Towards Lagrangian formulations of mixed-symmetry Higher Spin Fields on AdS-space within BFV-BRST formalism

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Abstract

The spectrum of superstring theory on the $\text{AdS}_5 \times S_5$ Ramond-Ramond background in tensionless limit contains integer and half-integer higher-spin fields subject at most to two-rows Young tableaux $Y(s_1, s_2)$. We review the details of a gauge-invariant Lagrangian description of such massive and massless higher-spin fields in anti-de-Sitter spaces with arbitrary dimensions. The procedure is based on the construction of Verma modules, its oscillator realizations and of a BFV-BRST operator for non-linear algebras encoding unitary irreducible representations of AdS group.

1 Introduction

Launch of LHC on the rated capacity assumes not only the answer on the question on existence of Higgs boson, the proof of supersymmetry display and a new insight on origin of Dark Matter [1], but permits one to reconsider the problems of an unique description of variety of elementary particles and all known interactions. In this relation, the development of higher-spin (HS) field theory in view of its close relation to superstring theory on constant curvature spaces, which operates with an infinite set of massive and massless bosonic and fermionic HS fields subject to multi-row Young tableaux (YT) $Y(s_1, \ldots, s_k)$, $k \geq 1$ (see for a review, [2]) seems by actual one. The paper considers the last results of constructing Lagrangian formulations (LFs) for free integer and half-integer HS fields on $\text{AdS}_d$-space with $Y(s_1, s_2)$ in Fröndal metric-like formalism within BFV-BRST approach [3] as a starting point for an interacting HS field theory in the framework of conventional Quantum Field Theory, and in part based on the results presented in [4, 5, 6, 7].

This method of Lorentz-covariant constructing LF for HS fields, developed originally in a way that applies to Hamiltonian quantization of gauge theories with a given LF, consists in a solution of the problem inverse to that of the

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method \cite{3} (as in the case of string field theory \cite{8} and in the early papers on HS fields \cite{9}) in the sense of constructing a classical gauge LF with respect to a nilpotent BFV–BRST operator $Q$.

In detail, the solution of inverse problem includes 4 steps:

- the realization of initial irrep conditions of AdS group, that extract the fields with a definite mass $m$ and generalized spin $s = (s_1, ..., s_k)$ \cite{10} as operator mixed-class constraints $o_I$ in a special Fock space $H$;
- the additive conversion (following to \cite{11}) of algebra $o_I$ into one of $O_I$: $O_I = o_I + o'_I$, $[o_I, o'_J] = 0$, determined on wider Fock space, $H \otimes H'$ with only first-class constraints $O_\alpha \subset O_I$;
- the construction of the Hermitian nilpotent BFV-BRST operator $Q'$ for non-linear superalgebra of converted operators $O_I$ which contains the BFV-BRST operator $Q$ for only subsystem of $O_\alpha$;
- the finding of Lagrangian $L$ for given HS field through corresponding scalar product $\langle \mid \rangle$ like $L \sim \langle \chi \mid Q \mid \chi \rangle$, to be invariant with respect to gauge transformations $\delta \mid \chi \rangle = Q \mid \Lambda \rangle$ with $\mid \chi \rangle$ containing initial HS field.

As compared to application of above algorithm for bosonic \cite{12} and fermionic \cite{5, 13} HS fields on $\mathbb{R}^{1,d-1}$ with standard resolution of the 2nd and 3rd steps due to the same Lie (super)algebra structure for $o_I, o'_I, O_I$: $[o_I, o_J] = f^K_{IJ}o_K$, their resolution already for totally-symmetric HS fields on $AdS_d$ space \cite{4, 14} are not so easy. It is revealed on stages of Verma module (VM) construction for $o'_I$ and its non-polynomial(!) oscillator realization in $H'$ because of AdS-radius $r^{-\frac{1}{2}}$ ($r = R/d(d-1)$ for scalar curvature $R$) \cite{4, 14}. In turn, a construction of BFV-BRST operator $Q'$ does not have the Lie-algebra form, $Q' = C^I O_I + \frac{1}{2} C^I C^J f^K_{IJ} P_K$ for (super)algebra of $O_I$ in transiting to $AdS$-space.

The main goals of the paper are to apply the above strategy to construct LFs for bosonic and fermionic HS fields on $AdS_d$-spaces subject to $Y(s_1, s_2)$.

2 Bosonic fields in AdS spaces

A massive integer spin $s = (s_1, s_2)$, $(s_1 \geq s_2)$, representation of the AdS group in an $AdS_d$ space is realized in a space of mixed-symmetry tensors,

$$\Phi_{(\mu_1, \nu_1) (\nu_2)} \equiv \Phi_{\mu_1 ... \mu_{s_1} \nu_1 ... \nu_{s_2}} (x) \leftarrow \begin{bmatrix} \mu_1 & \mu_2 & \cdots & \mu_{s_1} \\ \nu_1 & \nu_2 & \cdots & \nu_{s_2} \end{bmatrix}, \quad (1)$$
subject to the Klein-Gordon (2), divergentless, traceless and mixed-symmetry equations (3) [for \(\beta = (2; 3) \iff (s_1 > s_2; s_1 = s_2)\):

\[
\begin{align*}
\nabla^2 + r \left[ (s_1 - \beta - 1 + d) (s_1 - \beta) - s_1 - s_2 \right] + m^2 \right] \Phi(\mu), (\nu), s_1 = 0, & (2) \\
(\nabla^{\mu_1}, \nabla^{\nu_1}, g^{\mu_1\mu_2}, g^{\nu_1\nu_2}, g^{\mu_1\nu_1}) \Phi(\mu), (\nu), s_1 = \Phi((\mu), (\nu), s_1) e_{\nu_2...\nu_2} = 0. & (3)
\end{align*}
\]

To obtain HS symmetry algebra (of \(\mathcal{O}_1\)) for a description of all integer HS fields, we introduce a Fock space \(\mathcal{H}\), generated by 2 pairs of creation \(a^+_\mu(x)\) and annihilation \(a^-_\mu(x)\) operators, \(i, j = 1, 2, \mu, \nu = 0, 1..., d - 1: [a^+_\mu, a^-_\nu] = -g_{\mu\nu}\delta_{ij}\), and a set of constraints for an arbitrary string-like vector \(\Phi \in \mathcal{H}\),

\[
\Phi = \sum_{n=0}^{\infty} \sum_{\nu=(\nu_1...\nu_n)} \Phi(\mu_1...\mu_n) (x) a^{\mu_1+} a^{\mu_2+} ... a^{\mu_{n+1}+} a^{\nu_1+} ... a^{\nu_n+} |0\rangle, \]

\[
\hat{l}_0|\Phi\rangle = (\nu_0 + \tilde{m}_0^2 + r((g_{00}^2 - 2\beta - 2)g_{01}^2 - g_{02}^2))|\Phi\rangle = 0, \quad \nu_0 = [D^2 - r \frac{d(d-6)}{4}], \]

\[
(l^i, l^j, t)|\Phi\rangle = (-\partial^j_D, a^\nu_{\mu} a^{\rho}_{\nu}, a^{\mu}_{\nu} a^{\nu}_{\mu})|\Phi\rangle = 0, \quad i < j,
\]

with number particles operators, \(\hat{g}_0 = -\frac{1}{2}(a^+_\mu, a^-_{\mu})\), central charge \(\tilde{m}_0^2 = m^2 + r\beta(\beta + 1)\), operator \(D_\mu = \partial_\mu - \omega_{\beta}(x)(\sum_i a^+_{\mu} a_{\beta}), a^{(+)\mu}(x) = e^\mu_\alpha(x) a^{(+)\alpha}\) with vielbein \(e^\mu_\alpha\), spin connection \(\omega_{\beta},\) tangent indices \(a, \beta\). Operator \(D_\mu\) is equivalent in its action in \(\mathcal{H}\) to the covariant derivative \(\nabla_\mu\) [with d’Alambertian \(D^2 = (D_a + \omega_{a\beta})D^\beta\)]. The set of 7 primary constraints (5), (6) with \(\{\alpha, \beta\}\) = \{\(\hat{l}_0, l^i, l^j, t\}\} are equivalent to Eqs. (2), (3) for all spins.

For Hermiticity of BFV-BRST operator (reality Lagrangian \(\mathcal{L}\)) the algebra with \(\alpha\) must be enlarged by adding the operators \(\{l^i_+, l^j_+, t^+\}\), resulting the HS symmetry algebra in AdS\(_d\) space with \(Y(s_1, s_2)\), denoted as \(A(Y(2, AdS_d))\). The maximal Lie subalgebra of operators \(l^i_+, l^j_+, g^0_+, l^i_+, t^+\) is isomorphic to \(sp(4)\) whereas the only nontrivial quadratic commutators in \(A(Y(2, AdS_d))\) are due to operators with \(D_\mu\): \(l^i_+, l^j_+, t^+\). For the aim of LF construction it is enough to have a simpler, (so called modified) algebra \(A_{mod}(Y(2, AdS_d))\), with operator \(l_0\) instead of \(\hat{l}_0\), so that AdS-mass term, \(\tilde{m}_0^2 + r((g_{00}^2 - 2\beta - 2)g_{01}^2 - g_{02}^2)\), will be restored later within conversion and properly construction of LF. Algebra \(A_{mod}(Y(2, AdS_d))\) contains 1 first-class constraint \(l_0\), 4 differential \(l^i_+, l^i_+, 8\) algebraic \(t, t^+, l_{ij}, l^+_{ij}\) second-class constraints \(\theta_\alpha\), operators \(g^0_+\), composing an invertible matrix: 

\[
\|[\theta_\alpha, \theta_\beta]\| = ||\Delta_{ab}(g^0_+)|| + (\mathcal{O}_1),
\]

and satisfies the non-linear relations (additional to ones for \(sp(4)\)) given by Table I

In the Table I the quantities \(K_{ik}^{hb}, W_{bk}^{ki}, X_{bk}^{ki}\) are quadratic in \(\mathcal{O}_1\) (see 6 for details)

\[
W_{bk}^{ki} = 2\varepsilon^{ki} \left[(g_{01} - g_{01}) t^{12} - t^{11} + t^{12} + t^{22}\right], \quad \varepsilon^{ki} = -\varepsilon^{ik}, \varepsilon^{12} = 1.
\]
3 Verma module, Fock space realization

The procedure of additive conversion for non-linear algebra $A_{\text{mod}}(Y(2), \text{AdS}_d)$ of $o_I$ into algebra $A_c(Y(2), \text{AdS}_d)$ of converted constraints $O_I$, $O_I = o_I + o_I'$, $\{o_I, o_J\}$ acting in Hilbert space $\mathcal{H} \otimes \mathcal{H}'$ with only first-class constraints $O_o$ may be realized in two ways resulting either to unconstrained or to constrained LF. For the former case, it means the conversion of the total set of second-class constraints $\{\theta_a\}$ for the latter the conversion of only differential and part of algebraic constraints: $l_i, l_i^+, t, t^+$ having restricting the algebra $A(Y(2), \text{AdS}_d)$ to the reduced non-linear algebra $A_c(Y(2), \text{AdS}_d) = \{l_i, g_0, l_i^+, t, t^+\}$ with off-shell traceless conditions on the fields and gauge parameters of final LF. For the aims of QFT an unconstrained LF is more preferable.

To find additional parts $o_I'$ we, first, determine the multiplication law for the algebra $A_c'(Y(2), \text{AdS}_d)$, which for compactly written multiplication law for $o_I$ given by Table 1 reads (see Refs. [1, 3, 4] for details)

$$[o_I, o_J] = f^K_{IJ}o_K - f^K_{IJ}o_M o_K.$$  \hfill (11)

Second, following generalization of Poincare–Birkhoff–Witt theorem, we construct VM, based on Cartan-like decomposition enlarged from one for $sp(4)$

$$A'(Y(2), \text{AdS}_d) = \{l_i^+, t^+, l_i^+\} \oplus \{g_0, l_0\} \oplus \{l_i, t', l_i'\} \equiv E^- \oplus H \oplus E^+.$$  \hfill (12)
Note, that in contrast to the case of Lie (super)algebra and totally-symmetric HS fields on AdS space \[5, 4, 14\], the negative root vectors \(l^+_1, l^+_2, l^+_2\) are not commuted, making the arbitrary vector \(|\tilde{N}\rangle_V = |n_{11}, n_{12}, n_{22}, n_1, n, n_2\rangle_V\)

\[
|\tilde{N}\rangle_V \equiv (l^+_1)^{n_{11}}(l^+_2)^{n_{12}}(l^+_2)^{n_{22}}(t^+)^m n(t^+_2)^n n_2|0\rangle_V, \quad E^+|0\rangle_V = 0
\]

from VM, (for highest weight vector \(|0\rangle_V, n_{ij}, n, n \in \mathbb{N}_0\), and arbitrary constants \(m_i\) with dimension of mass) by not proper one for \(t^+, l^+_2\) ! That non-trivial entanglement are resolved within iterative procedure, so that the VM for algebra \(A(Y(2), AdS_d)\) may be constructed. Omitting tedious technical details (see Ref.\[4\]), note that by the crucial difference here is the presence of so-called basic block \(\hat{t}^l\) enlarging Lie part \(t^l\) in \(t^l = t^l_L + \hat{t}^l\) : \(\hat{t}^l|_{r=0} = 0\), from which the result of the action of all \(\omega^l_i\) on vector \(|\tilde{N}\rangle_V\) is found. The realization of the VM in formal power series (due to \(r\)) in degrees of creation and annihilation operators \((B, B^+) = b_i, b^+_i, b^q_i, b_i, b_i, b^+_i, b, b^+_i\) in \(H^\prime\) whose number coincides to ones of 2nd-class constraints is solved too. As a result, the Cartan generators have the boundary conditions: \((g^0_i, l^0_0) = (h^l_i, m^2_0) + O(B, B^+),\)


\[
\sum_{m=1}^{n_{ij}} \left( \frac{2r}{m^2_2} \right)^m (b^+_2)^{m-1} [b^+_2 \left( \frac{h^2 - h^1 + 2b^+ b}{(2m)!} \right) + (b^+_2)^{m+1}] \right) - \frac{b^+_2 b^+_2}{(2m)!} (h^2 - h^1 + b^+ b) b^2_2 \\
- \sum_{m=0}^{n_{ij}} \left( \frac{2r}{m^2_2} \right)^{m+1} \left( \frac{1}{(2m+1)!} \right) (b^+_2)^{m+1} (b^+_2 \left( \frac{h^2 - h^1 + 2b^+ b + b^+_2 b^+_2}{(2m+1)!} \right) \right) - \frac{b^+_2 b^+_2}{(2l+1)!} (h^2 - h^1 + b^+ b) b \\
+ \frac{m_1}{m_2} b^+_2 (b_2^+)^{2(m+l+1)} \left( b_2^+ \left( \frac{h^2 - h^1 + 2b^+ b + b^+_2 b^+_2}{(2l+1)!} \right) \right),
\]

whereas the rest operators \(\omega^l_i(B, B^+)\) may be found in \[7\].
Therefore, the solution of the second problem on construction of the VM for algebra $A(Y(2), AdS_d)$ and its oscillator realization is found.

4 BRST operator for non-linear algebra

The system of $O_I$ forming non-linear algebra $A_c(Y(2), AdS_d)$ with multiplication law following from Eq. (11):

$$\{O_I, O_J\} = F^K_{IJ}(O)O_K, \quad F^K_{IJ}(O) = f^K_{IJ} - (f^K_{JM} + f^K_{JM})o^I_M + f^K_{JM}O_M \quad (16)$$

and Table I now has no the form of closed algebra, because of presence non-trivial Jacobi identities for 6 triples $(L_1, L_2, L_0), (L^+_1, L^+_2, L_0), (L_i, L^+_i, L_0)$. Indeed, there exists a set of third order structural functions in terminology of Ref. [3] resolving those identities (see [6]). The construction of a BFV-BRST operator $Q'$ for $A_c(Y(2), AdS_d)$, in case of the Weyl ordering for quadratic combinations of $O_I$ in the r.h.s. of $[O_I, O_J]$ and for the $(CP)$-ordering for the ghost coordinates $C^I$: $\eta_0, \eta^0_G, \eta_i, \eta^i_G, \eta_{ij}, \eta, \eta^+$, and their conjugated momenta $P_I$: $P_0, P_G^i, P_s, P^+_i, P^+_s, P_{ij}, P^+_{ij}, P^+_s$, is a more complicated task than for totally-symmetric HS fields on AdS$_d$ [11 [14].

The nilpotent operator $Q'$ has the terms in third degree in ghosts $C^I$ [6],

$$Q' = Q'_1 + Q'_2 + [r^2\eta_0 \eta_i \eta_j \varepsilon^{ij} \left\{ \frac{1}{2} \sum_k (G^k_0[P^+_k P_2^+ - P^+ P^+_1] + iP^+_1 \sum (-1)^1 P^+_G) - i(L^+_1 P^+ - L^+_2 P^+_2 + 2L^+_2 P^+_2 P^+_1) \right\}
+ r^2 \eta_0 \eta_i \eta_j \left\{ \left( \sum_k (-1)^{k \frac{1}{2}} G^k_0 \sum I P^+_G + 2(L^+_2 P^+_2 - L^+_1 P^+_1) \right) P^+_1 \right\}
+ \varepsilon^{ij} \delta_{2}(1) \left( \sum_k \left( \frac{1}{2} T P^+ - 2L^+_1 P^+_2 \delta_k \right) P^+_G + 2L^+_2 P - T P^+_2 \right) P^+_2
+ 2(T^+ P^+ - L^+_2 P^+_2) P^+_1 \right\} - T \left( P^+_G P_s^2 \delta_{2} \delta^2 = 2P^{11} P^+_2 \delta^2 \delta^2 = 2 \sum_k (-1)^k \right.
\times \left( (G^k_0 P^{11} + iL^+_1 P^+_G) \delta^2 \delta^2 - (G^k_0 P^{22} + iL^+_2 P^+_G) \delta^2 \delta^2 \right)P^+_1 \right\} + h.c. \right\}, \quad (17)$$

with the standard form for linear $Q'_1$ and quadratic $Q'_2$ terms in ghosts $C^I$.

The Hermiticity of operator $Q'$ is defined by the rule: $Q'^+ K = KQ'$, for operator $K = 1 \otimes K' \otimes 1_{gh}$, with non-degenerate operator $K'$ providing the Hermiticity of the additional parts $o_I'$ in $\mathcal{H}'$.

5 Unconstrained Lagrangian formulation

BFV-BRST operator $Q$ for 1st-class constraints $O_a = \{L_0, L^i, L^i, T\}$ is extracted from $Q'$ (17) by collecting the terms with ghosts $\eta^G_G$ being by BRST-
invariant enlarged number particle operators \( \sigma^i + h^i = G^i_0 + \text{ghosts} \) and inessential operators \( B^i \) for further derivation of an LF,

\[
Q' = Q + \eta^i_G (\sigma^i + h^i) + B^i P^i_G.
\]

(18)

The same is applied to a physical vector \(| \chi \rangle \in \mathcal{H}_{\text{tot}} = \mathcal{H} \otimes \mathcal{H}' \otimes \mathcal{H}_{\text{gh}} \), \(| \chi \rangle = | \Phi \rangle + | \Phi_A \rangle \), with \(| \Phi \rangle \) given in (4). From commutativity, \([Q, \sigma^k] = 0 \) and choice of a representation for Hilbert space (as in SFT \([8]\)) it follows the spectral problem from the equation \( Q'|\chi \rangle = 0 \),

\[
Q|\chi \rangle = 0, \quad (\sigma^i + h^i)|\chi \rangle = 0, \quad gh(|\chi \rangle) = 0,
\]

(19)

thus determining the spectrum of spin values and proper eigenvectors,

\[
h^i(s_i) = -(s_i + \frac{d-\beta}{2} - 2\delta^{i2}), \quad |\chi \rangle_{(s_1,s_2)},
\]

(20)

As differed to the second equation in (19) the first equation is valid only in the subspace of \( \mathcal{H}_{\text{tot}} \) with the zero ghost number.

After substitution: \( h^i \rightarrow h^i(s_i) \) operator \( Q(s_1,s_2) \), is nilpotent on each subspace \( \mathcal{H}_{\text{tot}}(s_1,s_2) \) whose vectors satisfy to the Eqs. (19) for (20). Hence, the equations of motion (one to one correspond to Eqs. (2), (3)), a sequence of reducible gauge transformations and Lagrangian action have the form

\[
Q(s_1,s_2)|\chi^0 \rangle_{(s_1,s_2)} = 0, \quad \delta |\chi^l \rangle_{(s_1,s_2)} = Q(s_1,s_2)|\chi^{l+1} \rangle_{(s_1,s_2)}, \quad l = 0, \ldots, 6
\]

(21)

\[
S(s_1,s_2) = \int d\eta_0 (s_1,s_2) \langle \chi^0 | K(s_1,s_2) Q(s_1,s_2) |\chi^0 \rangle_{(s_1,s_2)}, \quad \text{for} \quad |\chi^0 \rangle \equiv |\chi \rangle.
\]

(22)

The corresponding LF for bosonic field with spin \( s \) subject to \( Y(s_1, s_2) \) is a reducible gauge theory of maximally \( L = 6 \)-th stage of reducibility.

### 6 Fermionic fields in AdS spaces

The construction of LF for half-integer HS fields subject to \( Y(s_1, s_2) \), \( s_i = n_i + \frac{1}{2} \) is more complicated due to presence of fermionic constraints, which follows from respective irrep conditions on spin-tensor \( \Phi_{(\mu)n_1, (\nu)n_2} \) (with suppressed spinor index \( A \)) being by Dirac, gamma-traceless and mixed-symmetry equations

\[
(\hat{i}\gamma^\mu \nabla_\mu - \hat{r} \hat{\gamma}^a (n_1 + \frac{d}{2} - \beta) - m, \ \gamma^\mu, \ \gamma^{\nu1}) \Phi_{(\mu)n_1, (\nu)n_2} = \Phi_{(\mu)n_1, (\nu)n_2} = 0. \]

The only peculiarities are as follows. Instead of case of HS symmetry algebra, we need to consider the case of respective superalgebra, and therefore the
construction of VM and BFV-BRST operator is more non-trivial, but exists (see for details [4, 7]). Because of presence in the total Hilbert space $\mathcal{H}_{tot}$ the bosonic ghosts of any power the stage of reducibility grows with spin $(s_1, s_2)$. At last, for the case of fermionic HS fields we must obtain Lagrangian which is linear in derivatives $\nabla_\mu$. But prescription which follows from bosonic case leads to second-order Lagrangian. However, this problem are effectively overcome by means of partial gauge fixing and solving of part of equations of motion. Doing so, the LF for mixed-symmetry fermionic HS fields may be constructed [5, 7].

7 Summary

We have briefly considered the method of constructing the LF for free massive mixed-symmetry HS fields on AdS$_d$ space in the framework of BFV-BRST approach. To do so, we have constructed new auxiliary representation for non-linear algebra which serve for conversion procedure of initial HS symmetry algebra. Then, we have sketched details of systematic way to find BFV-BRST operator for non-linear operator algebra and presented a proper construction of gauge LF basically for bosonic HS fields. The Eqs. (21), (22) present the basic results of the paper being the first step to interacting theory, following in part to the research [15].

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