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“Light” Higgs and warped models: Case for a GIGANTIC INTERNATIONAL HADRON COLLIDER

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The LHC seems to have made a monumental discovery, Higgs-like particle of mass around 125 GeV with properties akin to a Standard Model Higgs. In the context of a warped theory of flavor, which is theoretically very attractive, this suggests Kaluza-Klein particle masses are likely to be above 10 TeV except possibly for a radion. The interpretation of the SM-like Higgs from the perspective of other interesting beyond the SM scenarios is also likely that the relevant scale is higher than accessible to the LHC. In light of these developments, deeper understanding of flavor and other fundamental issues requires a gigantic international hadron collider [GIHC] perhaps with cm energy of $\approx$ 100 TeV [1]. It is suggested that a *global effort* should be made for constructing this machine for resolving many questions that SM cannot answer.

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1. Introduction

Discovery of a Higgs-like object of mass around 125 GeV by the LHC experiments [2] in 2012 is quite a monumental one: its bound to prove as a watershed in our understanding of the workings of Elementary Particle Physics. So far the properties of this particle seem rather similar to those of a Standard Model [SM] Higgs [3]. Interpreted in the context of one model of new physics that has compelling appeal, especially as a Theory of Flavor, namely warped models of flavor and hierarchy, this seems to imply that Kaluza-Klein resonances that are predicted in these models are over 10 TeV [4, 5, 6]. This means except possibly for a light (few hundred GeV) scalar, called radion [7], in these models no other signal for new physics is likely to appear at the LHC [8].

Actually, well known constraints from kaon mixing [9, 10] had already been suggesting rather strongly that KK-masses are quite difficult to be less than 10 TeV. So, although electroweak precision constraints can be overcome by enforcing custodial symmetry and thereby the KK-scale lowered to around 3 TeV, the resulting set up needs some degree of tuning to satisfy kaon-mixing constraints unless the scale is above approximately 10 TeV.

Note that even with a KK-scale of 10 TeV, warped models of flavor score a big success in that the traditional flavor constraints of around 10^4 TeV get lowered to around 10 TeV. Moreover, these models then no longer need imposition of custodial symmetry; after all this idea, clever as it is, has to introduce additional degrees of freedom and renders the models more intricate. Of course, this simplicity at 10 TeV (over 3 TeV) comes at an expense as the emergence of the electroweak scale out of 10 TeV is regarded as needing tuning of $O(10^{-3})$ range, so this tuning is worse compared to the case when KK masses are around 3 TeV by about one order of magnitude. It is not clear, at least to this author, how serious an issue this is. This extent of tuning is clearly a far cry from the original problem of tuning of $O(10^{-34})$ if the relevant scale is $O(10^{19})$ GeV and Randall-Sundrum (RS) ideas were not invoked.

It is important to remind ourselves that even if the interpretation of the Higgs-like particle as being largely SM-like gets confirmed there are still numerous unanswered questions. The search for answers will undoubtedly require a new high energy collider. In the late 80's and 90's considerable effort was mounted towards a pp machine at 40 TeV (the SSC). The machine was abadoned only because of budgetary and political concerns not for any technical reasons. It stands to reason then that over 25 years later, a machine at (say) 100 TeV energy should be feasible in so far as technical know- how is concerned. Such a machine will require a genuine international effort and should be based on recognizing the geo- political realities of the day.

2. Warped models of hierarchy and flavor

Assuming the recently discovered particle at 125 GeV is confirmed to be (mostly) a SM-like Higgs particle, it will still require a mechanism to stabilize its mass against large radiative corrections. One very attractive way to do this was suggested by Randall and Sundrum [11] invovlving the notion of a warped extra dimension. As is well knowm, with this idea this particular weak-planck hierarchy is addressed by putting the Higgs on the infa-red (IR) or TeV brane.

Interesting as it already is, the RS idea of warped space is even more suitable as a geometric theory of flavor. This is realized by putting the SM gauge fields as well as fermions in the 5D RS bulk resulting in a remarkable framework that can address simultaneously both hierarchy and flavor puzzles [12, 13, 14]

Here are some of the highlights of this picture. The huge disparity in the oberved fermion masses is naturally accomodated as in the underlying 5D theory the corresponding localization parameters are all of O(1) [15]. The fermion masses are of course an input and the RS-picture can not claim to predict them but what is remarkable is that after the masses are put in by hand, it leads to a natural understanding of the severe suppresion in FCNC amongst the light quarks. Indeed despite tree-level FC interactions involving KK-gluons (resulting from rotation from interaction to mass basis), these FC currents are suppressed roughly at the same level as the FC-loops in the SM so that an RS-GIM mechanism arises [17, 18]. As in the SM all the FCNCs are driven primarily by the heaviness of the top quark [19]. Once the KK masses are taken to be $\gtrsim$ 10 TEV even the severe constraints imposed by the smallness of $\Delta m_K, \varepsilon_K$, from neutral kaons, can be accomodated with little or no tuning [20, 21].

While the RS idea is extremely attractive as it can provide simultaneous resolution to Planck-EW hierrachy and also an understanding of the flavor puzzle, it is based on a strong assumption that warping extends over many orders of magnitude from the EW scale to the Planck. In the absence of any compelling phenomenological constraint and/or experimental evidence and since the RS-set up provides an interesting theory of flavor by itself, it may be worth while to consider if RS is a viable theory of flavor alone. In that more modest scenario[22], called "Little Randall Sundrum (LRS)", a volume-truncated RS background is used only to address the hierachy between the EW (IR) scale of O(0.1 TeV) to the flavor (UV) scale around 10^3 or 10^4 TeV[22, 23]. Even in this modest set up constraints from $K-\bar{K}$ require $m_{KK} \gtrsim$ 10 TeV.

Thus the bottom line is that whether we have RS or LRS, flavor constraints require $m_{KK} \gtrsim$ 10 TeV. But once KK particles are that heavy, the "bonus" is that EW constraints may be automatically satisfied and there may not be a compelling need for imposing custodial symmetry [24]. This means that the theoretical setup is more economical. Of course this comes with a price-tag that tuning of O(10^{-3}) is necessary but it is unclear if this should be considered that big a drawback. Indeed, it should be recognized that this order of tuning is drastically different from what is needed to address the original EW-Planck hierarchy, requiring tuning to the level of $\approx 10^{-34}$!. It is simply not obvious that nature would choose to remove this remaining O(10^{-3}) tuning at the cost of making the theory more complicated by extending SU(2) to SU(2)XSU(2)XU(1) and by the introduction of new degrees of freedom to enforce, in the example of RS models, custodial symmetry [24].

In the past several years considerable amount of effort was put into studying signals at the LHC for the lightest KK particles, such as the gluon [25, 26],the graviton [27, 28, 29] and gauge bosons that RS/LRS models predict [30]. These studies have shown that KK-particles with masses greater than about three TeV will be difficult to see at the LHC . Thus if KK masses are constrained to be above $\approx$ 10 TeV as suggested above, then the varification of RS models will necessitate colliders with energy much greater than at the CERN-LHC.

Fig. 1) is reproduced from [31]. This fig gives an indication of the expected signal and its significance for KK gluon production and its detection via its decays to $t\bar{t}$. Study includes some appropriate cuts to enhance signals. The maximum collider energy studied there is 60 TeV. This fig suggests that the next generation of supercollider with energy around 100 TeV could be quite effective in directly searching for warped resonances with masses around 10-20 TeV.

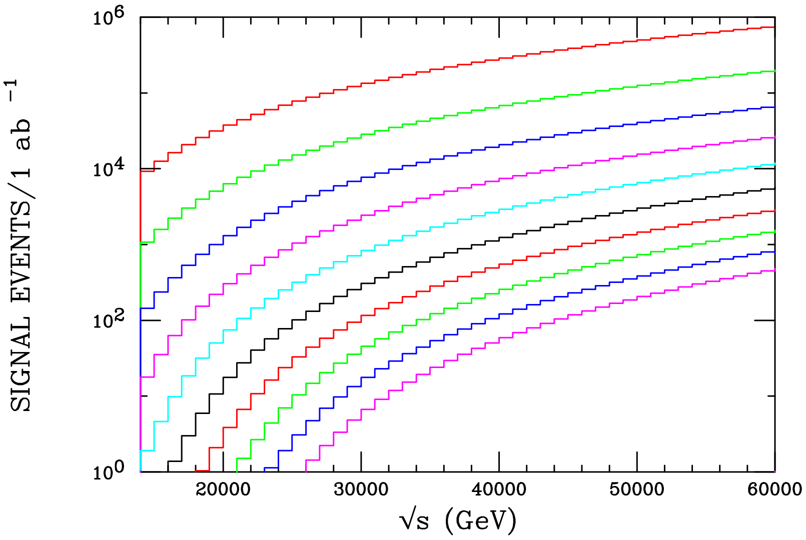

Figure 1: Expected rate for KK gluon → top pairs is shown versus collider energy for KK glu masses from 3 to 12 TeV. Branching fractions and efficiencies are neglected. For cuts used and other details see the original ref. [31].

If this simpler picture (*i.e.* without including additional particles to impose custodial symmetry) of RS-models with $m_{KK} \gtrsim 10$ TeV is correct then the only signal of a warped underlying theory that we may see at the LHC is from a radion as in these models it is expected to have a mass of several hundred GeV to ≈ a TeV.

Feasibility of such signals is examined in [8] and Fig. 2 and Fig. 3 are from that study. From these figs the reach of the LHC at 14 TeV for the detection of the radion decays via WW and $\gamma\gamma$ are shown. It seems that if the radion is relatively light and $\lesssim$ about 250 GeV, the LHC may have a chance of seeing it, though appreciable fraction of the allowed parameter space, for larger masses, is unlikley to be accessible to the LHC. [Since these figs are using 100/fb, with higher luminosity the reach may go somewhat beyond 250 GeV but for $kL \gtrsim 10$, much heavier masses will be quite difficult].

Given the many important questions in the SM that still remain unanswered, the currently observed paucity of new physics signals, most likely, just means that the relevant scales are higher than the reach of the LHC runs at 7 or 8 TeV. This may of course change in the next few years as LHC starts to run at higher energy ≈ 14 TeV. At least for the case of the very attractive RS models, 14 TeV is unlikely to be enough as suggested in the preceding discussion.

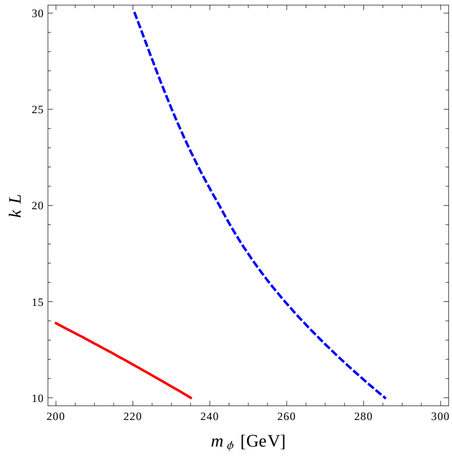

Figure 2: The 3σ (dashed) and 5σ (solid) contours, in the (m_ϕ, kL) plane, for $\phi \to W^+W^- \to l^+l^-\nu\bar{\nu}$ at the LHC with $100/fb$ at 14 TeV, with $\Lambda_\phi = 10$ TeV; here m_ϕ is the radion mass, $10 \lesssim kL \lesssim 30$ covers the range from LRS to RS and Λ_ϕ is the characteristic KK-scale. Fig taken from [8] where further details may be found.

2.1 Lessons from our past: I. ν Oscillations

At first sight it seems the properties of the Higgs-like scalar (125 GeV) are quite consistent with the SM expectations. In the context of RS models it means that the KK-scale is very likely heavier than 3 TeV so it will be difficult to get experimental verification at the LHC. To some degree, the RS models had been amended to try to accomodate such a light scale with the desire (at least in part) that the lower mass scale will be relevant at LHC; of course the lower mass scale also ameliorates the amounting of tuning that is needed. However, from flavor constraints and/or simplicity of the RS models, scale less than 10 TeV is quite difficult. Verification of these interesting ideas then will take additional work and a more powerful machine, perhaps O(100 TeV) cm energy.

In this context it may be worthwhile to remember that we encountered something analogous in

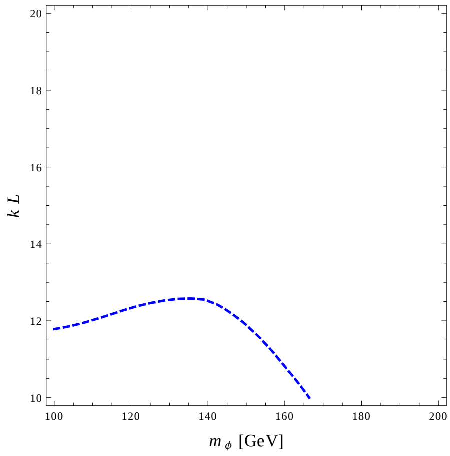

Figure 3: The 3σ contour, in the (m_ϕ, kL) plane, for $\phi \to \gamma\gamma$ at the LHC with $100/fb$ at 14 TeV, with $\Lambda_\phi = 10$ TeV; from [8].

the search for neutrino mass and oscillation. In the 70's and early 80's experimental constraints over and over showed that $\Delta m_\nu^2 \lesssim 1 eV^2$. But while there were often debates and doubts, the community did not abandon these searches as it was felt that 0 mass neutrino is difficult to understand as we knew of no symmetry forcing $m_\nu = 0$. Indeed it took another decade or more of hard work and reduction of the bounds to $\Delta m_\nu^2 \lesssim 10^{-4} eV^2$ before neutrino oscillations were finally discovered!.

While understanding of Electroweak-Planck hierarchy may well be a technical issue, occurrence of the replicas of flavors is a well established fact and understanding these is a pressing issue. RS gives a nice geomoetric interpretation. To hunt for its experimental evidence we may well need to go to higher energy collider with energy appreciably higher than the LHC (14 TeV).

2.2 Lessons from our past: II. ε_K

The point of view being espoused here is that the underlying BSM framework should give some understanding of flavors ("Who ordered the muon?"); flavors are an established experimental fact and therefore represent a much more tangible and pressing issue than “naturalness" or hierarchy. Efforts at hadron collider always need to be complemented by intensity/sensitivity frontier. The current tests of the SM-CKM paradigm are only around 10-15%. It is not very sensible not to pursue more stringent and accurate tests. Recall the indirect CP violation parameter for $K_L \to \pi\pi$, $\varepsilon_K \approx 10^{-3}$!. History of Particle Physics would have been completely different if experiments seeking kaon CP had been stopped even at O(1%).

Concurrent with efforts at a very high energy collider, it is imperative that more precise tests of the SM in the realm of “null" tests [32] for CP violation, for neutron edm , for lepton flavor violation etc. be pursued with as high a priority as possible.

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