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ON MASSIVE HIGHER SPIN INTERACTIONS

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We discuss a possibility to extend a Fradkin-Vasiliev formalism of constructing consistent cubic interaction vertices to the cases where vertex contains massive and/or massless higher spin fields. As an illustration we provide application of this formalism to the gravitational interactions of massless and partially massless spin-5/2 fields.

Keywords: *higher spins, frame-like description, Fradkin-Vasiliev formalism.*

1 Fradkin-Vasiliev formalism

Let us first of all briefly remind what is Fradkin-Vasiliev formalism [1,2] developed for the construction of consistent cubic interaction vertices among the massless higher spin fields. The main ingredient of this formalism is the so-called frame-like description of massless higher spin fields [3–5]. Its main features can be described as follows.

- Each massless higher spin field is described by a set of one-forms Φ (physical, auxiliary and extra ones).
- Each field has its own gauge transformation

  $$\delta\Phi = D\xi + \dots$$

  where dots stand for the terms without derivatives.
- For each field a gauge invariant object (two-form) can be constructed

  $$\mathcal{R} = D \wedge \Phi + \dots$$

  where again dots stand for the terms without derivatives.
- Using these objects the free Lagrangian can be rewritten in a explicitly gauge invariant form

  $$\mathcal{L}_0 \sim \sum \mathcal{R} \wedge \mathcal{R}.$$

There exist three types of possible cubic vertices:

- trivial: $\mathcal{L} \sim \mathcal{R}\wedge\mathcal{R}\wedge\mathcal{R}$, i.e constructed using gauge invariant two-forms only and thus trivially gauge invariant (hence the name);
- abelian: $\mathcal{L} \sim \mathcal{R} \wedge \mathcal{R} \wedge \Phi$, which contain one-form and whose gauge invariance (up to total derivative) follows from the Bianci identities;
- non-abelian: $\mathcal{L} \sim \mathcal{R} \wedge \Phi \wedge \Phi$, which look similar to the ones in the Yang-Mills theories and whose gauge invariance requires introduction of non-trivial corrections to the gauge transformations.

All the non-abelian vertices can be constructed by the following deformation procedure:

- take the most general quadratic deformation of curvatures in the form: $\Delta\mathcal{R} \sim \Phi \wedge \Phi$;
- take the most general linear deformation of gauge transformations $\delta\Phi \sim \Phi\xi$;
- require that deformed curvatures transform covariantly, i.e. $\delta\hat{\mathcal{R}} \sim \mathcal{R}\xi$;
- extract cubic vertex as a part of interacting Lagrangian $\mathcal{L} \sim \sum \hat{\mathcal{R}} \wedge \hat{\mathcal{R}}$, which is just the free Lagrangian but with the initial curvatures replaced by the deformed ones.

Vasiliev has shown [6] that any non-trivial cubic vertex for massless completely symmetric fields with spins s_1, s_2 and s_3 having up to

$$N = s_1 + s_2 + s_3 - 2$$

derivatives can be obtained as a linear combination of abelian and non-abelian vertices.

The Fradkin-Vasiliev formalism was initially developed and effectively applied for the construction of cubic vertices for the massless higher spin fields (see e.g. [7–12]). As we have seen the two main ingredients of this formalism are frame-like description and gauge invariance. But frame-like gauge invariant description exists for the massive higher spin fields as well [13,14]. Thus it seem natural to extend this formalism to the case of cubic vertices containing massive and/or massless fields. Some examples for electromagnetic and gravitational interactions of massive fields already exist [15–18]. In what follows we apply such formalism for gravitational interaction of partially massless spin-5/2 field as a simplest non-trivial fermionic case.

Note that in the frame-like description most of the auxiliary and extra fields are mixed symmetry (spin-) tensors (γ-traceless in fermionic cases)

$$\Phi^{a_1\dots a_{s-1},b_1\dots b_k}$$

and this make all calculations rather involved (especially in the fermionic cases). One of the possible ways to simplify investigations is to restrict ourselves with particular space-time dimension $d=4$ and use a multispinor frame-like formalism where all fields are still one forms but with all local indices replaced by spinor ones $a \to (\alpha\dot\alpha)$. For the spin $\frac{5}{2}$ case we are interested in here it means for example:

$$\begin{aligned} &\Psi^a, \quad (\gamma\Psi)=0 \quad \Leftrightarrow \quad \Psi^{\alpha\beta\dot\alpha}, \Psi^{\alpha\dot\alpha\dot\beta}, \\ &\Omega^{[ab]}, \quad \gamma_a\Omega^{ab}=0 \quad \Leftrightarrow \quad \Omega^{\alpha\beta\gamma}, \Omega^{\dot\alpha\dot\beta\dot\gamma}. \end{aligned}$$

Thus in what follows we will work in $(A)dS_4$ space with background frame $e^{\alpha\dot\alpha}$ and covariant derivative D normalized so that ($\Lambda=-\lambda^2$)

$$D\wedge D\xi^\alpha = 2\lambda^2 E^{\alpha\beta}\xi_\beta, \qquad E^{\alpha\beta}=\frac{1}{2}e^\alpha{}_{\dot\alpha}\wedge e^{\beta\dot\alpha}.$$

2 Massless spin $\frac{5}{2}$

In this section we begin with the massless case that will be useful for the comparison. The free Lagrangian in AdS_4 space can be written as follows [13]:

$$\begin{aligned} \mathcal{L}_0 &= \psi_{\alpha\beta\dot\alpha}e^\alpha{}_{\dot\beta}D\psi^{\beta\dot\alpha\dot\beta} + \frac{3\lambda}{2}\psi_{\alpha\beta\dot\alpha}E^\alpha{}_\gamma\psi^{\beta\gamma\dot\alpha} \\ &\quad -\frac{\lambda}{2}\psi_{\alpha\beta\dot\alpha}E^{\dot\alpha}{}_{\dot\beta}\psi^{\alpha\beta\dot\beta} + h.c. \end{aligned} \tag{1}$$

This Lagrangian is invariant under the following local gauge transformations:

$$\delta_0\psi^{\alpha\beta\dot\gamma} = D\xi^{\alpha\beta\dot\gamma} + e_\gamma{}^{\dot\gamma}\eta^{\alpha\beta\gamma} + \lambda e^{(\alpha}{}_{\dot\delta}\xi^{\beta)\dot\gamma\dot\delta}. \tag{2}$$

We will need also an auxiliary field $\Omega^{\alpha\beta\gamma}$ (though it does not enter the free Lagrangian) with the corresponding gauge transformations:

$$\delta_0\Omega^{\alpha\beta\gamma} = D\eta^{\alpha\beta\gamma} + \lambda^2 e^{(\alpha}{}_{\dot\delta}\xi^{\beta\gamma)\dot\delta}. \tag{3}$$

Following the general procedure we construct two gauge invariant objects (similar to the curvature and torsion in the spin-2 case):

$$\begin{aligned} \mathcal{R}^{\alpha\beta\gamma} &= D\Omega^{\alpha\beta\gamma} + \lambda^2 e^{(\alpha}{}_{\dot\delta}\psi^{\beta\gamma)\dot\delta}, \\ \mathcal{T}^{\alpha\beta\dot\gamma} &= D\psi^{\alpha\beta\dot\gamma} + \lambda e^{(\alpha}{}_{\dot\delta}\psi^{\beta)\dot\gamma\dot\delta} + e_\delta{}^{\dot\gamma}\Omega^{\alpha\beta\delta}. \end{aligned} \tag{4}$$

Note that there is an essential difference between spin-2 and spin-5/2 cases as far as the zero torsion condition is concerned. In the spin-2 case this condition simply allows one to express Lorentz connection in terms of physical frame field, while in spin-5/2 case it also put physical field on shell:

$$\mathcal{T}=0 \quad \Rightarrow \quad \Omega=\Omega(\psi) \quad \oplus \quad \frac{\delta S}{\delta\psi}=0.$$

Using these gauge invariant objects the free Lagrangian can be rewritten in the form:

$$\mathcal{L}_0 = a_1\mathcal{R}_{\alpha\beta\gamma}\mathcal{R}^{\alpha\beta\gamma} + a_2\mathcal{T}_{\alpha\beta\dot\gamma}\mathcal{T}^{\alpha\beta\dot\gamma} + h.c., \tag{5}$$

where coefficients $a_{1,2}$ must be adjusted so that auxiliary field Ω do not enter.

Now let us turn to the gravitational interactions. It turns out that deformations for the spin-$\frac{5}{2}$ correspond just to the minimal substitution rules: $D \to D+\omega$, $e \to e+h$:

$$\begin{aligned} \Delta\mathcal{R}^{\alpha\beta\gamma} &= c_0[\omega^{(\alpha}{}_\delta\Omega^{\beta\gamma)\delta} + \lambda^2 h^{(\alpha}{}_{\dot\alpha}\psi^{\beta\gamma)\dot\alpha}], \\ \Delta\mathcal{T}^{\alpha\beta\dot\alpha} &= c_0[\omega^{(\alpha}{}_\gamma\psi^{\beta)\gamma\dot\alpha} + \omega^{\dot\alpha}{}_{\dot\beta}\psi^{\alpha\beta\dot\beta} \\ &\quad +\lambda h^{(\alpha}{}_{\dot\beta}\psi^{\beta)\dot\alpha\dot\beta} + h_\gamma{}^{\dot\alpha}\Omega^{\alpha\beta\gamma}]. \end{aligned} \tag{6}$$

At the same time deformations for the gravitational curvature and torsion have the form:

$$\begin{aligned} \Delta R^{\alpha\beta} &= b_0[\Omega^{(\alpha}{}_{\gamma\delta}\Omega^{\beta)\gamma\delta} + 2\lambda^2\psi^{(\alpha}{}_{\gamma\dot\alpha}\psi^{\beta)\gamma\dot\alpha} \\ &\quad +\lambda^2\psi^{(\alpha}{}_{\dot\alpha\dot\beta}\psi^{\beta)\dot\alpha\dot\beta}], \\ \Delta T^{\alpha\dot\alpha} &= 2b_0[\Omega^\alpha{}_{\beta\gamma}\psi^{\beta\gamma\dot\alpha} + 2\lambda\psi^\alpha{}_{\beta\dot\beta}\psi^{\beta\dot\alpha\dot\beta} + h.c.]. \end{aligned} \tag{7}$$

In this, non-trivial (on-shell) part of gauge transformations looks like:

$$\begin{aligned} \delta\hat{\mathcal{R}}^{\alpha\beta\gamma} &= R^{(\alpha}{}_\delta\eta^{\beta\gamma)\delta}, \\ \delta\hat{\mathcal{T}}^{\alpha\beta\dot\alpha} &= R^{(\alpha}{}_\gamma\xi^{\beta)\gamma\dot\alpha} + R^{\dot\alpha}{}_{\dot\beta}\xi^{\alpha\beta\dot\beta}, \\ \delta\hat{R}^{\alpha\beta} &= 2b_0\mathcal{R}^{(\alpha}{}_{\gamma\delta}\eta^{\beta)\gamma\delta}. \end{aligned} \tag{8}$$

Now we consider the following interacting Lagrangian, which is just the sum free spin-5/2 and spin-2 Lagrangians with the initial curvatures replaced by the deformed ones:

$$\begin{aligned} \mathcal{L} &= a_1\hat{\mathcal{R}}_{\alpha\beta\gamma}\hat{\mathcal{R}}^{\alpha\beta\gamma} + a_2\hat{\mathcal{T}}_{\alpha\beta\dot\gamma}\hat{\mathcal{T}}^{\alpha\beta\dot\gamma} \\ &\quad +a_0\hat{R}_{\alpha\beta}\hat{R}^{\alpha\beta} + h.c. \end{aligned} \tag{9}$$

For the Lagrangian (9) to be invariant under the transformations (8) we have to put:

$$3a_1c_0 = 4a_0b_0.$$

Note that the cubic vertex extracted from this Lagrangian contains terms with up to 2 derivatives in agreement with [19–21].

3 Partially massless spin $\frac{5}{2}$

Now let us turn to the partially massless spin-$\frac{5}{2}$ (recall that in four dimensions such field has four physical degrees of freedom corresponding to helicities $\pm\frac{5}{2}$, $\pm\frac{3}{2}$). Correspondingly, gauge invariant description requires two fields (main and Stueckelberg ones) and the free Lagrangian has the form:

$$\begin{aligned}\mathcal{L}_0 &= \psi_{\alpha\beta\dot\alpha}e^\alpha{}_{\dot\beta}D\psi^{\beta\dot\alpha\dot\beta} - \psi_\alpha e^\alpha{}_{\dot\alpha}D\psi^{\dot\alpha} \\ &+\frac{\alpha_1}{2}[3\psi_{\alpha\beta\dot\alpha}E^\alpha{}_\gamma\psi^{\beta\gamma\dot\alpha} - \psi_{\alpha\beta\dot\alpha}E^{\dot\alpha}{}_{\dot\beta}\psi^{\alpha\beta\dot\beta}] \\ &+3\alpha_2[\psi_{\alpha\beta\dot\alpha}E^{\alpha\beta}\psi^{\dot\alpha} - \psi_{\alpha\dot\alpha\dot\beta}E^{\dot\alpha\dot\beta}\psi^\alpha] \\ &-3\alpha_1\psi_\alpha E^\alpha{}_\beta\psi^\beta + h.c.\end{aligned} \quad (10)$$

Here $\alpha_1{}^2 = \frac{\lambda^2}{4}$, $\alpha_2{}^2 = -\frac{5\lambda^2}{12}$. This Lagrangian is invariant under the following gauge transformations:

$$\begin{aligned}\delta_0\psi^{\alpha\beta\dot\alpha} &= D\xi^{\alpha\beta\dot\alpha} + \alpha_1 e^{(\alpha}{}_{\dot\beta}\xi^{\beta)\dot\alpha\dot\beta} \\ &+e_\gamma{}^{\dot\alpha}\eta^{\alpha\beta\gamma} + \alpha_2 e^{\dot\alpha(\alpha}\xi^{\beta)}, \\ \delta_0\psi^\alpha &= D\xi^\alpha + 3\alpha_2 e_{\beta\dot\alpha}\xi^{\alpha\beta\dot\alpha} + 3\alpha_1 e^\alpha{}_{\dot\alpha}\xi^{\dot\alpha}.\end{aligned} \quad (11)$$

Correspondingly, we will need two auxiliary fields (note that$V^{\alpha\beta\gamma}$ is a zero form):

$$\delta_0\Omega^{\alpha\beta\gamma} = D\eta^{\alpha\beta\gamma}, \qquad \delta V^{\alpha\beta\gamma} = 6\alpha_2\eta^{\alpha\beta\gamma}. \quad (12)$$

Each of these four fields has its own gauge invariant object:

$$\begin{aligned}\mathcal{R}^{\alpha\beta\gamma} &= D\Omega^{\alpha\beta\gamma} - \frac{4\alpha_2}{5}E^{(\alpha}{}_\delta V^{\beta\gamma)\delta}, \\ \mathcal{T}^{\alpha\beta\dot\alpha} &= D\psi^{\alpha\beta\dot\alpha} + e_\gamma{}^{\dot\alpha}\Omega^{\alpha\beta\gamma} \\ &+\alpha_1 e^{(\alpha}{}_{\dot\beta}\psi^{\beta)\dot\alpha\dot\beta} + \alpha_2 e^{\dot\alpha(\alpha}\psi^{\beta)}, \\ \Psi^\alpha &= D\psi^\alpha + 3\alpha_2 e_{\beta\dot\alpha}\psi^{\alpha\beta\dot\alpha} \\ &+3\alpha_1 e^\alpha{}_{\dot\alpha}\psi^{\dot\alpha} - E_{\beta\gamma}V^{\alpha\beta\gamma}, \\ \mathcal{V}^{\alpha\beta\gamma} &= DV^{\alpha\beta\gamma} - 6\alpha_2\Omega^{\alpha\beta\gamma}.\end{aligned} \quad (13)$$

Similarly to the massless case, the zero torsion conditions not only allows one to express auxiliary fields in terms of physical ones, but simultaneously put physical fields on shell:

$$\mathcal{T} = 0 \quad \Rightarrow \quad \Omega = \Omega(\psi) \quad \oplus \quad \frac{\delta S}{\delta\psi} = 0,$$

$$\Psi = 0 \quad \Rightarrow \quad V = V(\psi) \quad \oplus \quad \frac{\delta S}{\delta\psi} = 0.$$

At last, the free Lagrangian in terms of these gauge invariant objects looks as follows:

$$\begin{aligned}\mathcal{L}_0 &= a_1\mathcal{R}_{\alpha\beta\gamma}\mathcal{R}^{\alpha\beta\gamma} + a_2\mathcal{T}_{\alpha\beta\dot\alpha}\mathcal{T}^{\alpha\beta\dot\alpha} \\ &+a_3\Psi_\alpha\Psi^\alpha + a_4\mathcal{V}_{\alpha\beta\gamma}E^\gamma{}_\delta\mathcal{V}^{\alpha\beta\delta} \\ &+a_5\mathcal{T}_{\alpha\beta\dot\alpha}e_\gamma{}^{\dot\alpha}\mathcal{V}^{\alpha\beta\gamma} + h.c.\end{aligned} \quad (14)$$

Note that there is an ambiguity in the choice of coefficients due to identity:

$$\begin{aligned}0 &\approx D(\mathcal{R}_{\alpha\beta\gamma}\mathcal{V}^{\alpha\beta\gamma}) \\ &= D\mathcal{R}_{\alpha\beta\gamma}\mathcal{V}^{\alpha\beta\gamma} + \mathcal{R}_{\alpha\beta\gamma}D\mathcal{V}^{\alpha\beta\gamma} \\ &= -6\alpha_2\mathcal{R}_{\alpha\beta\gamma}\mathcal{R}^{\alpha\beta\gamma} + \frac{12\alpha_2}{5}\mathcal{V}_{\alpha\beta\gamma}E^\gamma{}_\delta\mathcal{V}^{\alpha\beta\delta}.\end{aligned}$$

Now let us turn to the gravitational interactions. Deformations for partially massless spin $\frac{5}{2}$ again correspond to the minimal substitution rules $D \to D + \omega$, $e \to e + h$, while deformations for the gravitational curvature and torsion are defined up to the possible field redefinitions:

$$h^{\alpha\dot\alpha} \Rightarrow h^{\alpha\dot\alpha} + \kappa_1 e^{\beta\dot\alpha}V^{\alpha\gamma\delta}V_{\beta\gamma\delta} + \kappa_2 e^{\alpha\dot\alpha}V^{\beta\gamma\delta}V_{\beta\gamma\delta} + \dots$$

Non-trivial (on-shell) part of gauge transformations looks like:

$$\begin{aligned}\delta\hat{R}^{\alpha\beta} &= 2b_1\mathcal{R}^{(\alpha}{}_{\gamma\delta}\eta^{\beta)\gamma\delta} + b_2\mathcal{R}^{\alpha\beta\gamma}\xi_\gamma + \dots \\ \delta\hat{\mathcal{R}}^{\alpha\beta\gamma} &= c_0R^{(\alpha}{}_\delta\eta^{\beta\gamma)\delta} \\ \delta\hat{\mathcal{T}}^{\alpha\beta\dot\alpha} &= c_0R^{(\alpha}{}_\gamma\xi^{\beta)\gamma\dot\alpha} + c_0R^{\dot\alpha}{}_{\dot\beta}\xi^{\alpha\beta\dot\beta}.\end{aligned} \quad (15)$$

The interacting Lagrangian is just the sum of free Lagrangians with deformed curvatures plus one possible abelian vertex:

$$\begin{aligned}\mathcal{L}_0 &= a_1\hat{\mathcal{R}}_{\alpha\beta\gamma}\hat{\mathcal{R}}^{\alpha\beta\gamma} + a_2\hat{\mathcal{T}}_{\alpha\beta\dot\alpha}\hat{\mathcal{T}}^{\alpha\beta\dot\alpha} \\ &+a_3\hat\Psi_\alpha\hat\Psi^\alpha + a_4\hat{\mathcal{V}}_{\alpha\beta\gamma}E^\gamma{}_\delta\hat{\mathcal{V}}^{\alpha\beta\delta} \\ &+a_5\hat{\mathcal{T}}_{\alpha\beta\dot\alpha}e_\gamma{}^{\dot\alpha}\hat{\mathcal{V}}^{\alpha\beta\gamma} + ia_0\hat{R}_{\alpha\beta}\hat{R}^{\alpha\beta} \\ &+a_6R_{\alpha\beta}\mathcal{V}^{\alpha\beta\gamma}\psi_\gamma + h.c.\end{aligned} \quad (16)$$

Gauge invariance fixes all the coefficients in deformations as well as coefficient a_6 of abelian vertex in terms of gravitational coupling constant c_0 hence we obtained one non-trivial vertex only. As in the massless case cubic vertex contains terms with up to two derivatives in agreement with [19].

Conclusion

Thus the Fradkin-Vasiliev formalism allows one systematically investigate cubic vertices for massless, partially massless and massive fields (in any combination). Here we use the multispinor frame-like formalism. Thus means a restriction to $d = 4$ case, but allows us to describe bosonic and fermionic fields on equal footing with possible generalization to arbitrary spins. Let us stress some points where good understanding is still lacking:

- ambiguities in the choice of free Lagrangians in terms of gauge invariant objects;
- admissible field redefinitions;
- on-shell equivalence of some vertices.

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О ВЗАИМОДЕЙСТВИЯХ МАССИВНЫХ ПОЛЕЙ С ВЫСШИМИ СПИНАМИ

Мы обсуждаем возможность расширить формализм Фрадкина-Васильева построения непротиворечивых кубических вершин взаимодействия на случаи, когда вершина содержит массивные и/или безмассовые поля высших спинов. В качестве иллюстрации мы даем применение этого формализма к гравитационному взаимодействию безмассовых и частично безмассовых полей со спином 5/2.

Ключевые слова: *высшие спины, реперный формализм, формализм Фрадкина-Васильева.*

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