

# Mass spectrum and vacuum structure of higher-dimensional non-abelian gauge theories with magnetic flux background

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(背景磁束を持つ高次元非可換ゲージ理論の質量スペクトルと真空構造)

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### Thesis Summary

The Standard Model (SM) has been remarkably successful in describing elementary particles and their interactions. However, there are still many limitations and problems to be explored. For instance, dark matter and neutrinos masses still remain a mystery, gravity is not unified with the other fundamental forces, and there is an extreme unnatural fine-tuning necessary to obtain the Higgs mass, also known as the hierarchy problem. One interesting approach to address these issues is to consider a higher-dimensional spacetime. The idea is that these higher dimensions can affect the low-energy four-dimensional effective theory. For example, the extra components of gauge fields generate scalars in the low-energy theory, which can be identified as the Higgs. This model, known as gauge-Higgs unification (GHU), can give a new perspective on understanding its origin and solving the hierarchy problem. Thus, by considering appropriate settings, it is possible to explain phenomena beyond the limitations of our four dimensions.

One attractive feature of these theories is that the extra-dimensional gauge field components can assume non-trivial background configurations, unlike the four-dimensional (4D) gauge fields of the SM. One simple possibility is to consider a constant background configuration, which is the vacuum expectation value (VEV) of the extra-dimensional gauge fields. In most GHU models, these VEVs are related to physical degrees of freedom of Wilson line (WL) phases, which are continuous moduli that parametrize physical vacua along flat directions of tree-level potentials for gauge fields. Thus, they are interesting candidates for the Higgs, having flat tree-level potentials and obtaining finite effective potentials through quantum corrections and a finite mass even at higher-loop level. In addition, in the context of grand unified theories (GUT), WL phases can contribute to breaking large gauge symmetries to the SM symmetry.

Another interesting option is to add a constant magnetic flux in the extra dimensions, leading to many desirable phenomenological implications. For instance, chiral fermions with a generation structure can be created in the effective theory, which is a fundamental characteristic of the SM. The flavor structure of quarks and leptons, such as masses and mixing angles, has been widely examined in this setup. In addition, the magnetic flux can break supersymmetry and play a crucial role in moduli stabilization within string theories. Recent research has been focusing on the mass spectrum of low-energy excitations near flux backgrounds, including quantum corrections. In models with six dimensions, the scalar excitations originating from the extra-dimensional gauge fields were shown to be massless, even at higher-loop level. They are identified as Nambu-Goldstone (NG) bosons, associated with the translational symmetry breaking caused by the flux background. Phenomenologically realistic models can be explored through symmetry breaking mechanisms, generating a finite mass for these NG bosons.

While extensive studies have been conducted on flux backgrounds with abelian gauge groups, non-

abelian gauge groups have received less attention. A more comprehensive understanding of these setups is crucial for constructing viable models considering flux backgrounds. Starting with six dimensions, we have investigated the mass spectra of an  $SU(n)$  pure Yang-Mills gauge theory with magnetic flux in the extra-dimensional torus. Including WL phases in the background reveals that their values along the flux direction have no impact on the masses of gauge fields. Compared to the abelian case, simply-connected gauge groups present a complexity in the mass spectrum due to the emergence of potentially tachyonic states. While attempts have been made to stabilize such systems, and some SUSY models explored tachyonic condensation, research on the vacuum structure in non-abelian cases remains limited.

As a next step, and the main focus of this work, we expand the spacetime to eight dimensions and analyze the vacuum structure of a non-abelian gauge theory. We aim to address the emergence of potentially tachyonic states, as previously mentioned. The extra dimensions are compactified on a 4D torus with magnetic flux in only two directions. We examine the dynamics of WL phases along the remaining two non-flux directions, where their values now contribute non-trivially to the masses of low-energy modes. We identify a parameter space within the WL phases where tachyonic states vanish for a given flux background. However, to determine the values of the WL phases in a vacuum, it is essential to calculate the quantum corrections since these phases have no potential at tree level. As a concrete example, we consider an  $SU(3)$  gauge theory and also introduce matter fields. In this setup, we elucidate the mass spectrum of 4D modes and the one-loop effective potential for the WL phases. Our analysis reveals the presence of local minima in the potential when matter fields are present. Thus, no tachyonic states appear in the low-energy mass spectrum given appropriate values of WL phases. In contrast, we found no local minima in the pure Yang-Mills case. Therefore, our setup offers a promising avenue for constructing realistic new theories beyond the SM, such as GUT and GHU frameworks. By combining the magnetic flux and WL phases in the background configuration, it is possible to create a wide range of symmetry breaking patterns. As a result, further research in this area can lead to diverse low-energy effective theories.