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LHC sensitivity to a Kaluza-Klein gluon in the two *b*-jets decay channel

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We examine a possibility to discover a Kaluza-Klein (KK) excitation of gluon in a warped extra-dimension model at the Large Hadron Collider, focusing on a decay channel of the KK gluon into a b-quark pair. It is known that, in a certain extension of the warped extra-dimension model, the third generation quarks could strongly couple to the KK gluon, as a result of appropriate bulk fermion mass parameters. Taking account of kinematical cuts to reduce background events, we show the model parameter space, which leads to a significance larger than 5σ with the integrated luminosity of 10 (100) fb^{-1}.

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I. INTRODUCTION

Although the Standard Model (SM) of particle physics has shown good agreement with almost all data of high-energy experiments, we expect new physics beyond the SM from some theoretical motivations such as a gauge hierarchy problem. A warped extra-dimension model proposed by Randall and Sundrum (RS) [1] is one of the promising candidates to explain the hierarchy between the Fermi scale and the Planck scale. In the RS model, there are two 3-branes that are located in different positions in the fifth dimension. The SM particles are confined in one of the 3-branes, called a "visible brane," while the other is called a "hidden brane." A graviton is allowed to propagate between the two branes. With this setup, the mass scale of a Higgs boson can be an electroweak scale naturally when the fifth dimension is warped appropriately and the gauge hierarchy problem is understood without suffering from a fine-tuning problem like the SM. Although it is sufficient to explain the gauge hierarchy problem when only the graviton propagates into the extra dimension, an extension of the RS model, where some of the SM particles also propagate into the bulk, has been studied from a phenomenological point of view (for example, see Ref. [2]). A generic consequence of such an extension of the RS model is that there are Kaluza-Klein (KK) excitations of the SM particles. It is, therefore, important to investigate possibilities of production and decay of KK particles at the Large Hadron Collider (LHC) as a direct test of the model.

The mass of KK particles is typically determined by the scale parameter Λ_{KK}. It has been shown that the KK excitations of the electroweak gauge bosons are significantly constrained by the electroweak precision measurements due to their large contributions to the oblique parameters. As a result, the scale of the KK mode Λ_{KK} is required to be $\Lambda_{\mathrm{KK}} > O(10^{2-3}\ \mathrm{TeV})$, which leads to an unwanted hierarchy between the electroweak scale $\Lambda_{\mathrm{EW}} \sim O(m_W)$ and Λ_{KK} [2,3]. Such a constraint could be somewhat lowered to $O(\mathrm{TeV})$ by introducing the custodial symmetry in the bulk [4] and additional contributions from the bulk SM fermions [5]. The phenomenology of introducing the bulk custodial symmetry has been studied, e.g., in Ref. [6].

Another serious constraint on the KK scale Λ_{KK} comes from processes mediated by flavor-changing neutral currents (FCNC). For example, a naive estimation of contributions of KK gauge bosons to a CP-violating parameter ϵ_K in the K^0-$\bar{K}^0$ mixing tells us that the KK scale should be $\Lambda_{\mathrm{KK}} > 20$ TeV. However, the bound on Λ_{KK} could be lowered to the scale that is allowed from the electroweak precision data, arranging the fermion sector of the model as appropriate for the choice of the bulk fermion masses or introducing some flavor symmetry (a useful and compact summary has been given in Ref. [7]). It should be noted that there is another study indicating that the KK gauge boson mass could be $O(\mathrm{TeV})$ without introducing the custodial symmetry on the bulk [8]. Thus we expect that the KK gauge bosons with a few TeV mass could be produced at the LHC, and it is worth examining signatures of these new particles using various decay channels.

In this paper, we study the possibility of observing the first KK excitation of gluon ($g_{\mathrm{KK}}^{(1)}$) at the LHC, using the decay channel to two b quarks, $g_{\mathrm{KK}}^{(1)} \to b\bar{b}$. Searching for $g_{\mathrm{KK}}^{(1)}$ at the LHC has been studied using a decay of $g_{\mathrm{KK}}^{(1)}$ into a top-quark pair, $g_{\mathrm{KK}}^{(1)} \to t\bar{t}$, e.g., in Refs. [7,9–11], since there is a naive expectation that the interaction of the

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right-handed top quark t_R with the KK gluon affects the electroweak and flavor processes less so that the large coupling of t_R could be allowed phenomenologically. On the other hand, the b-quark couplings to the KK gluon have been chosen to be negligibly suppressed in the literature due to the FCNC constraints. In our analysis, however, since the Yukawa sector of the RS model is still controversial (e.g., Ref. [12]), we adopt the left- and right-handed b-quark couplings to the KK gluon as phenomenological parameters and study the possibility of observing the KK gluon through the two b-jets channel at the LHC.

As will be shown later, a single production of $g^{(1)}_{\rm KK}$ is possible only through pair annihilation of the quarks. Thus, its production in the s channel is relatively suppressed when the couplings of light quarks to the KK gluon are small so that the experimental lower bound on $g^{(1)}_{\rm KK}$ is of order 1 TeV in both the Tevatron [13] and the LHC [14,15]. Note that these experimental bounds have been obtained using the decay channel $g^{(1)}_{\rm KK} \to t\bar{t}$. The associate production of $g^{(1)}_{\rm KK}$ decaying to $t\bar{t}$ has been studied in Ref. [16].

In our study, we focus on the following process, $pp \to g^{(1)}_{\rm KK} \to b\bar{b}$. In general, it is hard to find a signal process using two b jets because of the huge QCD background. We find that, imposing efficient kinematical cuts, extraction of signal events from the background is possible. For example, a significance could be larger than 5σ for the $g^{(1)}_{\rm KK}$ mass up to 1.1 TeV with the integrated luminosity of 10 fb^{-1} and up to 1.4 TeV with 100 fb^{-1}.

This paper is organized as follows. In the next section, we briefly review the RS model with bulk fermions and gauge bosons. Our numerical results are shown in Sec. III. Section IV is devoted to the summary and discussion.

II. MODEL SETUP

We consider a five-dimensional space-time with a nonfactorizable geometry,[1]

$$ds^2 = e^{-2\sigma}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2, \qquad \mu, \nu = 0, 1, 2, 3, \tag{2.1}$$

where $\sigma = k|y|$, $\eta_{\mu\nu} = \mathrm{diag}(-1, 1, 1, 1)$, y is the coordinate of the fifth dimension, and k determines the curvature of the AdS$_5$. The coordinate y is compactified on an orbifold $S^1/\mathbf{Z}_2$ of a radius r_c, with $-\pi r_c \le y \le \pi r_c$. The orbifold fixed points at $y = 0$ and $y = \pi r_c$ are the locations of two 3-branes, which are called the hidden brane and the visible brane, respectively. At the visible brane, the effective mass scale is given to be $M_P e^{-\pi k r_c}$, associated with the TeV scale provided $kr_c \simeq 12$. Note that M_P is the four-dimensional Planck scale, thus the gauge hierarchy problem is solved in this model. In our scenario, we assume that the SM Higgs is located at the visible brane, while the other SM fields and the gravity are present in the five-dimensional bulk. We are interested in the case in which the third generation of quarks couples to the KK gluons strongly. The part of the model relevant to our analysis is then written by an $SU(3)$ gauge field A^a_M and a Dirac fermion Ψ with the five-dimensional coordinates labeled by capital latin letters, $M = (\mu, y)$ and the adjoint index of the gauge group, a. The five-dimensional bulk action of the gauge field and fermion is given by

$$S_5 = -\int d^4x \int dy \sqrt{-G} \times \left[-\frac{1}{4} F^a_{MN} F^{MNa} + i\bar{\Psi}\gamma^M D_M \Psi + i m_\Psi \bar{\Psi}\Psi \right], \tag{2.2}$$

where $G = \det(G_{MN})$, the gauge field strength is defined by $F^a_{MN} = \partial_M A^a_N - \partial_N A^a_M + i f_{abc} A^b_M A^c_N$ with the structure constant f^{abc}, and $\gamma_M = (\gamma_\mu, \gamma_5)$ is defined in curved space as $\gamma_M = e^\alpha_M \gamma_\alpha$, where e^α_M is the funfbein and γ_α are the Dirac matrices in a flat space. The covariant derivative is written by $D_M = \partial_M + \Gamma_M + i g_5 A_M$, where Γ_M is the spin connection and g_5 is the five-dimensional gauge coupling constant. For the metric (2.1), the spin connection is given by $\Gamma_\mu = \frac{1}{2}\gamma_5\gamma_\mu \frac{d\sigma}{dy}$ and $\Gamma_5 = 0$. The bulk fermion mass m_Ψ is parametrized as

$$m_\Psi = ck\epsilon(y), \tag{2.3}$$

where c is an arbitrary dimensionless parameter and $\epsilon(y)$, which is 1 for $y > 0$ and -1 for $y < 0$, is responsible for making the mass term even under the $\mathbf{Z}_2$ symmetry.

We work in a unitary gauge $A_5 = 0$ and decompose A_M and Ψ in the KK modes,

$$\Phi(x^\mu, y) = \frac{1}{\sqrt{2\pi r_c}} \sum_{n=0}^{\infty} \Phi^{(n)}(x^\mu) f_n(y), \tag{2.4}$$

where $\Phi = \{A_\mu, e^{-2\sigma}\psi\}$ and the KK modes $f_n(y)$ obey the orthonormal condition

$$\frac{1}{2\pi r_c} \int_{-\pi r_c}^{\pi r_c} dy e^{(2-s)\sigma} f_n(y) f_m(y) = \delta_{nm}, \tag{2.5}$$

with $s = 2, 1$ for A_μ, Ψ. Substituting (2.4) with the solution of f_n into (2.2) and integrating the y direction, we find the gauge coupling of a gauge boson KK mode n to the zero-mode fermion as

$$g^{(n)} = g_4 \frac{1-2c}{e^{(1-2c)\pi k r_c} - 1} \frac{k}{N_n} \times \left[J_1\left(\frac{m_n}{k} e^\sigma\right) + b_1(m_n) Y_1\left(\frac{m_n}{k} e^\sigma\right) \right], \tag{2.6}$$

where J_1 and Y_1 are the standard Bessel functions of the first and second kind, N_n is a normalization factor, $b_1(m_n)$ is the constant, m_n is the mass of the nth KK mode, and g_4 is the four-dimensional $SU(3)$ gauge coupling, related to the five-dimensional gauge coupling $g_4 = g_5/\sqrt{2\pi r_c}$. More detailed discussion is given, for example, in

[1] We follow the convention in Ref. [17].

Ref. [17]. Note that, because of the orthonormal condition (2.5), self-interactions of the gauge fields between different modes are not allowed. It means that the KK gluon only decays to a pair made up of a quark and an antiquark.

We are interested in a situation where the third generation of quarks couples to the KK gluon strongly, compared to the four-dimensional QCD coupling. Under this setup, we study the process $pp \to g_{\rm KK}^{(1)} \to b\bar{b}$, where $g_{\rm KK}^{(1)}$ is the first excitation mode of the KK gluon. The coupling between the KK mode and the fermions is given by (2.6), which is determined by the bulk mass parameter c. We consider the following scenarios with various values of couplings:

$$\frac{g_{Q_3}^{(1)}}{g_4} = \frac{g_t^{(1)}}{g_4} = \frac{g_b^{(1)}}{g_4} = 4, \qquad \frac{g_{\rm light}^{(1)}}{g_4} = 0, \tag{2.7}$$

$$\frac{g_{Q_3}^{(1)}}{g_4} = 1, \qquad \frac{g_t^{(1)}}{g_4} = \frac{g_b^{(1)}}{g_4} = 4, \qquad \frac{g_{\rm light}^{(1)}}{g_4} = 0, \tag{2.8}$$

$$\frac{g_{Q_3}^{(1)}}{g_4} = 1, \qquad \frac{g_t^{(1)}}{g_4} = 4, \qquad \frac{g_b^{(1)}}{g_4} = \frac{g_{\rm light}^{(1)}}{g_4} = 0, \tag{2.9}$$

where Q_3 is the third generation of the left-handed quark, t and b are the right-handed top and bottom quarks, and "light" means the quarks of the first two generations. In (2.7), couplings of all the quarks of the third generation to the KK gluon is strong while the coupling between the KK gluon and the light quarks is vanishing. The latter choice is motivated by the constraint coming from the FCNC and the electroweak precision measurement. In (2.8), the KK gluon strongly couples to the right-handed quarks only. The coupling to the left-handed quark is comparable to the QCD coupling g_4. This choice has been studied to analyze the decay of the KK gluon to top and antitop quarks [11]. In (2.9), the difference from (2.8) is that we take the KK gluon coupling to the right-handed bottom quark to be zero. It is a choice motivated by the constraint from the flavor physics and the electroweak precision measurement [7]. With the above choice of parameters, we perform the numerical analysis of the process $pp \to g_{\rm KK}^{(1)} \to b\bar{b}$.

III. NUMERICAL ANALYSIS

We analyze the possibility of observing effects of the KK gluon predicted by the presented model in the $b\bar{b}$ final states at the LHC. We simulated the signal $pp \to g_{\rm KK}^{(1)} \to b\bar{b}$ and possible background processes, initial/final state radiations, hadronization, and decays using PYTHIA 8.160 [18,19] and the Monte Carlo generator using leading-order expressions of matrix elements. All samples were generated for pp collisions at $\sqrt{s} = 14$ TeV using the CTEQ6L1 parton distribution functions [20]. The factorization scale Q_F for the $2 \to 1$ processes (e.g., $pp \to g_{\rm KK}^{(1)}$) was chosen to be equal to the invariant mass of the final particle whereas the scale Q_F for the $2 \to 2$ process was chosen to be equal to the smaller of the transverse masses of the two outgoing particles. The renormalization scale Q_R for the $2 \to 1$ processes was chosen to be equal to the invariant mass of the final particle whereas the scale Q_R for the $2 \to 2$ process was chosen to be equal to the square root of the product of transverse masses of the two outgoing particles. To save time in the massive simulations of $ab \to cd$ processes, we applied the phase space cuts $\hat{p}_T(c) > 50$, $\hat{p}_T(d) > 50$, and $M_{c,d} > 400$ GeV on the transverse momentum and invariant mass of the final particles in their center-of-mass system.

For the simulation of the effects of a detector, we used DELPHES 1.9 [21], a framework for a fast simulation of a generic collider experiment. The fast simulation of the detector includes a tracking system, a magnetic field of a solenoidal magnet affecting tracks of charged particles, calorimeters, and a muon system. The reconstructed kinematical values are smeared according to the settings of the detector simulation. For the jets reconstruction, DELPHES uses the FASTJET tool [22,23] with several implemented jet algorithms. In our simulations, we used the data file with standard settings for the ATLAS detector, provided by the tool. We used the k_T algorithm [24] with a cone radius parameter $R = 0.7$. The b-tagging efficiency is assumed to be 40%, independently on a transverse momentum and a pseudorapidity of a jet. A fake rate of a b-tagging algorithm is assumed to be 10% for c jets and 1% for light and gluon jets. These settings for b-tagging are standard for the ATLAS detector in the DELPHES 1.9 tool. No trigger inefficiencies are included in this analysis.

We assume the following set of event selection criteria:

(1) The event must have exactly 2 b-tagged jets with the transverse momentum $p_T > 100$ GeV, the pseudorapidity $|\eta| < 2.5$, and invariant mass $M_{b\bar{b}} > M_{b\bar{b}}^{\rm min}$.

(2) The event must have no other jet with $p_T > 20$ GeV, $|\eta| < 4.9$.

(3) The event must have no electron or muon with $p_T > 10$ GeV, $|\eta| < 2.5$.

(4) The reconstructed transverse missing energy of the event must be $E_T^{\rm miss} < 50$ GeV.

Criterion 1 for sufficiently high $M_{b\bar{b}}^{\rm min}$ effectively suppresses the QCD background processes (e.g., gg and $q\bar{q}$, $q \in \{u, d, s, c, b\}$, production). Criterion 2 suppresses a top-antitop pair production in both the QCD and the RS model, with the subsequent decay of the top quarks to jets. Criteria 3 and 4 effectively suppress other decay channels of a top quark decay.

We simulated the signal process for couplings (2.7), (2.8), and (2.9) and for the masses of the KK gluon between 1 and 1.5 TeV. For the analysis, samples of 10^6 signal events were used. Assuming the integrated luminosity of 10 fb^{-1} per year (during a low luminosity LHC run), it corresponds to the data collected during the period with the length from 2.6 up to almost 200 years, depending on the $g_{\mathrm{KK}}^{(1)}$ mass and couplings. In Fig. 1, distributions of a $b\bar{b}$-invariant mass without and with the simulated detector effects and the selection criteria for $M_{g_{\mathrm{KK}}^{(1)}} = 1$ TeV and couplings (2.7), (2.8), and (2.9) are presented. All plots are scaled to the integrated luminosity of 10 fb^{-1}.

For the presented selection criteria, the most important background processes are the QCD production of pairs of (anti)quarks and gluons ($q\bar{q}(gg) \to gg$, $q'\bar{q}'(gg) \to q\bar{q}$, $qg \to qg$, $qq' \to qq'$; q, $q' \in \{u, d, s, c, b\}$). In the analysis, we used 50×10^6 simulated background events. Due to an extremely high cross section, it corresponds to the data collected only during the 1.6×10^{-3} year (assuming the integrated luminosity of 10 fb^{-1} per year). In Fig. 2, the invariant mass distribution of the detected b jets (or objects supposed to be b jets) is plotted.

As a signature of new physics, we use the number of selected events. For the integrated luminosity of 10 and 100 fb^{-1}, we estimated the number of expected observed signal and background events (S and B) and the statistical significance $S/\sqrt{B}$. The significance of the deviation from the SM is proportional to the square root of the integrated luminosity. Therefore, it is easy to recompute the results

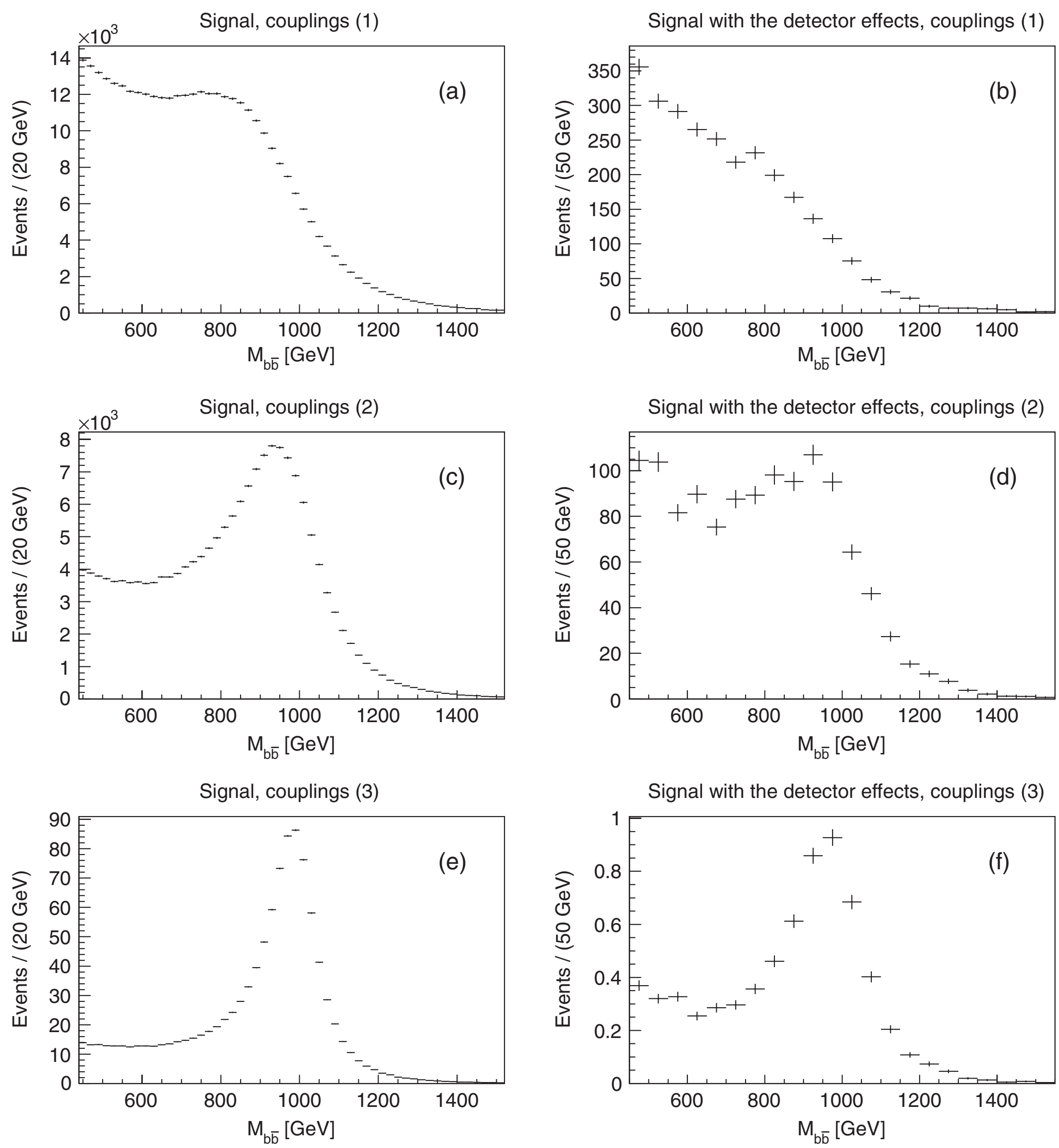

FIG. 1. The invariant mass distribution of the $b\bar{b}$ pairs for the signal process $pp \to g_{\mathrm{KK}}^{(1)} \to b\bar{b}$ without [(a), (c), and (e)] and with [(b), (d), and (f)], the simulated effects of the ATLAS detector and the selection criteria (with $M_{b\bar{b}}^{\mathrm{min}} = 450$ GeV). $M_{g_{\mathrm{KK}}^{(1)}} = 1$ TeV was assumed and three scenarios with couplings (2.7), (2.8), and (2.9) were studied [marked as (1), (2), and (3), in the figure]. The number of events in the histogram is scaled to the integrated luminosity of 10 fb^{-1} for pp collisions at $\sqrt{s} = 14$ TeV.

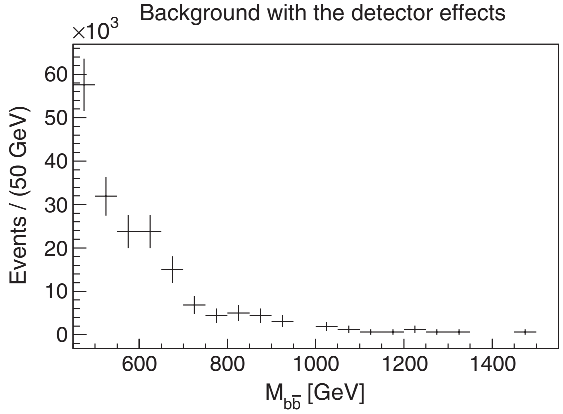

FIG. 2. The invariant mass distribution of the detected b-jets pairs for the background processes with the simulated effects of the ATLAS detector and the selection criteria (with $M_{b\bar{b}}^{\min} = 450$ GeV). The number of events in the histogram is scaled to the integrated luminosity of 10 fb^{-1} for pp collisions at $\sqrt{s} = 14$ TeV.

for higher integrated luminosity. We studied the effects of the variation of $M_{b\bar{b}}^{\min}$ on the statistical significance. In the presented results, we use the value of $M_{b\bar{b}}^{\min}$, for which the statistical significance $S/\sqrt{B}$ is maximal.

In Table I, we present the statistical significance $S/\sqrt{B}$ of our model for various values of $M_{g_{\mathrm{KK}}^{(1)}}$ and couplings. As expected, the deviation from the SM is strongly dependent on the coupling of a right-handed b quark to a KK gluon. For the first set of couplings (2.7), the effects of KK gluons could be observable with the significance of 5σ for the mass of a KK gluon up to 1.1 TeV and the integrated luminosity of 10 fb^{-1} or for the mass of a KK gluon up to 1.4 TeV and the integrated luminosity of 100 fb^{-1}. For the second set of couplings (2.8), the effects of KK gluons could be observable with the significance of 5σ for the mass of a KK gluon up to 1.2 TeV and the integrated luminosity of 100 fb^{-1}. Due to the extremely low cross section of the signal process, for the third set of couplings (2.9) the effects of KK gluons are unobservable.

IV. SUMMARY

We studied the possibility of observing the effects of the first excitation of a KK gluon, predicted by the extension of the RS model. In our work, we focused on the final states with two b jets. We prepared appropriate Monte Carlo simulations of the signal and background processes for the pp collisions with the energy $\sqrt{s} = 14$ TeV at the LHC and simulated the effects of the ATLAS detector and the selection criteria. As a signature of new physics, we used the number of selected events. We studied three scenarios (2.7), (2.8), and (2.9) with various couplings of a KK gluon to b and t quarks. We estimated the significance $S/\sqrt{B}$ of our model. For the integrated luminosity of 100 fb^{-1}, the effects of a KK gluon will be observable with significance 5σ in the scenario (2.7) with strong coupling of b and t quarks to a KK gluon for the mass of a KK gluon up to 1.4 TeV. In the scenario (2.8), when a KK gluon strongly couples to right-handed b and t quarks only, the effects of new physics will be observable for the mass of a KK gluon up to 1.2 TeV. Even from the integrated luminosity of 10 fb^{-1}, the deviation from the SM could be observable with the significance of several sigmas for the mass of a KK gluon up to 1.5 TeV and scenarios (2.7) and (2.8). The effects of a KK gluon in the scenario (2.9) with vanishing coupling of a KK gluon to a right-handed b quark will not be observable.

TABLE I. The statistical significance $S/\sqrt{B}$ of our model for various values of $M_{g_{\mathrm{KK}}^{(1)}}$ and couplings estimated for 10 and 100 fb^{-1}. The presented errors correspond to the statistical errors related to our Monte Carlo simulations.

$\frac{g_{\mathrm{light}}^{(1)}}{g_4}$	$\frac{g_{Q_3}^{(1)}}{g_4}$	$\frac{g_b^{(1)}}{g_4}$	$\frac{g_t^{(1)}}{g_4}$	$M_{g_{\mathrm{KK}}^{(1)}}$ [TeV]	$M_{b\bar{b}}^{\min}$ [GeV]	$S/\sqrt{B}$ for 10 fb^{-1}	$S/\sqrt{B}$ for 100 fb^{-1}
				1.0	690	7.3 ± 0.5	24 ± 2
				1.1	720	5.0 ± 0.4	17 ± 1
0	4	4	4	1.2	720	3.4 ± 0.3	11 ± 1
				1.3	750	2.3 ± 0.2	7.7 ± 0.7
				1.4	940	1.7 ± 0.2	5.7 ± 0.7
				1.5	940	1.2 ± 0.2	4.0 ± 0.7
				1.0	720	4.4 ± 0.3	15 ± 1
				1.1	940	3.0 ± 0.4	10 ± 1
0	1	4	4	1.2	940	2.0 ± 0.3	7 ± 1
				1.3	940	1.4 ± 0.2	4.7 ± 0.7
				1.4	1340	0.9 ± 0.5	3 ± 2
				1.5	1340	0.9 ± 0.4	3 ± 1
0	1	0	4	1.0	820	0.033 ± 0.003	0.11 ± 0.01

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