CP from STRINGS

Ideas and Problems

(No predictions...)

MORIOND EW 2002

T. Dent, Michigan U.

1. CP as gauge symmetry
2. CP as geometry
3. CP as scalar field VEVs
4. Problems of ~~CP~~ in SUSY
5. Problems of strings
6. A "positive" result

CP: 4D symmetry, $\psi_L(x_\mu) \to -\sigma_2 \psi_L^*(x^\mu)$

Strings: 10D, $G_L = SO(9,1)$

$G_g = GL(9,1)$

$G_{YM} = E_8^2,\ SO(32)$

Connection? $CP \in G_L \times G_g \times G_{YM}$

(discrete) <u>gauge</u> symm.

Choi, Kaplan, Nelson

Dine, Leigh, McIntire

$\sigma_2 \psi_L^*$ in same irrep as ψ_L in 10D

↳ Majorana-Weyl ✓

↳ real irreps ✓ (take $Q_\psi \to -Q_\psi$ in G_{YM})

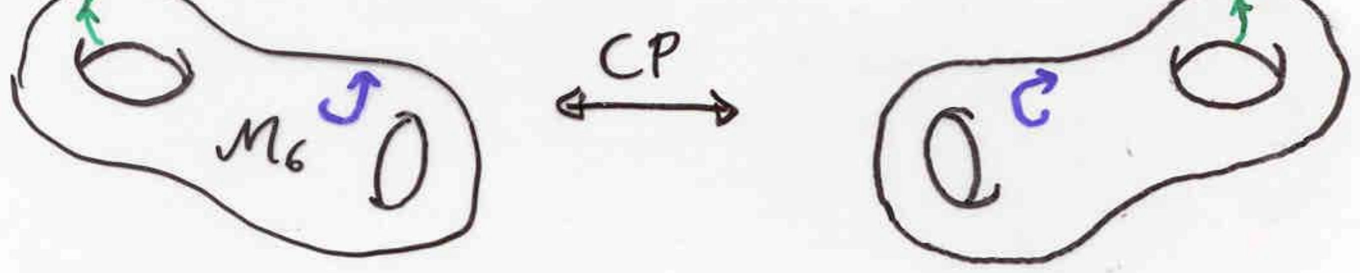
P is <u>improper</u> Lorentz in 4D

BUT <u>proper</u> Lorentz in 10D

$\det K_L = -1$

$$\left(\begin{array}{cccc|c} 1 & & & & \\ & -1 & & & 0 \\ & & -1 & & \\ & & & -1 & \\ \hline & & 0 & & K_L \end{array}\right) \begin{array}{l} \updownarrow x^\mu \\ \\ \updownarrow x^m \end{array}$$

Reverses orientation of $\mathcal{M}_6$



Strominger, Witten '85

Gauge symm. $\rightarrow$ conserved to all orders
+ nonperturbatively... $\theta_{tree} = 0$

Broken spontaneously by $\mathcal{M}_6$ ($G_L \rightarrow SO(3,1)$
$G_{YM} \rightarrow SU(3) \times SU(2) \times U(1) \times$ ...)
or scalar fields at $E \ll \frac{1}{L_s}$

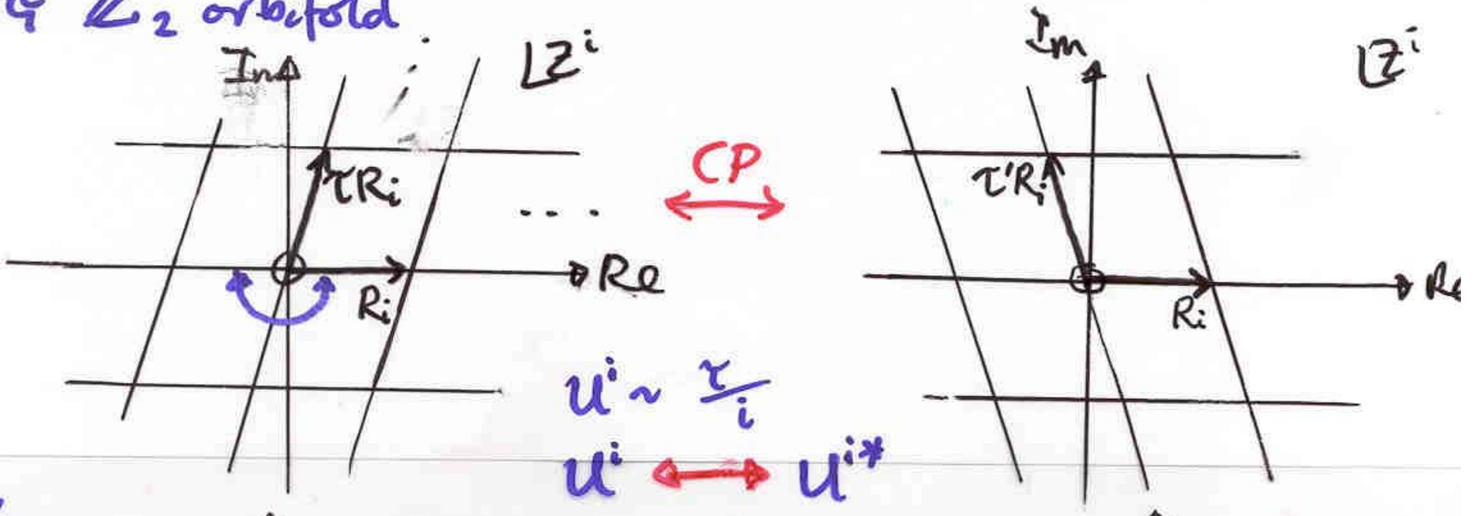
$\hookrightarrow$ calculable $y^u_{ij} = y^u_{ij}(g_{MN}(\mathcal{M}_6), \ldots)$

In practice: too hard for general $\mathcal{M}_6$

Easier: orbifolds $\dfrac{T^6}{\Gamma} \sim \dfrac{T^2 \times T^2 \times T^2}{\mathbb{Z}_N \times \mathbb{Z}_M}$

trade x^M $M = 4, \ldots, 9 \Rightarrow Z^{1,2,3}$ $\boxed{CP : Z^i \rightarrow Z^{i*}}$

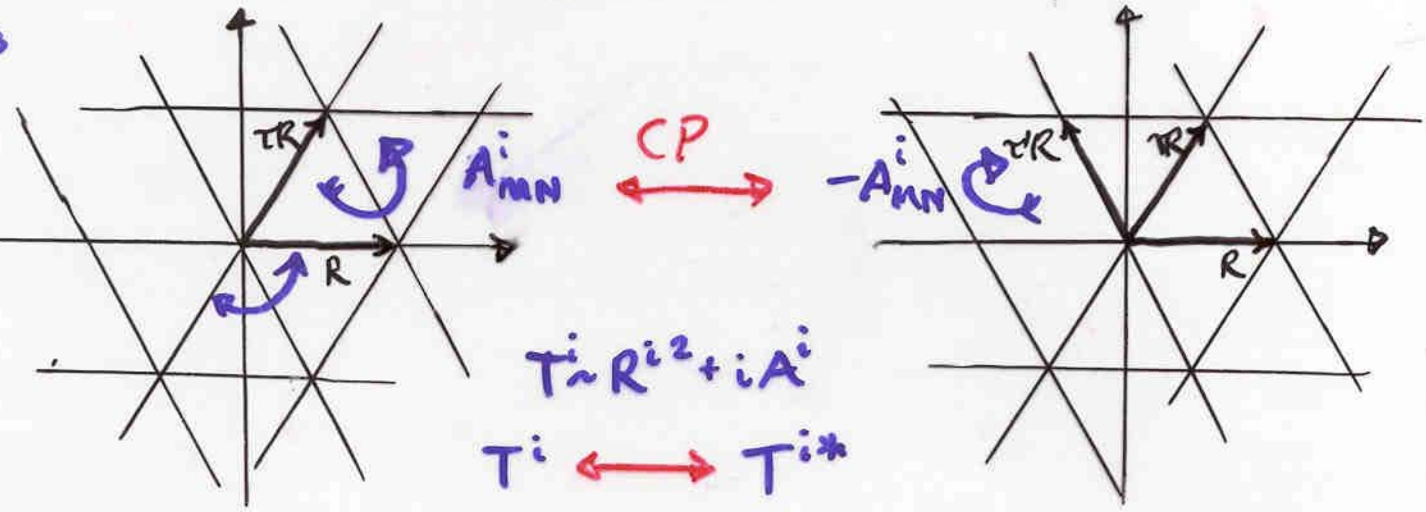
EG $\mathbb{Z}_2$ orbifold



$U^i \sim \frac{\tau}{i}$

$U^i \longleftrightarrow U^{i*}$

$\mathbb{Z}_3$



$T^i \sim R^{i2} + iA^i$

$T^i \longleftrightarrow T^{i*}$

Orbifolds → calculate $y^{u,d,e}(U^i, T^i)$ exactly

In practice: $\left(\text{simple enough to calculate}\right) \bigcap \left(\text{Realistic}\right) = \phi$

→ toy models, unrealistic but still $\cancel{CP}$.

NOTE – "MODULI"

U^i, T^i can vary continuously

↳ $U^i(x^\mu)$, $T^i(x^\mu)$

Unbroken SUSY → $V = 0$ → $V(T^i, U^i) = 0$

→ MASSLESS SCALARS

After $\cancel{\text{SUSY}}$: $V(T^i, U^i) \neq 0$

$$\mathcal{L} = \int d^4x \; - y_u^{ij}(U,T)\, \bar{q}_L^i u_R^j H \; - V(U,T)$$

$+ \ldots$

$+$ SUSY – breaking

V stabilizes U_i, T_i

↳ generically, $\cancel{\text{SUSY}}$ $\begin{cases} \text{is fn. of } U_i, T_i \\ \text{violates CP} \ldots \end{cases}$

Expect non-SM signals of $\cancel{CP}$ ☹

non-MFV

Supersymmetric CP problem

"Most of SUSY parameter space is ruled out"...

Expt: EDM's

$|d_n| < 6.3 \times 10^{-26}$ e cm — Harris et al.

$|d_e| < 4.3 \times 10^{-27}$ e cm — Commins et al. [improvements soon?]

$|d_{Hg}| < 2.1 \times 10^{-28}$ e cm — Romalis et al.

SM: negligibly small predictions $\lesssim 10^{-30}$ e cm ($\ll$)

SUSY: Gaugino masses $M_a \, \lambda_\alpha \lambda_a$ $\quad a = \overset{3}{SU(3)}, \overset{2}{SU(2)}, \overset{1}{U(1)}$

$\hookrightarrow \phi_a$

"B-term" $\quad B\mu \, H_u H_D$

"A-terms" $\quad A^u_{ij} \, y^u_{ij} \, \tilde{Q}_i \, \tilde{u}^c_j \, H_u$

Invariant phases; $\phi_{\frac{1}{2}} - \phi_3$, $\mathrm{Arg}((B\mu)^* \mu M_3^*) \equiv \phi_B$,

$\mathrm{Arg}(A^{U,D,L}_{ij} M_3^*) \equiv \phi_{A^{UDL}_{ij}}$

Estimate e.g.

$$d_n \sim \left[a 10^{-23} \sin \begin{Bmatrix} \phi_{\frac{1}{2}} - \phi_3 \\ \phi_\mu \end{Bmatrix} + b 10^{-24} \sin \phi_{A_{u,d}} \right] \text{e cm}$$

$a, b \sim \left(\frac{200\,G}{M_{\tilde{q}}}\right.$

$\phi_{SUSY} \lesssim 10^{-2}$ $\quad$ CF. $\delta_{CKM} = 0.5 - 1$

"Solutions":

- Heavy squarks of 1st + 2nd generations
- "Cancellations" – mostly excluded by d_{Hg}
- Small phases – "approximate CP conservation" Eyal, N... Dine et al '0...

  $\delta_{CKM}, \phi_{SUSY} < 0.1$ $\epsilon_K, \frac{\epsilon'}{\epsilon}$ from SUSY

  predicted $A_{CP}(B \to J/\psi K_S) < 0.1$

[NOTE: δ_{CKM} <u>can</u> be $O(1)$ with $\mathrm{Arg}\, y_{ij} < 10^{-2}$ ...
view J_{CP} as a small number. Need to know flavour structure]

Can string models provide a reason for
$\begin{cases} \text{small } \phi_{SUSY} \\ \text{large } \delta_{CKM} \end{cases}$?

Abel + Servant "CP and Flavour in Type I String Models"
↳ (some) $\phi_{SUSY} = 0$ from $\begin{cases} U(1) \text{ horizontal flavour symm.} \\ \text{special form of } \underline{\text{SUSY}} \text{ dynamics} \end{cases}$

[But : • incomplete, "string-inspired"
• problems of its own...]

String problems

Actual string models with MSSM
$\rightarrow$ difficult!

usually MSSM + extra $U(1)$'s
+ exotic matter
⋮

e.g. Lebedev ('01) calculate $J_{CP}(T)$
BUT full model has >3 generations
heavy matter <u>assumed to decouple</u> ...

decoupling "unwanted" matter <u>can</u> affect $\begin{cases} V_{CKM}, \\ y_{ud} \end{cases}$ TD(
need to know explicit mechanism

Generic string problems:
- $V_0 \neq 0$ after $\cancel{SUSY}$ "cosmological constant problem"
- mechanism of $\cancel{SUSY}$ - unknown
- difficult to stabilize all scalars

Generating flavour : $y = y(T, U)$ $^{(u)}$ difficult to get correct $\begin{cases} m_q \\ V_{CKM} \end{cases}$

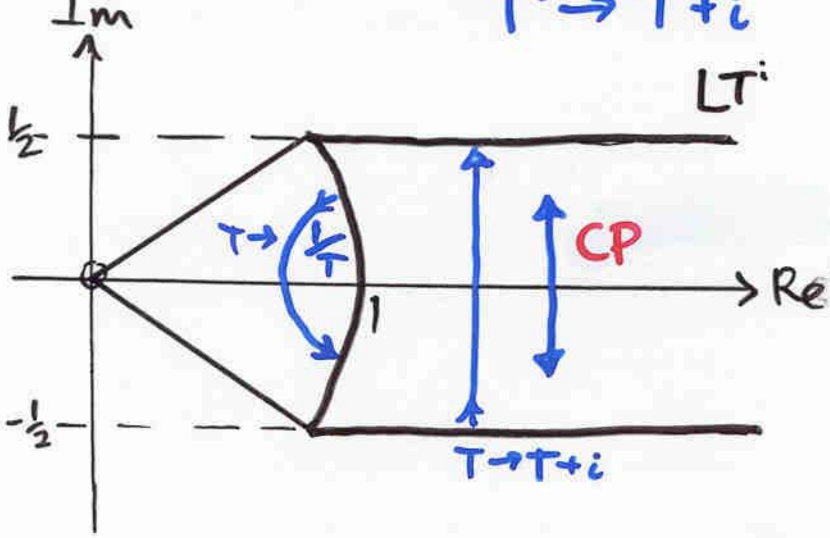
$y_{eff} = y(T,U)\langle X \rangle$
$\hookrightarrow$ nonrenormalizable

Result using string symmetries

TD('01)

Exact symmetry $\quad T^i \to \frac{1}{T^i}$ $\qquad T = R^2 + iA$

$\qquad\qquad\qquad\quad T^i \to T^i + i$



If $\operatorname{Im} T = \pm\frac{1}{2}$: $T \to T^*$ is physically <u>invariant</u>

If $\quad T = 1 \quad$: $T \to T^*$ " " " $\left(T \to \frac{1}{T}\right)$

↪ CP is <u>not violated</u>!

$V(T)$ has symmetry → $T=1$, $T = e^{i\pi/6}$ stationary

"Approximate CP":

if $\langle T \rangle$ is near $\begin{cases} \operatorname{Im} T = \pm\frac{1}{2} \\ |T| = 1 \end{cases}$, $\cancel{CP}$ is "small"

need to know flavour structure...

- CP has a natural "home" in string theory

  (geometric symmetry)

- Suffers from usual problems of string phenomenology : $\begin{cases} \text{huge \# models} \\ \text{none of them really work} \end{cases}$

e.g. 3 gen + correct Yukawas → J_{CP}

- "Stringy" symmetry helps to interpret / rule out models

- Experimental results with flavour / ~~CP~~ beyond CKM would make us happy ...

  (SUSY flavour / ~~CP~~ even better!)