Supersymmetry breaking

Wess&Bagger ch. X?

Assume spontaneous breaking of SUSY (cf. O'Raifeartaigh)

At low energy ($E < m_{\cancel{SUSY}}$) should get

effective theory with only soft terms encoding $\cancel{SUSY}$.

renormalizable

dim ≤ 3 (preserves UV properties)

$$\mathcal{L}_{MSSM} = \mathcal{L}_{SUSY} + \mathcal{L}_{soft}$$

around 1 TeV (very roughly)

mass splittings m_i, M_a

nonholomorphic trilinear couplings A_{ijk}

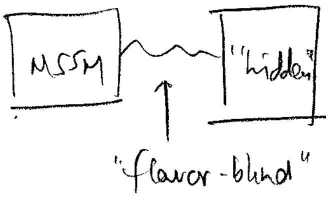
bilinear B_{ij}

New parameters: 124 → 105 (on top of SM)

Problem: with generic parameters, violates experimental constraints (not so strange!) if we can detect them, can also rule things

- "SUSY flavor problem" unsuppressed flavor-changing
- "SUSY CP problem" complex parameters ⇒ much more CP violation than in SM

Idea for solution:



This is called "XXXX mediation"

gauge — " —
gravity — " —
mirror — " —
anomaly — " —
mirage — " —

⇒ various restrictions on $\mathcal{L}_{soft}$

In practice: impose severe restrictions on 105 parameters (e.g. keep 3) for simplicity

(One way of thinking)

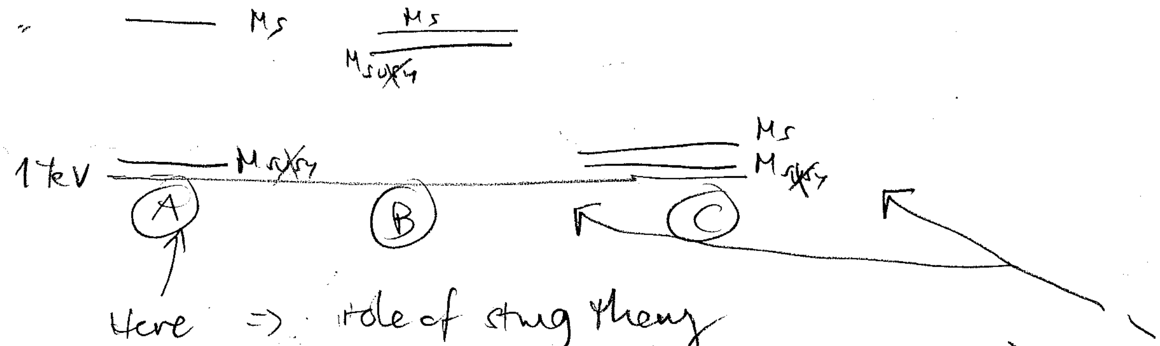
Logic:

pick a parameter

MSSM from string theory

Ex: • Heterotic
• Type IIA/B + D-Branes } about equally successful

Big picture:



Here $\Rightarrow$ role of string theory
generate $\mathcal{L}_{eff}$ (but non-minimal...)

Here: eg. Ibanez et al 2001 (cf. Zwiebach)
get SM (nasty) spectrum

One huge problem: moduli stabilization (more later
— solutions only next time)

Leave aside these

$(z_1, z_2, z_3) \to (z_1, -z_2, z_3)$

MSSM from D6-branes on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ (Cvetic et al 2000)

Chiral fermions (perhaps main problem for sugra phenomenology)

not only Weyl, ψ_L must also not have ψ_R in conjugate rep (cf. QCD vs. EW)

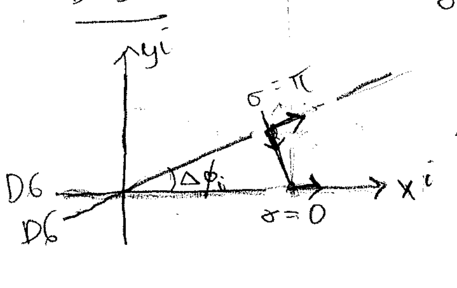
a) branes at orbifold (or conifold) sing

b) nontrivial angles

$i = 1,2,3$

T^6: $Z^i = X^i + iY^i$ embedding coords of open string $X(\sigma,\tau)$...

BCs:



$\sigma=0$: $\partial_\sigma X^i = \partial_\tau Y^i = 0$
Neumann Dirichlet

$\sigma=\pi$: $\partial_\sigma X^i + \tan \Delta\phi_i \, \partial_\sigma Y^i = 0$

(rotate $\begin{pmatrix} \cos & \sin \\ -\sin & \cos \end{pmatrix} \begin{pmatrix} \partial_\sigma X^i \\ \partial_\sigma Y^i \end{pmatrix}$, normalize $\frac{1}{\cos\Delta\phi}$)

Mode exp $\quad Z \sim \sum \alpha_n z^n, \ldots \quad \psi = \sum \psi_n z^n$ (Polchinski)

$\swarrow X + i\,l$ $\quad e^{i(\sigma + i\tau)}$

BCs : shift $n \to n + \varepsilon_i \qquad \varepsilon_i = \frac{\Delta\phi_i}{\pi} \quad \Rightarrow m^2 = \ldots$

sometimes $D6_a - D6_b$ strings called "twisted" (not here)

$\Rightarrow$ no fermionic zero mode (ψ_0^i) on T^6, but still ψ_0^μ $\leftarrow 0,1,2,3$

$\Rightarrow$ spacetime spinor in $3+1$

GSO proj $\Rightarrow$ single chiral fermion in bifundamental.

Note : $\circ$ only if at intersection point is massless (i.e. not M_s mass)

$\circ$ bifundamental $(\square_a, \overline{\square}_b)$

Supersymmetry

(Polchinski)

wrap "special Lagrangian" 3-cycles

here this means $\pm\phi_a^1 \pm \phi_a^2 \pm \phi_a^3 = 0 \pmod{2\pi}$

(if eg. $\phi_a^1 = 0$, $\mathcal{N} = 2$ SUSY

so want $\phi_a^i \neq 0$, some stack a)

Generation replication by topology

cf. Candelas et al "Triadophilia"

(cf. old Het compactification: $\chi(CY_3) = \#$ generations (net))

Here: each intersection $\Rightarrow$ 1 copy of chiral fermion

Some more torus stuff:

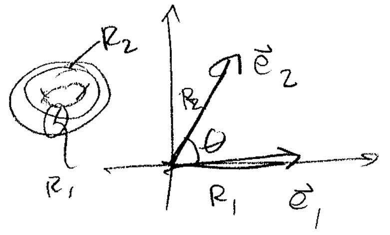
introduce torus area (cf. $\tilde{G} \to \tilde{\tilde{G}}$ last time) $T_1 \sim R_1 R_2$ $\quad \frac{1}{2}(T + \bar{T})$ Kähler moduli

for worldsheet, not useful as integrated over – pick one

for spacetime, very important

eg. determines tree level gauge couplings

cf. DBI $\quad \frac{1}{g^2} \operatorname{tr} F^2 \xrightarrow[\text{wrap}]{} \frac{V}{g^2} \operatorname{tr} F^2$

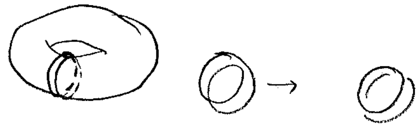


$\vec{e}_1 = (0, R_1)$

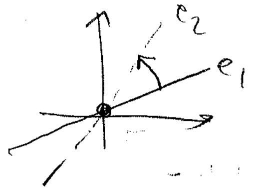
$\vec{e}_2 = (R_2 \cos\theta, R_2 \sin\theta)$

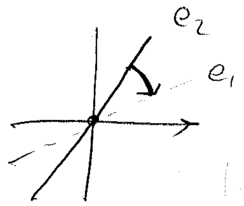
1-cycle on 2-torus $\Pi_a = p_a \vec{e}_1 + q_a \vec{e}_2$

restrict to $\gcd(p_a, q_a) = 1$ (otherwise can decay) — but does decay? check energetics



elementary intersection theory:





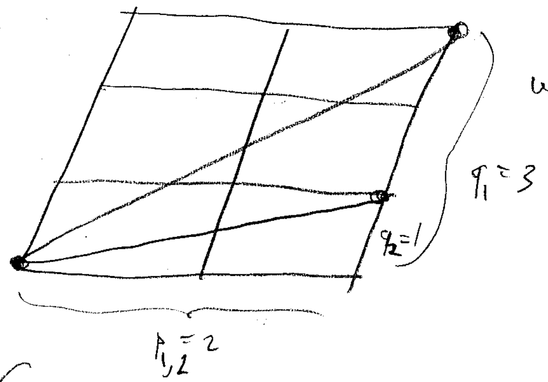
$e_1 \circ e_2 = +1$

$e_2 \circ e_1 = -1$

$I_{ab} = \Pi_a \circ \Pi_b = p_a q_b - q_a p_b$

note: antisymmetric ($\Rightarrow I_{aa} = 0$, makes sense)

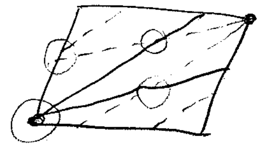
Ex



wrapping $= (p_1, q_1) = (2, 3)$

$(p_2, q_2) =$

Fund. cell



$$
\begin{aligned}
I_{12} &= p_1 q_2 - p_2 q_1 \\
&= 2\cdot 1 - 2\cdot 3 \\
&= -4
\end{aligned}
$$

For one brane:

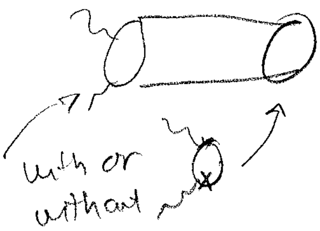
$$\tan\phi = \frac{p}{q}\,\frac{R_1}{R_2\sin\theta} + \cot\theta$$

i.e. torus parameters

$(p,q) \to \phi$ (of course)

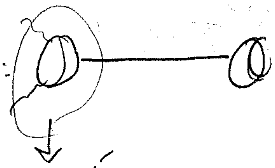
Tadpole cancellation

cf. Polchinski
Marcus "Intro to Orientifolds"



$\xrightarrow[l \to \infty]{} \int_0^\infty dl$ replace by $\int_0^\Lambda dl = \Lambda$ (or $\Lambda^2, \ldots$)

note $l \to \infty$:

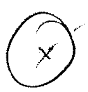


disk amplitude:

("Hawking radiation", cf. Klebanov-Hashimoto)

OK

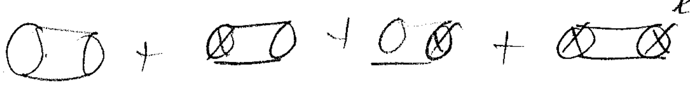
but



tadpole diagram (field theory: —o ; biology: ~~•)

one solution (cf. Type I in 10d)

orientifold here: ≈ allow unoriented worldsheets ⊗



crosscap: $\mathbb{RP}^2$ (unoriented)

$$\xrightarrow{l \to \infty} (N \cdot N - N_0 \cdot N - N \cdot N_0 + N_0^2)\Lambda = (N - N_0)^2 \Lambda \Rightarrow \text{set } N - N_0 = 0$$

↑ # D-branes

O-plane charge $= 2^{d/2}$ D-brane charge

(in 10d: $2^5 = 32 \Rightarrow$ put 32 D-branes $\to SO(32)$)

Consider where ▯▯ are at right angles

Here eg. $\underline{OO} \propto N^2$

is generalized to $\underline{OO} \propto I_{ab} N_a N_b$ (no sum on a/b (would be zero then)) $\Rightarrow$ factorize again $\Rightarrow$ (linear in $N_a)^2 = 0$ $\Rightarrow$ linear in $N_a = 0$
with angles

sets $\sum_a N_a q_a^1 q_a^2 q_a^3 - 16 = 0$

linear in N_a

cubic in p, q

$\vdots$

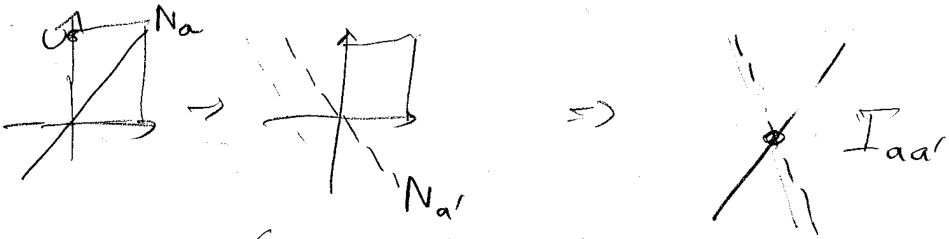
TADPOLE CONSTRAINTS

Notes

Tapole constraints $\Rightarrow$ Anomaly cancellation (not $\Leftarrow$)
(cf. Polchinski; Uranga hep-th/...)

Now also have image stacks $N_a \xrightarrow{\Omega R} N_{a'}$

eg. if $R: \begin{array}{l} x \to -x \\ y \to y \end{array}$



$(p_{a'}, q_{a'}) = (-p_a, q_a)$ (*)

$\Rightarrow$ generations $= I_{ab} - I_{ab'}$

One problem with this : Prob: 2b

Also note: (*) is for $U_1 = \mathrm{Re}\, U = 0$

if $U_1 = \frac{1}{2}$, define $\tilde{p}_a = \begin{cases} p_a, & U_1 = 0 \\ p_a + \frac{1}{2} q_a, & U_1 = \frac{1}{2} \end{cases}$

then still $(\tilde{p}_{a'}, q_{a'}) = (-\tilde{p}_a, q_a)$

<u>Finally, solve tadpole constraints</u>

! Can usually find solutions, but often restrictive since eg. the 16 is fixed by N_a and all integers!

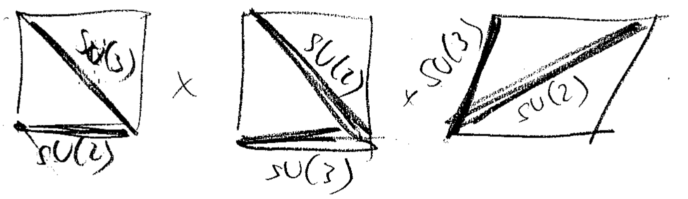
Impose:

- gauge group contains $SU(3)_c \times SU(2)_{ew} \times U(1)_Y$
- three generations $I_{ab} = 3$, $I_{ab'} = 0$ with SM reps
- supersymmetric ($\mathcal{N} = 1$, not $\mathcal{N} = 2$!) ~~total~~ embedding

Notice: $USp(4) = SU(2)$

$\Rightarrow$ 6-stack solution Cvetic, Shiu, Uranga =: CSU

eg.



Ex

q_L q_R