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Aspen 2/05

STRING THEORY – THE EARLY YEARS

A PERSONAL PERSPECTIVE

Some of the topics have been written up in three recent preprints:

hep-th/0007117 (Scherk)

hep-th/0007118 (Susskind)

hep-th/0011078 (Susy)

I will discuss the period 1960–85 at a rate of about 2 minutes per year.

DISCLAIMER: I make no pretense of balance, fairness, or objectivity.

ITP Colloquium – May 2001

OUTLINE

- 1960 - 68 The analytic S matrix
- 1968 - 70 The dual resonance model
- 1971 - 73 The NSR model
- 1974 - 75 Gravity + unification
- 1975 - 79 Supersymmetry + supergravity
- 1979 - 85 Superstrings
- Concluding comments

1960-68 THE ANALYTIC S MATRIX

GOAL: Theory of hadrons

UC Berkeley was center of universe

(Chew, Mandelstam, Weinberg, Glashow ...)

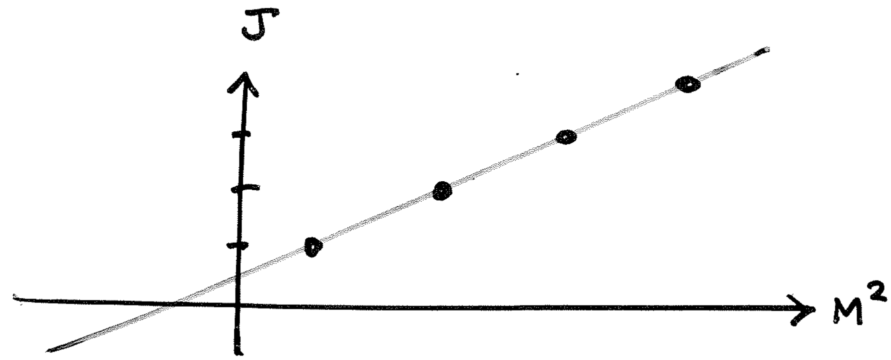
I was grad student there 1962-66

(so was David Gross)

PRINCIPLES:

- Only on-shell S Matrix is physical. Field theory is misguided.
- Unitarity and analyticity
- Bootstrap conjecture
- Analyticity in angular momentum

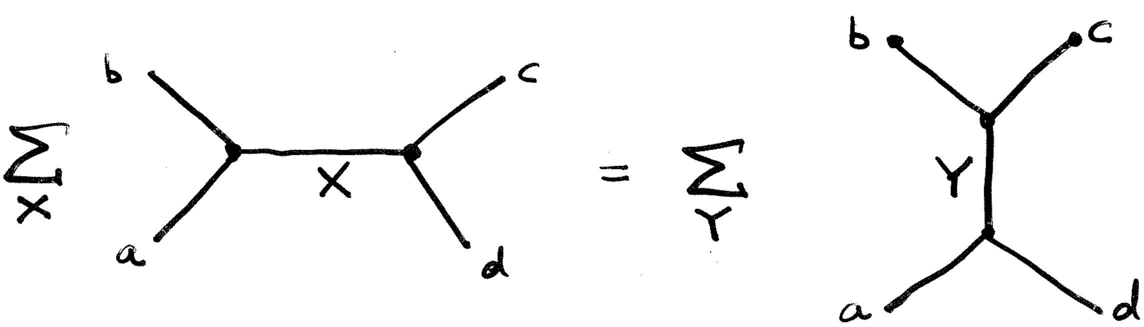
Regge Pole Theory

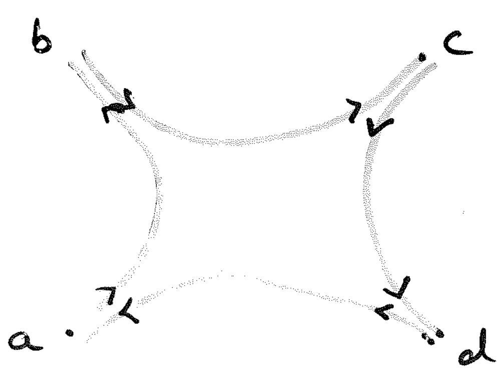


$$A(s,t) \sim \beta(t)\,(s/s_0)^{\alpha(t)} \quad , \quad t<0$$

$$\alpha' \sim 1.0\ (\mathrm{GeV})^{-2}$$

Duality





meson - meson scattering

1968-70 THE DUAL RESONANCE MODEL

Veneziano formula

$$T = A(s,t) + A(s,u) + A(t,u)$$

$$A(s,t) = \frac{\Gamma(-\alpha(s))\,\Gamma(-\alpha(t))}{\Gamma(-\alpha(s) - \alpha(t))}$$

where $\alpha(s) = \alpha(0) + \alpha' s$

This function gives an explicit realization of duality and Regge behavior in the "narrow resonance approximation". The motivation was phenomenological, but this turned out to be a tree amplitude in a theory!

Virasoro formula

$$T = \frac{\Gamma(-\frac{1}{2}\alpha(s))\,\Gamma(-\frac{1}{2}\alpha(t))\,\Gamma(-\frac{1}{2}\alpha(u))}{\Gamma(-\frac{1}{2}\alpha(t)-\frac{1}{2}\alpha(u))\,\Gamma(-\frac{1}{2}\alpha(s)-\frac{1}{2}\alpha(u))\,\Gamma(-\frac{1}{2}\alpha(s)-\frac{1}{2}\alpha(t))}$$

has similar virtues.

- N-particle generalization of Veneziano formula:

$$A_N = \int \Pi dy_i\, \mu(y) \prod_{i<j} (y_i - y_j)^{\alpha' k_i \cdot k_j}$$

This has cyclic symmetry in the N external lines.

- N-particle generalization of Virasoro formula

$$T_N = \int \Pi d^2 z_i\, \mu(z) \prod_{i<j} |z_i - z_j|^{\alpha' k_i \cdot k_j}$$

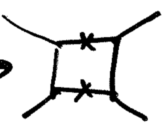
This has total symmetry in the N external lines.

Both of these formulas were shown to have a consistent factorization on a spectrum of single-particle states described by an ∞ number of oscillators

$\{a_m^\mu\}$ $\quad \mu = 0, 1, \ldots, d-1$
$\quad m = 1, 2, \ldots$ (2 sets for S-V case)

Eventually these formulas were interpreted as describing the scattering of modes of a relativistic string: open strings in the first case & closed strings in the second case. Amazingly, the formulas preceded the interpretation!

Having found the factorization, it became possible to study radiative corrections (loop amplitudes)

I was at Princeton & collaborated with Gross, Neveu, & Scherk in studying one-loop amplitudes. In particular, we found new singularities in the "nonplanar" open-string loop $s \to$  .

These appeared to be unitarity-violating branch points. Lovelace argued they would be poles for $\alpha(0) = 1$ & $d = 26$. Later they were interpreted as due to closed strings.

1971-73 NSR MODEL

RAMOND – string analog of Dirac eqn

$$p^\mu = \int_0^{2\pi} P^\mu(\sigma)\, d\sigma$$

$$\gamma^\mu = \int_0^{2\pi} \Gamma^\mu(\sigma)\, d\sigma$$

$$F_n = \int_0^{2\pi} e^{-in\sigma}\, \Gamma \cdot P\, d\sigma \quad , \quad n \in \mathbb{Z}$$

$$F_0 = \gamma \cdot p + \text{oscillator terms}$$

$(F_0 + m)|\psi\rangle = 0$ for a free fermionic string

Super-Virasoro algebra:

$$\{F_m, F_n\} = 2L_{m+n} + \frac{c}{3} m^2 \delta_{m,-n}$$

$$[L_m, F_n] = \left(\frac{m}{2} - n\right) F_{m+n}$$

$$[L_m, L_n] = (m-n) L_{m+n} + \frac{c}{12} m^3 \delta_{m,-n}$$

NS bosons

similar structure, but periodic $P^\mu(\sigma)$ replaced by antiperiodic $H^\mu(\sigma)$

$$G_r = \int_0^{2\pi} e^{-ir\sigma} H\cdot P\, d\sigma \qquad r \in \mathbb{Z}+1/2$$

satisfy a similar super-Virasoro algebra.

The string world-sheet theory

$$S = \int d\sigma\, d\tau \left\{ \partial_\alpha X^\mu \partial^\alpha X_\mu - i\bar{\Psi}^\mu \rho^\alpha \partial_\alpha \Psi_\mu \right\}$$

has 2d supersymmetry

$$\delta X^\mu = \bar{\epsilon}\Psi^\mu$$

$$\delta \Psi^\mu = -i\rho^\alpha \epsilon\, \partial_\alpha X^\mu$$

discovered by Gervais & Sakita (1971).

Neveu, Charles Thorn, & I

assembled these bosons & fermions into a consistent interacting theory.

In 1972 I discovered the need for $d=10$.

- GGRT — light-cone gauge quantization of strings

- No-ghost theorem — Brower, Goddard & Thorn, JHS

— moved to Caltech —

- Fermion-fermion scattering — JHS & C.C. Wu

<u>Other developments in this period:</u>

- Completion & acceptance of the standard model

- The Wess-Zumino model

Understandably, string theory rapidly fell out of favor.

1974-75: GRAVITY & UNIFICATION

String theory of hadrons had problems:

- tachyons
- $d = 10$ or 26
- massless particles with $J \leq 2$.

Several years of attempts to do better were unsuccessful.

In 1974, when Joël Scherk was spending a half year at Caltech, we decided to try to interpret the spin 2 state as a graviton. (Yoneya, too)

To account for Newton's constant we estimated that

$$\alpha' \sim (1/m_P)^2$$

instead of $(1\,\text{GeV})^{-2}$ — a change by a factor of 10^{38}.

This had several advantages:

- gravity was required by the theory
- There are no UV divergences
- Extra dimensions could be a good thing
- YM gauge field also appeared naturally and could account for the other forces.

I was very excited and decided to dedicate my life to this.

It was puzzling to me — and still is — why it took 10 years to convince most other physicists that this is a good idea.

1975-79 SUSY + SUGRA

N=1, D=4 supergravity

Ferrara, Freedman, Van Nieuwenhuizen;

Deser, Zumino

N=1, D=10 & N=4, D=4 super YM

Brink, Scherk, & JHS

N=8, D=4 supergravity

Cremmer, Julia

N=1, D=11 supergravity

Cremmer, Julia, Scherk

I also worked with Brink, Ramond, & Gell-Mann on a (not very successful) study of superspace supergravity.

Gliozzi, Scherk, Olive (GSO)

proposed a projection of the RNS spectrum that removed roughly half the states (including the tachyon).

Then they did the following counting:

$$f_{NS}(w) = \sum_{n=0}^{\infty} d_{NS}(n)\, w^n$$

$$= \frac{1}{2\sqrt{w}} \left(\prod_{m=1}^{\infty} \left(\frac{1+w^{m-1/2}}{1-w^m} \right)^8 - \prod_{m=1}^{\infty} \left(\frac{1-w^{m-1/2}}{1-w^m} \right)^8 \right)$$

$$f_R(w) = \sum_{n=0}^{\infty} d_R(n)\, w^n$$

$$= 8 \prod_{m=1}^{\infty} \left(\frac{1+w^m}{1-w^m} \right)^8$$

In 1829, Jacobi discovered that

$$f_R(w) = f_{NS}(w)$$

Thus the number of bosons & fermions match at every mass level.

1979-85 SUPERSTRINGS

In 1979, following a year at the Ecole Normale, I spent a month in the summer at CERN. There Michael Green and I began a long + exciting collaboration.

Our first goal was to understand better why the GSO projected RNS string theory has spacetime supersymmetry.

Michael had several extended stays at Caltech and I had one in London. We also worked together several summers in Aspen.

MBG + JHS (partially, also with LARS BRINK)

- Developed a new light-cone gauge formalism in which spacetime susy of the spectrum and interactions was easily proved

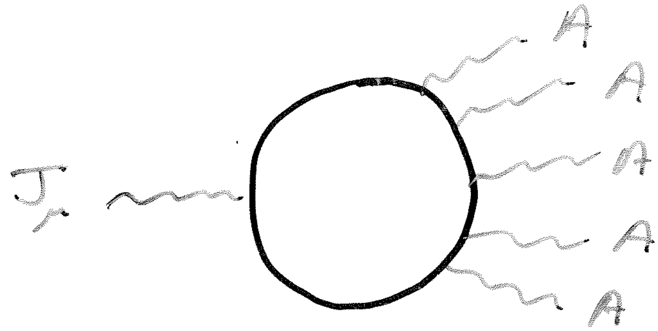
- Used this formalism to compute various tree and one-loop amplitudes and elucidate their properties

- Formulated (and named) the type I, type IIA, and type IIB superstring theories

- Formulated superstring field theory in the light-cone gauge

- Formulated a covariant world-sheet theory with manifest spacetime susy.

ANOMALIES



$$\partial_\mu J^\mu \sim \epsilon^{\mu_1 \cdots \mu_{10}} F_{\mu_1 \mu_2} \cdots F_{\mu_9 \mu_{10}}$$

Type I superstrings are well-defined at tree-level for $G = SO(n)$ or $Sp(n)$.

In every case they are chiral (i.e., parity violating) and the $d = 10$ SYM sector is anomalous.

It appeared unlikely that superstrings could accomodate parity violation, but a better analysis was required.

We worked on this problem for almost two years, until the crucial breakthroughs were made in August 1984 (in Aspen).

I won't belabor the details here — just state the conclusion:

Anomalies can cancel for a theory with $N=1$ susy in $d=10$, only if the YM gauge group is

$$SO(32) \quad \text{or} \quad E_8 \times E_8 .$$

The $SO(32)$ case could be accommodated by type I superstrings, but we didn't know a superstring theory with gauge group $E_8 \times E_8$.

Before the end of 1984 there were two other major developments:

The heterotic string - Gross, Harvey, Martinec, Rohm

Calabi-Yau compactification - Candelas, Horowitz, Strominger, + Witten.

By the beginning of 1985, string theory - with the goal of unification - had become a mainstream activity.

THE END (& the beginning)