INTRODUCTION

Solutions to the Planck-weak hierarchy problem of the Standard Model (SM) invoke new particles at TeV scale. Such new physics is likely to give a signal at the upcoming LHC, provided that the new states have a non-negligible coupling to the SM particles. This Calchep model implements the solution to the hierarchy problem based on the Randall-Sundrum (RS1) framework with a warped extra dimension [1]. The most distinctive novel feature of this scenario is the existence of a spin-2 Kaluza-Klein (KK) gravitons whose masses and couplings to the SM are set by the TeV scale and therefore, the KK gravitons appear in experiments as widely separated resonances.

The RS1 framework is based on a slice of AdS_5 space where 5D "bulk" fields live and after dimensional reduction one arrives at the effective 4D description in terms of a tower of the KK modes of the 5D bulk fields. We will simply label the KK modes of 5D fields by integers $n, m, q, \ldots$. Owing to the warped geometry, the relationship between the $5D$ mass scales and those in an effective $4D$ description depends on the location in the extra dimension. The $4D$ $(n = 0)$ zero-mode graviton is localized near the "UV/Planck" brane which has a Planckian fundamental scale, whereas the Higgs sector is localized near the "IR/TeV" brane where it is stable near a warped-down fundamental scale of order TeV. This large hierarchy of scales can be generated via a modest-sized radius of the $5^{\rm th}$ dimension: $\text{TeV}/\bar{M}_P \sim e^{-k\pi R}$, where k is the curvature scale and R is the proper size of the extra dimension; $kR \approx 11$. Furthermore, based on the AdS/CFT correspondence RS1 is conjectured to be dual to $4D$ composite Higgs models. The model addresses the flavor structure of the SM through localization of fermions in the warped bulk. This picture offers a unified geometric explanation of both the hierarchy and the flavor puzzles, without introducing a flavor problem.

The Calchep model implements the production and decay of $n = 1$ KK graviton following the scenario proposed in [2, 3]. In this scenario, graviton production and decay via light fermion channels are highly suppressed and the decay into photons is negligible. Decays of KK graviton are dominated by top quark and Higgs due to their profile being near TeV brane, resulting in the enhanced couplings to KK gravitons which are also localized at the TeV brane. Furthermore, by the equivalence theorem, $W_L^\pm$ and Z_L are effectively the *un*physical Higgs ("would-be" Goldstone bosons) and are therefore localized near the TeV brane (just like the physical Higgs). So, the decay widths in the W_L/Z_L channels are the same size as in those of the physical Higgs/top quark. Moreover, due to heaviness of top quark combined with constraint from shift in $Zb\bar{b}$, certain choices of profiles for t_R and $(t, b)_L$ are allowed and in the current implementation the extreme case with t_R localized on the TeV brane and with $(t, b)_L$ having close to a flat profile is considered.

MODEL PARAMETERS AND COUPLINGS

A general formula for couplings of $m^{\rm th}$ and $n^{\rm th}$ modes of the bulk field (denoted by F) to the $q^{\rm th}$ level KK gravitons (denoted by G) is:

$$\mathcal{L}_G = \sum_{m,n,q} C^{FFG}_{mnq} \frac{1}{\bar{M}_P} \eta^{\mu\alpha}\eta^{\nu\beta} h^{(q)}_{\alpha\beta}(x) T^{(m,n)}_{\mu\nu}(x) \tag{1}$$

where $h^q_{\alpha\beta}(x)$ corresponds to the KK graviton, $T^{(m,n)}_{\mu\nu}(x)$ denotes the $4D$ energy-momentum tensor of the modes of the bulk field, $\bar{M}_P \approx 2.4 \times 10^{18}$ GeV is the reduced $4D$ Planck scale and C^{FFG}_{mnq} is the overlap integral of the wavefunctions of the 3 modes.

We will consider only those couplings relevant for production and decay. Since $q\bar{q}$ annihilation to KK graviton is suppressed, the production is dominated by gluon fusion. The gluons and photons have a flat profile and their coupling to KK gravitons is given by the above formula with:

$$C^{AAG}_{00n} = e^{k\pi R} \frac{2\left[1 - J_0\left(x^G_n\right)\right]}{k\pi R \left(x^G_n\right)^2 \left|J_2\left(x^G_n\right)\right|} \tag{2}$$

where $J_{0,2}$ denote Bessel functions and $x^G_n = 3.83, 7.02, 10.17, 13.32$ gives masses of the first 4 KK gravitons: $m^G_n = ke^{-k\pi R} x^G_n$.

As mentioned above, the decays of KK graviton are dominated by right-handed top quark and Higgs (including longitudinal W/Z using equivalence theorem). With this approximation, the couplings relevant for decay are:

$$\mathcal{L}_G \ni \frac{e^{k\pi R}}{\bar{M}_P} \eta^{\mu\alpha}\eta^{\nu\beta} h^{(q)}_{\alpha\beta}(x) T^{t_R,H}_{\mu\nu}(x) \tag{3}$$

Parameters	Physical meaning	Default value
$c \equiv k/\bar{M}_P$	Ratio of the AdS curvature scale to the Planck mass	1
m_1^G (TeV)	Mass of the $n=1$ KK graviton	1.5 TeV

TABLE I: Parameters of the model

Constraints	Physical meaning
x_1	Graviton coupling to particles localized on the TeV brane
Ggg	Extra suppression factor for the particles having flat profile

TABLE II: Constraints of the model

giving the partial decay widths [4]:

$$\Gamma\left(G \to t_R \bar{t}_R\right) \approx N_c \frac{(c\, x_n^G)^2\, m_n^G}{320\pi} \tag{4}$$

$$\Gamma\left(G \to hh\right) \approx \frac{(c\, x_n^G)^2\, m_n^G}{960\pi} \tag{5}$$

$$\Gamma\left(G \to W_L^+ W_L^-\right) \approx \frac{(c\, x_n^G)^2\, m_n^G}{480\pi} \tag{6}$$

$$\Gamma\left(G \to Z_L Z_L\right) \approx \frac{(c\, x_n^G)^2\, m_n^G}{960\pi} \tag{7}$$

where $N_c = 3$ is number of QCD colors, $c \equiv k/\bar{M}_P$, and we have neglected masses of final state particles in phase space factors. These are the only important decay channels for the $n = 1$ graviton KK mode which is the only mode implemented in the code.

Due to the $\bar{M}_P\, e^{-k\pi R} = m_n^G/(x_n^G c)$ relation, we have two free parameters in the model which we choose to be c and m_n^G . As mentioned before, $x_1^G = 3.83$ for the first graviton resonance. It is easy to see that all the couplings of the $n = 1$ graviton to particles localized on the TeV brane are $\sim$ to the factor:

$$x_1 \equiv x_1^G c/M_1^G. \tag{8}$$

Couplings of the $n = 1$ graviton to the gluons and photons have an additional volume suppression factor:

$$Ggg \equiv \frac{2\left[1 - J_0\left(x_n^G\right)\right]}{k\pi R\left(x_n^G\right)^2 \left|J_2\left(x_n^G\right)\right|}. \tag{9}$$

The model free parameters and the constraints are summarized in the Tables.I and II respectively. As discussed in [2], with current experimental constraints we may expect that $0 < c < 2$ and $m_1^G \gtrsim 3$ TeV .

The Calchep model is implemented in the unitary gauge and includes all the SM interactions. We emphasize that the aim of this implementation is to capture the relevant phenomenology of the model described above. Thus the only new particle in the implementation compared to SM is $n = 1$ KK graviton with the particle name "hh". In the Table.III we give the beyond SM vertices implemented in the model and their Lorentz structure [4].

The total decay width, branching fractions and the production cross section for the $n = 1$ graviton KK mode as a function of its mass are given in figures 2, 1 and 3 respectively. An example of a kinematical distribution, namely the transverse momentum of the muon pair, is given in figure 4. The actual process and cuts are described in the plot.

Vertex	Lorentz structure
hhZ_LZ_L	$m_z^2 Z_\mu Z_\nu hh^{\mu\nu}$
hhW_LW_L	$m_w^2 W_\mu W_\nu hh^{\mu\nu}$
$hhHH$	$\partial_\mu H \partial_\nu H hh^{\mu\nu}$
$hht_R\bar{t}_R$	$T_{\mu\nu}^{t_R} hh^{\mu\nu}$
$hhGG$	$T_{\mu\nu}^{G} hh^{\mu\nu}$
$hhAA$	$T_{\mu\nu}^{A} hh^{\mu\nu}$

TABLE III: Vertices of the model. Explicit expressions for the energy-momentum tensors $T_{\mu\nu}^{t_R}$, $T_{\mu\nu}^{G}$, $T_{\mu\nu}^{A}$ can be found in [4].

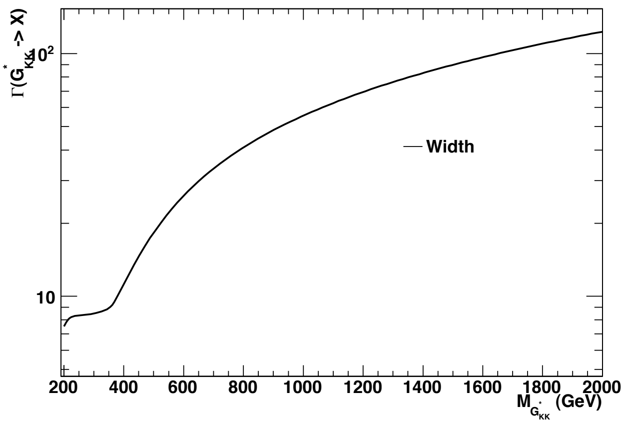

FIG. 1: Total width

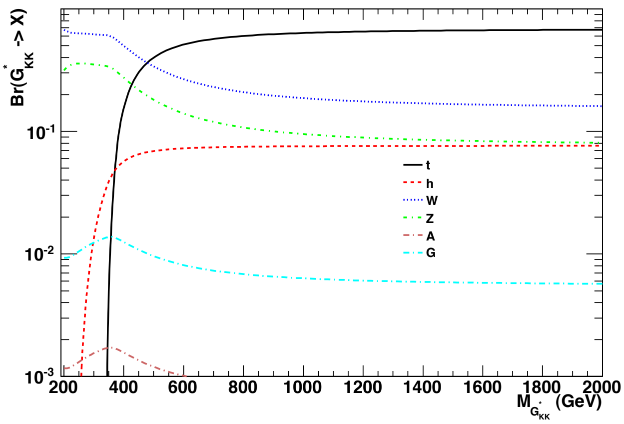

FIG. 2: Branching fractions

VALIDATION

We have verified that our implementation reproduces the results derived in [2]. Furthermore figure 5 verifies the expected $1 - \cos^2\theta$ behavior for the longitudinal W from the graviton decay [5]. This plot presents the angular distribution of the W^+ in the graviton rest system, where the angle is set by the direction of boosting of the graviton rest system.

[1] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999) [arXiv:hep-ph/9905221].
[2] K. Agashe, H. Davoudiasl, G. Perez, A. Soni, Phys. Rev. **D76** (2007) 036006. [hep-ph/0701186].
[3] A. L. Fitzpatrick, J. Kaplan, L. Randall, L. -T. Wang, JHEP **0709**, 013 (2007). [hep-ph/0701150].
[4] T. Han, J. D. Lykken and R. J. Zhang, Phys. Rev. D **59**, 105006 (1999) [arXiv:hep-ph/9811350].
[5] O. Antipin, A. Soni, JHEP **0810**, 018 (2008). [arXiv:0806.3427 [hep-ph]].

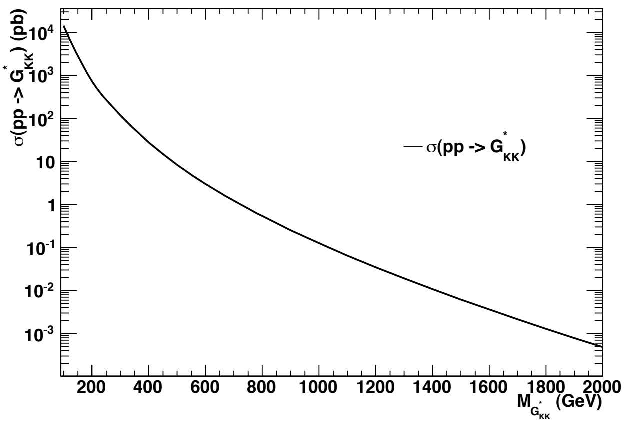

FIG. 3: Production cross section pp @ 7TeV

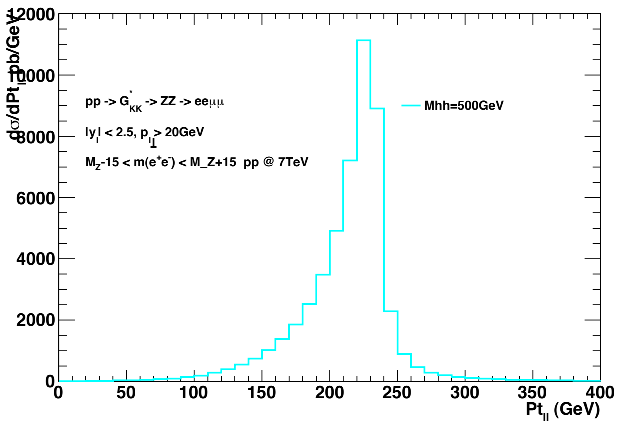

FIG. 4: Transverse momentum distribution of the muon pair

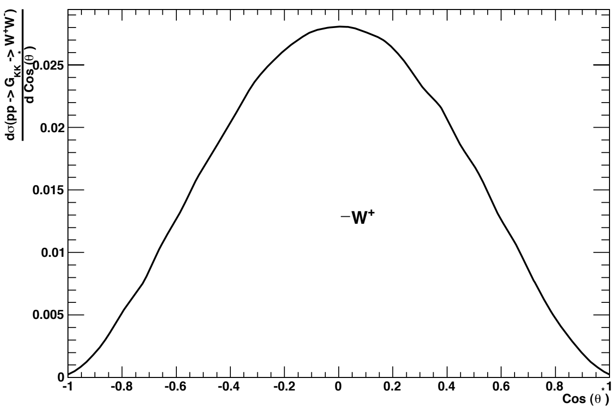

FIG. 5: Angle in the rest frame of the graviton between the W^+ and the direction of boosting of the graviton rest frame.