

The specificity of searches for W' , Z' and γ' coming from extra dimensions

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ABSTRACT: We discuss the specificity of searches for hypothetical W' , Z' and γ' bosons at hadron colliders in single top quark and $\mu^+\nu_\mu$ production and Drell-Yan processes assuming these particles to be the Kaluza-Klein excitations of the gauge bosons of the Standard Model. In this case any process mediated by W is also mediated by the whole KK tower of its excitations, whereas to the processes mediated by Z and γ there is not only a contribution from their KK towers, but also from that of the graviton. The contributions of the towers above W' , Z' and γ' and above the first excitation of the graviton are included with the help of effective four-fermion Lagrangians. We compute the cross-sections of these processes taking into account the contributions of the Standard Model gauge bosons, of their first KK modes and of the corresponding KK towers and discuss the impact of the interference between them. For pp-collisions at the LHC with the center of mass energy 14 TeV we found specific changes of the distribution tails due to the interference effects. Such a modification of distribution tails is characteristic for the processes mediated by particles coming from extra dimensions and should always be taken into account when looking for them.

KEYWORDS: Phenomenology of Large extra dimensions

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1 Introduction

Many theories and theoretical schemes for physics beyond the Standard Model (SM) predict the existence of massive charged and neutral vector particles in addition to the gauge bosons of the SM. Such particles can arise either due to an extension of the SM gauge group [1–8], or as excitations of the SM gauge bosons (see, for example [9–13]); the lowest excitations of W , Z and γ are usually called W' , Z' and γ' .

The physical properties and the interactions of these particles are different in different models. In some models they can have couplings similar to those of the SM gauge bosons and can mediate the same processes with SM particles. In paper [14] it was noted that in this case a nontrivial interference between the contributions of W and W' to various processes could influence an experimental observation of the latter in the energy range close to its mass or the exclusion limits for it. In particular, the negative interference resulted in observed weaker exclusion limits in the case of the left-interacting compared to the right-interacting W' [15]. The interference and its consequences were also discussed in papers [16–20].

If the additional vector bosons are found at the LHC, there arises the problem of determining the theory beyond the SM, to which they correspond. To solve this problem one has to study the specific features of the additional vector bosons in different models. In the present paper we will do it for the excitations of the SM gauge bosons in models with universal extra dimensions (UED), which have been widely discussed lately [21–33].

In such brane-world models, not only the gravity, but also certain fields of the SM propagate either in the flat bulk [21–23], or in the Randall-Sundrum bulk [24–33]. It is very natural to assume that only the SM gauge fields may propagate in the bulk since there is no consistent mechanism for trapping them on the brane [34]. In contrast, such a mechanism exists for the fermion fields [34], and therefore the fermions may be trapped on a brane or localized in its neighborhood.

Here we will consider a scenario, where only gauge fields live in the bulk of a stabilized brane-world model [35–37], i.e., in the bulk between the branes with the separation distance

stabilized by a scalar field and with a warped bulk metric different from that of the Randall-Sundrum model [38]. Unlike the UED models with the flat bulk [21–23], such models give rise to different wave functions for the fields of different tensor type and, for this reason, do not necessarily lead to the KK number conservation. Therefore, a production of single KK states is possible in such a scenario. However, FCNC currents, which are strongly suppressed by the present-day experimental data, do not appear in this case since the neutral currents have the same diagonal structure as in the SM.

In the case where only the SM gauge fields propagate in the Randall-Sundrum bulk, the masses of the KK excitations of the SM gauge bosons have to be approximately larger than 20 TeV in order not to contradict the EW precision data [25]. Such heavy states are obviously out of the reach of the 14 TeV LHC (one might hope to detect the states at the 33 TeV LHC, if such a collider is realized). However, in the stabilized brane-world models, where the warp factor is different from the exponential of a linear function, as it is in the Randall-Sundrum model, the couplings of KK modes to the SM fields might be significantly different from those in the Randall-Sundrum model and, as a result, lighter KK excitations of the SM fields may be allowed. A study of such stabilized brane-world models has been carried out in papers [37, 39], and it was found that they may also solve the hierarchy problem of the gravitational interaction, give rise to the masses of KK excitations in the TeV energy range, but the corresponding equations cannot be solved exactly and should be studied numerically.

In order to present better the physics of the processes mediated by the KK excitations of gauge bosons, here we will not carry out such calculations for a specific stabilized brane-world model, but rather give a qualitative description of the phenomena taking for the masses values close to the proposed benchmark Snowmass 2013 parameter points [33], which have been chosen to cover the energy range of the LHC experiments at 14 TeV. Such a choice of the KK masses seems to be very useful for comparing our results with experimental data at the 14 TeV LHC. Though in our case, unlike in paper [33], the SM fermions are supposed to be localized on a brane and the coupling constants of the KK modes are assumed to be the same, as in the SM, it is not difficult to reproduce our results with different values of coupling constants.

A study along these lines of collider processes mediated by the excitations of the SM electroweak gauge bosons propagating in the bulk of a stabilized brane-world model was performed in paper [40] exposing the role of the interference. Here we will briefly recall the results of this paper and elaborate them for a number of processes mediated by both charged and neutral gauge bosons and their KK excitations, taking into account also the contribution of the graviton resonances in the latter case. We consider both the processes with charged and neutral KK excitations, because all of them should manifest simultaneously in the LHC experiments.

The processes mediated by the neutral particles including the graviton excitations have been discussed in [41] within the framework of the unstabilized Randall-Sundrum model for the masses of the first KK excitations lying below 2 TeV, this energy range having been studied by the LHC nowadays [42]. The presence of a destructive interference between γ' and Z' resonances in models with large extra dimensions was already noted in paper [43]

without taking into account the contributions of the higher excitations. Here we extend the analysis of the processes with the intermediate neutral particles to a more general setting of stabilized Randall-Sundrum models and to a larger, not yet excluded, energy range taking into account contributions of the KK towers and all the interferences.

2 Effective interactions

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 SM. If we consider these theories for the energy or momentum transfer much smaller, than the masses of the KK-excitations, 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. In the case, where only the gravity propagates in the bulk of a stabilized brane-world model, the resulting Lagrangian turns out to be [44]

$$L_{\text{eff}} = \frac{C}{\Lambda_\pi^2 M_1^2} T^{\mu\nu} \tilde{\Delta}_{\mu\nu,\rho\sigma} T^{\rho\sigma}, \tag{2.1}$$

$$\tilde{\Delta}_{\mu\nu,\rho\sigma} = \frac{1}{2} \eta_{\mu\rho} \eta_{\nu\sigma} + \frac{1}{2} \eta_{\mu\sigma} \eta_{\nu\rho} - \left(\frac{1}{3} - \frac{\delta}{2} \right) \eta_{\mu\nu} \eta_{\rho\sigma}. \tag{2.2}$$

Here $T^{\mu\nu}$ stands for the energy-momentum tensor of the SM fields, M_1 is the mass of the first tensor resonance, Λ_π is its (inverse) coupling constant to the SM fields, the constant δ takes into account the contribution of the scalar modes, the dimensionless constant C is defined by the geometry of the model and can be computed numerically. In particular, in paper [44] it was found to be equal approximately to 1.8 in the stabilized Randall-Sundrum model. In this paper it was also noted that if the center of mass energy is close to the mass of the first resonance, its contribution should be taken into account exactly, whereas the rest of the tower can still be approximated by Lagrangian (2.1) with the effective coupling constant $0.8/(\Lambda_\pi^2 M_1^2)$ instead of $1.8/(\Lambda_\pi^2 M_1^2)$.

A contact interaction Lagrangian can be obtained in the same way for the interactions mediated by the $SU(2) \times U(1)$ bulk gauge fields [40]. 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 $U(1)_{\text{em}}$, 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 pass in the standard way to the charged vector fields W_μ^\pm and the physical neutral vector fields Z_μ and A_μ . After the spontaneous symmetry breaking the neutral component of the brane Higgs field acquires the vacuum value $v/\sqrt{2}$, and there arises a quadratic interaction of the KK modes of the vector fields proportional to the product of the values of the wave functions of the modes on the brane and to M_W^2 for charged fields and to M_Z^2 for neutral fields. Due to this interaction the zero modes of the fields W_μ^\pm and Z_μ acquire masses and the KK modes are no longer the mass eigenstates; the

latter are now superpositions of the modes [45]. But if the mass scale generated by the Higgs field 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 [45]. In this approximation the masses of the excitations of the W and Z bosons, as well as those of the photon, should be treated as nearly equal. This is due to the fact that all vector fields satisfy the same equation of motion in the bulk, and for this reason the KK masses of their excitations are the same, which is also true for more complicated models [46]. It is also worth noting that a model-independent analysis based only on the properties of the SM gauge group representations carried by the fields of heavy charged and neutral bosons coupled to leptons also leads to a similar degeneracy of their masses [47].

The interaction vertices of the KK modes and the fields of the SM are the same as those of the zero modes. Integrating out the heavy modes, we again arrive at an effective Lagrangian for the interaction of the SM fields due to the excitations of the $SU(2) \times U(1)$ gauge bosons

$$L_{\text{eff}} = \frac{g^2}{M^2} \left(C_W J^{+\mu} J_{\mu}^- + C_Z J^{(0)\mu} J_{\mu}^{(0)} + C_A J_{em}^{\mu} J_{em\mu} \right), \quad (2.3)$$

M being the energy scale of the model, g denoting the $SU(2)$ gauge coupling constant and $J_{\mu}^+, J_{\mu}^{(0)}, J_{em}^{\mu}$ being the SM weak charged, weak neutral and electromagnetic currents. The constants C_W, C_Z, C_A are again model dependent and can be estimated only in a specific model.

In the case of the $SU(2) \times U(1)$ gauge fields in the 5-dimensional bulk, one can pass to the axial gauge, where the components corresponding to the extra dimension are equal to zero. Thus, the gauge sector of the original 5-dimensional theory does not add scalar fields to the effective four-dimensional theory. In any brane-world model, the mass spectrum of gauge fields is defined by a Sturm-Liouville eigenvalue problem with Neumann boundary conditions, the wave functions $w_n(y)$ of the fields $A_{\mu}^n(x)$ with definite masses being its solutions. Due to this fact the wave function of the massless zero mode is constant in the extra dimension, which guarantees the universality of its coupling constant [34]. In particular, in the Randall-Sundrum model [38], the masses of the lower excitations of vector fields are approximately given by the zeros of the Bessel function $J_0(M_n/k)$ [25] (k being the energy scale of the model), whereas those of the tensor fields are approximately given by the corresponding zeros of the Bessel function $J_1(M_n/k)$ [48], which are always larger [49]. Thus, if the energy scale of the model is in the TeV energy range, the masses of the modes appear to be also in the TeV energy range. In fact, this is valid in stabilized brane-world models as well. We have already noted in the Introduction that the phenomenological constraints on the masses of the gauge boson excitations in paper [25] do not apply, in general, to stabilized models because the warp factor of a stabilized brane-world model differs from the exponential of a linear function in the unstabilized Randall-Sundrum model.

We will be interested in the case where the masses of the modes and the mass gaps between them are quite large, say, of the order of a few TeV. In particular, in the UED models with the energy scale 1 TeV, the mass of the lowest gauge boson excitations and that of the first graviton excitation are (almost) the same, whereas in the unstabilized Randall-

Sundrum model they are 2.4 TeV for the lowest gauge boson excitations and 3.8 TeV for the lowest graviton excitation, their ratio being approximately equal to 1.6 and tending to 1 for the higher excitations. Thus, we expect this ratio to be of the order of unity, and will use the value 1.5 in our subsequent calculations.

Below we will consider some processes with the Kaluza-Klein electroweak gauge bosons at the energies accessible at the LHC supposing that the masses of W' , Z' and γ' are within this energy range. Similar to the approach of paper [44] we exactly take into account the contributions of the first Kaluza-Klein modes, whereas the contributions of all the other modes are taken into account by means of the effective contact interaction (2.3), from which the contribution of the first mode is subtracted.

Symbolic and numerical computations, including simulations of the SM background for the LHC, have been performed by means of the CompHEP package [50, 51], into which the corresponding Feynman rules for the new states and interactions have been implemented.

3 Two-body processes mediated by excitations of gauge bosons

First we consider the simpler case of the W boson and its KK tower. The coupling constants of its excitations and their masses essentially depend on the fundamental parameters of a stabilized brane-world model, which is also true for the excitations of other particles to be discussed below. In particular, in paper [44] the masses of the graviton excitations were explicitly calculated in terms of the fundamental parameters, which turned out to be a rather complicated task.

As we mentioned in the Introduction, for our study we choose values for the excitations masses in the energy range of the LHC, but not yet excluded, and close to the Snowmass 2013 benchmarks [33]. We also note that for all the taken parameter points the width of an excitation is not larger than its mass as it should be.

Then the effective interaction Lagrangian of the W boson KK tower in the energy range close to the mass of the W' boson looks like

$$L_{eff.W.KK} = \frac{g_1}{\sqrt{2}}(J^{+\mu}W_{\mu}^{\prime-} + J^{-\mu}W_{\mu}^{\prime+}) - \frac{g_1^2}{2M_{W',sum}^2}J^{+\mu}J_{\mu}^-, \quad (3.1)$$

where g_1 is the coupling constant of W' to the weak charged current $J^{+\mu}$ and $M_{W',sum}$ is the mass parameter taking into account the contribution of the KK tower above W' . Thus, this Lagrangian has three free parameters, including the W' mass.

Under these assumptions we will study the processes $pp \rightarrow t\bar{b} + X$ and $pp \rightarrow \mu^+\nu_{\mu} + X$ at the LHC. We start with the single top production. It occurs due to the weak process $u\bar{d} \rightarrow t\bar{b}$, which is mediated by the W boson and its KK tower. In our approximation the amplitude of the process can be represented by the diagrams

$$\text{Diagram 1} + \text{Diagram 2} + \text{Diagram 3} \quad (3.2)$$

The contact term CW is, in fact, Fermi's interaction with the coupling constant $g_1^2/(2M_{W',sum}^2)$. Explicit calculations in UED models with flat extra dimension and in

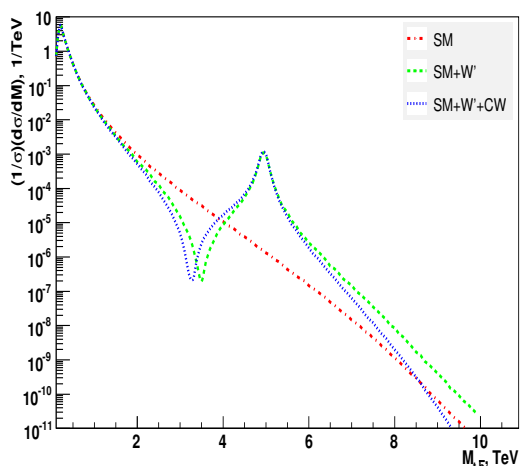


Figure 1. Invariant mass distribution for the single top production at the LHC with the center of mass energy 14 TeV for $M_{W'} = 5\text{ TeV}$, $\Gamma_{W'} = 0.17\text{ TeV}$ with and without the contribution of the W' KK tower.

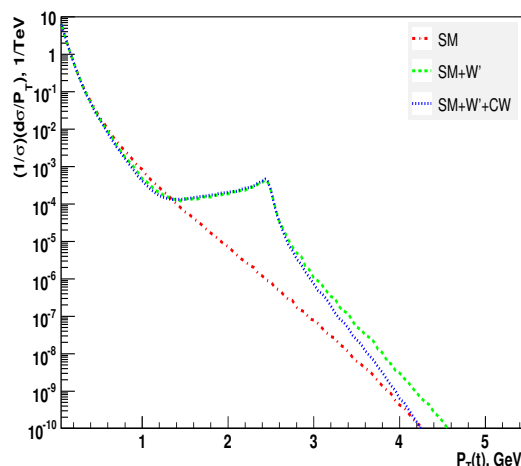


Figure 2. P_T distribution for the single top production at the LHC with the center of mass energy 14 TeV for $M_{W'} = 5\text{ TeV}$, $\Gamma_{W'} = 0.17\text{ TeV}$ with and without the contribution of the W' KK tower.

certain stabilized brane-world models show that this effective mass is just a little larger than that of W' .¹ In the present paper we will take the value $1.4M_{W'}$, previously used in [40], as the effective mass of the KK tower above W' and will apply the same relation to the excitations of the other gauge bosons.

For simplicity we will also assume that the coupling constants for all the excitations of the SM gauge bosons are the same as those of the gauge bosons themselves. Then the amplitude corresponding to diagrams (3.2) is equal to

$$\frac{g^2}{2}(\bar{d}\gamma_\mu(1 - \gamma_5)u)(\bar{t}\gamma^\mu(1 - \gamma_5)b) \left(\frac{1}{p^2 - M_W^2} + \frac{1}{p^2 - M_{W'}^2} - \frac{1}{M_{W'_{sum}}^2} \right). \quad (3.3)$$

The last term in the brackets effectively takes into account the contribution of the sum of the one-boson-exchange diagrams with all the modes above the W' boson. This structure of the amplitude manifests the origin of the interference between the contributions of different diagrams.

The cross-sections of this process can be obtained by calculating the corresponding partonic cross-sections and integrating them with the parton distribution functions, and in so doing we neglect the light quark masses. In particular, for $M_{W'} = 5\text{ TeV}$, the corresponding distributions in the invariant mass of the $t\bar{t}$ pair and in the transverse momentum of the top quark have been calculated for the first SM diagram only, for the sum of the first two diagrams ($SM + W'$), and for all three diagrams ($SM + W' + CW$) and presented in figures 1 and 2.

¹We recall once again that the effective mass is a way to parameterize the sum of the contributions of the KK tower above the first resonance. This point is also discussed in sections II and III of paper [44].

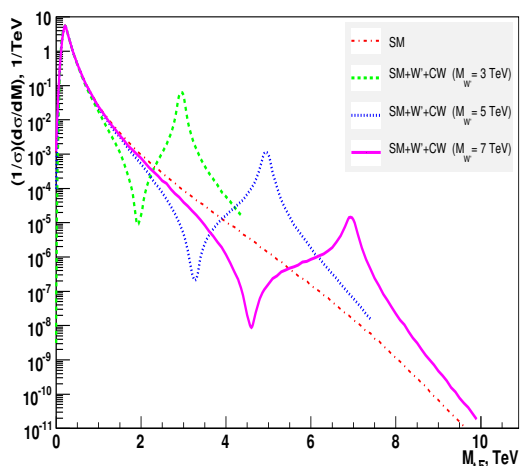


Figure 3. Invariant mass distribution for the single top production at the LHC with the center of mass energy 14 TeV for three different values of $M_{W'}$ mass: $M_{W'} = 3$ TeV, $\Gamma_{W'} = 0.10$ TeV; $M_{W'} = 5$ TeV, $\Gamma_{W'} = 0.17$ TeV; $M_{W'} = 7$ TeV, $\Gamma_{W'} = 0.23$ TeV.

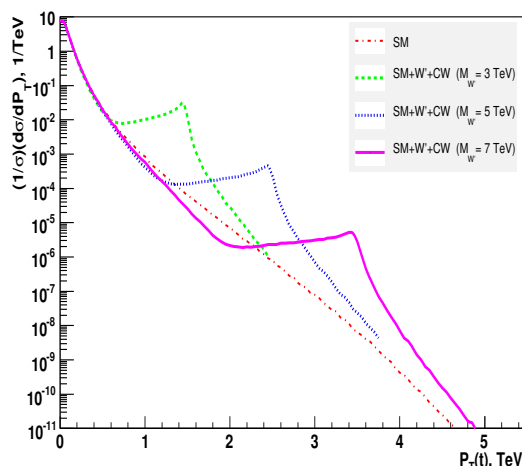


Figure 4. P_T distribution for the single top production at the LHC with the center of mass energy 14 TeV for three different values of $M_{W'}$ mass: $M_{W'} = 3$ TeV, $\Gamma_{W'} = 0.10$ TeV; $M_{W'} = 5$ TeV, $\Gamma_{W'} = 0.17$ TeV; $M_{W'} = 7$ TeV, $\Gamma_{W'} = 0.23$ TeV.

These figures clearly show that the interference with the contribution of the rest of the KK tower changes the curves significantly (similar curves were obtained in papers [14] and [40] for the masses of the W' boson 1 TeV and 2 TeV).

In order to study the dependence of these results on the W' mass, here we calculated these distributions with the complete set of diagrams (3.2) for two more values of W' mass, $M_{W'} = 3$ TeV, $M_{W'} = 7$ TeV, which also belong to the energy range not yet studied at the LHC. For these values of the W' mass its widths have been found to be 0.10 TeV and 0.23 TeV. The results, together with those for W' mass 5 TeV, are presented in figures 3 and 4 so that for each curve only that energy range is shown where the contribution of the higher excitations can be approximated by the contact term CW . Our estimates show that, if the coupling of the W' boson to the SM fields is of the same order, as that of the W boson, the interference effects due to the contribution of the rest of the KK tower are, in principle, observable for the W' boson mass as large as 7 TeV.

The process $pp \rightarrow \mu^+ \nu_\mu + X$ can be treated in the same way. The corresponding diagrams can be easily obtained from diagrams (3.2) by replacing the top quark by the neutrino and the \bar{b} quark by the positive muon. The cross-sections of this process have been calculated for the same values of the mass of the W' boson and the same characteristics of its KK tower, the resulting plots being presented in figures 5 and 6. We see that the plots look very much like those for the top quark production.

The case of the Z' boson and γ' turns out to be more complicated, because in theories with extra dimensions the KK graviton gr' and its tower also contribute to all the processes mediated by the neutral vector boson. (To be precise, there is one more tower that contributes to all these processes, namely that of the scalar radion. But the contribution of the

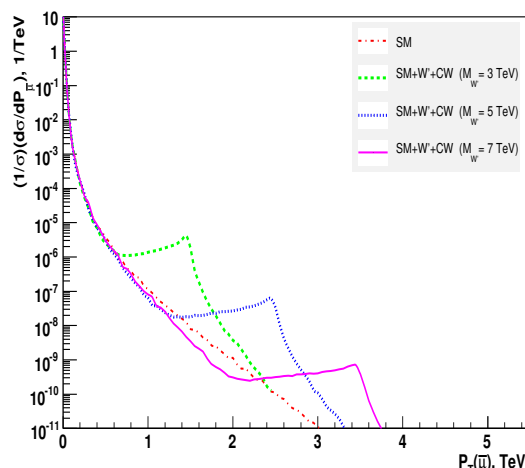
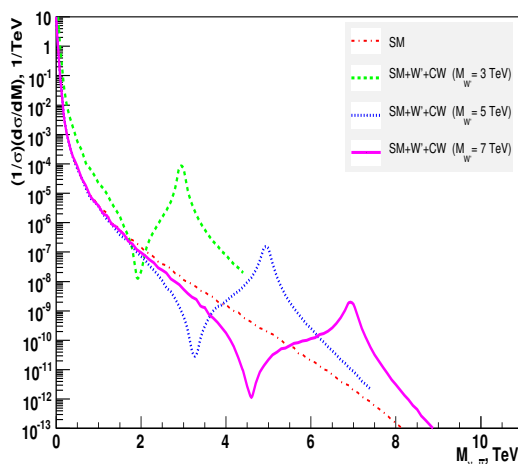


Figure 5. Invariant mass distribution for the μ^+ production at the LHC with the center of mass energy 14 TeV for three different values of $M_{W'}$ mass: $M_{W'} = 3$ TeV, $\Gamma_{W'} = 0.10$ TeV; $M_{W'} = 5$ TeV, $\Gamma_{W'} = 0.17$ TeV; $M_{W'} = 7$ TeV, $\Gamma_{W'} = 0.23$ TeV.

Figure 6. P_T distribution for the μ^+ production at the LHC with the center of mass energy 14 TeV for three different values of $M_{W'}$ mass: $M_{W'} = 3$ TeV, $\Gamma_{W'} = 0.10$ TeV; $M_{W'} = 5$ TeV, $\Gamma_{W'} = 0.17$ TeV; $M_{W'} = 7$ TeV, $\Gamma_{W'} = 0.23$ TeV.

scalar modes is suppressed by the factor $(m_q/M)^2$, m_q being the mass of a first generation quark and M being the fundamental energy scale of the order of several TeV [44]. For this reason the contribution of the scalar modes is negligible and we discard it completely.) An example of processes mediated by Z' , γ' and the corresponding KK towers is the Drell-Yan process $pp \rightarrow \mu^+\mu^- + X$.

This process has been already studied at the LHC for the center of mass energies 7 TeV and 8 TeV with the result that heavy narrow neutral resonances decaying to muon or electron pairs should be heavier than 2.6 TeV [52]. In what follows, we will carry out calculations of cross-sections of this process for the center of mass energy 14 TeV and the masses of KK resonances larger than this exclusion limit.

The process is mainly due to two partonic processes $u\bar{u} \rightarrow \mu^+\mu^-$ and $d\bar{d} \rightarrow \mu^+\mu^-$, the first one giving the main contribution. In the general case there are three KK towers that essentially contribute to these processes and their lowest excitations may be present in the LHC energy range: Z' , γ' and the first massive tensor graviton gr' . As we explained in the previous section, we neglect the contribution from the interaction with the Higgs field to the KK masses of the vector field excitations and take the masses of the first two modes γ' and Z' to be the same and equal to $M_{\gamma'} = M_{Z'} = 5$ TeV. The corresponding widths of the γ' and Z' resonances have been calculated and turned out to be $\Gamma_{\gamma'} = 0.10$ TeV and $\Gamma_{Z'} = 0.15$ TeV respectively.

As we explained in the previous section, the mass of the graviton excitation should be taken approximately equal to $M_{gr'} = 7.5$ TeV in this case, and its (inverse) coupling constant is chosen to be $\Lambda_\pi = 10$ TeV, whereas the width $\Gamma_{gr'} = 0.41$ TeV has been calculated with the help of the formulas of paper [44].

The effective Lagrangians for the KK towers of γ and Z have the same form as (3.1) with the weak charged current $J^{+\mu}$ replaced by the electromagnetic current and the weak neutral current respectively. In this case the process $u\bar{u} \rightarrow \mu^+\mu^-$ is described in our approximation by the following diagrams:

The equation (3.4) shows six Feynman diagrams for the process $u\bar{u} \rightarrow \mu^+\mu^-$. The diagrams are arranged in three rows and two columns, separated by plus signs. The first row contains three diagrams: a s-channel exchange of a photon (γ), a s-channel exchange of a Z boson, and a s-channel exchange of a new photon (γ'). The second row contains three diagrams: a s-channel exchange of a new Z boson (Z'), a contact interaction labeled $C\gamma$, and a contact interaction labeled CZ . The third row contains two diagrams: a s-channel exchange of a new graviton (gr') and a contact interaction labeled Cgr . The label (3.4) is positioned to the right of the diagrams.

For simplicity, we will again assume that the coupling constants of the lowest excitations are the same as those of the zero modes. Then the contact term $C\gamma$ is a local product of two electromagnetic currents with the effective coupling constant $e^2/M_{\gamma'_{sum}}^2$, and the contact term CZ is a local product of two weak neutral currents with the effective coupling constant $g^2(\cos(\theta_W))^{-2}/M_{Z'_{sum}}^2$; for the chosen masses of γ' and Z' boson the effective masses turn out to be $M_{\gamma'_{sum}} = M_{Z'_{sum}} = 7\text{TeV}$. The contact term Cgr is given by formula (2.1), from which the contribution of the first graviton excitation has been subtracted, i.e., with the coupling constant $(C - 1)/(\Lambda_\pi^2 M_{gr'}^2)$. In the stabilized Randall-Sundrum model we approximately have $C \approx 1.8$ [44], in UED models with the flat extra dimension the constant turns out to be $C \approx 1.5$. In our subsequent calculations we will assume $C = 1.7$. Of course, there are the same diagrams with the up quark replaced by the down quark. The structure of the amplitude corresponding to diagrams (3.4) is much more complicated, than in the case of the W' boson (3.3).

We have calculated the cross-sections of the process $pp \rightarrow \mu^+\mu^- + X$ for the sum of the first two diagrams (SM), for the sum of the first four diagrams (SM + γ' + Z') and for the sum of the first six diagrams (SM + γ' + Z' + $C\gamma$ + CZ). The corresponding distributions are plotted in figures 7 and 8 (such distributions for smaller and unequal masses of $M_{\gamma'}$ and $M_{Z'}$ have been obtained in [40]). It is clear that the interference with the contact interaction terms is quite definite and is very similar to that in the single top production.

The cross-sections of the process $pp \rightarrow \mu^+\mu^- + X$ taking into account all the diagrams were calculated as well and are also shown in figures 7 and 8. In these calculations the diagrams of gluon-gluon fusion to the excitations of the graviton, which are important at

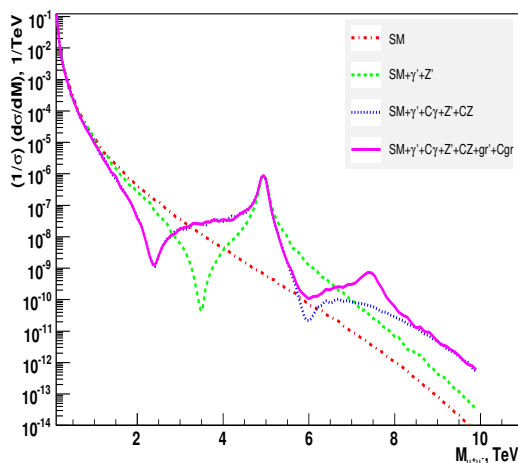


Figure 7. Invariant mass distribution for the Drell-Yan process at the LHC with the center of mass energy 14 TeV for $M_{\gamma'} = M_{Z'} = 5$ TeV, $\Gamma_{\gamma'} = 0.10$ TeV, $\Gamma_{Z'} = 0.15$ TeV, $M_{gr'} = 7.5$ TeV, $\Gamma_{gr'} = 0.41$ TeV.

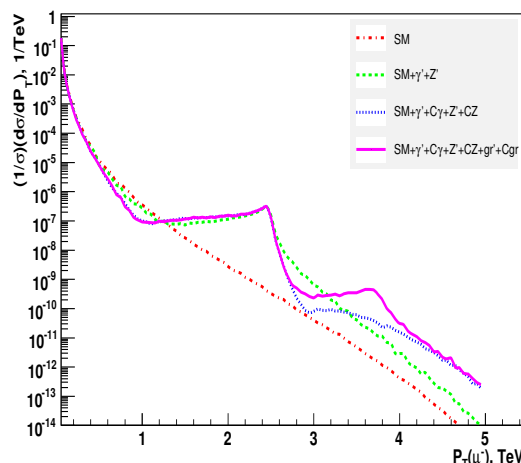


Figure 8. P_T distribution for the Drell-Yan process at the LHC with the center of mass energy 14 TeV for $M_{\gamma'} = M_{Z'} = 5$ TeV, $\Gamma_{\gamma'} = 0.10$ TeV, $\Gamma_{Z'} = 0.15$ TeV, $M_{gr'} = 7.5$ TeV, $\Gamma_{gr'} = 0.41$ TeV.

the LHC and are shown below, were also taken into account.

$$+ \quad (3.5)$$

The calculations of the cross-sections of the process $pp \rightarrow \mu^+ \mu^- + X$ taking into account all the diagrams (3.4) and (3.5) were carried out for two more sets of excitation masses. The results for the set $M_{\gamma'} = M_{Z'} = 3$ TeV, $M_{gr'} = 4.5$ TeV ($M_{\gamma'_{sum}} = M_{Z'_{sum}} = 4.2$ TeV, $\Gamma_{\gamma'} = 0.06$ TeV, $\Gamma_{Z'} = 0.09$ TeV, $\Gamma_{gr'} = 0.14$ TeV, $\Lambda_\pi = 8$ TeV) are shown in figures 9 and 10, and those for the set $M_{\gamma'} = M_{Z'} = 7$ TeV, $M_{gr'} = 10.5$ TeV ($M_{\gamma'_{sum}} = M_{Z'_{sum}} = 9.8$ TeV, $\Gamma_{\gamma'} = 0.15$ TeV, $\Gamma_{Z'} = 0.22$ TeV, $\Gamma_{gr'} = 0.57$ TeV, $\Lambda_\pi = 14$ TeV,) are shown in figures 11 and 12.

An interesting feature of all these plots is the absence of an interference between the first graviton KK excitation and that of the Z boson (the interference with the photon and its excitations is forbidden in QFT). One can rigorously prove that there is no interference in the distributions in the invariant mass of the $\mu^+ \mu^-$ -pair, because the interference terms vanish after the integration over the angles. Explicit calculations show that the interference is also equal to zero for the distributions in the transverse momentum.

4 Concluding remarks

At this point we have to make several remarks. First, as it was noted in [40], there is a good reason to believe that the interference picture discussed here is not destroyed by the NLO corrections. The pole structure of the amplitude, which leads to the non-trivial interference, is clearly not affected by the QCD corrections to the external lines and to the

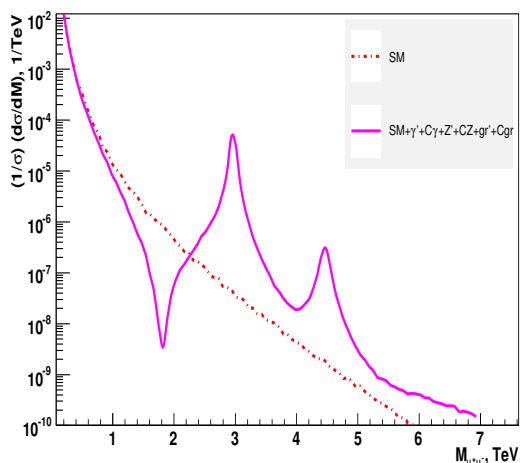


Figure 9. Invariant mass distribution for the Drell-Yan process at the LHC with the center of mass energy 14 TeV for $M_{\gamma'} = M_{Z'} = 3$ TeV, $\Gamma_{\gamma'} = 0.06$ TeV, $\Gamma_{Z'} = 0.09$ TeV, $M_{g_{r'}} = 4.5$ TeV, $\Gamma_{g_{r'}} = 0.14$ TeV.

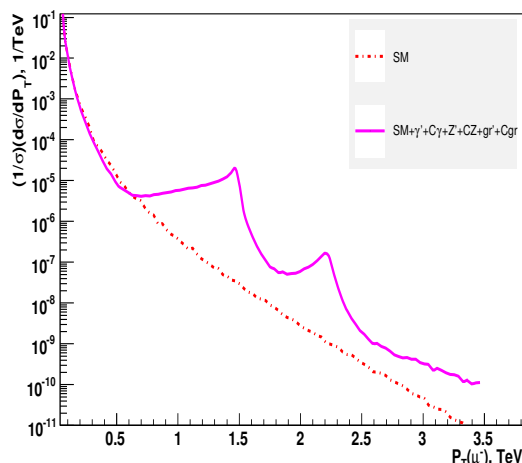


Figure 10. P_T distribution for the Drell-Yan process at the LHC with the center of mass energy 14 TeV for $M_{\gamma'} = M_{Z'} = 3$ TeV, $\Gamma_{\gamma'} = 0.06$ TeV, $\Gamma_{Z'} = 0.09$ TeV, $M_{g_{r'}} = 4.5$ TeV, $\Gamma_{g_{r'}} = 0.14$ TeV.

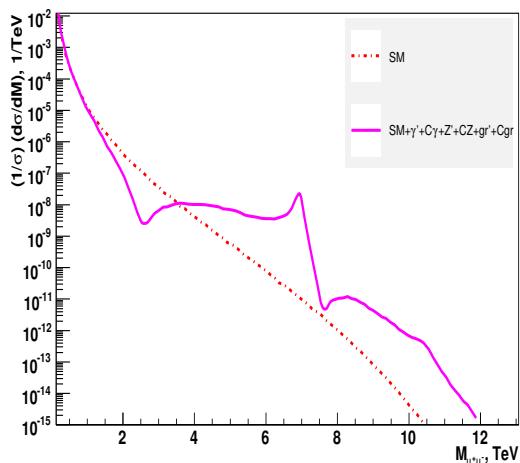


Figure 11. Invariant mass distribution for the Drell-Yan process at the LHC with the center of mass energy 14 TeV for $M_{\gamma'} = M_{Z'} = 7$ TeV, $\Gamma_{\gamma'} = 0.15$ TeV, $\Gamma_{Z'} = 0.22$ TeV, $M_{g_{r'}} = 10.5$ TeV, $\Gamma_{g_{r'}} = 0.57$ TeV.

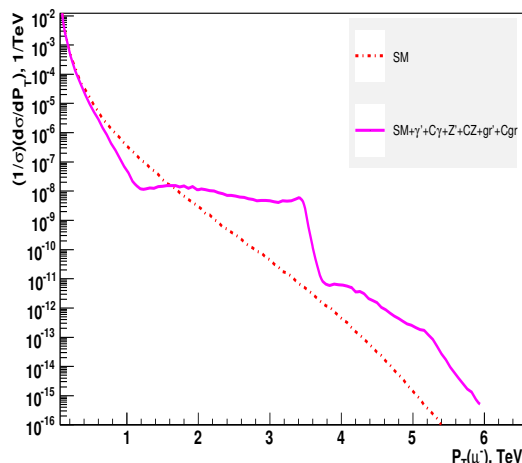


Figure 12. P_T distribution for the Drell-Yan process at the LHC with the center of mass energy 14 TeV for $M_{\gamma'} = M_{Z'} = 7$ TeV, $\Gamma_{\gamma'} = 0.15$ TeV, $\Gamma_{Z'} = 0.22$ TeV, $M_{g_{r'}} = 10.5$ TeV, $\Gamma_{g_{r'}} = 0.57$ TeV.

vertices. The most dangerous terms seem to be those of self-energy diagrams, but they are defined so as to vanish on the mass shell and therefore contribute only to the particle widths and to the renormalization of mass.

Second, the presence of just W'' or Z'' or γ'' can produce similar effects. But if such effects are found, it is easy to improve our approach by taking into account the contributions of W'' , Z'' and γ'' exactly and approximating the contributions of the towers

above them by contact interactions (however, in order to handle such a situation the high luminosity and high energy regime of the LHC operation would be needed). As we have seen, the contribution to the amplitude of the tower above a mode is of the same order as the contribution of the mode proper away from the resonance. Thus, on the basis of our analysis one can think that there should be distinct differences between the KK scenario and that with only two excitations of the SM electroweak gauge bosons. Therefore, an observation of such interference effects for W' , Z' , γ' and the presence of the first tensor KK graviton can be interpreted as a strong argument in favor of the existence of extra dimensions.

Third, we would like to note once again that the masses of W' , Z' , and γ' resonances are nearly degenerate, and therefore one should observe resonances with practically the same masses in the single top and $\mu^+\nu_\mu$ production processes and Drell-Yan processes, which is an interesting prediction of models with extra dimensions.

Finally, we would also like to mention here that the scenario discussed in the present paper is very close to the framework of warped extra dimension with the Standard Model fields propagating in it [33], if one considers only the processes, to which the excitations of the SM fermions do not contribute.

Thus, our analysis shows that in order to search correctly for the Kaluza-Klein excitations of SM particles, in particular, to put correctly exclusion limits, it is necessary, in modeling the signal, to sum the contributions to the amplitudes of all the KK modes above the resonances and to take into account their interference with the contribution of the resonances. Our calculations of the single top and $\mu^+\nu_\mu$ production and Drell-Yan processes also show that the lowest excitations of the SM gauge bosons, as well as that of the graviton, may be in principle observed at the LHC with the center of mass energy 14 TeV if their masses are below 10 TeV. However, realistic simulations taking into account the backgrounds are needed in order to find the LHC collider potential in searches for KK states including the interference with the rest of KK towers.

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