ADD extra dimensional gravity and di-muon production at LHC

I. Golutvin [1], A. Sapronov [2], M. Savina [3], S. Shmatov [4]
Laboratory of Particle Physics,
Joint Institute for Nuclear Research

Abstract

A possibility to observe TeV-scale gravity signals at the LHC is discussed. The ADD scenario with large extra dimensions is considered and its LHC discovery potential is derived studying by muon pairs with large invariant masses.

1 Introduction. ADD scenario overview

Recently several new models of low-scale gravity were proposed based on brane world ideas [1, 2]. In this work we concentrate on phenomenology of the first of them, the ADD scenario with flat space-time geometry. We derive the LHC discovery potential to observe one of several new phenomena appearing in ADD. Namely, we consider modification of the Standard Model dimuon continuum due to contributions from multiple virtual KK-modes of graviton.

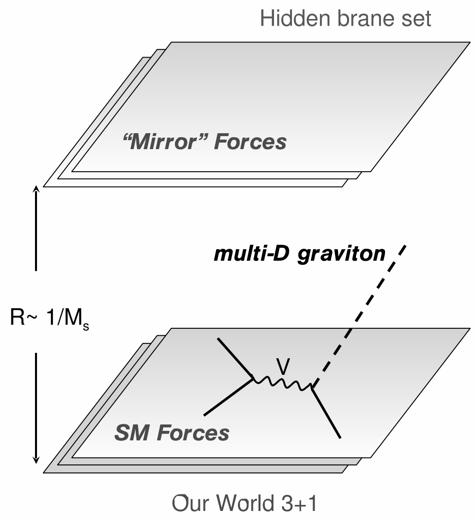

Figure 1: The ADD world with two stacks of branes one of which is hidden.

The ADD model [1] implies that n (n=1..6) extra spatial dimensions can exist in addition to our three compactified on a n-sphere with a radius R (the simlpest case). Then R is called the compactification radius and it does not have to be the planckian size, but can be really such a large as tenths of millimeter or smaller. Usual consideration is that all of the Standard Model fields are confined on a three-brane embedded in a $(3+n)$-dimensional space referred as the bulk (Fig. 1). It is the reason why we don not observe any effects from extra dimensions up to the energy scale $1/R$ when fundamental multidimensional structure can be distinguished. In this model graviton is only multidimensional field what can travel

[1]golutvin@sunse.jinr.ru
[2]sapronov@sunse.jinr.ru
[3]savina@theor.jinr.ru
[4]shmatov@cern.ch

through the bulk. In the model the planckian scale M_{Pl} is no longer fundamental but it becomes the effective scale connected with the true fundamental multidimensional scale M_S in such a way:

$$M_{Pl} = M_S^{1+n/2} R^{n/2} \tag{1}$$

So we can observe possible effects from multidimensional gravity at the energies above $\approx M_S$ and if desired to be probed at the LHC the fundamental mass scale should be adjusted to the order of 1 or a few TeV.

The characteristic picture of ADD model is the existence of Kaluza-Klein modes of graviton (these modes will be massive and the mass value is $m_{KK} = 2\pi k/R$, k is a mode number). These modes must be light: in dependence on a number of extra dimensions at the fundamental scale $M_S \approx 1$ TeV mass values for the first graviton excitation start from $\approx 10^{-3}$ eV for $n = 2$ up to maximal ≈ 10 MeV for $n = 6$. More details about of ADD phenomenology can be found, for example in [3, 4].

Setting $M_S \approx 1$ TeV one can calculate extra dimensions radius $R \approx M_S^{-1} \times\ (M_{Pl}/M_S)^{2/n} \approx 10^{(32/n)} \times 10^{-17}$ cm. The case $n = 1$ gives unacceptably large values of R because the Newton law validity is established down to 0.2 mm [5]. In the case $n = 2$ the radius value about 1mm, the fundamental scale value $M_S \approx 1$ TeV is the most probably excluded by astrophysics and cosmological arguments (see for example [3, 6]). The closest permissible value of M_S for $n = 2$ is about 30 TeV that is obviously out of the scope of observations on modern and future accelerators. Thus the most favorable set of parameters appears to be $n = 3$, $M_S \approx 1$ TeV and $R \approx 10^{-4}$ mm.

Existing data analysis gave no positive results, but only constraints. LEP experiments have closely investigated possibilities of presence of large extra dimensions. One of the evidences would be direct KK-graviton production in $e^+e^- \to \gamma G$ process. Measurement of final states with photons and missing energy showed no deviation from the Standard Model predictions and put constraints on M_S – from 1.5 TeV to 0.75 TeV for a number of extra dimensions from two to five respectively [7].

Virtual graviton production at the LEP was searched for in processes with pair-production of fermions and gauge bosons: $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$, $\gamma\gamma$, ZZ, W^+W^- [8]. None of the processes exhibited evidence for virtual graviton production and constraints established for M_S are around 1.2 TeV.

TEVATRON experiments CDF and D0 having searched for final states with missing transverse energy in processes with photons in final state observed no signal. The CDF collaboration has also searched for events with one or two jets and large missing transverse energy [9]. Virtual graviton production might have been seen as a distortion of mass spectra and angular distributions of electron and muon pairs as well as diphotons in the final state. The largest experimental sensitivity was achieved by the combined analysis of electron pairs and the diphoton channels performed by the D0 collaboration at Run I and Run II. The data agree with the SM predictions for Drell-Yan electron-pair production, direct diphoton production and an instrumental background. The current lower limit on M_S derived at TEVATRON are around 1.1 TeV [10].

2 LHC discovery limit

In the section above we have pointed out that the characteristic feature of ADD is the existence of light KK-gravitons which could be directly produced at colliders (real graviton production) or observed through contact interactions as virtual KK-graviton exchange. Experimental signals for ADD scenario might be found in dijet, dilepton, diphoton mass spectra and missing energy distributions. The missing energy phenomenon corresponds to real graviton production, whereas the first three signals account for virtual graviton production. Real gravitons carry away a fraction of the total energy produced in a hard collision, in other words induce energy leakage from the interaction point. Virtual gravitons make contribution to the SM diagrams for Drell-Yan processes as well as for gamma pair production which results in significant modification of these spectra. An amplitude of each separate graviton contribution is suppressed by $\sim 1/M_{Pl}$, however the production cross section counts many contributions (large number of gravitons with the same mass value defined by a mode number k, see above, is taken into account with a state density $N(\mathcal{E})$) and this circumstance induces crucial enhancement of graviton production cross section so effective suppression will be only by $(1/M_S)^2$.

The cross section of Drell-Yan process with Kaluza-Klein terms can be factorized as:

$$\sigma = \sigma_{SM} + \sigma_4\eta + \sigma_8\eta^2, \tag{2}$$

where the first and the third terms correspond to the SM and Kaluza-Klein contributions respectively, while the second one characterizes an interference between the SM and gravity. Here η is given by

$$\eta = \frac{\mathcal{F}}{M_S^4}, \qquad \mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{\hat{s}}\right) & for \quad n = 2, \\ \frac{2}{n-2} & for \quad n > 2. \end{cases} \tag{3}$$

where $\hat{s}$ is the center-of-mass energy. Exact expressions for σ_{SM}, $\sigma_4\eta$ and $\sigma_8\eta^2$ can be found at [11].

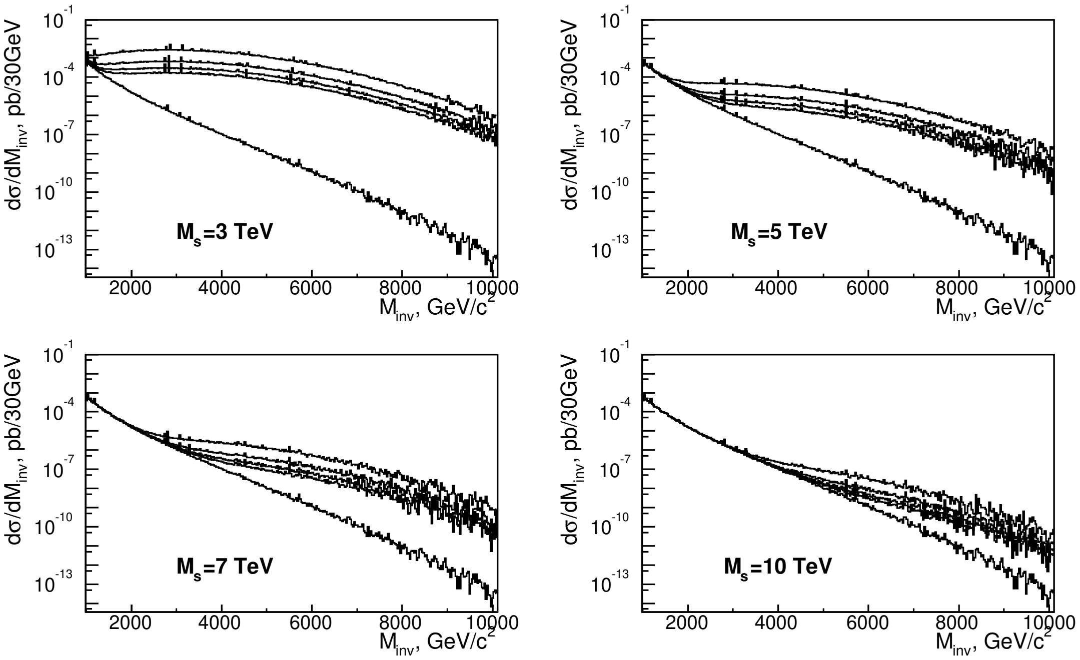

Figure 2: Muon invariant mass for different number of extra dimensions n (ADD). From bottom to top: SM, n = 6, 5, 4, 3. Four values of the fundamental gravity scale M_S are considered.

The characteristic scale value M_S with a number of extra dimensions n pinpoint the region of dilepton invariant masses M_{ll} sensitive to extra dimensions. The Fig. 2 demonstrates the invariant mass distributions of muon pairs for the pure Standard Model (lower curve) and for scenarios with n = 3, 4, 5, 6 extra dimensions. Cases with four different values of M_S (3, 5, 7, 10 TeV) were considered. Those differential cross sections, $d\sigma/dM_{\mu\mu}$, were obtained following [11] taking into account the next-leading-order QCD corrections (using the K factor of 1.38).

In order to estimate the LHC sensitivity to new physics coming from extra dimensions in our analysis we used typical kinematics and geometrical acceptance of one of the LHC experiments, CMS, which is, as with ATLAS, expected to be able to trigger and identify hard muons with a transverse momentum up to several TeV. The dimuon is accepted when both decay muons are within detector system covering the pseudorapidity region of $|\eta| \leq 2.4$. In addition, the cut $p_T \geq 20$ GeV/c was applied on each muon. No cuts were made on isolation of muons in the tracker and the calorimeter. The total efficiency dimuon selection, ε, is about 83÷91 %. To take into account a detector resolution of a muon momentum the parametrization $\delta p_T \approx 4\%\sqrt{p_T/TeV}$ was used.

The expected significance was computed by method based on counting signal and background events in a certain signal region. The estimator $S_{c12} = 2(\sqrt{N_S + N_B} - \sqrt{N_B})$ [12] where N_S and N_B are the number of signal and background events in the invariant mass interval above 1 TeV was used for this purpose.

The ADD model discovery limit as a function of the M_S scale is shown on the Fig. 3. Filled area between two curves ($n = 3$ and $n = 6$) shows the upper limit on M_S for different numbers of extra dimensions with a 5σ significance. As it may be seen, the scale $M_S \approx 6$ TeV can be reached at integrated luminosity of 100 fb^{-1} even for the most unfavorable case with $n = 6$. For more promising scenario where the number of extra dimensions is minimal ($n = 3$) the accessible level is extended up to 7.5 TeV.

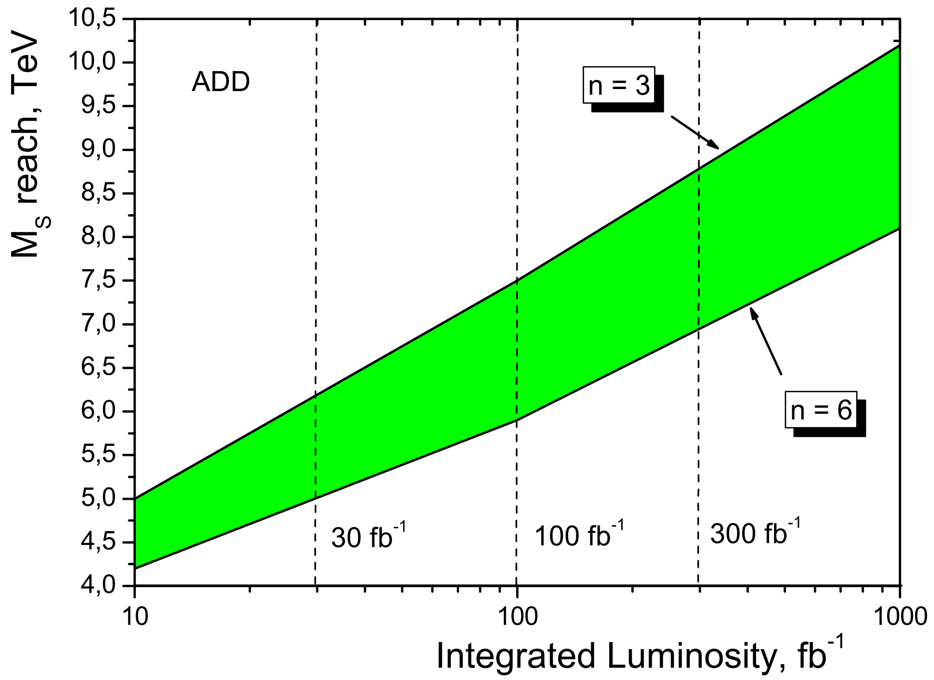

Figure 3: 5σ limit on M_S for the number of extra dimensions $n = 3, 4, 5, 6$.

Note that these estimates are very close to earlier results [11] which were obtained having used the maximum likelyhood method and Bayesian approach. In this cases the LHC limit extracted from combined dielectron and dimuon analysis is about $6.9 \div 10.2$ TeV for $n = 6 \div 2$. Generally, the detector performances for electron and muon measurements are widely different and muon and electron modes should be analized separetely.

3 Systematics uncertainties

As it was discussed above, the physics beyond the Standard Model can manifest itself as deviations from the standard behavior of Drell-Yan spectra. At that, these distortions may be both positive and negative, in other words a dilepton continuum can rise like in the ADD scenario considered above or equally well fall dawn in dependence on a theoretical scenario (for instance, in scenario with non-commutative extra dimensions – see Ref. [3]). And what is more, a region of dilepton invariant masses where these effects are occurred is not fixed by a mass window. It can be more or less narrow resonance state above the dilepton continuum (like in the RS1 scenario [2] or extended gauge models [13]), or just the smooth enough up(down)ward dimuon distribution slope in a wide invariant mass interval. For correct extraction of signal events from a background we should understand reliability of calculations of a dilepton spectrum within the Standard Model to keep under control all possible sources of errors and systematic uncertainties. This systematics can be related to an accuracy of theoretical calculations, an accuracy of phenomenological determination of PDF's and a roughness of experimental data – detector resolution, goodness of fits etc.

A possible theoretical ambiguity in such studies is induced by incomplete accounting of contributions from QCD and electroweak higher order quantum corrections to processes considered. As it was mentioned before current calculations were done in the leading order for the CTEQ6 with K-factor of 1.38 which was used to take into account next-to-leading-order contributions. It is expected here that a total value of additional NNLO contributions does not exceed 5 %.

A phenomenological origin of PDF gives one another systematic error. First of all, estimations of a cross section obtained by using different sets of structure functions are not quite equal. These results are varying within ± 7 % for $M_{ll} \geq 1$ TeV.

In addition, there are uncertainties within the bounds of the same set (so called *internal* uncertainties) coming from an accuracy of the global analysis of experimental data and from experimental measurement errors. A recently developed PDF building technique goes beyond the "standard" paradigm of extracting of only one "best fit". Last versions of PDF contain a set of various alternative fits obtained by subjective tuning of specific degrees of freedom for this PDF [14]. Applying standard statistical methods one can analyze internal uncertainties comprehensively. These uncertainties are increasing crucially for very large values of x (or Q^2) and in the small-x region. For instance, uncertainty bands for CTEQ6M set of PDF's are stayed to be about of 2.6 %(6 %) for $u(d)$-quarks respectively in the region of x values from $10^{-3} \div 10^{-4}$ up to 0.3 at $Q^2 = 10$ GeV^2, and these uncertainties grow rapidly for the large x up to of 100 % at x=0.6 ÷ 0.7 [15].

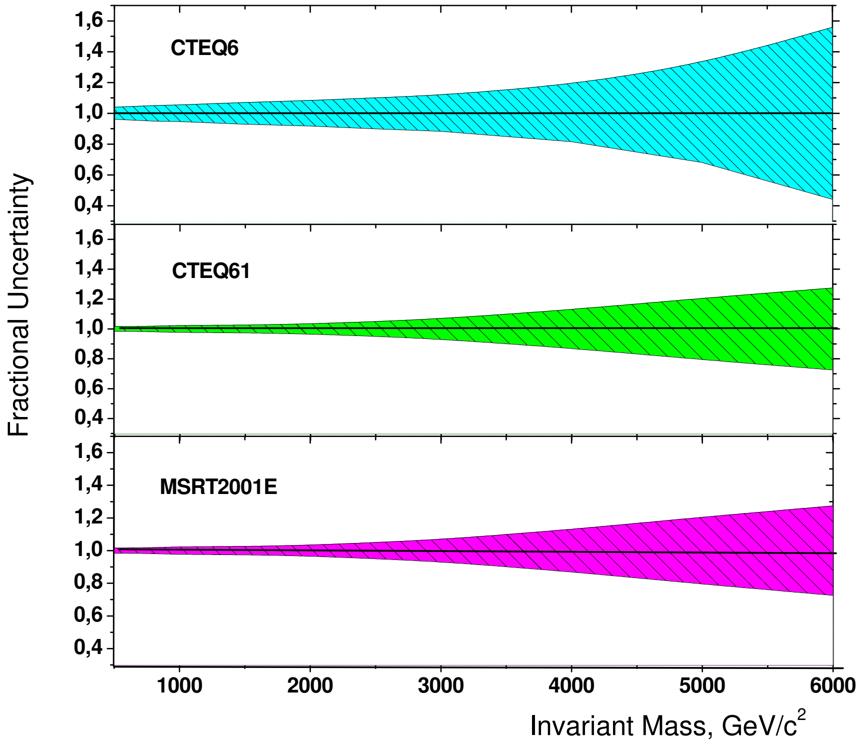

Figure 4: Uncertainties in calculations of production cross section for Drell-Yan processes as a function of dimuon invarinat mass. Cases of different PDF's (CTEQ6, CTEQ61 and MRST2001E) are considered.

Course, an ambiguity in theoretical calculations of the Drell-Yan cross section due to *internal* uncertainties of PDF can also turn out to be very large. Thus for invariant masses available to data from the TEVATRON (~ 0.6 TeV) this uncertainty is order to theoretical one and does not exceed ± 6 %, but an error will increase strongly for large values of invariant masses up to $\sim 10 \div 15$ % for 3 TeV (Fig. 4).

Therefore, PDF related incorrectness of calculations can reduce significantly a possibility to derive

ADD signals. For example, their counting decreases of the fundamental mass scale reachable at LHC from 7.5 TeV (for n=3) down to 6.5 TeV. It should be noted that around the region (near 2.5 TeV) the error coming from PDF's is order to statistical one which is estimated for integrated luminosity of 300 fb^{-1} (about three years of LHC operation in the high-luminosity regime).

Today, the current analysis of PDF sets shows that PDF uncertainties contribute significantly in Drell-Yan calculation ambiguity. One expect, that new data from both working machines, the TEVATRON and HERA, and especially from the LHC in future will extend an available for analysis range of x and Q^2 and will allow to extract parton distribution functions more precisely. Moreover, a definite progress is also being expected from the theoretical side that will be induced by precise counting both higher twist terms and nonperturbative QCD effects [15].

Acknowledgements

Authors would like to thank D. Bardin, E. Boos, V. Rubakov, and S. Slabospitsky for enlightening and helpful discussions. We are very grateful to G. Landsberg to provide us the ADD generator code. A.S. would also like to acknowledge specially Organizing Committee for hospitality and very interesting scientific program of the Conference.

References

[1] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali "The Hierarchy Problem and New Dimensions at a Millimeter", Phys. Lett. B429 (1998) 263, hep-ph/9803315; I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, and G. Dvali "New Dimensions at a Millimeter to a Fermi and Superstrings at a TeV", Phys. Lett. B436 (1998) 257, hep-ph/9804398.
Superstring realization of the model can be found in
D. Cremades, L.E. Ibanez, F. Marchesano "Standard Model at Intersecting D5-branes: Lowering the String Scale", Nucl. Phys. B643 (2002) 93, hep-th/0205074; C. Kokorelis "Exact Standard model Structures from Intersecting D5-Branes", Nucl.Phys. B677 (2004) 115, hep-th/0207234

[2] L. Randall and R. Sundrum, "A large mass hierarchy from a small extra dimension", Phys. Rev. Lett. 83 (1999) 3370, hep-ph/9905221; "An alternative to compactification", Phys. Rev. Lett. 83 (1999) 4690, hep-th/9906064

[3] V.A. Rubakov, "Large and infinite extra dimensions", Uspekhi Fizicheskih Nauk 171 (2001) 913 (in Russian), hep-ph/0104152 (English version).

[4] D.I. Kazakov, "Beyond the Standard Model", hep-ph/0411064

[5] C.D. Hoyle, U. Schmidt, B.R. Heckel, E.G. Adelberger, J.H. Gundlach, D.J. Kapner and H.E. Swanson "Sub-millimeter tests of the gravitational inverse-square law: A search for "large" extra dimensions", Phys. Rev. Lett. 86 (2001) 1418, hep-ph/0011014

[6] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, "Phenomenology, Astrophysics and Cosmology of Theories with Sub-Millimeter Dimensions and TeV Scale Quantum Gravity", Phys. Rev. D59 (1999) 086004, hep-ph/9807344

[7] L3 Collaboration, P. Achard et al., "Single photon and multiphoton events with missing energy in e+ e- collisions at lep", CERN-EP/2003-086, Phys. Lett. B587 (2004) 16, hep-ex/0402002

[8] D. Abbaneo et al. "A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model", hep-ex/0212036

[9] CDF Collaboratipon, D. Acosta et al., "Limits on extra dimensions and new particle production in the exclusive photon and missing energy signature in p anti-p collisions at s**(1/2) = 1.8 TeV", Phys. Rev. Lett. 89 (2002) 281801, hep-ex/0205057

[10] D0 Collaboration, B. Abbott et al., "Measurement of the high mass Drell-Yan cross-section and limits on quark electron compositeness scales", Phys. Rev. Lett. 82 (1999) 4769, hep-ex/9812010

[11] K. Cheung, G. Landsberg, "Drell-Yan and diphoton production at hadron colliders and low scale gravity model", Phys. Rev. D62 (2000) 076003, hep-ph/9909218;
K. Cheung, "Collider phenomenology for models of extra dimensions", hep-ph/0305003.

[12] S.I. Bityukov and N.V. Krasnikov, "On observability of signal over background", CMS CR 2000/004; S.I. Bityukov and N.V. Krasnikov, "Observability and Probability of Discovery in Future Experiments", CMS IN 1999/027, hep-ph/9908402

[13] M. Cvetic and S. Godfrey, Summary of the Working Subgroup on Extra Gauge Bosons of the PDF long-range planning study to Electro-weak Symmetry Breaking and Beyond Standard Model, eds. T. Barklow et al., World Scientific, 1995; hep-ph/9504216; T.G. Rizzo, Proceedings of the 1996 DPF/DPB Summer Study on New Directions for High Energy Physics-Snowmass96, Snowmass, CO, 25 June - 12 July, 1996;
J.L. Hewett and T.G. Rizzo "Low-energy phenomenology of superstring inspired E(6) models", Phys. Rept. 183 (1989) 193 hep-ph/0108274

[14] "The LHAPDF Interface", http://durpdg.dur.ac.uk/lhapdf/

[15] J. Pumplin et al., "New Generation of Parton Distributions with Uncertainties from Global QCD Analysis", JHEP 0207 (2002) 012, hep-ph/0201195