String Theory and Particle Physics

I. Modern String Theory &
implications for particle physics –D-branes

II. Supersymmetric Standard Model
w/ intersecting D-branes (particle spectrum &couplings)

III. New non-perturbative effects: D-instanons
Phenomenological implications: Majorana neutrino masses, μ-parameter, modified Yukawa couplings

Ralph Blumenhagen, M. C., Timo Weigand, hep-th/0609191
M. C., Robert Richter, Timo Weigand, hep-th/0703028 & work in progress

IV. Conclusions/outlook

Quest to unify forces of nature ⇨

Green&Schwarz'84

String Theory – most promising candidate

as a consistent (finite) quantum theory of strings where elementary particles arise as massless excitations of strings.

In particular, gravitons - massless excitations of closed strings

Quantum gravity for free!

Standard Model of elementary particle interactions (strong, weak & electromagnetic) based on Non-Abelian Gauge theory

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

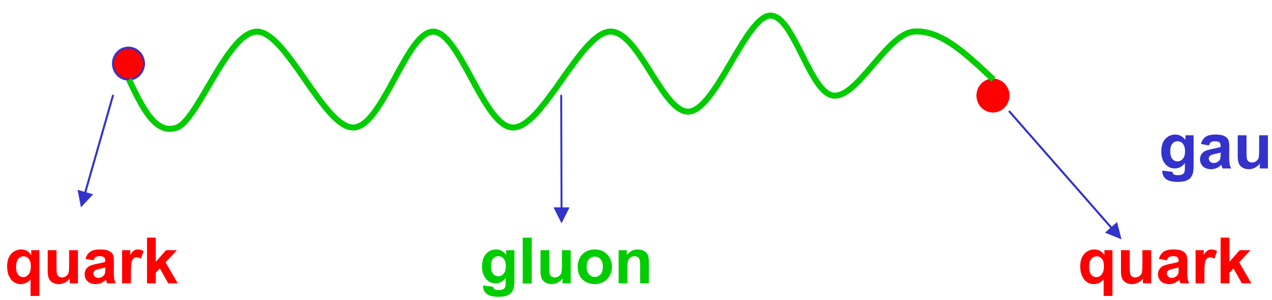
Force mediated via spin 1-particles: gluons,W-bosons&photon

3-families:

$Q_L \sim (\ \underline{3},\ \ \underline{2},\ \ {}^1/_6\ )$ – quarks

$L \sim (\ \underline{1},\ \ \underline{2},\ \ -1\ )$ – leptons, etc.

chiral matter



gauge interactions

& Supersymmetry

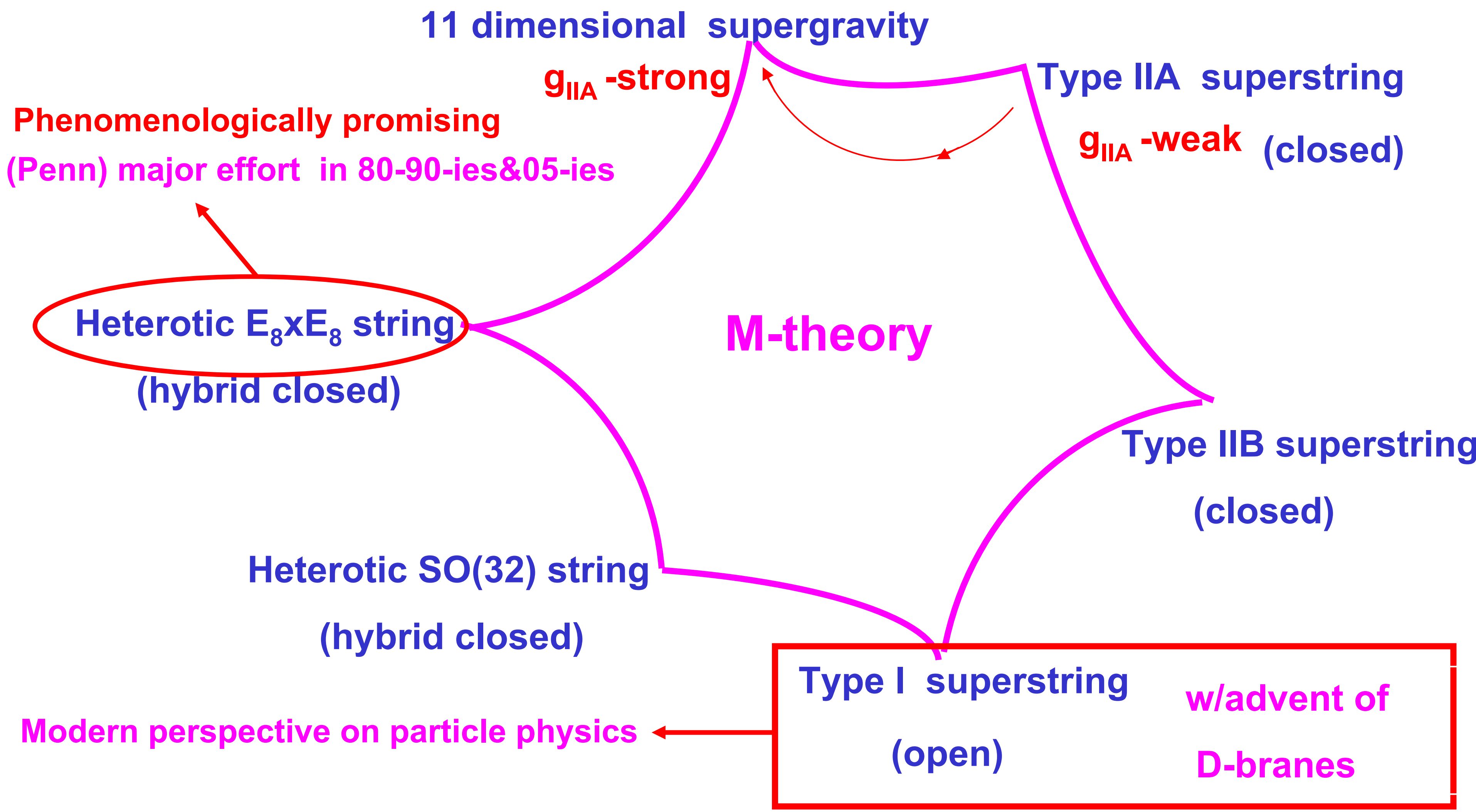
Modern String Theory (w/ D-branes) – geometric origin!

Perturbative String Theories (small string coupling)

Hull&Townsend'94

Witten'95

Non-perturbative Unification

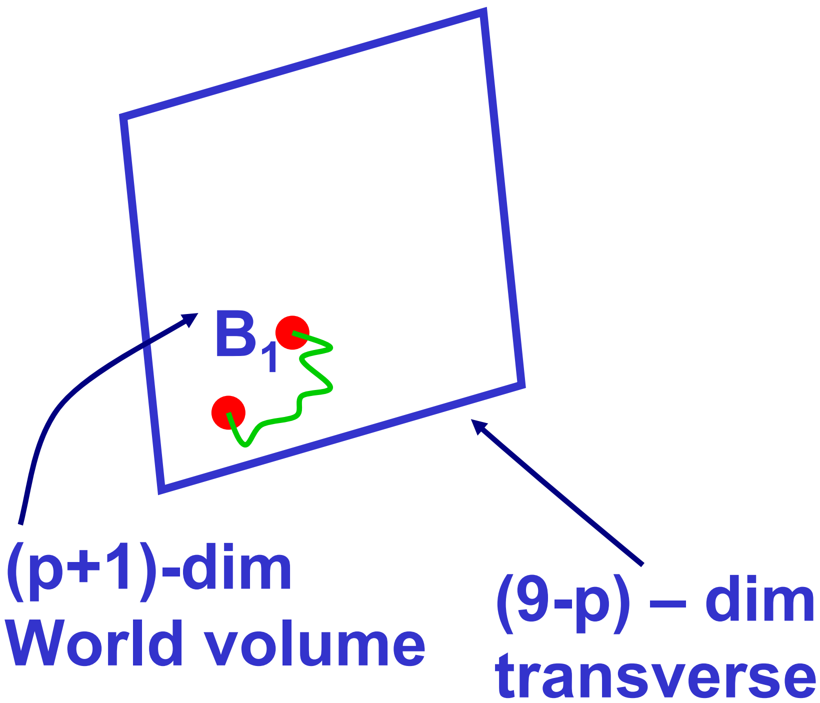


Different String Theories related to each other by Weak-Strong Coupling DUALITY

Polchinski'96

D-branes & non-Abelian gauge theory

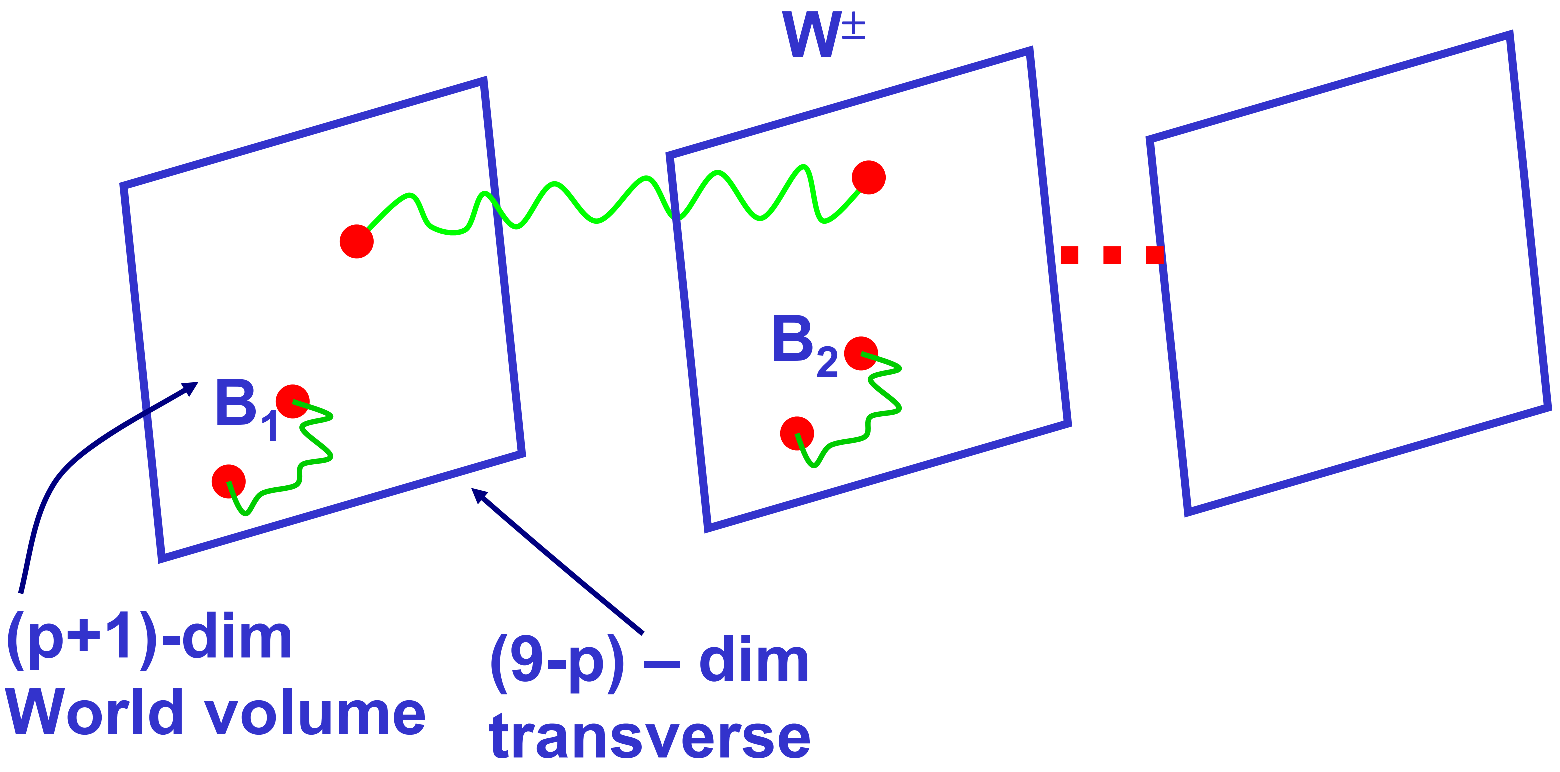
D p-branes



B_1=U(1) spin-one particles as massless excitations of open strings w/boundaries on a D-brane

D-branes & non-Abelian gauge theory

D p-branes

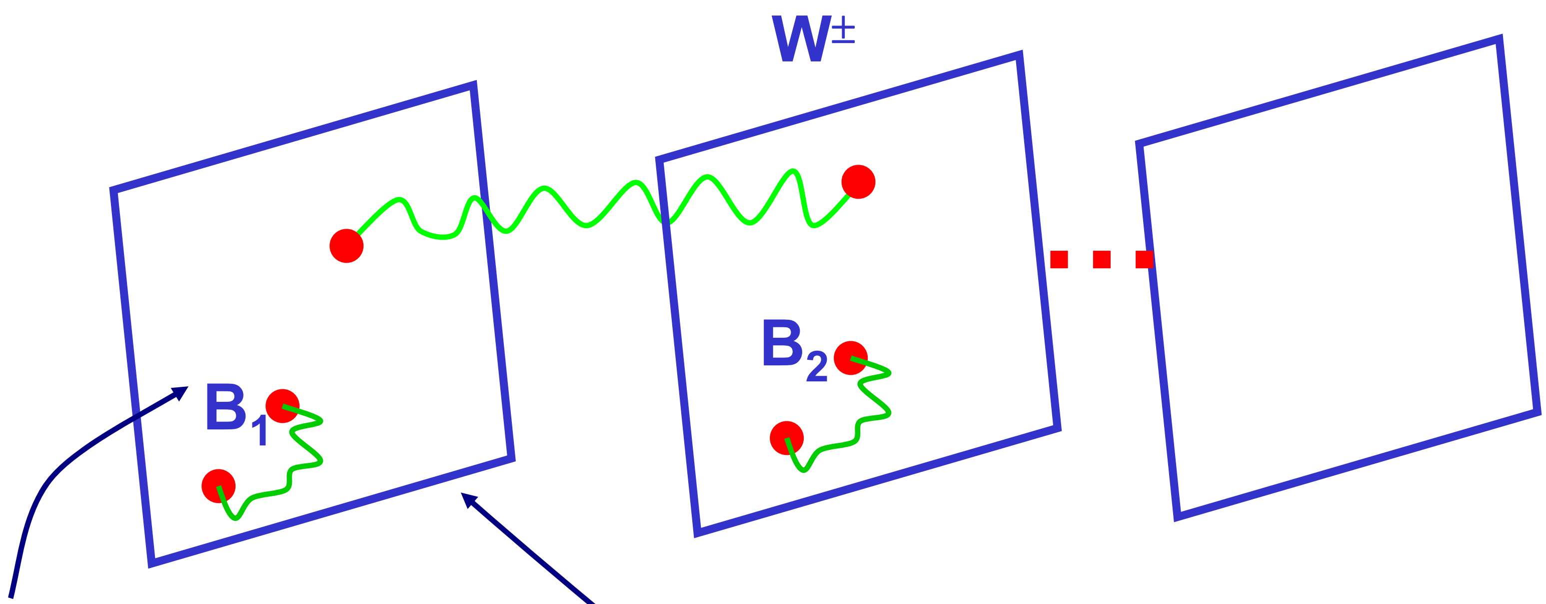


$U_1(1) \times U_2(1) \times \ldots U_N(1)$ N D-branes

Polchinski'96

D-branes & non-Abelian gauge theory

D p-branes



(p+1)-dim
World volume

(9-p) – dim
transverse

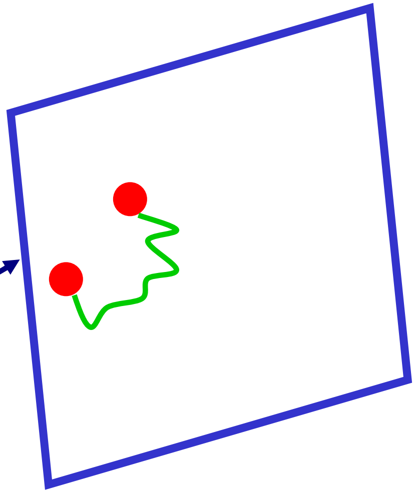
$U_1(1) \times U_2(1) \times \ldots U_N(1)$ → $U(N)$

N-coincident D-branes

non-Abelian gauge symmetry

DIGRESSION-Dual Nature of D-branes

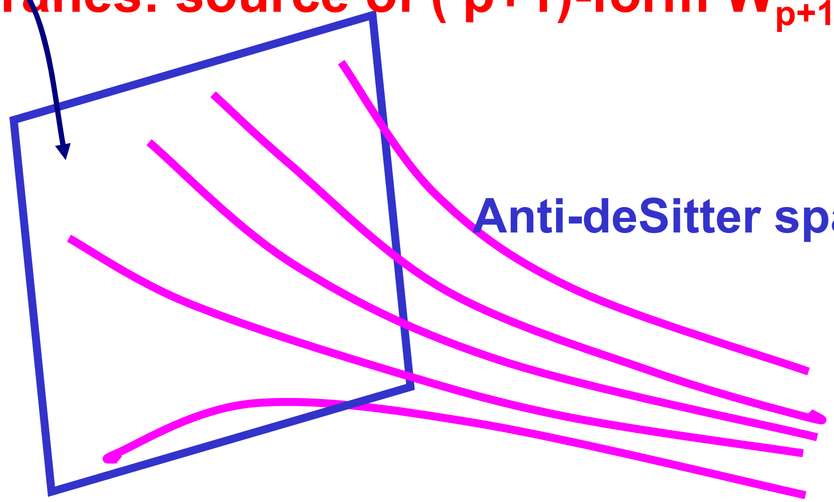
D p-branes:boundaries of open strings



(Conformal) Field Theory

(p+1)-dim
World volume

D p-branes: source of (p+1)-form W_{p+1}potential & curve space-time



Anti-deSitter space-time (negative cosmol. const.)

Related?

Yes!

Maldacena'97

Anti-deSitter/Conformal Field Theory Correspondence AdS/CFT

DIGRESSION: Gravitational role of branes

Black Holes in string theory

First constructions suitable for microscopic counting (w/Youm'95,w/Tseytlin'95,..Kallosh et al.'93-present…)

Microscopic properties Strominger&Vafa'96, …w/Tseytlin '95-'96, w/Larsen'97-'00….

Brane World Randall&Sundrum'99

[related -first supergarity domain walls w/Griffies&Rey'92,… w/Soleng'94-'96 (review)]

Source for ``Gravity Fluxes''

Can fix the shape of compactified space-

…Giddings,Kachru &Polchinski'01..,KKLT'03…w/Li&Liu'04…

Stabilisation of Moduli (no time!)

c.f., F. Quevedo's talk

Back to FIELD THEORY SIDE of D-branes

(as boundaries of open strings)

(i) non-Abelian gauge symmetry

N-coincident D-branes → U(N)

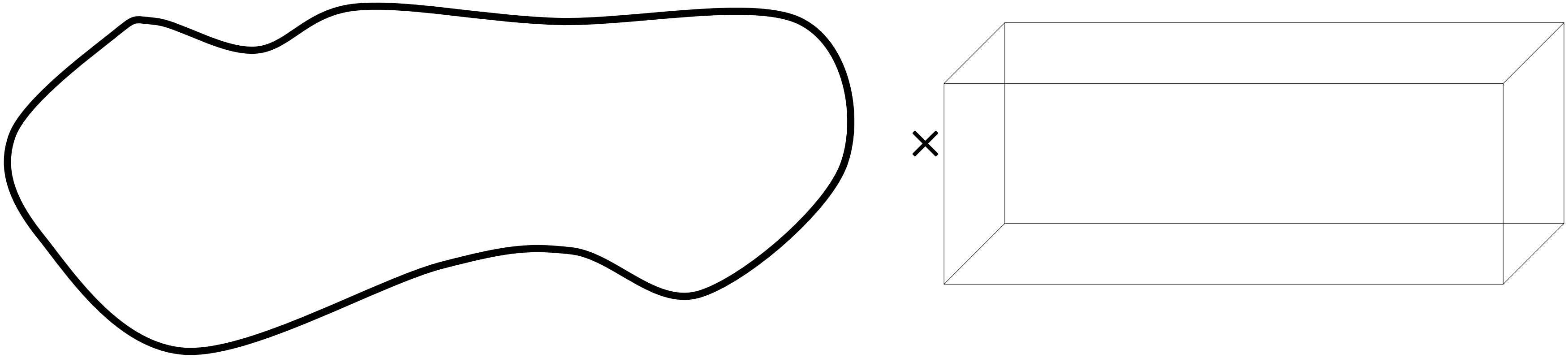
(ii) Appearance of matter → turn to compactification

Compactification

D=9+1 → D=3+1

↑

X_6-special space (Calabi-Yau) × $M_{(1,3)}$-flat



Compactification

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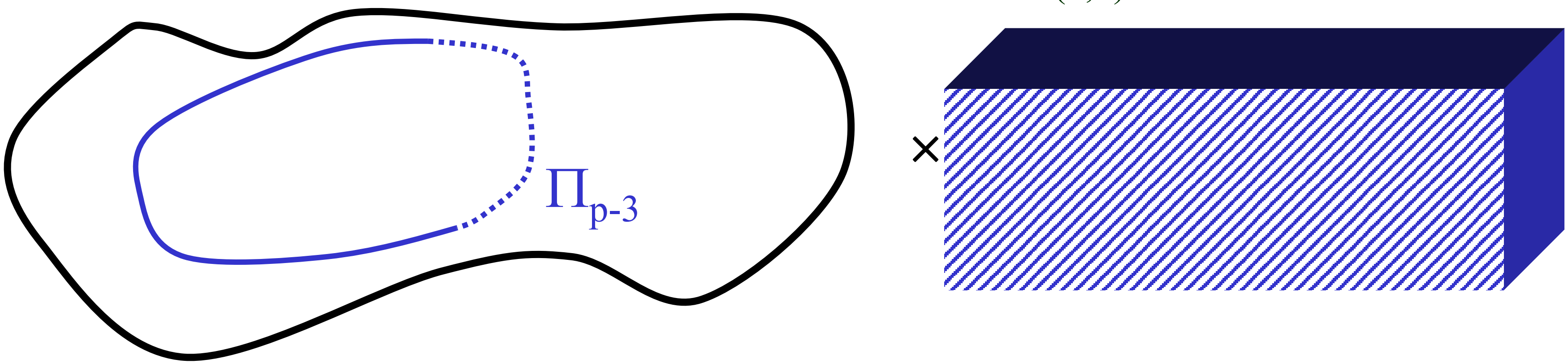


D p-branes – extend in p+1 dimensions:

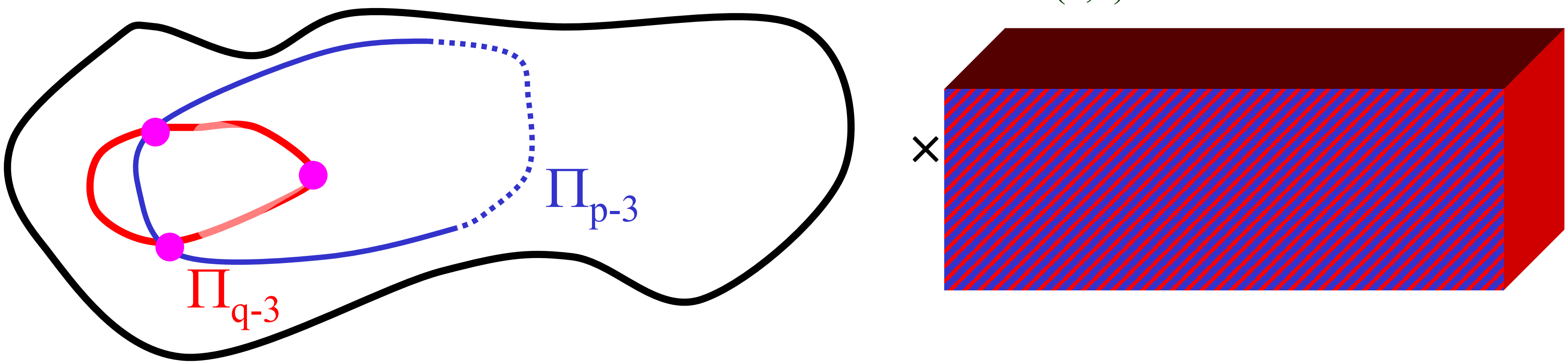
3+1-our world $M_{(3,1)}$;(p-3)-wrap Π_{p-3} cycles of X_6

Compactification

D=9+1 ⟶ D=3+1

↑

X_6-special space (Calabi-Yau) × $M_{(1,3)}$-flat



$\Pi_{q-3} \cap \Pi_{p-3}$

$\Pi_{q-3} \subset \Pi_{p-3}$

⇓

Rich structure

D p-branes – extend in p+1 dimensions:

3+1-our world $M_{(3,1)}$;(p-3)-wrap Π_{p-3} cycles of X_6

D q-branes – extend in q+1 dimensions:

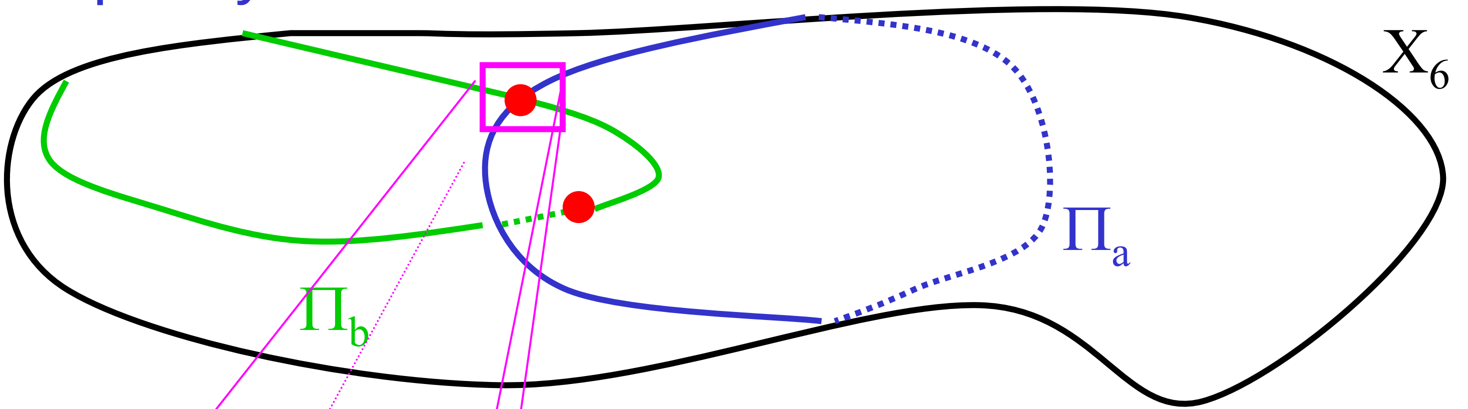
3+1-our world $M_{(3,1)}$;(q-3)-wrap Π_{q-3} cycles of X_6

Penn efforts, early '00: D-branes at singularities& Wilson lines

…w/Wang&Plümacher'00; w/Wang&Uranga'01…

Intersecting D6-branes

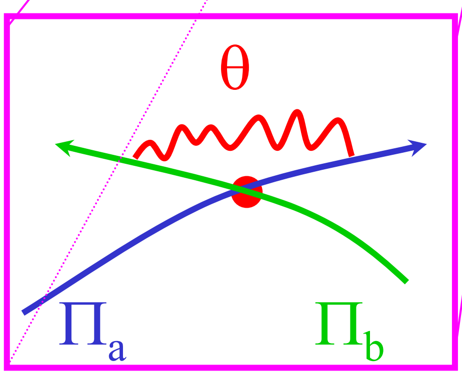
wrap 3-cycles Π



In internal space intersect at points:

Number of intersections $[\Pi_a] \circ [\Pi_b]$ - topological number

Geometric origin of family replications!

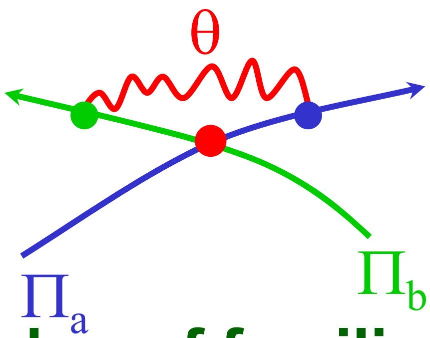


Berkooz, Douglas & Leigh '96

At each intersection-massless string excitation-
spin ½ field ψ - matter candidate

Geometric origin of matter!

Engineering of Standard Model



N_a- D6-branes wrapping Π_a

N_b- D6-branes wrapping Π_b

$$U(N_a) \times U(N_b)$$

$\Psi \sim (N_a, \overline{N}_b)$ - $[\Pi_a]°[\Pi_b]$ – number of families

$N_a = 3$, $N_b = 2$, $[\Pi_a]°[\Pi_b] = 3$

$$U(3)_C \times U(2)_L$$

$\Psi \sim (3, 2)$ - 3 copies of left-handed quarks

Global consistency conditions (D6-brane charge conserv. in internal space)

& supersymmetry conditions (constraining!) - technical (no time!)

⬇

Building Blocks of Supersymmetric Standard Model

Explicit Constructions

Special six-dimensional internal space (special Calabi-Yau) :

compact flat **w/isolated singularities**

↓ ↓

Torus T^6 **modded out by discrete symmetry $(Z_N \times Z_M)$** ⇒

Orbifold $T^6/(Z_N \times Z_M)$

[Toy example T^2/Z_2]

String theory can be quantised exactly employing

conformal field theory techniques **Dixon et al'85; w/Dixon'85; M.C.'86-'87**

Explicit constructions(CFT-techniques):

Toroidal Orbifolds: $T^6/\mathbb{Z}_N \times \mathbb{Z}_M$ geometric phase

- Large (infinite) classes of non-supersymmetric Standard Models [Berlin/Munich group'00-'01],[Madrid group'00-'01]

- First three-family supersymmetric Standard Model on $\mathbb{Z}_2 \times \mathbb{Z}_2$ orientifold [M.C.,Shiu,Uranga '01]

- Majority of supersymmetric constructions on $\mathbb{Z}_2 \times \mathbb{Z}_2$ orientifolds:

i. Semi-realistic constructions (including $SU(5)$ GUT's)

Systematic searches [Penn group'03-'05], ····

Further models [Texas A&M group '06-'07]

ii. Coupling calculations

-Yukawa couplings [Cremades,Ibàñez,Marchesano'03],[M.C., Papadimitriou '03 (full CFT calculation)],

-Kähler potential [Lüst,Mayr,Richter,Stieberger '04] ,

-One-loop threshold corrections [Lüst,Stieberger '03], etc.

iii. Counting (landscape) [Munich group'05], [Douglas& Taylor '06]

- Other Orbifolds:

[Blumenhagen et al.'03], [Honecker'03],[Honecker,Ott'05]

- Abstract RCFT constructions ((Non-geometric phase) -large classes of semi-realistic models

[Dijkstra,Huiszoon,Schellekens'04],[Anastasopoulos,Dijkstra,Kiritsis,Schellekens

Three-family SM model w/$SU(2)_L \times SU(2)_R$ directly ($Z_2 \times Z_2$ orbifold)

$\ell^i \equiv 2\,m^i$

III	$[U(4)_C \times SU(2)_L \times SU(2)_R]_{observable} \times [U(2)$*$\times Sp(8)]_{hidden}$								
stack	N	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\square\square}$	$n_{\boxminus}$	b	c	d	d'	2
a	8	$(1,0)\times(1,3)\times(1,-3)$	0	0	3	-3	0	0	0
b	2	$(0,1)\times(1,0)\times(0,-2)$	0	0	-	0	-6	6	0
c	2	$(0,1)\times(0,-1)\times(2,0)$	0	0	-	-	-6	6	0
d	4	$(2,-1)\times(1,3)\times(1,3)$	$\chi_1 = 24\chi_3/(4-9\chi_3^2)$						
2	8	$(1,0)\times(0,-1)\times(0,2)$	$\chi_2 = \frac{1}{2}\chi_3,\ \beta_2^g = -5$						

non-zero Intersections w/hidden sector chiral exotics

wrapping nos. of SM

Cremades,Ibáñez&Marchesano’02

Embedding in $Z_2 \times Z_2$ orbifold-allows for consistent construction

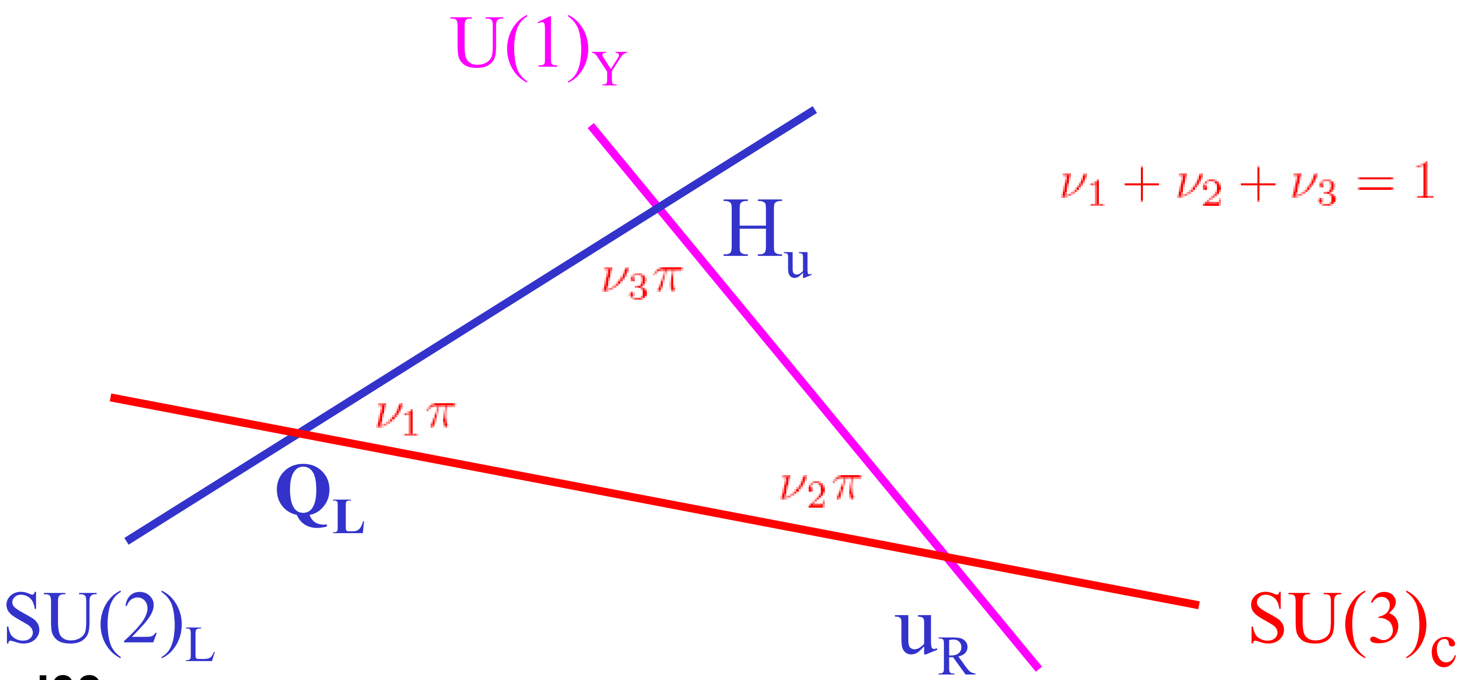
w/ Langacker, Li &Liu, hep-th/0407178

*”hidden sector” (unitary) branes - necessary for global consistency

(charge conservation)

Yukawa Couplings

Intersections in internal space (schematic on i^{th}-two-torus)



$$\nu_1 + \nu_2 + \nu_3 = 1$$

w/Papadimitriou'03

(Conformal Field Theory Techniques)

$$Y = (2\pi)^{\frac{3}{2}} g_{st} \prod_{i=1}^{3} \left[\frac{\Gamma(1-\nu_1^i)\Gamma(1-\nu_2^i)\Gamma(1-\nu_3^i)}{\Gamma(\nu_1^i)\Gamma(\nu_2^i)\Gamma(\nu_3^I)} \right]^{\frac{1}{4}} \sum_I \exp\left(-\frac{A_I^1 + A_I^2 + A_I^3}{2\pi\alpha'}\right)$$

Geometric!

quantum part

classical part A_I^i -triangle areas on i^{th} two-torus lattice

Cremades, Ibáñez, Marchesano'03

Status

- $\mathcal{O}(100)$ toroidal orientifold models (geometric phase) with semi-realistic features

-typically suffer from chiral exotics
-problems with realistic Yukawa couplings
-moduli stabilization issues

$\longrightarrow$ "The devil is in the details"
though further progress and more promising models are being constructed

- RCFT constructions-promising:

-models without chiral exotics
-couplings can be in principle be calculated, but hard
-non-geometric phase–moduli stabilization?

Specific coupling issues

- Neutrino masses – Dirac and of order of charged sector masses

Majorana neutrino masses – absent

- μ-parameter – typically absent
- SU(5) GUT models – absent $10\,10\,5_H$-couplings

Pertrurbative absence of all such couplings due to violation of ``anomalous'' U(1)

→non-pertubative effects due to D-instantons

(non-perturbative violation of ``anomalous'' U(1))

Related work (contemporary with hep-th/0609191)

[Giddings&Maharana'06]

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

[Ibáñez,Uranga, hep-th/0609213] - also emphasis on charged (open sector) superpotential coupling corrections

[Florea,Kachru,McGreevy,Saulina, hep-th/0610003] c.f. S. Kachru's talk

"New generation" of papers (contemporary with hep-th/07003028)

[Abel,Goodsell, hep-th/0612110]

[Akerblom,Blumenhagen,Lüst,Plauschinn,Schmidt-Sommerfield,hep-th/0612132]

[Bianchi,Kiritsis, hep-th/0702015],

[Bianchi,Fucito,Morales arXiv:0704.0784[hep-th]]

[Argurio,Bertolini,Ferretti,Lerda,Petersson aeXiv:0704.0262[hep-th]]

[Ibáñez,Schellekens,Uranga,arXiv:0704.1079[hep-th]] extensive RCFT search for global models

[Akerblom,Blumenhagen, Lüst,Schmidt-Sommerfeld, arXiv:0705.2366[hep-th]] one-loop & holomorphic coupling corrections

Instantons–Heuristics

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

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

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

Rules:

- Instanton sector corresponds to local minimum of (full) string action

$\longrightarrow$ $E2$-brane volume minimizing

- Integrate over zero modes localized on $E2$

$\longrightarrow$ All fermionic zero modes have to appear for relevant instanton induced couplings exactly once

Focus: induced superpotential terms involving charged matter fields Φ_i

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

Gauge potential sourced by D6-brane-transforms uder $U(1)_a$! →
exponential not gauge invariant under $U(1)_a$!

$$e^{-S_{E2}} \rightarrow e^{i\,Q_a(E2)\,\Lambda_a}\ e^{-S_{E2}}: \ Q_a(E2) = \frac{\ell_s^3}{2\pi} N_a\ \Xi \circ (\Pi_a - \Pi'_a)$$

Consequence:

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

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

$\longrightarrow$ This selection rule explained in terms of fermionic zero modes:

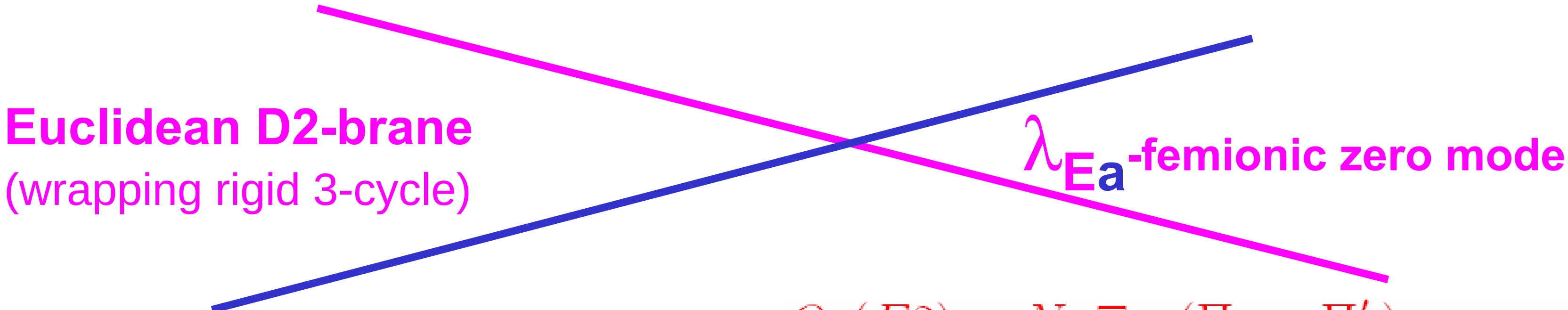
Constraints on Zero Fermionic Modes:

I. 3-cycle wrapped by instanton:RIGID & invariant under orientifold projection

II. Zero modes (strings between $E2$ and $D6_a$):

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

One single fermionic zero mode λ_a



$D6_a$-brane

$Q_a(E2) = N_a \, \Xi \circ (\Pi_a - \Pi'_a)$

in agreement with $e^{-S_{E2}} \longrightarrow e^{i\,Q_a(E2)\,\Lambda_a} \; e^{-S_{E2}}$

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

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

Develop CFT INSTANTON CALCULUS to determine such non-perturbatively induced superpotential couplings quantitatively (technical, no time!)

Phenomenological Implications:

Effects on Superpotential Matter Couplings

One can generate perturbatively forbidden matter couplings:

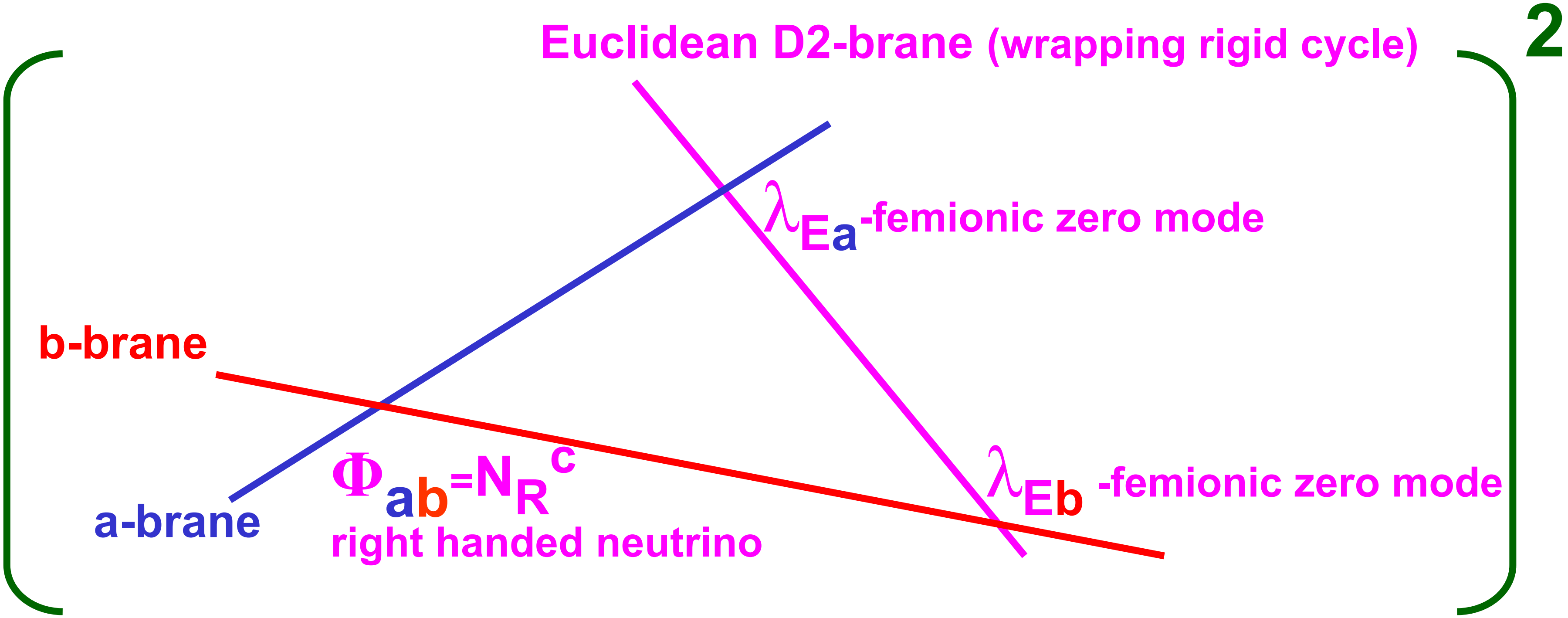
I. Majorana masses for right-handed neutrinos
$\longrightarrow$ Neutrino Dirac masses $W_H = H^+ L_L (N_R)^c$ typically present, and of order of charged sector masses

Majorana mass $W_m = M_m (N_R)^c (N_R)^c$ perturbatively forbidden

Note, N_R^c -Standard Model singlets, typically charged under additional anomalous $U(1)_c \times U(1)_d$, say as $(1, -1)$.

Majorana Neutrino Masses:

D2-instanton wraps [2+1 (euclidean time)]=3-cycle $[\Pi_{E2}]$



There is non-zero non-pertubative coupling: $M_m N_R^c N_R^c$

D2-instanton w/ $[\Pi_{SM}]^\circ[\Pi_{E2}] = 0$, $[\Pi_a]^\circ[\Pi_{E2}] = 2$ & $[\Pi_b]^\circ[\Pi_{E2}] = -2$

→ fermionic zero modes appear precisely ONCE and thus M_m non-zero

Geometric!

$\longrightarrow$ Non-pert. Majorana coupling:

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

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

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

Possible within natural regime for

$0.4 \cdot R_{D6} > R_{E2} > 0.2 \cdot R_{D6}$ (assume x=$\mathcal{O}$ (1)).

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

[M. C., Robert Richter, Timo Weigand, hep-th/0703028]

Aim:

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

• Realize correct suppression scale for Majorana masses

• Exemplify CFT computation $\longrightarrow$ determine x exactly

Construct supersymmetric 3-stack GUT model:

$N_c = 5$: SU(5)-GUT stack $\qquad N_a = N_b = 1$

sector	representation	matter
(c, c')	Antisym	$\mathbf{10}$
(c, a)	$(\overline{c}, a)$	$\overline{\mathbf{5}}$
(c, b)	$(c, \overline{b})$	$\mathbf{5}_H$
(a, b)	$(\overline{a}, b)$	N_R^c

with correct zero mode structure

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

Constraining!

Extensive search merely leads to local set-up with 4 families of $\mathbf{10}$ and 32 N_R^c

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

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

$x =$

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

$e^{Z'}$–one-loop contribution [Akerblom et al. arXiv:0705.236[he-th]]

Overall exponential suppression scale fixed by SUSY:

$$\frac{\mathrm{Vol}_{E2}}{\mathrm{Vol}_{\Pi_c}} = \Big(\prod_I \frac{(n^I_{E2})^2 + (\widetilde{m}^I_{E2})^2 U_I^2}{(n^I_c)^2 + (\widetilde{m}^I_c)^2 U_I^2} \Big)^{1/2} = \frac{8}{57}$$

• Sum up contributions from all 64 factorizable E2-instantons, taking leading contribution (smallest triangle)

$\longrightarrow M_M \simeq 10^{10} GeV$

for triangles of order string scale (as required)

• Together with perturbative Dirac masses of $\mathcal{O}$(TeV) (due to Yukawa couplings of the type $\overline{\mathbf{5}}\,\mathbf{5}_H\,\mathbf{1}$)

$\longrightarrow$ Can engineer small neutrino masses of $\mathcal{O}$(1eV) via see-saw mechanism.

II. Further applications:

- μ -term $\mu H^+ \, H^-$ forbidden perturbatively

$\longrightarrow$ can well be generated by $E2$-instantons!

$\longrightarrow$ appropriate volume ratio may yield $\mu \simeq \mathcal{O}(\mathrm{TeV})$

- R-parity violating couplings in the MSSM can be induced (constrains!)
- GUT $SU(5)$ suffer from absence of pert. Yukawa couplings $\mathbf{10}\,\mathbf{10}\,\mathbf{5}_H$,

Can be generated by $E2$-instantons!

[R.Blumenhagen,M.C.,R.Richter,T.Weigand,UPR-1180-T]

But no more time!

Summary/Outlook

(a) Major progress: development of techniques **for consistent constructions on orbifolds w/intersecting D-branes** (primarily on toroidal orbifolds)

(b) Sizable number of semi-realistic models**; systematic searches** (not-fully realistic-typically some chiral exotic matter)

(c) Coupling calculation –Yukawa couplings, etc.

(d) Non-perturbative (D-instanton) effects:

New hierarchical couplings:

Majorana neutrino masses →seesaw mechanism realised within a local model

μ-parameter, SU(5) GUT Yukawa couplings,…

Challenge: search for global models with realistic features realising D-instanton effects!

Foresee further progress:

(a) DEVELOPMENT of TECHNIQUES! → generalize constructions to general Calabi Yau spaces

(b) Further study of non-perturbative effects:
Vacuum de-/re-stabilisation: SUSY breaking/open-string moduli stabilisation
effects of additional zero modes: non-rigid cycles, instanton cycle recombination, etc.

R.Blumenhagen,M.C. R.Richter,T. Weigand. Wotk in progress

(c) Quantitatively improve realistic model constructions, including further progress on globally consistent models with desired non-perturbative effects

FULLY REALISTIC CONSTRUCTIONS
particle spectrum & interactions?

NOT THERE YET, BUT GETTING BETTER AT IT

EFFORTS PRESENTED PLAYING KEY ROLE