Supersymmetry Breaking in the Hidden Sector on Magnetized Torus Model

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Today, I will talk about the model, D7 brane on **magnetized torus model**, constructed by our senior colleague.
(Roughly speaking, my work is a continuation of this.)

He has already (partially) succeeded in
realizing the **Standard Model** (**SM**).

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My work involves

constructing its **supersymmetry breaking sector**, or **hidden sector**.

Introduction & Review

Let me introduce **magnetized torus model** at first.

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I hope **Shimada-kun** have already explained important topics, especially the realization of the **SM** in the previous talk.

Then, I will focus on following two selected subjects and finish the review part briefly.

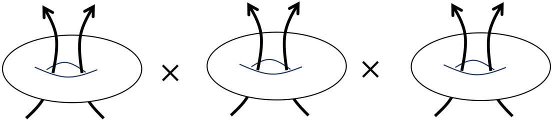
- Magnetized torus model
- Zero-mode equation and the degeneracy

[2] D. Cremades, L. E. Ibanez, and F. Marchesano, JHEP **05** (2004) 079, arXiv:hep-th/0404229.
[3] K. Choi and C. Kim, Springer, 2020.

Magnetized torus model

The **magnetized torus model** is obtained by

- compactifying $\mathbf{10}$D super Yang-Mills theory into $\boldsymbol{T^2 \times T^2 \times T^2}$.
- introducing the flux in extra-dimensions $\boldsymbol{\langle A_\mu \rangle = 0,\ \langle A_i \rangle \neq 0}$.



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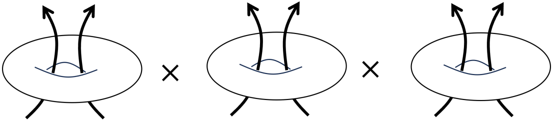

One of the benefit is that [3]

we can obtain chiral theories even in a flat geometry.

Zero-mode equation and the degeneracy

In its 4D effective theory, only zero modes appear.

Those modes obey the **zero mode equations**.

$$\left[\partial_i - \frac{\pi}{2\,\mathrm{Im}\,\tau_i} M_{ab}^{(i)}\right] f_{ab}^{(i)} = 0 \qquad i \text{ is a tori index.}$$

The properties of the solution $f^{(i)}$ can be different

when we choose the different **background flux** $M^{(i)}$, defined as

$$\langle A_i \rangle = \frac{\pi}{\mathrm{Im}\,\tau_i} M^{(i)} z_i$$

(Note that $M_{ab}^{(i)}$ appearing in **zero mode equations** is the difference of $M^{(i)}$ in the VEV of $\langle A_i \rangle$ above.)

[2] D. Cremades, L. E. Ibanez, and F. Marchesano, JHEP **05** (2004) 079, arXiv:hep-th/0404229.

The VEVs $\langle A_i \rangle$ also carry the gauge symmetry in its effective theory.

For example, we assume the VEV

$$\langle A_1 \rangle = \frac{\pi}{\mathrm{Im}\,\tau_i} M^{(1)} z_1 = \frac{\pi z_1}{\mathrm{Im}\,\tau_i} \begin{array}{cc} \begin{pmatrix} N_1 \times \mathbb{I}_2 & & \\ & N_2 & \\ & & N_3 \end{pmatrix} & \begin{array}{c} 2 \\ 1 \\ 1 \end{array} \end{array}$$

- It breaks original gauge symmetry
  $U(4) \to U(2) \times U_A(1) \times U_B(1)$.
- The zero mode equation splits into several equations (e.g. $i = 1$)

$$\left[\partial_1 - \frac{\pi}{2\,\mathrm{Im}\,\tau_1} M^{(1)}\right] f^{(1)} = 0$$

$$\left[\partial_1 - \frac{\pi}{2\,\mathrm{Im}\,\tau_1} N_1\right] f^{(1)}_{U(2)} = 0 \qquad \left[\partial_1 - \frac{\pi}{2\,\mathrm{Im}\,\tau_1} N_2\right] f^{(1)}_{A} = 0 \qquad \left[\partial_1 - \frac{\pi}{2\,\mathrm{Im}\,\tau_1} N_3\right] f^{(1)}_{B} = 0$$

$$U(2) \qquad\qquad U_A(1) \qquad\qquad U_B(1)$$

Summary so far

Once we choose the **background flux** (and other options)

- gauge symmetry can be broken spontaneously.
- we can obtain a chiral effective theory by **zero mode equations**
- and its degeneracy corresponds to a generation in **SM**.

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In the previous works [1],

- realizations of the gauge group $\boldsymbol{U(3)_C \times U(2)_L \times U(1)_Y}$
- and the generations of the matter.
- computing the effective Yukawa coupling constant

[4] H. Abe, T. Kobayashi, K. Sumita, and S. Uemura, Nucl. Phys. B **863** (2012) 1–18, arXiv:1204.5327 [hep-th].
[5] N. Arkani-Hamed, T. Gregoire, and J. Wacker, JHEP **03** (2002) 055, arXiv:hep-th/0101233.

Supersymmetry

Our startline theory is 10D SYM

$$\mathcal{L} = \frac{1}{g^2}\,\mathrm{Tr}\left[-\frac{1}{4}F^{MN}F_{MN} + \frac{i}{2}\bar{\lambda}\Gamma^M D_M \lambda\right]$$

$\Downarrow$ Rewriting for 4D $\mathcal{N} = 1$ superspace [5]

$$\mathcal{L} = \int \mathrm{d}^4\theta\,\mathcal{K} + \left\{\int \mathrm{d}^2\theta\,\left(\frac{1}{4g^2}\mathcal{W}^\alpha\mathcal{W}_\alpha + \mathcal{W}\right) + \text{ h.c. }\right\}$$

$$S = \int \mathrm{d}^{10}X\,\sqrt{-G}\mathcal{L}$$

$\Downarrow$ Compactify $\mathbb{R}^6$ to $T^2 \times T^2 \times T^2$

$$\mathcal{L} = \sum_{\text{KK modes}} \int \mathrm{d}^4\theta\,\mathcal{K} + \left\{\int \mathrm{d}^2\theta\,\left(\frac{1}{4g^2}\mathcal{W}^\alpha\mathcal{W}_\alpha + \mathcal{W}\right) + \text{ h.c. }\right\}$$

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$$\mathcal{L} = \sum_{\text{KK modes}} \int \mathrm{d}^4\theta\, \mathcal{K} + \left\{ \int \mathrm{d}^2\theta \left(\frac{1}{4g^2} \mathcal{W}^\alpha \mathcal{W}_\alpha + \mathcal{W} \right) + \text{ h.c.} \right\}$$

If we ignoe the excited mdoes, we obtain the 4D effective theory.

In this formulation, **at least $\mathcal{N} = 1$ supersymmetry** is manifest since it is written in terms of 4D $\mathcal{N} = 1$ superspace.

Hidden sector

Motivation

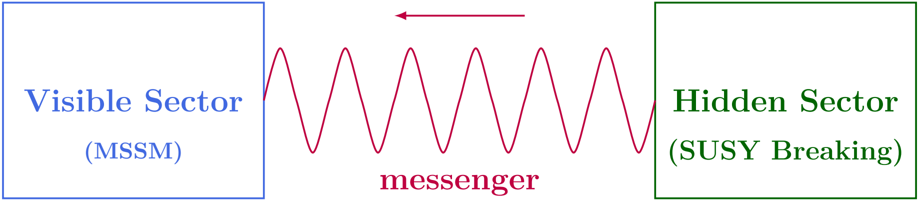
[6] J. Wess and J. Bagger, Princeton University Press.
[7] S. P. Martin, arXiv:hep-ph/9709356.

We have discussed some techniques of the **magnetized torus model**.

From now, we consider a **supersymmetry breaking** mechanism.

It is well-know that when we realize the **supersymmetry breaking** in the **MSSM** sector, undesirable things could happen [6, 7].

We prepare **different sector** (**hidden sector**) from the **MSSM sector**.



We have not yet considered the effect of the messenger.

(It can be a future work.)

In terms of the **magnetized torus model**, this is expressed by the flux as

$$\boldsymbol{M} = \left(\begin{array}{c|c} \boxed{\begin{array}{c}\textbf{Visible Sector}\\ \textbf{(MSSM)}\end{array}} & \\ \hline & \boxed{\begin{array}{c}\textbf{Hidden Sector}\\ \textbf{(SUSY Breaking)}\end{array}} \end{array}\right)$$

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I will talk about

- determining the flux M_{hidden}
- finding the kinematic scale Λ by computing **renormalization group equation** (**RGE**) for the gauge coupling constant.

$\longrightarrow$ This Λ could determine the **SUSY breaking scale** since it is the only dimensional parameter appearing in the potential.

Determining the flux M_{hidden}

There are so many possibilities for choosing the flux number.

(in addition parities and Wilson line, etc...)

In this talk, I refer the flux

$$M^{(1)} = \left(\begin{array}{c|cc} 0 & & \\ \hline & -10 & \\ & & 0 \end{array}\right), \quad M^{(2)} = \left(\begin{array}{c|cc} H & & \\ \hline & 1 & \\ & & 0 \end{array}\right),$$

$$M^{(3)} = \begin{array}{cc} \left(\begin{array}{c|cc} 0 & & \\ \hline & H_1 & \\ & & H_2 \end{array}\right) & \begin{array}{c} X \\ N \\ Y \end{array} \end{array}$$

which breaks the symmetry $U(N+2) \to U(1)_X \times U(N) \times U(1)_Y$.

Field contents are

$$\mathbf{\Phi_1} = \left(\begin{array}{c|c} & \\ \hline & \\ & \boldsymbol{Q} \end{array}\right), \quad \mathbf{\Phi_2} = \left(\begin{array}{c|c} & \boldsymbol{X} \\ \hline & \\ & \end{array}\right), \quad \mathbf{\Phi_3} = \left(\begin{array}{c|c} & \\ \hline \tilde{\boldsymbol{Q}} & \\ & \end{array}\right)$$

and $\#\boldsymbol{Q}, \#\tilde{\boldsymbol{Q}} = \mathbf{6}$ and $\#\boldsymbol{X} = \mathbf{1}$ where # denotes the degeneracy.

This theory includes the **Yukawa coupling term** in its effective theory

$$\boldsymbol{X}\tilde{\boldsymbol{Q}}\boldsymbol{Q}$$

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$$\boldsymbol{X\tilde{Q}Q}$$

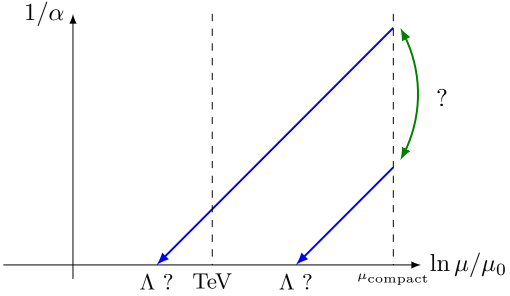
$$\boldsymbol{U(N)}$$

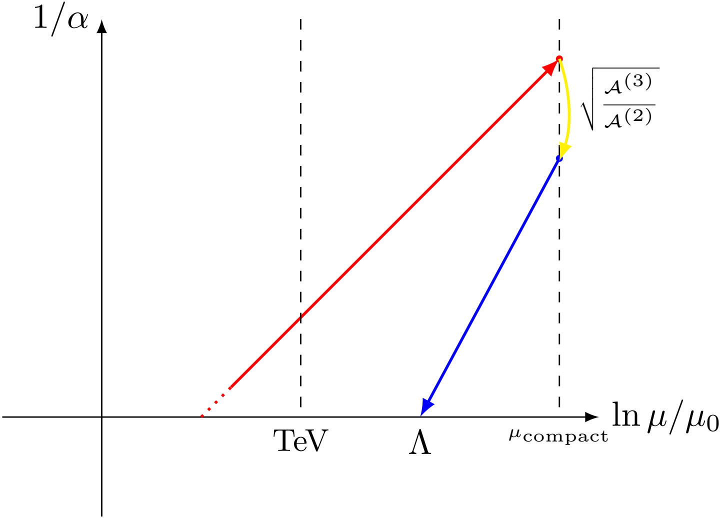
Finding the kinematic scale $\boldsymbol{\Lambda}$

Fermions in **hidden sector** can be confined in the certain **scale $\boldsymbol{\Lambda}$**.

$$\tilde{Q}Q \quad \longrightarrow \quad \langle \tilde{Q}Q \rangle = M$$

The **kinematic scale $\boldsymbol{\Lambda}$** is determined by solving **RGE** for coupling constant (like QCD), but we need to find the initial condition!





$$\boldsymbol{g_{4\mathrm{D}} = \frac{\mathcal{A}^{(1)}\mathcal{A}^{(2)}}{g^2_{\text{vis.}}} = \frac{\mathcal{A}^{(1)}\mathcal{A}^{(3)}}{g^2_{\text{hid.}}}}\ \text{when}\ \boldsymbol{\mu = \mu_{\text{compact}}}$$

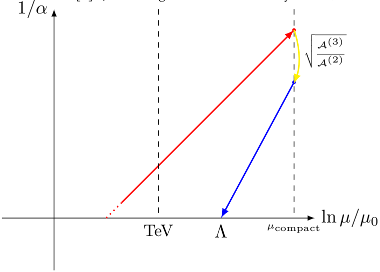
Initial condition for the **visible sector** [8]:

$$\mu_0 = 209\ \mathrm{GeV}, \quad g_0 \sim 1.678.$$

β function in the **visible sector** [9]:

$$\beta_{\mathrm{vis.}}(g) = -\frac{g^3}{16\pi^2} \cdot 6 \quad \text{(though SQCD)}$$

[8] Particle Data Group Collaboration, Phys. Rev. D 110 (Aug, 2024) 030001.
[9] J. Terning, Oxford University Press, 2006.



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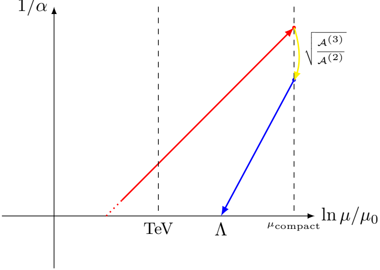

After finding the initial condition for the **hidden sector**,

we find the kinematic scale $\boldsymbol{\Lambda}$ as by solving **RGE** again:

$$\boxed{\boldsymbol{\Lambda \sim 5.8 \times 10^{12}\ \mathrm{GeV}}}$$

β function in the **hidden sector**:

$$\beta_{\mathbf{hid.}}(g) = -\frac{g^3}{16\pi^2} \cdot 3$$

Summary

- We could realize **SM** by considering the D7-brane on **magnetized torus model**, in certain degrees.
- However, it still remains at least $\mathcal{N} = 1$ supersymmetry in its $4D$ effective theory, and then we would like to consider **supersymmetry breaking** and prepare the **hidden sector**.
- We determined the**supersymmetry breakingscale** by computing **RGE** for the gauge coupling constant.

Future works

- Finding VEV $\langle X \rangle$ by writing the potential.

Backups

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[1] B. Chin, *Realization of the Standard Model by D7-Branes on a Magnetized Torus (translated)*, Master's thesis, Waseda University, 2024.

[2] D. Cremades, L. E. Ibanez, and F. Marchesano, *Computing Yukawa Couplings from Magnetized Extra Dimensions*, JHEP **05** (2004) 079, arXiv:hep-th/0404229.

[3] K.-S. Choi and C.-ŭ. Kim, *Quarks and Leptons from Orbifolded Superstring*, no. volume 954 in Lecture Notes in Physics. Springer, Cham, second edition ed., 2020.

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[5] N. Arkani-Hamed, T. Gregoire, and J. Wacker, *Higher dimensional supersymmetry in 4D superspace*, JHEP **03** (2002) 055, arXiv:hep-th/0101233.

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