D-branes, D-instantons & Particle Physics Models

Developments in String Model Building

Perturbative & Non-perturbative Effects

(Focus on Type II String Theories)
D-instanton Effects:
Hierarchical Non-Perturbative Superpotential Couplings
Ralph Blumenhagen, M.C., Timo Weigand, hep-th/0609191
original paper

Particle Physics Implications:
M.C., Robert Richter, T. Weigand, hep-th/0703028 neutrino Majoranas
R. Blumenhagen, M.C., D. Lüst, R. Richter, T. Weigand, 0707.1871 (PRL) 10 10 5 GUT coupling
M.C., P. Langacker, 0803.253 Dirac neutrino masses
M.C., T. Weigand, 0711.0209 (PRL), 0807.3953 first global models/SUSY breaking

& M.C., Jim Halverson & R. Richter, 0905.3379 systematic (bottom-up) analysis of MSSM multi-D-brane stack models
Other (formal) developments

R. Blumenhagen, M.C., R. Richter, T. Weigand, 0708.0403
multi-instantons & recombination

M.C., R. Richter, T. Weigand, 0803.138  N=1 multi-BPS instantons

M.C., Iñaki Garcia-Etxebarria & R. Richter, 0905.1694
D-instanton intersecting at angles, issues of massive instanton modes

No time → Strings’09
• Large classes of perturbatively constructed four-dimensional $N=1$ supersymmetric vacua

$\rightarrow$ Major activity w/ Intersecting D6-brane (Type IIA) constructions: semi-realistic, supersymmetric three-family Standard Models and SU(5) GUT models

• Question: How non-perturbative effects modify features of perturbative string vacua?

$\rightarrow$ Focus on Type IIA Euclidean D-instanton effects: Euclidean D2 $[E2]$–instantons; $W$-superpotential corrections

[Type I (IIB) global models with E1 instantons - no time]
D-brane instantons may generate perturbatively absent couplings – new hierarchical scales, suppressed by $e^{-\frac{1}{g_s}}$

→ Implications for hierarchical couplings of the SM

- Small Neutrino masses:
  (i) seesaw: Majorana masses $10^{11}$ GeV $< M_M < 10^{15}$ GeV;
  (ii) small Dirac masses $10^{-3}$ eV

- Hierarchically small $\mu$-terms of order $\mathcal{O}(\text{TeV})$

- Top $\mathcal{O}(100 \text{ GeV})$ – bottom $\mathcal{O}(10 \text{ GeV})$ mass hierarchy

- Hierarchically suppressed supersymmetry breaking
Extensive past literature on instantons in string theory ...

New string instanton effects in (open string) charged sector:
[Blumenhagen, M.C., Weigand, hep-th/0609191]
[Ibañez, Uranga hep-th/0609213]
- charged matter coupling corrections

[Florea, Kachru, McGreevy, Saulina 0610003]
- supersymmetry breaking

Further developments: many papers...
Outline

1. **Motivation** - done!
2. **Brief status of intersecting D-brane constructions**
3. **D-Instantons:** Type IIA w/ Euclidean D2-brane – focus on superpotential corrections due to rigid O(1) D-instantons
   - Instanton zero modes
4. **Specific applications:**
   - Small neutrino masses
   - Other couplings: $10105_H$ of SU(5) GUT, $\mu$ of MSSM, Polonyi-type SUSY breaking – time-permitting
   - Local GUT set-ups & first global GUT examples – no time
   - Classification of (local) MSSM multi-stack quivers w/D-instantons
5. **Conclusions and outlook**
Model Building with Intersecting D-branes

Engineering of semi-realistic constructions w/ Intersecting D6-branes wrapping three-cycles \( \Pi \) — Standard Model:
- Non-Abelian gauge symmetry \( SU(3)_C \times SU(2)_L \times U(1)_Y \)
  \( \rightarrow \) \( U(N) \) as a stack of \( N \)-coincident D-branes
- Chiral matter quarks & leptons
  \( \rightarrow \) at intersections of D-branes in internal space; bi-fund.

\[ \Phi_{ab} \]

- Family replication 3-copies of fermion families
  \( \rightarrow \) no. of D-brane intersections in internal space \( \Pi_a \circ \Pi_b \)
  \( \rightarrow \) Origin of Standard Model Geometric!
Intersecting D-brane GUT’s

$U(5)_a \times U(1)_b$ configurations contain the spectrum:

- bi-fundamental reps.: say, $(5_a, 1_b), (\bar{5}_a, 1_b)$
- [at intersections of $U(5)_a$ and $U(1)_b$ D-branes]
- & anti-symmetric reps.$10_a$ (& symmetric $15_a$)
- [Intersections of $D_a$ branes and their orientifold image $D'_a$]

A geometric framework for Georgi Glashow SU(5) GUT’s.
Status

- $\mathcal{O}(100)$ inequivalent global toroidal orbifold SM & GUT models (geometric phase) with semi-realistic features
- typically suffer from chiral exotics – limitations of orbif. constr.
- realistic (Yukawa) couplings? – focus in the rest
- moduli stabilization? – separate topic

Rational Conformal Field Theory constructions-promising

[Schellekens et al.]:
- models without chiral exotics
- couplings in principle calculated, but hard & hierarchy?
- non-geometric phase–moduli stabilization?

- New Developments: (local) F-theory GUT’s/SM’s...

[Donagi,Wijnholt 0802.2969],[Beasley,Heckman,Vafa 0802.3391]...

c.f. Vafa’s talk
Specific (Type II) coupling issues:

- Neutrino masses (if there) - Dirac & of order of charged sector masses
  Majorana neutrino masses – absent
- $\mu$-parameter – typically absent
- SU(5) GUT models – absent $10 \ 10 \ 5_H$-couplings
- Hierarchical supersymmetry breaking, e.g., à la Polonyi

Perturbative absence of all such couplings due to violation of “anomalous” U(1)

→ Turn to non-perturbative effects & non-perturbative
violation of anomalous U(1)
**Instantons–Heuristics**

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

Euclidean $Dp$-brane wrapping internal $(p+1)$-cycle

$\rightarrow$ for Type IIA relevant objects are Euclidean $D2$-branes ($E2$-branes), wrapping three-cycles $\Xi$

**Rules:**

- Instanton sector corresponds to local minimum of (full) string action
  $\rightarrow$ $E2$-brane volume minimizing on internal sLag $\Xi$
- Integrate over zero modes localized on $E2$
  $\rightarrow$ All fermionic zero modes have to appear for relevant instanton induced couplings exactly once
Effects of axion gauging for D-instantons: Euclidean $D_p$-brane on internal $p + 1$-cycle $\Xi$ ($p=2$ E2-instanton)

\[ W_{np} \propto e^{-S_{Ep}} = \exp \left[ \frac{2\pi}{\ell_{s,1}} \left( -\frac{1}{g_s} \int_\Xi \text{Vol}_\Xi + i \int_\Xi C_{p+1} \right) \right] \]

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

\[ e^{-S_{Ep}} \to e^{iQ_a(Ep)} \Lambda_a e^{-S_{Ep}}: \]

\[ Q_a = N_a \int \delta(\Xi) \wedge \delta(\Pi_a^q - 3) \wedge e^{F_a} = N_a \Xi \circ (\Pi_a - \Pi'_a) \]

Consequence:

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

\[ W = \prod_i \Phi_i e^{-S_{Ep}} \quad \text{with} \quad \sum_i Q(\Phi_i) + Q_a(Ep) = 0 \forall a \]

Non-perturbative breakdown of global $U(1)$ symmetry possible.
Zero mode structure - Summary

Distinguish 2 types of zero modes:
(i) uncharged (E2-E2 sector)
(ii) charged (E2-D6 sector) under $U(1)_a$:

(i) Zero modes uncharged under $U(1)_a$ for O(1)-instantons:
4 bosonic modes $x^i_E \leftrightarrow$ Poincaré inv. in 4D & only 2 fermionic modes: $\theta_\alpha$
Ensured for: $E2 = E2'$ (homologically) , $E2$-wrap rigid 3-cycles $\Xi$, i.e. absence of additional zero modes.
→ yields correct superpot. measure: $\int d^4 x_E d^2 \theta$

Other (multi-)instanton superpotential contributions
multi-instantons & recombination, zero-mode lifting due to fluxes...

[Blumenhagen,MC,Richter,Weigand 0708.0403], [Garcia-Etxebarria,Uranga 0711.1430], [MC,Richter,Weigand 0803.2513],
[Garcia-Etxebarria,Marchesano,Uranga 0805.0713], [Buican,Franco 0806.1964], [MC,/Garcia-Etxebarria,Richter, 09051694] new; no time
(ii) Charged Zero modes strings between $E2$ and $D6_a$:

$\rightarrow$ Localized at each intersection of $E2$ and $D6_a$:

One fermionic zero mode $\lambda_a$ per inters. Stringy&Geometric!

\[ \text{Number of } \lambda_a \text{ modes} = \text{Intersection number } \Xi \circ (\Pi_a - \Pi'_a) \]

\[ \text{Total } U(1)_a \text{ charge} = Q_a(E2) = N_a \Xi \circ (\Pi_a - \Pi'_a) \]

Note $e^{-S_{E2}} \rightarrow e^{i Q_a(E2)} \Lambda_a e^{-S_{E2}}$ – confirms index thrm.
Contributions to Matter Couplings

Building blocks: disk-level couplings of two $\lambda$ modes to matter $\Phi_{ab}$: $S = \int_{\Xi} \lambda_a \Phi_{ab} \overline{\lambda}_b$

In instanton effective action

$$\int d^4 x d^2 \theta d\lambda_a d\overline{\lambda}_b e^{-S_{cl}} + \int_{\Xi} \lambda_a \Phi_{ab} \overline{\lambda}_b \leadsto \phi_{ab} e^{-S_{cl}}.$$
Implications: Superpotential Couplings

Examples:

I. Majorana neutrino masses – time for only this example
II. Nonperturbative Dirac neutrino masses
II. 10 10 5 GUT Coupling
IV. Polonyi-type Coupling
I. Majorana masses for right-handed neutrinos

→ SM constructions with neutrino Dirac masses

\[ H^+ L_L (N_R)^c \]

If present, of order of charged sector masses

Majorana masses \( M_m (N_R)^c (N_R)^c \) perturbatively forbidden

\( N_R^c \) – SM singlets, typically charged under anomalous \( U(1)_a \times U(1)_b \), say as \((1, -1)\).
Non-pert. coupling possible if $CY_3$ possesses rigid 3-cycle $\Xi$ with zero mode structure:

$$\Xi \cap \Pi_{SM} = \Xi \cap \Pi_a = \Xi \cap \Pi'_b = 0$$

$$[\Xi \cap \Pi'_a]^- = 2, \ [\Xi \cap \Pi'_a]^+ = 0, \ [\Xi \cap \Pi_b]^+ = 2, \ [\Xi \cap \Pi_b]^- = 0.$$ 

Four $-\bar{\lambda}_a^{1,2}$ and $\lambda_b^{1,2}$ absorbed via the two disk diagrams:
Non-pert. Majorana coupling:

\[ W_m = M_m \left( N_R \right)^c \left( N_R \right)^c \]

with \( M_m = x M_s e^{-\frac{2\pi}{\ell^3 s} \frac{\text{Vol} E_2}{\text{Vol} D_6}} \)

Use \( \frac{1}{\alpha_{\text{GUT}}} = \frac{1}{\ell^3 s g_s} \text{Vol} D_6 \rightarrow M_m = x M_s e^{-\frac{2\pi}{\alpha_{\text{GUT}}} \frac{\text{Vol} E_2}{\text{Vol} D_6}} \)

For seesaw mechanism need \( 10^{11} \text{GeV} < M_m < 10^{15} \text{GeV} \)

Possible within natural regime for

\[ 0.4 \cdot R_{D6} > R_{E2} > 0.2 \cdot R_{D6} \quad \text{(w/} \quad x=O(1)\text{)}. \]

Concrete local realization on \( T^6 / \mathbb{Z}_2 \times \mathbb{Z}'_2 \)

\[ \text{[M. C., Robert Richter, Timo Weigand, hep-th/0703028]} \]

Local 4-family supersymmetric 3-stack GUT model:

\[ U(5)_c \times U(1)_a \times U(1)_b \quad \text{w/} \quad O(1) \text{ E2-instanton} \]

\{ Exemplify CFT computation \( \rightarrow \) determine \( x \) exactly \}
IV. Polonyi Term and gauge mediated SUSY breaking

Polonyi field: Charged hidden sector $S_{-1a,1b}$ chiral field at intersection of $a$ and $b$ stack of D-branes

Monomials in $S$ forbidden perturbatively, but due to D-instantons Polonyi term:

$$W = \mu^2 S, \quad \text{w/} \quad \mu^2 = M_S^2 e^{-S_{\text{inst}}}$$

Type IIB– [Aharony,Kachru,Silverstein 0708.0493];

Type I/IIA GUT′s– [MC,Weigand 0711.0209,0807.3953];

F-th.GUT′s– [Heckman,Marsano,Saulina,Schafer-Nameki,Vafa 0808.1286],
Hierarchical couplings: neutrino Majorana masses or small Dirac masses/ Yukawa couplings...

→ Typically demonstrated within local Type IIA set-up with chiral SU(5) GUT’s

Challenge: global models

Turn to Type I theory with magnetized D9-branes
First chiral GUT’s on globally defined Calabi-Yau spaces (algebraic geometry): [M.C., T. Weigand, 0711.0209, 0807.3953]

→ four-family SU(5) GUT’s with Majorana masses or Polonyi term in the desirable regime
Most examples w/ O(1)-instantons based on SU(5) GUT’s
How about Multi-stack (local) Standard Models?
Addressed for Madrid Quiver [Ibanez,Richter,08111583]

→ Systematic Analysis of Instanton Effects for MSSM
w/ Halverson & Richter, 0905.3379

related work [Leontaris,0903.3691],[Anastasopoulos,Kiritsis,Lionetto,0905.3044]
Employ three-stack MSSM $U(3)_a \times U(2)_b \times U(1)_c$

& four-stack MSSM $U(3)_a \times U(2)_b \times U(1)_c \times U(1)_d$
Analysis of spectra

[Anastasopoulos, Dijkstra, Kiritsis, Schellekens, 0605226]

- R-handed quarks realized as anti-symmetric of $SU(3)$
- leptons and neutrinos realized as (anti-) symmetrized tensors of $U(1) (SU(2))$
- impose tadpole cancelation (absence of non-Abelian anomalies)
- impose the massless hypercharge $U(1)_Y$

$\rightarrow$ many quivers (order 10000) with MSSM-like matter content
Analysis at non-perturbative level:

• MSSM models with potentially desirable Yukawa texture
• MSSM + 3 right-handed neutrinos

In addition one requires:

• absence of R-parity violating couplings also at non-perturbative level
• presence of top perturbative Yukawa couplings
• O(1) instanton induces a desired Yukawa coupling which do not simultaneously generate $\mu$ term
• neutrino masses via seesaw mechanism or non-perturbative Dirac neutrino masses
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Table 9: Spectrum for the solutions with \(U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c - \frac{1}{2}U(1)_d\)
Obtain on the order of 50 models with MSSM spectrum &
and potentially desirable Yukawa textures
specific examples analyzed in detail \(\rightarrow\)
Further constrain models with correct hierarchical couplings
\(\rightarrow\) work in progress...
Summary

Overview of Model Building with D-branes and D-instantons: Implications for charged matter couplings w/ new hierarchy: mainly O(1) instantons (neutrino masses, Some Yukawa couplings, SUSY breaking, etc.)

→ within local (Type IIA) as well as global (Type I) chiral GUT’s

→ classification of (local) MSSM multi-stack models – constrained

[Challenge: semi-realistic (three-family) global models w/ stabilized moduli]

Status summarized in a review:

D-Brane Instantons in Type II String Theory, w/R. Blumenhagen, S. Kachru & T. Weigand, 0902.3251