STRONG WW SCATTERING AND RESONANCES AT LHC

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Abstract

The low energy dynamics of the general strongly interacting symmetry breaking sector can be easily described using effective chiral Lagrangians. Indeed, the enhancement in WW scattering at LHC, that would imply the existence of such an strong interaction, can be described with just two chiral parameters. These techniques have been shown to reproduce remarkably well the low-energy pion-pion scattering data, which follows a similar formalism. In this work we first review the LHC sensitivity to those two chiral parameters (in the hardest case of non-resonant low-energy WW scattering). Later it is shown how we can predict the general resonance spectrum of the strongly interacting symmetry breaking sector. For that purpose, we use the inverse amplitude method which is also very successful reproducing the lightest hadronic resonances from data in the low-energy non resonant region. We thus present an study of the regions in parameter space where one, two or no resonances may appear.

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The Strongly Interacting Symmetry Breaking Sector

In the Standard Model we need a Symmetry Breaking Sector (SBS) in order to explain the masses of the electroweak gauge bosons. Otherwise, the interactions of these particles would not be renormalizable and would violate unitarity. This fact is specially evident in the scattering of longitudinal gauge bosons ($V_L$).

The simplest model of $SU(2)_L \times U(1)_Y$ spontaneous breaking, preserves renormalizability and restores unitarity by adding a complex doublet to the Standard Model (SM). Three of these new degrees of freedom are nothing but the Goldstone Bosons (GB) that become the longitudinal components of the gauge bosons through the Higgs mechanism. The remaining scalar field, known as the Higgs boson, should be observable. That is the Minimal Standard Model (MSM). But this is not the only way to build the SBS. Indeed there are other models with many more particles like the Higgs, no Higgs at all, vector fields, etc... whose masses are expected in the range of a few TeV or less.

If we do not find at LHC particles much lighter than 1 TeV belonging to the SBS, then the interactions of longitudinal gauge bosons would grow until they become strong. In such case, we expect an enhancement in the process $V_L V_L \rightarrow V_L V_L$ at LHC. Another typical feature of strong interactions that saturate unitarity are resonances, and we also expect that some of them would show up at LHC. The above two sentences about the strongly interacting SBS may seem too vague. In addition, strong models are non-perturbative and it is pretty hard to obtain reliable predictions on observables or on the possible resonances. That is why here we will address the following two questions:

What could we measure?
What resonance spectrum do we expect?

The Electroweak Effective Chiral Lagrangian

The underlying theory that breaks the SM $SU(2)_L \times U(1)_Y$ group down to $U(1)_{EM}$ is unknown to a large extent. Basically, what we know is the following:

- There should be a system with a global symmetry breaking yielding three GB.
- The scale of this new interactions is $v \approx 250$ GeV.
- The electroweak $\rho$ parameter is very close to one.

This last requirement is most naturally satisfied if the electroweak SBS respects the so called custodial symmetry $SU(2)_{L+R}$\(^1\). Demanding just three GB, we are lead to a breaking from $SU(2)_L \times SU(2)_R$ down to $SU(2)_{L+R}$\(^2\,3\). Most of the models of symmetry breaking, including the Minimal Standard Model follow this breaking scheme. Formally it is the same breaking pattern of the chiral symmetry in QCD with just two massless quarks. Although a rescaled version of QCD is not valid in our case, we can still borrow the formalism\(^4\), which works remarkably well with the pion-pion scattering data\(^5\).

In our case we are interested in the longitudinal gauge bosons, which somehow are equivalent to the GB. Hence, the chiral lagrangian is built as a derivative expansion using GB fields. In the amplitudes, the derivatives become external momenta or energy. It is therefore a low-energy expansion. There is only one possible term with two derivatives that respects the above
symmetry breaking pattern:

$$L^{(2)} = \frac{v^2}{4} \text{tr} D_\mu U D^\mu U^\dagger$$

(1)

where the GB fields $\pi^i$ are collected in the $SU(2)$ matrix $U = \exp(i\pi^i \sigma^i/v)$ and $D_\mu$ is the usual $SU(2)_L \times U(1)_Y$ covariant derivative. It is important to remark that the above lagrangian only depends on the symmetry structure and the scale. Its predictions for $V_L V_L$ scattering are universal. The dependence on the different models appears at next order through two phenomenological parameters:

$$L^{(4)} = L_1 (\text{tr} D_\mu U D^\mu U^\dagger)^2 + L_2 (\text{tr} D_\mu U D^\nu U^\dagger)^2$$

(2)

Notice that we have only given the operators which are relevant for $V_L V_L \rightarrow V_L V_L$ (working also at lowest order in the electroweak corrections). Nevertheless, we have to keep in mind that this formalism is only valid when there are no light ($\simeq$ few hundred GeV) particles. Otherwise we should have to include such states in our description.

The values of $L_1$ and $L_2$ depend on the model, but we expect them to be in the range $10^{-2}$ to $10^{-3}$. In Table 1 we give the values for two reference models: the MSM with a 1 TeV Higgs as well as for a QCD-like model.

We therefore have an answer to the first question. In case the SBS is strongly interacting, we can measure the chiral parameters $L_1$ and $L_2$. We will now review a study of the LHC sensitivity to the chiral parameters in the hardest non-resonant case.

In Table 2 we give the statistical significance ($s=$signal/$\sqrt{\text{backg.}}$) to distinguish between the ”zero model” (where all the couplings are set to zero) and a model with some given values of $L_i$. Following we give results for 400fb$^{-1}$ of integrated luminosity at $\sqrt{s}$=14TeV. That corresponds to both experiments working at full design luminosity during two years. We only consider the processes $W^\pm Z^0 \rightarrow W^\pm Z^0$ and $W^+ W^- \rightarrow Z^0 Z^0$ in the cleanest decays, where the $W$’s and the $Z$’s decay to $\nu_e e, \nu_\mu \mu$ and $e^- e^+, \mu^- \mu^+$, respectively. For further details on the calculation we refer to [?]. Notice that we are giving statistical significances with and without ”jet tagging”, that could help us to separate $V_L V_L$ scattering from other processes involving quarks. We will comment the results in the conclusions.

**Resonance spectrum**

Resonances and the saturation of unitarity are the most characteristic features of strong interactions. In our case, we expect them to appear at the TeV scale. For instance, the MSM becomes strong when $M_H \simeq 1$TeV. In such case we expect a very broad scalar resonance around 1 TeV. In QCD-like models one expects a vector resonance around 2 TeV.

| Reference Model          | $L_1$  | $L_2$  |
|--------------------------|--------|--------|
| MSM ($M_H \sim 1$ TeV)   | 0.007  | -0.002 |
| QCD-like                 | -0.001 | 0.001  |

Table 1: Chiral Parameters for different reference models.
Chiral lagrangians by themselves are not able to reproduce resonances. Their amplitudes are obtained as polynomials in the momenta and masses, and therefore they do not even satisfy unitarity. There is however a technique, known as the Inverse Amplitude Method (IAM), that is able to unitarize these amplitudes. When applied to pion and kaon physics, it has successfully reproduced the lowest resonances \(^9\)). In the electroweak context it has been applied to the reference models \(^{10}\). Using the parameters in Table 1, a Higgs-like or a technirho are found in their corresponding models.

What we present in Figure 1 is a scan of the \(L_1, L_2\) parameter space using the IAM. Using this method it is possible to obtain an estimate of the mass and width of the resonances that would appear at LHC (below 3 TeV), depending on the values of the chiral parameters \(^{11}\)). We can find three types of resonances:

- Neutral and scalar. The usual Higgs boson is the typical example, that is why we will denote them as \(H\). If the width becomes larger than 25% of the mass we will call them \(S_0\) (saturation).
- Charged and vector-like. For example the technirho that appears in QCD-like models. Generically we will denote them by \(\rho\). Again, if they become too wide we will call them \(S_1\).
- Doubly charged and scalar. There are only models where they are very light. In this channel, some values of the chiral parameters are forbidden due to conflicts with renormalizability \(^{12}\)) and causality \(^{11}\)). Such parameters correspond to the black area. Only very broad saturation shapes are admitted, but in any case they should be interpreted as resonances.

**Conclusions**

- The study of this kind of physics will require the ultimate performance at LHC (\(\sqrt{s}\), and integrated luminosity), as well as in the detectors (jet tagging efficiency, etc).
- It seems possible to determine \(L_1\) and \(L_2\) to the 3\(\sigma\) level if their absolute value is not smaller than \(10^{-3}\) (See Table 2). A precision of \(10^{-3}\) seems extremely hard to achieve.
- Depending on the values of \(L_1\) and \(L_2\) we could find one or two resonances, a resonant channel and another one with saturation, or two channels with saturation. (See Figure 1)
- It is even possible that we do not see any resonance at all at LHC (grey area in Figure 1). The corresponding values of the \(L_i\) are \(\simeq 10^{-3}\) and thus it could be possible that we do not get any clear signal of strong interactions at LHC.

|                  | \(L_1\)    |                  | \(L_2\)    |
|------------------|------------|-----------------|------------|
| \(s_{W^\pm Z^0}\) | \(10^{-2}\) | \(10^{-2}\)     | \(5 \times 10^{-3}\) |
| \(s_{Z^0}\)     | \(1.4\)    | \(5.2\)         | \(1.2\)    |
|                  | \(10^{-2}\) | \(10^{-2}\)     | \(5 \times 10^{-3}\) |
| \(s_{W^\pm Z^0\ tagging}\) | \(2.0\)    | \(8.4\)         | \(1.8\)    |
| \(s_{Z^0Z^0\ tagging}\) | \(13.2\)   | \(3.6\)         | \(4.6\)    |

Table 2: Statistical significances for different values of \(L_1\) and \(L_2\) at LHC.
Figure 1.- The different areas in parameter space represent what resonances or saturation effects appear for different $L_1, L_2$ parameters. There could be neutral scalar ($H$) or charged vector ($\rho$) resonances, as well as saturation effects in the neutral scalar ($S_0$), charged vector ($S_1$) or doubly charged scalar channel ($S_2$).

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