D-brane Instanton Corrections in Type IIA String Theory

and their phenomenological applications

based on:

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Motivation: G2 - IIA duality

M-theory on G2	Type $IIA/\Omega\overline{\sigma}$ on CY_3
non-abelian gauge symmetries due to	
codim.4 singularities, e.g.:	D6-branes wrapping sLag 3-cycles:
A_{N-1}-type singularity	N D6-branes away from O6-plane
$\longrightarrow SU(N)$	$\longrightarrow U(N) = SU(N) \times U(1)$
D_M -type singularity	$2M$ D6-branes on top of O6-plane
$\longrightarrow SO(2M)$	$\longrightarrow SO(2M)$
localised chiral fermions at	
codim. 7 singularities, e.g.:	intersection points of D6-branes:
$A_{N_1+N_2-1}$-type singularity	$N_1 \cap N_2$ branes away from $O6$
D_N-type singularity	$N \cap N'$ (branes and images) on $O6$

Motivation: G2 - IIA duality

perturbative IIA limit:
$U(1)$ gauge factors from $U(N) = SU(N) \times U(1)$
• in general: $U(1)$ massive due to $B \wedge F$-type coupling in CS action $\leftrightarrow$ Green-Schwarz-mechanism
• specific linear combinations may or may not remain massless
• massive $U(1)$ present as global perturbative symmetries constraining perturbatively allowed couplings

M-theory limit:
massive $U(1)$ decouples completely: $m_{U(1)} \longrightarrow \infty$ as $g_s \longrightarrow \infty$

for consistency with $G2$-lift:
non-perturbative effects must break global $U(1)$ and generate perturbatively forbidden couplings in IIA picture

Motivation: Stringy Hierarchies

(extensions of) MSSM contain
couplings at poorly understood scale, e.g.:
$\rightsquigarrow$ Majorana masses for right-handed neutrinos of order
$10^8 GeV < M_M < 10^{15} GeV$
$\rightsquigarrow$ hierarchically small μ-terms of order M_Z
In many string models, these are among the perturbatively forbidden couplings!

If realized non-perturbatively as

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

they would be exponentially suppressed w.r.t. string scale
$\leftrightarrow$ stringy realisation of peculiar scale of certain MSSM couplings?

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]

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

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

stringy instantons not describable as gauge instantons!

recent related work:

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

[Ibanez,Uranga, hep-th/0609213];[I,U,Schellekens,arXiv:0704.1079]

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

[Bianchi,Fucito,Morales,arXiv:0704.0784]

[Argurio et al.,arXiv:arXiv:0704.0262]

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:
   - Majorana masses: example + CFT on $T^6/\mathbb{Z}_2 \times \mathbb{Z}'_2$
   - μ-terms, proton decay,...
5. Conclusions

Briefing on Type IIA model building

Compactify Type IIA string theory on
$\mathcal{M}^{(10)} = \mathcal{M}^{(4)} \times CY_3$ quotiented by $\Omega\,(-1)^{F_L}\,\overline{\sigma}$

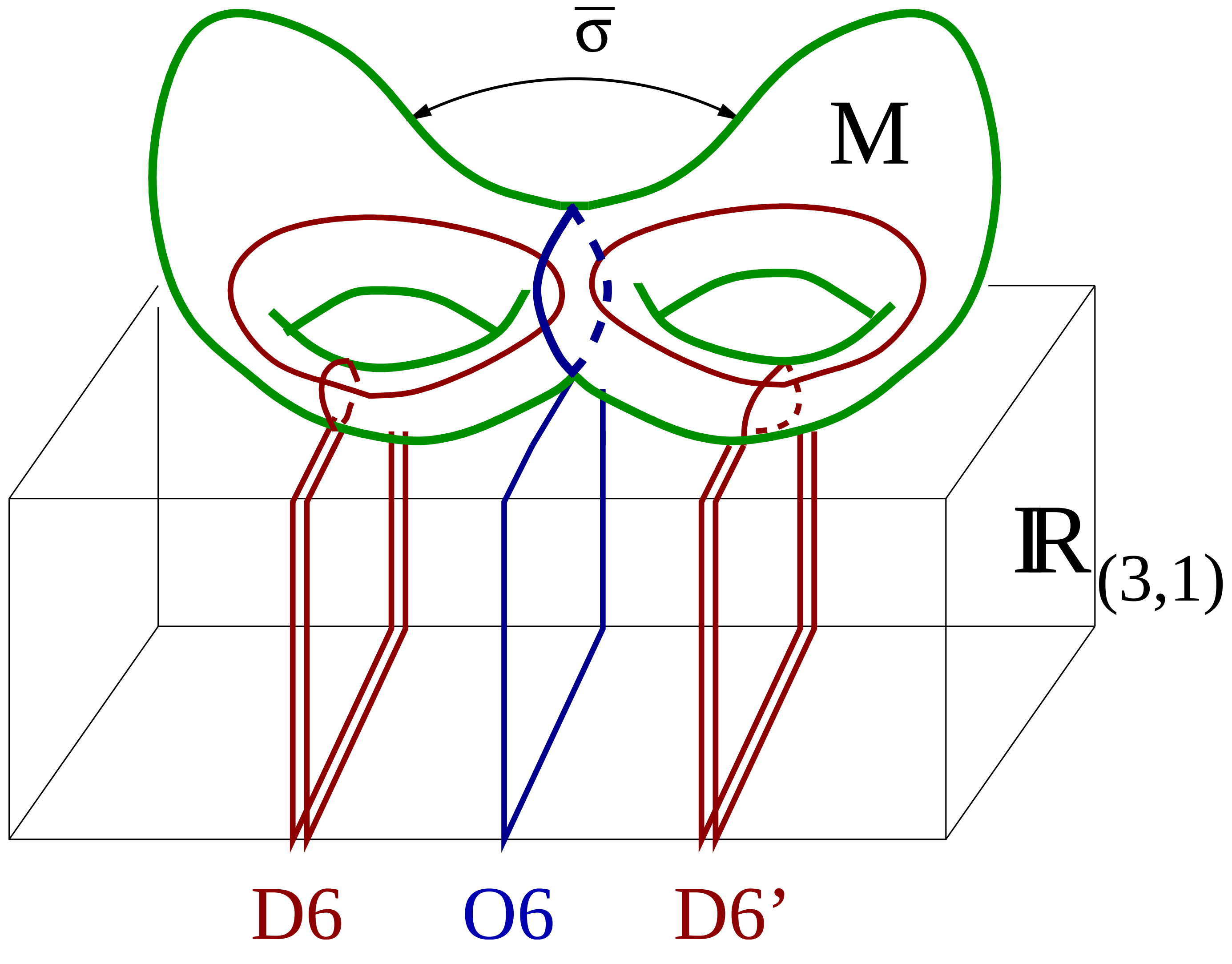
Ω: worldsheet parity, F_L: left-handed fermion number

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

$\rightsquigarrow$ 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

TAD: $\sum_a N_a(\Pi_a + \Pi'_a) - 4\Pi_{O6} = [0]$
$D6$-branes should wrap sLags preserving same SUSY as $O6$

chiral matter at non-trivial intersection of internal 3-cycles
chiral number of generations in $(\overline{N}_a, N_b)$: $\Pi_a \circ \Pi_b$
(top. intersection number)



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

Anomalous $U(1)$ 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

Anomalous $U(1)$ and GS-mechanism

CS-coupling induces gauging of global axionic shift symmetry:

under $U(1)_a$ gauge transformation the RR-form C_3, KK-reduced on 3-cycle $\widetilde{\Pi}$, transforms as

$$
\begin{aligned}
A_a &\longrightarrow A_a + d\Lambda_a \\
\int_{\widetilde{\Pi}} C^{(3)} &\longrightarrow \int_{\widetilde{\Pi}} C^{(3)} + Q_a(\widetilde{\Pi})\Lambda_a
\end{aligned}
$$

with $Q_a(\widetilde{\Pi}) = \frac{\ell_s^3}{2\pi}\, N_a\, \widetilde{\Pi} \circ (\Pi_a - \Pi_{a'})$

Instantons-Heuristics

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

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

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

$\rightsquigarrow$ relevant objects are Euclidean $D2$-branes

$\leftrightarrow$ (certain) IIA limit of membrane instantons on $G2$

Rules:

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

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 $U(1)_a$!
$e^{-S_{E2}} \longrightarrow e^{i\,Q_a(E2)\,\Lambda_a}\; e^{-S_{E2}}$: $Q_a(E2) = N_a\;\Xi \circ (\Pi_a - \Pi'_a)$

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_α, $\overline{\theta}_{\dot\alpha}$
- 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 $\frac{1}{2}([\Xi \cap \Xi']^{\pm} + [\Xi \cap \Pi_{O6}]^{\pm})$

need to absorb latter two types: Kähler potential or higher fermionic couplings

for contribution to W_{np}, only 2 uncharged zero modes θ_α:

- Ξ has to be rigid
- $\Xi = \Xi'$ such that $\overline{\theta}_{\dot\alpha}$ can be projected out

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
$\rightsquigarrow$ at chiral intersection: 1 single fermionic zero mode λ_a

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

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

Instanton calculus - Outline

Wanted: (physical) matter couplings induced by
$W_{np} \simeq \prod_{i=1}^{M} \Phi_{a_i,b_i}\, e^{-S_{E2}}$

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

Compute (physical) correlator in E_2-background

$$\langle \phi_{a_1,b_1} \cdot \ldots \cdot \phi_{a_{M-2},b_{M-2}} \cdot \psi_{a_{M-1},b_{M-1}} \cdot \psi_{a_M,b_M} \rangle_{E2-\mathrm{inst}} =$$
$$\int d^4\tilde{x}_E\, d^2\tilde{\theta} \sum_{\mathrm{conf.}} \prod_a \left(\prod_{I=1}^{[\Xi\cap\Pi_a]^+} d\tilde{\lambda}_{a,I}\right) \left(\prod_{I=1}^{[\Xi\cap\Pi_a]^-} d\tilde{\overline{\lambda}}_{a,I}\right)$$
$$\prod_k \langle \Phi^k_{a_{k_1},b_{k_1}} \cdot \ldots \cdot \Phi^k_{a_{k_r},b_{k_r}} \rangle^{g_k}_{\prod \lambda_k}$$

Instanton calculus - Outline

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

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

2) all λ_a and the two θ_α 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 $E2 - D6$: $(g_s)^{-1}$
  one-loop diagram (annulus/Möbius): $(g_s)^0$
- all vertex operators carry $(g_s)^0$
  ($\simeq$ frame where all tree pert. terms at $\frac{2\pi}{g_s}$)
- proper norm. of measure in terms of

$$\tilde{x}^\mu_E = \frac{x^\mu_E}{2}\sqrt{\frac{2\pi\mathcal{V}_{E2}}{g_s}}, \qquad \tilde{\theta}^\alpha = \theta^\alpha\sqrt{\frac{2\pi\mathcal{V}_{E2}}{g_s}} \qquad \tilde{\lambda} = \lambda\sqrt{\frac{2\pi}{g_s}} \text{ cf.}$$

D3-D(-1): `[Billo et al.'03]`

Instanton calculus - Outline

Consequence:
from $d^4\tilde{x}_E\, d^2\tilde{\theta}$: $\frac{2\pi}{g_s}\,\mathcal{V}_{E2}$

no additional powers of g_s picked up iff:

- each disk carries precisely 2 λ_a vertices
- in annulus/Möbius amplitudes: no λ_a vertices appear
- and no worldsheets of genus higher than 1 are considered

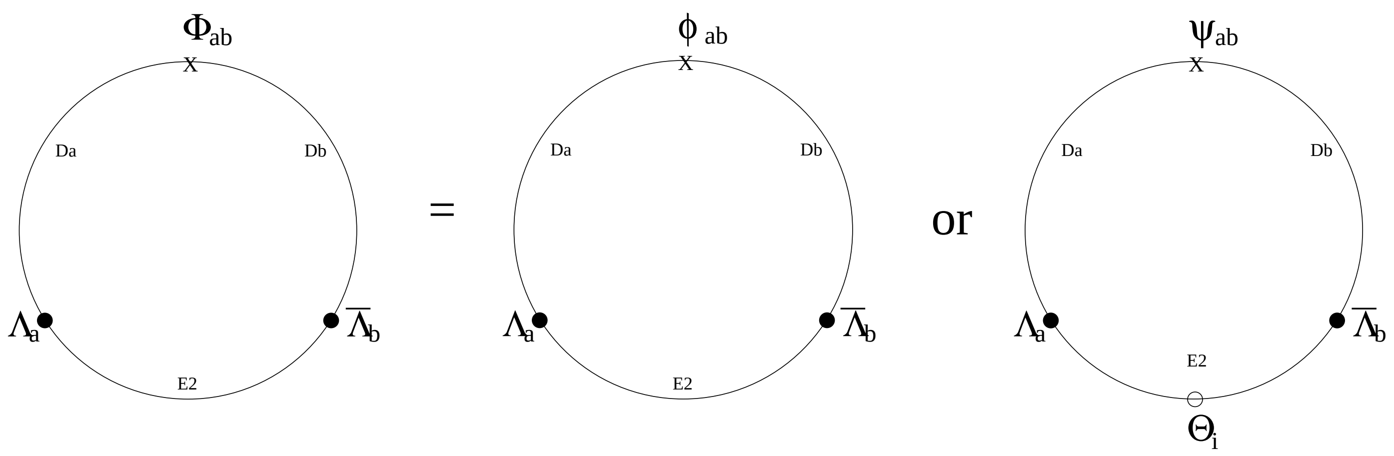
Focus on physical couplings of above type, i.e. arising at lowest order in g_s

Instanton calculus - Disks

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

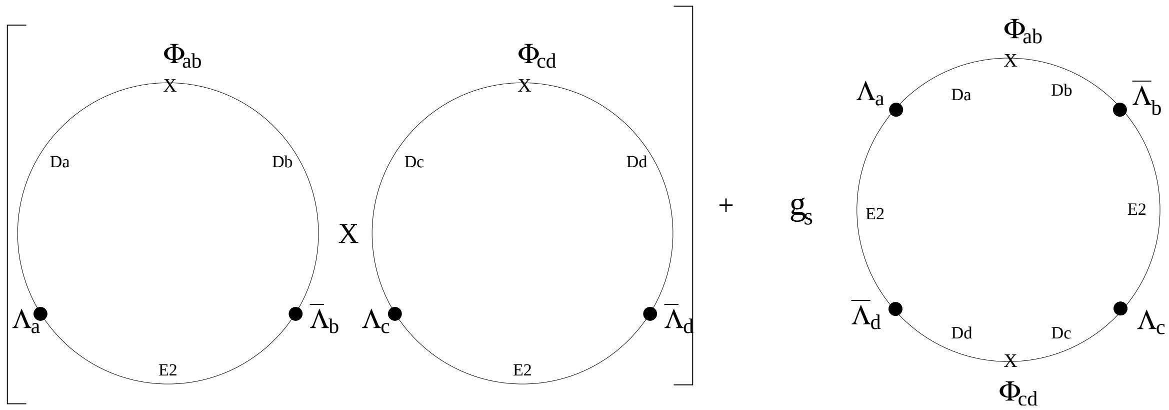
$$\sum_{n=1}^{\infty} \frac{1}{n!} (\langle 1 \rangle_{disk})^n = exp(-S_{E2})$$

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



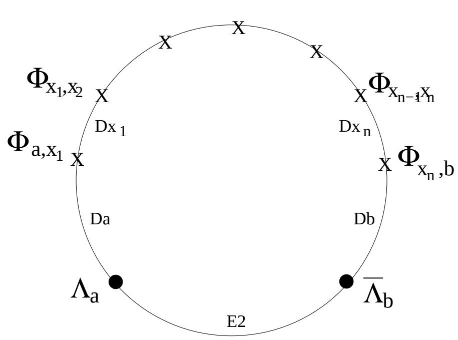
Instanton calculus - Disks

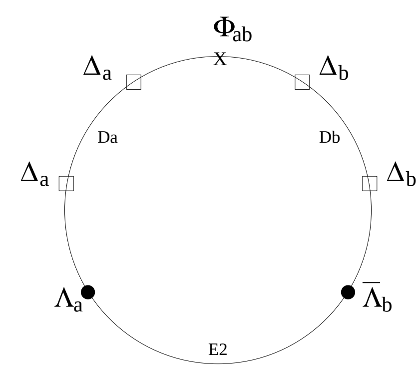
- only order g_s^0 diagrams



- 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
and omit zero modes

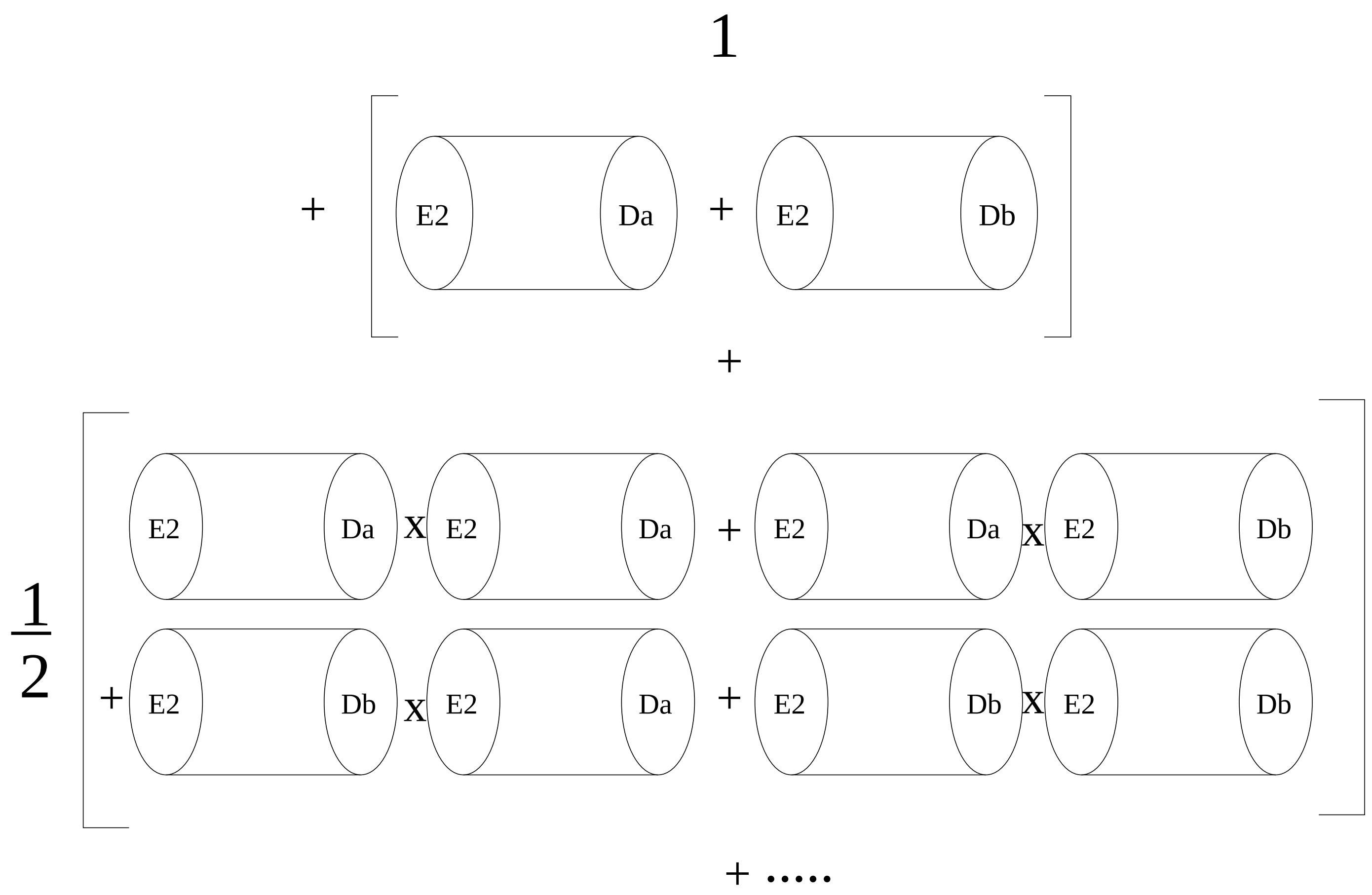
$$\sum_{n=0}^{\infty} \frac{1}{n!} \left(\sum_a \left[Z'^A(E2, D6_a) + Z'^A(D6'_a, E2) \right] + Z'^M(E2, O6) \right)^n$$
$$= \exp\left(Z'_0\right),$$

$\rightsquigarrow$ regularized 1-loop determinant
related to β-function [Akerblom et al., hep-th 0612132]

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

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

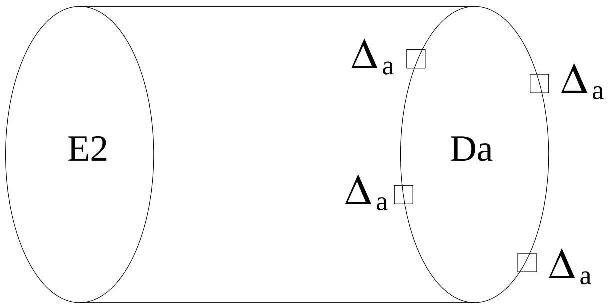
Instanton calculus - 1-loop amplitudes



Instanton calculus - 1-loop amplitudes

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

$$\langle \Phi_{a_1,b_1}(p_1)\cdot \ldots \cdot \Phi_{a_M,b_M}(p_M)\rangle_{E2-\text{inst}} =$$

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

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

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

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

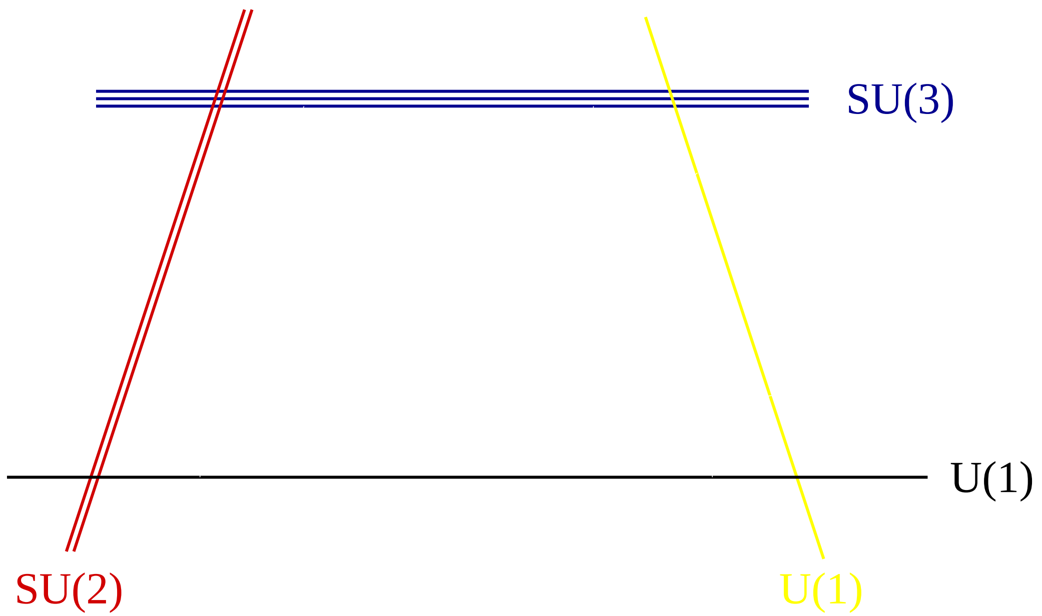
$$W = \sum_{E2} \overbrace{e^{-S_{E2}(U)}}^{\text{complex structure}} f\left(\overbrace{\exp\left(-\frac{T}{\alpha'}\right)}^{\text{WS disk instantons}}, \overbrace{\exp\left(-\frac{\text{tr}(\Delta)}{\alpha'}\right)}^{\text{D6 moduli}}, \Phi_{ab}\right)$$

Matter couplings

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)	$(U_R)^c$	$3\times(\overline{3},1)_{(-1,1,0)}$	$-4/3$
(a',c)	$(D_R)^c$	$3\times(\overline{3},1)_{(-1,-1,0)}$	$2/3$
(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

massive i.e. perturbative global symmetries:
baryon number $Q_B = Q_a$, lepton number $Q_L = Q_b,\ Q_c,\ Q_d$
massless hypercharge $U(1)_Y = \frac{1}{3}U(1)_a - U(1)_c + U(1)_d$
$\rightsquigarrow$ 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 $10^8\mathrm{GeV} < M_m < 10^{15}\mathrm{GeV}$

Possible <u>without fine tuning</u> for $0.4 \cdot R_{D6} > R_{E2} > 0.2 \cdot R_{D6}$

(provided x of order 1)

Concrete realisations on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2'$

Aim:

• Provide example of model with rigid $E2$-brane and suitable zero mode structure $\rightsquigarrow$ highly constraining

• Realize correct suppression scale for Majorana masses

• Exemplify CFT computation $\rightsquigarrow$ determine x exactly

Rigid sLags on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2'$ with discrete torsion:

[BCMS hep-th/0502095]

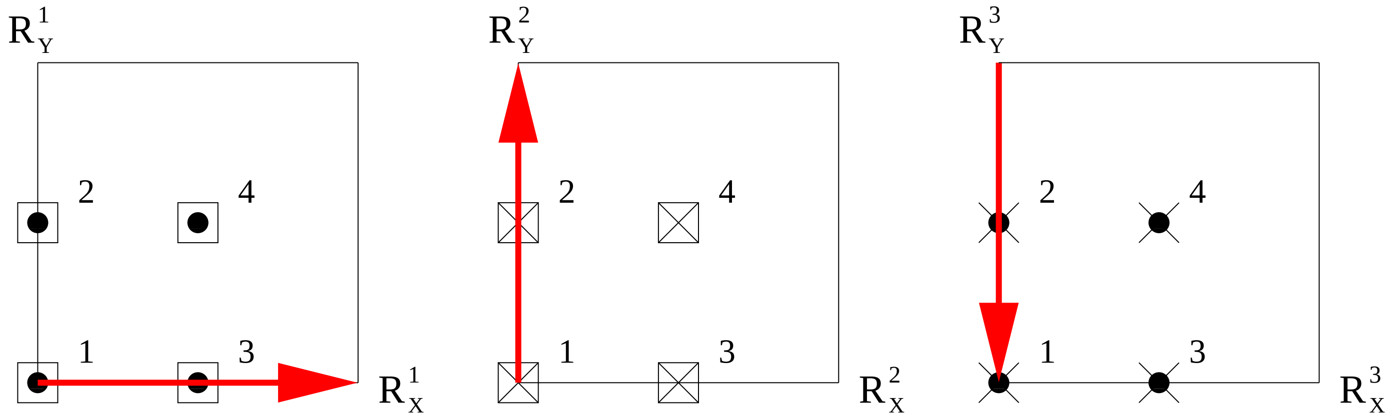
rigid fractional cycles:

• Stuck at orbifold fixed points in all three twisted sectors (fractional cycles)

• homological sum of bulk cycle $S^1 \times S^1 \times S^1$ and $\sum_g \mathbb{P}^1_g \times S^1$ from each twisted sector g

Absence of uncharged fermionic zero modes beyond θ^α requires $E2 = E2'$

Concrete realisations on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2'$



From details of orientifold action on twisted cycles:
8×8 such invariant rigid cycles
Construct supersymmetric local 3-stack GUT-like model:

sector	I_{xy}	representation	matter
(c, c')	4	Antisym	**10**
(c, a)	24	$(\overline{c}, a)$	$\overline{\mathbf{5}}$
(c, b)	-24	$(c, \overline{b})$	$\mathbf{5}_H$
(a, b)	32	$(\overline{a}, b)$	N_R^c

Concrete realisations on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2'$

Indeed:

$[\Pi_{E2} \cap \Pi_a]^+ = 2, \quad [\Pi_{E2} \cap \Pi_b]^- = 2, \quad [\Pi_{E2} \cap \Pi_c]^\pm = 0$

Perform detailed CFT computation of instanton induced Majorana mass by evaluation disks for each instanton

Result: $< \nu^A \nu^B >_{E2_i} = \frac{2\pi}{g_s} \mathcal{V}_{E2} \, \overrightarrow{v}^T \mathcal{M} \, \overrightarrow{v} \, (2\pi)^4 \delta^4(k^A + k^B)$

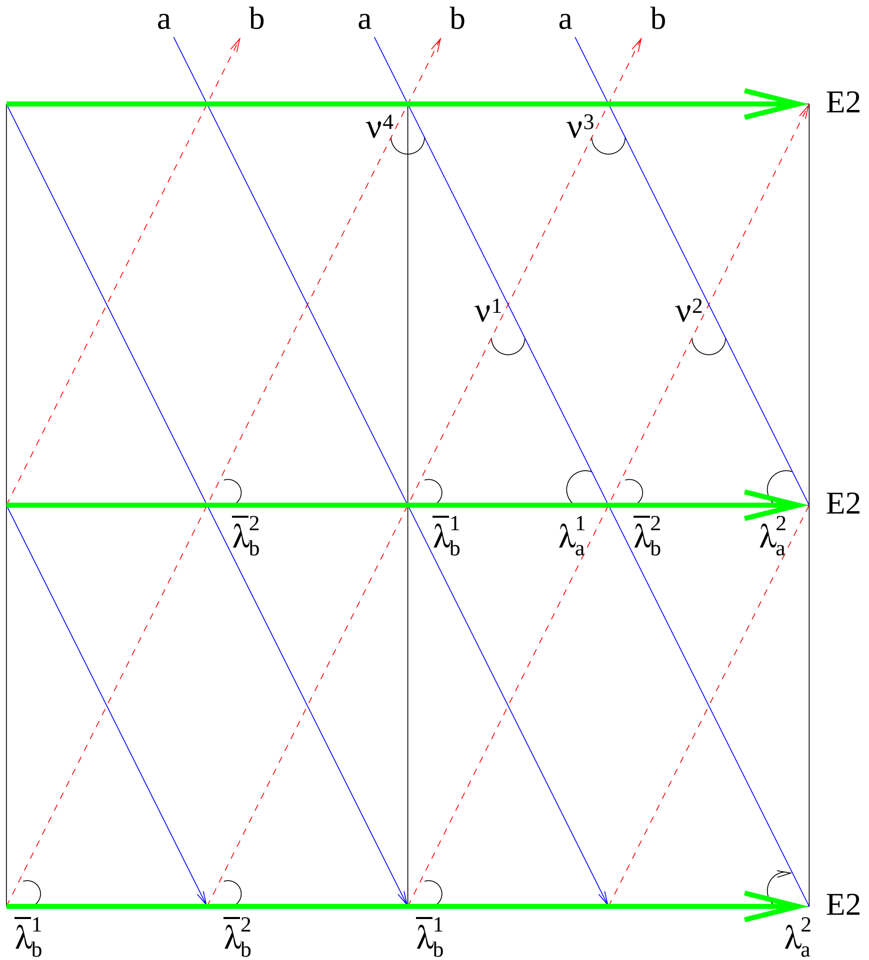
$$\mathcal{M} = x \, M_s \, e^{-\frac{2\pi}{\alpha_{\mathrm{GUT}}} \frac{8}{57}} \begin{pmatrix} A_i & 0 & B_i & 0 \\ 0 & C_i & 0 & D_i \\ B_i & 0 & E_i & 0 \\ 0 & D_i & 0 & F_i \end{pmatrix},$$

$x =$

$$\frac{(4\pi)^{3/2}\pi^2}{16} \left[\Gamma_{1-\theta^1_{ab}, 1-\theta^1_{E2a}, 1+\theta^1_{E2b}} \prod_{I=2}^3 \Gamma_{-\theta^I_{ab}, -\theta^I_{E2a}, 1+\theta^I_{E2b}} \right]^{\frac{1}{2}} \; e^{Z'}$$

Concrete realisations on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2'$

Family mixing pattern depends on suppression by worldsheet instantons, i.e. size of triangles
involves Kahler and open string (position) moduli



Concrete realisations on $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2'$

Sum up contributions from all 64 factorizable E2-instantons, taking leading contribution (smallest triangle)
$\rightsquigarrow$ $M_M \simeq 10^{10} GeV$
for triangles of order string scale (as required)

together with pert. Dirac masses from $\overline{\mathbf{5}}\,\mathbf{5}_H\,\mathbf{1}$ of electroweak scale
$\rightsquigarrow$ small neutrino masses of $\mathcal{O}(1eV)$ via see-saw mechanism

Further applications

• in many concrete IBW constructions:
μ -term $\mu H^+ H^-$ forbidden perturbatively
$\rightsquigarrow$ can well be generated by $E2$-instantons!
$\rightsquigarrow$ appropriate volume ratio may "explain" why $\mu \simeq \mathcal{O}(M_Z)$

• 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
$\rightsquigarrow$ How do we explain this in view of $G2 - IIA$ duality?

• In principle $E2$ effects can also break "welcome" perturbative global $U(1)$ such as Q_B, Q_L:
Have to ensure absence of dim. 4 proton decay operators of type

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

Conclusions

Breakdown of perturbative global U(1) via E2-brane instantons in Type IIA solves puzzle about agreement with $G2 - IIA$ duality

studied explicit CFT description
general rules for disk and one-loop contributions

formalism applicable to vacua with exactly solvable CFT:
toroidal orientifolds, Gepner Model orientifolds

implications on phenomenology and model building:
generation of hierarchies without fine-tuning in context of Majorana masses/ μ-terms
$\rightsquigarrow$ gave explicit local example for see-saw mechanism
Challenge: present global models with rigid cycles and realistic spectrum