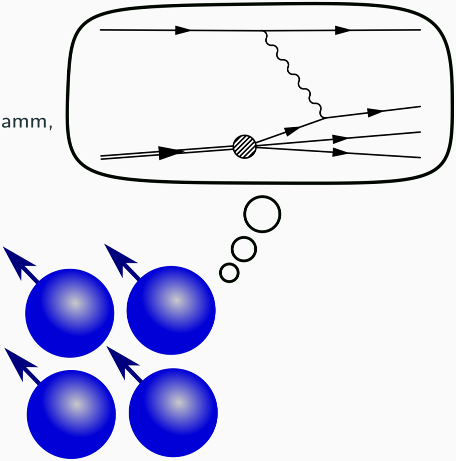
From Qubits to Quarks: Parton Physics on a Quantum Computer

Scott Lawrence
with Andrei Alexandru, Paulo Bedaque,
Siddhartha Harmalkar, Hersh Kumar, Henry Lamm,
Neill Warrington, and Yukari Yamauchi
(NuQS Collaboration)

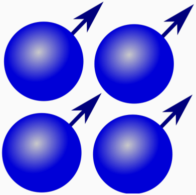
1903.08807, 1906.11213, 1908.10439

17 October 2019

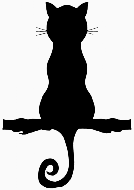
UNIVERSITY OF MARYLAND



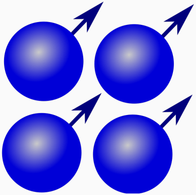
Quantum Simulation



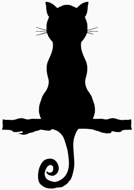
$\Longleftrightarrow$



Quantum Simulation

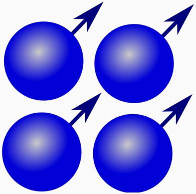


$\Longleftrightarrow$

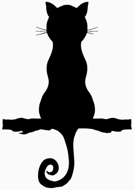


$$|0000\rangle, |0001\rangle, |0010\rangle, \cdots \quad \Longleftrightarrow \quad |\text{alive}\rangle, |\text{dead}\rangle$$

Quantum Simulation



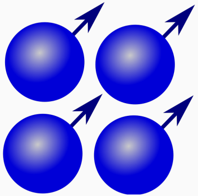
$\Longleftrightarrow$



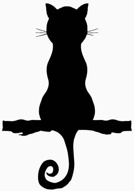
$$|0000\rangle, |0001\rangle, |0010\rangle, \cdots \quad \Longleftrightarrow \quad |\text{alive}\rangle, |\text{dead}\rangle$$

$$e^{-i(H_1+H_2)\Delta t} \approx e^{-iH_1\Delta t} e^{-iH_2\Delta t}$$

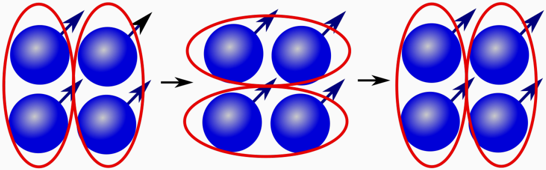
Quantum Simulation



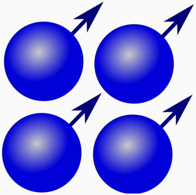
$\iff$



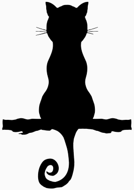
$$|0000\rangle\,,\,|0001\rangle\,,\,|0010\rangle\,,\cdots \quad \iff \quad |\text{alive}\rangle\,,\,|\text{dead}\rangle$$



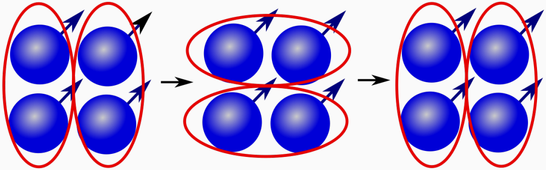
Quantum Simulation



$\Longleftrightarrow$



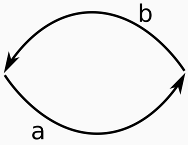
$|0000\rangle, |0001\rangle, |0010\rangle, \cdots \quad \Longleftrightarrow \quad |\text{alive}\rangle, |\text{dead}\rangle$



$$f(x) = \int \mathrm{d}z \; e^{ixP^+z} \langle P| e^{iHz} \bar{\psi}(z) e^{-iHz} \gamma^+ \psi(0) |P\rangle$$

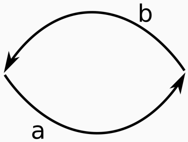
Hamiltonian $\mathbb{Z}_2$ Gauge Theory

$$H = \sigma_x(a) + \sigma_x(b) + \sigma_z(a)\sigma_z(b)$$



Hamiltonian $\mathbb{Z}_2$ Gauge Theory

$$H = \sigma_x(a) + \sigma_x(b) + \sigma_z(a)\sigma_z(b)$$

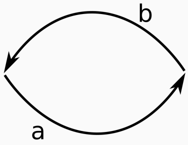


The gauge transformation operator: $\sigma_x(a)\sigma_x(b)$.

$$|00\rangle \leftrightarrow |11\rangle \text{ and } |01\rangle \leftrightarrow |10\rangle$$

Hamiltonian $\mathbb{Z}_2$ Gauge Theory

$$H = \sigma_x(a) + \sigma_x(b) + \sigma_z(a)\sigma_z(b)$$



The gauge transformation operator: $\sigma_x(a)\sigma_x(b)$.

$$|00\rangle \leftrightarrow |11\rangle \text{ and } |01\rangle \leftrightarrow |10\rangle$$

Physical states: $|P=0\rangle = |00\rangle + |11\rangle$, $|P=1\rangle = |01\rangle + |10\rangle$

Unphysical states: $|00\rangle - |11\rangle$, $|01\rangle - |10\rangle$

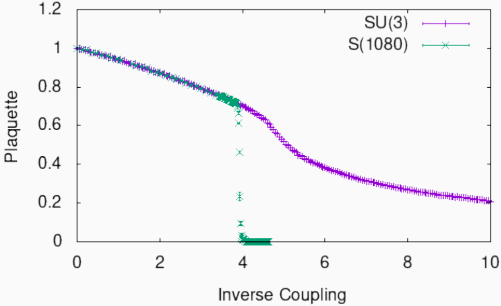
Simulating $SU(3)$

$2^N < \infty$ **The Hilbert spaces don't match!**

Simulating $SU(3)$

$2^N < \infty$ **The Hilbert spaces don't match!**

$$S(1080) = \left\langle \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}, \begin{pmatrix} 1 & \mu_2 & \mu_1 \\ \mu_2 & \mu_1 & 1 \\ \mu_1 & 1 & \mu_2 \end{pmatrix}, \begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & e^{i\pi/3} \\ 0 & e^{i\pi/3} & 0 \end{pmatrix} \right\rangle$$



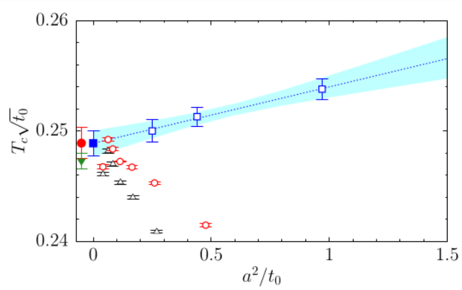
1906.11213; Henry Lamm's talk yesterday

Simulating $SU(3)$

$2^N < \infty$ **The Hilbert spaces don't match!**

$$S(1080) = \left\langle \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}, \begin{pmatrix} 1 & \mu_2 & \mu_1 \\ \mu_2 & \mu_1 & 1 \\ \mu_1 & 1 & \mu_2 \end{pmatrix}, \begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & e^{i\pi/3} \\ 0 & e^{i\pi/3} & 0 \end{pmatrix} \right\rangle$$

$$S = \sum \mathrm{Re}\,\mathrm{Tr}\, U_p + \mathrm{Re}\,\mathrm{Tr}\, U_p^2$$



1906.11213; Henry Lamm's talk yesterday

Adiabatically Preparing a Proton

Take a time-varying (slowly) Hamiltonian $H(t)$.

Prepare an eigenstate of $H(0)$, with a gap of Δ.

When $\dot{H}/\Delta^2 \ll 0$, time-evolution will keep us in the eigenstate.

Time needed to prepare ground state: Δ^{-2}

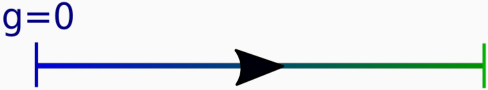
Adiabatically Preparing a Proton

Take a time-varying (slowly) Hamiltonian $H(t)$.

Prepare an eigenstate of $H(0)$, with a gap of Δ.

When $\dot{H}/\Delta^2 \ll 0$, time-evolution will keep us in the eigenstate.

Time needed to prepare ground state: Δ^{-2}



- Free fermions and glue (massive)
- Ground state exactly prepared
- Small gap ($O(\frac{1}{V})$)

- Hadrons
- Large gap (m_π)

Total circuit size: $O(V^3)$

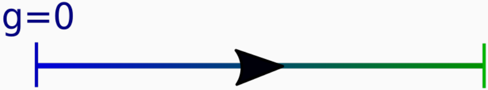
Adiabatically Preparing a Proton

Take a time-varying (slowly) Hamiltonian $H(t)$.

Prepare an eigenstate of $H(0)$, with a gap of Δ.

When $\dot{H}/\Delta^2 \ll 0$, time-evolution will keep us in the eigenstate.

Time needed to prepare ground state: Δ^{-2}



- Free fermions and glue (massive)
- Ground state exactly prepared
- Small gap ($O(\frac{1}{V})$)

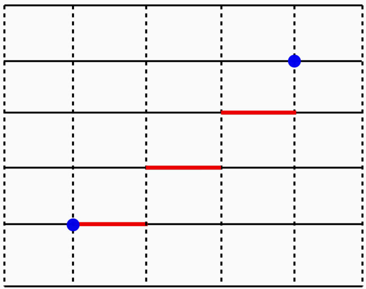
- Hadrons
- Large gap (m_π)

Total circuit size: $O(V^3)$

Or, Phys.Rev.Lett. 121 (2018) no.17, 170501; Henry Lamm, SL

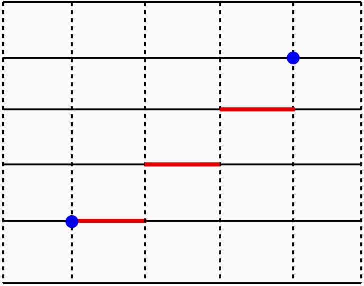
Parton Physics

$$f(x) = \int \mathrm{d}z \; e^{ixP^+z} \langle P| \, e^{iHz} \bar{\psi}(z) e^{-iHz} \, W(z;0) \gamma^+ \psi(0) \, |P\rangle$$



Parton Physics

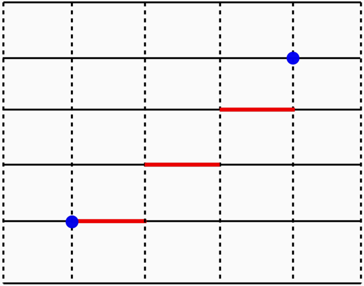
$$f(x) = \int \mathrm{d}z\; e^{ixP^+z}\,\langle P|\, e^{iHz}\bar{\psi}(z)e^{-iHz}\, W(z;0)\gamma^+\psi(0)\,|P\rangle$$



$$W^{\mu\nu}(q) = \int \mathrm{d}^4x\; e^{iqx}\left\langle e^{iHx^0} J^\mu(\vec{x})e^{-iHx^0} J^\nu(\vec{0})\right\rangle_{\mathrm{proton}}$$

Parton Physics

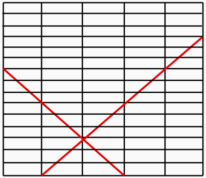
$$f(x) = \int \mathrm{d}z \; e^{ixP^+ z} \left\langle P \right| e^{iHz} \bar{\psi}(z) e^{-iHz} W(z;0) \gamma^+ \psi(0) \left| P \right\rangle$$

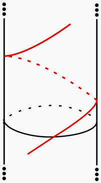


$$W^{\mu\nu}(q) = \int \mathrm{d}^4 x \; e^{iqx} \left\langle e^{iHx^0} J^\mu(\vec{x}) e^{-iHx^0} J^\nu(\vec{0}) \right\rangle_{\text{proton}}$$

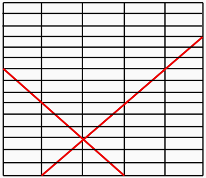
$$H = H_0 + \epsilon_x(t) J^\mu(\vec{x}) + \epsilon_0(0) J^\nu(\vec{0})$$

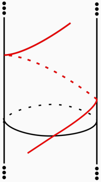
Prospects

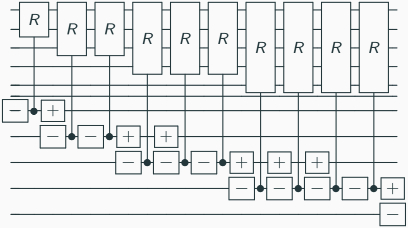




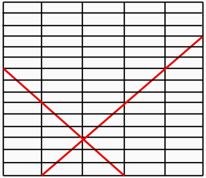
Prospects

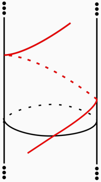


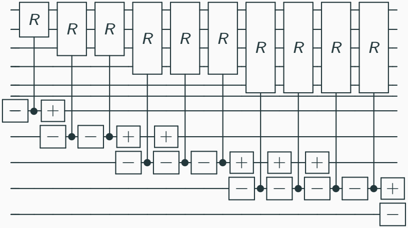




Prospects

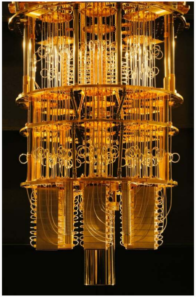




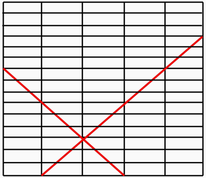
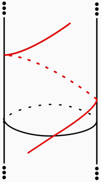
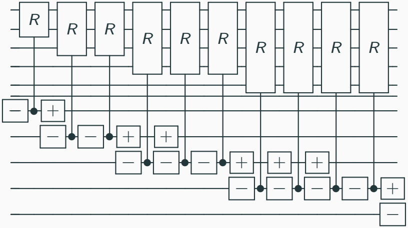


Need $\sim 10^6$ **qubits.**

So far: 50 qubits

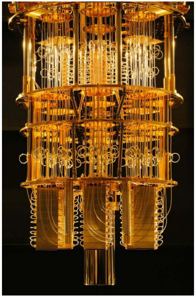
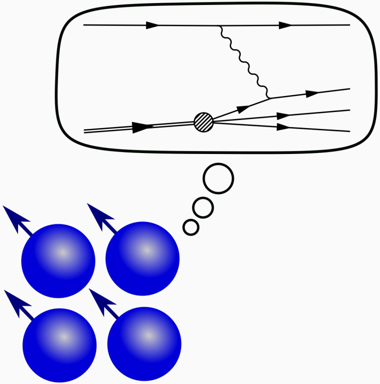


Prospects

Need $\sim 10^6$ qubits.

So far: 50 qubits

Thirring PDF

$$H = \int \mathrm{d}x \, \bar{\psi} \left(\partial\!\!\!/ + m \right) \psi + g^2 \left(\bar{\psi}\psi \right)^2$$

Staggered discretization:

$$H = \sum_r \frac{1}{2}(-1)^r \left(\chi_r^\dagger \chi_{r+1} + \chi_{r+1}^\dagger \chi_r \right) + m(-1)^r \chi_r^\dagger \chi_r - g^2 \chi_r^\dagger \chi_r \chi_{r+1}^\dagger \chi_{r+1}$$

Parton distribution function:

$$f(x) = \int \mathrm{d}z \, e^{ixP^+ z} \langle P | \, e^{iHz} \bar{\psi}(z) e^{-iHz} \gamma^+ \psi(0) \, | P \rangle$$