D-Instantons (& Lifting of Zero Modes)

Non-perturbative Effects & String Vacuum

(Primarily Type IIA String Theory side – Geometric)

I. D-instantons & particle physics:

Focus on rigid O(1) instantons & Superpotential Couplings

Ralph Blumenhagen,M.C.,Timo Weigand,hep-th/0609191

original paper

Further work:

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 in GUT

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

II. Formal developments: U(1) instantons

R.Blumenhagen,M.C.,R.Richter,T.Weigand,0708.0403

U(1) instanton 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

Review:

R Blumenhagen,M.C.,S.Kachru,T.Weigand, 0902.3251

• Large classes of perturbatively constructed four-dimensional N=1 supersymmetric vacua

$\longrightarrow$ Major activity within Type IIA (Intersecting D6-branes)

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

$\longrightarrow$ D-brane Instantons

D-brane instantons may generate perturbatively absent charge matter couplings – new hierarchical scales, suppressed by $e^{-\frac{1}{g_s}}$

$\longrightarrow$ Potential 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 μ-terms of order $\mathcal{O}$(TeV)
- Top $\mathcal{O}$ (100 GeV) – bottom $\mathcal{O}$ (10 GeV) mass hierarchy

- Hierarchically suppressed supersymmetry breaking

Extensive past literature on instantons in string theory ...

New stringy 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...

Turin/Rome group,Muncih group, Madrid/CERN group, Penn Group, Stanford group, etc.

c.f., Lerda's talk; Uranga's talk

Outline

1. (Very) Brief status of intersecting D-brane constructions
2. D-Instantons: Heuristics/ zero modes

- Rigid O(1) D-instantons - direct contrib. to superpotential

i Summary for specific SM couplings
ii Local GUT set-ups & first global GUT examples – no time
iii Classification of (local) MSSM multi-stack quivers w/D-instantons

- Other Instantons w/ potential superpot contrib.

i Instanton recombination across lines of marginal stability c.f.Uranga's talk
ii Gauge instantons - Higgs vs. Coulomb phase
iii D-instantons intersecting at angles -massive zero modes

3. Conclusions and outlook

Model Building with Intersecting D-branes

[Blumenhagen,Görlich,Körs,Lüst'00],[Aldazabal,Ibáñez,Rabadan,Uranga'00]...

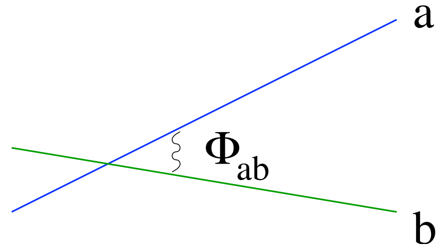
Engineering of semi-realistic constructions w/ Intersecting D6-branes wraping three-cycles Π – Standard Model:

– Non-Abelian gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$

$\longrightarrow$ U(N) as a stack of N-coincident D-branes

– Chiral matter quarks & leptons

$\longrightarrow$ at intersections of D-branes in internal space;bi-fund.



– Family replication 3-copies of fermion families

$\longrightarrow$ no. of D-brane intersections in internal space $\Pi_a \circ \Pi_b$

$\longrightarrow$ Origin of Standard Model Geometric!

Intersecting D-brane GUT's

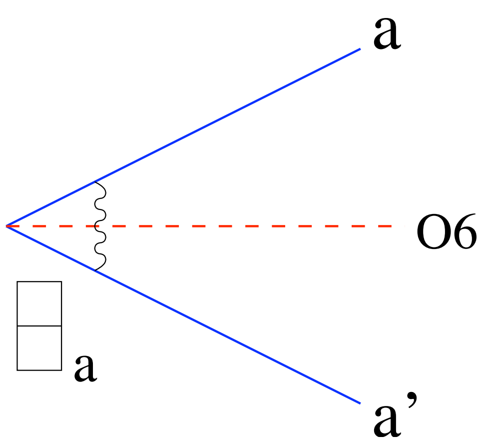
$U(5)_a \times U(1)_b$ configurations contain the spectrum:

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 – $\frac{1}{2}(\Pi'_a \circ \Pi_a \, - \, \Pi_O \circ \Pi_a)$

[& symmetric reps. 15_a – $\frac{1}{2}(\Pi'_a \circ \Pi_a \, + \, \Pi_O \circ \Pi_a)$]

[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 SUSY 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

[M.C.,Uranga,Shiu, hep-th/0107143,017166]..., c.f., Antoniadis's talk

Rational Conformal Field Theory constructions-promising

[Dijkstra, Huiszoon,Schellekens, hep-th/0411129]...
-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., Heckman's talk; Vafa's talk; Schäfer-Nameki's talk

Specific (Type II) coupling issues:

- Neutrino masses (if there) -Dirac & of order of charged sector masses

Majorana neutrino masses – absent

- μ-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)

$\longrightarrow$ Turn non-perturbative violation of anomalous U(1)

D-Instantons–Heuristics

Relevant objects in Type IIA : Euclidean $D2$-branes (E2-branes), wrapping three-cycles Ξ

Rules: quantize (open) strings – zero modes
determine effective instanton action

Key features:

• Instanton sector – local minimum of (full) string action
$\longrightarrow$ $E2$-brane volume minimizing on internal sLag Ξ
• Integrate over zero modes localized on $E2$
$\longrightarrow$ In path integral each fermionic zero mode has to appear for relevant instanton induced couplings exactly once

D-instantons – Heuristics

Euclidean E2-brane on internal three-cycle Ξ:

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

C_3 Ramond-Ramond three-form transforms under $U(1)_a$ of D_a-brane

(due to Chern-Simons terms in D-brane Wess-Zumino action expansion) $\longrightarrow$

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

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

$$Q_a(E2) = N_a \int \delta(\Xi)\wedge\delta(\Pi^a_{q-3})\wedge e^{F_a} = N_a\,\Xi\circ(\Pi_a - \Pi'_a)$$

Consequence:

If $Q_a(E2) \neq 0$ for some a, superpotential for charged fields:

$W = \prod_i \Phi_i\; e^{-S_{E2}}$ w/ $\sum_i Q_a(\Phi_i) + Q_a(E2) = 0$ for every a.

Non-perturbative breakdown of $U(1)_a$

D-instantons introduce a new hierarchy

couplings $\propto \mathcal{R}e\left(e^{-S_{E2}}\right) = e^{-\frac{2\pi}{\ell_s^3\, g_s}\mathrm{Vol}_{E2}}$

Use $\frac{1}{\alpha_{\mathrm{GUT}}} = \frac{1}{\ell_s^3\, g_s}\mathrm{Vol}_{D6} \longrightarrow \mathcal{R}e\left(e^{-S_{E2}}\right) = e^{-\frac{2\pi}{\alpha_{\mathrm{GUT}}}\frac{\mathrm{Vol}_{E2}}{\mathrm{Vol}_{D6}}}$

Stringy!

In general no field theory analog à la gauge instantons

Zero modes - Summary

I. Uncharged (E2-E2 sector)

4 bosonic: x_E^μ - Goldstones of breakdown of Poincaré invariance in 4D

4 fermionic: θ^α and $\overline{\tau}^{\dot{\alpha}}$ - Goldstinos of $\mathcal{N}=2$ SUSY on CY to $\mathcal{N}=1$

Additional zero modes:

Non-rigid cycles:

$b^1(E2)_-$ – χ^α bosonic

$b^1(E2)_+$ – $(c, \overline{\chi}^{\dot{\alpha}})$ – (fermionic,bosonic)

Intersection of instantons & their orientifold images:

$\frac{1}{2}(\Xi' \circ \Xi - \Pi_O \circ \Xi)$ – ν^α bosonic

$\frac{1}{2}(\Xi' \circ \Xi + \Pi_O \circ \Xi)$ – $(n, \overline{\nu}^{\dot{\alpha}})$ – (fermionic,bosonic)

Rigid O(1) instantons – special!

i Rigid cycles Ξ $(b^1(E2){=}0$ – no diffeomorf. zero modes)

ii Homologically $\Xi = \Xi'$ (no zero modes due to Ξ & Ξ' inters.)

& $\overline{\tau}^{\dot{\alpha}}$ projected out

[Argurio,Bertolini,Franco,Kachru,hep-th/0703236],...

$\longrightarrow$ 4 bosonic modes x_E^μ & only 2 fermionic modes θ_α

yield directly superpotential measure: $\int d^4 x_E \, d^2\theta$

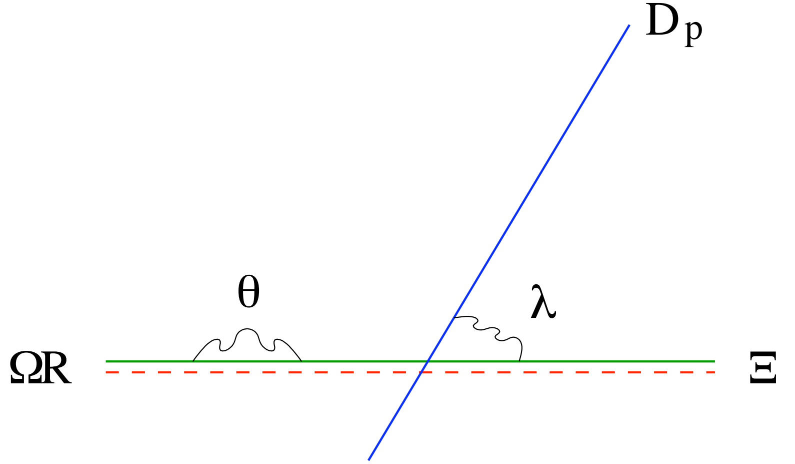
(Other instantons & zero mode lifting later)

II. Charged Zero modes from strings between $E2$ and $D6_a$:

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

One fermionic zero mode λ_a per intersection

Stringy & Geometric!

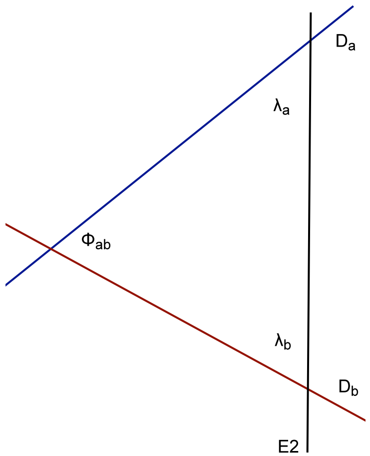


Total $U(1)_a$ charge of λ_a modes $Q_a(E2) = N_a \, \Xi \circ (\Pi_a - \Pi'_a)$

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

Contributions to Matter Couplings

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



In instanton effective action

$\int d^4x d^2\theta d\lambda_a d\overline{\lambda}_b e^{-S_{E2} + \int_{\Xi} \lambda_a \, \Phi_{ab} \overline{\lambda}_b} \rightsquigarrow \phi_{ab} e^{-S_{E2}}$

Details of instanton calculus, including prescriptions for loop contributions in

[Blumenhagen,M.C.,Weigand hep-th/0609191];

further work: [M.C.,Richter,Weigand hep-th/070302],

[Akerblom,Blumenhagen,Lüst,Schmidt-Sommerfeld 0705.2366]...

Superpotential due to O(1) instantons:

Specific coupling w/ each $U(1)_a$ charge violated by $\sum_i Q_a^i$

• Engineer intersections of O(1) instantons with D_a-branes w/ total charges of λ_a's: $Q_a(E2) = -\sum_i Q_a^i$

• Identify disc diagrams that soak up each λ precisely ones

Specific Examples:

i Majorana neutrino masses original papers,...

ii Nonpert. Dirac neutrino masses [M.C.,Langacker, 0803.2876]

iii 10 10 5 GUT couplings

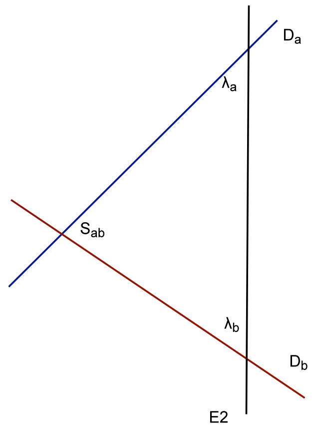
[Blumenhagen,M.C.,Lüst,Richter,Weigand,0707.1871]

one-instanton effect $\longrightarrow g_s \rightarrow 1$ (M-theory on G_2)

iv Polonyi-type couplings $\longrightarrow$

IV. Polonyi Term and gauge mediated SUSY breaking

Polonyi field: Charged hidden sector $S_{-1_a,1_b}$ chiral field at a& b brane intersection (couples to SM fields – gauge mediated SUSY breaking):



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

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

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 superpotential couplings (neutrino masses, Yukawa couplings...)

Typically demonstrated within local orbifold Type IIA chiral SU(5) GUT's

Challenge: global models

Type I theory with magnetized D9-branes $\longrightarrow$

First chiral GUT's on globally defined Calabi-Yau spaces (algebraic geometry) [M.C.,T.Weigand, 0711.0209,0807.3953]

$\longrightarrow$ 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 [Ibáñez,Richter,08111583]

$\longrightarrow$ Systematic Analysis of Instanton Effects for MSSM

[M.C., Halverson & Richter, 0905.3379]

related work – specific multi-stack models

[Leontaris,0903.3691],[Anastasopoulos,Kiritsis,Lionetto,0905.3044]

Perturbative Analysis of three- and four-stack MSSM Spectra

à la [Anastasopoulos,Dijkstra,Kiritsis,Schellekens,hep-th/0605226]

$\longrightarrow$ of order 10000 quivers

Analysis at non-perturbative level:

MSSM models with potentially desirable Yukawa textures

[• 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 μ term

• neutrino masses via seesaw or non-perturbative Dirac masses]

$\longrightarrow$ on the order of 50 models w/ potentially desirable textures

$\longrightarrow$ further work

Other [U(1)] instantons & superpotential contrib.?

Major issue: lifting $\overline{\tau}^{\dot{\alpha}}$ modes

multi-instantons & instanton recombination,

zero-mode lifting due to fluxes (hard for $\overline{\tau}^{\dot{\alpha}}$)

[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],...

I. Instanton Recombinations & Superpotential

First example within CFT: $U(1) \times U(1) \rightarrow O(1)$

(intersection of U(1) instanton with its orientifold image)

[Blumenhagen,MC,Richter,Weigand, 0708.0403]

Multi-instantons across lines of marginal stability

[Garcia-Etxebarria,Uranga, 0711.1430],...

Primarily for $\mathcal{N} = 2$ – i.e. non-chiral matter, but ...

[Collinucci,Soler,Uranga, 0904.1133]; c.f., Uranga's talk

II. Gauge instantons in string theory

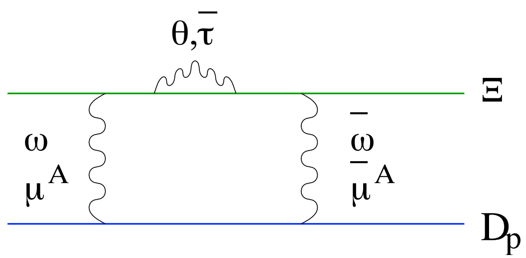
Maximal $\mathcal{N}=4$ SYM as D3-E(-1) in flat space

[The ADHM construction of moduli space as its Higgs branch

[Witten,hep-th/9511030].]

Engineer systems with less SUSY:

e.g., Type IIA D6 and E2 wrapping homologically the same sLag 3-cycles in internal space



Zero modes for $\mathcal{N}=4$ gauge instantons:

- E2-E2: θ^A_α, $\overline{\tau}^A_{\dot\alpha}$ (Goldstinos); x_μ, χ_{AB} (Goldstones)
- E2-D6: $\omega_{\dot\alpha}$ (bosonic spinor), μ^A (fermionic scalar)

Effective action:

$$S_{inst} = -2\pi i\tau + \frac{g_0^2}{4}(\bar{\omega}\omega)^2 + \bar{\omega}\chi^2\omega - \frac{2i}{\sqrt{8}}\bar{\mu}^A\mu^B\chi_{AB}$$
$$+ \; i\bar{\tau}_A^{\dot{\alpha}}(\bar{\mu}^A\omega_{\dot{\alpha}} + \mu^A\bar{\omega}_{\dot{\alpha}})$$

$$g_0^2 = 4\pi(4\pi^2\alpha')^{-2}g_s \quad ; \quad \tau = C_0 - \frac{i}{g_s}$$

Supersymmetry transformations (setting some background vevs to zero):

$$\delta x_{\alpha\dot{\alpha}} = i\bar{\xi}_{\dot{\alpha}A}\theta_\alpha^A \qquad \delta\theta_\alpha^A = 0$$
$$\delta\chi_m = i\Sigma_m^{AB}\bar{\xi}_A\bar{\tau}_B \qquad \delta\bar{\tau}_A = \vec{D}\cdot\vec{\sigma}\bar{\xi}_A$$
$$\delta\omega_{\dot{\alpha}} = i\bar{\xi}_{\dot{\alpha}A}\mu^A \qquad \delta\mu^A = 0$$

FT [Dorey,Hollowood,Khoze,Mattis] or CFT [Green,Gutperle];[Billò et al.]

Saturation of $\overline{\tau}$ modes

Due to interaction w/ charged zero modes $\overline{\tau}$ modes get lifted

$$S_{inst}(\overline{\tau},\ldots) = S'_{inst}(\ldots) + i\overline{\tau}^{\dot{\alpha}}_{A}(\bar{\mu}^{A}\omega_{\dot{\alpha}} + \mu^{A}\bar{\omega}_{\dot{\alpha}}) \qquad (1)$$

Within path integral:

$$\begin{aligned} \Delta W &= \int d^8\overline{\tau} \int [\ldots] e^{-S_{inst}(\overline{\tau},\ldots)} \\ &= \int [\ldots]\,(\bar{\mu}\omega + \mu\bar{\omega})^8 e^{-S'_{inst}(\ldots)} \end{aligned}$$

i.e., saturation of $\overline{\tau}$ modes!

Moduli space w/ two branches $[D3 - E(-1)]$

- **Higgs branch:** VEV to instanton-brane modes ω.
  Instanton dissolves as flux into the brane;
  low energy interpretation as gauge theory instantons.
- **Coulomb branch:** VEV to instanton modes χ.
  Instanton taken away from brane in directions perpendicular to both.

Two branches connected through small instanton ($\omega = \chi = 0$).

Reduction to less SUSY

Applies to any gauge instanton with unlifted Coulomb branch & expected to contribute to superpotential

c.f.,[Akerblom,Blumenhagen,Lüst,Plauschinn,Schmidt-Sommerfeld, hep-th/0612132] -ADS superpotential...

Lesson I:

$\overline{\tau}$ lifted iff instanton & brane wrap homolog. same cycles

(though isolated instantons subleading to gaugino condens. on brane zero mode lifting – due to backreaction of the brane)

evidence –[M.C.Garcia-Etxebarria,Richter,0905.1694]

Lesson II: Gauge instantons without λ's

(appear only at chiral intersections of instantons and branes)

cannot contribute to the violation of anomalous U(1)

III. Instantons intersecting at angles (away from O-planes)

At intersections : λ's modes

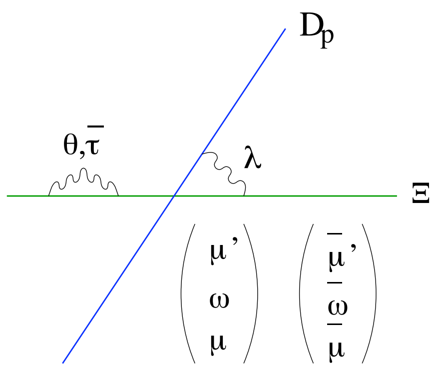
(violate U(1)'s & generate charged matter couplings)

Could massive zero modes lift $\overline{\tau}^{\dot{\alpha}}$?

(related [Heckman,Marsano,Saulina,Schafer-Nameki,Vafa, 0808.128])

Elucidate the proposal by performing detailed CFT calc.:

[MC.,Garcia-Etxebarria,Richter, 09051694]



At each intersection, in addition to massless λ's, localized massive modes: $(\mu, \omega^{\dot{\alpha}}, \mu')$ & $(\bar{\mu}, \bar{\omega}^{\dot{\alpha}}, \bar{\mu}')$

$E2-D6$ interaction terms:

$$S^{E2-D6} = \overline{\tau}\,(\overline{\omega}\,\mu + \overline{\mu}\,\omega) + i\vec{D}\cdot\omega\,\vec{\sigma}\,\bar{\omega} + \\ + m_{\overline{\mu}}\,\overline{\mu}\,\mu' + m_{\mu}\,\mu\,\overline{\mu}' + m_{\omega}\,\omega\,\overline{\omega} + \cdots$$

For SUSY intersections: masses equal – $m_{\overline{\mu}} = m_{\mu} = m_{\omega}$

Supersymmetry transformations:

$\delta_{\overline{\xi}}\mu' = \overline{\xi}\omega \qquad \delta_{\overline{\xi}}\omega = \overline{\xi}\mu \qquad \delta_{\overline{\xi}}\mu = 0 \qquad \delta_{\overline{\xi}}\overline{\tau} = \overline{\xi}\tau^c D^c$

(contrast with the SUSY transf. for gauge instantons)

Lesson:

Interaction term with $\overline{\tau}^{\dot{\alpha}}$ – same as gauge instanton

Mass terms – additional fermionic fields μ' and $\overline{\mu}'$

$\longrightarrow$ Cannot soak up zero modes!

No contribution to superpotential

Summary

Overview of D-instanton Effects (primarily Type II/I):

• Particle physics Implications: charged matter couplings-new hierarchy

Focus on Rigid O(1) Instantons – direct superpotential contributions: (neutrino masses, some Yukawas , SUSY breaking, etc).

$\longrightarrow$ within local (Type IIA)& global (Type I) chiral GUT's

$\longrightarrow$ classification of (local) MSSM multi-stack models

w/potential for realistic textures – constrained

• Formal Developments: U(1) instantons & superpot.

i Instanton recombination across lines of marginal stability

ii Gauge instantons (revisited) – Higgs vs. Coulomb branch & superpot.

iii U(1) instantons intersecting at angles – cannot contribute

Challenges:

three-family (global) SM models w/ realistic couplings
(& stabilized moduli)

Further Insights into D-instantons $\longrightarrow$ F-theory