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Determination of the fundamental scale of gravity and the number of space–time dimensions from high energetic particle interactions

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Abstract

Within the ADD-model, we elaborate an idea by Vacavant and Hinchliffe [J. Phys. G 27 (2001) 1839] and show quantitatively how to determine the fundamental scale of TeV-gravity and the number of compactified extra dimensions from data at LHC. We demonstrate that the ADD-model leads to strong correlations between the missing E_T in gravitons at different center of mass energies. This correlation puts strong constraints on this model for extra dimensions, if probed at $\sqrt{s} = 5.5$ TeV and $\sqrt{s} = 14$ TeV at LHC.

Recently string theory motivated models with additional space–time dimensions have moved into the center of attention in high energy physics. Depending on the size of the extra dimensions and the geometry of space–time three different kinds of extra dimensional models are usually discussed: the model of universal extra dimensions [2] which allows all particles to propagate into the new dimensions, the model of Randall and Sundrum (RS) [3] with one "gravity-only" extra dimension and the ADD-model [4,5] with many "gravity-only" extra dimensions. Especially the RS- and ADD-models allow the introduction of a new fundamental scale M_D of gravity in the TeV range. This drastic increase of the coupling strength of gravity on small scales compared to the Planck scale results in a vast amount of potentially observable effects:

- black hole production in colliders and ultra high energetic cosmic rays (UHECR) [6–16];
- increased neutrino cross sections in UHECR interactions [17–20];
- virtual graviton exchange processes [21–25];
- direct graviton production as Kaluza–Klein resonances [1,21,22,26–33].

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Present limits on the new fundamental scale and the size and number of extra dimensions have been obtained from: direct measurements of the gravitational inverse square law [34], hadron–hadron interactions at Tevatron [35,36], modifications of cosmic ray cross sections [11,37–39] and supernova explosions and cooling [40,41].

While supernova cooling gives a very tight constraint of $M_D > 500$ TeV for $\delta = 2$, more than two extra dimensions lead to constraints of M_D of the order of a TeV. The Tevatron data constraints M_D to be of the order or above 1 TeV.

In this Letter we elaborate on an idea by Vacavant and Hinchliffe [1]. They discuss qualitatively how to determine the number of extra dimensions from the ratio of cross sections for missing transverse energy at different center-of-mass (CMS) energies. In addition to their analysis we focus on quantitative predictions and the strong correlations of the cross sections for graviton production at LHC within the ADD-model.

Our presentation of the cross section for missing energy at $\sqrt{s} = 5.5$ TeV and $\sqrt{s} = 14$ TeV pp collisions allows to directly read off both the M_D and δ values from the experimentally measured missing energy cross sections from graviton production. Furthermore, we show that the ADD-model predicts very strong correlations of these cross sections for different CMS energies providing a crucial test of the ADD-scenario.

For the calculations employed here we use the leading order parton + parton → graviton + parton cross sections given in [21]. The reader should be aware that the use of leading order cross sections can only be justified up to parton–parton center of mass energies of $\sqrt{\hat{s}} \leqslant 6M_D$. Thus, for $M_D \leqslant 2$ TeV and $\sqrt{s_{\rm pp}} = 14$ TeV the present results might achieve corrections. The differential cross section for the production of a jet and a graviton in pp interactions is then obtained by folding the two particle cross sections with the parton distribution functions f_i (here we use CTEQ6 [42,43]):

$$\frac{d^3\sigma}{dy\,dp_T\,dm}(AB \to \text{jet} + G) = 2p_T \sum_{\text{partons}} \int_{x_{\min}}^{1} dx_a \, \frac{x_a x_b}{x_a - \frac{m_T}{\sqrt{s}} e^y} \times f_a\big(x_a, Q^2\big) f_b\big(x_b, Q^2\big) \frac{d^2\sigma}{d\hat{t}\,dm}(ab \to cG) \quad (1)$$

with the transverse graviton mass m_T, the rapidity y, $Q^2 = 2\hat{s}\hat{t}\hat{u}/(\hat{s}^2 + \hat{t}^2 + \hat{u}^2)$, and

$$\frac{d^2\sigma}{dt\,dm} = S_{\delta-1} \frac{M_{\rm Pl}^2}{M_D^{2+\delta}} m^{\delta-1} \frac{d\sigma_m}{dt}, \quad (2)$$

m being the mass of the graviton and $S_{\delta-1}$ the surface of the δ-unit sphere. $d\sigma_m/dt$ is the elementary cross section for the production of a graviton of mass m [21]. It is interesting to note that the $1/M_{\rm Pl}^2$ in the transition matrix is cancelled by the phase space factor resulting in an enhanced cross section $\propto 1/M_D^{2+\delta}$.

Due to their small interaction cross section with standard model particles and their long lifetimes gravitons escape the detector region without a signal. Thus, gravitons will be observed indirectly by missing transverse energy.

Here we quantify the energy loss by demanding a minimum missing transverse energy $E_{T,\min}$ in the mid-rapidity range ($-3 \leqslant y \leqslant 3$):

$$\sigma(AB \to \text{jet} + G)|_{E_{T,\min}} = \int_{-3}^{3} dy \int_{E_{T,\min}}^{\infty} dE_T \times \int_{0}^{\sqrt{s}/2} dm \, \frac{d\sigma(AB \to \text{jet} + G)}{dy\,dp_T\,dm}. \quad (3)$$

In Fig. 1 we show the integrated cross section for missing energy as given by Eq. (3) for four extra dimensions. The lines (from top to bottom) show the results for different values of the fundamental scale M_D from 1 to 6 TeV. As a check we compare to [1] (symbols).

Let us now focus on how to extract the fundamental scale and the number of space–time dimensions in the ADD-model from data. The cross section for a mono-jet- and missing energy event depends on M_D and δ, however, information on the cross section at only one CM-energy leads to a set of different possible δ and M_D. Here, we suggest to combine more than one cross section measurements at different CMS energies. This allows to determine the δ and M_D value, uniquely.

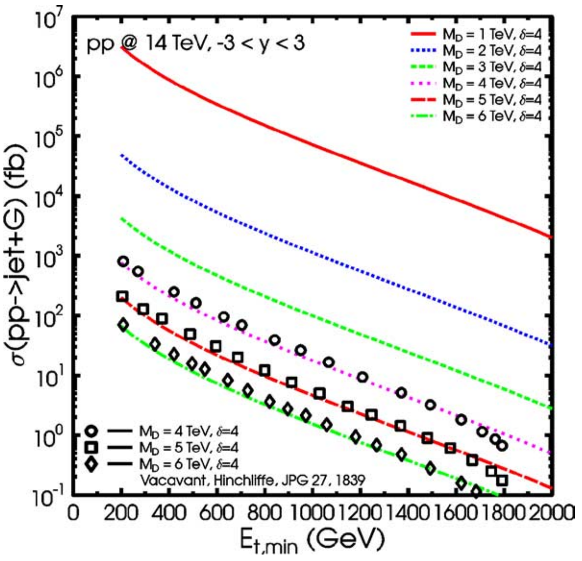

Fig. 1. Integrated cross section for missing $E_T > E_{T,\min}$ in pp-collisions at $\sqrt{s} = 14$ TeV for four extra dimensions and different fundamental scales M_D. Lines denote our calculation, symbols show calculations by [1].

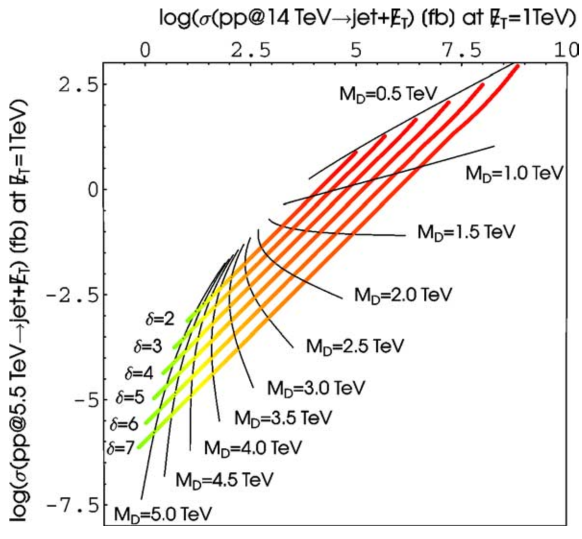

Fig. 2. Combinations of cross section at $E_{T,\min} = 1$ TeV for pp collisions at $\sqrt{s} = 5.5$ TeV (vertical axis) and $\sqrt{s} = 14$ TeV (horizontal axis). The thick lines denote possible cross section combinations from the ADD-model for fixed values of δ and varying M_D. The thin lines indicate equi-M_D values on the thick lines.

To be specific we chose for the following analysis pp collisions at $\sqrt{s} = 14$ TeV and $\sqrt{s} = 5.5$ TeV. If at $\sqrt{s} = 5.5$ TeV only Pb + Pb data will be available, our proton–proton prediction could be scaled up by the number of binary collisions to the heavy system (neglecting shadowing corrections).

For both CMS energies we extract the δ and M_D dependent cross sections at $E_{T,\min} = 1$ TeV. Fig. 2 shows the extracted combinations of cross sections consistent with the ADD-model. The thick lines denote calculations for fixed δ and varying M_D while the thin lines indicate fixed M_D values. From this correlation plot two qualitatively different conclusions can be drawn when data becomes available:

- If the measurements are off the thick lines, the missing energy cannot be explained by graviton production in the ADD-model.
- If the measurements are compatible with one of the thick lines, the missing energy can be attributed to graviton production in the ADD-scenario. Even more, the number of extra dimensions δ and the new fundamental scale M_D can be directly extracted from Fig. 2.

In conclusion, within the ADD-model we predict strong correlations between the missing energies observed at different CMS energies at LHC. If the observed energy loss is in agreement with the present calculation it is possible to extract both the number of extra dimensions and the fundamental scale of gravity, uniquely, at the LHC.

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