SUSY2013 @ ICTP, Aug 30, 2013

Effective theories of magnetized D-branes and their phenomenological aspects

Hiroyuki Abe

Waseda U., Tokyo, JAPAN

Based on

T. Kobayashi, H. Ohki, K. Sumita & H.A.,
“Superfield description of 10D SYM theory with magnetized extra dimensions”,
Nucl. Phys. B863 (2012) 1-18, arXiv:1204.5327 [hep-th]

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A.,
“Phenomenological aspects of 10D SYM theory with magnetized extra dimensions”,
Nucl. Phys. B870 (2013) 30-54, arXiv:1211.4317 [hep-ph]

in collaboration with
Tatsuo Kobayashi (Kyoto U.), Hiroshi Ohki (KMI, Nagoya U.),
Akane Oikawa & Keigo Sumita (Waseda U.)

Plan of this talk

I. Introduction
II. MSSM from magnetized D9
III. Phenomenological aspects
IV. Summary and prospects

I. INTRODUCTION

Hierarchical elements of our world

	Observed
(m_u, m_c, m_t)	$(2.3 \times 10^{-3}, 1.28, 1.74 \times 10^{2})$
(m_d, m_s, m_b)	$(4.8 \times 10^{-3}, 0.95 \times 10^{-1}, 4.18)$
(m_e, m_μ, m_τ)	$(5.11 \times 10^{-4}, 1.06 \times 10^{-1}, 1.78)$
$\lvert V_{\rm CKM} \rvert$	$\begin{pmatrix} 0.97 & 0.23 & 0.0035 \\ 0.23 & 0.97 & 0.041 \\ 0.0087 & 0.040 & 1.0 \end{pmatrix}$

	Observed
$(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$	$< 2 \times 10^{-9}$
$\lvert m^2_{\nu_1} - m^2_{\nu_2} \rvert$	7.50×10^{-23}
$\lvert m^2_{\nu_1} - m^2_{\nu_3} \rvert$	2.32×10^{-21}
$\lvert V_{\rm PMNS} \rvert$	$\begin{pmatrix} 0.82 & 0.55 & 0.16 \\ 0.51 & 0.58 & 0.64 \\ 0.26 & 0.61 & 0.75 \end{pmatrix}$

Dimensionful parameters in GeV unit

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Dimensionful parameters in GeV unit

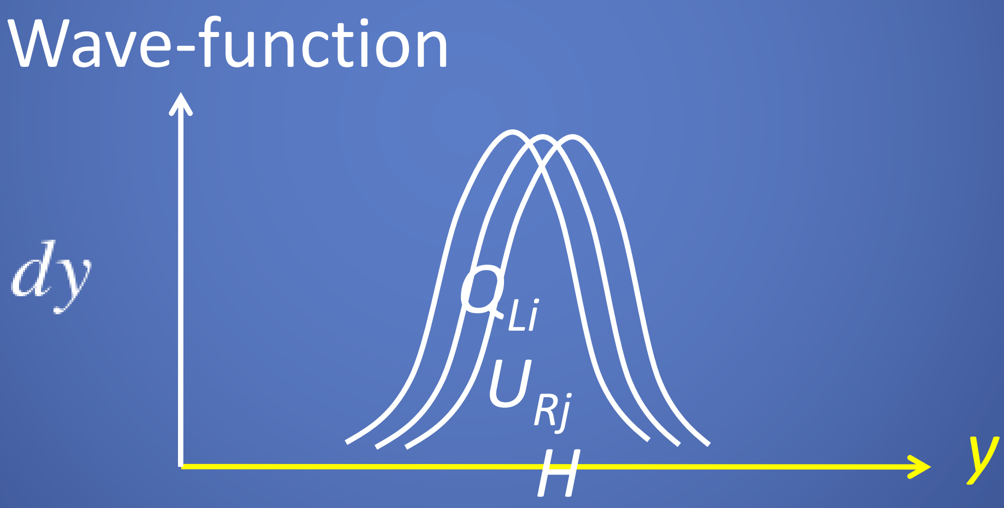
God put the hierarchy among the elements?

Hierarchy by dynamics

N. Arkani-Hamed & M. Schmaltz '00

Y_{ij} can be determined by an overlap integral of wave-functions in extra dims

$$Y_{ij} = \int dy$$



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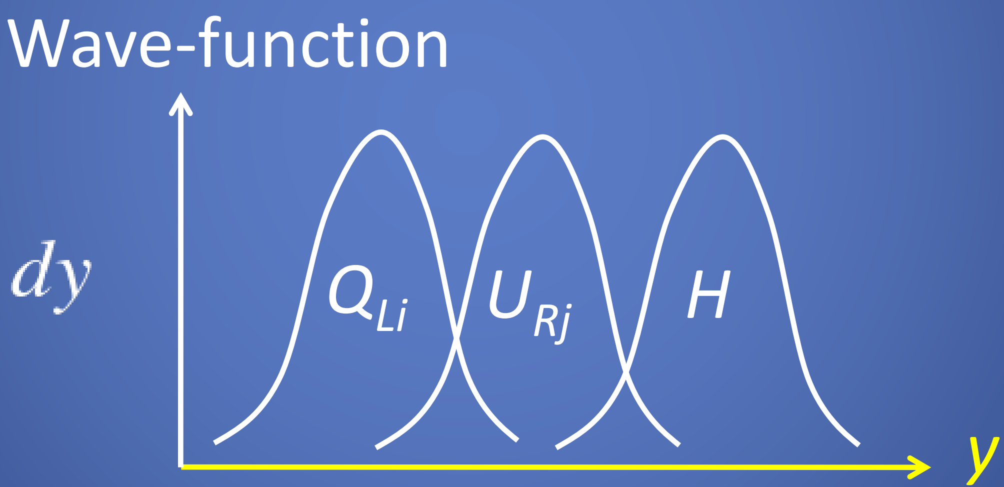
Hierarchy by dynamics

N. Arkani-Hamed & M. Schmaltz '00

Y_{ij} can be determined by an overlap integral of wave-functions in extra dims

$$Y_{ij} = \int dy \quad \sim 10^{-5}$$



Nontrivial wave-function profile can be a source of hierarchy in 4D spacetime

A toy model

- 6D U(1) gauge theory $\quad$ *M*, *N* = 0, 1, 2, 3, 4, 5

$$\mathcal{L} = -\frac{1}{4g^2} F^{MN} F_{MN} + \frac{i}{2g^2} \bar{\lambda} \Gamma^M D_M \lambda$$

$$F_{MN} = \partial_M A_N - \partial_N A_M \qquad D_M \lambda = (\partial_M - i A_M) \lambda$$

A toy model

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- Torus compactification $x_M = (x_\mu, y_m)$ $m = 4,5$

$$y_m \sim y_m + 1$$

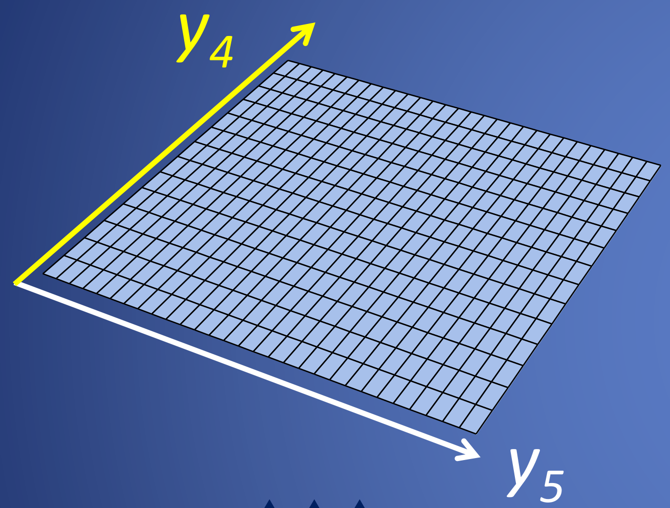
$$\lambda(x,y) = \sum_n \chi_n(x) \otimes \psi_n(y),$$
$$A_m(x,y) = \sum_n \varphi_{n,m}(x) \otimes \phi_{n,m}(y)$$

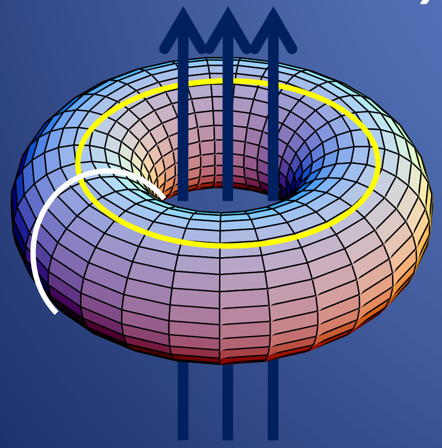
Magnetic flux in T^2

$$B = F_{45} = 2\pi M$$

M = integer (Dirac quantization condition)

$$A_4 = 0\,, \quad A_5 = 2\pi M y_4$$





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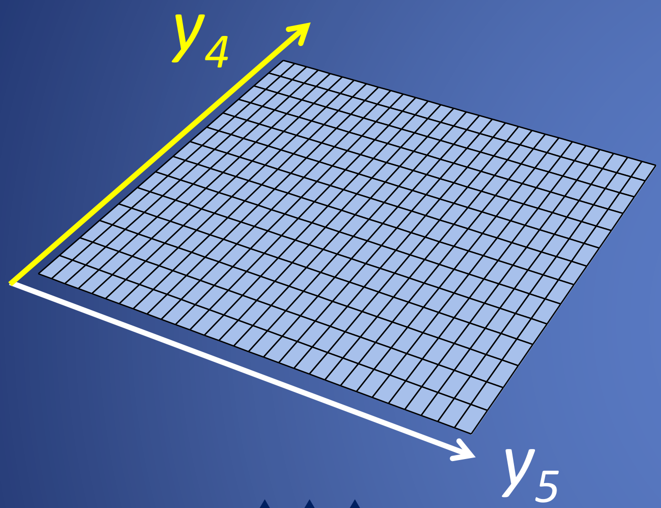
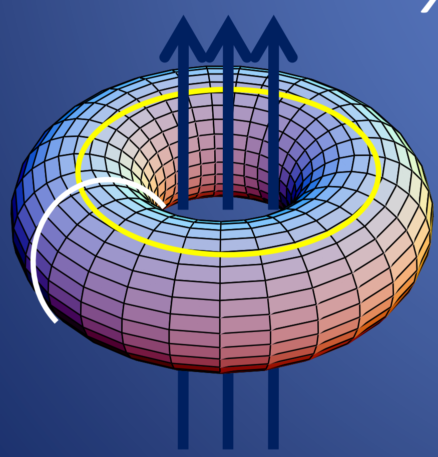


$$A_4 = 0\,, \quad A_5 = 2\pi M y_4$$

$$A_m(y_4+1, y_5) = A_m(y_4, y_5) + \partial_m \chi_4$$
$$A_m(y_4, y_5+1) = A_m(y_4, y_5) + \partial_m \chi_5$$



$$\psi(y_4+1, y_5) = e^{iq\chi_4}\psi(y_4, y_5)$$
$$\psi(y_4, y_5+1) = e^{iq\chi_5}\psi(y_4, y_5)$$

$$\chi_4 = 2\pi M y_5,$$
$$\chi_5 = 0.$$

Properties of the zero-modes

D. Cremades, L. E. Ibanez & F. Marchesano '04

***M* chiral zero-modes** *j = 0, 1, 2, …, M - 1*

$$\psi_+^j = \Theta^j(y_4, y_5) = N_j e^{-M\pi y_4^2} \vartheta \begin{bmatrix} j/M \\ 0 \end{bmatrix} (M(y_4 + i y_5), Mi)$$

$\psi_- = 0$: no normalizable zero-modes

Properties of the zero-modes

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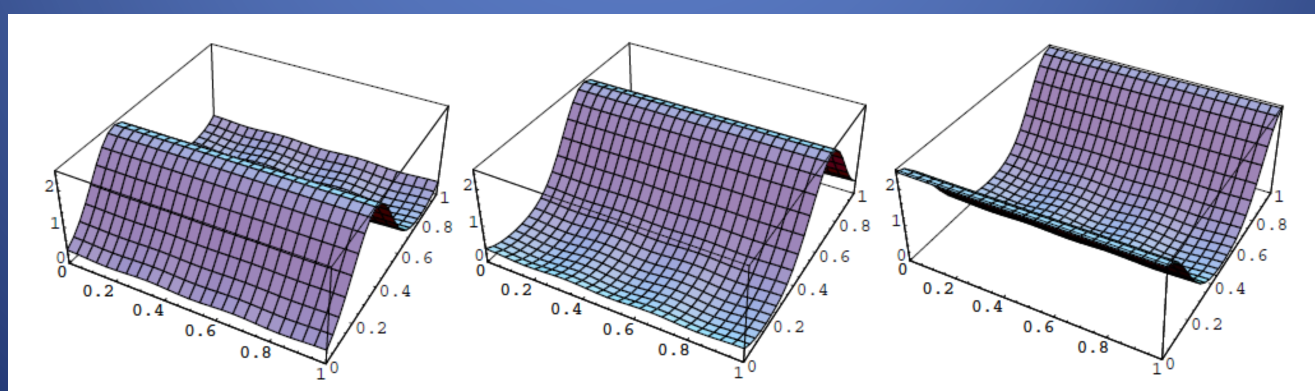
Wavefunction localization $|\psi_+^j|^2$, $M = 3$



II. MSSM FROM MAGNETIZED D9

10D $U(N)$ SYM theory

The action

$$S = \int d^{10}X \sqrt{-G}\,\frac{1}{g^2}\,\mathrm{Tr}\left[-\frac{1}{4}F^{MN}F_{MN} + \frac{i}{2}\bar{\lambda}\Gamma^M D_M\lambda\right]$$

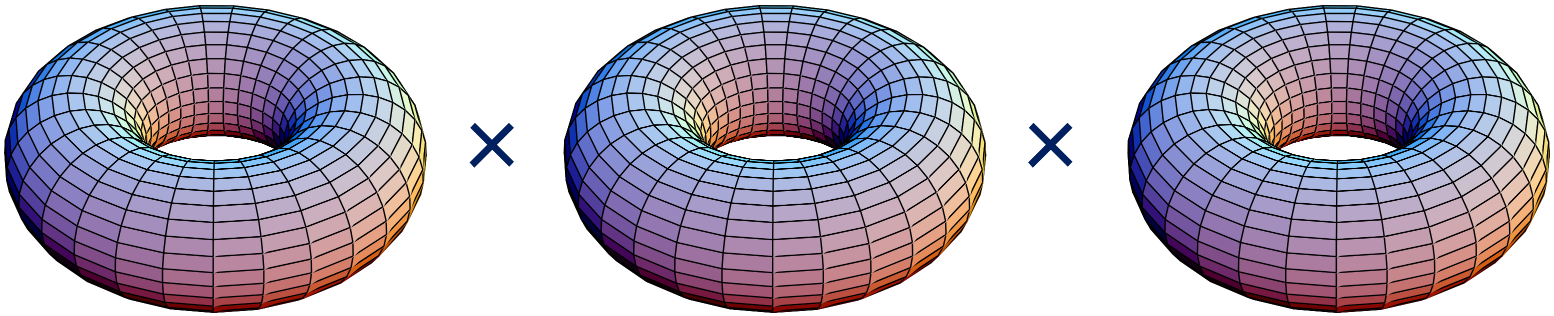
$$\begin{aligned} F_{MN} &= \partial_M A_N - \partial_N A_M - i[A_M, A_N], \\ D_M\lambda &= \partial_M\lambda - i[A_M, \lambda], \end{aligned}$$

10D vector ： A_M （M = 0, 1, 2, … , 9）

10D Majorana-Weyl spinor ： λ $\lambda^C = \lambda$ $\Gamma\lambda = +\lambda$

Periods and areas

The torus compactification $T^2 \times T^2 \times T^2$



The periods

$$y^m \sim y^m + 2$$

$$g_{mn} = \begin{pmatrix} g^{(1)} & 0 & 0 \\ 0 & g^{(2)} & 0 \\ 0 & 0 & g^{(3)} \end{pmatrix}$$

Periods and areas

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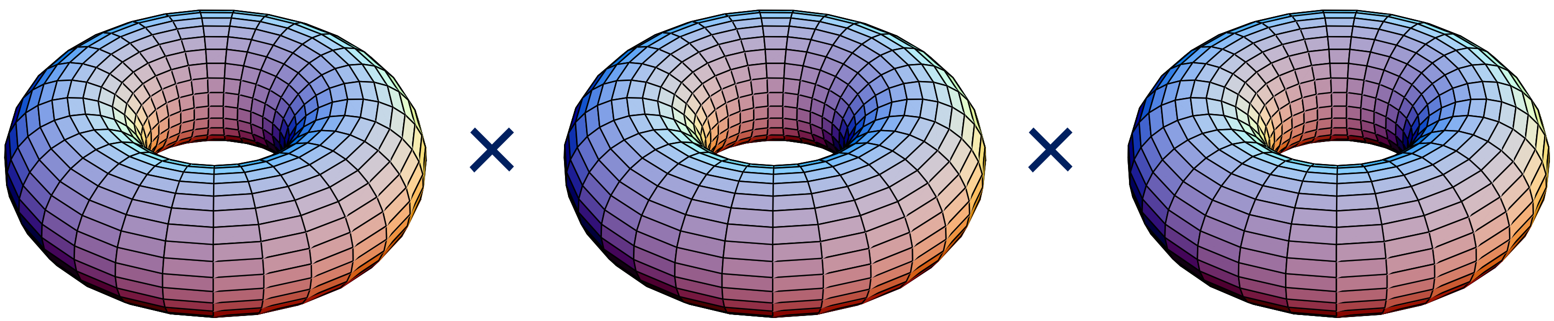


The periods

$$y^m \sim y^m + 2$$

τ_i : the complex structure

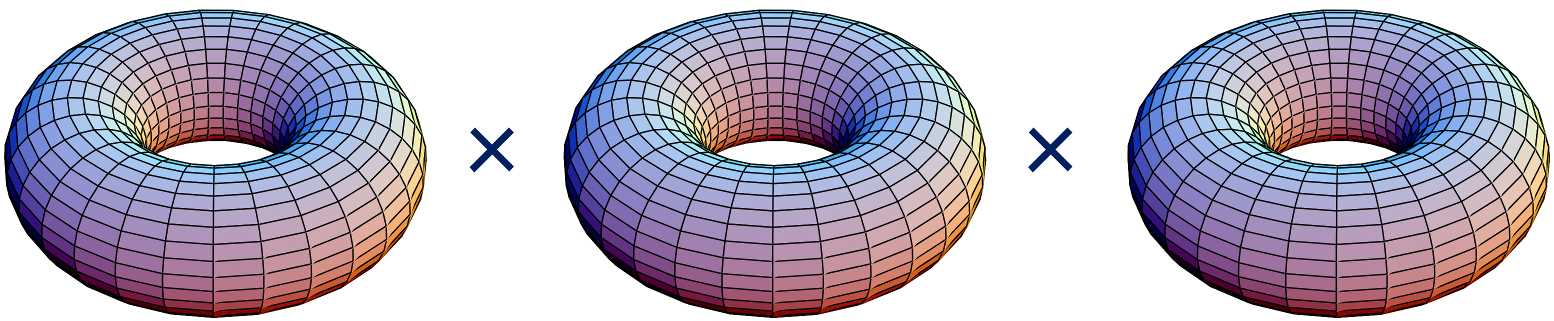
$$g_{mn} = \begin{pmatrix} g^{(1)} & 0 & 0 \\ 0 & g^{(2)} & 0 \\ 0 & 0 & g^{(3)} \end{pmatrix}$$

$$g^{(i)} = (2\pi R_i)^2 \begin{pmatrix} 1 & \mathrm{Re}\,\tau_i \\ \mathrm{Re}\,\tau_i & |\tau_i|^2 \end{pmatrix}$$

$i = 1,2,3$

Periods and areas

The torus compactification $T^2 \times T^2 \times T^2$



The periods

$$y^m \sim y^m + 2$$

The area of each T^2

$$\mathcal{A}^{(i)} = (2\pi R_i)^2 \, \mathrm{Im}\, \tau_i$$

$i = 1,2,3$

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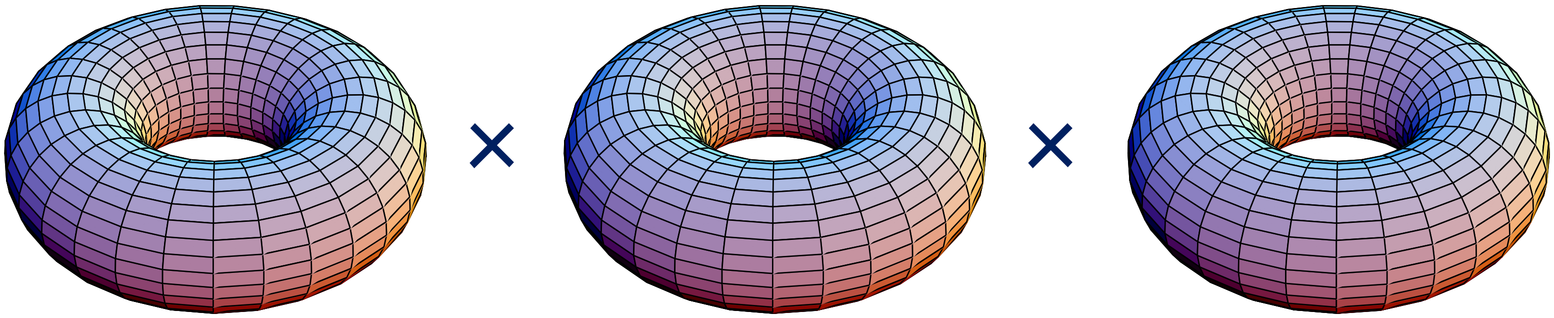

τ_i : the complex structure

The complex coordinate

$$z^i \equiv \frac{1}{2}(y^{2+2i} + \tau_i\, y^{3+2i}), \qquad z^{\bar{i}} \equiv (z^i)^*,$$

$i = 1,2,3$

4D decomposition

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

10D vector : $A_M = (A_\mu, A_m) = (A_\mu, A_i)$ $\quad i = 1,2,3$

4D vector & three complex scalars

10D Majorana-Weyl spinor : $\lambda = (\lambda_0, \lambda_i)$

Four 4D Weyl spinors

4D decomposition

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Four 4D Weyl spinors

$$\Gamma^{(i)}\lambda_0 = +\lambda_0, \qquad \Gamma^{(i)}\lambda_j = +\lambda_j \quad (i = j), \qquad \Gamma^{(i)}\lambda_j = -\lambda_j \quad (i \neq j),$$

$\Gamma^{(i)}$: The chirality operator for 6D spacetime (x_μ, z_i)

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Four 4D Weyl spinors

$$\lambda_0 = \lambda_{+++}, \qquad \lambda_1 = \lambda_{+--}, \qquad \lambda_2 = \lambda_{-+-}, \qquad \lambda_3 = \lambda_{--+}.$$

$$\Gamma^{(i)}\lambda_0 = +\lambda_0, \qquad \Gamma^{(i)}\lambda_j = +\lambda_j \quad (i=j), \qquad \Gamma^{(i)}\lambda_j = -\lambda_j \quad (i \neq j),$$

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$\mathcal{N} = 1$ supermultiplets : $V = \{A_\mu, \lambda_0\}, \quad \phi_i = \{A_i, \lambda_i\}$

4D decomposition

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

10D vector : $A_M = (A_\mu, A_m) = (A_\mu, A_i)$ $i = 1,2,3$

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$\mathcal{N}=1$ supermultiplets : $\boldsymbol{V} = \{A_\mu, \lambda_0\}, \quad \phi_i = \{A_i, \lambda_i\}$

$\mathcal{N}=1$ superfields :

$$V \equiv -\theta\sigma^\mu\bar{\theta}A_\mu + i\bar{\theta}\bar{\theta}\theta\lambda_0 - i\theta\theta\bar{\theta}\bar{\lambda}_0 + \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}D,$$

$$\phi_i \equiv \frac{1}{\sqrt{2}}A_i + \sqrt{2}\theta\lambda_i + \theta\theta F_i,$$

Abelian Flux background

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

The Abelian flux & WL in 10D $U(N)$ SYM

$$\langle A_i \rangle = \frac{\pi}{\mathrm{Im}\,\tau_i}\left(M^{(i)}\,\bar{z}_{\bar{i}} + \bar{\zeta}_i\right)$$

$$M^{(i)} = \mathrm{diag}(M_1^{(i)}, M_2^{(i)}, \ldots, M_N^{(i)}),$$ Magnetic fluxes

$$\zeta_i = \mathrm{diag}(\zeta_1^{(i)}, \zeta_2^{(i)}, \ldots, \zeta_N^{(i)}),$$ Wilson-lines

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We take $N = 8$ in the following model building

10D U(8) SYM model

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

The Abelian flux U(8) → $U(4)_C \times U(2)_L \times U(2)_R$

$$F_{2+2r,3+2r} = 2\pi \begin{pmatrix} M_C^{(r)}\mathbf{1}_4 & & \\ & M_L^{(r)}\mathbf{1}_2 & \\ & & M_R^{(r)}\mathbf{1}_2 \end{pmatrix}$$

$r = 1,2,3$

10D U(8) SYM model

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$r = 1,2,3$

Wilson-lines $\rightarrow U(3)_C \times U(2)_L \times U(1)_{C'} \times U(1)_{R'} \times U(1)_{R''}$

$$\zeta_r = \begin{pmatrix} \zeta_C^{(r)} \mathbf{1}_3 & & & & \\ & \zeta_{C'}^{(r)} & & & \\ & & \zeta_L^{(r)} \mathbf{1}_2 & & \\ & & & \zeta_{R'}^{(r)} & \\ & & & & \zeta_{R''}^{(r)} \end{pmatrix}$$

Flux-induced three generations

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

Flux ansatz

$$
\begin{aligned}
(M_C^{(1)}, M_L^{(1)}, M_R^{(1)}) &= (0, +3, -3),\\
(M_C^{(2)}, M_L^{(2)}, M_R^{(2)}) &= (0, -1, 0),\\
(M_C^{(3)}, M_L^{(3)}, M_R^{(3)}) &= (0, 0, +1),
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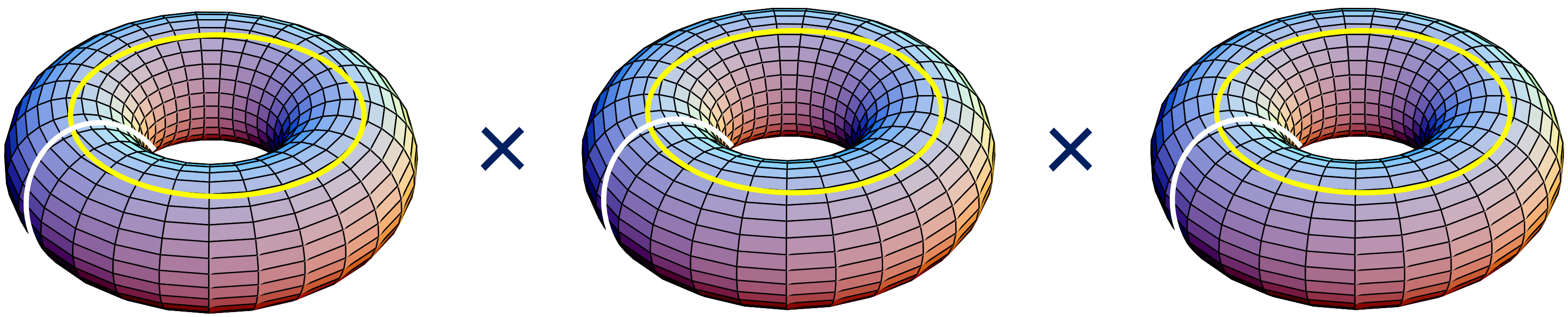

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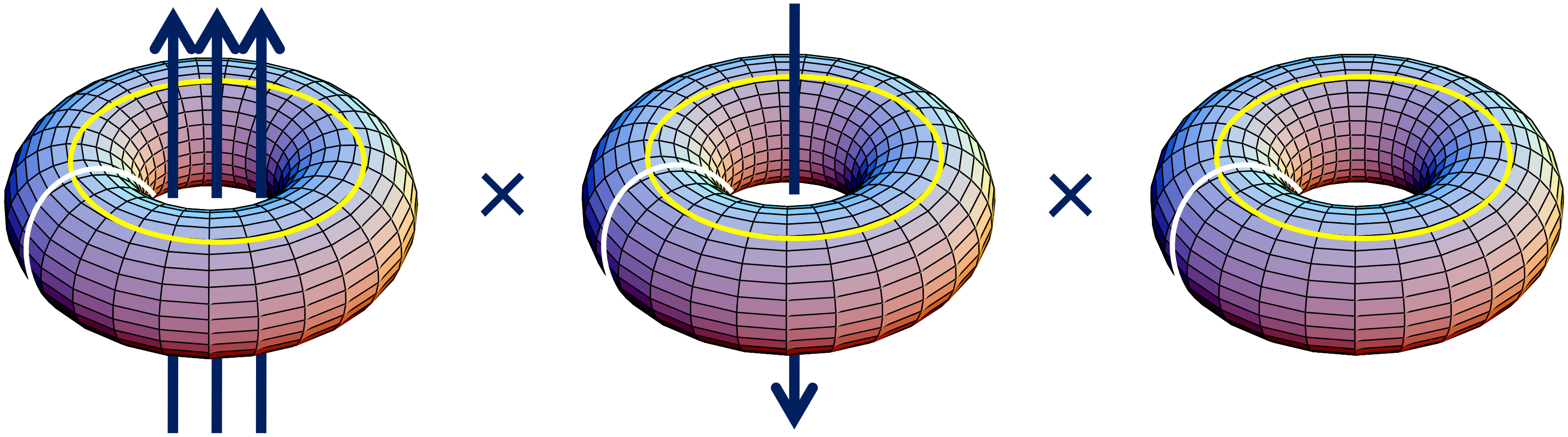

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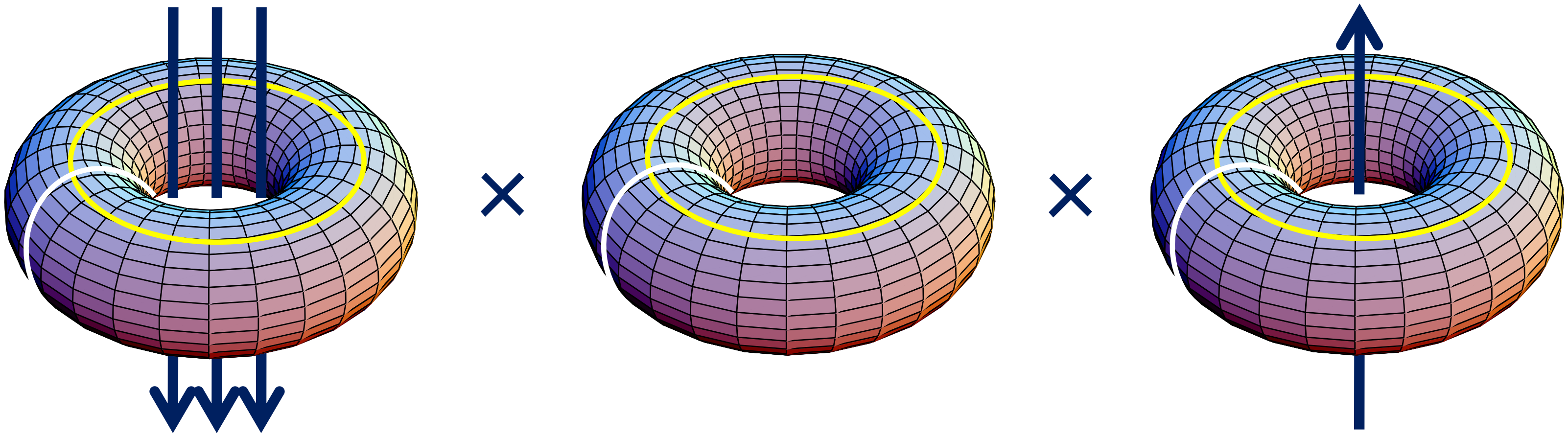

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$$

→ Three generations of quarks and leptons and six generations of Higgs

SUSY conditions

T. Kobayashi, H. Ohki, K. Sumita & H.A. ’12

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→ Three generations of quarks and leptons and six generations of Higgs

SUSY conditions

$$\langle A_i \rangle = \frac{\pi}{\mathrm{Im}\,\tau_i}\left(M^{(i)}\,\bar{z}_{\bar{i}} + \bar{\zeta}_i\right)$$

$$\begin{aligned} h^{\bar{i}j}\left(\bar{\partial}_{\bar{i}}\langle A_j\rangle + \partial_j\langle \bar{A}_{\bar{i}}\rangle\right) &= 0,\\ \epsilon^{\mathrm{jkl}} e_{\mathrm{k}}{}^{k} e_{\mathrm{l}}{}^{l}\partial_k\langle A_l\rangle &= 0,\end{aligned}$$

SUSY conditions

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

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\epsilon^{\mathrm{jkl}} e_{\mathrm{k}}{}^{k} e_{\mathrm{l}}{}^{l} \partial_k \langle A_l \rangle &= 0,
\end{aligned}
$$

⇔ $\mathcal{A}^{(1)}/\mathcal{A}^{(2)} = \mathcal{A}^{(1)}/\mathcal{A}^{(3)} = 3$

SUSY conditions

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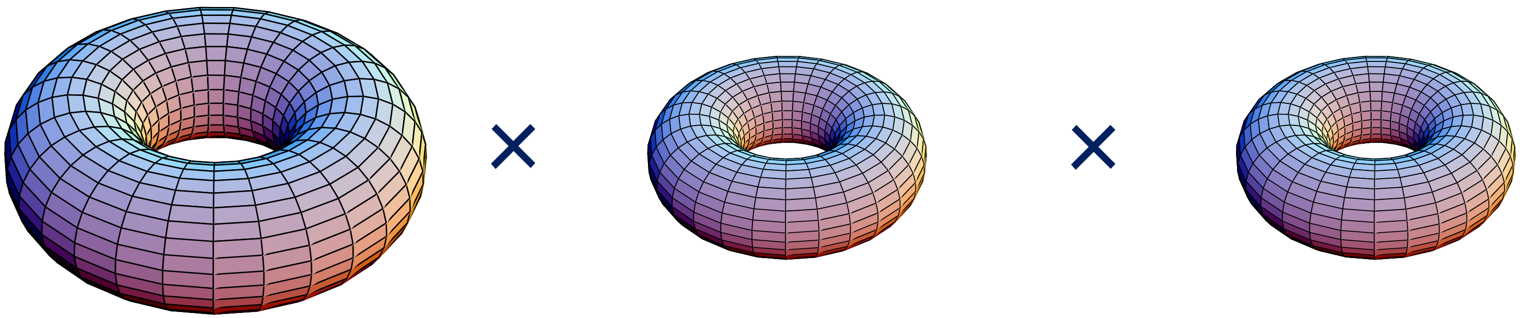
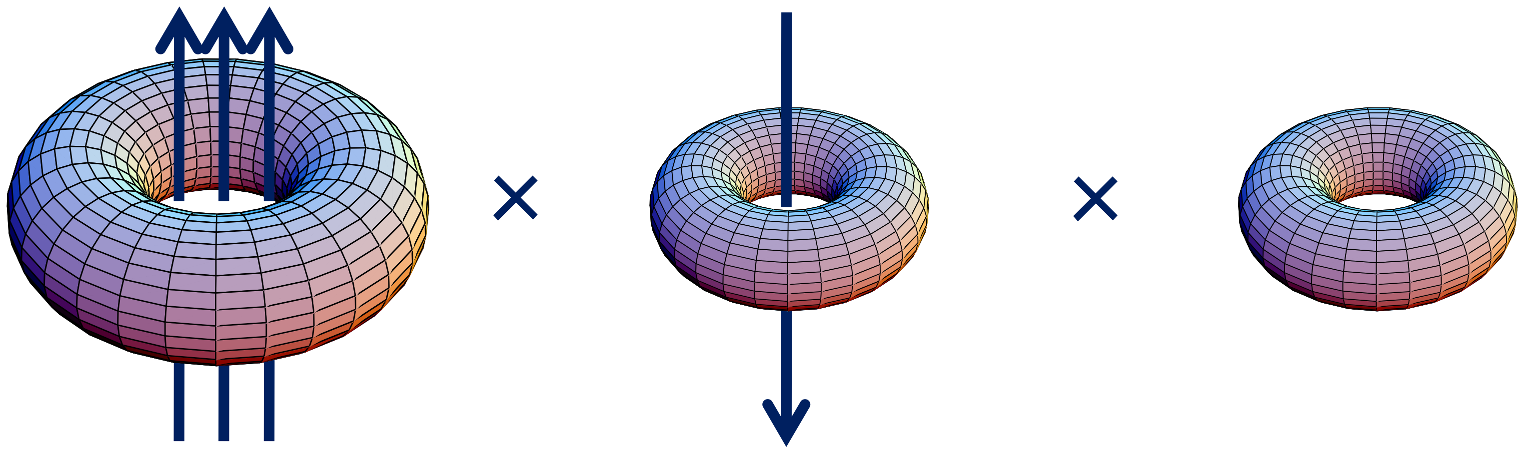


SUSY conditions

$$\begin{aligned} h^{\bar{i}j}\left(\bar{\partial}_{\bar{i}}\langle A_j\rangle + \partial_j\langle \bar{A}_{\bar{i}}\rangle\right) &= 0, \\ \epsilon^{\mathrm{jkl}} e_{\mathrm{k}}{}^{k} e_{\mathrm{l}}{}^{l} \partial_k\langle A_l\rangle &= 0, \end{aligned} \quad \Leftrightarrow \quad \mathcal{A}^{(1)}/\mathcal{A}^{(2)} = \mathcal{A}^{(1)}/\mathcal{A}^{(3)} = 3$$

SUSY conditions

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

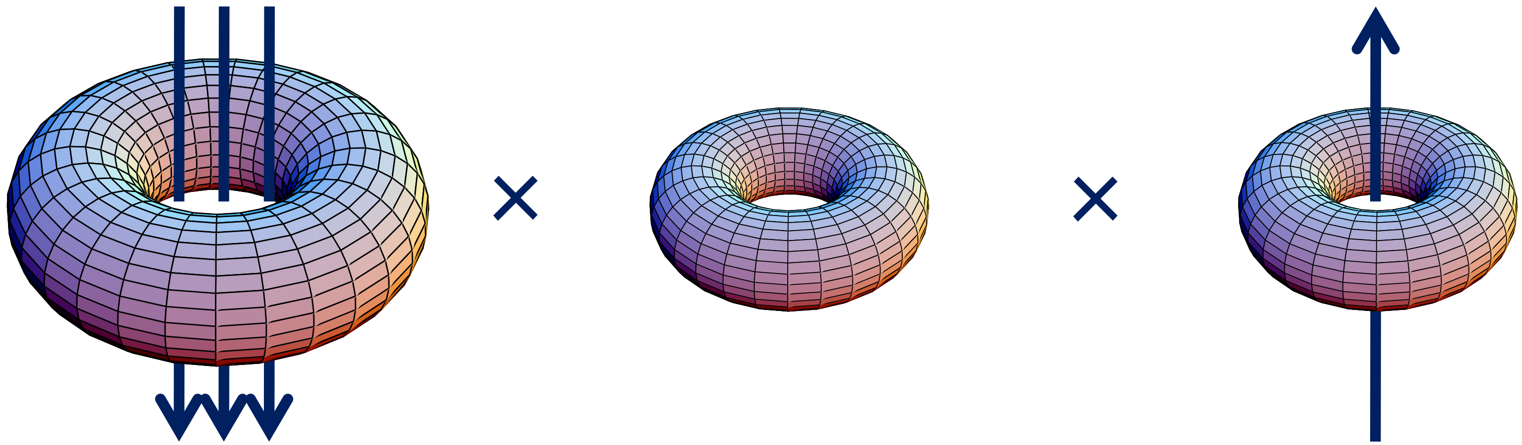


SUSY conditions

$$\begin{aligned} h^{\bar{i}j}\left(\bar{\partial}_{\bar{i}}\langle A_j\rangle + \partial_j\langle \bar{A}_{\bar{i}}\rangle\right) &= 0, \\ \epsilon^{\mathrm{jkl}} e_{\mathrm{k}}{}^{k} e_{\mathrm{l}}{}^{l} \partial_k \langle A_l\rangle &= 0, \end{aligned} \quad \Leftrightarrow \quad \mathcal{A}^{(1)}/\mathcal{A}^{(2)} = \mathcal{A}^{(1)}/\mathcal{A}^{(3)} = 3$$

SUSY conditions

T. Kobayashi, H. Ohki, K. Sumita & H.A. ’12



SUSY conditions

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\epsilon^{\mathrm{jkl}} e_{\mathrm{k}}{}^{k} e_{\mathrm{l}}{}^{l} \partial_k \langle A_l\rangle &= 0,
\end{aligned}
\quad \Leftrightarrow \quad \mathcal{A}^{(1)}/\mathcal{A}^{(2)} = \mathcal{A}^{(1)}/\mathcal{A}^{(3)} = 3
$$

Matter zero-modes

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. ’13

Zero-modes in ϕ_i

$$\phi_1^{\mathcal{I}_{ab}} = \left(\begin{array}{cc|c|cc} \Omega_C^{(1)} & \Xi_{CC'}^{(1)} & 0 & \Xi_{CR'}^{(1)} & \Xi_{CR''}^{(1)} \\ \Xi_{C'C}^{(1)} & \Omega_{C'}^{(1)} & 0 & \Xi_{C'R'}^{(1)} & \Xi_{C'R''}^{(1)} \\ \hline \Xi_{LC}^{(1)} & \Xi_{LC'}^{(1)} & \Omega_L^{(1)} & H_u^K & H_d^K \\ \hline 0 & 0 & 0 & \Omega_{R'}^{(1)} & \Xi_{R'R''}^{(1)} \\ 0 & 0 & 0 & \Xi_{R''R'}^{(1)} & \Omega_{R''}^{(1)} \end{array}\right)$$

$$\phi_2^{\mathcal{I}_{ab}} = \left(\begin{array}{cc|c|cc} \Omega_C^{(2)} & \Xi_{CC'}^{(2)} & Q^I & 0 & 0 \\ \Xi_{C'C}^{(2)} & \Omega_{C'}^{(2)} & L^I & 0 & 0 \\ \hline 0 & 0 & \Omega_L^{(2)} & 0 & 0 \\ \hline 0 & 0 & 0 & \Omega_{R'}^{(2)} & \Xi_{R'R''}^{(2)} \\ 0 & 0 & 0 & \Xi_{R''R'}^{(2)} & \Omega_{R''}^{(2)} \end{array}\right)$$

$$\phi_3^{\mathcal{I}_{ab}} = \left(\begin{array}{cc|c|cc} \Omega_C^{(3)} & \Xi_{CC'}^{(3)} & 0 & 0 & 0 \\ \Xi_{C'C}^{(3)} & \Omega_{C'}^{(3)} & 0 & 0 & 0 \\ \hline 0 & 0 & \Omega_L^{(3)} & 0 & 0 \\ \hline U^J & N^J & 0 & \Omega_{R'}^{(3)} & \Xi_{R'R''}^{(3)} \\ D^J & E^J & 0 & \Xi_{R''R'}^{(3)} & \Omega_{R''}^{(3)} \end{array}\right)$$

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Matter zero-modes

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. '13

Zero-modes in ϕ_i

Six generations of Higgs (K = 1,2,…,6)

Three generations of left-handed quarks and leptons (I = 1,2,3)

$$\phi_1^{\mathcal{I}_{ab}} = \left(\begin{array}{cc|c|cc} \Omega_C^{(1)} & \Xi_{CC'}^{(1)} & 0 & \Xi_{CR'}^{(1)} & \Xi_{CR''}^{(1)} \\ \Xi_{C'C}^{(1)} & \Omega_{C'}^{(1)} & 0 & \Xi_{C'R'}^{(1)} & \Xi_{C'R''}^{(1)} \\ \hline \Xi_{LC}^{(1)} & \Xi_{LC'}^{(1)} & \Omega_L^{(1)} & H_u^K & H_d^K \\ \hline 0 & 0 & 0 & \Omega_{R'}^{(1)} & \Xi_{R'R''}^{(1)} \\ 0 & 0 & 0 & \Xi_{R''R'}^{(1)} & \Omega_{R''}^{(1)} \end{array}\right) \qquad \phi_2^{\mathcal{I}_{ab}} = \left(\begin{array}{cc|c|cc} \Omega_C^{(2)} & \Xi_{CC'}^{(2)} & Q^I & 0 & 0 \\ \Xi_{C'C}^{(2)} & \Omega_{C'}^{(2)} & L^I & 0 & 0 \\ \hline 0 & 0 & \Omega_L^{(2)} & 0 & 0 \\ \hline 0 & 0 & 0 & \Omega_{R'}^{(2)} & \Xi_{R'R''}^{(2)} \\ 0 & 0 & 0 & \Xi_{R''R'}^{(2)} & \Omega_{R''}^{(2)} \end{array}\right)$$

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Three generations of right-handed quarks and leptons (J = 1,2,3)

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T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. '13

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Three generations of right-handed quarks and leptons (J = 1,2,3)

on orbifold T^6/Z_2

Matter zero-modes

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. '13

Zero-modes in ϕ_i on orbifold T^6/Z_2

$$\phi_1^{\mathcal{I}_{ab}} = \left(\begin{array}{cc|c|cc} \Omega_C^{(1)} & \Xi_{CC'}^{(1)} & 0 & 0 & 0 \\ \Xi_{C'C}^{(1)} & \Omega_{C'}^{(1)} & 0 & 0 & 0 \\ \hline 0 & 0 & \Omega_L^{(1)} & H_u^K & H_d^K \\ \hline 0 & 0 & 0 & \Omega_{R'}^{(1)} & \Xi_{R'R''}^{(1)} \\ 0 & 0 & 0 & \Xi_{R''R'}^{(1)} & \Omega_{R''}^{(1)} \end{array}\right)$$

$$\phi_2^{\mathcal{I}_{ab}} = \left(\begin{array}{cc|c|cc} 0 & 0 & Q^I & 0 & 0 \\ 0 & 0 & L^I & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{array}\right)$$

$$\phi_3^{\mathcal{I}_{ab}} = \left(\begin{array}{cc|c|cc} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & 0 \\ \hline U^J & N^J & 0 & 0 & 0 \\ D^J & E^J & 0 & 0 & 0 \end{array}\right)$$

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T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. '13

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We assume the remaining exotics (as well as extra U(1) gauge bosons) become massive due to some nonperturbative and/or higher-order (and/or anomaly and/or Higgs) effects

4D effective action

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

(Extended to local SUSY)

$$S_{\mathcal{N}=1} = \int d^4x\sqrt{-g^C}\Big[-3\int d^4\theta\,\bar{C}C\,e^{-K/3} + \Big\{\int d^2\theta\Big(\frac{1}{4}\sum_a f_a W^{a,\alpha}W^a_\alpha + C^3 W\Big) + \text{h.c.}\Big\}\Big]$$

$$\begin{aligned}
K &= K^{(0)}(\bar{\Phi}^{\bar{m}},\Phi^m) + Z^{(\mathcal{Q})}_{\bar{\mathcal{I}}\mathcal{J}}(\bar{\Phi}^{\bar{m}},\Phi^m)\bar{\mathcal{Q}}^{\bar{\mathcal{I}}}\mathcal{Q}^{\mathcal{J}},\\
W &= \lambda^{(\mathcal{Q})}_{\mathcal{I}\mathcal{J}\mathcal{K}}(\Phi^m)\mathcal{Q}^{\mathcal{I}}\mathcal{Q}^{\mathcal{J}}\mathcal{Q}^{\mathcal{K}},\\
f_a &= S \quad (a=1,2,3),
\end{aligned}$$

$$\mathcal{Q}^{\mathcal{I}} = \{Q^I, U^J, D^J, L^I, N^J, E^J, H_u^K, H_d^K\}, \qquad \Phi^m = \{S, T_r, U_r\},$$

4D effective action

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

- S : dilaton
- T_r : Kähler moduli
- U_r : complex structure moduli

from the rth T^2 (r = 1,2,3)

$$K = K^{(0)}(\bar{\Phi}^{\bar{m}}, \Phi^m) + Z^{(\mathcal{Q})}_{\bar{\mathcal{I}}\mathcal{J}}(\bar{\Phi}^{\bar{m}}, \Phi^m)\bar{\mathcal{Q}}^{\bar{\mathcal{I}}}\mathcal{Q}^{\mathcal{J}},$$

$$W = \lambda^{(\mathcal{Q})}_{\mathcal{I}\mathcal{J}\mathcal{K}}(\Phi^m)\mathcal{Q}^{\mathcal{I}}\mathcal{Q}^{\mathcal{J}}\mathcal{Q}^{\mathcal{K}},$$

$$f_a = S \quad (a = 1, 2, 3),$$

Moduli dependence completely deatermined at the leading order

$$\mathcal{Q}^{\mathcal{I}} = \{Q^I, U^J, D^J, L^I, N^J, E^J, H_u^K, H_d^K\}, \qquad \Phi^m = \{S, T_r, U_r\},$$

4D effective action

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

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$$W = \lambda^{(\mathcal{Q})}_{\mathcal{I}\mathcal{J}\mathcal{K}}(\Phi^m)\mathcal{Q}^{\mathcal{I}}\mathcal{Q}^{\mathcal{J}}\mathcal{Q}^{\mathcal{K}},$$

$$\lambda^{(Q_y)}_{IJK}(\Phi^m) = \sum_{m=1}^{6} \delta_{I+J+3(m-1),K}\,\vartheta\begin{bmatrix} \frac{3(I-J)+9(m-1)}{54} \\ 0 \end{bmatrix}\left(3\left(\bar{\zeta}_{Q_L} - \bar{\zeta}_{Q_R}\right), 54iU_1\right)$$

III. PHENOMENOLOGICAL ASPECTS OF MAGNETIZED D9

Sample values of parameters

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. '13

Higgs VEVs

$v_u = v \sin\beta,\ v_d = v\cos\beta$ and $v = 174$ GeV

$$\begin{aligned} \tan\beta &= 25 \\ \langle H_u^K \rangle &= (0.0,\ 0.0,\ 2.7,\ 1.3,\ 0.0,\ 0.0)\, v_u \times \mathcal{N}_{H_u}, \\ \langle H_d^K \rangle &= (0.0,\ 0.1,\ 5.8,\ 5.8,\ 0.0,\ 0.1)\, v_d \times \mathcal{N}_{H_d}, \end{aligned}$$

$$\mathcal{N}_{H_u} = 1/\sqrt{2.7^2 + 1.3^2}$$

$$\mathcal{N}_{H_d} = 1/\sqrt{2(0.1^2 + 5.8^2)}$$

Sample values of parameters

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. '13

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$$\begin{aligned}
\tan\beta &= 25 \\
\langle H_u^K \rangle &= (0.0,\, 0.0,\, 2.7,\, 1.3,\, 0.0,\, 0.0)\, v_u \times \mathcal{N}_{H_u}, \\
\langle H_d^K \rangle &= (0.0,\, 0.1,\, 5.8,\, 5.8,\, 0.0,\, 0.1)\, v_d \times \mathcal{N}_{H_d},
\end{aligned}$$

$$\mathcal{N}_{H_u} = 1/\sqrt{2.7^2 + 1.3^2}$$

$$\mathcal{N}_{H_d} = 1/\sqrt{2(0.1^2 + 5.8^2)}$$

Moduli VEVs and Wilson-lines

$$\pi s = 6.0, \quad \rightarrow \quad 4\pi/{g_a}^2 = 24 \quad \text{at} \quad M_{\rm GUT} = 2.0 \times 10^{16} \text{ GeV}$$

$$\begin{aligned}
(t_1, t_2, t_3) &= (3.0,\, 1.0,\, 1.0) \times 2.8 \times 10^{-8}, \\
(\tau_1, \tau_2, \tau_3) &= (4.1i,\, 1.0i,\, 1.0i), \\
(\zeta_Q, \zeta_U, \zeta_D, \zeta_L, \zeta_N, \zeta_E) &= (1.0i,\, 1.9i,\, 1.4i,\, 0.7i,\, 2.2i,\, 1.7i),
\end{aligned}$$

Quark masses and CKM mixings

as well as charged lepton masses

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. '13

At the EW scale through 1-loop MSSM RGEs with y_t

	Sample values	Observed
(m_u, m_c, m_t)	$(3.1 \times 10^{-3}, 1.01, 1.70 \times 10^{2})$	$(2.3 \times 10^{-3}, 1.28, 1.74 \times 10^{2})$
(m_d, m_s, m_b)	$(2.8 \times 10^{-3}, 1.48 \times 10^{-1}, 6.46)$	$(4.8 \times 10^{-3}, 0.95 \times 10^{-1}, 4.18)$
(m_e, m_μ, m_τ)	$(4.68 \times 10^{-4}, 5.76 \times 10^{-2}, 3.31)$	$(5.11 \times 10^{-4}, 1.06 \times 10^{-1}, 1.78)$
$\lvert V_{\mathrm{CKM}} \rvert$	$\begin{pmatrix} 0.98 & 0.21 & 0.0023 \\ 0.21 & 0.98 & 0.041 \\ 0.011 & 0.040 & 1.0 \end{pmatrix}$	$\begin{pmatrix} 0.97 & 0.23 & 0.0035 \\ 0.23 & 0.97 & 0.041 \\ 0.0087 & 0.040 & 1.0 \end{pmatrix}$

A semi-realistic pattern from non-hierarchical paramters

Majorana masses for N^J

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. '13

Furthermore, if we assume nonperturbative and/or higher-order effects yielding

$$W_{\rm eff} = M^{(N)}_{IJ} N^I N^J$$

with

$$M^{(N)} = \begin{pmatrix} 1.1 & 1.3 & 0 \\ 1.3 & 0 & 3.2 \\ 0 & 3.2 & 1.8 \end{pmatrix} \times 10^{12}\ {\rm GeV}$$

then …

Neutrino masses and PMNS mixings

as well as the previous charged lepton masses

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. '13

At the EW scale through 1-loop MSSM RGEs with y_t

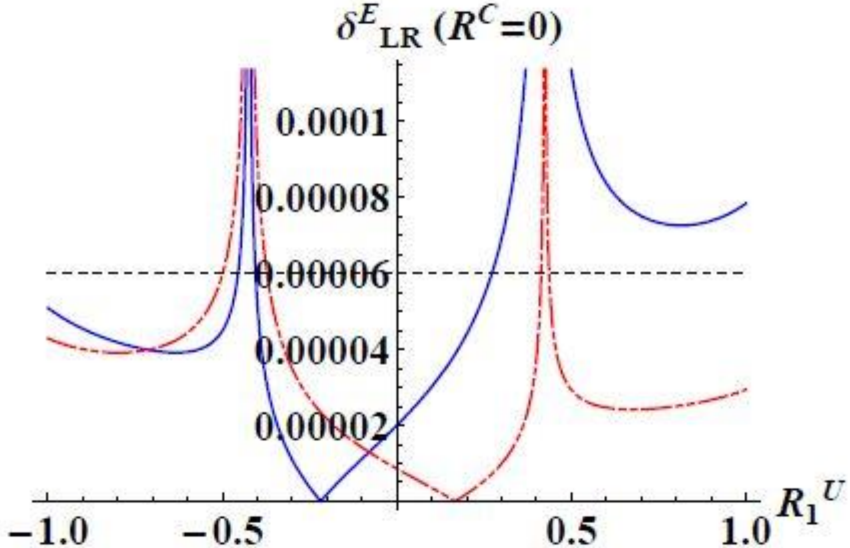
	Sample values	Observed
$(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$	$(3.6 \times 10^{-19}, 8.8 \times 10^{-12}, 2.7 \times 10^{-11})$	$< \ 2 \times 10^{-9}$
$\lvert m_{\nu_1}^2 - m_{\nu_2}^2 \rvert$	7.67×10^{-23}	7.50×10^{-23}
$\lvert m_{\nu_1}^2 - m_{\nu_3}^2 \rvert$	7.12×10^{-22}	2.32×10^{-21}
$\lvert V_{\mathrm{PMNS}} \rvert$	$\begin{pmatrix} 0.85 & 0.46 & 0.25 \\ 0.50 & 0.59 & 0.63 \\ 0.15 & 0.66 & 0.73 \end{pmatrix}$	$\begin{pmatrix} 0.82 & 0.55 & 0.16 \\ 0.51 & 0.58 & 0.64 \\ 0.26 & 0.61 & 0.75 \end{pmatrix}$

A semi-realistic pattern from non-hierarchical paramters

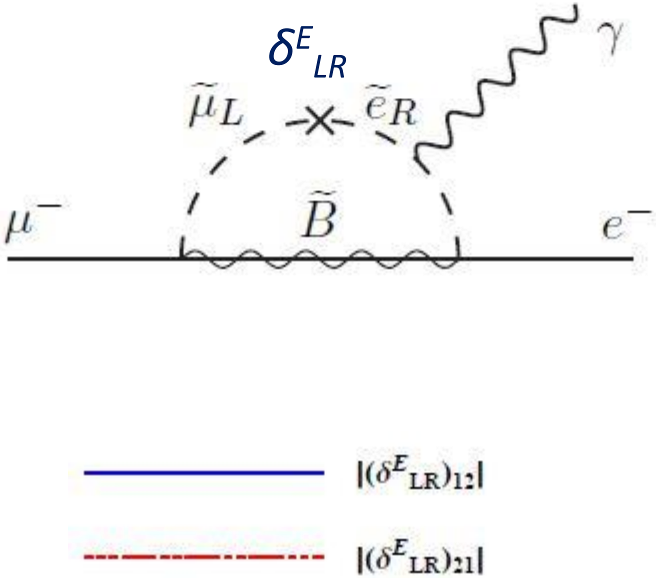
Modulus mediated SUSY flavor violations

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. ’13

The most stringent bound from $\mu \to e\gamma$ on $\delta^E{}_{LR}$



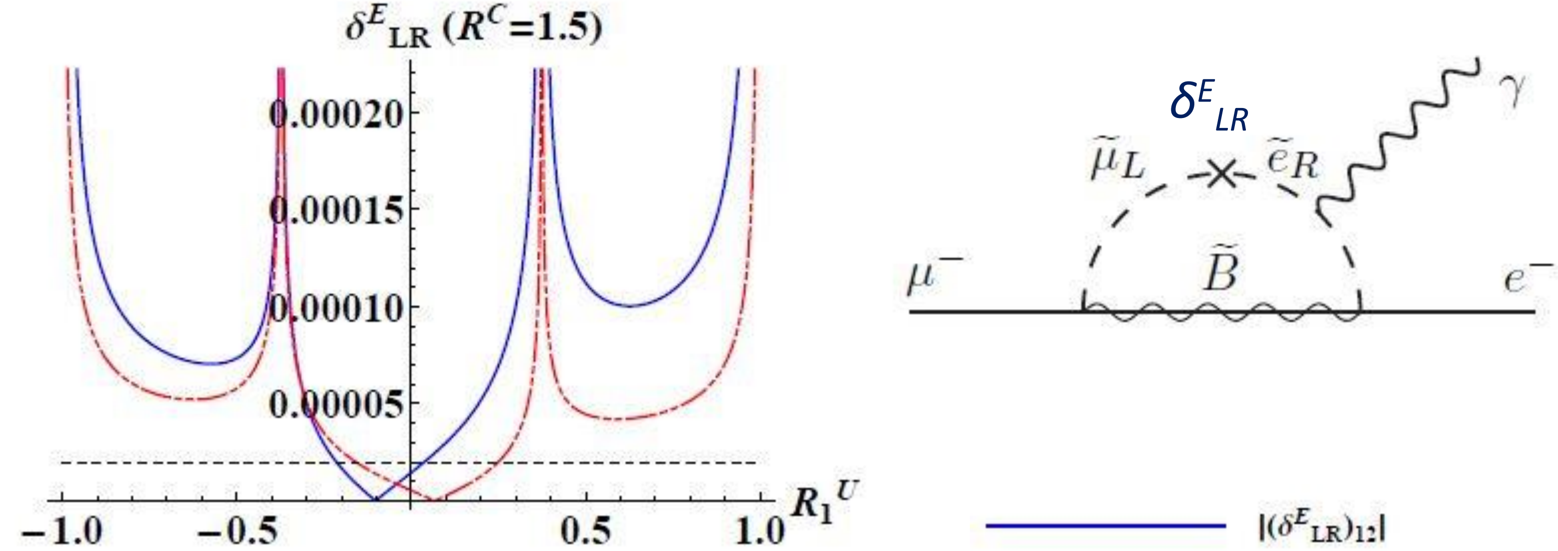
$M_{SB} = 1$ TeV $\quad R^U_{r\neq 1} = 0.9,\ R^T_r = 1$



Modulus & anomaly mediated SUSY flavor violations

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. '13

The most stringent bound from $\mu \to e\gamma$ on $\delta^E{}_{LR}$

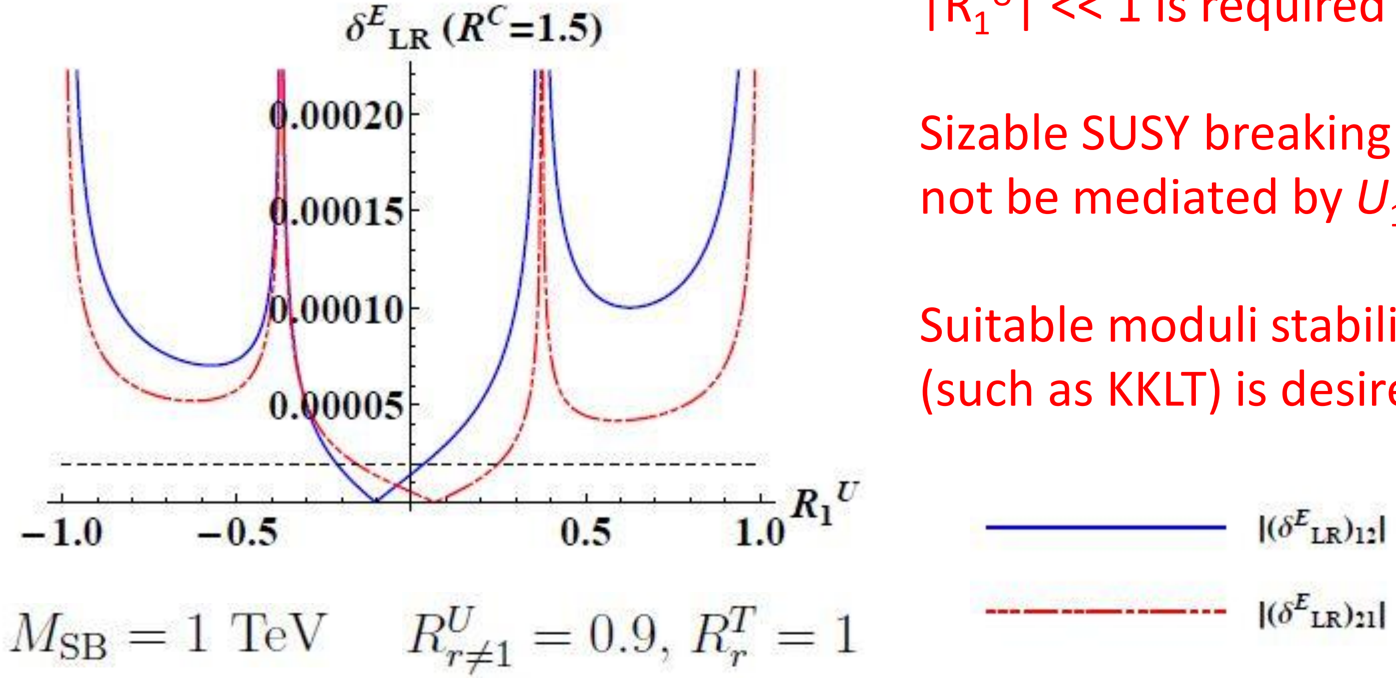


$M_{SB} = 1$ TeV $\quad R^U_{r\neq 1} = 0.9,\ R^T_r = 1$

Modulus & anomaly mediated SUSY flavor violations

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. '13

The most stringent bound from $\mu \to e\gamma$ on δ^E_{LR}



$|R_1^U| << 1$ is required

Sizable SUSY breaking can not be mediated by U_1

Suitable moduli stabilization (such as KKLT) is desired

IV. SUMMARY AND PROSPECTS

MSSM from magnetized D9

The magnetic flux determines (yields) almost everything at low energy:

- Gauge symmetries, chirality, # of generations
- Semi-realistic flavor structures

  (from non-hierarchical VEVs of fields)
- Moduli-mediated superparticle spectra

MSSM from magnetized D9

The magnetic flux determines (yields) almost everything at low energy:

- Gauge symmetries, chirality, # of generations
- Semi-realistic flavor structures

  (from non-hierarchical VEVs of fields)
- Moduli-mediated superparticle spectra

The other choices of flux? (Flavor landscape)

T. Kobayashi, H. Ohki, K. Sumita, Y. Tatsuta & H.A., arXiv:1307.1831 [hep-th]

MSSM from magnetized D5-D9 or D3-D7

Generalizations are straightforward

T. Horie, K. Sumita & H.A., in preparation

- A systematic inclusion of hidden (and then messenger) sectors

- The same (semi-realistic) flavor structure with non-universal gaugino masses would be possible

MSSM from magnetized D5-D9 or D3-D7

Generalizations are straightforward

T. Horie, K. Sumita & H.A., in preparation

- A systematic inclusion of hidden (and then messenger) sectors

  ⟶ Gauge mediated contribution also calculable

- The same (semi-realistic) flavor structure with non-universal gaugino masses would be possible

MSSM from magnetized D5-D9 or D3-D7

Generalizations are straightforward

T. Horie, K. Sumita & H.A., in preparation

- A systematic inclusion of hidden (and then messenger) sectors

  ⟶ Gauge mediated contribution also calculable

- The same (semi-realistic) flavor structure with non-universal gaugino masses would be possible

  ⟶ Little hierarchy, 125 GeV Higgs mass, … ?

Remaining issues

- Nonperturbative effects, higher-order corrections, deviation (departure) from a toroidal geometry, …
- Moduli stabilization, dynamical SUSY breaking, …
- Cosmological aspects, …

Thank you!

APPENDIX

Wilson-lines in magnetized T^2

D. Cremades, L. E. Ibanez & F. Marchesano '04

Magnetic flux with Wilson-line $\zeta \sim \langle A_5 + iA_4 \rangle$

Zero-mode wavefunctions are just

shifted by ζ in magnetized T^2

$$\psi(z) \to \psi(z+\zeta) \qquad z \sim y_4 + iy_5$$

Desired Hierarchical structures would be obtained by the shift

10D SYM theory on $(T^2)^3$

The torus compactification $T^2 \times T^2 \times T^2$

$$S = \int d^{10}X \sqrt{-G} \frac{1}{g^2} \mathrm{Tr}\left[-\frac{1}{4} F^{MN} F_{MN} + \frac{i}{2} \bar{\lambda} \Gamma^M D_M \lambda \right]$$

$$ds^2 = G_{NN} dX^M dX^N = \eta_{\mu\nu} dx^\mu dx^\nu + g_{mn} dy^m dy^n$$

$$X^M = (x^\mu, y^m) \qquad \eta_{\mu\nu} = \mathrm{diag}(-1,+1,+1,+1)$$

$$\mu = 0,1,2,3$$

$$m = 4,\ldots,9$$

$$g_{mn} = \begin{pmatrix} g^{(1)} & 0 & 0 \\ 0 & g^{(2)} & 0 \\ 0 & 0 & g^{(3)} \end{pmatrix}$$

i = 1,2,3

$$g^{(i)} = (2\pi R_i)^2 \begin{pmatrix} 1 & \mathrm{Re}\,\tau_i \\ \mathrm{Re}\,\tau_i & |\tau_i|^2 \end{pmatrix}$$

Superfield description of 10D SYM

N. Arkani-Hamed, T. Gregoire & J. Wacker '02

The action in the superspace

$$\begin{aligned} S &= \int d^{10}X\,\sqrt{-G}\,\frac{1}{g^2}\,\mathrm{Tr}\left[-\frac{1}{4}F^{MN}F_{MN}+\frac{i}{2}\bar{\lambda}\Gamma^M D_M\lambda\right] \\ &= \int d^{10}X\sqrt{-G}\left[\int d^4\theta\,\mathcal{K}+\left\{\int d^2\theta\left(\frac{1}{4g^2}\mathcal{W}^\alpha\mathcal{W}_\alpha+\mathcal{W}\right)+\mathrm{h.c.}\right\}\right] \end{aligned}$$

$$\left\{\begin{aligned} \mathcal{K} &= \frac{2}{g^2}h^{\bar{i}j}\mathrm{Tr}\left[\left(\sqrt{2}\bar{\partial}_{\bar{i}}+\bar{\phi}_{\bar{i}}\right)e^{-V}\left(-\sqrt{2}\partial_j+\phi_j\right)e^V+\bar{\partial}_{\bar{i}}e^{-V}\partial_j e^V\right]+\mathcal{K}_{\mathrm{WZW}}, \\ \mathcal{W} &= \frac{1}{g^2}\epsilon^{\mathrm{ijk}}e_{\mathrm{i}}{}^{i}e_{\mathrm{j}}{}^{j}e_{\mathrm{k}}{}^{k}\mathrm{Tr}\left[\sqrt{2}\,\phi_i\left(\partial_j\phi_k-\frac{1}{3\sqrt{2}}[\phi_j,\phi_k]\right)\right], \\ \mathcal{W}_\alpha &\equiv -\tfrac{1}{4}\bar{D}\bar{D}e^{-V}D_\alpha e^V \end{aligned}\right.$$

SUSY gauge background

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

The *F*- and *D*-flat directions

$$\begin{cases} D = -h^{\bar{i}j}\left(\bar{\partial}_{\bar{i}}A_j + \partial_j \bar{A}_{\bar{i}} + \frac{1}{2}[\bar{A}_{\bar{i}}, A_j]\right), \\ \bar{F}_{\bar{i}} = -h_{j\bar{i}}\,\epsilon^{\mathrm{jkl}} e_{\mathrm{j}}{}^{j} e_{\mathrm{k}}{}^{k} e_{\mathrm{l}}{}^{l}\left(\partial_k A_l - \frac{1}{4}[A_k, A_l]\right) \end{cases}$$

4D Lorentz & SUSY preserving background

$$\langle A_i \rangle \neq 0, \qquad \langle A_\mu \rangle = \langle \lambda_0 \rangle = \langle \lambda_i \rangle = \langle F_i \rangle = \langle D \rangle = 0.$$

Fluctuations around the VEVs

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

$$V \equiv \langle V \rangle + \tilde{V}, \qquad \phi_i \equiv \langle \phi_i \rangle + \tilde{\phi}_i, \qquad \langle \phi_i \rangle = \langle A_i \rangle / \sqrt{2}$$

The action for the fluctuations (tildes omitted)

$$\begin{cases} \mathcal{K} = \frac{2}{g^2} h^{\bar{i}j} \mathrm{Tr} \Big[\bar{\phi}_{\bar{i}} \phi_j + \sqrt{2} \Big\{ \Big(\boxed{\bar{\partial}_{\bar{i}} \phi_j + \frac{1}{\sqrt{2}} [\langle \bar{\phi}_{\bar{i}} \rangle, \phi_j]} + \mathrm{h.c.} \Big) + \frac{1}{\sqrt{2}} [\bar{\phi}_{\bar{i}}, \phi_j] \Big\} V \\ \qquad + (\bar{\partial}_{\bar{i}} V)(\partial_j V) + \frac{1}{2} \left(\bar{\phi}_{\bar{i}} \phi_j + \phi_j \bar{\phi}_{\bar{i}} \right) V^2 - \bar{\phi}_{\bar{i}} V \phi_j V \Big] + \mathcal{K}^{(\mathrm{D})} + \mathcal{K}^{(\mathrm{br})} \\ \mathcal{W} = \frac{1}{g^2} \epsilon^{\mathrm{ijk}} e_{\mathrm{i}}{}^{i} e_{\mathrm{j}}{}^{j} e_{\mathrm{k}}{}^{k} \mathrm{Tr} \Big[\sqrt{2} \Big(\boxed{\partial_i \phi_j - \frac{1}{\sqrt{2}} [\langle \phi_i \rangle, \phi_j]} \Big) \phi_k - \frac{2}{3} \phi_i \phi_j \phi_k \Big] + \mathcal{W}^{(\mathrm{F})} \end{cases}$$

Kaluza-Klein wavefunctions

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

KK mode expansion

$$\begin{cases} V(x^\mu, \boldsymbol{z}, \bar{\boldsymbol{z}}) = \sum_{\boldsymbol{n}} \left(\prod_i f_0^{(i),n_i}(z^i, \bar{z}^{\bar{i}}) \right) V^{\boldsymbol{n}}(x^\mu), \\ \phi_j(x^\mu, \boldsymbol{z}, \bar{\boldsymbol{z}}) = \sum_{\boldsymbol{n}} \left(\prod_i f_j^{(i),n_i}(z^i, \bar{z}^{\bar{i}}) \right) \phi_j^{\boldsymbol{n}}(x^\mu), \end{cases}$$

$$\boldsymbol{z} = (z^1, z^2, z^3),\ \bar{\boldsymbol{z}} = (\bar{z}^{\bar{1}}, \bar{z}^{\bar{2}}, \bar{z}^{\bar{3}}),\ \boldsymbol{n} = (n_1, n_2, n_3) \text{ and } n_i \in \mathbf{Z}$$

We focus on the massless zero-modes in ϕ_j and omit n_i

Zero-mode equations

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

Zero-mode equations

$$\begin{cases} \bar{\partial}_{\bar{i}} f_j^{(i)} + \frac{1}{2}\left[\langle \bar{A}_{\bar{i}} \rangle, f_j^{(i)}\right] = 0 & (i = j), \\ \partial_i f_j^{(i)} - \frac{1}{2}\left[\langle A_i \rangle, f_j^{(i)}\right] = 0 & (i \neq j). \end{cases}$$

Abelian flux background

$$\langle A_i \rangle = \frac{\pi}{\mathrm{Im}\,\tau_i}\left(M^{(i)}\,\bar{z}_{\bar{i}} + \bar{\zeta}_i\right)$$

$$M^{(i)} = \mathrm{diag}(M_1^{(i)}, M_2^{(i)}, \ldots, M_N^{(i)}),$$

$$\zeta_i = \mathrm{diag}(\zeta_1^{(i)}, \zeta_2^{(i)}, \ldots, \zeta_N^{(i)}),$$

SUSY conditions

$$h^{\bar{i}j}\left(\bar{\partial}_{\bar{i}}\langle A_j \rangle + \partial_j \langle \bar{A}_{\bar{i}} \rangle\right) = 0,$$

$$\epsilon^{\mathrm{jkl}} e_{\mathrm{k}}{}^{k} e_{\mathrm{l}}{}^{l} \partial_k \langle A_l \rangle = 0,$$

Zero-mode equations

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

Zero-mode equations

$$\begin{cases} \bar{\partial}_{\bar{i}} f_j^{(i)} + \frac{1}{2}\left[\langle \bar{A}_{\bar{i}} \rangle,\, f_j^{(i)}\right] = 0 & (i = j), \\ \partial_i f_j^{(i)} - \frac{1}{2}\left[\langle A_i \rangle,\, f_j^{(i)}\right] = 0 & (i \neq j). \end{cases}$$

These are exactly the same equations as those for the Dirac zero-modes on T^2 (in the complex coordinate)

↓

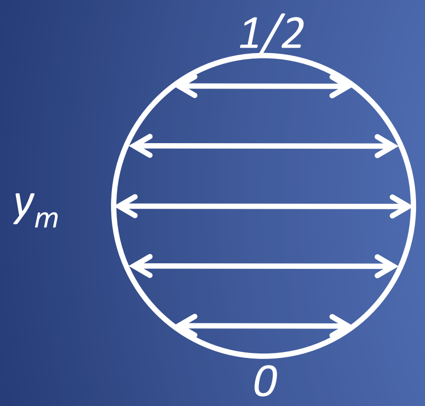
Wavefunctions are characterized by the Jacobi theta function

Magnetized orbifolds

K.S. Choi, T. Kobayashi, H. Ohki & H.A. '08 - '09

Orbifold by Z_2 projection operator P ($P^2=1$)

$$\lambda_{\pm}(x,-y) = \pm P \lambda_{\pm}(x,y) P^{-1}$$



$P\lambda P^{-1} = +\lambda$

$P\lambda P^{-1} = -\lambda$

$$\psi^{j}_{even}(y) = \frac{1}{\sqrt{2}}\left(\psi^{j}(y) + \psi^{M-j}(y)\right)$$

$$\psi^{j}_{odd}(y) = \frac{1}{\sqrt{2}}\left(\psi^{j}(y) - \psi^{M-j}(y)\right)$$

# of zero-modes

M	0	1	2	3	4	5	6	7	8	9	10
even	1	1	2	2	3	3	4	4	5	5	6
odd	0	0	0	1	1	2	2	3	3	4	4

Orbifold projections

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. '12

T^6/Z_2 orbifold

$$^\forall m = 4,5 \text{ and } ^\forall n = 6,7,8,9$$

$$\begin{aligned} V(x, y_m, -y_n) &= +PV(x, y_m, +y_n)P^{-1}, \\ \phi_1(x, y_m, -y_n) &= +P\phi_1(x, y_m, +y_n)P^{-1}, \\ \phi_2(x, y_m, -y_n) &= -P\phi_2(x, y_m, +y_n)P^{-1}, \\ \phi_3(x, y_m, -y_n) &= -P\phi_3(x, y_m, +y_n)P^{-1}, \end{aligned}$$

does not break SUSY preserved by the flux

$$P_{ab} = \begin{pmatrix} -\mathbf{1}_4 & 0 & 0 \\ 0 & +\mathbf{1}_2 & 0 \\ 0 & 0 & +\mathbf{1}_2 \end{pmatrix}$$

projects out many exotic modes without affecting MSSM contents

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projects out many exotic modes without affecting MSSM contents

Parameterization of Wilson-lines

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

Wilson-lines affecting MSSM contents are

$$\zeta_C^{(1)} - \zeta_L^{(1)} \equiv \zeta_Q, \qquad \zeta_{R'}^{(1)} - \zeta_C^{(1)} \equiv \zeta_U, \qquad \zeta_{R''}^{(1)} - \zeta_C^{(1)} \equiv \zeta_D,$$
$$\zeta_{C'}^{(1)} - \zeta_L^{(1)} \equiv \zeta_L, \qquad \zeta_{R'}^{(1)} - \zeta_{C'}^{(1)} \equiv \zeta_N, \qquad \zeta_{R''}^{(1)} - \zeta_{C'}^{(1)} \equiv \zeta_E,$$

These shifts the position of the quasi-localization of MSSM matter fields *Q*,*U*,*D*,*L*,*N*,*E* in extra dimensions

We search numerical values of these parameters which yield some realistic patterns of the quark and lepton masses and mixings

Moduli VEVs

T. Kobayashi, H. Ohki, K. Sumita & H.A. '12

- S : dilaton
- T_r : Kahlër moduli
- U_r : complex structure moduli

from the rth T^2 (r = 1,2,3)

$$\langle S\rangle \equiv s+\theta^2 F^S, \qquad \langle T_r\rangle \equiv t_r+\theta^2 F_r^T, \qquad \langle U_r\rangle \equiv u_r+\theta^2 F_r^U$$

$$\mathrm{Re}\, s = g^{-2}\prod_{r=1}^{3}\mathcal{A}^{(r)}, \qquad \mathrm{Re}\, t_r = g^{-2}\mathcal{A}^{(r)}, \qquad u_r = i\bar{\tau}_r$$

F^S, F_r^T, F_r^U : moduli mediated SUSY breaking

Soft SUSY breaking parameters

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. ’13

SUSY breaking (reference) scale $M_{\rm SB} \equiv \sqrt{K_{S\bar{S}}}\,F^S$

Ratios of *F*-terms

$$R_r^T = \frac{\sqrt{K_{T_r\bar{T}_r}}\,F_r^T}{M_{\rm SB}}, \qquad R_r^U = \frac{\sqrt{K_{U_r\bar{U}_r}}\,F_r^U}{M_{\rm SB}}, \qquad R^C = \frac{1}{4\pi^2}\frac{F^C/C_0}{M_{\rm SB}}$$

We analyzed SUSY flavor structures by varying these ratios, especially R_1^U

Comments on μ-parameter

T. Kobayashi, H. Ohki, A. Oikawa, K. Sumita & H.A. '12

We assume nonperturbative and/or higher-order effects yielding $W_{\rm eff} = \mu_{KL} H_u^K H_d^L$

with μ_{KL} satisfying

$$\sum_{K,L} (U_{H_u})^K_{\hat{K}} \, \mu_{KL} \, (U^\dagger_{H_d})^L_{\hat{L}} = \delta_{\hat{K}\hat{L}} \, \mu_{\hat{K}}, \qquad |\mu_{\hat{K}=1}| \ll M_{\rm GUT} \lesssim |\mu_{\hat{K}\neq 1}|,$$

$$(U_{H_{u,d}})^K_{\hat{K}=1} = \langle H^K_{u,d} \rangle / v_{u,d},$$

in order five of six Higgs fields to be decoupled below the GUT scale.