Flux tubes, domain walls and orientifold planar equivalence

Agostino Patella

CERN

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Orientifold planar equivalence

OrQCD

$SU(N)$ gauge theory ($\lambda = g^2 N$ fixed) with N_f Dirac fermions in the antisymmetric representation

is equivalent in the large-N limit and in a common sector to

AdQCD

$SU(N)$ gauge theory ($\lambda = g^2 N$ fixed) with N_f Majorana fermions in the adjoint representation

if and only if C-symmetry is not spontaneously broken.

Gauge-invariant common sector

AdQCD	Bosonic C-even	Fermionic C-even	Bosonic C-odd	Fermionic C-odd
	$\Updownarrow$			
OrQCD	Bosonic C-even		Bosonic C-odd	
	Common sector			

Gauge-invariant common sector

AdQCD	Bosonic C-even	Fermionic C-even	Bosonic C-odd	Fermionic C-odd
	$\Updownarrow$			
OrQCD	Bosonic C-even		Bosonic C-odd	
	Common Sector			

$$e^{-N^2 W(J)} = \int \mathcal{D}A\mathcal{D}\psi\mathcal{D}\bar{\psi} \ \exp\left\{-S(A,\psi,\bar{\psi}) + N^2 \int J(x)O(x)d^4x\right\}$$

$$\lim_{N\to\infty} W_{Or}(J) = \lim_{N\to\infty} W_{Ad}(J)$$

Gauge-invariant common sector

AdQCD	Bosonic C-even	Fermionic C-even	Bosonic C-odd	Fermionic C-odd
	$\Updownarrow$			
OrQCD	Bosonic C-even		Bosonic C-odd	
	Common Sector			

$$e^{-N^2 W(J)} = \int \mathcal{D}A\mathcal{D}\psi\mathcal{D}\bar{\psi}\ \exp\left\{-S(A,\psi,\bar{\psi}) + N^2 \int J(x)O(x)d^4x\right\}$$

$$\lim_{N\to\infty} \frac{\langle O(x_1)\cdots O(x_n)\rangle_{c,Or}}{N^{2-2n}} = \lim_{N\to\infty} \frac{\langle O(x_1)\cdots O(x_n)\rangle_{c,Ad}}{N^{2-2n}}$$

Gauge-invariant common sector

AdQCD	BOSONIC C-EVEN	FERMIONIC C-EVEN	BOSONIC C-ODD	FERMIONIC C-ODD
	$\Updownarrow$			
OrQCD	BOSONIC C-EVEN		BOSONIC C-ODD	
	COMMON SECTOR			

$$e^{-N^2 W(J)} = \int \mathcal{D}A\mathcal{D}\psi\mathcal{D}\bar{\psi}\ \exp\left\{ -S(A,\psi,\bar{\psi}) + N^2 \int J(x)O(x)d^4x \right\}$$

$$\lim_{N\to\infty} \frac{\langle O(x_1)\cdots O(x_n)\rangle_{c,Or}}{N^{2-2n}} = \lim_{N\to\infty} \frac{\langle O(x_1)\cdots O(x_n)\rangle_{c,Ad}}{N^{2-2n}}$$

$$\lim_{N\to\infty} \langle 0|O|0\rangle_{Or} = \lim_{N\to\infty} \langle 0|O|0\rangle_{Ad}$$

Gauge-invariant common sector

AdQCD	Bosonic C-even	Fermionic C-even	Bosonic C-odd	Fermionic C-odd
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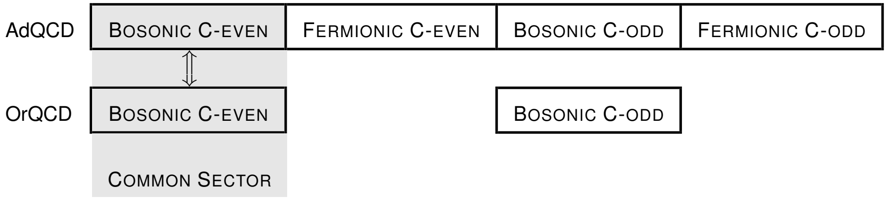
$$\lim_{N\to\infty} \langle a|O|b\rangle_{Or} = \lim_{N\to\infty} \langle a|O|b\rangle_{Ad}$$

Gauge-invariant common sector



$$e^{-N^2 W(J)} = \int \mathcal{D}A\mathcal{D}\psi\mathcal{D}\bar{\psi}\ \exp\left\{-S(A,\psi,\bar{\psi}) + N^2 \int J(x)O(x)d^4x\right\}$$

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$$\lim_{N\to\infty} \langle a|O|b\rangle_{Or} = \lim_{N\to\infty} \langle a|O|b\rangle_{Ad}$$

$$\lim_{N\to\infty} \langle a|e^{-tH}|b\rangle_{Or} = \lim_{N\to\infty} \langle a|e^{-tH}|b\rangle_{Ad}$$

Gauge-invariant common sector

AdQCD	Bosonic C-even	Fermionic C-even	Bosonic C-odd	Fermionic C-odd
	$\Updownarrow$			
OrQCD	Bosonic C-even		Bosonic C-odd	
	Common Sector			

$$e^{-N^2 W(J)} = \int \mathcal{D}A\mathcal{D}\psi\mathcal{D}\bar{\psi}\ \exp\left\{-S(A,\psi,\bar{\psi}) + N^2 \int J(x)O(x)d^4x\right\}$$

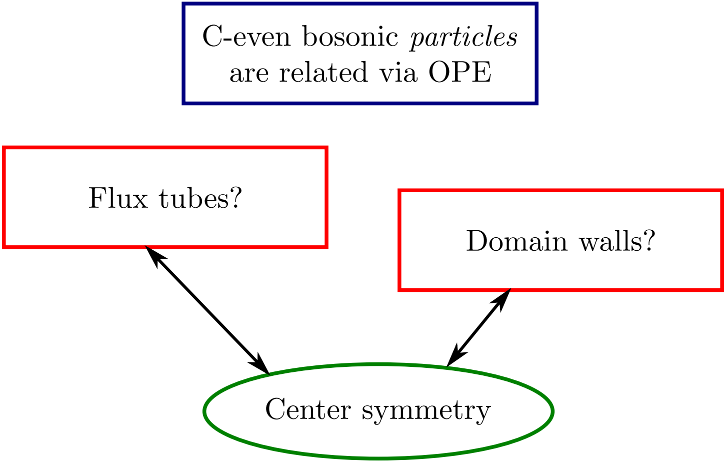
$$\lim_{N\to\infty} \frac{\langle O(x_1)\cdots O(x_n)\rangle_{c,Or}}{N^{2-2n}} = \lim_{N\to\infty} \frac{\langle O(x_1)\cdots O(x_n)\rangle_{c,Ad}}{N^{2-2n}}$$

$$\lim_{N\to\infty} \langle a|O|b\rangle_{Or} = \lim_{N\to\infty} \langle a|O|b\rangle_{Ad}$$

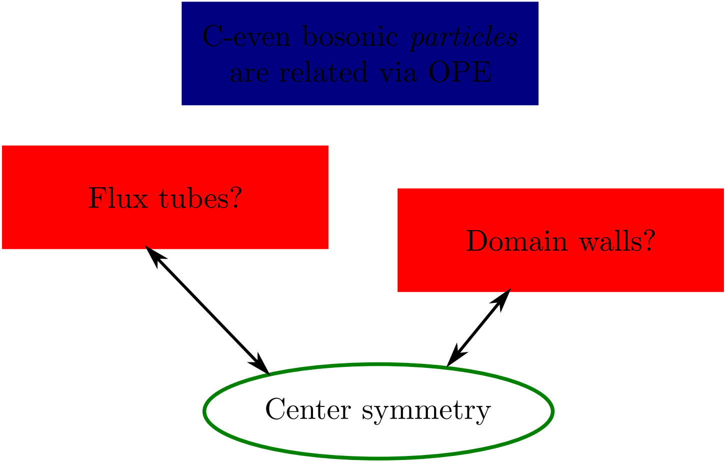
$$\lim_{N\to\infty} \langle a|e^{-tH}|b\rangle_{Or} = \lim_{N\to\infty} \langle a|e^{-tH}|b\rangle_{Ad}$$

Symmetries **inside** the common sector are the same in AdjQCD and OrientiQCD.

Overview


C-even bosonic *particles*
are related via OPE
Flux tubes?
Domain walls?
Center symmetry

Overview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Symmetry (mis)matching

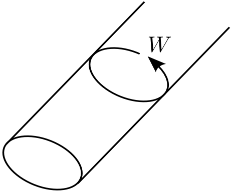
A center transformation around a compact dimension $\hat{z}$ is a local gauge transformation, that is periodic modulo an element of the center Z_N.

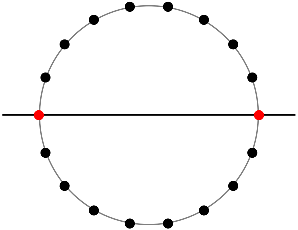
$$A_\mu(x) \rightarrow \Omega(x) A_\mu(x) \Omega^\dagger(x) + i\Omega(x)\partial_\mu \Omega^\dagger(x)$$

$$\psi(x) \rightarrow R[\Omega(x)]\psi(x)$$

$$\Omega(x + L\hat{z}) = \Omega(x) e^{\frac{2\pi i k}{N}}$$

$$\mathrm{tr}\ W \rightarrow e^{\frac{2\pi i k}{N}}\ \mathrm{tr}\ W$$





Even-N OrQCD: Z_2
Odd-N OrQCD: –

AdQCD: Z_N
Only Z_2 maps the common sector into itself

OPE $\Rightarrow$ OrQCD($N = \infty$) has at least a Z_2 symmetry

Symmetry (mis)matching

Z_N symmetry

$$\langle \mathrm{tr}\ W \rangle = 0$$

$$\langle \mathrm{tr}\ (W^2) \rangle = 0$$

$$\langle \mathrm{tr}\ (W^3) \rangle = 0$$

$$\vdots$$

$$\langle \mathrm{tr}\ (W^N) \rangle \neq 0$$

Symmetry (mis)matching

Z_N symmetry	Z_2 symmetry
$\langle \mathrm{tr}\ W \rangle = 0$	$\langle \mathrm{tr}\ W \rangle = 0$
$\langle \mathrm{tr}\ (W^2) \rangle = 0$	$\langle \mathrm{tr}\ (W^2) \rangle \neq 0$
$\langle \mathrm{tr}\ (W^3) \rangle = 0$	$\langle \mathrm{tr}\ (W^3) \rangle = 0$
$\vdots$	$\vdots$
$\langle \mathrm{tr}\ (W^N) \rangle \neq 0$	$\langle \mathrm{tr}\ (W^N) \rangle \neq 0$

Symmetry (mis)matching

Z_N symmetry	Z_2 symmetry	OrQCD$(N=\infty)$
$\langle \mathrm{tr}\ W \rangle = 0$	$\langle \mathrm{tr}\ W \rangle = 0$	$\frac{1}{N} \langle \mathrm{tr}\ W \rangle_{Or} = \frac{1}{N} \langle \mathrm{tr}\ W \rangle_{Adj} = 0$
$\langle \mathrm{tr}\ (W^2) \rangle = 0$	$\langle \mathrm{tr}\ (W^2) \rangle \neq 0$	$\frac{1}{N} \langle \mathrm{tr}\ (W^2) \rangle_{Or} = \frac{1}{N} \langle \mathrm{tr}\ (W^2) \rangle_{Adj} = 0$
$\langle \mathrm{tr}\ (W^3) \rangle = 0$	$\langle \mathrm{tr}\ (W^3) \rangle = 0$	$\frac{1}{N} \langle \mathrm{tr}\ (W^3) \rangle_{Or} = \frac{1}{N} \langle \mathrm{tr}\ (W^3) \rangle_{Adj} = 0$
$\vdots$	$\vdots$	$\vdots$
$\langle \mathrm{tr}\ (W^N) \rangle \neq 0$	$\langle \mathrm{tr}\ (W^N) \rangle \neq 0$	

Is Z_N a symmetry for OrQCD$(N=\infty)$?

A quantum mechanical analogy

$$H = \frac{p_x^2 + p_y^2}{2m} + \frac{1}{2} m \omega_x^2 x^2 + \frac{1}{2} m \omega_y^2 y^2$$

T_ℓ is an operator with defined angular momentum ℓ

$$\langle 0 | T_0 | 0 \rangle \neq 0$$

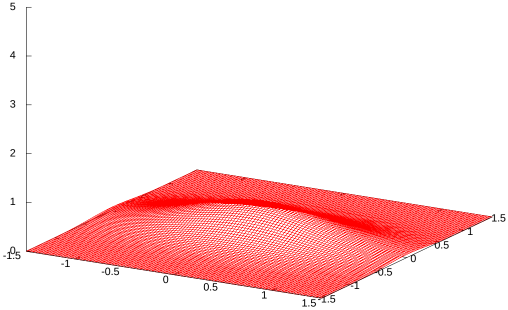
$$\langle 0 | T_1 | 0 \rangle = 0$$

$$\langle 0 | T_2 | 0 \rangle \neq 0$$

$$\ldots$$

A quantum mechanical analogy

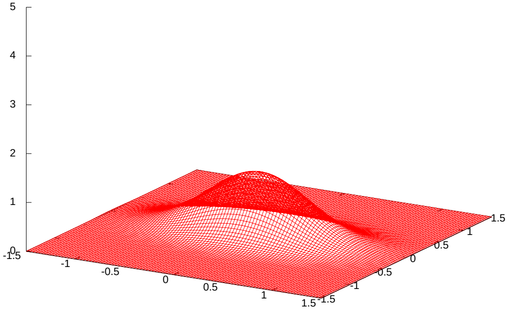
$$H = \frac{p_x^2 + p_y^2}{2m} + \frac{1}{2} m \omega_x^2 x^2 + \frac{1}{2} m \omega_y^2 y^2$$



Vacuum probability distribution in coordinate-space for $\hbar = 1$

A quantum mechanical analogy

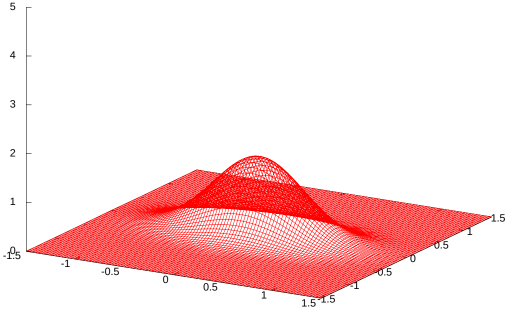
$$H = \frac{p_x^2 + p_y^2}{2m} + \frac{1}{2} m \omega_x^2 x^2 + \frac{1}{2} m \omega_y^2 y^2$$



Vacuum probability distribution in coordinate-space for $\hbar = 0.5$

A quantum mechanical analogy

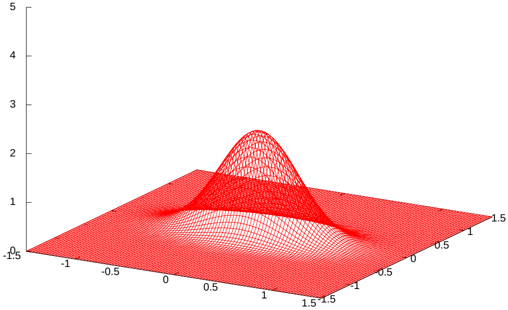
$$H = \frac{p_x^2 + p_y^2}{2m} + \frac{1}{2} m\omega_x^2 x^2 + \frac{1}{2} m\omega_y^2 y^2$$



Vacuum probability distribution in coordinate-space for $\hbar = 0.4$

A quantum mechanical analogy

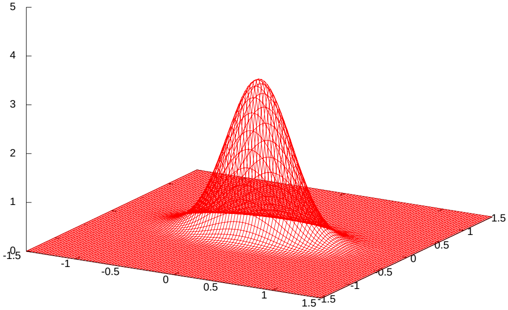
$$H = \frac{p_x^2 + p_y^2}{2m} + \frac{1}{2} m\omega_x^2 x^2 + \frac{1}{2} m\omega_y^2 y^2$$



Vacuum probability distribution in coordinate-space for $\hbar = 0.3$

A quantum mechanical analogy

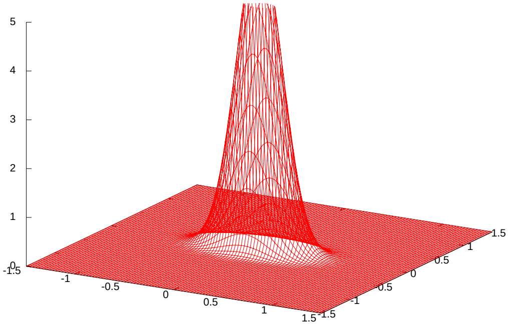
$$H = \frac{p_x^2 + p_y^2}{2m} + \frac{1}{2} m \omega_x^2 x^2 + \frac{1}{2} m \omega_y^2 y^2$$



Vacuum probability distribution in coordinate-space for $\hbar = 0.2$

A quantum mechanical analogy

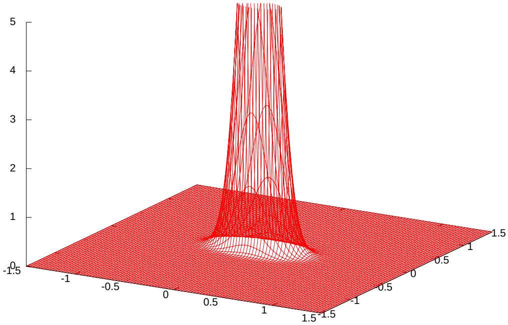
$$H = \frac{p_x^2 + p_y^2}{2m} + \frac{1}{2} m\omega_x^2 x^2 + \frac{1}{2} m\omega_y^2 y^2$$



Vacuum probability distribution in coordinate-space for $\hbar = 0.1$

A quantum mechanical analogy

$$H = \frac{p_x^2 + p_y^2}{2m} + \frac{1}{2} m \omega_x^2 x^2 + \frac{1}{2} m \omega_y^2 y^2$$



Vacuum probability distribution in coordinate-space for $\hbar = 0.05$

A quantum mechanical analogy

$$H = \frac{p_x^2 + p_y^2}{2m} + \frac{1}{2} m\omega_x^2 x^2 + \frac{1}{2} m\omega_y^2 y^2$$

$$\lim_{\hbar \to 0} |\psi_0(x)|^2 = \delta^2(\mathbf{r})$$

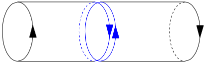
$$\lim_{\hbar \to 0} \langle 0 | T_\ell | 0 \rangle = 0 \qquad \text{for } \ell \neq 0$$

The vacuum is invariant under rotations, but the Hamiltonian is not!

Two-point functions of Polyakov loops

AdQCD

$$\lim_{N\to\infty} \langle P(x) P^\dagger(y) \rangle_c \neq 0$$

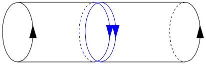


$$\langle P(x) P(y) \rangle_c = 0$$

OrQCD

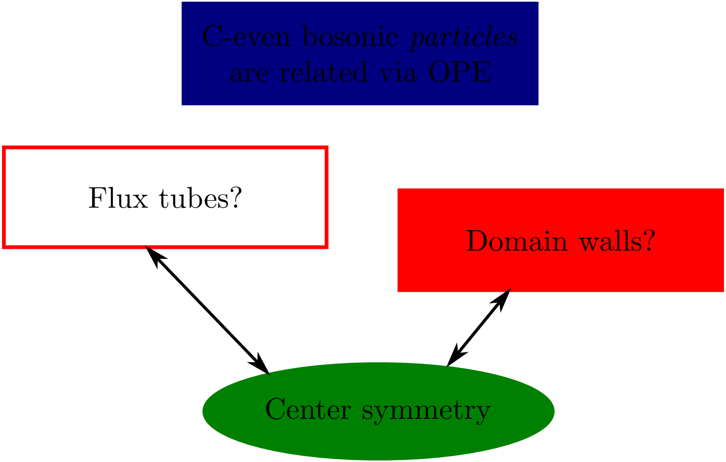
$$\lim_{N\to\infty} \langle P(x) P^\dagger(y) \rangle_c \neq 0$$

$$\lim_{N\to\infty} \langle P(x) P(y) \rangle_c = 0$$



$$\langle \mathrm{Re}P(0) \mathrm{Re}P(x) \rangle_{c,Or} = \langle \mathrm{Re}P(0) \mathrm{Re}P(x) \rangle_{c,Ad}$$
$$\langle P(0) P(x) \rangle_{c,Or} + \langle P(0) P(x)^\dagger \rangle_{c,Or} = \langle P(0) P(x)^\dagger \rangle_{c,Ad}$$

Overview


C-even bosonic *particles* are related via OPE
Flux tubes?
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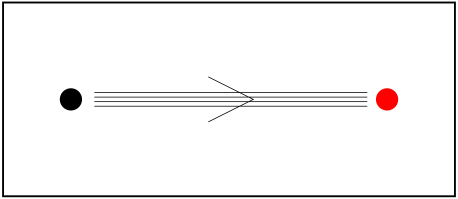
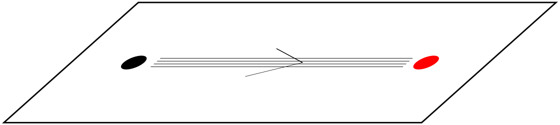
External charges



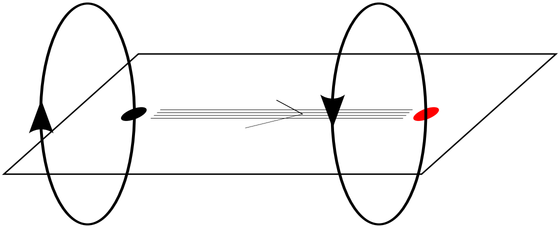
$$G^A(x)|open-string\rangle \equiv \left[\frac{1}{g^2}D_iE_i^A(x) - \psi^\dagger T_{\mathcal{R}}^A\psi(x)\right]|open-string\rangle = \rho_{ext}^A(x)|open-string\rangle$$

External charges



$$G^A(x)|open - string\rangle \equiv \left[\frac{1}{g^2} D_i E_i^A(x) - \psi^\dagger T^A_{\mathcal{R}} \psi(x)\right] |open - string\rangle = \rho^A_{ext}(x)|open - string\rangle$$

External charges



$$\langle P(\mathbf{x})P^\dagger(\mathbf{y})\rangle_{YM} \propto \text{partition function of YM coupled to a static quark in } \mathbf{x} \text{ and a static antiquark in } \mathbf{y} = \sum_{\substack{\text{open-string}\\ \text{states}}} m_n e^{-\beta V_n(|\mathbf{x}-\mathbf{y}|)}$$

$$G^A(x)|open-string\rangle \equiv \left[\frac{1}{g^2}D_i E_i^A(x) - \psi^\dagger T_{\mathcal{R}}^A \psi(x)\right]|open-string\rangle = \rho_{ext}^A(x)|open-string\rangle$$

Bosonic and fermionic open strings

$$\langle \mathrm{Re}P(0)\mathrm{Re}P(x)\rangle_{c,Or} = \langle \mathrm{Re}P(0)\mathrm{Re}P(x)\rangle_{c,Ad}$$

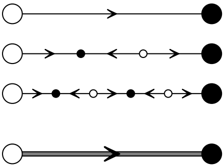
$$\langle P(0)P(x)\rangle_{c,Or} \quad + \quad \langle P(0)P(x)^{\dagger}\rangle_{c,Or} \quad = \quad \langle P(0)P(x)^{\dagger}\rangle_{c,Ad}$$

Bosonic and fermionic open strings

$$\langle \mathrm{Re}P(0)\mathrm{Re}P(x)\rangle_{c,Or} = \langle \mathrm{Re}P(0)\mathrm{Re}P(x)\rangle_{c,Ad}$$

$$\langle P(0)P(x)\rangle_{c,Or} \quad + \quad \underbrace{\langle P(0)P(x)^\dagger\rangle_{c,Or}}_{\substack{\text{bosonic oriented} \\ \tilde{\sigma}_b}} \quad = \quad \langle P(0)P(x)^\dagger\rangle_{c,Ad}$$

Oriented bosonic open string in OrQCD

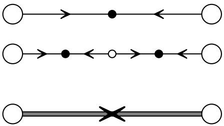


Bosonic and fermionic open strings

$$\langle \mathrm{Re}P(0)\mathrm{Re}P(x)\rangle_{c,Or} = \langle \mathrm{Re}P(0)\mathrm{Re}P(x)\rangle_{c,Ad}$$

$$\underbrace{\langle P(0)P(x)\rangle_{c,Or}}_{\substack{\text{fermionic unoriented} \\ \tilde{\sigma}_f}} + \underbrace{\langle P(0)P(x)^\dagger\rangle_{c,Or}}_{\substack{\text{bosonic oriented} \\ \tilde{\sigma}_b}} = \langle P(0)P(x)^\dagger\rangle_{c,Ad}$$

Unoriented fermionic open string in OrQCD



Bosonic and fermionic open strings

$$\langle \mathrm{Re}P(0)\mathrm{Re}P(x)\rangle_{c,Or} = \langle \mathrm{Re}P(0)\mathrm{Re}P(x)\rangle_{c,Ad}$$

$$\begin{array}{cccccc}
\langle P(0)P(x)\rangle_{c,Or} & + & \langle P(0)P(x)^\dagger\rangle_{c,Or} & = & \color{red}{\langle P(0)P(x)^\dagger\rangle_{c,Ad}} \\
 & & \text{bosonic oriented} & = & \text{bosonic oriented} \\
 & & \tilde{\sigma}_b & = & \sigma_b \\
\text{fermionic unoriented} & & & = & \text{fermionic oriented} \\
\tilde{\sigma}_f & & & = & \sigma_f
\end{array}$$

Oriented open string in AdQCD

Bosonic and fermionic open strings

$$\langle \mathrm{Re}P(0)\mathrm{Re}P(x)\rangle_{c,Or} = \langle \mathrm{Re}P(0)\mathrm{Re}P(x)\rangle_{c,Ad}$$

$$\begin{array}{ccccc}
\langle P(0)P(x)\rangle_{c,Or} & + & \langle P(0)P(x)^\dagger\rangle_{c,Or} & = & \langle P(0)P(x)^\dagger\rangle_{c,Ad} \\
 & & \text{bosonic oriented} & = & \text{bosonic oriented} \\
 & & \tilde{\sigma}_b & = & \sigma_b \\
\text{fermionic unoriented} & & & = & \text{fermionic oriented} \\
\tilde{\sigma}_f & & & = & \sigma_f
\end{array}$$

Supersymmetry $(N_f = 1)$

- SUSY implies degeneracy between bosons and fermions.
- The external charges explictly break SUSY.
- However SUSY breaking is a boundary effect.

$$\sigma_b = \sigma_f$$

Bosonic and fermionic string tensions in SYM

- The **Hamiltonian**.

$$H = \int \left[\frac{1}{2g^2} E_i^A E_i^A + \frac{1}{2g^2} B_i^A B_i^A + \frac{i}{2g^2} \bar{\lambda} \gamma_i D_i^{Adj} \lambda \right] d^3x$$

- The **supercharges** in the (on-shell) de Wit-Freedman formalism.

$$[S, A_i^A(x)] = \gamma_i \lambda^A(x)$$
$$\{S_\alpha, \lambda_\beta^A(x)\} = -\frac{1}{4} F_{\mu\nu}^A(x) [\gamma^\mu, \gamma^\nu]_{\alpha\beta}$$
$$[S, G^A(x)] = 0$$
$$\{S, \bar{S}\} = 2(\gamma^0 H - \gamma_k \Pi_k)$$
$$\sum_\alpha (S^\dagger)^\alpha S_\alpha = 4H$$

- The supercharges and the Hamiltonian do not commute in general.

$$[S, H] = \int \gamma^0 \lambda^A G^A \, d^3x$$

Bosonic and fermionic string tensions in SYM

$$\sum_{\alpha}(S^{\dagger})^{\alpha} S_{\alpha} = 4H \qquad [S,H] = \int \gamma^0 \lambda^A G^A \, d^3x = \int \gamma^0 \lambda^A \rho^A_{ext} \, d^3x$$

- Consider the eigenstates in the string sector.

$$H\,|B,n\rangle = (\sigma^b R + O(R^0))\,|B,n\rangle^b$$
$$H\,|F,n\rangle = (\sigma^f R + O(R^0))\,|F,n\rangle^f$$

- Choose a bosonic state $|B,n\rangle$.

$$4\sigma^b R = \sum_{\alpha} \langle B,n|\,(S^{\dagger})^{\alpha} S_{\alpha}\,|B,n\rangle = \sum_{\alpha,n'} \left|\langle F,n'|\, S_{\alpha}\,|B,n\rangle\right|^2$$

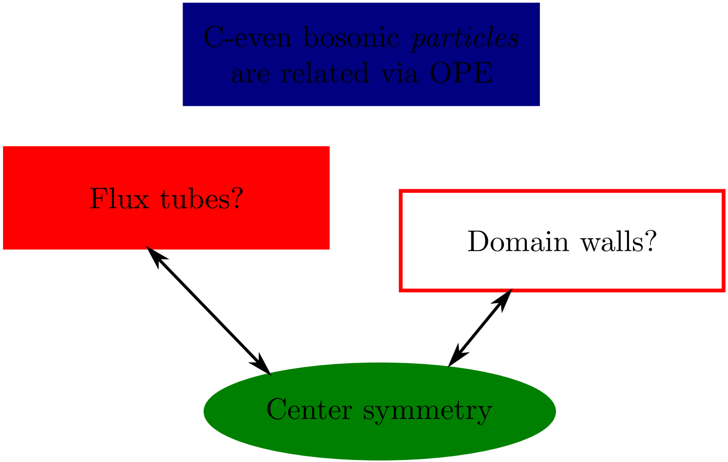
- At least one fermionic state $|F,n'\rangle$ and one index α exist with the following property:

$$\langle F,n'|\, S_{\alpha}\,|B.n\rangle = O\left(\sqrt{R}\right)$$

- Computing the matrix element of $[S,H]$...

$$(\sigma^b - \sigma^f)\frac{\langle F,n'|\, S_{\alpha}\,|B,n\rangle}{R^{1/2}} + O\left(\frac{1}{R^{3/2}}\right) = \frac{1}{R^{3/2}}\langle F,n'| \int d^3x\, (\gamma_0 \lambda^A)_{\alpha} \rho^A_{ext}\,|B,n\rangle$$

Overview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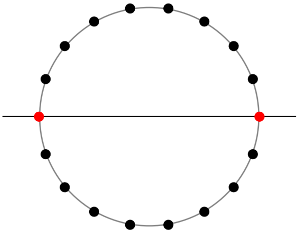
Center symmetry

Deconfined phase

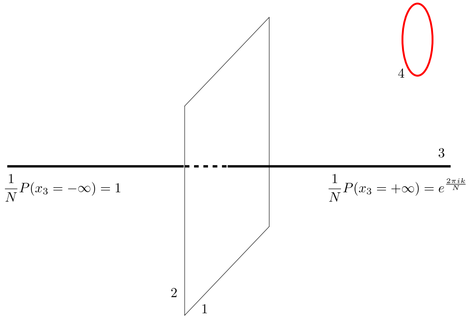
Effective potential for the Polyakov loop $W = e^{iv}\mathbf{1}_N$

$$\frac{V_{Ad}(e^{iv})}{N^2} = 0$$

$$\frac{V_{Or}(e^{iv})}{N^2} = \frac{\pi^2}{24\beta^4} - \frac{1}{24\pi^2\beta^4}(\pi^2 - [2v \mod 2\pi]^2)^2$$



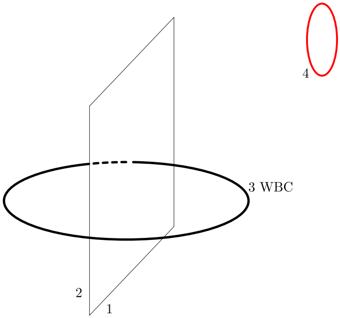
Domain wall, 't Hooft loop and Dirac string



$$\sigma(\beta) \propto k(N-k)$$

$$\text{for } k = \frac{N}{2} : \sigma(\beta) \propto N^2$$

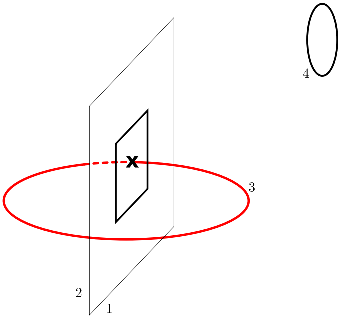
Domain wall, 't Hooft loop and Dirac string



$$\text{WBC:} \quad P(x_1, x_2, x_3 + L) = e^{\frac{2\pi i k}{N}} P(x_1, x_2, x_3)$$

$$Z_{wall} = \lim_{L_3 \to \infty} \mathrm{tr}_{L_3, WBC} \left[e^{-\beta H} \right] \propto e^{-L_1 L_2 \sigma(\beta)}$$

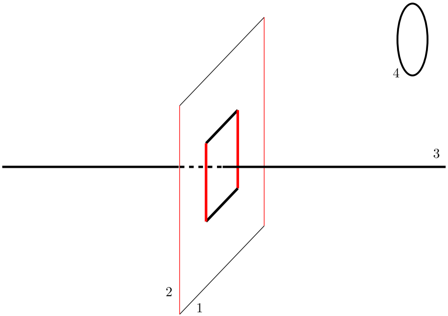
Domain wall, 't Hooft loop and Dirac string



$$Z_{wall} = \lim_{L_3 \to \infty} \mathrm{tr}_{\beta,TBC} \left[e^{-L_3 H} e^{\frac{4\pi i}{g} \int \mathrm{tr}\ E_4 Y_k\ dx_1 dx_2} \right] \propto e^{-L_1 L_2 \sigma(\beta)}$$

$$e^{2\pi i Y_k} = e^{\frac{2\pi i k}{N}}$$

Domain wall, 't Hooft loop and Dirac string

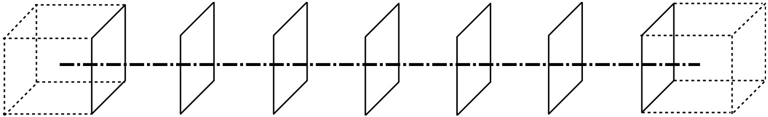


$$Z_{wall} = \langle 0 | e^{-L_2 H_{Dirac}(L_1, \beta)} | 0 \rangle \propto e^{-L_1 E_{Dirac}(L_2, \beta)} = e^{-L_1 L_2 \sigma(\beta)}$$

The operator $H_{Dirac}(L_1, \beta)/N^2$ is in the common sector and has a well defined large-N limit.

$$\lim_{N \to \infty} \frac{\sigma_{Or}(\beta)}{N^2} = \lim_{N \to \infty} \frac{\sigma_{Ad}(\beta)}{N^2}$$

Hamiltonian for the Dirac string



$$H_{Dirac} = \frac{a^2 N}{2\lambda} \sum_{\mathbf{x}} \mathrm{tr}\, \vec{\mathcal{E}}(\mathbf{x})^2 + \frac{N}{2\lambda a} \sum_{\Box} \Re e \mathrm{tr}\, (\mathbf{1} - z_{\Box} U_{\Box}) + H_F$$

$$z_{\Box} = \begin{cases} -1 & \text{if } \Box \text{ goes around the Dirac string} \\ 1 & \text{elsewhere} \end{cases}$$

Conclusions

- In the large-N limit, OrQCD has a Z_2 center symmetry. However its vacuum (in the confined phase) is symmetric under Z_N transformations.
- Orientifold planar equivalence holds in a larger sector than the particle sector.
- In the open-string sector, orientifold planar equivalence holds nontrivially both for bosonic and fermionic strings.
- Orientifold planar equivalence holds also for the domain wall interpolating between the two vacua $P/N = \pm 1$ (in the deconfined phase).