Composite Vectors and Scalars in Theories of Electroweak Symmetry Breaking

Antonio Enrique Cárcamo Hernández.

Scuola Normale Superiore di Pisa.

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Based on: R. Barbieri, A. E. Cárcamo Hernández, G. Corcella, R. Torre and E. Trincherini, JHEP **3** (2010)068
A. E. Cárcamo Hernández and R. Torre, Nuclear Physics B 841 (2010) 188-204.

The Standard Model

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c²	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^- W bosons	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

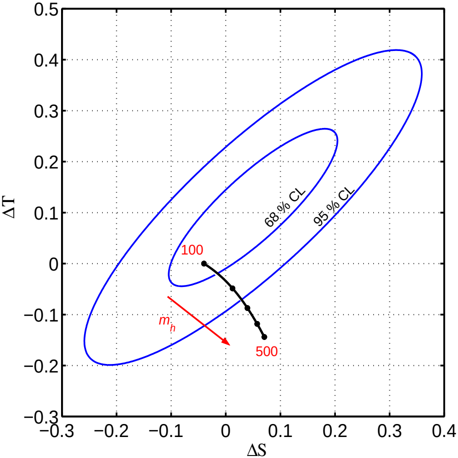
$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\psi$$ The gauge sector

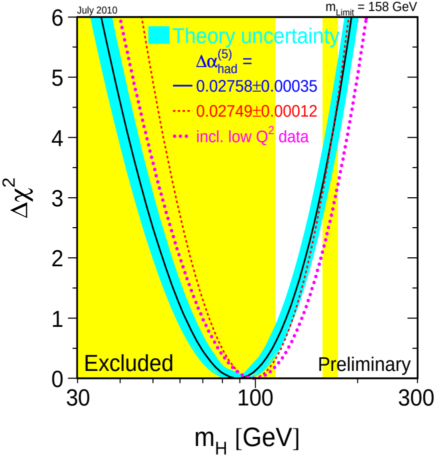
$$+ \psi_i\lambda_{ij}\psi_j h + h.c$$ The flavor sector

$$+ \left|D_\mu h\right|^2 - V(h)$$ The EWSB sector

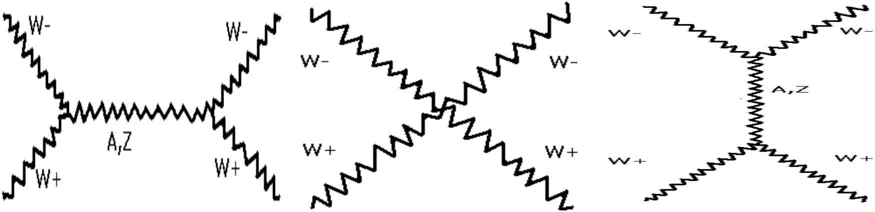
$$+ N_i M_{ij} N_j$$ The ν mass sector (if Majorana)

Role of the Higgs boson in EWPT and WW scattering

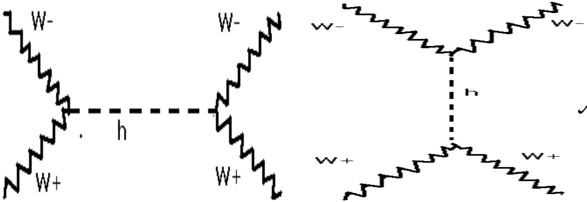




$$T=\frac{\Pi_{33}(0)-\Pi_{WW}(0)}{M_W^2}=\frac{\Pi_{ZZ}(0)}{M_Z^2}-\frac{\Pi_{WW}(0)}{M_W^2},\qquad S=\frac{g}{g'}\left.\frac{d\Pi_{30}\left(q^2\right)}{dq^2}\right|_{q^2=0}$$



$$\mathcal{A}_{Gauge} \simeq g^2 \left(\frac{E}{M_W} \right)^2$$

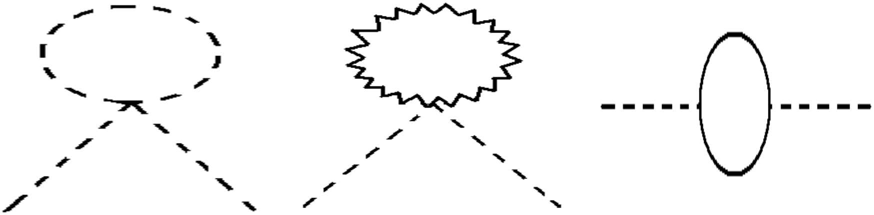


$$\mathcal{A}_{Higgs} \simeq -g^2 \left(\frac{E}{M_W} \right)^2$$

$$\mathcal{A} = \mathcal{A}_{Gauge} + \mathcal{A}_{Higgs} \simeq g^2 \left(\frac{M_H}{2M_W} \right)^2$$

The Higgs boson unitarize the WW scattering provided that $M_H \lesssim 700$ GeV.

Quantum Instability of the Higgs boson mass



$$\int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m^2} \; \alpha \; \Lambda^2 \qquad\qquad \int \frac{d^4k}{(2\pi)^4} \frac{k^2}{(k^2 - m^2)^2} \; \alpha \; \Lambda^2$$

$$m_H^2 \sim \; m_0^2 - (115 GeV)^2 \left(\frac{\Lambda}{400 GeV} \right)^2$$

To have $m_H \approx 100$ GeV for $\Lambda \simeq 10^{19}$ GeV an extreme fine tunning of 34 decimals in the bare squared Higgs boson mass has to be performed. This is the hierarchy problem of the Standard Model.

Two paradigms for Electroweak Symmetry Breaking

There are two pictures of the Electroweak Symmetry Breaking (EWSB):

- Weakly coupled, as the Standard Model (SM), supersymmetric extensions of the SM, Little Higgs, Gauge Higgs Unification models.
- Strongly coupled, as Technicolor, Composite Higgs, Strongly Interacting Light Higgs (SILH), Composite Vectors, Randall-Sundrum (RS) models, Higgsless RS bulk models.

The lack of direct experimental evidence of the Higgs boson together with the hierarchy problem provides a plausible motivation for considering strongly coupled theories of EWSB.

Electroweak Chiral Lagrangian

The EWSB without the Higgs boson can be formulated in terms of the Electroweak Chiral Lagrangian (EWCL) [5]:

$$\mathcal{L}_{SB} = \frac{v^2}{4} \left\langle D_\mu U \left(D^\mu U\right)^\dagger \right\rangle - \frac{v}{\sqrt{2}} \sum_{i,j} \left(\bar{u}_L^{(i)} d_L^{(i)}\right) U \begin{pmatrix} \lambda_{ij}^u u_R^{(j)} \\ \lambda_{ij}^d d_R^{(j)} \end{pmatrix} + h.c\,, \qquad (1)$$

where:

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

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

Under $SU(2)_L \times SU(2)_R$, one has:

$$u \equiv \sqrt{U} \to g_R u h^\dagger = h u g_L^\dagger\,, \qquad U \to g_L U g_R\,, \qquad (2)$$

where $h = h(u, g_L, g_R)$ is an element of $SU(2)_{L+R}$. The local $SU(2)_L \times U(1)_Y$ invariance is now manifest in the Lagrangian (1) with:

$$U \to g_L(x)\, U\, g_Y^\dagger(x)\,, \qquad g_L(x) = \exp\left(i\theta_L^a(x)\tau^a/2\right),$$

$$g_Y(x) = \exp\left(i\theta_Y(x)\tau^3/2\right). \qquad (3)$$

In the unitary gauge $\langle U \rangle = 1$, it is immediate to see that the chiral Lagrangian (1) gives the mass terms for the W and Z gauge bosons with

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1\,. \tag{4}$$

A term like

$$c_3\, v^2 \left\langle T^3 U^\dagger D_\mu U \right\rangle^2 \tag{5}$$

invariant under the local $SU(2)_L \times U(1)_Y$ but not under the global $SU(2)_L \times SU(2)_R$ symmetry is therefore forbidden. Its presence would undo the $\rho = 1$ relation.

The effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{gauge} + \mathcal{L}_{SB}, \qquad \mathcal{L}_{gauge} = -\frac{1}{2g^2} \left\langle W_{\mu\nu} W^{\mu\nu} \right\rangle - \frac{1}{2g'^2} \left\langle B_{\mu\nu} B^{\mu\nu} \right\rangle$$

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

$$\Lambda = 4\pi v \approx 3\ \mathrm{TeV} \tag{6}$$

$$SU(2)_L \times U(1)_Y \to U(1)_Q$$

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

The EWCL suffers, however, of two main problems [5]:

- The violation of unitarity in WW scattering, evaluated at the tree-level, below the cutoff Λ. This is due to the fact that $\mathcal{A}(W_L W_L \to W_L W_L) \approx \frac{s}{v^2}$ and $\mathcal{A}(W_L W_L \to f\bar{f}) \approx \frac{m_f \sqrt{s}}{v^2}$.
- The inconsistency of the electroweak observables S and T when compared with the experimental data if evaluated at the one-loop level with Λ as ultraviolet cutoff.

These problems point toward the existence of new degrees of freedom below the cutoff. This motivates the introduction of new composite particles such as composite scalars and composite vectors in the EWCL.

Effective Lagrangian

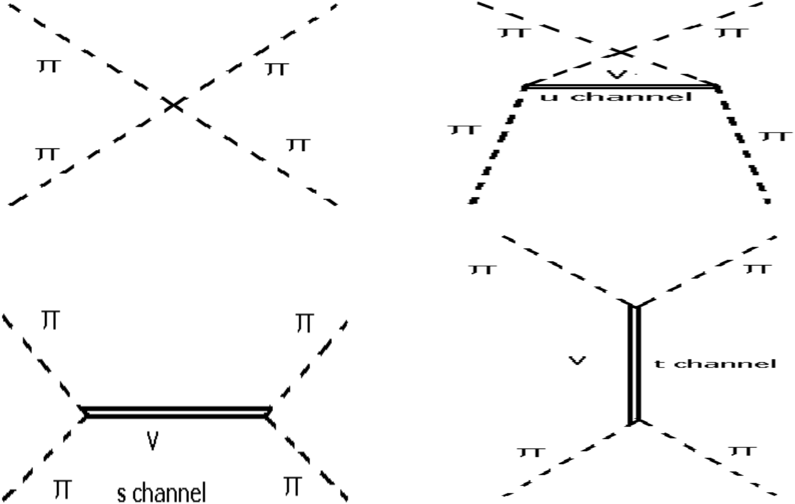
$$
\begin{aligned}
\mathcal{L} \;=\;& \frac{v^2}{4}\left\langle D_\mu U\left(D^\mu U\right)^\dagger\right\rangle - \frac{1}{2g^2}\left\langle W_{\mu\nu}W^{\mu\nu}\right\rangle - \frac{1}{2g'^2}\left\langle B_{\mu\nu}B^{\mu\nu}\right\rangle \\
& -\frac{1}{4}\left\langle \hat{V}^{\mu\nu}\hat{V}_{\mu\nu}\right\rangle + \frac{M_V^2}{2}\left\langle V^\mu V_\mu\right\rangle - \frac{ig_V}{2\sqrt{2}}\left\langle \hat{V}^{\mu\nu}[u_\mu, u_\nu]\right\rangle \\
& -\frac{f_V}{2\sqrt{2}}\left\langle \hat{V}^{\mu\nu}\left(uW_{\mu\nu}u^\dagger + u^\dagger B_{\mu\nu}u\right)\right\rangle + \frac{ig_K}{2\sqrt{2}}\left\langle \hat{V}_{\mu\nu}V^\mu V^\nu\right\rangle \\
& +g_1\left\langle V_\mu V^\mu u^\alpha u_\alpha\right\rangle + g_2\left\langle V_\mu u^\alpha V^\mu u_\alpha\right\rangle + g_3\left\langle V_\mu V_\nu[u^\mu, u^\nu]\right\rangle \\
& +g_4\left\langle V_\mu V_\nu\{u^\mu, u^\nu\}\right\rangle + g_5\left\langle V_\mu\left(u^\mu V_\nu u^\nu + u^\nu V_\nu u^\mu\right)\right\rangle \\
& +ig_6\left\langle V_\mu V_\nu\left(uW^{\mu\nu}u^\dagger + u^\dagger B^{\mu\nu}u\right)\right\rangle + \frac{g_V^2}{8}\left\langle [u^\mu, u^\nu]\left[u_\mu, u_\nu\right]\right\rangle
\end{aligned}
\tag{7}
$$

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

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

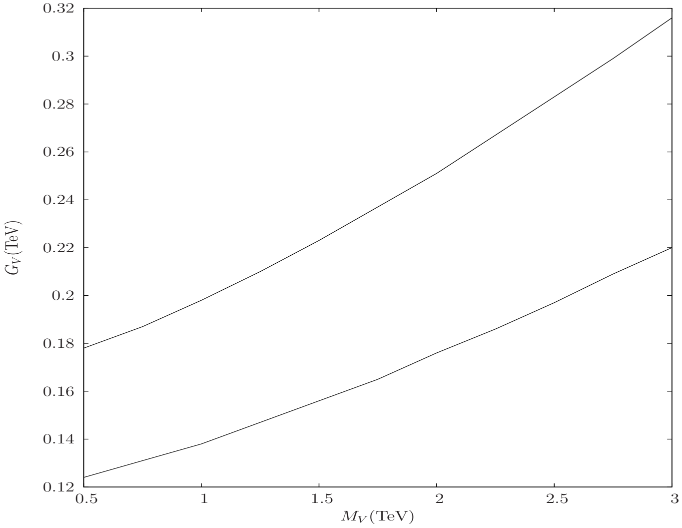
$$
V_\mu = \frac{1}{\sqrt{2}}\tau^a V_\mu^a, \qquad \hat{V}_{\mu\nu} = \nabla_\mu V_\nu - \nabla_\nu V_\mu, \qquad u_\mu = u_\mu^\dagger = iu^\dagger D_\mu U u^\dagger,
$$

$$
\nabla_\mu V = \partial_\mu V + [\Gamma_\mu, V], \qquad \Gamma_\mu = \frac{1}{2}\left[u^\dagger\left(\partial_\mu - iB_\mu\right)u + u\left(\partial_\mu - iW_\mu\right)u^\dagger\right]
$$



$$A(s,t,u) = \frac{s}{v^2} - \frac{G_V^2}{v^4}\left[3s + M_V^2\left(\frac{s-u}{t-M_V^2} + \frac{s-t}{u-M_V^2}\right)\right]$$

where we have set $g_V M_V = G_V$.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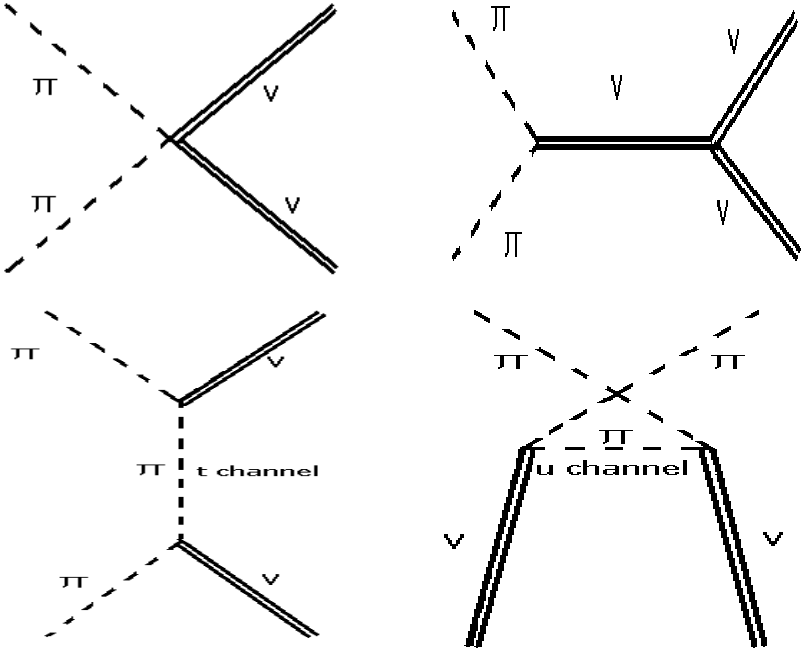
M_V(TeV)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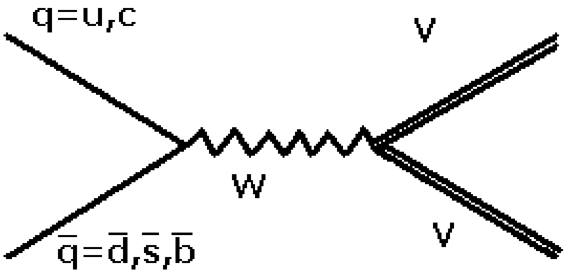
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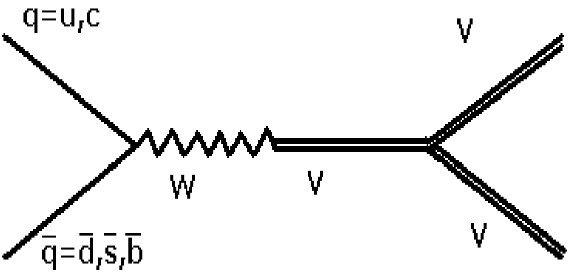
q̄=d̄,s̄,b̄


q=u,c
V
W
V
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q̄=d̄,s̄,b̄

The various amplitudes have the following asymptotic behaviour:

$$A\left(W_L W_L \to V_L V_L\right) \sim \frac{s^2}{v^2 M_V^2}, \qquad A\left(W_L W_L \to V_L V_T\right) \sim \frac{s^{\frac{3}{2}}}{v^2 M_V} \quad (8)$$

$$A\left(q\overline{q} \to VV\right) \sim \frac{s}{M_V^2}, \qquad \text{with a small coefficient} \quad (9)$$

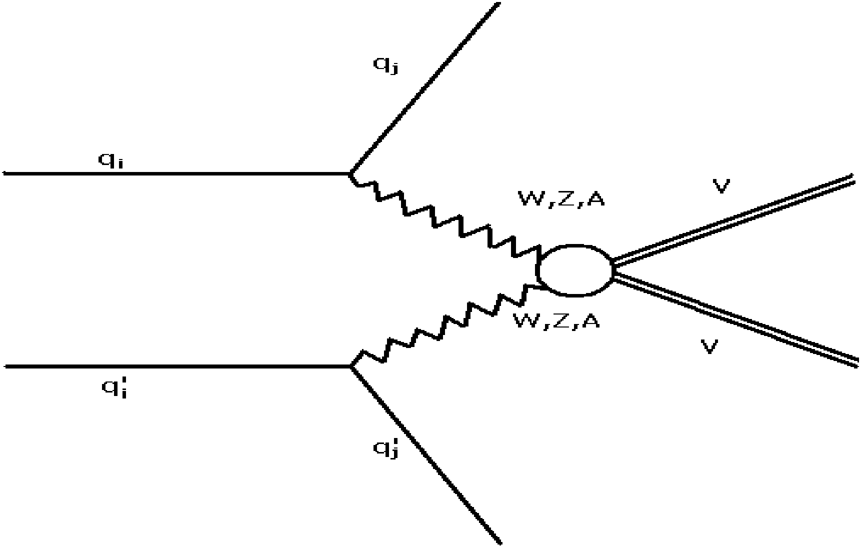
The scattering amplitudes for the processes $W_L W_L \to V_L V_L$ and $W_L W_L \to V_L V_T$ will grow at most as $\frac{s}{v^2}$ and the $q\overline{q} \to VV$ scattering amplitude will go as a constant only when [1]:

$$g_K = \frac{1}{g_V}, \qquad f_V = 2g_V, \qquad g_3 = -\frac{1}{4} \quad (10)$$

$$g_1 = g_2 = g_4 = g_5 = 0, \qquad g_6 = \frac{1}{2} \quad (11)$$

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

Pair production cross section by Vector Boson Fusion



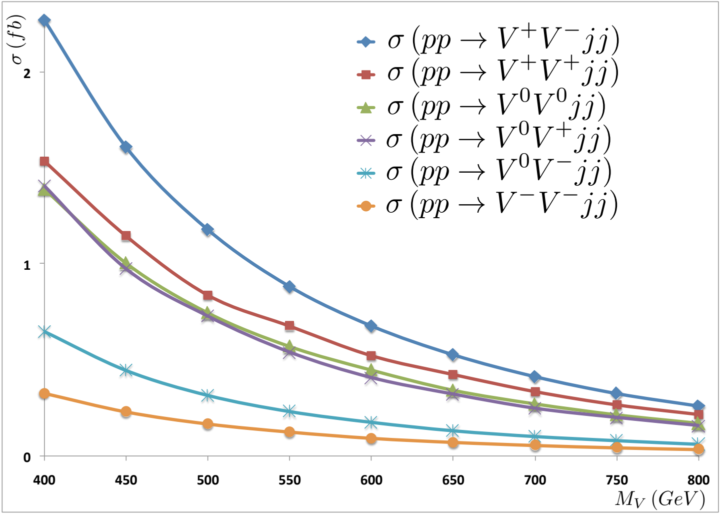


Figure 2: Total cross section at the LHC for pair production of heavy vectors via vector boson fusion in a Gauge Model as a function of the heavy vector masses at $\sqrt{S} = 14$ TeV. The acceptance cuts $p_{Tj} > 30$ GeV and $|\eta| < 5$ for the forward quark jets have been imposed. R. Barbieri, A. E. Cárcamo Hernández, G. Corcella, R. Torre, E. Trincherini, JHEP 3 (2010)068.

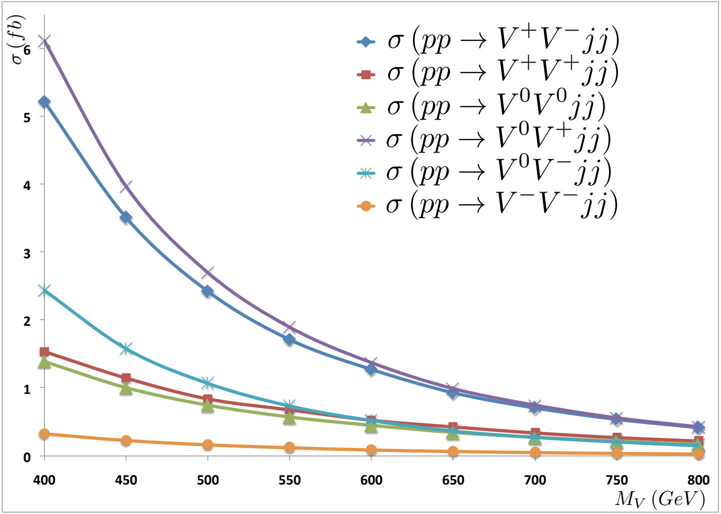


Figure 3: Total cross section at the LHC for pair production of heavy vectors via vector boson fusion in a composite model as a function of the heavy vector masses at $\sqrt{S} = 14$ TeV, $p_{T\,j} > 30$ GeV and $|\eta| < 5$. Here all the parameters are kept as in the Gauge Model except for $g_K g_V = 1/\sqrt{2}$ rather than 1. R. Barbieri, A. E. Cárcamo Hernández, G. Corcella, R. Torre, E. Trincherini, JHEP 3 (2010)068.

Drell Yan Pair production cross sections

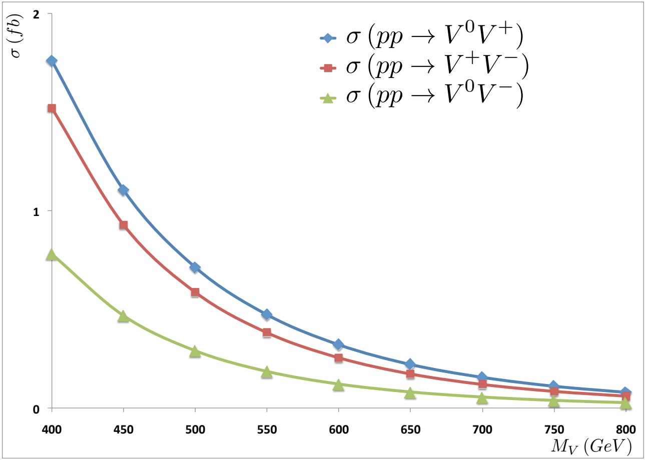


Figure 4: Total cross section at the LHC for pair production of heavy vectors via Drell–Yan $q\bar{q}$ annihilation in a gauge model as a function of the heavy vector masses at $\sqrt{S} = 14$ TeV. R. Barbieri, A. E. Cárcamo Hernández, G. Corcella, R. Torre, E. Trincherini, JHEP 3 (2010)068.

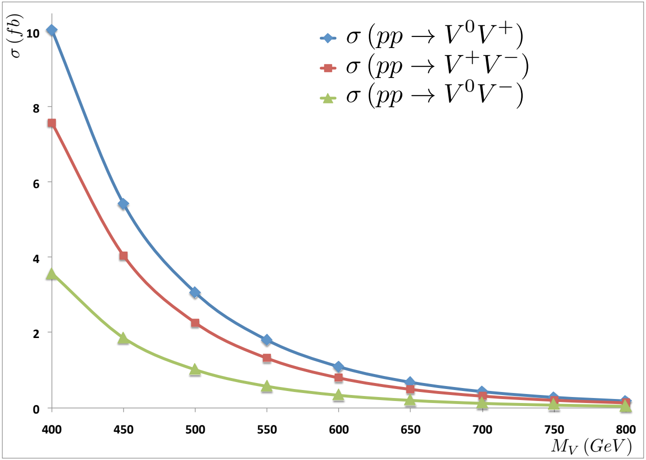


Figure 5: Total cross section at the LHC for pair production of heavy vectors via Drell-Yan $q\bar{q}$ annihilation in a composite model as a function of the heavy vector masses at $\sqrt{S} = 14$ TeV. R. Barbieri, A. E. Cárcamo Hernández, G. Corcella, R. Torre, E. Trincherini, JHEP 3 (2010)068.

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 for $\int \mathcal{L} dt = 100\ \text{fb}^{-1}$ 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(%)
$V^0 V^0$	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

The basic Lagrangian

The $\frac{SU(2)_L \times SU(2)_R}{SU(2)_{L+R}}$ Chiral Lagrangian with vector and scalar resonances is:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_\chi + \mathcal{L}^V + \mathcal{L}_h + \mathcal{L}_{h-V}, \tag{12}$$

where:

$$\mathcal{L}_\chi = \frac{v^2}{4}\left\langle D_\mu U \left(D^\mu U\right)^\dagger\right\rangle - \frac{1}{2g^2}\left\langle W_{\mu\nu}W^{\mu\nu}\right\rangle - \frac{1}{2g'^2}\left\langle B_{\mu\nu}B^{\mu\nu}\right\rangle , \tag{13}$$

$$\begin{aligned}
\mathcal{L}^V \quad = \quad & -\frac{1}{4}\left\langle \hat{V}^{\mu\nu}\hat{V}_{\mu\nu}\right\rangle + \frac{M_V^2}{2}\left\langle V^\mu V_\mu\right\rangle - \frac{ig_V}{2\sqrt{2}}\left\langle \hat{V}_{\mu\nu}[u^\mu, u^\nu]\right\rangle \qquad (14)\\
& -\frac{g_V}{\sqrt{2}}\left\langle \hat{V}_{\mu\nu}\left(uW^{\mu\nu}u^\dagger + u^\dagger B^{\mu\nu}u\right)\right\rangle - \frac{1}{8}\left\langle [V_\mu, V_\nu][u^\mu, u^\nu]\right\rangle \\
& +\frac{i}{2}\left\langle V_\mu V_\nu\left(uW^{\mu\nu}u^\dagger + u^\dagger B^{\mu\nu}u\right)\right\rangle + \frac{ig_K}{4\sqrt{2}}\left\langle \hat{V}_{\mu\nu}[V^\mu, V^\nu]\right\rangle \\
& +\frac{g_V^2}{8}\left\langle [u_\mu, u_\nu][u^\mu, u^\nu]\right\rangle , \qquad (15)
\end{aligned}$$

$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{m_h^2}{2}h^2 + \frac{v^2}{4}\left\langle D_\mu U \left(D^\mu U\right)^\dagger\right\rangle \left(2a\frac{h}{v} + b\frac{h^2}{v^2}\right), \qquad (16)$$

$$\mathcal{L}_{h-V} = \frac{dv}{8g_V^2} h \left\langle V_\mu V^\mu \right\rangle . \qquad (17)$$

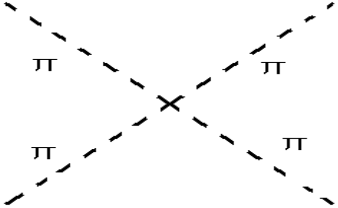
The Lagrangian (12), for the special values

$$a = \frac{1}{2}, \quad b = \frac{1}{4}, \quad d = 1, \quad g_K = \frac{1}{g_V}, \quad g_V = \frac{v}{2M_V}, \qquad (18)$$

is obtained from a gauge theory based on $SU(2)_L \times SU(2)_C \times U(1)_Y$ spontaneously broken by two Higgs doublets (with the same VEV) in the limit $m_H \gg \Lambda$ for the mass of the L-R-parity odd scalar H. The choice:

$$a = \sqrt{1 - \frac{3G_V^2}{v^2}}, \qquad G_V \equiv g_V M_V, \qquad G_V \leq v/\sqrt{3}. \qquad (19)$$

guarantees a good asymptotic behavior of elastic $W_L W_L$ scattering, while $g_V g_K = 1$ ensures that $\mathcal{A}\left(\pi^a \pi^b \to V_L^c V_L^d\right)$ grows at most like s/v^2.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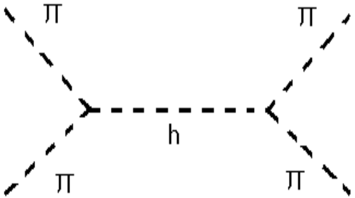
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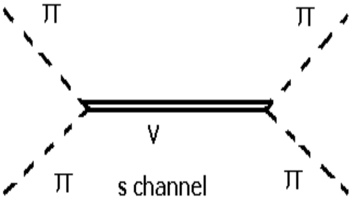
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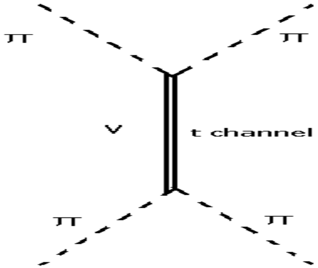
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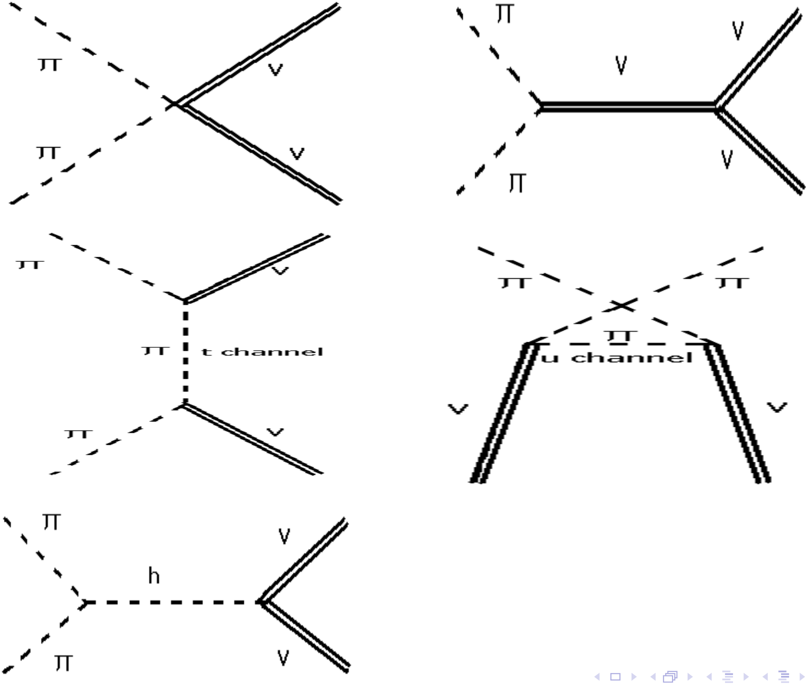
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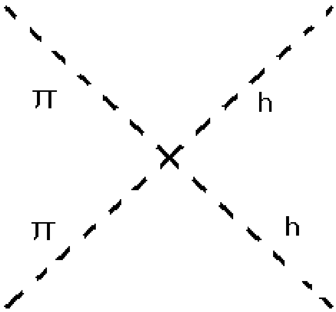
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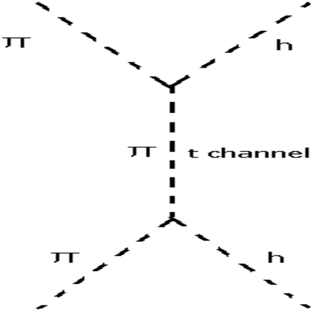
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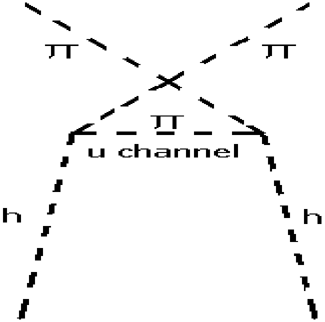
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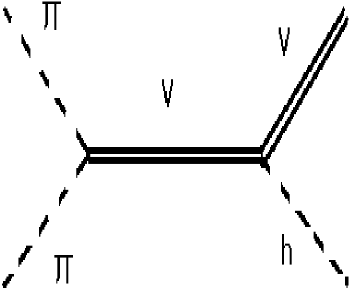
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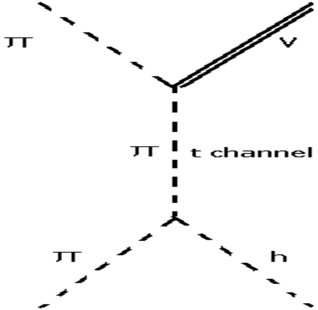
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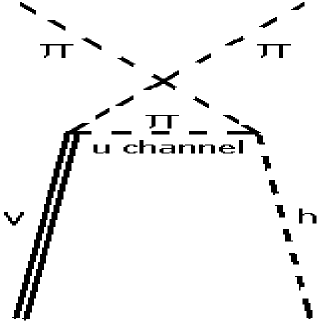
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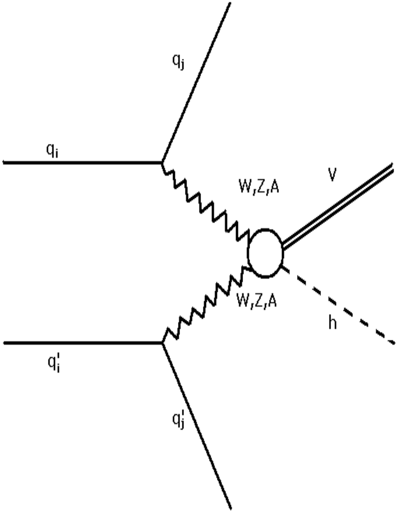
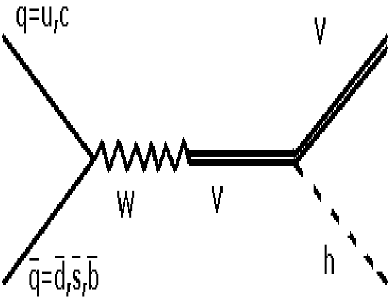
Associated production of *Vh* total cross sections





G_V	a	d	VBF(fb)	DY(fb)
$\sqrt{5}v/4$	$1/4$	0	0.10	0
$\sqrt{5}v/4$	$1/4$	1	0.18	7.30
$\sqrt{5}v/4$	$1/4$	2	1.28	29.20
$v/2$	$1/2$	0	0.33	0
$v/2$	$1/2$	1	0.10	9.12
$v/2$	$1/2$	2	1.15	36.48
$v/\sqrt{6}$	$1/\sqrt{2}$	0	0.43	0
$v/\sqrt{6}$	$1/\sqrt{2}$	1	0.17	13.68
$v/\sqrt{6}$	$1/\sqrt{2}$	2	1.82	54.72

G_V	a	d	VBF(fb)	DY(fb)
$\sqrt{5}v/4$	$1/4$	0	0.05	0
$\sqrt{5}v/4$	$1/4$	1	0.18	3.03
$\sqrt{5}v/4$	$1/4$	2	1.10	12.12
$v/2$	$1/2$	0	0.16	0
$v/2$	$1/2$	1	0.12	3.79
$v/2$	$1/2$	2	1.07	15.16
$v/\sqrt{6}$	$1/\sqrt{2}$	0	0.22	0
$v/\sqrt{6}$	$1/\sqrt{2}$	1	0.20	5.69
$v/\sqrt{6}$	$1/\sqrt{2}$	2	1.66	22.76

Table: Total cross sections for the associated production of hV^+ final state by VBF and DY at the LHC for $\sqrt{s} = 14$ TeV as functions of the different constants for $M_V = 700$ GeV and $M_V = 1$ TeV.

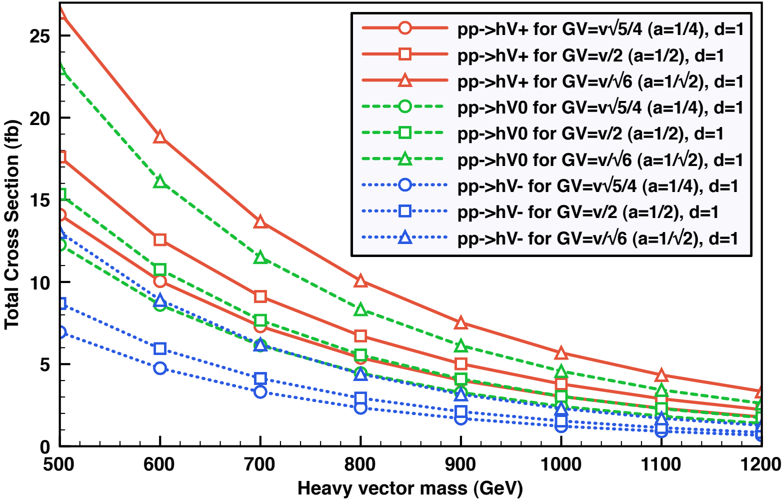


Figure 6: Total cross sections for the Vh **associated productions via Drell–Yan** $q\bar{q}$ **annihilation as functions of the heavy vector mass at the LHC for** $\sqrt{S} = 14$ **TeV, for** $m_h = 180$ **GeV, for different values of** G_V **and for** $d = 1$**.**

A. E. Cárcamo Hernández and R. Torre, Nuclear Physics B 2010.

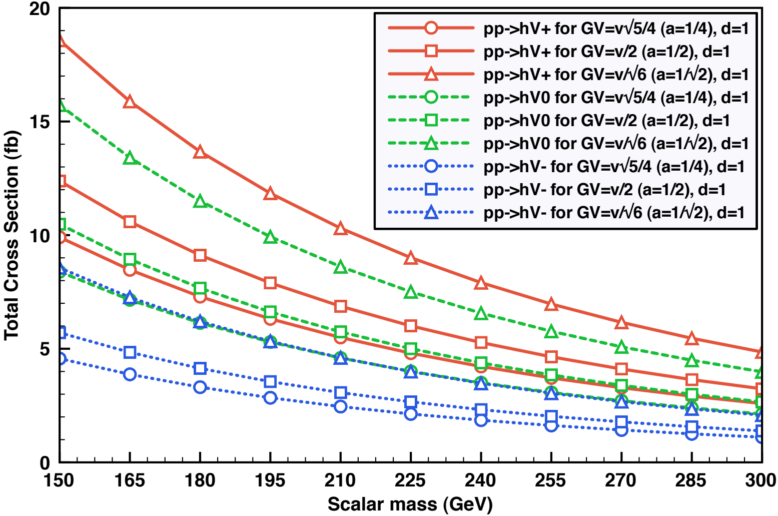


Figure 7: Total cross sections for the Vh associated productions via Drell–Yan $q\bar{q}$ annihilation as functions of the scalar mass at the LHC for $\sqrt{s} = 14$ TeV, for $M_V = 700$ GeV, for different values of G_V and for $d = 1$.

A. E. Cárcamo Hernández and R. Torre, Nuclear Physics B 2010.

Same-sign di-lepton and tri-lepton events

Decay Mode	di-leptons (%)	tri-leptons (%)
$V^0 h \to W^+ W^- W^+ W^-$	8.9	3.2
$V^\pm h \to W^\pm Z W^+ W^-$	4.5	1.0

Where $BR\left(h \to W^+ W^-\right) \approx 1$ is assumed. For a reference integrated luminosity of $\int \mathcal{L} dt = 100$ fb^{-1} and for $M_V = 700$ GeV and $M_V = 1$ TeV, we obtain the total number of same sign di-lepton and tri-lepton events:

G_V	a	di-leptons	tri-leptons
$\sqrt{5}v/4$	$1/4$	102.4	30.3
$v/2$	$1/2$	128.0	37.8
$v/\sqrt{6}$	$1/\sqrt{2}$	192.0	56.7

G_V	a	di-leptons	tri-leptons
$\sqrt{5}v/4$	$1/4$	41.0	12.0
$v/2$	$1/2$	51.0	15.1
$v/\sqrt{6}$	$1/\sqrt{2}$	76.6	22.6

Conclusions

- The phenomenology of 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 and one singlet scalar.
- The total cross sections at the LHC for the vector pair production by Vector Boson Fusion and Drell-Yan annihilation are of order of few *fb*. The numbers of same sign Dilepton and Trilepton events at the LHC with an integrated luminosity of $100fb^{-1}$ are of order of 10.
- For a vector with a mass between 500 GeV and 1 TeV and for $m_h = 180$ GeV, the main production mechanism at the LHC of a composite vector together with a composite scalar is by Drell-Yan annihilation. The order of magnitude of the cross sections is about 10 fb for a reasonable choice of the parameters. The expected same sign di-lepton and tri-lepton events are of the order of $10 - 100$ for an integrated luminosity of 100 fb^{-1}.

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Extra Slides

From $SU(2)_{L+R}$ invariance and Bose symmetry, the $\pi^a\pi^b \to \pi^c\pi^d$, $\pi^a\pi^b \to V_L^c V_L^d$, $\pi^a\pi^b \to hh$ and $\pi^a\pi^b \to V_L^c h$ scattering amplitudes are:

$$\begin{aligned}
\mathcal{A}\left(\pi^a\pi^b \to \pi^c\pi^d\right) &= A(s,t,u)\,\delta^{ab}\delta^{cd} + A(t,s,u)\,\delta^{ac}\delta^{bd} \\
&+ A(u,t,s)\,\delta^{ad}\delta^{bc} \\
\mathcal{A}\left(\pi^a\pi^b \to V_L^c V_L^d\right) &= \mathcal{A}(s,t,u)^{\pi\pi\to VV}\,\delta^{ab}\delta^{cd} \\
&+ \mathcal{B}(s,t,u)^{\pi\pi\to VV}\,\delta^{ab}\delta^{cd} \\
&+ \mathcal{B}(s,u,t)^{\pi\pi\to VV}\,\delta^{ab}\delta^{cd} \\
\mathcal{A}\left(\pi^a\pi^b \to hh\right) &= \mathcal{A}(s,t,u)^{\pi\pi\to hh}\,\delta^{ab}\,, \\
\mathcal{A}\left(\pi^a\pi^b \to V_L^c h\right) &= \mathcal{A}(s,t,u)^{\pi\pi\to Vh}\,\epsilon^{abc}\,.
\end{aligned} \tag{20}$$

The choice:

$$a = \sqrt{1 - \frac{3G_V^2}{v^2}}\,, \qquad G_V \equiv g_V M_V\,, \qquad G_V \leq v/\sqrt{3}. \tag{21}$$

guarantees a good asymptotic behavior of elastic $W_L W_L$ scattering, while $g_V g_K = 1$ ensures that $\mathcal{A}\left(\pi^a\pi^b \to V_L^c V_L^d\right)$ grows at most like s/v^2.

$$
\begin{aligned}
\mathcal{A}(s,t,u)^{\pi\pi\to\pi\pi} &\approx \frac{s}{v^2}\left(1-a^2-\frac{3g_V^2M_V^2}{v^2}\right)\\
&+ \frac{g_V^2M_V^4}{v^4}\left[\frac{(u-s)}{t}+\frac{(t-s)}{u}\right],\\
\mathcal{A}(s,t,u)^{\pi\pi\to VV} &\approx \left(\frac{ad}{2v^2}-\frac{1}{4v^2}\right)\left(s-2M_V^2\right),\\
\mathcal{B}(s,t,u)^{\pi\pi\to VV} &\approx \frac{u-t}{2v^2}\left[\frac{s}{2M_V^2}\left(g_Vg_K-1\right)-1+\frac{3g_Vg_K}{2}\left(1+\frac{M_V^2}{s}\right)\right]\\
&-\frac{g_V^2M_V^2u}{v^4}\left(1+\frac{4M_V^2}{s}+\frac{2M_V^2}{u}\right),\\
\mathcal{A}(s,t,u)^{\pi\pi\to hh} &\approx -\frac{1}{v^2}\left[\left(b-a^2\right)s+\frac{am_h^2}{2}\left(3-4a\right)\right]\\
\mathcal{A}(s,t,u)^{\pi\pi\to Vh} &\approx \frac{ig_VM_V\left(t-u\right)}{v}\left[\left(\frac{a}{v^2}-\frac{d}{8g_V^2M_V^2}\right)+\frac{a\left(M_V^2-m_h^2\right)}{v^2s}\right]\\
&+\frac{id\left(t-u\right)}{8g_VM_Vvs}\left(m_h^2-2M_V^2\right) \qquad (22)
\end{aligned}
$$

G_V	a	d	VBF (fb)	DY (fb)
$\sqrt{5}v/4$	$1/4$	0	0.05	0
$\sqrt{5}v/4$	$1/4$	1	0.09	3.31
$\sqrt{5}v/4$	$1/4$	2	0.62	13.24
$v/2$	$1/2$	0	0.15	0
$v/2$	$1/2$	1	0.05	4.14
$v/2$	$1/2$	2	0.56	16.56
$v/\sqrt{6}$	$1/\sqrt{2}$	0	0.20	0
$v/\sqrt{6}$	$1/\sqrt{2}$	1	0.08	6.20
$v/\sqrt{6}$	$1/\sqrt{2}$	2	0.89	24.80

G_V	a	d	VBF (fb)	DY (fb)
$\sqrt{5}v/4$	$1/4$	0	0.02	0
$\sqrt{5}v/4$	$1/4$	1	0.08	1.23
$\sqrt{5}v/4$	$1/4$	2	0.49	4.92
$v/2$	$1/2$	0	0.07	0
$v/2$	$1/2$	1	0.06	1.54
$v/2$	$1/2$	2	0.48	6.16
$v/\sqrt{6}$	$1/\sqrt{2}$	0	0.09	0
$v/\sqrt{6}$	$1/\sqrt{2}$	1	0.09	2.30
$v/\sqrt{6}$	$1/\sqrt{2}$	2	0.75	9.20

Table: Total cross sections for the associated production of hV^- final state by VBF and DY at the LHC for $\sqrt{s} = 14$ TeV as functions of the different parameters for $M_V = 700$ GeV and $M_V = 1$ TeV.

G_V	a	d	VBF(fb)	DY(fb)
$\sqrt{5}v/4$	$1/4$	0	0.08	0
$\sqrt{5}v/4$	$1/4$	1	0.14	6.14
$\sqrt{5}v/4$	$1/4$	2	0.99	24.56
$v/2$	$1/2$	0	0.24	0
$v/2$	$1/2$	1	0.08	7.67
$v/2$	$1/2$	2	0.90	30.68
$v/\sqrt{6}$	$1/\sqrt{2}$	0	0.32	0
$v/\sqrt{6}$	$1/\sqrt{2}$	1	0.13	11.51
$v/\sqrt{6}$	$1/\sqrt{2}$	2	1.42	46.04

G_V	a	d	VBF(fb)	DY(fb)
$\sqrt{5}v/4$	$1/4$	0	0.04	0
$\sqrt{5}v/4$	$1/4$	1	0.13	2.43
$\sqrt{5}v/4$	$1/4$	2	0.79	9.74
$v/2$	$1/2$	0	0.11	0
$v/2$	$1/2$	1	0.09	3.04
$v/2$	$1/2$	2	0.78	12.16
$v/\sqrt{6}$	$1/\sqrt{2}$	0	0.15	0
$v/\sqrt{6}$	$1/\sqrt{2}$	1	0.15	4.57
$v/\sqrt{6}$	$1/\sqrt{2}$	2	1.22	18.28

Table: Total cross sections for the associated production of hV^0 final state by VBF and DY at the LHC for $\sqrt{s} = 14$ TeV as functions of the different constants for $M_V = 700$ GeV and $M_V = 1$ TeV.

Composite versus gauge models

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

$$\mathcal{L}_V^{\text{gauge}} = \mathcal{L}_\chi^{\text{gauge}} - \frac{1}{2g_C^2}\left\langle v_{\mu\nu} v^{\mu\nu} \right\rangle - \frac{1}{2g^2}\left\langle W_{\mu\nu} W^{\mu\nu} \right\rangle - \frac{1}{2g'^2}\left\langle B_{\mu\nu} B^{\mu\nu} \right\rangle , \quad (23)$$

where

$$v_\mu = \frac{g_C}{2} v_\mu^a \tau^a \quad (24)$$

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

$$\mathcal{L}_\chi^{\text{gauge}} = \frac{v^2}{2}\left\langle D_\mu \Sigma_{RC} \left(D^\mu \Sigma_{RC}\right)^\dagger \right\rangle + \frac{v^2}{2}\left\langle D_\mu \Sigma_{CL} \left(D^\mu \Sigma_{CL}\right)^\dagger \right\rangle . \quad (25)$$

Denoting collectively the three gauge vectors by

$$v_\mu^I = (W_\mu, v_\mu, B_\mu), \quad I = (L, C, R), \quad (26)$$

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

$$D_\mu \Sigma_{IJ} = \partial_\mu \Sigma_{IJ} - i v_\mu^I \Sigma_{IJ} + i \Sigma_{IJ} v_\mu^J . \quad (27)$$

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

$$v_\mu^I \to \sigma_I^\dagger v_\mu^I \sigma_I + i\sigma_I^\dagger \partial_\mu \sigma_I \equiv \Omega_\mu^I, \quad \Sigma_{IJ} \to \sigma_I^\dagger \Sigma_{IJ} \sigma_J = 1, \tag{28}$$

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

$$\mathcal{L}_\chi^{\text{gauge}} = v^2 \left\langle (v_\mu - i\Gamma_\mu)^2 \right\rangle + \frac{v^2}{4} \left\langle u_\mu^2 \right\rangle, \tag{29}$$

where

$$u_\mu = \Omega_\mu^R - \Omega_\mu^L, \quad \Gamma_\mu = \frac{1}{2i}(\Omega_\mu^R + \Omega_\mu^L), \quad v_\mu = V_\mu + i\Gamma_\mu \tag{30}$$

by use of the identity:

$$v_{\mu\nu} = \hat{V}_{\mu\nu} - i[V_\mu, V_\nu] + \frac{i}{4}[u_\mu, u_\nu] + \frac{1}{2}(uW_{\mu\nu}u^\dagger + u^\dagger B_{\mu\nu} u). \tag{31}$$

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

$$g_V = \frac{1}{2g_C} = \frac{1}{g_K}, \quad g_3 = -\frac{1}{4}, \quad g_6 = \frac{1}{2}, \quad f_V = 2g_V \quad M_V = g_C v \tag{32}$$

with $G_V = g_V M_V$.

A well behaved theory at all energies

Let us consider the following $SU(2)_L \times SU(2)_C \times U(1)_Y$ invariant non-linear sigma model Lagrangian:

$$\mathcal{L}_V^{\text{gauge}} = \mathcal{L}_\chi^{\text{gauge}} - \frac{1}{2g_C^2}\left\langle v_{\mu\nu} v^{\mu\nu} \right\rangle - \frac{1}{2g^2}\left\langle W_{\mu\nu} W^{\mu\nu} \right\rangle - \frac{1}{2g'^2}\left\langle B_{\mu\nu} B^{\mu\nu} \right\rangle , \quad (33)$$

where

$$v_\mu = \frac{g_C}{2} v_\mu^a \tau^a \quad (34)$$

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

$$\mathcal{L}_\chi^{\text{gauge}} = \frac{v^2}{2}\left\langle D_\mu \Sigma_{YC} \left(D^\mu \Sigma_{YC}\right)^\dagger \right\rangle + \frac{v^2}{2}\left\langle D_\mu \Sigma_{CL} \left(D^\mu \Sigma_{CL}\right)^\dagger \right\rangle \quad (35)$$

$$\Sigma_{RC} = \left(1 + \frac{h+H}{2v}\right) U_{YC} , \qquad U_{RC} = \exp\left[\frac{i}{2v}\left(\pi + \sigma\right)\right] , \quad (36)$$

$$\Sigma_{CL} = \left(1 + \frac{h-H}{2v}\right) U_{CL} , \qquad U_{CL} = \exp\left[\frac{i}{2v}\left(\pi - \sigma\right)\right] , \quad (37)$$

$V\left(\Sigma_{YC},\Sigma_{CL}\right)$ is the scalar potential, which has the form

$$V\left(\Sigma_{YC},\Sigma_{CL}\right)=\frac{\mu^2 v^2}{2}\left\langle\Sigma_{YC}\Sigma_{YC}^{\dagger}\right\rangle+\frac{\mu^2 v^2}{2}\left\langle\Sigma_{CL}\Sigma_{CL}^{\dagger}\right\rangle-\frac{\lambda v^4}{4}\left(\left\langle\Sigma_{YC}\Sigma_{YC}^{\dagger}\right\rangle\right)^2 -\frac{\lambda v^4}{4}\left(\left\langle\Sigma_{CL}\Sigma_{CL}^{\dagger}\right\rangle\right)^2-\kappa v^4\left\langle\Sigma_{YC}\Sigma_{CL}^{\dagger}\Sigma_{CL}\Sigma_{YC}^{\dagger}\right\rangle . \quad (38)$$

where $\pi=\pi^a\tau^a$ and $\sigma=\sigma^a\tau^a$, with:

$$m_h^2=4v^2\left(\lambda+\kappa\right) , \qquad m_H^2=4v^2\left(\lambda-\kappa\right) . \quad (39)$$

The covariant derivatives appearing in (35) are given by

$$\begin{aligned} D_\mu U_{YC} &= \partial_\mu U_{YC}-iB_\mu U_{YC}+iU_{YC}v_\mu , \\ D_\mu U_{CL} &= \partial_\mu U_{CL}-iv_\mu U_{CL}+iU_{CL}W_\mu . \end{aligned} \quad (40)$$

The U fields can be written as $U_{YC}=\sigma_Y\sigma_C^{\dagger}$ and $U_{CL}=\sigma_C\sigma_L^{\dagger}$ where the $\sigma_{L,C,Y}$ are elements of $SU\left(2\right)_{L,C,R}/H$ respectively. These σ_I with $I=L,C,Y$ transform under the full $SU\left(2\right)_L\times SU\left(2\right)_C\times U\left(1\right)_Y$ as $\sigma_I\to g_I\sigma_I h^{\dagger}$.

By applying the gauge transformation

$$v_\mu^I \to \sigma_I^\dagger v_\mu^I \sigma_I + i\sigma_I^\dagger \partial_\mu \sigma_I = \Omega_\mu^I, \qquad\qquad U_{IJ} \to \sigma_I^\dagger U_{IJ} \sigma_J = 1\,,$$

and after the gauge fixing $\sigma_Y = \sigma_L^\dagger = u^2 = U = e^{\frac{i\hat{\pi}}{v}}$ and $\sigma_C = 1$, which implies that $U_{YC} = U_{CL}$ (i.e. $\hat{\sigma} = 0$), so we have:

$$\begin{aligned}\mathcal{L}_\chi^{\text{gauge}} &= v^2\left(1 + \frac{h^2 + H^2}{4v^2} + \frac{h}{v}\right)\left(\left\langle \left(v_\mu - i\Gamma_\mu\right)^2\right\rangle + \frac{1}{4}\left\langle u_\mu u^\mu\right\rangle\right) \\ &- \frac{1}{2}\left(2vH + hH\right)\left\langle u^\mu \left(v_\mu - i\Gamma_\mu\right)\right\rangle\,, \end{aligned} \tag{41}$$

where

$$\begin{aligned} u_\mu &= \Omega_\mu^Y - \Omega_\mu^L = iu^\dagger D_\mu U u^\dagger, \\ \Gamma_\mu &= \frac{1}{2i}\left(\Omega_\mu^Y + \Omega_\mu^L\right) = \frac{1}{2}\left[u^\dagger\left(\partial_\mu - iB_\mu\right)u + u\left(\partial_\mu - iW_\mu\right)u^\dagger\right]. \end{aligned} \tag{42}$$

Now by setting

$$v_\mu = V_\mu + i\Gamma_\mu\,, \tag{43}$$

by using the identity

$$v_{\mu\nu} = V_{\mu\nu} - i\left[V_\mu, V_\nu\right] + \frac{i}{4}\left[u_\mu, u_\nu\right] + \frac{1}{2} f^+_{\mu\nu}\,, \tag{44}$$

where $f^+_{\mu\nu} = uW_{\mu\nu}u^\dagger + u^\dagger B_{\mu\nu}u$, by redefining $V_\mu \to \frac{g_C}{\sqrt{2}} V_\mu$, and taking the mass of the L-R-parity odd H given in (39) infinitely large, $\mathcal{L}^{\text{gauge}}$ coincides with $\mathcal{L}_{\text{eff}}$ in (12) up to operators irrelevant for the processes under consideration, only for the values of the parameters:

$$\begin{aligned} &g_V = \frac{1}{2g_C} = \frac{1}{g_K} = \frac{v}{2M_V}, \qquad f_V = 2g_V, \\ &a = \frac{1}{2}, \qquad b = \frac{1}{4}, \qquad d = 1, \qquad G_V = \frac{v}{2}\,, \\ &M_V = g_C v = \tfrac{1}{2} g_K v = \tfrac{v}{2g_V} \end{aligned} \tag{45}$$

Preliminar results on Signals and Backgrounds

Signal	σ (fb)
$pp \to V^+V^-jj \to W^+W^-ZZjj \to l\not{E}_T jjlljjjj \to 3l6j\not{E}_T$	$0(10^{-2})$
$WZ6j \to 3l6j\not{E}_T$	$0(10^{-1})$
$t\bar{t}Hjj \to t\bar{t}WWjj \to WWWW4j \to 3l6j\not{E}_T$	
$2t2\bar{t} \to WWWW4j \to 3l6j\not{E}_T$	
$t\bar{t}H \to t\bar{t}ZZ \to WWZZjj \to l\not{E}_T jjlljj2j \to 3l6j\not{E}_T$	$0(10^{-2})$
$WWZZjj \to l\not{E}_T jjlljjjj \to 3l6j\not{E}_T$	
$t\bar{t}Wjjjj \to WWW6j \to 3l6j\not{E}_T$	
$t\bar{t}Zjj \to WWZ4j \to l\not{E}_T jj\tau\tau 4j \to l\not{E}_T jjl\not{E}_T l\not{E}_T 4j \to 3l6j\not{E}_T$	
$WWWZjj \to l\not{E}_T jjjjlljj \to 3l6j\not{E}_T$	$0(10^{-3})$
$t\bar{t}Zjj \to WW\tau\tau 4j \to l\not{E}_T l\not{E}_T l\not{E}_T 2j\not{E}_T 4j \to 3l6j\not{E}_T$	
$t\bar{t}Hjj \to WWll4j \to l\not{E}_T jjll4j \to 3l6j\not{E}_T$	
$WZZjj \to l\not{E}_T ll\tau\tau 2j \to l\not{E}_T ll2j\not{E}_T 2j\not{E}_T 2j \to 3l6j\not{E}_T$	

Signal	σ (fb)
$pp \to V^+V^+jj \to W^+W^+ZZjj \to l\not{E}_T l\not{E}_T jjjjjj \to 3l6j\not{E}_T$	$0(10^{-1})$
Backgrounds	
$t\bar{t}H \to WWHjj \to WWWWjj \to 2l6j\not{E}_T$ $t\bar{t}W2j \to WWW4j \to 2l6j\not{E}_T$	$0(10^{-1})$
$WWWW2j \to 2l6j\not{E}_T$ $HWW2j \to WWW4j \to 2l6j\not{E}_T$ $HW4j \to WWW4j \to 2l6j\not{E}_T$	$0(10^{-3})$
$HWZZ \to WWWZZ \to 2l6j\not{E}_T$ $HWZ2j \to WWZ4j \to 2l6j\not{E}_T$	$0(10^{-4})$
$HWWZ \to WWWWZ \to 2l6j\not{E}_T$ $HWWW \to WWWWW \to 2l6j\not{E}_T$	$0(10^{-5})$