Breaking higher-spin symmetry in the bulk

V.E. Didenko
(with A.V. Korybut)

February 23, 2024

Motivation

- String theory comes from higher-spin symmetry breaking?
  Old ideas [D.Gross'88; S.Konshtein, M.Vasiliev'89]
  Not that old [R.Metsaev'99; B.Sundborg'01; E.Witten'01; M.Bianchi, J.F.Morales, H.Samtleben'03]
  Recent [A.Sagnotti'11; M.Vasiliev'18]

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- Mathematical tools to approach nonlinear HS dynamics
  Generating formulation [M.Vasiliev'89'92'03; V.D'22; V.D., A.Korybut'23]
  Locality problem [S.Prokushkin, M.Vasiliev'98; S.Giombi, X.Yin'10; S.Sleight, M.Taronna'18; V.D., O.Gelfond, A.Korybut, M.Vasiliev'18-24; D.Ponomarev'17; Y.Neiman'23]

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- Goal: Recover field spectrum in d dimensions by spontaneous breaking of HS symmetry in $d+1$. A proper HS vacuum is required.

HS equations

- Metric like approach
  Dates back to (Fang-)Fronsdal'78

$$
\Box\phi^{\alpha(s)} - D^{\alpha} D_{\mu}\phi^{\mu\alpha(s-1)} + \frac{1}{2} D^{\alpha} D^{\alpha}\phi^{\alpha(s-2)\mu}{}_{\mu} -
$$
$$
- m_s^2\phi^{\alpha(s)} + 2\lambda g^{\alpha\alpha}\phi^{\alpha(s-2)\mu}{}_{\mu} = O(\phi^2) + O(\phi^3) + \dots ,
$$
$$
m_s^2 = -\lambda((s-2)(d+s-3)-s)
$$

[Huge list of people. Different tools including the holographic reconstruction. Stuck at quartic order]

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$$m_s^2 = -\lambda((s-2)(d+s-3)-s)$$

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- Unfolded approach [M.Vasiliev] $\mathrm{d}^2 = 0$

$$\mathrm{d}w + [W_0, w]_* = \mathbf{e}\wedge\mathbf{e}C'$$
$$\mathrm{d}C + W_0 * C - C * \pi(W_0) = 0$$

$w = w(Y|x)$ and $C = C(Y|x)$, $W_0(Y|x)$ is the AdS vacuum

HS equations

- nonlinear corrections

$$\mathrm{d}w + w * w = \Upsilon(w, w, C) + \Upsilon(w, w, C, C) + \dots$$
$$\mathrm{d}C + w * C - C * \pi(w) = \Upsilon(w, C, C) + \Upsilon(w, C, C, C) + \dots$$

Υ's are determined from $\mathrm{d}^2 = 0$ modulo field redefinition (locality issue!)

$$w \to w + f_w(w, C..C)\,, \quad C \to C + f_C(C..C)$$

or systematically using Vasiliev's equations.

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- Simplest vacuum

$$w = W_0 \quad \text{– AdS}\,, \qquad C = 0$$

- Goal: Find w and C that solve HS e.o.m manifesting Poincaré symmetry in one dimension less.

A hint from classical double copies

- Kerr-Shield ansatz for a black hole

$$g_{mn} = g_{0\,mn} + M\phi k_m k_n$$

Solves the linearized and full Einstein eqs. at a time.

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solves Klein-Gordon for $s = 0$, Maxwell for $s = 1$

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- Kerr-Shield multicopy for any s (VD, A.Matveev, M.Vasiliev, 2008); for $s = 0, 1, 2$ (Monteiro, O'Connell, White, 2014); in any d (VD, N.Dosmanbetov'23)

$$\Box\phi_{m_1\dots m_s} - sD_n D_{(m_1}\phi^n{}_{m_2\dots m_s)} = -\frac{2}{l^2}(s-1)(s+1)\phi_{m_1\dots m_s}$$

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- Weyl multicopy (VD, A.Matveev, M.Vasiliev, 2008)

$$\text{Weyl}_s = \frac{(\text{Maxwell})^s}{(\text{scalar})^{s-1}}$$

A hint from classical double copies

- Multicopies as a free data for HS interactions

$$w^{(1)} = \sum_s a_s w_s \,, \quad C^{(1)} = \sum_s a_s C_s$$

w_s, C_s stand for s-multicopy.

- Leading order HS nonlinearities (Vasiliev)

$$D_0 C^{(2)} + [w^{(1)}, C^{(1)}]_* = -\frac{\eta}{2}\mathbf{e}^{\alpha\dot{\alpha}} y_\alpha \int \mathrm{d}\bar{u}\mathrm{d}\bar{v} \int_0^1 \mathrm{d}\tau$$

$$e^{i\bar{u}_{\dot{\alpha}}\bar{v}^{\dot{\alpha}}}\left((1-\tau)\partial_1 - \tau\partial_2\right)_{\dot{\alpha}} C^{(1)}(\tau y, \bar{y}+\bar{u}) C^{(1)}((1-\tau)y, \bar{y}+\bar{v}) + h.c.$$

A hint from classical double copies

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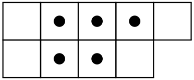
$$e^{i\bar u_{\dot\alpha}\bar v^{\dot\alpha}}((1-\tau)\partial_1-\tau\partial_2)_{\dot\alpha}C^{(1)}(\tau y,\bar y+\bar u)C^{(1)}((1-\tau)y,\bar y+\bar v)+h.c.$$

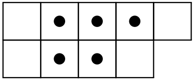
- Zeroth copy $s=0$ forms a closed sector at this order [VD, A.Korybut'22]

$$a_s=0\,,\quad s>0$$

HS dynamics of symmetric fields

Fields w, C should contain traceless diagrams

$$\omega^{a(s-1),\, b(n)} = \mathrm{d}x^{\mu}\omega_{\mu}^{a(s-1),\, b(n)} =$$  $, \qquad 0 \leq n \leq s-1$

$$C^{a(m),\, b(s)} =$$  $, \qquad m \geq s$

Generating realization

$$w = w(y_\alpha, \mathbf{y}^a_\alpha | x)\,, \quad C = C(y_\alpha, \mathbf{y}^a_\alpha | x)\,, \quad \alpha = 1,2\,, \quad a = 0 \dots d$$

w, C are then two-row diagrams provided (Howe duality)

$$[w, t_{\alpha\beta}]_* = [C, t_{\alpha\beta}]_* = 0\,, \quad t_{\alpha\beta} = \frac{1}{4i}(\mathbf{y}^a_\alpha \mathbf{y}_{a\beta} + y_\alpha y_\beta)$$

$$(f * g)(y, \vec{\mathbf{y}}) = \int f\,(y+u, \vec{\mathbf{y}} + \vec{\mathbf{u}})\, g\,(y+v, \vec{\mathbf{y}} + \vec{\mathbf{v}})\, e^{iu_\alpha v^\alpha + i\vec{\mathbf{u}}_\alpha \vec{\mathbf{v}}^\alpha}\,,$$

HS dynamics of symmetric fields

Off-shell HS algebra: Sp(2) singlets of y_α, $\mathbf{y}^a_\alpha$ endowed with *-product

On-shell HS algebra: Factor of the off-shell algebra over a two-sided ideal

$$\mathrm{Id} = t_{\alpha\beta} * A^{\alpha\beta} = A^{\alpha\beta} * t_{\alpha\beta}$$

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On-shell HS algebra: Factor of the off-shell algebra over a two-sided ideal

$$\text{Id} = t_{\alpha\beta} * A^{\alpha\beta} = A^{\alpha\beta} * t_{\alpha\beta}$$

If $f_{1,2}$ are on-shell, then

$$f_1 * f_2 = f_3 + \text{Id}$$

HS algebra deforms in interaction leading to a deformation of the ideal.

Generating interactions

Off-shell form $Y = (y, \mathbf{y})$

$$\mathrm{d}w + w * w = \Upsilon(w, w, C) + \Upsilon(w, w, C, C) + \dots$$

$$\mathrm{d}C + w * C - C * \pi(w) = \Upsilon(w, C, C) + \Upsilon(w, C, C, C) + \dots$$

$$\pi f(y, \mathbf{y}) = f(-y, \mathbf{y})$$

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Vasiliev's trick:

$$w \to W(z; Y|x) := \omega(Y|x) + W_1(z; Y|x) + W_2(z; Y|x) + \dots ,$$

$$\mathrm{d}_x W + W * W = 0$$

star product is extended to (z, Y) – space

Generating interactions

Generating equations [VD'22; VD, A.Korybut'23]
star product:

$$(f*g)(z;Y) = \int f\left(z+u', y+u; \mathbf{y}\right) \star g\left(z-v, y+v+v'; \mathbf{y}\right) e^{iu_\alpha v^\alpha + iu'_\alpha v'^\alpha}\,,$$

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Equations:

$$\mathrm{d}_x W + W * W = 0\,,$$
$$\mathrm{d}_z W + \{W, \Lambda\}_* + \mathrm{d}_x \Lambda = 0\,,$$
$$\mathrm{d}_x C + \big(W(z'; y, \vec{\mathbf{y}}) * C - C * W(z'; -y, \vec{\mathbf{y}})\big)\Big|_{z'=-y} = 0$$

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$$\Lambda=\mathrm{d}z^\alpha z_\alpha\int_0^1\mathrm{d}\tau\,\tau C(-\tau z,\vec{\mathbf{y}})e^{i\tau z_\alpha y^\alpha}$$

$$\frac{\partial}{\partial z^\alpha}\Lambda^\alpha=C*\delta\,,\quad \delta=e^{izy}\,,\quad \delta*f(z)=f(z)*\delta=f(0)\delta$$

Generating interactions

- Deformation of the $sp(2)$

$$
\begin{aligned}
&[t_{\alpha\beta}, t_{\gamma\delta}]_* = \epsilon_{\alpha\gamma} t_{\beta\delta} + \epsilon_{\beta\gamma} t_{\alpha\delta} + \epsilon_{\alpha\delta} t_{\beta\gamma} + \epsilon_{\beta\delta} t_{\alpha\gamma}\,, \\
&\mathrm{d}_x t_{\alpha\beta} + [W, t_{\alpha\beta}]_* = 0\,, \\
&\mathrm{d}_z t_{\alpha\beta} + [\Lambda, t_{\alpha\beta}]_* = 0
\end{aligned}
$$

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$$\mathrm{d}_x t_{\alpha\beta} + [W, t_{\alpha\beta}]_* = 0\,,$$

$$\mathrm{d}_z t_{\alpha\beta} + [\Lambda, t_{\alpha\beta}]_* = 0$$

- Manifest form

$$t_{\alpha\beta} = \frac{1}{4i}(\vec{\mathbf{y}}_\alpha \cdot \vec{\mathbf{y}}_\beta + y_\alpha y_\beta) - z_\alpha z_\beta \int_0^1 \mathrm{d}\tau\, \tau(1-\tau)\, C(-\tau\vec{\mathbf{y}}z; \vec{\mathbf{y}}\otimes\vec{\mathbf{y}})\, e^{i\tau zy}$$

Quest for a new vacuum

- Restriction imposed – no spins other than $s = 0$
- Poincaré global symmetry

$$ds^2 = \frac{1}{\rho^2}(\mathrm{d}\rho^2 + \eta^{ij}\mathrm{dx}_i\mathrm{dx}_j)$$

$$\mathbf{y}^a = \begin{cases} \mathbf{y}^j = \vec{\mathbf{y}}\,, & a = j < d \\ i\bar{y}\,, & a = d \end{cases},$$

- On-shell representative (traceless condition)

$$\Delta_{\alpha\beta} C := \left(\eta^{ij}\frac{\partial}{\partial \mathbf{y}^{i\alpha}}\frac{\partial}{\partial \mathbf{y}^{j\beta}} - \frac{\partial}{\partial \bar{y}^{\alpha}}\frac{\partial}{\partial \bar{y}^{\beta}} - y_\alpha y_\beta\right) C = 0\,.$$

- Protected AdS

$$W_0 = \frac{i}{2\rho}\left(\mathrm{dx}^j\, \mathbf{y}_j^\alpha (y - \bar{y})_\alpha + \mathrm{d}\rho\, y_\alpha \bar{y}^\alpha\right)$$

Quest for a new vacuum

- Ansatz

$$C = \rho^2 e^{iy_\alpha \bar{y}^\alpha}\, T(p, q; \rho)\,, \quad p = -\rho^2\, \vec{\mathbf{y}}^\alpha \cdot \vec{\mathbf{y}}^\beta y_\alpha y_\beta\,, \qquad q = 2i\rho^2\, y_\alpha \bar{y}^\alpha$$

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- Fock projector

$$e^{iy\bar{y}} * e^{iy\bar{y}} = \frac{1}{4} e^{iy\bar{y}}$$

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- Ansatz

$$C=\rho^2 e^{iy_\alpha\bar{y}^\alpha}\,T(p,q;\rho)\,,\qquad p=-\rho^2\,\vec{\mathbf{y}}^\alpha\cdot\vec{\mathbf{y}}^\beta y_\alpha y_\beta\,,\qquad q=2i\rho^2\,y_\alpha\bar{y}^\alpha$$

- Fock projector

$$e^{iy\bar{y}}*e^{iy\bar{y}}=\frac{1}{4}e^{iy\bar{y}}$$

- Equations to solve

$$\cancel{\mathrm{d}_z W_0}+\{W_0,\Lambda[C]\}_*+\mathrm{d}_x\Lambda[C]=0\,,$$

$$\left(\eta^{ij}\frac{\partial}{\partial\mathbf{y}^{i\alpha}}\frac{\partial}{\partial\mathbf{y}^{j\beta}}-\frac{\partial}{\partial\bar{y}^\alpha}\frac{\partial}{\partial\bar{y}^\beta}-y_\alpha y_\beta\right)C=0$$

$$\Lambda_\alpha=\rho^2\int_0^1\mathrm{d}\tau\tau\,z_\alpha e^{i\tau z(y-\bar{y})}\,T(\tau^2p,-\tau q;\rho)$$

- Algebraic conditions

$$[D, \Lambda_\alpha]_* = -i\rho\frac{\partial}{\partial\rho}\Lambda_\alpha\,,$$
$$[\vec{P}, \Lambda_\alpha]_* = 0$$

$$[\vec{P}, \bullet]_* = i\vec{\mathbf{y}}^\alpha\left(\frac{\partial}{\partial\bar{y}^\alpha} + \frac{\partial}{\partial y^\alpha}\right) - i\left(y - \bar{y} - i\frac{\partial}{\partial z}\right)^\alpha \frac{\partial}{\partial\vec{\mathbf{y}}^\alpha}\,,$$
$$[D, \bullet]_* = -iy^\alpha\frac{\partial}{\partial\bar{y}^\alpha} - i\bar{y}^\alpha\frac{\partial}{\partial y^\alpha} + \epsilon^{\alpha\beta}\frac{\partial^2}{\partial z^\alpha\,\partial\bar{y}^\beta}$$

Solution

- Algebraic conditions

$$[D,\Lambda_\alpha]_* = -i\rho\frac{\partial}{\partial\rho}\Lambda_\alpha\,,$$
$$[\vec{P},\Lambda_\alpha]_* = 0$$

$$[\vec{P},\bullet]_* = i\vec{\mathbf{y}}^\alpha\left(\frac{\partial}{\partial\bar{y}^\alpha}+\frac{\partial}{\partial y^\alpha}\right) - i\left(y-\bar{y}-i\frac{\partial}{\partial z}\right)^\alpha\frac{\partial}{\partial\vec{\mathbf{y}}^\alpha}\,,$$
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- Explicit result $(x_1 = -\vec{\mathbf{y}}^\alpha\cdot\vec{\mathbf{y}}^\beta y_\alpha y_\beta\,,\quad x_2 = 2iy_\alpha\bar{y}^\alpha)$

$$C = e^{iy_\alpha\bar{y}^\alpha}\left(\nu_1\,\rho^2 + \nu_2\,\rho^{d-2}\oint \mathrm{d}z\,\frac{e^z}{z^2}\left(1+\frac{x_1}{z^2}+\frac{x_2}{z}\right)^{\frac{d-4}{2}}\right)$$

Properties

- The scalar vacuum is linearly exact and on-shell

$$\phi(\vec{x},\rho) := C(0|x) = \nu_1\,\rho^2 + \nu_2\,\rho^{d-2}\,,$$
$$\Upsilon(w, C..C) = \Upsilon(w, w, C..C) = 0$$

- Global symmetry is the Poincaré algebra at the boundary
- T is polynomial in even dimensions

$$T_{d=8} = \nu_1\,\rho^2 + \nu_2\,\rho^4\left(1 + \frac{x_1^2}{120} + \frac{x_2^2}{6} + \frac{x_1}{3} + x_2 + \frac{x_1 x_2}{12}\right)\,,$$

- Gegenbauer polynomials

$$\oint \mathrm{d}z\,\frac{e^z}{z^2}\left(1 - \frac{2xy}{z} + \frac{y^2}{z^2}\right)^{-\alpha} = \sum_n \frac{y^n}{(n+1)!}\,C_n^{(\alpha)}(x)\,.$$

Conclusion

- The natural vacuum of the HS theory is AdS space with zero values of the rest of the fields. It is shown AdS remains protected even in the presence of a nonzero scalar ϕ stretched along radial direction

$$\phi(\vec{x}, \rho) = \nu_1 \rho^2 + \nu_2 \rho^{d-2}$$

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- Scalar excitation breaks space-time symmetry down to the Poincaré in one dimension less. This implies the linear fluctuations about the modified vacuum offer a free theory in the Minkowski space-time. Parameters ν_1, ν_2 being dimensionful are likely to define the form of the HS broken spectrum

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Thank you!