Physics from open string wavefunctions

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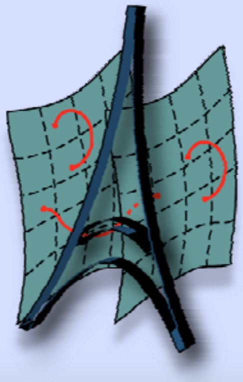

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Outline

- Type II String Theory model building

- Open string wavefunctions

- Recent progress

- Conclusions

String Theory and Particle Physics

- String Theory has the right features for a unified framework of Gravitation and Particle Physics. Two important predictions:

    - Gravity

    - Matter fields transforming in gauge group representations

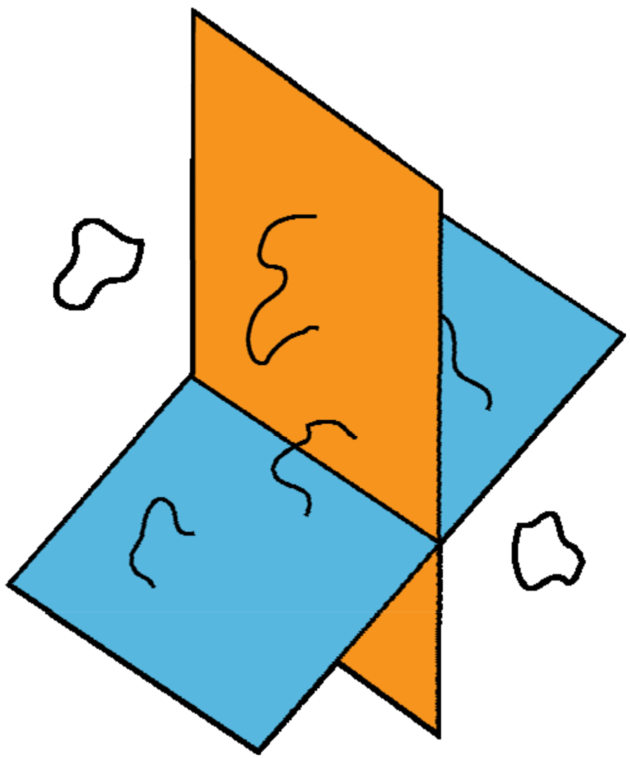
- Despite the difficulties to accomodate the Standard Model (large landscape of string vacuum solutions), a lot of progress have been carried out in last decade.

- Two major lines of attack:

    - Heterotic model building

    - Type II (D-brane) model building

D-brane model building

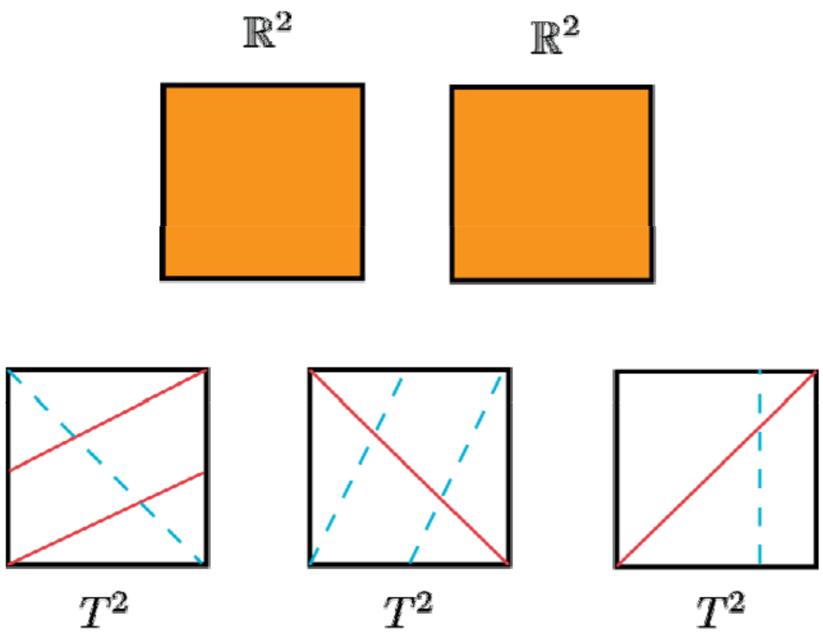


- Open strings lead to U(N), SO(2N), USp(N) gauge theories in the worldvolume of Dp-branes and their intersections, with fermions in (mainly) bifundamental representations.

- Several (dual) frameworks:
    - Intersecting D6-branes
    - D3/D7-branes at singularities
    - Magnetized D9-branes (type I strings)
    - ...

Intersecting D6-branes I

- E.g. consider stacks of D6-branes filling Minkowski and wrapping 3-cycles of a internal 6-torus.



$$\prod_a U(N_a)$$

$$[\Pi_a] = (n_a^1, m_a^1) \times (n_a^2, m_a^2) \times (n_a^3, m_a^3)$$

Intersection num.: $I_{ab} = \prod_{i=1}^{3} (n_a^i m_b^i - m_a^i n_b^i)$

- I_{ab} bifundamental chiral fermions $(N_a, \bar{N}_b)$ localized at the intersections

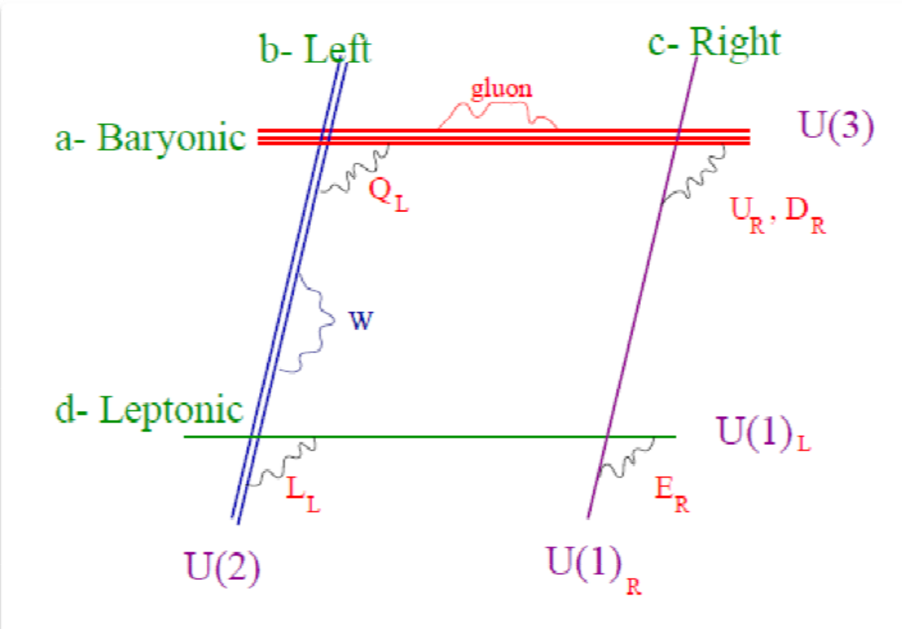
- Orientifold/orbifold action requires also mirror branes ⇨ symmetric/antisymmetric reps., orthogonal gauge groups...

- N = 1 SUSY condition: $\sum_{i=1}^{3} \frac{m_a^i}{n_a^i} \tau^i = \frac{m_a^1 m_a^2 m_a^3}{n_a^1 n_a^2 n_a^3} \tau^1 \tau^2 \tau^3$

Intersecting D6-branes II

[Cremades, Ibanez, Marchesano '02]

- E.g. 3-generation local MSSM model



N_α	(n_α^1, m_α^1)	(n_α^2, m_α^2)	(n_α^3, m_α^3)
$N_a = 3$	$(1, 0)$	$(g, 1)$	$(g, -1)$
$N_b = 1$	$(0, 1)$	$(1, 0)$	$(0, -1)$
$N_c = 1$	$(0, 1)$	$(0, -1)$	$(1, 0)$
$N_d = 1$	$(1, 0)$	$(g, 1)$	$(g, -1)$

- One of the U(1)'s becomes massive through the Green-Schwarz mechanism

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

Magnetized D9-branes

- Intersecting D6-branes are dual to configurations of magnetized D9-branes, filling 4D Minkowski and the whole 6-dimensional internal space

$$F_{z^k \bar{z}^k} = \frac{\pi i}{\text{Im } \tau^k} \begin{pmatrix} \frac{m_a^k}{n_a^k} \mathbb{I}_{N_a} & & \\ & \frac{m_b^k}{n_b^k} \mathbb{I}_{N_b} & \\ & & \ldots \end{pmatrix}$$

- Magnetization in D9-branes Higgsses the gauge group: $G_{unbr} = \prod_\alpha G_\alpha$

⟹ W-bosons, scalars and fermions in bifundamental reps.

- SUSY condition becomes: $J \wedge J \wedge F_2 - \frac{1}{3} F_2 \wedge F_2 \wedge F_2 = 0$

- Open strings are charged under F_2 ⟹ localization of wavefuntions

Open string wavefunctions I

- This system admits a description in terms of field theory, where the D9-brane d.o.f. are given by 10D Super Yang-Mills

$$S = -\int dx^{10} (\det g)^{1/2} \mathrm{Tr} \left[\frac{1}{4} F_{MN} F^{MN} + \bar{\chi} \Gamma^M D_M \chi \right]$$

- Open strings can be understood as wavefunctions. These arise from standard KK reduction as eigenfunctions of the internal Dirac and Laplace operators

$$D_m D^m \Phi^i = -m_\Phi^2 \Phi^i \; , \qquad \gamma^m D_m \psi = m_\psi \psi^*$$

- Magnetized torus ⇨ Landau levels

- Number of massless modes given by the Dirac index I_{ab}

Open string wavefunctions II

[Cremades, Ibanez, Marchesano '04]

- Solutions for a 2-tori given in terms of Jacobi theta functions

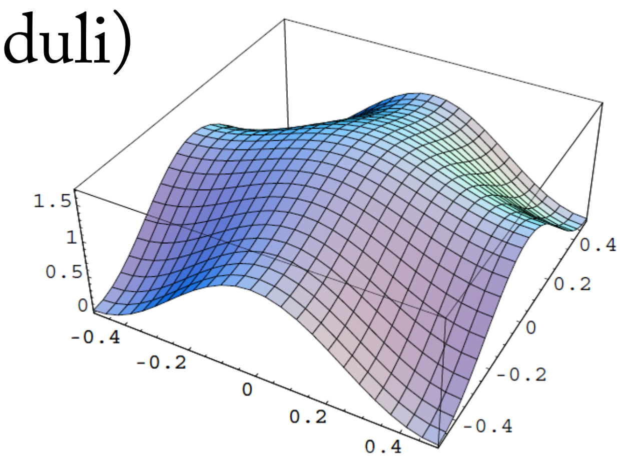
$$\psi^{j,I_{ab}}(\tau,z) \sim \exp\left[\frac{i\pi|I_{ab}|z\text{Im }z}{\text{Im }\tau}\right]\cdot\vartheta\left[\begin{array}{c}\frac{j}{|I_{ab}|}\\ 0\end{array}\right](|I_{ab}|z\,,\,|I_{ab}|\tau)\,, \qquad j=0\ldots|I_{ab}|-1$$

- Under global monodromies transform with the right U(1) charge

$$z \to z+1\,, \qquad \psi^{j,I_{ab}} \to e^{i\pi|I_{ab}|\text{Im }z/\text{Im }\tau}\ \psi^{j,I_{ab}}$$
$$z \to z+\tau\,, \qquad \psi^{j,I_{ab}} \to e^{i\pi|I_{ab}|\text{Im }\bar{\tau}z/\text{Im }\tau}\ \psi^{j,I_{ab}}$$

- Localization effects (depending on W.L. moduli)

- For higher dim. factorizable tori, products of theta functions



Open string wavefunctions III

- Open string wavefunctions are the target-space analogous of vertex operators in the worldsheet CFT

- O.P.E:

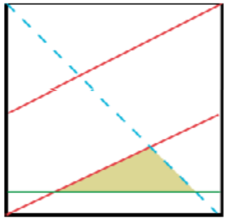
$$\psi^{i,I_{ab}} \cdot \psi^{j,I_{ca}} = \mathcal{A}^{-1/2}(2\mathrm{Im}\ \tau)^{1/4} \left|\frac{I_{ab}I_{ca}}{I_{bc}}\right|^{1/4} \cdot \sum_{m=0}^{I_{bc}-1} \psi^{i+j+I_{ab}m, I_{cb}}(z) \cdot \vartheta \begin{bmatrix} \frac{I_{ca}i - I_{ab}j + I_{ab}I_{ca}m}{|I_{ab}I_{bc}I_{ca}|} \\ 0 \end{bmatrix} (0\ ,\ \tau|I_{ab}I_{bc}I_{ca}|)$$

- Physical observables as overlap integrals of wavefunctions.

E.g. Yukawa couplings,

[Cremades,Ibanez,Marchesano]
[Di Vecchia et al.]
[Antoniadis,Kumar,Panda]

$$Y_{ijk} = \int_{T^2} \psi_i^{a\dagger}\Gamma^m \psi_j^b \phi_{k,m}^c f_{abc} \sim \vartheta \begin{bmatrix} \frac{i}{|I_{ab}|} + \frac{j}{|I_{ca}|} + \frac{k}{|I_{bc}|} \\ 0 \end{bmatrix} (0\ ,\ \tau|I_{ab}I_{bc}I_{ca}|)$$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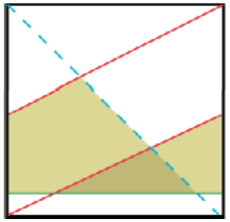

$+ \dots$

Closed string fluxes I

- In the last years closed string fluxes have become a new ingredient for model building

  - Stabilization of compactification moduli
  - de Sitter vacua
  - Inflation
  - ...

- Fluxes have also interesting effects on D-branes

  - Soft-terms/moduli stabilization
  - D-terms and superpotentials
  - Instanton zero-mode lifting
  - Warp effects

Closed string fluxes II

- Perhaps better understood in the D3/D7-brane picture: 3-form fluxes

$$\boxed{G_3 = F_3 - SH_3} \Rightarrow \text{ISD 3-form (e.o.m.)}$$

backreaction (warping): $ds^2 = Z^{-1/2} ds^2_{\mathbb{R}^{1,3}} + Z^{1/2} ds^2_{\mathcal{M}_6}$ $\Rightarrow$ Randall-Sundrum

- Stabilization of dilaton, c.structure moduli and D7-brane positions

- Example: global MSSM flux vacua (T^6/Z_2 x Z_2 orbifold)

[Marchesano, Shiu '05]

N_α	(n^1_α, m^1_α)	(n^2_α, m^2_α)	(n^3_α, m^3_α)
$N_a = 6$	$(1,0)$	$(3,1)$	$(3,-1)$
$N_b = 2$	$(0,1)$	$(1,0)$	$(0,-1)$
$N_c = 2$	$(0,1)$	$(0,-1)$	$(1,0)$
$N_d = 2$	$(1,0)$	$(3,1)$	$(3,-1)$
$N_{h_1} = 2$	$(-2,1)$	$(-3,1)$	$(-4,1)$
$N_{h_2} = 2$	$(-2,1)$	$(-4,1)$	$(-3,1)$
$N_f = 8$	$(1,0)$	$(1,0)$	$(1,0)$

Magnetized D7-branes

$$G_3 = 2(d\bar{z}^1 dz^2 dz^3 + dz^1 d\bar{z}^2 dz^3 + dz^1 dz^2 d\bar{z}^3 + d\bar{z}^1 d\bar{z}^2 d\bar{z}^3)$$

Recent progress I

-We have developed techniques to compute open string wavefunctions in the presence of closed string fluxes (and magnetization)

- In terms of D9-branes (type I strings) these fluxes correspond to compactifications on elliptic fibrations (T^2 over a four dimensional base B_4) with RR 3-form fluxes (S-dual to heterotic strings with torsion)

- Simple examples given by twisted tori: $B_4 = T^4$

[Dasgupta et al.]
[Schultz]
[PGC, Grana]
[Lust et al.]

$$de^a = \frac{1}{2} f^a_{bc} e^b \wedge e^c$$

Recent progress II

[PGC, Marchesano '09]

- In the filed theory limit there are modified internal Dirac and Laplace-Beltrami operators which account for the effect of the closed string background on the open string fluctuations.

W-bosons:

$$D^m D_m W^{\alpha\beta} - 2(\partial_m \log Z) D^m W^{\alpha\beta} = -Z^{1/2} m_W^2 W^{\alpha\beta}$$

Charged scalars:

$$D^m D_m \Phi^{p,\alpha\beta} - [\nabla_m^{\mathcal{M}_6}, \nabla^{\mathcal{M}_6 p}]\Phi^{m,\alpha\beta} - 2(\partial_k \log\, Z) D^{[k}\Phi^{p],\alpha\beta} + \\ + 2i\Phi^{m,\alpha\beta}(F_m{}^{p,\alpha} - F_m{}^{p,\beta}) + e^{\phi/2}(\tilde{D}_m \Phi^{n,\alpha\beta})F_n{}^{mp} = -Z^{1/2} m_\Phi^2 \Phi^{p,\alpha\beta}$$

Matter fields:

$$\Gamma_{(4)}\left(\not{D}^{\mathcal{M}_6} + \frac{1}{4}e^{\phi/2}\not{F}_3 - \frac{1}{2}\not{\partial}\ln Z\right)\psi = Z^{1/4} m_\psi \mathcal{B}_6^* \psi^*$$

- Notice that for this case there is no known worldsheet CFT, so the field theory description is the only possibility

Recent progress III

- Solutions are found using the non-abelian Fourier transform

$$\psi_{\vec{\omega}}(g) = \sum_{\gamma \in \Gamma} \pi_{\vec{\omega}}(\gamma g) \varphi(\vec{s}_0)$$

- Classified by irreducible unitary reps. of the 4D gauge algebra which results from KK reduction

$$[D_m, D_n] = -f^p_{mn} D_p + i F^\alpha_{mn} U_\alpha$$
$$[D_m, U_\alpha] = [U_\alpha, U_\beta] = 0$$

- Similar observations made in other contexts
  - Fluxless CY [Douglas et al. '08]
  - WZW models

Recent progress IV

- In models with circle fibrations, wavefunctions are similar to the ones in the fluxless case but with oblique magnetization

$$\psi^{(j_1,j_2)} \sim e^{i\pi(\mathbf{N}\cdot\vec{z})\cdot(\mathrm{Im}\ \mathbf{\Omega_U})^{-1}\cdot\mathrm{Im}\ \vec{z}}\ \vartheta\begin{bmatrix}\vec{j}\\0\end{bmatrix}(\mathbf{N}\cdot\vec{z};\ \mathbf{N}\cdot\mathbf{\Omega_U})\ e^{2\pi i(k_3x^3+k_6x^6)}$$

$$\vec{z} = \begin{pmatrix}x^4\\x^2\end{pmatrix} + \mathbf{\Omega_U}\cdot\begin{pmatrix}x^1\\x^5\end{pmatrix} \qquad \mathbf{\Omega_U} = \bar{\mathbf{B}}^{-1}\cdot\bar{\mathbf{U}}\cdot\bar{\mathbf{B}}\cdot\mathbf{\Omega}$$

$$\mathbf{N} = \begin{pmatrix}-I^1_{\alpha\beta} & -k_6M\\ k_6M & I^2_{\alpha\beta}\end{pmatrix} \quad \mathbf{U} = \begin{pmatrix}\cos\phi & \sin\phi\\ -\sin\phi & \cos\phi\end{pmatrix} \quad \tan\phi = \frac{\rho_{\mathrm{cl}}}{\rho_{\mathrm{op}}}$$

- Open/closed string duality

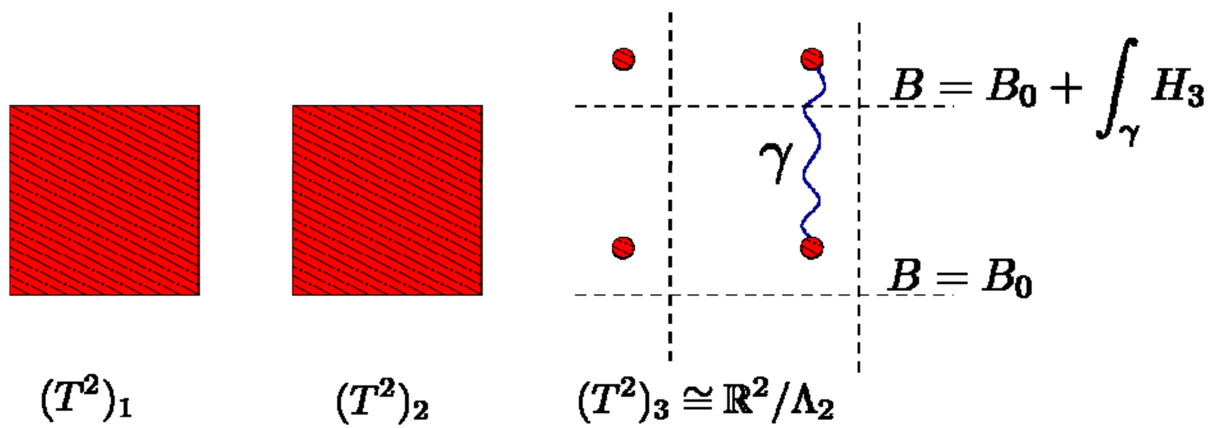
closed string		open string
e^6	$\leftrightarrow$	A
x^6	$\leftrightarrow$	Λ
F_3	$\leftrightarrow$	ω_3

[Becker '07]
[Sethi '07]
[Evslin, Minasian '08]
[PGC, Marchesano '09]

- O.P.E. for oblique magnetization worked out recently [Antoniadis et al. '09]

Recent progress V

- The analysis in terms of open string wavefuntions reveals that
  - D7-brane KK modes are not affected by closed string fluxes
  - D7-brane windings suffer Landau degeneracies ⇨ thresholds



Mass formula:

$$m_W^2 = \left(\frac{k_3}{R_3}\right)^2 + \left(\frac{k_6}{R_6}\right)^2 + (n+1)\rho + (2k-n)\frac{\sigma_+\sigma_-}{\rho} \qquad k, n \in \mathbb{Z}$$

Recent progress VI

[Shiu et al. '08]

- Open string wavefunctions are affected by the warping
- For massless D7-brane (neutral) modes

$$\boxed{\psi \sim Z^p}$$

whereas the kinetic terms are also rescalled

$$\boxed{\int_{\mathbb{R}^{1,3}} dx^4 \bar{\chi}\partial\chi \int_{T^4} dy^4 Z^q}$$

D7		
4D Field	p	q
gauge boson/modulus	0	1
gaugino/modulino	3/8	
Wilson line	0	0
Wilsonino	$-1/8$	

Conclusions

- Open strings ending in Dp-branes provide a good context to embed semi-realistic chiral gauge theories in String Theory

- In the field theory limit these are described in terms of open string wavefunctions, which play a similar role to vertex operators in CFT

- Wavefunctions are useful for computing 4D observables in models which admit a higher dimensional sugra description

- 4D couplings are given in terms of overlap integrals

- Techniques for computing open string wavefunctions in flux compactifications are being developed

- These may provide us also with hints on the 2D CFT of flux compactifications

- Some effort along these directions is still required

Thank you!