Extra dimensions in photon-induced two lepton final states at the CERN-LHC

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We discuss the potential of the photon-induced two lepton final states at the LHC to explore the phenomenology of the Kaluza-Klein (KK) tower of gravitons in the scenarios of the Arkani-Hamed, Dimopoulos and Dvali (ADD) model and Randall-Sundrum (RS) model. The sensitivity to model parameters can be improved compared to the present LEP or Tevatron sensitivity.

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I. INTRODUCTION

The general purpose Large Hadron Collider (LHC) experiments ATLAS and CMS at CERN have central detectors with a pseudorapidity \( \eta \) coverage 2.5 for tracking system and 5.0 for calorimetry. However, the significant amount of particles and energy flow are in the very forward directions and not detected by these detectors. Moreover, some parts of the cross sections measured by the central detectors may belong to the elastic scattering and ultraperipheral collisions. For deeper understanding of the physics from very forward region additional equipments are needed. ATLAS and CMS collaborations have a program of forward physics with extra detectors located in a region nearly 100m-400m from the interaction point [1]. These forward detectors will be installed as close as a few mm to the beamline. The physics program of this new instrumentation covers soft and hard diffraction, high energy photon induced interactions, low-\( x \) dynamics with forward jet studies, large rapidity gaps between forward jets, and luminosity monitoring [1, 2, 3].

One of the main goal of these forward detectors is to tag the protons with some energy fraction loss \( \xi = E_{\text{loss}}/E_{\text{beam}}. \) Specifically, ATLAS and CMS in standard running conditions will have forward detectors positioned at 220m and 420m from interaction point with an acceptance of \( 0 < \xi < 0.15 \) [4, 5]. TOTEM experiment at 147m and 220m from CMS interaction point together with standard CMS-TOTEM at 420m have an overall acceptance \( 0.0015 < \xi < 0.5 \). When the forward detectors are installed closer to the interaction points, higher \( \xi \) is obtained.

One of the well known applications of the forward detectors is the high energy photon induced interaction with exclusive two lepton (\( e^+e^- \) or \( \mu^+\mu^- \)) final states. Two quasi-real photons emitted by each proton interact each other to produce two leptons \( \gamma\gamma \rightarrow \ell^+\ell^- \). Deflected protons and their energy loss will be detected by the forward detectors mentioned above but leptons will go to central detector. Charged leptons with rapidity \( |\eta| < 2.5 \) and \( p_T > (5-10) \text{GeV} \) will be identified by the central detector. Photons emitted with small angles by the protons show a spectrum of virtuality \( Q^2 \) and energy \( E_{\gamma} \). This is described by the equivalent photon approximation [6, 7] which differs from the point-like electron positron case by taking care of the electromagnetic form factors in the equivalent photon spectrum and effective \( \gamma\gamma \) luminosity

\[
dN = \frac{\alpha}{\pi} \frac{dE_{\gamma}}{E_{\gamma}} \frac{dQ^2}{Q^2} \left[ (1 - \frac{E_{\gamma}}{E}) (1 - \frac{Q_{\min}^2}{Q^2}) F_E + \frac{E_{\gamma}^2}{2E^2} F_M \right]
\]

where

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\[ Q_{\min}^2 = \frac{m_p^2 E^2}{E(E - E_{\gamma})}, \quad F_E = \frac{4m_p^2 G_E^2 + Q^2 G_M^2}{4m_p^2 + Q^2} \]  

Here \( E \) is the energy of the proton beam which is related to the photon energy by \( E_{\gamma} = \xi E \) and \( m_p \) is the mass of the proton. The magnetic moment of the proton is \( \mu_p = 7.78 \). \( F_E \) and \( F_M \) are functions of the electric and magnetic form factors. The cross section \( d\sigma_{\gamma\gamma\rightarrow\ell\ell} \) for the subprocess \( \gamma\gamma \rightarrow \ell^+\ell^- \) should be integrated over the photon spectrum

\[
d\sigma = \int \frac{dL_{\gamma\gamma}}{dW} d\sigma_{\gamma\gamma\rightarrow\ell\ell}(W) dW
\]

where the effective photon luminosity \( dL_{\gamma\gamma}/dW \) is given by

\[
\frac{dL_{\gamma\gamma}}{dW} = \int Q_{\min}^2 dQ_1^2 \int Q_{\min}^2 dQ_2^2 \int y_{\min}^{y_{\max}} d\frac{W}{2y} f_1(y) f_2(y) \frac{W^2}{4y} (Q_1^2, Q_2^2). 
\]

with

\[ y_{\min} = \text{MAX}(W^2/(4\xi_{\max} E), \xi_{\min} E) , \quad y_{\max} = \xi_{\max} E, \quad f = \frac{dN}{dE_{\gamma} dQ^2} \]

Here \( W \) is the invariant mass of the two photon system \( W = 2E\sqrt{\xi_1 \xi_2} \) and maximum virtuality is \( Q_{\max}^2 = 2 \text{GeV}^2 \).

The lepton pair production by two photon fusion yields very clean final states and it is convenient to use it as a luminosity monitor for the LHC. As it was discussed in Ref.\[8\] the main possible contamination comes from the proton dissociation into \( X, Y \) system, \( pp \rightarrow X + \ell^+\ell^- + Y \) where \( X \) and \( Y \) are baryon excitations such as \( N^*, \Delta \) isobars. To reduce this contribution it was proposed to impose a cut on the transverse momentum of the photon pair \( |q_1 + q_2| < (10 - 30) \text{MeV} \). In actual experiment this cut should be applied on the lepton pair. It is shown in some detail in ref.\[8\] that the cut of 30 MeV on the transverse momentum of the lepton pair is possible although a cut of at least 5 GeV is needed for individual lepton detection. However, in theoretical calculations, if one uses equivalent photon approximation the subprocess \( \gamma\gamma \rightarrow \ell^+\ell^- \) is factorized. In this case, this cut can be applied through effective photon luminosity using the relation between \( Q^2 \) and transverse momentum of the photon \( q_t \)

\[ Q^2 = Q_{\min}^2 + \frac{q_t^2}{1 - E_{\gamma}/E} \]

This is why we have kept integration over \( Q^2 \) in the luminosity expression above. In Fig\[1\] effective \( \gamma\gamma \) luminosity is shown with and without transverse momentum cut imposed on the photon pair.

It is clear that the photon-induced two lepton final states with invariant di-photon mass \( W > 1 \text{ TeV} \) seems highly attractive to probe new physics beyond the Standard Model(SM) with available luminosity. In this work, we explore the phenomenology of extra dimensions in the framework of the Arkani-Hamed, Dimopoulos and Dvali(ADD) model of large extra dimensions and Randall-Sundrum (RS) model of warped extra dimensions via the photon induced process \( pp \rightarrow p\ell^+\ell^- p \) at the LHC.

II. ADD MODEL OF LARGE EXTRA DIMENSIONS

It is well known that there is a large difference in energy between the electroweak scale which is a few hundreds of GeV and gravity scale that is the Planck scale \( M_{Pl} \sim 10^{19} \text{GeV} \) in a four dimensional spacetime. This is called the hierarchy problem in particle physics. In string theory, extra space dimensions higher than three has already been contained. Following the string theory ideas, three space dimensional world is called a "wall" or 3-brane where all Standard Model particles are confined to this wall. The D-dimensional spacetime, \( D = 3 + \delta + 1 \), with \( \delta \) extra space dimensions is called "bulk" where 3-brane is embedded in it. The way how to handle hierarchy problem depends on the models.
According to the model proposed by Arkani-Hamed, Dimopoulos and Dvali SM fields can not go out of the 3-brane while gravity propagates in the bulk \[^9\]. In D dimensions, the solutions of the linearized equations of motion of the metric field are the Kaluza-Klein tower. After integrations over extra dimensions, resulting 4-dimensional fields are the Kaluza-Klein modes. KK zero mode field is massless corresponding to the graviton in 4-dimensions but KK excited modes are massive. In this model extra dimensions are compactified with a compactification radius \( r_c \sim \text{mm-fermi} \) (or \( 1/r_c \sim \text{eV-MeV} \)) which determines the KK mode spacing. This mode spacing is very small when compared to typical collider energies which allows the summation over large number of KK states in the final states or in the propagator. Because of this large compactification radius, ADD model is known as the large extra dimension model. The overall effect of the KK states makes the gravity strong in \( D = 4 + \delta \) dimensions and thus its effective interactions in 4-dimensions with the Standard Model particles are sizable at collider energies. It is possible to relate the Planck Mass \( M_{Pl} \) to the corresponding scale \( M_D \) in D-dimensions through the compactified volume \( V_\delta \) by the relation

\[
M_{Pl}^2 = V_\delta M_D^{2+\delta} \tag{8}
\]

It is assumed that \( M_D \) is in TeV region and \( M_{Pl} \) becomes large due to large higher dimensional volume of \( V_\delta \) with \( \delta = 2 - 7 \). This situation suggests that Planck scale \( M_{Pl} \) is no longer fundamental scale. However, the large gap between the electroweak and Planck scale is compensated by the large compactification scale of the extra dimensions.

Let us now calculate the Feynman amplitude for the subprocess \( \gamma \gamma \rightarrow \ell^+ \ell^- \) by adding an s-channel diagram with KK graviton exchange to the t and u channel diagrams of electromagnetic interaction \[^10\].

\[
iM_{KK} = \sum_n [\bar{u}(p_1)\Gamma_1^{\mu\nu} v(p_2) \frac{i\kappa}{\delta - m_n^2} \Gamma_1^{\alpha\beta\rho\sigma} e_\rho(k_1)e_\sigma(k_2)] \tag{9}
\]

where \( k_1, k_2, p_1, p_2 \) and \( e_\rho(k_i) \) are incoming photon, outgoing lepton momenta and polarization vectors of photons. The coherent sum is over KK modes. Vertex functions \( \Gamma_1^{\alpha\beta\rho\sigma} \) for \( KK - \gamma \gamma \) and \( \Gamma_2^{\mu\nu} \) for \( KK - \ell \ell \) are given below

\[
\Gamma_1^{\alpha\beta\rho\sigma} = -\frac{i\kappa}{2} [(k_1 \cdot k_2) C^{\alpha\beta\rho\sigma} + D^{\alpha\beta\rho\sigma}] \tag{10}
\]

\[
\Gamma_2^{\mu\nu} = -\frac{i\kappa}{8} [\gamma^\mu (p_1^\nu - p_2^\nu) + \gamma^\nu (p_1^\mu - p_2^\mu)] \tag{11}
\]
coupling constant $\kappa$ is related to the Newton constant $G_N^{4+\delta}$ in $D = 4 + \delta$ dimension by $\kappa^2 = 16\pi G_N^{4+\delta}$. Explicit forms of the tensors $C^{\alpha\beta\sigma}$ and $D^{\alpha\beta\sigma}$ are given in the appendix. Tensor $B_{\mu\nu\alpha\beta}$ in the propagator of KK graviton is

$$B_{\mu\nu\alpha\beta} = \eta_{\mu\alpha}\eta_{\nu\beta} + \eta_{\mu\beta}\eta_{\nu\alpha} - \frac{2}{3}\eta_{\mu\nu}\eta_{\alpha\beta}$$

(12)

where $\eta_{\mu\nu}$ is the metric tensor of the flat space in 4-dimensions.

The summation over Kaluza-Klein modes can be calculated without specifying any specific process. Since the KK tower is an infinite sum, ultraviolet divergences are present in tree level process. Thus we need a cutoff procedure. For phenomenological applications following result was obtained in the literature $^{10}$

$$\kappa^2 D(\hat{s}) = \kappa^2 \sum_n \frac{i}{\hat{s} - m_n^2} = \frac{16\pi}{\Lambda_c^4}$$

(13) for $\delta > 2$

where $\Lambda_c$ is the cutoff energy. The expression connecting the unknown cutoff energy $\Lambda_c$ to the fundamental scale $M_D$ is not known without the knowledge of full theory. The relation $\Lambda_c < M_D$ can be written based on the string theory. In practical calculation the equality $M_D \approx \Lambda_c$ corresponds to the lower limit of the fundamental scale $M_D$. In every part of this work containing the KK graviton propagator of ADD model we set $M_D \approx \Lambda_c$ and limits on $M_D$ always mean its lower limit.

The whole squared amplitude which consists of electromagnetic, KK and interference parts has been calculated in terms of Mandelstam invariants $\hat{s}$ and $\hat{t}$, neglecting lepton masses

$$|M|^2 = |M_{em}|^2 + |M_{KK}|^2 + |M_{int}|^2,$$

(15)

$$|M_{em}|^2 = -8g_e^2\left[\frac{\hat{s} + \hat{t}}{\hat{t}} + \frac{\hat{t}}{s + \hat{t}}\right],$$

(16)

$$|M_{KK}|^2 = |\kappa^2 D(\hat{s})|^2[-\frac{\hat{t}}{\hat{s}^3} + 2\hat{t}\hat{s} + 3\hat{t}\hat{s}^2 + 4\hat{t}^2\hat{s}],$$

(17)

$$|M_{int}|^2 = -2g_e^2\kappa^2\frac{1}{2}(D(\hat{s}) + D^*(\hat{s}))|\hat{s}^2 + 2\hat{t}\hat{s} + 2\hat{s}\hat{t}|,$$

(18)

where the factor due to initial spin average is absent. Starting from Fig 3 to the rest of the work the cross sections will be multiplied by a factor of 2 to include both electrons and muons in the final states. Collider signals of virtual graviton exchange may lead to the deviations from the SM in the magnitude of the cross section and in the angular behaviour of the final leptons is given in Fig 4 in the center of mass frame of the subprocess for the acceptance region $0.1 < \xi < 0.5$ and $M_D = 1500$ GeV. The difference between the KK graviton contribution and the SM part is sizable in magnitude and in shape.
FIG. 2: Cross section of the process $pp \to p\ell^+\ell^-p$ as a function of the transverse momentum cut of the final leptons with and without KK graviton exchange for $M_D = 1500$ GeV and for three acceptance regions of forward detectors.

III. RS MODEL OF WARPED EXTRA DIMENSIONS

An alternative way to handle the large hierarchy between electroweak and gravity scales is the one proposed by Randall and Sundrum in which curvature in higher dimensions is responsible for removing this large hierarchy. The metric in 5D is obtained as a solution to Einstein’s equations under the 4D Poincare invariance \[11\]

\[ ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2, \]

where $y$ is the 5th dimension which is parametrized as $y = r_c|\Phi|$ with $r_c$ being the compactification radius of the extra dimension. Angular coordinate $\Phi$ has the limits of $0 \leq |\Phi| \leq \pi$. First term in this metric is the 4D Minkowski spacetime metric multiplied by an exponential factor that is called warp factor containing fifth dimension and the degree of the curvature $k$. In this model, two 3-brane with opposite and equal tensions stand at the boundaries of a 5D Anti-de-Sitter space. Each boundary includes 4D Minkowski metric and $y$ is orthogonal to each 3-brane. The distance between the two walls is $y = \pi r_c$. Gravity propagates in 5th dimension and localized on the wall at $y = 0$ called Planck brane. The other wall at $y = \pi r_c$ is referred to TeV brane where SM fields live on. Starting with 5D action, interaction of the KK gravitons with the matter fields can be found in the 4D effective lagrangian

\[ L = -\frac{1}{M_{Pl}}T^{\alpha\beta}(x)h^{(0)}_{\alpha\beta}(x) - \frac{1}{\Lambda_x}T^{\alpha\beta}(x)\sum_{n=1}^{\infty}h^{(n)}_{\alpha\beta}(x) \]

where $T^{\alpha\beta}(x)$ is the energy momentum tensor of the matter field in the Minkowski space and $\tilde{M}_{Pl} = M_{Pl}/\sqrt{8\pi}$ is the reduced Planck scale. $h^{(n)}_{\alpha\beta}(x)$ indicates the KK modes of the graviton on the 3-brane. It is seen that the masless zero KK mode decouples from the sum and its coupling strength is $1/M_{Pl}$. The massive KK states has the coupling of $(1/\Lambda_x) \sim 1/$TeV with $\Lambda_x = e^{-kr_c}\pi\tilde{M}_{Pl}$. The 4D effective action based on the RS model leads to the relation between 5D fundamental Planck scale $M$ and usual 4D reduced Planck scale

\[ \tilde{M}_{Pl}^2 = \frac{M^3}{k}(1 - e^{-2kr_c}\pi). \]
FIG. 3: 95% C.L. search reach for $M_D$ as a function of integrated LHC luminosity for two acceptance regions shown in plots (a) and (b). In the plot (b), a cut of 500 GeV is imposed on the transverse momenta of the final state leptons. Lower curves are the results from the cut on the transverse momentum of the incoming photon pair.

It is assumed that $k \sim M_{Pl}$ then the above relation states $M \sim M_{Pl}$. Therefore, there is no additional hierarchy created by the model. When $k r_c$ is taken to be $\sim 10 - 12$ all the physical processes happen in TeV scale on TeV-brane. This fact states that the hierarchy is generated by the warp factor.

The mass spectrum of the KK modes of the graviton in the RS model is given by [11]

$$m_n = x_n k e^{-k r_c \pi} = x_n \beta \Lambda_{\pi}, \quad \text{with } \beta = \frac{k}{M_{Pl}}$$

where $x_n$ are the roots of the Bessel function of order 1 $J_1(x_n) = 0$. The first values are $x_1 = 3.83$, $x_2 = 7.02$ and $x_3 = 10.17$. The scale of the masses is $m_n \sim \Lambda_{\pi} \sim$ TeV on the ground of $\beta \sim 1$. This fact demonstrates that the effect of each excitation should be seen separately at colliders. The RS scenario is described by two parameters $\Lambda_{\pi}$ and $\beta$ which are appropriate for phenomenological applications. In the squared amplitude for $\gamma \gamma \rightarrow \ell^+ \ell^-$ the only difference from the ADD case occurs in the following form of the graviton propagator

$$\kappa^2 D(\hat{s}) = \frac{2}{\Lambda_{\pi}^2} \sum_{n=1}^{\infty} \frac{1}{\hat{s} - m_n^2 + i \Gamma_n m_n}, \quad \Gamma_n = \rho m_n^2 \left(\frac{m_n}{\Lambda_{\pi}}\right)^2$$

with $\rho = 1$ is used in the width $\Gamma_n$ of the individual KK graviton. Constraint on the parameter $\beta$ can be found for the first graviton mode with mass $m_1$. The estimation for 95% C.L. parameter exclusion region is shown in Fig[5] for the integrated LHC luminosities: 50 fb$^{-1}$, 100 fb$^{-1}$ and 200 fb$^{-1}$, with the acceptance region $0.1 < \xi < 0.5$.

In the approximation $m_n^2 >> s$ the KK graviton propagator takes the form

$$\kappa^2 D(\hat{s}) = \frac{2}{\beta^2 \Lambda_{\pi}^4} \sum_{n=1}^{\infty} \frac{-1}{x_n^2}$$

Fig[6] shows 95% C.L. search reaches in the $\Lambda_{\pi} - \beta$ plane for an acceptance region of $0.1 < \xi < 0.5$ and LHC luminosities given before. Calculations concerning the exclusion contours for other acceptance limits $0.0015 < \xi < 0.5$ and $0.05 < \xi < 0.5$ were done. As in the case of the ADD model these results show almost the same curves with convenient transverse momentum cutoffs on the individual final leptons. Thus we have not presented them here.
IV. CONCLUSION

 Photon–photon collision at LHC with di-photon invariant mass $W > 1$ TeV allows to study physics at TeV scale beyond the SM with a sufficient luminosity. There is no existing collider with this property except the LHC itself. It is worth mentioning that two lepton final state is the cleanest channel to search for any deviation from the SM physics. For this reason, we have investigated how the photon-induced two lepton final state can extend the bounds on the model parameters of extra dimensions in the framework of the ADD and RS models. Taking an acceptance region of $0.1 < \xi < 0.5$ we have obtained constraints on the fundamental scale $M_D$ in the ADD model for a LHC luminosity interval $1-200$ fb$^{-1}$. Exclusion regions of the parameter pairs $\beta - m_1$ and $\Lambda_\pi - \beta$ have been provided for the LHC luminosities $50 fb^{-1}$, $100 fb^{-1}$ and $200 fb^{-1}$. Possible contamination coming from baryon excitations can be removed by an upper cut on the transverse momentum of the incoming photon pair $|\vec{q}_1 + \vec{q}_2| < 30$ MeV. An overall acceptance extends between $\xi = 0.0015$ and $\xi = 0.5$. We have showed that the region $0.0015 < \xi < 0.5$ with a cut of $p_t > 450 - 500$ GeV on final leptons yields equivalent results to the region of $0.1 < \xi < 0.5$ with $p_t > 10$ GeV. Excluded area of the model parameters that we have found from the process $pp \to p\ell\ell p$ extends to wider regions than the case of the colliders LEP and Tevatron [12]. Certainly, the challenging process is the Drell-Yan process at the LHC itself which will have the best sensitivity to the KK tower parameters [13].

APPENDIX A

Symbols $C^{\alpha\beta\rho\sigma}$ and $D^{\alpha\beta\rho\sigma}$ that were used in the coupling of KK states and photons in the text are defined as follows

\begin{align*}
C^{\alpha\beta\rho\sigma} & = \eta^{\alpha\rho} \eta^{\beta\sigma} + \eta^{\alpha\sigma} \eta^{\beta\rho} - \eta^{\alpha\beta} \eta^{\rho\sigma} \\
D^{\alpha\beta\rho\sigma} & = \eta^{\alpha\beta} k_1^\rho k_2^\sigma - (\eta^{\alpha\rho} k_1^\beta k_2^\sigma + \eta^{\alpha\sigma} k_1^\beta k_2^\rho - \eta^{\beta\rho} k_1^\alpha k_2^\sigma) - (\eta^{\beta\sigma} k_1^\alpha k_2^\rho + \eta^{\beta\rho} k_1^\sigma k_2^\alpha - \eta^{\rho\sigma} k_1^\alpha k_2^\beta) \tag{A1}
\end{align*}
FIG. 5: 95% C.L. exclusion region for the parameters $\beta$ and $m_1$ at three different integrated LHC luminosities; 50 fb$^{-1}$, 100 fb$^{-1}$ and 200 fb$^{-1}$. Curves in the Fig. (b) are obtained with the cut on the transverse momentum of the incoming photon pair. Excluded regions are defined by the area over the curves.

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FIG. 6: 95% C.L. constraints on the parameter plane $\Lambda$ and $\beta$ at three different integrated LHC luminosities; $50 fb^{-1}$, $100 fb^{-1}$ and $200 fb^{-1}$. Curves in the Fig. (b) are obtained with the cut on the transverse momentum of the incoming photon pair. Excluded regions are defined by the area below the curves.