CHIRAL FOUR-DIMENSIONAL STRING COMPACTIFICATIONS WITH INTERSECTING D-BRANES

ANGEL M. URANGA

IFT/IMAFF, MADRID

PLAN OF THE TALKS

LECT. I BASICS OF INTERSECTING D-BRANE WORLDS

- INTRODUCTION : STRING PHENOMENOLOGY
- BRANE WORLDS AND D-BRANES
  - PROPERTIES OF D-BRANES
  - CHIRALITY FROM D-BRANES
- INTERSECTING BRANE - WORLDS
  - CONSTRUCTION AND EXAMPLES

LECT. II MORE ADVANCED CONSTRUCTIONS

- COMMENTS ON SUPERSYMMETRY
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  - NON SUSY MODEL BUILDING
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LECT. III D-BRANES AT SINGULARITIES

- D BRANES AT SINGULARITIES AND CHIRALITY
- D3 - AND D7 - BRANES AT ORBIFOLD SINGUS

  MSSM - LIKE CONSTRUCTIONS & EXAMPLES
- COMPARISON OF DIFF. CLASSES OF MODELS

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- INTRODUCTION
  - STRING PHENOMENOLOGY
    - HETEROTIC APPROACH
    - D BRANE WORLD APPROACH
- D-BRANES
  - BASIC PROPERTIES
  - CHIRALITY AND INTERSECTING D-BRANES
- COMPACTIFICATIONS WITH INTERSECTING BRANES
  - TOROIDAL COMPACTIFICATION GENERALIZATION
  - PHENOMENOLOGICAL PROPERTIES
- CONCLUSIONS

A PARTIAL LIST OF REFERENCES

CHIRALITY IN A TDUAL SETUP (MAGNETIC FLUX)

- BACHAS '95
- ANGELANTONJ, ANTONIADIS, DUDAS, SAGNOTTI '00

BRANES AT ANGLES (EARLY WORK)

- BERKOOZ, DOUGLAS, LEIGH '96
- BLUMENHAGEN, GÖRLICH, KÖRS '99
- FORSTE, HONECKER, SCHREYER '00

COMPACTIFICATIONS WITH INTERSECTING BRANES IN TORI, CY, ... AND CHIRAL SPECTRUM

- BLUMENHAGEN, GÖRLICH, KÖRS, LÜST '00
- ALDAZABAL, FRANCO, IBAÑEZ, RABADAN, A.U. '00
- BLUMENHAGEN, KÖRS, LÜST '00
- IBAÑEZ, MARCHESANO, RABADAN '01
- BLUMENHAGEN, KÖRS, LÜST, OTT '01
- CVETIC, SHIU, A.U. '01
- CREMADES, IBAÑEZ, MARCHESANO '02
- BLUMENHAGEN, BRAUN, KÖRS, LÜST '02
- A.U. '02
- ...

INTRODUCTION

- STRING THEORY PROVIDES A DESCRIPTION OF GAUGE AND GRAVITATIONAL INTERACTIONS IN A UNIFIED FRAMEWORK CONSISTENT AT THE QUANTUM LEVEL
- IF STRING THEORY IS REALIZED IN NATURE IT SHOULD BE ABLE TO LEAD TO GAUGE SECTORS WITH SPECIFIC STRUCTURE

GAUGE GROUP $SU(3)_c \times SU(2)_W \times U(1)_Y$

CHIRAL FERMIONS $3 \times [(3,2)_{1/6} + (\bar{3},1)_{1/3} + (\bar{3},1)_{-2/3} + (1,2)_{-1/2} + (1,1)_1 + (1,1)_0]$

SCALAR HIGGS $(1,2)_{-1/2}$

- ROUGH FEATURES
  - NONABELIAN GAUGE SYMMETRIES
  - CHIRALITY
  - REPLICATION
  - PROTON STABILITY ...

PLUS DETAILED FEATURES

- YUKAWA, GAUGE COUPLINGS, ...

SIMPLY UNEXPLAINED IN GAUGE THEORY SETUP

- EXPLAIN/REPRODUCE IN A MICROSCOPIC THEORY LIKE STRING THEORY ?

STRING PHENOMENOLOGY

- STRING THEORIES PROPAGATE IN SPACETIMES OF TEN DIMENSIONS, AND USUALLY HAVE A HIGH DEGREE OF SUPERSYMMETRY
  - LARGE ARBITRARINESS IN CONSTRUCTING FOUR-DIMENSIONAL MODELS
    E.G. CHOICE OF COMPACTIFICATION MANIFOLD
  - NOT ALL REGIMES ARE ACCESSIBLE TO OUR COMPUTATIONAL TOOLS
    E.G. PERTURBATION THEORY IN g_s, α'
- $\Rightarrow$ EXTREMELY UNLIKELY THAT WE FIND "THE" STRING THEORY OF THE WORLD BY "TRIAL AND ERROR"
- PURPOSE OF STRING PHENOMENOLOGY [FOR THIS TALK]

I. DESCRIBE DIFFERENT SETUPS WHICH LEAD TO SAME KIND OF PHYSICS AS THE STANDARD MODEL [AT ROUGH LEVEL, E.G. NONABELIAN GAUGE, REPLICATED CHIRAL FMS]

II. WITHIN EACH SETUP, CONSTRUCT EXPLICIT EXAMPLES AS CLOSE AS POSSIBLE TO S.M. AND EXTRACT GENERIC, ROBUST FEATURES
$\Rightarrow$ NATURAL PREDICTIONS OF THE SETUP

PROTOTYPICAL EXAMPLE

COMPACTIFICATION OF HETEROTIC STRING

10D: GRAVITATIONAL AND GAUGE INTERACTIONS, WITH GAUGE GROUP $G = E_8 \times E_8$ OR $SO(32)$, PROPAGATE OVER 10D SPACETIME.

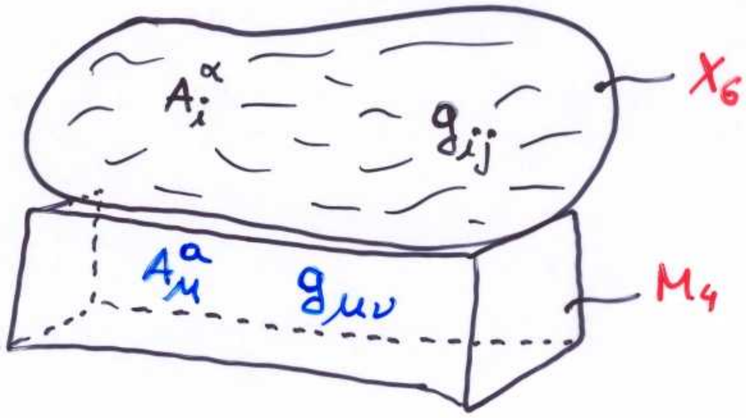
TO OBTAIN 4D PHYSICS, CHOOSE SPACETIME $M_4 \times X_6$ WITH COMPACTIFICATION MANIFOLD X_6

[E.G. CALABI-YAU ⇒ N=1 SUPERSYMMETRY]

TO OBTAIN SMALLER 4D GAUGE GROUP, TURN ON BACKGROUND OF INTERNAL GAUGE FIELDS IN $H \subset G$ ⇒ 4D GAUGE GROUP IS GIVEN BY ELEMENTS OF G COMMUTING WITH H.

[E.G. $H = SU(3)$ BACKGROUND ⇒ 4D E_6 GAUGE GROUP
$H = SU(5) \times Z_2$ BACKGROUND ⇒ 4D $SU(3) \times SU(2) \times U(1)$]

PICTURE



4D CHIRAL FERMIONS ARISE NATURALLY. MOREOVER, REPLICATION OF FAMILIES IS NATURAL AS WELL, AND IS RELATED TO TOPOLOGY OF X_6 AND GAUGE BACKGROUND

[E.G. "STANDARD EMBEDDING" ⇒ #FAM = $\chi(X_6)$]

▲ COUPLINGS AND SCALES FOR HETEROTIC

10D GRAVITATIONAL AND GAUGE INTERACTIONS

$$\int d^{10}x \; M_s^8/g_s^2 \; R_{(10d)} \; ; \; \int d^{10}x \; M_s^6/g_s^2 \; F_{(10d)}^2$$

KALUZA-KLEIN COMPACTIFICATION TO 4D

$$\int d^4x \; \frac{M_s^8 V_6}{g_s^2} \; R_{(4d)} \; ; \; \int d^4x \; \frac{M_s^6 V_6}{g_s^2} \; F_{(4d)}^2$$

4D PLANCK SCALE AND GAUGE COUPLING

$$M_P^2 = M_s^8 V_6 / g_s^2 \simeq 10^{19} \text{ GeV}$$

$$1/g_{YM}^2 = M_s^6 V_6 / g_s^2 \simeq O(0,1)$$

OBTAIN $\boxed{M_s = g_{YM} M_P \simeq 10^{18} \text{ GeV}}$. VERY LARGE!

▲ EXPLICIT REALISTIC HETEROTIC MODELS HAVE BEEN CONSTRUCTED OVER THE YEARS

[CY WITH NON STANDARD EMBEDDING, ORBIFOLDS..]

GENERAL FEATURES OF MODELS IN THIS SETUP

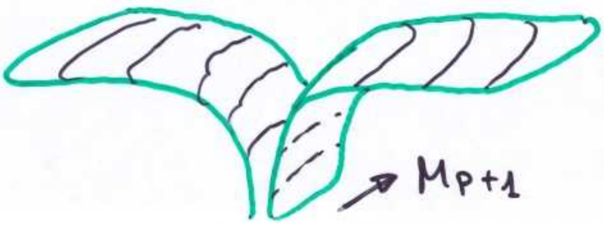
- ☺ $M_s \sim 10^{17} - 10^{18}$ GeV
- ☺ N=1 SUSY COMPULSORY TO AVOID HIERARCHY
- ☺ LARGE M_s HELPS IN MAKING PROTON STABLE
- ☺ UNIFICATION OF COUPLINGS, QUITE OK

...

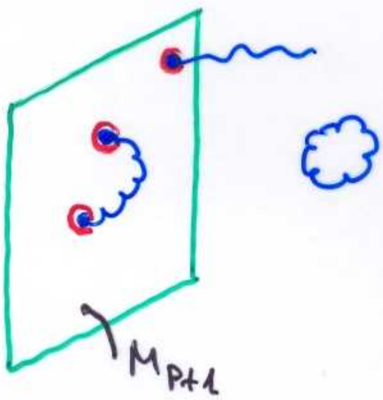
- ☹ HOW TO BREAK SUPERSYMMETRY ($\Lambda \simeq 0$) ?
- ☹ HOW TO STABILIZE MODULI ? [GAUGINO CONDENSATION ?, ...]

DBRANES IN STRING THEORY

- OUR MOTIVATION: DBRANES OFFER A BRAND-NEW MECHANISM FOR NONABELIAN GAUGE SYMMETRIES IN STRING THEORY.
- TYPE II STRING THEORIES CONTAIN CERTAIN SOLITON-LIKE STATES IN THEIR SPECTRUM, WITH P+1 EXTENDED DIMENSIONS P-BRANES ORIGINALLY FOUND AS SOLUTIONS OF SUPEGRAVITY EQUATIONS



- POLCHINSKI '95: PERTURBATION OF STRING THEORY AROUND THIS TOPOLOGICAL DEFECTS IS EQUIVALENT TO INTRODUCING OPEN STRINGS IN THE THEORY, WITH ENDS ON THE (P+1)-DIMENSIONAL HYPERPLANE, VOLUME OF THE BRANE → DP-BRANE



- CLOSED SECTOR: FLUCTUATIONS AROUND VACUUM: GRAVITAT. DYNAMICS, ETC
- OPEN SECTOR: FLUCTUATIONS OF THE SOLITON, DPBRANE

▲ SPECTRUM OF OPEN STRINGS WITH BOTH ENDS ON A DP-BRANE

U(1) GAUGE GROUP

9-P SCALARS } "GOLDSTONES"

FERMIONS

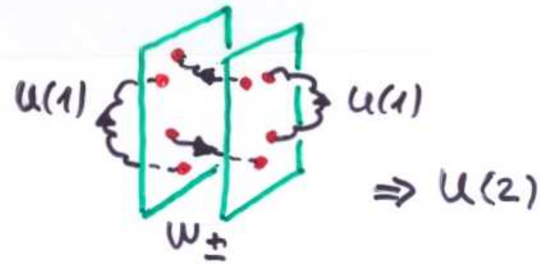
U(1) VECTOR MULTIPLET W.R.T. 16 UNBROKEN SUSY'S IN P+1 DIMENSIONS [E.G. 4D N=4]

▲ OPEN STRING SPECTRUM ON A STACK OF n DP'S

U(n) GAUGE GROUP

9-P ADJOINT SCALARS

ADJOINT FERMIONS



U(n) VECTOR SUPERMULTIPLET

W.R.T. 16 UNBROKEN SUPERSYMMETRIES

⇒ NONABELIAN GAUGE SYMMETRIES !

▲ USEFUL PROPERTIES OF D BRANES

- CHARGED UNDER RR (P+1)-FORM $\int_{W_{p+1}} C_{p+1}$
- PRESERVE 1/2 SUSY OF THE BACKGROUND
- BPS STATE: CHARGE ~ TENSION
- OPEN STRING SPECTRUM IS LOCALIZED ON THE DP-BRANE WORLD-VOLUME

[DIRAC-BORN-INFELD EFFECTIVE ACTION ⇒ ⇒ (P+1) DIMENSIONAL (SUPER) YANG-MILLS AT LOW ENERGIES]

⇒ BRANE-WORLD IDEA

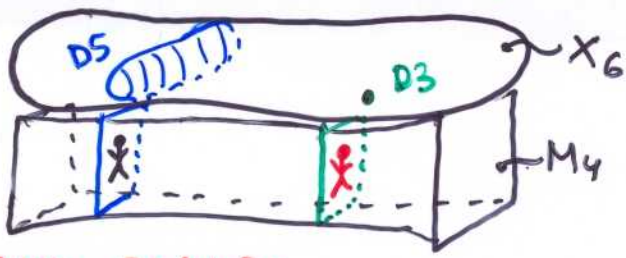
BRANE-WORLDS

- DBRANES ALLOW FOR GAUGE SECTORS LOCALIZED ON SUBSPACES OF SPACETIME, IN A CONSISTENT AND MICROSCOPICALLY WELL DEFINED FRAMEWORK.

- STRING THEORY REALIZATION OF THE BRANE WORLD IDEA [(ANTONIADIS), ARKANI-HAM. DIMOPOULOS, DVALI]

- GRAVITY PROPAGATES IN 10D: 4D GRAVITY IS REPRODUCED BY COMPACTIFICATION $\Rightarrow M_4 \times X_6$

- GAUGE INTERACTIONS PROPAGATE IN (P+1) DIMENSIONS WORLDVOLUME OF A STACK OF DPBRANES:
4D GAUGE INTERACTIONS OBTAINED BY TAKING DP WORLDVOLUME $M_4 \times \Sigma_{p-3}$, WITH $\Sigma_{p-3} \subset X_6$



COUPLINGS AND SCALES

FROM 10d $\int d^{10}x \, \frac{M_s^{\,8}}{g_s^{\,2}} R_{(10d)} \quad ; \quad \int d^{p+1}x \, \frac{M_s^{\,p-3}}{g_s} F^2_{(p+1\, d)}$

TO 4D $\int d^4x \, \frac{M_s^{\,8} V_6}{g_s^{\,2}} R_{(4d)} \quad ; \quad \int d^4x \, \frac{M_s^{\,p-3} V_\Sigma}{g_s} F^2_{(4d)}$

$$M_P^{\,2} = M_s^{\,8} V_6 / g_s^{\,2}$$

$$1/g_{YM}^{\,2} = M_s^{\,p-3} V_\Sigma / g_s$$

$$\boxed{M_P^{\,2} g_{YM}^{\,2} = \frac{M_s^{\,11-p}}{g_s} V_\perp}$$

GEOMETRIC EXPLANATION OF HIERARCHY
LOW M_s POSSIBLE BY E.G. TAKING LARGE $V_\perp$
[LOW M_s NOT COMPULSORY, E.G. IN SUSY MODELS]

DBRANES AND CHIRALITY

- DBRANES PRESERVE QUITE A LOT OF SUSY

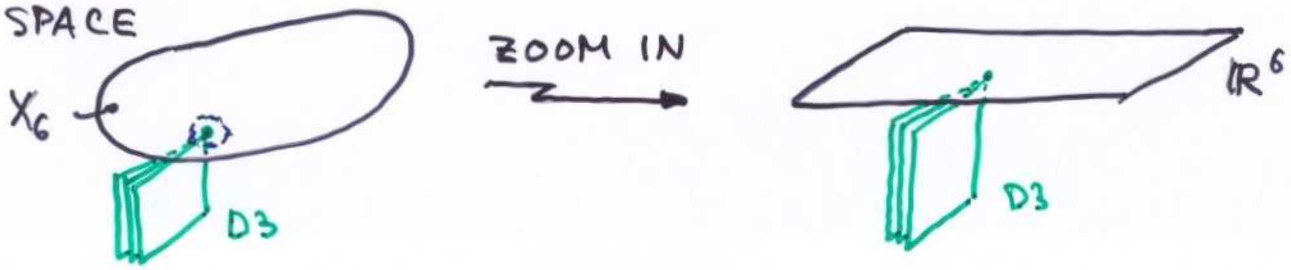
  16 SUSYS [EQUIV. 4D $N=4$]

  → TOO MUCH TO ALLOW FOR CHIRALITY

  [LEFT-RIGHT FERMION PAIRS IN EACH MULTIPLET]

- IT IS NONTRIVIAL TO BUILD CONFIGURATIONS OF DBRANES LEADING TO CHIRAL 4D OPEN STRING SPECTRUM.

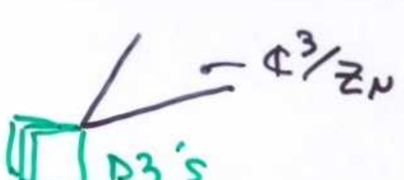
EX. ISOLATED DBRANES IN SMOOTH TRANSVERSE SPACE



- TWO WELL STUDIED "CHIRAL" CONFIGURATIONS

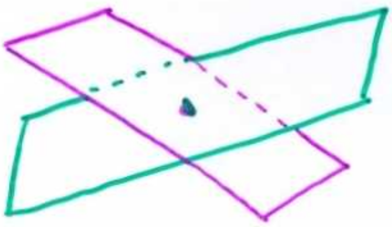
- DBRANES AT SINGULARITIES [DOUGLAS, MOORE; DOUGLAS, GREENE, MORRISON]

  EX: D3 AT ORBIFOLD $\mathbb{C}^3/\mathbb{Z}_N$



ORBIFOLD PROJECTION DISTINGUISHES FM. CHIRALITY.

- NON ISOLATED DBRANES: INTERSECTING DBRANES



EX: TWO D6 INTERSECT OVER 4D

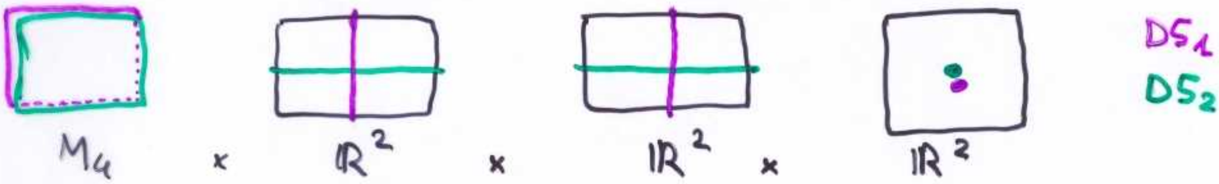
OPEN STRINGS STRETCHED BETWEEN DBRANES MAY PRODUCE CHIRAL FERMIONS

[BERKOOZ, DOUGLAS, LEIGH]

WHAT KIND OF INTERSECTING DBRANES ACTUALLY LEAD TO 4D CHIRALITY ?

▲ **HEURISTIC ARGUMENT**

ATTEMPT: TWO STACKS OF D5 BRANES IN FLAT 10D INTERSECTING OVER 4D

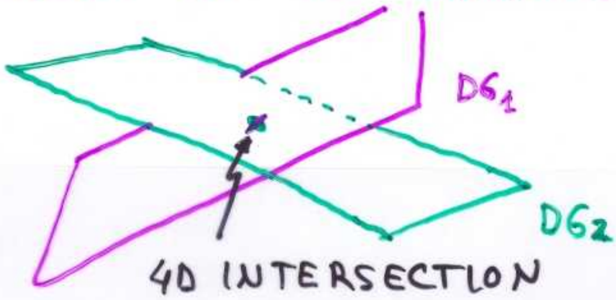


4D CHIRAL MATTER CANNOT APPEAR FROM $D5_1$-$D5_2$ STRINGS. SEPARATING BRANES IN LAST $\mathbb{R}^2$ MAKES THOSE STATES MASSIVE, BUT CHIRAL MATTER CANNOT BE MADE MASSIVE!

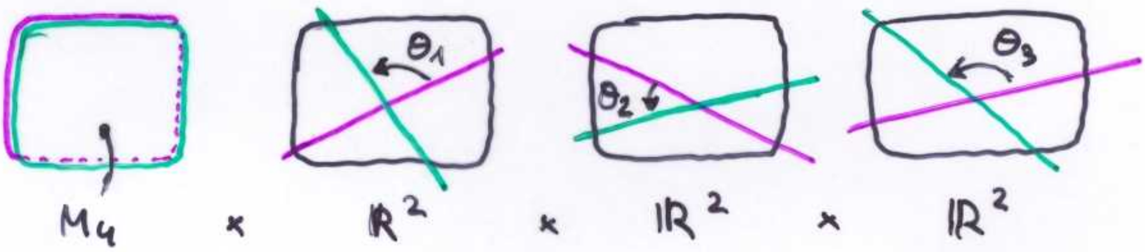
▲ SIMILAR ANALYSIS LEADS TO:

4D CHIRALITY IS POSSIBLE AT 4D INTERSECTION OF TWO STACKS OF D6 BRANES

PICT. 1:



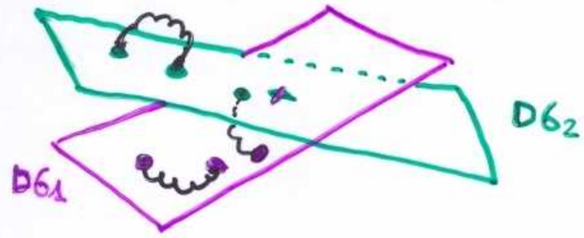
PICT. 2:



- NOT POSSIBLE TO AVOID INTERSECTION BY MOVING BRANES. CONSISTENT WITH CH. MATTER. INDEED $D6_1$ - $D6_2$ SECTOR PRODUCES CH. FERMIONS

OPEN STRING SPECTRUM FOR TWO STACKS OF D6-BRANES INTERSECTING OVER 4D

- THREE OPEN STRING SECTORS



LOCAL GEOMETRY GIVEN BY θ_i, ANGLES IN $\mathbb{R}^6$

$6_1 6_1$: 7D FIELDS, 16 SUSYS
U(n_1) GAUGE GROUP
3 REAL ADJOINT SCALARS
FERMIONS

$6_2 6_2$: 7D FIELDS, 16 SUSYS [NOT SAME AS ABOVE]
U(n_2) GAUGE GROUP
3 REAL ADJOINT SCALARS
FERMIONS

$6_1 6_2 + 6_2 6_1$ 4D FIELDS, LOCALIZED AT INTERSECTION
4D CHIRAL FERMION IN $(n_1, \bar{n}_2)$
LIGHT SCALARS IN $(n_1, \bar{n}_2)$

- SCALARS AND COMMON SUPERSYMMETRY

$$\alpha' M^2 = \tfrac{1}{2}(\theta_1 + \theta_2 - \theta_3) \,,\quad \tfrac{1}{2}(\theta_1 - \theta_2 + \theta_3),$$
$$\tfrac{1}{2}(-\theta_1 + \theta_2 + \theta_3) \,,\quad 1 - \tfrac{1}{2}(\theta_1 + \theta_2 + \theta_3).$$

4D N=1 COMMON SUSY IF $\theta_1 \pm \theta_2 \pm \theta_3 = 0$
4D N=2 COMMON SUSY IF E.G. $\theta_1 \pm \theta_2 = 0$, $\theta_3 = 0$
4D N=4 COMMON SUSY IF $\theta_1 = \theta_2 = \theta_3 = 0$

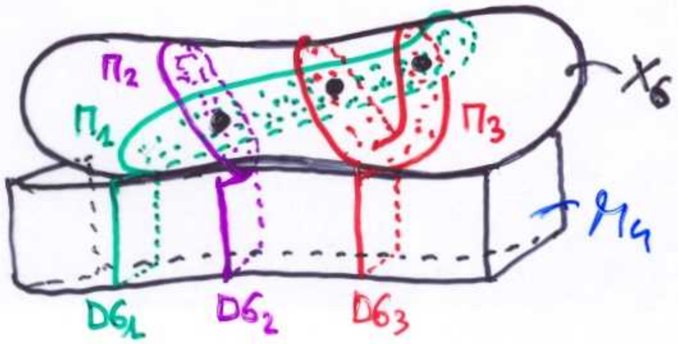
COMPACTIFICATION

- IN FLAT 10D, CHIRAL FERMIONS AT INTERSECTION ARE 4D, BUT GAUGE INTERACTIONS REMAIN 7D, GRAVITY IS STILL 10D.

  ⇒ NEED TO CONSIDER COMPACTIFICATION.

- GENERAL IDEA:

  TAKE 10D SPACETIME $M_4 \times X_6$ [E.G. WITH X_6 C.Y.] TO GET 4D GRAVITY, AND CONSIDER D6-BRANES WRAPPED ON COMPACT 3-CYCLES $\Pi_a \subset X_6$ INTERSECTING AT POINTS IN X_6



10D GRAVITY $\xrightarrow{KK}$ 4D GRAVITY

7D GAUGE $\xrightarrow{KK}$ 4D GAUGE

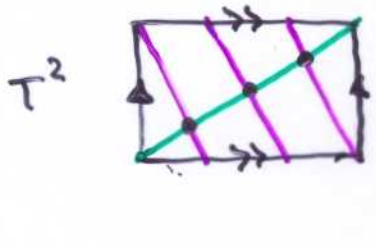
INTERSECT. $\longrightarrow$ 4D CHIRAL FERMIONS

- REMARKABLE PROPERTY:

  TWO 3-CYCLES IN A COMPACT 6-MANIFOLD X_6 MAY INTERSECT AT SEVERAL POINTS

  → REPLICATED FERMIONS WITH SAME Q. NUMBERS

  ANALOGY : 1-CYCLES IN T^2

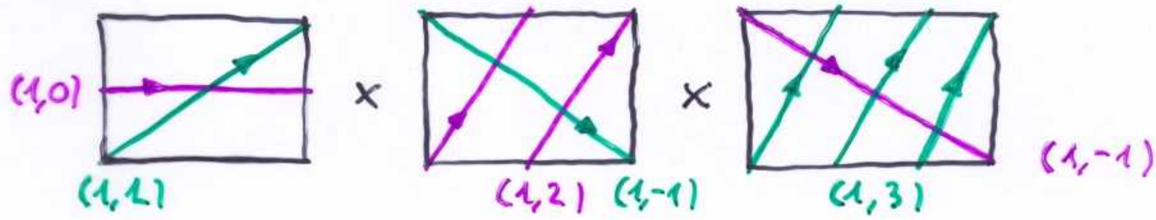


TOROIDAL COMPACTIFICATION

- TO KEEP LIFE SIMPLE, CONSIDER TOROIDAL COMPACTIFICATION $X_6 = T^6 = T^2 \times T^2 \times T^2$
- ALSO FOR SIMPLICITY, LET EACH STACK OF N_a $D6_a$ BRANES WRAP A 3 CYCLE $\Pi_a \subset X_6$, PRODUCT OF THREE 1-CYCLES, EACH ON A T^2 FACTOR

  LABEL EACH 1-CYCLE IN i^{TH} T^2 BY (n_a^i, m_a^i)

  = # WRAPPING IN HORIZONTAL, VERTICAL DIRECTION



\# INTERSECTIONS IN ONE T^2 : $n_a m_b - m_a n_b$

\# INTERSECTIONS OF Π_a, Π_b IN T^6

$$I_{ab} = (n_a^1 m_b^1 - m_a^1 n_b^1) \times (n_a^2 m_b^2 - m_a^2 n_b^2) \times$$
$$\times (n_a^3 m_b^3 - m_a^3 n_b^3)$$

- IT IS USEFUL TO INTRODUCE THE 3-HOMOLOGY CLASS $[\Pi_a]$: "VECTOR OF RR CHARGES"
  - 1-HOMOLOGY CLASS IN T^2: $n[a] + m[b]$

    3-HOMOLOGY CLASS IN T^6: $[\Pi_a] = \bigotimes_{i=1}^{3} (n_a^i [a_i] + m_a^i [b_i])$

    - ENCODES INFO ABOUT RR CHARGE OF $D6_a$
    - INTERSECTION NUMBER OF HOMOLOGY CLASSES IS ABOVE # INTERSECTIONS

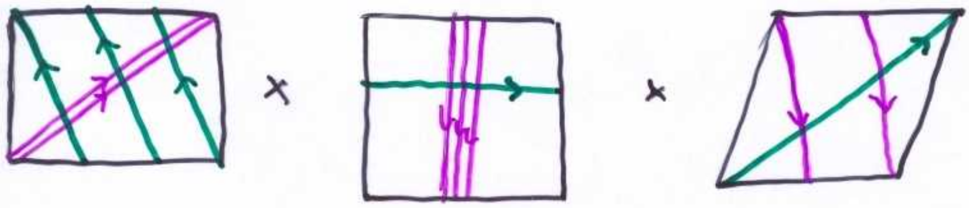
$$I_{ab} = [\Pi_a] \cdot [\Pi_b]$$

(USING $[a_i] \cdot [b_j] = \begin{cases} 1 & i=j \\ 0 & i \neq j \end{cases}$ AND LINEARITY)

FINAL CONFIGURATION

N_a D6-BRANES WRAPPED ON 3-CYCLES Π_a, CHARACTERIZED BY WRAPPING NUMBERS (n_a^i, m_a^i) ON EACH T^2, $i=1,2,3$.

NUMBER OF INTERSECTION POINTS I_{ab}



SPECTRUM

- CLOSED STRING SECTOR: GRAVITON + PARTNERS
- OPEN STRING SECTOR:

$6_a 6_a$ $\quad$ $\left.\begin{array}{l} U(N_a) \text{ GAUGE GROUP} \\ 6 \text{ REAL ADJOINT SCALARS} \\ 4 \text{ ADJOINT MAJ. FERMIONS} \end{array}\right\} N=4$

$6_a 6_b + 6_b 6_a$ $\quad$ $I_{ab}\ (N_a, \overline{N}_b)$ CHIRAL FERMIONS

+ LIGHT SCALARS

[INTERSECTIONS MAY (NOT) PRESERVE SOME SUSY DEPENDING ON ANGLES, MODULI]

LARGE CLASS OF 4D THEORIES WITH INTERESTING NONABELIAN GAUGE SYMMETRIES AND CHIRAL FERMIONS

$\Rightarrow$ EXPLORE FURTHER AS POSSIBLE SETUP FOR PHENOMENOLOGICAL MODELS

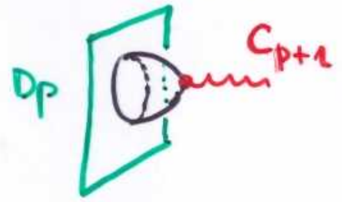
OBS SEE LATER FOR EXTENSIONS BEYOND TORUS

A CONSISTENCY CONDITION

- STRING THEORIES WITH OPEN STRING SECTORS MUST SATISFY A CRUCIAL CONSISTENCY CONDITION

  RR TADPOLE CANCELLATION

- D-BRANES ACT AS SOURCES FOR RR P-FORMS

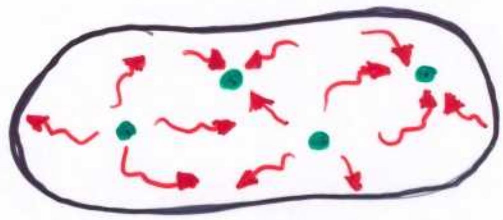


$\rightarrow \int_{Dp} C_{p+1}$

TADPOLE DIAGRAM
$\sim$ RR CHARGE

- REQUIRE THAT TOTAL RR CHARGE VANISHES IN COMPACT X_6 [GAUSS' LAW]

$$[\Pi_{tot}] = \sum_a N_a [\Pi_a] = 0$$



- EQUIV. REQUIRE CONSISTENCY OF EQ. OF MOTION

$$S_{C_7} = \int_{X_{10}} H_8 \wedge * H_8 + \sum_a N_a \int_{M_4 \times \Pi_a} C_7 =$$

$$= \int_{X_{10}} C_7 \wedge dH_2 + \sum_a N_a \int_{X_{10}} C_7 \wedge \delta(\Pi_a) \leftarrow \text{DELTA 3-FORM ON } \Pi_a$$

$$\Rightarrow \quad dH_2 = \sum_a N_a \, \delta(\Pi_a)$$

INTEGRABILITY $\quad \sum_a N_a [\Pi_a] = 0$

OBS: EQUIV. ZERO MODE OF C_7 ON X_6 HAS NO KINETIC TERM, BUT HAS A SOURCE TERM $\sim [\Pi_{tot}]$

$$S_\phi = Q_{tot} \int_{M_4} \phi \quad \xrightarrow{\text{E.O.M}} \quad Q_{tot} = 0$$

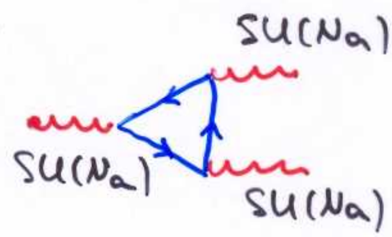
ANOMALY CANCELLATION

CANCELLATION OF RR TADPOLES IMPLIES CANCELLATION OF 4D CHIRAL ANOMALIES

CUBIC NONABELIAN ANOMALIES

RECALL $\prod_a U(N_a)$ GAUGE

I_{ab} $(N_a, \bar{N}_b)$ FMS.



$SU(N_a)^3$ ANOMALY = # FUND − # ANTIFUND =

$$= \sum_b I_{ab} N_b$$

RR TADPOLE CANCELLATION IS $\sum_b N_b [\Pi_b] = 0$

MULTIPLY BY $[\Pi_a]$

$$0 = \sum_b N_b [\Pi_a] \cdot [\Pi_b] = \sum_b N_b I_{ab} \quad \text{OK}$$

OBS NOTICE THAT RR TADPOLE CANCELLATION IS SLIGHTLY STRONGER THAN CUBIC NONABELIAN ANOMALY CANCELLATION

REQUIRES # FUND = # ANTIFUND

ALSO FOR $N_a = 1, 2$

[NO ANOMALY IN GAUGE THEORY]

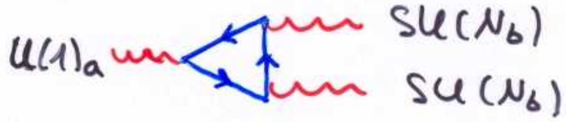
⇒ RELEVANT OBSERVATION TOWARDS THE END.

CANCELLATION OF MIXED $U(1)_a - SU(N_b)^2$ ANOMALY

ALSO ENSURED FROM RR TADPOLE CANCELLATION

RECEIVES TWO CONTRIBUTIONS

TRIANGLE DIAGRAMS



$A_{ab} \sim N_a I_{ab} \sim \#$ BIFUNDAMENLALS $(\square_a, \overline{\square}_b)$

GREEN - SCHWARZ DIAGRAMS

$U(1)_a$ GAUGE BOSON MIXES WITH A

RR 2-FORM B_a VIA KK REDUCTION OF

$$N_a \int_{D6_a} C_5 \wedge \mathrm{tr}\, F_a \xrightarrow{KK} N_a \int_{M_4} \mathrm{tr}\, F_a \wedge B_a \quad \text{WITH} \quad B_a = \int_{\Pi_a} C_5$$

DUALS OF B's, SCALARS ϕ_b COUPLE TO $SU(N_b)$

GAUGE BOSONS VIA KK REDUCTION OF

$$\int_{D6_b} C_3 \wedge \mathrm{tr}\, F_b \wedge F_b \xrightarrow{KK} \int_{M_4} \phi_b \,\mathrm{tr}\, F_b \wedge F_b \quad \text{WITH} \quad \phi_b = \int_{\Pi_b} C_3$$

DUALITY RELATION IS $\quad dB_a = I_{ab} * d\phi_b$

TOTAL CONTRIBUTION FROM GREEN-SCHWARZ IS

$A_{ab}' \sim N_a I_{ab}$

CANCELLATION : TRIANGLE + G. S. = 0.

OBS: STÜCKELBERG MASSES

ANY $U(1)$ GENERATOR WITH $B \wedge F$ COUPLING

GETS MASSIVE $(\sim M_s)$  $\sim m^2 A_\mu^2$

$\Rightarrow$ ALL ANOMALOUS AND SOME NON ANOMALOUS

$U(1)$'s GET MASSIVE, DISSAPPEAR FROM LOW ENGY.

A STANDARD-MODEL LIKE EXAMPLE

- CONSIDER A D6-BRANE CONFIGURATION DEFINED BY THE FOLLOWING

$$N_1 = 3 \qquad (1,2)\times(1,-1)\times(1,-2)$$
$$N_2 = 2 \qquad (1,1)\times(1,-2)\times(-1,5)$$
$$N_3 = 1 \qquad (1,1)\times(1,0)\times(-1,5)$$
$$N_4 = 1 \qquad (1,2)\times(-1,1)\times(1,1)$$
$$N_5 = 1 \qquad (1,2)\times(-1,1)\times(2,-7)$$
$$N_6 = 1 \qquad (1,1)\times(3,-4)\times(1,-5)$$

- INTERSECTION NUMBERS ARE

$$I_{12}=3 \quad I_{13}=-3 \quad I_{14}=0 \quad I_{15}=0 \quad I_{16}=-3$$
$$I_{23}=0 \quad I_{24}=6 \quad I_{25}=3 \quad I_{26}=0 \quad I_{34}=-6$$
$$I_{35}=-3 \quad I_{36}=0 \quad I_{45}=0 \quad I_{46}=6 \quad I_{56}=3$$

- A $U(1)$ LINEAR COMBINATION, PLAYING ROLE OF HYPERCHARGE, REMAINS MASSLESS

$$Q_Y = -\tfrac{1}{3}\, Q_1 - \tfrac{1}{2}\, Q_2 - Q_3 - Q_5$$

SPECTRUM [W.R.T. STANDARD MODEL GROUP]

$$SU(3)\times SU(2)\times U(1)_Y \times \ldots\ldots$$

$$3\,(3,2)_{1/6} + 3\,(\bar{3},1)_{-2/3} + 3\,(\bar{3},1)_{1/3} +$$
$$+\,6\,(1,2)_{-1/2} + 3\,(1,2)_{1/2} + 6\,(1,1)_{1} + 3\,(1,1)_{-1} + 9\,(1,1)_{0}$$

OBS QUITE NICE, BUT SIX EXTRA $SU(2)$ DOUBLETS

GENERALIZATION, ABSTRACTION

CLEARLY, THE ABOVE SETUP IS NOT RESTRICTED TO TOROIDAL MODELS

- WE MAY TAKE ANY COMPACT 6MANIFOLD X_6
  [E.G. ANY CY_3 → 4D $N=2$ IN CLOSED SECTOR]
- PICK A SET OF 3-CYCLES Π_a ON WHICH WRAPPED D6-BRANES ARE STABLE
- [E.G. SPECIAL LAGRANGIAN 3CYCLES → 4D $N=1$ 6_a6_a]
  WRAP N_a D6 BRANES ON THE 3-CYCLE Π_a MAKING SURE THEY SATISFY RR TADPOLE CANCELLATION $\sum_a N_a [\Pi_a] = 0$
- FINAL SPECTRUM IS [E.G. CY_3, SLAG CASE]

6_a6_a $\quad U(N_a)$ $\quad N=1$ VECT. MULT.
$\quad b_1$ ADJ $\quad N=1$ CH. MULT. $\quad [b_1 = b_1(\Pi_a)]$

$6_a6_b + 6_b6_a$ $\quad I_{ab}\,(N_a, \overline{N}_b)$ CH. FERMIONS + LIGHT SCALARS

WITH $I_{ab} = [\Pi_a]\cdot[\Pi_b]$

OBS
- PURELY TOPOLOGICAL : AS EXPECTED FROM CHIRALITY ⇝ ROBUST UNDER DEFORMATIONS
- PHENOMENOLOGY SIMILAR TO TOROIDAL CASE EXCEPT FOR DIFFERENCE IN 6_a6_a SECTOR
- CY_3 IS DIFFICULT, BUT SOME EXAMPLES OF SM MODELS EXIST [BLUMENHAGEN, BRAUN, KORS, LUST ; A.U.]

PHENOMENOLOGICAL FEATURES

PROPERTIES NATURAL IN THIS SETUP

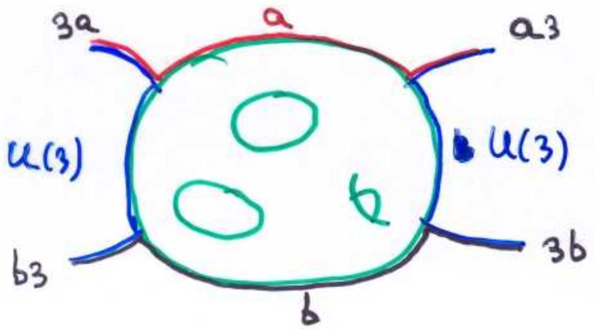
- VERY OFTEN, NONSUSY [SEE BELOW FOR RELATED ISSUES, ALSO FOR SUSY MODEL BUILDING]

  → NEED LOW $M_S \sim$ TeV TO AVOID HIERARCHY

- PROTON IS STABLE

  U(1) WITHIN U(3) IS BARYON NUMBER.
  SURVIVES AS A GLOBAL SYMMETRY, EXACTLY UNBROKEN IN PERTURBATION THEORY

  DIAGRAMMATICALLY



  VERTEX INSERTIONS MUST COMBINE SO THAT NET OUTGOING − INGOING # TRIPLETS VANISHES

  SMALL $U(1)_B$ VIOLATION VIA INSTANTON EFFECTS

  → PROTON STABILITY IS WELCOME IN LOW M_S.

- NO GAUGE COUPLING UNIFICATION, IN GENERAL.

$$1/g_{YM,a}^2 = \frac{M_s^3 \, V_{\Pi_a}}{g_s}$$

  GAUGE COUPLINGS RELATED TO GEOMETRIC VOLUMES

  $\sin^2\theta_W$ MAY BE ADJUSTED/REPRODUCED, NOT PREDICTED

- GEOMETRIC INTERPRETATION OF THE HIGGS

HIGGS MULTIPLET ARISES AS LIGHT SCALAR AT INTERSECTIONS. [MASSLESS IN SUSY CASE, LIGHT MASSIVE OR TACHYONIC IN NONSUSY]

HIGGS VEV CORRESPONDS TO BRANE RECOMBINAT.

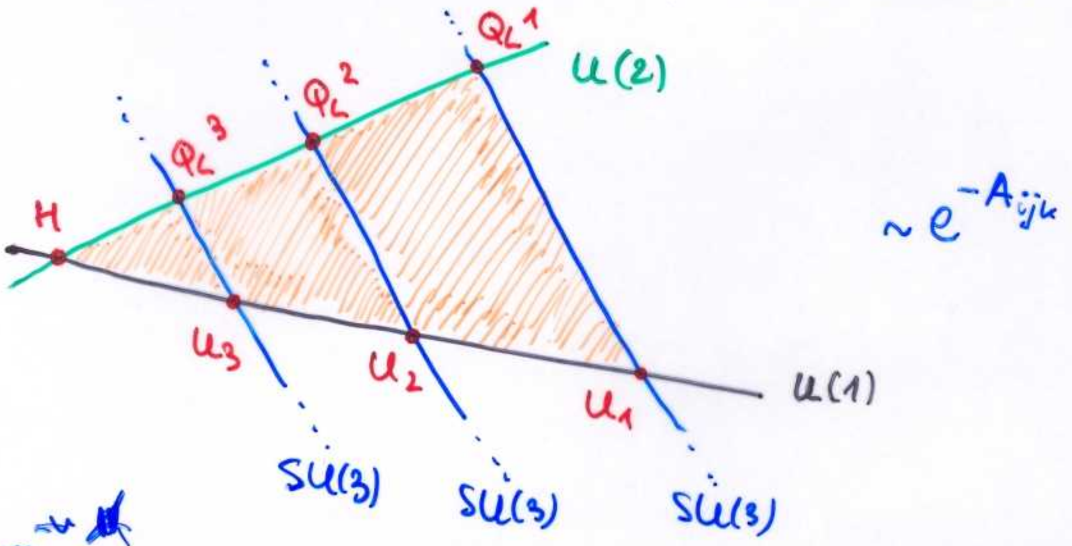
CAN BE MADE CONSISTENT WITH STRING SCALE

E.G. IN NONSUSY $M_W \sim M_H \sim \sqrt{\theta_i}\, M_S \quad \theta_i \ll 1.$

- NATURAL EXPONENTIAL HIERARCHIES OF YUKAWA COUPLINGS

YUKAWA COUPLINGS AMONG FIELDS AT INTERSECT'S ARISE FROM OPEN STRING WORLDSHEET INSTANTONS

[NON PERTURBATIVE IN α'; TREE LEVEL IN g_s]



CONCLUSIONS

- CONFIGURATIONS WITH INTERSECTING DBRANES LEAD TO AN INTERESTING CLASS OF 4D THEORIES WITH NON-ABELIAN GAUGE GROUPS AND CHARGED CHIRAL FMS.
- SIMPLE CONSTRUCTIONS LEAD TO SPECTRA (REASONABLY) SIMILAR TO THOSE OF S.M.
- INTERESTING PHENOMENOLOGICAL FEATURES
  - PROTON STABILITY
  - YUKAWA STRUCTURE
  - GEOMETRIC HIGGS INTERPRETATION
  - ...
- TOWARD AN ALTERNATIVE TO HETEROTIC PARADIGM.

CHIRAL FOUR-DIMENSIONAL STRING COMPACTIFICATIONS WITH INTERSECTING D-BRANES

ANGEL M. URANGA

IFT/IMAFF, MADRID

PLAN OF THE TALKS

LECT. I BASICS OF INTERSECTING D-BRANE WORLDS

- INTRODUCTION : STRING PHENOMENOLOGY
- BRANE WORLDS AND D-BRANES
  - PROPERTIES OF D-BRANES
  - CHIRALITY FROM D-BRANES
- INTERSECTING BRANE-WORLDS
  - CONSTRUCTION AND EXAMPLES

LECT. II MORE ADVANCED CONSTRUCTIONS

- COMMENTS ON SUPERSYMMETRY
- ORIENTIFOLD PLANES
  - NON SUSY MODEL BUILDING
  - SUSY MODEL BUILDING

LECT. III D-BRANES AT SINGULARITIES

- D BRANES AT SINGULARITIES AND CHIRALITY
- D3- AND D7-BRANES AT ORBIFOLD SINGUS
  MSSM-LIKE CONSTRUCTIONS & EXAMPLES
- COMPARISON OF DIFF. CLASSES OF MODELS

ADVANCED MODEL BUILDING

WITH

INTERSECTING D-BRANES

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IFT/IMAFF, MADRID

BASED ON: IBAÑEZ, MARCHESANO, RABADAN TH/0105155

CVETIC, SHIU, A.U. TH/0107143

OUTLINE OF THE TALK

- REVIEW OF INTERSECTING BRANE-WORLDS
- DISCUSSION ON SUPERSYMMETRY OF THESE CONSTRUCTIONS

  TACHYONS, NS NS TADPOLES, ETC.

  - NON-SUSY MODEL BUILDING

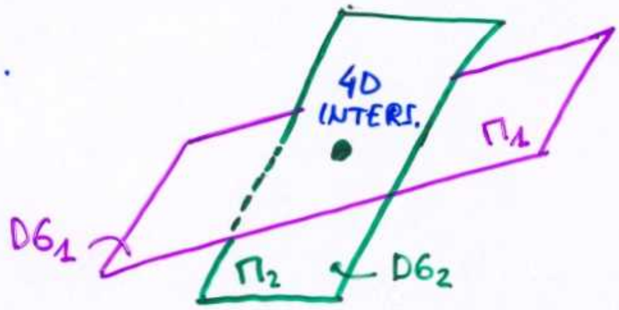
    GETTING JUST THE STANDARD MODEL

  - SUSY MODEL BUILDING

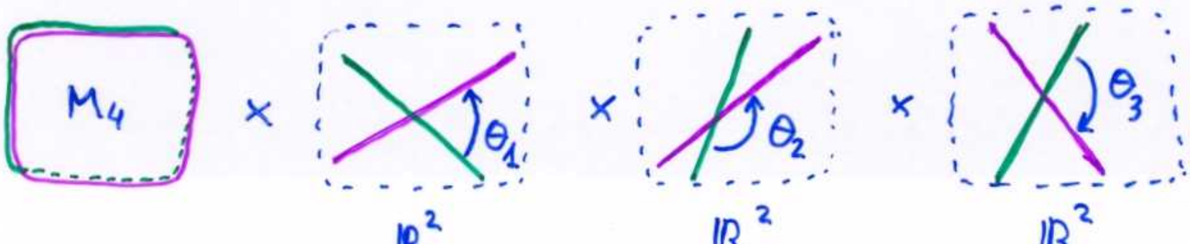
    ATTEMPTS TO GET JUST THE MSSM
- CONCLUSIONS

INTERSECTING DBRANE MODELS [BERKOOZ, DOUGLAS, LEIGH]

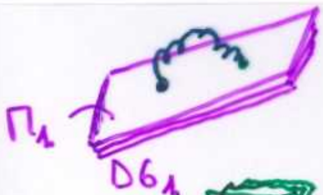
- D-BRANES INTERSECTING AT ANGLES CAN LEAD TO CHIRAL FERMIONS
- THE PROTOTYPICAL CONFIGURATION TO GET 4D CHIRAL FERMIONS IS TWO SETS OF TYPE IIA D6-BRANES IN FLAT 10D, INTERSECTING OVER A 4D SPACE.



ANOTHER EQUIVALENT PICTURE $M_{10} = M_4 \times \mathbb{R}^2 \times \mathbb{R}^2 \times \mathbb{R}^2$

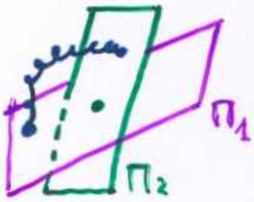


THREE OPEN STRING SECTORS



$6_1 \rightsquigarrow 6_1$ $U(N_1)$ GAUGE BOSONS [+ STUFF] PROPAGATING ON Π_1

$6_2 \rightsquigarrow 6_2$ $U(N_2)$ GAUGE BOSONS [+ STUFF] PROPAGATING ON Π_2

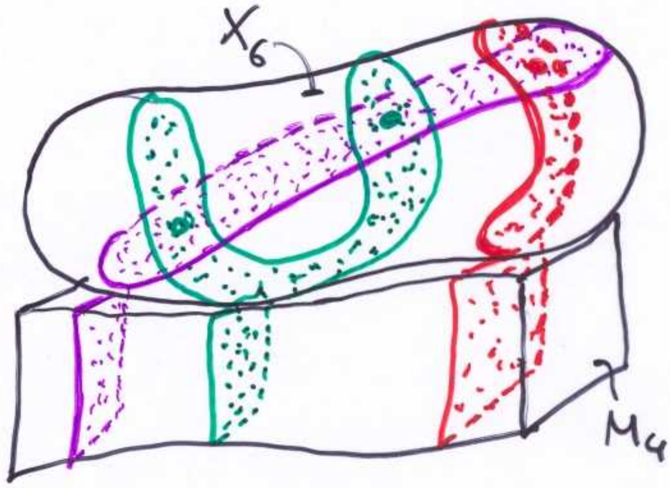


$6_1 \rightsquigarrow 6_2$ 4D CHIRAL FERMION IN $(N_1, \overline{N_2})$
[+ SCALARS, SEE LATER]
LOCALIZED AT 4D INTERSECTION

INTERSECTING BRANE WORLDS

CONSIDER THE FOLLOWING LARGE CLASS OF MODELS: TYPE IIA THEORY ON $M_4 \times X_6$ WITH SEVERAL STACKS OF N_a $D6_a$-BRANES WRAPPED ON 3-CYCLES $\Pi_a \subset X_6$

SPECTRUM



4D GRAVITY

4D GAUGE $\prod_a U(N_a)$

[+ PARTNERS]

4D CH. FERMIONS

$\sum_{a,b} I_{ab} \; (\square_a, \bar{\square}_b)$

$I_{ab} = [\Pi_a] \cdot [\Pi_b]$ = # INTERSECTIONS

[+ SCALARS]

OBS CHIRAL... ANOMALIES?

STRING THEORY CONSISTENCY CONDITIONS

EQS. OF MOTION FOR $C_7 \Rightarrow$ GAUSS LAW

OVERALL CHARGE MUST VANISH IN COMPACT X_6

$$\sum_a N_a \, [\Pi_a] = 0$$

$\Rightarrow$ AUTOMATIC VANISHING OF NONAB. ANOMALIES

MIXED $U(1)$ ANOMALIES CANCEL VIA A GREEN SCHWARZ MECHANISM

$\Rightarrow$ SOME $U(1)$'S GET MASSIVE

MODEL BUILDING WITH T^6

[BERLIN GROUP, MADRID GROUP]

- CONSIDER THE SIMPLEST INTERNAL SPACE

  SIX-TORUS $\quad T^6 = T^2 \times T^2 \times T^2$

  WE TAKE OUR D6'S TO WRAP A 1-CYCLE ON EACH T^2, WRAP n^i TIMES HORIZONTALLY AND m^i TIMES VERTICALLY, ON i^{TH} T^2

EX:

$(1,1) \qquad (1,-2) \qquad (0,1)$

- THE N_a $D6_a$-BRANES HAVE WRAPPING NUMBERS $(n_a^i, m_a^i) \to$ DETERMINE THE 3-CYCLE Π_a

  $D6_a$ AND $D6_b$ INTERSECT A NUMBER OF TIMES

$$I_{ab} = (n_a^1 m_b^1 - m_a^1 n_b^1) \times (n_a^2 m_b^2 - m_a^2 n_b^2) \times (n_a^3 m_b^3 - m_a^3 n_b^3)$$

- GAUSS LAW: $\sum_a N_a [\Pi_a] = 0$

  GIVES CONSTRAINTS

$$\sum_a N_a n_a^1 n_a^2 n_a^3 = 0$$

$$\sum_a N_a n_a^1 n_a^2 m_a^3 = 0; \text{ ETC}$$

$$\sum_a N_a n_a^1 m_a^2 m_a^3 = 0; \text{ ETC}$$

$$\sum_a N_a m_a^1 m_a^2 m_a^3 = 0$$

- SPECTRUM

  GAUGE GROUP $\quad \bigotimes_a U(N_a)$ + PARTNERS

  CH. FERMIONS $\quad \bigoplus_{a,b} I_{a,b} \, (\square_a, \bar{\square}_b)$

OBS: RR TADPOLES $\Rightarrow$ ANOMALIES CANCEL

OBS SUPERSYMMETRY

GENERICALLY, EVEN EN FLAT 10D, THE SYSTEM OF TWO SETS OF D6-BRANES BREAKS ALL SUSYS. IN FACT, THE $6_1 \rightsquigarrow 6_2$ SPECTRUM NOTICES BOTH BRANES AND IS GENERICALLY NONSUSY. LIGHTEST FIELDS ARE... [IN $M_S = 1$]

4D WEYL FERMION $\quad M^2 = 0$

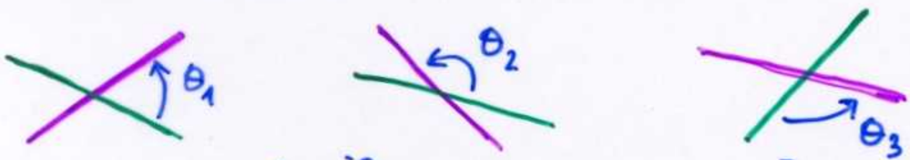
COMPLEX SCALARS $\quad M^2 = \frac{1}{2}(\theta_1 + \theta_2 - \theta_3)$

" $\quad M^2 = \frac{1}{2}(\theta_1 - \theta_2 + \theta_3)$

" $\quad M^2 = \frac{1}{2}(-\theta_1 + \theta_2 + \theta_3)$

" $\quad M^2 = 1 - \frac{1}{2}(\theta_1 + \theta_2 + \theta_3)$

THE REQUIREMENT THAT SOME SUPERSYMMETRY IS PRESERVED BY BOTH D6'S, IS, Π_1 AND Π_2 ARE RELATED BY A ROTATION IN THE SU(3) SUBGROUP OF SO(6)



$$\text{ROTATION} = \begin{bmatrix} e^{i\theta_1} & & & & & \\ & e^{-i\theta_1} & & & & \\ & & e^{i\theta_2} & & & \\ & & & e^{-i\theta_2} & & \\ & & & & e^{i\theta_3} & \\ & & & & & e^{-i\theta_3} \end{bmatrix}$$

EQUIVALENTLY, $\theta_1 \pm \theta_2 \pm \theta_3 = 0$

FOR SOME CHOICE OF SIGNS

COMMENTS ON SUPERSYMMETRY

ALL ABOVE MODELS ARE NON-SUPERSYMMETRIC

- ARGUMENT: WE START WITH TYPE IIA THEORY AND INTRODUCE D6-BRANES. RR TADPOLE CANCELLATION REQUIRES THAT, IN A SENSE, WE MUST INTRODUCE OBJECTS WITH OPPOSITE RR CHARGES ("ANTIBRANES")

  $\Rightarrow$ NON-SUPERSYMMETRIC CONFIGURATION

- EQUIVALENTLY: A SUPERSYMMETRIC CONFIG. OF D6-BRANES WOULD BE, AS A WHOLE, A BPS STATE.

  FOR BPS STATES, TENSION = CHARGE.

  SINCE RR TADPOLES IMPLY CHARGE = 0, THEN TENSION = 0, AND THE ONLY SUSY CONFIG. IS THE TYPE IIA VACUUM [NO BRANE AT ALL]

- $\rightsquigarrow$ WAY OUT:

  INTRODUCE OBJECTS WITH NEGATIVE TENSION AND NEGATIVE CHARGE, WHICH PRESERVE SAME SUSY AS D6 BRANES

  ORIENTIFOLD 6-PLANES

  INTERESTING EXTENSION OF ABOVE MODELS, WITH SEVERAL USES [SEE BELOW]

  E.G. ALLOW FOR SUPERSYMMETRIC MODEL BUILDING.

ISSUES ON NON-SUPERSYMMETRIC MODELS

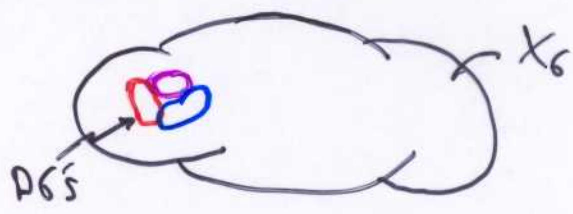
TACHYONS AT INTERSECTIONS

NON SUSY INTERSECTIONS MAY CONTAIN TACHYONIC SCALARS

- IT IS POSSIBLE TO CHOOSE GEOMETRY TO GET NON SUSY NON TACHYONIC CONFIGURATIONS
  [METASTABLE CONFIGURATIONS ]
- POSSIBLE PHENOMENOLOGICAL APPLICATION
  TACHYON AS HIGGS

HIERARCHY PROBLEM

- MODELS IN T^6 SUFFER A HIERARCHY PROBLEM.
  LACK OF SUSY REQUIRES $M_s \sim TeV$ TO AVOID HIERARCHY $M_W \ll M_s$
  TO GENERATE LARGE M_P, WE NEED LARGE VOL.
  BUT D6 BRANES SPAN ALL DIRECTIONS IN T^6
  $\Rightarrow$ TOO LIGHT KK REPLICAS OF SM GAUGE BOSONS IF ONE ATTEMPTS LARGE M_P, LOW M_S.
- MILD PROBLEM, VERY SPECIFIC OF T^6 MODELS.
  NOT PRESENT IN MORE GENERAL CY MODELS, E.G. WITH D6 BRANES WRAPPED ON SMALL 3CYCLES IN A LARGE CY_3.



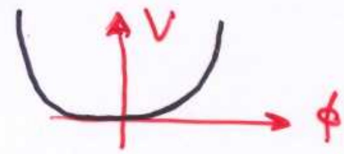
NS-NS TADPOLES

- NON SUSY MODELS HAVE UNCANCELLED TADPOLES FOR CERTAIN NS NS FIELDS
  E.G. GRAVITON, DILATON, MODULI
- CONTRARY TO RR TADPOLES, DO NOT SIGNAL AN INCONSISTENCY OF THE THEORY.
  FIELDS HAVE KINETIC TERMS. TADPOLES MEAN THAT SOLUTION TO EQ. OF MOTION INVOLVE NONTRIVIALLY KINETIC TERM.
  TADPOLE BALANCED AGAINST KINETIC
- NAMELY, TADPOLE MEANS THAT FLAT M_4 SPACE AND CONSTANT DILATON, ETC ARE NOT SOLUTIONS OF EQ. OF MOTION; E.G. BECAUSE OF COSMOLOGICAL CONSTANT FROM D6 BRANE TENSION.
  → REDEFINE VACUUM CONFIGURATION
  VERY INVOLVED IN PRACTICE [DUDAS, MOURAD; BLUMENHAGEN, FONT]
  CURVATURE, NAKED SINGUS, ...
- PROPOSALS
  - STICK TO N=1 SUSY MODELS [SEE LATER]
    NICE, BUT ISSUES EVENTUALLY RE-ARISE AT SUSY BREAKING STAGE
  - IGNORE THE ISSUE OF NS NS TADPOLES !

⇒ REVIEW BEST MODELS IN EACH PHILOSOPHY.

A NICE FIELD THEORY ANALOGY [BACHAS]

CONSIDER A 4D $U(1)$ GAUGE FIELD THEORY, WITH CHARGED FERMIONS AND A CHARGED CMPLX. SCALAR ϕ WITH $V(\phi) = \lambda(\phi^*\phi)^2$



SOLUTION TO CLASSICAL E.O.M. $\langle\phi\rangle = 0$

→ PHYSICS IS: UNBROKEN $U(1)$, MASSLESS FERMIONS, MASSLESS ϕ, ...

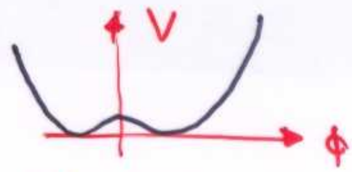
CONFIGURATION NOT A SOLUTION OF CLASSICAL E.O.M.

$\langle\phi\rangle = v$

→ PHYSICS IS: SPONTANEOUSLY BROKEN $U(1)$, MASSIVE FERMIONS, ALSO TADPOLE FOR ϕ.

WHICH IS CLOSEST TO REAL PHYSICS OF SYSTEM?

QUANTUM CORRECTIONS GENERATE A MASS TERM FOR ϕ, AND A VEV DEVELOPS



BEST APPROXIMATION TURNS OUT TO BE NOT A SOLUTION OF CLASSICAL E.O.M.

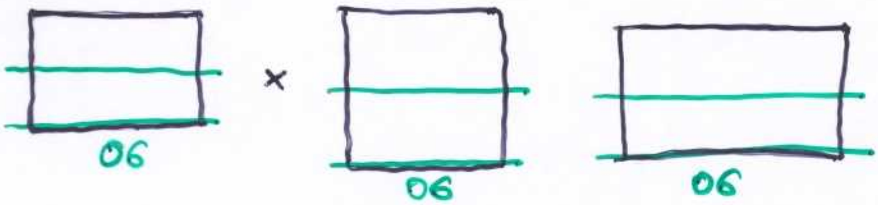
ANALOGOUSLY, "PERHAPS THE PRICE FOR GETTING A GOOD DESCRIPTION OF THE LOW ENERGY WORLD FROM STRING THEORY MAY BE TO ALLOW FOR SMALL METRIC, DILATON, MODULI TADPOLES IN THE CLASSICAL DESCRIPTION OF THE GROUNDSTATE"

[ESTIMATE OF SMALL, ONE PART IN 10^{30}]

DETOUR : ORIENTIFOLD PLANES

- CONSIDER TYPE IIA THEORY ON X_6, AND MOD OUT BY Ω [WORLDSHEET ORIENTATION REVERSAL] TIMES A Z_2 SYMMETRY OF X_6, g.

EX: T^6 MODDED OUT BY Ωg, WITH $g: z_i \to \bar{z}_i$



SET OF FIXED POINTS OF g IS AN ORIENTIFOLD PLANE

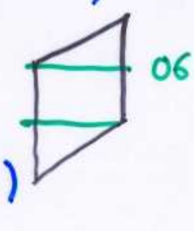
ABOVE CASE : x_i = ARBITRARY, $y_i = 0, R/2 \to$ O6 PLANE WRAPPED ON $(1,0) \times (1,0) \times (1,0)$

- NOVELTIES :
  - IF WE INTRODUCE D6 BRANES ON $[\Pi_a]$, WE MUST INTRODUCE ORIENTIFOLD IMAGES UNDER g D6 BRANE ON IMAGE 3-CYCLE $[\Pi_{a^*}]$

EX: FOR $g: z_i \to \bar{z}_i$

$$N_a\,(n_a^i, m_a^i) \overset{\Omega g}{\longleftrightarrow} N_a\,(n_a^i, -m_a^i)$$

OR FOR TILTED TORI



$$N_a\,(n_a^i, m_a^i) \overset{\Omega g}{\longleftrightarrow} N_a\,(n_a^i, -n_a^i - m_a^i)$$

[DEFINING $\tilde{m}_a = m_a + n_a/2$ $\quad (n_a, \tilde{m}_a) \leftrightarrow (n_a, -\tilde{m}_a)$

A TECHNICAL DETAIL

- DIFFICULTY IN GETTING S.M. WITH ODD NUMBER OF FAMILIES IN T^6 MODELS WITH RECTANGULAR TWO-TORI

3(3,2) SHOULD COME FROM $I_{ab} + I_{ab^*}$

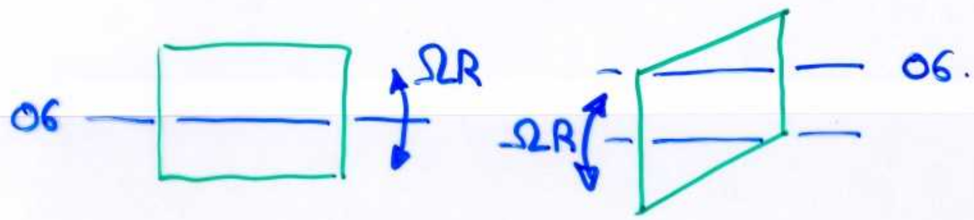
$$I_{ab} = \prod_{i=1}^{3} (n_a^i m_b^i - n_b^i m_a^i) \qquad (n_b, m_b)$$

$$\updownarrow$$

$$I_{ab^*} = \prod_{i=1}^{3} (n_a^i (-m_b^i) - n_b^i m_a^i) \qquad (n_b, -m_b)$$

$\Rightarrow$ $I_{ab} + I_{ab^*}$ = EVEN

- DIFFICULTY SOLVED BY THE BERLIN GROUP OBSERV. THAT TWO-TORI TILTED BY A DISCRETE AMOUNT ALLOW FOR ΩR QUOT.



ACTION ON $(n_b, m_b) \rightarrow (n_b, -m_b - n_b)$

ALLOWS $I_{ab} + I_{ab^*}$ = EVEN, ODD

NOTATION: LABEL WRAPPING NUMBERS AS $(n, \tilde{m})$ WITH $\tilde{m} = m + \frac{1}{2} n$

EX: $(1, \tilde{\frac{1}{2}})$ IS $n=1, m=0$

- PROPERTIES OF O6PLANES

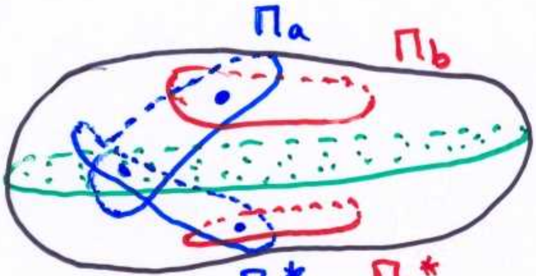
PRESERVE SAME SUSY AS D6'S ON SAME 3CYCLE

HAVE NEGATIVE TENSION, CARRY NEGATIVE RR CHARGE [EQUAL TO -4 IN D6 CHARGE UNITS]

$\Rightarrow$ MODIFY RR TADPOLE CONDITION

$$\Sigma_a N_a[\Pi_a] + \Sigma_a N_a[\Pi_a^*] - 4[\Pi_{O6}] = 0$$

PICTURE:

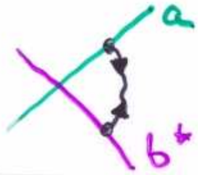


- OPEN STRING SPECTRUM NOW CONTAINS NEW SECTORS

aa $U(N_a)$

$ab+ba+$
$+a^*b^*+b^*a^*$ $I_{ab}\,(N_a,\overline{N}_b)$

ab^*+b^*a+
$+a^*b+ba^*$ $I_{ab^*}\,(N_a,N_b)$



aa^*+a^*a $n_{\boxminus}\,\boxminus_a + n_{\square\square}\,\square\square_a$ WITH $n_{\boxminus}+n_{\square\square} = I_{aa^*}$

AGAIN: NEW RR TADPOLE CANCELLATION CONDITIONS GUARANTEE THE CANCELLATION OF 4D CHIRAL ANOMALIES WITH NEW SPECTRUM

BEST MODEL IN NON-SUSY SETUP

[FORGET/ POSTPONE NSNS TADPOLS]

GETTING "JUST" THE STANDARD MODEL

[IBAÑEZ, MARCHESANO, RABADAN]

- ALL MODELS FROM D6-BRANES ON ANY X_6 WITHOUT O6-PLANES, AND LEADING TO S.M. GROUP, CONTAINS SIX EXTRA FERMIONS IN $SU(2)_W$ DOUBLET REPR. BEYOND S.M. CONTENT

RECALL THAT RR TADPOLE CANCELLATION REQUIRES # FUND = # $\overline{\text{FUND}}$ EVEN FOR SU(2) IN S.M. THEORIES

Q_L	$3(3,\bar{2})$	9 $\overline{\text{FUND}}$'S
L	$3(\bar{1},2)$	3 FUNDS

$\Rightarrow$ STILL NEED SIX SU(2) FUNDS $\rightarrow$ EXOTIC BEYOND S.M.

IMR SOLUTION

IN MODELS WITH O6-PLANES, SPECTRUM CONTAINS REPS. $(N_a, \bar{N}_b)$ AND (N_a, N_b)

PROPOSAL

Q_L	$2(3,\bar{2})$	6 $\overline{\text{FUND}}$
Q_L	$(3,2)$	3 FUND $\leftarrow$ THANKS TO PRESENCE OF O6
L	$3(\bar{1},2)$	3 FUND

NO EXTRA MATTER BEYOND S.M IS IN PPLE NEEDED

GENERAL IDEA

- CONSIDER IIA THEORY ON X_6 WITH O6-PLANES
- INTRODUCE FOUR STACKS OF D6-BRANES LEADING TO

$$U(3)_a \times U(2)_b \times U(1)_c \times U(1)_d$$

WITH INTERSECTION NUMBERS

$$I_{ab} = 1 \quad I_{ab^*} = 2 \quad I_{ac} = -3 \quad I_{ac^*} = -3$$

$$I_{bd} = 0 \quad I_{db^*} = -3 \quad I_{cd} = -3 \quad I_{cd^*} = 3$$

OBS: CHECK THAT # FUND = # $\overline{\text{FUND}}$ EVEN FOR $SU(2)$, $U(1)$

SPECTRUM (BEFORE ANALYSIS OF $U(1)$'S)

$$U(3) \times U(2) \times U(1) \times U(1) \qquad (R_a, R_b)_{q_c, q_d}$$

$$(3,\bar{2})_{0,0} + 2(3,2)_{0,0} + 3(\bar{3},1)_{1,0} + 3(\bar{3},1)_{-1,0} +$$

$$+ 3(1,\bar{2})_{0,-1} + 3(1,1)_{-1,1} + 3(1,1)_{1,1}$$

A LINEAR COMBINATION OF $U(1)$'S PLAYS THE ROLE OF HYPERCHARGE

$$Q_Y = \tfrac{1}{6} Q_a - \tfrac{1}{2} Q_c + \tfrac{1}{2} Q_d$$

SPECTRUM UNDER $SU(3)_a \times SU(2)_b \times U(1)_Y$ IS JUST S.M.

$$3 \times (Q_L, U, D, L, E, \nu_R)$$

NEED TO MAKE SURE THAT Q_Y DOES NOT COUPLE TO RR 2-FORMS

[AND HOPEFULLY THAT REMAINING $U(1)$'S DO!]

EXPLICIT REALIZATIONS OF THESE INTERSECTION NUMBERS EXIST!

IMR: TOROIDAL ORIENTIFOLD $T^6/\Omega R$

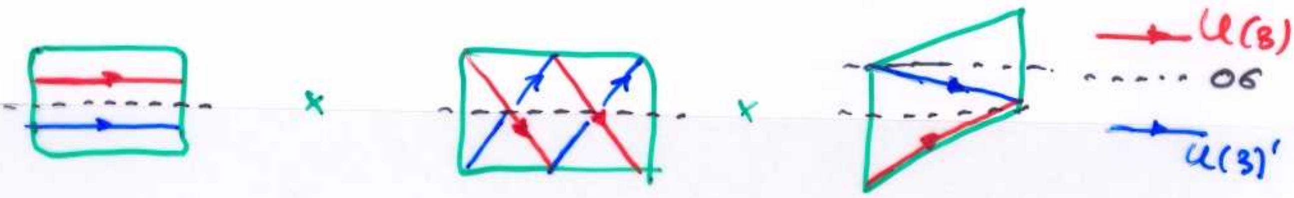
INFINITE FAMILIES OF EXAMPLES

- WITH JUST THE S.M. CHIRAL CONTENT

[PLUS ADJOINTS IN $6_a 6_a$ SECTORS]

EX:

N_a	(n_a^1, m_a^1)	(n_a^2, m_a^2)	$(n_a^3, \tilde{m}_a^3)$
3	(1,0)	(2,−1)	(1, 1/2)
2	(0,1)	(1,0)	(1, 3/2)
1	(1,−3)	(1,0)	(0,1)
1	(1,0)	(0,1)	(1, 3/2)



OBS ADDITIONAL D6 VOLUME "$N=4$" PARTNERS

⇒ NEED E.G. RADIATIVELY GENERATED MASSES

SEARCH FOR SUSY MODELS IS ON!

SEARCH FOR MORE GENERAL GEOMETRIES IS ON!

EX BY BERLIN GROUP IN ORIENT. QUINTIC CY

BY A.U. IN NON-CY GEOMETRIES

BEST MODELS IN SUSY SETUP

[FORGET/ POSTPONE SUSY BREAKING]

[CVETIC, SHIU, A.U.]

MAIN OBSERVATION IS THAT D6 BRANES AT ANGLES [I.E. GENERATING 4D CHIRALITY] GENERATE NONZERO RR CHARGE ALONG SEVERAL INDEPENDENT HOMOLOGY CLASSES

(n_a, m_a) , $(n_a, -m_a)$

$$[\Pi_a] = n_a^1 n_a^2 n_a^3 [a_1][a_2][a_3] + m_a^1 m_a^2 m_a^3 [a_1][b_2][b_3] + \dots [b_1][a_2][b_3] + \dots [b_1][b_2][a_3]$$

WE NEED TO CANCEL RR CHARGES WITH O6 PLANES [PRESERVE SAME SUSY AS D6'S BUT CARRY OPPOSITE RR CHARGES]

NEED MODELS WITH AT LEAST MORE THAN ONE KIND OF O6-PLANE

$\Rightarrow$ LEADS TO TOROIDAL ORBIFOLDS (MOD ΩR)

$T^6/\{\Omega R, \Omega R'\}$

BUT GROUP LAW $\Rightarrow$ $\Omega R\, \Omega R' = RR'$

SO $(T^6/RR')/\Omega R$

MODEL BUILDING WITH THE $T^6/\mathbb{Z}_2\times\mathbb{Z}_2$ ORIENTIFOLD

[CVETIC, SHIU, A.U]

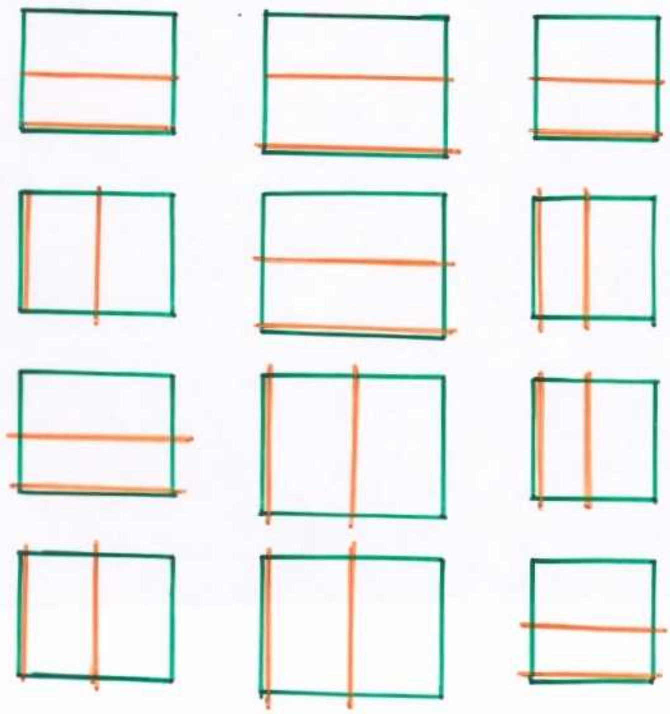
CONSIDER TYPE IIA THEORY ON T^6 MODDED BY

$$\theta: (z_1, z_2, z_3) \to (-z_1, z_2, -z_3)$$

$$\omega: (z_1, z_2, z_3) \to (z_1, -z_2, -z_3)$$

$$\Omega R: (z_1, z_2, z_3) \to (\bar{z}_1, \bar{z}_2, \bar{z}_3)$$

MAIN FEATURE: RICH STRUCTURE OF O6-PLANES



ΩR — O6 $[\Pi_{\Omega R}] = 8[a_1][a_2][a_3]$

$\Omega R\theta$ — O6 $[\Pi_{\Omega R\theta}] = 8[b_1][a_2][b_3]$

$\Omega R\omega$ — O6 $[\Pi_{\Omega R\omega}] = 8[a_1][b_2][b_3]$

$\Omega R\theta\omega$ — O6 $[\Pi_{\Omega R\theta\omega}] = 8[b_1][b_2][a_3]$

ENOUGH TO ALLOW INTRODUCTION OF D6 BRANES AT ANGLES AND PRESERVE SUPERSYMMETRY.

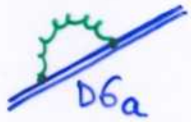
- INTRODUCE $D6_a$-BRANES WITH WRAPPINGS (n_a^i, m_a^i) AND THEIR IMAGES [UNDER $\theta, \omega, \Omega R$]
- IMPOSE GAUSS' LAW, I.E. CHARGE CANCELLATION

$$\sum_a N_a [\Pi_a] + \text{IMAGES} + [\Pi_{O6}] = 0$$

$\Rightarrow$ BUNCH OF CONSTRAINTS ON N_a, n_a^i, m_a^i, SIMILAR TO ABOVE T^6 CASE.

FINAL SPECTRUM

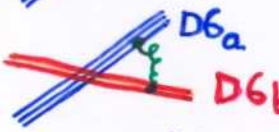
AFTER WORKING OUT MANY DETAILS, THE MASSLES SPECTRUM FOLLOWS FROM THE VERY SIMPLE RULES

- 

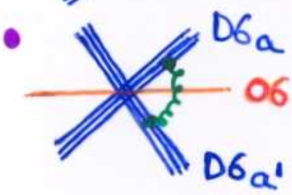
$6_a \sim 6_a$ $U(N_a)$ GAUGE GROUP [PLUS STUFF]

- 

$6_a \sim 6_b$ $I_{ab}\,(N_a, \bar{N}_b)$ $I_{ab} = [\Pi_a]\cdot[\Pi_b]$

- 

$6_a \sim 6_{b'}$ $I_{ab'}\,(N_a, N_b)$ $I_{ab'} = [\Pi_a]\cdot[\Pi_{b'}]$

- 

$6_a \sim 6_{a'}$ $n_{\tiny\text{A}}\; \text{A}_a + n_{\tiny\text{S}}\; \text{S}_a$

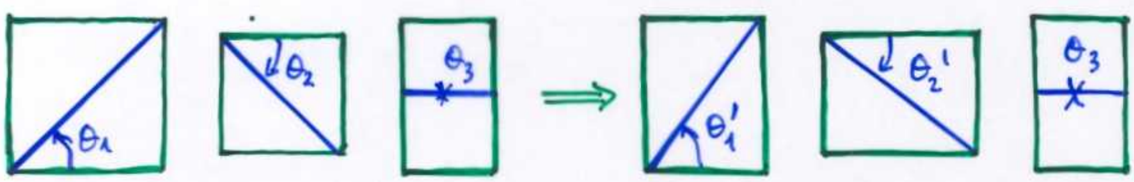
$$\begin{matrix} n_{\text{S}} \\ n_{\text{A}} \end{matrix} = -\frac{1}{2}\left[I_{aa'} \mp 4\, I_{a,O6} \right]$$

THESE CHIRAL FERMIONS COME WITH MASSLESS SCALAR PARTNERS IF THE MODEL IS SUSY

SUSY MODEL BUILDING: MAKE SURE THAT ALL STACKS SATISFY $\theta_1 + \theta_2 + \theta_3 = 0$

WHERE $\theta_i = \text{ARCTAN}\left[\frac{m^i}{n^i} \left(\frac{R_2}{R_1}\right)^i \right]$

THIS IMPOSES CONSTRAINTS ON THE COMPLEX STRUCTURE MODULI OF THE T^2's $\chi_i = (R_2/R_1)_i$

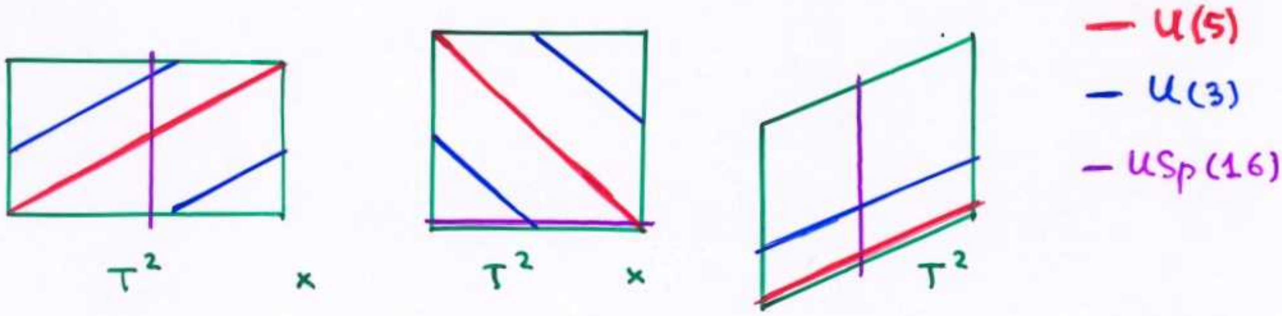


SUSY CONFIGURATION NONSUSY CONFIGURATION

A 4-FAMILY SUSY-GUT EXAMPLE

LET US PICK OUR D6-BRANE STACKS AS

N_a	$(n_a^1, m_a^1) \times (n_a^2, m_a^2) \times (n_a^3, m_a^3)$	
• 10	$(1,1) \times (1,-1) \times (1,0)$	$\to U(5)$
• 6	$(1,1) \times (1,-1) \times (1,0)$	$\to U(3)$
• 16	$(0,1) \times (1,0) \times (0,-1)$	$\to USp(16)$



THE MODEL IS SUPERSYMMETRIC FOR

$$\mathrm{ARCTAN}\, \chi_1 - \mathrm{ARCTAN}\, \chi_2 + \mathrm{ARCTAN}\,(\chi_3/2) = 0$$

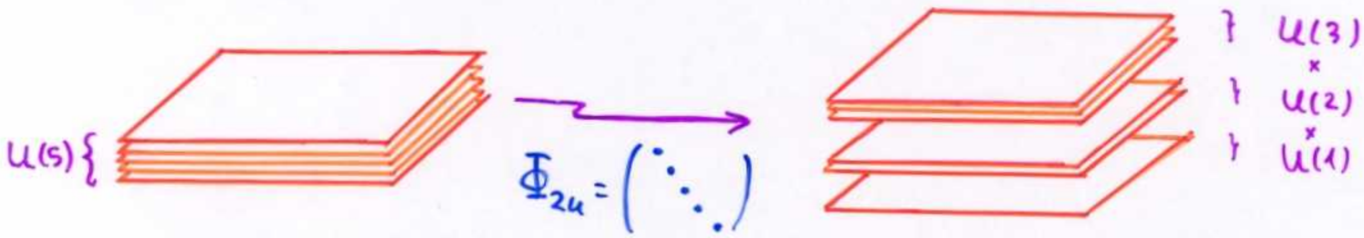
SPECTRUM: $U(5) \times U(3) \times USp(16)$

$$3(24+1,1,1) + 3(1,8+1,1) + 3(1,1,119+1) +$$

$$+ 4(\overline{10},1,1) + \underbrace{(5,1,16) + 4(\overline{5},3,1)}_{\text{NET } 4\times\underline{5}} + (1,3,16) + 4(1,3,1)$$

IT IS A 4-FAMILY GUT MODEL

OBS THE ADJOINT $\underline{24}$ IS A MODULUS, FLAT DIRECTION, PARAMETRIZES SPLITTING OF STACK OF 5 D6-BRANES.



A 3-FAMILY SM-LIKE EXAMPLE

LET US PICK D6-BRANE STACKS AS

	N_a	$(n_a^1, m_a^1) \times (n_a^2, m_a^2) \times (n_a^3, m_a^3)$	
• A_1	8	$(0,1) \times (0,-1) \times (2,-1)$	$\to U(1)$
	2	$(1,0) \times (1,0) \times (2,-1)$	
• B_1	4	$(1,0) \times (1,-1) \times (1,1)$	$\to U(2)$
	2	$(1,0) \times (0,1) \times (0,-1)$	
• C_1	6 + 2	$(1,-1) \times (1,0) \times (1,0)$	$\to U(3) \times U(1)$
	4	$(0,1) \times (1,0) \times (0,-1)$	

SUPERSYMMETRIC FOR $\chi_1 : \chi_2 : \chi_3 = 1 : 3 : 2$

MOST $U(1)$'S ARE ANOMALOUS, AND GET MASSIVE DUE TO THE GREEN-SCHWARZ MECHANISM

A SUITABLE ANOMALY-FREE LINEAR COMBINATION PLAYS THE ROLE OF HYPERCHARGE.

UNDER THE SM-LIKE GAUGE GROUP, THE SPECTRUM IS

$$SU(3) \times SU(2) \times U(1)_Y \times \ldots$$

$B_1 C_1$ $\quad (3,\bar{2})_{1/6} + (1,\bar{2})_{-1/2} \to Q_L, L$

$B_1 C_1'$ $\quad 2(3,2)_{1/6} + 2(1,2)_{-1/2} \to Q_L, L$

$A_1 C_1$ $\quad 3(\bar{3},1)_{1/3} + 3(\bar{3},1)_{-2/3} \to u, D$

$\quad 3(1,1)_1 + 3(1,1)_0 \qquad E, \nu_R$

$A_1 B_1$ $\quad 6(1,\bar{2})_{1/2} + 6(1,\bar{2})_{-1/2} \to H_u, H_D$

+ CHIRAL EXOTIC MATTER, NOT POSSIBLE TO GET RID OF

$(\bar{3},1)_{1/3} + (\bar{3},1)_{-2/3} + 2(3,1)_{1/6} + (1,1)_1 + (1,1)_0 +$

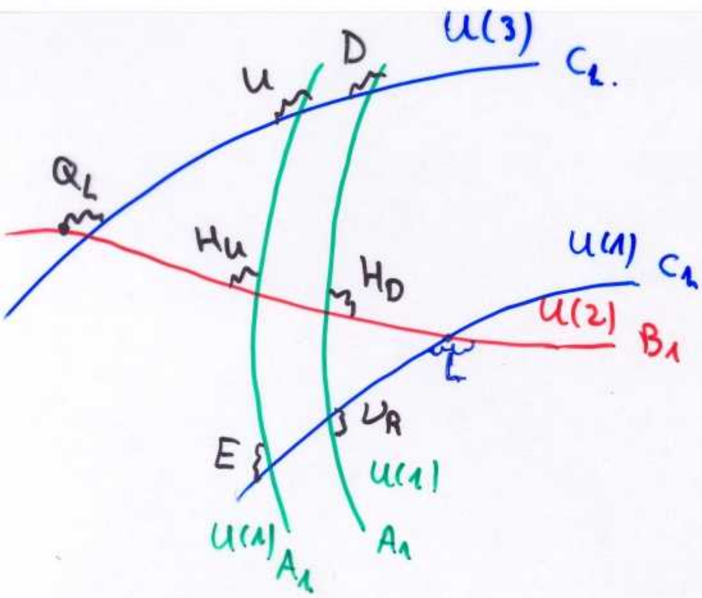
$+ 4(1,2)_0 + 2(1,1)_{-1/2} + 2(1,1)_0 + 2(1,3)_0$

BUT GOOD ENOUGH AS A TOY MODEL.

COMPLETE SPECTRUM

Sector	$U(3)\times U(2)\times USp(2)\times USp(2)\times USp(4)$	Q_3	Q_1	Q_2	Q_8	Q_8'	Q_Y	Q_8-Q_8'	Field
A_1B_1	$3\times 2\times(1,\overline{2},1,1,1)$	0	0	-1	±1	0	$\pm\frac{1}{2}$	±1	H_U, H_D
	$3\times 2\times(1,\overline{2},1,1,1)$	0	0	-1	0	±1	$\pm\frac{1}{2}$	∓1	H_U, H_D
A_1C_1	$2\times(\overline{3},1,1,1,1)$	-1	0	0	±1	0	$\frac{1}{3},-\frac{2}{3}$	$1,-1$	U, D
	$2\times(\overline{3},1,1,1,1)$	-1	0	0	0	±1	$\frac{1}{3},-\frac{2}{3}$	$-1,1$	U, D
	$2\times(1,1,1,1,1)$	0	-1	0	±1	0	$1,0$	$1,-1$	E, ν_R
	$2\times(1,1,1,1,1)$	0	-1	0	0	±1	$1,0$	$-1,1$	E, ν_R
B_1C_1	$(3,\overline{2},1,1,1)$	1	0	-1	0	0	$\frac{1}{6}$	0	Q_L
	$(1,\overline{2},1,1,1)$	0	1	-1	0	0	$-\frac{1}{2}$	0	L
B_1C_2	$(1,2,1,1,4)$	0	0	1	0	0	0	0	
B_2C_1	$(3,1,2,1,1)$	1	0	0	0	0	$\frac{1}{6}$	0	
	$(1,1,2,1,1)$	0	1	0	0	0	$-\frac{1}{2}$	0	
B_1C_1'	$2\times(3,2,1,1,1)$	1	0	1	0	0	$\frac{1}{6}$	0	Q_L
	$2\times(1,2,1,1,1)$	0	1	1	0	0	$-\frac{1}{2}$	0	L
B_1B_1'	$2\times(1,1,1,1,1)$	0	0	-2	0	0	0	0	
	$2\times(1,3,1,1,1)$	0	0	2	0	0	0	0	

SCHEMATIC PICTURE OF THE RELEVANT BRANES



SUPERSYMMETRY BREAKING?

WE SAID MODELS ARE SUPERSYMMETRIC FOR A PARTICULAR CHOICE OF TORUS PARAMETERS χ_i.

BUT $(R_2/R_1)_i$ ARE MODULI OF THE COMPACTIFICATION

Q1 • IS SUPERSYMMETRY BROKEN IF WE CHANGE χ_i FROM THESE CHOICES?

Q2 • WHAT IS THE EFFECT ON THE 4D FIELD THEORY?

IN SHORT, χ_i TURN OUT TO COUPLE TO 4D GAUGE THEORY AS FAYET-ILIOPOULOS PARAMETERS. FOR A GIVEN BRANE $D6_a$, ITS $U(1)_a$ GAUGE MULTIPLET GETS AN FI $\sim \xi_a = \theta_1^a + \theta_2^a + \theta_3^a$ [KACHRU, MCGREEVY; WITTEN]

A2 • THERE ARISES A D-TERM POTENTIAL

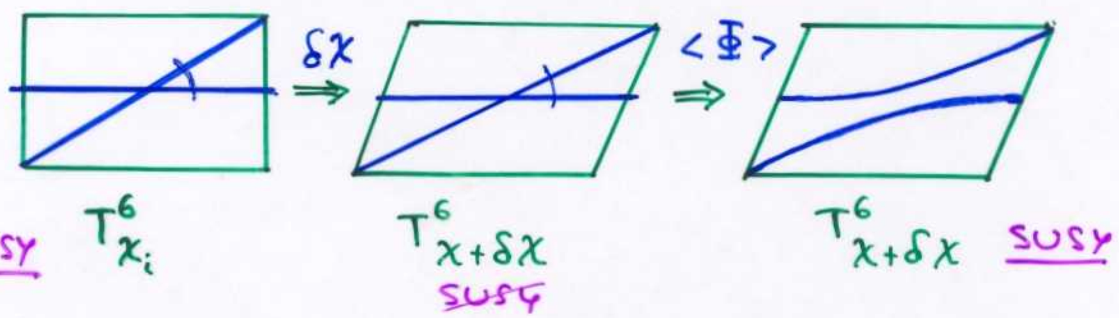
$$\mathcal{L} \sim [\, \Phi^* (T^A)\, \Phi - \xi_a]^2$$

WHICH ALSO INVOLVES THE CHARGED FIELDS Φ, LIVING AT INTERSECTIONS.

THE F.I. TERM MAKES THEM TACHYONIC AND TRIGGERS A HIGGS MECHANISM $\Rightarrow$ BRANES RECOMBINE

A1. AT THE ENDPOINT OF TACHYONIC SCALAR CONDENSATION, GAUGE SYMMETRY IS BROKEN BUT SUPERSYMMETRY IS RESTORED.

SCHEM. PICTURE



CONCLUSIONS

- IMPORTANT ISSUES CONCERNING THE SUPERSYMMETRY (OR NOT) OF MODELS
- TWO POSSIBLE APRROACHES

  NON SUSY MODELS

  SUSY MODELS
- EXPLICIT MODELS ARE VERY CLOSE TO CHIRAL STRUCTURE OF S.M.

  HOWEVER, VERY RELEVANT ISSUES REMAIN OPEN QUESTIONS

  - NS NS TADPOLES
  - SUSY BREAKING
- MUCH WORK IS NEEDED ON:
  - PHENOMENOLOGICAL ISSUES
  - THESE THEORETICAL ISSUES

CHIRAL FOUR-DIMENSIONAL STRING COMPACTIFICATIONS WITH INTERSECTING D-BRANES

ANGEL M. URANGA

IFT/IMAFF, MADRID

PLAN OF THE TALKS

LECT. I BASICS OF INTERSECTING D-BRANE WORLDS

- INTRODUCTION : STRING PHENOMENOLOGY
- BRANE WORLDS AND D-BRANES
  - PROPERTIES OF D-BRANES
  - CHIRALITY FROM D-BRANES
- INTERSECTING BRANE - WORLDS
  - CONSTRUCTION AND EXAMPLES

LECT. II MORE ADVANCED CONSTRUCTIONS

- COMMENTS ON SUPERSYMMETRY
- ORIENTIFOLD PLANES
  - NON SUSY MODEL BUILDING
  - SUSY MODEL BUILDING

LECT. III D-BRANES AT SINGULARITIES

- D BRANES AT SINGULARITIES AND CHIRALITY
- D3 - AND D7 - BRANES AT ORBIFOLD SINGUS

  MSSM - LIKE CONSTRUCTIONS & EXAMPLES
- COMPARISON OF DIFF. CLASSES OF MODELS

FROM BRANES AT SINGULARITIES

TO PARTICLE PHYSICS

Angel M. Uranga

C.E.R.N.

In collaboration with

G. Aldazabal, L.E. Ibáñez, F. Quevedo

hep-th/0005067

OUTLINE

- MOTIVATION

  WHY BRANES?

  WHY SINGULARITIES?

- BRANES AT ORBIFOLD SINGULARITIES

  STACKS OF D3-BRANES

  INTRODUCTION OF D7-BRANES

- MODEL BUILDING

  (MS)SM FROM D3/D7 AT Z_3 SINGU.

  LEFT-RIGHT SYMMETRIC EXTENSIONS

  [GENERALIZATION TO OTHER SINGUS.]

- EMBEDDING INTO A COMPACT SPACE

  I.E. RECOVERING 4D-GRAVITY

- PHENOMENOLOGY

  GAUGE COUPLING UNIFICATION

  PROTON DECAY

  YUKAWA COUPLINGS

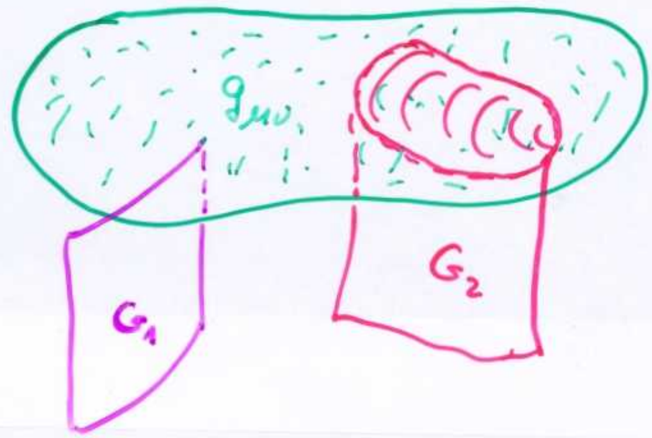
- CONCLUSIONS

WHY BRANES ?

BRANE WORLD SCENARIO [ARKANI-HAMED, DIMOPOULOS, DVALI].

PHENOMENOLOGY BEYOND THE STANDARD MODEL INVOLVING EXTRA DIMENSIONS IN A NEW FASHION

- GRAVITY PROPAGATES OVER ALL OF A HIGHER DIMENSIONAL SPACETIME [BULK]
- GAUGE INTERACTIONS ARE LOCALIZED, PROPAGATE ONLY ON CERTAIN SUBSPACES [BRANES]



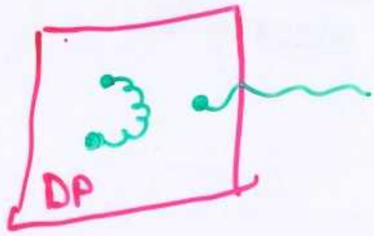
NATURAL EMBEDDING IN STRING THEORY USING DBRANES

- GAUGE FIELDS PROPAGATE ON THEIR WORLDVOLUME
- COUPLE CONSISTENTLY TO "BULK" FIELDS: GRAVITY, ETC [ANTONIADIS, ADD]

QUESTION: HOW TO CONSTRUCT REALISTIC BRANE MODELS IN STRING THEORY ?

[REALISTIC : CHIRAL
STANDARD MODEL GROUP
THREE FAMILIES
[$N=1$ SUSY, AT LEAST IN THIS TALK]]

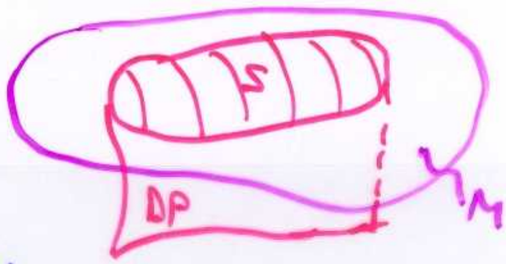
- DP-BRANES ARE EXTENDED SOLITONS OF STRING THEORY [WITH P SPATIAL DIMENSIONS] DEFINED AS SUBSPACES WHERE OPEN STRINGS CAN END. [POLCHINSKI]



- FIELDS PROPAGATING ON THE WORLDVOLUME CANNOT BE ADDED BY HAND

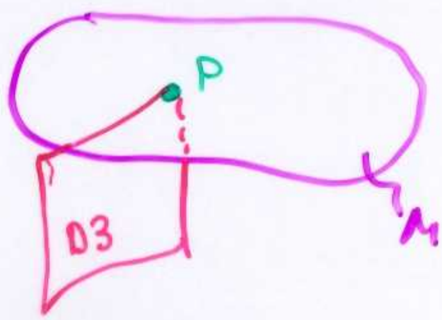
  THEY CORRESPOND TO FLUCTUATIONS OF THE THEORY AROUND THE SOLITON BACKGROUND, AND MUST BE COMPUTED BY QUANTIZING THE OPEN STRINGS ENDING ON THE BRANES

- WORLDVOLUME FIELD CONTENT FOR A D-BRANE WRAPPED ON A SUBSPACE S OF SPACETIME M, DEPENDS ON PROPERTIES OF S AND ON HOW IT IS EMBEDDED IN M



- SIMPLEST SITUATION

  D3-BRANES WITH FOUR FLAT DIMENSIONS, SITTING AT A POINT "P" IN TRANSVERSE SPACE

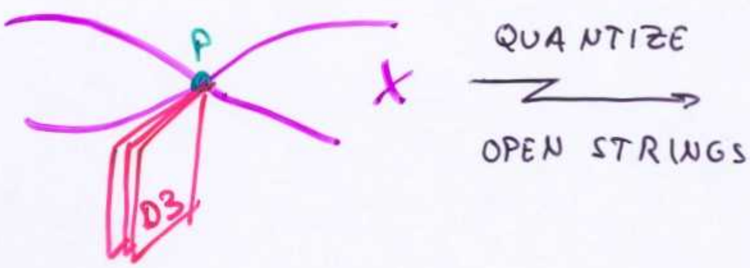


PROPERTIES OF WORLDVOLUME THEORY DEPEND ON THE <u>LOCAL GEOMETRY OF M AROUND P</u>

BOTTOM-UP APPROACH AT EMBEDDING STANDARD MODEL INTERACTIONS IN STRING THEORY

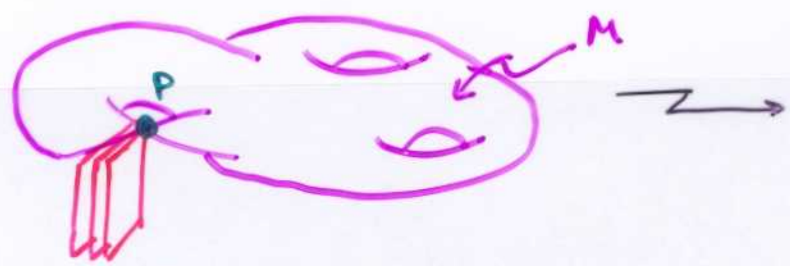
TWO STEP PROCEDURE:

I. LOOK FOR LOCAL GEOMETRIES $X \ni P$ SUCH THAT D3-BRANES AT P LEAD TO INTERESTING REALISTIC WORLDVOLUME FIELD THEORIES



4D GAUGE INT.
CHIRALITY
SM GROUP
THREE FAMILIES

II. IN ORDER TO RECOVER 4D GRAVITY [INSTEAD OF 10D IN NONCOMPACT MODELS X] EMBED LOCAL GEOMETRIES X IN A GLOBALLY COMPACT MODEL



4D GAUGE AS BEFORE
4D GRAVITY

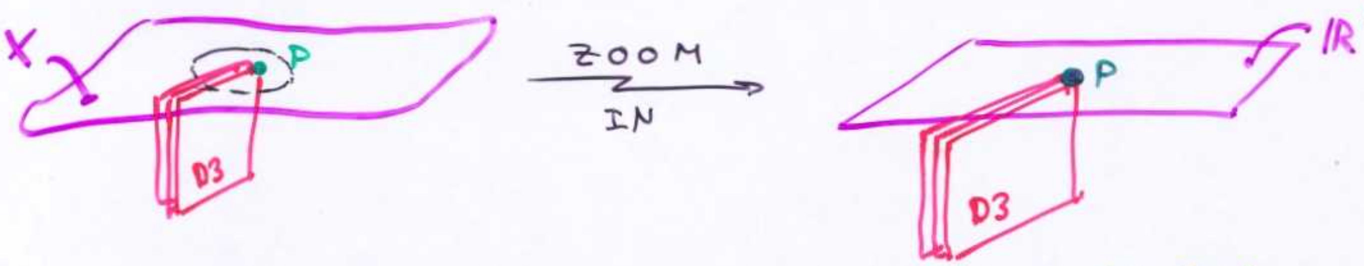
ADVANTAGES

- TECHNICALLY IT IS EASIER TO LOOK FOR X
- MANY PHENOMENOLOGICAL ISSUES CAN BE ADDRESSED JUST KNOWING X, THEY ARE INSENSITIVE TO THE DETAILS OF M.

WHY SINGULARITIES ?

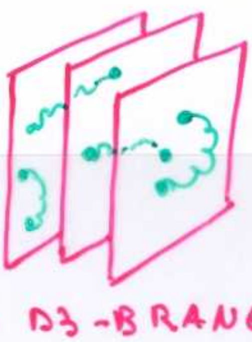
AN ESSENTIAL FEATURE OF PARTICLE PHYSICS IS CHIRALITY

IT CANNOT BE REPRODUCED IN STRING THEORY MODELS WITH D3-BRANES AT SMOOTH POINTS P



WORLDVOLUME FIELD THEORY IS SAME AS FOR D3-BRANES IN FLAT SPACE.
[FAR AWAY CURVATURE EFFECTS NOT FELT BY D3'S]

SPECTRUM: FOR n COINCIDENT D3-BRANES
[I.E. STRING ENDPOINTS CARRY A CHARGE WITH n POSSIBLE VALUES, "COLOR"]



n D3-BRANES

$U(n)$ GAUGE GROUP
- $U(1)^n$ FROM SAME BRANE STRINGS
- CHARGED BOSONS FROM DIFF. BRANES

6 REAL SCALARS IN ADJOINT
- $6n$ EIGENVALUES → BRANE POSITIONS
- GOLDSTONE BOSONS

4 MAJORANA FERMIONS IN ADJOINT
- GOLDSTINOS OF BROKEN SUSY'S

[IN FACT $N=4$ SUPERSYMMETRY → NONCHIRAL
$SU(4)$ R-SYMMETRY → ISOMETRIES OF $\mathbb{R}^6$.
SCALARS IN $\underline{6}$, FERMIONS IN $\underline{\underline{4}}$]

CHIRALITY MAY BE EASILY ACHIEVED BY LOCATING THE D3-BRANES AT SINGULAR POINTS IN TRANSVERSE SIX-DIMENSIONAL SPACE.

A LARGE [BUT NOT COMPLETE] CLASS OF SINGULARITIES, EASY TO TREAT IN STRING THEORY

ORBIFOLD SINGULARITIES

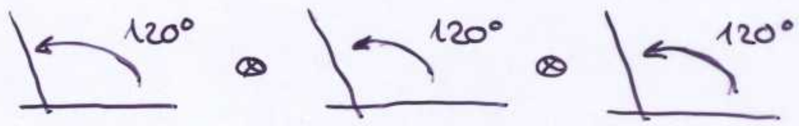
[DIXON, HARVEY VAFA, WITTEN]

1. TAKE FLAT 6D SPACE 

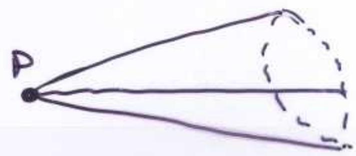
2. IDENTIFY POINTS RELATED BY A Z_N ROTATION

$$(z_1, z_2, z_3) \to (e^{2\pi i \frac{a_1}{N}} z_1, e^{2\pi i \frac{a_2}{N}} z_2, e^{2\pi i \frac{a_3}{N}})$$

EXAMPLE: Z_3 $\quad V = (a_1, a_2, a_3)/N = (1,1,-2)/3$

θ: 

ORIGIN = FIXED POINT OF Z_N ACTION, BECOMES A CONICAL SINGULARITY IN THE QUOTIENT



SPECTRUM

CLOSED STRING SECTOR

"UNTWISTED": • PROPAGATE IN TEN DIMENSIONS
• Z_N INVARIANT STATES OF FLAT SPACE THEORY
• GRAVITON, DILATON ETC.
• UNBROKEN SUSY IF $a_1 + a_2 + a_3 = 0$

"TWISTED": • LOCALIZED AT SINGULARITY
• SET OF SINGLET MULTIPLETS
• PARAMETRIZE SMOOTHING OF SINGU.
• BEHAVE LIKE AXIONS (PQ SYMMETRY)

IN ORDER TO OBTAIN GAUGE DEGREES OF FREEDOM

INTRODUCE n D3-BRANES AT ORIGIN IN $\mathbb{C}^3/\mathbb{Z}_N$

RECALL: IF WE WERE IN $\mathbb{C}^3$ [FLAT SPACE]

$U(n)$ GAUGE BOSONS $\qquad$ $U(n)$ VECTOR MULT.

ADJ. FERMIONS [$\underline{4}$ OF $SU(4)$] $\xrightarrow[\text{LANGUAGE}]{N=1 \text{ SUSY}}$ 3 ADJ. CHIRAL Φ_i

ADJ. SCALARS [$\underline{6}$ OF $SU(4)$] $\qquad$ [$\underline{3}$ OF $SU(3) \subset SU(4)$]

HOWEVER, WE ARE IN $\mathbb{C}^3$ MOD $\mathbb{Z}_N$ [$\subset SU(3) \subset SU(4)$]

PROJECT ONTO $\mathbb{Z}_N$ - INVARIANT STATES

- NON-TRIVIAL $\mathbb{Z}_N$ ACTION ON GLOBAL QUANTUM NUMBER

VECTOR MULTIPLET → INVARIANT

CHIRAL MULT. → $(\Phi_1, \Phi_2, \Phi_3) \to (e^{2\pi i \frac{a_1}{N}} \Phi_1, e^{2\pi i \frac{a_2}{N}} \Phi_2, e^{2\pi i \frac{a_3}{N}} \Phi_3)$

- POSSIBLE $\mathbb{Z}_N$ ACTION ON GAUGE QUANTUM NUMBERS

THROUGH $U(n)$ MATRIX OF ORDER N

$$\gamma_{\theta,3} = \mathrm{diag}\,(\mathbb{1}_{n_0}, e^{2\pi i \frac{1}{N}} \mathbb{1}_{n_1}, \ldots, e^{2\pi i \frac{N-1}{N}} \mathbb{1}_{n_{N-1}}); \ \sum n_i = n$$

D3-BRANES ON $\mathbb{C}^3/\mathbb{Z}_N$ = D3-BRANES ON $\mathbb{C}^3$ MOD

[DOUGAS & MOORE] $\qquad$ COMBINED $\mathbb{Z}_N$ ACTION

VECTOR MULT. V $\qquad$ $V = \gamma_{\theta,3}\, V\, \gamma_{\theta,3}^{-1}$

CHIRAL MULT. Φ_i $\qquad$ $\Phi_i = e^{2\pi i \frac{a_i}{N}} \gamma_{\theta,3}\, \Phi_i\, \gamma_{\theta 3}^{-1}$

SPECTRUM $\quad$ VECTOR MULT. $\quad U(n_0) \times U(n_1) \times \ldots \times U(n_{N-1})$

CHIRAL MULT. $\quad \sum_{i=0}^{N-1} [(n_i, \overline{n}_{i+a_1}) + (n_i, \overline{n}_{i+a_2}) + (n_i, \overline{n}_{i+a_3})]$

$$[= \sum_i \sum_{r=1}^{3} (n_i, \overline{n}_{i+a_r})]$$

LARGE CLASS OF GAUGE THEORIES !

FIRST LOOK AT MODEL BUILDING

HINT: REPLICATION OF MATTER MULTIPLETS WHEN SEVERAL ENTRIES IN Z_N TWIST $v = (a_1, a_2, a_3)/N$ ARE EQUAL MOD N.

3-FAMILY MODELS ARISE ONLY FROM Z_3 TWIST $v = (1, 1, -2)/3$

[MOREOVER, THIS IS THE UPPER BOUND [IN CONTRAST WITH OTHER STRING PHENOMENOLOGY APPROACHES, LIKE CALABI-YAU COMPACTIFICATION OF HETEROTIC $\# \text{GEN} = \chi(M_{CY})$]]

FAMILIES RELATED TO NUMBER OF TRANSVERSE DIMENSIONS.

SPECTRUM FOR $\mathbb{C}^3/Z_3$

$$U(n_0) \times U(n_1) \times U(n_2)$$

$$3 \left[(n_0, \bar{n}_1, 1) + (1, n_1, \bar{n}_2) + (\bar{n}_0, 1, n_2) \right]$$

REALISTIC MODELS ? CONSIDER $n_0 = 3,\ n_1 = 2,\ n_2 = 1$

$$U(3) \times U(2) \times U(1)$$

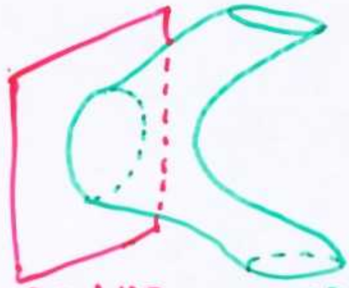
$$3 \left[(3, 2) + (1, 2) + (\bar{3}, 1) \right]$$

GAUGE ANOMALIES !!

THERE MUST BE SOMETHING WE ARE MISSING...

STRING THEORY CONSISTENCY CONDITIONS

THERE ARE NON-TRIVIAL CONSISTENCY CONDITIONS TO BE IMPOSED ON CONFIGURATIONS OF D3-BRANES AT SINGULARITIES



D-BRANE - STRING COMPTON SCATTERING

D-BRANES ARE CHARGED UNDER CLOSED STRING FIELDS

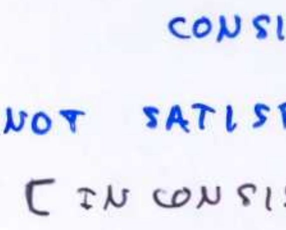
[POLCHINSKI]

GAUSS LAW

IN A COMPACT SPACE, ALL CHARGES UNDER A GIVEN FIELD MUST ADD TO ZERO.

BETTER: FOR A FIELD WITH COMPACT SUPPORT ALL CHARGES MUST ADD TO ZERO.

D3-BRANES AT SINGULARITIES ARE CHARGED UNDER CLOSED STRING TWISTED MODES [WHICH ARE LOCALIZED AT SINGULARITY → COMPACT SUPPORT]



COMPUTATION SHOWS THAT TOTAL CHARGE UNDER k-th TWISTED MODE IS $\mathrm{Tr}\,\gamma_{\theta^k,3}$, HENCE

$$\text{CONSISTENCY} \Rightarrow \mathrm{Tr}\,\gamma_{\theta^k,3} = 0 \qquad k=1,\dots,N-1$$

- NOT SATISFIED BY PREVIOUS EXAMPLES

[INCONSISTENCY SHOWS UP AS ANOMALY]

IN FACT, ONLY SOLUTION FOR Z_3 IS

$U(n) \times U(n) \times U(n)$

$3[(n,\bar{n},1) + (1,n,\bar{n}) + (\bar{n},1,n)]$

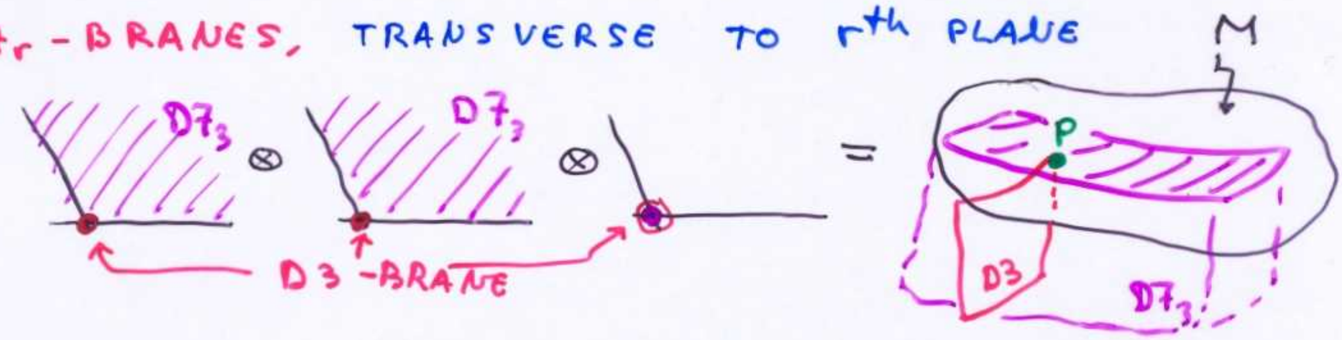
NOT TOO PROMISING...

MORE D-BRANES AT SINGULARITIES

THE CONFIGURATION CAN BE ENRICHED BY INTRODUCING NEW ADDITIONAL OBJECTS

A "CANONICAL" CHOICE, IN THE SENSE THAT IT PRESERVES $\mathcal{N}=1$ SUSY, IS TO INTRODUCE $D7_r$-BRANES, TRANSVERSE TO r^{th} PLANE

EX:



MAIN EFFECT APPEARANCE OF NEW FIELDS, CHARGED UNDER D3-BRANE GAUGE GROUP, FROM QUANTIZING OPEN STRINGS FROM D3 TO D7 [& VICE V.]

SPECTRUM: EASILY COMPUTED, BY SPCIFYING A $\mathbb{Z}_N$ ACTION $\gamma_{\theta,7}$ ON D7-BRANES

$$\gamma_{\theta,7} = \mathrm{diag}\left(1\!\!1_{u_0},\ e^{2\pi i \frac{1}{N}} 1\!\!1_{u_1},\ \ldots,\ e^{2\pi i \frac{N-1}{N}} 1\!\!1_{u_{N-1}}\right)$$

AND IMPOSING THE $\mathbb{Z}_N$ PROJECTION

CHIRAL MULT. 37_3 $\quad \Phi = e^{-\pi i \frac{a_3}{N}}\, \gamma_{\theta,3}\, \Phi\, \gamma_{\theta,7_3}^{-1}$

[ASSUME a_3 EVEN] $7_3 3$ $\quad \Phi = e^{-\pi i \frac{a_3}{N}}\, \gamma_{\theta,7_3}\, \Phi\, \gamma_{\theta,3}^{-1}$

WE OBTAIN CHIRAL MULTIPLETS

$$\sum_{i=0}^{N-1} \left[(n_i;\ \bar{u}_{i-a_3/2}) + (\bar{n}_i;\ u_{i+a_3/2}) \right]$$

NEW FUNDAMENTAL FLAVOURS UNDER D3-GROUP

D7-GROUP WORKS AS A GLOBAL SYMMETRY

[IN NONCOMPACT CASE, D7 MUCH HEAVIER THAN D3]

STRING THEORY CONSISTENCY CONDITIONS

D7-BRANES ALSO CARRY CHARGE UNDER CLOSED STRING TWISTED FIELDS $\sim \mathrm{Tr}\,\gamma_{\theta^k, 7_r}$

- CONSISTENCY CONDITIONS $\Rightarrow$

$\Rightarrow$ Σ D3 CHARGES + Σ D7-CHARGES = 0

COMPUTATION GIVES FOLLOWING CONSTRAINT ON Z_N ACTIONS ON D3-, D7-BRANES

$$8\prod_{r=1}^{3} \sin\left(\frac{\pi k a_r}{N}\right) \mathrm{Tr}\,\gamma_{\theta^k,3} + 2\sum_{r=1}^{3} \sin\left(\frac{\pi k a_r}{N}\right) \mathrm{Tr}\,\gamma_{\theta^k,7_r} = 0$$

$k = 1, \dots, N-1$

- IT IS POSSIBLE TO CHECK THAT, IF THEY ARE SATISFIED, THE GAUGE THEORY ON D3-BRANES

33 $\quad U(n_0) \times U(n_1) \times \dots \times U(n_{N-1})$.

$$\sum_{i=0}^{N-1} [(n_i, \bar{n}_{i+a_1}) + (n_i, \bar{n}_{i+a_2}) + (n_i, \bar{n}_{i+a_3})]$$

$37_r + 7_r3 \quad \sum_{i=0}^{N-1} [(n_i ; \bar{u}_{i-a_r/2}) + (\bar{n}_i ; u_{i+a_r/2})]$

IS FREE OF GAUGE NONABELIAN ANOMALIES

[PROOF: CANCELLATION OF $SU(n_i)$ CUBIC ANOMALY:

$$\sum_{r=1}^{3} (n_{i+a_r} - n_{i-a_r}) + \sum_{r}^{3} (u_{i+a_r/2} - u_{i-a_r/2}) = 0$$

RECALL: $\mathrm{Tr}\,\gamma_{\theta^k,3} = \sum_i e^{2\pi i k i/N} n_i \rightarrow n_i = \frac{1}{N} \sum_k e^{-2\pi i k i/N} \mathrm{Tr}\,\gamma_{\theta^k,3}$

SIMILARLY FOR $D7_r$-BRANES. SUBSTITUTE $\rightarrow$

$$\rightarrow 8\prod_r \sin\left(\frac{\pi k a_r}{N}\right) \mathrm{Tr}\,\gamma_{\theta^k 3} + \sum_r 2\sin\frac{\pi k a_r}{N} \mathrm{Tr}\,\gamma_{\theta^k 7_r} = 0$$

QED.]

MODEL BUILDING : TOWARDS (MS) SM

NEW TRY TO BUILD A REALISTIC THREE FAMILY MODEL WITH STANDARD MODEL GROUP.

- CHOOSE $\mathbb{C}^3/\mathbb{Z}_3$
- CHOOSE $\gamma_{\theta,3} = \mathrm{diag}\,(\mathbb{1}_3, e^{2\pi i \frac{1}{3}}\mathbb{1}_2, e^{2\pi i \frac{2}{3}}\mathbb{1}_1)$

33 $\quad U(3) \times U(2) \times U(1)$

$$3\left[(3,2)_{1,-1,0} + (1,2)_{0,1,-1} + (\bar{3},1)_{-1,0,1} \right]$$

ANOMALOUS, BECAUSE D3-BRANES ALONE DO NOT VERIFY GAUSS' LAW

- INTRODUCE D7-BRANES SUCH THAT

$$\sum_{r=1}^{3} \mathrm{Tr}\,\gamma_{\theta,7_r} + 3\,\mathrm{Tr}\,\gamma_{\theta,3} = 0 \quad \text{IS SATISFIED.}$$

CHOOSE E.G. $\gamma_{\theta,7_1} = \gamma_{\theta,7_2} = \gamma_{\theta,7_3} = \mathrm{diag}\,(e^{2\pi i\frac{1}{3}}, e^{2\pi i \frac{2}{3}}\mathbb{1}_2)$

$37_r, 7_r3$, $r=1,2,3$ [3 COPIES]

$$(3,1;1)_{1,0,0} + (\bar{3},1;2)_{-1,0,0} + (1,1;1)_{0,0,-1} + (1,2;2)_{0,1,0}$$

NON-ABELIAN STRUCTURE IS PRETTY CLOSE

BUT WHAT ABOUT ALL THOSE $U(1)$'s ??

IN FACT, THEY ARE GENERICALLY <u>ANOMALOUS</u>

[E.G. $U(1)_{\subset U(3)} - SU(2)^2$ ANOMALY $= 3 \times (+1) \times \frac{1}{2} \times 3 \neq \underline{\underline{0}}$]

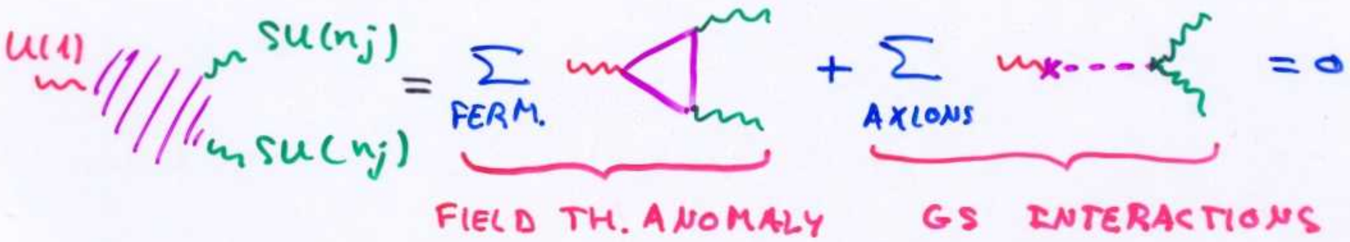
- INCONSISTENCY ? OVERLOOKED SUBTLETIES ?

U(1) ANOMALY CANCELLATION [IBAÑEZ, RABADAN, A.U.] (12)

EVEN AFTER IMPOSING STRING THEORY CONSISTENCY CONDITIONS, MIXED U(1) ANOMALIES IN $U(n_0) \times U(n_1) \times \cdots \times U(n_{N-1})$ DO NOT VANISH

$$U(1)_i - SU(n_j)^2 \; : \; A_{ij} = \frac{1}{2} n_i \sum_{r=1}^{3} \left(\delta_{j,i+a_r} - \delta_{j,i-a_r} \right)$$

- STRING MIRACLE : THE THEORY IS NEVERTHELESS CONSISTENT DUE TO THE PRESENCE OF ADDITIONAL GREEN-SCHWARZ INTERACTIONS



- EQUIVALENTLY : A SET OF CLOSED STRING TWISTED MODES, COUPLING AS AXIONS $\Phi_k \, F_i \wedge \tilde{F}_i$ TRANSFORM UNDER ANOMALOUS U(1)'S

$$A_\mu \to A_\mu + \partial_\mu \lambda \;\Rightarrow\; \phi_k \to \phi_k + \lambda$$

CONSEQUENCES:

ϕ_k BECOME LONGITUDINAL COMPONENTS OF [POPPITZ] ANOMALOUS U(1)'S, WHICH GAIN MASS $\sim M_s$

$\Rightarrow$ GENERICALLY, ONLY A UNIQUE NON-ANOMALOUS U(1) $\Rightarrow$ ONE A UNIQUE LIGHT U(1)

$$\left[Q_{diag} = \sum_{i=0}^{N-1} Q_{n_i} / n_i \right]$$

[PROOF : $U(1)_{diag} - SU(n_j)^2 : \sum_i A_{ij} / n_i = \frac{1}{2} \sum_i \sum_r \left(\delta_{j,i+a_r} - \delta_{j,i-a_r} \right)$

$= \frac{1}{2} \sum_r (1-1) = 0$]

REALISTIC (MS) SM-LIKE MODEL REVISITED

OUT OF THE THREE $U(1)$'S IN $U(3) \times U(2) \times U(1)$, ONLY $Q_{diag} = \frac{1}{3} Q_3 + \frac{1}{2} Q_2 + Q_1$ REMAINS MASSLESS. A PRIORI, NO GUARANTEE TO OBTAIN CORRECT HYPERCHARGE ASSIGNMENTS.

HOWEVER, IT WORKS : $Y = - Q_{diag}$

SPECTRUM $\qquad SU(3) \times SU(2) \times U(1)_Y$

$$3 \, [\underbrace{(3,2)_{1/6}}_{Q_L} + \underbrace{(1,2)_{1/2}}_{H_u} + \underbrace{(\bar{3},1)_{-2/3}}_{u}] +$$

$$+ 3 \, [\underbrace{(3,1;1)_{-1/3} + (\bar{3},1;2)_{1/3}}_{\text{NET } D} + \underbrace{(1,2;2)_{-1/2}}_{L, H_D} + \underbrace{(1,1;1)_{1}}_{E}]$$

OBS : NOT QUITE MSSM

- EXTRA VECTOR-LIKE QUARKS $\Big\}$ POSSIBLE IF WE BREAK D7-GROUP
- NEED TO SPLIT L AND H_D
- HIGGS SECTOR IS ALSO TRIPLICATED
- ν_R COULD ARISE FROM 77- OR BULK MODES

REALISTIC LR SYMMETRIC EXTENSIONS

WORKING ANALOGOUSLY $\qquad Q_{B-L} = -2 \, Q_{diag}$!

$$33 \begin{cases} SU(3) \times SU(2) \times SU(2) \times U(1)_{B-L} \\ 3 \, [\underbrace{(3,2,1)_{1/3}}_{Q_L} + \underbrace{(1,2,2)_0}_{H_u} + \underbrace{(\bar{3},1,2)_{1/3}}_{Q_R}] + \end{cases}$$

$$73, 37 \; \{ + 3 \, [(3,1,1)_{-2/3} + (\bar{3},1,1)_{2/3} + \underbrace{(1,2,1)_{-1}}_{L_L} + \underbrace{(1,1,2)_{+1}}_{L_R}]$$

OBS : SAME COMMENTS AS ABOVE [VECTOR-LIKE $\underline{3}$'s]

EASY TO MODIFY AND GET ADDITIONAL DOUBLETS

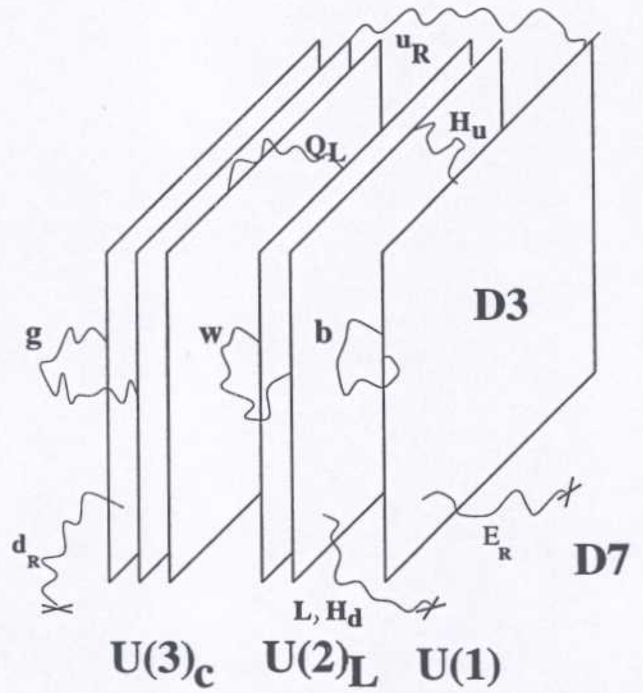


Figure 3: D-brane configuration of a SM $\mathbb{Z}_3$ orbifold model. Six D3-branes (with worldvolume spanning Minkowski space) are located on a $\mathbb{Z}_3$ singularity and the symmetry is broken to $U(3) \times U(2) \times U(1)$. For the sake of visualization the D3-branes are depicted at different locations, even though they are in fact on top of each other. Open strings starting and ending on the same sets of D3-branes give rise to gauge bosons; those starting in one set and ending on different sets originate the left-handed quarks, right-handed U-quarks and one set of Higgs fields. Leptons, and right-handed D-quarks correspond to open strings starting on some D3-branes and ending on the D7-branes (with world-volume filling the whole figure).

EMBEDDING INTO A COMPACT SPACE

ABOVE CONSTRUCTION GIVES CORRECT 4D GAUGE INTERACTIONS $\rightsquigarrow$ SM.

HOWEVER, IN NON-COMPACT MODELS GRAVITY REMAINS 10-DIMENSIONAL. WE NEED TO MAKE TRANSVERSE DIMENSIONS COMPACT TO OBTAIN 4D GRAVITATIONAL LAW.

EMBED OUR LOCAL STRUCTURES INTO A GLOBALLY COMPACT MODEL

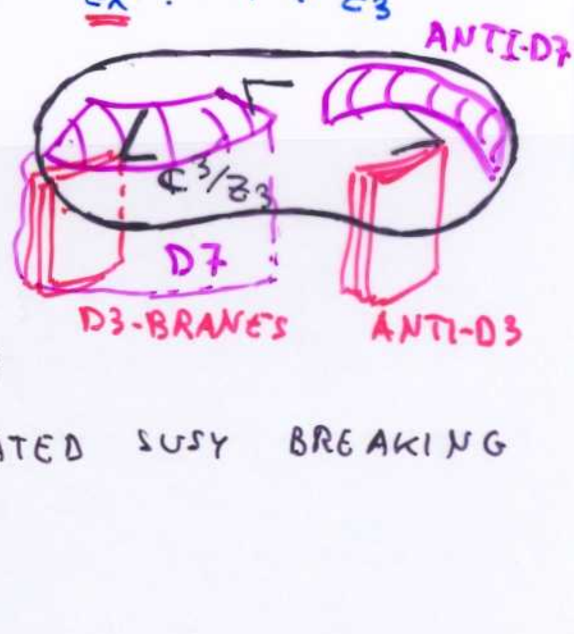
$\mathbb{C}^3/\mathbb{Z}_3$ SINGU.
D3 - BRANES
D7 - BRANES

MAIN DIFFICULTY: CONSISTENCY [GAUSS LAW] REQUIRES TOTAL D-BRANE CHARGE MUST BE ZERO

POSSIBILITIES

* INTRODUCE ANTI D3- AND ANTI D7-BRANES AT DISTANT LOCATIONS

EX: $T^6/\mathbb{Z}_3$



- ANTIBRANES CARRY NEGATIVE D-BRANE CHARGE
- SUSY IS BROKEN IN ANTIBRANE SECTOR: GRAVITATIONALLY MEDIATED SUSY BREAKING

* INTRODUCE ORIENTIFOLD-PLANES AT DISTANT LOCATIONS

- O-PLANES CARRY NEGATIVE D-BRANE CHARGE
- THEY PRESERVE $N=1$ SUSY

[- F THEORY GENERALIZATION]

EXAMPLE [ALDAZABAL, IBÁÑEZ, QUEVEDO, A.U.]

T^6/Z_3 MODDED OUT BY $\Omega R (-)^{F_L}$ [SAME AS BEFORE]

INTRODUCE N D3-BRANES $\Omega R (-)^{F_L}$ TADPOLE $\Rightarrow$

$\Rightarrow N = 32$

INTRODUCE D7, $\overline{\text{D7}}$ BRANES $\Rightarrow \#\text{D7} = \#\overline{\text{D7}}$

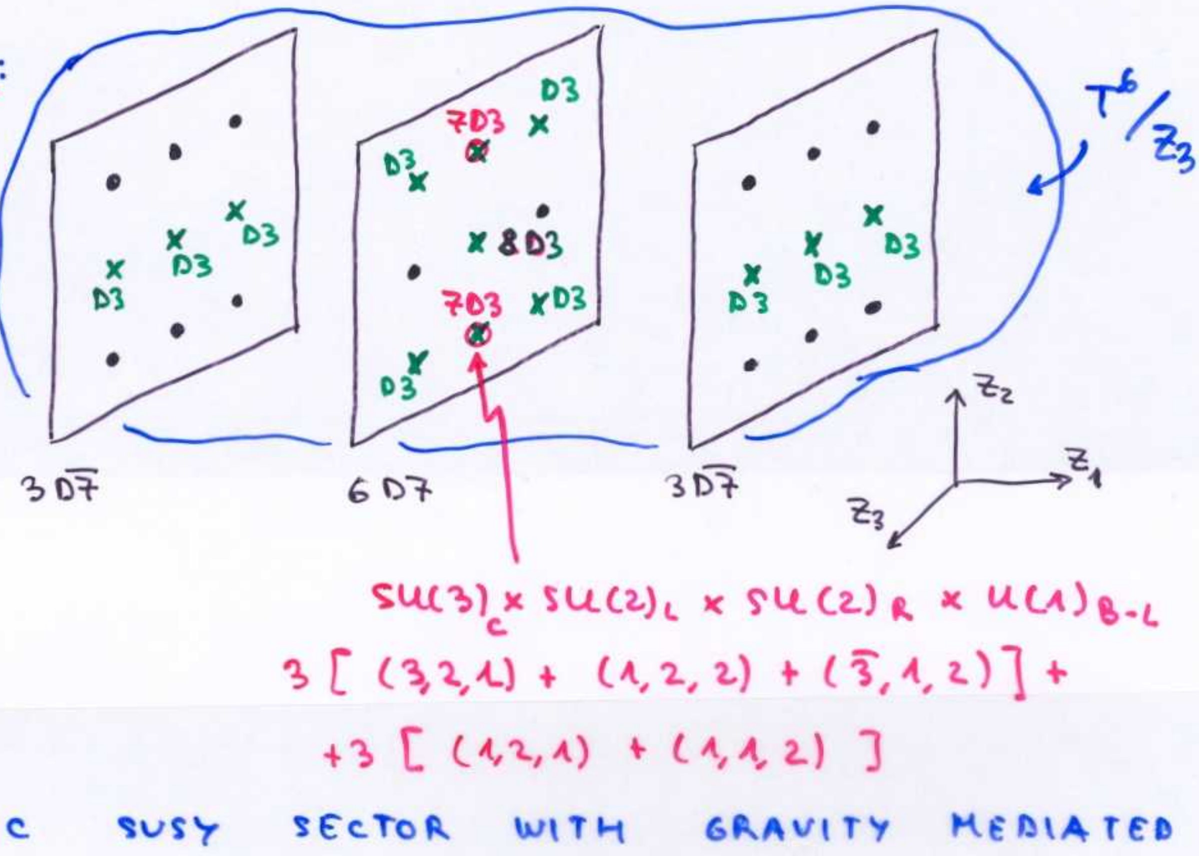
TWISTED TADPOLE CANCELLATION

ORIGIN: $\mathrm{Tr}\,\gamma_{\theta,7} - \mathrm{Tr}\,\gamma_{\theta,\bar{7}} + 3\,\mathrm{Tr}\,\gamma_{\theta,3} = -12$

OTHER θ^2- FIXED PT.: $\mathrm{Tr}\,\gamma_{\theta,7,p} - \mathrm{Tr}\,\gamma_{\theta,\bar{7},p} + 3\,\mathrm{Tr}\,\gamma_{\theta,3,p} = 0$

PICTURE:

(*)



$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$3\,[\,(3,2,1) + (1,2,2) + (\bar{3},1,2)\,] +$

$+3\,[\,(1,2,1) + (1,1,2)\,]$

REALISTIC SUSY SECTOR WITH GRAVITY MEDIATED SUPERSYMMETRY BREAKING

(*) DETAILED DESCRIPTION

$z_1 = 0$ $\quad \gamma_{\theta,7} = (1_2, \alpha 1_2, \alpha^2 1_2) \quad \gamma_{\omega,7} = (\alpha, \alpha^2, 1_2, 1_2)$

$\gamma_{\theta,3(0,0,0)} = (\alpha 1_4, \alpha^2 1_4) \quad \gamma_{\theta,3(0,\pm1,0)} = (1_3, \alpha 1_2, \alpha^2 1_2)$

$\gamma_{\theta,3(0,\pm1,\pm1)} = 1$

$z_1 = \pm 1$ $\quad \gamma_{\theta,\bar{7}} = 1_3 \quad \gamma_{\omega,\bar{7}} = (1, \alpha, \alpha^2) \quad \gamma_{\theta,3(\pm1,0,p)} = 1.$

SCALES

IN MODELS WITH SM EMBEDDED ON A SET OF D3-BRANES

- GAUGE COUPLING g_{YM}^2 = STRING COUPLING λ_s
- 4d PLANCK MASS $M_{4d} = \frac{M_s^4}{\lambda_s M_c^3}$ [ISOTROPICAL]

[10 d ACTION $\int d^{10}x \, \frac{M_s^8}{\lambda_s^2} R^{(10d)} \to \int d^4x \, \underbrace{\frac{M_s^8}{\lambda_s^2 M_c^6}}_{\sim M_{4d}^2} R^{(4d)}$]

λ_s, M_{4d} FIXED BY EXPERIMENT

WE MAY CHOOSE M_s, M_c, KEEPING M_{4d} CORRECT.

- SUSY MODELS

  SUSY PROTECTS HIERARCHY, M_s IS ARBITRARY [$M_s \gtrsim 1$ TeV] UNTIL WE KNOW MORE ABOUT BREAKING OF SUPERSYMMETRY

- SUSY VISIBLE SECTOR + GRAVITATIONALLY MEDIATED SUSY BREAKING

  WE MAY EXPECT $M_{SUSY} \sim \frac{M_s^2}{M_P} = 1\,\text{TeV} \to$

  $\to M_s \sim 10^{11}$ GeV, $M_c \sim 10^8$ GeV.

- NONSUSY MODEL BUILDING

  $M_{SUSY} \sim M_s \sim 1$ TeV

  $M_c \sim 10^{-2}$ GeV [ISOTROPICAL]

SOME PHENOMENOLOGICAL ISSUES

SINCE THE BASIC STRUCTURE OF THE FIELD THEORY DEPENDS ON THE LOCAL STRUCTURE OF THE SINGULARITY AND BRANES, SEVERAL PHENOMENOLOGICAL ISSUES CAN BE DISCUSSED WITHOUT DETAILED KNOWLEDGE OF FULL COMPACT MODEL.

GAUGE COUPLING UNIFICATION

NORMALIZATION OF GAUGE COUPLINGS FOR A SET OF D3-BRANES AT $\mathbb{C}^3/\mathbb{Z}_N$ SINGULARITY WITH GROUP $SU(3)\times SU(2)\times U(1)_{diag}$

[RECALL $Q_{diag} = \frac{1}{3} Q_3 + \frac{1}{2} Q_2 + Q + \cdots + Q$]

$g_3 : g_2 : g_1$ GO AS $1 : 1 : \frac{5}{3} + 2(N-2)$

DEPENDS ONLY ON N, ORDER OF $\mathbb{Z}_N$ TWIST !

$$\sin^2\theta_W = \frac{3}{6N-4} \quad \text{AT STRING SCALE}$$

COMMENTS:

- FOR $\mathbb{Z}_3$, $\sin^2\theta_W \simeq 0.214$, NOT TOO BAD.
- GETS WORSE AS N INCREASES: $\mathbb{Z}_5 \to 0.115$
- ONE LOOP RUNNING TO LOW ENERGIES:

  WRONG SIGN FOR SM

  GOOD AGREEMENT FOR LR IF $M_S \sim 10^{12}$ GeV
  $M_{SU(2)_R} \sim 1$ TeV.

YUKAWA COUPLINGS

PHYSICAL YUKAWA COUPLINGS DEPEND ON KÄHLER POTENTIAL, I.E. FIELD NORMALIZATION. SO, EVEN THOUGH SUPERPOTENTIAL IS CONTROLLED BY SINGULARITY STRUCTURE, CONCLUSIONS ARE RATHER MODEL DEPENDENT.

UP-TYPE QUARK MASSES

ARISE FROM COUPLINGS $\epsilon_{ijk}\ (33)_i\ (33)_j\ (33)_k$

ONCE H_u PICK VEVS, $\epsilon_{ijk}\ (Q_L)_i\ (H_u)_j\ (u)_k$

"NAKED" MASS MATRIX IS ANTISYMMETRIC →

→ TWO DEGENERATE QUARKS, AND ONE MASSLESS

KÄHLER POTENTIAL EFFECTS IMPROVE THE SITUATION, CAN ACCOMODATE QUARK HIERARCHY.

DOWN-TYPE QUARK MASSES

COUPLINGS $\quad (33)_r\ (37_r)\ (7_r3)$

$\quad (Q_L)_r\ (H_D)_r\ (D)_r$

EACH DOWN QUARK IS ASSOCIATED TO A D7-BRANE TYPE. CLEVER D7-BRANE GEOMETRIES ALLOW TO ACCOMODATE HIERARCHY.

LEPTON MASSES

NO RENORMALIZABLE INTERACTIONS $H_D L E$.
NON-RENORMALIZABLE, POSSIBLE BUT VERY MODEL DEPENDENT.

CONCLUSION ENOUGH FLEXIBILITY, BUT NO PREDICTION, NOT EVEN GENERIC.

CONCLUSIONS

- WE HAVE PRESENTED A POSSIBLE EMBEDDING OF (SUPERSYMMETRIC) STANDARD MODEL PHYSICS IN STRING THEORY, IN A BRANE-WORLD SETUP
- CONCRETELY, IN TERMS OF A SET OF D3-BRANES SITTING AT A SINGULARITY IN TRANSVERSE SPACE, IN THE PRESENCE OF ADDITIONAL D7-BRANES.
- IN THIS SETUP
  - CONSTRUCTION OF REALISTIC MODELS
  - NUMBER OF GENERATIONS BOUNDED ≤ 3
  - INTERESTING APPEARANCE OF HYPERCHARGE
  - REASONABLE PREDICTION FOR $\sin^2\theta_W$
- WE HAVE EMBEDDED SUCH CONFIGURATIONS IN GLOBALLY COMPACT MODELS, IN ORDER TO REPRODUCE 4D GRAVITY.
- WE HAVE ADDRESSED SEVERAL PHENOMENOLOGICAL ISSUES FOR THESE CONFIGURATIONS

FURTHER WORK

- IMPROVE MODEL BUILDING
- PHENOMENOLOGY
  - SUSY BREAKING
  - HOW DO SINGULARITIES AFFECT EXPERIMENTAL SIGNATURES?
- ALTERNATIVE SM EMBEDDINGS IN STRING TH.

COMPARISON OF PHENOM. STRING VACUA

	M_s	PROTON	UNIF.	YUKAWA	SPCECT.	# FAM
HETEROTIC	M_p	ok	ok	$\sim$	$\sim\downarrow$	$\sim\uparrow$
NONSUSY INTERSECT.	TeV	ok	$\downarrow$	$\sim$	ok	$\sim$
SUSY INTERSEC.	ANY	ok	$\downarrow$	$\sim$	$\sim$	$\downarrow$
D3 AT. SINGU. (SUSY)	ANY	ok	ok	$\downarrow$	$\sim$	ok