Featureless Bosonic Insulators

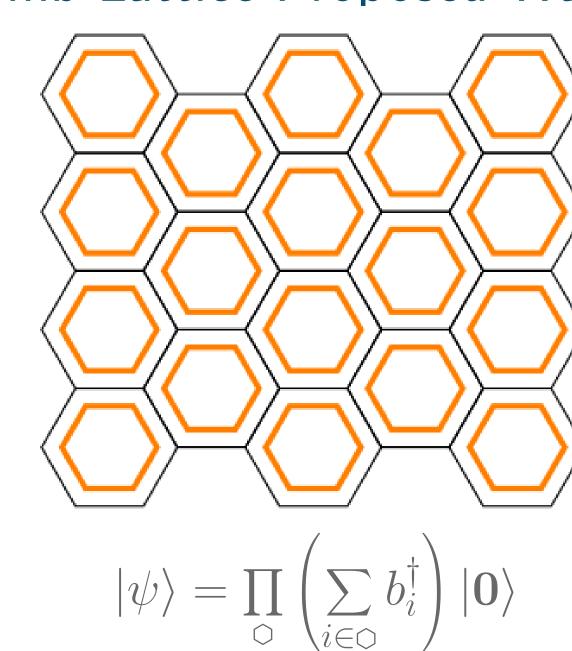
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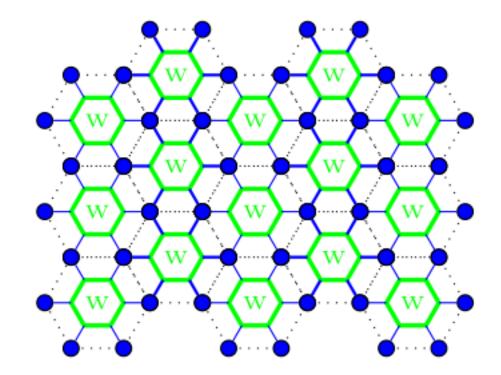
Bela Bauer Station Q

Honeycomb Lattice Proposed Wavefunction



PEPS Construction of Honeycomb F.B.I.

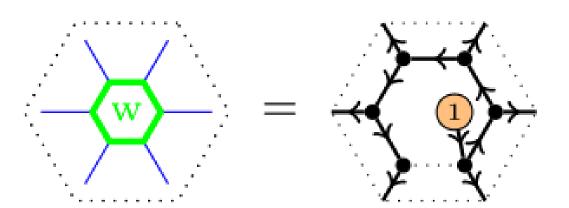
A wavefunction written as a product of local operators acting on a product state can be turned into a tensor network.



Virtual W-state on each plaquette used to synchronize the creation operators in the sum $\sum b_i^{\mathsf{T}}$

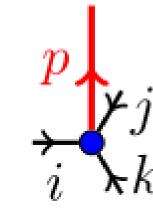
 $|W\rangle = |000001\rangle + |000010\rangle + |000100\rangle + |001000\rangle + |010000\rangle + |100000\rangle$

PEPS Construction of Honeycomb FBI



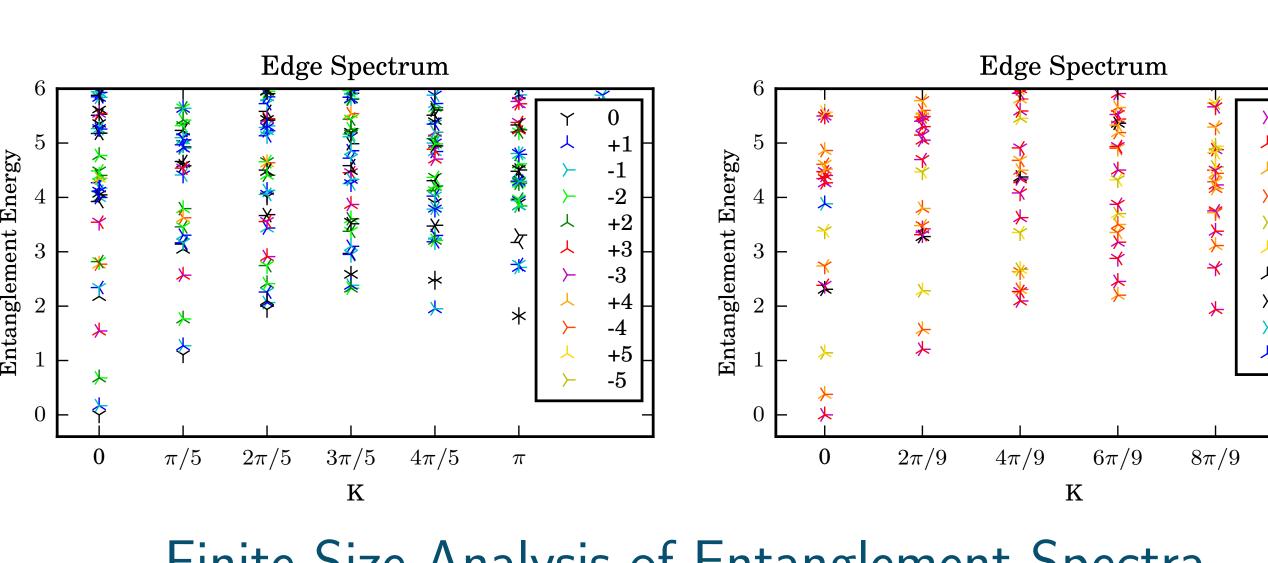
$|W\rangle = |100...\rangle + ...$

- W-State can be factored and put on hexagon sites
- Each black directed string has either charge 0 or 1
- Charge conserved

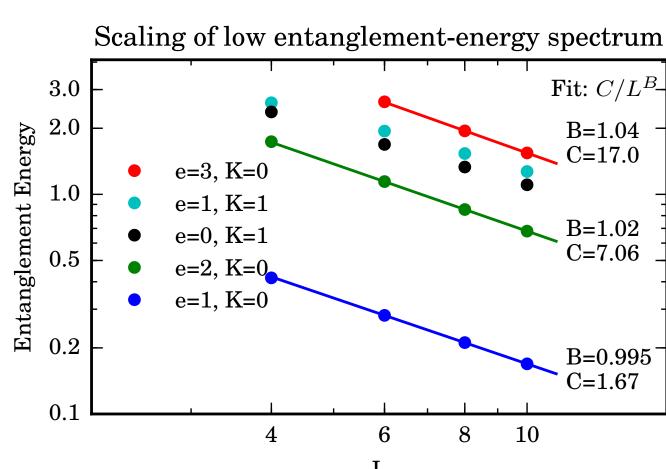


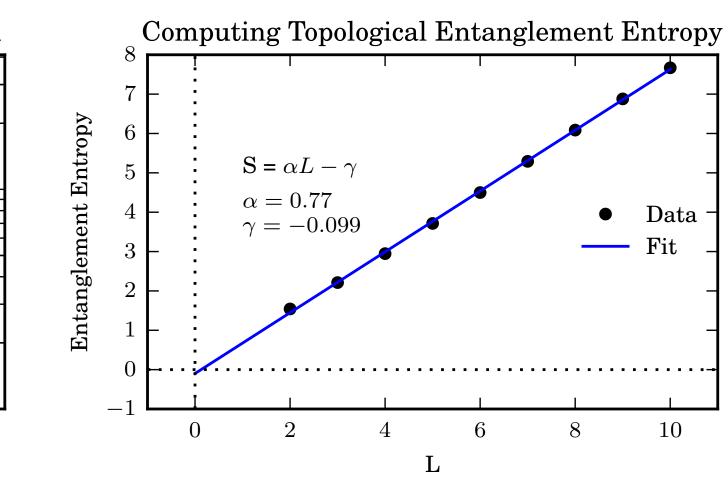
- Projects' the three virtual qubits coming into each vertex on to a state in physical Hilbert space
- Physical state is either $|0\rangle, |1\rangle, |2\rangle, |3\rangle$
- Charge conserved

Entanglement Spectrum



Finite Size Analysis of Entanglement Spectra





Conformal Charge

Number of sites in cut

c = 1

Conformal Weights

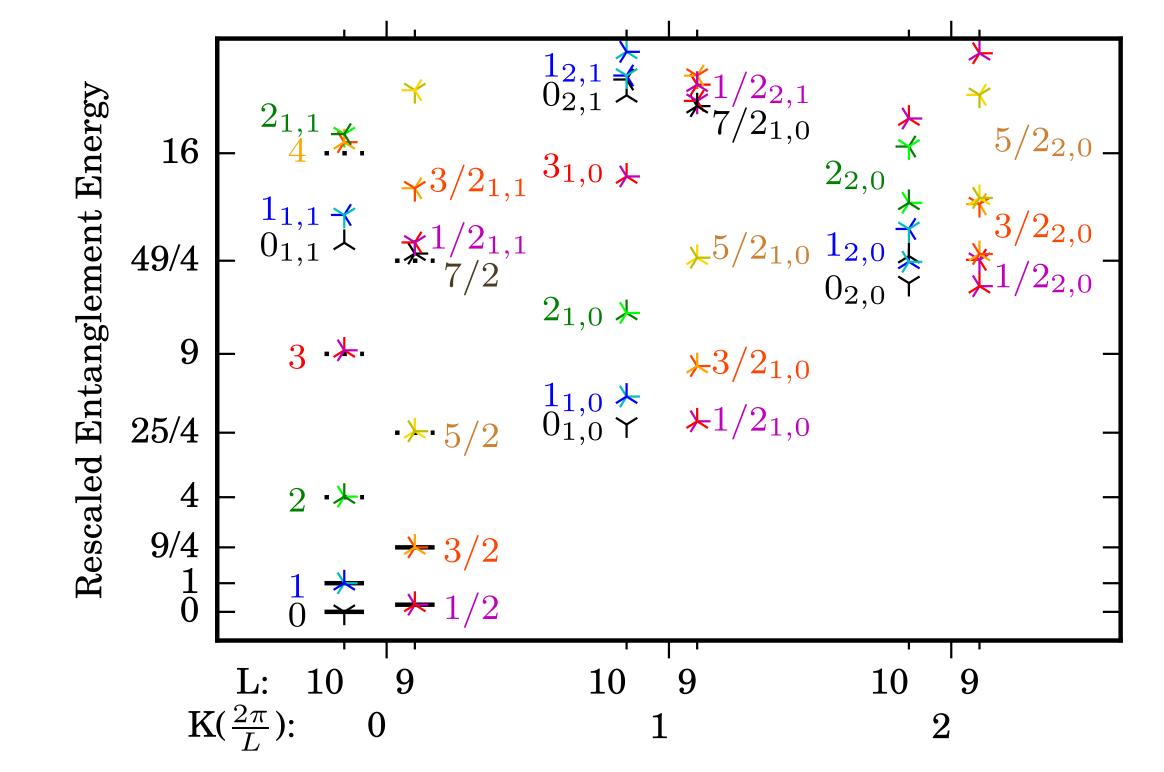
We can match the rescaled entanglement energies to the conformal weights of a free bosonic CFT.

$$\mathbf{P} = \frac{2\pi}{L} (\mathbf{L_0} - \bar{\mathbf{L}_0}) = \frac{2\pi}{L} (em + n - \bar{n})$$

$$\mathbf{H} = \frac{2\pi}{L} (\mathbf{L_0} + \bar{\mathbf{L}_0}) = \frac{2\pi}{L} (\frac{\kappa e^2}{2} + \frac{m^2}{2\kappa} + \frac{n + \bar{n}}{2})$$

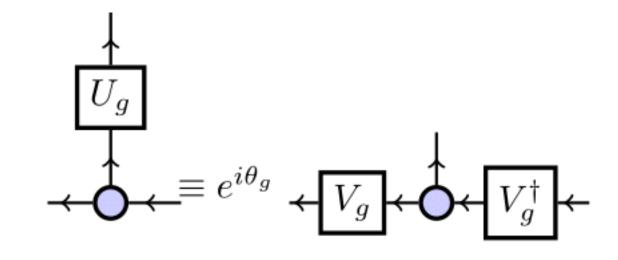
$$\mathbf{H} \propto e^2 + \frac{m^2}{\kappa^2} + \frac{1}{\kappa}(n + \bar{n})$$

CFT Identification of Gapless Entanglement Edge

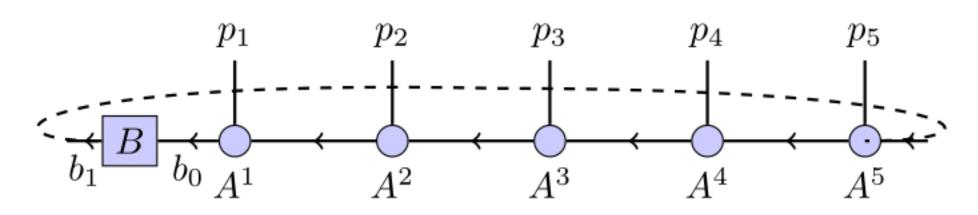


Detecting 1D SPT Order

If U_q is a global symmetry and $|\psi\rangle$ is translationally invariant, then the MPS representation satisfies:



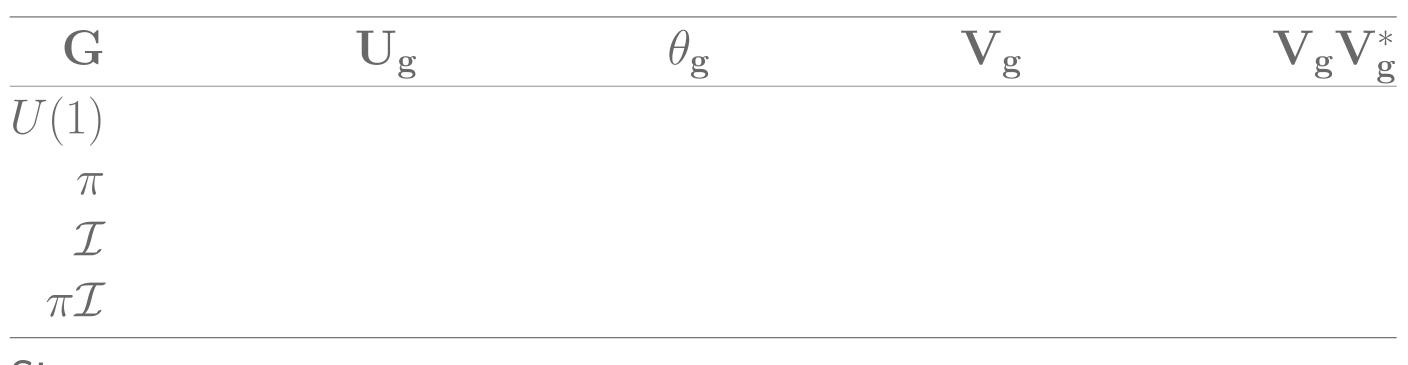
Boundary conditions on a MPS can be represented by a matrix ${\cal B}$ which acts like:



With PBC (B = I), the group action leaves the state invariant. With OBC $(B = |i\rangle\langle i|)$, the group action rotates between states that differ only near the boundary; these edge states transform as $V_q \otimes V_q^{\dagger}$. V_q represents the group projectively. Equivalence classes of projective representations (enumerated by $H^2(G;U(1))$) classify 1D SPT phases.

Symmetry Protection of the Honeycomb FBI

For the state on a cylinder with odd circumference, and the zig-zag entanglement cut defined in the upper left picture, we have the following:



Since

$$V_{\pi\mathcal{I}}V_{\pi\mathcal{I}}^* = -I$$
 or $V_{\pi}V_{\mathcal{I}} = -V_{\mathcal{I}}V_{\pi},$

the representation is in the nontrivial class of

$$H^2(\mathbb{Z}_2 \times \mathbb{Z}_2^{\mathcal{I}}; U(1)) = \mathbb{Z}_2.$$

Relation to known 1D physics

- Haldane insulator
- Unitarily equivalent to the AKLT state
- Distinct phase under $\mathbb{Z}_2 \times \mathbb{Z}_2^{\mathcal{I}}$
- \blacksquare Can be connected adiabatically to L=1 cylinder FBI
- Two dimensional classification is $H^3(\mathbb{Z}_2 \times \mathbb{Z}_2^{\mathcal{I}}; U(1)) = \mathbb{Z}_2^4$

References

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