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# GRAVITON EXCHANGE EFFECTS ON DIJET PRODUCTION IN $pp$-INTERACTIONS AT $\sqrt{s} = 14$ TeV

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Эффекты обмена гравитоном при рождении пар струй
в $pp$-взаимодействиях при $\sqrt{s} = 14$ ТэВ

Рассмотрены эффекты, возникающие при обмене виртуальными гравитонами в протон-протонных взаимодействиях в детекторе ATLAS на LHC. Исследованы сечение взаимодействия при больших $E_T$ и угловые распределения пар струй. Оценена достижимая чувствительность эксперимента на LHC к параметру модели с дополнительными измерениями пространства.

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Graviton Exchange Effects on Dijet Production
in $pp$-Interactions at $\sqrt{s} = 14$ TeV

The effects of the virtual graviton exchange on the dijet production in proton–proton collisions in the ATLAS detector at the LHC are considered. The high $E_T$ cross section and the angular distribution for dijet production are examined. A sensitivity of the LHC to a parameter of the model with extra dimensions is estimated.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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It is believed that the LHC will reach the energy horizons where the Standard Model (SM) becomes invalid. Indeed, at present the SM is not satisfactory, because some problems of high energy physics — hierarchy problem, small neutrino mass, CP-violation, unification of gravity with other three forces of Nature, etc., — cannot be explained within the framework of the SM. In the last decade a number of models with extra dimensions have been considered for resolving the hierarchy problem. These models would be useful in the sense of explanation of other problems beyond the SM (see, e. g., [1]).

In the model proposed in [2] the authors add $N_{ED}$ extra flat dimensions to the space–time structure, i. e., our world, $3+1-d$ brane, is embedded in a higher-dimensional structure — bulk. All SM particles are confined in the brane, and only for gravitons $N_{ED}$ dimensions of the bulk are transparent.

Another possible extension of space–time [3] is a 5-$d$ bulk with a non-factorizable geometry. The only single extra dimension, finite or infinite, is warped by an exponential factor. All SM particles live in the $3+1-d$ brane.

In the model with universal extra dimensions [4] the scenario where all SM particles can propogate in the whole bulk was realised.

Further, we will follow the model proposed in [2]. In this scenario the relation between the effective Planck scale for the bulk $(M_{\rm eff})$ and for the $3+1-d$ brane $(M_{\rm Pl})$ is governed by the equation

$$M_{\rm Pl}^2 = 8\pi M_{\rm eff}^{N_{ED}+2} R^{N_{ED}}, \tag{1}$$

where all $N_{ED}$ extra dimensions are compactified to a radius $R$. Note, that if one puts $M_{\rm eff} \sim \mathcal{O}\ (1\,{\rm TeV})$ to avoid the hierarchy problem, $R$ becomes very large for $N_{ED}=1$ ($\sim 10^8$ km) and varies from $\mathcal{O}\ (0.1\ {\rm mm})$ to a few fm when $N_{ED}$ ranges from 2 to 7.

The addition of extra dimensions leads to numerous excited states for the particles living in bulk. The tower of graviton states with nonzero momentum which couple to SM particles is called Kaluza–Klein (KK) excitation. The mass spectrum of graviton KK states is given by $m_l^2 = l^2/R^2$, where $l = 1, 2, 3 ....$ The universal coupling is obtained by summing over all the KK states. Direct emission or effects caused by virtual exchanges of KK states will be detectable in particle interactions at accessible energies [5]. Comprehensive investigation of graviton-involving subprocesses was done in [6–8]. It was shown that virtual graviton exchange effects are sensitive to the ultraviolet cutoff $M_S \sim \mathcal{O}(M_{\rm eff})$, which is nesessary to keep undivergent the sum over KK states. The cross section of $2 \to 2$ subprocesses in the presence of large extra dimensions was parametrized by the variable $\eta = \mathcal{F}/M_S^4$: the pure graviton exchange part is quadratic in $\eta$, and the interference one is linear in $\eta$. Different formalisms lead to the following definitions of $\mathcal{F}$:

$$\mathcal{F} = 1, \qquad [6] \tag{2}$$

$$\mathcal{F} = \begin{cases} \log(\frac{M_S^2}{s}) & N_{ED} = 2 \\ \frac{2}{N_{ED}-2} & N_{ED} > 2, \end{cases} \qquad [7] \tag{3}$$

$$\mathcal{F} = \frac{2\lambda}{\pi} = \pm\frac{2}{\pi}. \qquad [8] \tag{4}$$

The LEP and Tevatron Collaborations have intensively searched for direct graviton productions in $e^+e^-$ and $pp$-interactions. The combined LEP limits for $M_S$ are $M_S > 1.6\,\mathrm{TeV}$ for $n = 2$ and $M_S > 0.66\,\mathrm{TeV}$ for $n = 6$ at the $95\,\%$ CL [9]. The CDF Collaboration limits for 368 $\mathrm{pb}^{-1}$ RUN II at the $95\,\%$ CL are $M_S > 1.18\,\mathrm{TeV}$ and $M_S > 0.83\,\mathrm{TeV}$ for $n = 2$ and $n = 6$, respectively [10].

The influence of the virtual graviton exchange on the dijet production in proton–proton collisions at the ATLAS may be a promising hint to the study of extra dimensional gravity scenarios. The angular distribution of the jets is sensitive to the new physics and less susceptible to the systematic uncertainties [11]. A typical signature would be a more isotropic dijet angular distribution than what is expected from the SM predictions and/or excess of the high-$E_T$ jets over the level predicted by QCD. The dijet angular distribution becomes especially interesting because it could reflect spin-2 nature of the gravitons.

We are starting with calculation of the dijet differential cross section $d\sigma/dP_T$ as a function of $P_T$ in proton–proton interactions at the center-of-mass energy 14 TeV using the factorization formula [12]

$$\sigma(pp \to 2\,\mathrm{jet}) = \sum \int dx_1 dx_2 d\hat{t} f_{a/p}(x_1, Q^2) f_{b/p}(x_2, Q^2) \frac{d\hat{\sigma}}{d\hat{t}}. \tag{5}$$

The sum runs over the contributing subprocesses and integration was performed over the initial parton momentum fractions $x_1$ and $x_2$.

Figure 1 shows the cross section for dijet production as a function of $P_T$ for several values of $M_S$. The parton–parton cross sections including effects from off-shell gravitons and their interference with the SM was taken from [13], where the formalism with the explicit $N_{ED}$ dependent cross section [7] (see (3)) was used. At $M_S \sim \infty$ the given cross section agrees with SM calculations. We used

CTEQ5L parametrization for the parton distribution functions. We choose the $Q^2$ scale of the parton distribution functions to be $2\hat{s}\hat{t}\hat{u}/(\hat{s}^2 + \hat{t}^2 + \hat{u}^2)$.

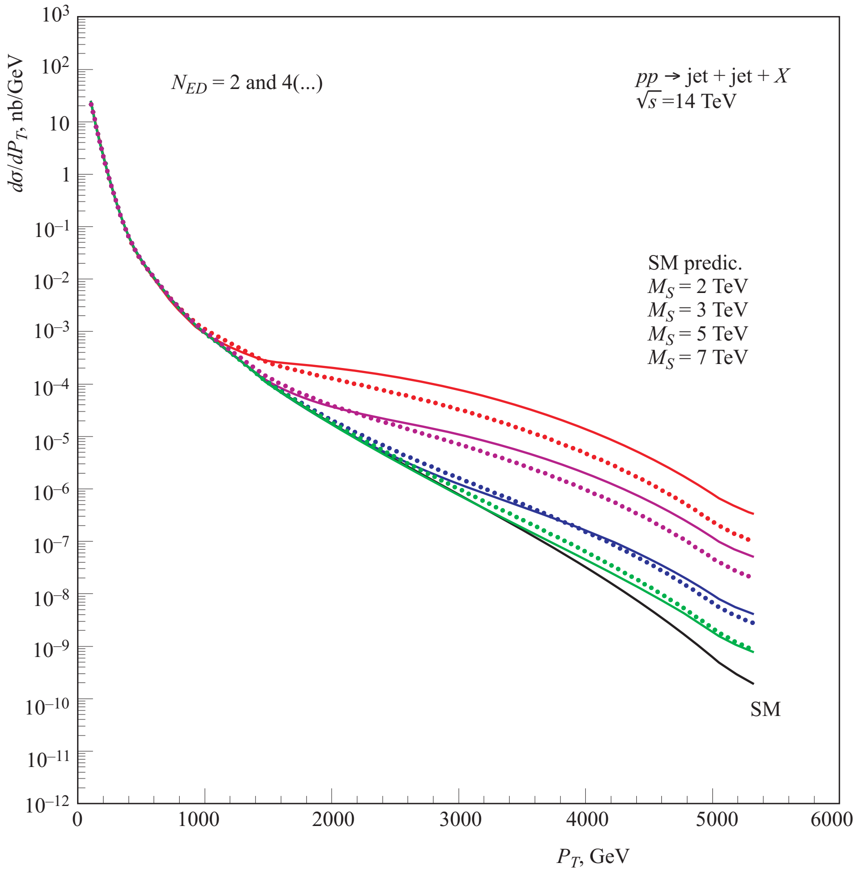


Fig. 1. The differential cross section $d\sigma/P_T$ for dijet production in $pp$-interactions as a function of $P_T$ for several values of $M_S$

The solid curves correspond to the case with $N_{ED} = 2$ extra dimensions, while the dotted lines are the results for $N_{ED} = 4$ for different string scales $M_S$. The SM prediction which was obtained by using $M_S = \infty$ is also shown. The effect is significantly large for the largest $P_T$ values. It is relevant to notice that the analysis of the rate of supernova cooling [14] and the absence of the cosmic gamma-ray background from relict gravitons [15] leads, at $N_{ED} = 2$, to $M_S > 30$ and 130 TeV, respectively.

Further, we study the dijet production cross section and the dijet angular distribution using the event generator PYTHIA for which graviton-induced $2 \to 2$

cross section parts also from [13] are implemented. The detector performance was simulated by using the ATLFAST [16] package which provides a reliable estimate of the detector response to hadronic jets. For this case CTEQ5L was also used. Initial- and final-state QCD and QED radiation were allowed. Jets were reconstructed down to $|\eta| \leqslant 5.0$ using ATLFAST with the cone size $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$, where $\phi$ is the azimuthal angle and $\eta$ is the pseudorapidity.

Figure 2 shows $(1/N)(dN/dE_T)$ for two leading jets versus $E_T$. The shown sensitivity corresponds to the integrated luminosity of $300\,\mathrm{fm}^{-1}$ for the SM cross section rate.

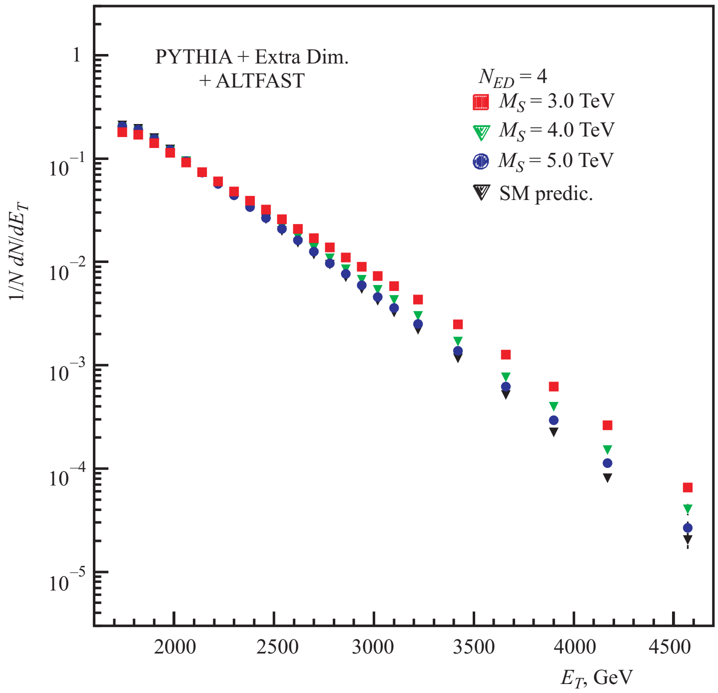


Fig. 2. The $E_T$ distribution for two leading jets showing the Standard Model predictions (closed triangles) and the effect of extra dimensions to the scales indicated. Integrated luminosity is assumed to be 300 $\mathrm{fb}^{-1}$

For the dijet angular distribution study we chose a variable $\chi$ defined as

$$\chi = \frac{u}{t} = \exp|(\eta_1 - \eta_2)| = \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}, \tag{6}$$

where $u, t$ are the usual Mandelstam variables for $2 \to 2$ subprocesses, $\eta_{1,2}$ are the pseudorapidities of the two leading jets; $\theta$ is the center-of-mass scattering angle. We study the normalised $(1/N)(dN/d\chi)$ distribution as a function of the string scale $M_S$ and $N_{ED}$ extra dimensions. The deviation of the dijet angular distribution from the SM predictions induced by graviton exchange for $N_{ED} = 4$ is shown in Fig. 3. For the string scale we put $M_S = 3, 4, 5$ and 7 TeV. This data sensitivity corresponds to the integrated luminosity of $100\,\mathrm{fm}^{-1}$.

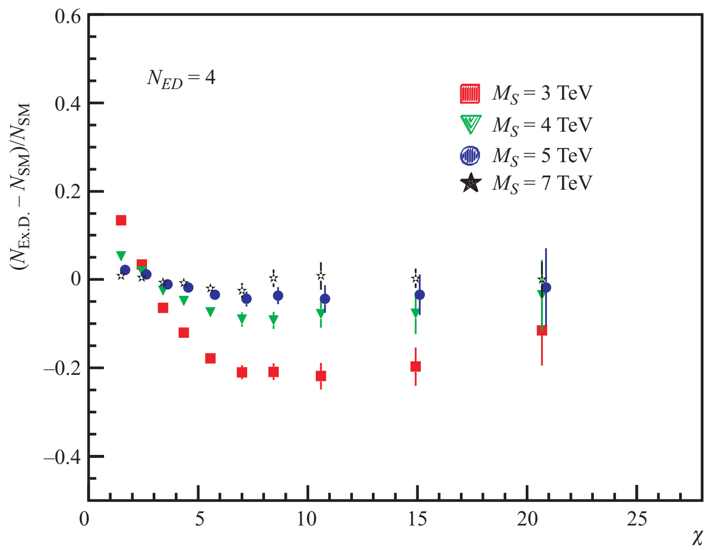


Fig. 3. Expected deviation from the Standard Model predictions for the angular distribution of dijet pairs for $N_{ED} = 4$ and various string scales $M_S$. Integrated luminosity is assumed to be 100 $\mathrm{fb}^{-1}$

The $N_{ED}$ dependence of dijet angular distributions is shown in Fig. 4, $a$, $b$, for $M_S = 3$ and 4 TeV, respectively. We can see that when $M_S$ increases the deviation from SM predictions should be inseparable for different $N_{ED}$.

We have also estimated the sensitivity reach on $M_S$ by using the angular distributions of dijet pairs in $pp$-interactions at 14 TeV. The resulting values varied from 8.0 to 4.5 TeV when $N_{ED}$ ranged from 2 to 6 at the 95 % CL for an integrated luminosity of $100\,\mathrm{fb}^{-1}$.

It should be clear that the deviations of the dijet angular distribution from the QCD predictions will also reveal other new physics phenomena, such as quark compositeness, existence of axigluons, etc. The capability of the ATLAS detector at the LHC to study quark compositeness was explored earlier [11], the inclusive jet transverse momentum spectrum and dijet angular distributions as would be observed by the detector were predicted.

In Fig. 5 we show the influence of quark compositeness on the dijet angular distribution, yielding a significant deviation from the SM predictions for the

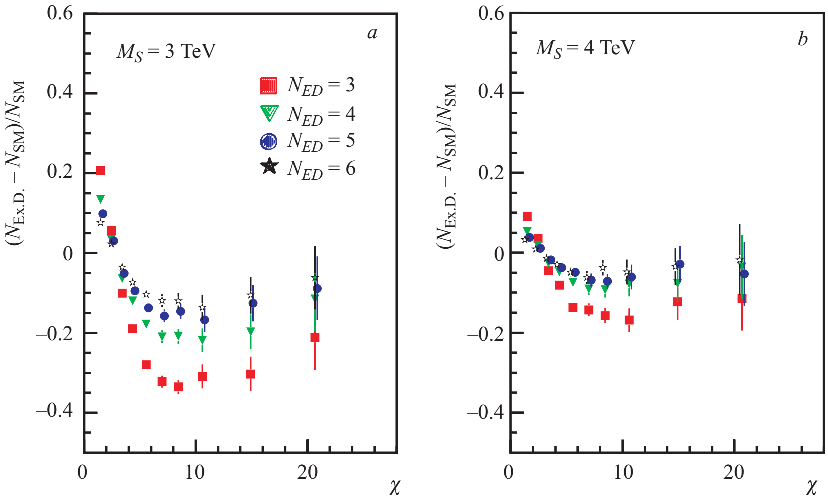


Fig. 4. Expected deviation from the Standard Model predictions for the angular distribution of dijet pairs for different $N_{ED}$ and two values of string scales $M_S$. Integrated luminosity is assumed to be 100 fb$^{-1}$

highest dijet invariant mass bins [11]. Here, we have not restricted dijet mass bins. The quark compositeness scale $\Lambda$ was assumed as indicated in the figure. To simulate the scenario with the quark substructure, the event generator PYTHIA was also used. The constructive interference case where all quarks are composite was considered. The same analysis prosedure as in the previous case was applied to the sample. In this case, the effect of quark compositeness is small. Deviation from the SM predictions at the highest dijet mass bin increases and can mask the effects from virtual graviton exchange.

Quark compositeness is one of the possible mimic sources for the non-SM predicted behavior of dijet angular distribution. It will be extremely important to carefully explore all possible sources if such a deviation would be observed in the high $E_T$ and/or the dijet angular distribution. In particular, quark compositeness and extra dimension effects will be distinguishable due to the different dependence upon dijet mass bins. The virtual graviton exchange will be excluded if no deviation from the SM predictions is observed.

Finally, we conclude that nondirect searches for graviton have viable opportunity to provide evidence for extra dimensions in proton–proton interactions. The high $E_T$ event cross section and dijet angular distribution analysis at the LHC can directly indicate new physics. The largest deviation from the SM prediction at LHC energies is obtained at relatively small $M_S$ and $N_{ED}$. Dijet angular distribution analysis at the ATLAS detector is able to probe the extra dimensions

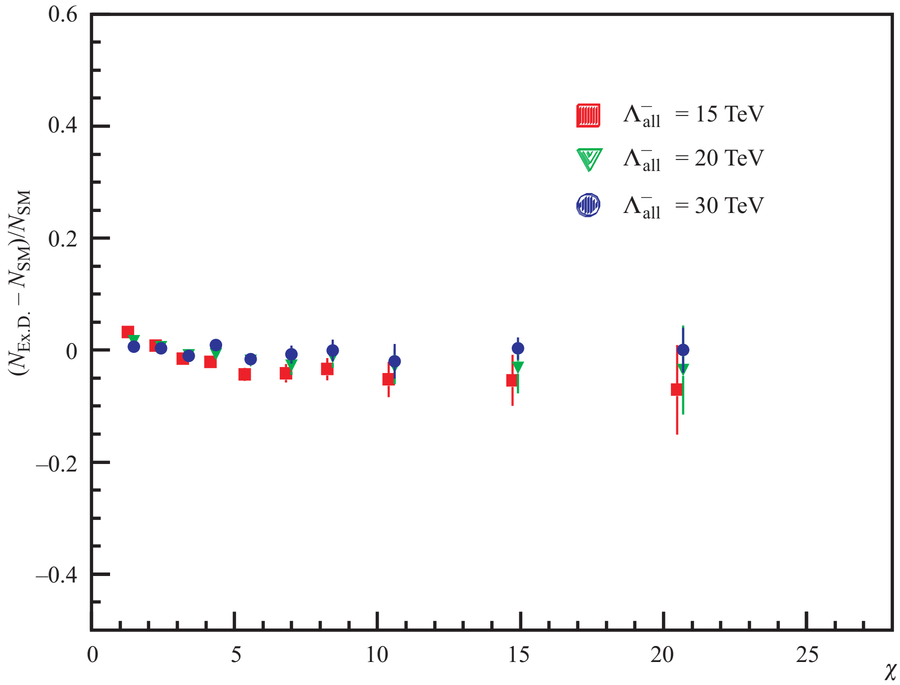


Fig. 5. Expected deviation from the Standard Model predictions for the angular distribution of dijet pairs at $\sqrt{s} = 14$ TeV for various values of the compositeness scale $\Lambda$. Integrated luminosity is assumed to be 100 fb$^{-1}$

string scale as much as 8 TeV for $N_{ED} = 2$ at the 95% CL and integrated luminosity 100 fb$^{-1}$.

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