

Higgs mass sensitivity and localization due to Fayet-Iliopoulos terms on 5D orbifolds

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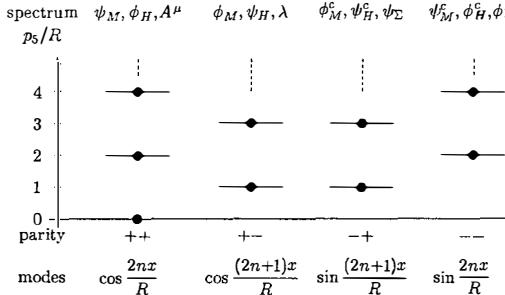


In this talk we review calculations of FI-tadpoles in 5 dimensional (non-)supersymmetric orbifold theories. Some consequences of these tadpoles are discussed: quadratic Higgs-mass sensitivity to a high scale, and localization of bulk matter fields to the orbifold fixed points.

1 Introduction

Models with 5 dimensional global supersymmetry compactified on orbifolds may be good candidates for extensions of the standard model and have interesting phenomenological applications. The orbifolds we consider in this talk can have both a supersymmetric (S^1/\mathbb{Z}_2) as well as a non-supersymmetric ($S^1/\mathbb{Z}_2 \times \mathbb{Z}'_2$) spectrum.

The underlying 5 dimensional $N = 1$ supersymmetry can give rise to many impressive ultra-violet properties while the orbifold compactification can produce phenomenologically interesting particle spectra. Let us mention a particular intriguing model proposed by Barbieri, Hall, Nomura (BHN)¹, which has some remarkable features: Although this model has the low energy spectrum identical to the standard model it is constructed from a supersymmetric theory with vector and hyper multiplets compactified on the orbifold $S^1/\mathbb{Z}_2 \times \mathbb{Z}'_2$. In the following table the Kaluza-Klein spectrum of this model is presented.



The parity assignment dictates the mode expansion of a given field. The field content of this model consists of a complex Higgs scalar ϕ_H , its Higgsino ψ_H , the standard model fermions ψ_M , their mirrors ψ_M^c , and the sfermions ϕ_M, ϕ_M^c that form 5 dimensional hyper multiplets. Whereas, the standard model gauge fields A_μ, A_5 , the two gauginos λ, ψ_Σ and real scalar Φ form a vector multiplet. The 5th component of the gauge field A_5 in 5 dimension and the real scalar Φ reside in ϕ_Σ . All these are all functions of the 5th dimension of with radius R .

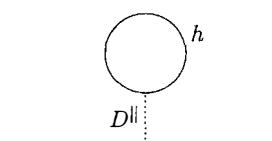
In this proceedings we consider two stability issues of such models in 5 dimensions that are consequences of divergent FI-terms: 1) Higgs mass sensitivity to the cut-off, and 2) localization of charged bulk matter. Before discussing these issues in the following sections, let us introduce them briefly here.

In the recent literature these types of orbifold models were claimed to have an extremely mild ultra-violet (UV) behavior²: the effective potential was claimed to be finite at one loop or even to all orders in perturbation theory. Others³ raised objections to such claims in the case of models that do not possess any global supersymmetry, that may provide an obvious UV-protection for the Higgs mass. It turned out that, like in 4 dimensional supersymmetric models, Fayet–Iliopoulos tadpole may introduce a quadratic divergence.

The second issue boils down to the question whether any configuration of brane and bulk fields is stable. Charged bulk fields can become strongly localized due to the effect of FI-terms in 5 dimensions induced at one loop. If this happens the original setup was not stable under quantum corrections and should therefore not be considered as the appropriate starting point for perturbative calculations.

2 The zero mode Fayet–Iliopoulos term

In supersymmetric field theory in 4 dimensions the FI-term is either quadratically divergent or vanishes at one loop. In the following we focus on the Higgs sector of the BHN–model to discuss the effect of the zero mode FI-term in the effective 4 dimensional theory. The diagram of the FI–contribution to the selfenergy of a scalar is given by:



The dotted line corresponds to the auxiliary field D^{\parallel} of the Abelian gauge multiplet in 4 dimensions. (The notation D^{\parallel} indicates that this the component of the triplet of auxiliary fields of the vector multiplet that has a KK zero mode after the orbifolding.) In ref.⁴ we have investigated

what happens to the FI-term in the effective field theory coming from 5 dimensions with a mass spectrum of the complex scalars of the hyper multiplet on $S^1/\mathbb{Z}_2 \times \mathbb{Z}'_2$. We denote the charges of the even and odd KK scalars by $q_n^{++} = -q_n^{--} = 1$. Formally, the expression for the one loop contribution to the FI term reads

$$\xi_0 = \sum_{n,\alpha} g q_n^{\alpha\alpha} \int \frac{d^4 p_4}{(2\pi)^4} \frac{1}{p_4^2 + (m_n^{\alpha\alpha})^2 + m^2}, \quad (1)$$

where $m_n^{\alpha\alpha} = 2n/R$ and the sum for $\alpha = +$ is over $n \geq 0$, while for $\alpha = -$ over $n > 0$. In order to be able to calculate this quantity in a rigorous way we employ dimensional regularization of a compact dimension introduced in ref.⁵

$$\xi_0 = g \int \frac{d^{D_4} p_4}{(2\pi)^{D_4}} \int_{\Theta} \frac{d^{D_5} p_5}{2\pi i} \left\{ \frac{\mathcal{P}^{++}(p_5)}{p_4^2 + p_5^2 + m^2} - \frac{\mathcal{P}^{--}(p_5)}{p_4^2 + p_5^2 + m^2} \right\}. \quad (2)$$

These integrals are defined as complex functions of the dimensions D_4 and D_5 by

$$\int_{\Theta} d^{D_5} p_5 \int d^{D_4} p_4 \equiv \int_{\Theta} \frac{dp_5}{2\pi i} \int_0^\infty dp_4 \mathcal{R}_4(p_4) \mathcal{R}_5(p_5) \quad (3)$$

with the regulator functions $\mathcal{R}_4(p_4)$ and $\mathcal{R}_5(p_5)$ given by

$$\mathcal{R}_4(p_4) = \frac{2\pi^{\frac{1}{2}D_4}}{\Gamma(\frac{1}{2}D_4)} p_4^3 \left(\frac{p_4}{\mu_4} \right)^{D_4-4}, \quad \mathcal{R}_5(p_5) = \frac{\pi^{\frac{1}{2}D_5}}{\Gamma(\frac{1}{2}D_5)} \left(\frac{p_5}{\mu_5} \right)^{D_5-1}. \quad (4)$$

With Θ the contour integration is denoted over the upper and lower half plane with an anti-clockwise orientation^{6,7}. Substituting the expressions of the pole functions

$$\mathcal{P}^{\pm\pm} = \frac{1}{2} \left(\pm \frac{1}{p_5} + \frac{\frac{1}{2}\pi R}{\tan \frac{1}{2}\pi R p_5} \right), \quad (5)$$

gives exactly the same result as the regulated FI term for one massless complex scalar:

$$\xi_0 = g \int \frac{d^{D_4} p_4}{(2\pi)^{D_4}} \int_{\Theta} \frac{d^{D_5} p_5}{2\pi i} \frac{1}{p_5} \frac{1}{p_4^2 + p_5^2 + m^2} = g \int \frac{d^{D_4} p_4}{(2\pi)^{D_4}} \frac{1}{p_4^2 + m^2}. \quad (6)$$

Since it behaves as a single particle contribution we can safely take $D_5 = 1$ giving the 4 dimensional quadratically divergent expression.

In ref.⁴ we have shown that the other gauge contributions give a finite correction and can therefore never cancel this quadratic divergence. According to ref.⁸ the correction to the Higgs mass due to this quadratically divergent FI-tadpole is relatively small if the cut-off (used to regulate the divergent integral) is taken to be around $5/R$. The motivation for this value of the cut-off is that beyond this value the power-running of the gauge couplings explodes. However, since in principle these are two different types of ‘‘cut-offs’’ (one is a regulator while the other corresponds to the scale of the gauge coupling Landau pole), it is not clear why they should simply be equal. The cut-off at $5/R$ corresponds to a numerical value of a few TeV. Of course, with a cut-off of this order the standard model does not require any fine-tuning in its Higgs sector and neither supersymmetry nor extra dimensions are required.

3 Localization of and due to Fayet–Iliopoulos terms

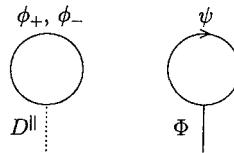
FI-terms in 5 dimensions do not only affect scalar masses, but they may also have important consequences for stability of such theories. In order not to complicate our discussion here, we

consider supersymmetric compactification on the orbifold S^1/\mathbb{Z}_2 , with a $U(1)$ vector multiplet (A_M, Φ, λ) and charged hyper multiplets (ϕ_+, ϕ_-, ψ) in the bulk.

The profile of FI-terms over the 5th dimension is rather intriguing: as observed in ref.^{8,9} the tadpole for D^{\parallel} leads to a FI-parameter

$$\xi_{\text{bulk}}(x) = \frac{g}{2} \left(\frac{\Lambda^2}{16\pi^2} + \frac{\ln \Lambda^2}{16\pi^2} \frac{1}{4} \partial_x^2 \right) [\delta(x) + \delta(x - \pi R)]. \quad (7)$$

The leading quadratic divergence is localized at the two branes as is signified by the delta-functions. The sub-leading logarithmic divergence is proportional to the second derivative of these delta-functions. Similar tadpoles arise for the derivative of the physical scalar Φ in the gauge multiplet, due to a fermion (hyperino) loop.¹⁰ In the picture below we give the diagrams for both the D^{\parallel} and the $\partial_x \Phi$ tadpole:



The combination $D^{\parallel} - \partial_x \Phi$ for these tadpoles is required by the remaining supersymmetry after compactification on the orbifold S^1/\mathbb{Z}_2 .⁷

The consequences of this shape of the FI-terms have been investigated in detail in ref.¹¹: the terms with double derivative on the delta-function, lead either to delta-like localization to or repulsion from the branes of charge bulk fields. The reason for this is the non-trivial background profile of the physical scalar Φ due to its FI-tadpoles, affects the shape of the zero mode of the bulk matter fields:

$$\phi_{0+}(x) = \exp \left\{ g \int_0^x dx' \Phi \right\} \bar{\phi}_{0+}. \quad (8)$$

This effect may be interpreted as a signal that one has started with a model with a distribution of the matter fields over the 5th dimension that is unstable under quantum corrections. Therefore, only models that do not have this type of instability should be considered as valid starting points for detailed phenomenological studies.

Another important (and related) requirement is, of course, gauge anomaly cancellation studied in refs.^{12,13,14}. In addition in ref.¹¹ the issue of a parity anomaly on S^1 is raised that can make an orbifold model ill-defined.

4 Conclusion

In this talk we have discussed two types of instabilities that can arise due to Fayet–Iliopoulos terms in 5 dimensional (supersymmetric) orbifold theories. In the non-supersymmetric BHN-model the quadratical divergence leads to a quadratic sensitivity of the Higgs mass to the cut-off. The FI-terms have a profile over the 5th dimension proportional to delta-functions localized at both boundaries and second derivatives of those delta-functions. This often leads to strong localization of the zero modes of charged bulk fields, which signals an instability in the initial distribution of matter over the 5 dimensional bulk and the 4 dimensional boundaries.

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