P2IO Report

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1 Project goals

The recent discovery of the Higgs boson at the Large Hadron Collider (LHC) at CERN in Geneva completes the last piece of the Standard Model (SM) of particle physics. However, the mechanism responsible for breaking the electroweak symmetry is not fully understood yet; there remain some questions unsolved like, for example, why the electroweak scale is so much smaller than the Planck scale or is there an explanation for the big hierarchy in the fermion masses, etc. During the last 40 years, many different models have been proposed to shed light on these questions: Supersymmetry, Little Higgs, Extra Dimensions (ED), etc. Looking for the possible signals of these models at the LHC is one of the most important tasks for the particle physicists. Both, the theoretical and the phenomenological implications must be tested carefully in order to discern the next step in particle physics.

The aim of our main project has been to study the implications of models based on ED on Higgs physics. The main production channel of the Higgs at the LHC, the so called glu-glu fusion, and its decays into vector bosons are very sensitive to any physics beyond the SM. At present it is far from clear how these ED models will affect $pp \to h \to VV$ process because of the presence of heavy vector-like Kaluza-Klein (KK) fermions that can mix with the SM chiral fermions. In fact, it is not yet clear how to implement the Yukawa terms in the lagrangian in order to solve the equations of motion (EOM) within these models. Different approaches with different outcomes have been proposed and our efforts have been in order to identify the origin of these discrepancies. We have considered a new approach based on the 4D KK decomposition and treated the Yukawa terms as a perturbation of the free lagrangian. The goal of our project was to be able to find a full and compact expression for this perturbation taking into account the effect of the whole KK tower in the EOM. There are many possible consequences of this result like studying not only the Higgs production and decay channels but also the top pair production and other processes at the LHC from a phenomenological point of view in order to do precise fits to the data. We expect that our results will be very helpful for the next run of the LHC in two years.

Current status of this project: We are already working on the manuscript that will be sent to a journal within a few weeks.

2 Description of work achieved

As mention before the aim of our main project has been to study the implications of models based on ED on Higgs physics. However, we soon noticed that it is not yet clear how to implement the Yukawa terms in the lagrangian in order to solve the EOM within these models. Checking the bibliography we realized that there are different approaches with different outcomes about this issue, so we focused our efforts in order to identify the origin of these discrepancies.

We considered first a new approach based on the 4D KK decomposition treating the Yukawa terms as a perturbation of the free lagrangian. The goal of this approach was to be able to find a full and compact expression for this perturbation taking into account the effect of the whole KK tower in the EOM. We have computed the fermion masses using this different approach that we shall refer to as the '4D' approach. To obtain the fermion profiles we considered only the free EOM, i.e., not including the Yukawa mass terms in the EOM. As a result, unlike the 5D case we will dicuss next, one needs to diagonalize the mass-mixing matrix among the fermion modes. Now, since there are infinite number of KK modes, the matrix is actually infinite dimensional and so diagonalizing it exactly can be a very challenging task. However, in some cases it is possible and that allowed us to compare the fermion masses obtained by diagonalizing the completely mass matrix with the ones obtained in the 5D case.

Within the '5D' approach one keeps the Yukawa mass terms that appear after electroweak symmetry breaking in the equations for the fermion profiles along the extra-dimension. The advantage of this approach is that here the mixing among *all* the KK modes of any fermion is automatically taken care of and so one does not have to diagonalize the mass matrix to obtain the masses after mixing. Hence, results obtained with this approach are 'exact' in the sense that they incorporate the effect of the full 5D theory. However, for a strictly brane localized Higgs, an ambiguity arises in the 5D approach. In this case, the Yukawa mass terms contain a delta function located on the brane (boundary), and as a result, applying the boundary conditions, necessary to solve EOM as well as recovering chiral 4D fields, becomes ambiguous since the presence of the delta function implies ‘jumps’ in the profiles exactly on the brane. To avoid this ‘jump problem’ one then has to follow some scheme, like shifting the delta Higgs away from the brane by a small amount (ϵ) before solving the EOM and then taking the limit to zero or giving the Higgs profile a narrow width (like a normalized box of small width) to solve the EOM and then taking the zero width limit.

We have found that the 4D calculation gives a different fermion mass spectrum under the two orderings of the calculation: depending whether we first take the limit $\epsilon \to 0$ (Higgs localization) and then $N \to \infty$ (here N denotes the index for the KK-level summation), or choose the inverse order, $N \to \infty$ and $\epsilon \to 0$ in a second step. We explain this non-commutativity as follows; these two 4D calculations are in fact appropriate for two different physical 5D models. Indeed, first taking $N \to \infty$ leads to a real 5D theory (not a truncated one) with complete (i.e. infinite) 5D field KK decompositions. Now imposing the $\epsilon \to 0$ limit, in this *real* 5D framework, is effectively equivalent to localize the Higgs scalar on the brane so that we end up with the wanted 5D scenario with a brane-localized Higgs field.

In contrast, the sense of taking $\epsilon \to 0$ before having completed the 5D theory (i.e. having taken $N \to \infty$) is not clear. In other words, it is not obvious that this sense is the usual field localization as it is realized within an hybrid 5D scenario: one is not yet in a pure 5D model. It is also difficult to find another possible physical meaning for $\epsilon \to 0$ in such a context. Hence, at the end of the calculation (i.e. after the second step $N \to \infty$) one obtains a 5D model which is difficult to interpret physically. Anyway, this final 5D model has no simple reason to be equivalent to the previous well defined 5D model with a brane-localized Higgs; the fact that the obtained mass spectrums are different demonstrates finally that these two 5D frameworks are physically different.

At present we are still analyzing our results and wroking in the redaction of the manuscript that will be sent to a journal within a few weeks.

3 Publications

None yet.

4 Relevance of the project within P2IO

In this research we have focused on a class of ED models that are motivated by the famous Randall-Sundrum (RS) proposition. In these models, unlike the original RS model, the SM fields can also propagate in the extra-dimensions and so, in the 4D effective theory picture obtained by KK decomposition, have associated towers of KK modes. These models have attracted a lot of interest in the present literature as putting fermions in the bulk can help to explain the fermion hierarchy in the SM but, more importantly from the LHC perspective, these models contain vector-like quarks that can potentially be observed. In this sense our results will allow to realize phenomenological calculations in these models that are related to the activity of the P2IO lab LAL/Orsay (involved in analyses on extra vector-like quarks which could be constituted by KK states) like studying not only the Higgs production and decay channels but also the top pair production and other processes at the LHC in order to do precise fits to the data. We expect that our results will be very helpful for the next run of the LHC in two years.

5 For end of contract post-docs: position after P2IO

None.