Electroweak Physics at LHC - TGCs and QGCs

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- Deviations from the SM: where? what? how?
- Anomalous Triple Gauge Couplings: dibosons
- Anomalous Quartic Gauge Couplings: tribosons, VV scattering
- Hot topic: Snowmass BNL 04/13, SM@LHC Freiburg 04/13, LHCEWWG 04/13, Snowmass 07/13, Dresden workshop 10/13

Extensions of the SM

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

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

with building blocks:

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

$$W_{\mu\nu} = \frac{i}{2}g\tau^I(\partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g\epsilon_{IJK}W^J_\mu W^K_\nu)$$

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

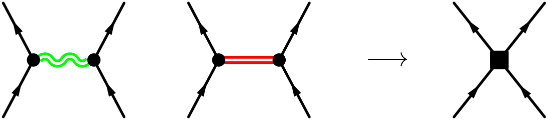
- Any EFT has higher-dimensional operators: Weinberg, 1979

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

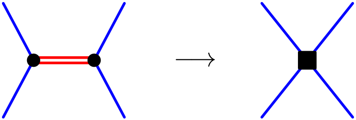
- without more fundamental theory $\Rightarrow$ no clue on the scale (neither on the coefficients)

Effective EW Dim. 6 Operators

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

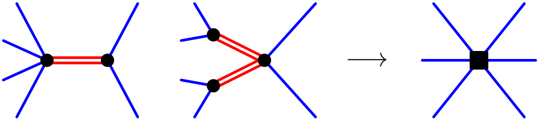


$$\mathcal{O}_{JJ}^{(I)} = \frac{1}{\Lambda^2}\mathrm{tr}\left[J^{(I)}\cdot J^{(I)}\right]$$

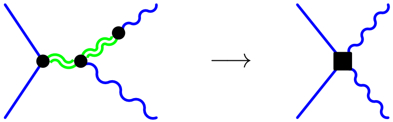


$$\mathcal{O}'_{h,1} = \frac{1}{F^2}\left(\left((D\Phi)^\dagger\Phi\right)\cdot\left(h^\dagger(D^\Phi)\right) - \frac{v^2}{2}|D\Phi|^2\right.$$

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



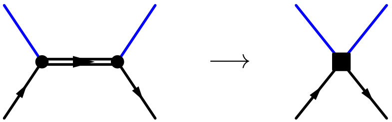
$$\mathcal{O}'_{h,3} = \frac{1}{\Lambda^2}\frac{1}{3}\left(\Phi^\dagger\Phi - v^2/2\right)^3$$



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

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

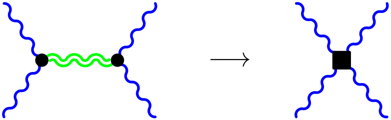
$$\mathcal{O}_{\Phi B} = -\frac{1}{\Lambda^2}\frac{1}{4}(\Phi^\dagger\Phi - v^2/2)B_{\mu\nu}B^{\mu\nu}$$



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

Effective Dim. 8 Operators

Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993



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

- 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

Classification of Operators (I): Dim 6

(always v^2 subtracted)

- Dimension-6 operators (CP-conserving)

$$\mathcal{O}_{WWW} = \text{Tr}[W_{\mu\nu} W^{\nu\rho} W_\rho^{\mu}]$$
$$\mathcal{O}_{W} = (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi)$$
$$\mathcal{O}_{B} = (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_{\partial\Phi} = \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right)$$
$$\mathcal{O}_{\Phi W} = \left(\Phi^\dagger \Phi\right) \text{Tr}[W^{\mu\nu} W_{\mu\nu}]$$
$$\mathcal{O}_{\Phi B} = \left(\Phi^\dagger \Phi\right) B^{\mu\nu} B_{\mu\nu}$$

- Dimension-6 operators (CP-violating)

$$\mathcal{O}_{\widetilde{W}W} = \Phi^\dagger \widetilde{W}_{\mu\nu} W^{\mu\nu} \Phi$$
$$\mathcal{O}_{\tilde{B}B} = \Phi^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu} \Phi$$

$$\mathcal{O}_{\widetilde{W}WW} = \text{Tr}[\widetilde{W}_{\mu\nu} W^{\nu\rho} W_\rho^{\mu}]$$
$$\mathcal{O}_{\widetilde{W}} = (D_\mu \Phi)^\dagger \widetilde{W}^{\mu\nu} (D_\nu \Phi)$$

	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{W}$	✓	✓	✓	✓	✓		✓	✓	✓	
$\mathcal{O}_{B}$	✓	✓		✓	✓					
$\mathcal{O}_{\Phi d}$			✓	✓						
$\mathcal{O}_{\Phi W}$			✓	✓	✓	✓				
$\mathcal{O}_{\Phi B}$				✓	✓	✓				
$\mathcal{O}_{\tilde{W}WW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{\tilde{W}}$	✓	✓	✓	✓	✓					
$\mathcal{O}_{\tilde{W}W}$			✓	✓	✓	✓				
$\mathcal{O}_{\tilde{B}B}$				✓	✓	✓				

Classification of Operators (II): Dim 8

(always v^2 subtracted)

- Dimension-8 operators (only $D_\mu \Phi$)

$$\mathcal{O}_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right] ,$$
$$\mathcal{O}_{S,1} = \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi \right] ,$$

- Dimension-8 operators (only field strength/mixed)

$$\mathcal{O}_{T,0} = \text{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \cdot \text{Tr}\left[W_{\alpha\beta} W^{\alpha\beta} \right] ,$$
$$\mathcal{O}_{T,1} = \text{Tr}\left[W_{\alpha\nu} W^{\mu\beta} \right] \cdot \text{Tr}\left[W_{\mu\beta} W^{\alpha\nu} \right] ,$$
$$\mathcal{O}_{T,2} = \text{Tr}\left[W_{\alpha\mu} W^{\mu\beta} \right] \cdot \text{Tr}\left[W_{\beta\nu} W^{\nu\alpha} \right] ,$$
$$\mathcal{O}_{T,5} = \text{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \cdot B_{\alpha\beta} B^{\alpha\beta} ,$$
$$\mathcal{O}_{T,6} = \text{Tr}\left[W_{\alpha\nu} W^{\mu\beta} \right] \cdot B_{\mu\beta} B^{\alpha\nu} ,$$
$$\mathcal{O}_{T,7} = \text{Tr}\left[W_{\alpha\mu} W^{\mu\beta} \right] \cdot B_{\beta\nu} B^{\nu\alpha} ,$$
$$\mathcal{O}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$$
$$\mathcal{O}_{T,9} = B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha} .$$

$$\mathcal{O}_{M,0} = \text{Tr}\left[W_{\mu\nu} W^{\mu\nu} \right] \cdot \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$
$$\mathcal{O}_{M,1} = \text{Tr}\left[W_{\mu\nu} W^{\nu\beta} \right] \cdot \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$
$$\mathcal{O}_{M,2} = \left[B_{\mu\nu} B^{\mu\nu} \right] \cdot \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right] ,$$
$$\mathcal{O}_{M,3} = \left[B_{\mu\nu} B^{\nu\beta} \right] \cdot \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right] ,$$
$$\mathcal{O}_{M,4} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} D^\mu \Phi \right] \cdot B^{\beta\nu} ,$$
$$\mathcal{O}_{M,5} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} D^\nu \Phi \right] \cdot B^{\beta\mu} ,$$
$$\mathcal{O}_{M,6} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\nu} D^\mu \Phi \right] ,$$
$$\mathcal{O}_{M,7} = \left[(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\mu} D^\nu \Phi \right] ,$$

Classification of Operators (III)

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0/1}$	✓	✓	✓						
$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2/3/4/5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0/1/2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

- Dim. 8 operators generate aQGCs, but not aTGCs
- generate neutral quartics
- Redundancy of the operators:
  - Equations of motion: $D_\mu W^{\mu\nu} = \Phi^\dagger (D^\nu \Phi) - (D^\nu \Phi)^\dagger \Phi + \ldots$
  - Gauge symmetry structure: $[D_\mu, D_\nu]\,\Phi \propto W_{\mu\nu}\Phi$
  - Integration by parts (up to total derivatives)
  - Leads to relations like:

$$\begin{aligned} \mathcal{O}_B &= \mathcal{O}_{\tilde{W}} + \frac{1}{2}\mathcal{O}_{WW} - \frac{1}{2}\mathcal{O}_{BB} \\ \mathcal{O}_{BW} &= -2\,\mathcal{O}_W - \mathcal{O}_{WW} \\ \mathcal{O}_{\partial W} &= -4\,\mathcal{O}_{WWW} + \text{gauge-fermion operators} \end{aligned}$$

Classification of Operators (IV)

Originally for heavy Higgses or Higgsless models

$$\mathcal{L}_\chi \ni \beta_1 \mathcal{L}_0' + \sum_i \alpha_i \mathcal{L}_i + \frac{1}{v} \sum_i \alpha_i^{(5)} \mathcal{L}^{(5)} + \frac{1}{v^2} \sum_i \alpha_i^{(6)} \mathcal{L}^{(6)} + \ldots \qquad \alpha_i^{(n)} = \frac{v^{n-4}}{\Lambda^{n-4}} C_i^n$$

$$\mathcal{L}_0' = \frac{v^2}{4} \mathrm{tr}\,[\mathbf{TV}_\mu]\,\mathrm{tr}\,[\mathbf{TV}^\mu]$$

$$\mathcal{L}_1 = \mathrm{tr}\,[\mathbf{B}_{\mu\nu}\mathbf{W}^{\mu\nu}]$$

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

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

$$\mathcal{L}_4 = \mathrm{tr}\,[\mathbf{V}_\mu\mathbf{V}_\nu]\,\mathrm{tr}\,[\mathbf{V}^\mu\mathbf{V}^\nu]$$

$$\mathcal{L}_5 = \mathrm{tr}\,[\mathbf{V}_\mu\mathbf{V}^\mu]\,\mathrm{tr}\,[\mathbf{V}_\nu\mathbf{V}^\nu]$$

$$\mathcal{L}_6 = \mathrm{tr}\,[\mathbf{V}_\mu\mathbf{V}_\nu]\,\mathrm{tr}\,[\mathbf{TV}^\mu]\,\mathrm{tr}\,[\mathbf{TV}^\nu]$$

$$\mathcal{L}_7 = \mathrm{tr}\,[\mathbf{V}_\mu\mathbf{V}^\mu]\,\mathrm{tr}\,[\mathbf{TV}_\nu]\,\mathrm{tr}\,[\mathbf{TV}^\nu]$$

$$\mathcal{L}_8 = \tfrac{1}{4}\mathrm{tr}\,[\mathbf{TW}_{\mu\nu}]\,\mathrm{tr}\,[\mathbf{TW}^{\mu\nu}]$$

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

$$\mathcal{L}_{10} = \tfrac{1}{2}\left(\mathrm{tr}\,[\mathbf{TV}_\mu]\,\mathrm{tr}\,[\mathbf{TV}^\mu]\right)^2$$

Classification of Operators (IV)

Originally for heavy Higgses or Higgsless models

$$\mathcal{L}_\chi \ni \beta_1 \mathcal{L}_0' + \sum_i \alpha_i \mathcal{L}_i + \frac{1}{v} \sum_i \alpha_i^{(5)} \mathcal{L}^{(5)} + \frac{1}{v^2} \sum_i \alpha_i^{(6)} \mathcal{L}^{(6)} + \ldots \qquad \alpha_i^{(n)} = \frac{v^{n-4}}{\Lambda^{n-4}} C_i^n$$

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

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

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

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

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

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

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

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:

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

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

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

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

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

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

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

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

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

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

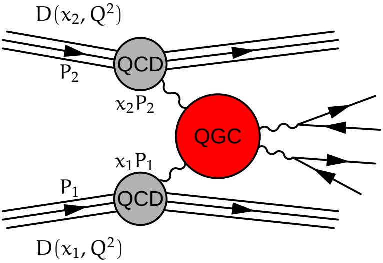
Anomalous Gauge Couplings at LHC

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):



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

$$\sigma \approx 0.05\,\text{pb}$$

Background:

- $t\bar{t} \to WbWb$, $\sigma \approx 50\,$pb
- Single t, misrec. jet: $\sigma \approx 5\,$pb
- QCD: $\sigma \approx 0.2\,$pb

Tagging and Cuts:

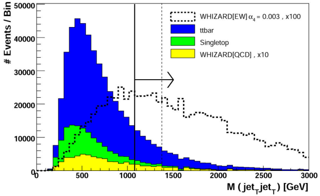
Mertens, 2006

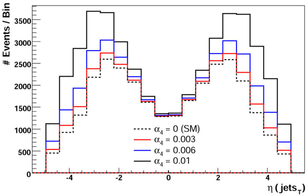
- $\ell\ell jj$-Tag, $\eta_{tag}^{min} < \eta_\ell < \eta_{tag}^{max}$, b-Veto
- $|\Delta\eta_{jj}| > 4.4$, $M_{jj} > 1080$ GeV
- [Minijet-Veto: $p_{T,j} < 30$ GeV]
- $E_j > 600, 400$ GeV, $p^1_{T,j} > 60, 24$ GeV

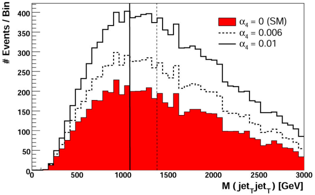
Improves $S/\sqrt{B}$ from 3.3 to 29.7

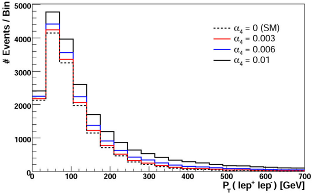
Limits suffer from

- Experiment: Background
- Theory: Definition of MEs









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

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

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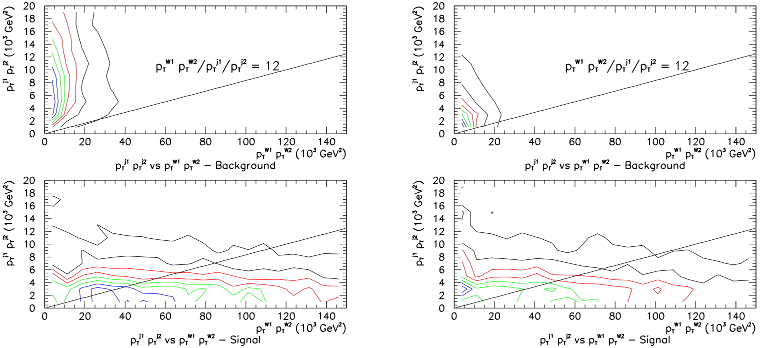
$$R_{p_T} = (p_T^{l_1} \cdot p_T^{l_2}) \;/\; (p_T^{j_1} \cdot p_T^{j_2})$$

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

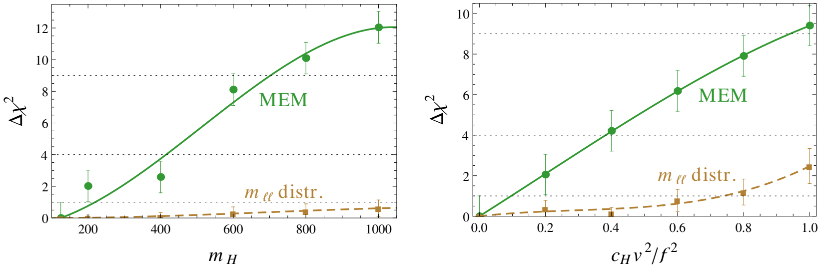


- Might allow to relax jet vetoes: gain for high pile-up!

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 possibility for gain of sensitivity

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

Classification of approaches

- Switch diff. operator bases (dep. on vertex): Snowmass EW White Paper

for the WWWW-Vertex:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8}$$

$$\alpha_4 + 2\cdot\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$$

for the WWZZ-Vertex:

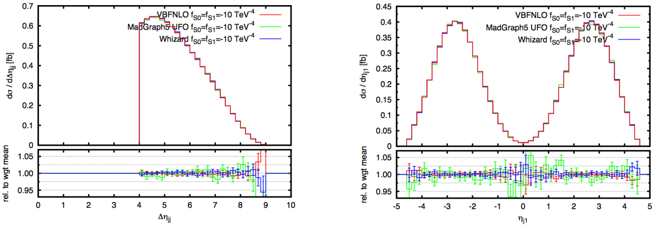
$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{16}$$

$$\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{16}$$

for the ZZZZ-Vertex:

$$\alpha_4 + \alpha_5 = \left(\frac{f_{S,0}}{\Lambda^4} + \frac{f_{S,1}}{\Lambda^4}\right)\frac{v^4}{16}$$

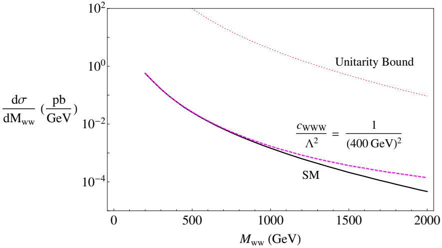
- Full agreement among generators: VBF@NLO, WHIZARD, Madgraph



Classification of approaches

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

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



- 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

Unique way of operator assignment?

- Usage of different measurements: $W\gamma$, WZ production: $WW\gamma$ vs. WWZ
- VVV and VBS to access the highest possible energies

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- Incoherent sum of channels at LHC prevent eliminating operators!
- Similar to B physics: observables process [decay] specific

(Integrating out) Resonances

Operator coefficients $\Rightarrow$ new physics scale Λ: $\alpha_i = v^k/\Lambda^k$

- Operator normalization is arbitrary
- Power counting can be intricate

New physics in electroweak sector:

- 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

- Simplest example: scalar singlet σ:

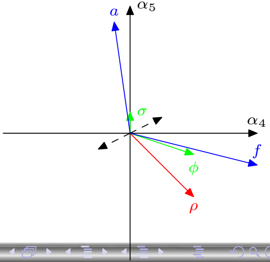
$$\mathcal{L}_\sigma = -\frac{1}{2}\left[\sigma(M_\sigma^2+\partial^2)\sigma - g_\sigma v \sigma \operatorname{tr}[\mathbf{V}_\mu \mathbf{V}^\mu] - h_\sigma \operatorname{tr}[\mathbf{T}\mathbf{V}_\mu]\operatorname{tr}[\mathbf{T}\mathbf{V}^\mu]\right]$$

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

- leads to anomalous quartic couplings (aQGCs)

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

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



Unitarity of Amplitudes

UV-incomplete theories could violate unitarity

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

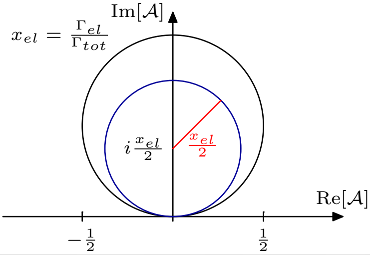
Optical Theorem (Unitarity of the S(cattering) Matrix):

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

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:

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



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 ($\mathcal{A}_{I,\text{spin}=J}$):

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

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

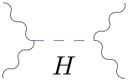
exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

$$I = 0: \qquad E \sim \sqrt{8\pi} v = 1.2\,\text{TeV}$$

$$I = 1: \qquad E \sim \sqrt{48\pi} v = 3.5\,\text{TeV}$$

$$I = 2: \qquad E \sim \sqrt{16\pi} v = 1.7\,\text{TeV}$$

Higgs exchange:

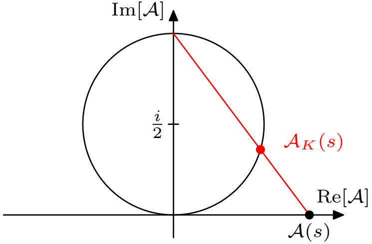


$$\mathcal{A}(s,t,u) = -\frac{M_H^2}{v^2} \frac{s}{s - M_H^2}$$

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

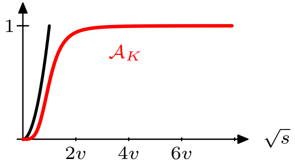
K-Matrix Unitarization and friends

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: $|\mathcal{A}(s)|^2 = \frac{s^2}{s^2+v^4} \overset{s\to\infty}{\to} 1$
- 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

Form factors

Modification of vertices:

$$\mathcal{A}_F(s) = \mathcal{A}(s) \cdot \left(1 + \frac{s}{\text{"}\Lambda\text{"}}\right)^{-p/2}$$

understood as resummed amplitude damps high-energy tails

VBS Simplified Models (I)

Alboteanu et al., 0806.4145; JRR/Kilian/Sekulla, 1307.8170; 1310.xxxx

Assumptions:

- LHC is in discovery reach of new physics
- Parameterize new physics by spin and mass
- Describe resonance physics by amplitude as correct as possible
- Use K-matrix unitarization to define a consistent model

Example: Scalar Singlet

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

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

VBS Simplified Models (II): Unitarized Resonances

Alboteanu et al., 2008; JRR et al., '13

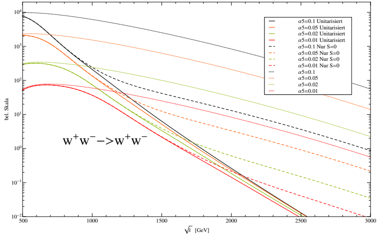
- Partial wave coefficients no longer polynomial:

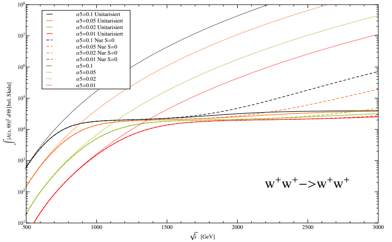
$$\mathcal{S}_0(s) = M^2 - \frac{s}{2} + \frac{M^4}{s} \log \frac{s}{s + M^2}$$

- Amplitudes and s-channel pole unitarized on same footing

$$A_{IJ}(s) = A_{IJ}^{(SM)}(s) + \Delta A_{IJ}^{(SM)}(s) \qquad \Delta A_{IJ}^{(SM)}(s) = F_{IJ}(s) + \frac{R_{IJ}(s)}{s - M^2}$$

- Include full SM + aTGCs + aQGCs (+ a HC)!





- Ongoing theoretical study

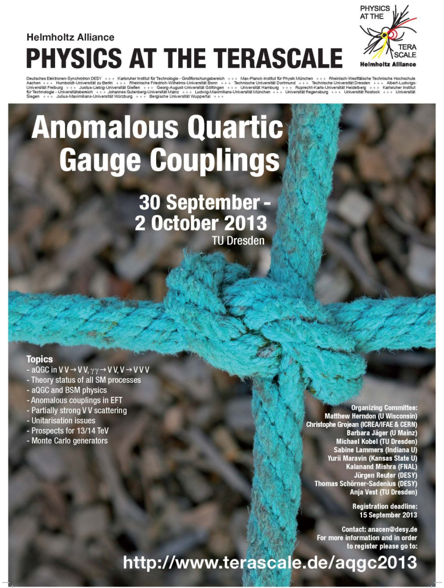
Kilian/JRR/Sekulla, 2013

- Very preliminary results

Summary/Conclusions

- SM deviations 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
- VBS Simplified Models: EFT approach for low-energy regime, unitarized by form factors in resonance scheme at high energies
- interpreted as resonances coupled to EW bosons
- Approach includes/generalizes standard EFT ansatz
- Issue of unitarity (PDFs help – but kill energy reach)
- Photon-induced processes: better sensitivity, but higher constraints!
- Sensitivity rises with number of intermediate states:
  - LHC sensitivity limited in pure EW sector: $\sim 1 - X$ TeV (???)
  - ILC : $1.5 - 6$ TeV
- Theory community is working hard on that!

AQGC Workshop Dresden 30.9.-2.10.2013



Backup Slides:

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: $s = (p_1 + p2)^2 \quad t = (p1 - p3)^2 \quad u = (p1 - p4)^2$

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

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

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

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

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

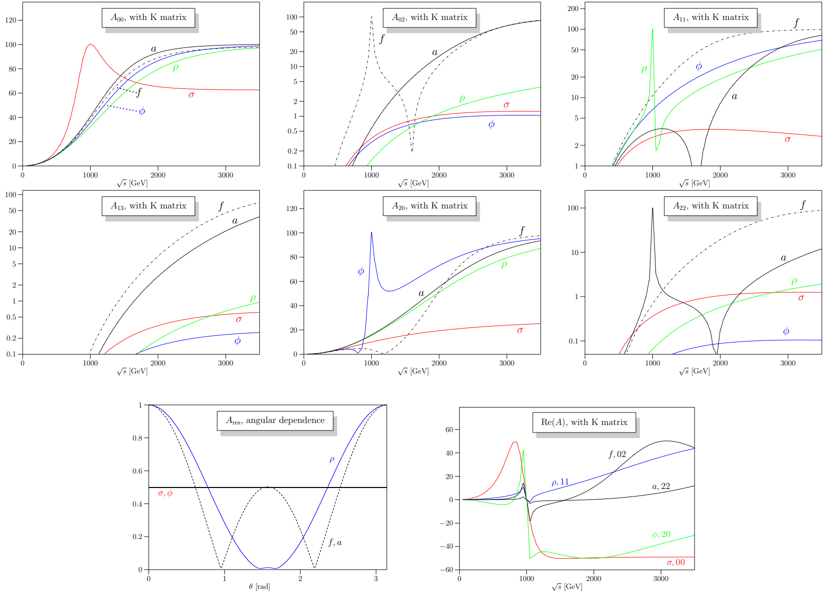
- (Clebsch-Gordan) Decomposition into isospin eigenamplitudes

$$\mathcal{A}(I=0) = 3\mathcal{A}(s,t,u) + \mathcal{A}(t,s,u) + \mathcal{A}(u,s,t)$$

$$\mathcal{A}(I=1) = \mathcal{A}(t,s,u) - \mathcal{A}(u,s,t)$$

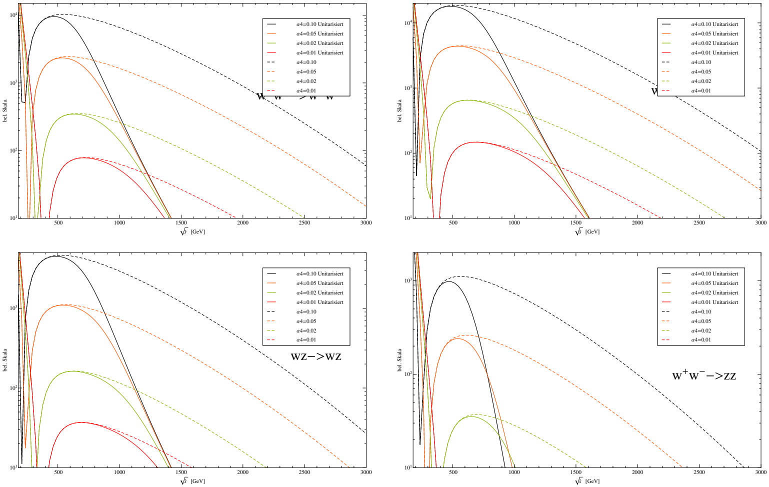
$$\mathcal{A}(I=2) = \mathcal{A}(t,s,u) + \mathcal{A}(u,s,t)$$

Eigenamplitudes



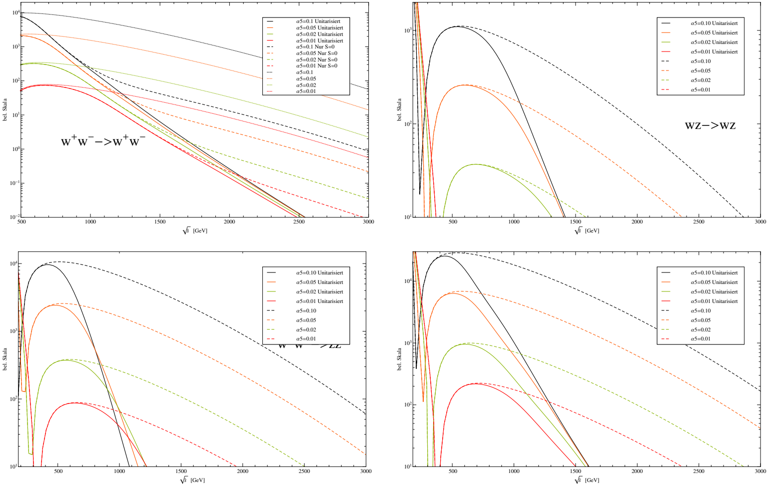
aQGCs: α_4

Kilian/JRR/Sekulla, 2013

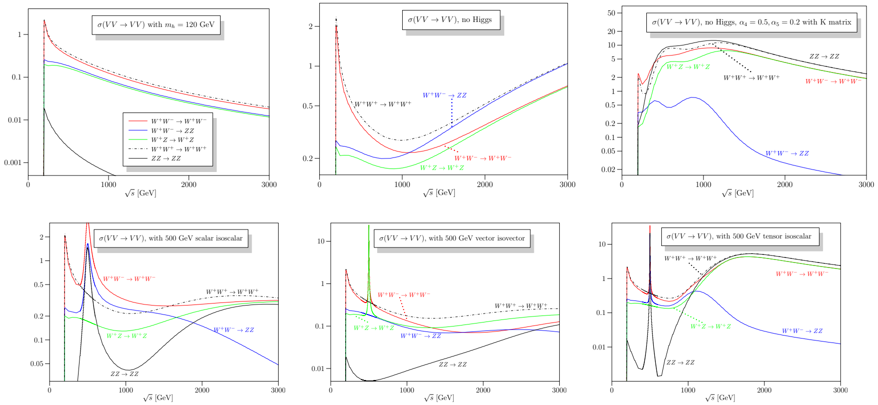


aQGCs: α_5

Kilian/JRR/Sekulla, 2013



“Partonic” cross sections

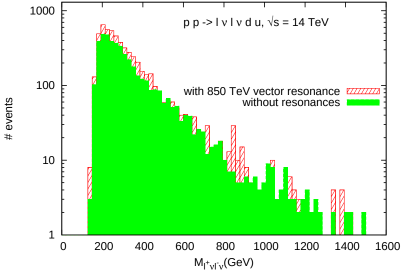


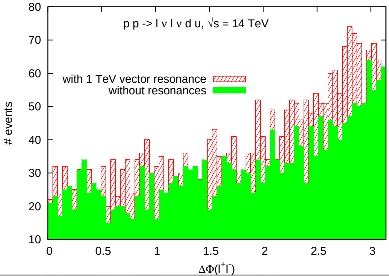
- $\sigma(\mathcal{VV} \to \mathcal{VV})$ in nb $\qquad M_R = 500$ GeV
- all amplitudes K-matrix unitarized
- Cut of 15° around the beam axis

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
  - $|\delta R(\ell\nu)| < 1.5$
  - $\theta(u/d) > 0.5°$
- 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

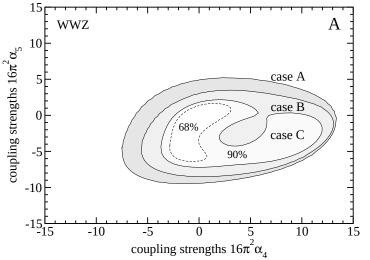




Backup: ILC example: Triboson production

$e^+e^- \to WWZ/ZZZ$, 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

$1\,\text{TeV}$, $1\,\text{ab}^{-1}$, 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

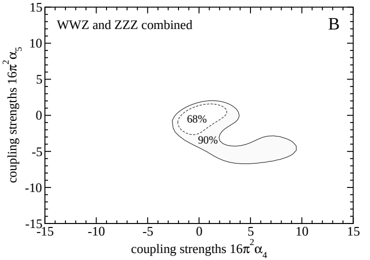
Veto against $E^2_{\text{mis}} + p^2_{\perp,\text{mis}}$

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

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