IL NUOVO CIMENTO Vol. 32 C, N. 3-4 Maggio-Agosto 2009
DOI 10.1393/ncc/i2009-10462-0

Colloquia: IFAE 2009

Probing EWSB through vector boson scattering at the LHC

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(ricevuto il 19 Settembre 2009; pubblicato online il 20 Novembre 2009)

Summary. — We estimate the power of the LHC in probing effects of strongly interacting symmetry breaking sector through vector boson scattering in a complete partonic analysis.

PACS 24.10.Lx – Monte Carlo simulations.
PACS 11.15.Ex – Spontaneous breaking of gauge symmetries.
PACS 12.60.-i – Models beyond the standard model.

1. – Introduction

The high-energy behaviour of Longitudinal Vector Boson Scattering (LVBS), $V_L V_L \to V_L V_L$, reflects the strength of the interactions in the symmetry breaking (SB) sector. The SM with a light Higgs predicts a big suppression of longitudinal boson scattering and a weakly coupled symmetry breaking sector, while without the Higgs LVBS grows with the scattering energy s and must be cut off by new strong dynamics at higher scales [1].

Heavy resonances from the SB sector are possible at LHC energy scale, however an equally likely signature is simply an excess of events at high energy in comparison with the SM predictions. This excess of events can be mimicked by the SM without the Higgs, whose predictions can be compared with more specific models. For instance, a promising alternative to the complete replacement of the Higgs mechanism is to interpret the Higgs as a pseudo-Goldstone boson of a new strongly interacting sector [2]. This class of models predicts in general a smaller excess than the *No Higgs* (NOH) case. On the other hand, models with lighter resonances normally predict a larger excess of events. Residing on this frontier, the NOH model represents a benchmark scenario for the study of strong SB dynamics.

A recent study [3] has estimated the power of the LHC to distinguish the *No Higgs* scenario from the SM through VBS in a complete partonic analysis of the $\mu\nu + 4$ jets channel. This result, complemented with the others important still unpublished channels, are presented in the following.

The only way to observe VBS at LHC is by looking at the vector bosons through their decays into fermions. Therefore, $V_L V_L \to V_L V_L$ is necessarily embedded in a more general gauge-invariant set comprehending all processes with six-parton final states. In order to have a good description of the high-energy behaviour of such processes it is necessary to compute the complete set of Feynman diagrams taking into account all

TABLE I. – *Expected number of events for $L = 200\,\mathrm{fb}^{-1}$ after all cuts, for each perturbative order. The contribution from the QCD background is essentially the same for the No Higgs and the SM case.*

Channel	$\mathcal{O}(\alpha_{\mathrm{EM}}^6)$(SM)	$\mathcal{O}(\alpha_{\mathrm{EM}}^6)$(NOH)	$\mathcal{O}(\alpha_{\mathrm{EM}}^4\alpha_S^2)$	$\mathcal{O}(\alpha_{\mathrm{EM}}^2\alpha_S^4)$
$4j\ell\nu$	128.4	381.6	92	1956
$4j\ell^+\ell^-$	10.6	52.8	8.8	220
$2j\ell^+\ell^-\ell'\nu$	2.8	9.9	0.8	0

irreducible backgrounds and their interferences with signal topologies, because of large gauge cancellations [4]. We have analyzed, from this six-parton perspective, the following channels: $pp \to 4j\ell\nu$, $pp \to 4j\ell^+\ell^-$ and $pp \to 2j\ell^+\ell^-\ell'\nu$, where j stands for any quark or gluon and ℓ, ℓ' for muons or electrons. Using the `PHANTOM` [5] event generator, a MC dedicated to processes with six partons in the final state, we have generated the electroweak part, $\mathcal{O}(\alpha_{\mathrm{EM}}^6)$, for the light Higgs and the *No Higgs* scenarios, and the $\mathcal{O}(\alpha_{\mathrm{EM}}^4\alpha_S^2)$ QCD background. For the $\mathcal{O}(\alpha_{\mathrm{EM}}^2\alpha_S^4)$ V+4jets QCD background of the semi-leptonic channels, we have used `MADEVENT` [6].

2. – Complete partonic analysis

The VBS experimental signature can be basically described by the presence of tag jets, two very energetic jets in the forward-backward direction, and two pairs of fermions associated with VB decays in the central region, with high transverse momenta. We have performed a cut-based selection in order to simultaneously characterize the signal and suppress the background for each channel, with the aim to optimize the probability to obtain experimental results outside the 95% confidence region (PBSM at 95% CL) for the SM, assuming the *No Higgs* scenario.

For tagging jets we required $\Delta\eta(j_f j_b) > 4.8$ and $M(j_f j_b) > 1000\,\mathrm{GeV}$. For the characterization of leptonic vector bosons we used $|\eta(\ell^\pm)| < 2$ and $p_T(V_{\mathrm{rec}}) > 200\,\mathrm{GeV}$. In the semi-leptonic channels, the dominant background is $V + 4$ jets, pushing us to a very tight characterization of the hadronic vector boson: we required $p_T(j_c) > 60\,\mathrm{GeV}$ and $70\,\mathrm{GeV} < M(j_c j_c) < 100\,\mathrm{GeV}$. For the isolation of both reconstructed bosons we imposed $\Delta\eta(Vj) > 0.6$. In addition, a further specialized set of cuts was applied to each channel to help in distinguishing the scenarios. For instance, in the $4j\ell\nu$ channel, top rejection is quite important. The expected numbers of events for $L = 200\,\mathrm{fb}^{-1}$ for each channel after all cuts are reported in table I.

The probability distribution for each scenario was computed by taking the MC prediction (table I) as the mean value and then estimating the associated uncertainties. We have assumed a Poissonian statistical distribution and modeled the theoretical uncertainty due to parton distributions, scale dependence and higher-order corrections with a 30% flat smearing around the mean value. For the semi-leptonic channels, the theoretical error for $V + 4$ jets totally overwhelms the possibility of appreciating differences between the scenarios. Fortunately, at LHC, it will be possible to get rid of this uncertainty using side-band techniques. The mass distribution of the central jets, $M(j_c j_c)$, is characterized by a peak in the range 70–100 GeV, due to vector boson decays. The peak is surrounded by a slowly varying region populated by jet pairs from the $V + 4$ jets

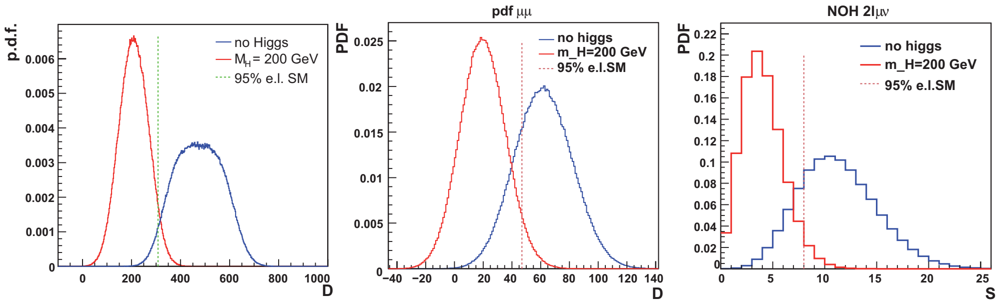

Fig. 1. – (Colour on-line) Probability distribution of the SM (red) and *No Higgs* (blue) scenarios. The vertical line is the 95% exclusion limit of the SM. The PBSM at 95% CL is reported in parentheses. The channels, from left to right, are: $4j\ell\nu$ (96.8%), $4j\ell^+\ell^-$ (77.1%) and $2j\ell^+\ell^-\ell'\nu$ (80.0%).

background. This almost flat distribution can be measured and interpolated to the peak region, providing an estimate of the $V + 4$ jets background which is free of theoretical errors.

Finally, we defined a discriminator D, which estimates the excess of events above the measured side-bands taking into account the theoretical and statistical errors of $\mathcal{O}(\alpha_{\rm EM}^6)+\mathcal{O}(\alpha_{\rm EM}^4\alpha_S^2)$ and the statistical errors of $V+4$ jets background. For the leptonic channel we directly used the number of events subjected to all sources of errors. Figure 1 shows the probability distributions for $L = 200\,\text{fb}^{-1}$ of the *No Higgs* and SM scenarios. The vertical line represents the 95% exclusion limit for the SM, which defines the PBSM at 95% CL for the *No Higgs* scenario. The PBSM at 95% CL is reported in the caption of fig. 1.

2·1. *Hadronic decays of vector bosons and jet algorithms.* – LVBS in the semi-leptonic channels contains a high-p_T vector boson decaying into two jets. These two jets are very likely to be quite close in η-ϕ space. Consequently, the choice of an appropriate jet algorithm plays an important role for this kind of analysis. We examine this problem in fig. 2, where the probability distributions are shown for different requirements on the minimum ΔR separation between jets. The large loss in discriminatory power is evident

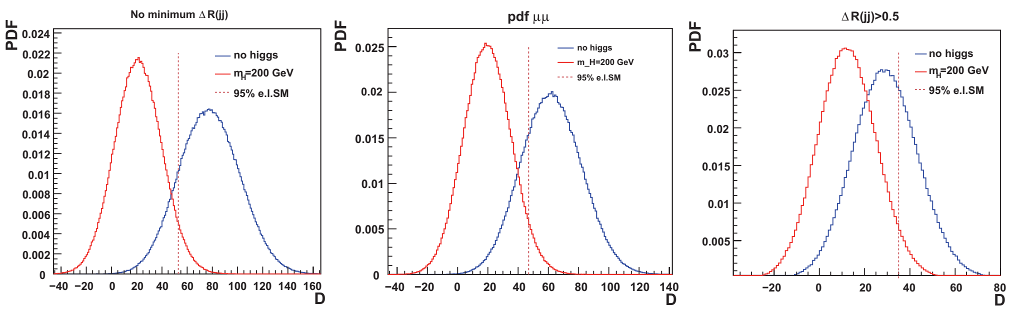

Fig. 2. – (Colour on-line) Probability distribution of SM (red) and *No Higgs* (blue) scenarios in the $4j\ell^+\ell^-$ channel, for different requirements on the minimum $\Delta R(jj)$ separation. From left to right: no $\Delta R(jj)$ requirement, $\Delta R(jj) > 0.3$, $\Delta R(jj) > 0.5$.

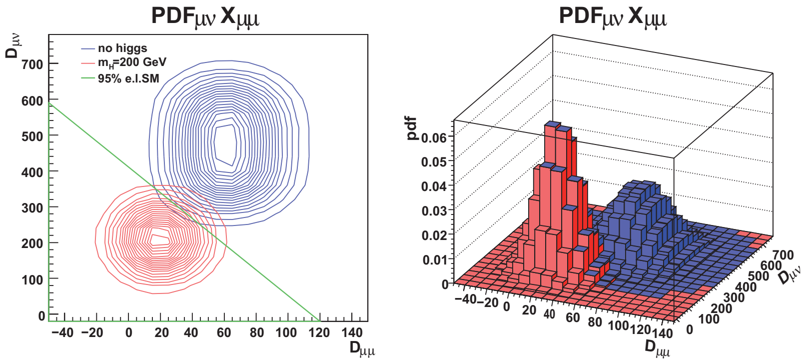

Fig. 3. – (Colour on-line) Probability distribution of SM (red) and *No Higgs* (blue) scenarios in terms of the discriminant of the semi-leptonic channels combined. The green line refers to the 95% exclusion limit for SM.

as the distributions merge into each other as the cone is enlarged. This problem must be understood and tackled in a hadronic environment, eventually testing alternative jet algorithms other than the cone-based ones.

2·2. *Combined channels*. – In order to have a better overall estimate of the discriminatory power of the full analysis, it is useful to combine all channels. In fig. 3, the procedure is illustrated for the combination of semi-leptonic channels. In order to define the surface that represents the 95% exclusion limit of the SM, we have used a criterion based on a likelihood-ratio test, separating the points in which the ratio of the *No Higgs* to the SM probability is less than a certain value a. The resulting PBSM at 95% CL are: 99.2% combining the semi-leptonic channels and 99.9% combining all three channels.

3. – Conclusions

We have estimated the power of the LHC in distinguishing the *No Higgs* scenario from the SM. For this, we have performed a complete partonic analysis generating full six-partons final states. We have developed a strategy to suppress the main backgrounds using strong selection cuts, aiming at optimizing the PBSM at 95% CL. With this approach we obtain a precise probabilistic meaning of the discriminatory power, which has been generalized to the combination of many channels. The final results show a very good discriminatory power between the scenarios. The important issue of resolving the hadronic decays of vector bosons must be better understood.

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