Anomalous Quartic Gauge Couplings - Theory Overview

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  - Higgs potential: stable vs. metastable vs. unstable !?
  - Higgs self-coupling vs. Higgs field scattering
  - Importance of longitudinal EW gauge bosons

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- Deviations from the SM: where? what? how?
- Anomalous Triple Gauge Couplings: dibosons

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  - Importance of longitudinal EW gauge bosons
- Deviations from the SM: where? what? how?
- Anomalous Triple Gauge Couplings: dibosons
- Anomalous Quartic Gauge Couplings: tribosons, VV scattering
- Remark: no CP-violating operators in the talk
- Hot topic: Snowmass BNL 04/13, SM@LHC Freiburg 04/13, Dresden workshop 10/13

Extensions of the SM

- Lagrangian of the EW SM (no fermions/QCD here):

$$\mathcal{L}_{EW} = -\frac{1}{2}\mathrm{tr}\left[W_{\mu\nu}W^{\mu\nu}\right] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\phi)^\dagger(D^\mu\phi) + \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$$

with building blocks:

$$D_\mu = \partial_\mu + \frac{i}{2}g\tau^I W_\mu^I + \frac{i}{2}g' B_\mu$$

$$W_{\mu\nu} = \frac{i}{2}g\tau^I(\partial_\mu W_\nu^I - \partial_\nu W_\mu^I + g\epsilon_{IJK}W_\mu^J W_\nu^K)$$

$$B_{\mu\nu} = \frac{i}{2}g'(\partial_\mu B_\nu - \partial_\nu B_\mu)$$

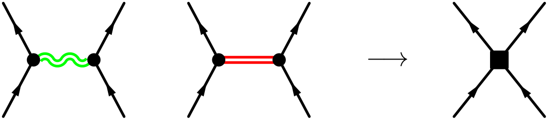
- Any EFT has higher-dimensional operators: Weinberg, 1979

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{a_i}{\Lambda}\mathcal{O}_i^{(5)} + \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \frac{e_i}{\Lambda^4}\mathcal{O}_i^{(8)} \cdots\right]$$

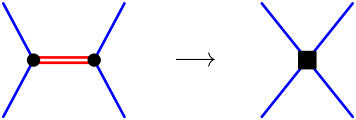
- without more fundamental theory $\Rightarrow$ no clue on the scale (neither on the coefficients)

Effective EW Dim. 6 Operators

Hagiwara/Hikasa/Peccei/Zeppenfeld, 1987; Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993

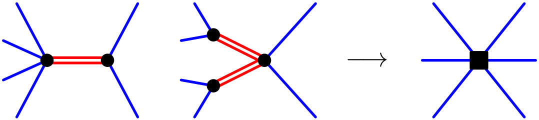


$$\mathcal{O}_{JJ}^{(I)} = \frac{1}{\Lambda^2} \mathrm{tr}\left[J^{(I)} \cdot J^{(I)} \right]$$

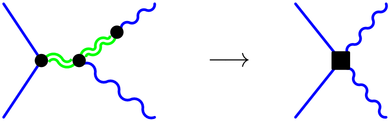


$$\mathcal{O}'_{h,1} = \frac{1}{F^2} \left((D\phi)^\dagger \phi \right) \cdot \left(h^\dagger (D^\phi) \right) - \frac{v^2}{2} |D\phi|^2$$

$$\mathcal{O}'_{hh} = \frac{1}{\Lambda^2} (\phi^\dagger \phi - v^2/2) \, (D\phi)^\dagger \cdot (D\phi)$$



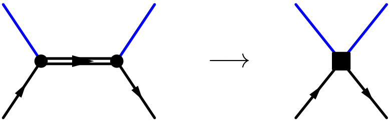
$$\mathcal{O}'_{h,3} = \frac{1}{\Lambda^2} \frac{1}{3} (\phi^\dagger \phi - v^2/2)^3$$



$$\mathcal{O}'_{WW} = -\frac{1}{\Lambda^2}\frac{1}{2}(\phi^\dagger\phi - v^2/2)\,\mathrm{tr}\left[W_{\mu\nu}W^{\mu\nu}\right]$$

$$\mathcal{O}_B = \frac{1}{\Lambda^2}\frac{i}{2}(D_\mu\phi)^\dagger(D_\nu\phi)B^{\mu\nu}$$

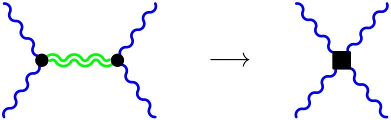
$$\mathcal{O}'_{BB} = -\frac{1}{\Lambda^2}\frac{1}{4}(\phi^\dagger\phi - v^2/2)B_{\mu\nu}B^{\mu\nu}$$



$$\mathcal{O}_{Vq} = \frac{1}{\Lambda^2}\overline{q}h(\not{D}h)q$$

Effective Dim. 8 Operators

Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993



$$\mathcal{O}_\lambda = \frac{i}{\Lambda^4}\mathrm{tr}\left[W_{\mu\nu} \times W^{\nu\rho}(\phi^\dagger \frac{\vec{\sigma}}{2}\left[D_\rho, D^\mu\right]\phi)\right]$$
$$\mathcal{O}_\kappa = (D^\mu\phi)^\dagger(D^\nu\phi)(\phi^\dagger\left[D_\mu, D_\nu\right]\phi)$$

- operators linked through e.o.m.
- SM: 59 independent operators (1 fermion gen.) Buchmüller/Wyler, 1986; Grzadkowski/Iskrzynski/Misiak/Rosiek, 2010
- Renormalization mixes operators
- Beware of power counting

Electroweak Chiral Lagrangian

Originally for heavy Higgses or Higgsless models

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

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

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

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

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

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

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

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

EW Chiral Lagragian $\rightarrow$ Eff. Building Blocks

Originally for heavy Higgses or Higgsless models

$$\mathcal{L}_{\text{eff}} = -\sum_{\psi} \overline{\psi}_L \Sigma M \psi_R + \beta_1 \mathcal{L}'_0 + \sum_i \alpha_i \mathcal{L}_i$$

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

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

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

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

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

$$\Delta S = -16\pi\alpha_1 \qquad \alpha_1 = 0.0026 \pm 0.0020$$

$$\Delta T = 2\beta_1/\alpha_{\text{QED}} \qquad \beta_1 = -0.00062 \pm 0.00043$$

$$\Delta U = -16\pi\alpha_8 \qquad \alpha_8 = -0.0044 \pm 0.0026$$

The Fundamental Building Blocks

- $\mathbf{V} = \Sigma(\mathbf{D}\Sigma)^\dagger$ (longitudinal vectors), $\mathbf{T} = \Sigma\tau^3\Sigma^\dagger$ (neutral component)
- Unitary gauge (no Goldstones): $\mathbf{w} \equiv 0$, i.e., $\Sigma \equiv 1$.

$$\mathbf{V} \longrightarrow -\frac{\mathrm{i}g}{2}\left[\sqrt{2}(W^+\tau^+ + W^-\tau^-) + \frac{1}{c_\mathrm{w}}Z\tau^3\right]$$
$$\mathbf{T} \longrightarrow \tau^3$$

- Gaugeless limit (only Goldstones) $(g, g' \to 0)$:

$$\mathbf{V} \longrightarrow \frac{\mathrm{i}}{v}\left\{\sqrt{2}\partial w^+\tau^+ + \sqrt{2}\partial w^-\tau^- + \partial z\tau^3\right\} + O(v^{-2})$$
$$\mathbf{T} \longrightarrow \tau^3 + 2\sqrt{2}\frac{\mathrm{i}}{v}\left(w^+\tau^+ - w^-\tau^-\right) + O(v^{-2})$$

So $\mathbf{T}$ projects out the neutral part:

$$\mathrm{tr}\left[\mathbf{TV}\right] = \frac{2\mathrm{i}}{v}\left[\partial z + \frac{\mathrm{i}}{v}\left(w^+\partial w^- - w^-\partial w^+\right)\right] + O(v^{-3})$$

Anomalous triple and quartic gauge couplings

$$\mathcal{L}_{TGC} = \mathrm{ie}\left[g_1^\gamma A_\mu \left(W_\nu^- W^{+\mu\nu} - W_\nu^+ W^{-\mu\nu}\right) + \kappa^\gamma W_\mu^- W_\nu^+ A^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2} W_\mu^{-\,\nu} W_{\nu\rho}^+ A^{\rho\mu}\right]$$
$$+ \mathrm{ie}\frac{c_\mathrm{w}}{s_\mathrm{w}}\left[g_1^Z Z_\mu \left(W_\nu^- W^{+\mu\nu} - W_\nu^+ W^{-\mu\nu}\right) + \kappa^Z W_\mu^- W_\nu^+ Z^{\mu\nu} + \frac{\lambda^Z}{M_W^2} W_\mu^{-\,\nu} W_{\nu\rho}^+ Z^{\rho\mu}\right]$$

SM values: $g_1^{\gamma,Z} = \kappa^{\gamma,Z} = 1$, $\lambda^{\gamma,Z} = 0$ and $\delta_Z = \frac{\beta_1 + g'^2\alpha_1}{c_\mathrm{w}^2 - s_\mathrm{w}^2}$ $\quad g_{1/2}^{VV'} = 1$, $h^{ZZ} = 0$

$$\Delta g_1^\gamma = 0 \qquad \Delta\kappa^\gamma = g^2(\alpha_2 - \alpha_1) + g^2\alpha_3 + g^2(\alpha_9 - \alpha_8)$$
$$\Delta g_1^Z = \delta_Z + \frac{g^2}{c_\mathrm{w}^2}\alpha_3 \qquad \Delta\kappa^Z = \delta_Z - g'^2(\alpha_2 - \alpha_1) + g^2\alpha_3 + g^2(\alpha_9 - \alpha_8)$$

$$\Delta g_1^{\gamma\gamma} = \Delta g_2^{\gamma\gamma} = 0 \qquad \Delta g_2^{ZZ} = 2\Delta g_1^{\gamma Z} - \frac{g^2}{c_\mathrm{w}^4}(\alpha_5 + \alpha_7)$$
$$\Delta g_1^{\gamma Z} = \Delta g_2^{\gamma Z} = \delta_Z + \frac{g^2}{c_\mathrm{w}^2}\alpha_3 \qquad \Delta g_1^{WW} = 2c_\mathrm{w}^2\Delta g_1^{\gamma Z} + 2g^2(\alpha_9 - \alpha_8) + g^2\alpha_4$$
$$\Delta g_1^{ZZ} = 2\Delta g_1^{\gamma Z} + \frac{g^2}{c_\mathrm{w}^4}(\alpha_4 + \alpha_6) \qquad \Delta g_2^{WW} = 2c_\mathrm{w}^2\Delta g_1^{\gamma Z} + 2g^2(\alpha_9 - \alpha_8) - g^2(\alpha_4 + 2\alpha_5)$$
$$h^{ZZ} = g^2\left[\alpha_4 + \alpha_5 + 2(\alpha_6 + \alpha_7 + \alpha_{10})\right]$$

Anomalous triple and quartic gauge couplings

$$\begin{aligned}\mathcal{L}_{QGC} = & e^2 \left[g_1^{\gamma\gamma} A^\mu A^\nu W_\mu^- W_\nu^+ - g_2^{\gamma\gamma} A^\mu A_\mu W^{-\nu} W_\nu^+ \right] \\ & + e^2 \frac{c_\mathrm{w}}{s_\mathrm{w}} \left[g_1^{\gamma Z} A^\mu Z^\nu \left(W_\mu^- W_\nu^+ + W_\mu^+ W_\nu^- \right) - 2 g_2^{\gamma Z} A^\mu Z_\mu W^{-\nu} W_\nu^+ \right] \\ & + e^2 \frac{c_\mathrm{w}^2}{s_\mathrm{w}^2} \left[g_1^{ZZ} Z^\mu Z^\nu W_\mu^- W_\nu^+ - g_2^{ZZ} Z^\mu Z_\mu W^{-\nu} W_\nu^+ \right] \\ & + \frac{e^2}{2 s_\mathrm{w}^2} \left[g_1^{WW} W^{-\mu} W^{+\nu} W_\mu^- W_\nu^+ - g_2^{WW} \left(W^{-\mu} W_\mu^+ \right)^2 \right] + \frac{e^2}{4 s_\mathrm{w}^2 c_\mathrm{w}^4} h^{ZZ} (Z^\mu Z_\mu)^2 \end{aligned}$$

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$$\Delta g_1^\gamma = 0 \qquad \Delta \kappa^\gamma = g^2(\alpha_2 - \alpha_1) + g^2 \alpha_3 + g^2 (\alpha_9 - \alpha_8)$$

$$\Delta g_1^Z = \delta_Z + \frac{g^2}{c_\mathrm{w}^2} \alpha_3 \qquad \Delta \kappa^Z = \delta_Z - g'^2(\alpha_2 - \alpha_1) + g^2 \alpha_3 + g^2 (\alpha_9 - \alpha_8)$$

$$\Delta g_1^{\gamma\gamma} = \Delta g_2^{\gamma\gamma} = 0 \qquad \Delta g_2^{ZZ} = 2 \Delta g_1^{\gamma Z} - \frac{g^2}{c_\mathrm{w}^4} (\alpha_5 + \alpha_7)$$

$$\Delta g_1^{\gamma Z} = \Delta g_2^{\gamma Z} = \delta_Z + \frac{g^2}{c_\mathrm{w}^2} \alpha_3 \qquad \Delta g_1^{WW} = 2 c_\mathrm{w}^2 \Delta g_1^{\gamma Z} + 2 g^2 (\alpha_9 - \alpha_8) + g^2 \alpha_4$$

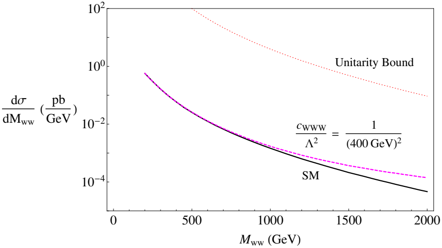
$$\Delta g_1^{ZZ} = 2 \Delta g_1^{\gamma Z} + \frac{g^2}{c_\mathrm{w}^4} (\alpha_4 + \alpha_6) \qquad \Delta g_2^{WW} = 2 c_\mathrm{w}^2 \Delta g_1^{\gamma Z} + 2 g^2 (\alpha_9 - \alpha_8) - g^2 (\alpha_4 + 2\alpha_5)$$

$$h^{ZZ} = g^2 \left[\alpha_4 + \alpha_5 + 2 (\alpha_6 + \alpha_7 + \alpha_{10}) \right]$$

Classification of approaches

- Translation between operator bases: Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993; Wudka, 1994; Degrande/Greiner/Kilian/Mattelaer/Mebane/Stelzer/Willenbrock/Zhang, 2012

$$
\begin{aligned}
\Delta g_1^\gamma &= 0 \\
\Delta g_1^Z &= c_W \frac{m_Z^2}{2\Lambda^2} \\
\Delta\kappa_\gamma &= (c_W + c_B)\frac{m_W^2}{2\Lambda^2} \\
\Delta\kappa_Z &= \delta_Z + (c_W - c_B \tan^2\theta_W)\frac{m_W^2}{2\Lambda^2} \\
\lambda_\gamma &= \lambda_Z = c_{WWW}\frac{3g^2 m_W^2}{2\Lambda^2}
\end{aligned}
$$



- Effective Field Theory description valid, if
  - $\hat{s} \ll \Lambda^2$: new physics out of direct LHC reach
  - Operator coefficients rather smallish, e.g. $c_{WWW} \lesssim 1$
  - No large logarithms in the game (resummation)
- Relation $\Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma$ invalidated by dim 8 operators

Classification of approaches

Remarks:

- EFT approach leads to new interaction vertices
- Coupling constants are EFT Lagrangian parameters
- Framework for higher-order corrections straightforward (though rarely needed)
- Threshold/soft-collinear resummation $\Rightarrow$ momentum-dependent couplings/form factors
- Anomalous couplings understood as effective vertices/vertex functions
- Nevertheless: Lagrangian for new physics reconstructable
- Parameterize new physics effects as new resonances/particles

Parameters and Scales, Resonances

α_i/operator coefficients measurable at LHC (and LC)

- $\alpha_i \ll 1$ (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:

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

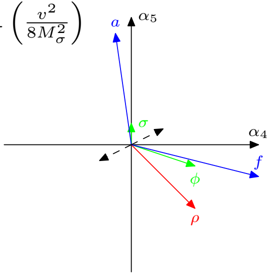
- Simplest example: scalar singlet σ:

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

- 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

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

Resonance	σ	ϕ	ρ	f	a
$\Gamma[g^2M^2/(64\pi v^2)]$	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	$\frac{1}{4}$	$\frac{3}{4}$	$\frac{5}{2}$	$-\frac{5}{8}$
$\Delta\alpha_5[(16\pi\Gamma/M)(v^4/M^4)]$	$\frac{1}{12}$	$-\frac{1}{12}$	$-\frac{3}{4}$	$-\frac{5}{8}$	$\frac{35}{8}$



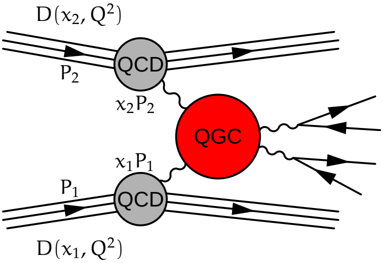
Anomalous Gauge Couplings at LHC

Anomalous quartic gauge couplings, by chiral EW Lagrangian:

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

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

(all leptons, incl. τ):



$$pp \to jj(ZZ/WW) \to jj\ell^-\ell^+\nu_\ell\bar{\nu}_\ell$$

$\sigma \approx 40$ fb

Background:

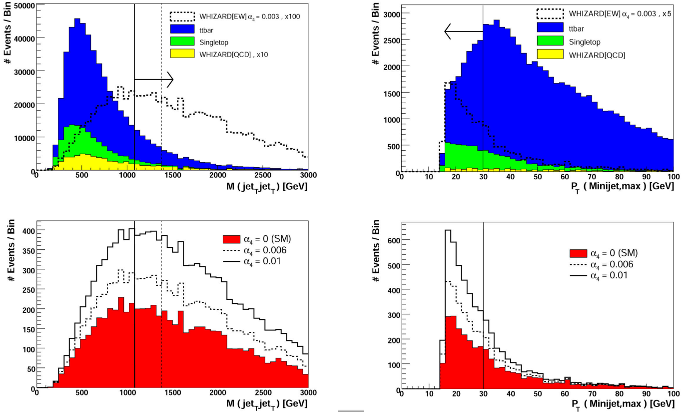
- $t\bar{t} \to WbWb$, $\sigma \approx 52$ pb
- Single t, misrec. jet: $\sigma \approx 4.8$ pb
- QCD: $\sigma \approx 0.21$ pb

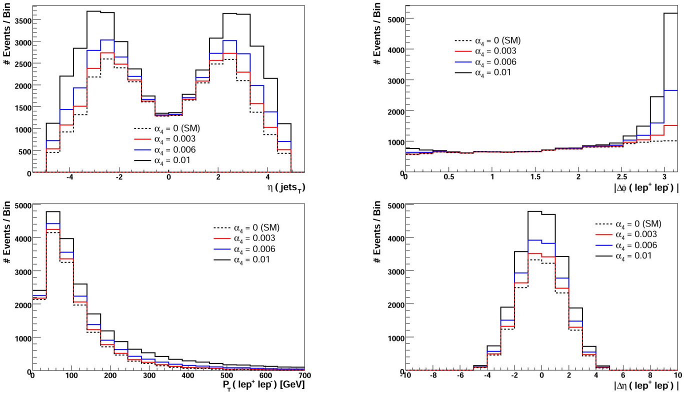
Tagging and Cuts:

Mertens, 2006

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

Improves $S/\sqrt{B}$ from 3.3 to 29.7



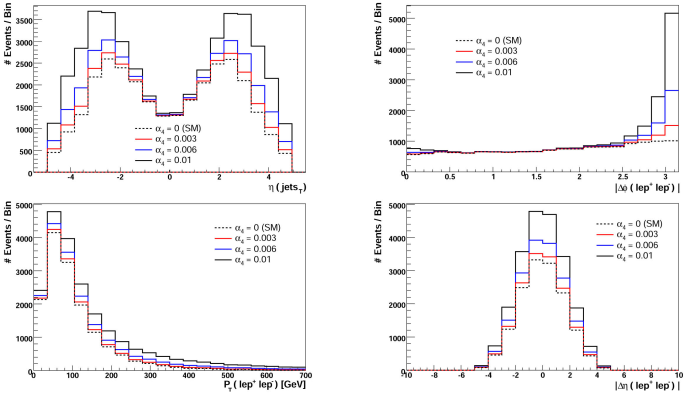


Results: (1σ Sensitivity to αs)

Coupl.	LHC ($100\,\text{fb}^{-1}$)	ILC ($1\,\text{ab}^{-1}$)
α_4	0.00160	0.0088
α_5	0.00098	0.0071

Limits for Λ [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



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Different Selection Criteria

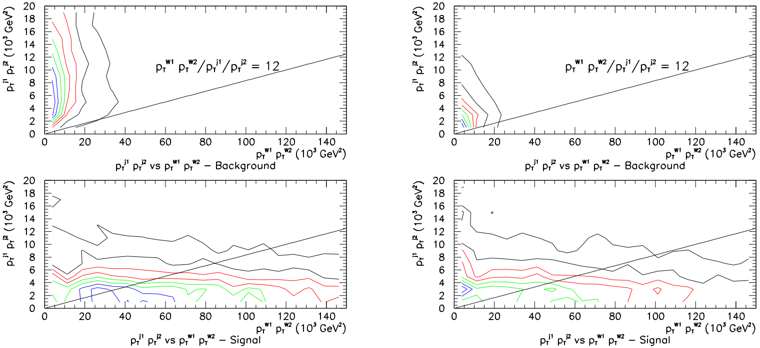
- General selection criteria
  - exactly 2 leptons within detector acceptance,
  - 2 tag jets with $2 < |\eta_j| < 5$ and opposite directions,
  - no b-tag
  - $M_{j_1 l_2}, M_{j_2 l_1} >$ 200 GeV
  - $M_{jj} >$ 400 GeV
  - $\Delta R_{jl} >$ 0.4
  - $p_T^{l_1}, p_T^{l_2} >$ 40 GeV
  - $|\eta_{l_1}|, |\eta_{l_2}| <$ 1.5
  - $\Delta\phi_{ll} >$ 2.5
  - $M_{ll} >$ 200 GeV
- Proposal of new variable Doroba/Kalinowski/Kuczmarski/Pokorski/Rosiek/Szleper/Tkaczyk, 1201.2768

$$R_{p_T} = (p_T^{l_1} \cdot p_T^{l_2}) \; / \; (p_T^{j_1} \cdot p_T^{j_2})$$

- Proposal of new variable Doroba/Kalinowski/Kuczmarski/Pokorski/Rosiek/Szleper/Tkaczyk, 1201.2768

$$R_{p_T} = (p_T^{l_1} \cdot p_T^{l_2}) \;/\; (p_T^{j_1} \cdot p_T^{j_2})$$

- Works well for $W^\pm W^\pm$, not feasible for W^+W^-



- Might allow to relax jet vetoes: gain for high pile-up!

- Remark: EWA works for selection, but shapes need not be the same

Unitarity of Amplitudes

UV-incomplete theories could violate unitarity

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

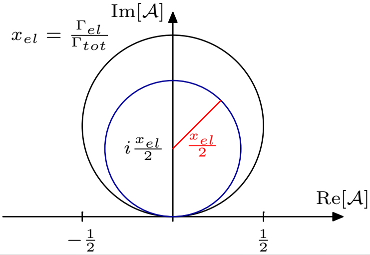
Optical Theorem (Unitarity of the S(cattering) Matrix):

$$\sigma_{\text{tot}} = \text{Im}\left[\mathcal{M}_{ii}(t=0)\right]/s \qquad t = -s(1-\cos\theta)/2$$

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

Assuming only elastic scattering:

$$\sigma_{\text{tot}} = \sum_\ell \frac{32\pi(2\ell+1)}{s} |\mathcal{A}_\ell|^2 \overset{!}{=} \sum_\ell \frac{32\pi(2\ell+1)}{s} \text{Im}\left[\mathcal{A}_\ell\right] \quad \Rightarrow \quad \boxed{|\mathcal{A}_\ell|^2 = \text{Im}\left[\mathcal{A}_\ell\right]}$$



Argand circle $\boxed{\left|\mathcal{A}(s) - \frac{i}{2}\right| = \frac{1}{2}}$

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 Lee,Quigg,Thacker, 1973

$$\mathcal{A}_\ell(s) = \frac{1}{32\pi} \int_{-s}^{0} \frac{dt}{s} \mathcal{A}(s,t,u) P_\ell(1+2t/s) \qquad \cos\theta = 1 + 2t/s$$

Remember Legendre polynomials: $P_0(s) = 1 \qquad P_1(s) = \cos\theta \qquad P_2(s) = (3\cos^2\theta - 1)/2$

- SM longitudinal isospin eigenamplitudes ($\mathcal{A}_{I,\text{spin}=J}$):

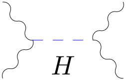
$$\mathcal{A}_{I=0} = 2\frac{s}{v^2} P_0(s) \qquad \mathcal{A}_{I=1} = \frac{t-u}{v^2} = \frac{s}{v^2} P_1(s) \qquad \mathcal{A}_{I=2} = -\frac{s}{v^2} P_0(s)$$

$$\boxed{\mathcal{A}_{0,0} = \frac{s}{16\pi v^2}} \qquad \boxed{\mathcal{A}_{1,1} = \frac{s}{96\pi v^2}} \qquad \boxed{\mathcal{A}_{2,0} = -\frac{s}{32\pi v^2}}$$

exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

$$I = 0: \qquad E \sim \sqrt{8\pi} v = 1.2\,\text{TeV}$$
$$I = 1: \qquad E \sim \sqrt{48\pi} v = 3.5\,\text{TeV}$$
$$I = 2: \qquad E \sim \sqrt{16\pi} v = 1.7\,\text{TeV}$$

Higgs exchange:



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

Unitarity: $M_H \lesssim \sqrt{8\pi} v \sim 1.2\,\text{TeV}$

Isospin decomposition

- Lowest order chiral Lagrangian (incl. anomalous couplings)

$$\mathcal{L} = -\frac{v^2}{4}\mathrm{tr}\left[\mathbf{V}_\mu \mathbf{V}^\mu\right] + \alpha_4 \mathrm{tr}\left[\mathbf{V}_\mu \mathbf{V}_\nu\right]\mathrm{tr}\left[\mathbf{V}^\mu \mathbf{V}^\nu\right] + \alpha_5\left(\mathrm{tr}\left[\mathbf{V}_\mu \mathbf{V}^\mu\right]\right)^2$$

- Leads to the following amplitudes: $s = (p_1 + p2)^2 \quad t = (p1 - p3)^2 \quad u = (p1 - p4)^2$

$$\boxed{\mathcal{A}(s,t,u) =:} \qquad \mathcal{A}(w^+w^- \to zz) = \frac{s}{v^2} + 8\alpha_5\frac{s^2}{v^4} + 4\alpha_4\frac{t^2+u^2}{v^4}$$

$$\mathcal{A}(w^+z \to w^+z) = \frac{t}{v^2} + 8\alpha_5\frac{t^2}{v^4} + 4\alpha_4\frac{s^2+u^2}{v^4}$$

$$\mathcal{A}(w^+w^- \to w^+w^-) = -\frac{u}{v^2} + (4\alpha_4 + 2\alpha_5)\frac{s^2+t^2}{v^4} + 8\alpha_4\frac{u^2}{v^4}$$

$$\mathcal{A}(w^+w^+ \to w^+w^+) = -\frac{s}{v^2} + 8\alpha_4\frac{s^2}{v^4} + 4\left(\alpha_4 + 2\alpha_5\right)\frac{t^2+u^2}{v^4}$$

$$\mathcal{A}(zz \to zz) = 8\left(\alpha_4 + \alpha_5\right)\frac{s^2+t^2+u^2}{v^4}$$

- (Clebsch-Gordan) Decomposition into isospin eigenamplitudes

$$\begin{aligned}\mathcal{A}(I=0) &= 3\mathcal{A}(s,t,u) + \mathcal{A}(t,s,u) + \mathcal{A}(u,s,t)\\ \mathcal{A}(I=1) &= \mathcal{A}(t,s,u) - \mathcal{A}(u,s,t)\\ \mathcal{A}(I=2) &= \mathcal{A}(t,s,u) + \mathcal{A}(u,s,t)\end{aligned}$$

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

- $\mathcal{L}_\sigma = -\frac{1}{2}\sigma\left(M_\sigma^2 + \partial^2\right)\sigma + \frac{g_\sigma v}{2}\sigma \mathrm{tr}\left[\mathbf{V}_\mu \mathbf{V}^\mu\right]$
- Feynman rules: $\sigma w^+ w^- : \; -\frac{2ig_\sigma}{v}(k_+ \cdot k_-) \qquad \sigma zz : \; -\frac{2ig_\sigma}{v}(k_1 \cdot k_2)$
- Amplitude (s-channel exchange): $\boxed{\mathcal{A}^\sigma(s,t,u) = \frac{g_\sigma^2}{v^2}\frac{s^2}{s-M^2}}$
- Isospin eigenamplitudes:

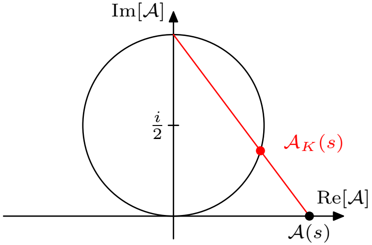
$$\begin{aligned}
\mathcal{A}_0^\sigma(s,t,u) &= \frac{g_\sigma^2}{v^2}\left(3\frac{s^2}{s-M^2} + \frac{t^2}{t-M^2} + \frac{u^2}{u-M^2}\right) \\
\mathcal{A}_1^\sigma(s,t,u) &= \frac{g_\sigma^2}{v^2}\left(\frac{t^2}{t-M^2} - \frac{u^2}{u-M^2}\right) \\
\mathcal{A}_2^\sigma(s,t,u) &= \frac{g_\sigma^2}{v^2}\left(\frac{t^2}{t-M^2} + \frac{u^2}{u-M^2}\right)
\end{aligned}$$

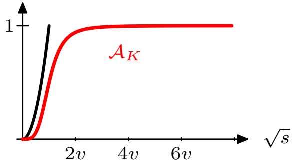
K-Matrix Unitarization and friends

K-Matrix unitarization

$$\mathcal{A}_K(s) = \frac{\mathcal{A}(s)}{1 - i\mathcal{A}(s)} = \mathcal{A}(s)\frac{1 + i\mathcal{A}(s)}{1 + \mathcal{A}(s)^2}$$

Unitarization by infinitely heavy and wide resonance





- Low-energy theorem (LET): $\frac{s}{v^2}$
- K-Matrix amplitude: $|\mathcal{A}(s)|^2 = \frac{s^2}{s^2+v^4} \overset{s\to\infty}{\longrightarrow} 1$
- Poles $\pm iv$: M_0, Γ large

Padé unitarization

separates higher chiral orders

$$\mathcal{A}_P(s) = \frac{\mathcal{A}^{(0)}(s)^2}{\mathcal{A}^{(0)}(s) - \mathcal{A}^{(1)}(s) - i\mathcal{A}^{(0)}(s)^2}$$

each partial wave dominated by single resonance

"Naive" Unitarization

Extreme case:

$$\mathcal{A}_N(s) = e^{i\mathcal{A}(s)} \sin\mathcal{A}(s)$$

Infinitely many resonances becoming denser for $s \to \infty$

Unitarizing the scalar singlet

Alboteanu/Kilian/JRR, 2008

$$\mathcal{A}^\sigma_{00}(s) = 3\frac{g_\sigma^2}{v^2}\frac{s^2}{s-M^2} + 2\frac{g_\sigma^2}{v^2}\mathcal{S}_0(s) \qquad \mathcal{A}^\sigma_{02}(s) = 2\frac{g_\sigma^2}{v^2}\mathcal{S}_2(s) \quad = A^\sigma_{22}(s)$$

$$\mathcal{A}^\sigma_{11}(s) = 2\frac{g_\sigma^2}{v^2}\mathcal{S}_1(s) \qquad \mathcal{A}^\sigma_{13}(s) = 2\frac{g_\sigma^2}{v^2}\mathcal{S}_3(s)$$

$$\mathcal{A}^\sigma_{20}(s) = 2\frac{g_\sigma^2}{v^2}\mathcal{S}_0(s)$$

- S-wave coefficients no longer polynomial, e.g.:

$$\mathcal{S}_0(s) = M^2 - \frac{s}{2} + \frac{M^4}{s}\log\frac{s}{s+M^2}$$

- s-channel pole must be explicitly subtracted:

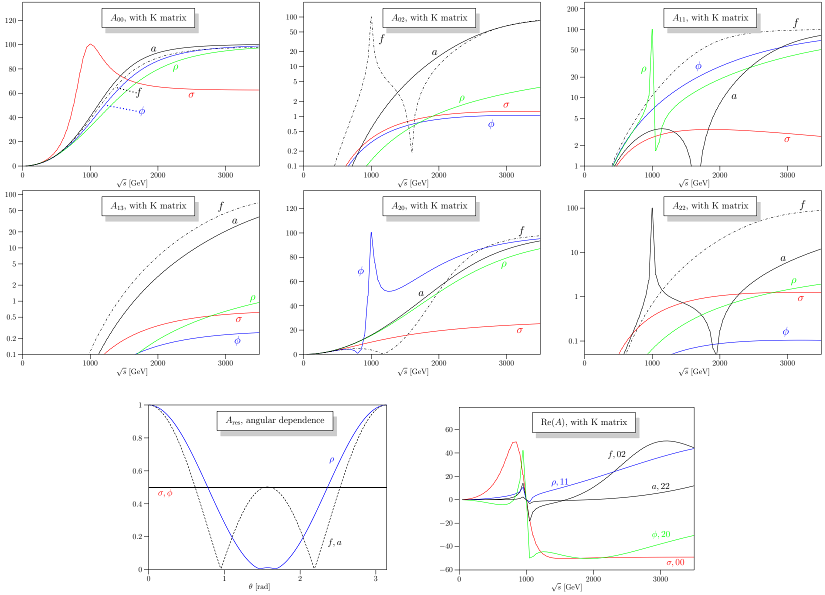
$$A_{IJ}(s) = A^{(0)}_{IJ}(s) + F_{IJ}(s) + \frac{G_{IJ}(s)}{s-M^2},$$

  - $F_{IJ}(s)$ is finite
  - $G_{IJ}(s) \propto s$ (vector), $\propto s^2$ (scalar, tensor)

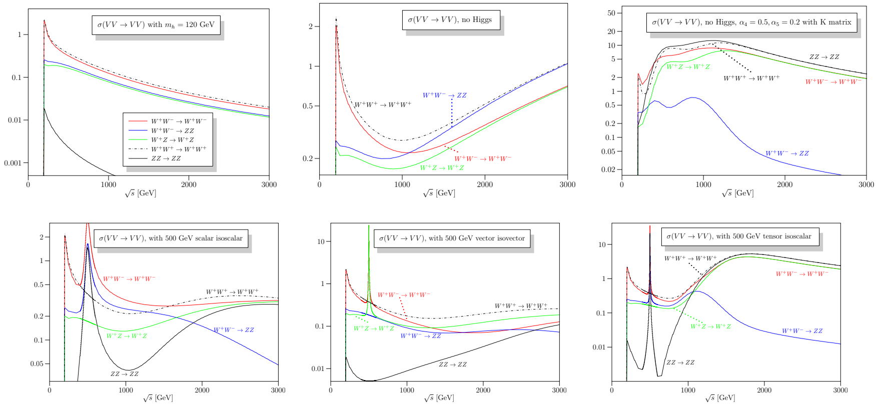
$$\hat{A}_{IJ}(s) = \frac{A_{IJ}(s)}{1 - \frac{i}{32\pi}A_{IJ}(s)} = A^{(0)}_{IJ}(s) + 32\pi i \Delta A_{IJ}(s),$$

$$\Delta A_{IJ}(s) = 32\pi i\left(1 + \frac{i}{32\pi}A^{(0)}_{IJ}(s) + \frac{s-M^2}{\frac{i}{32\pi}G_{IJ}(s) - (s-M^2)\left[1 - \frac{i}{32\pi}\left(A^{(0)}_{IJ}(s) + F_{IJ}(s)\right)\right]}\right)$$

Eigenamplitudes



“Partonic” cross sections

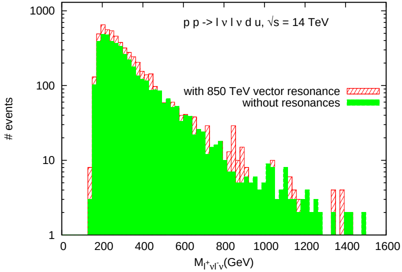


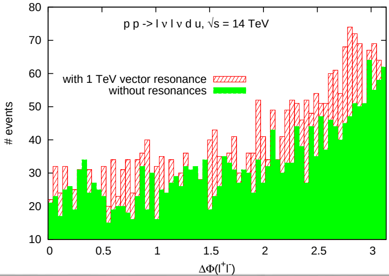
- $\sigma(\mathcal{VV} \to \mathcal{VV})$ in nb $\quad M_R = 500$ GeV
- all amplitudes K-matrix unitarized
- Cut of 15° around the beam axis

LHC Example: Vector Isovector

Alboteanu/Kilian/JRR, 2008

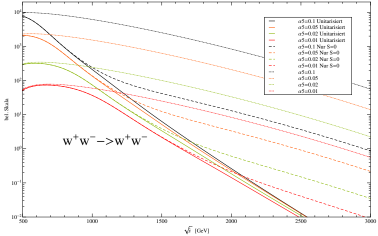
- Example: 850 GeV vector resonance, coupling $g_\rho = 1$
- (Theory) Cuts:
  - $p_\perp(\ell\nu) > 30$ GeV
  - $|\delta R(\ell\nu)| < 1.5$
  - $\theta(u/d) > 0.5^\circ$
- Integrated luminosity: 225 fb^{-1}
- Discriminator: angular correlations $\Delta\phi(\ell\ell)$
- Ongoing ATLAS study
  - More kinematic observables
  - Comparison and validation phase
  - first reproduce SM
  - then anom. couplings/BSM resonances

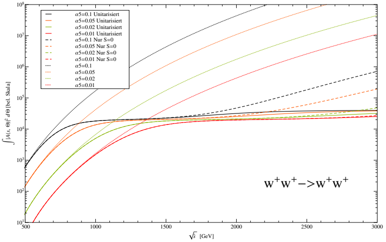




Including Higgs Operators

- Higgs has been discovered (sic!)
- Include more operators, e.g. $(D_\mu\phi)^\dagger W^{\mu\nu}(D_\nu\phi)$, $(\partial(\phi^\dagger\phi))^2$: usually called $\mathcal{O}_B$, $\mathcal{O}_W$, $\mathcal{O}_{WW}$, $\mathcal{O}_{WWW}$ etc.
- both anom. V^3 + V^4 and HVV etc. couplings !
- Implemented for an ATLAS study in WHIZARD





- Ongoing theoretical study

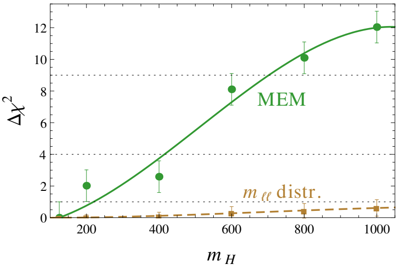
Kilian/JRR/Sekulla, 2013

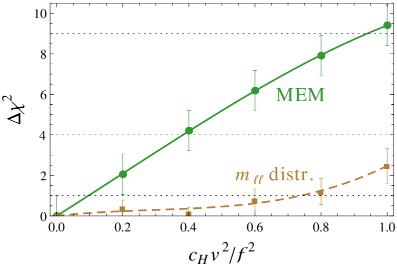
- Very preliminary results

Matrix Element Method (MEM)

Kondo, 1988; Dalitz/Goldstein, 1992; CDF; D∅; Freitas/Gainer, arXiv:1212.3598

- Construct a likelihood from the squared matrix elements
- Marginalize over invisible particles
- Case study for $pp \to jjW^+W^+$ Freitas/Gainor, 2012
- Up to now only compared to dilepton mass: $m_{\ell\ell}$



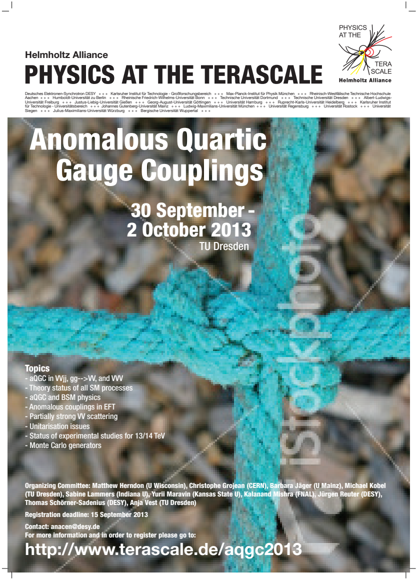


- Important cross-check for experimentalists: Cut-based vs. MVA vs. MEM

Summary/Conclusions

- New Physics in EW effective Lagrangian (SM + higher-dim. op.)
- Triple/Quartic gauge couplings measured either
  - via diboson production
  - via triple boson production
  - via vector boson scattering
- Unified description for different channels difficult
- EFT approach for low-energy regime, unitarized by form factors in resonance scheme at high energies
- interpreted as resonances coupled to EW bosons
- "Correct" description for first resonance (also [very] broad)
- Beyond that: assure unitarity (K matrix)
- Approach includes standard EFT ansatz
- Sensitivity rises with number of intermediate states:
  - LHC sensitivity limited in pure EW sector: $0.8 - 3$ TeV (???)
  - ILC : $1.5 - 6$ TeV
- More and intensive studies needed

AQGC Workshop Dresden 30.9.-2.10.2013



Backup: The Effective W approximation

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

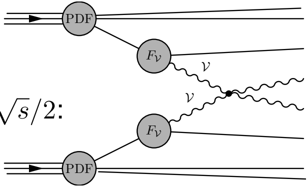
$$\sigma(q_1 q_2 \to q_1' q_2' \mathcal{V}_1' \mathcal{V}_2') \approx \sum_{\lambda_1,\lambda_2} \int dx_1\, dx_2\, F^{\lambda_1}_{q_1 \to q_1' \mathcal{V}_1}(x_1)\, F^{\lambda_2}_{q_2 \to q_2' \mathcal{V}_2}(x_2)\, \sigma^{\lambda_1 \lambda_2}_{\mathcal{V}_1 \mathcal{V}_2 \to \mathcal{V}_1' \mathcal{V}_2'}(x_1 x_2 s)$$

- In addition to Weizsäcker-Williams: longitudinal polarisation

$$F^{+}_{q \to q' \mathcal{V}}(x) = \frac{(V-A)^2 + (V+A)^2(1-x)^2}{16\pi^2 \quad x} \left[\ln \left(\frac{p^2_{\perp,\max} + (1-x) m^2_{\mathcal{V}}}{(1-x) m^2_{\mathcal{V}}} \right) - \frac{p^2_{\perp,\max}}{p^2_{\perp,\max} + (1-x) m^2_{\mathcal{V}}} \right]$$

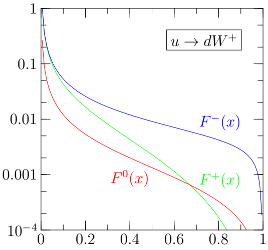
$$F^{-}_{q \to q' \mathcal{V}}(x) = \frac{(V+A)^2 + (V-A)^2(1-x)^2}{16\pi^2 \quad x} \left[\ln \left(\frac{p^2_{\perp,\max} + (1-x) m^2_{\mathcal{V}}}{(1-x) m^2_{\mathcal{V}}} \right) - \frac{p^2_{\perp,\max}}{p^2_{\perp,\max} + (1-x) m^2_{\mathcal{V}}} \right]$$

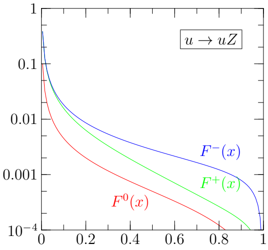
$$F^{0}_{q \to q' \mathcal{V}}(x) = \frac{V^2 + A^2}{8\pi^2} \frac{2(1-x)}{x} \frac{p^2_{\perp,\max}}{p^2_{\perp,\max} + (1-x) m^2_{\mathcal{V}}}$$



- Dominant contribution from small $\mathcal{V}$ virtualities
- Transverse momentum cutoff $p_{\perp,\max} \leq (1-x)\sqrt{s}/2$:
  - longitudinal pol.: finite for $p_{\perp,\max} \to \infty$
  - Transversal pol.: logarithmic singularity

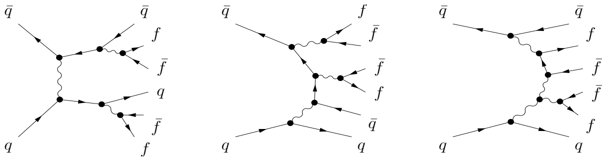
- EWA structure functions: W (left) and Z (right)





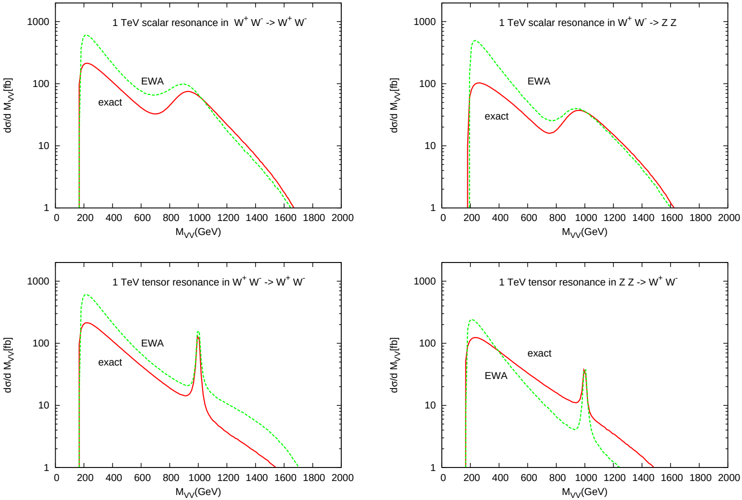
  - Emission from u, $\sqrt{s} = 2$ TeV
  - preferred at high energy: transversal emission

- 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

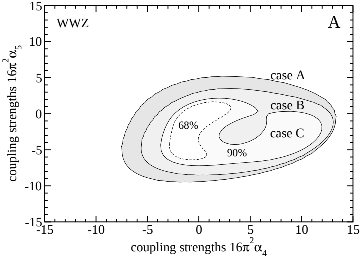


- Effective W approx. vs. WHIZARD full matrix elements
- Shapes/normalization of distributions heavily affected
- **EWA: Sideband subtraction completely screwed up!**

Backup: ILC example: 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, $1\,\text{ab}^{-1}$, 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

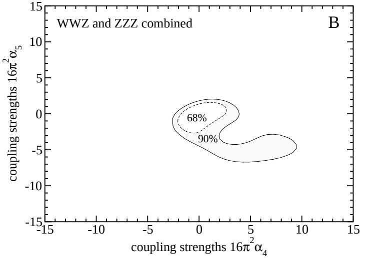
Veto against $E^2_{\text{mis}} + p^2_{\perp,\text{mis}}$

No angular correlations yet

Backup: ILC example: 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, $1\,\mathrm{ab}^{-1}$, 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 $E^2_{\mathrm{mis}} + p^2_{\perp,\mathrm{mis}}$

No angular correlations yet

Vector Boson Scattering

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

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

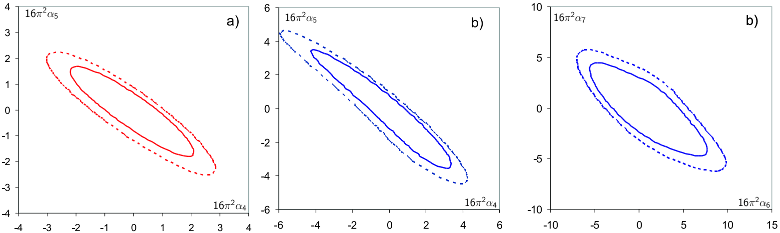
Process	Subprocess	σ [fb]
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$WW \to WW$	23.19
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$WW \to ZZ$	7.624
$e^+e^- \to \nu\bar{\nu} q\bar{q}q\bar{q}$	$V \to VVV$	9.344
$e^+e^- \to \nu e q\bar{q}q\bar{q}$	$WZ \to WZ$	132.3
$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to ZZ$	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	$\sigma-$	$\sigma+$
$16\pi^2\alpha_4$	-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

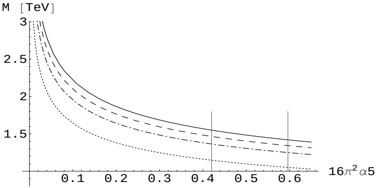


Backup: Interpretation as limits on resonances

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

$SU(2)$ conserving scalar singlet

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

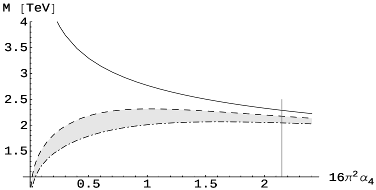


$f = 1.0$ (full), 0.8 (dash), 0.6 (dot-dash), 0.3 (dot)

$SU(2)$ 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