https://doi.org/10.46813/2023-145-003

STUDYING THE RESONANCE PRODUCTION CROSS-SECTION OF THE HEAVY VECTORS WITHIN HEAVY VECTOR TRIPLET MODEL

T.V. Obikhod, I.A. Petrenko
Institute for Nuclear Research NAS of Ukraine, Kyiv, Ukraine
E-mail: obikhod@kinr.kiev.ua

In the context of TeV-scale extensions of the Standard Model both the experimental data and the construction of phenomenological models for the new heavy bosons searches are used by us. Heavy particles are predicted by the Simplified Model to describe only the on-shell resonance, have to be compared with LHC data. Bosons V' created and decay according to the process pp->V'->Vh (V=W, Z) have certain properties that can be modeled within the Heavy Vector Triplet model using the Madgraph computer program. We have calculated the production cross sections of heavy particles using the experimental constraints in the parameter space (c_H, c_F) imposed on the benchmark scenario. The nature of the functional dependence of the cross section on the mass of the new boson, as well as the mechanism for the heavy particle production is studied with variation of the model parameters.

PACS: 12.60.−i, 14.80.−j

INTRODUCTION

As Higgs boson properties have been measured with increasing precision, it has become an ideal tool to conduct new-physics searches. There are several questions related to the electroweak symmetry breaking mechanism, for example to the radiative corrections to Higgs boson mass and to an extended scalar sector of Higgs boson. Such phenomena have been predicted in many extensions of the Standard Model (SM), among which are heavy vector bosons which couple to the Higgs boson (as in models with warped extra dimensions). Prominent examples of searches for heavy vector bosons are direct searches for new heavy particles (instead of W, Z bosons in Fig. 1) decaying into Higgs boson.

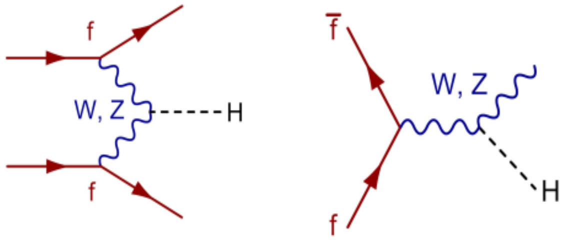

Fig. 1. Feynman diagrams for left: vector boson fusion (VBF) production process; right: associated Higgs boson production process [1]

The purpose of our paper is the study of characteristics of such new heavy particles in the framework of new phenomenological model according to the latest experimental restrictions.

1. EXPERIMENTAL DATA AND THE NEED FOR A NEW THEORETICAL INTERPRETATION

The experimental searches for new heavy particles were performed by ATLAS [2, 3] and CMS [4, 5]. The ATLAS collaboration recently released results of a search for a new heavy particle decaying into a Higgs and a W boson [6], Fig. 2.

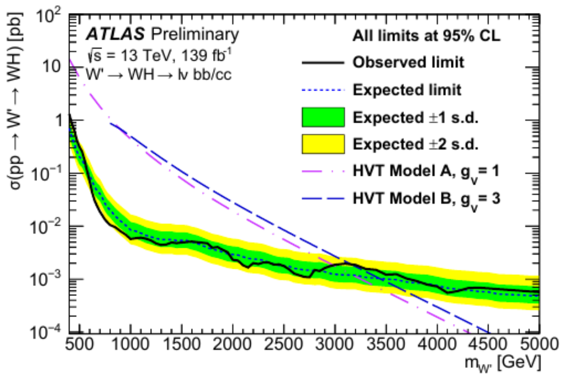

Fig. 2. Expected and observed upper limits at 95% CL on the production cross section for pp→W'→WH and the theory curves for Models A (B) with corresponding couplings g_V = 1 (3)

There is the search for an excess in the invariant mass distribution of the ℓνbb final state with excluded W′ masses below 2.95 and 3.15 TeV for two benchmark models. Processes of type pp → WH/ZH were summarized and numerically discussed for the total cross sections, taking into account all available higher-order corrections of the strong QCD interactions, Fig. 3.

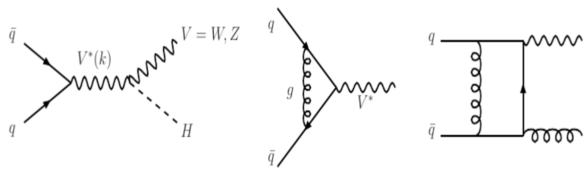

Fig. 3. Left: hadronic collisions, (leading order, LO) are affected by large uncertainties arising from center: higher-order QCD corrections to the production cross section (the next-to-leading order, NLO), right: the next-to-next-to-leading order NNLO, from [7]

The total cross section for the subprocess is obtained by integrating over k^2:

$$\sigma_{LO}(q\bar{q} \to VH) = \frac{G_F^2 M_V^4}{288\pi\,\hat{s}}\left(\upsilon_q^2 + a_q^2\right)\lambda^{1/2}\left(M_V^2, M_H^2; \hat{s}\right)\times \frac{\lambda\left(M_V^2, M_H^2; \hat{s}\right) + 12 M_V^2/\hat{s}}{\left(1 - M_V^2/\hat{s}\right)^2},$$

where the reduced quark couplings to the gauge bosons are given in terms of the electric charge and the weak isospin of the fermion as:

$$a_q = 2I_q^3,\ \upsilon_q = 2I_q^3 - 4Q_q s_W^2\text{, V=Z;}$$

$$\upsilon_q = -a_q = \sqrt{2}\text{, V=W;}$$

$$s_W^2 = 1 - c_W^2 \equiv \sin^2\theta_W.$$

The impact of QCD corrections quantified by calculating the K-factor is defined as the ratio of the cross sections for the process at HO (NLO or NNLO), over the cross section at LO:

$$K_{HO} = \frac{\sigma_{HO}(pp \to HV + X)}{\sigma_{LO}(pp \to HV)}.$$

The NLO K-factor is increasing as function of Higgs mass from K_{NLO} = 1.27 to K_{NLO} = 1.29. The NNLO contributions increase the K-factor by 1% - 3.5% for the high value of Higgs mass, [7].

So, the experimental and modeled data of such processes show a significant increase to the cross section from the loop corrections and, accordingly, require modification of the coupling constants. Such requirements provide some models of theoretical interpretations of the results and restrict benchmark regions of the parameter space. It is clear that precise predictions must be made in TeV-scale simplified extensions of SM which have to be compared with LHC data. Some qualitative predictions could be interpreted in the context of the heavy vector triplet (HVT) model parameterized on the new coupling constant and connected with the existence of a set of new heavy particles.

2. HEAVY VECTOR TRIPLET MODEL AND CHARACTERISTICS OF HEAVY PARTICLES

HVT is the type of particle with high mass and the set of three vectors, $V_\mu^\pm, V_\mu^0$ = 1,2,3, spin-1 bosons (two charged and one neutral):

$$V_\mu^\pm = \frac{V_\mu^1 \mp iV_\mu^2}{\sqrt{2}},\ V_\mu^0 = V_\mu^3,$$

which can describe $V_\mu^\pm, V_\mu^0$ system notated as W'/Z'. The new phenomenological Lagrangian incorporates kinetic terms, SM interactions and HVT interactions

$$L_V = -\frac{1}{4} D_{[\mu}V_{\nu]}^a D^{[\mu}V^{\nu]a} + \frac{m_V^2}{2} V_\mu^a V^{\mu a}$$
$$+ ig_V c_H V_\mu^a H^+ \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V_\mu^a J_F^{\mu a}$$
$$+ \frac{g_V}{2} c_{VVV} \in_{abc} V_\mu^a V_\nu^b D^{[\mu}V^{\nu]c}$$
$$+ g_V^2 c_{VVHH} V_\mu^a V^{\mu a} H^+ H \ - \frac{g}{2} c_{VVW} \in_{abc} W^{\mu\nu a} V_\mu^b V_\nu^c,$$

where

$\tau^a = \sigma^a/2,\ \ c_F V \cdot J_F \to c_l V \cdot J_l + c_q V \cdot J_q + c_3 V \cdot J_3$ currents with different couplings to leptons, light quarks and the third quark family. There is the parameterization of the interaction terms V, H and fermionic fields with a coupling g_V. Similarly, the insertion of W is weighted by coupling g. The first line of the above equation contains the V kinetic and mass terms, plus trilinear and quadrilinear interactions with the vector bosons from the covariant derivatives,

$$D_{[\mu}V_{\nu]}^a = D_\mu V_\nu^a - D_\nu V_\mu^a,\ \ D_\mu V_\nu^a = \partial_\mu V_\nu^a + g \in^{abc} W_\mu^b V_\nu^c,$$

the second line contains direct interactions of V with the Higgs current,

$$iH^+\tau^a \overleftrightarrow{D}^\mu H = iH^+\tau^a \overleftrightarrow{D}^\mu H - iD^\mu H^+ \tau^a H$$

and with the SM left-handed fermionic currents, $J_F^{\mu a}$, (c_H controls the V interactions with the SM vectors and with the Higgs and in particular its decays into bosonic channels, c_F describes interaction with fermions, which is responsible for both the resonance production by Drell-Yan (DY) and for its fermionic decays).

The third-fourth lines contain 3 new operators and free parameters, c_{VVV}, c_{VVHH} and c_{VVW} and they do not contribute directly to V decays and production processes.

For the HVT, there are two overarching models, termed Model A and Model B. Model A is the extended gauge symmetry whereas Model B is more likely to be a composite Higgs. The dominant branching ratio in the Model B and the subdominant in Model A is the decay into Higgs boson and a Vector boson, (Fig. 4).

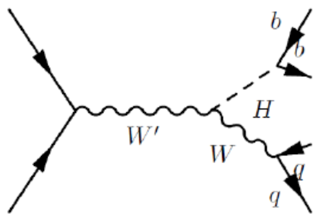

Fig. 4. Feynman diagram for hadronic decay of the heavy vector boson, W'

The neutral mass eigenvalues of heavy vector boson V_μ^0 are expressed through the SM Z boson and one heavy vector of mass M_0

$$Tr\left[M_N^2\right] = m_Z^2 + M_0^2,$$
$$Det\left[M_N^2\right] = m_Z^2 M_0^2\ .$$

In the charged sector the mass eigenvalues of charged heavy vector boson are expressed through the SM W boson and one heavy vector of mass M_+

$$Tr\left[M_C^2\right] = m_W^2 + M_+^2,$$
$$Det\left[M_C^2\right] = m_W^2 M_+^2\ .$$

In the following, we will use two models A [8] and B [9], describing the heavy vectors, with fixed c

for A model: $c_H \sim -g^2/g_V^2$, $c_F \sim 1$;

for B model: $c_H \sim c_F \sim 1$,

and free parameters – the resonance coupling g_V and its mass M_V.

Two main production processes of the new vectors V'in proton-proton collision are DY and VBF. The purpose of our paper is to calculate production cross-sections of heavy vectors at different parameters and to compare them with known results.

3. RESULTS OF CALCULATIONS

Experimental data, presented in Fig. 2 show the upper limits on the production cross-section for pp → W' times the branching fraction of W' →WH process at 13 TeV. The masses below 2.95 TeV are excluded with coupling constant g_V = 1 for the HVT benchmark Model A. For Model B masses below 3.15 TeV are excluded with coupling constant g_V = 3. Taking into account the experimental constrains in the (c_H , c_F) plane for the benchmark points at M_V = 2 TeV [10], we calculated the production cross sections for heavy particles (Table 1), taking into account the benchmark scenario for A and B models.

Table 1

Production cross sections for pp→V'→Vh (V=W, Z) processes at 14 TeV

Channels		Model	Production cross sections, (pb)
pp→W'→Wh	pp→Z'→Zh	A: c_H= - 0.5 c_q= -1 c_3= -1, c_l= -1	0.6793 ± 0.0007
		B: c_H= - 0.7 c_q= 1 c_3= 1, c_l= 1	0.6874 ± 0.00078
		A: c_H= - 0.5 c_q= -1 c_3= -1, c_l= -1	0.5917 ± 0.00061
		B: c_H= - 0.7 c_q= 1 c_3= 1, c_l= 1	0.5969 ± 0.00064
pp→W'→Wh	pp→Z'→Zh	A: c_H= 0 c_q= -1 c_3= -1, c_l= -1	0.6775 ± 0.00068
		B: c_H= - 1 c_q= 1 c_3= 1, c_l= 1	0.6853 ± 0.00072
		A: c_H= 0 c_q= -1 c_3= -1, c_l= -1	0.5909 ± 0.00061
		B: c_H= - 1 c_q= 1 c_3= 1, c_l= 1	0.5951 ± 0.00058

From Table 1 we do not see a significant difference in the values of the cross sections for the production processes of V'(W' or Z') for model A and model B, although quantitatively the cross section for the production of a boson Z' is somewhat smaller than that of a boson W'.

Let's consider new range of parameter space and new energies at the LHC for the calculations of production cross sections and masses of new heavy particles. Using Madgraph_aMC@NLO program [11] and corresponding parameter space, we calculated production cross sections for pp → W' → Wh process at the fixed c_H=1, presented below in Table 2.

Table 2

Production cross sections for pp → W' → Wh process at 14 TeV

c_F (cq, cl, c3)	Production cross sections, (pb)
1	0.5969±0.00062±systematics
2	0.5987±0.00064±systematics
3	0.5992±0.00062±systematics
4	0.5991±0.00059±systematics
5	0.6003±0.00072±systematics
6	0.6±0.0006±systematics
7	0.5989±0.00054±systematics
8	0.5974±0.00069±systematics
9	0.596±0.00058±systematics
10	0.5927±0.00069±systematics

The two main production mechanisms of the new vectors are DY and VBF. DY is the dominant production mechanism as the partonic cross-section is large when the V' coupling to fermions is much larger than the one to vector bosons in all regions of parameter space. VBF process has a chance of being comparable to DY if c_H is not suppressed. If the coupling to fermions is suppressed, $c_F \approx 0$, VBF becomes the dominant production mechanism, the fermionic decays are suppressed and thus the total resonance width is twice the di-boson one. This makes VBF more interesting at the LHC at 14 TeV, to explore specific scenarios with suppressed coupling to fermions. In Fig. 5 we show the ratio of the production cross-section by DY and VBF as a function of the cF/cH ratio, for different processes (pp → V' → Vh (V=W, Z)) at the LHC at 14 TeV (c_F is expressed in values of cq, cl, c3).

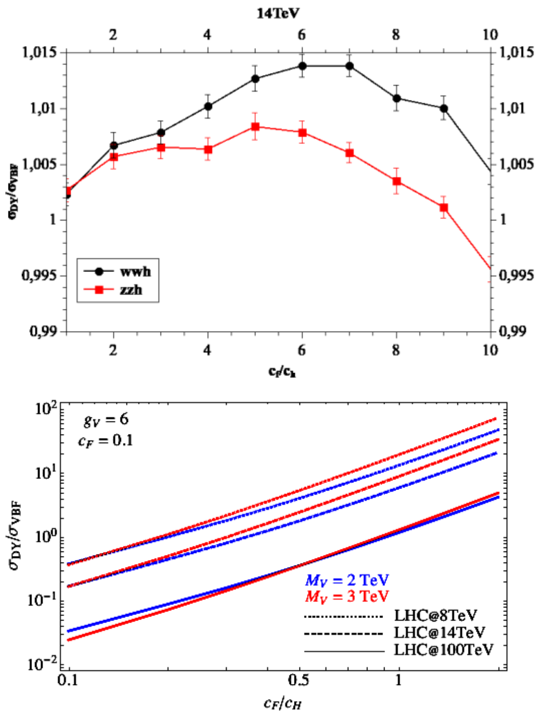

Fig. 5. The ratio of DY and VBF production cross-sections as a function of the c_F/c_H ratio for up: M_V=2 TeV, c_H=1; down: results from [10]

Comparison of the calculated results shows that if in region c_F/c_H ~ 1 there is an approximate coincidence of the quantitative and qualitative behavior of the cross sections, then with an increase in the ratio c_F/c_H, we observe a peak and a decrease in the dependence curve. In addition, the process with the W boson has a significantly larger DY cross section compared to the Z boson. At large c_F/c_H~10, we see the predominance of the VBF process of production of a heavy boson above DY one.

The study of the properties of a heavy boson is associated with the determination of its mass as a key parameter included in the calculation of observable quantities. We have calculated the V' boson masses at energies of 14 and 100 TeV. The corresponding results are shown in Fig. 6.

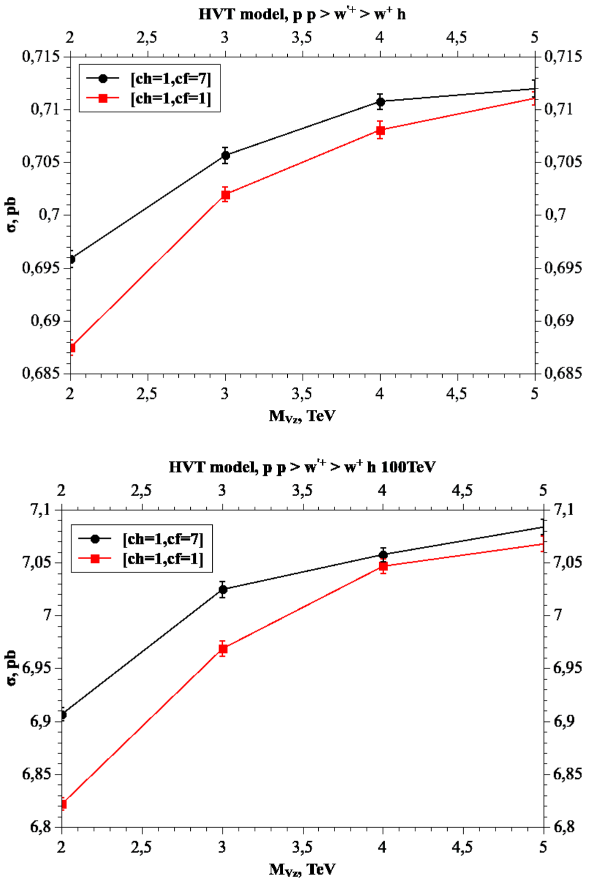

Fig. 6. Production cross section of heavy boson W' as a function of its mass with different parameter space at the energies: up – 14 TeV; down – 100 TeV

Comparison of the performed calculations presented in Fig. 6 shows the same nature of the growth of cross sections for different sets of parameters and energies, however quantitatively at 100 TeV the cross section grows by an order of magnitude and after 5 TeV there is a tendency to reach saturation. We also calculated the dependence of the cross section on the mass Z' for the restricted experimental data presented in the parameter space (c_H, c_F) [10], presented in Fig. 7.

The obtained results are approximately the same one as for the case shown in Fig. 6, but the production cross section for Z' boson is smaller than for heavy boson W'.

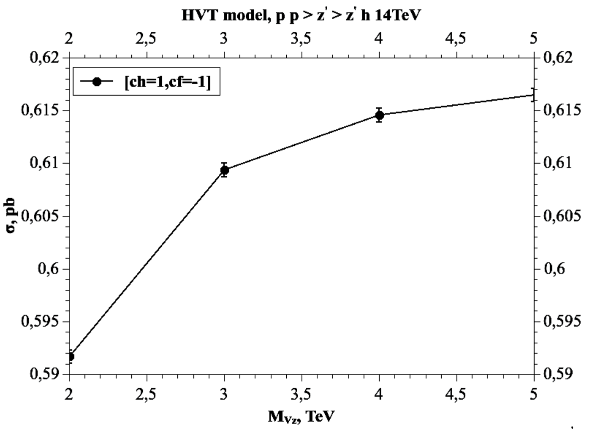

Fig. 7. Production cross section of heavy boson Z' formation as a function of its mass at the energy 14 TeV

CONCLUSIONS

We have done the production cross sections calculations of heavy bosons, their masses and dependence on the certain benchmark scenario for c_F and c_H. We have found different values of the cross sections for different parameters and showed that qualitatively the character of behavior of the cross section from mass remains the same for different particles (W' or Z') and different energies, although quantitatively the cross sections for the production of heavy bosons are 10 times larger at 100 TeV compared to similar calculations at 14 TeV. We compared the cross section ratio DY/VBF with previous calculations by D. Pappadopulo, A. Thamm, R. Torre and A. Wulzer and found a numerical agreement in the same parameter range. However, further study of the nature of the cross section showed the predominance of the process VBF at c_F/c_H~10.

REFERENCES

1. URL: https://en.wikipedia.org/wiki/Higgs_boson #cite_ref-HprodLHC_107-3.
2. ATLAS Collaboration. Search for W Z resonances in the fully leptonic channel using pp collisions at s = 8 TeV with the ATLAS detector // arXiv:1406.4456.
3. ATLAS Collaboration. Search for new phenomena in the dijet mass distribution using pp collision data at s = 8 TeV with the ATLAS detector // arXiv:1407.1376.
4. CMS Collaboration. Search for narrow t + b resonances in the leptonic final state at √ s = 8 TeV // CMS-PAS-B2G-12-010.
5. CMS Collaboration. Search for new resonances decaying via WZ to leptons in proton-proton collisions at s = 8 TeV // arXiv:1407.3476.
6. ATLAS Collaboration. Search for heavy resonances decaying into a W boson and a Higgs boson in final states with leptons and b-jets in 139 fb^{-1} of pp collisions at s = 13 TeV with the ATLAS detector // ATLAS-CONF-2021-026.
7. O. Brein, A. Djouadi, R. Harlander. NNLO QCD corrections to the Higgs-strahlung processes at hadron colliders // arXiv:hep-ph/0307206.

8. V. Barger, W.Y. Keung, and Ernest Ma. Gauge model with light W and Z bosons // *Phys. Rev.* 1980, D 22, p. 727.
9. R. Contino, D. Marzocca, D. Pappadopulo, and R. Rattazzi. On the effect of resonances in composite Higgs phenomenology // *JHEP*. 2011, v. 10 081, arXiv:1109.1570.
10. D. Pappadopulo, A. Thamm, R. Torre, A. Wulzer. Heavy Vector Triplets: Bridging Theory and Data // arXiv:1402.4431 [hep-ph].
11. J. Alwall et al. The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations // arXiv:1405.0301 [hep-ph].

Article received 06.03.2023

ВИЗНАЧЕННЯ ПЕРЕРІЗУ РЕЗОНАНСНОГО УТВОРЕННЯ ВАЖКИХ ВЕКТОРІВ У HEAVY VECTOR TRIPLET МОДЕЛІ

Т.В. Обіход, Є.О. Петренко

У контексті тераелектронвольтних розширень Стандартної моделі нами використовуються як експериментальні виміри, так і побудовані феноменологічні моделі для пошуку нових важких бозонів. Важкі частинки, що передбачені спрощеною моделлю, яка побудована для опису тільки резонансу на оболонці, необхідно порівнювати з даними на LHC. Бозони V’, що утворюються і розпадаються відповідно до процесу pp->V’->Vh (V=W, Z), мають певні властивості, які можна змоделювати в рамках Heavy Vector Triplet моделі за допомогою комп'ютерної програми Madgraph. Ми розрахували перерізи утворення важких частинок V’ з використанням експериментальних обмежень у просторі параметрів (c_H, c_F), які накладено на еталонний сценарій. Досліджено характер функціональної залежності перерізу при основних параметрах моделі від маси нового бозона, а також механізм народження таких частинок.