

# PROTON DECAY AND D-BRANES

①

based on these papers

EW "Deconstruction..."

T Freedman and EW "Threshold Corrections..."

I Klebanov & EW "Proton Decay and Intersecting D-Brane Models"

LET'S FIRST REVIEW PROTON

DECAY FROM THE VIEWPOINT

OF FOUR-DIMENSIONAL GRAND

UNIFICATION

2

$$SU(3) \times SU(2) \times U(1) \subset SU(5)$$

MINIMAL GROUP THEORY  
EMBEDDING

$$\left( \begin{array}{c|c} SU(3) & X, Y \\ \hline \bar{X}, \bar{Y} & SU(2) \end{array} \right)$$

$X, Y =$  new  
color triplet  
gauge bosons

SU(5) WORKS PERFECTLY FOR

QUARK AND LEPTON QUANTUM NUMBERS

$$\bar{5} \begin{pmatrix} \bar{d} \\ \bar{d} \\ \bar{d} \\ \nu \\ e \end{pmatrix}$$

$$10 \begin{pmatrix} 0 & \bar{u} & \bar{u} & u & d \\ & 0 & \bar{u} & u & d \\ & & 0 & u & d \\ \vdots & & & & 0 & e & \tau \\ & & & & e & \tau & 0 \end{pmatrix}$$

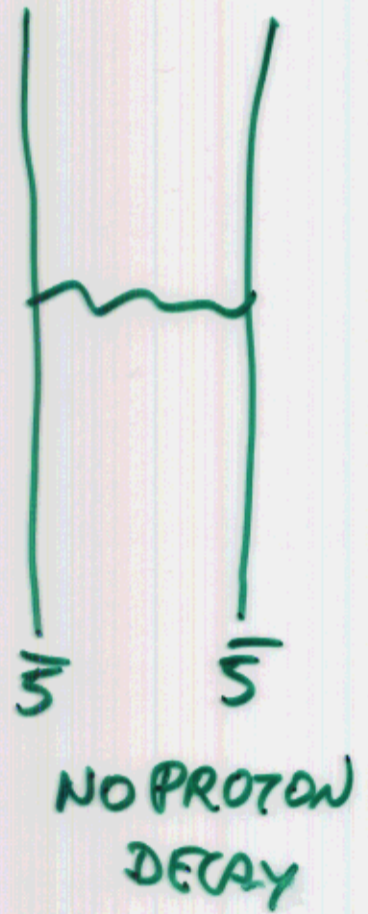
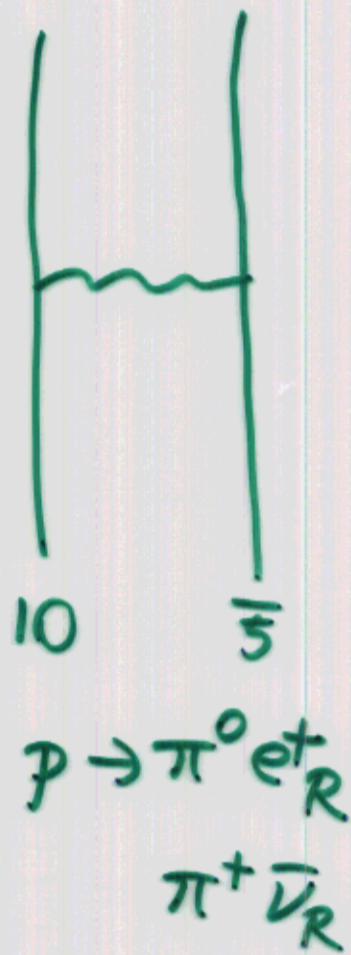
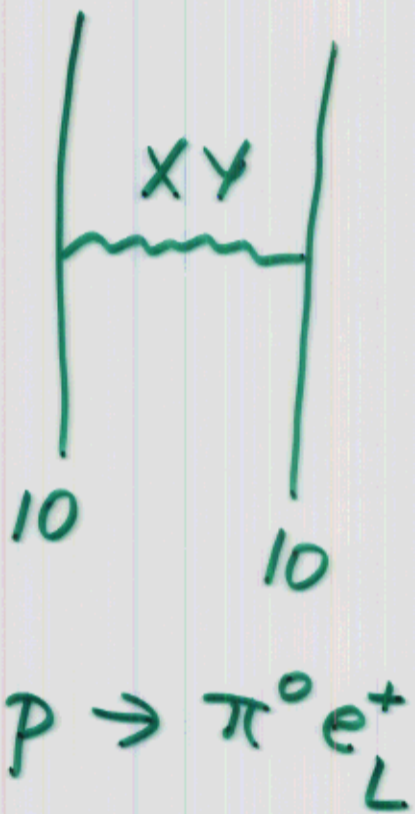
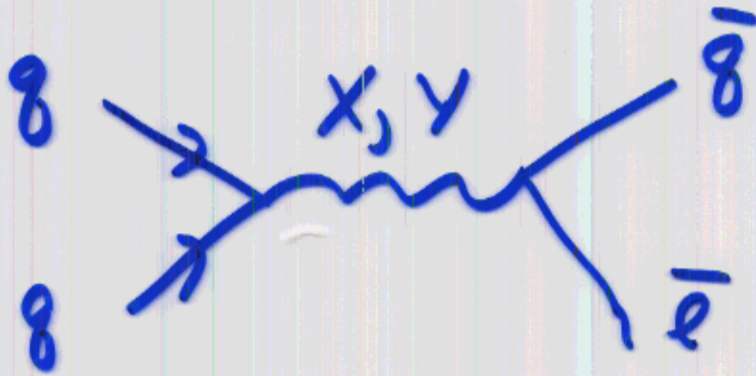
$$\text{ONE GENERATION} = \bar{5} \oplus 10$$

# MOST FUNDAMENTAL NEW

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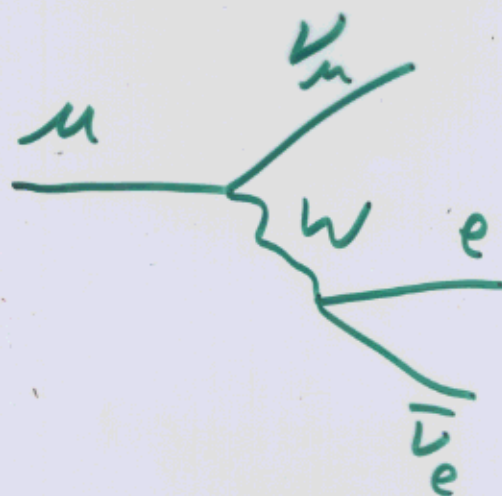
PREDICTION :

PROTON DECAY



BY ANALOGY WITH (SAY) MUON ④

DECAY



$$\Gamma \sim \left( \frac{\alpha}{M_W^2} \right)^2 M_\mu^5$$

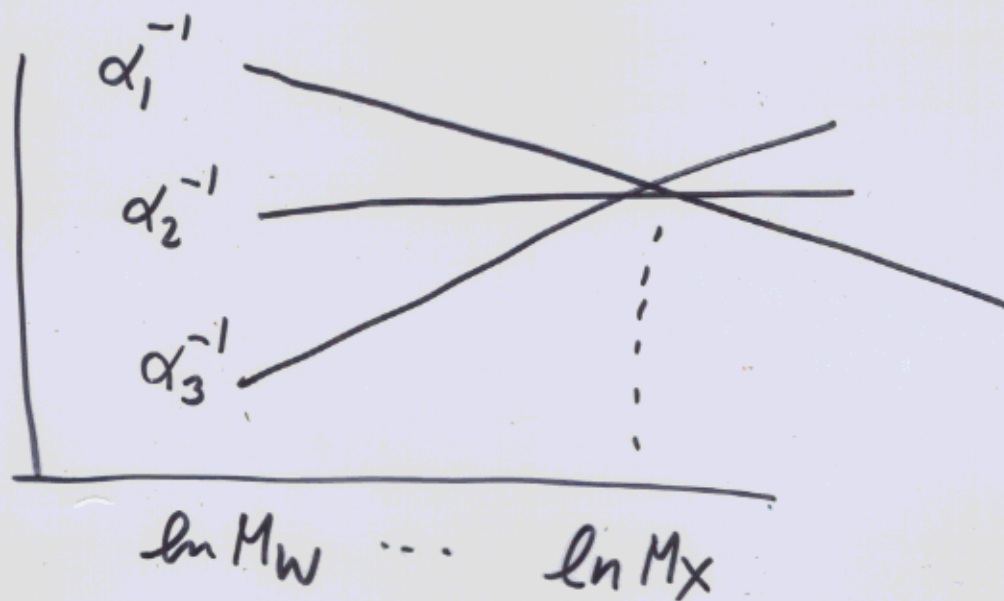
WE GET A CRUDE ESTIMATE  
OF PROTON DECAY RATE

$$\Gamma \sim \left( \frac{\alpha}{M_X^2} \right)^2 m_{\text{proton}}^5$$

~~etc~~

WHAT IS  $M_X$ ?

(5)



BY EXTRAPOLATING OBSERVED  
COUPLINGS TO HIGH ENERGIES, IT  
IS FOUND THAT FOR

$$\sin^2 \theta_W \sim .2$$

THEY DO MEET AT A HIGH  
ENERGY THAT IS INTERPRETED AS  $M_X$   
GIVES  $M_X \sim 10^{14}$  GeV

THIS IS NICE AS IT IS RELATIVELY ⑥  
CLOSE TO BUT BELOW  $M_{\text{Planck}}$

AND IT LEADS TO A

PROTON LIFETIME  $\sim 10^{29}$  years

WHICH MADE AN INVITING TARGET

SAME IDEAS ALSO LEAD TO

$$m_\nu \sim \frac{M_W^2}{M_X} \sim .1 \text{ eV}$$

WHICH WE NOW KNOW TO

BE ABOUT RIGHT

HOWEVER BY THE EARLY 1980's

(7)

IT WAS CLEAR THAT

$$\sin^2 \theta_W \approx .20$$

IS CLOSE, BUT NOT CLOSE ENOUGH,

AND THAT

$$\tau_{\text{proton}} \gg 10^{29} \text{ years}$$

CURE FOR BOTH VIA

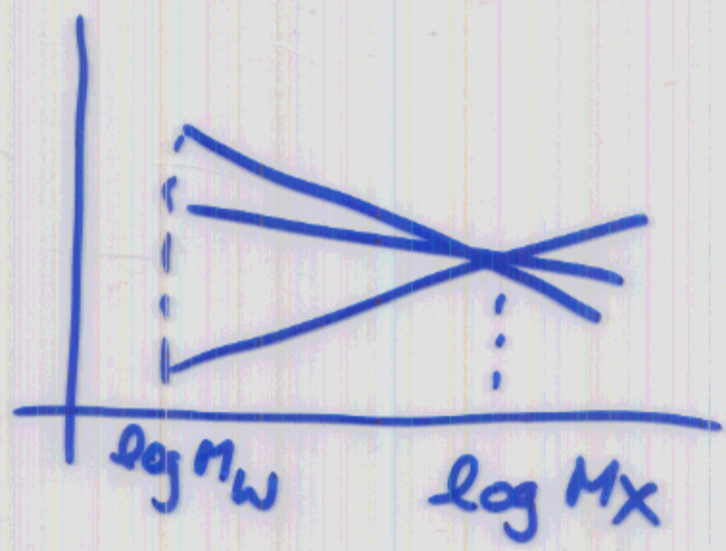
SUPERSYMMETRY

INCLUDE SUSY PARTNERS

OF STANDARD MODEL GAUGE

BOSONS - LOWERS  $\beta$  FUNCTIONS

AND SLOWS RGE EVOLUTION



RAISES  $M_X$  TO  $10^{16}$  GeV AND

$\tau_{\text{PROTON}}$  (IF X DOMINATES) TO

$\sim 10^{36}$  years



ALSO, THE SUSY PARTNERS OF

HIGGS BOSONS MODIFY THE

PREDICTION FOR  $\sin^2 \theta_W$  TO

$$\sin^2 \theta_W \sim .23,$$

VERY CLOSE TO THE MODERN

EXPERIMENTAL VALUE.

AND OF COURSE "LOW ENERGY"

SUSY CAN MAKE THE SMALLNESS

OF THE ELECTROWEAK SCALE NATURAL

WEAK SCALE SUSY ALSO

BRINGS AN ASSORTMENT OF

NETTLESOME PROBLEMS FOR WHICH

WE DON'T HAVE REALLY CONVINCING

ANSWERS

NOTABLY: UNWANTED NEW POSSIBILITIES

FOR VIOLATION OF

FLAVOR, CP,

LEPTON NUMBER, BARYON NUMBER

FOR TODAY WE FOCUS ON BARYON  
NUMBER

IN THE STANDARD MODEL, THE ONLY <sup>(11)</sup>  
FIELDS CARRYING BARYON NUMBER  
ARE QUARKS, AND THE LOWEST  
DIMENSION OPERATOR VIOLATING BARYON  
NUMBER HAS DIMENSION SIX:

$$qqq\bar{l}$$

SO

$$\mathcal{L}_{\text{eff}}^{\Delta B} \sim \frac{\text{coupling}}{(\text{MASS})^2} qq\bar{q}\bar{l}$$

LEADING TO OUR ESTIMATE OF  $\tau_{\text{PROTON}}$

WITH SUSY, THERE ARE SCALARS CARRYING BARYON NUMBER

IN FACT QUARK SUPERFIELDS

$$Q = \phi_q + \theta q + \dots$$

LEPTON SUPERFIELDS

$$L = \phi_l + \theta l + \dots$$

AND THERE IS A POTENTIAL FOR CATASTROPHICALLY FAST PROTON DECAY

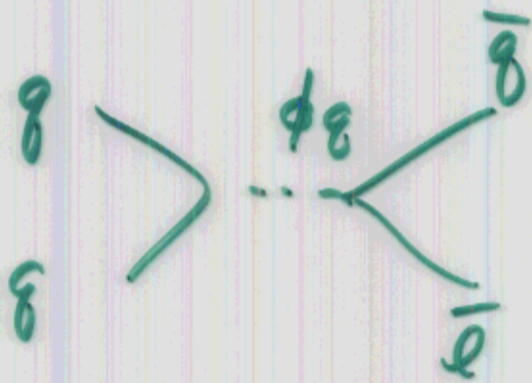
BY RENORMALIZABLE - OR

DIMENSION FOUR - OPERATORS:

$$\int d^4x d^2\theta (QQQ + Q\bar{Q}L) + h.c.$$

$$= \int d^4x (\phi_g q q + \phi_g \bar{q} l + h.c.)$$

⇒ PROTON AS SHORT-LIVED AS MUON



IT IS CUSTOMARY - BUT NOT (14)  
PARTICULARLY ATTRACTIVE - TO  
ASSUME A DISCRETE SYMMETRY  
SUCH AS R-PARITY TO DISPOSE  
OF THEM.

EVEN IF THIS IS DONE,  
SUPERSYMMETRY GIVES ANOTHER  
POTENTIAL MECHANISM FOR  
PROTON DECAY...

# DIMENSION FIVE OPERATORS

(15)

$$\frac{g^2}{M_X} \int d^4x d^2\theta \, QQQL$$

CANNOT BE FORBIDDEN BY ANY

GLOBAL SYMMETRY OF A

FOUR-DIMENSIONAL SU(5) MODEL;

BUT HIGHLY MODEL-DEPENDENT

LEADS TO NOVEL PROTON DECAY MODES

e.g.

$$p \rightarrow K \bar{\nu}$$

HIGHLY MODEL-DEPENDENT, BUT

(16)

IN SIMPLEST FOUR-DIMENSIONAL

MODELS GET

$$\tau_p \lesssim 10^{32} \text{ years}$$

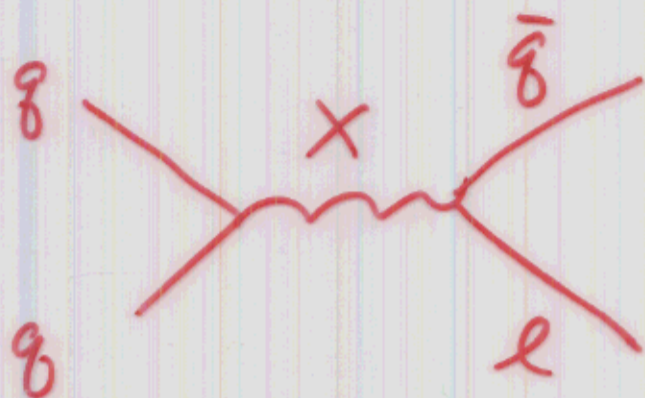
UNDER A LOT OF PRESSURE FROM

CURRENT BOUNDS

$$\tau_p^{\text{expt}} \gtrsim 10^{33} \text{ years}$$



AND WE HAVE THE DIMENSION  
SIX MECHANISM



WHICH IS STILL MODEL-DEPENDENT,  
BUT LESS SO, AND LEADS TO

$$\tau_{\text{PROTON}} \sim 10^{36} \text{ years} \quad \text{FOR } p \rightarrow \pi^0 e^+$$

AS I SAID BEFORE.

THE PRESENT EXPERIMENTAL

BOUND ON  $p \rightarrow \pi^0 e^+$

IS ABOUT  $4 \times 10^{33}$  years

AND A NEXT GENERATION

EXPERIMENT MIGHT REACH VERY

CLOSE TO  $10^{35}$  years

SO WITH A PREDICTION OF

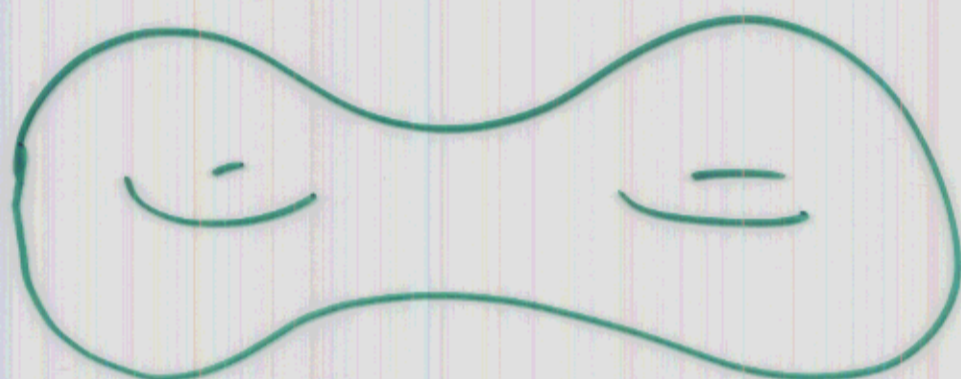
$10^{36}$  years, WE MISS, BUT NOT

BY MUCH

WHAT HAPPENS IN STRING  
MODELS? I WON'T SAY  
ANYTHING ABOUT DIMENSION  
FIVE (OR FOUR) OPERATORS; I'LL  
JUST ASSUME THEY DON'T DOMINATE.

(FOR EXAMPLE, EXTRA DIMENSIONS  
GIVE NEW POSSIBILITIES OF DISCRETE  
SYMMETRIES THAT MIGHT FORBID  
THEM,)

CONSIDER, FOR EXAMPLE,  
THE HETEROTIC STRING ON A  
CALABI-YAU, SAY WITH SYMMETRY  
BREAKING BY WILSON LOOPS TO  
IMITATE GUT SYMMETRY BREAKING



INFINITELY MANY COLOR  
TRIPLET GAUGE BOSONS  $X_i$

(21)

AMPLITUDE

$$g_{st}^2 \sum_i \frac{c_i^2}{M_{X_i}^2}$$

THE SUM OVER KK HARMONICS  
CONVERGES AND ~~THE~~ RESULT IS  
QUALITATIVELY SIMILAR TO  
THE FIELD THEORY ANSWER

$$\frac{g^2}{M_X^2}$$

BUT THIS IS A PROBLEM IN WHICH QUALITATIVE INFORMATION ISN'T ENOUGH - AS I EXPLAINED, AN ENHANCEMENT OF  $2\pi$  IN THE AMPLITUDE WOULD MAKE ALL THE DIFFERENCE

I'D PRESUME SUCH AN ENHANCEMENT DOES ARISE ON SOME CALABI-YAU'S IN SOME REGIONS OF MODULI SPACE

FROM A MODERN POINT OF VIEW, THE HETEROTIC STRING ON A CALABI-YAU IS DUAL TO MANY OTHER MODELS

(23)

FOR EXAMPLE, MIRROR SYMMETRY SAYS THAT MOST CALABI-YAU'S ARE  $T^3$ -FIBERED, AND WE GET ...

(AMONG OTHER  
POSSIBILITIES)

HETEROTIC STRING ON  
 $T^3$ -FIBERED CALABI-YAU



M-THEORY ON A  $K3$ -FIBERED  
MANIFOLD OF  $G_2$  HOMOLOGY



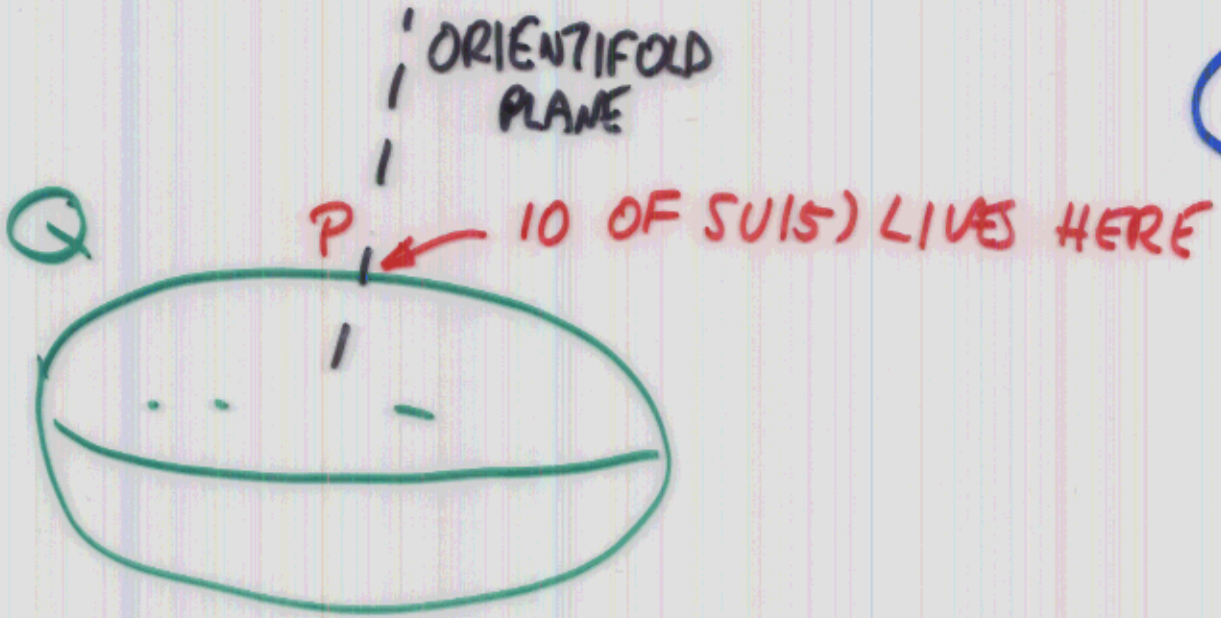
Type IIA WITH INTERSECTING  
D-BRANES



KLEBANOV AND I EXPLORED THIS FOR INTERSECTING D-BRANE MODELS, WHERE SOMETHING INTERESTING AND "MODEL-INDEPENDENT" CAN BE SAID -

INTERESTING BECAUSE A FIELD THEORY ANALYSIS GIVES A U.V. DIVERGENCE WHICH IS CUT OFF BY STRINGY EFFECTS ... SO THE PROTON LIFETIME IS "STRINGY"

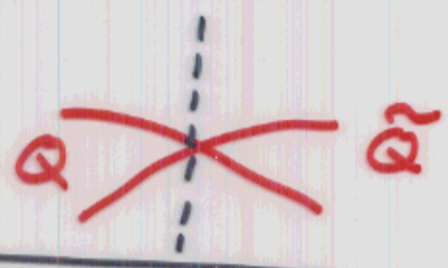
TO SPOIL THE PUNCHLINE,  
HOWEVER, WE FOUND - ONCE WE  
PUT IN REALISTIC NUMBERS LIKE  
 $\alpha_{GUT} \approx 1/25$  - THAT THE  
STRINGY EFFECTS ROUGHLY  
CANCELED OUT - WE DIDN'T  
END UP WITH THE ENHANCED  
PROTON DECAY THAT WE HOPED  
FOR.



WILSON LINES ON Q:

$$SU(5) \rightarrow SU(3) \times SU(2) \times U(1)$$

10 OF SU(5) WHERE Q MEETS  
ORIENTIFOLD PLANE



ALDIZABAL, FRANCO, IBANEZ, RABADAN, URANGA 2001

CVETIC, SHIU, URANGA, 2001; CVETIC, PAPADIMITRIOU, SHIU  
2002

BERKOOZ, DOUGLAS LEIGH 1996

TO GET THE ~~10~~

10 10 10 10 AMPLITUDE FOR

PROTON DECAY, WE EXCHANGE

COLOR TRIPLET PARTICLES THAT LIVE

ON Q BETWEEN PARTICLES IN THE 10

THERE ARE INFINITELY MANY

KALUZA-KLEIN HARMONICS, COLOR TRIPLETS

OF MASS  $M_i$ , WAVEFUNCTION  $\Psi_i(x)$

$$\underbrace{\frac{g^2}{M_X^2}}_{\text{GUTS}} \rightarrow g_{st} \underbrace{\sum_i \frac{|\Psi_i(p)|^2}{M_i^2}}_{\text{KALUZA-KLEIN FIELD THEORY}}$$

THAT IS THE FELD THEORY

(28)

ANSWER, BUT THE SUM DIVERGES

$$\sum_i \frac{\Psi_i(P) \bar{\Psi}_i(Q)}{M_i^2} = G(P, Q)$$

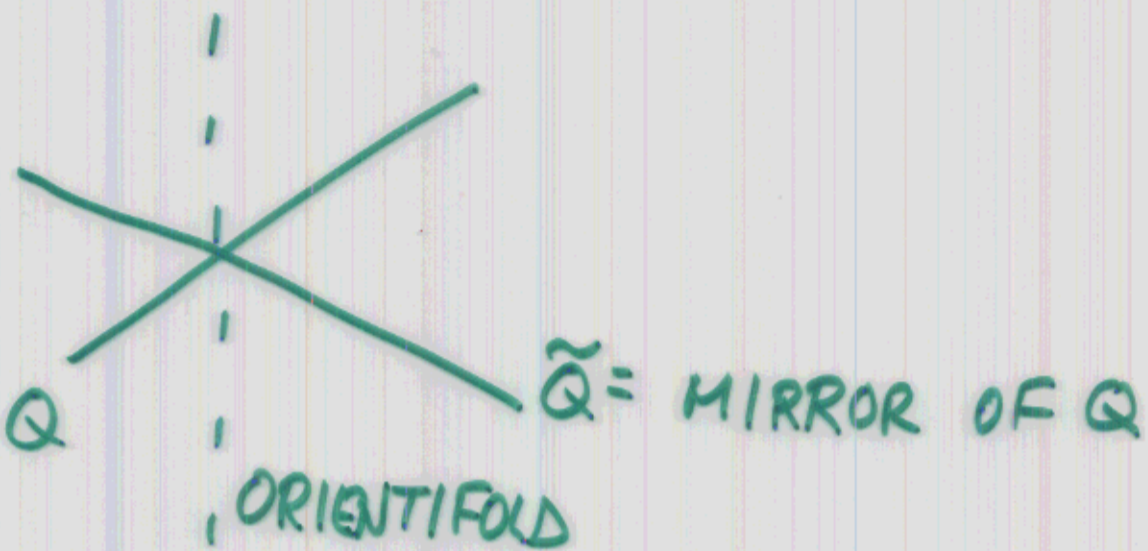
GREEN'S FUNCTION  
OF  $\nabla^2 = \text{LAPLACIAN}$   
ON D-BRANE  $Q$

$$G(P, Q) \rightarrow \frac{1}{4\pi |P-Q|} \quad \text{FOR } Q \rightarrow P$$

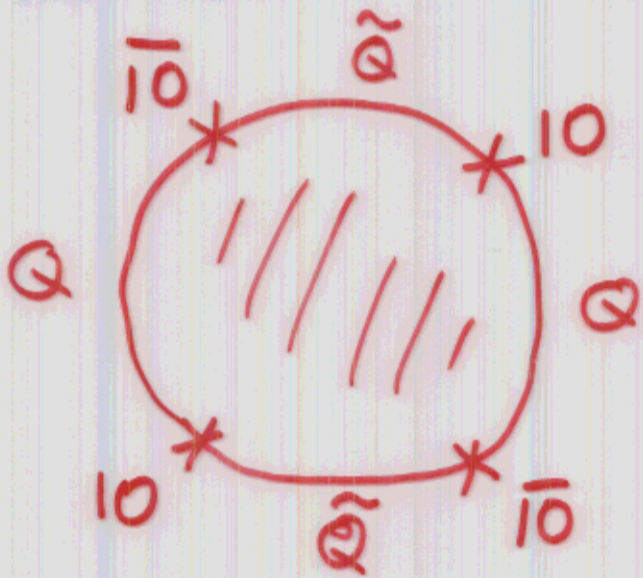
SO

$$\sum_i \frac{|\Psi_i(P)|^2}{M_i^2} = \infty$$

THE SUM WILL CLEARLY BE CUT OFF IN STRING THEORY



FOUR-POINT FUNCTION ON DISC



CORRELATOR OF "TWIST FIELDS"

(DIXON-FRIEDAN-MARTINEC-SHENKER Vafa-HAMIDI 1987)

ABEL-OWEN

CVETIC - PAPADIMITRIOU

GAWA-NARAIN-SARMADI

ANTONIADIS - BENAKLI - LAEGIER

APPLIKATIONS  
OF TWIST  
CORRELATORS TO  
D-BRANES

30

THE AMPLITUDE COMES OUT TO BE

$$2\pi g_s \alpha' \cdot \int_0^1 \frac{dx}{x(1-x)} \prod_{i=1}^3 \left( \frac{\sin \pi \theta_i}{F(\theta_i, 1-\theta_i; 1; x) F(\theta_i, 1-\theta_i; 1; 1-x)} \right)^{1/2}$$

WHERE  $\theta_i$  ARE ROTATION ANGLES

BETWEEN  $Q$  AND  $\tilde{Q}$

(31)

NUMERICALLY, THE INTEGRAL  
IS LARGE, ABOUT 7-11  
DEPENDING ON  $\theta_i$

THIS ALONE WOULD GIVE  
THE ENHANCEMENT WE WERE  
HOPING FOR.

THERE IS ONE MORE PLACE AN  
AN ENHANCEMENT COMES FROM:  
ONE-LOOP THRESHOLD CORRECTION (TFEW)  
FACTOR OF 10-15 IN SIMPLEST MODELS



HOWEVER, PUTTING IT ALL

(32)

TOGETHER, WE GET AN UNLUCKY  
FACTOR OF  $8\pi^2$ :

$$\frac{A_{st}}{A_{GUT}} = \frac{L(Q)^{2/3} I}{8\pi^2} \frac{g_{st}^{1/3}}{\alpha_{GUT}^{1/3}} \frac{M_X^2}{M_{GUT}^2}$$

$L(Q)^{2/3}$  = THRESHOLD FACTOR

I FROM TWIST CORRELATOR

$\left(\frac{g_{st}}{\alpha_{GUT}}\right)^{1/3}$  BECAUSE THE KALUZA-KLEIN  
SUM DIVERGED

$\frac{M_X^2}{M_{GUT}^2}$  : STRING THEORY ANSWER INVOLVES  $M_{GUT}$   
WHILE GUT'S INVOLVE  $M_X$

WE ENDED UP WITH

$$\tau_p \approx 2 \times 10^{36} \text{ YEARS}$$

ESSENTIALLY THE STANDARD ANSWER  
AND TOO LONG TO OBSERVE

WOULD OTHER MODELS GIVE THE  
ENHANCEMENT WE WERE HOPING FOR?  
SURELY SOME MIGHT, MAYBE  
EVEN THE M-THEORY ANALOG  
OF THIS ONE