Universidad de Oviedo

The Importance of Being Disconnected: Principal Extension Gauge Theories

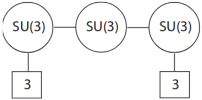
Antoine Bourget

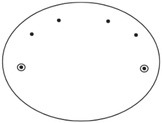
Bern, July 17, 2018

Work with Alessandro Pini and Diego Rodriguez-Gomez (1804.01108)

Gauge theories initially formulated using simple Lie algebras. Possible extensions include:

- Products of many Lie algebras / groups





[Gaiotto, 0904.2715]

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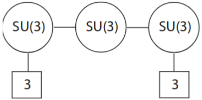

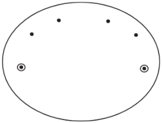

[Gaiotto, 0904.2715]

- Global structure (π_1) of the group

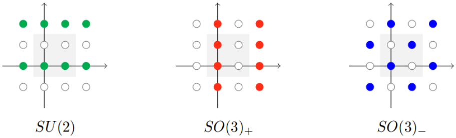

Figure 1: The weights of line operators of gauge theories with $\mathbf{g} = su(2)$.

[Aharony, Seiberg, Tachikawa, 1305.0318]

- What about the global structure π_0 of the group?

Recent interest on discrete gauging (recall Hanany's talk).
Gauging of a discrete symmetry allows for new Coulomb branch geometries

	Discrete gauge group action on the Coulomb Branch:									CFT data:			
parent	$\mathbb{Z}_2$	$\widetilde{\mathbb{Z}}_2$	$\mathbb{Z}_3$	$\widetilde{\mathbb{Z}}_3$	$\mathbb{Z}_4$	$\widetilde{\mathbb{Z}}_4$	$\mathbb{Z}_5$	$\mathbb{Z}_6$	$\widetilde{\mathbb{Z}}_6$	k_F	$24a$	$12c$	h
$[II^*,E_8]$										12	95	62	0
$[III^*,E_7]$										8	59	38	0
$[IV^*,E_6]$	$[II^*,F_4]$									6	41	26	0
$[I_0^*,D_4\chi_0]$	$[III^*,B_3]$		$[II^*,G_2]$							4	23	14	0
$[IV,A_2\chi_{\frac{1}{2}}]$	$[IV^*,A_2]$				$[II^*,B_1]$					3	14	8	0
$[III,A_1\chi_{\frac{2}{3}}]$			$[III^*,A_1]$							$\frac{8}{3}$	11	6	0
$[II,\chi_{\frac{4}{5}}]$							$[II^*,\varnothing]$			–	$\frac{43}{5}$	$\frac{22}{5}$	0
$[I_0,\varnothing]$	$[I_0^*,\varnothing]$		$[IV_1^*,\varnothing]$		$[III^*,\varnothing]$			$[II^*,\varnothing]$		–	5	2	0
$[II^*,C_5]$										7	82	49	5
$[III^*,C_3C_1]$										(5,8)	50	29	3
$[IV^*,C_2U_1]$	$[II^*,C_2]$									(4,?)	34	19	2
$[I_0^*,C_1\chi_0]$	$[III^*,C_1]$	$[III^*,U_1\rtimes\mathbb{Z}_2]$								3	18	9	1
$[I_4,U_1]$	$[I_2^*,\varnothing]$	$[I_2^*,\varnothing]$								1	6	3	0
$[II^*,A_3\rtimes\mathbb{Z}_2]$										14	75	42	4
$[III^*,A_1U_1\rtimes\mathbb{Z}_2]$										(10,?)	45	24	2
$[IV^*,U_1]$	$[II^*,\varnothing]$									5	30	15	1
$[I_1^*,\varnothing]$										–	17	8	0
$[II^*,A_2\rtimes\mathbb{Z}_2]$										14	71	38	3
$[III^*,U_1\rtimes\mathbb{Z}_2]$										7	42	21	1
$[IV_1^*,\varnothing]$										–	$\frac{55}{2}$	$\frac{25}{2}$	0
$[I_0^*,C_1\chi_0]$	$[III^*,C_1]$	$[III^*,U_1\rtimes\mathbb{Z}_2]$	$[II^*,C_1]$	$[II^*,U_1\rtimes\mathbb{Z}_2]$						3	18	9	1
$[I_2,U_1]$	$[I_1^*,\varnothing]$	$[I_1^*,\varnothing]$								1	6	3	0
$[I_0,\varnothing]$			$[IV_{\sqrt{2}}^*,\varnothing]$	$[IV_{\sqrt{2}}^*,\varnothing]$						–	5	2	0
$[I_0,C_1\chi_0]$	$[I_0^*,\chi_0]\times\mathbb{H}$	$[I_0^*,C_1\chi_0]$	$[IV_1^*,\varnothing]\times\mathbb{H}$	$[IV^*,U_1]$	$[III^*,\varnothing]\times\mathbb{H}$	$[III^*,U_1\rtimes\mathbb{Z}_2]$		$[II^*,\varnothing]\times\mathbb{H}$	$[II^*,U_1\rtimes\mathbb{Z}_2]$	1	6	3	1
$[I_0,\varnothing]$	$[I_0^*,\varnothing]$	$[I_0^*,\varnothing]$	$[IV_1^*,\varnothing]$	$[IV_1^*,\varnothing]$	$[III^*,\varnothing]$	$[III^*,\varnothing]$		$[II^*,\varnothing]$	$[II^*,\varnothing]$	–	5	2	0

[Argyres, Martone, 1611.08602]

Alternative approach : start from a disconnected gauge group.

In this work

- We consider a special class of non-connected groups
- We focus on 4d $\mathcal{N} = 2$ SCFTs
- We look at local physics and use algebraic counting tools.

Outline

Principal Extension Groups

The Coulomb branch Index

The Higgs Branch of SQCD and the Global Symmetry

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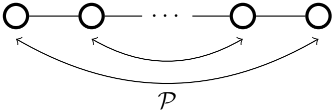
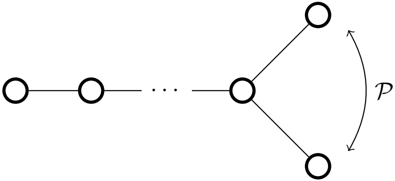
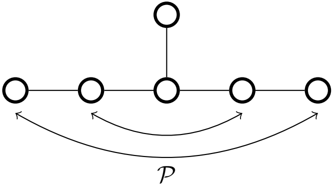


D_N



E_6



Principal Extension Groups

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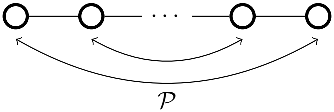

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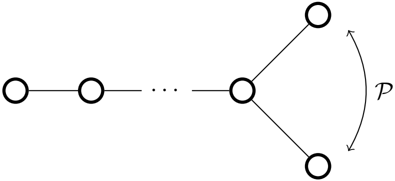

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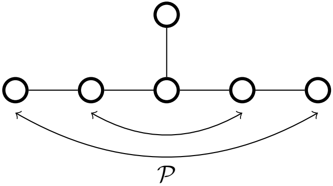

Definition of *principal extension*

$$\widetilde{G} = G_{\mathrm{adj}} \rtimes_{\varphi} \Gamma_{\mathrm{outer}}$$

Examples :

$$\widetilde{\mathrm{SU}}(N) = \mathrm{SU}(N) \rtimes_{\varphi} \{1, \mathcal{P}\}$$

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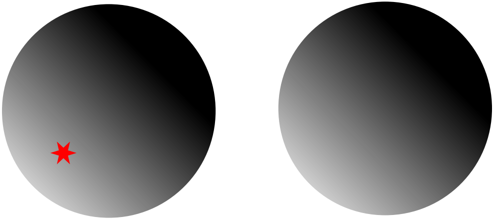

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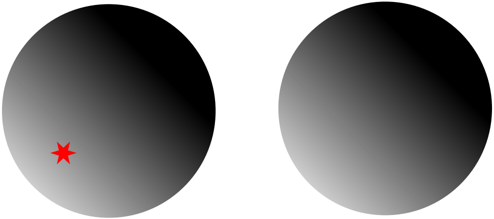
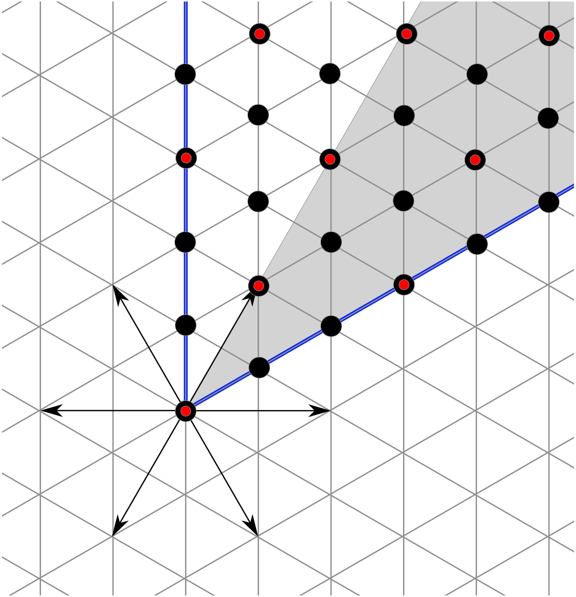


$(X, 1)$ $(X, \mathcal{P})$

In the case of $\mathrm{SU}(N)$, this is related to complex conjugation:

$$\overline{X} = A^{-1}\mathcal{P}(X)A\,, \qquad A^{T} = (-1)^{N-1}A \qquad \text{and} \qquad \det A = 1\,.$$

Representations ($\widetilde{\mathrm{SU}}(3)$ example)



Outline

Principal Extension Groups

The Coulomb branch Index

The Higgs Branch of SQCD and the Global Symmetry

Recall the superconformal index for a theory with gauge group G and some fundamental matter multiplets:

$$\mathcal{I} = \int \mathrm{d}\eta_G(X)\, \mathrm{PE}\Big[\sum_{i \in \text{multiplets}} f^{\mathcal{R}_i}\, \chi_{\mathcal{R}_i}(X) \Big]\,;$$

where

$$f^V = -\frac{\sigma\,\tau}{1-\sigma\,\tau} - \frac{\rho\,\tau}{1-\rho\,\tau} + \frac{\sigma\,\rho - \tau^2}{(1-\rho\,\tau)\,(1-\sigma\,\tau)}\,,$$

$$f^{\frac{1}{2}H} = \frac{\tau\,(1-\rho\,\sigma)}{(1-\rho\,\tau)\,(1-\sigma\,\tau)}\,.$$

In the limit

$$\tau \to 0, \qquad \rho\sigma =: t\,.$$

we have

$$f^{V} = t, \qquad f^{\frac{1}{2}H} = 0\,.$$

This gives the *Coulomb branch index* [Gadde, Rastelli, Razamat, 1110.3740].

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$$\mathcal{I}_G^{\mathrm{Coulomb}}(t) = \int_G \mathrm{d}\eta_G(X) \frac{1}{\det\left(1 - t\Phi_{\mathrm{Adj}}(X)\right)}\,,$$

This is Molien's formula for the Hilbert series of invariants of the adjoint representation.

What is a Hilbert Series

Let R be a Noetherian graded ring with $R_0 = \mathbb{C}$,

$$R = \bigoplus_{n \in \mathbb{N}} R_n \,.$$

The Hilbert series of R is

$$\mathrm{HS}\,(R, t) = \sum_{n \in \mathbb{N}} t^n \dim_{\mathbb{C}} R_n \,.$$

Example :

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For polynomial rings, the Hilbert series is always a rational function [Hilbert, 1890.xxxx]

If the ring is a *complete intersection*,

$$\mathrm{HS}\left(\mathbb{C}[\mathrm{Gens}]/(\mathrm{Rels}), t\right) = \frac{\prod_{\mathrm{Rels}} \left(1 - t^{\mathsf{deg}(\mathrm{Rels})}\right)}{\prod_{\mathrm{Gens}} \left(1 - t^{\mathsf{deg}(\mathrm{Gens})}\right)}$$

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Example:

$$\mathrm{HS}\left(\mathbb{C}[x_1, x_2, x_3]/(x_1 x_2 - x_3^2), t\right) = 1 + 3t + 5t^2 + ... = \frac{1 - t^2}{(1-t)^3}$$

Particular case: freely-generated ring

$$\mathbb{C}[\mathbf{x}]^G \cong \mathbb{C}[I_1, \ldots, I_m]\,, \qquad HS(\mathbb{C}[\mathbf{x}]^G, t) = \frac{1}{\prod_{i=1}^{m}(1 - t^{\deg I_i})}\,.$$

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In general, Hironaka decomposition for invariant rings:

$$\mathbb{C}[\mathbf{x}]^G \cong \bigoplus_{j=1}^{p} J_j \mathbb{C}[I_1, \ldots, I_m]$$

$$HS(\mathbb{C}[\mathbf{x}]^G, t) = \frac{\sum_{j=1}^{p} t^{\deg J_j}}{\prod_{i=1}^{m}(1 - t^{\deg I_i})}.$$

Consider a finite group G, and a (finite-dimensional complex) representation V. Consider the ring of invariants

$$\mathbb{C}[V]^G.$$

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For a large class of groups ("reductive"),

$$\frac{1}{|G|}\sum_{g\in G} \longrightarrow \int_G \mathrm{d}\eta_G(X).$$

For a class function f,

$$\int_{\widetilde{\mathrm{SU}}(N)} \mathrm{d}\eta_{\widetilde{\mathrm{SU}}(N)}(X) f(X) = \frac{1}{2}\left[\int \mathrm{d}\mu_N^+(z) f(z) + \int \mathrm{d}\mu_N^-(z) f(z^{\mathcal{P}})\right]$$

[Wendt, 1999]

with

$$\mathrm{d}\mu_N^+(z) = \prod_{j=1}^{N-1} \frac{\mathrm{d}z_j}{2\pi i z_j} \prod_{\alpha \in R^+(A_{N-1})} (1 - z(\alpha)) \ ,$$

and

$$N \text{ even:} \qquad \mathrm{d}\mu_N^-(z) = \prod_{j=1}^{N/2} \frac{\mathrm{d}z_j}{2\pi i z_j} \prod_{\alpha \in R^+(B_{N/2})} (1 - z(\alpha)) \ .$$

$$N \text{ odd:} \qquad \mathrm{d}\mu_N^-(z) = \prod_{j=1}^{(N-1)/2} \frac{\mathrm{d}z_j}{2\pi i z_j} \prod_{\alpha \in R^+(C_{(N-1)/2})} (1 - z(\alpha)) \ .$$

Computation for $\mathrm{SU}(N)$:

$$\mathcal{I}^{\mathrm{Coulomb}}_{\mathrm{SU}(N)}(t) = \frac{1}{\prod_{i=2}^{N}(1-t^i)}\,,$$

corresponds to

$$\mathbb{C}[\phi_{ij}]^{\mathrm{SU}(N)} \cong \mathbb{C}[\mathrm{Tr}(\phi^k)_{k=2,\ldots,N}]\,,$$

polynomial ring without any relation.

Computation for $\widetilde{\mathrm{SU}}(N)$:

$$\mathcal{I}^{\mathrm{Coulomb}}_{\widetilde{\mathrm{SU}}(N)}(t) = \frac{\sum\limits_{k_1<\cdots<k_r \text{ odd}} t^{k_1+\cdots+k_r}}{\prod\limits_{i \text{ even}} (1-t^i) \prod\limits_{i \text{ odd}} (1-t^{2i})},$$

Why?

$$\mathrm{Tr}((\phi^{\mathcal{P}})^k) = (-1)^k \mathrm{Tr}(\phi^k) .$$

There are "holes" in the structure of invariants.

Invariant theory interpretation:

1. The *primary* invariants I_k for $2 \leq k \leq N$ defined by

$$I_k = \begin{cases} \mathrm{Tr}(\phi^k) & \text{for } k \text{ even} \\ \mathrm{Tr}(\phi^k)^2 & \text{for } k \text{ odd} \end{cases} .$$

2. The *secondary* invariants

$$J_{k_1,\dots,k_r} = \prod_{i=1}^{r} \mathrm{Tr}(\phi^{k_i}) \,,$$

   for $k_1, \dots, k_r$ odd and $3 \leq k_1 < \cdots < k_r \leq N$, with r even ($r = 0$ corresponds to the trivial invariant 1).

Relations (among others):

$$J^2_{k_1,\dots,k_r} - I_{k_1} \dots I_{k_r} = 0 \,,$$

For $N \geq 5$ the Coulomb branch of $\mathcal{N} = 2\ \widetilde{\mathrm{SU}}(N)$ gauge theories (of genus 0) is not freely generated.

See also [Argyres, Martone, 1804.03152]
[Bourton, Pini, Pomoni, 1804.05396]

The Non-Freely Generated Coulomb Branch

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Example for $N = 5$: Coulomb branch parametrized by I_2, I_3, I_4, I_5, $J_{3,5}$ with relation $J_{3,5}^2 = I_3 I_5$.

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Complex singularity of complex dimension 2 parametrized by I_2 and I_4.

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Higgs branch Hilbert Series

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Consider the $\mathcal{N}=2$ $\mathrm{SU}(N)$ gauge theory with $2N$ fundamental hypers.

$$W \sim \mathrm{Tr}\,\tilde{Q}\phi Q \qquad \Longrightarrow \qquad Q\tilde{Q} - \frac{1}{N}(\mathrm{Tr}\,Q\tilde{Q})\mathbf{1}_N = 0$$

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Higgs branch Hilbert series: [Hanany, Feng, He, Mekareeya, Benvenuti,...]

$$H_{\mathrm{SU}(N)} = \int \mathrm{d}\eta_{\mathrm{SU}(N)}(X) \frac{\det\left(1 - t^2\Phi_{\mathrm{Adj}}(X)\right)}{\det\left(1 - t\Phi_{\mathrm{F}}(X)\right)^{2N} \det\left(1 - t\Phi_{\bar{\mathrm{F}}}(X)\right)^{2N}} .$$

Refine using $(S)U(2N)$ global fugacities. Example

$$H_{\mathrm{SU}(3)} = 1 + t^2\left(\chi_{10001} + 1\right) + 2t^3\chi_{00100} + t^4\left(\chi_{01010} + \chi_{10001} + \chi_{20002} + 1\right) + \ldots$$

Now $\widetilde{SU}(N)$

$$H_{\widetilde{SU}(N)} = \int \mathrm{d}\eta_{\widetilde{\mathrm{SU}}(N)}(X) \frac{\det\left(1 - t^2 \Phi_{\mathrm{Adj}}(X)\right)}{\det\left(1 - t\chi^{\mathrm{Flav}}_{10\ldots0} \otimes \Phi_{\mathrm{F}\bar{\mathrm{F}}}(X)\right)} \,,$$

What is the flavor symmetry group?

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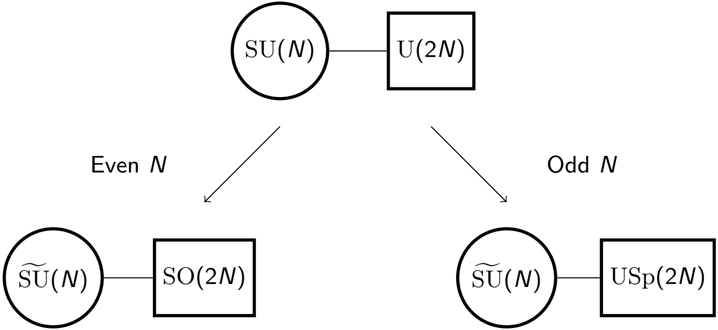
What is the flavor symmetry group?

Mesons satisfy symmetry / antisymmetry relations depending on the parity of N.

The Higgs Branch of SQCD



Examples

$$\mathcal{H}_{SU(3)} = 1 + 36t^2 + 40t^3 + 630t^4 + 1120t^5 + 7525t^6 + \ldots$$
$$\mathcal{H}_{\widetilde{SU}(3)} = 1 + 21t^2 + 20t^3 + 336t^4 + 560t^5 + 3850t^6 + \ldots$$

The mesons are symmetric

$$\begin{aligned}\mathcal{H}_{\widetilde{SU}(3)} \quad = \quad & 1 + [2,0,0]_{C_3}\, t^2 + \left([0,0,1]_{C_3} + [1,0,0]_{C_3}\right) t^3 \\ & + \left(2\,[0,1,0]_{C_3} + 2\,[0,2,0]_{C_3} + [4,0,0]_{C_3} + 2\right) t^4 + \ldots .\end{aligned}$$

$$\mathcal{H}_{SU(4)} = 1 + 64t^2 + 2156t^4 + 49035t^6 + \ldots$$

$$\mathcal{H}_{\widetilde{SU}(4)} = 1 + 28t^2 + 1106t^4 + 24381t^6 + \ldots$$

The mesons are anti-symmetric

$$\begin{aligned}\mathcal{H}_{(4,\,8)} \quad &= \quad 1 + [0,1,0,0]_{D_4}\, t^2 + \Big(2\,[0,0,0,2]_{D_4} + 2\,[0,0,2,0]_{D_4} \\ &\quad +2\,[0,2,0,0]_{D_4} + 2\,[2,0,0,0]_{D_4} + [4,0,0,0]_{D_4} + 2\Big)\, t^4 \\ &\quad +\ldots\end{aligned}$$

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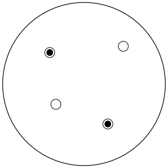
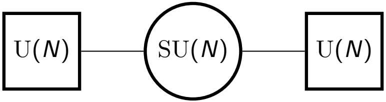
On a space-time manifold with non-trivial cycles, one can define gauge bundles with disconnected groups. Put the class $\mathcal{S}$ theory





on $\mathcal{C} \times \mathbb{R}^{1,2} \times S^1$ with:

- Twisted punctures
- Twist along S^1.

The twisted sector (alone) has been studied

[Mekareeya, Song, Tachikawa, 1212.0545]

The index for a sphere with 3 punctures is

$$\tilde{I} = \sum_{\lambda} \prod_{i=1,2,3} \frac{\tilde{K}_{\Lambda_i}(\mathbf{a}_i)\tilde{P}_\lambda(\mathbf{a}_i t^{\Lambda_i})}{\tilde{K}_\rho \tilde{P}_\lambda(t^\rho)}$$

$\Longrightarrow$ "TQFT" structure of superconformal index.

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[Mekareeya, Song, Tachikawa, 1212.0545]

The index for a sphere with 3 punctures is

$$\tilde{I} = \sum_{\lambda} \prod_{i=1,2,3} \frac{\tilde{K}_{\Lambda_i}(\mathbf{a}_i)\tilde{P}_{\lambda}(\mathbf{a}_i t^{\Lambda_i})}{\tilde{K}_{\rho}\tilde{P}_{\lambda}(t^{\rho})}$$

$\Longrightarrow$ "TQFT" structure of superconformal index.

Work in progress : combined sectors.

Conclusion

- Representation theory of principal extension allows to construct interesting Lagrangian $\mathcal{N} = 2$ SCFTs
- They have non freely generated CBs in general
- They are type A theories with orthogonal / symplectic global symmetries

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Further explorations:

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Thank you for your attention!