Title: Aspects of Quantum Pohlmeyer Reduced Theory for AdS5 x S5 Superstring

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Abstract: We will discuss recent progress in computing quantum corrections to S-matrix and partition function of Pohlmeyer reduction for AdS5 x S5 superstring theory.

Quantum Pohlmeyer reduced theory for $AdS_5 \times S^5$ superstring

Arkady Tseytlin

- Review

- 2-loop corrections to partition function of PR theory

Y. Iwashita, R. Roiban and A.T., to appear

- S-matrix of PR theory

B. Hoare and A.T., arXiv:1104.2423

Related: poster of Ben Hoare and talk of Luis Miramontes

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Aim :

solve string theory in $AdS_5 \times S^5$ from first principles
– conformal invariance, supersymmetry
and integrability

(i) find S-matrix and justify
Asymptotic Bethe Ansatz for the spectrum

(ii) understand theory on cylinder (closed string): TBA

Quantum string theory in $AdS_5 \times S^5$:

GS superstring on $\frac{PSU(2,2|4)}{SO(1,4)\times SO(5)}$
analogy with exact solution of $O(n)$ model (Zamolodchikovs)
or principal chiral model (Polyakov-Wiegmann) ?
2d CFT – no mass generation (mass scale from gauge fixing)

problem of direct approach:
lack of manifest 2d Lorentz symmetry :
S-matrix depends on two rapidities (not on difference)
symmetry constraints on it are not manifest, ...

An alternative approach?
Classically equivalent 2d Lorentz invariant action
describing same physical degrees of freedom

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"Pohlmeyer reduction" :

reformulation of gauge-fixed $AdS_5 \times S^5$ superstring
in terms of current-type variables
preserving 2d Lorentz invariance

classically equivalent (equivalent integrable structure);
what about relation at the quantum level?

a way towards exact solution of quantum $AdS_5 \times S^5$ superstring?

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Integrable + 2d scale-invariant (UV finite) model
a fermionic generalization of non-abelian Toda theory

- intimately related to (classical) $AdS_5 \times S^5$ GS model
- action quadratic in fermions with standard 2d kinetic terms

(hidden 2d susy, ...)

- has 2d Lorentz invariant S-matrix

for an equivalent set of 8+8 physical massive excitations:
an alternative interacting generalization of same free theory

- very special UV finite massive integrable model:

deserves study regardless question about equivalence
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Some history

K. Pohlmeyer (1976):
Discovery of integrability (existence of ∞ of conservation laws)
of *classical* O(3) sigma model via relation to sine-Gordon theory:
O(4) sigma model$\rightarrow$ complex sine-Gordon theory.
Integrability of O(n) model: Backlund transformations
to generate solutions and higher conserved charges.

But why reduction relevant?
Assumed classical 2d conf. inv. which is broken at quantum level

Quantum O(3) and sin-Gordon theories are different
but integrability itself extends to quantum level
[Polyakov (1977); Zamolodchikov, Zamolodchikov (1979)]

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Pohlmeyer reduction was not used much in the next 20 years... but came to light in the context of string theory :

Technical tool : classical solutions

• construction of classical string solutions in constant-curvature spaces – de Sitter and anti de Sitter [Barbashov, Nesterenko, 1981; de Vega, Sanchez, 1993]

• construction of classical string solutions in $AdS_5 \times S^5$ representing semiclassical string states [Hofman, Maldacena,2006; Dorey et al,2006; Jevicki et al,2007; Hoare, Iwashita, A.T., 2009; Hollowood, Miramontes, 2009; ...]

• construction of euclidean open-string world-surfaces related to Wilson loops (SYM scattering amplitudes at strong coupling) [Alday, Maldacena, 2009; Alday, Gaiotto, Maldacena, 2009; Dorn et al, 2009; Jevicki, Jin, 2009, ...]

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Pohlmeyer reduction

Original example: S^2-sigma model $\rightarrow$ Sine-Gordon theory

$$L = \partial_+ X^m \partial_- X^m - \Lambda(X^m X^m - 1)\,, \qquad m = 1, 2, 3$$

Equations of motion:

$$\partial_+ \partial_- X^m + \Lambda X^m = 0\,, \quad \Lambda = \partial_+ X^m \partial_- X^m\,, \quad X^m X^m = 1$$

Stress tensor: $\mathrm{T}_{\pm\pm} = \partial_\pm X^m \partial_\pm X^m$

$$\mathrm{T}_{+-} = 0\,, \quad \partial_+ \mathrm{T}_{--} = 0\,, \qquad \partial_- \mathrm{T}_{++} = 0$$

implies $\mathrm{T}_{++} = f(\sigma_+)$, $\mathrm{T}_{--} = h(\sigma_-)$
using the conformal transformations $\sigma_\pm \rightarrow F_\pm(\sigma_\pm)$ can set

$$\partial_+ X^m \partial_+ X^m = \mu^2\,, \qquad \partial_- X^m \partial_- X^m = \mu^2\,, \qquad \mu = \mathrm{const}$$

3 unit vectors in 3-dimensional Euclidean space:

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$$X^m\,, \qquad X^m_+ = \mu^{-1}\partial_+ X^m\,, \qquad X^m_- = \mu^{-1}\partial_- X^m$$

X^m is orthogonal to X^m_+ and X^m_- $(X^m \partial_\pm X^m = 0)$
remaining $SO(3)$ invariant quantity is scalar product

$$\partial_+ X^m \partial_- X^m = \mu^2 \cos 2\varphi$$

then

$$\partial_+ \partial_- \varphi + \frac{\mu^2}{2} \sin 2\varphi = 0$$

following from sine-Gordon action [Pohlmeyer, 1976]

$$\widetilde{L} = \partial_+ \varphi \partial_- \varphi + \frac{\mu^2}{2} \cos 2\varphi$$

2d Lorentz invariant despite explicit constraints

Classical solutions and integrable structures
(Lax pair, Backlund transformations, etc) are directly related
e.g., SG soliton mapped into rotating folded string on S^2:
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Analogous construction for S^3 model gives
Complex sine-Gordon model (Pohlmeyer; Lund, Regge 76)

$$\widetilde{L} = \partial_+\varphi\partial_-\varphi + \cot^2\varphi\,\partial_+\theta\partial_-\theta + \frac{\mu^2}{2}\cos 2\varphi$$

φ, θ are $SO(4)$-invariants:

$$\mu^2\cos 2\varphi = \partial_+ X^m \partial_- X^m$$
$$\mu^3\sin^2\varphi\,\partial_\pm\theta = \mp\tfrac{1}{2}\epsilon_{mnkl}X^m\partial_+X^n\partial_-X^k\partial_\pm^2 X^l$$

In the case of AdS_2 or AdS_3:
replace $\sin\varphi \to \sinh\phi$, ...

String-theory interpretation: string on $R_t \times S^n$

(i) conformal gauge
(ii) $t = \mu\tau$ to fix conformal diff's:

$\partial_\pm X^m \partial_\pm X^m = \mu^2$ are Virasoro constraints
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Similar construction for AdS_n case:
string on $AdS_n \times S^1_\psi$ with $\psi = \mu\tau$
e.g., reduced theory for string on $AdS_3 \times S^1$

$$\widetilde{L} = \partial_+\phi\partial_-\phi + \coth^2\varphi\,\partial_+\chi\partial_-\chi - \frac{\mu^2}{2}\cosh 2\phi$$

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Comments:

- Virasoro constraints are solved by a special choice of variables related nonlocally to original string coordinates
- Reduced and string theories: equivalent as classical integrable systems: Lax pairs are gauge-equivalent
- Although the reduction is not explicitly Lorentz invariant the resulting Lagrangian turns out to be 2d Lorentz invariant
- Reduced theory is formulated in terms of manifestly $SO(n)$ invariant variables: "blind" to original global symmetry
- PR may be thought of as a formulation in terms of physical d.o.f. – coset space analog of flat-space l.c. gauge with 2d Lorentz symmetry unbroken

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PR for bosonic string on $R_t \times F/G$

F/G-coset sigma model: symmetric space

$$\mathrm{f} = \mathrm{p} \oplus \mathrm{g}\,, \qquad [\mathrm{g},\mathrm{g}] \subset \mathrm{g}\,, \qquad [\mathrm{g},\mathrm{p}] \subset \mathrm{p}\,, \qquad [\mathrm{p},\mathrm{p}] \subset \mathrm{g}$$

$$J = f^{-1}df = \mathcal{A} + P\,, \qquad \mathcal{A} \in \mathrm{g}\,, \quad P \in \mathrm{p}$$

$$L(f) = -\mathrm{Tr}(P_+ P_-)\,, \qquad f \in F$$

G gauge transformations: $f \to fg,\ \ g \in G$
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Currents $J = \mathcal{A} + P$ as fundamental variables:

EOM : $D_+ P_- = 0\,, \quad D_- P_+ = 0\,, \qquad D = d + [\mathcal{A},\ ]$

Maurer-Cartan : $D_- P_+ - D_+ P_- + [P_+, P_-] + \mathcal{F}_{+-} = 0$

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gauge fixing that solves $\mathrm{Tr}(P_+P_+) = -\mu^2$

$$P_+ = \mu\, T = \text{const}\,, \qquad T \in \mathrm{p} = \mathrm{f} \ominus \mathrm{g}, \qquad \mathrm{Tr}(TT) = -1$$

- choice of special element T : decomposition of f

$$\mathrm{f} = \mathrm{p} \oplus \mathrm{g}\,, \qquad \mathrm{p} = T \oplus \mathrm{n}\,, \qquad \mathrm{g} = \mathrm{m} \oplus \mathrm{h}\,, \qquad [T, \mathrm{h}] = 0$$

- T determines h , i.e. defines subgroup $H \subset G$
- $\mathrm{Tr}(P_-P_-) = -\mu^2$ is solved by introducing $g \in G$

$$P_- = \mu\, g^{-1} T g$$

$D_-P_+ = 0$ is solved by $\mathcal{A}_- = (\mathcal{A}_-)_{\mathrm{h}} \equiv A_-$
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G/H gauged WZW action with integrable potential:

$$L = -\frac{1}{2}\mathrm{Tr}(g^{-1}\partial_+ g g^{-1}\partial_- g) + \text{WZ term}$$

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Pohlmeyer-reduced theory for F/G coset sigma model
[Bakas, Park, Shin 95; Grigoriev, A.T. 07; Miramontes 08]

equivalent eqs of motion; equivalent integrable structure

special case of non-abelian Toda theory:
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Comments :

- Reduced equations of motion in "on-shell" gauge $A_\pm = 0$:

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$$(g^{-1}\partial_+ g)_{\rm h} = 0\,, \qquad (\partial_- g g^{-1})_{\rm h} = 0$$

- $F/G = S^n = \frac{SO(n+1)}{SO(n)}$, $G/H = \frac{SO(n)}{SO(n-1)}$:
$H = SO(n-1)$ gauge fixing on g (Euler angles)
and integrating out $A_\pm$: generalized SG model

$$\widetilde{L} = \partial_+\varphi\partial_-\varphi + G_{pq}(\varphi,\theta)\partial_+\theta^p\partial_-\theta^q + \frac{\mu^2}{2}\cos 2\varphi$$

metric G_{pq} in kinetic term for $n = 2, 3, 4, ...$

$$ds_2^2 = d\varphi^2\,, \qquad ds_3^2 = d\varphi^2 + \cot^2\varphi\, d\theta^2$$

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String Theory in $AdS_5 \times S^5$

$$AdS_5 \times S^5 = \frac{SO(2,4)}{SO(1,4)} \times \frac{SO(6)}{SO(5)} = \frac{SU(2,2)}{Sp(2,2)} \times \frac{SU(4)}{Sp(4)}$$

GS superstring:

replace $\frac{\widehat{F}}{G} = \frac{\text{SuperPoincare}}{\text{Lorentz}}$ in flat case by

$$\frac{\widehat{F}}{G} = \frac{PSU(2,2|4)}{Sp(2,2) \times Sp(4)}$$

basic superalgebra $\widehat{\mathrm{f}} = psu(2,2|4)$

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$$\widehat{\mathrm{f}} = \mathrm{f}_0 \oplus \mathrm{f}_1 \oplus \mathrm{f}_2 \oplus \mathrm{f}_3\,, \qquad [\mathrm{f}_i, \mathrm{f}_j] \subset \mathrm{f}_{i+j \bmod 4}$$

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Virasoro : $\quad {\rm STr}(P_+ P_+) = 0 \,, \qquad {\rm STr}(P_- P_-) = 0$

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Pohlmeyer reduced theory

Bosons :

Virasoro solved by fixing special G-gauge
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$$P_+ = \mu\, T\,, \qquad P_- = \mu\, g^{-1} T g\,, \qquad \mu = \text{const}$$

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Fermions :

impose partial κ-symmetry gauge

$$Q_{1-} = 0\,, \qquad Q_{2+} = 0$$
$$\Psi_1 \equiv Q_{1+} \in \mathrm{f}_1\,, \qquad \Psi_2 \equiv g Q_{2-} g^{-1} \in \mathrm{f}_3$$

residual κ-symmetry fixed by demanding $\{\Psi_{1,2}, T\} = 0$

$$\widehat{\mathrm{f}} = \widehat{\mathrm{f}}^{\perp} + \widehat{\mathrm{f}}^{\parallel}\,, \qquad [\widehat{\mathrm{f}}^{\perp}, T] = 0\,, \qquad \{\widehat{\mathrm{f}}^{\parallel}, T\} = 0$$

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$$\Psi_{_R} = \frac{1}{\sqrt{\mu}} \Psi_1^{\parallel}, \qquad \Psi_{_L} = \frac{1}{\sqrt{\mu}} \Psi_2^{\parallel}$$

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Remarkably, exists local action for $g, A_\pm, \Psi_{R,L}$ reproducing remaining classical equations:

Gauged WZW model for

$$\frac{G}{H} = \frac{Sp(2,2)}{SU(2)\times SU(2)} \times \frac{Sp(4)}{SU(2)\times SU(2)}$$

with integrable potential and fermionic terms:

$$\widetilde{L} = L_{\rm gWZW}(g,A) + \mu^2\,{\rm Str}(g^{-1}TgT)$$

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- fields $g, A_\pm, \Psi_{R,L}$ are 8×8 supermatrices, e.g.
$g = {\rm diag}(a,b)\,, \qquad a\in Sp(2,2), \quad b\in Sp(4)$
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$g' = h^{-1}gh, \quad A'_\pm = h^{-1}(A_\pm + \partial_\pm)h, \quad \Psi'_{L,R} = h^{-1}\Psi_{L,R}h$

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Equations of motion in $A_\pm = 0$ gauge:
fermionic generalization of non-abelian Toda equations

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resembles both WZW model based on a supergroup
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$$G = U(1,1) \times U(2), \qquad H = [U(1)]^4$$

PR: [complex sin-Gordon + complex sinh-Gordon] + fermions

Similar lower-dimensional models

$AdS_2 \times S^2$:

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PR model for superstring on $AdS_2 \times S^2$

PR Lagrangian: same as $n = 2$ supersymmetric sine-Gordon

$$\widetilde{L} = \partial_+\varphi\partial_-\varphi + \partial_+\phi\partial_-\phi + \frac{\mu^2}{2}(\cos 2\varphi - \cosh 2\phi)$$
$$+ \beta\partial_-\beta + \gamma\partial_-\gamma + \nu\partial_+\nu + \rho\partial_+\rho$$
$$- 2\mu\left[\cosh\phi\ \cos\varphi\ (\beta\nu + \gamma\rho) + \sinh\phi\ \sin\varphi\ (\beta\rho - \gamma\nu)\right]$$

equivalent to:

$$L = \partial_+\Phi\partial_-\Phi^* - |W'(\Phi)|^2 + \psi_L^*\partial_+\psi_L + \psi_R^*\partial_-\psi_R$$
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bosonic part is of $AdS_2 \times S^2$ bosonic reduced model if

$$W(\Phi) = \mu\cos\Phi\,, \qquad |W'(\Phi)|^2 = \frac{\mu^2}{2}(\cosh 2\phi - \cos 2\varphi)$$

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- 2d Poincare $\mathfrak{so}(1,1) \in \mathbb{R}^{1,1}$
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(cf. choice of BMN vacuum)

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$AdS_3 \times S^3$:

$\widehat{\mathfrak{h}} = \left[\mathfrak{u}(1) \Subset \mathfrak{psu}(1|1) \oplus \mathfrak{psu}(1|1)\right]^{\oplus 2} \ltimes \mathfrak{u}(1)$
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Reduction procedure may work at quantum level
only in conformally invariant case (like $AdS_5 \times S^5$ string)
Consistency requires that reduced theory is also UV finite

gWZW + free fermions is finite;
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Relation of reduced theory and string theory at quantum level?

compare quantum partition functions

One-loop partition function:

semiclassical expansion near counterparts
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characteristic frequencies – same 1-loop partition function
[Iwashita, Hoare, A.T. 09]

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Long folded (S, J) spinning string $(m \sim \ln S,\ \mu \sim J)$

$$Y_0 + iY_5 = \cosh(m\sigma)\, e^{i\kappa\tau}, \quad Y_1 + iY_2 = \sinh(m\sigma)\, e^{i\kappa\tau}$$
$$X_1 + iX_2 = e^{i\mu\tau}, \qquad \kappa^2 = m^2 + \mu^2$$

corresponding PR solution:
in $AdS_3 \times S^1$

$$L = (\partial\phi)^2 + \coth^2\phi\,(\partial\chi)^2 - \tfrac{1}{2}\mu^2\cosh 2\phi$$
$$\phi = \ln\tfrac{\kappa+m}{\mu}, \qquad \chi = -\tfrac{m}{\mu}\sigma$$

in $AdS_5 \times S^5$

$$g = \begin{pmatrix} 0 & \frac{\kappa}{\mu}v & -\frac{m}{\mu}v & 0 \\ -\frac{\kappa}{\mu}v^* & 0 & 0 & \frac{m}{\mu}v^* \\ \frac{m}{\mu}v & 0 & 0 & -\frac{\kappa}{\mu}v \\ 0 & -\frac{m}{\mu}v^* & \frac{\kappa}{\mu}v^* & 0 \end{pmatrix}, \qquad v = e^{-i\frac{\kappa^2\tau}{\nu}}$$

$$A_+ = \frac{i(m^2+\kappa^2)}{2\mu}\mathrm{diag}(1,-1,1,-1)$$
$$A_- = \frac{i\mu}{2}\mathrm{diag}(1,-1,1,-1)$$

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$$L = (\partial\phi)^2 + \coth^2\phi\,(\partial\chi)^2 - \tfrac{1}{2}\mu^2 \cosh 2\phi$$
$$\phi = \ln\tfrac{\kappa+m}{\mu}, \qquad \chi = -\tfrac{m}{\mu}\sigma$$

in $AdS_5 \times S^5$

$$g = \begin{pmatrix} 0 & \frac{\kappa}{\mu}v & -\frac{m}{\mu}v & 0 \\ -\frac{\kappa}{\mu}v^* & 0 & 0 & \frac{m}{\mu}v^* \\ \frac{m}{\mu}v & 0 & 0 & -\frac{\kappa}{\mu}v \\ 0 & -\frac{m}{\mu}v^* & \frac{\kappa}{\mu}v^* & 0 \end{pmatrix}, \qquad v = e^{-i\frac{\kappa^2\tau}{\nu}}$$

$$A_+ = \frac{i(m^2+\kappa^2)}{2\mu}\mathrm{diag}(1,-1,1,-1)$$
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same fluctuations as in string case –
same 1-loop partition function: $Z^{(1)}_{PR} = Z^{(1)}_{string}$

$\mu \to 0$ limit (rescaled by κ^2):

$$m^2_{AdS_3} = 4\,, \qquad 2 \times m^2_{AdS_5} = 2$$
$$5 \times m^2_{S_5} = 0\,, \qquad 8 \times m^2_F = 1$$

String partition function: $(f_{tot} = \sqrt{\lambda} + f)$

$$\Gamma = -\ln Z = \frac{1}{2\pi} f(\lambda) \kappa^2 V_2$$

$$f(\lambda) = a_1 + \frac{a_2}{\sqrt{\lambda}} + O(\frac{1}{(\sqrt{\lambda})^2})$$

$$a_1 = -3 \ln 2\,, \qquad a_2 = -K$$

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String theory 2-loop correction :

$$a_2 = a_{2B} + a_{2F} = K - 2K = -K$$

Catalan's constant comes from sunset integrals with AdS_5 modes transverse to AdS_3 (i.e. $m^2_{AdS_5} = 2$) [Roiban, Tirziu, A.T., 2007]

$$I[m_1^2, m_1^2, m_1^2] \equiv \int \frac{d^2p_1 d^2p_2 d^2p_3\, \delta^{(2)}(p_1+p_2+p_3)}{(p_1^2+m_1^2)(p_2^2+m_2^2)(p_3^2+m_3^2)}$$

$$I[4,2,2] = \frac{1}{(4\pi)^2} K\,, \qquad I[2,1,1] = -\frac{2}{(4\pi)^2} K$$

K-terms thus absent in $AdS_3 \times S^3$ case [Iwashita, Roiban, A.T.]

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Step towards exact solution: S-matrix
Integrable theory – determined by 2-particle S-matrix
expand action around trivial vacuum
$g = \mathbf{1},\ A_{\pm} = 0,\ \Psi_{R} = \Psi_{L} = 0$
find two-particle scattering amplitude
for the 8+8 elementary massive excitations

$$g = e^{\eta}, \qquad \eta \in \mathfrak{g}$$

decompose η into coset ("physical") and subgroup ("gauge") parts

$$\eta = X + \xi, \qquad X \in \mathfrak{m}, \qquad \xi \in \mathfrak{h}$$

$A_{+} = 0$ gauge: preserves 2d Lorentz inv
Integrate over A_{-}: delta-function constraint on ξ

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Integrable theory – determined by 2-particle S-matrix
expand action around trivial vacuum
$g = \mathbf{1},\ A_{\pm} = 0,\ \Psi_{R} = \Psi_{L} = 0$
find two-particle scattering amplitude
for the 8+8 elementary massive excitations

$$g = e^{\eta}, \qquad \eta \in \mathfrak{g}$$

decompose η into coset ("physical") and subgroup ("gauge") parts

$$\eta = X + \xi, \qquad X \in \mathfrak{m}, \qquad \xi \in \mathfrak{h}$$

$A_{+} = 0$ gauge: preserves 2d Lorentz inv
Integrate over A_{-}: delta-function constraint on ξ

$$\partial_{+}\xi - \frac{1}{2}[X,\ \partial_{+}X] - \frac{1}{2}[\xi,\ \partial_{+}\xi] + \ldots = 0$$

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solving for ξ gives action for physical d.o.f. $(X,\ \Psi_R,\ \Psi_L)$

$$\widetilde{L} = \frac{k}{4\pi}\,\mathrm{STr}\Big(\ \frac{1}{2}\partial_+ X\partial_- X - \frac{\mu^2}{2}X^2$$

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$$+\frac{1}{12}[X,\partial_+ X][X,\partial_- X] + \frac{\mu^2}{24}[X,[X,T]]^2$$

$$-\frac{1}{4}[\Psi_L T,\Psi_L][X,\partial_+ X] - \frac{1}{4}[\Psi_R, T\Psi_R][X,\partial_- X]$$

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remaining symmetry: global part o gauge group H

$$(X,\ \Psi_R,\ \Psi_L) \to h^{-1}(X,\ \Psi_R,\ \Psi_L)h$$

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basic fields $X = Y \oplus Z$, $\Psi = \zeta \oplus \chi$ in 8×8 matrix

$$\begin{pmatrix} SU(2)_1 & Y & 0 & \zeta \\ Y & SU(2)_{\dot{1}} & \chi & 0 \\ 0 & \chi & SU(2)_2 & Z \\ \zeta & 0 & Z & SU(2)_{\dot{2}} \end{pmatrix}$$

introduce bosonic $(a, \dot{a})$ and fermionic $(\alpha, \dot{\alpha})$ indices= 1,2:
$SU(2)_1$: a $\quad SU(2)_2$: α $\quad SU(2)_{\dot{1}}$: $\dot{a}$ $\quad SU(2)_{\dot{2}}$: $\dot{\alpha}$

$$L = \partial_+ Y_{a\dot{a}} \partial_- Y^{\dot{a}a} - \mu^2 Y_{a\dot{a}} Y^{\dot{a}a}$$

$$+ \partial_+ Z_{\alpha\dot{\alpha}} \partial_- Z^{\dot{\alpha}\alpha} - \mu^2 Z_{\alpha\dot{\alpha}} Z^{\dot{\alpha}\alpha}$$

$$+ i\zeta_{L\, a\dot{\alpha}} \partial_+ \zeta_L{}^{\dot{\alpha}a} + i\zeta_{R\, a\dot{\alpha}} \partial_- \zeta_R{}^{\dot{\alpha}a} - 2i\mu \zeta_{L\, a\dot{\alpha}} \zeta_R{}^{\dot{\alpha}a}$$

$$+ i\chi_{L\, \alpha\dot{a}} \partial_+ \chi_L{}^{\dot{a}\alpha} + i\chi_{R\, \alpha\dot{a}} \partial_- \chi_R{}^{\dot{a}\alpha} - 2i\mu \chi_{L\, \alpha\dot{a}} \chi_R{}^{\dot{a}\alpha}$$

$$- \frac{2\pi}{3k} \left(Y_{a\dot{a}} Y^{\dot{a}a} \partial_+ Y_{b\dot{b}} \partial_- Y^{\dot{b}b} - Y_{a\dot{a}} \partial_+ Y^{\dot{a}a} Y_{b\dot{b}} \partial_- Y^{\dot{b}b} \right) + \ldots$$

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combine $Y_{a\dot{a}}$, $Z_{\alpha\dot{\alpha}}$, $\zeta_{a\dot{\alpha}}$, $\chi_{\alpha\dot{a}}$ into

$$\Phi_{A\dot{A}}\,, \qquad A = (a, \alpha)$$

S-matrix acting on 2-particle state:

$$\mathbb{S}\,|\Phi_{A\dot{A}}(\vartheta_1)\Phi_{B\dot{B}}(\vartheta_2)\rangle = S^{C\dot{C},D\dot{D}}_{A\dot{A},B\dot{B}}(\theta,k)\,|\Phi_{C\dot{C}}(\vartheta_1)\Phi_{D\dot{D}}(\vartheta_2)\rangle$$

Lorentz invariance: two-particle S-matrix depends on
$\theta = \vartheta_1 - \vartheta_2$, $\qquad p_{i\,0} = \mu\cosh\vartheta_i$, $\qquad p_{i\,1} = \mu\sinh\vartheta_i$

Remarkably, resulting S-matrix group-factorizes :

$$S^{C\dot{C},D\dot{D}}_{A\dot{A},B\dot{B}}(\theta,k) = (-1)^{[B][\dot{A}]+[D][\dot{C}]}S^{CD}_{AB}(\theta,k)S^{\dot{C}\dot{D}}_{\dot{A}\dot{B}}(\theta,k)$$

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and fields in bi-fundamental representation:
S-matrix should group-factorize

• happens in l.c. gauge $AdS_5 \times S^5$ superstring S-matrix
invariant under product supergroup $PSU(2|2) \times PSU(2|2)$
[Kloze,MacLoughlin,Roiban,Zarembo 06;
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• field contents of l.c. superstring and reduced theory
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S-matrix : 10 functions $K_n(\theta, k)$

$$S_{AB}^{CD}(\theta,k) = \begin{cases} K_1(\theta,k)\ \delta_a^c\delta_b^d + K_2(\theta,k)\ \delta_a^d\delta_b^c\,, \\ K_3(\theta,k)\ \delta_\alpha^\gamma\delta_\beta^\delta + K_4(\theta,k)\ \delta_\alpha^\delta\delta_\beta^\gamma\,. \\ K_5(\theta,k)\ \epsilon_{ab}\epsilon^{\gamma\delta}\,, \quad K_6(\theta,k)\ \epsilon_{\alpha\beta}\epsilon^{cd}\,, \\ K_7(\theta,k)\ \delta_a^d\delta_\beta^\gamma\,, \qquad K_8(\theta,k)\delta_\alpha^\delta\delta_b^c\,, \\ K_9(\theta,k)\ \delta_a^c\delta_\beta^\delta\,, \qquad K_{10}(\theta,k)\ \delta_\alpha^\gamma\delta_b^d\,, \end{cases}$$

$$K_1(\theta,k) = K_3(\theta,-k) = 1 + \frac{i\pi}{2k}\tanh\frac{\theta}{2} + \mathcal{O}(\frac{1}{k^2})$$

$$K_2(\theta,k) = K_4(\theta,-k) = -\frac{i\pi}{k}\coth\theta + \mathcal{O}(\frac{1}{k^2})$$

$$K_5(\theta,k) = -K_6(\theta,-k) = -\frac{i\pi}{2k}\,\mathrm{sech}\,\frac{\theta}{2} + \mathcal{O}(\frac{1}{k^2})$$

$$K_7(\theta,k) = -K_8(\theta,-k) = -\frac{i\pi}{2k}\,\mathrm{cosech}\,\frac{\theta}{2} + \mathcal{O}(\frac{1}{k^2})$$

$$K_9(\theta,k) = K_{10}(\theta,-k) = 1 + \mathcal{O}(\frac{1}{k^2})$$

compare to l.c. gauge tree-level $AdS_5 \times S^5$ string S-matrix :

$\bar{K}_n \equiv (K_n)_{string}$ depend separately on 2 rapidities and $\frac{1}{k} \to \frac{1}{\sqrt{\lambda}}$

$$\bar{K}_{1,3} = 1 \pm \frac{2\pi}{\sqrt{\lambda}}(\sinh\vartheta_1 - \sinh\vartheta_2)^2 + \mathcal{O}(\frac{1}{(\sqrt{\lambda})^2})$$
$$\bar{K}_{2,4} = \pm\frac{8\pi}{\sqrt{\lambda}}\sinh\vartheta_1 \sinh\vartheta_2 + \mathcal{O}(\frac{1}{(\sqrt{\lambda})^2})$$
$$\bar{K}_{5,6} = \frac{8\pi}{\sqrt{\lambda}}\sinh\vartheta_1 \sinh\vartheta_2 \sinh\frac{\vartheta_1-\vartheta_2}{2} + \mathcal{O}(\frac{1}{(\sqrt{\lambda})^2})$$
$$\bar{K}_{7,8} = \frac{8\pi}{\sqrt{\lambda}}\sinh\vartheta_1 \sinh\vartheta_2 \cosh\frac{\vartheta_1-\vartheta_2}{2} + \mathcal{O}(\frac{1}{(\sqrt{\lambda})^2})$$
$$\bar{K}_{9,10} = 1 \mp \frac{2\pi}{\sqrt{\lambda}}(\sinh^2\vartheta_1 + \sinh^2\vartheta_2) + \mathcal{O}(\frac{1}{(\sqrt{\lambda})^2})$$

Tree-level S-matrix of $AdS_5 \times S^5$ PR model :

- unitary and crossing-symmetric
- satisfies group factorisation, but not Yang-Baxter equation:

clash between relativistic invariance, trigonometric structure and manifest non-abelian symmetry $H = [SU(2)]^4$
(string S-matrix is not Lorentz inv. but does satisfy YBE)

- K_n are same as in q-deformed $\mathfrak{psu}(2|2) \ltimes \mathbb{R}^3$

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$AdS_2 \times S^2$ case

PR model equivalent to $\mathcal{N} = 2$ supersymmetric sine-Gordon
tree + 1-loop corrections agree with expansion of known
exact S-matrix of $\mathcal{N} = 2$ susy SG
[Kobayashi, Uematsu 91; Ahn 91; Shankar, Witten 78]

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$$Y = \prod_{l=1}^{\infty} \frac{\Gamma\left(\frac{1}{2k} - \frac{i\theta}{2\pi} + l\right)\Gamma\left(-\frac{1}{2k} - \frac{i\theta}{2\pi} + l - 1\right)\Gamma\left(-\frac{i\theta}{2\pi} + l - \frac{1}{2}\right)\Gamma\left(-\frac{i\theta}{2\pi} + l + \frac{1}{2}\right)}{\Gamma\left(\frac{1}{2k} - \frac{i\theta}{2\pi} + l + \frac{1}{2}\right)\Gamma\left(-\frac{1}{2k} - \frac{i\theta}{2\pi} + l - \frac{1}{2}\right)\Gamma\left(-\frac{i\theta}{2\pi} + l - 1\right)\Gamma\left(-\frac{i\theta}{2\pi} + l\right)}$$

manifestly invariant under (2,2) susy
which in PR model framework is interpreted as

$$\mathfrak{so}(1,1) \in (\widehat{\mathfrak{f}}^{\perp} \ltimes \mathbb{R}^{1,1}) \,, \qquad \widehat{\mathfrak{f}}^{\perp} = \mathfrak{psu}(1|1) \oplus \mathfrak{psu}(1|1)$$

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$$S_{sg}(\theta, k) \otimes S_1(\theta, k) \otimes S_1(\theta, k)$$

$$S_{sg} = \frac{\sinh\theta + i\sin\frac{\pi}{k}}{\sinh\theta - i\sin\frac{\pi}{k}}$$

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$$Y = \prod_{l=1}^{\infty} \frac{\Gamma\left(\frac{1}{2k} - \frac{i\theta}{2\pi} + l\right)\Gamma\left(-\frac{1}{2k} - \frac{i\theta}{2\pi} + l - 1\right)\Gamma\left(-\frac{i\theta}{2\pi} + l - \frac{1}{2}\right)\Gamma\left(-\frac{i\theta}{2\pi} + l + \frac{1}{2}\right)}{\Gamma\left(\frac{1}{2k} - \frac{i\theta}{2\pi} + l + \frac{1}{2}\right)\Gamma\left(-\frac{1}{2k} - \frac{i\theta}{2\pi} + l - \frac{1}{2}\right)\Gamma\left(-\frac{i\theta}{2\pi} + l - 1\right)\Gamma\left(-\frac{i\theta}{2\pi} + l\right)}$$

manifestly invariant under (2,2) susy
which in PR model framework is interpreted as

$$\mathfrak{so}(1,1) \in (\widehat{\mathfrak{f}}^{\perp} \ltimes \mathbb{R}^{1,1}) \,, \qquad \widehat{\mathfrak{f}}^{\perp} = \mathfrak{psu}(1|1) \oplus \mathfrak{psu}(1|1)$$

$AdS_2 \times S^2$ case

PR model equivalent to $\mathcal{N} = 2$ supersymmetric sine-Gordon
tree + 1-loop corrections agree with expansion of known
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$AdS_3 \times S^3$ case

- here $a, \dot{a}, \alpha, \dot{\alpha}$ are vector $SO(2)$ indices

4+4 fields $Y_{a\dot{a}}$, $Z_{\alpha\dot{\alpha}}$, $\zeta_{a\dot{\alpha}}$, $\chi_{\alpha\dot{a}}$ (with $Y_{a\dot{a}} = \epsilon_{ab}\epsilon_{\dot{a}\dot{b}}Y_{b\dot{b}}$, etc.)
can again be packaged into single $\Phi_{A\dot{A}}$

- S-matrix again group-factorizes

S_{AB}^{CD} expressed in terms of 12 functions $L_n(\theta, k)$
with similar tree ($\frac{1}{k}$) and 1-loop ($\frac{1}{k^2}$) terms

- $H = U(1) \times U(1)$ invariant S-matrix satisfies YBE

- Supersymmetry ?

by analogy with $AdS_2 \times S^2$ case
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susy : $\mathfrak{t} \ltimes u(1) \ltimes \mathbb{R}^{1,1}$; should act on factor S-matrix S_{AB}^{CD}

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\begin{aligned}
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$\mathfrak{R}$ and $\mathfrak{L}$: bosonic $u(1) \oplus u(1)$ generators

$\mathfrak{Q}_{\pm\mp}/\mathfrak{S}_{\pm\mp}$: 2+2 positive/negative chirality supercharges

$\mathfrak{P}_+$, $\mathfrak{P}_+$: 2 central extensions – 2-d momenta

This is not manifest symmetry of 1-loop S-matrix but quantum-deformed :

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$\mathfrak{P}_+$, $\mathfrak{P}_+$: 2 central extensions – 2-d momenta

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Exact S-matrix of $AdS_3 \times S^3$ PR model:

- assume q-deformed (4,4) supersymmetry is exact symmetry
- fix phase factor from unitarity, crossing and 1-loop data

$$L_{1,3} = \frac{1}{2}\Big[P_1(\theta,k)\frac{\cosh\left(\frac{\theta}{2}\pm\frac{i\pi}{k}\right)}{\cosh\frac{\theta}{2}} + P_2(\theta,k)\frac{\sinh\left(\frac{\theta}{2}\mp\frac{i\pi}{k}\right)}{\sinh\frac{\theta}{2}}\Big]$$

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$$\mathfrak{so}(1,1) \in (\mathfrak{psu}(2|2) \oplus \mathfrak{psu}(2|2) \ltimes \mathbb{R}^2)$$

bosonic part $[su(2)]^{\oplus 4}$ is also quantum-deformed
- in similar bosonic G/H theories with non-abelian H conjectured soliton S-matrix has q-deformed symmetry [Hollowood, Miramontes, 2009-11]
$q = e^{-i\frac{\pi}{k}}$-deformation appears in WZW-related contexts

Remarkably, exists relativistic S-matrix with such q-deformed supersymmetry, and it satisfies YBE [Hoare, A.T. 2011]:

given by a trigonometric relativistic limit of 2-parameter q-deformed $\mathfrak{psu}(2|2) \oplus \mathfrak{psu}(2|2) \ltimes \mathbb{R}^3$ R-matrix constructed by Beisert and Koroteev, 2008; Beisert 2010:

$$g \to \infty, \qquad\qquad q = e^{-i\frac{\pi}{k}}$$

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