A “composite” scalar-vector system at the LHC

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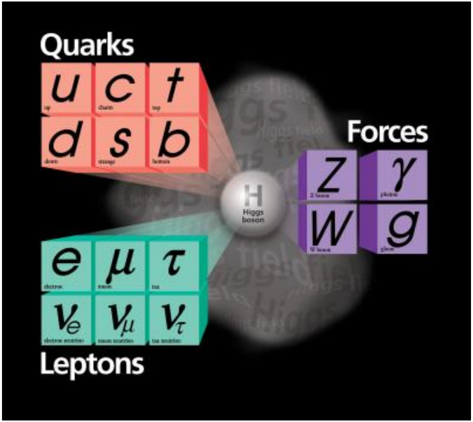
Based on the papers
R. Barbieri, A. E. Carcamo, G. Corcella, R. T. and E. Trincherini: arXiv:0911.1942 [hep-ph]
A. E. Carcamo and R. T. arXiv:1005.3809 [hep-ph]

The Standard Model: Particle content

- **Vectors (Forces)**: gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ spontaneously broken to $SU(3)_C \times U(1)_e$
- **Fermions (Matter)**: 3 generations of quarks and leptons
- **Scalars? (Higgs?)**: the Higgs boson
  1. A scalar doublet under $SU(2)_L$ interacting with all other fields acquires a VEV
  2. W, Z bosons acquire a mass with the spontaneous breaking $SU(2)_L \times U(1)_Y \to U(1)_e$
  3. Leptons and quarks acquire a mass through Yukawa couplings to the Higgs boson



Tevatron

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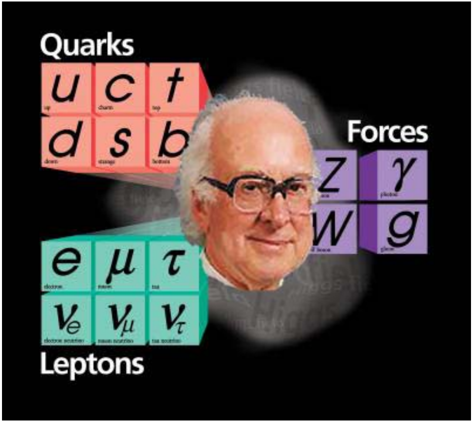


Tevatron + R. T.

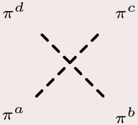
Unfortunately this is the only Higgs we have seen so far!

Why do we need the Higgs boson?

- To generate the masses of all the massive particles (weak gauge bosons and fermions)
- To keep S-matrix unitarity in longitudinal WW scattering

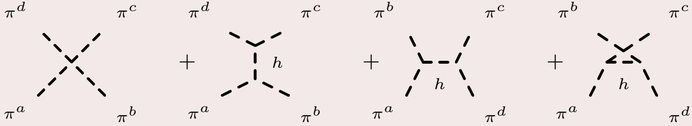
The $W_L W_L \to W_L W_L$ scattering without the Higgs boson

$$\mathcal{A}\left(\pi\pi \to \pi\pi\right) = \mathcal{A}\left(s,t,u\right)\delta^{ab}\delta^{cd} + \mathcal{A}\left(t,s,u\right)\delta^{ac}\delta^{bd} + \mathcal{A}\left(u,t,s\right)\delta^{ad}\delta^{bc} \tag{1}$$



$$\Rightarrow \quad \mathcal{A}\left(s,t,u\right) = \frac{s}{v^2} \tag{2}$$

The $W_L W_L \to W_L W_L$ scattering with the Higgs boson



$$\mathcal{A}\left(s,t,u\right) = -\frac{m_h^2}{v^2}\frac{s}{s-m_h^2} \tag{3}$$

Make it without an Higgs boson: an example

- The masses can be generated by a non-linear sigma model based on the non-linear field $U = e^{i\frac{\pi^a \sigma^a}{v}}$ containing the Goldstone bosons field
- The exchange of a new massive particles, can turn the asymptotic amplitude for $W_L W_L \to W_L W_L$ to a constant up to a cut-off
- An effective field theory based on the $SU(2)_L \times SU(2)_R / SU(2)_{L+R}$ global symmetry containing a new massive vector triplet V_μ^a can be constructed with a cut-off $\Lambda \approx 4\pi v \approx 3$ TeV

One vector below the cut-off: the general Lagrangian

$$\mathcal{L}^V = \mathcal{L}_\chi + \mathcal{L}^V_{kin} + \mathcal{L}^V_{int} . \tag{4}$$

$$\mathcal{L}_\chi = \frac{v^2}{4}\left\langle D_\mu U \left(D^\mu U\right)^\dagger \right\rangle - \frac{1}{2g^2}\left\langle W_{\mu\nu}W^{\mu\nu}\right\rangle - \frac{1}{2g'^2}\left\langle B_{\mu\nu}B^{\mu\nu}\right\rangle \tag{5}$$

$$\mathcal{L}^V_{kin} = -\frac{1}{4}\left\langle \hat{V}_{\mu\nu}\hat{V}^{\mu\nu}\right\rangle + \frac{M_V^2}{2}\left\langle V_\mu V^\mu\right\rangle \tag{6}$$

$$\begin{aligned}\mathcal{L}^V_{int} \quad = \quad & -\frac{ig_V}{2\sqrt{2}}\left\langle \hat{V}_{\mu\nu}[u^\mu, u^\nu]\right\rangle - \frac{f_V}{2\sqrt{2}}\left\langle \hat{V}_{\mu\nu}\left(uW^{\mu\nu}u^\dagger + u^\dagger B^{\mu\nu}u\right)\right\rangle \\ & + \frac{ig_K}{4\sqrt{2}}\left\langle \hat{V}_{\mu\nu}[V^\mu, V^\nu]\right\rangle - \frac{1}{8}\left\langle [V_\mu, V_\nu][u^\mu, u^\nu]\right\rangle + \frac{g_V^2}{8}\left\langle [u_\mu, u_\nu][u^\mu, u^\nu]\right\rangle ,\end{aligned} \tag{7}$$

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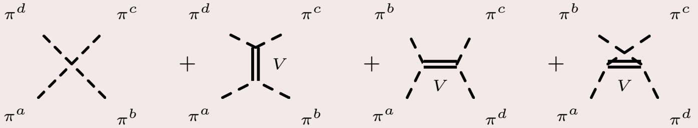
An example: vector resonance exchange

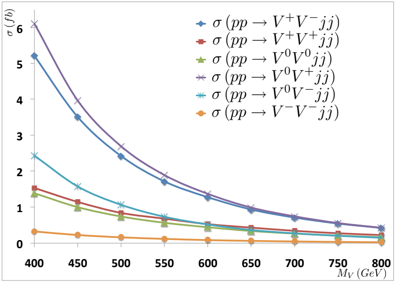


$$\mathcal{A}(s,t,u) = \left[\frac{s}{v^2} - \frac{G_V^2}{v^4}\left[3s + M_V^2\left(\frac{s-u}{t-M_V^2} + \frac{s-t}{u-M_V^2}\right)\right]\right] \quad (4)$$

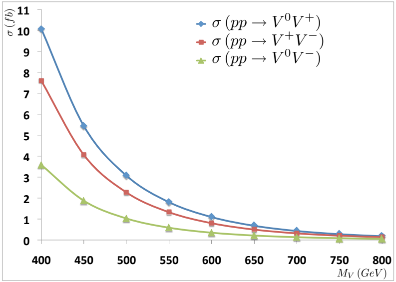
- For $G_V = g_V M_V = \frac{v}{\sqrt{3}}$ the asymptotic amplitude reduces to a constant
- However the unitarity is not formally restored up to all energies (the coefficients of the partial wave expansion of the scattering amplitude grow logarithmically with s even in the case $G_V = \frac{v}{\sqrt{3}}$)

Total cross sections for the pair production of heavy vector bosons

- The pair production of vector resonances is important since it is sensitive to different couplings with respect to the single production (in particular the trilinear coupling g_K)
- Total cross sections at the LHC ($\sqrt{s} = 14$ TeV) for $G_V = 200$ GeV, $F_V = 2G_V$ and $g_k = 1/(\sqrt{2}g_V)$ as functions of the heavy vector mass have been obtained with the matrix element generator CalcHEP



Vector Boson Fusion ($p_T > 30$ GeV, $|\eta| < 5$)



Drell-Yan

R. Barbieri, A. E. Carcamo, G. Corcella, R. T., E. Trincherini, 2009

Sharing the task of unitarizing $W_L W_L$ scattering

- If only a vector or only a scalar is relevant with a mass below the cut-off its coupling to the Goldstone bosons is completely constrained by the elastic unitarity bound
- The presence of both a scalar and a vector with masses below the cut-off makes it possible to relax these constraints

One vector below the cut-off: the general Lagrangian

$$\mathcal{L}_{\mathit{eff}} = \mathcal{L}^V + \mathcal{L}_h + \mathcal{L}_{h-V} \,. \tag{5}$$

$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{m_h^2}{2}h^2 + \frac{v^2}{4}\left\langle D_\mu U \left(D^\mu U\right)^\dagger\right\rangle \left(2a\frac{h}{v} + b\frac{h^2}{v^2}\right) \,, \tag{6}$$

$$\mathcal{L}_{h-V} = \frac{dv}{8g_V^2} h \left\langle V_\mu V^\mu \right\rangle \tag{7}$$

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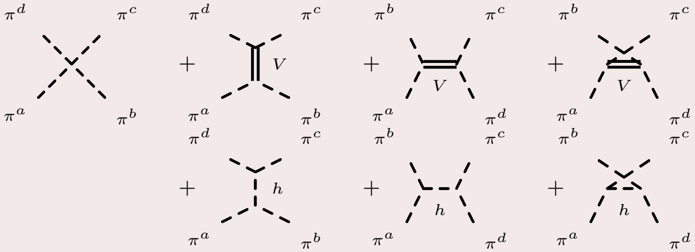

$$\mathcal{A}(s,t,u) = \frac{s}{v^2}\left(1 - a^2 - \frac{3 g_V^2 M_V^2}{v^2}\right) + \frac{g_V^2 M_V^4}{v^4}\left[\left(\frac{(u-s)}{t} + \frac{(t-s)}{u}\right)\right] \quad (5)$$

- The elastic unitarity constraint reduces to a relation between the couplings a and $g_V = G_V/M_V$

Asymptotic behavior of the relevant amplitudes

Asymptotic amplitudes

$$\mathcal{A}\left(s,t,u\right)^{\pi\pi\to\pi\pi} \approx \frac{s}{v^2}\left(1-a^2-\frac{3g_V^2M_V^2}{v^2}\right)+\frac{g_V^2M_V^4}{v^4}\left[\left(\frac{(u-s)}{t}+\frac{(t-s)}{u}\right)\right] \quad (6a)$$

$$\mathcal{A}\left(s,t,u\right)^{\pi\pi\to V_LV_L} \approx \left(\frac{ad}{2v^2}-\frac{1}{4v^2}\right)\left(s-2M_V^2\right) \quad (6b)$$

$$\mathcal{B}\left(s,t,u\right)^{\pi\pi\to V_LV_L} \approx \frac{u-t}{4v^2}\left[1+\frac{3M_V^2}{s}\right]-\frac{g_V^2M_V^2u}{v^4}\left(1+\frac{4M_V^2}{s}+\frac{2M_V^2}{u}\right) \quad (6c)$$

$$\mathcal{A}\left(s,t,u\right)^{\pi\pi\to hh} \approx -\frac{1}{v^2}\left(\left(b-a^2\right)s+\frac{am_h^2}{2}\left(3-2a\right)\right) \quad (6d)$$

$$\mathcal{A}\left(s,t,u\right)^{\pi\pi\to V_Lh} \approx \frac{ig_VM_V\left(t-u\right)}{v}\left[\frac{a}{v^2}-\frac{d}{8g_V^2M_V^2}\right]+\frac{ig_VM_V\left(t-u\right)}{vs}\left[\frac{a}{v^2}\left(M_V^2-m_h^2\right)+\frac{d}{8g_V^2M_V^2}\left(m_h^2-2M_V^2\right)\right] \quad (6e)$$

Asymptotic behavior of the relevant amplitudes

For the choice of the parameters

Gauge parameters

$$a = \frac{1}{2}\,, \qquad b = \frac{1}{4}\,, \qquad d = 1\,, \qquad g_V = \frac{v}{2M_V} \tag{7}$$

the theory reduces to the $SU(2)_L \times SU(2)_C \times SU(2)_R$ gauge theory spontaneously broken by 2 Higgs doublets in the case of very heavy $L-R$-parity odd Higgs and all the asymptotic amplitudes but $B(s,t,u)$ turn to constants

Asymptotic amplitudes (the gauge case)

$$\mathcal{A}(s,t,u)^{\pi\pi\to\pi\pi} \approx \frac{M_V^2}{4v^2}\left[\left(\frac{(u-s)}{t}+\frac{(t-s)}{u}\right)\right] + O\left(\frac{m_h^2}{v^2}\right), \tag{8a}$$

$$\mathcal{A}(s,t,u)^{\pi\pi\to V_L V_L} \approx O\left(\frac{m_h^2}{v^2}\right), \tag{8b}$$

$$\mathcal{B}(s,t,u)^{\pi\pi\to V_L V_L} \approx -\frac{t}{4v^2} - \frac{M_V^2}{4v^2}\left(\frac{u+3t}{s}+2\right), \tag{8c}$$

$$\mathcal{A}(s,t,u)^{\pi\pi\to hh} \approx -\frac{m_h^2}{4v^2}, \tag{8d}$$

$$\mathcal{A}(s,t,u)^{\pi\pi\to V_L h} \approx \frac{iM_V^2(u-t)}{4v^2 s} + O\left(\frac{m_h^2}{v^2}\right). \tag{8e}$$

Scalar and vector pair productions

$W_L W_L \to W_L W_L$ unitarity constrain

$$a = \sqrt{1 - \frac{3 g_V^2 M_V^2}{v^2}} \tag{9}$$

- Since the vector V doesn't contribute to the scalar pair production, the results are the same we would have for example in the case of a Strongly Interacting Light Higgs (SILH) (R. Contino, C. Grojean, M. Moretti, F. Piccinini and R. Rattazzi, 2010)
- The total cross section for the vector pair production is lowered with respect to the case without a light scalar since the unitarity bound requires a lower G_V value ($G_V < v/\sqrt{3}$) and the exchange of the scalar doesn't suffice for compensating this decrease
- The associated scalar-heavy vector production with the constraint (9) depends on 2 parameters for fixed M_V and m_h: g_V and d.

Total cross section for the DY associated production at the LHC

- The DY associated production is the main production mechanism at the LHC
- Total cross sections for the associated scalar-heavy vector production at the LHC at 14 TeV for $M_h = 180$ GeV and different values of the couplings g_V and d

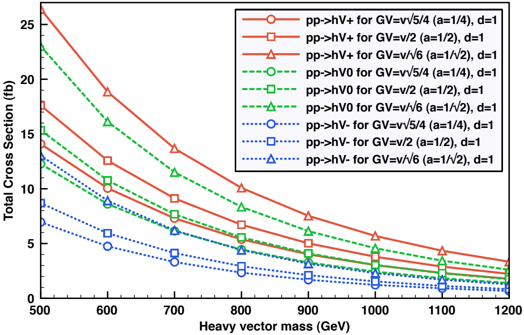

Figure: A. E. Carcamo and R. T, 2010

- A signal could be accessible to the LHC but...
- .. a careful study of the background is required to understand if the signal can emerge

Summary

- If a "standard" light Higgs boson doens't exist, a strongly interacting dynamics can be responsible for the EWSB and new degrees of freedom can become relevant at the Fermi scale
- We studied the case in which both a scalar and a vector are relevant with a mass below the cut-off with a model independent approach
- The pair production phenomenology produced by such a spectrum can be interesting at the LHC...
- ... but an analysis of the background is necessary

Thanks to A. E. Carcamo, R. Barbieri, E. Trincherini, S. Rychkov and G. Corcella

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Some references

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