Scattering of Massive States in Pure Spinor

Subhroneel Chakrabarti

The Institute of Mathematical Sciences, Chennai (India)

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With Sitender P. Kashyap & Mritunjay Verma

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Introduction

- Pure Spinor formulation is a manifestly super-Poincare covariant worldsheet theory of superstrings.

  Berkovits

- Tremendously successful in computing of scattering of massless string states – at loop levels surpasses the well-known RNS formalism approach.

  Berkovits, Chandia, Mafra, Gomez, Schlotterer,…

- The massive states remained comparatively unexplored. Unintegrated vertex for 1^{st} massive state was constructed by Berkovits & Chandia (hep-th/0204121). DDF-like construction was given by Jusinskas (1406.1902).
- General arguments established equivalence between PS and RNS/GS formalism. Explicit equivalence known for massless states.

  Berkovits; Berkovits, Mafra…

- Explicit equivalence for massive states?

1-slide summary of PS formalism

- The worldsheet action is $S = \frac{1}{\pi\alpha'}\int d^2z \;\; \partial X^m \bar{\partial} X_m + p_\alpha \partial\theta^\alpha + w_\alpha \partial\lambda^\alpha$

- The commuting Majorana-Weyl spinor λ satisfies the pure spinor constraint

$$\lambda\gamma^m\lambda = 0$$

- Spacetime SUSY is made manifest in terms of the GS variables Π^m, d_α
- The PS constraint implies a gauge invariance $\delta w_\alpha = \Lambda_m(\gamma^m\lambda)_\alpha$, which is dealt with by working with gauge invariant currents

$$N^{mn} = w\gamma^{mn}\lambda \qquad\qquad J = w_\alpha\lambda^\alpha$$

- Our ordering convention for any composite object is $\{\Pi^m, d_\alpha, \partial\theta^\alpha, N^{mn}, J, \lambda^\alpha\}$
- BRST operator takes a simple form

$$Q = \oint dz \lambda^\alpha d_\alpha$$

Vertex operators in PS

- All vertex operators are of the form

$$V \sim \sum_i O_i \quad S_i \longrightarrow \text{Appropriate superfields}$$

$$O_i \in \{\Pi^m, d_\alpha, \partial\theta^\alpha, N^{mn}, J, \lambda^\alpha\}$$

- For n-th massive state, the unintegrated vertex V must have conformal weight = n and ghost number = 1.

- $\{\Pi^m, d_\alpha, \partial\theta^\alpha, N^{mn}, J\}$ All have conformal weight = 1, ghost no. = 0.
- λ^α has conformal weight = 0 but ghost number =1.

Unintegrated vertex

- Constructing the vertex requires determining the superfields S_i in terms of the physical superfield representing the supermultiplet such that the BRST condition is satisfied.

$$QV = 0 \longrightarrow \sum_i (QO_i)S_i + O_i(QS_i) = 0 \implies \sum_i \tilde{O}_i \tilde{S}_i = 0$$

- Ideally, we would like to set all $\tilde{S}_i = 0$ and solve for the Superfields.

- However, due to pure spinor constraint, not all of the $\tilde{O}_i$ are actually independent. So one needs to take care of that.

1^{st} Massive states in open superstrings

- The first massive supermultiplet contains $b_{mnp}, g_{mn}, \psi^{\alpha}_{m}$

84 44 128

- These physical fields satisfy

$$k^m b_{mnp} = k^m g_{mn} = k^m \psi^{\alpha}_{m} = 0$$

$$(\gamma^m \psi_m)_\alpha = 0 \qquad \eta^{mn} g_{mn} = 0$$

$$k^m k_m = -\frac{1}{\alpha'}$$

- Berkovits-Chandia constructed the unintegrated vertex for this supermultiplet. All superfields must be expressed in terms of the physical on-shell superfield B_{mnp} and its super-covariant derivative.

hep-th/0204121

Berkovits-Chandia construction

$$V = \partial\lambda^\alpha A_\alpha(X,\theta) + :\partial\theta^\beta\lambda^\alpha B_{\alpha\beta}(X,\theta): + :d_\beta\lambda^\alpha C^\beta_\alpha(X,\theta): + :\Pi^m\lambda^\alpha H_{m\alpha}(X,\theta): + :J\lambda^\alpha E_\alpha(X,\theta): + :N^{mn}\lambda^\alpha F_{\alpha mn}(X,\theta):$$

$$\longleftrightarrow \quad V \sim \sum_i O_i\, S_i$$

$$B_{\alpha\beta} = (\gamma^{mnp})_{\alpha\beta}B_{mnp} \quad , \quad C^\alpha{}_\beta = (\gamma^{mnpq})^\alpha{}_\beta C_{mnpq}$$

$$\gamma^{m\alpha\beta}F_{\beta mn} = 0 \quad , \quad (\gamma^m H_m)_\alpha = 0$$

$\longleftarrow$ $\delta V = Q\Lambda$ and field redefinition

recall that all operators were not indpendent

$$:N^{mn}\lambda^\alpha:(\gamma_m)_{\alpha\beta} - \frac{1}{2}:J\lambda^\alpha:(\gamma^n)_{\alpha\beta} = \alpha'\partial\lambda^\alpha(\gamma^n)_{\alpha\beta}$$

$\longrightarrow$ follows from pure spinor constraint

$$\Downarrow$$

$$-2:N_{st}\lambda^\alpha\lambda^\beta:(\gamma^{vwxy}\gamma^{[s})_{\alpha\beta}K^{t]}{}_{vwxy} + :J\lambda^\alpha\lambda^\beta:(\gamma^{vwxy}\gamma_s)_{\alpha\beta}K^s{}_{vwxy} + \alpha'\lambda^\alpha\partial\lambda^\beta\left[2(\gamma^{vwxys})_{\alpha\beta}\eta_{st}K^t{}_{vwxy} + 16(\gamma^{wxy})_{\alpha\beta}K^s{}_{wxys}\right] = 0$$

introduce lagrange multiplier superfield K^s_{mnpq}

Berkovits-Chandia construction

- QV + (Lagrange multiplier term) = 0 gives

- Formidable set of equations, but it was solved!

- All Superfields were expressed in terms of a

Single superfield B_{mnp} and its supercovariant derivative $D_\alpha B_{mnp}$.

- Rest frame analysis showed this superfield B_{mnp}

contains all the 128 bosonic + 128 fermionic d.o.f

$$(\gamma_{mnpqr})^{\alpha\beta}\left[D_\alpha B_{\beta\sigma} - \gamma^s_{\alpha\sigma} H_{s\beta}\right] = 0$$

$$(\gamma_{mnpqr})^{\alpha\beta}\left[D_\alpha H_{s\beta} - \gamma_{s\alpha\sigma} C^\sigma{}_\beta\right] = 0$$

$$(\gamma_{mnpqr})^{\alpha\beta}\left[D_\alpha C^\sigma{}_\beta + \delta^\sigma{}_\alpha E_\beta + \frac{1}{2}(\gamma^{st})^\sigma{}_\alpha F_{\beta st}\right] = 0$$

$$(\gamma_{mnpqr})^{\alpha\beta}\left[D_\alpha A_\beta + B_{\alpha\beta} + \alpha'\gamma^s_{\beta\sigma}\partial_s C^\sigma{}_\alpha - \frac{\alpha'}{2}D_\beta E_\alpha + \frac{\alpha'}{4}(\gamma^{st}D)_\beta F_{\alpha st}\right]$$
$$= 2\alpha'\gamma^{\alpha\beta}_{mnpqr}\gamma^{vwxys}_{\alpha\beta}\eta_{st}K^t{}_{vwxy}$$

$$(\gamma_{mnp})^{\alpha\beta}\left[D_\alpha A_\beta + B_{\alpha\beta} + \alpha'\gamma^s_{\beta\sigma}\partial_s C^\sigma{}_\alpha - \frac{\alpha'}{2}D_\beta E_\alpha + \frac{\alpha'}{4}(\gamma^{st}D)_\beta F_{\alpha st}\right]$$
$$= 16\alpha'\gamma^{\alpha\beta}_{mnp}\gamma^{wxy}_{\alpha\beta}\eta_{st}K^s{}_{wxys}$$

$$(\gamma_{mnpqr})^{\alpha\beta}D_\alpha E_\beta = (\gamma_{mnpqr}\gamma^{vwxy}\gamma_s)^\alpha{}_\alpha K^s{}_{vwxy}$$

$$(\gamma_{mnpqr})^{\alpha\beta}D_\alpha F^{st}_\beta = -2(\gamma_{mnpqr}\gamma^{vwxy}\gamma^{[s})^\alpha{}_\alpha K^{t]}{}_{vwxy}$$

What more do we want?

- Vertex operators are used to compute scattering amplitudes. For this one needs the full covariant θ expansion of the vertex.

- The BC construction only allows one to perform a θ expansion in *rest frame.*

- We also need a general prescription to repeat this feat for integrated vertex and for all higher massive states.
- Goals-
  1. Give a systematic procedure to construct massive vertices in PS .

  2. The procedure must also allow one to perform the full covariant θ expansion of the vertex.

  3. Compute scattering of massive states, compare with RNS and extend the explicit equivalence to include massive states.

A systematic procedure to construct massive vertex

- Step 1: For the n-th massive state, write down the most general operator of form

$$V \sim \underbrace{\sum_i O_i}_{\text{conf wt} = n \text{ and gh no.} = 1 \text{ operator}} \ \underbrace{S_i}_{\text{unknown superfield with proper indices}}$$

- *Example:* For n=1,

$$\begin{aligned} V \;\; &= \;\; \partial\lambda^\alpha A_\alpha(X,\theta) + :\partial\theta^\beta\lambda^\alpha B_{\alpha\beta}(X,\theta): + :d_\beta\lambda^\alpha C^\beta_{\ \alpha}(X,\theta): + :\Pi^m\lambda^\alpha H_{m\alpha}(X,\theta): \\ &\quad + :J\lambda^\alpha E_\alpha(X,\theta): + :N^{mn}\lambda^\alpha F_{\alpha mn}(X,\theta): \end{aligned}$$

- Step 2: For each physical field in the supermultiplet, introduce a superfield defined as

$$B_i\Big|_{\theta=0} \equiv b_i \quad , \quad \forall i = 1(1)n_B$$
$$F_i\Big|_{\theta=0} \equiv f_i \quad , \quad \forall i = 1(1)n_F \; .$$

and promote all algebraic conditions on the physical fields to superfields. *We will call these Superfields* ***physical Superfields.***

Example: For n=1, $B_{mnp}\Big|_{\theta=0} \equiv b_{mnp} \quad , \quad G_{mn}\Big|_{\theta=0} = g_{mn} \quad , \quad \Psi_{m\alpha}\Big|_{\theta=0} = \psi_{m\alpha}.$

$$k^m \psi_{m\alpha} = 0 \to k^m \Psi_{m\alpha} \equiv 0 \quad , \quad (\gamma^m \psi_{(m})_{\alpha} = 0 \to (\gamma^m \Psi_{(m})_{\alpha} \equiv 0$$

$$k^m b_{mnp} = 0 \to k^m B_{mnp} \equiv 0 \quad , \quad k^m g_{mn} = 0 \to k^m G_{mn} \equiv 0$$

- Step 3: Derive all constraints between operators O_i at conformal weight n and ghost no. 2. These constraints are either due to pure spinor constraint or due the OPE of various constituent objects.
- Handle the constraints either by introducing Lagrange multiplier Superfields or by solving them to eliminate some operators in favor of others.
- Incorporate them in the BRST condition QV=0.

- *Example:* for n=1,

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$$+\alpha'\lambda^\alpha\partial\lambda^\beta\left[2(\gamma^{vwxys})_{\alpha\beta}\eta_{st}K^t{}_{vwxy} + 16(\gamma^{wxy})_{\alpha\beta}K^s{}_{wxys}\right] = 0$$

- Step 4: Use representation theory of the little group SO(9) to write down ansatz for each unknown Superfields S_i as a linear combination of the physical Superfields B_i, F_i.

- *Example:* For n=1, we had the superfield $F_{\alpha mn}$ appearing in the vertex. We can decompose it as

$$F_{\alpha mn} \Rightarrow \begin{cases} F_{\alpha\, 0a} \\ F_{\alpha\, ab} \end{cases}$$

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$\mathbf{16}$ (in $\mathbf{16} \otimes \mathbf{9}$): unphyscial irrep; $\mathbf{128}$: physical irrep

$F_{\alpha\, ab} \longrightarrow \mathbf{16} \otimes \mathbf{36} = \mathbf{16} \oplus \mathbf{128} \oplus \mathbf{432}$

- *Therefore there are 2 independent tensor structures linear in the physical superfield Ψ_α^m in terms of which $F_{\alpha m n}$ can be expressed.*

$$F_{\alpha m n} = a\, k_{[m} \Psi_{n]\alpha} + b\, k^s (\gamma_{s[m]} \Psi_{n]})_\alpha$$

- Step 5: Write down similar ansatz for supercovariant derivative of the physical fields using representation theory.

$$D_\alpha F_i = \sum_j s_j^{(i)} B_j \;\; \forall i = 1(1)n_F$$
$$D_\alpha B_i = \sum_j \hat{s}_j^{(i)} F_j \;\; \forall i = 1(1)n_B$$

- *Example:* For n=1,

$$D_\alpha G_{mn} = a_1 k^p (\gamma_{p(m} \Psi_{n)})_\alpha$$

$$\mathbf{16} \otimes \mathbf{44} = \mathbf{128} \oplus \mathbf{576} \longrightarrow \text{unphysical irrep}$$

- *We will see soon that these relations are the ones which will allow us to perform completely covariant θ expansion of the vertex.*

- Step 6: Solve for the unknown co-efficients in the ansatz by requiring

    1. The ansatz solves QV=0.

    2. The ansatz are consistent with the definitions of the physical superfields.

    3. All the ansatz are mutually consistent.

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New result consistent with BC vertex!

3. *Readily extended to integrated vertex which was constructed for the first time for n=1 .* (see Sitender's talk right after this!)

4. *For 1^{st} massive states, this vertex gives same result as RNS.*

θ - *expansion*

- After fixing the unknown coefficients, we get

$$D_\alpha \Psi_{s\beta} = \frac{1}{16} G_{sm} \gamma^m_{\alpha\beta} + \frac{i}{24} k_m B_{nps} (\gamma^{mnp})_{\alpha\beta} - \frac{i}{144} k^m B^{npq} (\gamma_{smnpq})_{\alpha\beta}$$

$$D_\alpha B_{mnp} = 12(\gamma_{[mn}\Psi_{p]})_\alpha + 24\alpha' k^t k_{[m}(\gamma_{|t|n}\Psi_{p]})_\alpha$$

$$\cancel{k}^{\alpha\beta} D_\alpha D_\beta \propto k^2$$

$$D_\alpha G_{sm} = 16 i k^p (\gamma_{p(s}\Psi_{m)})_\alpha$$

- Schematically these gives a set of recursion relations which can be leveraged to get the θ expansion

$$D^{(\ell+1)}\Psi_{s\beta} \sim D^\ell G_{sm} + D^\ell B_{mnp}$$

$$D^\ell B_{mnp} \sim D^{(\ell-1)}\Psi_{s\beta}$$

$$D^\ell G_{mn} \sim D^{(\ell-1)}\Psi_{s\beta}$$

$$D \equiv \theta^\alpha D_\alpha$$

θ - *expansion*

$$
\begin{aligned}
&\Psi_{s\beta} \\
= \quad & \psi_{s\beta} + \frac{1}{16}(\gamma^m\theta)_\beta \; g_{sm} - \frac{i}{24}(\gamma^{mnp}\theta)_\beta k_m b_{nps} - \frac{i}{144}(\gamma_s{}^{npqr}\theta)_\beta k_n b_{pqr} \\
& -\frac{i}{2}k^p(\gamma^m\theta)_\beta(\psi_{(m}\gamma_{s)p}\theta) - \frac{i}{4}k_m(\gamma^{mnp}\theta)_\beta(\psi_{[s}\gamma_{np]}\theta) - \frac{i}{24}(\gamma_s{}^{mnpq}\theta)_\beta k_m(\psi_q\gamma_{np}\theta) \\
& -\frac{i}{6}\alpha' k_m k^r k_s(\gamma^{mnp}\theta)_\beta(\psi_p\gamma_{rn}\theta) + \frac{i}{288}\alpha'(\gamma^{mnp}\theta)_\beta k_m k^r k_s(\theta\gamma^q{}_{nr}\theta) \; g_{pq} \\
& -\frac{i}{192}(\gamma^{mnp}\theta)_\beta k_m(\theta\gamma^q{}_{[np}\theta)g_{s]q} - \frac{i}{1152}(\gamma_{smnpq}\theta)_\beta k^m(\theta\gamma_{npt}\theta) \; g^{qt} \\
& -\frac{i}{96}k^p(\gamma^m\theta)_\beta(\theta\gamma_{pq(s}\theta) \; g_{m)q} - \frac{1}{1728}(\gamma^{mnp}\theta)_\beta k_m(\theta\gamma^{tuvw}{}_{nps}\theta)k_t b_{uvw} \\
& -\frac{1}{864\alpha'}(\gamma_s\theta)_\beta(\theta\gamma^{npq}\theta)b_{npq} - \frac{1}{10368}(\gamma_s{}^{mnpq}\theta)_\beta k_m(\theta\gamma_{tuvwnpq}\theta)k^t b^{uvw} \\
& -\frac{1}{864}(\gamma^m\theta)_\beta(\theta\gamma^{npq}\theta)b_{npq}k_m k_s - \frac{1}{576}(\gamma_{smnpq}\theta)_\beta k^m(\theta\gamma^{tun}\theta)b_u{}^{pq}k_t \\
& -\frac{1}{96\alpha'}(\gamma^m\theta)_\beta(\theta\gamma^{qr}{}_{(s}\theta)b_{m)rq} + \frac{1}{96}(\gamma^m\theta)_\beta(\theta\gamma^{nqr}\theta)k_n k_{(s}b_{m)qr} \\
& +\frac{1}{96}(\gamma^{mnp}\theta)_\beta k_m(\theta\gamma^r{}_{q[n}\theta)b_{ps]r}k^q + O(\theta^4)
\end{aligned}
$$

Tree level amplitudes in PS

- N-point amplitudes

$$\mathcal{A}_N = \langle V_1 V_2 V_3 \int U_4 \cdots \int U_N \rangle$$

focus on 3-pt $\implies \langle V_1 V_2 V_3 \rangle$

- Factorizes in two parts

$$\mathcal{A}_3 \sim \langle V_1 V_2 V_3 \rangle_{PSS} \, \langle e^{ik_1 \cdot X} \ldots \rangle$$

- The PSS measure is normalized as

$$\langle \lambda^3 \theta^5 \rangle_{PSS} = 1$$

Tree level amplitudes in PS

- We need to evaluate $\langle V_1 V_2 V_3 \rangle_{PSS}$ subjected to $\langle \lambda^3 \theta^5 \rangle_{PSS} = 1$.

- Each unintegrated vertex is at ghost no. 1, so $V_1 V_2 V_3 \sim \lambda^3$ is automatic.

- We need to just θ expand all 3 vertices and keep only those terms from the product which has 5 θ's.

$$V_1 V_2 V_3 \to V_1 V_2 V_3 \Big|_{\theta^5}$$

- Taking into account all such terms and incorporating plane wave part, we get the full answer.

Equivalence to RNS for massive states

- We now have all the ingredients to compute scattering amplitudes of massless and 1st massive states using PS formalism.
- This allows us to directly compare them with corresponding RNS formalism and establish explicit equivalence.
- Consider all *massless-massless-massive* 3-point functions for a *fixed order.*
- Let the relative normalization be defined as

$$\mathcal{N}_{RNS} = g_{field}\,\mathcal{N}_{PS}$$

- We keep $\mathcal{N}_{PS} = 1$ and keep the relative normalization g_{field} in RNS vertex operators.

$a = \text{gluon},\ \chi = \text{gluino}$

Correlator	RNS	PS
$\langle aaa \rangle$	$-g_a^3\sqrt{2\alpha'}$	$\frac{i}{180}$
$\langle a\chi\chi \rangle$	$\frac{1}{\sqrt{2}} g_a g_\chi^2$	$\frac{1}{360}$
$\langle aab \rangle$	$6 g_a^2 g_b \sqrt{2\alpha'}$	$\frac{i}{20}$
$\langle \chi\chi b \rangle$	$-\frac{1}{2\sqrt{2}} g_\chi^2 g_b$	$\frac{1}{480}$
$\langle aag \rangle$	$-g_a^2 g_g$	$-\frac{1}{80}$
$\langle \chi\chi g \rangle$	$\sqrt{\alpha'} g_\chi^2 g_g$	$\frac{i\alpha'}{80}$
$\langle a\chi\psi \rangle$	$-\frac{16\alpha'}{\sqrt{2}} g_a g_\chi g_\psi$	$\frac{1}{5}$
$\langle \chi a\psi \rangle$	$-\frac{16\alpha'}{\sqrt{2}} g_a g_\chi g_\psi$	$\frac{1}{5}$

all massless

2-massless & 1 massive

fix g_a

fix g_χ

$a = \text{gluon}, \chi = \text{gluino}$

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2-massless & 1 massive

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all massless

2-massless & 1 massive

$\rightarrow$ fix g_a

$\rightarrow$ fix g_χ

$\rightarrow$ fixg_b

$\rightarrow$ fixg_g ✓

$\rightarrow$ fixg_ψ

Exactly matches! $\rightarrow$ non-trivial consistency check

PS = RNS

$$(g_a)^3 = \frac{-i}{180\sqrt{2\alpha'}} \quad , \qquad (g_\chi)^2 = \frac{\sqrt{2}}{360\ g_a}.$$

$$g_b = \frac{i}{120\sqrt{2\alpha'}\ g_a^2} \quad , \qquad g_g = \frac{1}{80\ g_a^2} \quad , \qquad g_\psi = -\frac{\sqrt{2}}{80\alpha' g_a g_\chi}$$

With these choices of relative normalizations, we have extended the explicit equivalence between PS & RNS amplitudes to include 1st massive states as well.

Summary & Outlook

- We have given a systematic procedure to construct massive vertices in PS formalism that also gives the covariant θ expansion to all orders.
- We have explicitly shown the equivalence between RNS & PS amplitudes for 1^{st} massive states.
- Can this construction be adapted to construct massive vertices in AdS backgrounds?
- N-point amplitudes for massive states? Higher Loop level?

  [Schlotterer's Talk]
- First principle derivation of this prescription? Off-shell states in PS?

SFT Website

- Please check out the following website

  http://string-field-theory.org

- Associated Zulip chat page

  https://sft.zulipchat.com

- Comments, suggestions, questions… - Harold Erbin & S.C

Thank you for listening
&
Stay Safe!