, \Delta \kappa^\gamma, \Delta \kappa^Z, \lambda^\gamma, \lambda^Z \)

Effects on Quartic Gauge Couplings

- \( \mathcal{O}(1/M^4) \), orthogonal (in \( \alpha_4-\alpha_5 \) space) to scalar case
WHIZARD

- Multi-Purpose event generator for collider and astroparticle physics
- Acronym: W, Higgs, Z, And Respective Decays (deprecated)
  - Fast adaptive multi-channel Monte-Carlo integration
  - Very efficient phase space and event generation
  - Optimized/-al matrix elements
- Recent version: 2.1.1 (18.09.2012)
  
  http://projects.hepforge.org/whizard
  und
  http://whizard.event-generator.org

- Parton shower ($k^\perp$-ordered and analytical)
- Underlying Event: preliminary (for 2.1)
- Arbitrary processes: matrix element generator (O’Omega)
- 2.0 Features: ME/PS matching, cascades, versatile new steering syntax, WHIZARD as shared library

- Interface to FeynRules
- Versatile input language: SINDARIN
Multi-Purpose event generator for collider and astroparticle physics

Focus: LHC, ILC, CLIC, SM, QCD, BSM

| MODEL TYPE                               | with CKM matrix | trivial CKM |
|------------------------------------------|-----------------|-------------|
| QED with $e, \mu, \tau, \gamma$         | QED             | QED         |
| QCD with $d, u, s, c, b, t, g$           | QCD             | QCD         |
| Standard model                           | SM              | SM          |
| SM with anomalous couplings              | SM_ac           | SM_ac       |
| SM with anomalous top couplings          | SM_top          | SM_top      |
| SM with K matrix                         | SM_KM           | SM_KM       |
| MSSM                                     | MSSM            | MSSM        |
| MSSM with Gravitinos                     | MSSM_Grav       | MSSM_Grav   |
| NMSSM                                    | NMSSM           | NMSSM       |
| extended SUSY models                     | PSSSM           | PSSSM       |
| Littlest Higgs                           | Littlest        | Littlest    |
| Littlest Higgs with ungauged $U(1)$      | Littlest_Eta    | Littlest_Eta|
| Littlest Higgs with $T$ parity           | Littlest_Tpar   | Littlest_Tpar|
| Simplest Little Higgs (anomaly free)     | Simplest        | Simplest    |
| Simplest Little Higgs (universal)        | Simplest_univ   | Simplest_univ|
| UED                                      | UED             | UED         |
| 3-Site Higgsless Model                   | Threeshl        | Threeshl    |
| Noncommutative SM (inoff.)               | NCSM            | NCSM        |
| SM with $Z'$                              | Zprime          | Zprime      |
| SM with Gravitino and Photino            | GravTest        | GravTest    |
| Augmentable SM template                  | Template        | Template    |

easy to implement new models

Interface to FeynRules

Versatile input language: SINDARIN
Anomalous Gauge Couplings at LHC

ILC: Beyer/Kilian/Krstonošić/Mönig/JR/Schröder/Schmidt, 2006
LHC: Mertens, 2006; Kilian/Kobel/Mader/JR/Schumacher

Anomalous quartic gauge couplings, by chiral EW Lagrangian:

\[ \mathcal{L}_4 = \frac{\alpha_4 g^2}{2} \left\{ \left[ (W^+ W^-) (W^- W^-) + (W^+ W^-)^2 \right] + \frac{2}{c_W^2} (W^+ Z) (W^- Z) + \frac{1}{2 c_W^4} (Z Z)^2 \right\} \]

\[ \mathcal{L}_5 = \frac{\alpha_5 g^2}{2} \left\{ (W^+ W^-)^2 + \frac{2}{c_W^2} (W^+ W^-) (Z Z) + \frac{1}{2 c_W^4} (Z Z)^2 \right\} \]

(all leptons, incl. \( \tau \)):

\[ pp \rightarrow jj (Z Z / W W) \rightarrow jj \ell^- \ell^+ \nu_\ell \bar{\nu}_\ell \]

\( \sigma \approx 40 \text{ fb} \)

Background:
- \( tt \rightarrow WbWb, \sigma \approx 52 \text{ pb} \)
- Single \( t \), misrec. jet: \( \sigma \approx 4.8 \text{ pb} \)
- QCD: \( \sigma \approx 0.21 \text{ pb} \)
Tagging and Cuts:

- $\ell\ell jj$-Tag, $\eta_{\text{tag}}^{\text{min}} < \eta_{\ell} < \eta_{\text{tag}}^{\text{max}}$, $b$-Veto
- $|\Delta\eta_{jj}| > 4.4$, $M_{jj} > 1080$ GeV
- Minijet-Veto: $p_T,j < 30$ GeV
- $E_j > 600, 400$ GeV, $p_T^{1,j} > 60, 24$ GeV

Improves $S/\sqrt{B}$ from 3.3 to 29.7
Results: (1σ Sensitivity to $\alpha_s$)

| Coupl. | ILC (1 ab$^{-1}$) | LHC (100 fb$^{-1}$) |
|--------|-------------------|---------------------|
| $\alpha_4$ | 0.0088 | 0.00160 |
| $\alpha_5$ | 0.0071 | 0.00098 |

Limits for $\Lambda$ [TeV]:

| 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    |
Isospin decomposition

- Lowest order chiral Lagrangian (incl. anomalous couplings)

\[ \mathcal{L} = -\frac{v^2}{4} \text{tr} [V_\mu V^\mu] + \alpha_4 \text{tr} [V_\mu V_\nu] \text{tr} [V^\mu V^{\nu}] + \alpha_5 (\text{tr} [V_\mu V^\mu])^2 \]

- Leads to the following amplitudes:

\[ A(s, t, u) = \begin{cases} 
A(w^+w^- \rightarrow zz) &= \frac{s}{v^2} + 8\alpha_5 \frac{s^2}{v^4} + 4\alpha_4 \frac{t^2 + u^2}{v^4} \\
A(w^+z \rightarrow w^+z) &= \frac{t}{v^2} + 8\alpha_5 \frac{t^2}{v^4} + 4\alpha_4 \frac{s^2 + u^2}{v^4} \\
A(w^+w^- \rightarrow w^+w^-) &= -\frac{u}{v^2} + (4\alpha_4 + 2\alpha_5) \frac{s^2 + t^2}{v^4} + 8\alpha_4 \frac{u^2}{v^4} \\
A(w^+w^+ \rightarrow w^+w^+) &= -\frac{s}{v^2} + 8\alpha_4 \frac{s^2}{v^4} + 4(\alpha_4 + 2\alpha_5) \frac{t^2 + u^2}{v^4} \\
A(zz \rightarrow zz) &= 8(\alpha_4 + \alpha_5) \frac{s^2 + t^2 + u^2}{v^4} \end{cases} \]

- (Clebsch-Gordan) Decomposition into isospin eigenamplitudes

\[ A(I = 0) = 3A(s, t, u) + A(t, s, u) + A(u, s, t) \]
\[ A(I = 1) = A(t, s, u) - A(u, s, t) \]
\[ A(I = 2) = A(t, s, u) + A(u, s, t) \]
Unitarity of Amplitudes

UV-incomplete theories could violate unitarity

Cross section:
\[ \sigma = \int d\Omega \frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} |\mathcal{M}|^2 \]

Optical Theorem (Unitarity of the S(cattering) Matrix):
\[ \sigma_{\text{tot}} = \text{Im} [\mathcal{M}_{ii}(t = 0)] / s \quad t = -s(1 - \cos \theta)/2 \]

Partial wave amplitudes:
\[ \mathcal{M}(s, t, u) = 32\pi \sum_{\ell} (2\ell + 1) A_{\ell}(s) P_{\ell}(\cos \theta) \]

Assuming only elastic scattering:
\[ \sigma_{\text{tot}} = \sum_{\ell} \frac{32\pi(2\ell + 1)}{s} |A_{\ell}|^2 = \sum_{\ell} \frac{32\pi(2\ell + 1)}{s} \text{Im} [A_{\ell}] \quad \Rightarrow \quad |A_{\ell}|^2 = \text{Im} [A_{\ell}] \]

Argand circle
\[ |A(s) - \frac{i}{2}| = \frac{1}{2} \]

Resonance:
\[ \mathcal{A}(s) = \frac{-M\Gamma_{\text{el}}}{s - M^2 + iM\Gamma_{\text{tot}}} \]

Counterclockwise circle, radius \( \frac{x_{el}}{2} \)

Pole at \( s = M^2 - iM\Gamma_{\text{tot}} \)
Unitarity in the EW sector: SM

- Project out isospin eigenamplitudes

\[ A_\ell(s) = \frac{1}{32\pi} \int_{-s}^{0} \frac{dt}{s} A(s, t, u) P_\ell(1 + 2t/s) \quad \cos \theta = 1 + 2t/s \]

Remember Legendre polynomials:

\[ P_0(s) = 1 \quad P_1(s) = \cos \theta \quad P_2(s) = (3\cos^2 \theta - 1)/2 \]

- SM longitudinal isospin eigenamplitudes (\( A_{I,\text{spin}=J} \)):

\[
\begin{align*}
    A_{I=0} &= 2 \frac{s}{v^2} P_0(s) \\
    A_{I=1} &= \frac{t - u}{v^2} = \frac{s}{v^2} P_1(s) \\
    A_{I=2} &= -\frac{s}{v^2} P_0(s)
\end{align*}
\]

\[
\begin{array}{|c|}
\hline
A_{0,0} = \frac{s}{16\pi v^2} \\
A_{1,1} = \frac{s}{96\pi v^2} \\
A_{2,0} = -\frac{s}{32\pi v^2} \\
\hline
\end{array}
\]

exceeds unitarity bound \(|A_{I,J}| \lesssim \frac{1}{2}\) at:

- \( I = 0 \): \( E \sim \sqrt{8\pi v} = 1.2 \) TeV
- \( I = 1 \): \( E \sim \sqrt{48\pi v} = 3.5 \) TeV
- \( I = 2 \): \( E \sim \sqrt{16\pi v} = 1.7 \) TeV

Higgs exchange:

\[ A(s, t, u) = -\frac{M_H^2}{v^2} \frac{s}{s - M_H^2} \]

Unitarity:

\[ M_H \lesssim \sqrt{8\pi v} \sim 1.2 \text{ TeV} \]
K-Matrix Unitarization and friends

K-Matrix unitarization

\[ A_K(s) = \frac{A(s)}{1 - iA(s)} = A(s) \frac{1 + iA(s)}{1 + A(s)^2} \]

Unitarization by infinitely heavy and wide resonance

- Low-energy theorem (LET): \( \frac{s}{v^2} \)
- K-Matrix amplitude:
  \[ |A(s)|^2 = \frac{s^2}{s^2 + v^4} \xrightarrow{s \to \infty} 1 \]
- Poles \( \pm iv \): \( M_0, \Gamma \) large

Padé unitarization

separates higher chiral orders

\[ A_P(s) = \frac{A^{(0)}(s)^2}{A^{(0)}(s) - A^{(1)}(s) - iA^{(0)}(s)^2} \]

each partial wave dominated by single resonance

“Naive” Unitarization

Extreme case:

\[ A_N(s) = e^{iA(s)} \sin A(s) \]

Infinitely many resonances
becoming denser for \( s \to \infty \)
BSM Unitarized Resonances: e.g. Scalar Singlet

Assumptions:

- LHC is able to detect a resonance in the EW sector
- Further resonances might exist, but out of reach or not detectable
- Describe 1st resonance by correct amplitude
- Use K-matrix unitarization to define a consistent model

Example: Scalar Singlet

- \( \mathcal{L}_\sigma = -\frac{1}{2} \sigma \left( M^2_\sigma + \partial^2 \right) \sigma + \frac{g_\sigma v}{2} \sigma \text{tr} \left[ V_\mu V^{\mu} \right] \)
- Feynman rules: \( \sigma w^+ w^- : -\frac{2ig_\sigma}{v} (k_+ \cdot k_-) \) \( \sigma z z : -\frac{2ig_\sigma}{v} (k_1 \cdot k_2) \)
- Amplitude (\( s \)-channel exchange):
  \[ A^\sigma (s, t, u) = \frac{g_\sigma^2}{v^2} \frac{s^2}{s-M^2} \]
- Isospin eigenamplitudes:
  \[
  A^0 (s, t, u) = \frac{g_\sigma^2}{v^2} \left( 3 \frac{s^2}{s-M^2} + \frac{t^2}{t-M^2} + \frac{u^2}{u-M^2} \right) \\
  A^1 (s, t, u) = \frac{g_\sigma^2}{v^2} \left( \frac{t^2}{t-M^2} - \frac{u^2}{u-M^2} \right) \\
  A^2 (s, t, u) = \frac{g_\sigma^2}{v^2} \left( \frac{t^2}{t-M^2} + \frac{u^2}{u-M^2} \right)
  \]
Unitarizing the scalar singlet

\[ A^\sigma_{00}(s) = 3 \frac{g^2}{v^2} \frac{s^2}{s-M^2} + 2 \frac{g^2}{v^2} S_0(s) \]
\[ A^\sigma_{02}(s) = 2 \frac{g^2}{v^2} S_2(s) = A^\sigma_{22}(s) \]
\[ A^\sigma_{11}(s) = 2 \frac{g^2}{v^2} S_1(s) \]
\[ A^\sigma_{13}(s) = 2 \frac{g^2}{v^2} S_3(s) \]
\[ A^\sigma_{20}(s) = 2 \frac{g^2}{v^2} S_0(s) \]

\[ \Delta A_{IJ}(s) = 32\pi i \left( 1 + \frac{i}{32\pi} A_{IJ}^{(0)}(s) + \frac{s - M^2}{i \frac{G_{IJ}(s)}{s - M^2}} \right) \]
Implementation and Taxonomy of Resonances

- Explicit “time arrow” in WHIZARD

$$\Delta A_{IJ} \left( \sum p \right)$$

- trace back pairs of momenta at quartic vertices to external legs
- guarantee for only $s$-channel insertions

Consider the following resonances:

$$\mathcal{L}_\sigma = -\frac{1}{2} \sigma \left( M^2_\sigma + \partial^2 \right) \sigma + \sigma j_\sigma$$

$$\mathcal{L}_\phi = -\frac{1}{2} \left[ \frac{1}{2} \text{tr} \left[ \phi \left( M^2_\sigma + \partial^2 \right) \phi \right] + \text{tr} \left[ \phi j_\phi \right] \right]$$

$$\mathcal{L}_\rho = \frac{1}{2} \left[ \frac{M^2_\rho}{2} \text{tr} \left[ \rho \mu \rho^\mu \right] - \frac{1}{4} \text{tr} \left[ \rho_{\mu \nu} \rho^{\mu \nu} \right] + \text{tr} \left[ j_\mu \rho \rho^\mu \right] \right]$$

$$\mathcal{L}_f = \mathcal{L}_{\text{kin}} - \frac{M^2_f}{2} f^{\mu \nu} f_{\mu \nu} + f^{\mu \nu} j_f^{\mu \nu}$$

$$\mathcal{L}_a = \mathcal{L}_{\text{kin}} - \frac{M^2_a}{4} \text{tr} \left[ t^{\mu \nu} t^{\mu \nu} \right] + \frac{1}{2} \text{tr} \left[ t^{\mu \nu} j_a^{\mu \nu} \right]$$

$$j_\sigma = \frac{g_\sigma v}{2} \text{tr} \left[ V_{\mu} V^{\mu} \right]$$

$$j_\phi = -\frac{g_\phi v}{2} \left( V_{\mu} \otimes V^{\mu} - \frac{\tau_{aa}}{6} \text{tr} \left[ V_{\mu} V^{\mu} \right] \right)$$

$$j_\rho = ig_\rho v^2 V^{\mu}$$

$$j_f^{\mu \nu} = -\frac{g_f v}{2} \left( \text{tr} \left[ V^{\mu} V^{\nu} \right] - \frac{g_{\mu \nu}}{4} \text{tr} \left[ V_{\rho} V^{\rho} \right] \right)$$

$$j_a^{\mu \nu} = -\frac{g_a v}{2} \left[ \frac{1}{2} \left( V^{\mu} \otimes V^{\nu} + V^{\nu} \otimes V^{\mu} \right) - \frac{g_{\mu \nu}}{4} V_{\rho} \otimes V^{\rho} \right.$$

$$- \frac{\tau_{aa}}{6} \text{tr} \left[ V^{\mu} V^{\nu} \right] + \frac{g_{\mu \nu} \tau_{aa}}{24} \text{tr} \left[ V_{\rho} V^{\rho} \right] \right]$$
Taxonomy of resonances/Loops

| Resonance                                           | $\sigma$ | $\phi$ | $\rho$ | $f$ | $a$ |
|-----------------------------------------------------|----------|--------|--------|-----|-----|
| $\Gamma[g^2 M^2 / (64\pi v^2)]$                     | 6        | 1      | $\frac{4}{3} \left( \frac{v^2}{M^2} \right)$ | $\frac{1}{5}$ | $\frac{1}{30}$ |
| $\Delta \alpha_4 [(16\pi \Gamma / M) (v^4 / M^4)]$ | 0        | $\frac{1}{4}$ | $\frac{3}{4}$ | $\frac{5}{2}$ | $-\frac{5}{8}$ |
| $\Delta \alpha_5 [(16\pi \Gamma / M) (v^4 / M^4)]$ | $\frac{1}{12}$ | $-\frac{1}{12}$ | $-\frac{3}{4}$ | $-\frac{5}{8}$ | $\frac{35}{8}$ |

- Loop corrections to LET can be switched on/off:
  ($\mu$ renormalization scale)
  
  \[ A_{C}^{1\text{-loop}}(s, t, u) = \frac{1}{16\pi^2} \left[ \left( \frac{1}{2} \ln \frac{\mu^2}{|s|} + 8C_5 \right) \frac{s^2}{v^4} + \left( \frac{t(s + 2t)}{6v^4} \ln \frac{\mu^2}{|t|} + 4C_4 \frac{t^2}{v^4} \right) + (t \leftrightarrow u) \right], \]

- Finite scheme-dep. matching coefficients/NLO counterterms
  (e.g. heavy Higgs regulator $\mu = M_H$)

\[
C_4 = -\frac{1}{18} \approx -0.056, \quad C_5 = \frac{9\pi}{16\sqrt{3}} - \frac{37}{36} \approx -0.0075.
\]

\[
\alpha_4^{(1)} = \frac{1}{16\pi^2} \left( C_4 - \frac{1}{12} \ln \frac{\mu^2}{\mu_0^2} \right),
\]

\[
\alpha_5^{(1)} = \frac{1}{16\pi^2} \left( C_5 - \frac{1}{24} \ln \frac{\mu^2}{\mu_0^2} \right).
\]
Eigenamplitudes

\[ A_{00}, \text{with K matrix} \]

\[ A_{02}, \text{with K matrix} \]

\[ A_{11}, \text{with K matrix} \]

\[ A_{13}, \text{with K matrix} \]

\[ A_{20}, \text{with K matrix} \]

\[ A_{22}, \text{with K matrix} \]

\[ A_{\text{res}}, \text{angular dependence} \]

\[ \text{Re}(A), \text{with K matrix} \]
Eigenamplitudes

\[ A_{00}, \text{ with K matrix} \]

\[ A_{02}, \text{ with K matrix} \]

\[ A_{11}, \text{ with K matrix} \]

\[ A_{13}, \text{ with K matrix} \]

\[ A_{20}, \text{ with K matrix} \]

\[ A_{22}, \text{ with K matrix} \]

\[ A_{\text{res}}, \text{ angular dependence} \]

\[ \text{Re}(A), \text{ with K matrix} \]
“Partonic” cross sections (I)

- Cross sections (in nb)
"Partonic" cross sections (I)

- Cross sections (in nb)
“Partonic” cross sections (II)

- $\sigma(VV \rightarrow VV)$ in nb $M_R = 500$ GeV
- all amplitudes K-matrix unitarized
- Cut of 15° around the beam axis
“Partonic” cross sections (II)

- $\sigma (VV \rightarrow VV)$ in nb $M_R = 500$ GeV
- all amplitudes K-matrix unitarized
- Cut of $15^\circ$ around the beam axis
The Effective $W$ approximation

- $M_V$, $\hat{t}_i$ small corrections, $V$ nearly onshell:

$$\sigma(q_1 q_2 \to q_1' q_2' \nu_1' \nu_2') \approx \sum_{\lambda_1, \lambda_2} \int dx_1 \, dx_2 \, F_{q_1 \to q_1'}^{\lambda_1} (x_1) \, F_{q_2 \to q_2'}^{\lambda_2} (x_2) \, \sigma_{\nu_1 \nu_2 \to \nu_1' \nu_2'}^{\lambda_1 \lambda_2} (x_1 x_2 s)$$

- In addition to Weizsäcker-Williams: longitudinal polarisation

$$F_{q \to q'}^{\nu_1} (x) = \frac{(V - A)^2 + (V + A)^2 (1 - x)^2}{16 \pi^2 \, x} \left[ \ln \left( \frac{p_{\perp,\text{max}}^2 + (1 - x) m_V^2}{(1 - x) m_V^2} \right) - \frac{p_{\perp,\text{max}}^2}{p_{\perp,\text{max}}^2 + (1 - x) m_V^2} \right]$$

$$F_{q \to q'}^{-\nu_1} (x) = \frac{(V + A)^2 + (V - A)^2 (1 - x)^2}{16 \pi^2 \, x} \left[ \ln \left( \frac{p_{\perp,\text{max}}^2 + (1 - x) m_V^2}{(1 - x) m_V^2} \right) - \frac{p_{\perp,\text{max}}^2}{p_{\perp,\text{max}}^2 + (1 - x) m_V^2} \right]$$

$$F_{q \to q'}^{\nu_1} (x) = \frac{V^2 + A^2}{8 \pi^2} \frac{2 (1 - x)}{x} \frac{p_{\perp,\text{max}}^2}{p_{\perp,\text{max}}^2 + (1 - x) m_V^2}$$

- Dominant contribution from small $V$ virtualities
- Transverse momentum cutoff $p_{\perp,\text{max}} \leq (1 - x) \sqrt{s}/2$:
  - longitudinal pol.: finite for $p_{\perp,\text{max}} \to \infty$
  - Transversal pol.: logarithmic singularity
EWA structure functions: $W$ (left) and $Z$ (right)

- Emission from $u$, $\sqrt{s} = 2$ TeV
- preferred at high energy: transversal emission

Problem: Irreducible background to weak-boson scattering

- Double ISR/FSR
- $t$-channel like diagrams

Coulomb-singularity (peak): cut on $p_{T,V} \gtrsim 30$ GeV
- Effective $W$ approx. vs. WHIZARD full matrix elements
- Shapes/normalization of distributions heavily affected
- EWA: Sideband subtraction completely screwed up!
LHC Example: Vector Isovector

- Example: 850 GeV vector resonance, coupling $g_\rho = 1$

- (Theory) Cuts:
  - $p_\perp (\ell \nu) > 30$ GeV
  - $|\delta R(\ell \nu)| < 1.5$
  - $\theta(u/d) > 0.5^\circ$

- Integrated luminosity: 225 fb$^{-1}$

- Discriminator: angular correlations $\Delta \phi(\ell \ell)$

- Ongoing ATLAS study
  
  *Kobel/JR/Schumacher*
  
  - Cut analysis/NN
  - More kinematic observables
  - Geant4 FullSim (special points)
  - all resonances, parameter scans
ILC Results: Triboson production

\[ e^+e^- \rightarrow W W Z/Z Z Z \], 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: \(M_{WW}^2, M_{WZ}^2, \angle(e^-, Z)\)

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

32 % hadronic decays

Durham jet algorithm

Bkgd. \(t\bar{t} \rightarrow 6\) jets

Veto against \(E_{\text{mis}}^2 + p_{\perp,\text{mis}}^2\)

No angular correlations yet
ILC Results: Triboson production

\[ e^+ e^- \rightarrow WWZ/ZZZ, \ \text{dep. on} \ (\alpha_4 + \alpha_6), (\alpha_5 + \alpha_7), \alpha_4 + \alpha_5 + 2(\alpha_6 + \alpha_7 + \alpha_{10}) \]

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: \( M_{WW}^2, M_{WZ}^2, \langle e^-, Z \rangle \)

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

32 \% hadronic decays

Durham jet algorithm

Bkgd. \( t\bar{t} \rightarrow 6 \) jets

Veto against \( E_{\text{mis}}^2 + p_{\perp,\text{mis}}^2 \)

No angular correlations yet
Vector Boson Scattering

1 TeV, 1 ab$^{-1}$, full 6f final states, 80% $e^-_R$, 60% $e^+_L$ polarization, binned likelihood

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

| Process | Subprocess | $\sigma$ [fb] |
|---------|------------|--------------|
| $e^+e^- \rightarrow \nu_e \bar{\nu}_e q\bar{q}q\bar{q}$ | $WW \rightarrow WW$ | 23.19 |
| $e^+e^- \rightarrow \nu_q \bar{\nu}_q q\bar{q}q\bar{q}$ | $WW \rightarrow ZZ$ | 7.624 |
| $e^+e^- \rightarrow \nu_q \bar{\nu}_q q\bar{q}q\bar{q}$ | $V \rightarrow VVV$ | 9.344 |
| $e^+e^- \rightarrow e^+e^- q\bar{q}q\bar{q}$ | $WZ \rightarrow WZ$ | 132.3 |
| $e^+e^- \rightarrow e^+e^- q\bar{q}q\bar{q}$ | $ZZ \rightarrow ZZ$ | 2.09 |
| $e^+e^- \rightarrow b\bar{b}X$ | $e^+e^- \rightarrow t\bar{t}$ | 414. |
| $e^+e^- \rightarrow q\bar{q}q\bar{q}$ | $e^+e^- \rightarrow W^+W^-$ | 3560.108 |
| $e^+e^- \rightarrow q\bar{q}q\bar{q}$ | $e^+e^- \rightarrow ZZ$ | 173.221 |
| $e^+e^- \rightarrow e^+e^- \nuq\bar{q}$ | $e^+e^- \rightarrow e^+e^- W$ | 279.588 |
| $e^+e^- \rightarrow e^+e^- \nuq\bar{q}$ | $e^+e^- \rightarrow e^+e^- Z$ | 134.935 |
| $e^+e^- \rightarrow X$ | $e^+e^- \rightarrow q\bar{q}$ | 1637.405 |

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

| Coupling | $\sigma^-$ | $\sigma^+$ |
|----------|------------|------------|
| $16\pi^2\alpha_4$ | -1.41 | 1.38 |
| $16\pi^2\alpha_5$ | -1.16 | 1.09 |

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

| Coupling | $\sigma^-$ | $\sigma^+$ |
|----------|------------|------------|
| $16\pi^2\alpha_4$ | -2.72 | 2.37 |
| $16\pi^2\alpha_5$ | -2.46 | 2.35 |
| $16\pi^2\alpha_6$ | -3.93 | 5.53 |
| $16\pi^2\alpha_7$ | -3.22 | 3.31 |
| $16\pi^2\alpha_{10}$ | -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

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

$SU(2)$ broken vector triplet

needs input from TGC covariance matrix

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

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

**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/Conclusions

- New Physics generically encoded in EW Chiral Lagrangian
- Triple/Quartic gauge couplings measured either
  - via triple boson production
  - via vector boson scattering
- Interpreted as resonances coupled to EW bosons
- “Correct” description for first resonance (also [very] broad)
- Beyond that: assure unitarity (K matrix)
- Sensitivity rises with number of intermediate states:
  - LHC sensitivity limited in pure EW sector: 0.6 – 2 TeV
  - ILC: 1.5 – 6 TeV
- Full analysis including all channels/backgrounds with WHIZARD
- Complete ATLAS study is under way
One Ring to Find them ... One Ring to Rule them Out
One Ring to Find them ... One Ring to Rule them Out