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BEYOND THE STANDARD MODEL

- EXPERIMENTAL DATA UP TO PRESENTLY AVAILABLE ENERGY (~ 200 GeV) AGREE WITH $\boxed{\text{HIGH PRECISION}}$ WITH SM PREDICTIONS.
- AT HIGHER ENERGY:
  1. GRAND-UNIFICATION SCALE $M_{GUT} \sim 10^{16}$ GeV
  2. PLANCK SCALE $M_{P\ell} = 1.2 \cdot 10^{19}$ GeV
- EVENTUALLY WE HAVE TO DEAL WITH $\boxed{\text{QUANTUM GRAVITY}}$ AND THE ONLY CONSISTENT THEORY FOR IT IS WITHIN STRING THEORY.
- ULTRAVIOLET (SHORT DISTANCE) DIVERGENCES IN FIELD THEORY ARE DUE TO THE POINTLIKE STRUCTURE OF CONSTITUENTS. PRESENT ALREADY IN CLASSICAL ELETRODYNAMICS. ONE INTRODUCES THE CLASSICAL ELECTRON RADIUS r_0 (UV CUTOFF) IN ORDER TO HAVE A FINITE SELF-ENERGY:

$$\frac{e^2}{r_0} = mc^2 \quad ; \quad r_0 = \frac{e^2}{mc^2} = \underbrace{\left(\frac{e^2}{\hbar c}\right)}_{\frac{1}{137}} \left(\frac{\hbar}{mc}\right)$$

- STRING EQ. OF MOTION

$$\left(\frac{\partial^2}{\partial\sigma^2} - \frac{\partial^2}{\partial\tau^2}\right) X^\mu(\tau,\sigma) = 0$$

AND BOUNDARY CONDITIONS

$$\frac{\partial X^\mu}{\partial\sigma}\cdot \delta X_\mu \Big|_{\sigma=\pi} - \frac{\partial X^\mu}{\partial\sigma}\cdot \delta X_\mu \Big|_{\sigma=0} = 0 \qquad 0 \le \sigma \le \pi$$

- CLOSED STRING : $X^\mu(\tau,\sigma) = X^\mu(\tau, \sigma+\pi)$

$$X^\mu(\tau,\sigma) = q^\mu + 2\alpha' p^\mu \tau + \frac{i}{2}\sqrt{2\alpha'}\cdot \sum_{n=1}^{\infty} \frac{1}{\sqrt{n}}\cdot$$

$$\cdot\left\{ a_n^\mu e^{-2in(\tau-\sigma)} - a_n^{+\mu} e^{2in(\tau-\sigma)} + \tilde{a}_n^\mu e^{-2in(\tau+\sigma)} - \right.$$

$$\left. - \tilde{a}_n^{+\mu} e^{2in(\tau+\sigma)} \right\}$$

- $\boxed{\text{OPEN STRING}}$ ~

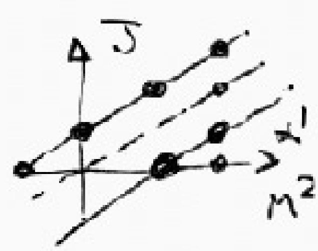
NEUMANN B.C. $\longrightarrow$ $\left.\dfrac{\partial X^\mu}{\partial \sigma}\right|_{\sigma=0,\pi} = 0$

DIRICHLET B.C. $\longrightarrow$ $\left.\delta X^\mu\right|_{\sigma=0,\pi} = 0$

IN THE CASE OF NEUMANN B.C.

$$X^\mu(\tau,\sigma) = q^\mu + 2\alpha' p^\mu \tau + i\sqrt{2\alpha'}\sum_{n=1}^{\infty}\frac{1}{\sqrt{n}}\left(a_n e^{-in\tau} - a_n^+ e^{in\tau}\right)\cos n\sigma$$

- $\boxed{\text{SPECTRUM OF OPEN STRING}}$



$$\alpha' M^2 = \sum_{n=1}^{\infty} n\, a_n^+ \cdot a_n - 1.$$

MASSLESS STATE : $a_1^{+\mu}|0,k\rangle$
$\downarrow$
$A^\mu(x)$ (GAUGE FIELD)

IN OPEN STRING THE GAUGE DEGREE OF FREEDOM ARE CONCENTRATED AT THE ENDPOINTS OF THE STRING

- $\boxed{\text{SPECTRUM OF CLOSED STRING}}$!

$$\frac{\alpha'}{2} M^2 = \sum_{n=1}^{\infty} n \left(a^+_n \cdot a_n + \tilde{a}^+_n \cdot \tilde{a}_n \right) - 2$$

$$\sum_{n=1}^{\infty} n \, a^+_n \cdot a_n = \sum_{n=1}^{\infty} n \, \tilde{a}^+_n \cdot \tilde{a}_n$$

MASSLESS STATES:

$$a_1^{+\mu} \tilde{a}_1^{+\nu} |0,k\rangle \longrightarrow \begin{array}{l} G_{\mu\nu} \text{ (GRAVITON)} \\ \phi \text{ (DILATON)} \\ B_{\mu\nu} \text{ (ANTISYMM. TENSOR)} \end{array}$$

- QUANTUM THEORY IS CONSISTENT IF $d=26$ BUT BOSONIC STRING HAS TACHYONS.

- $\boxed{\text{FIELD THEORY LIMIT : } \alpha' \to 0}$

STRING THEORY $\xrightarrow{\alpha' \to 0}$ FIELD THEORY

(THEORY WITH QUANTUM GRAVITY) (THEORY WITHOUT QUANTUM GRAVITY).

SPECIAL RELATIVITY $\xrightarrow{c \to \infty}$ GALILEAN MECHANICS

QUANTUM MECHANICS $\xrightarrow{\hbar \to 0}$ CLASSICAL MECHANICS

- $\boxed{\text{SUPERSTRING}}$

1. ADDITIONAL FERMIONIC OSCILLATORS WITH TWO SECTORS (NS $\to$ BOSONS ; R $\to$ FERM.)
2. $d = 10$ INSTEAD OF $d = 26$
3. NO TACHYON BECAUSE GSO PROJECTION
4. SPACE-TIME SUPERSYMMETRY
5. MASSLESS SPECTRUM

CLOSED STRING

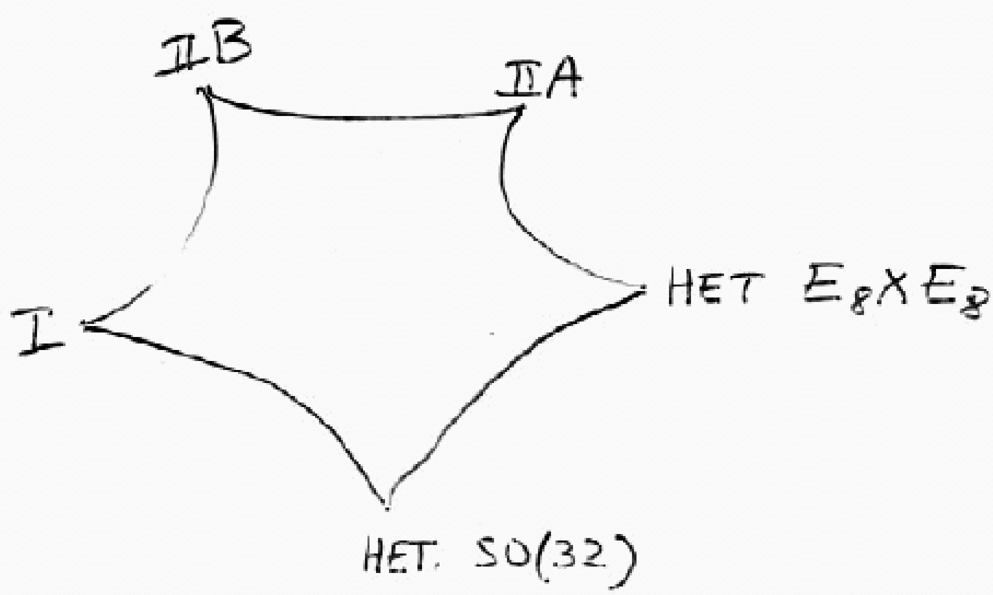
$(G_{\mu\nu}, \phi, B_{\mu\nu})$ in NS-NS SECTOR

$\left.\begin{cases} C_\mu, C_{\mu\nu\rho} & \text{IN IIA} \\ C, C_{\mu\nu}, C_{\mu\nu\rho\sigma} & \text{in IIB} \end{cases}\right\}$ R-R SECTOR / ψ^μ GRAVITINO, ψ DILATINO in R-NS + NS-R

• $\boxed{\text{5 CONSISTENT SUPERSTRING THEORIES IN } d=10}$

IIA	CLOSED	NON-CHIRAL
IIB	CLOSED	CHIRAL
I	OPEN + CLOSED	CHIRAL
HET. $E_8 \times E_8$	CLOSED	CHIRAL
HET. $SO(32)$	CLOSED	CHIRAL

THEY ARE PERTURBATIVELY ($g_s \to 0$) INEQUIVALENT, BUT ARE DIFFERENT LIMITS OF THE SAME AND UNIQUE THEORY : $\boxed{\text{M-THEORY}}$ $\boxed{\text{11-DIM THEORY}}$



D(IRICHLET) - BRANES

- LOW-ENERGY STRING EFFECTIVE ACTION FOR IIA + IIB THEORIES:

$$S = \frac{1}{2\kappa_{10}^{2}} \int d^{10}x \sqrt{-G} \Big\{ R - \frac{1}{2} G^{\mu\nu} \partial_\mu \phi \, \partial_\nu \phi$$

DILATON

$$- \frac{1}{2\cdot 3!} F_{\mu\nu\rho} F^{\mu\nu\rho} e^{-\phi} - \sum_p \frac{1}{2(p+2)!} F_{p+2}^{2} \, e^{\frac{3-p}{2}\phi} +$$

$$+ \text{fermions} + O(\alpha') \Big\} \; ; \quad \boxed{2\kappa_{10}^2 = (2\pi)^7 (\alpha')^4 g_s^2}$$

(STRING CORRECTIONS)

FIELD STRENGHTS:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \; ; \quad F_{\mu\nu\rho} = \partial_\mu B_{\nu\rho} + \partial_\nu A_{\rho\mu} + \partial_\rho A_{\mu\nu} \quad \text{etc.}$$

• LOOK FOR SOLUTIONS OF THE CLASSICAL EQS. OF MOTION OBTAINED FROM THE LOW-ENERGY STRING EFFECTIVE ACTION: (8)

$$(ds)^2 = G_{\mu\nu} dx^\mu dx^\nu = H(r)^{-\frac{7-p}{8}} \eta_{\alpha\beta} dx^\alpha x^\beta + H(r)^{\frac{p+1}{8}} \eta_{ij} dx^i dx^j$$

$$\mu \equiv (\alpha, i) \quad ; \quad \alpha = 0, \dots p \quad ; \quad i = p+1, \dots 9$$

$$e^{-(\phi-\phi_0)} = H(r)^{\frac{p-3}{4}} \; ; \; A_{01\dots p} = \frac{1}{H} - 1$$

WITH

$$H = 1 + \frac{K_p N}{r^{\overset{7-p}{(d-3)}}} \quad ; \quad r = \sum_i x_i^2$$

$$K_p = \frac{2\varkappa_{10} \tau_p}{(7-p)\,\Omega_{8-p}} \leftarrow \text{VOLUME OF THE (8-p)-DIM. SPHERE}$$

$$\text{BRANE TENSION} = \frac{M}{\text{p-VOLUME}} = \int d^{9-p}x \, \theta_{00} = \tau_p N$$

$$\text{BRANE CHARGE} = \frac{1}{\sqrt{2}\,\varkappa_{10}} \int_{S^{8-p}} e^{-\frac{p-3}{2}\phi} {}^*F_{8-p} =$$

$$= \sqrt{2}\,\varkappa_{10} \tau_p N = \mu_p N \quad ;$$

• IN STRING THEORY THE Dp-BRANES ARE CHARACTERIZED BY THE FACT THAT OPEN STRINGS HAVE THEIR ENDPOINTS ATTACHED TO THEM

(DIRICHLET BOUNDARY CONDITIONS)

SPECTRUM OF OPEN STRINGS GIVEN B.

$$\alpha' p_{\parallel}^2 + \sum_{n=1}^{\infty} n\, a_n^{+} a_n + \sum_{r=1/2}^{\infty} r\, \psi_r^{+} \psi_r - \frac{1}{2} = 0$$

MASSLESS STATES : $\left(\psi^{\alpha +}_{+1/2} \, ; \, \psi^{i+}_{1/2}\right)|0,p\rangle$

GAUGE FIELD LIVING ON THE BRANE

TRANSLATIONAL MODE IN THE TRANSVERSE SPACE
↓
HIGGS FIELD

COORDINATES OF A Dp-BRANE ARE :

$$\left(A^{\alpha} \quad , \quad X^{i} \equiv 2\pi\alpha' \Phi^{i} \right)$$

ABELIAN [U(1)] GAUGE THEORY ON THE WORLD VOLUME OF A Dp-BRANE.

• A SYSTEM OF N COINCIDENT Dp-BRANES HAS A U(N) NON ABELIAN GAUGE THEORY.

ONE HAS N^2 MASSLESS STATES CORRESPONDING TO A U(N) GAUGE FIELD.

IN CONCLUSION

- OPEN STRINGS $\Longleftrightarrow$ FIELDS OF THE STANDARD MODEL OR OF ITS EXTENSION

THEY LIVE ON THE Dp-BRANE.

"TOP DOWN" APPROACH (1985 →)

- START WITH 10-DIM. HETEROTIC STRING ($E_8 \times E_8$) COMPACTIFY 6 OF 10 DIMENSION (ON CALABI-YAU MANIFOLD) SO THAT

$$E_8 \times E_8 \longrightarrow \underbrace{E_6 \times E_6}_{\text{GRAND-UNIFIED GROUP}}$$

→ BROKEN THEN TO THE SM GROUP.

- GRAND-UNIFICATION SCALE

$$M_{GUT} \sim \frac{1}{R} \sim 10^{16}\,\text{GeV} \Longrightarrow R \sim 10^{-30}\,\text{cm}$$

RADIUS OF COMPACTIFIED DIMENSIONS.

- EXTRA-DIMENSIONS + STRING EFFECTS NOT DIRECTLY OBSERVABLE AT PRESENT (OR FUTURE) EXPERIMENTS.

- IN ORDER TO COMPARE WITH EXPERIMENTS (DONE AT 10^3 GeV) ⟹ HUGE EXTRAPOLATIONS STRING DYNAMICS MUST BE UNDERSTOOD VERY PRECISELY !!

BOTTOM UP APPROACH (1999 →)

- LOOK AT D-BRANE CONFIGURATIONS WITH WORLD VOLUME RESEMBLING AS MUCH AS POSSIBLE THE SM (EVEN BEFORE COMPACTIFYING 6 OF 10 DIMS.)

  1. GAUGE GROUP $SU(3) \otimes SU(2) \otimes U(1)_Y$
  2. 3 GENERATIONS OF CHIRAL QUARKS + LEPTONS
  3. NATURAL APPEARENCE OF THE WEAK HYPERCHARGE Y + CORRECT VALUES OF Y FOR QUARKS + LEPTONS.

- INTERESTING MODELS BASED ON D3-BRANES AT ORBIFOLD SINGULARITY

$$M^{10} \to M^4 \otimes \frac{R^6}{Z^3}$$

Aldazabal et al. (hep-th/0005067)

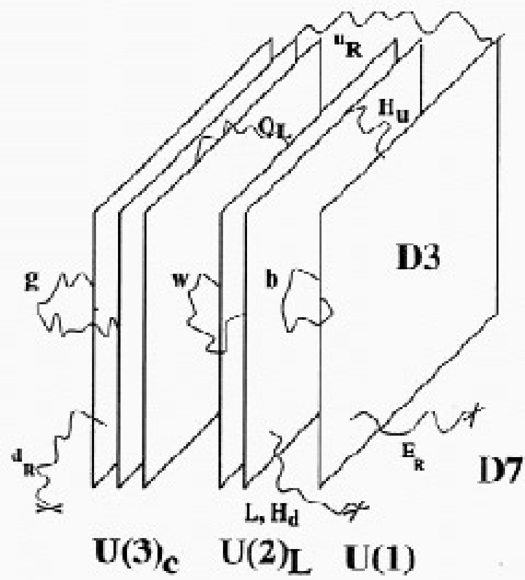


Figure 3: D-brane configuration of a SM $\mathbb{Z}_3$ orbifold model. Six D3-branes (with worldvolume spanning Minkowski space) are located on a $\mathbb{Z}_3$ singularity and the symmetry is broken to $U(3) \times U(2) \times U(1)$. For the sake of visualization the D3-branes are depicted at different 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).

GAUGE COUPLING UNIFICATION

TREE LEVEL (AT M_S)

$$g_3^2 : g_2^2 : g_1^2 = 1 : 1 : \frac{11}{3}$$

$$\sin^2\theta_W = \frac{3}{14} = 0.215$$

RUNNING TO LOW ENERGY

$$\sin^2\theta_W(M_Z) = \frac{3}{14}\left(1 + \frac{11}{6\pi}\alpha(M_Z)\left(b_2 - \frac{3}{11}b_1\right)\log\frac{M_S}{M_Z}\right)$$

$$\frac{1}{\alpha_3(M_Z)} = \frac{3}{14}\left(\frac{1}{\alpha(M_Z)} - \frac{1}{2\pi}\left(b_1 + b_2 - \frac{14}{3}b_3\right)\log\frac{M_S}{M_Z}\right)$$

IN SM ONE-LOOP CORRECTION HAS A WRONG SIGN

$$\sin^2\theta_W(M_Z) = 0.18 \quad ; \quad M_S = 2.2\cdot 10^{15}\,\mathrm{GeV}$$

$$0.204 \qquad\qquad 10^{10}\,\mathrm{GeV}$$

$\boxed{\text{EXP. VALUE } 0.231}$

IN A LEFT-RIGHT SYMMETRIC MODEL

$$\sin^2\theta_W(M_Z) = 0.231 \quad ; \quad M_S = 9\cdot 10^{11}\,\mathrm{GeV}$$

EQUAL PRECISION AS MSSM !!

- 3 - GLUON AMPLITUDE

$$\mathcal{A}(1,2,3) = \underbrace{C_0 N_D^3}_{\hookrightarrow\, 4 g_{YM;p+1} = 4 \cdot 2 g_{open} (2\alpha')^{\frac{p-3}{4}}} A(1,2,3)\, \mathrm{Tr}\left(\lambda^{a_1}\lambda^{a_2}\lambda^{a_3} - \lambda^{a_3}\lambda^{a_2}\lambda^{a_1}\right)$$

$$\mathrm{Tr}(\lambda^a \lambda^b) = \frac{1}{2}\delta^{ab}$$

$$A(1,2,3) = (\varepsilon_1 \cdot p_2)(\varepsilon_2 \cdot \varepsilon_3) + (\varepsilon_2 \cdot p_3)(\varepsilon_1 \cdot \varepsilon_3) + (\varepsilon_3 \cdot p_1)(\varepsilon_1 \cdot \varepsilon_2)$$

- 4 - GLUON AMPLITUDE

$$\frac{\Gamma(1-\alpha' s)\,\Gamma(1-\alpha' t)}{\Gamma(1-\alpha' s-\alpha' t)} = 1 - \frac{(\alpha')^2 st}{6}$$

STRING CORRECTION CORRESPONDING TO AN OPERATOR OF DIMENSION 8.

IN hep-ph/0001166

$$\frac{d\sigma}{d\cos\theta}\left(e^+e^- \to 2\gamma\right) = \frac{d\sigma}{d\cos\theta}\left(e^+e^- \to 2\gamma\right)\Big|_{SM}\left[1 + \frac{\pi^2 u t}{12 M_s^4}\right]$$

$$\frac{d\sigma}{d\cos\theta}\left(e^+e^- \to e^+e^-\right) = \frac{d\sigma}{d(\cos\theta)}\left(e^+e^- \to e^+e^-\right)\Big|_{SM}\left|\frac{\Gamma\left(1-\frac{s}{M_s^2}\right)\Gamma\left(1-\frac{t}{M_s^2}\right)}{\Gamma\left(1-\frac{s+t}{M_s^2}\right)}\right|^2$$

FROM LEP DATA $\Longrightarrow$ $M_s \gtrsim 1$ TeV

REMEMBER THAT KALUZA-KLEIN EXCITATIONS OF GAUGE BOSONS GIVE RISE TO OPERATORS OF DIMENSION 6 (AS 4-FERMION INTERACTION)

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