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Abstract

We consider the effective Lagrangian due to the exchange of heavy KK tensor graviton and scalar radion states in a stabilized RS1 model and compute explicitly the corresponding effective coupling constants. The Drell-Yan lepton pair production at the Tevatron and the LHC is analyzed in two situations, when the first KK resonance is too heavy to be directly detected at the colliders, and when the first KK resonance is visible but other states are still too heavy. In the first case the effective Lagrangian reduces to a contact interaction of SM particles, whereas in the second case it includes a coupling of SM particles to the first KK mode and a contact interaction due to the exchange of all the heavier modes. It is shown that in both cases the contribution from the invisible KK tower leads to a modification of final particles distributions. In particular, for the second case a nontrivial interference between the first KK mode and the rest KK tower takes place. Expected 95% CL limits for model parameters for the Tevatron and the LHC are given. The numerical results are obtained by means of the CompHEP code, in which all new effective interactions are implemented providing a tool for simulation of corresponding events and a more detailed analysis.

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ЭФФЕКТИВНЫЕ КОНТАКТНЫЕ ВЗАИМОДЕЙСТВИЯ В СТАБИЛИЗИРОВАННОЙ RS1 МОДЕЛИ МИРА НА БРАНЕ

Препринт НИИЯФ МГУ № 2009-4/848

Аннотация

В стабилизированной RS1 модели рассмотрен эффективный лагранжиан, возникающий вследствие обмена тяжелыми Калуца-Клейновскими (КК) тензорными и скалярными гравитонами, и найдены в явном виде соответствующие эффективные константы связи. Проанализированы процессы Дрелла-Яна парного рождения лептонов на Тэватроне и LHC для случая, когда первый КК резонанс слишком тяжел для прямого рождения, а также для случая, когда первый КК резонанс может быть явно обнаружен, но остальные моды оказываются слишком тяжелыми для прямого рождения. В первом случае эффективный лагранжиан сводится к контактному взаимодействию частиц Стандартной модели, в то время как второй случай включает в себя взаимодействие частиц Стандартной модели с первой КК модой и контактное взаимодействие, обусловленное остальными более тяжелыми модами. Показано, что в обоих случаях вклад башни КК мод ведет к модификации распределения конечных частиц. В частности, во втором случае имеется нетривиальная интерференция между первой КК модой и остальными модами. Получены ограничения на параметры модели для Тэватрона и LHC на уровне достоверности 95%. Численные результаты получены с помощью программного пакета CompHEP, в который включены эти новые эффективные взаимодействия, что позволяет детально моделировать соответствующие процессы.

1 Introduction

Nowadays there are many theoretical schemes, which predict new interactions beyond the Standard Model, mediated by new particles, but these new particles may be too heavy to be directly found in experiments. Thus, it is worthwhile to consider the situation, where the energies accessible at the existing and the upcoming colliders are well below the threshold of production of these new particles. In this case the new interactions, predicted by a particular model, are reduced to contact interactions of the Standard Model particles, which are defined by the model at hand.

Consideration of models with extra dimensions (see, [1, 2, 3, 4, 5, 6, 7]) leads to a very definite prediction for the structure of the contact interaction operators entering the effective Lagrangian. In particular, the contact interactions arising in such models are universal in the sense that they are characterized by only one dimensional constant. An experimental observation of such contact interactions could be a strong argument in favor of models with extra dimensions. Contact interactions due to summation of the exchange of Kaluza-Klein (KK) towers within the ADD scenario were studied in [8]. The collider phenomenology of the contact interactions appearing below the production threshold of KK modes in the RS1 model, such as changes of distribution tails, was discussed in [9]. Contact interactions were also considered in theories with warped universal extra dimensions, where contributions of KK vector boson towers to Fermi's constant were estimated [5].

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. If we consider such a theory 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 action of the theory. This can be easily done, if the self-interaction of the modes is weak, and one can drop it as well. As a result, we get a certain contact interaction of the Standard Model fields for each bulk field of the multidimensional theory. The particular structure of the contact interaction Lagrangian is fixed by the corresponding structure of the SM current coupled to the zero mode of a bulk field and by the spin-density matrix of its KK modes. This leads to a number of very concrete predictions for collider phenomenology.

The bulk field, which appears in any theory with extra dimensions, is the gravitational field, and in the present paper we restrict ourselves to considering this field only.

One of the most interesting brane world models is the Randall-Sundrum model with two branes [10] (the RS1 model). It is a consistent model based on an exact solution for gravity interacting with two branes in 5-dimensional space-time. If our world is located on the negative tension brane, it is possible to explain the weakness of the gravitational interaction by the warp factor in the metric. A flaw of this model is the presence of a massless scalar mode, – the radion, which describes fluctuations of the branes with respect to each other. As a consequence, one gets a scalar-tensor theory of gravity on the branes, the scalar component being described by the radion. It turns out that the coupling of the massless radion to matter on the negative tension brane contradicts the existing restrictions on the scalar component of the gravitational interaction, and in order the model be phenomenologically acceptable the radion must acquire a mass. The latter is equivalent to the stabilization of the brane separation distance, i.e. it must be defined by the model parameters. The models, where the interbrane distance is fixed in this way, are called stabilized models, unlike the unstabilized models, where the interbrane distance can be arbitrary. Below we will discuss the contact interactions of the Standard Model particles, which arise in the stabilized RS1 model proposed in [11].

2 The Effective Lagrangian and two body processes with KK gravitons

In the parameterization, which is often used in the ordinary RS1 model, the effective Lagrangian for the stabilized RS1 model in the energy range below the production threshold of KK resonances takes the form [12]:

$$L_{eff} = \frac{1.82}{\Lambda_\pi^2 m_1^2} T^{\mu\nu} \tilde{\Delta}_{\mu\nu,\rho\sigma} T^{\rho\sigma}, \quad (1)$$

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

where Λ_π is the coupling constant of the first tensor KK resonance, m_1 is its mass and δ stands for the contribution of the scalar modes,

$$T_{\mu\nu} = 2\frac{\delta L_{SM}}{\delta\gamma^{\mu\nu}} - \gamma_{\mu\nu} L_{SM} \quad (3)$$

is the energy-momentum tensor canonically built from the Standard Model Lagrangian L_{SM}. To estimate the corresponding coupling constants we should specify the model parameters. Let us suppose that the lowest scalar mode, the radion, has the mass of the order of $2TeV$. Such situation can be realized if $\Lambda_\pi \simeq 8TeV$, $m_1 \simeq 3.83TeV$ (see [12]), in this case δ turns out to be $\delta \approx 0.7$.

We would like to note that although Lagrangian (1) was calculated for stabilized RS1 model, such form of effective contact interaction appears in a variety of brane world models. Thus, the limits obtained for the overall coupling in the stabilized RS1 model can be used for obtaining restrictions on the parameters of some other models with extra dimensions.

Interaction Lagrangian (1) leads to quite definite processes with the SM particles, which are determined by the structure of the energy-momentum tensor $T^{\mu\nu}$. The latter is a sum of the energy-momentum tensors of the free SM fields and of contributions from the interaction terms, which are proportional to the SM coupling constants. One can easily see that for massless vector fields the trace of the energy-momentum tensor vanishes, and the scalar degrees of freedom do not contribute to the effective interaction. They can contribute to the effective interaction, if one takes into account the conformal anomaly of massless fields. The anomalous part of the energy-momentum tensor turns out to be

$$\Delta T_{\mu\nu} = \frac{\beta(g)}{6g}\left(\eta_{\mu\nu} - \frac{\partial_\mu\partial_\nu}{\Box}\right) F_{\rho\sigma}F^{\rho\sigma},$$

which gives the well-known expression for the anomalous trace of this tensor

$$\Delta T^{\mu}_{\mu} = \frac{\beta(g)}{2g} F_{\rho\sigma} F^{\rho\sigma},$$

where $\beta(g)$ is the beta function. The structure of this anomalous term in the energy-momentum tensor is such that the interaction due to the exchange of tensor particles vanishes, and only the interaction due to the exchange of scalar particles remains. However, this interaction is rather suppressed compared to the one due to the exchange of tensor particles, because the trace of the energy-momentum tensor is proportional to the particle mass that is much smaller than both m_1 and Λ_π. A possibility to observe the scalar component of the effective interaction may be due to the Higgs-radion mixing [13, 14].

The lowest order effective Lagrangian in the SM couplings contains a sum of various four-particle (not only 4-fermions, but also 2-fermions–2-bosons, 4-bosons) effective operators, which are gauge invariant with respect to the SM gauge group and lead to a well defined phenomenology. The Lagrangian involves only three free parameters Λ_π, m_1 and δ, where Λ_π, m_1 parameterize the common overall coupling and δ parameterizes the relative contribution of the scalar radion field (or fields as takes place in the stabilized RS model). Experimental observation of production processes following from the effective Lagrangian (1) or restrictions on their cross-sections allow one to estimate the multidimensional energy scale, provided one gets a theoretical estimate for the product of the parameters m_1 and Λ_π in (1).

In the leading order only the neutral currents of the same generation SM fields are involved. These new interactions do not lead to additional decay modes. Possible new decays of the SM particles from the effective Lagrangian may only be present in the next order in the SM couplings, when charged currents appear in the SM energy-momentum tensor. Also new effective 4-particle operators following from the SM energy-momentum tensor obviously do not lead to flavor changing neutral currents. In the tree level approximation there are several processes following from the effective Lagrangian, which appear only at loop level in the SM such as $gg \to l^+l^-$, $gg \to ZZ(W^+W^-)$, $e^+e^- \to gg$, $\gamma\gamma \to gg$ etc. In [12] analytical expressions for the total and differential cross sections for the processes $gg \to l^+l^-$, $gg \to ZZ(W^+W^-)$, $q\bar{q} \to l^+l^-$, $q\bar{q} \to ZZ(W^+W^-)$, $e^+e^- \to f\bar{f}$, $e^+e^- \to gg$, $\gamma\gamma \to f\bar{f}$, $\gamma\gamma \to gg$ are presented (with nonzero masses of the final state particles). In the cases, where colliding gluons produce massive final particles, there is also a scalar radion contribution, which is proportional to the parameter δ^2 of the order of 1 and to the trace anomaly coefficient $(\beta(g_s)/2g_s)^2$. Numerically it is about 100 times smaller than the corresponding tensor contribution.

Symbolic and numerical computations have been performed by means of the version of the CompHEP [15] package realized on basis of the FORM [16] symbolic program. The Feynman rules following from the effective Lagrangian have been implemented into this version of the CompHEP. Such an implementation allows one to use the code for event generation and to perform analysis in future more realistic studies.

As shown for the RS1 model in [9] the exchange of a tower of the KK gravitons in the energy range below the KK production threshold leads to an increase of the invariant mass tail of produced particles. For the Drell-Yan process it is demonstrated in Figs. 1, 2. The process $gg \to l^+l^-$

contributes to the Drell-Yan process and it was included in our numerical simulations. As will be demonstrated below, even in the case when the first KK resonance lies in the energy range accessible for a detection one should take into account the contribution from all the other KK states.

Using the standard χ^2 analysis and taking into account the expectations for systematic uncertainties (detector smearing, electroweak, QCD scale, PDF) and statistic uncertainties of the SM dilepton invariant mass shape (see experimental data [17] for the Tevatron and Monte-Carlo simulations [18] for the LHC) we obtain the current Tevatron limit for the coupling parameter at 95% CL and estimate expected experimental limits for this parameter (Table 1) that may be reached at the Tevatron for higher luminosities and for various luminosities at the LHC.

Table 1: Experimental limits for the coupling parameter at 95% CL that may be reached at the Tevatron and the LHC using Drell-Yan process for some values of integrated luminosity L.

TEVATRON ($\sqrt{s} = 1.96\ TeV$)		LHC ($\sqrt{s} = 14\ TeV$)	
$L,\ fb^{-1}$	$\frac{0.91}{\Lambda_\pi^2 m_1^2}$ at 95% $CL,\ TeV^{-4}$	$L,\ fb^{-1}$	$\frac{0.91}{\Lambda_\pi^2 m_1^2}$ at 95% $CL,\ TeV^{-4}$
1	1.185	10	$0.238 \cdot 10^{-2}$
2	0.995	20	$0.203 \cdot 10^{-2}$
3	0.900	30	$0.184 \cdot 10^{-2}$
5	0.790	50	$0.164 \cdot 10^{-2}$
10	0.664	100	$0.140 \cdot 10^{-2}$

The Tevarton limit for $1fb^{-1}$ of integrated luminosity expressed in terms of parameter M_s^{GRW} introduced in [19]

$$M_s^{GRW} = \left(\frac{1}{2\pi} \cdot \frac{0.91}{\Lambda_\pi^2 m_1^2} \right)^{-\frac{1}{4}}$$

gives $M_s^{GRW}(1fb^{-1}) = 1.52\ TeV$, which is in a good agreement with the corresponding limit from the cited experimental paper [17].

The last string of Table 1 contains limits corresponding to the highest value of collider luminosity:

$$Tevatron(10fb^{-1}):\ \frac{0.91}{\Lambda_\pi^2 m_1^2} \times TeV^4 < 0.66, \quad LHC(100fb^{-1}):\ \frac{0.91}{\Lambda_\pi^2 m_1^2} \times TeV^4 < 0.0014. \quad (4)$$

Figures 1 and 2 demonstrate distributions corresponding to values (4). These limits may be used for estimating the lowest value of parameter Λ_π from a requirement that the width of a resonance be smaller than its mass: $\Gamma_1 < m_1/\xi$, where ξ is some number, $\xi > 1$. Using limits (4) and equation for the total graviton width [12] $\Gamma_1 \approx \frac{m_1^3}{\Lambda_\pi^2 \cdot 4\pi} \frac{97}{80}$ we get:

$$Tevatron:\ \Lambda_\pi > 0.61 \cdot \xi^{1/4}\, TeV, \quad LHC:\ \Lambda_\pi > 2.82 \cdot \xi^{1/4}\, TeV, \quad \xi > 1. \quad (5)$$

One of the effects in searches for KK resonances below the production threshold of the first state is an enhancement of the effective coupling due to KK summation in comparison to the

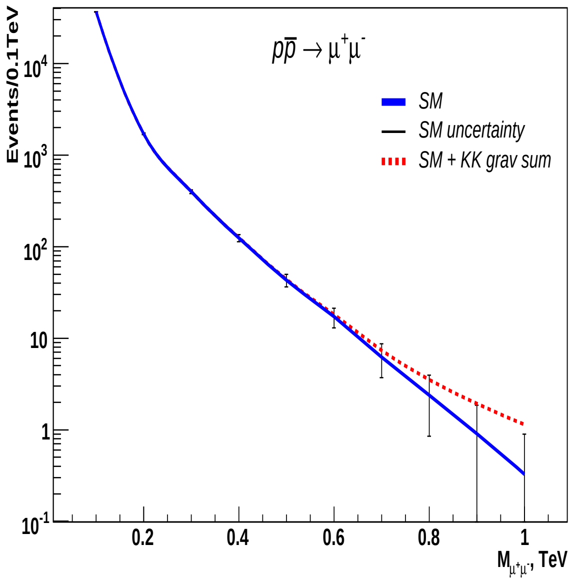

Figure 1: Dilepton invariant mass distribution for 95% CL parameter $\frac{0.91}{\Lambda_\pi^2 m_1^2} \times TeV^4$=0.66 for the Tevatron ($L = 10 fb^{-1}$)

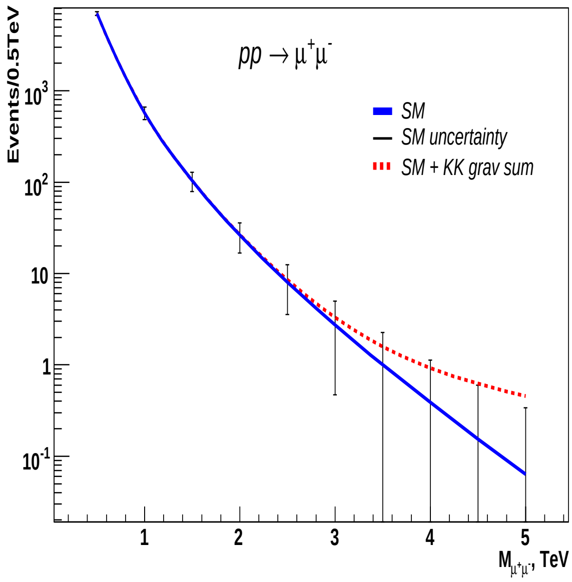

Figure 2: Dilepton invariant mass distribution for 95% CL parameter $\frac{0.91}{\Lambda_\pi^2 m_1^2} \times TeV^4$=0.0014 for the LHC ($L = 100 fb^{-1}$)

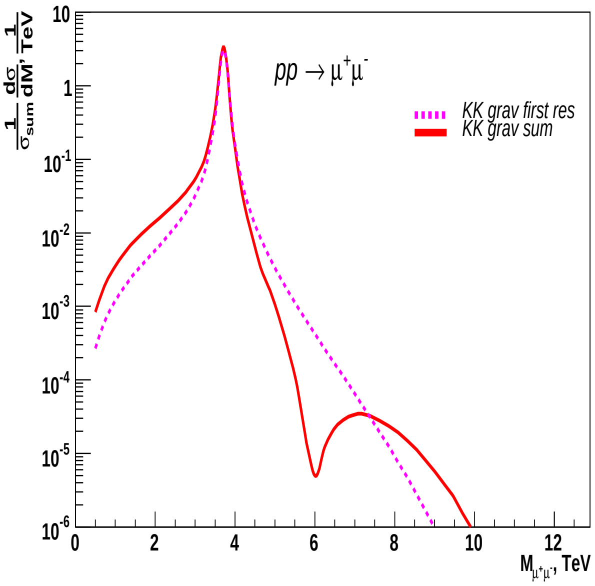

Figure 3: The normalized dilepton invariant mass distribution from the first KK resonance plus the sum of KK tower states starting from the second mode (solid line) and from the first KK resonance only (dashed line) for M_{res} = 3.83 TeV, Γ_{res} = 0.08 TeV, Λ_π = 8 TeV for the LHC

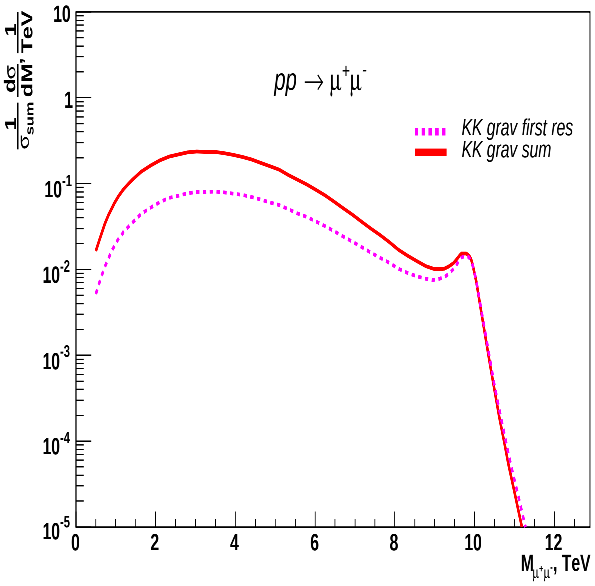

Figure 4: The normalized dilepton invariant mass distribution from the sum of KK tower states starting from the first KK mode (solid line) and from the first KK mode only (dashed line) for $M_{res} = 10\ TeV$, $\Gamma_{res} = 0.5\ TeV$, Λ_π = 14 TeV for the LHC

first mode contribution below the threshold only. To illustrate changes in distributions due to KK tower contributions we run simulations for two parameter points with the first KK resonance being in and out of directly detectable regions. The first point ($m_1 = 3.83\ TeV$, $\Lambda_\pi = 8\ TeV$, $\Gamma_1 = 0.08\ TeV$) was already discussed. Such an RS resonance is close to the direct reach limits expected for the LHC [9]. For the second point ($m_1 = 10\ TeV$, $\Lambda_\pi = 14\ TeV$, $\Gamma_1 = 0.5\ TeV$) the mass of the first KK excitation is close to collider energy limit and it is not directly observable. For both points we can use the low energy effective Lagrangian approach. The effective Lagrangian allows us in both cases to sum up the contributions from all the KK modes or from all except the first one, and in this way to take into account their influence on the background tail [12]. As one can see from Fig. 3 and Fig. 4, the additional substrate from the KK tower increases the production rate more than 3 times in the invariant mass region below the resonance mass. The situation is significantly different above the resonance, where in addition to the resonance pike there is an area with a minimum due to a destructive interference between the first KK resonance and the remaining KK tower contribution [12]. This local minimum takes place at the value of invariant mass $M_{min} \approx 1.5 m_1$. The growth of the invariant mass after the minimum is strongly suppressed by parton distribution functions leading to an additional bump in the invariant mass shape. But this bump is unlikely to be visible in the experiment on top of the SM background.

In conclusion, one should stress that in order to perform correct searches for KK resonances not only interferences with the SM if non-vanishing and computed NLO QCD corrections [20] should be included into corresponding generators, but also the influence of those KK states, which are not reachable directly.

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ЭФФЕКТИВНЫЕ КОНТАКТНЫЕ ВЗАИМОДЕЙСТВИЯ В СТАБИЛИЗИРОВАННОЙ RS1 МОДЕЛИ МИРА НА БРАНЕ

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