Looking for Large Extra Dimensions in the Early LHC Data

Z. Usubov*

Joint Institute for Nuclear Research, Dubna, Russia

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Abstract

We explore the opportunity to look for large extra dimensions in the early stages of the LHC running. The high-$E_T$ dijet production is analyzed via a novel kinematic variable when the machine center-of-mass energy varies from 7 TeV through 10 TeV to 14 TeV and the accumulated data range from 0.5 to 8 fb$^{-1}$. The estimations of the reach in the effective scale $M_S$ for different numbers of large extra dimensions are presented.

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1 Introduction

There is a common belief that the Large Hadron Collider (LHC) will provide a key insight into the electroweak symmetry breaking in the Standard Model (SM). Even if the Higgs sector will be established by the Tevatron or forthcoming LHC experiments we will still have few fundamental motivations for physics beyond the SM: the existence of dark matter and dark energy, flavor mixing and CP violation, quadratic mass divergences in scalar sector, unified descriptions of the SM and quantum theory of gravity, baryon asymmetry, hierarchy problem, neutrino masses, etc.

*On leave of absence from Institute of Physics, Baku, Azerbaijan
The main efforts for completely formulated models beyond SM are dedicated to the supersymmetry - the highway of new physics expectations. One of the possible avenues beyond the SM is the models with large extra dimensions, namely the models in which our space-time is not 3+1-dimensional at all. These models offer the possibility of reducing the real gravity scale to a value as small as $\mathcal{O}(1 \text{ TeV})$.

In the model\cite{1} the authors add $N_{ED}$ spatial extra flat dimensions to the space-time structure, i.e. our world, 3+1-dimensional 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. Thus, the extra dimensions would be probed only via graviton interactions.

Another possible extension of space-time\cite{2} is a 5-dimensional bulk with a nonfactorizable geometry. The only single extra dimension, finite or infinite, is warped by an exponential factor. In this case the effective Planck scale varies from $10^{19}$ GeV to few TeV across the 5th dimension.

In the model with the universal extra dimension\cite{3} the extra space coordinate is accessed by all SM particles. One of the features of this model is the possibility of providing interesting dark matter candidates: the lightest Kaluza-Klein photons and neutrinos\cite{4}.

The size of extra dimensions in various theories varies in a wide range from $\mathcal{O}(1 \text{ fm})$ to infinity. In the latter case they are hidden.

After August 2009 CERN announcement the particle physicists pin their hopes to the 3.5 TeV per beam run in 2009-2010. Of course, the early objects of the study will be commissioning and operation stability of the accelerator and detectors. After the ”rediscovery” of the SM – W, Z, J/ψ, Υ, τ, $t\bar{t}$, $2-\text{jet}$, etc. will be produced copiously at the LHC – the search for physics beyond it will begin. Signatures of new physics at the TeV scale will obviously be probed in parallel with these efforts.

The rest of this note is organized as follows. The next section gives a brief description of flat extra dimensions as introduced in\cite{1}. Section 3 describes our strategy for the search for large extra dimensions at the LHC. In Section 4 we present the details of our simulation and analysis technique. Section 5 is the summary of our analysis itself. We examine large extra dimensions with the novel kinematic variable. The sensitivity of the results to the choice of the parton distribution functions and energy smearing in the hadron calorimeter

\footnote{The existence of extra spatial dimensions is the main feature of string theories in which the characteristic size is of order of the Planck length, $1.6 \times 10^{-33}$ cm}
is also demonstrated. In this Section we estimate the LHC reach for effective energy scale of the large extra dimensions. We end with the conclusions in Section 6.

## 2 One Possible Extension of Space-Time Dimensions

We will follow the theoretical framework proposed in [1] (hereafter ADD). In this scenario the relation between the effective Planck scale for the bulk ($M_{\text{eff}}$) and for the 3+1-dimensional brane ($M_{\text{Pl}}$) is governed by the equation

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

(1)

where all $N_{\text{ED}}$ extra dimensions are compactified to a radius $R$. Note that if one puts $M_{\text{eff}} \sim \mathcal{O}(1 \text{ TeV})$ to avoid the hierarchy problem, $R$ becomes very large for $N_{\text{ED}} = 1$ ($R \sim 10^8 \text{km}$) and varies from $\sim 0.1 \text{ mm}$ to a few fm when $N_{\text{ED}}$ ranges from 2 to 7. This speculation leads to the distortion of the usual inverse square law of gravity at $r < R$. Experimentally allowed values for the compactified radius of extra dimensions must be smaller than 44 $\mu$m [5].

The addition of extra dimensions leads to numerous excited states for the particles living in the 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, which leads to the strength of interactions with SM particles of the order of $1/M_{\text{eff}}$. Thus, direct emission of gravitons or effects caused by virtual exchanges of KK states will be detectable in SM particle interactions at accessible energies.

Comprehensive investigation of graviton-involving subprocesses was done in [6, 7, 8]. It was shown that virtual graviton exchange effects are sensitive to the ultraviolet cutoff $M_S \sim \mathcal{O}(M_{\text{eff}})$, which is necessary to keep the sum over KK states nondivergent. If energy scale is above $M_S$, the string dynamics should be taken into account. The cross section of $2 \rightarrow 2$ 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 $\mathcal{F}$:

$$\mathcal{F} = 1,$$

(2)
\[ F = \begin{cases} \log \left( \frac{M_S^2}{2N_{ED}^2} \right) & N_{ED} = 2 \\ \frac{2 \lambda}{\pi} = \pm \frac{2}{\pi} & N_{ED} > 2, \end{cases} \]  

(3)

Obviously, the SM prediction is recovered in the limit \( M_S \to \infty \).

The LEP and Tevatron Collaborations have intensively searched for direct graviton productions in \( e^+e^- \) and \( p\bar{p} \) interactions. The combined LEP limits for \( M_S \) are \( M_S > 1.6 \) TeV for \( N_{ED} = 2 \) and \( M_S > 0.66 \) TeV for \( N_{ED} = 6 \) at the 95\% CL\[9\]. The CDF and D0 Collaborations have looked for large extra dimensions using different channels\[10, 11\]. The best limits on \( M_S \) are 2.09–1.29 TeV at the 95\% CL for \( N_{ED} = 2 – 7 \), obtained by D0\[11\] using dielectron and diphoton channels within the formalisms\[7\].

\section{The Strategy for Extra Dimension Study at the LHC}

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. A typical signature would be a more isotropic dijet angular distribution than expected from the SM predictions and/or excess of the high-\( E_T \) jets over the level predicted by QCD. The angular distribution of the jets is sensitive to the new physics and less susceptible to the systematic uncertainties\[12\]. The dijet angular distribution becomes especially interesting because it could reflect the spin-2 nature of the gravitons.

The analysis of dijet angular distribution is quite often based on the variable \( \chi \)

\[ \chi = \frac{\hat{u}}{\hat{t}} = \exp| (\eta_1 - \eta_2) | = \frac{1 + |\cos \theta^*|}{1 - |\cos \theta^*|}, \]  

(5)

where \( \hat{u}, \hat{t} \) are the usual Mandelstam variables for \( 2 \to 2 \) subprocesses, \( \eta_{1,2} \) are the pseudorapidities of the leading jets, \( \theta^* \) is the center-of-mass scattering angle.

Earlier we defined the new kinematic variable\[14\] for the high-\( E_T \) dijet final state and showed that this variable was very useful for analysis of quark
compositeness at the LHC. We define the dimensionless variable $\alpha_Z$ in $pp$ interactions at center-of-mass energy $E_{CM}$ as $\frac{E_{CM}}{2} \times \frac{P_{T1} + P_{T2}}{P_{T1} \times P_{T2}}$.

\[ \alpha_Z \equiv \frac{E_{CM}}{2} \times \frac{P_{T1} + P_{T2}}{P_{T1} \times P_{T2}}. \] (6)

The estimation of the effective energy scale $M_S$ in this study is based on the analysis of $\alpha_Z$. To describe the whole distribution with a single parameter we consider the variable

\[ R_{\alpha_Z} = \frac{N(\alpha_Z < \alpha^0_Z)}{N(\alpha_Z > \alpha^0_Z)}, \] (7)

where $N(\alpha_Z > \alpha^0_Z)$ ($N(\alpha_Z < \alpha^0_Z)$) is the number of dijet events with $\alpha_Z > \alpha^0_Z$ ($\alpha_Z < \alpha^0_Z$).

In order to know to what extent the observations either conform or disprove the spatial large extra dimensions scenario we consider the significance

\[ S = \frac{|R_{\alpha_Z}(ED) - R_{\alpha_Z}(SM)|}{\sigma}, \] (8)

where $\sigma$ is calculated as the sum in quadrature of $\sigma_{SM}$ and $\sigma_{ED}$.

Figure 1: The ratio of the $P_T$ distribution of two leading jets in the model with large extra dimensions to the one predicted by the Standard Model.
4 Data simulation for the generic LHC detector

The simulation of the $pp$ collision was performed with the event generator PYTHIA6.4\cite{15}. The parton-parton cross sections at the tree level including the effects from off-shell gravitons and their interference with the SM were taken from\cite{16} and properly incorporated in PYTHIA. We employ the leading-order CTEQ6L1\cite{17} pdfs everywhere unless otherwise stated and use PYTHIA6.4 default choices for $Q^2$ definition as well as factorization/renormalization scales. The initial-state and final-state QCD and QED radiation and multiple interactions were enabled. The events were generated with the hard subprocess transverse momentum $p_T > 1$ TeV.

![Figure 2](image)

Figure 2: The Standard Model prediction for the dijet angular distribution compared to the model with large extra dimensions expectations at different energy scales $M_S$: (a) the dijet invariant mass $M_{jj} > 2$ TeV; (b) $M_{jj} > 2.4$ TeV. The integrated luminosity is assumed to be 2 fb$^{-1}$ and $E_{CM} = 10$ TeV.
The detector performance was simulated by using the publicly available PGS-4 package written by J. Conway and modified by S. Mrenna for the generic LHC detector. The calorimeter granularity is set to $(\Delta \phi \times \Delta \eta) = (0.10 \times 0.10)$. Energy smearing in the hadronic calorimeter of the generic LHC detector is governed by

$$\frac{\Delta E}{E} = \frac{a}{\sqrt{E}} \oplus b \quad (E \text{ in GeV}),$$

where the stochastic term factor is $a = 0.8$ and the constant factor is $b = 0.03$. Jets were reconstructed down to $|\eta| \leq 3$ using the $k_T$ algorithm implemented in PGS-4. We chose $D = 0.7$ for the jet resolution parameter and required that both leading jets carried a transverse momentum $P_{T1}^{j2} > 100 \text{ GeV}$. We use the simplified output from PGS-4, namely, a list of two most energetic jets. The average $P_T$ and invariant mass of the leading jets are $<P_T^{j1}> = 1.12 \text{ TeV}$, $<P_T^{j2}> = 1.01 \text{ TeV}$, $<m_{j1j2}> = 2.46 \text{ TeV}$, respectively.

5 Effect of Large Extra Dimensions on Early LHC Data

Even in the early stages of its operation, the LHC allows one to reach very large values of jet transverse energy and dijet invariant mass. This kinematic region of dijet production has never been studied before.

The model with large extra dimensions, as has already been noted, can manifest itself through the deviation of the jet transverse momentum and/or dijet angular distributions from the QCD prediction. In Fig. 1 we plot the ratio of the $P_T$ distribution of the two hardest jets, $R_{PT}$, derived in the ADD model with different $M_S$ to the $P_T$ distribution predicted by the SM. The number of extra dimensions $N_{ED}$ was chosen to be four. The enhancement of the ADD model cross section over the SM prediction is obvious at high values of jet $P_T$. Figure 1 as well as Figs. 2,3 hereafter examine the effects of large extra dimensions at $E_{CM} = 10 \text{ TeV}$ and the shown sensitivity corresponds to the integrated luminosity of $2 \text{ fb}^{-1}$.

A comparison between the dijet angular distribution predicted by the SM and induced by the ADD model is shown in Fig. 2. Plots (a) and (b) correspond to the normalized $\chi$ distributions, $(1/N)(dN/d\chi)$, for two values of $M_S$ and two lower limits for $M_{jj}$, 2.0 and 2.4 TeV respectively. The data were obtained at

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2 We add in the PGS-4 simulation of energy smearing in the hadronic calorimeter the constant term
Figure 3: The Standard Model prediction for the normalized $\alpha_Z$ distribution (see the text) compared to the predictions of the model with large extra dimensions at different energy scales $M_S$: (a) the number of compactified extra dimensions $N_{ED} = 3$; (b) $N_{ED} = 4$. The integrated luminosity is assumed to be $2 \text{ fb}^{-1}$ and $E_{CM} = 10 \text{ TeV}$.

$N_{ED} = 3$. Obviously, the effect of extra dimensions is most pronounced in the high dijet mass region.

The normalized $\alpha_Z$ distributions predicted by the SM and the ADD model for $N_{ED} = 3$ and 4 are demonstrated in Fig. 3(a) and Fig. 3(b), respectively. Various points correspond to different values of $M_S$. Compared to the $\chi$ distributions of Fig. 2(a), we have a robust signal for $\alpha_Z$ from large extra dimensions at $M_{jj} > 2 \text{ TeV}$ already. The net result is that the significance as defined in Eq.(8) for $\alpha_Z$ at $M_{jj} > 2 \text{ TeV}$ is more than $15(13)$ times larger than that for the $\chi$ distribution for $M_S=5(6) \text{ TeV}$. As becomes apparent from the figure, extra dimensions lead to enhancement (abatement) of the distributions at $\alpha_Z < 8.0 (\alpha_Z > 8.0)$ in comparison to the SM prediction.

The sensitivity of the future LHC experiments to the parameter $M_S$ up...
Figure 4: Expected LHC reach on the effective energy scale $M_S$ as a function of the collider integrated luminosity for different numbers of extra dimensions $N_{ED}$: (a) $E_{CM} = 7$ TeV; (b) $E_{CM} = 10$ TeV and (c) $E_{CM} = 14$ TeV.

to which the effects of large extra dimensions can be observed for $E_{CM} = 7$, 10 and 14 TeV are summarized in Figs. 4(a), 4(b) and 4(c), respectively. The corresponding $M_S$ reach is shown for $N_{ED}=3$, 4 and 5 as a function of the accumulated luminosity. The data were obtained with the significance as defined in Eq.(8) close to $S = 3$, for which we can claim that we have strong evidence for the observed signal. The parameters $\alpha_Z^0$ used for $E_{CM} = 7$, 10 and 14 TeV are $\alpha_Z^0 = 6.1$, 8.2 and 10, respectively. The calculations were done with the inclusion of statistical uncertainties alone.

One of the main uncertainties in the interpretation of new physics at the LHC detectors will come from parton distribution functions (pdfs). Unfortunately, the pdfs are not so well determined in the kinematic region with high transverse momentum jets. In order to show the effect of the choice of pdfs we plot in
Figure 5: The influence of the choice of the parton distribution functions on $\alpha_Z$ and $R_{\alpha Z}$ (see the text for details).

Figs. 5(a), (b) the normalized $\alpha_Z$ distribution obtained with the leading order (LO) and next-to-leading order (NLO) CTEQ6\cite{17} and MSTW2008\cite{19} pdfs, respectively. Shown is the prediction of the ADD model with $M_S = 6$ TeV and $N_{ED} = 4$. The ratios of the $R_{\alpha Z}$ obtained with the LO (NLO) CTEQ6 to the one obtained with the LO (NLO) MSTW2008,

$$R_1 = \frac{R_{\alpha Z}(CTEQ6L1)}{R_{\alpha Z}(MSTW2008lo)} \quad \text{and} \quad R_2 = \frac{R_{\alpha Z}(CTEQ6M1)}{R_{\alpha Z}(MSTW2008nlo)},$$

are demonstrated in Figs. 5(c), (e) (Figs. 5(d), (f)). The ratios are shown as a function of $E_{CM}$ for 2 fb$^{-1}$ of data. Figures 5(c), (d) and (e), (f) correspond to the predictions of the ADD models with $M_S=5$ and 6 TeV, respectively. As
can be seen in these figures, $R_{\alpha Z}$ shows significant dependence on the choice of pdfs. The ratios used also depend on $E_{CM}$. In view of pdfs used we can conclude that the estimations of $M_S$ can be affected by the choice of pdfs. On the other hand, $\alpha_Z$ measurements at the LHC would be used to constrain the proton pdfs.

To examine another source of the uncertainties coming from hadron calorimeter energy smearing, we show in Fig. 6 the ratio of $R_{\alpha Z}$ derived with the stochastic term factor in Eq.(9) $a=1.0$ to the one derived with $a=0.5$

$$R_E = \frac{R_{\alpha Z}(a = 1.00)}{R_{\alpha Z}(a = 0.5)}.$$  

Figure 6(a) illustrates the dependence of above ratio on $E_{CM}$ for the SM prediction, and Figs. 6(b), (c) illustrate the one for the ADD model. Figure 6 exhibits
rather low sensitivity of $R_{\alpha Z}$ to stochastic term factor $a$ in the range from 0.5 to 1.

6 Conclusions

We examined the capability of the LHC experiments to observe large extra dimensions in the early stages of the running considering that the LHC would have accumulated luminosity in the range from 0.5 to 8.0 fb$^{-1}$ and $E_{CM}$ varies from 7 TeV through 10 TeV to 14 TeV. The distribution of the novel variable $\alpha Z$ might provide direct hint to observation of the extra dimensions as well as dijet transverse momentum and angular distributions.

The variable $\alpha Z$ is more sensitive to the influence of large extra dimensions and can be effective for estimation of the energy scale $M_S$. This variable can show robust signatures for new physics even with low integrated luminosity.

Note that collider signatures of different new physics scenarios often mimic each others. The use of different kinematic variables or combinations of them can offer an important tool for discriminating between new physics models.

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