D-brane Standard Model-Like and Scalar Dark Matter in Type IIA Superstring Theory

Adil Belhaj$^1$, Karim Douhou$^2$, Salah Eddine Ennadifi$^2$

$^1$LIRST, Faculté Polydisciplinaire, Université Sultan Moulay Slimane, Béni Mellal, Morocco
$^2$LHEP-MS, Faculté des sciences de Rabat, Université Mohammed V, Rabat, Morocco

Abstract

In light of the present LHC Run II at $\sqrt s = 13$ TeV, string y standard-like model is studied. Concretely, a singlet $S$ scalar-extended SM given in terms four stacks of intersecting D6-branes in a type IIA superstring compactification producing a large gauge symmetry is examined. The involved scales are dealt with. According to the dark matter relic density, the mass of the scalar dark matter beyond the SM $m_S \lesssim 10^3$ GeV and the corresponding Higgs portal couplings $\lambda_{SH} \lesssim 10^{-8}$ are approached.

Keys words: LHC; Standard Model; D-brane; String Theory; Dark Matter.

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1 Introduction

More recently, many excesses with beyond the Electroweak scale $\sim 10^2 \text{GeV}$ from LHC Run-II with $pp$ collisions at $13 \text{ TeV}$ have been reported \cite{1, 2}. These events have received a huge interest exploring different approaches and methods using analytical and simulating studies. These methods have been extensively investigated to provide possible physical interpretations of such problems. Concretely, various attempts have been suggested using models relying on extensions of the Standard Model of Particle Physics (SM) \cite{3, 4, 5, 6, 7, 8, 9}. In this way, the important investigation is based on the incorporation of singlet scalars to SM sector. In particular, the corresponding physics could be associated with a scalar field $S$ with a mass beyond $10^2 \text{GeV}$. In the $pp$ collision, the processes for producing such a scalar field are naturally obtained using two possible ways based on the fusion of either the gluons

$$gg \rightarrow SS \rightarrow SM, \quad (1.1)$$

or the quarks

$$qq \rightarrow SS \rightarrow SM. \quad (1.2)$$

In these scenarios, the couplings of such a field could be then described by the following effective terms

$$\zeta \supset \left( \frac{S}{\Lambda} \right) \left( G_{\mu\nu}^{a}G_{\mu\nu}^{a} + F_{\mu\nu}F_{\mu\nu} \right). \quad (1.3)$$

Here, $F_{\mu\nu}$ and $G_{\mu\nu}$ are the strong and the electromagnetic fields, respectively. These terms could predict the associated excesses and production channels.

It has been proposed that effective field theory models can be derived using the compactification of type II superstrings and related models allowing one to present a possible interpretation of such a new physics \cite{10, 11, 12, 13, 14, 15}. In string theory, the particle physics ingredients can be provided by intersecting D-branes wrapping non trivial cycles in orientifold compactifications. In this discussion, the gauge symmetries can be derived from stacks of D-branes filling the four dimensional space-time while the matter fields reside at their intersections. The latters are associated with intersection numbers corresponding to restrictions of additional global U(1)’s exhibited by the compactification scenario. In this way, the stringy effects can produce corrections to the superpotential by including the missing coupling terms being relevant for the fermion masses. This feature can bring an acceptable effective low-energy realization for SM-like and their extensions \cite{16, 17, 18, 19, 20, 21, 22, 23}. Such models usually are represented by graphs encoding the gauge symmetry and matter content in terms of vertices and edges, as in quiver dual discussions. These fundamental pieces allow for an possible exploration of several physical problems without the need of a
physical defined model. More precisely, the possible interaction couplings can be obtained using quantum numbers associated with graph theory representation of D6-brane models. This graph theory method provides a rich D-brane discussion in type II superstring compactifications [24, 25, 26, 27, 28].

The aim of this work is to contribute to these activities by investigating a stringy scalar-extended SM in terms of intersecting D-brane models in type IIA superstring compactifications. To be concrete, we build a gauge theory from intersecting D6-branes wrapping non trivial 3-cycles in a type IIA orientifold geometry. In particular, we consider a model with $U(3) \times Sp(1) \times U(1) \times U(1)$ gauge symmetry. In the corresponding SM-like, an added singlet scalar $S$, in the presence of the standard Higgs doublet $H$, generates the SM particle masses. According to the known data, the VEV $\langle S \rangle$ and the mass scale of the involved new $m_s$ scalar provide a probe of the stringy physics effect in the SM and a possible scalar dark matter (DM) candidate.

The organization of this paper is follows. In section 2, we present a gauge model from four stacks of intersecting D6-branes wrapping 3-cycles in type IIA geometry. This compactification gives $U(3) \times Sp(1) \times U(1) \times U(1)$ gauge symmetry. In section 3, we propose a stringy singlet scalar extension of the SM in terms of D6-branes in type IIA superstring. In section 4, we approach the involved high scales associated with the new scalar mass $m_s$ probing the stringy effect in the SM scale. In section 5, we present a stringy scalar DM. The last section is devoted to concluding remarks.

## 2 D6-brane SM-Like in type IIA superstring

Motivated by the recently LHC Run-II activities and the large emergence of scalar moduli in string theory compactifications, we study a scalar extension of the SM by assuming that the corresponding physics involves a stringy origin from of a low-scale $M_s \ll M_{Planck}$ effect. To be precise, we will consider a singlet scalar field under the SM gauge symmetry originated from string theory. It is recalled that non perturbative string theory requires the introduction of objects called D-branes providing nonabelian gauge symmetries in the lower dimensional compactifications. These extended objects have been explored for phenomenological applications in string theory framework. In fact, type II superstrings contain various solutions of Dp-branes considered as as $(p + 1)$-dimensional subspaces on which open strings are stretched [29]. The spectrum of fluctuations of such a physics is obtained by quantizing closed strings and open strings living on such Dp-branes. Indeed, quantum descriptions of such objects are given in terms of nonabelian gauge theories in $(p + 1)$-dimensional physical spaces. The corresponding physics has been extensively studied in order to look for models close to the reality. It has been suggested that such kind of models can be embedded in type II
superstring compactifications in the presence of D-branes producing four dimensional gauge theories. In particular, it has been learned how many non trivial gauge models are obtained using different methods. One method is based on singular limits of type II superstrings by exploring the geometric engineering method \cite{30}. In this method, the gauge symmetry and the matter can be derived from the geometry of the internal space by wrapping D2-branes on blowing down cycles in the K3-fibration manifolds. Another way, which will be interested in here, is based on intersecting D\(p\)-branes in type II superstrings \cite{31}. More precisely, we thus construct a type IIA stringy model based on four stacks of intersecting D6-branes in the presence of a flavor symmetry distinguishing various matter fields from each others especially quarks. It is noted, in passing, that D5-branes in type IIB could be also used. The latter can be related D6-brane through mirror symmetry in the Calabi-Yau manifolds. In the intersecting D6-brane representation, the studied model is described by the following gauge symmetry

\[ U(3)^a \times Sp(1)^b \times U(1)^c \times U(1)^d. \]  

(2.1)

Here, the \(Sp(1) \simeq SU(2)\) weak factor symmetry arises from the D6-wrapped on an orientifold invariant 3-cycle \((b = b^*)\). It has been observed that there is no difference between the quark doublets since they involve all the same \(U(1)^{a,c,d}\) abelian charges. A deeper investigation reveals that one can examine a D6-brane model from the compactification of type IIA superstring on three factors of the the torus \(T^2\) known by factorisable torus backgrounds \(\prod_{i=1}^{3} T^2_i\). The toroidal D6-brane configuration that we consider here is in non-supersymmetric. Indeed, even if we consider a compactification where supersymmetry remains unbroken, RR tadpole conditions imply that in a chiral D-brane configuration supersymmetry will be broken in the open string sector of the theory. However, it is still possible to ask if some open string subsector will preserve some amount of supersymmetry. Or, what are the D-brane conditions preserving a common supersymmetry when wrapping a generic compact manifold. Moreover, for consistencies, the cancelation of potential anomalies arising from the low energy chiral spectrum is implied by the RR tadpole conditions, and mixed an higher anomalies are cancelled by the generalized Green-Schwarz mechanism. As a consequence of such a mechanism, some Abelian gauge bosons will get massive, eliminating the corresponding \(U(1)\) gauge symmetry from the effective theory being of great importance in constructing semi-realistic models. In this compactification, the intersection numbers are given in terms of the wrapping numbers of the D6-branes around the \(T^2\) factors. An adequate choice of such numbers gives intersections listed in table 1.

In this type IIA representation, the three left-handed quarks \(q_i\) are localized at the intersections of D6-branes \(a\) and \(b\) while the right-handed quarks, \(\bar{u}_i\) and \(\bar{d}_i\) split into two up quarks \(\bar{u}^{2,3}\) and one down quark \(\bar{d}^3\) being localized at intersection of the D6-branes \(a\) and
Table 1: Intersection numbers of the SM spectrum. The other ones are set to zero.

| Sector | Intersection | ac | ac* | ad | ad* | db | dc* |
|--------|--------------|----|-----|----|-----|----|-----|
|        | 3            | -2 | -1  | -1 | -2  | 3  | -3  |

$c/c^*$, respectively. Two down quarks $d_1^\pm$ and one up quark $u_1^\pm$ are localized at the intersection of the D6-branes $a$ and $d/d^*$. However, the three left-handed leptons $\ell^i$ appear at the intersection of D6-branes $b$ and $d/c, c^*$, respectively. Moreover, the three right-handed electrons $e^i$ are localized at the intersection of D6-branes $d$ and $c$. Finally, the Higgs doublet $H$ appears at the intersection of D6-branes $b$ and $c/c^*$. It has been remarked that the matter fields are associated with a linear combination of $U(1)_{a,c,d}$ recovering the SM hypercharge. The four $U(1)_{a,b,c,d}$ symmetries $Q_a, Q_b, Q_c$ and $Q_d$ have clear interpretations in terms of known global symmetries of the SM, i.e., baryon, lepton and isospin numbers. Thus, all these known global symmetries are in fact gauge symmetries in such stringy constructions. The hypercharge is given here by the anomaly-free linear combination $Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c - \frac{1}{2}Q_d$. This D6-brane model can be graphically illustrated in the figure 1.

Figure 1: 4-Stack Stringy SM-Like. Bold lines denote D6-branes and thin lines denote chiral and scalar spectrum.

It is observed from the figure 1 that the 4D Yukawa coupling terms can be derived with respect to the symmetry charges illustrated in the table 2.

In fact, the $U(1)_{a,c,d}$ field charges can be used to get the possible Yukawa couplings associated with the interaction terms for the heavy quarks and leptons. Computations show that these terms can be given by
Table 2: SM spectrum and their U(1)\(_{a,c,d}\) charges for \(Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c - \frac{1}{2}Q_d\). The index 
\(i = 1, 2, 3\) is the family index.

\[
\begin{array}{cccccccccc}
\text{Fields} & q^i & \ell^i & \tau^i & H \\
\text{Rep} & (3,3,2) & (3,1) & (3,1) & (1,1) \\
Q_a & 3 & -1 & 1 & 0 \\
Q_c & 0 & 1 & 0 & 1 \\
Q_d & 0 & 0 & 1 & -1 \\
Y & 1/6 & -2/3 & 1/3 & -1/2 \\
\end{array}
\]

These charges allow one to express the following Lagrangian

\(\zeta_{Yuk} = y_c H^t q^c + y_t H^t q^t + y_b H q^b + y_e H \ell^e \tau^e\),

where \(y'\)s are coupling constants associated with the Higgs-fermion interaction strengths between such terms.

### 3 Stringy singlet scalar extension

An inspection in the above model reveals that the missing phenomenologically desired coupling terms can be recovered by the U(1)’s charged scalars which can be explored to extend the SM spectrum [24, 25, 26]. Besides the dilaton and the axion living in ten dimensions, a scalar can be obtained from many roads using the compactificaion scenario in type II superstrings. In particular, it can be derived from the geometric deformation of the internal space including the antisymmetric B-field of the NS-NS sector. It has been shown that this contribution involves the complex structure deformations, the complexified Kähler deformations or both. Or, it comes from the R-R gauge fields on non trivial cycles of the internal geometry in closed string sector. In open string sector, however, the scalars can be obtained from the moduli space of deformations of special Lagranagian submanifolds, associated with the middle-homology of the internal space, where D6-branes can wrap. String theory compactification complexifies these scalars by adding the Wilson lines obtained from the gauge fields.
living on such D6-branes. Here, we consider a scalar associated with such an open string sector. This operation generates the missing interaction terms with respect to the above discussed U(1) symmetry charges. A close inspection shows that the new scalar must have the charges listed in table 3.

| Sector | Field | Rep | $Q_a$ | $Q_c$ | $Q_d$ | $Y$ |
|--------|-------|-----|------|------|------|-----|
| cd     | $S$   | 1(1,1) | 0 | 1 | -1 | 0 |

Table 3: New scalar $S$ and its U(1)${}_{c,d}$ charges.

These charges can be handled to engineer a D6-brane model. The corresponding data is represented in the figure 2.

![Figure 2: Stringy scalar and its associated U(1)$_{c,d}$ charges indicated by the dotted line.](image)

In the present D6-brane model, the absent terms are now generated from the higher order terms. Thus, they will be suppressed by factors $\langle S \rangle^n / M_s^m$, where $n$ and $m$ are power integer numbers. It is noted that $M_s$ indicates the string mass and $\langle S \rangle$ its VEV. Indeed, these terms take the following forms

$$Q_{c,d} \left( S H^\dagger q \bar{u} \right) = Q_{c,d} \left( S \right) + Q_{c,d} \left( H \right) + Q_{c,d} \left( q \right) = Q_{c,d} \left( \bar{u} \right) = 0,$$

$$Q_{c,d} \left( S^* H q \bar{d} \right) = 0, \quad Q_{c,d} \left( S^* H q q \bar{u} \right) = 0, \quad (3.1)$$

$$Q_{c,d} \left( S^2 \left( H^\dagger \bar{u} \right)^2 \right) = 0.$$

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These new charges provide the following Lagrangian

\[
\mathcal{L}'_{\text{Yuk}} = M_s^{-1} \left( y_u S H^\dagger \bar{q} u + y_d S^* H \bar{q} d + y_s S^* H \bar{q} s \right) + M_s^{-3} y_\nu S^2 (H^i)^2.
\] (3.2)

In the D6-brane representation, the VEV \( \langle S \rangle \) induces the missing Yukawa coupling terms, along with the Higgs VEV, it generates the masses for these light fermions (3.2). Compared to the previous contributions given in (2.3), they are suppressed by the string mass scale \( M_s \) with a high suppression for the left-handed neutrino terms.

4 Probe of the stringy scales

It turns out that results beyond the interaction terms could be derived from type IIA superstring moving on particular geometries. Concretely, they include the involved string scale \( M_s \) with the VEV \( \langle S \rangle \) and the mass \( m_s \) of the scalar field \( S \). After the electroweak symmetry breaking by the Higgs VEV at \( \langle H \rangle \approx 246 \text{ GeV} \), appropriate combinations of fermion masses, for which their net scalar-fermion couplings could be absorbed, give approximate values of the new scales. In particular, using the left-handed neutrino mass terms appearing in (3.2) with an upper bound of \( m_{\nu_\tau} \lesssim 1 \text{ eV} \), we can predict the string scale \( M_s \). The calculation gives the following scale

\[
M_s = \frac{y_{\nu_\tau} m_u^2}{y_u^2 m_\nu} \sim 10^4 \text{ GeV},
\] (4.1)

and then the scalar field VEV \( \langle S \rangle \) becomes

\[
\langle S \rangle = \frac{y_c}{y_s} M_s \frac{m_s}{m_c} \sim 10^3 \text{ GeV}.
\] (4.2)

At this level, it is worth noting that there are two new high scales: one belongs to the low-string scale \( M_s \) (4.1), and the other belongs to the VEV of the new scalar \( \langle S \rangle \) given in eq.(4.2). Besides the partial explanation of the fermion mass hierarchies and the smallness of neutrino masses, these new scales appearing in (4.1) and (4.2), allow a possibility to probe the type IIA stringy effect at the SM scale through the mass of the new scalar \( S \). It is remarked that the most general renormalizable scalar potential consistent with the model scalar spectrum reads as

\[
V(H, S) = V(H) + \mu_S^2 S^2 + \lambda_{SS} S^4 + \lambda_{SH} (H^\dagger H) S^2
\] (4.3)
Form the potential, we can derive the mass of this scalar. Indeed, one reads the mass of scalar $S$ as

$$m_S = \sqrt{\mu_S^2 + \lambda_{SH} v_H^2} \leq 10^3 \text{GeV}. \quad (4.4)$$

It is noted that the constraint $\mu_S^2 > 0$ implies the following inequality

$$m_S > \sqrt{\lambda_{SH} v_H}. \quad (4.5)$$

At this stage, one see clearly that for the strong scalar-SM coupling value $\lambda_{SH} \sim 1$, the mass of the new scalar can go over the SM scale. This high scale physics effects that result in a stringy prediction for physics beyond the SM push to ask whether the present LHC Run II at $\sqrt{s} = 13$ TeV could be able to see more significant stringy physics directly. Then, we should see what insights on related modern physics problems, especially DM, can be brought.

5 Stringy scalar Dark Matter

The scalar singlet $S$, introduced in this type IIA D6-model, interacts with the SM particles through the Higgs portal. It is suggested that if such a scalar is real and stable, it could constitute a viable dark matter (DM) candidate. Indeed, a global U(1) symmetry removing the odd power couplings can be assumed in the simple scalar potential of the present model given in (4.3) to guarantee the DM stability. It has been pointed out that such a scalar singlet model is the simplest UV-complete theory containing a WIMP. After the electroweak symmetry breaking, the scalar DM candidate $S$ can be annihilated into all SM particles through the portal coupling $\lambda_{SH}$. This operation can be illustrated in figure 3.

![Figure 3: Higgs exchange diagrams for the scalar DM annihilation.](image)

In the present model, there are only two relevant parameters for the DM investigation, namely the physical DM mass $m_S$ (4.4) and the Higgs portal coupling $\lambda_{SH}$. In fact, the latter is however enough to allow for a contribution to the invisible decay of the Higgs boson, scattering of $S$ on nucleons through Higgs exchange, and annihilation into SM particles.
This can lead to possible indirect detection signatures and an allowed thermal relic density of DM \[32, 33\]. In this way, the relic density in the present universe is approximately given by the annihilation cross-section of our scalar DM as

\[
\Omega_{DM=S} = \frac{0.1 \text{pb}}{h^2 \langle \sigma_{\text{ann}}v_S \rangle_{SS \to SM}} \simeq 0.2
\] (5.1)

where \(h\) is the Hubble constant and where \(\langle \sigma_{\text{ann}}v_S \rangle\) is the velocity-averaged annihilation cross-section. Using (4.1), (4.2), (4.4) and taking into account the dilution of the scalar DM, we show that the resulting scalar DM abundance is

\[
\Omega_S \simeq 0.2 \left( \frac{\lambda_{SH}}{10^{-8}} \right)^3 \frac{\langle S \rangle}{m_S}.
\] (5.2)

It follows for some mass range \(m_S\) of the singlet scalar \(S\) that the natural values of \(\lambda_{SH}\) reproduce not only the observed DM relic density \(\Omega_{DM} \simeq 0.2\) (4.4), but also predict a cross section for scattering on nucleons being not far from the current direct detection limit. Thus, once the relic density constraints are used, one can make definite predictions in this model as well as in different experiments and their interplay. Given the parameter space of the model

\[\{m_S, \lambda_{SH}\},\] (5.3)

we display the range of the parameters given in the plan parameterized by \(m_S\) and \(\lambda_{SH}\). Moreover, we find the allowed region for the correct relic abundance for the scalar DM satisfying the current constraint \[32, 33\]. According to (4.2), (4.4), the likely mass range of the scalar DM is

\[10^2 \text{GeV} \leq m_S \leq 10^3 \text{GeV}.
\] (5.4)

This data requires the Higgs portal coupling range

\[10^{-10} \leq \lambda_{SH} \leq 10^{-8}.
\] (5.5)

In this approach, the larger (smaller) values of \(\lambda_{SH}\) reduces (enhances) the \(S\) relic density by increasing (decreasing) the annihilation cross-section. In particular, the overall predicted signal for scattering on nucleons and the annihilation into SM particles are considered. This can be illustrated in figure 4.

Due to this effect, the dependence constraints are significantly different than one might have expected. Thus, we take the view here that the singlet scalar DM might provide only a fraction of (more than) the total DM density which is considered as a logical possibility.
Figure 4: Higgs exchange diagrams for scattering with a nucleon.

6 Conclusion and related remarks

In this work, we have investigated the stringy physics effect at low scales in a string-inspired gauge theory derived from the compactification of the type IIA superstring with D6-brane configurations. More precisely, we have examined four stacks of intersecting D6-branes wrapped on non-trivial cycles in type IIA geometry. This model has been combined with a singlet scalar \( S \) to produce an extended SM spectrum. The associated effective scalar potential generates different coupling scales relative to the allowed perturbative and the higher order suppressed terms. Associating the allowed perturbative terms with the known heavy quarks and leptons, and using the higher order generated terms corresponding to known light quarks and neutrinos, the hierarchy of fermion masses finds a possible explanation through higher order terms suppressed by the factors \( \langle S \rangle^n / M_s^m \). Using known data, we have discussed the stringy effect by examining the new scales, the low-string scale \( M_s \sim 10^4 \text{GeV} \) and the singlet scalar VEV \( \langle S \rangle \sim 10^3 \text{GeV} \). Then, we have investigated the possibility to consider this new scalar as a viable DM connected to SM via the Higgs-mediated coupling \( \lambda_{SH} \). Using the current constraints of the DM relic density \( \Omega_{DM} \simeq 0.2 \), we have approached the mass of the scalar DM \( m_S \) (5.3), bounded the range of the Higgs portal coupling \( \lambda_{SH} \) (5.5), and then we have dealt with the extreme cases.

This work comes up with many open questions related to DM problems using string theory. In particular, a natural question is associated with the physics of the QCD axion scalar field discussed in terms of the Peccei-Quinn \( U(1)_{PQ} \) symmetry corresponding to electroweak and supersymmetry breaking scales in the context of closed and open string models. Moreover as argued, the D6-brane physics finds naturally a place in M-theory compactifications on G2 manifolds. It would be interesting to understand such problems from M-theory point of view.

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