Atomic Quantum Simulation of Dynamical Gauge Fields using Quantum Links

Uwe-Jens Wiese

Albert Einstein Center for Fundamental Physics

Institute for Theoretical Physics, Bern University

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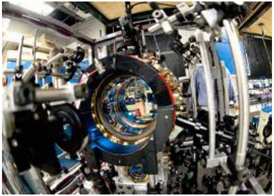
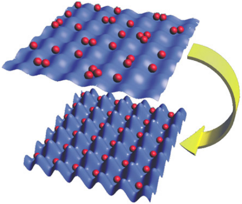
Collaboration:
Debasish Banerjee, Michael Bögli,
Pascal Stebler, Philippe Widmer (Bern)
Marcello Dalmonte, Enrique Rico Ortega, Peter Zoller (Innsbruck)
Markus Müller (Madrid)

Outline

Outline

Ultra-cold atoms in optical lattices





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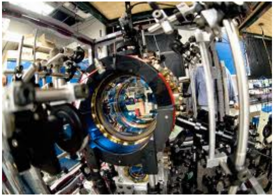

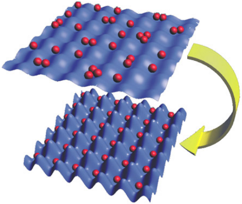

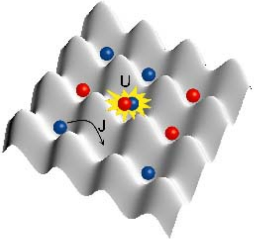

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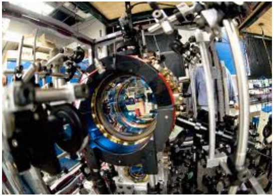
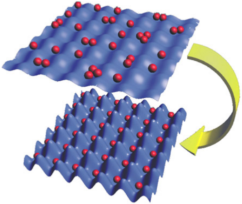
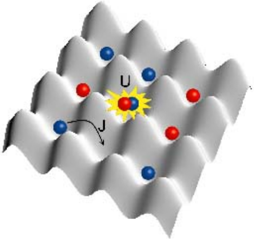
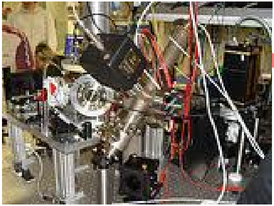
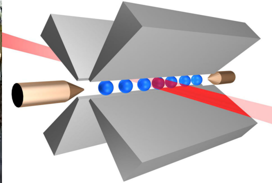






Trapped ions





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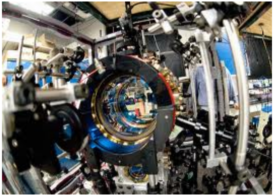

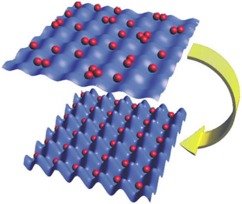

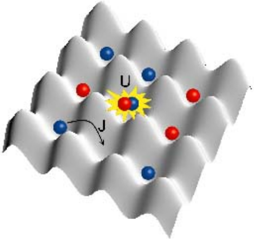

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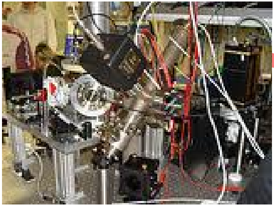
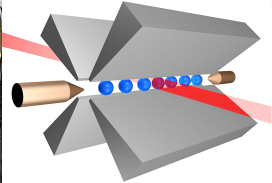
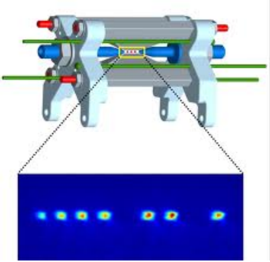




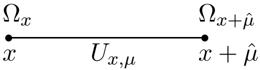


Outline

Wilson's classical link variables

$$U_{x,\mu} = \exp(G_\mu(x + \tfrac{\hat{\mu}a}{2})) \in SU(N), SO(N), Sp(N)$$

and their behavior under gauge transformations



$${}^\Omega U_{x,\mu} = \Omega_x U_{x,\mu} \Omega^\dagger_{x+\hat{\mu}}$$

Resulting anti-Hermitean non-Abelian vector potential

$$G_\mu(x) = igG^a_\mu(x)\frac{\lambda^a}{2}, \;\; a \in \{1, 2, \ldots, d_G\}$$

and its behavior under gauge transformations

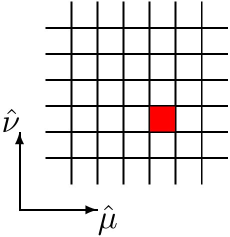
$${}^\Omega G_\mu(x) = \Omega(x)(G_\mu(x) + \partial_\mu)\Omega(x)^\dagger$$

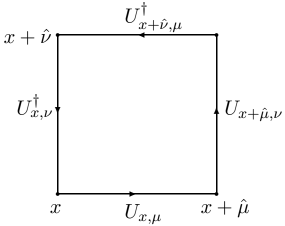
Non-Abelian field strength

$$G_{\mu\nu}(x) = \partial_\mu G_\nu(x) - \partial_\nu G_\mu(x) + [G_\mu(x), G_\nu(x)]$$

and its behavior under gauge transformations

$${}^\Omega G_{\mu\nu}(x) = \Omega(x) G_{\mu\nu}(x) \Omega(x)^\dagger$$





Gauge invariant plaquette action

$$S[U] = -\frac{1}{g^2} \sum_{x,\mu<\nu} \mathrm{Tr}(U_{x,\mu} U_{x+\hat{\mu},\nu} U^{\dagger}_{x+\hat{\nu},\mu} U^{\dagger}_{x,\nu} + \mathrm{h.c.})$$

Classical continuum limit

$$S[U] \to -\frac{1}{2g^2} \int d^4x \ \mathrm{Tr}(G_{\mu\nu} G_{\mu\nu})$$

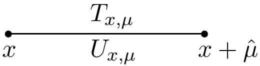
Functional integral using Haar measure

$$Z = \prod_{x,\mu} \int_G dU_{x,\mu} \exp(-S[U])$$

defines a quantum field theory using continuous classical field variables as fundamental degrees of freedom. Wilson (1974)

Outline

$U(1)$ quantum link model



$$U = S_1 + iS_2 = S_+, \;\; U^\dagger = S_1 - iS_2 = S_-$$

Generator E of $U(1)$ gauge transformations

$$[E, U] = U, \;\; [E, U^\dagger] = -U^\dagger, \;\; E = S^3, \;\; [U, U^\dagger] = 2E$$

Generator of $U(1)$ gauge transformations

$$G_x = \sum_\mu (E_{x-\hat{\mu},\mu} - E_{x,\mu})$$

$U(1)$-invariant Hamiltonian "action" operator

$$H = -J \sum_{x,\mu<\nu} (U_{x,\mu} U_{x+\hat{\mu},\nu} U^\dagger_{x+\hat{\nu},\mu} U^\dagger_{x,\nu} + \text{h.c.}), \;\; [H, G_x] = 0$$

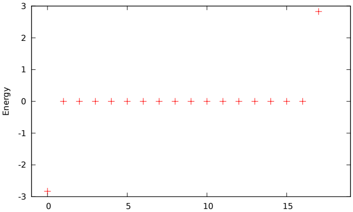
Functional integral of a quantum link model

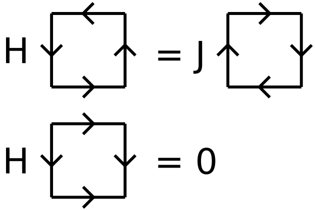
$$Z = \text{Tr}\exp(-\beta H)$$

defines a gauge theory using discrete quantum variables

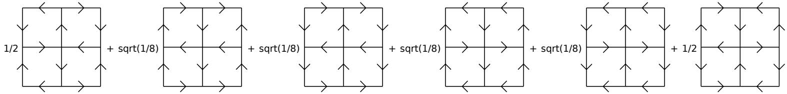
Chandrasekharan, UJW, Nucl. Phys. B492 (1997) 455

Spectrum of the $U(1)$ quantum link model on a 2×2 lattice

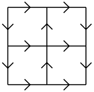




Ground state of the quantum link model on a 2×2 lattice

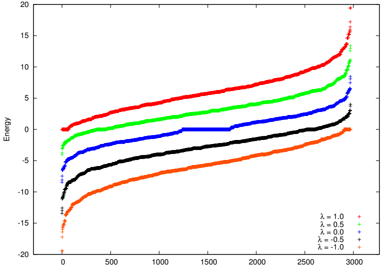


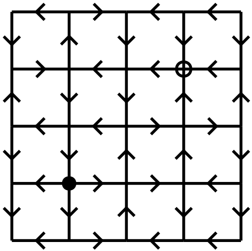
Excited state without flippable plaquettes



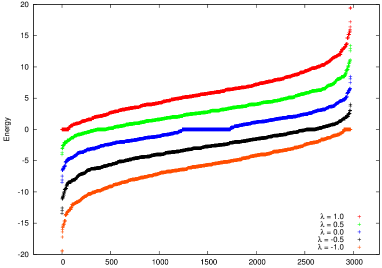
Banerjee, Widmer, UJW

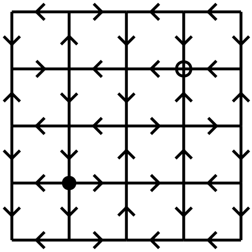
Spectra for $H = -J\sum_{\Box}(U_{\Box} + U_{\Box}^{\dagger}) + \lambda\sum_{\Box}(U_{\Box} + U_{\Box}^{\dagger})^2$



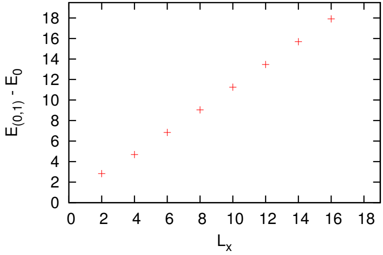


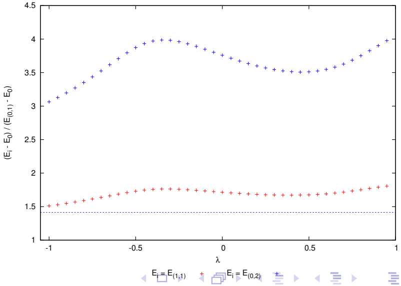
Spectra for $H = -J\sum_\Box (U_\Box + U_\Box^\dagger) + \lambda \sum_\Box (U_\Box + U_\Box^\dagger)^2$



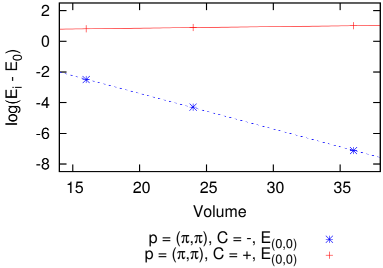


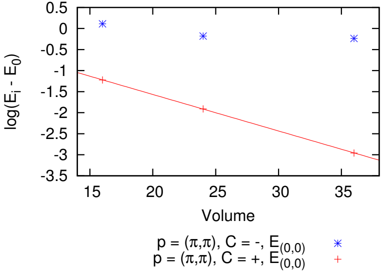
String tension and energy of fluxes $(2,0)/(1,0)$, $(1,1)/(1,0)$

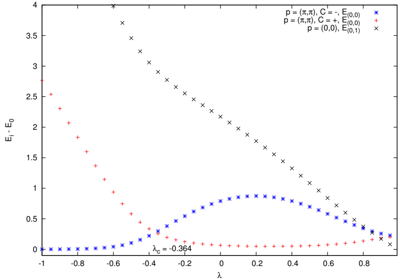


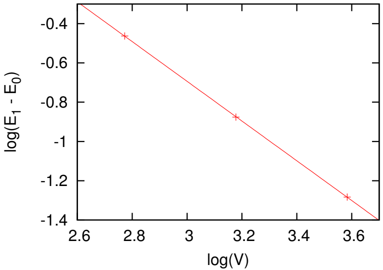


Ground state splitting as a function of the lattice volume

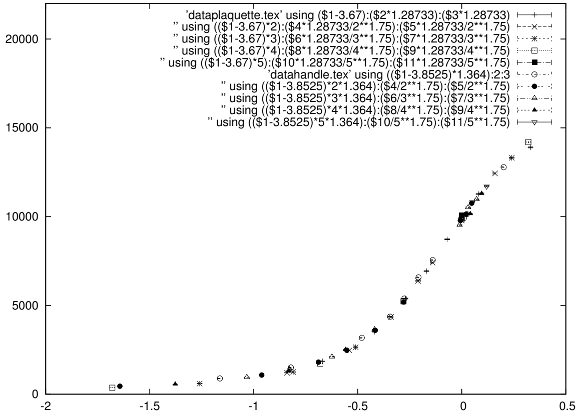








Numerical simulation of a $(2+1)$-d $U(1)$ quantum link model with the first efficient cluster algorithm for a gauge theory



The system has a second order finite-temperature phase transition in the universality class of the 2-d Ising model, at which charge conjugation is spontaneously broken. Classical simulations can be used to validate a corresponding quantum simulator.

Chandrasekharan, Gerber, Pepe, Stebler, UJW

Developments related to quantum link models

- 1982: Construction of $U(1)$ and $SU(2)$ discrete gauge models by Horn

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- 2009: Design of a $U(1)$ quantum link simulator with Rydberg ions by Weimer, Müller, Lesanovsky, Zoller, and Büchler

$U(N)$ quantum link operators

$$U^{ij} = S_1^{ij} + iS_2^{ij}, \; U^{ij\dagger} = S_1^{ij} - iS_2^{ij}, \; i,j \in \{1,2,\ldots,N\}, \; [U^{ij},(U^\dagger)^{kl}] \neq 0$$

$SU(N)_L \times SU(N)_R$ gauge transformations of a quantum link

$$[L^a, L^b] = if_{abc}L^c, \; [R^a, R^b] = if_{abc}R^c, \; a,b,c \in \{1,2,\ldots,N^2-1\}$$

$$[L^a, R^b] = [L^a, E] = [R^a, E] = 0$$

Infinitesimal gauge transformations of a quantum link

$$[L^a, U] = -\lambda^a U, \; [R^a, U] = U\lambda^a, \; [E, U] = U$$

$U(N)$ quantum link operators

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$SU(N)_L \times SU(N)_R$ gauge transformations of a quantum link

$$[L^a, L^b] = i f_{abc} L^c, \ [R^a, R^b] = i f_{abc} R^c, \ a,b,c \in \{1,2,\ldots,N^2-1\}$$

$$[L^a, R^b] = [L^a, E] = [R^a, E] = 0$$

Infinitesimal gauge transformations of a quantum link

$$[L^a, U] = -\lambda^a U, \ [R^a, U] = U\lambda^a, \ [E, U] = U$$

Algebraic structures of different quantum link models

$U(N)$: $U^{ij}, \ L^a, \ R^a, E, \ 2N^2 + 2(N^2-1) + 1 = 4N^2 - 1$ $SU(2N)$ generators

$SO(N)$: $O^{ij}, \ L^a, \ R^a, \ N^2 + 2\frac{N(N-1)}{2} = N(2N-1)$ $SO(2N)$ generators

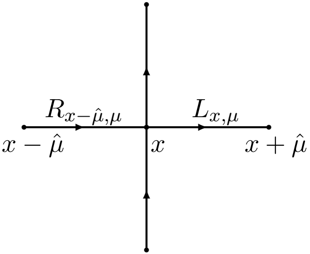
$Sp(N)$: $U^{ij}, \ L^a, \ R^a, \ 4N^2 + 2N(2N+1) = 2N(4N+1)$ $Sp(2N)$ generators

Brower, Chandrasekharan, UJW, Phys. Rev. D60 (1999) 094502

Consequences for non-Abelian quantum link simulators

- $U(1)$ embedded in $SU(2)$: minimal representation $\{2\}$
- $U(2)$ embedded in $SU(4)$: minimal representation $\{4\}$
- $U(3)$ embedded in $SU(6)$: minimal representation $\{6\}$
- $SU(2)$ embedded in $SU(4)$: minimal representation $\{6\}$
- $SU(3)$ embedded in $SU(6)$: minimal representation $\{20\}$
- $Sp(1) = SU(2)$ embedded in $Sp(2) = SO(5)$: minimal rep. $\{4\}$
- $SO(3) = SU(2)$ embedded in $SO(6) = SU(4)$: minimal rep. $\{4\}$

A non-Abelian gauge theory quantum simulator requires at least 4 states per link.



Generator of $SU(N)$ gauge transformations

$$G_x^a = \sum_\mu (R^a_{x-\hat{\mu},\mu} + L^a_{x,\mu})$$

$U(N)$-invariant Hamiltonian "action" operator

$$H = -J \sum_{x,\mu<\nu} \mathrm{Tr}(U_{x,\mu} U_{x+\hat{\mu},\nu} U^\dagger_{x+\hat{\nu},\mu} U^\dagger_{x,\nu} + \text{h.c.}), \ [H, G_x^a] = 0$$

Functional integral of a quantum link model

$$Z = \mathrm{Tr}\exp(-\beta H)$$

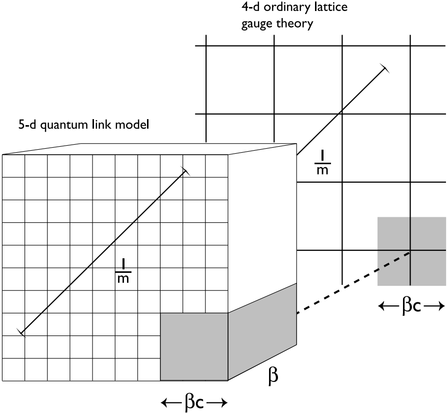
defines a quantum field theory using discrete variables

Low-energy effective action of a quantum link model

$$S[G_\mu] = \int_0^\beta dx_5 \int d^4x \, \frac{1}{2e^2} \left(\mathrm{Tr} \; G_{\mu\nu} G_{\mu\nu} + \frac{1}{c^2} \mathrm{Tr} \; \partial_5 G_\mu \partial_5 G_\mu \right) , \; G_5 = 0$$

undergoes dimensional reduction from $4+1$ to 4 dimensions

$$S[G_\mu] \to \int d^4x \, \frac{1}{2g^2} \mathrm{Tr} \; G_{\mu\nu} G_{\mu\nu}, \; \frac{1}{g^2} = \frac{\beta}{e^2}, \; \frac{1}{m} \sim \exp\left(\frac{24\pi^2\beta}{11Ne^2} \right)$$

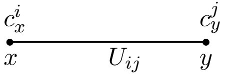


Outline

Fermionic rishons at the two ends of a link

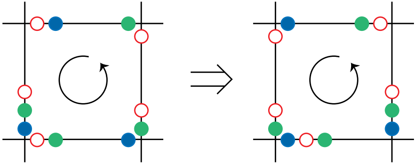
$$\{c_x^i, c_y^{j\dagger}\} = \delta_{xy}\delta_{ij},\ \{c_x^i, c_y^j\} = \{c_x^{i\dagger}, c_y^{j\dagger}\} = 0$$

Rishon representation of link algebra



$$U_{xy}^{ij} = c_x^i c_y^{j\dagger},\ L_{xy}^a = c_x^{i\dagger}\lambda_{ij}^a c_x^j,\ R_{xy}^a = c_y^{i\dagger}\lambda_{ij}^a c_y^j,\ E_{xy} = \frac{1}{2}(c_y^{i\dagger}c_y^i - c_x^{i\dagger}c_x^i)$$

Can a "rishon abacus" implemented in ultra-cold atoms or trapped ions be used as a quantum simulator?



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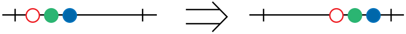

det $U_{x,\mu}$

Outline

Hamiltonian for staggered fermions and $U(1)$ quantum links

$$H = -t \sum_x \left[\psi_x^\dagger U_{x,x+1} \psi_{x+1} + \mathrm{h.c.} \right] + m \sum_x (-1)^x \psi_x^\dagger \psi_x + \frac{g^2}{2} \sum_x E_{x,x+1}^2$$

Hamiltonian for staggered fermions and $U(1)$ quantum links

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$$U_{x,x+1} = b_x b_{x+1}^\dagger, \; E_{x,x+1} = \frac{1}{2} \left(b_{x+1}^\dagger b_{x+1} - b_x^\dagger b_x \right)$$

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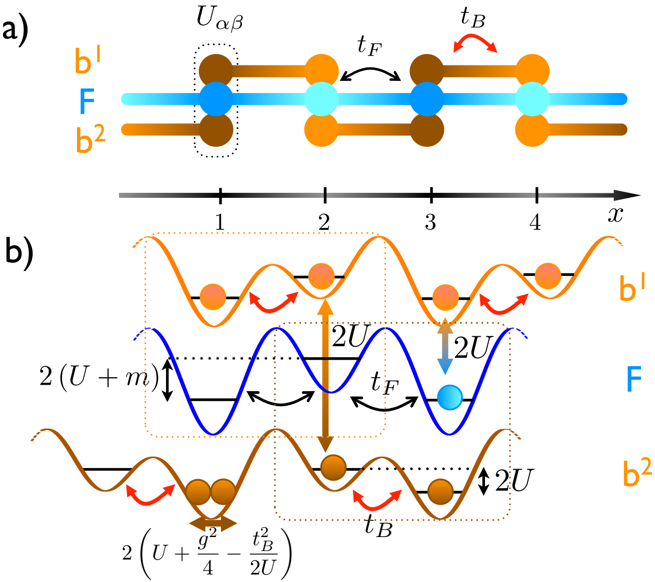
Microscopic Hubbard model Hamiltonian

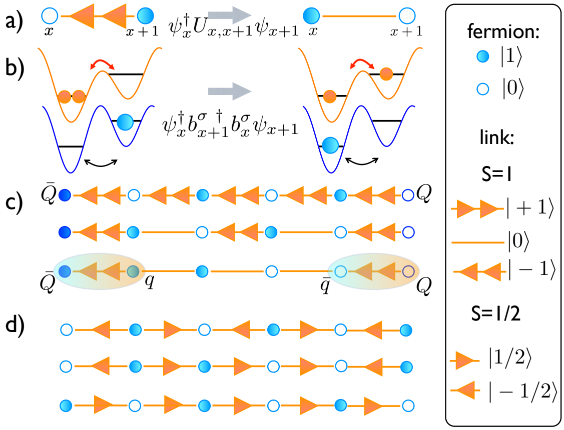
$$\begin{aligned} \widetilde{H} &= \sum_x h_{x,x+1}^B + \sum_x h_{x,x+1}^F + m \sum_x (-1)^x n_x^F + U \sum_x \widetilde{G}_x^2 \\ &= -t_B \sum_{x \text{ odd}} b_x^{1\dagger} b_{x+1}^1 - t_B \sum_{x \text{ even}} b_x^{2\dagger} b_{x+1}^2 - t_F \sum_x \psi_x^\dagger \psi_{x+1} + \mathrm{h.c.} \\ &+ \sum_{x,\alpha,\beta} n_x^\alpha U_{\alpha\beta} n_x^\beta + \sum_{x,\alpha} (-1)^x U_\alpha n_x^\alpha \end{aligned}$$

Optical lattice with Bose-Fermi mixture of ultra-cold atoms



Banerjee, Dalmonte, Müller, Rico Ortega, Stebler, UJW, Zoller

Quantum simulation of string breaking and quenched dynamics



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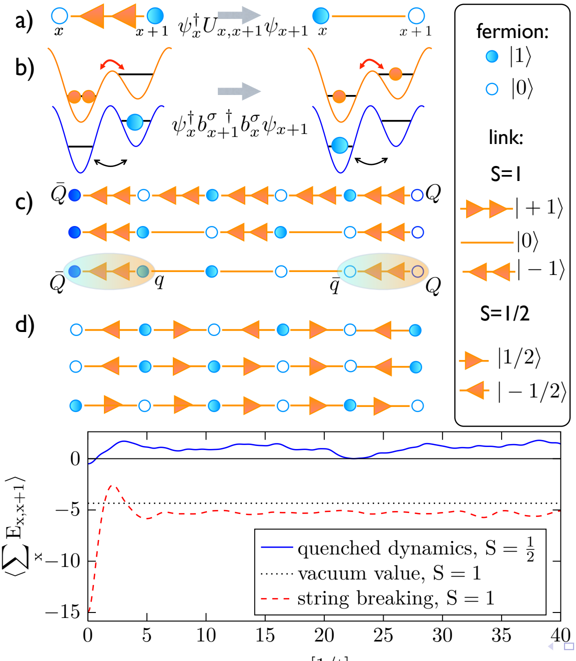

Outline

d-dimensional $SU(N)$ gauge theory with staggered fermions

$$
\begin{aligned}
H &= -t \sum_{\langle xy \rangle} \left(s_{xy} \psi_x^{i\dagger} U_{xy}^{ij} \psi_y^j + \mathrm{h.c.} \right) + m \sum_x (-1)^x \psi_x^{i\dagger} \psi_x^i \\
&+ \frac{g^2}{2} \sum_{\langle xy \rangle} \left(L_{xy}^a L_{xy}^a + R_{xy}^a R_{xy}^a \right) + \frac{g'^2}{2} \sum_{\langle xy \rangle} E_{xy}^2 \\
&- \frac{1}{4g^2} \sum_{\langle wxyz \rangle} \left(U_{wx} U_{xy} U_{yz} U_{zw} + \mathrm{h.c.} \right) - \gamma \sum_{\langle xy \rangle} \left(\det U_{xy} + \mathrm{h.c.} \right)
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Meson, constituent quark, and glueball operators

$$
M_x = \psi_x^{i\dagger} \psi_x^i, \quad Q_{x,\pm k} = c_{x,\pm k}^{i\dagger} \psi_x^i, \quad \Phi_{x,\pm k,\pm l} = c_{x,\pm k}^{i\dagger} c_{x,\pm l}^i
$$

form a local $U(2d+1)$ algebra at each site x, thus providing a formulation in terms of manifestly $SU(N)$ gauge invariant objects. However, the conserved rishon number gives rise to a $U(1)$ gauge symmetry on the links

$$
N_{xy} = c_x^{i\dagger} c_x^i + c_y^{i\dagger} c_y^i, \quad [N_{xy}, H] = 0
$$

1-d $SO(3)$ gauge theory with adjoint staggered fermions

$$
\begin{aligned}
H &= -t \sum_{\langle xy \rangle} \left(\psi_x^{i\dagger} O_{xy}^{ij} \psi_y^j + \text{h.c.} \right) + m \sum_x (-1)^x \psi_x^{i\dagger} \psi_x^i \\
&= -t \sum_{\langle xy \rangle} \left(B_{x,+}^\dagger B_{y,-} + \text{h.c.} \right) + m \sum_x (-1)^x M_x
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Majorana rishons in the $\{4\}$ representation of $SO(6)$

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Meson, baryon, and glueball operators

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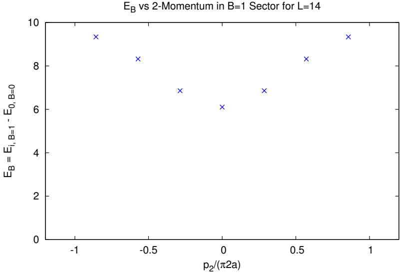
form a local $SO(4)$ algebra at each site x, thus providing a formulation in terms of manifestly $SO(3)$ gauge invariant objects, in this case without any additional gauge symmetry on the links.

Spectrum in the $B = 1$ sector (including 4-fermion coupling)



$M_B \approx 6t$

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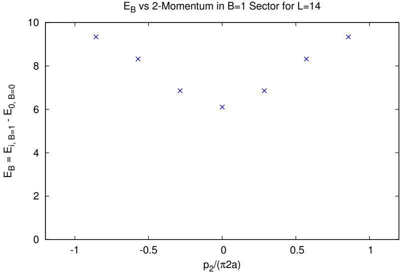
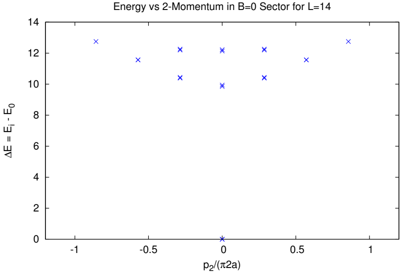


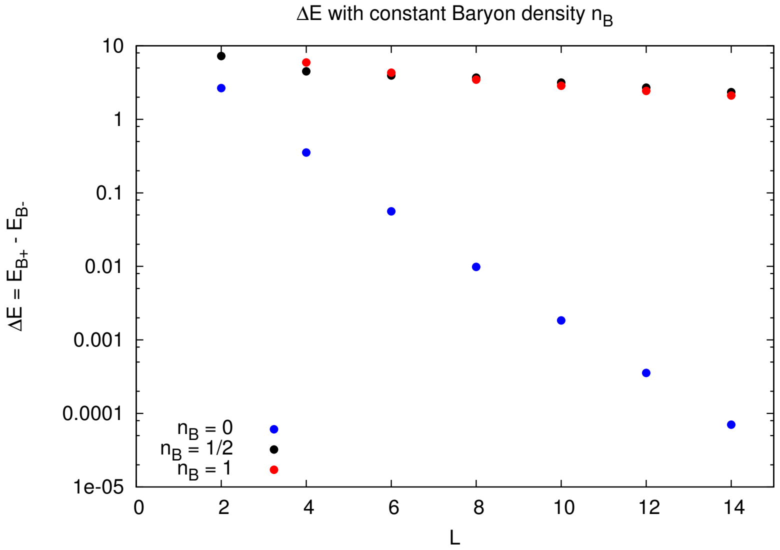
$$M_B \approx 6t$$

Spectrum in the $B = 0$ sector



$$M_{B\overline{B}} \approx 10t < 2M_B$$

Restoration of chiral symmetry at baryon density $n_B \geq \frac{1}{2}$



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