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# Exploring alternative symmetry breaking mechanisms at the LHC with 7, 8 and 10 TeV total energy

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**ABSTRACT:** In view of the announcement that in 2012 the LHC will run at 8 TeV, we study the possibility of detecting signals of alternative mechanisms of ElectroWeak Symmetry Breaking, described phenomenologically by unitarized models, at energies lower than 14 TeV. A complete calculation with six fermions in the final state is performed using the PHANTOM event generator. Our results indicate that at 8 TeV some of the scenarios with TeV scale resonances are likely to be identified while models with no resonances or with very heavy ones will be inaccessible, unless the available luminosity will be much higher than expected.

**KEYWORDS:** Beyond Standard Model, Standard Model

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## 1 Introduction

Tantalizing hints of a 125 GeV Higgs boson have been recently reported by both ATLAS, CMS [1, 2] and, more recently, by CDF and D0 [3]. However the evidence is not yet conclusive and the possibility that the excess of events is nothing more than a statistical fluctuation cannot be ruled out. In the meanwhile the allowed range for the Higgs mass continues to shrink. In this context, the role played by high energy vector boson scattering, either as the final test of the nature of the Higgs boson or as the main testing ground for Beyond the Standard Model descriptions of ElectroWeak Symmetry Breaking (EWSB), remains as crucial as ever.

In previous works [4–6], we have shown that at 14 TeV the LHC will very probably be able to determine whether the symmetry breaking sector interacts strongly. If there are heavy resonances around the TeV scale, with  $50 \text{ fb}^{-1}$  of integrated luminosity it will be possible to observe an excess of events in Vector Boson Scattering (VBS) with respect to the SM predictions. If no heavy resonances are present or they are much heavier than the accessible scale, the LHC, with a higher luminosity of about  $100 \text{ fb}^{-1}$ , will still produce an excess of events sufficient to determine the strong nature of the symmetry breaking sector. If a Higgs is discovered, distinguishing a composite Higgs from an elementary and weakly coupled one using only VBS data may require a very large luminosity, possibly above  $400 \text{ fb}^{-1}$ .

The LHC is scheduled to operate at low energy until the end of 2012. It has been recently announced that the center of mass energy for the 2012 run will be 8 TeV, as widely expected. In this paper we discuss the possibility of detecting signals of unitarized models of EWSB at the LHC with 7, 8 and 10 TeV total energy. The 7 TeV case corresponds to the energy of the 2011 run. To our knowledge an analysis of VBS based on last year data set has not been published, yet. Despite the modest luminosity, it would provide a useful warm up exercise and allow validation of the theoretical description of the dominant backgrounds. The 10 TeV case refers to the possibility that after the long shutdown following the 2012 run, the LHC might resume operation at an energy lower than 14 TeV. A comparison of

the results for the three energies with those at 14 TeV presented in [6] illustrates the effects of the LHC energy on these kind of studies where high mass final states are looked for.

QCD corrections to boson-boson production via vector boson fusion [7–10] at the LHC have been computed and turn out to be below 10%. VBFNLO [11], a Monte Carlo program for vector boson fusion, double and triple vector boson production at NLO QCD accuracy, limited to the leptonic decays of vector bosons, has been released. First results for the NLO corrections to  $W + 4j$  production have appeared [12].

## 2 Unitarized Models and their parameters

As an alternative to full model building it is possible to capture the generic behaviour of any symmetry breaking scheme using EffectiveField Theory (EFT) methods, in particular the ElectroWeak Chiral Lagrangian (EWChL) [13–19]. The EWChL provides a systematic expansion of the full unknown Lagrangian in terms of the fields which are relevant at energies much lower than the symmetry breaking scale and does not require a detailed knowledge of the full theory.

Introducing the matrix

$$\Sigma(x) = \exp\left(\frac{i\sigma^a\omega^a(x)}{v}\right), \tag{2.1}$$

where  $\sigma^a$  are the Pauli matrices and  $v \approx 246$  GeV is the decay constant of the Goldstone bosons  $\omega^a(x)$  ( $a = 1, 2, 3$ ), which gives the correct masses to the vector ones, the only two dimension-4 operators which respect all required symmetries and are relevant for the study of VBS are:

$$\mathcal{L}_4 = \alpha_4 (\text{Tr}[V^\mu V^\nu])^2, \tag{2.2}$$

$$\mathcal{L}_5 = \alpha_5 (\text{Tr}[V_\mu V^\mu])^2, \tag{2.3}$$

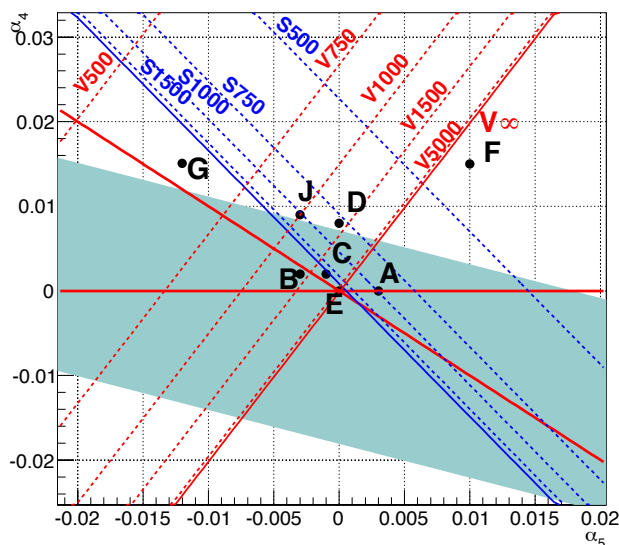
where  $V_\mu \equiv (D_\mu \Sigma) \Sigma^\dagger$ .

It is then possible to apply Unitarization Methods, using the lowest order terms in the scattering amplitudes as building blocks of all order expressions which respect unitarity at arbitrary energy and agree up to a finite order with the perturbative result.

A number of unitarization schemes have been implemented in the PHANTOM event generator [20], within a full six partons in the final state framework, as described in [6] to which we refer for additional details.

Possible models are characterized by the unitarization scheme and by the values of the chiral parameters  $\alpha_4, \alpha_5$  in eqs. (2.2), (2.3). The value of these parameters affect the low energy predictions, and therefore are constrained by data.

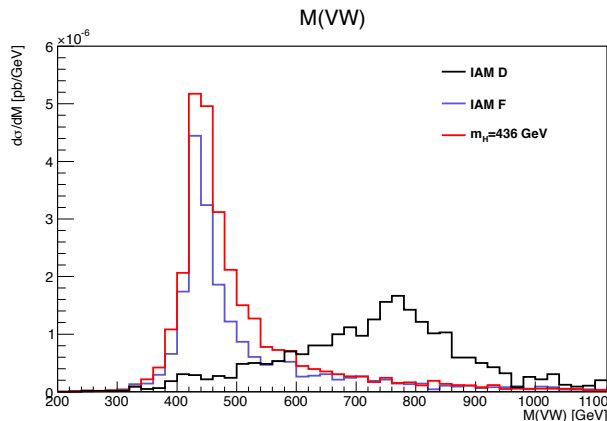
The most stringent constraints come from their contribution to the  $T$ -parameter [24]. In calculations where dimensional regularization has been used [21, 25], the logarithmic divergent contributions to the  $T$ -parameter are weakly dependent on the cut-off scale and are small, according to [26]:  $-0.32 < \alpha_4 < 0.085$  and  $-0.81 < \alpha_5 < 0.21$  at 99% CL with a cut-off scale  $\Lambda = 2$  TeV. In [22], it was argued that there are quadratic divergences hidden by the dimensional regularization procedure, then, using a higher-derivatives regularization,



**Figure 1.** Allowed region for the  $\alpha_4, \alpha_5$  parameters [21–23]. The dotted lines indicate the mass of resonances generated in the IAM method, and the solid blue and red lines give the limits below which no resonance of the corresponding type is generated. The two solid black lines correspond to the unitarity and causality constraints derived in [23]. The dots and the corresponding capital letters correspond to the models we have studied in [6] and here.

the quadratic divergent contributions to the  $T$ -parameter have been derived. The resulting allowed region in the  $(\alpha_4, \alpha_5)$  plane is shown by the solid band in figure 1, where  $\Lambda_B = 2 \text{ TeV}$  has been assumed, which we intend as a lower limit for this parameter. Arguments based on unitarity and causality also constrain these parameters [23] and the associated limits are indicated with the black lines. In figure 1 the dots show the vector and scalar resonance masses [27, 28] produced by the Inverse Amplitude Method (IAM) as a function of the chiral parameters in the scenarios we have studied in [6] and here.

Models A, B, C, D, E have already been considered in [6, 29] for an LHC center of mass energy of 14 TeV. For our present study, we have selected three representative scenarios of a strong symmetry breaking sector, all of them are instances of the Inverse Amplitude Method of unitarization. The IAM procedure has the nice feature that, beside the perturbative expansion of the amplitude obtained from the EWChL plus the additional terms in eq. (2.2), no additional parameters is used. The resonances are produced by the method itself. On the contrary, in the KM method resonant states must be introduced by hand. We have considered one scenario without resonances, with chiral parameters  $(0, 0)$ , called IAM E, which is slightly enhanced with respect to the no-Higgs scenario due to the higher order terms. This model has the smallest cross section for the processes we study here, while in the  $2j\ell^\pm\ell^\pm\nu\nu$  channel, where no resonance is present, its production rate is typically larger than the rate in models which contain resonant states [6]. As a consequence, the IAM E model is the most difficult one to detect among all instances we have examined for this study and represents the lower limit for the possible effects of



**Figure 2.**  $VV$ -system mass distribution in the  $\ell\nu + 4$  jets channel at 7 TeV at  $\mathcal{O}(\alpha_{EM}^6)$  for the IAM D, IAM F models and for the SM with  $m_H = 436$  GeV. The selection cuts shown in table 1 have been applied.

unitarized models. In the second scenario, IAM G with parameters  $(15, -12) \times 10^{-3}$ , a 0.6 TeV vector resonance dominates the scattering cross section. This is an example of models with light resonances. A third scenario, IAM J with parameters  $(9, -3) \times 10^{-3}$ , contains a scalar and a vector resonance, both at 1 TeV, and can be taken as representative of models with relatively heavy resonances which, however, are not so heavy to be totally undetectable at the energies which will be available next year.

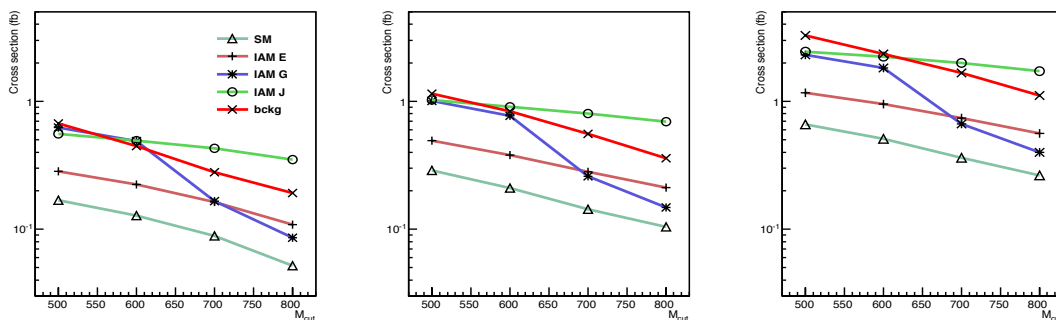
Models in which only scalar resonances are expected have been neglected because their predictions are very similar to those obtained in the SM for a Higgs of the same mass and therefore, the prospect for their discovery can be inferred from the detailed studies dedicated to the SM Higgs searches. This behaviour is demonstrated in figure 2 where the mass distribution of the  $VV$ -system in the  $\ell\nu + 4j$  channel is shown for three different scenarios at 7 TeV. The IAM F scenario, with parameters  $(15, 10) \times 10^{-3}$ , admits a 436 GeV scalar resonance. It is compared with the SM with a 436 GeV Higgs boson and with the IAM D scenario,  $(8, 0) \times 10^{-3}$ , studied in a previous work [6], with a scalar resonance at 0.8 TeV and a vector one at about 1.4 TeV. Comparing figure 2 with figure 2 of ref. [6], it can be noticed that the 1.4 TeV resonance has essentially disappeared. As a consequence we have limited ourselves to models with relatively light resonances.

### 3 Results

We have concentrated on the three final states which are most relevant for detecting strong scattering signals: the  $\ell\nu + 4$  jets semi-leptonic channel, the  $2jW^+W^- \rightarrow 2j\ell^+\ell^-\nu\bar{\nu}$  channel and the  $3\ell\nu + 2$  jets channel which is useful in the search for vector resonances. In table 1, we show the set of kinematical cuts applied in each of these channels in order to enhance the discrepancy between the strong scenarios and the predictions of the Standard Model with a light Higgs and to improve the signal to background ratio. In this paper we have taken the Higgs mass to be 170 GeV. The exact value of this parameter, within the limits derived from precision data, is immaterial. A detailed analysis of kinematical cuts and

$p_T(j) > 30 \text{ GeV}$	$p_T(\ell) > 70/70/20 \text{ GeV}$
$p_T^{miss} > 70/20/20 \text{ GeV}$	$p_T(j_c) > 70 \text{ GeV}$
$\eta(j) < 6.5$	$\eta(\ell) < 2/2/3$
$\Delta\eta(j_f j_b) > 4/4/3$	$\Delta\eta(V_{rec} j) > 0.6$
$\Delta R(jj) > 0.3$	$M(\ell\ell) > 20 \text{ GeV}$
$M(jj) > 60 \text{ GeV}$	$M(j_f j_b) > 700/600/100 \text{ GeV}$
$p_T(V_{rec}) > 70/100 \text{ GeV}$	$ M(V_{rec} j) - M_{TOP}  > 15 \text{ GeV}$
$M(j\ell) > 180 \text{ GeV}$	$ p_T(\ell^+) - p_T(\ell^-)  > 100 \text{ GeV}$

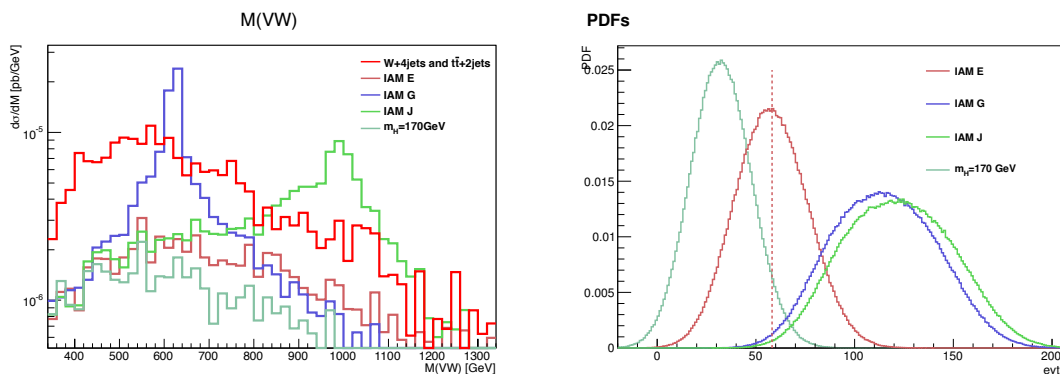
**Table 1.** Kinematical cuts applied on the analysis. Different values correspond to different channels in the order  $4j\ell\nu$ ,  $2j\ell\ell\nu$  and  $2j3\ell\nu$ .  $j_f, j_b$  refer to the most forward and most backward of the jets.  $j_c$  indicates one of the central jets in the  $4j\ell\nu$  channel.  $V_{rec}$  stands for the boson which is reconstructed from the lepton and neutrino momenta, the latter obtained from the requirement that  $(p_\ell + p_\nu)^2 = M_W^2$  and is meaningful only for  $4j\ell\nu$  and  $2j3\ell\nu$ . The constraints on the last line apply only to the  $2j\ell\ell\nu$  channel.



**Figure 3.** Cross section in femtobarns after all selection cuts in table 1 for 7, 8 and 10 TeV of center of mass energy at four different values of the minimum invariant mass of the reconstructed  $VV$ -system in the  $\ell\nu + 4$  jets channel for the IAM E, IAM G and IAMJ models. The lines are only meant to guide the eye. For comparison we show also the SM predictions for  $m_H = 170 \text{ GeV}$  and the background from  $V + 4j$  and  $t\bar{t} + jets$  production.

of the optimization of exclusion probabilities is presented in [4–6]. Here we use a looser set of cuts to compensate for the lower energies. It should be pointed out that, while a cut based treatment is perfectly adequate for a preliminary analysis at parton level, a more sophisticated Multi Variate Analysis would certainly provide better results. On the other hand a more realistic implementation of experimental uncertainties and hadronization effects would in all likelihood work in the opposite direction. The results of all channels, including those not discussed in the following, could be combined in order to improve the sensitivity.

The semi-leptonic channel with one charged lepton, electron or muon, and four jets in



**Figure 4.** On the *left*, the invariant mass distribution of the two central jets, the lepton and the reconstructed neutrino (according to prescription of [4])  $M(j_c j_c \ell \nu)$  for  $\sqrt{s} = 10$  TeV. On the *right*, probability distribution of the number of events above the measured background for  $50 \text{ fb}^{-1}$  and  $M_{\min}(VV) > 500$  GeV. The vertical line indicates the 95%CL in the SM.

the final state gives the best discriminating power because of its high rate. Both vector and scalar resonances are produced. Figure 3 shows the cross section after all selection cuts in table 1, for 7, 8 and 10 TeV center of mass energy and for different minimum invariant mass of the  $VV$  reconstructed system, whose distribution for  $\sqrt{s} = 10$  TeV is shown on the left side of figure 4. At 7 TeV, with  $25 \text{ fb}^{-1}$  and  $M_{\min}(VV) > 500$  GeV, 7 events above background can be expected for the IAM E model, to be compared with a SM EW prediction of 4 events and a background of about 16 events. These numbers increase to 29 and 16 at 10 TeV for the IAM E model and for the SM respectively. The corresponding predictions for the background is 86 events. The IAM E scenario is the most unfavourable one since it does not predict any type of resonance.

The Probability Distribution Functions (PDFs) of the number of events expected for each scenario at  $50 \text{ fb}^{-1}$  of integrated luminosity, with 10 TeV of center of mass energy and considering  $VV$ -system masses above 500 GeV is shown on the right side of figure 4. Here and in the following, the PDF's are computed assuming Poissonian statistical fluctuations of the number of events computed by the MC and a theoretical error on the number of signal events which we model as a flat distribution of  $\pm 30\%$  from the actual value [4, 5]. It is important to remark that we consider  $W + 4$  jets and  $t\bar{t} + 2$  jets as backgrounds which can be precisely measured in complementary regions of phase space, hence unaffected by theoretical uncertainties. The contributions from  $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ , on the other hand, which describe the production of two vector bosons in association with a pair of jets, are affected by both theoretical and statistical uncertainties.

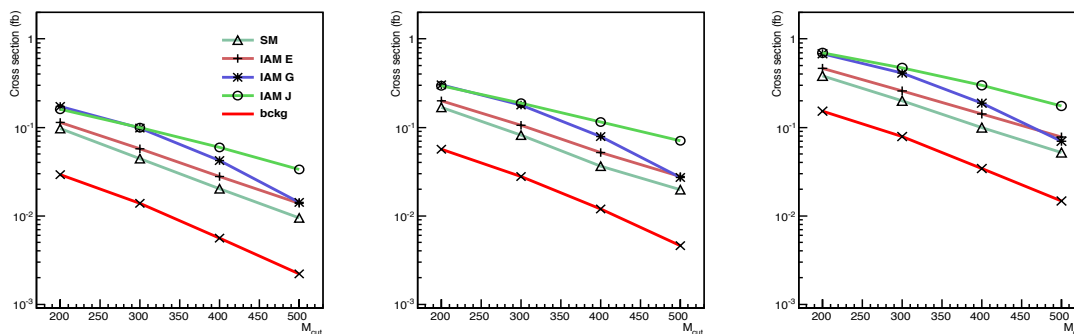
In the plot the vertical line represents the 95% limit of the light Higgs distribution. We therefore compute what we call the PBSM@95%CL (Probability Beyond the SM at 95% Confidence Level) for the various scenarios as the probability that a number of events larger than the 95% limit occurs.

The PBSM@95%CL assuming one of the three alternative models is reported in table 2. The IAM G and IAM J scenarios, with resonances at or below one TeV, have a better than 70% chance to yield results outside the 95% CL for the SM already at 7 TeV with  $25 \text{ fb}^{-1}$ ,



	IAM E			IAM G			IAM J		
L\E	7	8	10	7	8	10	7	8	10
25	16.06 <sup>a</sup>	19.03 <sup>a</sup>	35.37 <sup>b</sup>	71.10 <sup>a</sup>	75.48 <sup>a</sup>	93.80 <sup>a</sup>	73.32 <sup>d</sup>	81.77 <sup>d</sup>	99.32 <sup>d</sup>
50	22.70 <sup>a</sup>	27.88 <sup>a</sup>	51.56 <sup>b</sup>	89.14 <sup>a</sup>	91.68 <sup>a</sup>	99.12 <sup>a</sup>	91.55 <sup>d</sup>	95.62 <sup>d</sup>	99.99 <sup>d</sup>
100	33.51 <sup>a</sup>	41.08 <sup>a</sup>	69.28 <sup>c</sup>	97.85 <sup>a</sup>	98.54 <sup>a</sup>	99.97 <sup>a</sup>	98.89 <sup>d</sup>	99.66 <sup>e</sup>	100 <sup>d</sup>
200	48.25 <sup>b</sup>	57.08 <sup>a</sup>	83.44 <sup>c</sup>	99.87 <sup>a</sup>	99.93 <sup>a</sup>	100 <sup>a</sup>	99.97 <sup>d</sup>	100 <sup>d</sup>	100 <sup>d</sup>

**Table 2.** PBSM@95%CL in the  $\ell\nu + 4$  jets channel with 25, 50, 100 and 200  $\text{fb}^{-1}$  of integrated luminosity, L. For each luminosity and model we have used the mass cut which gives the best probability. They are specified by the superscript according to the following scheme: <sup>a</sup>, <sup>b</sup>, <sup>c</sup>, <sup>d</sup>, <sup>e</sup> for 500, 600, 700, 800, 900 GeV respectively.



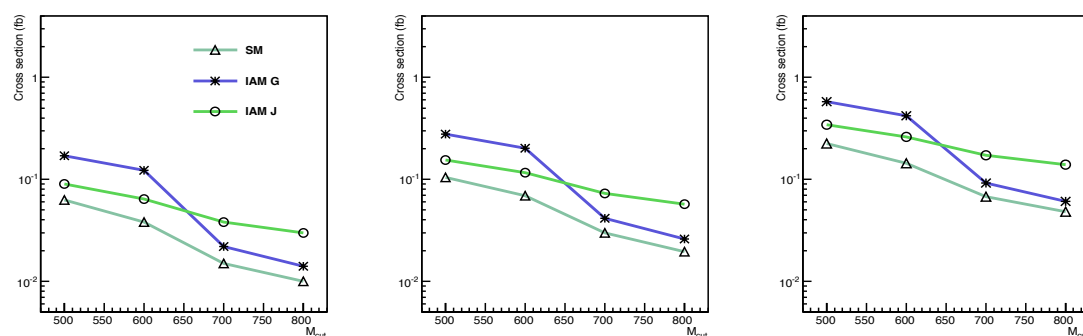
**Figure 5.** Cross section in femtobarns after all selection cuts for 7, 8 and 10 TeV of center of mass energy at four different values of the minimum invariant mass of the lepton pair in the  $(WW)\ell\nu\ell\nu + 2j$  channel for the IAM E, IAM G and IAMJ models. For comparison we show also the SM predictions for  $m_H = 170$  GeV and the background from  $t\bar{t} + jets$  production.

which grows larger than 90% at 10 TeV. Increasing the energy from 7 to 8 TeV has a modest effect for the IAM G scenario while it is more beneficial for the IAM J case with its heavier resonances. The IAM E scenario, and all cases with no resonances or very heavy ones, requires higher luminosities: about  $50 \text{ fb}^{-1}$  at 10 TeV and about  $200 \text{ fb}^{-1}$  at 8 TeV to reach a probability of at least 50% to exceed the SM 95% CL.

The leptonic channel in which two  $W$  bosons decay to opposite sign leptons, each either an electron or a muon, is sensitive to both scalar and vector resonances and is very important in general for the study of strong  $WW$  scattering even though the invariant mass of the boson pair cannot be directly measured. The mass of the charged leptons pair has been shown in ref. [6] to be an effective variable for the separation of unitarized models from the SM. At 7 TeV only a handful of events are expected for  $L = 100 \text{ fb}^{-1}$  of integrated luminosity, whereas for 10 TeV, with  $L = 25 \text{ fb}^{-1}$ , 12, 10, 6 and 5 events could be produced for IAM J, IAM G, IAM E and the SM respectively for  $M_{\ell\ell'} > 300$  GeV as can be extracted from the cross sections in figure 5. The corresponding PBSM@95%CL are

	IAM E			IAM G			IAM J		
L\E	7	8	10	7	8	10	7	8	10
25	8.47 <sup>a</sup>	10.44 <sup>b</sup>	14.23 <sup>a</sup>	24.41 <sup>a</sup>	36.49 <sup>a</sup>	51.83 <sup>a</sup>	27.17 <sup>b</sup>	42.69 <sup>b</sup>	65.68 <sup>a</sup>
50	10.02 <sup>a</sup>	13.06 <sup>b</sup>	18.94 <sup>a</sup>	35.83 <sup>a</sup>	53.23 <sup>a</sup>	70.07 <sup>a</sup>	37.90 <sup>b</sup>	61.95 <sup>b</sup>	84.73 <sup>b</sup>
100	12.63 <sup>a</sup>	17.34 <sup>b</sup>	26.37 <sup>b</sup>	52.81 <sup>a</sup>	72.07 <sup>a</sup>	84.59 <sup>a</sup>	56.76 <sup>b</sup>	81.94 <sup>b</sup>	95.97 <sup>b</sup>
200	16.49 <sup>a</sup>	24.08 <sup>b</sup>	36.35 <sup>b</sup>	71.87 <sup>a</sup>	86.74 <sup>a</sup>	93.23 <sup>a</sup>	76.92 <sup>b</sup>	94.91 <sup>b</sup>	99.50 <sup>b</sup>

**Table 3.** PBSM@95%CL in the  $(WW)\ell\nu\ell\nu+2j$  channel with 25, 50, 100 and 200  $\text{fb}^{-1}$  of integrated luminosity, L. For each luminosity and model we have used the mass cut which gives the best probability. They are specified by the superscript according to the following scheme: <sup>a</sup>, <sup>b</sup> for 300, 400 GeV respectively.



**Figure 6.** Cross section in femtobarns after all selection cuts for 7, 8 and 10 TeV of center of mass energy at four different values of the minimum invariant mass of the reconstructed  $VV$ -system in the  $3\ell\nu+2$  jets channel for the IAM G and IAMJ models. For comparison we show also the SM predictions for  $m_H = 170$  GeV.

reported in table 3. Despite the smaller background this channel is less efficient than the  $\ell\nu+4$  jets one discussed previously. The IAM E model has a probability of less than 15% of producing an excess even at 10 TeV with a luminosity of 25  $\text{fb}^{-1}$ . For the IAM G and IAM J models the probability is below 30% at 7 TeV and 25  $\text{fb}^{-1}$ . With this luminosity, which is slightly more optimistic than the 15  $\text{fb}^{-1}$  officially expected in 2012, the probability exceeds 50% only at 10 TeV. As obvious, at higher luminosity our predictions are much more optimistic.

The three leptons channel can contribute in scenarios in which vector resonances are present, as is the case of the IAM G and IAM J models. The cross sections are reported in figure 6 as a function of the minimum reconstructed invariant mass of the  $WZ$  pair. The corresponding exclusion probabilities are shown in table 4 for luminosities ranging from 25 to 200  $\text{fb}^{-1}$ . The probability to observe strong scattering in the IAM G case is above 50% already at 7 TeV with 25  $\text{fb}^{-1}$  and grows significantly with the collider energy. In the IAM J scenario, since the scalar resonance does not appear in this final state, the probability of observing an excess is markedly smaller. The probability for the IAM E non-resonant

	IAM G			IAM J		
L\E	7	8	10	7	8	10
25	50.53 <sup>a</sup>	63.18 <sup>a</sup>	82.05 <sup>a</sup>	21.74 <sup>d</sup>	29.28 <sup>d</sup>	48.50 <sup>e</sup>
50	71.93 <sup>a</sup>	82.12 <sup>a</sup>	93.99 <sup>a</sup>	31.02 <sup>d</sup>	43.24 <sup>e</sup>	68.63 <sup>e</sup>
100	88.13 <sup>a</sup>	94.08 <sup>a</sup>	98.97 <sup>b</sup>	43.83 <sup>e</sup>	63.71 <sup>e</sup>	86.42 <sup>e</sup>
200	97.09 <sup>b</sup>	98.94 <sup>b</sup>	99.95 <sup>b</sup>	63.63 <sup>e</sup>	82.62 <sup>e</sup>	96.56 <sup>e</sup>

**Table 4.** PBSM@95%CL in the  $3\ell\nu + 2$  jets channel with 25, 50, 100 and 200  $\text{fb}^{-1}$  of integrated luminosity, L. For each luminosity and model we have used the mass cut which gives the best probability. They are specified by the superscript according to the following scheme: <sup>a</sup>, <sup>b</sup>, <sup>c</sup>, <sup>d</sup>, <sup>e</sup> for 500, 600, 700, 800, 900 GeV respectively.

scenario is negligible and has been omitted.

## 4 Conclusions

In this paper we have studied the probability of finding a number of events exceeding the 95% confidence limit for the Standard Model in unitarized models of Electroweak Symmetry Breaking. We have focused on models based on the Inverse Amplitude Method. Our results indicate that at 8 TeV, the energy of the 2012 LHC run, some of the scenarios with TeV scale resonances are likely to be identified while models with no resonances or with very heavy ones will be inaccessible. In the absence of a positive result, it will be possible to obtain more stringent limits on the values of  $\alpha_4$  and  $\alpha_5$ , at least within a specified unitarization scheme. If reaching the design energy of 14 TeV will prove more difficult than expected, an energy of 10 TeV would already significantly increase the LHC reach.

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