PHYSICAL REVIEW D **85,** 055006 (2012)

Implications on the minimal universal extra dimension model from the early LHC data on $\ell + \not{E}_T$ signal

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(Received 12 December 2011; published 5 March 2012)

Recently, the ATLAS and CMS collaborations reported their search for a new heavy gauge boson W' with one lepton plus missing transverse momentum. We find that $W^{(2)}$, the second Kaluza-Klein (KK) state of the W boson in the minimal universal extra dimension (mUED) model, can be a good candidate for this signal, as its branching ratio into $\ell\nu$ is sizable. Moreover, nearly degenerate KK mass spectra in the mUED model yield generically very soft standard model particles accompanying $W^{(2)}$ from the subsequent decays of the second KK quarks and gluons. In a hadron collider, this indirect $W^{(2)}$ production is difficult to distinguish from the $W^{(2)}$ single production. The involved strong interactions make it more important than the single production. The early LHC data on $\ell + \not{E}_T$ signal for 1.1 fb^{-1} integrated luminosity is shown insufficient to limit our model. However, the results show that the present LHC 5.6 fb^{-1} data can cover most of the reasonable parameter space of the mUED model.

DOI: 10.1103/PhysRevD.85.055006 PACS numbers: 14.80.Rt, 14.70.Pw

I. INTRODUCTION

The performance of the LHC in 2010 and 2011 has been captivatingly successful. The initial goal of integrated luminosity in 2011 was 1 fb^{-1}, but already 5.6 fb^{-1} data had been delivered, respectively, to the ATLAS and CMS detectors by the end of 2011 [1]. Even with partial and early data of the LHC, significant constraints have been made on many new physics models such as supersymmetry models [2], Z' models [3], and W' models [4].

One of the most sensitive and clean probes for new physics is the event with a highly energetic electron or muon and the large missing transverse energy $\not{E}_T$. The CMS [5] and ATLAS collaborations [6] have reported the analysis of $\ell + \not{E}_T$ data corresponding to an integrated luminosity of 36 pb^{-1}. Both experiments found no excess beyond the standard model (SM) expectations. Using a reference W' model, in which a heavy W' has the same left-handed fermionic couplings and vanishing interactions with the SM gauge bosons, the lower bound on the W' mass has been made to be about 1.4 TeV. Recently, it is far more refined to be 2.27 TeV with 1 fb^{-1} luminosity data collected in 2011 [7]. Their implications on various new physics models, such as the nonuniversal gauge interaction model [8], minimal walking technicolor model [9], and left-right model [10], have been extensively studied.

We find that the universal extra dimension (UED) model has a good candidate to mimic the W' decaying into $\ell\nu$, the second Kaluza-Klein (KK) mode of the W boson, $W^{(2)}$. In addition, the minimal version of the UED model, called the mUED model [11], has the additional enhancement of the $W^{(2)}$ production at the LHC. The UED model is based on a single flat extra dimension of size R, compactified on an S_1/Z_2 orbifold. This fifth-dimensional space is accessed by all the SM fields. Thus, all the SM fields have an infinite number of KK excited states, of which zero modes are identified to the SM fields. At tree level, the KK number n is conserved by the fifth-dimensional momentum conservation but broken to the KK parity at loop level. Because of the KK parity conservation, the lightest KK particle with odd KK parity is stable and becomes a good candidate of the cold dark matter. In the mUED model, the boundary kinetic terms are assumed to vanish at the cutoff scale Λ. Radiative corrections to the KK masses are finite and calculable: the first KK mode of the $U(1)_Y$ gauge boson $B^{(1)}$ is the lightest KK particle [12]. The thermal relic density of $B^{(1)}$ with mass around 500 GeV can explain all of the dark matter [13]. In order to avoid over-closing the Universe, the $B^{(1)}$ mass is constrained to be below about 600 GeV [14].

Various phenomenological study of the mUED has been done with laboratory data in the literature [15]. The KK mass scale $1/R$ has been constrained indirectly by the ρ parameter [16], electroweak precision tests [17], muon $g-2$ measurement [18], and the flavor-changing neutral currents [19] and directly by D0 group at the Tevatron [20]. The lower limit of $1/R \gtrsim 300$ GeV has been set, based on the combination.

There are two distinctive features that differentiate the mUED model from other new physics models: the nearly degenerate KK mass spectra of new particles and the presence of heavy parity-even ($n = 2$) particles [21,22]. These two features leave very interesting phenomenology associated with the second KK modes, especially $W^{(2)}$.

In this paper, we examine the production of the $W^{(2)}$ boson, followed by its decay into $\ell\nu$ in the mUED model, and study the constraints by the early LHC data. Because

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of the kinematic suppression by nearly degenerate KK mass spectra, the KK-number conserving decays of $W^{(2)} \to f^{(2)}\bar{f}'^{(0)}$ and $W^{(2)} \to f^{(1)}\bar{f}'^{(1)}$ are not dominant. The KK-number violating decays into two SM fermions at one-loop level are considerable. Moreover, we notify that there are sizable indirect productions of the $W^{(2)}$ boson in the decays of heavier colored KK states of $n = 2$, *i.e.*, the second KK quarks $Q^{(2)}$ and gluons $g^{(2)}$. The SM particles, which are by-products of these cascade decays, are generically very soft due to the degenerate masses of the second KK states. Thus, the transverse mass distribution of the leptons from indirectly produced $W^{(2)}$ is similar to that from singly produced $W^{(2)}$. This indirect production is more important than the direct production. This is our main result.

The paper is organized as follows. In Sec. II, we briefly describe the model and discuss the production and decay of the $W^{(2)}$ boson. Section III is devoted to the analysis with the data collected at the LHC and Tevatron. We conclude in Sec. IV.

II. PRODUCTIONS AND DECAYS OF THE $W^{(2)}$ BOSON IN THE MUED MODEL

The UED model is based on an additional extra dimension y with size R where all the SM fields propagate. The fifth dimension y is compactified on an S_1/Z_2 orbifold for generating zero-mode chiral fermions. We assign odd parity under the Z_2 orbifold symmetry to the zero-mode fermion with wrong chirality. This extends the fermion sector into $SU(2)$-doublet quark $Q(x, y)$ and $SU(2)$-singlet quark $q(x, y)|_{q=u,d}$. After compactification, we obtain a four-dimensional effective Lagrangian with the zero modes and the KK excited states. Focused on the phenomenology of the second KK modes of the W boson, we present the relevant KK expansions of

$$\begin{aligned}
V_\mu(x, y) &= \frac{1}{\sqrt{\pi R}}\left[V_\mu^{(0)}(x) + \sqrt{2}\sum_{n=1}^{\infty} V_\mu^{(n)}(x)\cos\frac{ny}{R}\right],\\
V_5(x, y) &= \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty} V_5^{(n)}(x)\sin\frac{ny}{R},\\
Q(x, y) &= \frac{1}{\sqrt{\pi R}}\left[Q_L^{(0)}(x) + \sqrt{2}\sum_{n=1}^{\infty}\left\{Q_L^{(n)}(x)\cos\frac{ny}{R}\right.\right.\\
&\qquad \left.\left. + Q_R^{(n)}(x)\sin\frac{ny}{R}\right\}\right],\\
q(x, y) &= \frac{1}{\sqrt{\pi R}}\left[q_R^{(0)}(x) + \sqrt{2}\sum_{n=1}^{\infty}\left\{q_R^{(n)}(x)\cos\frac{ny}{R}\right.\right.\\
&\qquad \left.\left. + q_L^{(n)}(x)\sin\frac{ny}{R}\right\}\right],
\end{aligned} \tag{1}$$

where $V^M = B^M, W^M, A^M, g^M$, and n is the KK number.

The nth KK mass of a gauge boson V is given by

$$M_{V^{(n)}}^2 = M_n^2 + m_0^2 + \delta m_{V^{(n)}}^2, \tag{2}$$

where $M_n = n/R$, m_0 is the corresponding SM particle mass and $\delta m_{(n)}^2$ is the radiative corrections. There are two types of radiative corrections to the KK mass, which break generically five-dimensional Lorentz invariance. The first is the bulk correction from compactification or nonlocal loop diagrams around the circle of the compactified dimension y. Since this propagation is over finite distances, these bulk corrections are well-defined and finite. The second type of radiative corrections are from the boundary kinetic terms, which are incalculable due to unknown physics at the cutoff scale Λ. The mUED model is based on the assumption that the boundary kinetic terms vanish at the cutoff scale Λ. The radiative correction to the KK mass of the $W^{(n)}$ bosons is given by [12]

$$\delta m_{W^{(n)}}^2 = -\frac{5}{2}\frac{g^2\zeta(3)}{16\pi^4}\frac{1}{R^2} + M_n^2\frac{15}{2}\frac{g^2}{16\pi^2}\ln\frac{\Lambda^2}{\mu^2}, \tag{3}$$

where the renormalization scale μ is normally set to be M_n.

A search for a charged heavy gauge boson W' at the LHC is being conducted in its leptonic decay channels with electron and muon final states, see Fig. 1. The relevant KK-number violating operator is

$$\mathcal{L}_{200} = i\hat{g}_{ff'}\left(\frac{g}{2}\frac{1}{16\pi^2}\ln\frac{\Lambda^2}{\mu^2}\right)\bar{f}\gamma^\mu P_L f' W_\mu^{(2)}, \tag{4}$$

where

$$\hat{g}_{\ell\nu} = \tfrac{9}{8}g'^2 - \tfrac{33}{8}g^2, \qquad \hat{g}_{qq'} = \tfrac{1}{8}g'^2 - \tfrac{33}{8}g^2 + 6g_s^2. \tag{5}$$

The branching ratios of $W^{(2)}$ have been computed in Ref. [23]. Depending on R^{-1}, $\mathrm{Br}(W^{(2)} \to l\nu) \sim 2$–$3\%$.

As depicted in Fig. 2, the single production of the $W^{(2)}$ boson is through the KK-number violating operator $\mathcal{L}_{200}$ with $f = q$. The production cross section is $\sigma(pp \to W^{(2)}) \sim \mathcal{O}(0.1)$ pb for $1/R = 500$ GeV [23].

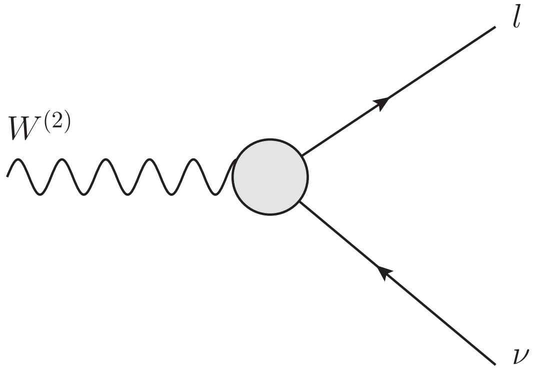


FIG. 1. Feynman diagrams for the decay of the $W^{(2)}$ boson.

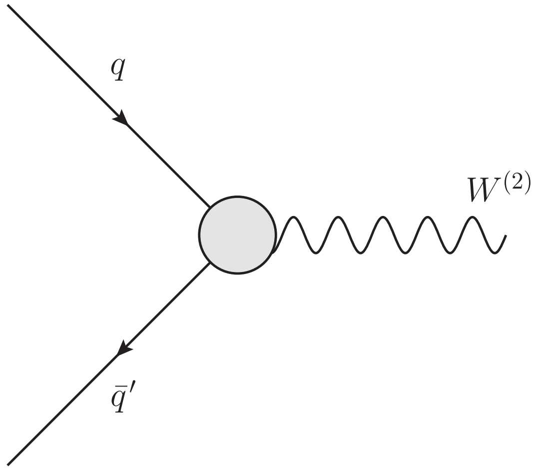


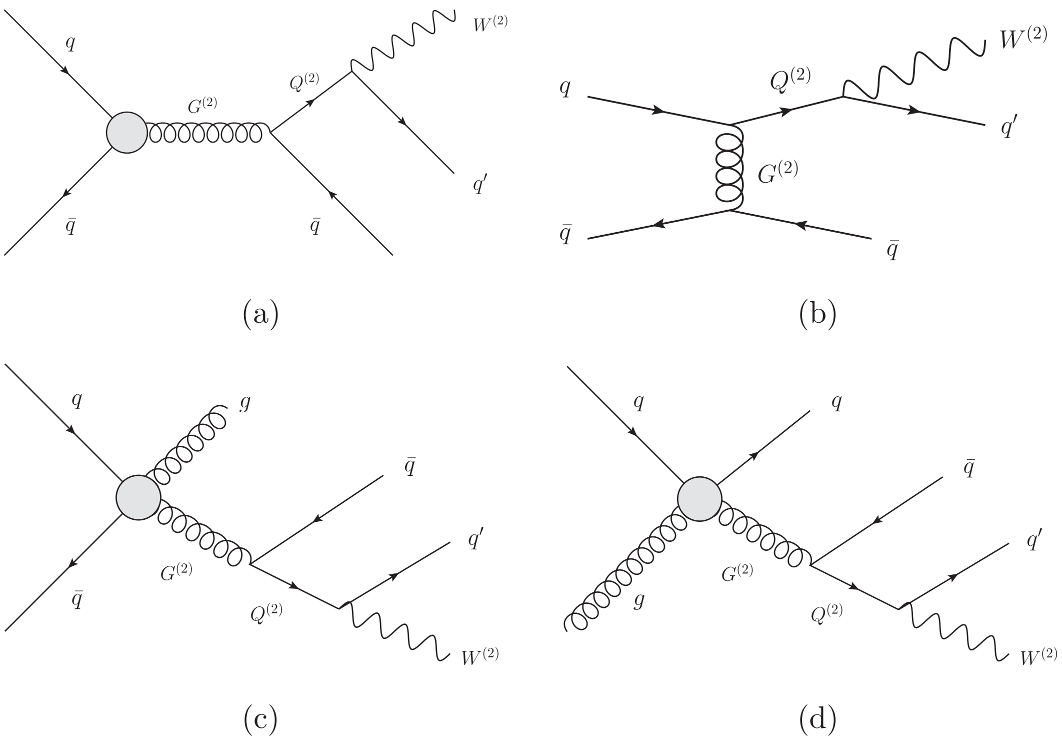
FIG. 2. Feynman diagrams for the single production of the $W^{(2)}$ boson.

At the LHC, the $W^{(2)}$ boson is also produced through the cascade decays of a heavier second KK modes, $Q^{(2)}$ and $g^{(2)}$. In the mUED model, the KK mass spectra are unambiguously fixed, leading to the hierarchy of $M_{g^{(2)}} > M_{Q^{(2)}} > m_{W^{(2)}}$. As shown in Fig. 3, the second KK gluon $g^{(2)}$ can decay into $Q^{(2)}q$ with a branching ratio of about 50%, and $Q^{(2)}$ decays into $W^{(2)}q'$ with a branching ratio of about 50%. Small mass differences of $M_{g^{(2)}} - M_{Q^{(2)}}$ and $M_{Q^{(2)}} - M_{W^{(2)}}$ make the accompanying SM quarks very soft. At a hadron collider, the phenomenological signature of the indirectly produced $W^{(2)}$ boson is likely to be indistinguishable from that of the singly produced $W^{(2)}$. As it shall be shown, this indirect production of $W^{(2)}$ is more important.

Figure 3 illustrates the indirect production of $W^{(2)}$ accompanying soft jets. In Fig. 3(a), $g^{(2)}$ is singly produced, followed by its decay of $g^{(2)} \to Q^{(2)}q$ and $Q^{(2)} \to W^{(2)}q'$. A nearly degenerate mass spectrum yields very soft jets. Note that the single production of $Q^{(2)}$ is not possible since the leading vertex $g - q - Q^{(2)}$ vanishes as required by gauge invariance [12]. Figures 3(b)–3(d) present associated production of the heavy second KK mode with a SM quark or gluon, $pp \to \bar{q}Q^{(2)}, gg^{(2)}, qg^{(2)}$. In order to show the softness of the accompanying SM jet, we present the four-momenta of the heavy second KK mode and the SM particle in the parton c.m. frame:

$$\begin{aligned} k^{\mu}_{(2)} &= (\sqrt{E^2 + M^2_{(2)}}, E), \\ k^{\mu}_{j} &= (E, -E), \quad \text{where } E = \frac{\hat{s} - M^2_{(2)}}{2\sqrt{\hat{s}}}. \end{aligned} \tag{6}$$

The steeply falling parton luminosities lead to the production of new heavy particles near the threshold at the LHC: the energy of the accompanying SM particle is quite low.



(a) (b)

(c) (d)

FIG. 3. Feynman diagrams for the production of the $W^{(2)}$ boson.

We summarize the indirect production processes as

$$\begin{aligned} &pp \to q\bar{q} \to Q^{(2)}\bar{q} \to W^{(2)}q'\bar{q}, \\ &pp \to q\bar{q} \to G^{(2)}g \to Q^{(2)}\bar{q}g \to W^{(2)}q'\bar{q}g, \\ &pp \to gq \to G^{(2)}q \to Q^{(2)}\bar{q}q \to W^{(2)}q'\bar{q}g. \end{aligned} \tag{7}$$

We impose the condition of the soft SM particles as $1\ \text{GeV} < p_T^j < 30\ \text{GeV}$ at the LHC. Note that the lower cut of 1 GeV is assigned to avoid the infrared and collinear divergences. Since the second KK quarks and gluons are produced through strong interactions, their production rates are very high, and the number of the $W^{(2)}$ boson produced from their decays is considerable.

We also include the subleading processes of the $W^{(2)}$ production associated with a quark or a gluon, *i.e.*, $pp \to q\bar{q} \to W^{(2)}g$ and $pp \to gq \to W^{(2)}q$. At the LHC, the cross section of $pp \to W^{(2)}g$ is much larger than that of $pp \to W^{(2)}q$. The same soft p_T^j cut is applied.

III. IMPLICATIONS ON THE $W^{(2)}$ MASS WITH THE EARLY LHC DATA

The CMS and ATLAS collaborations have reported the results of the search for the W' boson through the leptonic decay channel. These events are triggered by a single isolated high-p_T lepton and the missing transverse energy of the opposite direction and are similar in magnitude. The transverse mass of the W' boson for candidate events is calculated as $M_T = \sqrt{2p_T \not{E}_T(1-\cos\phi)}$, where ϕ is the azimuthal opening angle between the lepton and the $\not{E}_T$. From the absence of the signal events in the early LHC data corresponding to an integrated luminosity of $1.1\ \text{fb}^{-1}$, an upper limit at 95% C.L. on the production cross section of W' times the branching ratio of its decay into $\ell\nu$ is set as a function of its mass. The present bounds on the mass of W' is in a reference model with SM couplings: at 95% C.L., the mass bounds are 2.27 TeV (CMS) with $1.03\ \text{fb}^{-1}$ electron data and $1.13\ \text{fb}^{-1}$ muon data and 2.23 TeV (ATLAS) with $1.04\ \text{fb}^{-1}$ data.

By comparing $\sigma(pp \to W^{(2)}j_{\text{soft}}) \times \text{Br}(W^{(2)} \to \ell\nu)$ with the experimental upper limit, we can determine the lower limit of the $W^{(2)}$ mass, which is shown in Fig. 4 with the reported CMS and ATLAS data. In order to show the importance of the indirect production of $W^{(2)}$, we separately present the events only from the single production and those including indirect production with soft jets. It is clear that the indirect production of $W^{(2)}$ is more important than the signal production of $W^{(2)}$. For example, the $M_{W^{(2)}} = 600$ GeV case has the indirect production of $W^{(2)}$ larger than its single production by a factor of 4. Even with enhanced production from the indirect production of $W^{(2)}$, however, the current upper limit is not sufficient to give a significant constraint on the $W^{(2)}$ mass.

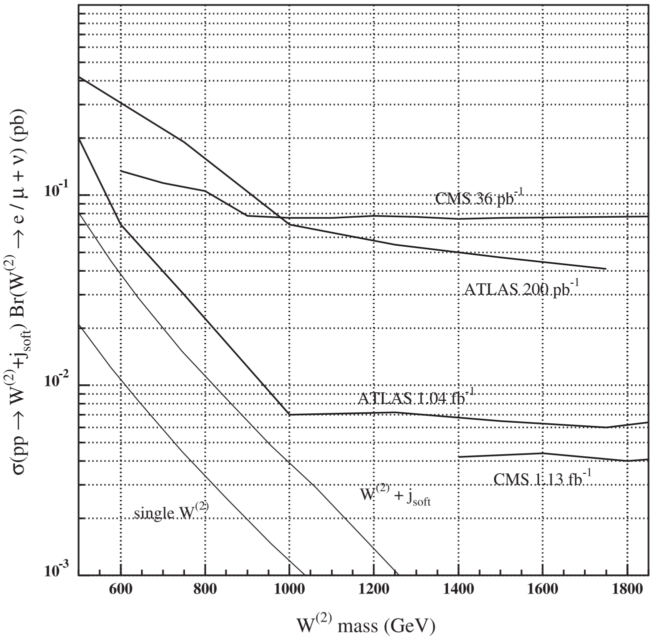


FIG. 4. LHC limits with a counting experiment in the search window $pp \to W' \to e\nu/\mu\nu$ for the $W^{(2)}$ boson in the mUED model.

We still remain optimistic about the future prospect of the LHC on probing the mUED model through the $W^{(2)} \to \ell\nu$ channel. As can be seen in Fig. 4, the enhancement of the integrated luminosity, from $200\ \text{pb}^{-1}$ to $1.1\ \text{fb}^{-1}$ at the ATLAS, improves the sensitivity on the upper limit on the W' mass by a factor of almost 10. With the current $5.6\ \text{fb}^{-1}$ data, the ATLAS and CMS are very likely to probe the mUED model for $M_{W^{(2)}} \lesssim 1$ TeV. By the end of 2012, we expect at least $10\ \text{fb}^{-1}$ data per experiment at the LHC. In the near future, the $W^{(2)} \to \ell\nu$ channel is to cover most parameter space $M_{W^{(2)}} \lesssim 1.2$ TeV, which is allowed by the observed relic density. And the inclusion of indirect $W^{(2)}$ production is crucial for the future prospect.

Aside from $W^{(2)}$ production, Nishiwaki *et al.* [23] have presented the bounds on $1/R$ with the current Higgs search bounds using $2\ \text{fb}^{-1}$ of data collected by the ATLAS [24] and CMS [25] groups at the LHC with the c.m. energy of 7 TeV. The absence of the Higgs boson signals in $H \to \gamma\gamma$ and $H \to WW \to l\nu l\nu$ channels constrain the $1/R$ depending on the Higgs boson mass, which can be translated into the lower bound on the $W^{(2)}$ mass. For instance, $1/R \gtrsim 400$ GeV for $m_h = 125$ GeV indicates $M_{W^{(2)}} \gtrsim 800$ GeV.

For completeness, we present the Tevatron limit with the data of $5.3\ \text{fb}^{-1}$ in Fig. 5. The p_T cut on the accompanying soft jet is $1\ \text{GeV} < p_T < 20\ \text{GeV}$. We find that the

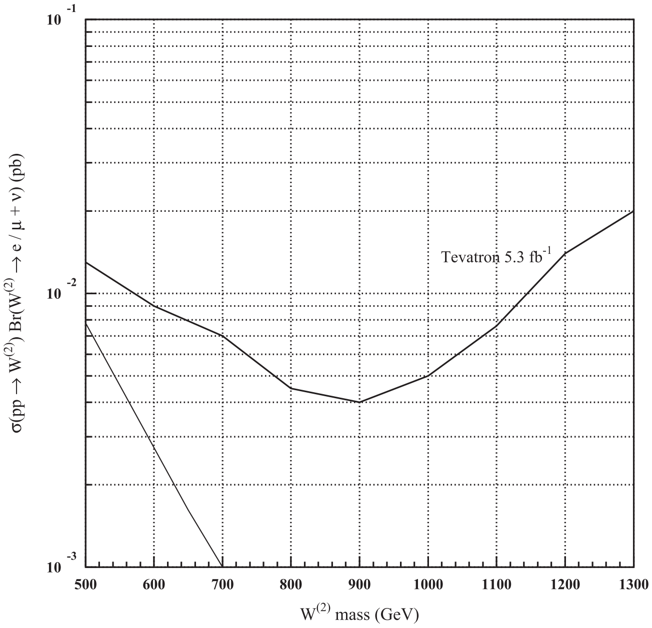


FIG. 5. Limits with the Tevatron data in the search window $pp \to W' \to e\nu/\mu\nu$ for the $W^{(2)}$ boson in the mUED model.

Tevatron data cannot give any constraint on the mUED model either. Even with the full data corresponding to an integrated luminosity of 10 fb^{-1}, it is difficult to probe the mUED model through this channel.

VI. CONCLUDING REMARKS

We have studied the production of the $W^{(2)}$ boson at the LHC to obtain the direct bound on the mUED model. We find that including indirect productions of the $W^{(2)}$ boson increases the production cross section by a few times and much improves the sensitivity of the bound on the $W^{(2)}$ mass. The reported LHC analysis based on the data corresponding to an integrated luminosity 1 fb^{-1} is not sufficient to put the direct bound. However, we expect that the currently accumulated data of 5.6 fb^{-1} will yield significant limit on the mUED model. It would be the first direct bound of the mUED model.

ACKNOWLEDGMENTS

This work is supported by the WCU program through the KOSEF funded by the MEST (R31-2008-000-10057-0). KYL is also supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Korean Ministry of Education, Science, and Technology (2010-0010916), and. S. C. is supported by the Basic Science Research Program through the NRF funded by the Korean Ministry of Education, Science, and Technology (KRF-2008-359-C00011).

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