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Kaluza–Klein gluon and b-jet forward–backward asymmetry

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ABSTRACT

The forward–backward asymmetry of b-quark jets on the Z-pole measured at LEP/SLD experiments shows us -2.8-σ deviation from the Standard Model (SM) prediction. We examine a possibility of Kaluza–Klein (KK) gluon to explain the A_{FB}^b data in a scenario based on the warped extra dimension model by Randall and Sundrum. In this scenario, the KK gluon strongly couples to b-quark by an appropriate choice of the bulk quark mass terms. We find that the A_{FB}^b data could be explained if the KK gluon mass is few hundred GeV. Constraints on our scenario from the hadron collider experiments are discussed.

Standard Model (SM) of particle physics has shown a good agreement with the results of electroweak experiments performed on the Z-pole [1], except for the forward–backward (FB) asymmetry of b-quark jets (A_{FB}^b). The experimental data of A_{FB}^b is [1]

$$A_{FB}^b(\text{exp}) = 0.0992 \pm 0.0016, \tag{1}$$

while the SM prediction is [1]

$$A_{FB}^b(\text{SM}) = 0.1037, \tag{2}$$

for the best fit of the SM. From (1) and (2) we find about $-2.8\ \sigma$ deviation. Although it might be caused due to a lack of our understanding of the b-jet data as discussed in Ref. [2], in this article we would like to examine a possibility of the deviation as an implication of new physics beyond the SM. The electroweak observables at the Z-pole experiments can be expressed in terms of the effective coupling g_α^f which denotes the interaction between Z and f_α, where f represents fermion species and $\alpha(=L, R)$ is their chirality. The radiative corrections to g_α^f consist of the gauge boson propagator corrections (so-called the oblique corrections) which are often parametrized by S and T [3], and the Zff vertex correction Δg_α^f. When the oblique correction is dominated by SM, the new physics contribution to the FB asymmetry, $A_{FB}^b(\text{NP})$, is given as follows [4]:

$$A_{FB}^b(\text{NP}) = A_{FB}^b(\text{SM}) - 0.0326\Delta g_L^b - 0.1789\Delta g_R^b. \tag{3}$$

It is convenient to define the additional new physics contribution to A_{FB}^b in the unit of 10^{-4}

$$\delta A_{FB}^b \equiv \left(A_{FB}^b(\text{NP}) - A_{FB}^b(\text{SM})\right) \times 10^{+4}. \tag{4}$$

The present experimental data (1) constrains the new physics contribution (4) as

$$\delta A_{FB}^b = -45 \pm 16, \tag{5}$$

at the 1-σ level.

Several attempts have been done to explain (5) based on various new physics models – e.g., supersymmetry [5], extended gauge symmetry [6], extra vector-like quarks [7], etc. Contribution of Kaluza–Klein (KK) particles of the SM fields in a variant of warped extra dimension model by Randall and Sundrum (RS) [8] is also one of the possibilities. In this model, the KK modes of gauge bosons and fermions contribute to both the oblique and Zbb vertex corrections. It has been shown that the KK modes of the electroweak gauge bosons give significantly large contribution to the oblique parameters since there is no custodial symmetry in the bulk. As a result, the scale of KK mode Λ_{KK} is strongly constrained from the electroweak data, say $\Lambda_{\text{KK}} > O(10^{2-3}\ \text{TeV})$, which leads to unwanted hierarchy between the electroweak scale $\Lambda_{\text{EW}} \sim O(m_W)$ and Λ_{KK} [9,10]. Such a constraint could be somewhat lowered to $O(\text{TeV})$ by introducing the custodial symmetry in the bulk, or additional contribution from the bulk SM fermions [11, 12]. Taking account of these constraints, the A_{FB}^b puzzle has been studied in a variant of RS model, e.g., in Refs. [13,14], where the deviation of A_{FB}^b is explained by the mixing of the Z boson and its KK states.

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In this article, we would like to study the KK gluon contribution to A^b_{FB} in the warped extra dimension model. It is known that, in warped extra dimension model, the 4D effective coupling of KK gluon and fermions is determined by the overlap of their wavefunctions in the fifth dimension. With an appropriate choice of the bulk quark mass terms, the coupling of the KK gluon to the b-quark could sizably enhanced while the others are suppressed. Then, the 1-loop KK gluon exchange could shift the Zbb vertex correction Δg^b_α without any shift to $\Delta g^f_\alpha (f \neq b)$. We find that, in this scenario, the puzzle of A^b_{FB} could be resolved when the 1st KK gluon mass is few hundred GeV. As mentioned above, the KK scale is constrained to be O(TeV) taking account of the contributions of KK W, Z bosons to oblique parameters. In this case the KK gluon mass also must be O(TeV) which cannot give sizable correction to Zbb vertex. Therefore our scenario of relatively light KK gluon faces difficulty in models which has been known so far. However it is worth studying the QCD corrections to the Zbb vertex independently from the structure of electroweak sector in warped extra dimension model.

Phenomenology of the KK gluon has been studied in, e.g., Ref. [15], focusing on the production and decay at LHC. The KK gluon in [15] is, however, assumed to couple strongly to the t_R quark and contribution to δA^b_{FB} is not considered.

Let us briefly review the interactions of the KK gauge boson to fermions in the warped extra dimension model. The model consists of a non-factorizable geometry on AdS_5 with metric

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}\,dx^\mu\,dx^\nu - dy^2, \tag{6}$$

where y is the coordinate of the fifth dimension and k denotes the AdS_5 curvature. Two 3-branes – “Planck” and “TeV” branes – locate at fixed points of S^1/Z_2 orbifold, $y = 0$ and $y = \pi r_c$, respectively. The hierarchy between the Planck and Electroweak scales can be explained reasonably when $kr_c \approx 11$. In general, if a SM fermion Ψ can propagate into the bulk, there is a 5D mass term $m_\Psi \bar\Psi \Psi$ in the 5D action without breaking the SM gauge symmetry. As shown in [16], the 5D fermion mass m_Ψ can be expressed as $m_\Psi = \nu_\Psi k\epsilon(y)$, where $\epsilon(y)$ is $+1$ for $y > 0$ while -1 for $y < 0$ to make the mass term to be Z_2-even. The wavefunction of the zero mode fermion, then, has the peak toward the Planck brane for $\nu_\Psi < -1/2$ and toward the TeV brane for $\nu_\Psi > -1/2$. The effective 4D interaction of a fermion $f^{(n)}$ and a gauge boson $A^{(m)}_\mu$ can be obtained by integrating the 5D action over y, where $f^{(n)}$ and $A^{(m)}_\mu$ are the 4D KK modes of the 5D fermion Ψ and gauge boson A_M, respectively, and n, m are positive integer. Then, the effective coupling of the zero mode fermion f $(= f^{(0)})$ and KK gauge boson $A^{(n)}$ is given as a function of the parameter ν_Ψ. The generic formula of $g^{ffA^{(n)}}$ can be found, e.g., in Ref. [10]. For $n = 1$, the coupling $g^{ffA^{(1)}}$ can be expanded in terms of ν_Ψ as follows:

$$g^{ffA^{(1)}} \approx g_{\rm SM} \begin{cases} -0.2 & (\nu_\Psi < -0.5), \\ 4.0 + 5.2\nu_\Psi - 4.6\nu_\Psi^2 + 2.1\nu_\Psi^3 & (\nu_\Psi > -0.5), \end{cases} \tag{7}$$

where $g_{\rm SM}$ denotes the SM gauge coupling in 4D. In Fig. 1 we depict a ratio $g^{ffA^{(1)}}/g_{\rm SM}$ as a function of ν_Ψ. We find that the coupling $g^{ffA^{(1)}}$ is enhanced significantly for $\nu_\Psi \gtrsim -0.4$ as compared to the SM gauge coupling $g_{\rm SM}$. On the other hand, the coupling $g^{ffA^{(n)}}$ is highly suppressed for $\nu_\Psi \lesssim -0.5$. The couplings of the higher KK mode of gauge boson with fermions are also highly suppressed when $\nu_\Psi \lesssim -0.5$. In the literature, the parameter ν_Ψ is considered as an origin of the hierarchy of 4D Yukawa couplings. The values of ν_Ψ for each flavor are constrained to reproduce the hierarchy of 4D Yukawa couplings [12]. In our study, however, we take ν_Ψ as model parameters to explain the A^b_{FB} data.

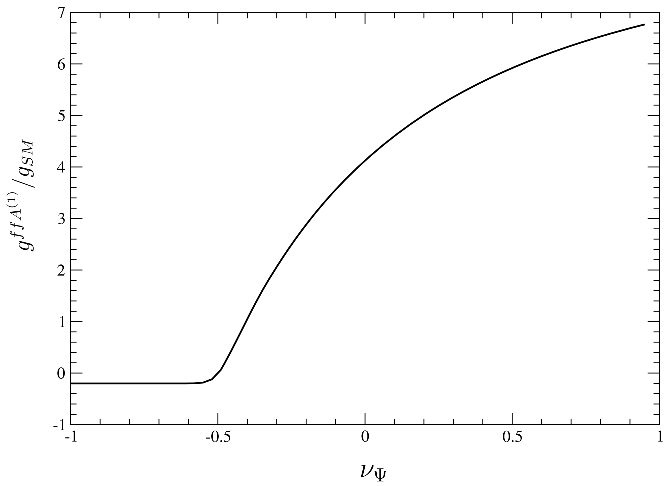

Fig. 1. The ratio of 4D effective coupling of the 1st KK mode of the gauge boson to the fermion, $g^{ffA^{(1)}}$, and the SM gauge coupling $g_{\rm SM}$ as a function of the parameter ν_Ψ.

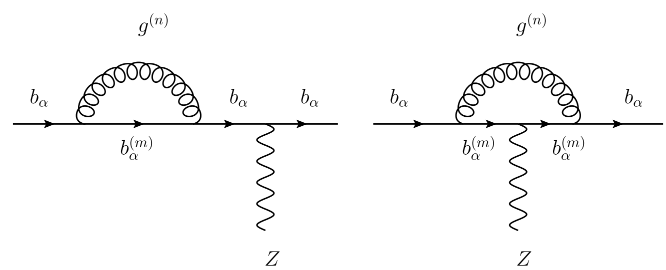

Fig. 2. The Feynman diagrams of 1-loop Zbb vertex.

Next, we examine the QCD correction to the Zbb vertex due to the exchange of the KK gluon $g^{(n)}$ and $b^{(m)}$-quarks. In our study, we consider possibilities that the b $(= b^{(0)})$-quarks strongly couple to $g^{(n)}$, which corresponds to cases $\nu_{Q_{3L}}$ or $\nu_{b_R} \gtrsim -0.5$, where $Q_{3L} = (t_L, b_L)$. We set $\nu_{\rm others} \lesssim -0.5$ for the other light quarks so that those couplings to $g^{(n)}$ are neglected. We do not consider the t-quark in the following because it does not contribute to Zff vertex through the QCD correction. Then, the contributions of KK gluon to Zbb vertex are determined by the ν-parameters for b_L, b_R and the KK gluon mass, $m_{g^{(1)}}$. From phenomenological point of view, it is useful to introduce a new parameter $\xi_\alpha \equiv g^{b_\alpha b_\alpha g^{(1)}}/g_s$, instead of the ν-parameters.

The Feynman diagrams of Zbb vertex via the KK gluon exchange are shown in Fig. 2. The vertex correction Δg^b_α $(\alpha = L, R)$ is given as follows:

$$\Delta g^b_\alpha = \frac{1}{\sqrt{4\sqrt{2}G_F m_Z^2}}\left(g^{bbZ}_\alpha \Sigma'(0) - \Gamma_{b_\alpha}\left(m_Z^2\right)\right), \tag{8}$$

where $\Sigma'(0)$ is the derivative of the self energy function of the external b-quark, whose mass is neglected. The scalar function $\Gamma_{b_\alpha}(m_Z^2)$ is the three point function of the $Zb_\alpha b_\alpha$ vertex at the momentum transfer $q^2 = m_Z^2$. The coupling of the Z-boson to b_α quarks is denoted by g^{bbZ}_α. We note that the ultra violet divergences are cancelled between the self energy and vertex diagrams from each KK state. However, the 1-loop corrections become infinite when one takes the sum of the finite contributions from whole KK towers. We, therefore, need to introduce a cut-off scale Λ to restrict the number of KK modes.

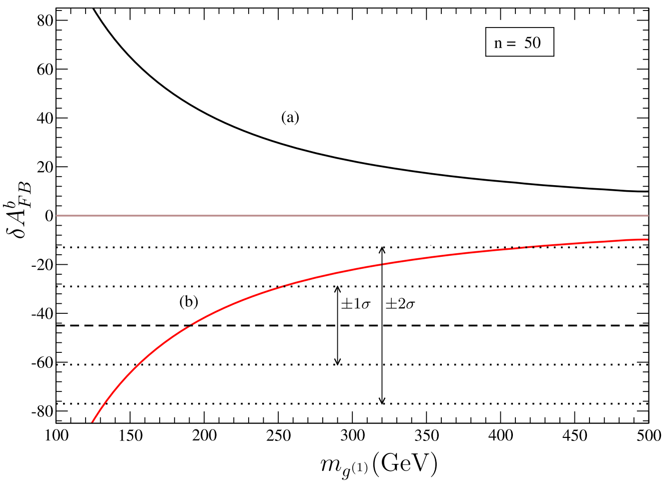

Fig. 3. The KK gluon and the KK b-quark contributions to δA^b_{FB} as a function of the 1st KK gluon mass, $m_{g^{(1)}}$. The upper and lower curves correspond to case (a) $(\xi_L, \xi_R) = (6, 0)$ and case (b) $(\xi_L, \xi_R) = (0, 6)$, respectively. The horizontal dotted lines denote the allowed ranges of δA^b_{FB} in 1- and 2-σ level.

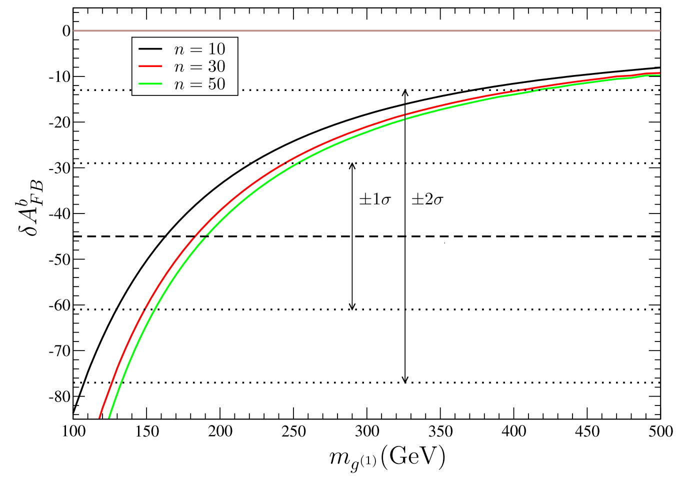

Fig. 4. The KK gluon contributions to δA^b_{FB} for the number of KK mode $n = 10, 30$ and 50 (from upper to lower curves). The couplings are $(\xi_L, \xi_R) = (0, 6)$.

The Naïve Dimensional Analysis (NDA) [17,18] has been adopted to determine the cut-off scale Λ. In NDA, the cut-off scale Λ is interpreted as an upper limit of energy scale in which a theory is perturbative. However, NDA tells us that the cut-off scale Λ in the RS model does not much differ from the Planck scale, and the number of KK modes which is effective below Λ is roughly $\sim 10^{15}$.[1] Instead of NDA, therefore, we assume much lower cut-off scale (a few TeV) so that the finite number of KK modes is considered in the numerical analysis.

In Fig. 3 we show contributions from the KK gluons and the KK b-quarks to δA^b_{FB} as a function of the 1st KK gluon mass. The upper and lower curves correspond to case (a) $(\xi_L, \xi_R) = (6, 0)$ and case (b) $(\xi_L, \xi_R) = (0, 6)$, respectively. Note that only Δg^b_L receives the KK gluon contribution in (a) while Δg^b_R in (b). The results in the figure are obtained for the number of KK modes, $n = 50$. The mass of the heaviest KK mode ($n = 50$) depends on the mass of 1st KK mode. For example, when $m_{g^{(1)}} = 200$ GeV, the mass of KK gluon and b-quarks for $n = 50$ is ~ 13 TeV. The horizontal dotted lines denote the allowed range of δA^b_{FB} in 1- and 2-σ level as indicated in the figure. In the 1-loop correction to Δg^b_α (8), the sign difference comes from the b_α-b_α-Z coupling g^b_α ($\alpha = L, R$). Since $g^b_\alpha \sim I_{3b} - Q_b \sin^2\theta_W$, we find the relative sign of g^b_L and g^b_R is opposite. This explains that the contribution to δA^b_{FB} shows the opposite direction between case (a) and (b), since the coefficients of Δg^b_L and Δg^b_R have same sign as shown in Eq. (3). Thus the KK gluon contribution to A^b_{FB} is favored when the KK gluon couples dominantly to b_R. In the case of $(\xi_L, \xi_R) = (0, 6)$, the allowed range of the 1st KK gluon mass is 150–250 GeV in 1-σ level (130–430 GeV in 2-σ level). The range of KK gluon mass shifts when the couplings (ξ_L, ξ_R) differ. A smaller value of ξ_R lowers the favored range of KK gluon mass. For example, when $\xi_R = 4$, the KK gluon mass which is allowed from A^b_{FB} is 90 GeV–150 GeV in 1-σ.

[1] The cut-off scale Λ in NDA for D-dimensional model is given by $\Lambda \sim ((4\pi)^{D/2}\Gamma(D/2)/g_D^2)^{1/(D-4)}$ [18], where g_D represents the D-dimensional gauge coupling. For the RS model, the cut-off scale is given by $\Lambda \sim l_5/g_5^2$ with $l_5 = 24\pi^3$ and the 5D gauge coupling is given by the 4D coupling as $g_5 = g_4\sqrt{\pi r_c}$. Now we count the number of KK mode In the strong coupling limit of the 4D theory, i.e., $g_4^2 \sim 16\pi^2$, If we then approximate the mass of the n-th KK mode $m_n \simeq n\pi k \exp(-\pi k r_c)$, the number of KK modes below the cut-off scale could be $\Lambda/(\pi k \exp(-\pi k r_c)) \sim 10^{15}$.

Table 1
Experimental data and the SM best fit of R_b and A_b [1]. The pull factor is defined as a deviation between data and the SM prediction normalized by the error.

	Exp.	SM best fit	Pull
R_b	0.21629 ± 0.00066	0.21562	1.0
A_b	0.923 ± 0.020	0.935	-0.6

We have so far examined the KK gluon contribution to A^b_{FB} for the number of KK mode $n = 50$. The dependence of δA^b_{FB} on the number of KK mode is shown in Fig. 4 for $n = 10$, 30 and 50. The couplings are fixed at $(\xi_L, \xi_R) = (0, 6)$. We find that, when $m_{g^{(1)}} = 200$ GeV, the difference of δA^b_{FB} between $n = 10$ and 50 is about few 10% while it is few % between $n = 30$ and 50.

The Zbb vertex correction Δg^b_R affects not only A^b_{FB} but also other electroweak observables for b-quark jets – for example, the partial decay rate R_b and the left-right asymmetry A_b. Here let us briefly mention about correlations between Δg^b_R and three observables A^b_{FB}, R_b, A_b. The experimental data and the SM prediction of R_b and A_b are summarized in Table 1. As A^b_{FB} (3), R_b and A_b can be expressed as [4]:

$$R_b(\text{NP}) = R_b(\text{SM}) - 0.78\Delta g^b_L + 0.14\Delta g^b_R, \tag{9}$$

$$A_b(\text{NP}) = A_b(\text{SM}) - 0.30\Delta g^b_L - 1.63\Delta g^b_R. \tag{10}$$

We consider $\Delta g^b_L = 0$ ($\xi_L = 0$) in the following. When the shift of Δg^b_R reduces the pull factor of A^b_{FB} from -2.8 (SM best) to -1.0, we find that the pull factors of (R_b, A_b) from their SM best fit $(1.0, -0.6)$ to $(-2.4, 0.7)$. Then χ^2 of three observables is reduced from 9.7 (SM best fit) to 7.5. From Fig. 3, the mass of 1st KK gluon which corresponds to the -1.0σ of A^b_{FB} data is about 250 GeV for $\xi_R = 6$. We conclude that, in a certain parameter space, the KK gluon contribution to the Zbb vertex could explain the A^b_{FB} data without affecting the current consistency of the other b-jet data, R_b and A_b.

To summarize, we have studied the KK gluon $g^{(n)}$ in the warped extra dimension model confronts the A^b_{FB} data at the LEP experiments, which differs from the SM prediction about -2.8σ. We consider a scenario in which the coupling of $g^{(1)}$ and the zero-mode b-quark could be a few times larger than the QCD coupling depending on the localization position of the bulk wave-function of b-quark. We examined the 1-loop correction of Zbb vertex via the KK modes exchange and found that the experimental data of A^b_{FB} could be explained when the KK gluon coupling to the right-handed b-quarks is sizable while to the left-handed b-quarks is highly suppressed. For example, the KK gluon with $m_{g^{(1)}} \sim 150$–250 GeV is favored from the data when $\xi_L = 0$ and $\xi_R = 6$. We should mention that, however, since the parameter ξ_R is defined as a ratio of the coupling of KK gluon to b_R-quarks to the QCD coupling g_s, our choice $\xi_R = 6$ is too large to be an expansion parameter of a perturbation theory. Therefore, our 1-loop calculations may be reliable when ξ_R is much smaller ($\xi_R \ll 6$). In such a case, to explain the A^b_{FB} data, the KK gluon mass is required to be sufficiently small, e.g., $m_{g^{(1)}} \ll 100$ GeV.

A few comments are in order. In our scenario the KK gluon dominantly couples to b_R. Then, the production process of $g^{(1)}$ at hadron collider is $b\bar{b} \to g^{(1)}$. The production rate of $g^{(1)}$ is, therefore, suppressed even if $g^{(1)}$ is relatively light, $\sim O(100$ GeV). Note that the gluon fusion process $gg \to g^{(1)}$ is forbidden, because the zero-mode wavefunction in the fifth dimension is just a constant, and the 4D effective coupling of g-g-$g^{(1)}$ is zero due to the orthonormality condition of gluon wavefunctions. Since the decay of $g^{(1)}$ is possible only through $g^{(1)} \to b\bar{b}$, we compared the cross section $\sigma(p\bar{p} \to g^{(1)} + X) \times \mathrm{Br}(g^{(1)} \to b\bar{b})$ with the results given by CDF Collaboration [19]. When $(\xi_L, \xi_R) = (0, 6)$, constraint on $m_{g^{(1)}}$ from Tevatron is $m_{g^{(1)}} > 157$ GeV in 2-σ level, which is consistent with the results obtained from A^b_{FB} in this Letter. The other possibilities of $g^{(1)}$ production at Tevatron are emission of $g^{(1)}$ from b or $\bar{b}$ quark ($p\bar{p} \to b\bar{b}g^{(1)}$), and a pair production of $g^{(1)}$ from gluon fusion, $gg \to g^{(1)}g^{(1)}$. After the decay of $g^{(1)}$, the final states are $b\bar{b}b\bar{b}$ in both cases and the excess of four b-jets event may be a signal at hadron collider experiments. Also the invariant mass distributions of two b-jets m_{jj} may show a peak at $m_{jj} = m_{g^{(1)}}$. Therefore, the analysis of four b-jet data at Tevatron is necessary to study further constraints on $g^{(1)}$. It is also interesting to study these processes at LHC, and the results will be given in our forthcoming paper [20].

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