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**).

My work involves

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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.

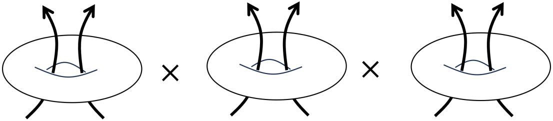
- Magnetized torus model
- Zero-mode equation and the degeneracy

Magnetized torus model

[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.

The **magnetized torus model** is obtained by

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



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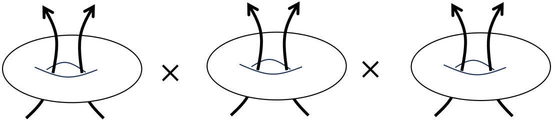

One of the benefit is that [3]

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

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

- 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**.

[1] B. Chin, Master's thesis, Waseda University, 2024.

Summary so far

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- and its degeneracy corresponds to a generation in **SM**.

In the previous works [1],

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

Supersymmetry

[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.

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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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

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

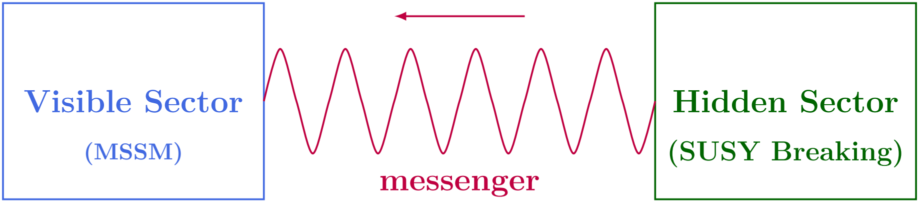
Motivation

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

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

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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

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

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

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

Field contents are

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

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

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

$$X\tilde{Q}Q$$

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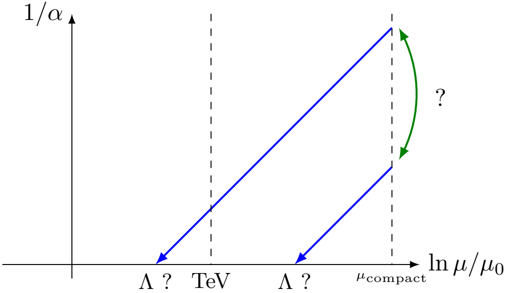
$$U(N)$$

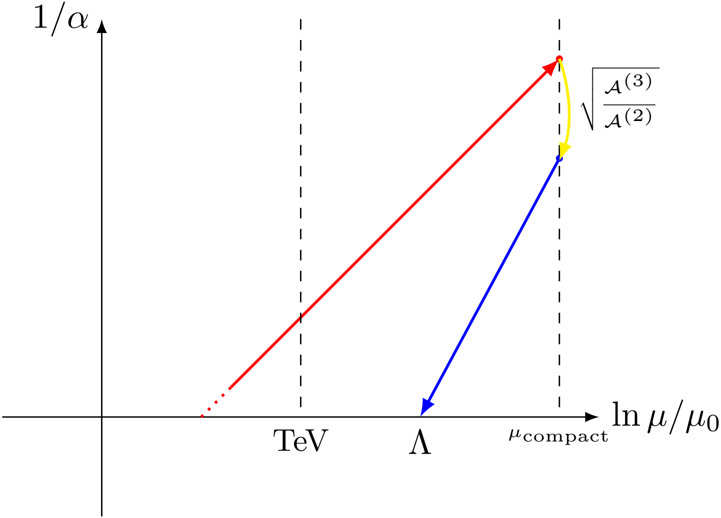
Finding the kinematic scale Λ

Fermions in **hidden sector** can be confined in the certain **scale Λ**.

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

The **kinematic scale Λ** is determined by solving **RGE** for coupling constant (like QCD), but we need to find the initial condition!





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

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

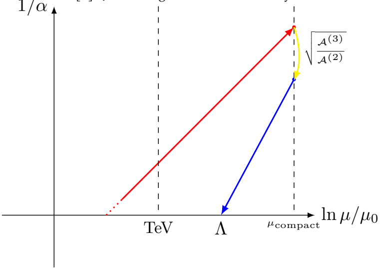
$$\mu_0 = 209 \text{ GeV}, \quad g_0 \sim 1.678.$$

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

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

[8] Particle Data Group Collaboration, Phys. Rev. D 110 (Aug, 2024) 030001.

[9] J. Terning, Oxford University Press, 2006.



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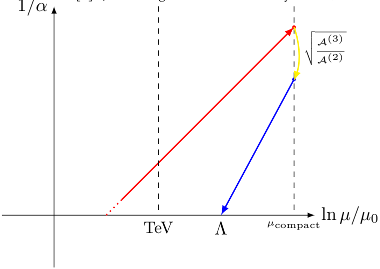

After finding the initial condition for the **hidden sector**, we find the kinematic scale Λ as by solving **RGE** again:

$$\Lambda \sim 5.8 \times 10^{12} \text{ GeV}$$

β function in the **hidden sector**:

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

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

References

[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.

[4] H. Abe, T. Kobayashi, H. Ohki, and K. Sumita, *Superfield description of 10D SYM theory with magnetized extra dimensions*, Nucl. Phys. B **863** (2012) 1–18, arXiv:1204.5327 [hep-th].

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

[6] J. Wess and J. Bagger, *Supersymmetry and Supergravity*. Princeton University Press, Princeton, N.J, 1992.

[7] S. P. Martin, *A Supersymmetry Primer*, arXiv:hep-ph/9709356.

References

[8] S. Navas, C. Amsler, T. Gutsche, C. Hanhart, J. J. Hernández-Rey, C. Lourenço, A. Masoni, M. Mikhasenko, R. E. Mitchell, C. Patrignani, C. Schwanda, S. Spanier, G. Venanzoni, C. Z. Yuan, K. Agashe, G. Aielli, B. C. Allanach, J. Alvarez-Muñiz, M. Antonelli, E. C. Aschenauer, D. M. Asner, K. Assamagan, H. Baer, S. Banerjee, R. M. Barnett, L. Baudis, C. W. Bauer, J. J. Beatty, J. Beringer, A. Bettini, O. Biebel, K. M. Black, E. Blucher, R. Bonventre, R. A. Briere, A. Buckley, V. D. Burkert, M. A. Bychkov, R. N. Cahn, Z. Cao, M. Carena, G. Casarosa, A. Ceccucci, A. Cerri, R. S. Chivukula, G. Cowan, K. Cranmer, V. Crede, O. Cremonesi, G. D'Ambrosio, T. Damour, D. de Florian, A. de Gouvêa, T. DeGrand, S. Demers, Z. Demiragli, B. A. Dobrescu, M. D'Onofrio, M. Doser, H. K. Dreiner, P. Eerola, U. Egede, S. Eidelman, A. X. El-Khadra, J. Ellis, S. C. Eno, J. Erler, V. V. Ezhela, A. Fava, W. Fetscher, B. D. Fields, A. Freitas, H. Gallagher, T. Gershon, Y. Gershtein, T. Gherghetta, M. C. Gonzalez-Garcia, M. Goodman, C. Grab, A. V. Gritsan, C. Grojean, D. E. Groom, M. Grünewald, A. Gurtu, H. E. Haber, M. Hamel, S. Hashimoto, Y. Hayato, A. Hebecker, S. Heinemeyer, K. Hikasa, J. Hisano, A. Höcker, J. Holder, L. Hsu, J. Huston, T. Hyodo, A. Ianni, M. Kado, M. Karliner, U. F. Katz, M. Kenzie, V. A. Khoze, S. R. Klein, F. Krauss,

References

M. Kreps, P. Križan, B. Krusche, Y. Kwon, O. Lahav, L. P. Lellouch, J. Lesgourgues, A. R. Liddle, Z. Ligeti, C.-J. Lin, C. Lippmann, T. M. Liss, A. Lister, L. Littenberg, K. S. Lugovsky, S. B. Lugovsky, A. Lusiani, Y. Makida, F. Maltoni, A. V. Manohar, W. J. Marciano, J. Matthews, U.-G. Meißner, I.-A. Melzer-Pellmann, P. Mertsch, D. J. Miller, D. Milstead, K. Mönig, P. Molaro, F. Moortgat, M. Moskovic, N. Nagata, K. Nakamura, M. Narain, P. Nason, A. Nelles, M. Neubert, Y. Nir, H. B. O'Connell, C. A. J. O'Hare, K. A. Olive, J. A. Peacock, E. Pianori, A. Pich, A. Piepke, F. Pietropaolo, A. Pomarol, S. Pordes, S. Profumo, A. Quadt, K. Rabbertz, J. Rademacker, G. Raffelt, M. Ramsey-Musolf, P. Richardson, A. Ringwald, D. J. Robinson, S. Roesler, S. Rolli, A. Romaniouk, L. J. Rosenberg, J. L. Rosner, G. Rybka, M. G. Ryskin, R. A. Ryutin, B. Safdi, Y. Sakai, S. Sarkar, F. Sauli, O. Schneider, S. Schönert, K. Scholberg, A. J. Schwartz, J. Schwiening, D. Scott, F. Sefkow, U. Seljak, V. Sharma, S. R. Sharpe, V. Shiltsev, G. Signorelli, M. Silari, F. Simon, T. Sjöstrand, P. Skands, T. Skwarnicki, G. F. Smoot, A. Soffer, M. S. Sozzi, C. Spiering, A. Stahl, Y. Sumino, F. Takahashi, M. Tanabashi, J. Tanaka, M. Taševský, K. Terao, K. Terashi, J. Terning, U. Thoma, R. S. Thorne, L. Tiator, M. Titov, D. R. Tovey, K. Trabelsi, P. Urquijo, G. Valencia, R. Van de Water,

References

N. Varelas, L. Verde, I. Vivarelli, P. Vogel, W. Vogelsang, V. Vorobyev, S. P. Wakely, W. Walkowiak, C. W. Walter, D. Wands, D. H. Weinberg, E. J. Weinberg, N. Wermes, M. White, L. R. Wiencke, S. Willocq, C. L. Woody, R. L. Workman, W.-M. Yao, M. Yokoyama, R. Yoshida, G. Zanderighi, G. P. Zeller, R.-Y. Zhu, S.-L. Zhu, F. Zimmermann, P. A. Zyla, J. Anderson, M. Kramer, P. Schaffner, and W. Zheng, *Review of particle physics*, Phys. Rev. D **110** (Aug, 2024) 030001.

[9] J. Terning, *Modern Supersymmetry: Dynamics and Duality*. Oxford University Press, Oxford, 2006.