Direct bound on the minimal Universal Extra Dimension model from the $t\bar{t}$ resonance search at the Tevatron

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Abstract

In the minimal Universal Extra Dimension (mUED) model, the second Kaluza-Klein (KK) gluon $g^{(2)}$ has loop-induced vertices with the standard model quarks, mediated by the first KK modes of the quark and the gluon/Higgs boson. With a top quark pair, this vertex is enhanced by the cooperation of the strong coupling of a gluon and the large Yukawa coupling of a top quark, leading to substantial branching ratio of $\text{BR}(g^{(2)} \rightarrow t\bar{t}) \approx 7\% - 8\%$. As the $g^{(2)}$ coupling with two gluons appears via dimension-6 operator, $q\bar{q} \rightarrow g^{(2)} \rightarrow t\bar{t}$ is the golden mode for the mUED model. Hence the best channel is the $t\bar{t}$ resonance search in $p\bar{p}$ collisions. The recent Tevatron data at $\sqrt{s} = 1.96$ TeV with an integrated luminosity of 8.7 fb$^{-1}$ are shown to give the first direct bound on the $g^{(2)}$ mass above 800 GeV. The implication and future prospect at the LHC are discussed also.

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I. INTRODUCTION

As the heaviest known fundamental particle, the top quark has unique properties within the standard model (SM) [1]. Its large Yukawa coupling to the Higgs boson enhances the loop-induced vertex of $h-g-g$, which leads to sufficiently large gluon fusion production of the SM Higgs boson. The large top quark mass also preserves its fundamental properties since it decays promptly before the hadronization, which enables us to measure the $W$ helicity in the top decay [2] and the top spin correlations [3]. Phenomenologically more attractive is that the top quark can be tagged. If produced near the threshold, the top quark is identified with a $b$-tagged jet and a $W$, or three jets of which the invariant mass is near the top quark mass. If highly boosted, it is tagged by the substructure of collimated jets [4].

The top tagging opens new channels to probe new physics beyond the SM, especially through resonant $t\bar{t}$ production. The $t\bar{t}$ resonances have been searched at the Tevatron [5–8] and at the LHC [9, 10]. No experiment has found any significant evidence, placing upper bounds on the production cross section times the branching ratio into $t\bar{t}$. The most recent results have been reported in the 36th International Conference on High Energy Physics (ICHEP 2012) based on the data with a total luminosity of 2.05 fb$^{-1}$ by the ATLAS experiment [11], 5 fb$^{-1}$ by the CMS [12], and 8.7 fb$^{-1}$ by the Tevatron [13].

Various new physics models have candidates for $t\bar{t}$ resonances such as CP-even and CP-odd heavy Higgs bosons in the MSSM [14], a scalar resonance in two-Higgs-doublet models [15], a vector particle like $Z'$ in extended gauge theories [16], $Z'$ in top-color assisted technicolor model [17], massive color-octet gauge bosons [18], a coloron [19], the first Kaluza-Klein (KK) gluon in the bulk Randal-Sundrum model [20] and in one or two extra dimensional models [21].

Another interesting candidate for $t\bar{t}$ resonance is the second KK gluon in the five-dimensional (5D) Universal Extra Dimension (UED) model [22]. This model has an additional single flat extra dimension of size $R$, compactified on an $S_1/Z_2$ orbifold. All the SM fields propagate freely in the whole five-dimensional spacetime, each of which has an infinite number of KK excited states. This model has drawn a lot of interest as providing solutions for proton decay [23], the number of fermion generations [24], and supersymmetry breaking [25]. Most of all, the conservation of KK parity makes this model more appealing: the compactification scale $R^{-1}$ can be as low as about 300 GeV; the lightest KK particle
(LKP) is a good candidate for the cold dark matter \[26\]. In the minimal version called the mUED model, incalculable boundary kinetic terms are assumed to vanish at the cut-off scale \(\Lambda\), leading to definite and well-defined radiative corrections to KK masses.

There are various indirect constraints on the lower bound on \(R^{-1} \gtrsim 300\) GeV from the \(\rho\) parameter \[27\], the electroweak precision tests \[28\], the muon \((g - 2)\) measurement \[29\], the flavor changing neutral currents \[30\], and the recent measurement of the Higgs boson mass 125 GeV \[31\]. An upper limit on \(R^{-1} \lesssim 1.6\) TeV is from dark matter constraints to avoid overclosing the universe \[26, 32\]. To date, however, no direct limits on the mUED have been placed by collider signatures, despite the intensive studies \[33\]. Difficulties are generic because of nearly degenerate KK mass spectrum. The most accessible new particles are the first KK modes produced in pairs, each of which decays into the missing LKP and a SM particle. Very small mass gap between any first KK mode and the LKP results in quite soft SM particles which are very challenging to observe especially at hadron colliders. If the UED model is extended including non-vanishing fermion bulk mass \(\mu\), called the split UED model \[34\], the second KK gauge boson has tree level vertices with the SM fermions. The search for high-\(p_T\) lepton plus large missing transverse energy by the CMS experiment, which can be explained by \(pp \rightarrow W^{(2)} \rightarrow \ell \nu\), has set quite strong exclusion limit on \(R^{-1} \gtrsim 800\) GeV for \(\mu > 100\) GeV \[35\].

As a smoking gun signal of the mUED at hadron colliders, we focus on the second KK gluon. Although its major decay modes are KK-number conserving into \(q^{(2)}q\) and \(q^{(1)}\bar{q}^{(1)}\), the decay into SM particles is also allowed by its even parity \[36, 38\]. This loop-induced decay, mediated by the first KK modes of quark and gluon/Higgs boson, is indeed substantial since the nearly degenerate KK mass spectrum suppresses the kinematic space of the KK-number conserving decay. In addition, large Yukawa coupling of the top quark enhances branching ratio of \(g^{(2)} \rightarrow t\bar{t}\). This \(g^{(2)}\) is a very good candidate for the \(t\bar{t}\) resonance. As shall be shown, the recent data at the Tevatron have set a significant direct bound on the mUED model. This is our main result.

The organization of the paper is as follows. In the next section, we briefly review the model and discuss the characteristic features of the loop-induced vertex of \(g^{(2)}\) with the SM particles. Section III deals with the production of the second KK gluon, followed by its decay into \(t\bar{t}\). The current data from the search for resonant \(t\bar{t}\) production by the CDF, D0, ATLAS, and CMS experiments are to be analyzed to constrain the model. Future prospects,
especially through dijet resonance at the LHC, shall be discussed also. We conclude in Sec. IV.

II. THE LOOP-INDUCED VERTEX OF $g^{(2)}$ IN THE MUED MODEL

The UED model is based on a flat 5D spacetime with the metric of

$$g_{MN} = \begin{pmatrix} g_{\mu\nu} & 0 \\ 0 & -1 \end{pmatrix},$$

(1)

where $M, N = 0, 1, \cdots, 4$, and $g_{\mu\nu} = \text{diag}(1, -1, -1, -1)$ is the four-dimensional (4D) metric. The word *universal* is from the setup that the whole 5D spacetime is accessible to all the SM fields. Each SM particle has an infinite tower of KK modes. Chiral SM fermions from vector-like 5D fermions are achieved by the compactification of the extra dimension on an $S^1/Z_2$ orbifold: the zero mode fermion with wrong chirality is removed by imposing odd parity under the orbifold projection $y \rightarrow -y$, called the $Z_2$ parity. The radius of $S^1$ is $R$. The detailed expressions for the KK expansion of the SM field are referred to Ref. [37, 38].

The KK mass is of geometrical origin, which is at tree level

$$M_{KK}^{(n)} = \begin{cases} \sqrt{M_n^2 + m_0^2} & \text{(Boson)}; \\ M_n + m_0 & \text{(Fermion)}, \end{cases}$$

(2)

where $M_n = nR^{-1}$, $n$ is called the KK number, and $m_0$ is the corresponding SM particle mass. Since $R^{-1} \gg m_0$, the KK mass spectrum with the given $n$ is generically degenerate. The radiative corrections to the KK masses [40] play a crucial role in the phenomenologies, determining whether a specific decay mode is kinematically allowed or not. In the mUED model where boundary kinetic terms vanish at the cutoff scale $\Lambda$, the radiative corrections to the KK masses are well-defined and finite.

A heavy KK mode decays. At tree level, the decay respects the conservation of KK number such as $g^{(2)} \rightarrow q\bar{q}^{(2)}$ and $g^{(2)} \rightarrow q^{(1)}\bar{q}^{(1)}$. However, the high degeneracy in the KK mass spectrum suppresses these decay modes because of small kinematic space. For example the second KK gluon mass for $R^{-1} = 300$ GeV and $\Lambda R = 20$ is about 698 GeV while the first KK light quark mass is about 344 GeV. Kaluza-Klein number violating decays, which occur at one loop level, can be significant. Note that KK parity $(-1)^n$ is still conserved at loop level.
For the phenomenological signatures of the second KK quark and gluon, it is important to note that some loop-induced KK-parity conserving couplings are forbidden or negligible:

1. The vertex of $q^{(2)}qg$ is negligible. The four dimensional operator $\bar{q}^{(2)}(2)\gamma_{\mu}^{\lambda}qg_{\mu}^{a}$ vanishes because of the gauge invariance. The next higher dimensional operator $\bar{q}^{(2)}(\sigma_{\mu\nu}^{\lambda})qF_{\mu\nu}^{a}$ is suppressed by $1/\Lambda$.

2. The vertex $g^2g$ is suppressed since it appears through dimension-6 operators [41]. In addition, the couplings do not have the logarithmic enhancement factor which is about $4.6 \sim 6.4$ for $\Lambda R = 20, 50$. Dimension-4 operators that would generate the vertex vanish by the unbroken 4D gauge invariance and the absence of the kinetic and mass mixing between $g$ and $g^{(2)}$.

In what follows, therefore, we ignore the above two kinds of vertices.

The loop-induced vertex of $g^{(2)}$ is only with the SM quarks, given by

$$
-\frac{i}{\sqrt{2}}g_{s}\sum_{X=L,R}^{2} \left( \tilde{m}_{h_{2}}^{2} - 2\frac{\tilde{m}_{h_{2}X}^{2}}{M_{2}^{2}} \right) \bar{f}_{X}q_{\mu}^{\lambda}P_{X}f_{X}g_{\mu}^{a(2)}
$$

$$
\equiv -\frac{i}{\sqrt{2}}g_{s}\left( \frac{1}{16\pi^{2}}\ln \frac{\Lambda^{2}}{Q^{2}} \right) \bar{f}_{X}q_{\mu}^{\lambda}P_{X}f_{X}g_{\mu}^{a(2)}
$$

where $P_{R,L} = (1 \pm \gamma^{5})/2$, $Q$ is the regularization scale, and $\tilde{m}$ is the boundary mass correction [40]. For the $g^{(2)}$ production, we adopt $Q = 2R^{-1}$. The effective couplings with $g^{(2)}$ of $t_{L,R}$ and $b_{L,R}$ are

$$
\hat{g}_{tL} = \frac{1}{8} \left[ 44g_{3}^{2} - 27g_{2}^{2} - g_{1}^{2} + 12h_{t}^{2} \right] \approx 6.2,
$$

$$
\hat{g}_{tR} = \frac{11}{2}g_{3}^{2} - 2g_{1}^{2} + 3h_{t}^{2} \approx 8.9,
$$

$$
\hat{g}_{bL} = \frac{1}{8} \left[ 44g_{3}^{2} - 27g_{2}^{2} - g_{1}^{2} \right] \approx 4.7,
$$

$$
\hat{g}_{bR} = \frac{11}{2}g_{3}^{2} - \frac{1}{2}g_{1}^{2} \approx 6.1.
$$

The couplings of $g^{(2)}$ with light up-type (down-type) quarks are the same as $\hat{g}_{tL,R}$ ($\hat{g}_{bL,R}$) except for the top Yukawa coupling. As explicitly shown in Eq. (4), the strong coupling of the gluon and the large Yukawa coupling of the top quark play in the same direction to increase the branching ratio such that $\text{BR}(g^{(2)} \rightarrow t\bar{t}) \approx 7\% - 8\%$, depending on the model parameters.

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1 We thank Ayres Freitas for pointing this out.
FIG. 1. Feynman diagram for $g^{(2)}$ production as a $t\bar{t}$ resonance at a hadron collider. A light bulb denotes the loop-induced vertex of $g^{(2)}$-$q\bar{q}$ with the first KK modes running in the loop.

III. DIRECT BOUNDS FROM THE $t\bar{t}$ RESONANCE SEARCH

The production of the second KK gluon is through $q\bar{q}$ annihilation. Even without large Yukawa couplings, light quarks also have sizable couplings with $g^{(2)}$, as can be seen from $\hat{g}_{bL,bR}$ in Eq. (3). The best channel to probe second KK modes at a hadron collider is the $q\bar{q}$ annihilation production of $g^{(2)}$, followed by the decay $g^{(2)} \to t\bar{t}$: see Fig. 1. Although other second KK gauge bosons like $Z^{(2)}$ and $\gamma^{(2)}$ also produce $t\bar{t}$ resonance signal, their electroweak production is much smaller than the $g^{(2)}$ production by an order of magnitude [36].

The production of $g^{(2)}$ has additional production channels associated with soft jets. At a hadron collider, the number of jets are measured in terms of jet multiplicity. If jets are very soft, however, they are very likely to be missed in the jet multiplicity. The heavy mass of $g^{(2)}$ and the steeply falling parton luminosities result in $g^{(2)}$ production near the threshold. The accompanying SM jets are generically soft. Soft jets tend to spread out. If the transverse momentum of soft jets are too low like below 20 GeV, soft jets cannot excite showers in the hadron calorimeter of the detector. Finally the jets with $|\eta_j| > 2.5$, going out of the barrel and end caps of the hadron calorimeter, are also missed. Therefore, we include the $g^{(2)}$ production with soft jets, such as $q\bar{q} \to gg^{(2)}$, $gq \to gg^{(2)}$, and $gg \to q\bar{q}g^{(2)}$. For the soft jets, we apply $p_T^j < 20$ GeV or $|\eta_j| > 2.5$.

We first present the expected signal and the observed upper bound at the Tevatron. Recently the Tevatron has improved the $t\bar{t}$ resonance search sensitivity by including all hadronic $t\bar{t}$ decays. The previous search was based on the final states of the lepton plus jets [5, 6]. All hadronic decay modes of $t\bar{t}$ have the advantages of larger branching ratio of $W$’s hadronic decay and the improved resolution of the invariant mass of $t\bar{t}$ due to the
FIG. 2. Expected and observed 95% C.L. upper limit on $\sigma(p\bar{p} \rightarrow g^{(2)} \rightarrow t\bar{t})$ as a function of $t\bar{t}$ invariant mass at the Tevatron with $\sqrt{s} = 1.96$ TeV.

In Fig. 2, we show the production cross section of $g^{(2)}$ multiplied by $\text{BR}(g^{(2)} \rightarrow t\bar{t})$, as a function of $g^{(2)}$ mass for $\Lambda R = 20, 30, 50$. For the signal event generator, we have used CalcHEP \[39\]. Larger $\Lambda R$ yields larger signal, since the loop-induced vertices increase logarithmically with $\Lambda R$, as can be seen in Eq. \[3\]. The Tevatron search for $t\bar{t}$ resonance based on the 4.8 fb$^{-1}$ data \[8\] has already set the lower bounds on $M_{g^{(2)}} \gtrsim 535$ GeV for $\Lambda R = 20$, $M_{g^{(2)}} \gtrsim 590$ GeV for $\Lambda R = 30$, and $M_{g^{(2)}} \gtrsim 710$ GeV for $\Lambda R = 50$. The most recent data with total luminosity of 8.7 fb$^{-1}$ \[13\] extend the exclusion region up to $M_{g^{(2)}} = 800$ GeV. Irrespective to the value of $\Lambda R$, the signal in the mUED model exceeds the observed 95% C.L. upper bound. The Tevatron group presented their analysis only up to the $t\bar{t}$ invariant mass of 800 GeV. If naively extrapolating the observation, we have $M_{g^{(2)}} \gtrsim 820$ GeV for $\Lambda R = 20$, $M_{g^{(2)}} \gtrsim 870$ GeV for $\Lambda R = 30$, and $M_{g^{(2)}} \gtrsim 920$ GeV for
FIG. 3. Expected and observed 95% C.L. upper limit on \(\sigma(pp \rightarrow g^{(2)} \rightarrow t\bar{t})\) as a function of \(t\bar{t}\) invariant mass at the LHC with \(\sqrt{s} = 7\) TeV. Observed limits include the recent results by ATLAS and CMS experiment.

\(\Lambda R = 50\). These are very significant direct bounds on \(M_{g^{(2)}}\) and thus the mUED model.

Figure 3 shows the expected signal in the mUED model and the observed 95% C.L. upper bound at the LHC with \(\sqrt{s} = 7\) TeV. We present the 200 pb\(^{-1}\) \cite{9} and 2.05 fb\(^{-1}\) data \cite{11} by the ATLAS experiment, and 4.6 fb\(^{-1}\) \cite{10} and 5.0 fb\(^{-1}\) data \cite{12} by the CMS experiment. Since we have included only the \(q\bar{q}\) annihilation production of \(g^{(2)}\), this is a conservative limit. The gluon fusion production, which is from dimension-6 operators, is expected small and thus neglected. Computing these operators from finite one-loop contributions is beyond the scope of this work. The signal is still quite below the upper bound set by the ATLAS and CMS experiments. Nevertheless we are still optimistic that the excellent performance of the LHC with high luminosity will eventually cover a large portion of the model parameter space, especially high \(M_{g^{(2)}}\) region.
Finally we notice one of unique features of $g^{(2)}$ in the mUED model, and suggest an optimal observable. As can be seen from the effective vertex of $g^{(2)}$-$q$-$\bar{q}$ in Eq. (3), the dependence of the model parameters ($R^{-1}, \Lambda R$) on the vertex is common for all SM quarks. The ratio of the $g^{(2)}$ decay rate into $t\bar{t}$ to that into $q\bar{q}$ is almost fixed by the SM parameters, independent of the model parameters. Minor dependence exists through the mass of $g^{(2)}$, which affects kinematics.

In Fig. 4 we show the ratio $\sum_{q=u,d,c,s,b} \text{BR}(g^{(2)} \rightarrow q\bar{q})/\text{BR}(g^{(2)} \rightarrow t\bar{t})$ as a function of the $g^{(2)}$ mass for $\Lambda R = 20, 50$. Two lines for $\Lambda R = 20, 50$ are almost identical, as expected from the common dependence of model parameters. In addition the value of this ratio is large about 3.5. This is attributed to the number of flavors although light quarks have smaller effective couplings with $g^{(2)}$ than the top quark because of their small Yukawa couplings. If $g^{(2)}$ is observed as a $tt$ resonance, we should see the same resonance in dijet channel with about 3.5 times larger rate. This is one of the most powerful signals of the mUED model. Recently the CMS and ATLAS experiments have reported their search for dijet resonance \[42\]. The current upper bounds are too weak to constrain the mUED model yet. With large data set, the future prospect at the LHC through the correlation between the $t\bar{t}$ and dijet channels is very promising.
IV. CONCLUSIONS

Despite of its various theoretical virtues, the minimal Universal Extra Dimension (mUED) model is one of the most elusive models to directly probe at a high energy collider. The near-degeneracy of the Kaluza-Klein (KK) mass spectrum buries the signals of the first KK modes, each of which decays into a very soft SM particle with missing transverse energy. Huge QCD backgrounds overwhelm the signals.

Turning our attention to the second KK mode, we have novel signatures of high mass resonances decaying into SM particles. This kind of vertex is radiatively generated with the first KK modes running in the loop. Since the KK-number conserving decay at tree level is kinematically reduced, loop-induced decay into the SM particles is enhanced. The near-degeneracy, which obscures the first KK mode signals, clears the second KK mode signals.

One of the golden modes to probe the mUED model is $p\bar{p} \to q\bar{q} \to g^{(2)} \to t\bar{t}$. Strong coupling of a gluon and large Yukawa coupling of a top quark play in the same direction to enhance the branching ratio of $g^{(2)} \to t\bar{t}$. The vertex $g\cdot g\cdot g^{(2)}$ appears from dimension-6 operators, which leads to the main $g^{(2)}$ production through $q\bar{q}$ annihilation. The $p\bar{p}$ collider can be more efficient.

We have shown that the recent Tevatron $t\bar{t}$ search with 8.7 fb$^{-1}$ data has set very significant direct bound on the mUED model. The $g^{(2)}$ mass below 800 GeV is excluded for all model parameters. If $\Lambda R = 50$, the lower bound is raised to about 920 GeV. At the LHC, the absence of the gluon fusion production of $g^{(2)}$ reduces the sensitivity. No direct bounds have been derived yet. However, the suggested correlation between the $t\bar{t}$ resonance and the dijet resonance is expected to enhance the sensitivity to probe the model.

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