D-brane Instanton Corrections in 4D String Vacua

The Seesaw Mechanism for D-brane Models

based on:

R. Blumenhagen, M. Cvetič, T.W., hep-th/0609191

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Motivation

String theory exhibits a huge number of perturbatively metastable 4D vacua
determined by zero mode approximation/
effective $\mathcal{N} = 1$ supergravity $S_{eff} \Leftrightarrow W, K, f$
SUSY vacuum given by: $DW = 0$ (+D-terms)

How do genuine quantum effects modify the landscape topography?
W not renormalized perturbatively
$\rightsquigarrow$ non-perturbative corrections crucial

Example:
Closed string sector in Type IIB orientifolds: dependence of W on Kähler moduli only by Euclidean D3-branes
decisive for IIB moduli fixing industry

Motivation

Non-perturbative effects in gauge sector of string vacua?

• relevant for stability of model in the first place (e.g. Π-stability for B-type branes)

• potential to break perturbative gauge or global symmetries

• may generate perturbatively absent couplings, exponentially suppressed w.r.t. string scale
$\rightsquigarrow$ come at genuinely stringy hierarchical scale
Indeed, MSSM does (most likely) exhibit couplings with badly understood strength:
$\rightsquigarrow$ Majorana masses for right-handed neutrinos of order $10^{11}GeV < M_M < 10^{15}GeV$
$\rightsquigarrow$ hierarchically small μ-terms of order $\mathcal{O}(M_Z)$

Motivation

Various non-perturbative effects in gauge sector studied in detail in literature, e.g.

worldsheet instantons in heterotic compactifications

[Dine,Seiberg,Wenn,Witten'86],[Distler,Greene'88],[Witten'99],

[Buchbinder,Donagi,Ovrut'02],[Beasley,Witten'03,'05]

worldsheet instantons in IIA brane models

[Kachru et al.'00],[Aganacic,Vafa'00]

M2/M5-brane effects in heterotic M-theory

[Becker,Becker,Strominger'95],[Harvey, Moore'99]

D3-D(-1) system in IIB

[Green,Gutperle'97],[Billo et al.'02],[Green,Stahn'03]

Motivation

This talk:

Effects of wrapped Euclidean D-branes in Type IIA Intersecting Brane Vacua

special focus on induced superpotential terms involving charged matter fields Φ_i

$$W_{np} \simeq \prod_{i=1}^{M} \Phi_i \, e^{-S_{inst.}}$$

violating global perturbative abelian symmetries

recent related work:

[Haack,Krefl,Lust,VanProeyen,Zagermann, hep-th/0609211]

[Ibanez,Uranga, hep-th/0609213]

[Florea,Kachru,McGreevy,Saulina, hep-th/0610003]

[Buican,Malyshev,Morrison,Wijnholt,Verlinde, hep-th/0610007]

Plan of the talk

1. Motivation
2. Reminder: Intersecting Brane Worlds and anomalous U(1)
3. E2-brane instanton generated superpotentials:
   - Heuristics
   - Zero mode structure
   - CFT instanton calculus
4. Applications:
   - Matter couplings (Majorana masses, proton decay)
   - Vacuum destabilisation and open string moduli fixing
5. E2-brane instanton generated D-terms
6. Dual formulations
7. Conclusions

Briefin on strin model buildin

Open Strings

- Type II A orientifolds: Intersecting Braneworlds (IBW)
- Type I: magnetized D9/D5-branes
- Type II B orientifolds: D7/D3-branes; branes at singularities

Main ingredients of IBW in IIA orientifolds:

- stacks of N_a coincident D6-branes $\longrightarrow U(N_a)$ gauge field on worldvolume
- intersection of stacks of N_a and N_b branes $\longrightarrow$ chiral fermion in $(N_a, \overline{N}_b)$

Idea: Combine various $U(N_a)$ gauge modules to construct an appropriate gauge group of quiver type $\prod_a U(N_a)$ at intersection of all stacks

Briefin on strin model buildin

Concretely: $\mathcal{M}^{(10)} = \mathcal{M}^{(4)} \times CY_3$

quotient Type IIA on $\mathcal{M}^{(10)}$ by $\Omega\,(-1)^{F_L}\,\overline{\sigma}$

Ω: worldsheet parity, F_L: left-handed fermion number

$\overline{\sigma}$: anti-holomorphic involution on CY_3

$\rightsquigarrow$ fixed-point locus of $\overline{\sigma}$: orientifold O6-plane $\mathcal{M}^{(4)} \times \Pi_{O6}$
carries RR and NS charge

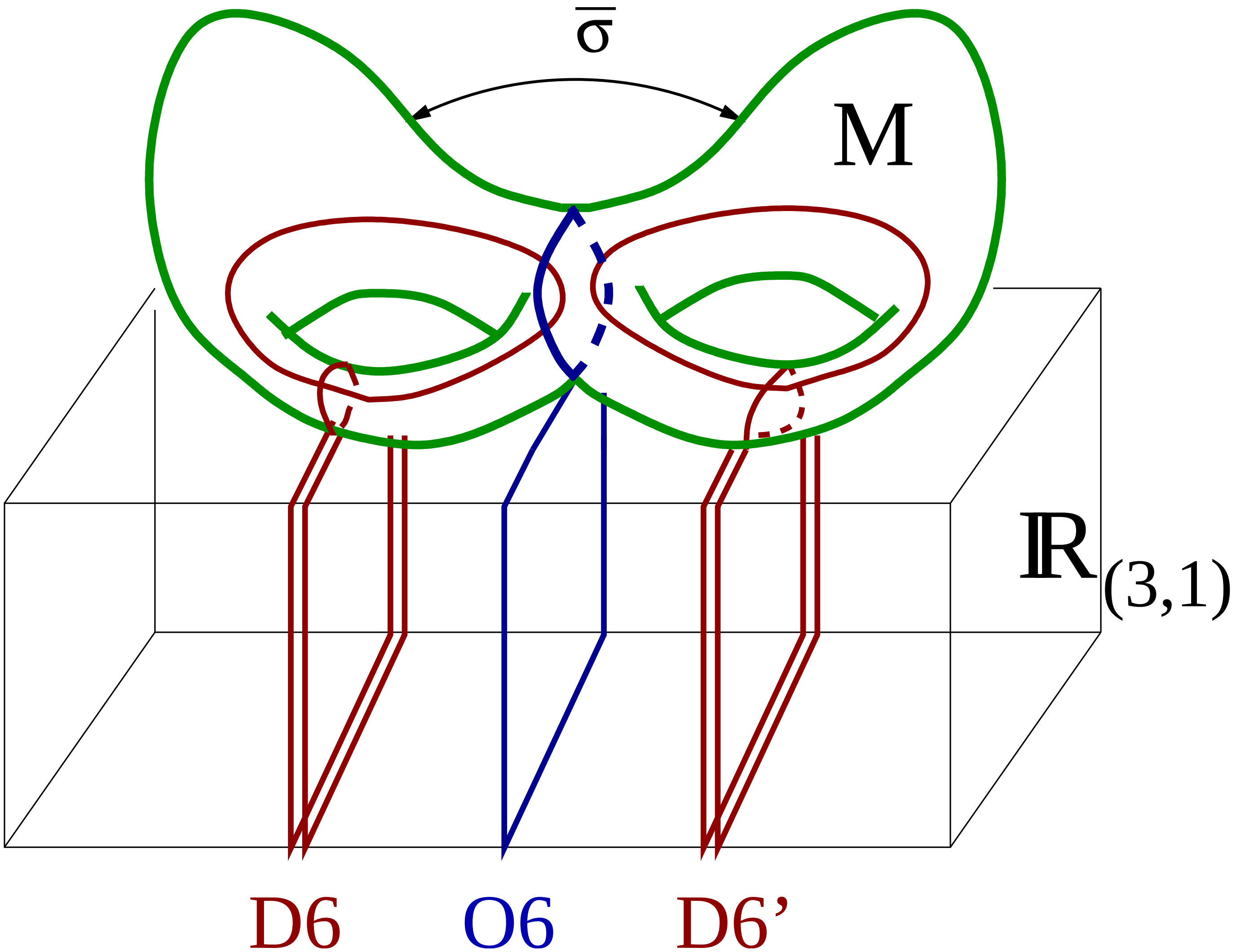
$\rightsquigarrow$ introduction of D6-branes for charge cancellation

N_a D6-branes wrap 3-cycles Π_a on CY_3 and fill $\mathcal{M}^{(4)}$

orientifold action $\rightsquigarrow$ include also image branes Π'_a

chiral matter localised at non-trivial intersection of internal 3-cycles

chiral number of generations is $(N_a, \overline{N}_b) = \Pi_a \circ \Pi_b$
(top. intersection number)



$\bar{\sigma}$
M
$\mathbb{R}_{(3,1)}$
D6
O6
D6'

Briefin on strin model buildin

Consistency conditions:
unbroken $\mathcal{N} = 1$ SUSY in 4D at string scale (stability)

- Π_a SUSY cycle = special Lagrangian
  $\longleftrightarrow J|_{\Pi_a} = 0, \qquad \Im(e^{i\theta_a}\Omega|_{\Pi_a}) = 0$
- same $\mathcal{N} = 1$ subalgebra preserved by Π_{O6} and each Π_a:
  $\longleftrightarrow \theta_a = 0 \;\; \forall a$

Tadpole cancellation for global consistency

$$\sum_a N_a(\Pi_a + \Pi'_a) - 4\Pi_{O6} = [0]$$

Note: Little known about sLags on general CY_3
$\Longrightarrow$ toroidal orientifolds $CY_3 = T^6/\mathbb{Z}_N \times \mathbb{Z}_M$
$\Longrightarrow$ abstract RCFT (Gepner Model orientifolds)

nomalous $U(1)$ and GS-mechanism

Specific signature of IBW:
gauge group $\prod_a U(N_a) = \prod_a SU(N_a) \times U(1)_a$
in general: $U(1)_a$ is anomalous
anomaly cancelled by 4D Green-Schwarz mechanism,
mediated by Chern-Simons coupling

$$S_{CS} = \sum_a N_a \, \mu_6 \int_{\mathbb{R}^{1,3} \times \Pi_a} e^{tr F_a} \sum_p C_{2p+1}$$

abelian gauge potential becomes massive and anomalous $U(1)_a$ survives as a global perturbative symmetry

Only specific linear combinations of $U(1)$s are massless
$\rightsquigarrow$ in realistic models: only $U(1)_Y$ massless, but:
additional perturbative $U(1)$ forbid some desirable matter couplings e.g. right-handed neutrino masses or μ-terms

nomalous $U(1)$ and GS-mechanism

Concretely:

A_I, B^I: sympl. basis of $H_3(X,\mathbb{Z})$,

α_I, β^I: dual basis of $H^3(X,\mathbb{Z})$

Expand: 3-cycle $\Pi_a = m_a^I\, A_I + n_{a,I}\, B^I$

RR 3-form $C^{(3)} = \ell_s^3 \left(C_I^{(0)}\, \alpha^I - D^{(0),I}\, \beta_I \right)$

CS-coupling induces gauging of global axionic shift symmetry:

under $A_{a,\mu} \to A_{a,\mu} + \partial_\mu \Lambda_a$

the axions $(C_I^{(0)}, D^{(0),I})$ transform as

$$C_I^{(0)} \to C_I^{(0)} + Q_I^a\, \Lambda_a, \qquad D^{(0),I} \to D^{(0),I} + P^{a,I}\, \Lambda_a$$

with

$$Q_I^a = -N_a \left(n_{a,I} - n'_{a,I} \right), \qquad P^{a,I} = N_a \left(m_a^I - {m'}_a^I \right)$$

Instantons-Heuristics

Strategy: Probe for non-pert. terms by computing suitable amplitudes in instanton background

Instanton background: presence of Euclidean E_p-brane wrapping internal $(p+1)$-cycle

On $X = CY_3$: $b_1(X) = 0 = b_5(X)$

$\rightsquigarrow$ relevant objects are Euclidean $E2$-branes

Rules:

- Instanton sector corresponds to local minimum of (full) string action
  $\rightsquigarrow$ $E2$-brane volume minimizing on internal sLag Ξ
- Integrate over all bosonic and fermionic zero modes localized on $E2$
  $\rightsquigarrow$ All fermionic zero modes have to appear in some vertex operator

Instantons-Heuristics

Consequence:

F-terms possible only if $E2$-sector is half-BPS w.r.t. $D6$-branes/$O6$-plane,
i.e. if Ξ SUSY w.r.t. Π_a, but $1/2$ SUSY broken due to localisation in 4D
$\rightsquigarrow$ 2 fermionic zero modes θ_i (Goldstinos)

D-terms only if $E2$-sector breaks all 4 supersymmetries, i.e. Ξ on sLag non-SUSY w.r.t. Π_a $\rightsquigarrow$ 4 fermionic zero modes θ_i, $\overline{\theta}_i$

focus on single-instanton contribs. to superpotential W

Instantons-Heuristics

$$W_{np} \propto e^{-S_{E2}} = \exp\left[-\frac{2\pi}{\ell_s^3}\left(\frac{1}{g_s}\int_\Xi \Re(\Omega_3) + i\int_\Xi C_3\right)\right]$$

exponential not gauge invariant under $U(1)_a$!

$e^{-S_{E2}} \to e^{2\pi i\, Q_a(E2)\, \Lambda_a}\; e^{-S_{E2}}$, where

$Q_a(E2) = N_a\; \Xi \circ (\Pi_a - \Pi_a')$

Consequence:

If $Q_a(E2) \neq 0$ for some a, no terms $W = e^{-S_{E2}}$ possible but:

$$W = \prod_i \Phi_i\; e^{-S_{E2}} \quad \text{with} \quad \sum_i Q(\Phi_i) + Q_a(E2) = 0 \;\; \forall a$$

non-perturbative breakdown of global $U(1)$ symmetry possible

How can we understand this selection rule in terms of fermionic zero modes?

Zero mode structure-Details

Distinguish 2 types of fermionic zero modes:

1) zero modes uncharged under $U(1)_a$:

- Goldstinos θ_i
- If cycle Ξ non-rigid:
  $b_1(\Xi)$ fermionic zero modes from open strings starting and ending on $E2 \leftrightarrow E2$-moduli
- additional zero modes also at intersection of Ξ and Ξ' counted by $\frac{1}{2}([\Xi \cap \Xi']^{\pm} - [\Xi \cap \Pi_{O6}]^{\pm})$

vertex ops of these uncharged zero modes can only combine properly with vertex ops of (uncharged) closed string fields

for W_{np} dependent only on open fields of gauge sector, they have to absent:
Ξ has to be rigid and $[\Xi \cap \Xi']^{\pm} = [\Xi \cap \Pi_{O6}]^{\pm}$

Zero mode structure-Details

2) zero modes charged under $U(1)_a$:
from strings between E_2 and $D6_a$
DN-boundary conditions in 4D, mixed boundary conditions along CY_3
$\rightsquigarrow$ 1/2 complex fermionic zero mode λ_a

zero modes	Reps.	number
$\lambda_{a,I}$	$(-1_E, \Box_a)$	$I = 1, \ldots, [\Xi \cap \Pi_a]^+$
$\overline{\lambda}_{a,I}$	$(1_E, \overline{\Box}_a)$	$I = 1, \ldots, [\Xi \cap \Pi_a]^-$
$\lambda_{a',I}$	$(-1_E, \overline{\Box}_a)$	$I = 1, \ldots, [\Xi \cap \Pi'_a]^+$
$\overline{\lambda}_{a',I}$	$(1_E, \Box_a)$	$I = 1, \ldots, [\Xi \cap \Pi'_a]^-$

total $U(1)_a$ charge of all zero modes:
$Q_a(E2) = N_a\, \Xi \circ (\Pi_a - \Pi'_a)$
in agreement with $e^{-S_{E2}} \rightarrow e^{2\pi i\, Q_a(E2)\, \Lambda_a}\; e^{-S_{E2}}$

Instanton calculus - Outline

Our object of desire is $W_{np} \simeq \prod_{i=1}^{M} \Phi_{a_i,b_i}\, e^{-S_{E2}}$

$\Phi_{a_i,b_i} = \phi_{a_i,b_i} + \theta\psi_{a_i,b_i}$: superfields at the intersection of Π_{a_i} with Π_{b_i}
suppress Chan-Paton labels for simplicity

W_{np} detected by correlator in E_2-background

$$\langle \phi_{a_1,b_1} \cdot \ldots \cdot \phi_{a_{M-2},b_{M-2}} \cdot \psi_{a_{M-1},b_{M-1}} \cdot \psi_{a_M,b_M} \rangle_{E2-\mathrm{inst}} =$$

$$\int d^4x\, d^2\theta \sum_{\mathrm{conf.}} \prod_a \left(\prod_{I=1}^{[\Xi\cap\Pi_a]^+} d\lambda_{a,I} \right) \left(\prod_{I=1}^{[\Xi\cap\Pi_a]^-} d\overline{\lambda}_{a,I} \right)$$

$$\prod_k \langle \Phi^k_{a_{k_1},b_{k_1}} \cdot \ldots \cdot \Phi^k_{a_{k_r},b_{k_r}} \rangle^{g_k}_{\prod \lambda_k}$$

Instanton calculus - Outline

Which ways of splitting the $\langle \ldots \rangle^{g_k}_{\prod \lambda_k}$ contribute to W?

1) Each factor has to involve at least one $E2$-boundary

2) all λ_a and the two θ_i modes have to appear precisely once

3) Holomorphy of W: only dependence on g_s via $exp(-S_{E2})$

$\rightsquigarrow$ analyse g_s-scaling of $\langle \ldots \rangle^{g_k}_{\prod \lambda_k}$:

- each disk: $(g_s)^{-1}$
  one-loop diagram (annulus/Möbius): $(g_s)^0$
- vertex ops for $\phi_{a_i,b_i}/\psi_{a_i,b_i}$: $(g_s)^0$
  (otherwise decouple as $g_s \to 0$)
  vertex ops for λ_a: $(g_s)^{1/2}$ cf. D3-D(-1): [Billo et al.'03]

Consequence:

each disk carries precisely two λ_a vertices

annulus/Möbius carries no λ_a vertices

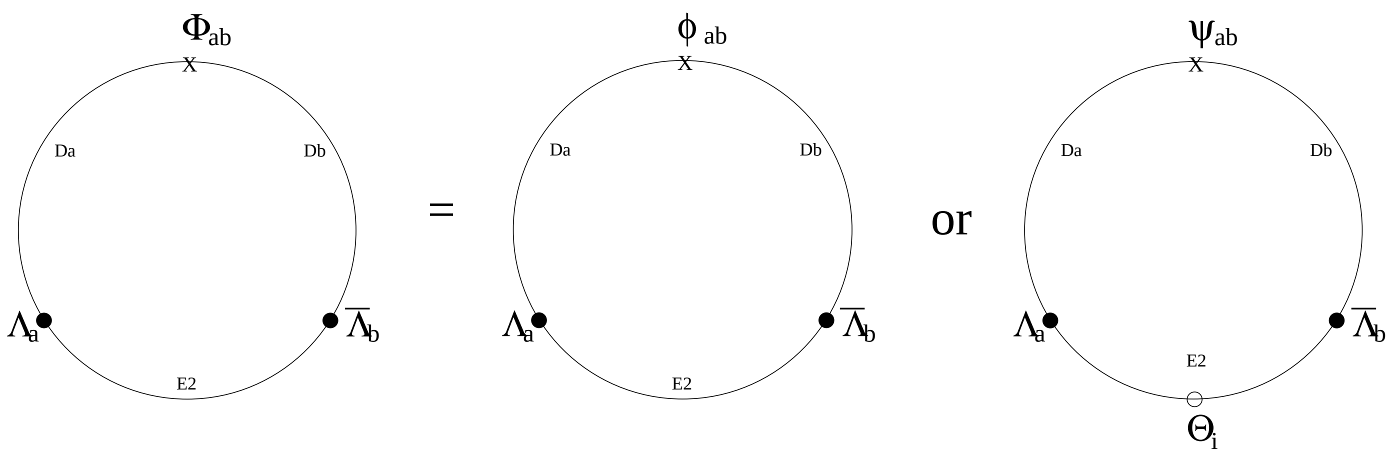
no worldsheets of genus higher than 1 contribute to W

Instanton calculus - Disks

- factor off vacuum disks cf.[Polchinski'94]

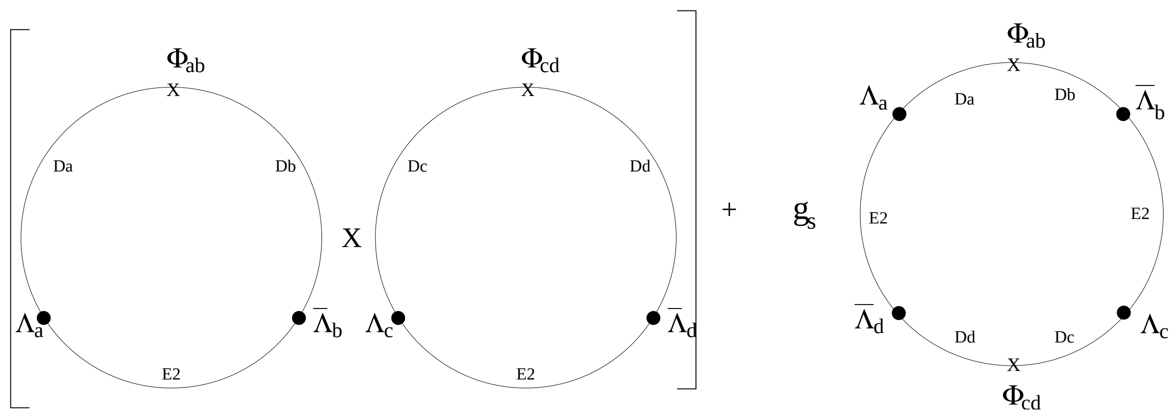
$$\sum_{n=1}^{\infty} \frac{1}{n!} (\langle 1 \rangle_{disk})^n = exp(-S_{E2})$$

- appropriate insertion of θ_i vertices hand in hand with insertion of $\phi_{a_i,b_i}/\psi_{a_i,b_i}$:



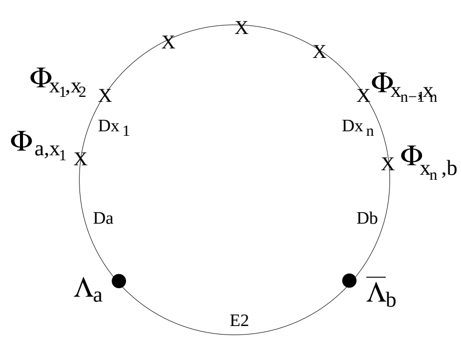
Instanton calculus - Disks

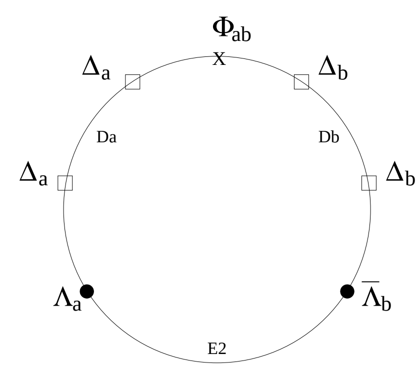
- only order g_s^0 diagrams



- also multi-insertion disks possible

e.g. if $D6$-brane has deformation moduli (superfields Δ_a),
insertion of arbitrary number of Δ_a
$\rightsquigarrow$ overall $\exp\left(-\frac{1}{\alpha'}\mathrm{tr}(\Delta_a)\right)$-dependence on open string moduli





Instanton calculus - 1-loop amplitudes

Recall: loop-amplitudes uncharged (no λ_a-insertion)

- factor off vacuum loops involving at least one $E2$ boundary:

$Z^A(E2, D6_a) = c \int_0^\infty \frac{dt}{t} \, \mathrm{Tr}_{E2,D6_a} \left(e^{-2\pi t L_0}\right) \neq 0$

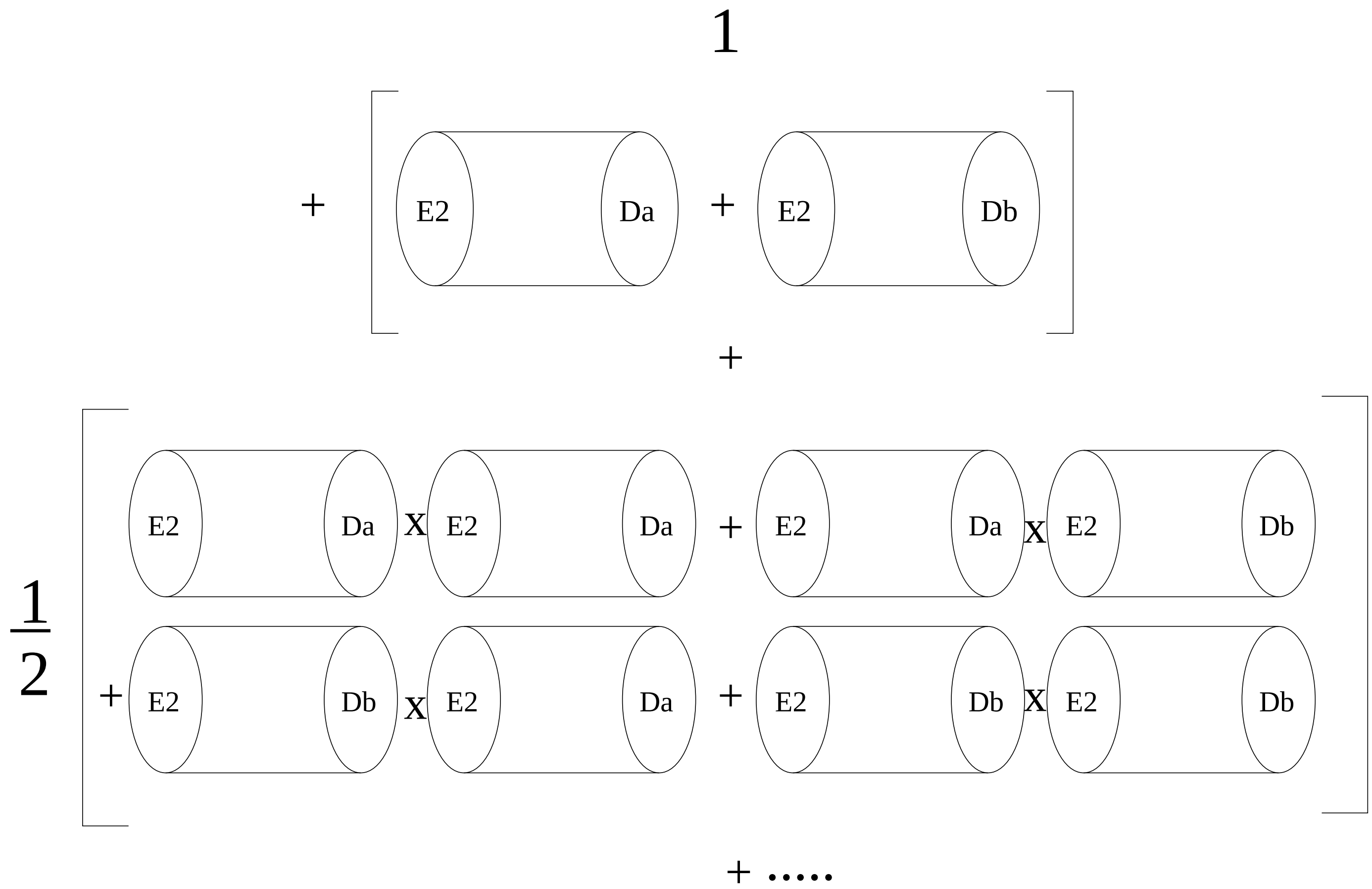
likewise $Z^M(E2, O6) \neq 0$, but

$Z^A(E2, E2) = 0 = Z^A(E2, E2')$ (due to supersymmetry preserved on $E2$ worldvolume) $\rightsquigarrow$

$$\sum_{n=0}^{\infty} \frac{1}{n!} \left(\sum_a \left[Z^A(E2, D6_a) + Z^A(D6'_a, E2) \right] + Z^M(E2, O6) \right)^n$$
$$= \exp\left(Z_0\right),$$

with $Z_0 = \sum_a \left[Z^A(D6_a, E2) + Z^A(D6'_a, E2) \right] + Z^M(E2, O6)$

Instanton calculus - 1-loop amplitudes



Instanton calculus - 1-loop amplitudes

Compare:

$\sum_{n=1}^{\infty} \frac{1}{n!}(\langle 1 \rangle_{disk})^n = e^{-S_{E2}} \leftrightarrow \sum_{n=1}^{\infty} \frac{1}{n!}(\langle 1 \rangle_{1-loop})^n = e^{Z_0}$

Interpretation of $exp(Z_0)$ as 1-loop determinant:

Z_0 divergent from $t \to \infty$ integration

($t \to 0$ divergence cancels)

$\rightsquigarrow$ in presence of bosonic zero mode: $exp(Z_0) \to \infty$

$\rightsquigarrow$ in presence of fermionic zero mode: $exp(Z_0) \to 0$

Cf. worldsheet instantons in het. (0,2)-models [Witten'99]):

$$W = \frac{\mathrm{Pfaff}(\overline{\partial}_{V_-})}{(det' \, \overline{\partial}_{\mathcal{O}})^2 \, (det \, \overline{\partial}_{\mathcal{O}(-1)})^2} \, \exp(-S_{\mathrm{inst}})$$

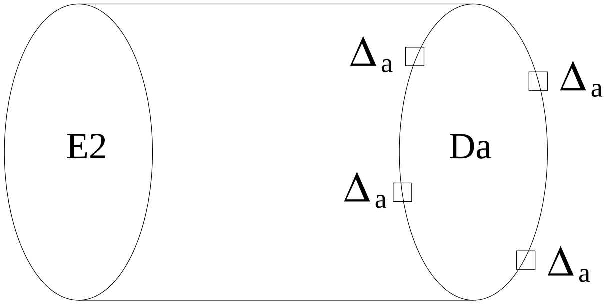
Instanton calculus - 1-loop amplitudes

As in heterotic string: remove bosonic and fermionic zero modes from 1-loop determinant!

$$\frac{\mathrm{Pfaff}'(\mathcal{D}_F)}{\sqrt{det'(\mathcal{D}_B)}} =$$

$$\exp\left(\sum_a \left[{Z'}^A(E2, D6_a) + {Z'}^A(E2, D6'_a)\right] + {Z'}^M(E2, O6)\right) .$$

• also attach chains of Φ_{a_i,b_i} to 1-loop diagrams with one boundary on $E2$
In particular: moduli Δ_a
$\rightsquigarrow$ moduli dependence of 1-loop determinant



Instanton calculus - Summary

$$\langle \Phi_{a_1,b_1}(x_1)\cdot\ldots\cdot\Phi_{a_M,b_M}(x_M)\rangle_{E2-\text{inst}} =$$

$$= \int d^4x\, d^2\theta \sum_{\text{conf.}} \prod_a \big(\prod_{i=1}^{[\Xi\cap\Pi_a]^+} d\lambda_a^i\big)\,\big(\prod_{i=1}^{[\Xi\cap\Pi_a]^-} d\overline{\lambda}_a^i\big)$$

$$\exp(-S_{E2}) \times \exp\left(Z_0'\right)$$

$$\times \langle\widehat{\Phi}_{a_1,b_1}[\vec{x}_1]\rangle_{\lambda_{a_1},\overline{\lambda}_{b_1}}\cdot\ldots\cdot\langle\widehat{\Phi}_{a_L,b_L}[\vec{x}_L]\rangle_{\lambda_{a_L},\overline{\lambda}_{b_L}} \times$$

$$\prod_k \langle\widehat{\Phi}_{c_k,c_k}[\vec{x}_k]\rangle^{\text{loop}}_{A(E2,D6_{c_k})}$$

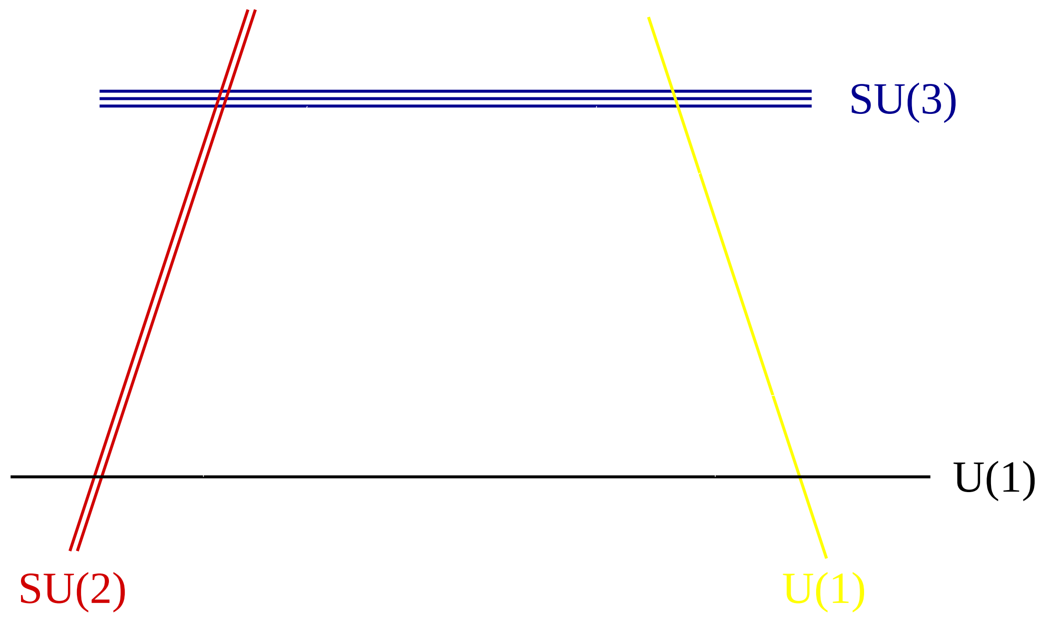
$$W = \sum_{E2} \overbrace{e^{-S_{E2}(U)}}^{\text{complex structure}} \; f\left(\overbrace{\exp\left(-\frac{T}{\alpha'}\right)}^{\text{WS disk instantons}}, \overbrace{\exp\left(-\frac{\mathrm{tr}(\Delta)}{\alpha'}\right)}^{\text{D6 moduli}}, \Phi_{ab} \right)$$

Matter couplings

Modulo the derived rules generation of important perturbatively forbidden matter couplings possible

• Most prominently: hierarchically large Majorana masses for right-handed neutrinos

For concreteness consider putative MSSM from IBW



Majorana Masses

Intersection	Matter	Rep.	Y
(a,b)	Q_L	$3\times(3,2)_{(1,0,0)}$	$1/3$
(a,c)	$(U_R)^c$	$3\times(\bar{3},1)_{(-1,1,0)}$	$-4/3$
(a',c)	$(D_R)^c$	$3\times(\bar{3},1)_{(-1,-1,0)}$	$2/3$
(b,d)	L_L	$3\times(1,2)_{(0,0,-1)}$	-1
(c,d)	$(E_R)^c$	$3\times(1,1)_{(0,-1,1)}$	2
(c',d)	$(N_R)^c$	$3\times(1,1)_{(0,1,1)}$	0

massless hypercharge $U(1)_Y = \frac{1}{3}U(1)_a - U(1)_c + U(1)_d$
baryon number $Q_B = Q_a$, lepton number $Q_L = Q_b$, Q_c, Q_d
massive i.e. perturbative global symmetries
$\rightsquigarrow$ Dirac mass $W_H = H^+ L_L (N_R)^c$ present, but
Majorana mass $W_m = M_m (N_R)^c (N_R)^c$ perturbatively forbidden

Majorana Masses

Non-pert. coupling possible if CY_3 possesses rigid 3-cycle Ξ with zero mode structure

$$\Xi \cap \Pi_a = \Xi \cap \Pi'_a = \Xi \cap \Pi_b = \Xi \cap \Pi'_b = \Xi \cap \Pi_c = \Xi \cap \Pi'_d = 0$$
$$[\Xi \cap \Pi'_c]^+ = 2, \; [\Xi \cap \Pi'_c]^- = 0, \; [\Xi \cap \Pi_d]^- = 2, \; [\Xi \cap \Pi_d]^+ = 0.$$

Non-pert. Majorana coupling:

$W_m = M_m \, (N_R)^c \, (N_R)^c$ with $M_m = x \, M_s \, e^{-\frac{2\pi}{\ell_s^3 \, g_s} \mathrm{Vol}_{E2}}$

Use $\frac{1}{\alpha_{\mathrm{GUT}}} = \frac{1}{\ell_s^3 \, g_s} \mathrm{Vol}_{D6} \rightsquigarrow M_m = x \, M_s \, e^{-\frac{2\pi}{\alpha_{\mathrm{GUT}}} \frac{\mathrm{Vol}_{E2}}{\mathrm{Vol}_{D6}}}$

For seesaw mechanism need $10^{11}\mathrm{GeV} < M_m < 10^{15}\mathrm{GeV}$

Easily possible within natural regime for
$0.4 \cdot R_{D6} > R_{E2} > 0.27 \cdot R_{D6}$

Proton decay?

Nice property of perturbative global $U(1)$ such as Q_B, Q_L:
Perturbative absence of dimension-four proton decay operators

$$W_4 = \lambda\,[Q_L\,(D_R)^c\,L_L] + \lambda'\,[(U_R)^c\,(D_R)^c\,(D_R)^c] + \lambda''\,[L_L\,L_L\,(E_R)^c]$$

$\rightsquigarrow$ Is proton unstable non-perturbatively?
Proton decay induced only if stable as long as $\lambda\lambda' \neq 0$
careful analysis of restrictive structure of boundary combinatorics and fermionic zero modes crucial:

- $[(U_R)^c\,(D_R)^c\,(D_R)^c]$ is possible if

$$[\Xi \cap \Pi_a]^+ = 1,\ \ [\Xi \cap \Pi_c]^- = 1,\ \ [\Xi \cap \Pi_c']^- = 2$$

$\rightsquigarrow$ $3 \times \lambda_a, 1 \times \overline{\lambda}_c, 2 \times \overline{\lambda}_{c'}$

Proton decay?

- $[L_L\, L_L\, (E_R)^c]$ likewise possible

- $[Q_L\, (D_R)^c\, L_L]$ not possible:
Minimal number of λ_a-modes if $E2$ on Ξ with

$$[\Xi \cap \Pi_a]^+ = 1 \rightarrow 3 \times \lambda_a \quad \text{due to} \quad N_a = 3$$

but Q_L and $(D_R)^c$ can only soak up 1 λ_a each!

$\leadsto$ no non-pert. dimension 4 proton decay operators induced in this manner

Additional couplings

• IBW GUT $SU(5)$ suffer from absence of pert. trilinear Yukawas $\mathbf{10}\,\mathbf{10}\,\mathbf{5}_H$, where $\mathbf{10}$ from (a,a')-intersection
Not generated by $E2$-instantons due to too many λ-modes

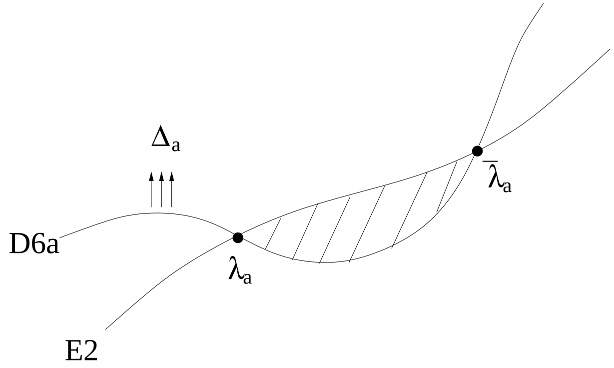
• depending on concrete construction μ -term $\mu H^+ H^-$ is often forbidden pertrubatively
$\rightsquigarrow$ can well be generated!

Vacuum destabilisation

Recall: All amplitudes require rigid $E2$ branes with no uncharged zero-modes! very restrictive!
2 kinds of destabilising terms can be induced:
• In presence of precisely to fermionic zero modes λ_a, $\overline{\lambda}_b$, open string tadpole

$$W = \Phi_{a,b}\; e^{-S_{E2}}$$

is possible.
• If $E2$-brane has only non-chiral (vector-like) $\lambda - \overline{\lambda}$ modes with $D6_a$, purely moduli dependent terms induced:



Vacuum destabilisation

Does this destroy all known perturbative brane vacua?

• Both rigidity and zero mode structure rule out these processes in most, though not all cases

• Interplay of several such terms can in principle also lead to fixing of open string moduli

$\rightsquigarrow$ systematic analysis in concrete examples required

• Cancellation of complete sum of these contributions likewise conceivable in principle (see Beasley/Witten)

$\rightsquigarrow$ remains to be seen!

D-terms

Recall: If $E2$ is half-BPS w.r.t. $D6$-branes: F-terms generated
If sLag Ξ of $E2$ breaks all SUSY $\rightsquigarrow$ 4 zero modes θ_i, $\overline{\theta}_i$ as required for non-pert. D-term

$D6 - E2$ zero modes: same structure of fermionic zero modes as in half-BPS case
absence of tachyons in bosonic sector guaranteed due to DN-boundary conditions in 4D!

$\rightsquigarrow$ no instability due to possible recombination modes, at most mild non-pert. deformation of D-term SUSY condition

D-terms/gauge kinetic functions

Expect FI-term $S_{FI} = \int d^4x \, d^2\theta \, d^2 \, \overline{\theta} \; V_{U(1)}$ arising from diagrams involving vert. op. for abelian gauge field on D6 and vector-like pairs of λ, $\overline{\lambda}$-modes
i.e. only $E2$-branes with zero net charge under $U(1)_a$ contribute to FI-term

D-term SUSY condition $\overset{\text{central charge}}{\longleftrightarrow}$ gauge couplings

$$\xi_a \simeq \operatorname{Arg} \int_{\Pi_a} \Omega_3, \quad f_a = \frac{1}{(2\pi)\, \ell_s^3} \left[\frac{1}{g_s} \left| \int_{\Pi_a} \Omega_3 \right| + i \int_{\Pi_a} C_3 \right]$$

$\rightsquigarrow$ expect likewise non-pert. corrections to gauge kinetic function
this time from half-BPS $E2$-branes, but again carrying no net $U(1)$ charge (non-chiral intersection)

Dual formulations

Type IIA orientifolds $\stackrel{\text{Mirror symmetry}}{\longleftrightarrow}$ Type I /Type IIB orientifolds $\stackrel{\text{S-duality}}{\longleftrightarrow}$ Heterotic $(0,2)$-models

1.) Type I:

D9-branes carrying (non-)abelian gauge bundle V_a

D5-branes wrapping holomorphic curves

2 types of axions:

universal axion from dim. red. of C_6 on $CY_3 \rightsquigarrow$ complexifies dilaton in S

Kähler axions: C_2 reduced on two-cycles of $CY_3 \rightsquigarrow$ complexify Kähler moduli

analogue of $E2$-branes in IIA: $E1/\ E5$-instantons

- $E1$: have to wrap rigid curves (isolated $\mathbb{P}_1$),

charged zero modes counted by $H^*(\mathbb{P}_1, V_a|_{\mathbb{P}_1} \otimes K^{1/2}_{\mathbb{P}_1})$

Dual formulations

- $E5$: wrap CY_3, carry bundle V_E,
uncharged zero modes = bundle moduli of V_E counted by
$H^1(CY_3, V_E \otimes V_E^*) \stackrel{!}{=} 0$
in addition: symmetric/antisymmetric matter in
$H^*(CY_3, \Lambda^2 V_E) \stackrel{!}{=} 0 \stackrel{!}{=} H^*(CY_3, \bigotimes_{sym} V_E)$

charged matter in $H^*(CY_3, V_a \otimes V_E), H^*(CY_3, V_a \otimes V_E')$
Note: complex structure and bundle moduli U and B contain no axions/Wilson lines!

$\rightsquigarrow$ general functional dependence possible

$$W = \sum_{E1} e^{-S_{E1}(T)}\, f(U, B, \Phi_{ab}) + \sum_{E5} e^{-S_{E5}(S,T)}\, f(U, B, \Phi_{ab}),$$

Dual formulations

2.) Type I directly S-dual to heterotic $Spin(32)/\mathbb{Z}_2$ string with $U(N)$-bundles
same strucutre also for $E_8 \times E_8$ string with general $U(N)$ bundles embedded
role of $E1/E5$ instantons played by worldsheet$/NS5$-brane instantons

3.) Type IIB orientifolds with $O3/O7$-planes
chiral matter on D7-branes wrapping holomorphic divisor and carrying gauge bundle V_a axions from dim. red. of C_4 along 4-cycles
$E3$-brane instantons:
rigid 4-cycle Γ_E: $h^0(\Gamma_E, N) = h^{(2,0)}(\Gamma_E) \stackrel{!}{=} 0$
absence of bundle moduli for $V_E = L$:$h^{(1,0)}(\Gamma_E) \stackrel{!}{=} 0$
additional charged zero modes if $E3$ and $D7$ brane overlap internally! [Ganor'96]

Conclusions

E2-brane instantons in Type IIA brane vacua allow for an explicit CFT description
general results for disk and one-loop contributions in agreement with dual descriptions in heterotic/IIB theory

formalism applicable to vacua with exactly solvable CFT: toroidal orientifolds, Gepner Model orientifolds
Challenge: present concrete models with rigid cycles

[Blumenhagen,Cvetič,Marchesano, Shiu'05], [Blumenhagen,Plauschinn'06]

implications on phenomenology and model building:
vacuum destabilisation/SUSY breaking, open string moduli fixing $\rightsquigarrow$ effects on open string landscape?
natural explanation of hierarchies in context of Majorana masses/ μ-terms
modification of D-term SUSY condition? extension of concept of Fukaya category?