Diphoton signal via Chern-Simons interaction in a warped geometry scenario

Nabarun Chakrabarty∗ and Biswarup Mukhopadhyaya†
Regional Centre for Accelerator-based Particle Physics,
Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad 211019, India

Soumitra SenGupta‡
Department of Theoretical Physics, Indian Association for the Cultivation of Science,
2A & 2B Raja S.C. Mullick Road, Kolkata 700032, India

Abstract

The Kalb-Ramond field, identifiable with bulk torsion in a 5-dimensional Randall Sundrum (RS) scenario, has Chern-Simons interactions with gauge bosons, from the requirement of gauge anomaly cancellation. Its lowest Kaluza Klein (KK) mode on the visible 3-brane can be identified with a spin-0 CP-odd field, namely, the axion. By virtue of the warped geometry and Chern-Simons couplings, this axion has unsuppressed interactions with gauge bosons in contrast to ultra-suppressed interactions with fermions. The ensuing dynamics can lead to a peak in the diphoton spectrum, which could be observed at the LHC, subject to the prominence of the signal. Moreover, the results can be numerically justified when the warp factor is precisely in the range required for stabilisation of the electroweak scale.

I. INTRODUCTION

Suppose there is a fundamental spin-0 particle in nature, whose couplings to all Standard Model (SM) particles are extremely suppressed, the only exception being pairs of gauge bosons. In such a case, such interactions should constitute the sum and substance of its phenomenology observable at the Large Hadron Collider (LHC), provided that it is within the kinematic reach of the latter.

Such a situation is not altogether far-fetched. A case in point is a CP-odd spin-0 axion field, in terms of which a Kalb-Ramond (KR) antisymmetric tensor field strength can be defined. As we shall emphasize further in the remaining part of this paper, the KR field exhibits some very interesting properties if it propagates in bulk in a (1+4) dimensional warped geometry scenario as proposed first by Randall and Sundrum. However, the theory is not in general anomaly-free if it arises from a still higher-dimensional scenario such as 10-dimensional supergravity. This problem is avoided (see section II) if the KR field is endowed with Chern-Simons (CS) terms couplings with gauge bosons, also propagating in the bulk. On compactification of the warped extra dimension, the CS term has unsuppressed interaction strengths of its zero mode with gauge boson pairs on the (1+3) dimensional visible brane. This unsuppressed character is in turn translated into the interaction of the axion field, in terms of which the zero-mode KR field strength is expressed. On the other hand, the fermionic couplings of the CS-axion turn out to be suppressed as an artefact of the given scenario. With a non-perturbatively acquired mass of this axion, it can have interesting LHC phenomenology where the CS-driven gluon fusion process can produce it, followed by its decays into gauge boson pairs, of which the most spectacular signal consists in diphoton invariant mass peaks. The expected rates of such peaks are estimated in this paper. We mention in this connection that a recent surge of interest on such diphoton peaks came with the apparent occurrence of a diphoton peak at about 750 GeV in the initial 13 TeV run of the LHC. It was first reported in the preliminary announcement of the 13 TeV run [2, 3] and corroborated in the recent reports in the recent Moriond meeting [4]. It led to an avalanche of explanations offered in context of various new physics scenarios (see for a representative list [5–33]). Even though the signal ultimately failed to persist, it could nonetheless glorify the importance of the diphoton final state in detecting a spin-0 TeV-scale resonance, that could indeed be a reality for higher axion masses.

As has been stated already, we present our study in the context of a five-dimensional Randall-Sundrum scenario with bulk space-time torsion identifiable with a Kalb-Ramond tensor field. The massless four-dimensional projection of this field is expressible in terms of an axion which may acquire a mass term non-perturbatively. While this axion field has extremely suppressed coupling with fermions on the four-dimensional visible brane, it can have enhanced interaction with gauge boson pairs via Chern-Simons (CS) terms. Using such CS terms as the driving dynamics, we examine the diphoton production rates in this study. To make matters more practical from the experimental perspective, we choose only those values of the warp factor in the five-dimensional geometry, which not only can explain the hierarchy between the Planck and electroweak scales, but also generate KK gauge boson masses above the lower bound set by LHC. We present our results for different axion masses.

This paper is planned as follows. In Section II, we in-

∗nabarunc@hri.res.in
†biswarup@hri.res.in
‡tpssg@iacs.res.in
The five-dimensional Einstein-Maxwell-Kalb-Ramond (EKMR) action in the Einstein frame reads

$$S_{\text{eff}} = \int d^5x \sqrt{-G} \left[ R - \frac{1}{4} F_{MN} F^{MN} \right] - \frac{1}{12} \Pi_{MNL} H^{MNL}$$

where

$$\Pi_{MNL} = H_{MNL} + \frac{2}{M^3/2} B_{[M} F_{NL]} + \frac{2}{M^3/2} W_i [M W_i^L]$$

Here $B_{NL}$ refers to the Kalb-Ramond (KR) two form in five-dimensions. Besides, $B_M(x, \phi)$, $W_i^L(x, \phi)$ and $G^b_{NL}(x, \phi)$ respectively refer to the $U(1)_Y$, $SU(2)_L$ and $SU(3)_c$ gauge fields in the bulk with $F_{NL}$, $W_{NL}$ and $G_{NL}^b$ as the corresponding field strengths. The gauge $SU(2)_L$ and $SU(3)_c$ gauge indices read $i$ and $b$ respectively. Further, KR gauge invariance allows us to do gauge fixing using $B_{\mu y} = 0$.

With the standard model (SM) gauge fields in the bulk, the Kaluza-Klein towers for them as well as the KR field on the visible brane are given by

$$B_{\mu \nu}(x, \phi) = \sum_{n=1}^{\infty} B^m_{\mu \nu}(x) \frac{\chi^n(\phi)}{\sqrt{r_c}}$$

$$C_\mu(x, \phi) = \sum_{n=1}^{\infty} C^n_\mu(x) \frac{\psi^n(\phi)}{\sqrt{r_c}}$$

where $C$ stands for the towers corresponding to the SM gauge fields, viz, $B$, $W$ and $G$. The zero-mode for the KR field obeys the following equation.

$$\frac{1}{r_c^2} \frac{d^2 \chi^0}{d \phi^2} = 0$$

The solution reads

$$\chi^0(\phi) = c_1 + c_2 |\phi|$$

Continuity of the first derivative of $\chi^0(\phi)$ at the orbifold fixed points $\phi = 0, \pm \pi$ gives $c_2 = 0$. $c_1$ is fixed using the orthonormality condition

$$\int e^{2kr_c |\phi|} \chi^n(\phi) \chi^m(\phi) d\phi = \delta_{mn}$$
This leads to the following zero-mode profiles.

\[
\chi^0(\phi) = \sqrt{2k\ell} e^{-kr_c \pi} \quad (\text{II.11})
\]

\[
\psi^0(\phi) = \frac{1}{\sqrt{2\pi}} \quad (\text{II.12})
\]

\[H_0^{\mu\nu\lambda}, \text{ the field strength of } B_0^{\mu\nu}, H_0^{\mu\nu\lambda} \text{ can be expressed as}\]

\[H_0^{\mu\nu\lambda} = \epsilon_{\mu\nu\lambda\rho} \partial^\rho a\]

Here \(a\) denotes a CP-odd scalar, called the KR axion. Such an axion acquires a mass term through non-perturbative effects confined to the TeV brane such as instanton corrections \[58\]. This mass is \textit{prima facie} a free parameter, and which can be around a TeV scale.\(^3\) The kinetic terms of \(a\) and its coupling to the SM gauge fields via the Chern-Simons terms take the form \[52\].

\[
S_{Kin} = -\frac{1}{2} \eta^{\mu\nu} \partial_\mu a \partial_\nu a \quad (\text{II.13})
\]

\[
S_{CS} = f \left[ aB_\mu B_\mu - aW_\mu W_\mu + aG_\mu B_\mu \right] \quad (\text{II.14})
\]

where, \(f = -\sqrt{\frac{e^{-kr_c \pi}}{2k\ell k_{r_c} M_F}}\) quantifies the coupling of the axion to the SM gauge bosons. Moreover, \(B_\mu = \frac{1}{2} \epsilon_{\mu\nu\lambda\rho} B_\nu B_\lambda\) etc. denote the dual of the original field strength.

It should be noted that the CS terms enable the axion to have enhanced coupling to gauge field pairs, by virtue of the specific nature of the warped geometry. In contrast, it has been found \[57\] that \(a\) has interaction to fermion pairs of the form \(\sim \frac{e^{-kr_c \pi}}{M_F}\). As a result, both its production rate via gluon fusion and its diphoton partial decay width are enhanced to an extent to be decided by the acquired mass of the axion on the TeV brane.

The expressions for the leading order decay widths of \(a\) to various \(VV\) (pair of gauge-bosons) states are

\[
\Gamma_{a \rightarrow \gamma\gamma} = \frac{1}{4\pi} f^2 m_a^3 \quad (\text{II.15})
\]

\[
\Gamma_{a \rightarrow gg} = \frac{2}{\pi} f^2 m_a^3 \quad (\text{II.16})
\]

\[
\Gamma_{a \rightarrow WW} = \frac{f^2 m_a^3}{2\pi} \left(1 - \frac{4m_W^2}{m_a^2}\right)^{3/2} \quad (\text{II.17})
\]

\[
\Gamma_{a \rightarrow ZZ} = \frac{f^2 m_a^3}{4\pi} \left(1 - \frac{4m_Z^2}{m_a^2}\right)^{3/2} \quad (\text{II.18})
\]

\[\text{III. ANALYSIS STRATEGY AND NUMERICAL PREDICTION.}\]

We have the following expression for a production cross section via gluon fusion

\[
\sigma_{pp \rightarrow a}(fb) = c_{gg} \frac{\Gamma_{a \rightarrow gg}(GeV)}{m_a s} \times 0.3894 \times 10^{12} \quad (\text{III.1})
\]

Here \(c_{gg}\) comes from convoluting over the parton densities.

\[
c_{gg} = \frac{\pi^2}{8} \int \frac{dx}{x} g(x) g\left(\frac{m_a^2}{xs}\right) \quad (\text{III.2})
\]

For practical purposes, we take \(c_{gg} \simeq 2137\). The cross section to the diphoton final state is then straightforwardly obtained by multiplying with the corresponding branching ratio.

\[
\sigma_{pp \rightarrow a \rightarrow \gamma\gamma} = \sigma_{pp \rightarrow a} \times \frac{\Gamma_{a \rightarrow \gamma\gamma}}{\Gamma_a} \quad (\text{III.3})
\]

The couplings of the axion to the gauge boson pairs are taken to be universal in this study. This makes the branching ratio to a given \(VV\) state independent of \(kr_c\), for a fixed axion mass.

Both the production cross section of \(a\) as well as its partial width to \(gg\) state are prone to QCD corrections. To encapsulate its effect, one can in principle scale both the production cross section as well the partial width by some \(K_{QCD}\). Considering that the dominant contribution to \(\Gamma_a\) comes from the \(gg\) state and that \(K_{QCD}\) is expected to be greater than unity, its effect in the diphoton cross section largely cancels out.

We mention in this context that we have also implemented the effective Lagrangian into the FeynRules package \[65\]. Subsequently the \(pp \rightarrow a\) cross section and its decay rates to various channels were cross checked using the tool MadGraph5_aMC@NLO \[67\].

The diphoton rate is very sensitive to \(kr_c\), precisely due to its exponential dependence on the latter. So are the masses of the graviton and gauge boson KK excited states. Different values for the parameter \(k/M_{Pl}\), all less than unity, have been chosen while plotting, so that the bulk curvature is less than the Planck scale \[68\]. Without this constraint, the classical solution of 5-dimensional Einstein’s equation cannot be trusted.

With \(k = 0.7M_{Pl}\) and requiring the first gauge boson KK excitation to be heavier than 3.4 TeV \[69\] \(^4\) leads

\[^4\text{The limit from the non-observation of dilepton peaks, as obtained in} [69], \text{depends on the decay width of the heavier vector boson. The limit is as strong as 4.05 TeV for the spin-1 particle having SM-like couplings to fermions, while it could be 3 TeV or lesser with narrower widths. Keeping in mind the fact that a first excited spin-1 KK state has weaker coupling than in the SM, we have taken the limit, somewhat conservatively, as 3.4}\]
to $kr_c \leq 11.72$. For a given $kr_c$, this upper bound gets tighter upon using a smaller value for $k$.

The initial results of the 13 TeV collisions have practically ruled out a diphoton resonance of mass less than 750 GeV that has ‘reasonable’ interaction strength with SM particles. For the spin-zero axion considered here, an exception may occur only if the warp factor $kr_c$ is way below what is required for addressing the hierarchy between the Planck and electroweak scales. However, higher masses are still within reach. We display the diphoton rates for axion masses around 1 TeV, 1.5 TeV and 2.5 TeV in Fig. 1. As expected, the rate goes down as the axion gets heavier. It is seen that a 1 TeV axion can have a production cross section of $\lesssim 5 \text{ fb}$ at $\sqrt{s} = 13 \text{ TeV}$, for $kr_c = 11.6$. This goes up to $\approx 10 \text{ fb}$ for $kr_c = 11.7$. Dynamically enhancing the rate by increasing $kr_c$ to still higher values will invariably come into conflict with the requirement of heavy KK states. Hence, to get an appreciable significance, one must wait till the LHC-13 gathers more data. The sensitivity however is marginally better for $\sqrt{s} = 14 \text{ TeV}$. For example, a 1 TeV axion can yield a $\approx 18 \text{ fb}$ cross section for the diphotons in this case. In principle, the other decay modes (such as digluons) can also be observed at the LHC. However, the observability of these are perhaps more challenging than that for the diphotons, since rates of ZZ - peaks undergo branching fraction suppression, while dijet peaks from gluon pairs are swamped by the background.

Fig. 2 quantitatively depicts the reach of the 13 TeV LHC in detecting a diphoton resonance that has its origin in the framework under study. While a 1 fb diphoton cross section can be predicted even for a 1.9 TeV axion, a more sizeable rate of 10 fb demands a much lighter axion ($\leq 1 \text{ TeV}$). The collider must gather appreciable luminosity to discern a feeble resonant diphoton rate ($< 1 \text{ fb}$, say) from the background. If, upon accumulation of the requisite luminosity, one notices such ‘clean’ diphoton peaks, the next step would be to see if the WW and ZZ peaks with correlated strengths are also noticeable. In case they are, one has to look further for the presence or absence of corresponding peaks with fermions. If such peaks are absent, then one will be directed to spinless particles which have unsuppressed couplings with gauge boson pairs but no interactions with fermions. One possible interpretation of such coincidence of observed phenomena may be CS dynamics embedded in a warped geometry. The exact estimate of the LHC reach for higher masses will require a careful analysis of cuts and their efficiencies corresponding to the high diphoton invariant mass.

IV. SUMMARY

In conclusion, a bulk KR field in a 5-dimensional bulk with RS warped geometry can be connected with an axion in 4-dimensions, which, with a non-perturbatively acquired mass, can lead to a bump in the diphoton spectrum. The most notable feature of this framework is that the production as well as decay of the axion is triggered by 5-dimensional Chern-Simons terms which are not ad hoc introduction but necessitated by the cancellation of gauge anomalies. Even if one makes the simplifying assumption of universal CS couplings for all gauge bosons, the diphoton rate for a 1 TeV axion can attain sizeable values at the 13 TeV LHC. However, a more realistic estimate is only expected to emerge after detector simulation is carried out. We remind that the novelty of the suggested scenario lies in the fact that the very same the warp factor, which is responsible for the reported dipho-
FIG. 2: Contours of constant cross section in the $m_\alpha$ vs $k_r$ plane. The region to the left of the vertical line is disallowed from the non-observation of a diphoton resonance below 750 GeV. Similarly, the region above the horizontal line is disallowed from KK gauge boson searches.

Acknowledgement

This work of NC and BM was partially supported by funding available from the Department of Atomic Energy, Government of India for the Regional Centre for Accelerator-based Particle Physics [RECAPP], Harish-Chandra Research Institute. SSG acknowledges the hospitality of RECAPP while this work was in progress. We also thank Shankha Banerjee, Subhadeep Mondal and Ashoke Sen for helpful discussions.
