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Extended Warped Extra-Dimensional Models and Their Physics Opportunities at Colliders

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Introduction: Although the monumental discovery of the Higgs particle puts the final piece of the Standard Model (SM), the stability of its mass against high-scale physics still remains as an open question that the SM cannot answer. The Randall-Sundrum model with two branes [1, 2] is a promising framework to address this issue, and the warped extra-dimensional models [3–6], where even the SM gauge and matter fields propagate in the bulk, additionally provide an attractive solution to the flavor hierarchy problem. These models predict rich phenomenology at the LHC, but no conclusive signals have been observed yet; in fact, flavor/CP violation constraints (without extra symmetries) already suggest that the mass scale of relevant new particles be of $\mathcal{O}(10)$ TeV [7–10] even before the LHC was turned on.

In light of this situation, models of extended warped extra dimensions [11] have been proposed to avoid these potential issues while not only keeping the virtue of solving gauge/flavor hierarchy problem but letting new particles [e.g., Kaluza-Klein (KK) excitations] accessible at the LHC. In this Letter of Interest, we discuss the idea of models of extended warped extra dimension and their phenomenological implications on energy-frontier collider phenomenology.

Extended Warped Model: The basic idea is to postulate an additional brane beyond the "Higgs" brane, where the SM Higgs field is localized, and to assume that the SM gauge fields (together with gravity) can propagate further in the extended bulk down to the additional brane (henceforth called IR brane). By contrast, the SM matter fields are confined in-between the usual UV brane and the Higgs brane, so if the Higgs brane is set to be $\mathcal{O}(10)$ TeV (at the expense of a little hierarchy issue), flavor/CP violation constraints can be avoided [11]. Now the IR brane is allowed to be of $\mathcal{O}(2-3)$ TeV without any severe tension with the existing limits, thus the LHC is capable of probing KK modes of the SM gauge fields and gravity. In addition, the usual leading decay channels of the lightest KK modes into top quark and Higgs boson are suppressed. This effect permits erstwhile subdominant channels to emerge significant. Therefore, collider phenomenology that has received less attention becomes an important aspect in exploring extra-dimensional models at the energy-frontier facilities, throughout the upcoming decade.

Cascade decays of warped vector resonances: A class of well-motivated scenarios is the process where a singly produced gauge KK particle (say, $A_{\rm KK}$) decays to a corresponding SM gauge particle (say, A) and a radion (denoted by φ) which subsequently decays into a pair of the SM gauge particles which are possibly different from the upstream gauge particle A [12]:

$$pp \to A_{\rm KK},\ A_{\rm KK} \to A\,\varphi,\ \varphi \to \gamma\gamma/WW/ZZ/gg\,. \tag{1}$$

In other words, the expected experimental signature involves a two-step cascade decay of a warped vector resonance, resulting in various combinations of three SM gauge bosons in the final state with sizable production cross-sections: for example, γgg, $g\gamma\gamma$, ggg, gV_hV_h, and W_lgg, with V_h and W_l denoting hadronic massive SM gauge bosons and leptonic W, respectively. We have performed a sensitivity study for those channels and found that they would allow for an excess of $\sim 3\sigma$ to more than $\sim 10\sigma$ at the high-luminosity (HL) LHC [12].

Tri-boson signals: An intriguing model variation under the aforementioned extended framework is to allow only electroweak (EW) gauge fields to propagate in the extended bulk while keeping the gluon field confined in-between the UV and Higgs branes [13]. Under this model setup, tri-boson signals, e.g., tri-photon, tri-W, $W\gamma\gamma$ etc are well motivated. Depending on the mass choices, in the case of three massive gauge bosons, they can be significantly boosted so that a novel signature of three "fat" W/Z jets can arise. We have performed a sensitivity study for the above tri-boson signatures, using the jet substructure techniques, and found that all channels would allow for more than $\sim 4-5\sigma$ significance even with an integrated luminosity of 300 fb^{-1} [13].

Boosted di-bosonic radion: An interesting region of parameter space for the above tri-boson signal is the region where the mass gap between the KK EW gauge and the radion is so large that the radion is significantly boosted. As a result, its decay products, two massive SM gauge bosons, are significantly boosted and merged, forming a "big fat" jet with multi-layered substructures. This signature is not well captured by existing searches in which conventional boosted techniques are adopted, so a dedicated search strategy with a targeted jet reconstruction algorithm is needed to improve the signal sensitivity.

We have developed respective jet substructure techniques to be sensitive to fully hadronic boosted di-boson jets and semi-leptonic boosted di-boson jets [14]. The application of the techniques to the fully hadronic boosted radion (i.e., $\varphi \to W_hW_h$) and the semi-leptonic boosted radion (i.e., $\varphi \to W_hW_l$) suggests that the associated searches at the LHC with an integrated luminosity of 300 fb^{-1} allow us to probe regions of parameter space in the $m_{W_{\rm KK}} - m_\varphi$ plane that have been unexplored by the existing searches. The techniques developed are generic enough to be straightforwardly applicable to similar boosted di-boson resonances in other models.

Four-jet signals of KK graviton: As gravity propagates in the extended bulk, its lightest KK mode can be accessible at the LHC, too. Like the KK gauge modes, its dominant decay channels into top quark and Higgs pairs in the standard framework become subdominant in the extended framework, whereas the decays to a radion pair and to a KK gauge particle and its corresponding SM gauge particle begin to "stand out". An interesting signature is the four-jet final state stemming from the processes, $G_{\rm KK} \to \varphi\varphi$, $\varphi \to gg$ (called "radion channel") and $G_{\rm KK} \to g g_{\rm KK}$, $g_{\rm KK} \to g\varphi$, $\varphi \to gg$ (called "KK gluon channel"), with $G_{\rm KK}$ and $g_{\rm KK}$ denoting the lightest KK graviton mode and the lightest KK gluon mode, respectively. These channels become more significant especially in the model variation where the SM gluon field is propagating in the extended bulk while the propagation of EW fields is restricted to the Higgs brane [15].

Depending on the underlying mass spectrum, one channel is leading to the other, and different search strategies are motivated due to the difference of the associated event topologies. We have performed a sensitivity study with a few well-motivated benchmark sets of parameter values giving well-separated four jets, and found that the HL-LHC (3,000 fb^{-1}) would be sensitive to the KK graviton signals by $\sim 2.5 - 5\sigma$ significance [15]. We further found that the radion channel can be the first discovery channel of KK graviton due to the effectiveness of the cuts designed for the event topology of the radion channel signal, while the KK gluon channel can serve as a cross-check to understand the structure of the underlying model.

Future plans: We are now considering a couple of follow-up studies. While a series of our works have showed that the (HL-)LHC would be able to explore parameter space of the extended warped models, the high-energy LHC ($\sqrt{s} = 27$ TeV) and the 100 TeV future collider will be excellent venues to explore deep in the parameter space (toward larger masses) or to carry out the precision studies for the models (upon discovery). So, we will investigate prospects of KK gauge particles and KK graviton at future (hadron) colliders, in terms of their experimental reaches and post-discovery analyses.

Second, the above-described KK graviton signals with light radions ($\lesssim 500$ GeV), which are relatively less constrained by existing bounds, are interesting to investigate. Owing to substantial mass gaps between such radion and KK states, the gluonic radion (i.e., $\varphi \to gg$) is significantly boosted, hence manifests itself as a merged radion jet. So, the KK graviton signal in the radion channel will appear as a dijet event, while that in the KK gluon channel will appear as a trijet event. Dedicated jet substructure techniques can reveal these signals, allowing us to explore different regions of parameter space.

Summary: Models of extended warped extra dimensions are an attractive framework as they not only retain the virtue of addressing the gauge/flavor hierarchy problems like the standard ones but contain new particles of a few TeV, allowing the models to be tested even in the upcoming LHC runs. Furthermore, collider techniques for searching for such new particles can inspire the search effort for other new physics models giving similar experimental signatures. Given rich phenomenology and potential impacts on collider physics, the research on the extended warped model will be an important aspect of not only the energy-frontier program but the theory-frontier program in the next decade.

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