Searches for W' and Z' in models with large extra dimensions

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Abstract

Characteristic features of processes mediated by gauge bosons are discussed in the framework of theories with large extra dimensions. It is shown that if gauge bosons propagate in the bulk, then there arises a destructive interference not only between W and W' (or Z and Z'), but also between W' and Z' and the Kaluza-Klein towers of higher excitations of W and Z bosons respectively. Specific calculations are made and plotted for the LHC with the center of mass energy 14 TeV.

1 Introduction

During the last years brane world models with "universal extra dimensions" are widely discussed in the literature [1]-[10]. In this case all the Standard Model fields except the Higgs field can propagate in the whole multidimensional space-time. This leads to some interesting phenomenological predictions, which will be discussed in this paper.

The characteristic feature of theories with compact extra dimensions is the presence of towers of Kaluza-Klein excitations of the bulk fields, all the excitations of a bulk field having the same type of coupling to the fields of the Standard Model. Let us suppose that for a bulk field ϕ (or a set of fields) of arbitrary tensor type in $(4+d)$-dimensional space-time the relevant part of the action looks like

$$S = \int \sqrt{-\gamma} d^{4+d}x\, L(\phi) + \int_{\text{brane}} d^4x\, (L_{(SM-\phi)} + gM^{-\frac{d}{2}} J_{SM} * \phi), \tag{1}$$

where $\gamma_{MN}\,(M, N = 0, 1, 2, 3, ..., 3+d\,, sign\,\gamma = +, -, \cdots, -)$ denotes the background metric in the bulk, $L(\phi)$ is the bulk Lagrangian of the field ϕ, the Lagrangian of the Standard Model fields, which do not propagate in the bulk, is denoted by $L_{(SM-\phi)}$, the interaction term $J_{SM} * \phi$ is the scalar product of the corresponding current of the Standard Model fields J_{SM} and the field ϕ on the brane, g being a four-dimensional (in general, dimensional) coupling constant and M being the fundamental energy scale of the $(4+d)$-dimensional theory defined by the gravitational interaction; we assume it to be in the TeV energy range.

It is a common knowledge that the bulk field $\phi(x, y)$, $x = \{x^\mu\}, y = \{x^i\}, (i = 4, ..., 3+d)$, can be expanded in Kaluza-Klein modes with definite masses $\phi^{(n)}(x)$ and their wave functions in the space of extra dimension $\psi^{(n)}(y)$ as follows:

$$\phi(x, y) = \sum_n \psi^{(n)}(y)\phi^{(n)}(x), \quad n = (n_1, ..., n_d). \tag{2}$$

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The current J_{SM} and the coupling constant g are completely defined by the interaction of the zero mode $\phi^{(0)}(x)$, which is a field of the Standard Model or the graviton field, with the fields of the four-dimensional Standard Model according to

$$gJ_{SM} = \frac{\delta L_{SM}^{int}}{\delta\phi^{(0)}} \,. \tag{3}$$

It is not difficult to show (see detailed derivation in [11]) that if we consider this theory for the energy or momentum transfer much smaller, than the masses of the KK-excitations $\phi^{(n)}$, $n \neq 0$, we can pass to the effective "low-energy" theory, which can be obtained by the standard procedure. Namely, we have to drop the momentum dependence in the propagators of the heavy modes and to integrate them out in the functional integral built with the original action. The action of the resulting theory looks like

$$\begin{aligned} S &= \int d^4x \left(\frac{1}{2}\partial_\mu\phi^{(0)} * \partial^\mu\phi^{(0)} - \frac{1}{2}M_0^2\,\phi^{(0)} * \phi^{(0)} + L_{int}(\phi^{(0)}) + gM^{-\frac{d}{2}}\psi^{(0)}(y_b)J_{SM} * \phi^{(0)} + \right. \\ &+ \left. L_{(SM-\phi)} + \frac{1}{2}g^2M^{-d}\left(\sum_{n\neq 0}\frac{(\psi^{(n)}(y_b))^2}{M_n^2}\right) J_{SM} * \Delta * J_{SM} \right), \end{aligned} \tag{4}$$

where M_n is the mass of the n-th mode and Δ is the tensor structure (the numerator) of the propagator with the momentum equal to zero, which is the same for all modes, $\{y_b\}$ denotes the coordinates of the brane in the space of extra dimensions. Thus, we get a contact interaction of the Standard Model fields

$$\lambda J_{SM} * \Delta * J_{SM}, \quad \lambda = \frac{1}{2}g^2M^{-d}\left(\sum_{n\neq 0}\frac{(\psi^{(n)}(y_b))^2}{M_n^2}\right), \tag{5}$$

the sum of all the other terms in (4) being the Lagrangian of the Standard Model L_{SM}. We see that the Lagrangian structure is fixed by the corresponding structure of the SM currents J_{SM} and the spin-density matrix of the propagating field Δ defined by the type of the field ϕ as shown in formula (4).

2 Effective Lagrangian for the gauge interaction

Here we discuss the case of contact interactions due to the $SU(2) \times U(1)$ gauge fields in the bulk. These fields are described in the bulk by vector potentials W_M and B_M, which give rise to four-dimensional vector and scalar fields. The latter are in the trivial and in the adjoint representations of $SU(2)$ and cannot break $SU(2) \times U(1)$ to $U(1)_{em}$, as it is necessary in the SM. For this reason, we assume that the gauge symmetry is broken in the standard way by the Higgs field on the brane. It is useful to introduce the charged vector fields

$$W_\mu^\pm = \frac{W_\mu^1 \mp W_\mu^2}{\sqrt{2}} \tag{6}$$

and the standard mixing of the neutral vector fields

$$\begin{aligned} Z_\mu &= W_\mu^3\cos\theta_W - B_\mu\sin\theta_W, \\ A_\mu &= W_\mu^3\sin\theta_W + B_\mu\cos\theta_W. \end{aligned} \tag{7}$$

After the spontaneous symmetry breaking the neutral component of the brane Higgs field acquires a vacuum value $v/\sqrt{2}$, and there arises a quadratic interaction of the vector fields of the form:

$$\frac{g^2v^2}{4}M^{-d}\sum_{m,n}\psi_m(L)\psi_n(L)\,\eta^{\mu\nu}W_\mu^{(m)+}W_\nu^{(n)-}, \tag{8}$$

$$\frac{(g^2+g'^2)v^2}{8} M^{-d} \sum_{m,n} \psi_m(L)\psi_n(L)\, \eta^{\mu\nu}\, Z_\mu^{(m)} Z_\nu^{(n)}\,, \tag{9}$$

$\psi_m(L)$ denoting the wave functions of the KK modes of the fields $W_\mu^\pm$ and Z_μ on the brane. Due to this interaction the KK modes are no longer the mass eigenstates; the latter are now superpositions of the modes [12]. But if the mass scale generated by the Higgs field gv is much smaller, than the mass of the first KK excitation – and it is exactly the scenario we are studying – this mixing of KK modes can be neglected [12]. The coupling of the KK modes to the fields of the SM is defined by that of the zero mode and looks like:

$$\begin{aligned} L_{int} &= \frac{g}{\sqrt{2}} M^{-\frac{d}{2}} \sum_{n>0} \psi_n(L)(J^{+\mu} W_\mu^{(n)-} + J^{-\mu} W_\mu^{(n)+}) + \\ &+ \frac{g}{\cos\theta_W} M^{-\frac{d}{2}} \sum_{n>0} \psi_n(L) J_{(0)}^\mu Z_\mu^{(n)} + e M^{-\frac{d}{2}} \sum_{n>0} \psi_n(L) J_{em}^\mu A_\mu^{(n)}, \end{aligned} \tag{10}$$

where $J_\mu^\pm$ and $J_{(0)}^\mu$ are the weak charged and neutral currents of the SM particles and J_{em}^μ is the electromagnetic current of the SM particles. Integrating out the heavy modes, we again arrive at the effective Lagrangian of form (5). Then taking into account that all the masses are proportional to M and the wave functions are proportional to $M^{d/2}$, we get the effective Lagrangian for the interaction of the Standard Model fields due to the excitations of the $SU(2)\times U(1)$ gauge bosons

$$L_{eff} = \frac{G_F M_W^2}{M^2} \left(C_W J^{+\mu} J_\mu^- + C_W J^{-\mu} J_\mu^+ + C_Z J^{(0)\mu} J_\mu^{(0)} + C_A J_{em}^\mu J_{em\,\mu} \right), \tag{11}$$

G_F denoting the Fermi constant. The constants C_W, C_Z, C_A are again model dependent and can be estimated only in a specific model. In particular, in the simplest model with two branes and one flat extra dimension the constants can be estimated as

$$C_W = \frac{\pi^2}{6\sqrt{2}}\,, \quad C_Z = \frac{\sqrt{2}\pi^2}{6\cos^2\theta_W}\,, \quad C_A = \frac{2\sqrt{2}\pi^2 \sin^2\theta_W}{3}\,.$$

Now let us estimate the constants entering the effective Lagrangian for the gauge interaction in the case of the the Randall-Sundrum bulk [13]. First of all, since the bulk is 5-dimensional, we can pass to the axial gauge, where the components corresponding to the extra dimension are equal to zero [14]. Thus, there is no scalar fields in the effective four-dimensional theory. The wave functions $w_n(y)$ of the fields $A_\mu^n(x)$ with definite masses are solutions of a Sturm-Liouville eigenvalue problem with Neumann boundary conditions. Due to this fact the wave function of the massless zero mode, unlike the one for the tensor zero mode, is constant in the extra dimension. The latter guarantees the universality of its coupling constant [15]. The wave functions of the excitations on the brane behave like $w_n(y)|_{y=L} \sim \sqrt{\tilde{k}}$, i.e. similar to the wave functions of the tensor modes. The masses of the modes appear to be also in the TeV energy range [14]. We will be interested in the cases where the masses of the modes and the mass gaps between the modes are quite large, say, of the order of few TeV.

Below we will consider some processes with the Kaluza-Klein electroweak gauge bosons at the energies accessible at LHC. It should be noted that the coupling constants and masses of the modes depend significantly on the particular model under consideration. We will also extract the first Kaluza-Klein mode from the effective Lagrangian (11) and suppose that the accessible energy is above the production threshold of the first Kaluza-Klein mode. These modes are called W' and Z' respectively. All the other modes will be taken into account by means of the contact effective interactions.

Symbolic and numerical computations, including simulations of the SM background for LHC, have been performed by means of the CompHEP package [16]. The corresponding Feynman rules have been implemented into the new version of the CompHEP.

3 Processes with Kaluza-Klein gauge bosons

In paper [17] it was shown in a model independent way that there exists a nontrivial destructive interference between the processes mediated by W and W'. If we assume that the gauge bosons propagate in the bulk, then the W boson is just the zero Kaluza-Klein mode, the W' boson is the first excitation and there exists an infinite tower of Kaluza-Klein modes above it. The same is of course valid for Z and γ. In this case we expect that the higher Kaluza-Klein modes can also interfere with the zero and the first modes.

Now let us turn to specific examples. As it was noted in the previous section, the coupling constants and masses of the modes depend significantly on the particular model. For simplicity we suppose that all the Kaluza-Klein modes have the same coupling constant as those of the Standard Model W, Z bosons and photon respectively. The masses of the W', Z' bosons and of the first Kaluza-Klein excitation of the photon are $M_{W'}$, $M_{Z'}$, $M_{\gamma'}$ respectively. The remaining towers of the modes were simulated in CompHEP with the help of artificial particles with the masses $M_{W'_sum}$, $M_{Z'_sum}$, $M_{\gamma'_sum}$ and neglected momentum in the propagators. Indeed, schematically we can write the amplitude squared as

$$\left|\frac{1}{p^2-M^2}+\frac{1}{p^2-M'^2}-\sum_{n=2}^{\infty}\frac{1}{M_n^2}\right|^2 = \left|\frac{1}{p^2-M^2}+\frac{1}{p^2-M'^2}-\frac{1}{M_{sum}^2}\right|^2, \tag{12}$$

where M_n correspond to the masses of the Kaluza-Klein modes. The latter formulas show the origin of the parameters which will be used below. The term $\frac{1}{M_{sum}^2}$ simply corresponds to the effective contact interaction (11).

Now let us consider particular processes including Kaluza-Klein gauge bosons. All the calculations were made for the LHC with the center of mass energy 14 TeV.

First we consider a process with W' boson plus the remaining tower of the modes, namely, the single top production. We suppose that the mass of the first mode $M_{W'} = 2\,\text{TeV}$, the effective mass $M_{W'_sum} = 2.8\,\text{TeV}$. The width of the W' resonance has been calculated to be $\Gamma_{W'} = 65.7\,\text{GeV}$. The distributions for processes $u\bar{d} \to t\bar{b}$ presented in Figures 1 and 2 give the main contribution to the process $pp \to t\bar{b}$ at the LHC.

We made calculations for the Standard Model W boson only, for the Standard Model W boson plus W' boson only and for the Standard Model W boson plus W' boson plus the remaining tower of Kaluza-Klein modes. It is clear from Figure 1 that the presence of the W' boson leads to a destructive interference at the energies smaller than the mass of the W' resonance. At the energies larger than the mass of the W' resonance we see that there is an increase of the distributions tails due to the existence of W' and the corresponding Kaluza-Klein modes in comparison with the case of the Standard Model W only (see Figure 1). Note that Kaluza-Klein modes above W' can lead to a quite considerable modification of the distributions, look at Figure 2.

Second we consider a process with Z' boson and γ' boson plus the remaining towers of the modes, namely, the Drell-Yan process with u quarks, which is also dominant at the LHC. We suppose that the masses of the first modes are $M_{Z'} = 2.3\,\text{TeV}$, $M_{\gamma'} = 2\,\text{TeV}$, and the effective masses are $M_{Z'_sum} = 3.2\,\text{TeV}$, $M_{\gamma'_sum} = 2.8\,\text{TeV}$. The widths of the Z' and γ' resonances have been found to be $\Gamma_{Z'} = 0.026\,\text{TeV}$ and $\Gamma_{\gamma'} = 0.021\,\text{TeV}$ respectively. The corresponding distributions are presented in Figures 3 and 4. One can see analogous properties of the distributions as those in the case of single top production.

There is a good reason to believe that the NLO corrections do not destroy this interference picture. First of all, it is clear that the corrections to the external lines do not alter the structure of the amplitude (12). Of course, the most dangerous terms seem to be those with the self-

energy of gauge bosons. But these self-energy terms are defined so as to vanish on the mass shell and contribute only to the particle widths and to the mass renormalization.

Thus, our analysis shows that the Kaluza-Klein modes should be taken into account because they can make contribution to the amplitudes of the corresponding processes. Of course, in principle single particles W'' or Z'' can also provide analogous effects, but simultaneous effects with Kaluza-Klein gravitons and W', Z' Kaluza-Klein modes can be interpreted in favor of the existence of extra dimensions.

Acknowledgments

The work was supported by grant of Russian Ministry of Education and Science NS-4142.2010.2, RFBR grants 08-02-92499-CNRSL_a, 08-02-91002-CERN_a and state contract 02.740.11.0244.

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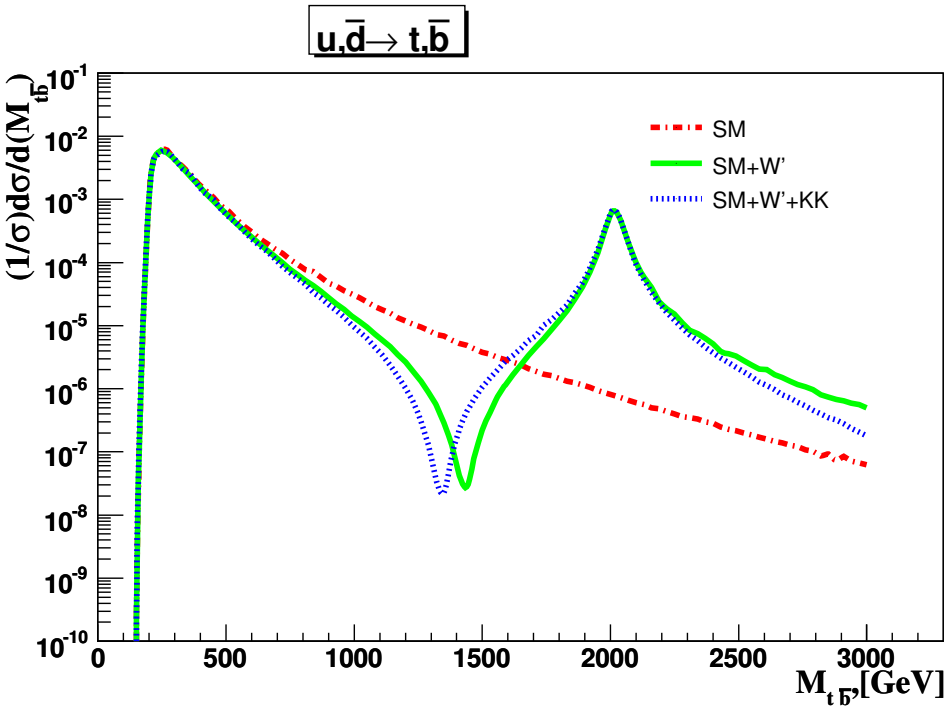

Figure 1: Invariant mass distribution for the single top production at the LHC

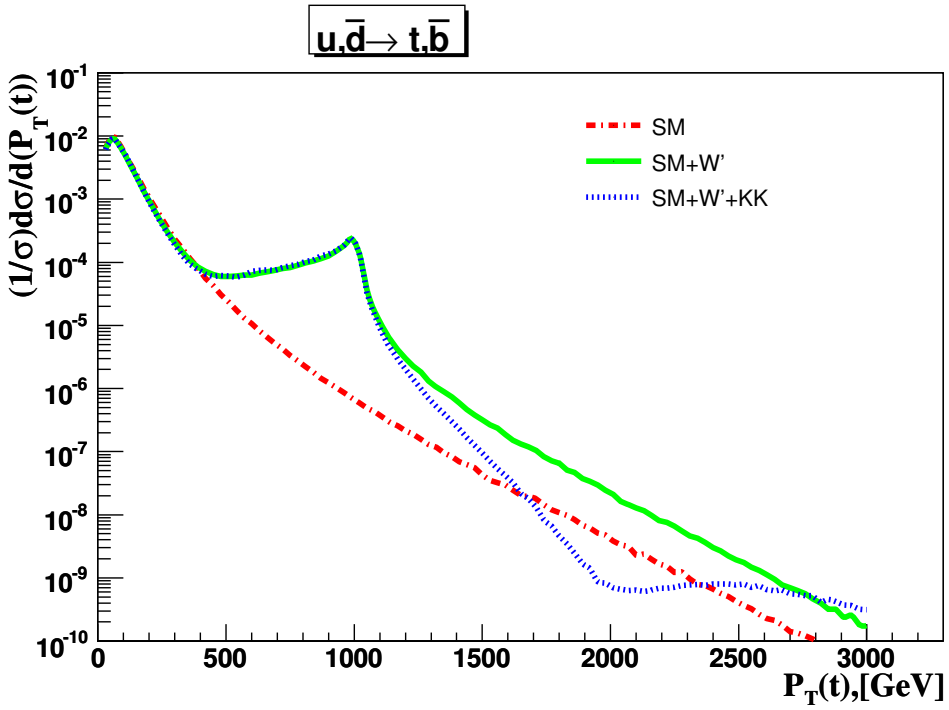

Figure 2: P_T distribution for the single top production at the LHC

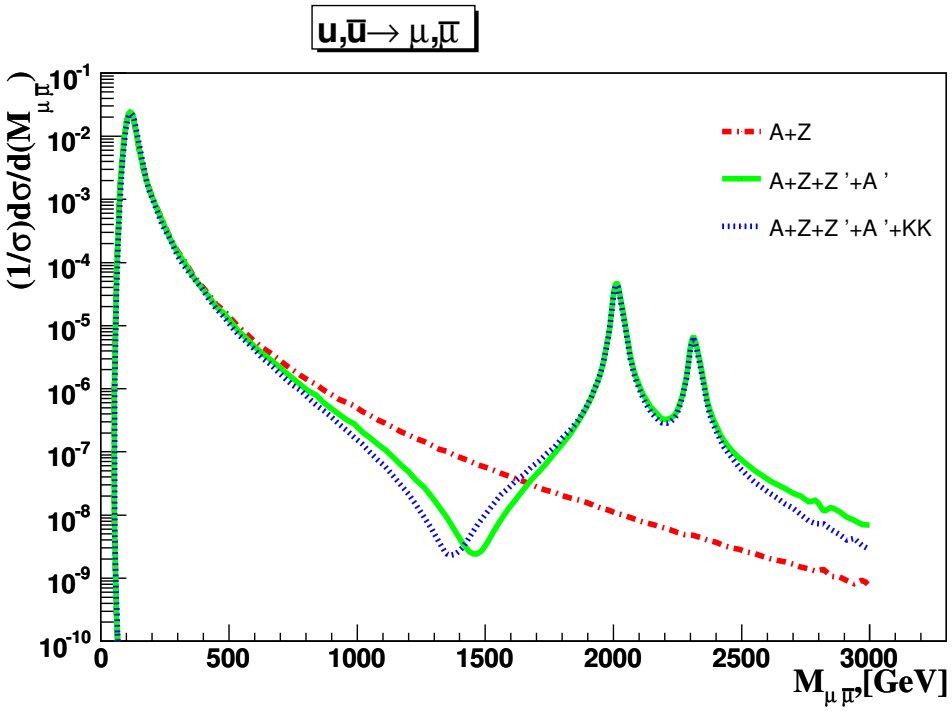

Figure 3: Invariant mass distribution for the Drell-Yan process at the LHC

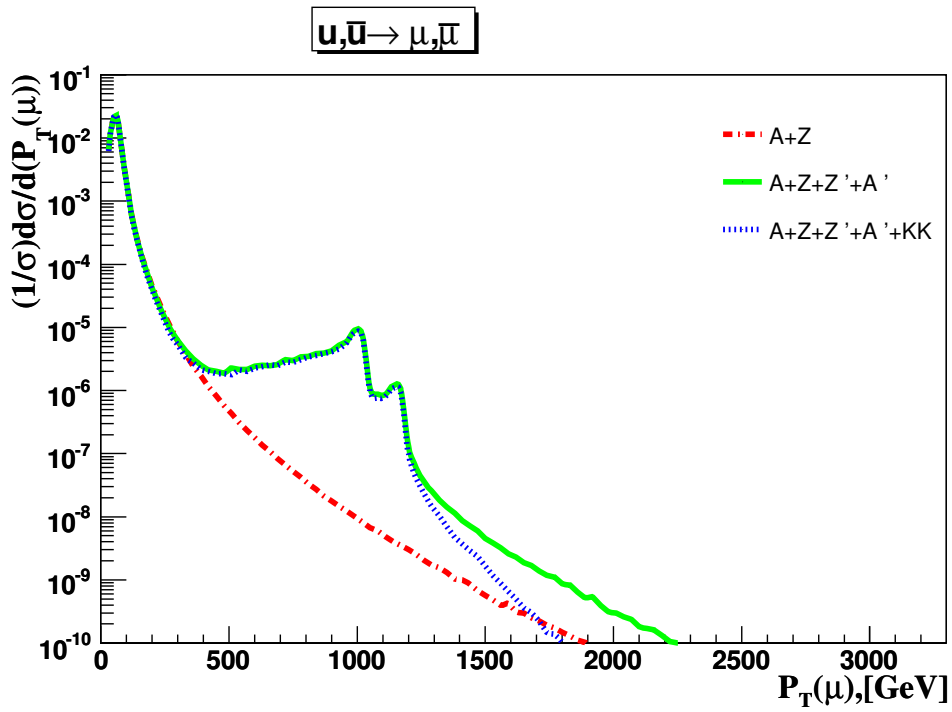

Figure 4: P_T distribution for the Drell-Yan process at the LHC