HEP in the new quantum era

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Based on: 2208.06750, with M. Li, X. Du, W. Qian, C. Salgado
Why Quantum computing?

Simulating Physics with Computers

Richard P. Feynman

“Nature isn’t classical ... and if you want to make a simulation of Nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem, because it doesn’t look so easy.”
What is Quantum computing?

Quantum algorithms

Quantum devices

Quantum problems

IBM Q

IONQ
Some recent works on quantum computing applications for HEP

Disclaimer: I will focus on work more relevant for jet physics in vacuum and in heavy ions
Quantum computing for HEP: ab initio QFT simulation

Quantum computers can, in principle, simulate scattering events ab initio.

Meaningful simulations will require thousands of high quality qubits!

Can we use QC's to tackle smaller problems?
Quantum computing for HEP: EFT approach

Full simulation is expensive, but the problem can be decomposed into several pieces

e.g. EFTs allow to explore the low energy sector in a first principle manner (no modeling)

\[ \sigma = H \otimes J_1 \otimes \cdots \otimes J_n \otimes S \]

Simulating collider physics on quantum computers using effective field theories

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![Graph showing transition rate vs coupling constant](image-url)
Quantum computing for HEP: fragmentation

Still for the low energy sector, away from $\Lambda_{\text{QCD}}$, parton showers can also get quantum improvement.

$\mathcal{H} = \mathcal{H}_C \otimes \mathcal{H}_P$

$U = S \cdot (C \otimes I)$

$U_c = \begin{pmatrix} \sqrt{1 - P_{jk}} & P_{jk} \\ P_{jk} & \sqrt{1 - P_{jk}} \end{pmatrix}$

All parton shower histories are in a superposition state.

A quantum algorithm for high energy physics simulations

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Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
(Dated: December 30, 2019)

A quantum walk approach to simulating parton showers

Khadeejah Bepari, Sarah Malik, Michael Spannowsky and Simon Williams
Quantum computing for HEP: evolution in media

For heavy ions physics, QC can be used to tackle real time evolution in the medium …

Quantum algorithms for transport coefficients in gauge theories

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… or compute transport coefficients

Quantum simulation of open quantum systems in heavy-ion collisions

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Quantum computing for jet quenching
Why quantum computing for jets in medium?

Many of the pheno relevant effects in jet quenching have a quantum origin.
Jet quenching in a QC: a possible approach

Integrating out $x^{-}$ the quark propagator satisfies

$$\left(i\partial_t + \frac{\partial^2}{2\omega} + gA^{-}(t,x) \cdot T\right) G(t,x;0,y) = i\delta(t)\delta(x - y)$$

Parton evolution is equivalent to 2+1d non-rel. QM

$$\mathcal{H}(t) = \frac{p^2}{2\omega} + gA^{-}(t,x) \cdot T = \mathcal{H}_K + \mathcal{H}_A(t)$$

Consider the simplest case:

1. $|q\rangle$ Fock space only
2. $T = 1$
3. Stochastic background (hybrid approach)
The quantum simulation algorithm

QComputers can **efficiently** simulate real time evolution ruled by:

\[ |\psi(t)\rangle = \exp(-iHt) |\psi(0)\rangle \]

The 5 main steps of the **Quantum Simulation Algorithm**:

1. Provide \( H = \sum_k H_k \) and \( \psi(0) \)

2. Encode the physical d.o.f’s in terms of qubits and decompose \( H_k \) in terms of gates

3. Prepare the initial wave function from a fiducial state \( (|0\rangle \otimes n_{\text{qubits}}) \)

4. Time evolve according to \( \exp(-iHt) \)

5. Implement a measurement protocol
Set up the algorithm

1. Provide $H = H_K + H_A(t)$ and $\psi(0) = \psi(p = 0) + \text{ensemble of } \{A, p_A\}

2. Encode the physical d.o.f’s in terms of qubits and write $H$ in terms of gates

   Introduce 2d spatial lattice with $N_s = 2^{n_0}$ sites per dimension

   $|x\rangle = |x_1, x_2\rangle = a_\perp |n_1, n_2\rangle$

   such that

   $H = \frac{P^2}{2E} + gA(t, X) \cdot T = H_K + H_A(t)$

   $\hat{P} |p\rangle = p |p\rangle$ \hspace{1cm} $\hat{X} |x\rangle = x |x\rangle \hspace{1cm} x, p \in \mathbb{Z}$

3. Prepare the initial wave function from a fiducial state ($|0\rangle ^\otimes n_{\text{qubits}}$)
4. Time evolve according to $U$

Assuming that field is static we use

$$U(L, 0) = \prod_{k=1}^{N_t} U(x_k^+; x_{k-1}^+)$$

$$U(x_k^+ + \delta x^+; x_k^+) \approx U_K(\delta x^+) U_A(\delta x^+, x_k^+)$$

$$\equiv \exp \left\{-i\delta x^+ \frac{\tilde{p}^2}{2p^+}\right\} \exp \left\{-ig\delta x^+ \hat{A}^- (x_k^+) T^a\right\}$$

Implement operators with a Fourier Transform in between

$$\exp \left\{-i\delta x^+ \frac{\tilde{p}^2}{2p^+}\right\} |\psi_p\rangle \xrightarrow{\text{qFT}} |p\rangle \xrightarrow{\text{qFT}} |x\rangle \exp \left\{-ig\delta x^+ \hat{A}^- (x_k^+) T^a\right\} |\psi_x\rangle$$
4. Time evolve according to $U$

Field insertions require probing the field value. This is done **classically**

\[
|0\rangle^{\otimes 2n_0} \rightarrow |\psi_0\rangle \xrightarrow{\text{Time evolution}} |\psi_L\rangle
\]

Requires $\mathcal{O}(N_{\text{states}})$ field evaluations; **Ok for resolving parton evolution**

**Major limitation of the approach due to classical treatment of medium**

Can be made more efficient with further discretization of the field values
Numerical results

Set up:

1. $T = 1$ (no colors) mostly

2. Static brick of length 10 fm

3. 5/6 qubits per spatial dimension (1024/4096 states in total).

4. We use 5 field configurations. These are determined by lattice spacing and the field strength

\[ g^2 \bar{\mu} = \sqrt{\frac{2\pi Q_s^2}{C_F L}} \]

Determined by saturation scale:

\[ \frac{\pi}{N_\perp m_g} \ll a_\perp \ll \frac{\pi}{Q_s} \]

(relevant physical region is covered)

Determined by lattice saturation conditions:

\[ a_\perp^2 Q_s^2 < \frac{4\pi^2}{3} \left[ \log\left( \frac{1}{a_\perp^2 m_g^2/\pi^2} + 1 \right) - \frac{1}{1 + a_\perp^2 m_g^2/\pi^2} \right]^{-1} \]

(edge effects are absent)
Numerical results

The jet quenching parameter on the lattice is easily obtained analytically:

\[
\hat{q} = \frac{1}{t} \int_{p,x,y} p^2 e^{-i p \cdot (y-x)} \langle W(y)^\dagger W(x) \rangle = g^2 \langle \nabla \mathcal{A}(0) \cdot \nabla \mathcal{A}(0) \rangle = \frac{g^4}{4\pi} C_F \tilde{\mu}^2 \left\{ \log \left( 1 + \frac{\pi^2}{a_s^2 m^2_\pi} \right) - \frac{1}{1 + \frac{a_s^2 m^2_\pi}{\pi^2}} \right\}
\]

In accordance with expected result w/wo kinetic terms

Deviation at large saturation values due to lattice
Numerical results

Same result but for two different lattices at infinite jet energy

\[ Q_s^2 = 6.73 \text{GeV}^2 \]

\[ Q_s^2 = 26.7 \text{GeV}^2 \]

\[ p^+ = \infty, U(1) \]

10 qubits

12 qubits

\# shots = 100 \times 2^{13}
Numerical results

Same results but for a SU(2) background

Random medium leads to emergent time dependence

\[ \langle \rho_a(x^+, x) \rho_b(y^+, y) \rangle = g^2 \mu^2(x) \delta_{ab} \delta^2(x - y) \delta(x^+ - y^+) \]
Numerical results

Energy independent terms might give sizable contribution!
Numerical results

Noise dominated error model: depolarizing channel

Available but not free
Prototype
Conclusion and Outlook

Quantum computing applications to HEP are still in their infancy

For jet quenching, the study of LPM physics can be better understood using these machines in the future

\[
|\psi\rangle = c_1 |q\rangle + c_2 |qg\rangle + c_3 |qgg\rangle + \cdots
\]

Quantum advantage becomes crucial!