Composite Vectors at the LHC

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Based on: R. Barbieri, A. E. Cárcamo Hernández, G. Corcella, R. Torre and E. Trincherini, JHEP **3** (2010)068

Introduction

There are two pictures of the Electroweak symmetry breaking:

- Weakly coupled, as supersymmetric extensions of the SM.
- Strongly coupled, as composite Higgs, Higgs as a PGB, Strongly Interacting Light Higgs, composite vectors, 5D Higgless models.

The lack of experimental evidence of the Higgs boson together with the hierarchy problem provides a plausible motivation for considering physics beyond the SM.

The electroweak symmetry breaking without the Higgs can be formulated in terms of the EW chiral Lagrangian [4]:

$$\mathcal{L}_{\chi}^{(2)} = \frac{v^2}{4}\mathrm{Tr}\left(D_{\mu}U^{\dagger}D_{\mu}U\right) \ , \tag{1}$$

where:

$$U = e^{2i\hat{\pi}/v}, \qquad \hat{\pi} = T^a\pi^a = \frac{1}{\sqrt{2}}\left[\begin{array}{cc} \frac{\pi^0}{\sqrt{2}} & \pi^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} \end{array}\right] \ , \qquad U \to g_L U g_R \ .$$

$$D_{\mu}U = \partial_{\mu}U - iB_{\mu}U + iUW_{\mu} \, , \qquad W_{\mu} = \frac{g}{2}\tau^a W_{\mu}^a \, , \qquad B_{\mu} = \frac{g'}{2}\tau^3 B_{\mu}^0 \, ,$$

The previous formulation implies that the electroweak symmetry is broken because of an underlying spontaneous breaking of a global symmetry, so that one has the following breaking patterns of global and local symmetries, respectively:

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to SU(2)_{L+R} \times U(1)_{B-L} \tag{2}$$

$$SU(2)_L \times U(1)_Y \to U(1)_Q \tag{3}$$

The effective Lagrangian

$$\mathcal{L}_{\text{eff}}^{\text{Univ}} = \mathcal{L}_{\text{gauge}}^{\text{SM}} + \frac{v^2}{4}\text{Tr}\left(D_\mu U^\dagger D_\mu U\right) - \frac{v}{\sqrt{2}}\sum_{i,j}\left(\bar{u}_L^{(i)} d_L^{(i)}\right) U \begin{pmatrix} \lambda_{ij}^u \, u_R^{(j)} \\ \lambda_{ij}^d \, d_R^{(j)} \end{pmatrix} + h.c. \tag{4}$$

provides an excellent description of particle physics, beyond the tree level, at energies below the ultraviolet cut-off:

$$\Lambda_\chi = 4\pi v \approx 3 \text{ TeV} \tag{5}$$

However, there are two problems [4]:

- the violation of unitary in WW scattering, if evaluated at the tree-level with $\mathcal{L}_{\text{eff}}^{\text{Univ}}$.
- the bad agreement with data of the electroweak observables S and T, if evaluated at the one-loop level with $\mathcal{L}_{\text{eff}}^{\text{Univ}}$, using Λ_χ as ultraviolet cut-off.

These problems point toward the existence of new degrees of freedom below the cut-off. This motivates the introduction of heavy vectors fields in the EW Chiral Lagrangian.

Effective Chiral Lagrangian with massive spin one fields.

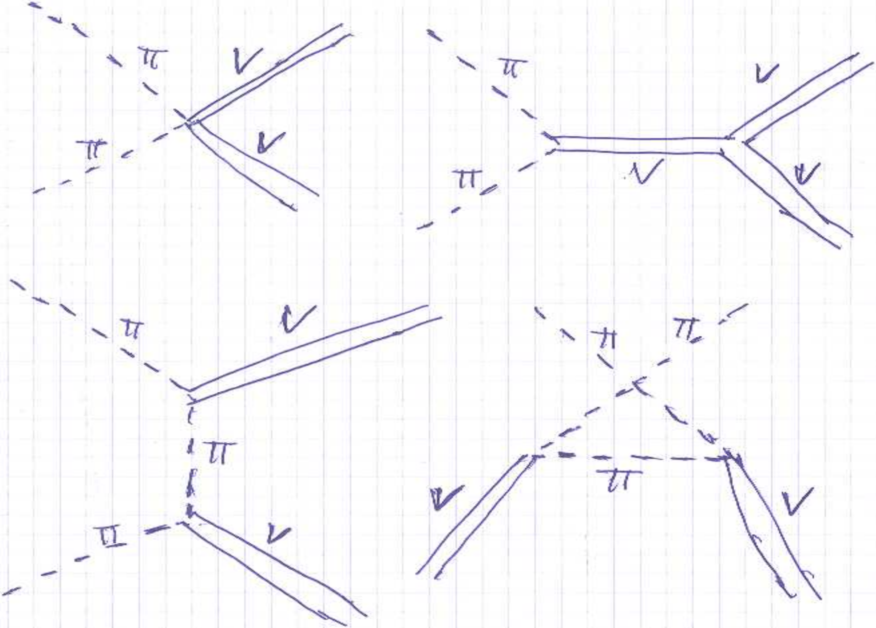
$$\begin{aligned}
\mathcal{L}^V &= \frac{v^2}{4}\left\langle D_\mu U \left(D^\mu U\right)^\dagger \right\rangle - \frac{1}{2g^2}\left\langle W_{\mu\nu}W^{\mu\nu}\right\rangle - \frac{1}{2g'^2}\left\langle B_{\mu\nu}B^{\mu\nu}\right\rangle \\
&-\frac{1}{4}\left\langle \hat{V}^{\mu\nu}\hat{V}_{\mu\nu}\right\rangle + \frac{M_V^2}{2}\left\langle V^\mu V_\mu\right\rangle - \frac{ig_V}{2\sqrt{2}}\left\langle \hat{V}^{\mu\nu}[u_\mu, u_\nu]\right\rangle \\
&-\frac{f_V}{2\sqrt{2}}\left\langle \hat{V}^{\mu\nu}\left(uW_{\mu\nu}u^\dagger + u^\dagger B_{\mu\nu}u\right)\right\rangle + \frac{ig_K}{2\sqrt{2}}\left\langle \hat{V}_{\mu\nu}V^\mu V^\nu\right\rangle \\
&+g_1\left\langle V_\mu V^\mu u^\alpha u_\alpha\right\rangle + g_2\left\langle V_\mu u^\alpha V^\mu u_\alpha\right\rangle + g_3\left\langle V_\mu V_\nu[u^\mu, u^\nu]\right\rangle \\
&+g_4\left\langle V_\mu V_\nu\{u^\mu, u^\nu\}\right\rangle + g_5\left\langle V_\mu\left(u^\mu V_\nu u^\nu + u^\nu V_\nu u^\mu\right)\right\rangle \\
&+ig_6\left\langle V_\mu V_\nu\left(uW^{\mu\nu}u^\dagger + u^\dagger B^{\mu\nu}u\right)\right\rangle \qquad (6)
\end{aligned}$$

$$U(x) = e^{i\hat{\pi}(x)/v}, \qquad \hat{\pi}(x) = \tau^a\pi^a = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}, \quad u \equiv \sqrt{U}$$

$$D_\mu U = \partial_\mu U - iB_\mu U + iUW_\mu, \qquad W_\mu = \tfrac{g}{2}\tau^a W_\mu^a, \qquad B_\mu = \tfrac{g'}{2}\tau^3 B_\mu^0,$$

$$V_\mu = \tfrac{1}{\sqrt{2}}\tau^a V_\mu^a, \qquad \hat{V}_{\mu\nu} = \nabla_\mu V_\nu - \nabla_\nu V_\mu, \qquad u_\mu = u_\mu^\dagger = iu^\dagger D_\mu U u^\dagger,$$

$$\nabla_\mu V = \partial_\mu V + [\Gamma_\mu, V], \qquad \Gamma_\mu = \tfrac{1}{2}\left[u^\dagger\left(\partial_\mu - iB_\mu\right)u + u\left(\partial_\mu - iW_\mu\right)u^\dagger\right]$$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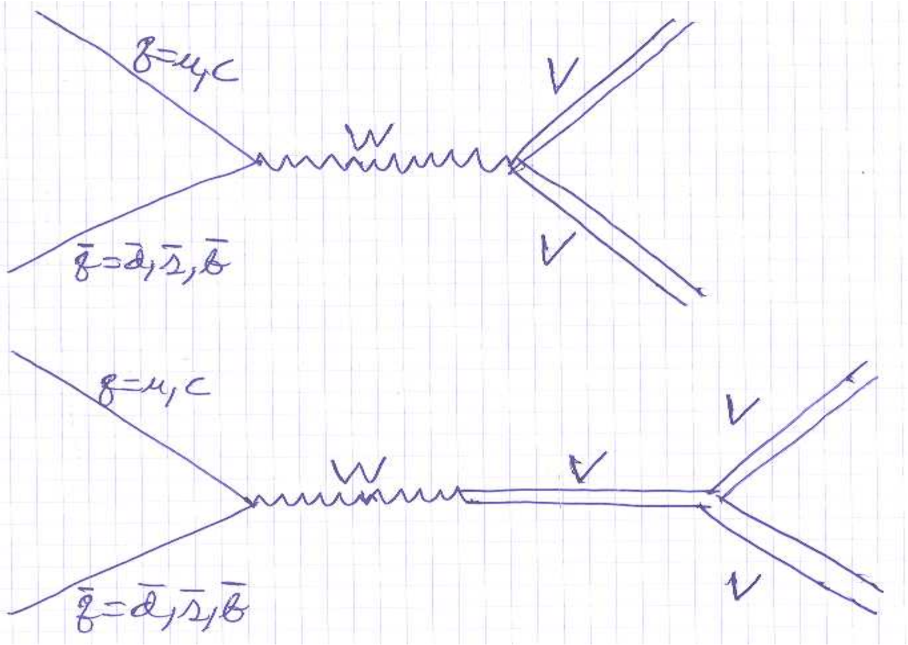
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The various amplitudes have the following asymptotic behaviour:

$$A\left(W_L W_L \rightarrow V_L V_L\right) \sim \frac{s^2}{v^2 M_V^2}, \qquad A\left(W_L W_L \rightarrow V_L V_T\right) \sim \frac{s^{\frac{3}{2}}}{v^2 M_V} \tag{7}$$

$$A\left(q\overline{q} \rightarrow VV\right) \sim \frac{s}{M_V^2}, \qquad \text{with a small coefficient} \tag{8}$$

The scattering amplitudes for the processes $W_L W_L \rightarrow V_L V_L$ and $W_L W_L \rightarrow V_L V_T$ will grow at most as $\frac{s}{v^2}$ and the $q\overline{q} \rightarrow VV$ scattering amplitude will go as a constant only when [1]:

$$g_K = \frac{1}{g_V}, \qquad f_V = 2g_V, \qquad g_3 = -\frac{1}{4} \tag{9}$$

$$g_1 = g_2 = g_4 = g_5 = 0, \qquad g_6 = \frac{1}{2} \tag{10}$$

which corresponds to the Gauge Model Scenario $(SU(2)_L \times SU(2)_C \times SU(2)_R \rightarrow SU(2)_{L+R+C})$.

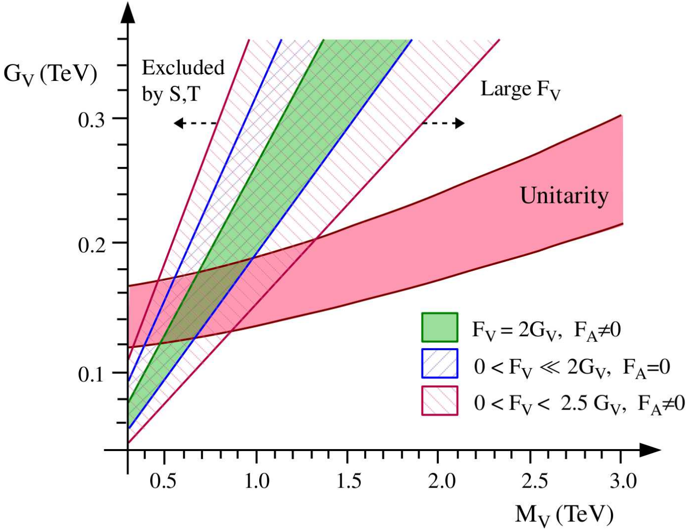
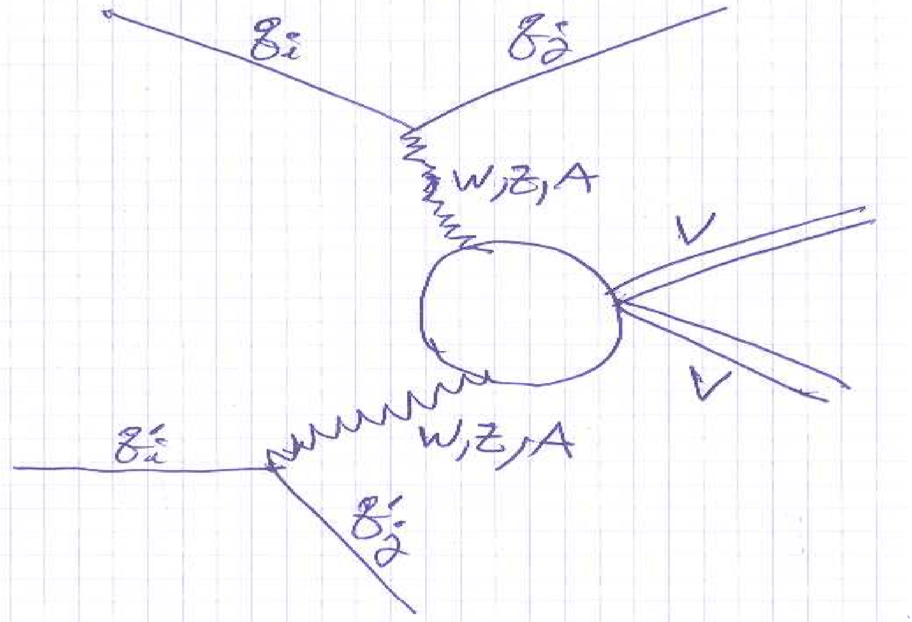


Figure 1: Summary of unitarity and EWPO constraints (at 95% C.L.) in the (M_V, G_V) plane from Barbieri, Isidori, Rychkov and Trincherini, '08.

Pair production cross section by Vector Boson Fusion.



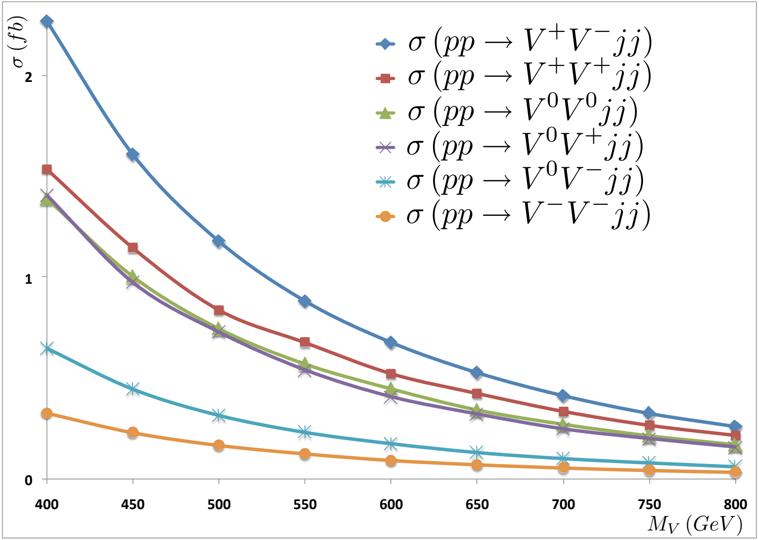


Figure 1: Total cross section at LHC for pair production of heavy vectors via vector boson fusion in a gauge model as a function of the heavy vector masses. Barbieri, Carcamo, Corcella,Torre, Trincherini, JHEP 3 (2010)068.

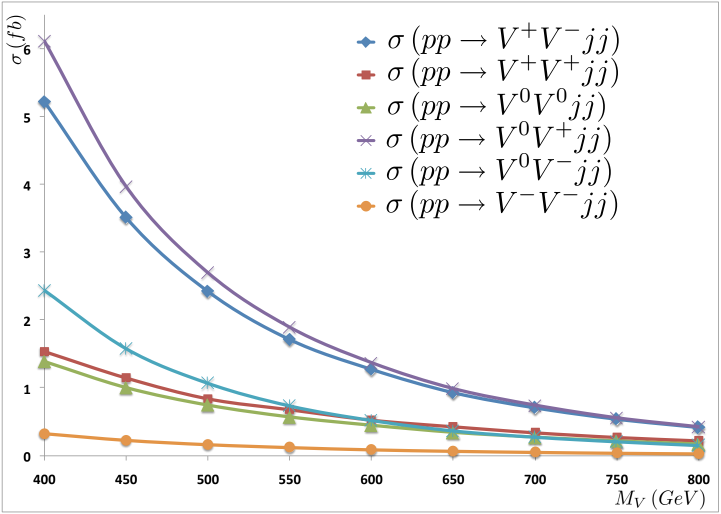


Figure 2: Total cross section at LHC for pair production of heavy vectors via vector boson fusion in a composite model as a function of the heavy vector masses. In the composite model all the parameter are kept as in the Gauge Model except for $g_K g_V = 1/\sqrt{2}$ rather than 1. Barbieri, Carcamo, Corcella, Torre, Trincherini, JHEP 3 (2010)068.

Drell Yan Pair production cross sections.

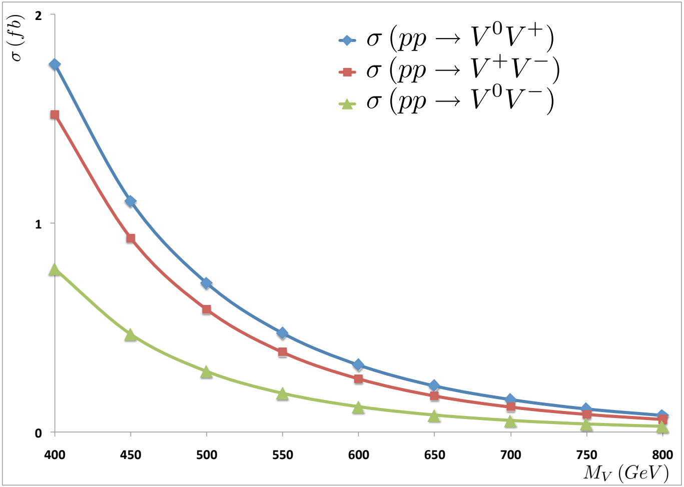


Figure 3: Total cross section at LHC for pair production of heavy vectors via Drell–Yan $q\bar{q}$ annihilation in a gauge model as a function of the heavy vector masses. Barbieri, Carcamo, Corcella,Torre, Trincherini, JHEP 3 (2010)068.

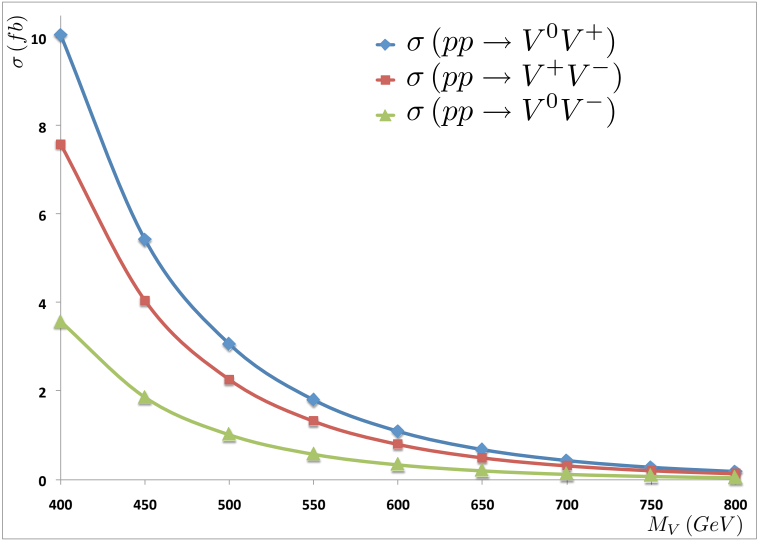


Figure 4: Total cross section at LHC for pair production of heavy vectors via Drell–Yan $q\bar{q}$ annihilation in a composite model as a function of the heavy vector masses. Barbieri, Carcamo, Corcella,Torre, Trincherini, JHEP 3 (2010)068.

Same-sign di-lepton and tri-lepton events.

Since the heavy vector have dominant decay mode into pair of SM Gauge bosons (with branching ratio very close to one), the vector pair production by VBF and DY will lead to 4 SM gauge bosons in the final state. The following Tables show the Cumulative branching ratios and the number of events at LHC with at least two same-sign leptons or three leptons (e or μ from W decays [1]. The heavy vector mass is taken to be $M_V = 500$ GeV.

	di-leptons(%)	tri-leptons(%)
V^0V^0	8.9	3.2
$V^{\pm}V^{\pm}$	4.5	-
$V^{\pm}V^0$	4.5	1.0

	di-leptons	tri-leptons
VBF (Gauge Model)	16	3
DY (Gauge Model)	5	1
VBF (Composite Model)	28	6
DY (Composite Model)	18	4

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- The phenomenology of the EWSB by unspecified strong dynamics can be described by a $\frac{SU(2)_L \times SU(2)_R}{SU(2)_{L+R}}$ effective Lagrangian which preserves the $SU(2)_L \times U(1)$ gauge invariance with massive spin one fields.

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- If heavy vectors exist with a mass in the $500 - 1000$ GeV range, they will most likely be discovered at LHC in single production or in association with one standard gauge boson.

Acknowledgements

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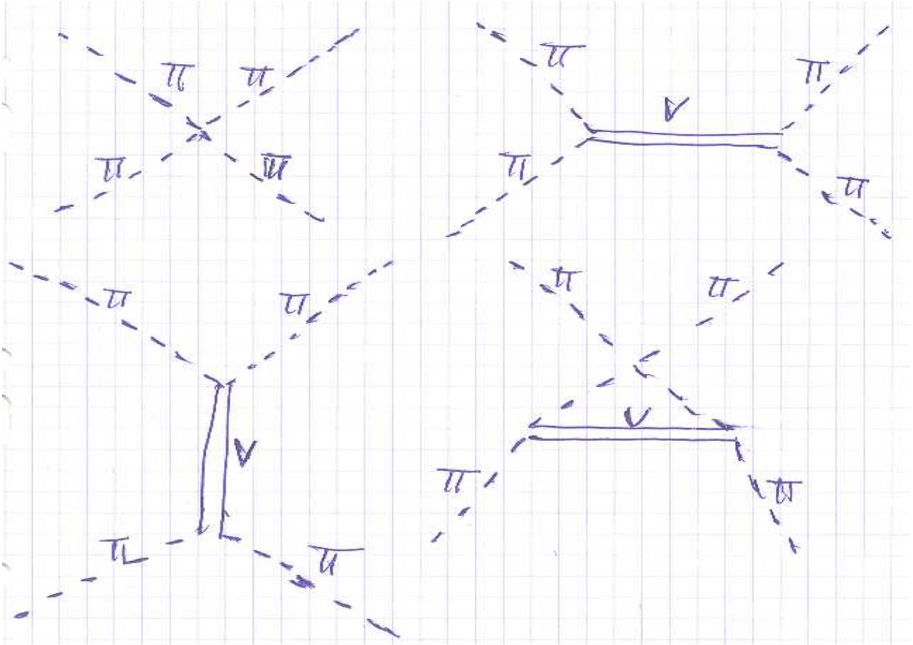
References

- R. Barbieri, A. E. Cárcamo Hernández, G. Corcella, R. Torre and E. Trincherini, JHEP **3** (2010)068.
- R. Barbieri, G. Isidori, V. S. Rychkov and E. Trincherini, Phys. Rev. D **78** (2008) 036012, hep-ph/0806.1624.
- A. E. Cárcamo Hernández, Proceedings of the First Young Researchers Workshop "Physics Challenges in the LHC Era" 2009, Ed. E. Nardi Frascati, May 11th and May 14th, 2009 (http://www.lnf.infn.it/sis/frascatiseries/Volume48/volume48.pdf).
- G. Isidori, hep-ph/0911.3219.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Composite versus gauge models.

Considering the following $SU(2)_L \times SU(2)_C \times SU(2)_R$ Lagrangian [1]:

$$\mathcal{L}_V^{\text{gauge}} = \mathcal{L}_\chi^{\text{gauge}} - \frac{1}{2g_C^2}\left\langle v_{\mu\nu} v^{\mu\nu}\right\rangle - \frac{1}{2g^2}\left\langle W_{\mu\nu} W^{\mu\nu}\right\rangle - \frac{1}{2g'^2}\left\langle B_{\mu\nu} B^{\mu\nu}\right\rangle , \tag{11}$$

where

$$v_\mu = \frac{g_C}{2} v_\mu^a \tau^a \tag{12}$$

is the $SU(2)_C$-gauge vector and the symmetry breaking Lagrangian is described by

$$\mathcal{L}_\chi^{\text{gauge}} = \frac{v^2}{2}\left\langle D_\mu \Sigma_{RC} \left(D^\mu \Sigma_{RC}\right)^\dagger\right\rangle + \frac{v^2}{2}\left\langle D_\mu \Sigma_{CL} \left(D^\mu \Sigma_{CL}\right)^\dagger\right\rangle . \tag{13}$$

Denoting collectively the three gauge vectors by

$$v_\mu^I = (W_\mu, v_\mu, B_\mu), \quad I = (L, C, R), \tag{14}$$

one has for the two bi-fundamental scalars Σ_{IJ}

$$D_\mu \Sigma_{IJ} = \partial_\mu \Sigma_{IJ} - i v_\mu^I \Sigma_{IJ} + i \Sigma_{IJ} v_\mu^J . \tag{15}$$

$\Sigma_{IJ} = \sigma_I \sigma_J^\dagger$, where σ_I are the elements of $SU(2)_I/H$. As the result of a gauge transformation

$$v_\mu^I \to \sigma_I^\dagger v_\mu^I \sigma_I + i\sigma_I^\dagger \partial_\mu \sigma_I \equiv \Omega_\mu^I, \quad \Sigma_{IJ} \to \sigma_I^\dagger \Sigma_{IJ} \sigma_J = 1, \tag{16}$$

and after the gauge fixing $\sigma_R = \sigma_L^+ \equiv u$ and $\sigma_C = 1$, one has

$$\mathcal{L}_\chi^{\text{gauge}} = v^2 \left\langle (v_\mu - i\Gamma_\mu)^2 \right\rangle + \frac{v^2}{4} \left\langle u_\mu^2 \right\rangle, \tag{17}$$

where

$$u_\mu = \Omega_\mu^R - \Omega_\mu^L, \quad \Gamma_\mu = \frac{1}{2i}(\Omega_\mu^R + \Omega_\mu^L), \quad v_\mu = V_\mu + i\Gamma_\mu \tag{18}$$

by use of the identity:

$$v_{\mu\nu} = \hat{V}_{\mu\nu} - i[V_\mu, V_\nu] + \frac{i}{4}[u_\mu, u_\nu] + \frac{1}{2}(uW_{\mu\nu}u^\dagger + u^\dagger B_{\mu\nu} u). \tag{19}$$

With the replacement $V_\mu \to \frac{g_C}{\sqrt{2}} V_\mu$, $\mathcal{L}_V^{gauge}$ coincides with $\mathcal{L}^V$ for

$$g_V = \frac{1}{2g_C} = \frac{1}{g_K}, \quad g_3 = -\frac{1}{4}, \quad g_6 = \frac{1}{2}, \quad f_V = 2g_V \quad M_V = g_C v \tag{20}$$

with $G_V = g_V M_V$.