Composite vectors at the LHC with CalcHEP

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This work is based on the paper written with R. Barbieri, A. Carcamo, G. Corcella and E. Trincherini (arXiv: 0911.1942)

Outline

1. An Higgs-less model with "composite" vectors
2. Implementation in CalcHEP and Numerical results
3. Summary and Perspective

The "atheistic" EWSB (slogan revisited)

Weak vs Strong EWSB

ElectroWeak Symmetry Breaking?

Weak

- A relatively light fundamental Higgs boson exists
- Perhaps with the embed of the SM in a proper supersymmetric framework
- The SM can be extrapolated up to energies much higher than the Fermi scale

Strong

- A fundamental Higgs boson doesn't exist
- New degrees of freedom become relevant at the Fermi scale
- Some new particles have to play the role of the Higgs boson in the EWSB
- An underlying unknown theory must be there and effective theories can be constructed to parametrize our ignorance

Composite vectors: a model independent approach

- We focus our attention on a new vector degree of freedom
- It is possible to be quite model independent in the description of a vector resonance
- In fact we only assume parity in the new strong sector, we keep the usual gauge invariance leaving out the Higgs boson, and we insist on $SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$ as relevant “approximate” symmetry ($g' \neq 0$ and $m_t - m_b \neq 0$)
- Consistently with this choice of the symmetry we introduce an iso-triplet vector state V_μ^a (that corresponds to a neutral V_μ^0 and two charged $V_\mu^\pm$ vector states)
- The Lagrangian for such a model can describe a light vector resonance with the mass around $1\,TeV$ (and even below) and contains as special cases many of the models in literature
- We also leave out direct interactions of the new vector resonance with fermions (e.g. with the third generation)

Composite vectors: the Lagrangian

- The total Lagrangian relevant for the production of such a vector resonance at the LHC is

Complete Lagrangian

$$\mathcal{L}^{V} = \mathcal{L}_{\chi} + \mathcal{L}_{kin}^{V}\left(M_V\right) + \mathcal{L}_{int}^{V}\left(g_V, f_V, g_K, g_1, \ldots, g_6\right) + \mathcal{L}_{contact}\left(h_1, \ldots, h_4\right) \quad (1)$$

- There are 14 parameters!
  M_V = mass of the resonance
  g_V = coupling to Goldstones
  f_V = coupling to Gauge bosons
  g_K = trilinear coupling
  $g_1, \ldots g_6$ = couplings for operators involving two vector resonances
  $h_1, \ldots h_4$ = couplings for "contact" operators not involving the vector resonance
- Requiring the equivalence with an extended gauge model based on the gauge group $G = SU(2)_L \times SU(2)_R \times SU(2)^N$ broken to the diagonal subgroup $H = SU(2)_{L+R+\ldots}$ by a generic non-linear σ-model we can smooth the bad asymptotic behavior of the amplitudes (in the gauge model they grow at most as s/v^2) and set relations among the many parameters in terms of the few gauge parameters
- There can be "small" deviations from the gauge model (as suggested for example by the violation of the relation $f_V = 2g_V$ in chiral QCD)
- This deviations from the gauge model are parametrized by many parameters

Composite vectors: double production

- However we have also many processes (in various charge configurations) to bind these parameters

Relevant Processes

$$
\begin{array}{ll}
WW \to WW & (M_V, g_V) \\
WW \to V & (M_V, g_V) \\
q\bar{q} \to V & (M_V, f_V) \\
\mathbf{WW} \to \mathbf{VV} & (M_V, g_V, g_K) \\
\mathbf{q\bar{q}} \to \mathbf{VV} & (M_V, g_V, f_V, g_K, g_6)
\end{array} \tag{2}
$$

- $WW \to WW$ scattering and single production already studied in literature (see the references in 0911.1942 [hep-ph])
- The double production is important for the measure of g_K and g_6 that are indispensable to distinguish different models
- The double production is relevant to quantify deviations from the gauge relation $g_K = 1/g_V$
- At the LHC can be relevant if the vector resonance is light enough (less than 1 TeV)
- In view of a final state analysis it's important to implement the model into a Matrix Element Generator and in a Parton Shower program

The FeynRules model generator

FeynRules by N. Christensen, C. Duhr and B. Fuks

- Mathematica package (simple to use!)
- Has many functions to check the correctness of the Lagrangian
- Can create models for many Matrix Element Generators (CalcHEP, MadGraph, Sherpa, etc.)

... but two main decifiencies:

- Cannot write new HELAS (Helicity Amplitudes Subroutines): this makes impossible to implement some models (e.g. our model) into MadGraph

WVV Interaction Lagrangian

$$\mathcal{L}_{WV^2} = \frac{g}{2}\epsilon^{abc}\left(\partial_\mu V_\nu^a - \partial_\nu V_\mu^a\right) V^{\nu\, b} W^{\mu\, c} \quad (3)$$

- Cannot automatically diagonalize Lagrangians on mass eigenstates: this makes much more difficult to implement models with mixing terms (e.g. our model)

WV Mixing Lagrangian

$$\mathcal{L}_{WV} = -\frac{g f_V}{2} V^{\mu\nu\, a}\partial_\mu W_\nu^a\,, \quad (4)$$

The CalcHEP Matrix Element Generator

CalcHEP by A. Pukhov, A. Belyaev and N. Christensen

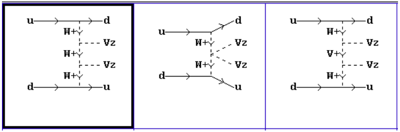
- Very user friendly interface (simple to use!)
- Allows the exclusion of intermediate particles
- Analytical squared amplitudes
- Numerical integration with Vegas (Importance Sampling Algorithm)
- Allows the application of kinematical cuts and can generate distributions
- Can generate partonic events in Les Houches LHE format that can be read by Pythia and Herwig
- Possibility of parallelization in Batch mode

... but again two main deficiencies:

- Does not allow the choice of the intermediate state (e.g. cannot simply select Vector Boson Fusion processes)
- Does not allow even the exclusion of intermediate particles in the Batch mode

The VBF and the DY processes

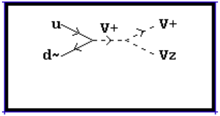
- Different implementations have been realized for the VBF and the DY pair production
- **VBF**: Very weak dependance on f_V: fix $f_V = 0$ and create a CalcHEP model



- **DY**: Strong dependance on f_V: diagonalize the Lagrangian introducing a direct coupling of the vector resonance with the fermions and create a CalcHEP model

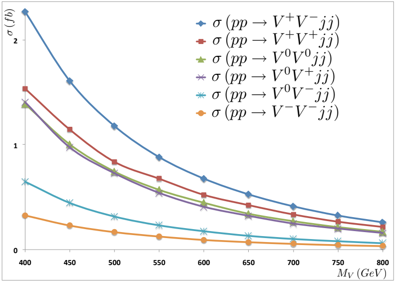
Diagonalization of the mixing terms

$$\frac{f_V}{2}\left(gD_\nu^{(SU(2))}W^{\mu\nu\,a}v_\mu^a + g'\partial_\nu B^{\mu\nu}v_\mu^3\right) = \frac{f_V}{2}\left(g^2\bar{\Psi}\gamma^\mu\frac{\sigma^a}{2}\Psi v_\mu^a + g'^2\frac{Y}{2}\bar{\Psi}\gamma^\mu\Psi v_\mu^3\right) \tag{5}$$

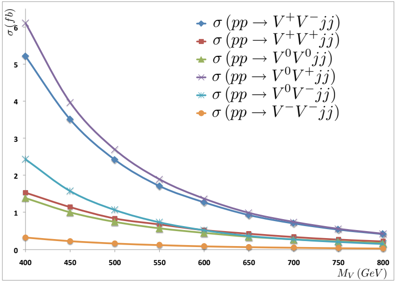


Numerical results for VBF $pp \to WW \to VV$ total cross sections

- Numerical total cross sections at the LHC ($\sqrt{s} = 14$ TeV) as functions of the composite vector mass. The values of the couplings are as in the gauge model, $G_V = 200$ GeV and for the two values $g_K = 1/g_V$ (called *gauge*) and $g_K = 1/(\sqrt{2}g_V)$ (called *composite*).
  Standard acceptance cuts for the forward quark jets: $p_T > 30$ GeV, $|\eta| < 5$



Gauge

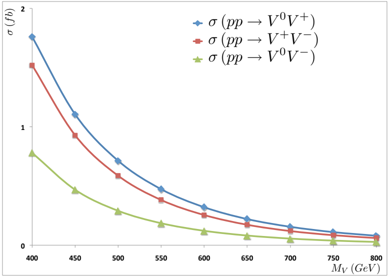


Composite

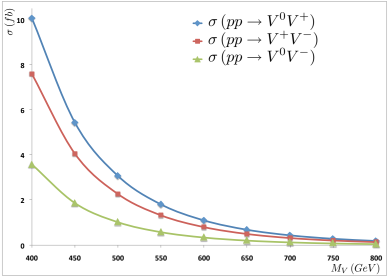
- Deviations from the minimal gauge model result in a great increase of total cross sections

Numerical results for DY $pp \to q\bar{q} \to VV$ total cross sections

- Numerical total cross sections at the LHC ($\sqrt{s} = 14$ TeV) as functions of the composite vector mass with the values of the couplings as in the gauge model, $F_V = 2G_V = 400$ GeV and for the two values $g_K = 1/g_V$ (called *gauge*) and $g_K = 1/(\sqrt{2}g_V)$ (called *composite*):



Gauge



Composite

- Deviations from the minimal gauge model different from that considered here may occur resulting in a further increase of the cross sections

Expected same sign di-lepton and tri-lepton events

- Since $\Gamma\left(V^{\pm} \to W^{\pm} Z\right) \approx 1$ and $\Gamma\left(V^{0} \to W^{+} W^{-}\right) \approx 1$
- The relevant branching ratios are

Table

	same sign 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

- For 100 fb^{-1} at $\sqrt{s} = 14$ TeV the expected numbers of events in a minimal gauge model (MGM) and in a "composite" model (comp) are given by

Table

	di-leptons	tri-leptons
VBF (MGM)	16	3
DY (MGM)	5	1
VBF (comp)	28	6
DY (comp)	18	4

Signal vs background: work in progress

- Partonic events in the LHE (Les Houches) format have been generated with CalcHEP
- These events have been passed to Pythia (by me) and to Herwig (by G. Corcella) to include parton shower, hadronization and underlying event for the study of exclusive observables like total transverse energy H_t or transverse missing energy MET (with kinematical cuts on p_T, η and ΔR currently under discussion with the Turin CMS group)
- As suggested by G. Corcella this study can also lead to a systematic analysis of Pythia vs Herwig
- In order to understand the visibility of a signal it is important to make also a study of the SM background
- The background for the pair production is quite difficult to be simulated since it contains many particles in the final state

Relevant background processes

$$pp \to 4W + 2j \qquad \textit{and} \qquad pp \to 2Z + 2W + 2j$$

where every gauge bosons decays into a pair of fermions

- CalcHEP is not suitable for the study of this background
- It is in program a study of the background with Alpgen

My project of automation

- Although there are many power tools to test models for new physics at three level, the "chain" that brings from a new Lagrangian "written on paper" to the generated events is not completely automated
- My experience: to implement my model and to test it I had to use many tools (FeynRules, CalcHEP, Pythia, Herwig, Alpgen, etc.) and many interfaces more or less evoluted among them
- This is not so "automatic" and not completely "for users"
- I think that it is possible to construct a script (or even a program with a user interface), that manages the interactions among the various tools, realizing a real interface (an example of such a script is given by the CalcHEP Batch script for which I implemented the LSF queue parallelization)
- This is a difficult task, but I think that it is increasingly important, especially in view of the first LHC data, to give to a wide range of users the possibility to quickly tests new physics models

Summary

- A strongly interacting dynamics can be responsible for the EWSB and some new degrees of freedom can become relevant at the Fermi scale
- We studied vectors in the framework of a global $SU(2)_L \times SU(2)_R$ symmetry spontaneously broken to the diagonal subgroup $SU(2)_{L+R}$ by the usual ElectroWeak Chiral Lagrangian for the Goldstone bosons ($\Lambda \approx 3$ TeV)
- In particular we studied the pair production of vector resonances ($M_V < 1$ TeV)
- The general Lagrangian describing these vector states has many parameters
- Gauge invariance takes care of the asymptotic behavior of the various amplitudes up to the cut-off fixing some constraints on the parameter space
- Deviations from the gauge model may occur and the resulting cross sections may be strongly increased
- The Lagrangian was implemented in CalcHEP using FeynRules
- This general framework can probably be tested at the LHC with a large statistics ($\int \mathcal{L} > 100 fb^{-1}$ at $\sqrt{s} = 14$ TeV)
- A careful analysis of the signal and the background is under discussion

The end

The end of this boring presentation...
...but the beginning of a new exciting physics era.

Enjoy the start of the LHC