BRST approach to Lagrangian Construction for Massive Higher Spin Fields

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Abstract

We review the recently developed general gauge invariant approach to Lagrangian construction for massive higher spin fields in Minkowski and AdS spaces of arbitrary dimension. Higher spin Lagrangian, describing the dynamics of the fields with any spin, is formulated with help of BRST-BFV operator in auxiliary Fock space. No off-shell constraints on the fields and gauge parameters are imposed. The construction is also applied to tensor higher spin fields with index symmetry corresponding to a multirow Young tableau.

1 Introduction

Higher spin field problem attracts much attention during a long time. At present, there exist the various approaches to this problem although the many aspects are still far to be completely clarified (see e.g. [1] for recent reviews of massless higher spin field theory). This paper is a brief survey of recent state of gauge invariant approach to massive higher spin field theory.

The standard BFV or BRST-BFV construction (see the reviews [2]) arose at operator quantization of dynamical systems with first class constraints. The systems under consideration are characterized by first class constraints in phase space T_a, $[T_a, T_b] = f^c_{ab}T_c$. Then BRST-BFV charge is introduced according to the rule

$$Q \;=\; \eta^a T_a + \frac{1}{2}\eta^b\eta^a f^c_{ab}\mathcal{P}_c, \qquad\qquad Q^2 = 0, \tag{1}$$

where η^a and $\mathcal{P}_a$ are canonically conjugate ghost variables (we consider here the case $gh(T) = 0$, then $gh(\eta^a) = 1$, $gh(\mathcal{P}_a) = -1$) satisfying the relations $\{\eta^a, \mathcal{P}_b\} = \delta^a_b$. After quantization the BRST-BFV charge becomes an Hermitian operator acting in extended space of states including ghost operators, the physical states in the extended space are defined by the equation $Q|\Psi\rangle = 0$. Due to the nilpotency of the BRST-BFV operator, $Q^2 = 0$, the physical states are defined up to transformation $|\Psi'\rangle = |\Psi\rangle + Q|\Lambda\rangle$ which is treated as a gauge transformation.

Application of BRST-BFV construction in the higher spin field theory [3] is inverse to above quantization problem. The initial point are equations, defining the irreducible representations of Poincare or AdS groups with definite spin and mass, the BRST-BFV operator is constructed on the base of these constraints and finally the higher spin Lagrangian is found on the base of BRST-BFV operator. Generic procedure looks as follows. The equations defining the representations are treated as the operators of first class constraints in some auxiliary Fock space. However, in the higher spin field theory a part of these constraints are non-Hermitian operators and in order to construct a Hermitian BRST-BFV operator we have to involve the operators which are Hermitian conjugate to the initial constraints and which are not the constraints. Then for closing the algebra to the complete set of operators we must add some more operators which are not constraints as well. Because of presence of such operators the standard BRST-BFV construction can not be applied it its literal form. However, as we will see, this problem can be solved.

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2 Massive bosonic field

We illustrate the method used for Lagrangian construction on the base of massive bosonic field in Minkowski d-dimensional space. It is well known that the totally symmetric tensor field $\Phi_{\mu_1\cdots\mu_s}$, describing the irreducible spin-s massive representation of the Poincare group must satisfy the following constraints

$$(\partial^2+m^2)\Phi_{\mu_1\cdots\mu_s}=0, \qquad \partial^{\mu_1}\Phi_{\mu_1\mu_2\cdots\mu_s}=0, \qquad \eta^{\mu_1\mu_2}\Phi_{\mu_1\cdots\mu_s}=0. \tag{2}$$

In order to describe all higher integer spin fields simultaneously it is convenient to introduce Fock space generated by creation and annihilation operators a_μ^+, a_μ with vector Lorentz index $\mu=0,1,2,\ldots,d-1$ satisfying the commutation relations

$$\left[a_\mu,a_\nu^+\right]=-\eta_{\mu\nu}, \qquad \eta_{\mu\nu}=(+,-,\ldots,-). \tag{3}$$

Then we define the operators

$$l_0=-p^2+m^2, \qquad l_1=a^\mu p_\mu, \qquad l_2=\tfrac{1}{2}a^\mu a_\mu, \tag{4}$$

where $p_\mu=-i\frac{\partial}{\partial x^\mu}$. These operators act on states in the Fock space

$$|\Phi\rangle \;=\; \sum_{s=0}^{\infty}\Phi_{\mu_1\cdots\mu_s}(x)a^{\mu_1+}\cdots a^{\mu_s+}|0\rangle \tag{5}$$

which describe all integer spin fields simultaneously if the following constraints on the states take place

$$l_0|\Phi\rangle=0, \qquad l_1|\Phi\rangle=0, \qquad l_2|\Phi\rangle=0. \tag{6}$$

If constraints (6) are fulfilled for the general state (5) then constraints (2) are fulfilled for each component $\Phi_{\mu_1\cdots\mu_s}(x)$ in (5) and hence the relations (6) describe all free massive higher spin bosonic fields simultaneously. Our purpose is to describe the Lagrangian construction for the massive higher spin fields on the base of BRST-BFV approach, therefore first what we should find is the Hermitian BRST-BFV operator. It means, we should have a system of Hermitian constraints. In the case under consideration the constraint l_0 is Hermitian, $l_0^+=l_0$, however the constraints l_1, l_2 are not Hermitian. We extend the set of the constraints l_0, l_1, l_2 adding two new operators $l_1^+=a^{\mu+}p_\mu$, $l_2^+=\frac{1}{2}a^{\mu+}a_\mu^+$. As a result, the set of operators l_0, l_1, l_2, l_1^+, l_2^+ is invariant under Hermitian conjugation. We want to point out that operators l_1^+, l_2^+ are not constraints on the space of bra-vectors (5) since they may not annihilate the physical states. Taking Hermitian conjugation of (6) we see that l_1^+, l_2^+ together with l_0 are constraints on the space of bra-vectors

$$\langle\Phi|l_0=0, \qquad \langle\Phi|l_1=0, \qquad \langle\Phi|l_2=0. \tag{7}$$

Algebra of the operators l_0, l_1, l_1^+, l_2, l_2^+ is open in terms of commutators of these operators. We will suggest the following procedure of consideration. We want to use the BRST-BFV construction in the simplest (minimal) form corresponding to closed algebras. To get such an algebra we add to the above set of operators, all operators generated by the commutators of l_0, l_1, l_1^+, l_2, l_2^+. Doing such a way we obtain two new operators

$$m^2 \qquad \text{and} \qquad g_0=-a_\mu^+a^\mu+\frac{d}{2}. \tag{8}$$

The resulting algebra are written in Table 1. In this table the first arguments of the commu-

	l_0	l_1	l_1^+	l_2	l_2^+	g_0	m^2
l_0	0	0	0	0	0	0	0
l_1	0	0	$l_0 - m^2$	0	$-l_1^+$	l_1	0
l_1^+	0	$-l_0 + m^2$	0	l_1	0	$-l_1^+$	0
l_2	0	0	$-l_1$	0	g_0	$2l_2$	0
l_2^+	0	l_1^+	0	$-g_0$	0	$-2l_2^+$	0
g_0	0	$-l_1$	l_1^+	$-2l_2$	$2l_2^+$	0	0
m^2	0	0	0	0	0	0	0

Table 1: Operator algebra generated by the constraints

tators and explicit expressions for all the operators are listed in the left column and the second argument of commutators are listed in the upper row.

Let us emphasize once again that operators l_1^+, l_2^+ are not constraints on the space of ket-vectors. The constraints in space of ket-vectors are l_0, l_1, l_2 (6) and they are the first class constraints in this space. Analogously, the constraints in space of bra-vectors are l_0, l_1^+, l_2^+ (7) and they also are the first class constraints but only in this space, not in space of ket-vectors. Since the operator m^2 is obtained from the commutator

$$[l_1, l_1^+] = l_0 - m^2, \tag{9}$$

where l_1 is a constraint in the space of ket-vectors (6) and l_1^+ is a constraint in the space of bra-vectors (7), then it can not be regarded as a constraint neither in the ket-vector space nor in the bra-vector space. Analogously the operator g_0 is obtained from the commutator

$$[l_2, l_2^+] = g_0, \tag{10}$$

where l_2 is a constraint in the space of ket-vectors (6) and l_2^+ is a constraint in the space of bra-vectors (7). Therefore g_0 can not also be regarded as a constraint neither in the ket-vector space nor in the bra-vector space.

One can show that a straightforward use of BRST-BFV construction as if all the operators l_0, l_1, l_2, l_1^+, l_2^+, g_0, m^2 are the first class constraints doesn't lead to the proper equations (6) for any spin. This happens because among the above hermitian operators there are operators which are not constraints (g_0 and m^2 in the case under consideration) and they bring two more equations (in addition to (6)) onto the physical field (5). Thus we must somehow get rid of these supplementary equations.

The method of avoiding the supplementary equations consists in constructing the new enlarged expressions for the operators of the algebra, so that the Hermitian operators which are not constraints will be zero.

Let us act as follows. We enlarge the representation space of the operator algebra by introducing the additional (new) creation and annihilation operators and enlarge expressions for the operators (see [4] for more details)

$$l_i \quad \longrightarrow \quad L_i = l_i + l'_i, \qquad\qquad l_i = \{l_0, l_1, l_1^+, l_2, l_2^+, g_0, m^2\}$$

The enlarged operators must satisfy two conditions:
1) They must form an algebra $[L_i, L_j] \sim L_k$;
2) The operators which can't be regarded as constraints must be zero or contain arbitrary parameters whose values will be defined later from the condition of reproducing the correct equations of motion.

In the case of higher spin fields in Minkowski space the algebra of the operators is a Lie algebra

$$[l_i, l_j] = f_{ij}^k \, l_k. \tag{11}$$

In this case we can construct the additional parts of the operators l'_i which satisfy the same algebra (11) $[l'_i, l'_j] = f_{ij}^k \, l'_k$ using the method described in [10] and since the initial operators l_i commute with the additional parts l'_j we get that the enlarged operators satisfy the same algebra $[L_i, L_j] = f_{ij}^k \, L_k$ (11). After this the BRST-BFV operators Q' can be constructed in the usual way (1).

Now one need to define the arbitrary parameters. As explained in [4] we should assume that the state vectors $|\Psi\rangle$ and the gauge parameters $|\Lambda\rangle$ in the extended Fock space, including the ghost fields, must be independent of the ghosts corresponding to the Hermitian operators which are not constraints. Let us denote these ghost as η_G and η_M corresponding to the extended operators $G_0 = g_0 + g'_0$ and $M^2 = m^2 + m'^2$ respectively.

Let us extract the dependence of the BRST-BFV operator on the ghosts η_G, $\mathcal{P}_G$, η_M, $\mathcal{P}_M$

$$Q' \quad = \quad Q + \eta_G(\sigma + h) + \eta_M(m^2 + m'^2) - \eta_2^+ \eta_2 \mathcal{P}_G + \eta_1^+ \eta_1 \mathcal{P}_M, \tag{12}$$

where $\sigma + h = g_0 + g'_0 + \textit{ghost fields}$, with h and m'^2 being the arbitrary parameters to be defined. After this the equation on the physical states in the BRST-BFV approach $Q'|\Psi\rangle = 0$ yields three equations

$$Q|\Psi\rangle = 0, \qquad gh(|\Psi\rangle) = 0, \tag{13}$$
$$(\sigma + h)|\Psi\rangle = 0, \qquad (m^2 + m'^2)|\Psi\rangle = 0. \tag{14}$$

From the two equations in (14) we find the possible values of h and m'^2 whereas equation (13) is equation on the physical state. This equation on the physical state can be obtained from the Lagrangian

$$-\mathcal{L} = \int d\eta_0 \, \langle \Psi | K Q | \Psi \rangle. \tag{15}$$

In eq. (15) above the standard scalar product in the Fock space is used and K is a specific invertible operator providing the reality of the Lagrangian (see [4] for more details). The latter acts as the unit operator in the entire Fock space, but for the sector controlled by the auxiliary creation and annihilation operators used at constructing the additional parts.

Because of nilpotensy of the BRST-BFV operator Q' (12) equation on the physical state (13) is invariant under the reducible gauge transformations

$$\delta|\Psi\rangle = Q|\Lambda\rangle, \qquad gh(|\Lambda\rangle) = -1, \tag{16}$$
$$\delta|\Lambda\rangle = Q|\Omega\rangle, \qquad gh(|\Omega\rangle) = -2. \tag{17}$$

We assume that the arbitrary parameters in eqs. (16), (17) have been fixed by conditions (14). Since all the ghost are fermionic we can not write a gauge parameter with ghost number -3 and therefore the chain of the gauge transformations is finite.

3 Lagrangian construction for the fermionic fields

The Lagrangian construction for the fermionic higher spin theories have two specific differences compared to the bosonic ones and demands some comments.

One of the specific features consists in that we have the fermionic operators in the algebra of constraints and corresponding them the bosonic ghosts. We can write these ghosts in any power in the Fock space states and therefore the gauge parameters can have an arbitrary negative number. As a result the chain of gauge transformations (16), (17) can be continued. But due to the first eq. of (14) the chain of the gauge transformations will be finite for each spin and the order of reducibility grows with the spin of the field (see [5] for further details).

Another specific features is that unlike the bosonic case, in the fermionic theory we must obtain Lagrangian which is linear in derivatives. But if we try to construct Lagrangian similar to the bosonic case (15) we obtain Lagrangian which will be the second order in derivatives. To overcome this problem one first partially fixes the gauge and partially solves some field equations. Then the obtained equations are still Lagrangian and thus we can derive the correct Lagrangian (see [5] for further details).

Using this method, the Lagrangians for the massive fermionic higher spin fields have been obtained [5].

4 Lagrangian construction for the fields in AdS

The main difference of the Lagrangian construction in AdS space is that the algebra generated by the constraints is nonlinear, but it has a special structure. The structure of the algebra looks like [6]

$$[l_i, l_j] = f_{ij}^k l_k + f_{ij}^{km} l_k l_m, \tag{18}$$

where f_{ij}^k, f_{ij}^{km} are constants. The constants f_{ij}^{km} are proportional to the scalar curvature and disappear in the flat limit.

We describe the method of finding the enlarged expressions for the operators of the algebra (18) [6], (see also [7]). First, we enlarge the representation space by introducing the additional creation and annihilation operators and construct new operators of the algebra $l_i \to L_i = l_i + l'_i$, where l'_i is the part of the operator which depends on the new creation and annihilation operators only (and constants of the theory like the mass m and the curvature).

Then we demand that the new operators L_i are in involution relations

$$[L_i, L_j] \sim L_k. \tag{19}$$

Since $[l_i, l'_j] = 0$ we have

$$\begin{aligned}[L_i, L_j] = [l_i, l_j] + [l'_i, l'_j] &= f_{ij}^k L_k - (f_{ij}^{km} + f_{ij}^{mk}) l'_m L_k + f_{ij}^{km} L_k L_m \\ &\quad - f_{ij}^k l'_k + f_{ij}^{km} l'_m l'_k + [l'_i, l'_j].\end{aligned}$$

Then in order to provide (19) the last three terms must be canceled. Thus we find the algebra of the additional parts

$$[l'_i, l'_j] = f_{ij}^k l'_k - f_{ij}^{km} l'_m l'_k \tag{20}$$

and also we find the deformed algebra for the enlarged operators

$$[L_i, L_j] = f_{ij}^k L_k - (f_{ij}^{km} + f_{ij}^{mk}) l'_m L_k + f_{ij}^{km} L_k L_m. \tag{21}$$

We see that the algebra (21) of the enlarged operators L_i is changed in comparison with the algebra (18) of the initial operators l_i.

There exists the method [10] which allows us to construct explicit expressions for the additional parts on the base of their algebra (20). Thus the problem of constructing of the additional parts for the nonlinear algebra (18) can be solved. Let us remind that the additional parts corresponding to operators which are not constraints must linearly contain arbitrary parameters (whose values will be defined later from the condition of reproducing the correct equations of motion) and therefore the trivial solution is not allowed.

Next we discuss the aspects of constructing the BRST-BFV operator caused by the nonlinearity of the operator algebra using the massive bosonic higher spin fields in AdS space [6], [7] as an example. The construction of BRST-BFV operator is based on following general principles:
1. The BRST-BFV operator Q' is Hermitian, $Q'^{+} = Q'$, and nilpotent, $Q'^{2} = 0$.
2. The BRST-BFV operator Q' is built using a set of first class constraints. In the case under consideration the operators $\tilde{L}_0$, L_1, L_1^+, L_2, L_2^+, G_0 are used as a set of such constraints.
3. The BRST-BFV operator Q' satisfies the special initial condition

$$Q'\Big|_{\mathcal{P}=0} = \eta_0\tilde{L}_0 + \eta_1^+L_1 + \eta_1L_1^+ + \eta_2^+L_2 + \eta_2L_2^+ + \eta_G G_0.$$

Straightforward calculation of the commutators allows us to find the algebra of the enlarged operators. In particular for the bosonic fields in AdS space we get the following commutation relations [6]

$$\begin{aligned}
[L_1, \tilde{L}_0] &= (\gamma-\beta)rL_1 + 4\beta rL_1^+L_2 - 4\beta rl_1'^+L_2 - 4\beta rl_2'L_1^+ \\
&\quad + 2\beta rG_0L_1 - 2\beta rl_1'G_0 - 2\beta rg_0'L_1, && (22)\\
[\tilde{L}_0, L_1^+] &= (\gamma-\beta)rL_1^+ + 4\beta rL_2^+L_1 - 4\beta rl_2'^+L_1 - 4\beta rl_1'L_2^+ \\
&\quad + 2\beta rL_1^+G_0 - 2\beta rl_1'^+G_0 - 2\beta rg_0'L_1^+, && (23)\\
[L_1, L_1^+] &= \tilde{L}_0 - \gamma rG_0 + 4(2-\beta)r(l_2'^+L_2 + l_2'L_2^+) \\
&\quad - 2(2-\beta)rg_0'G_0 + (2-\beta)r(G_0^2 - 2G_0 - 4L_2^+L_2). && (24)
\end{aligned}$$

All possible ways to order the operators in the right hand sides of (22)–(24) can be described in terms of arbitrary real parameters ξ_1, ξ_2, ξ_3, ξ_4, ξ_5. The arbitrariness in the BRST-BFV operator caused by the parameter ξ_i is resulted in arbitrariness of introducing the auxiliary fields in the Lagrangians and hence does not affect the dynamics of the basic field (see [6] for the details). After that, the construction of the Lagrangians for the fields in AdS space goes the practically the same way as for fields in Minkowsky space.

Using this method, the Lagrangians for the bosonic [6] and for fermionic [8] massive higher spin fields in AdS space have been constructed.

5 Fields corresponding to an arbitrary Young tableau

Now we consider the Lagrangian construction for the fields corresponding to non sqaure Young tableau using a Young tableau with 2 rows ($s_1 \ge s_2$)

$$\Phi_{\mu_1\cdots\mu_{s_1},\nu_1\cdots\nu_{s_2}}(x) \quad\longleftrightarrow\quad \begin{array}{|c|c|c|c|c|c|}\hline \mu_1 & \mu_2 & \cdots & \cdots & \cdots & \mu_{s_1} \\ \hline \nu_1 & \nu_2 & \cdots & \nu_{s_2} & \multicolumn{2}{c}{} \\ \cline{1-4} \end{array}. \qquad (25)$$

The tensor field is symmetric with respect to permutation of each type of the indices[1] $\Phi_{\mu_1\cdots\mu_{s_1},\nu_1\cdots\nu_{s_2}}(x) = \Phi_{(\mu_1\cdots\mu_{s_1}),(\nu_1\cdots\nu_{s_2})}(x)$ and in addition must satisfy the following equations

$$\begin{aligned}
&(\partial^2 + m^2)\Phi_{\mu_1\cdots\mu_{s_1},\nu_1\cdots\nu_{s_2}}(x) = 0, && (26)\\
&\partial^{\mu_1}\Phi_{\mu_1\cdots\mu_{s_1},\nu_1\cdots\nu_{s_2}}(x) = \partial^{\nu_1}\Phi_{\mu_1\cdots\mu_{s_1},\nu_1\cdots\nu_{s_2}}(x) = 0, && (27)\\
&\eta^{\mu_1\mu_2}\Phi_{\mu_1\mu_2\cdots\mu_{s_1},\nu_1\cdots\nu_{s_2}} = \eta^{\nu_1\nu_2}\Phi_{\mu_1\cdots\mu_{s_1},\nu_1\nu_2\cdots\nu_{s_2}} = \eta^{\mu_1\nu_2}\Phi_{\mu_1\cdots\mu_{s_1},\nu_1\cdots\nu_{s_2}} = 0, && (28)\\
&\Phi_{(\mu_1\cdots\mu_{s_1},\nu_1)\cdots\nu_{s_2}}(x) = 0. && (29)
\end{aligned}$$

[1] The indices inside round brackets are to be symmetrized.

Then we define Fock space generated by creation and annihilation operators

$$[a_i^\mu, a_j^{+\nu}] = -\eta^{\mu\nu}\delta_{ij}, \qquad \eta^{\mu\nu} = diag(+,-,-,\cdots,-) \qquad i,j=1,2. \tag{30}$$

The number of pairs of creation and annihilation operators one should introduce is determined by the number of rows in the Young tableau corresponding to the symmetry of the tensor field. Thus we introduce two pairs of such operators. An arbitrary state vector in this Fock space has the form

$$|\Phi\rangle \;=\; \sum_{s_1=0}^{\infty}\sum_{s_2=0}^{\infty} \Phi_{\mu_1\cdots\mu_{s_1},\nu_1\cdots\nu_{s_2}}(x)\; a_1^{+\mu_1}\cdots a_1^{+\mu_{s_1}} a_2^{+\nu_1}\cdots a_2^{+\nu_{s_2}}|0\rangle. \tag{31}$$

To get equations (26)–(29) on the coefficient functions we introduce the following operators

$$l_0 = -p^\mu p_\mu + m^2, \qquad l_i = a_i^\mu p_\mu, \qquad l_{ij} = \frac{1}{2}a_i^\mu a_{j\mu} \qquad g_{12} = -a_1^{+\mu} a_{2\mu} \tag{32}$$

where $p_\mu = -i\partial_\mu$. One can check that restrictions (26)–(29) are equivalent to

$$l_0|\Phi\rangle = 0\,, \qquad l_i|\Phi\rangle = 0\,, \qquad l_{ij}|\Phi\rangle = 0\,, \qquad g_{12}|\Phi\rangle = 0 \tag{33}$$

respectively.

Now we can generalize this construction to the fields corresponding to k-row Young tableau. For this purpose one should introduce Fock space generated by k pairs of creation and annihilation operators (30), where $i,j = 1,2,\ldots,k$, and then introduce operators[2] (32), but now with $i,j = 1,2,\ldots,k$. After this the Lagrangian construction can be carried out as usual [9]. Using this method Lagrangians for the massive bosonic field corresponding to 2-rows Young tableau was constructed in [9].

6 Summary

In this paper we have briefly considered the basic principles of gauge invariant Lagrangian construction for massive higher spin fields[3]. This method can be applied to any free higher spin field model in Minkowski and AdS spaces. It is interesting to point out that the Lagrangians obtained possess a reducible gauge invariance and for the fermionic fields the order of reducibility grows with value of the spin. Recent applications of BRST-BFV approach to interaction higher spin theories are discussed in [12].

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[2] Operator g_{12} is generalized to operators $g_{ij} = -a_i^{+\mu} a_{j\mu}$ where $i < j$.

[3] Lagrangian construction for massless higher spin fields see [11]

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