Qiskit | Fall Fest
Quantum Computing Workshop

Research Talk:

Quantum simulation of jet quenching

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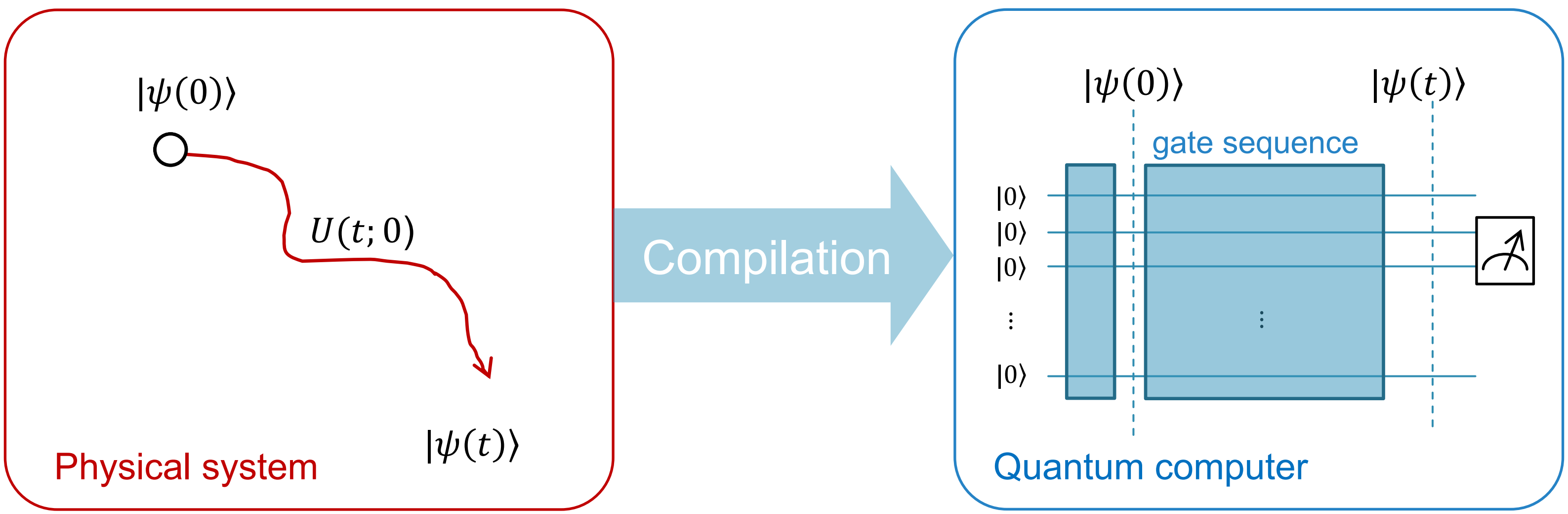
What is Quantum Simulation?

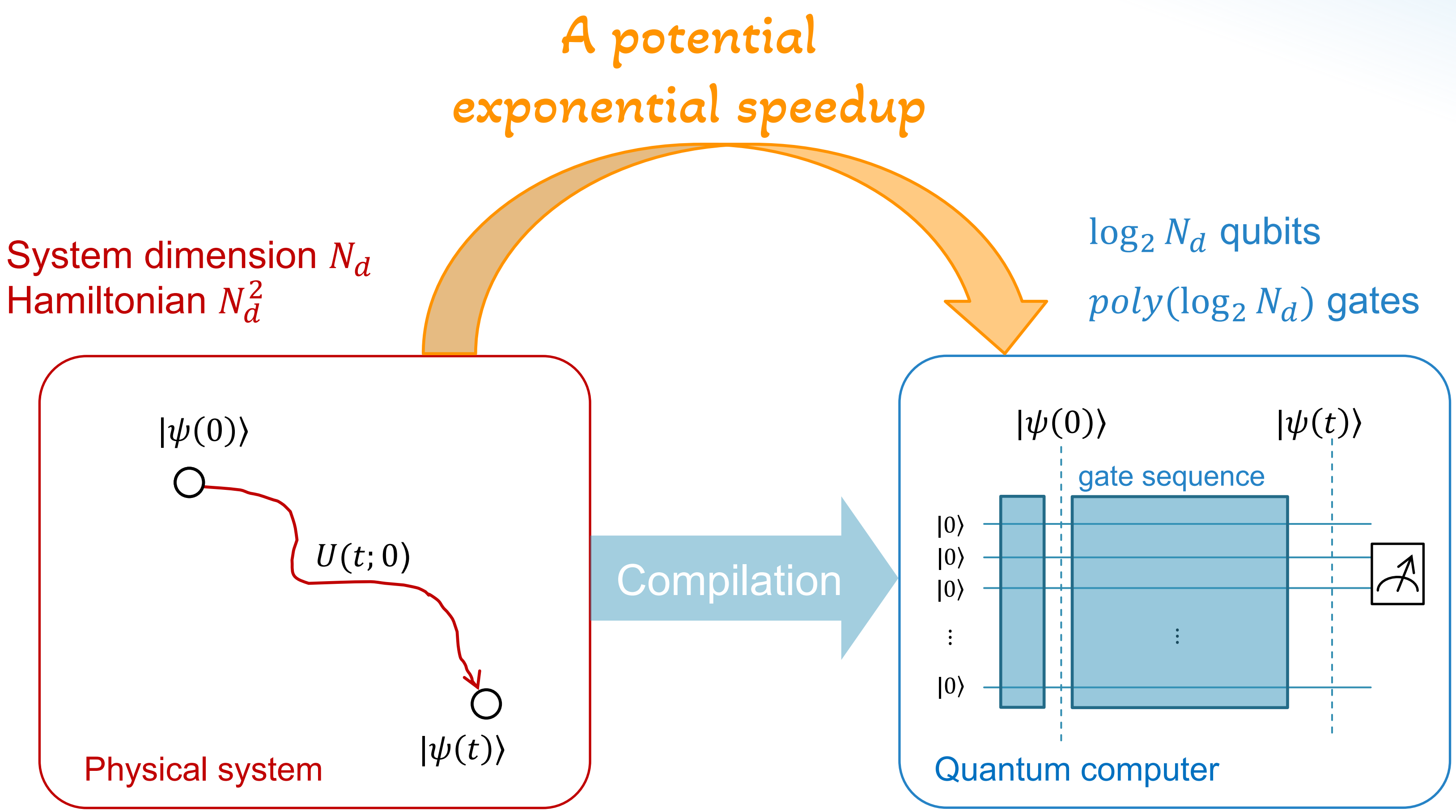
Time evolution in quantum dynamics is given by

$$|\psi(t_f)\rangle = \underbrace{\mathcal{T}\, e^{-i\int_{t_i}^{t_f} dt\, H(t)}}_{U(t_f;\,t_i)\ \textit{evolution operator}} |\psi(t_i)\rangle$$

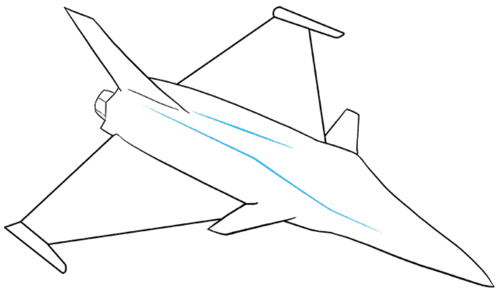
Hamiltonian



Why Quantum Simulation?



What is jet quenching?



"Jet"

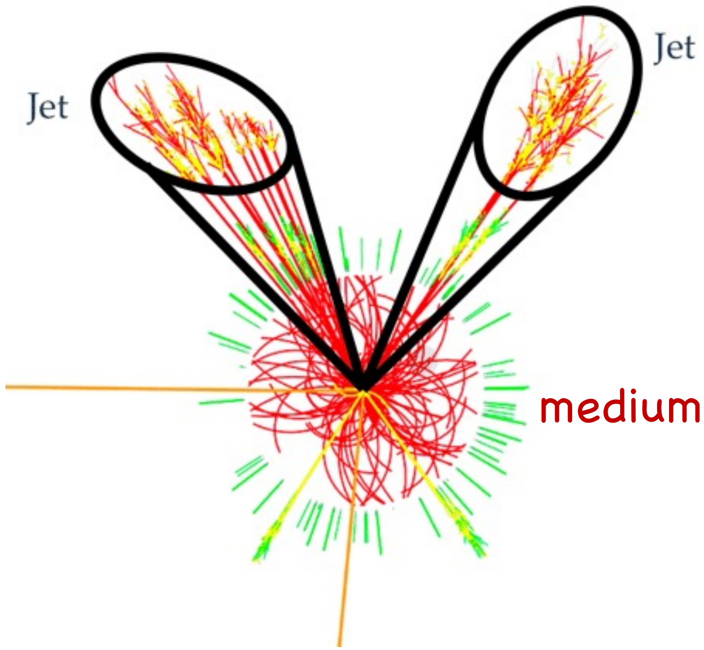
A rapid stream

"Quenching"

A rapid cooling process

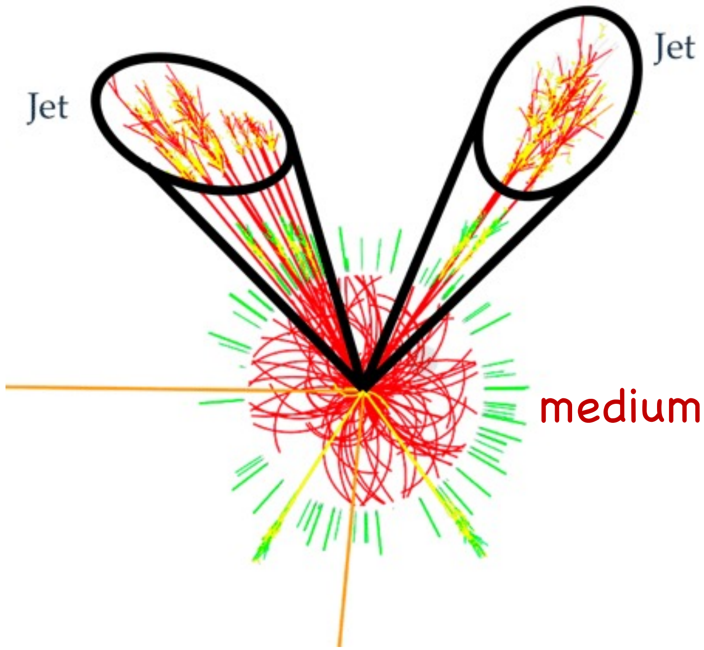
What is jet quenching?

In heavy ion collisions, a jet is a cone-shaped beam of energetic particles. When propagating through the hot medium, it loses energy due to jet-medium interaction, a phenomenon known as ***jet quenching***.

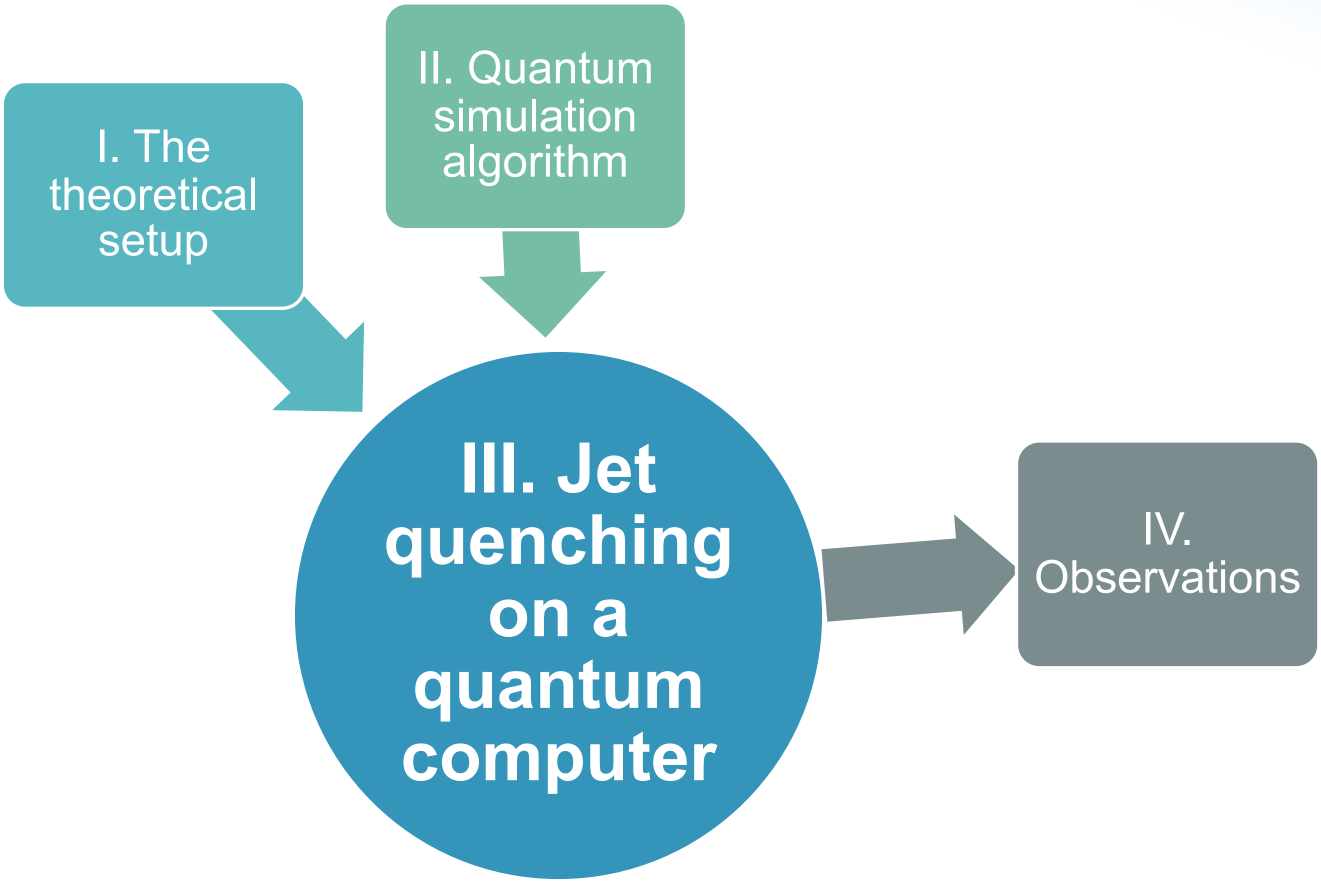


Why jet quenching?

Jet evolution → Medium properties → Formation of matter

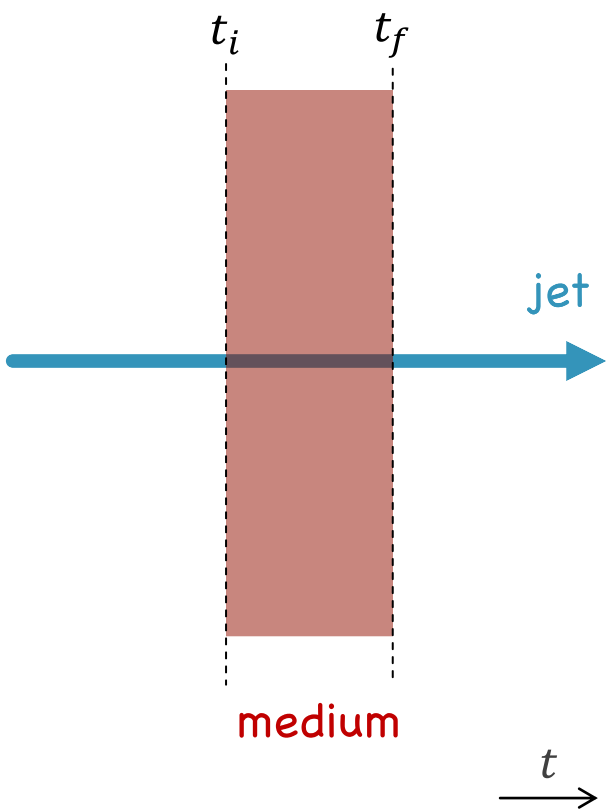


Outline


I. The theoretical setup
II. Quantum simulation algorithm
III. Jet quenching on a quantum computer
IV. Observations

The theoretical setup

We consider the propagation of a highly energetic quark, the jet, in the presence of a dense medium, the field A.



$$|\psi(t_f)\rangle = \underbrace{\mathcal{T}\, e^{-i\int_{t_i}^{t_f} dt\, H(t)}}_{U(t_f;t_i)} |\psi(t_i)\rangle$$

$$H(t) = \boxed{H_k} + \boxed{H_A(t)}$$

Kinetic energy

Medium interaction

Quantum simulation algorithm

Construction with five generic steps:

1) **Input**
   - ✓ The system Hamiltonian
2) **Encoding**
3) **Initial state preparation**
4) **Time evolution**
5) **Measurement**

Quantum simulation algorithm: (2) Encoding

A map between physical basis states and qubit states:

$$|\beta(\boldsymbol{p}_\perp, c)\rangle \leftrightarrow |01\ldots0\rangle$$

N_d physical states (transverse momentum $\boldsymbol{p}_\perp$ and color c)

$$|\beta(\boldsymbol{p}_\perp, c)\rangle = |\boldsymbol{p}_\perp\rangle \otimes |c\rangle$$

$n_Q = \log_2 \mathrm{N}_d$ qubit states

$$|01\ldots0\rangle = |0\rangle \otimes |1\rangle \otimes \cdots \otimes |0\rangle$$

e.g., $|1,3\rangle \to |01,11\rangle \to |0\rangle \otimes |1\rangle \otimes |1\rangle \otimes |1\rangle$
$\to |\uparrow\rangle \otimes |\downarrow\rangle \otimes |\downarrow\rangle \otimes |\downarrow\rangle,$

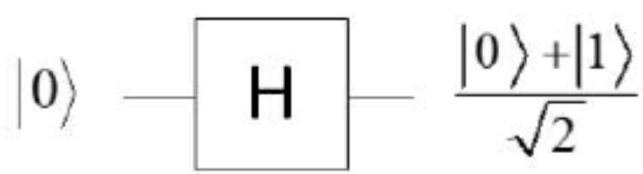
Quantum simulation algorithm: (3) Initial state preparation

Superposition state: $|\psi(t)\rangle = \sum_{\beta} c_{\beta}(t)|\beta\rangle$

We take $|\psi(0)\rangle$ as the zero transverse momentum and a fully balanced superposed color state,

$$|\psi(0)\rangle = |\boldsymbol{p}_{\perp} = \boldsymbol{0}_{\perp}\rangle \otimes \boxed{\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)}$$

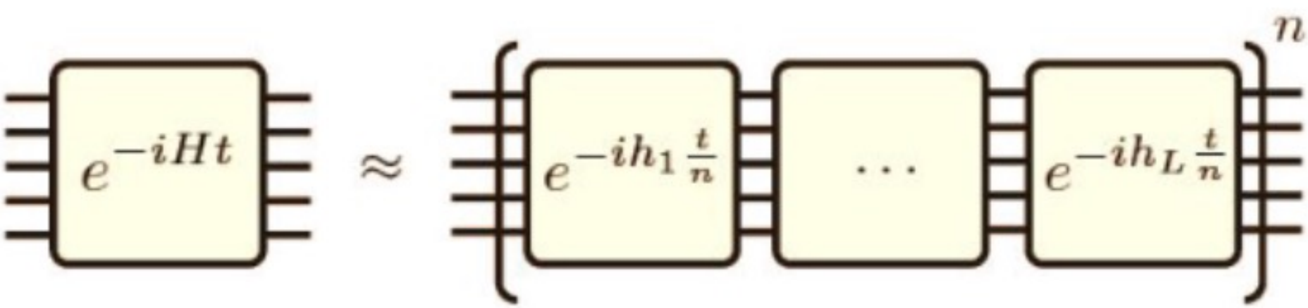
Which gate could prepare such a state?



Quantum simulation algorithm: (4) Time evolution

The full evolution operator decomposed into a sequence of small steps

$$U(t_f; t_i) = \lim_{n\to\infty} \prod_{k=1}^{n} U(t_k\ ; t_{k-1})$$



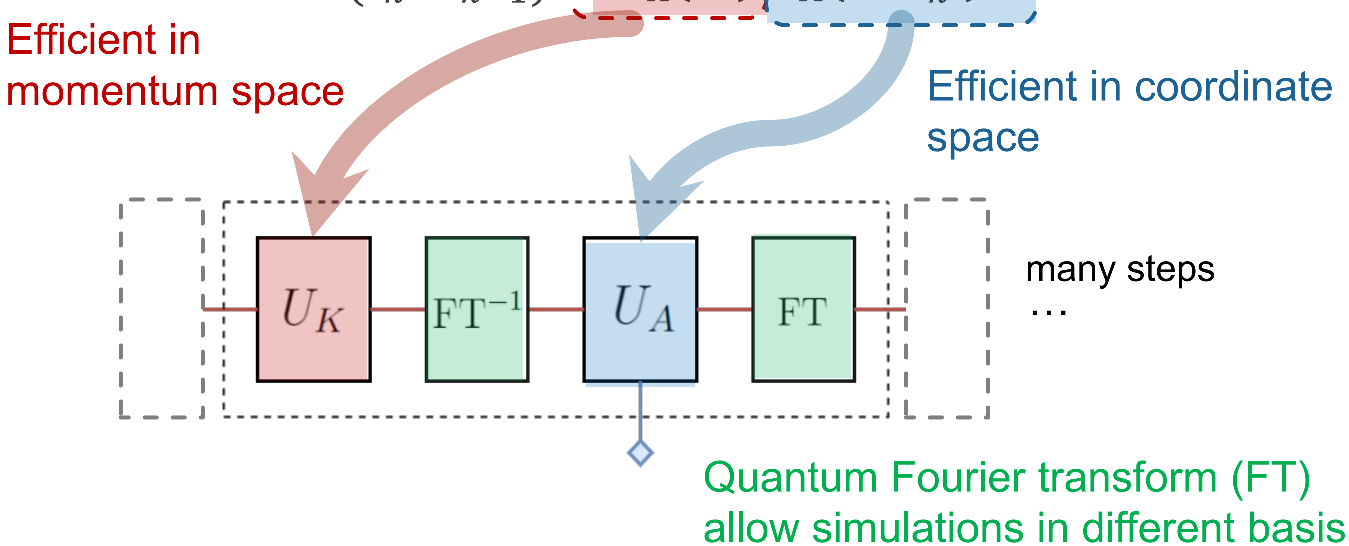
Quantum simulation algorithm: (4) Time evolution

The full evolution operator decomposed into a sequence of small steps

$$U(t_f;t_i) = \lim_{n\to\infty} \prod_{k=1}^{n} U(t_k\,;t_{k-1})$$

Each step-wise evolution decomposed into the kinetic energy and the medium interaction:

$$U\big(t_k\,;t_{k-1}\big) \approx \boxed{\mathrm{U_K}(\delta t)}\,\boxed{\mathrm{U_A}(\delta t, t_k\,)}$$



Quantum simulation algorithm: (5) Measurement

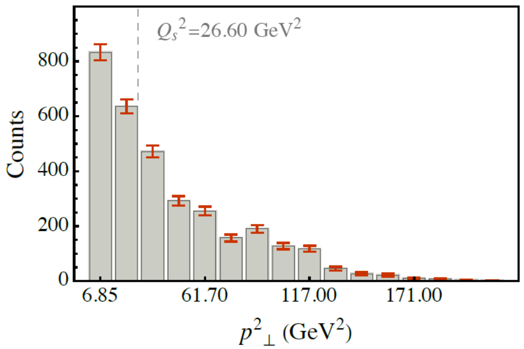
When measured, the quantum state collapses to a momentum and color eigenstate:

$$|\psi(t)\rangle = \sum_{\beta} c_{\beta}(t)|\beta\rangle \quad \rightarrow |\beta\rangle$$

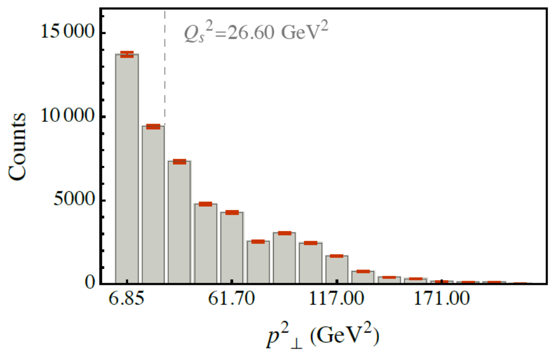
$$\left|q_0 q_1 \dots q_{n_Q - 1}\right\rangle \quad \rightarrow |01 \dots 0\rangle$$

Quantum simulation algorithm:
(5) Measurement

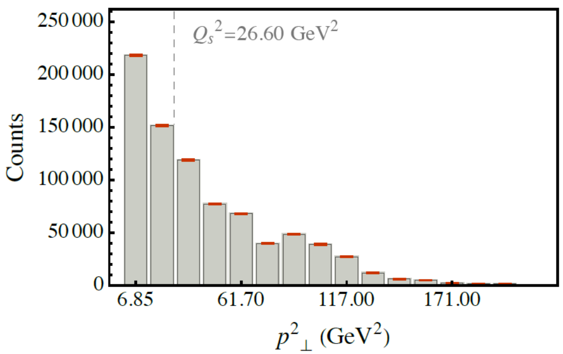
By performing multiple measurements (shots), we are able to reconstruct the distribution of the jet state in momentum space.



3200 shots



51200 shots



819200 shots

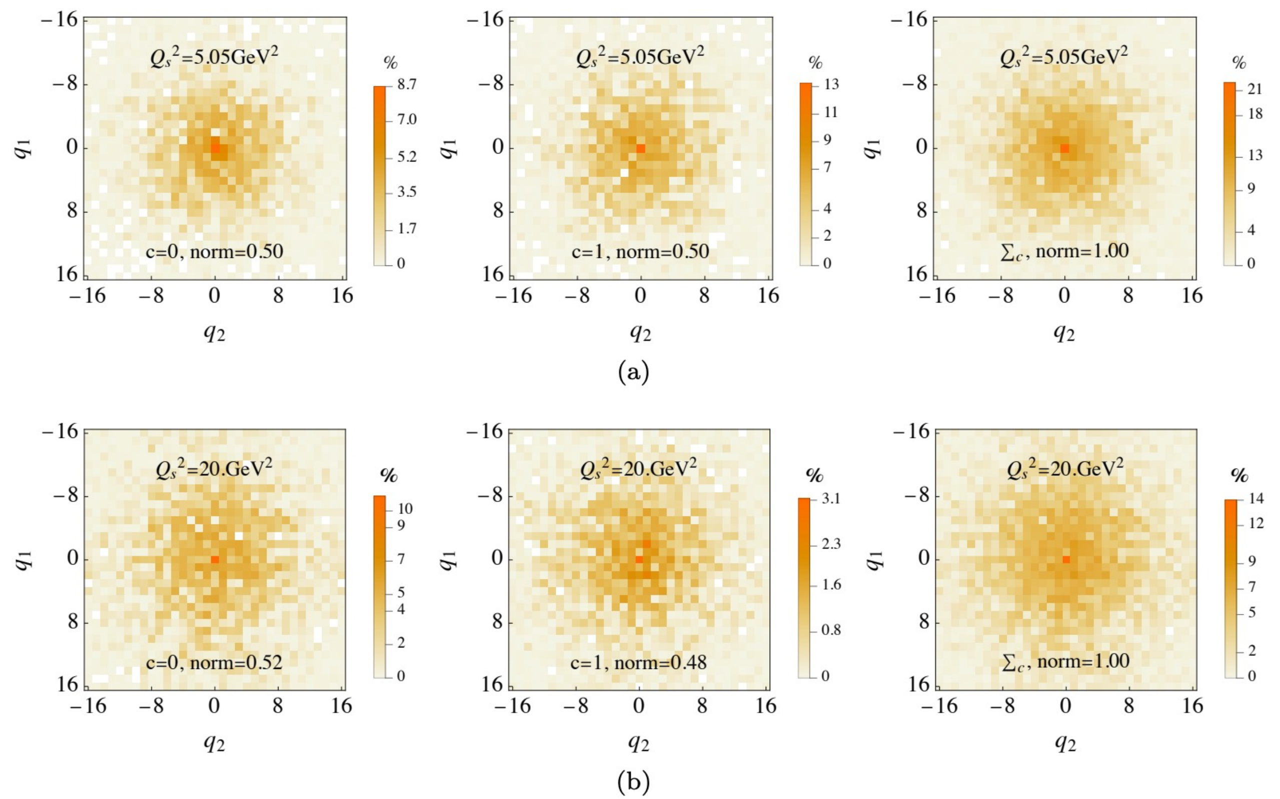
Statistical uncertainty decreases as the number of counts increases

Observations: Momentum broadening

Recall that the initial state is a zero momentum and a balanced superposed color state. The final state momentum distribution:

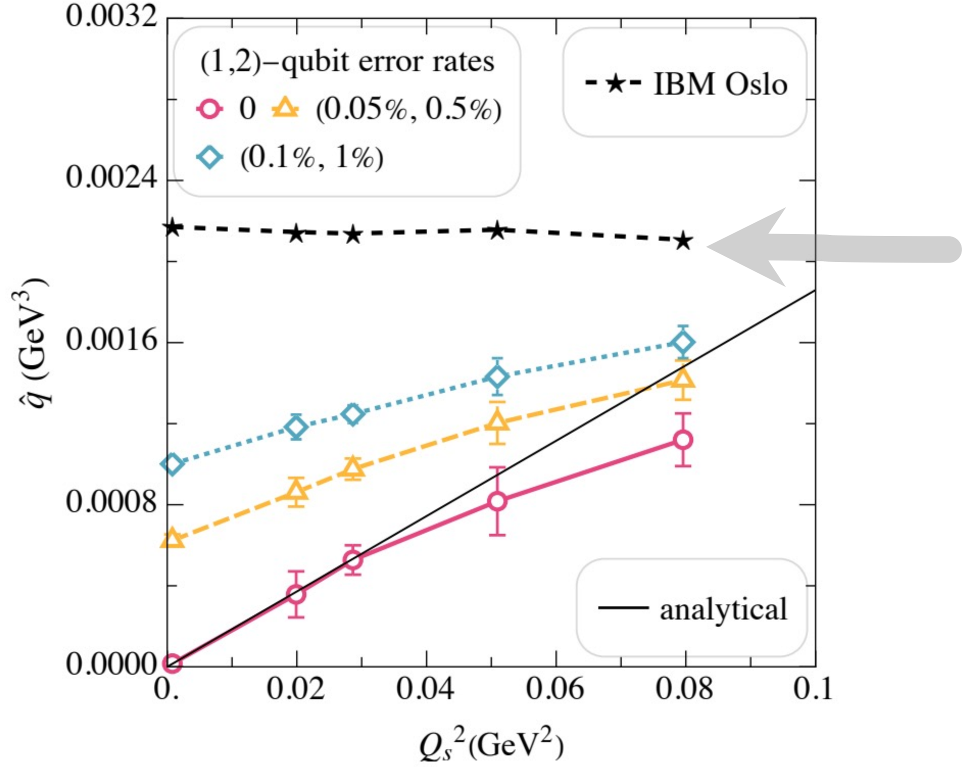
Weaker medium

Stronger medium



Simulations in a noisy quantum computer

Quenching parameter as a function of the field strength:



noise overwhelms physics

Summary

In this work:

- ✓ We constructed a digital quantum circuit that tracks the evolution of a quark jet in the presence of a medium background and studied the quenching effects.

Find more in the article: J. Barata, X. Du, M. Li, W. Qian, C. A. Salgado, "Medium induced jet broadening in a quantum computer", Phys. Rev. D 106, 074013(2022), arXiv:2208.06750 [hep-ph]

Future work plans:

- ❑ Incorporating multiple particles into the jet, e.g., jet as a superposition state $|q\rangle + |qg\rangle$.
- ❑ Optimization of the quantum circuit, e.g., reducing the circuit depth.

Thank you!