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EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

IGFAE
Instituto Galego de Física de Altas Enerxías

STATE

# Quantum simulation of jet quenching


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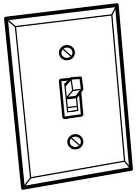
Jet quenching in the quark-gluon plasma, Trento, 17 June 2022

# Outline

1. Introduction to quantum computing (QC)
2. Applications in HEP/NP
3. Our recent work in jet quenching

# Introduction to QC

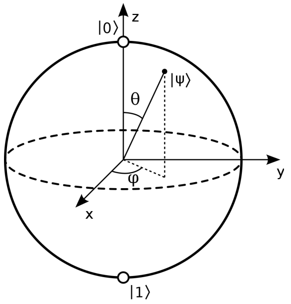
- Classical computers:
  - classical bit: 0, 1
  - classical gates: AND, OR, NOT, Bitwise logic gates
  - deterministic nature



- Quantum computers:
  - quantum bit (qubit): $|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$
  - implementation: two-level quantum systems

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle, \; |\alpha|^2 + |\beta|^2 = 1$$

  - quantum gates: **unitary operators**
  - features: **superposition** & **entanglement**
  - states only collapse when measured



# Developments in QC

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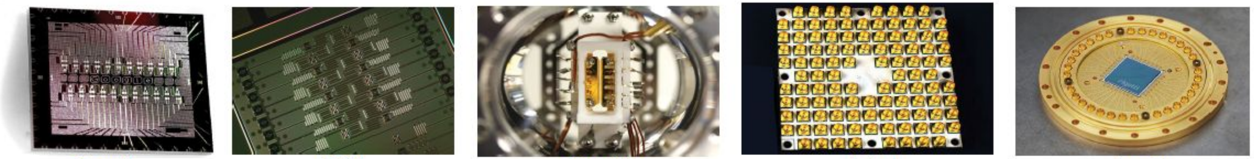
Quantum computing has come a long way in past 40 years — Feynman (1981)

- Toffoli Gate (1980)
- Shor's Algo (1994)
- Error Correction (1995)
- Variational Eigensolver (2014)
- Quantum Machine Learning (2017)

Currently, we are in the **Noisy Intermediate-Scale Quantum (NISQ)**: qubits and quantum operations are substantially imperfect. Nonetheless,

Preskill (2018)

Image from Jong's talk (2022)



Google | IBM | Rigetti | Intel | IonQ

Qiskit

Cirq

XANADU

Recently, "Quantum Simulation for High Energy Physics", 2204.03381 (2022)

# Why are we interested in QC?

*"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical"* (Richard Feynman)

- <u>Many problems are inherently quantum mechanical.</u>
- <u>Vast amount (exponential) of encoded information</u> in a many-qubit state:

  Impossible to compete on classical computers; Nature does it automatically
- High <u>scalability</u> in quantum applications (compact encoding)
- Many-body problems and quantum computing are similar by nature
- Rapid progress in hardware, software, algorithms, benchmark

~ 100 qubits, improved volume, speed

IBM, 2110.14108 (2021)

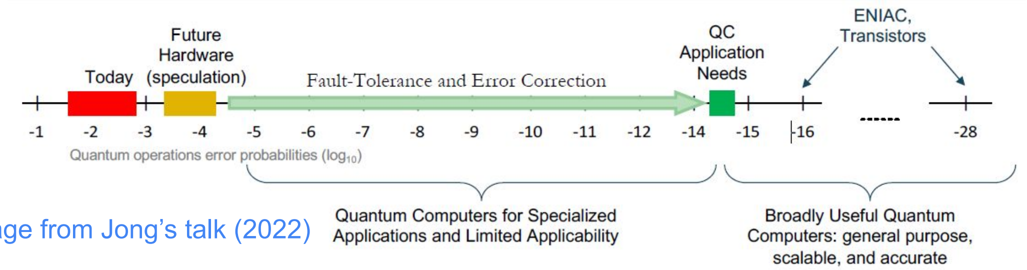



Image from Jong's talk (2022)

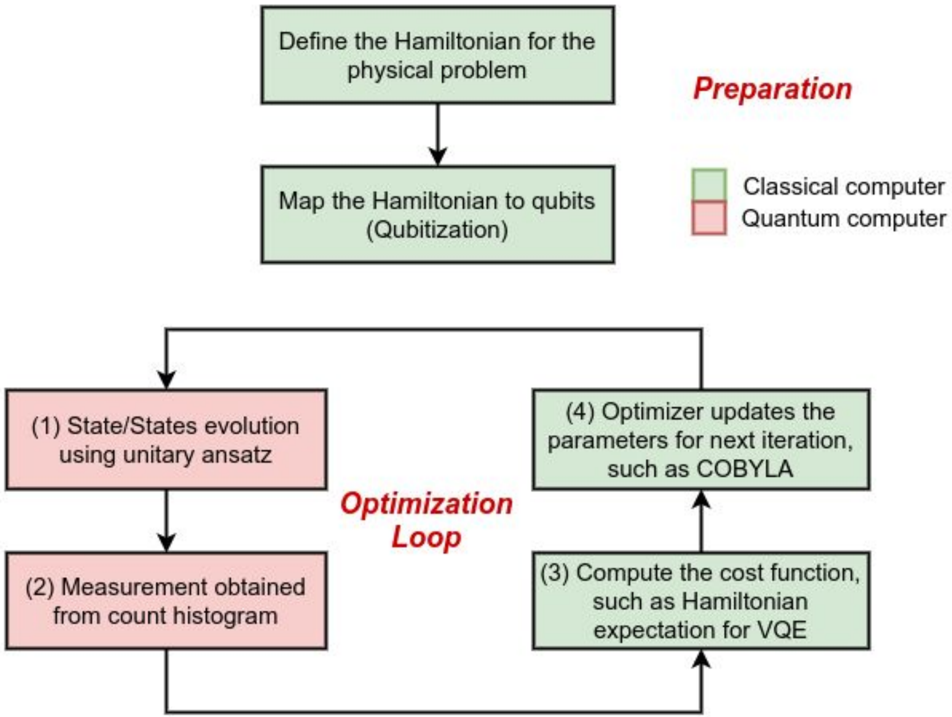
# Applications in HEP/NP

Two main directions:

- **Variational Quantum Eigensolver (VQE)**, a hybrid optimization algorithm, widely-used in quantum chemistry, many variants

- **Quantum Phase Estimation (QPE)**, prepare, evolve, fourier transform, measure to find quantum state of the system (eigenvector)

# VQE paradigm, hybrid optimization approach




Peruzzo et al., 1304.3061 (2013)

Inspired by **Variational Principle**

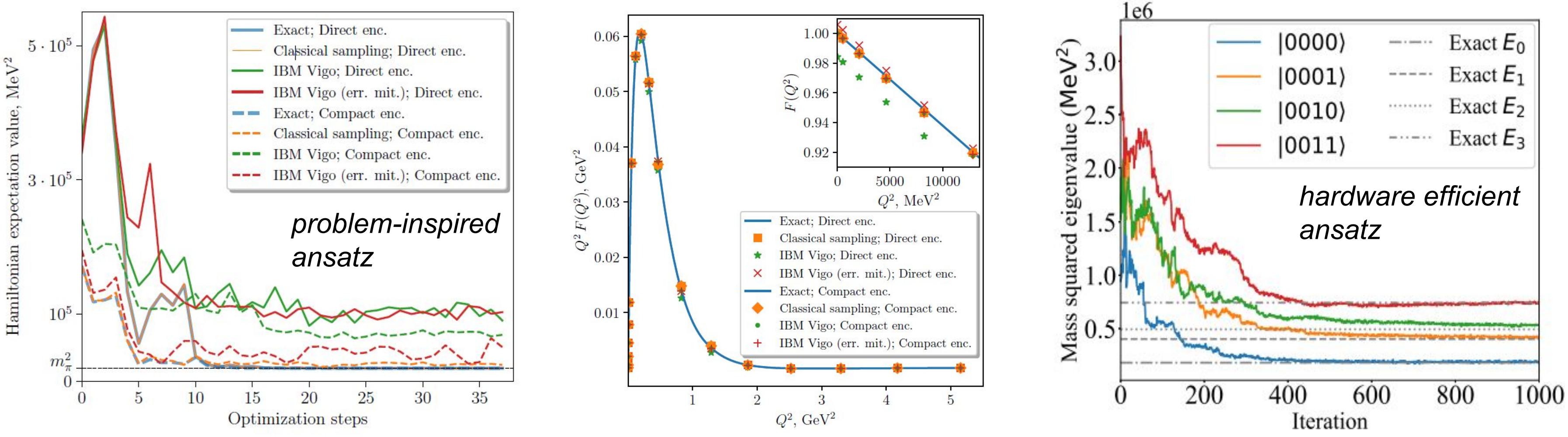
Large group of QC approaches (UCC, QAOA, etc); very successful in quantum chemistry

Review at Bharti et al., 2101.08448 (2021)

With optimized/finalized quantum state, we compute additional observables directly or indirectly on the quantum circuit

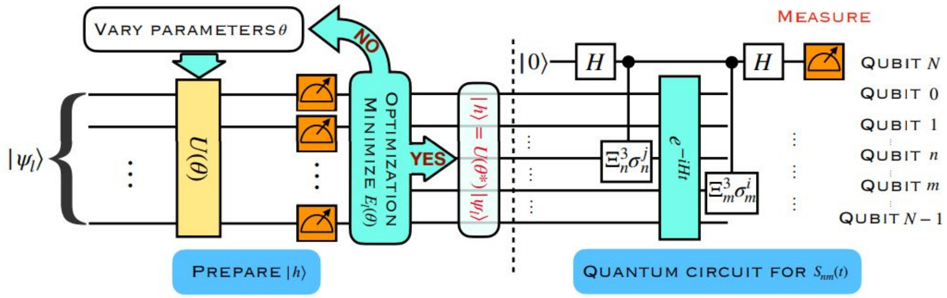
# Quantum simulation of quantum field theory in the light-front formulation

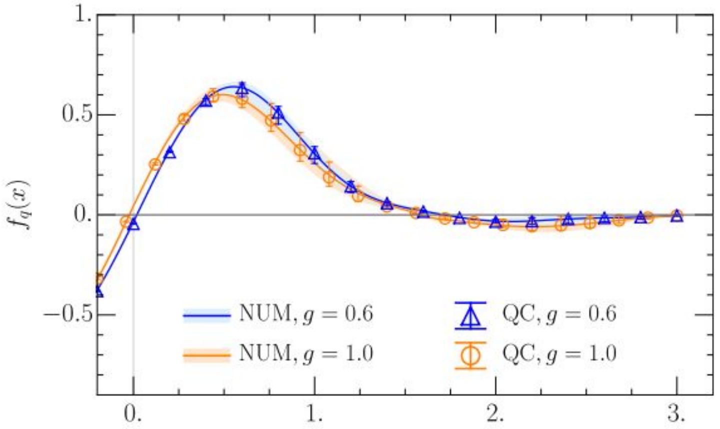
Kreshchuk, Jia, Kirby, Goldstein, Vary, Love, 2011.13443 (2020) & 2009.07885 (2020)
WQ, Basili, Pal, Luecke, Vary, 2112.01927 (2021)




Direct/Compact qubit encoding and careful design of ansatz in VQE calculation for bound state properties.

# Partonic Structure by Quantum Computing



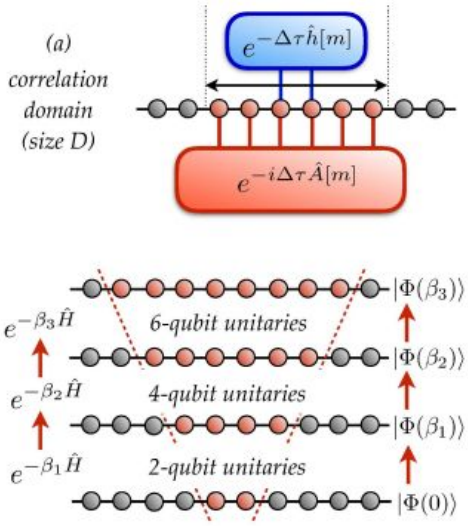

Evaluate PDF for 1+1 Nambu-Jona-Lasinio (NJL) model

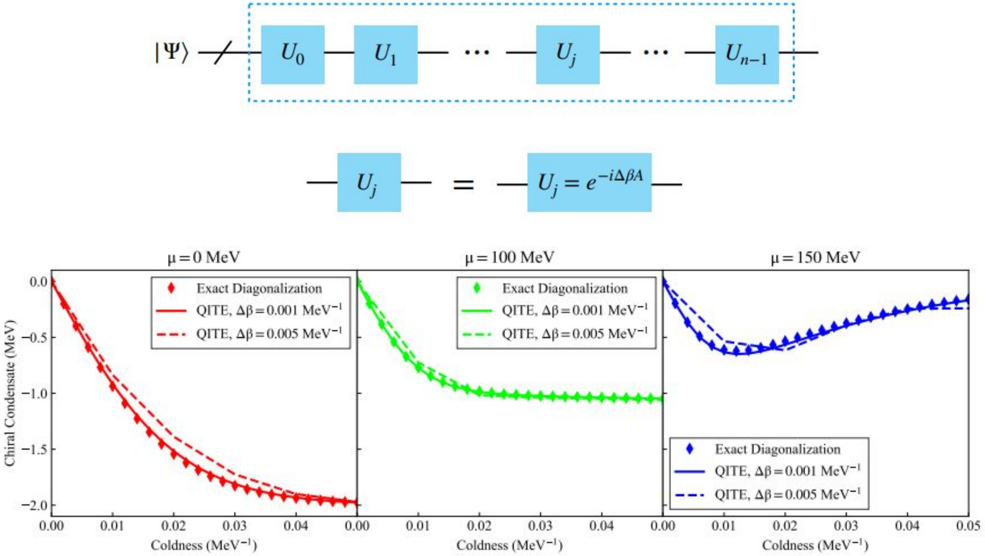
Li et al., 2106.03865 (2021)

# Quantum Imaginary Time Evolution (QITE) & Quantum Simulation of Chiral Phase Transitions

Motta et al., 1901.07653 (2020)

Czajka, Kang, Ma, Zhao, 2112.03944 (2021)




Competitors of VQE & application to 1+1 NJL model

# Quantum Simulation Algorithm

1. Define problem Hamiltonian
2. Encode Hamiltonian onto basis
3. Prepare initial states
4. Evolution
5. Measurement protocol

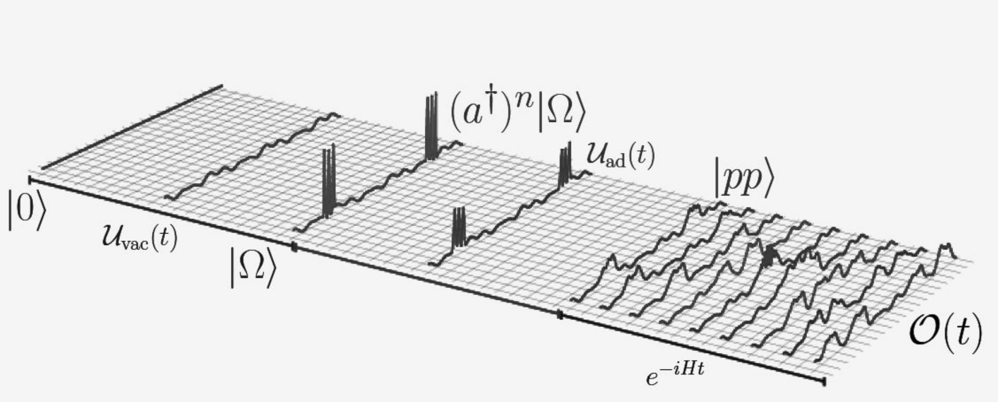
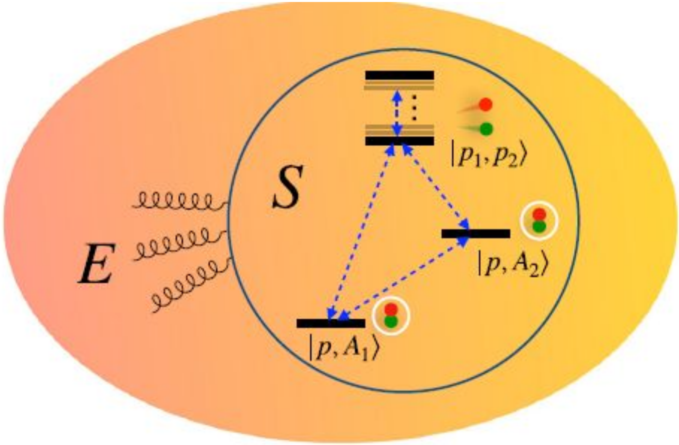


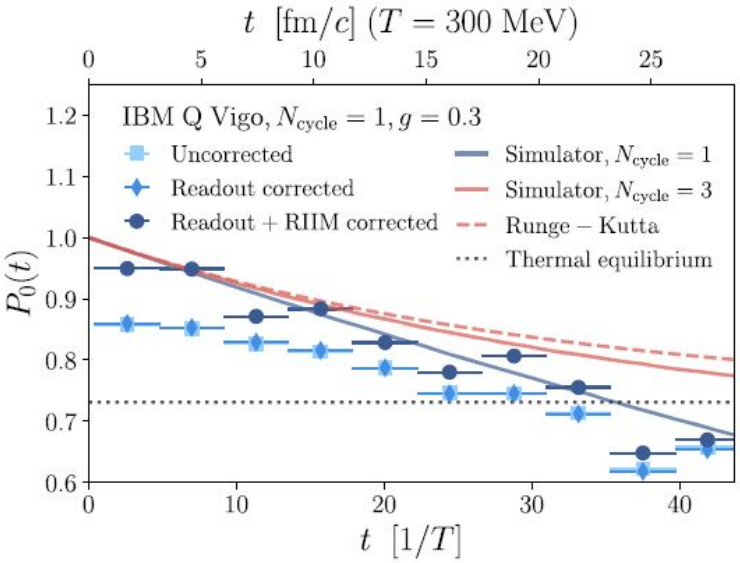

Image from Lamm's talk (2021)

Wiesner, 9603028 (1996); Zalka, 9603026 (1996)

# Quantum simulation of open quantum systems in heavy-ion collisions

Jong, Metcalf, Mulligan, Ploskon, Ringer, Yao, 2010.03571 (2021)

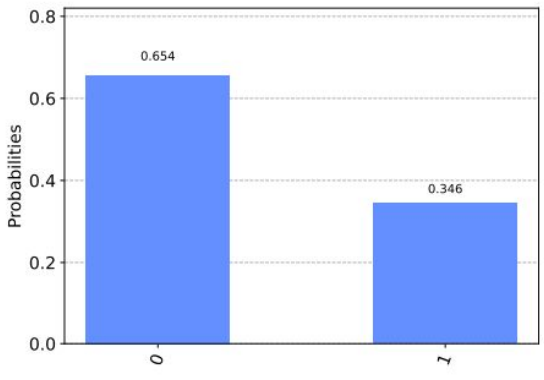


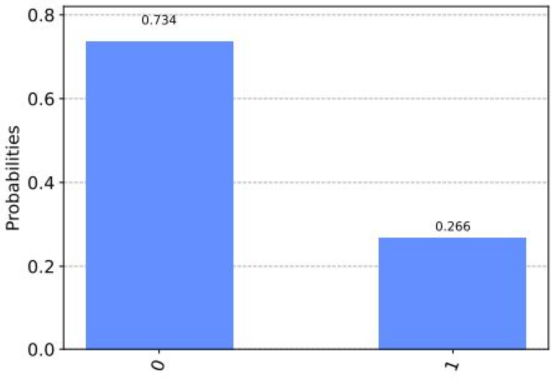

Simulating Lindblad equation for hard probes in thermal bath

# Quantum Simulation of Light-Front QCD for Jet Quenching in Nuclear Environments

Yao, 2205.07902 (2022)




(a) Vacuum case.

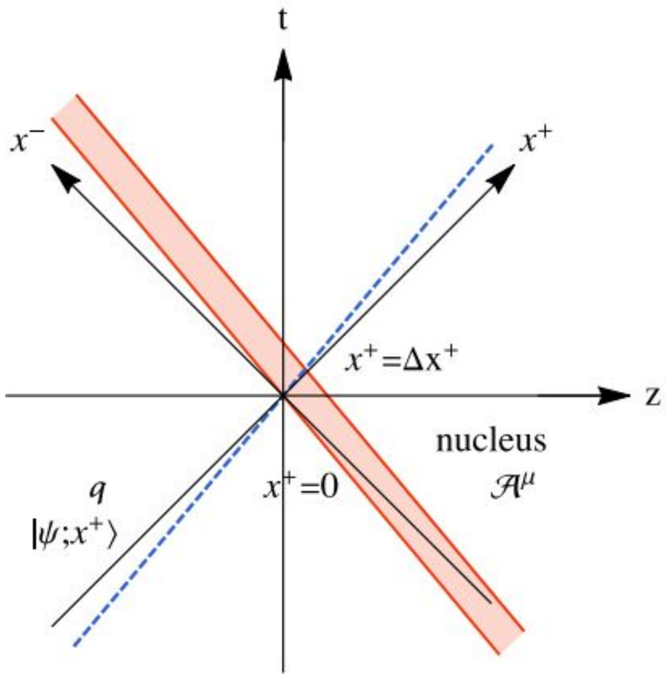



(b) Medium case.

Demo of Landau-Pomeranchuk-Migdal (LPM) effect observed in the quantum simulator (2+1 scalar fields, allowing 1-particle and 2-particle state splitting)

# Ongoing work:
# Medium induced jet broadening in a quantum computer

Barata, Salgado, 2104.04661 (2021)
(In preparation) Barata, Du, Li, Salgado, WQ




M. Li, Zhao, Maris, Chen, Y. Li, Tuchin, Vary, 2002.09757 (2020)

High-energy quark moving close to the light cone scattering on a dense nucleus medium

$$\mathcal{L}_q = \overline{\Psi}(i\gamma^\mu D_\mu - m)\Psi$$

$$D^\mu \equiv \partial_\mu I + ig\mathcal{A}^\mu$$

Light-front Hamiltonian becomes:

$$P^-(x^+) = P^-_{\rm KE} + V_{\rm A}(x^+) = \frac{p_\perp^2}{p^+} + gA(x^+)\cdot T$$

# Background field

The background field uses the MV model

$$\langle\langle \rho_a(\vec{x}_\perp, x^+)\rho_b(\vec{y}_\perp, y^+)\rangle\rangle = g^2\tilde{\mu}^2\delta_{ab}\delta^2(\vec{x}_\perp - \vec{y}_\perp)\delta(x^+ - y^+)$$

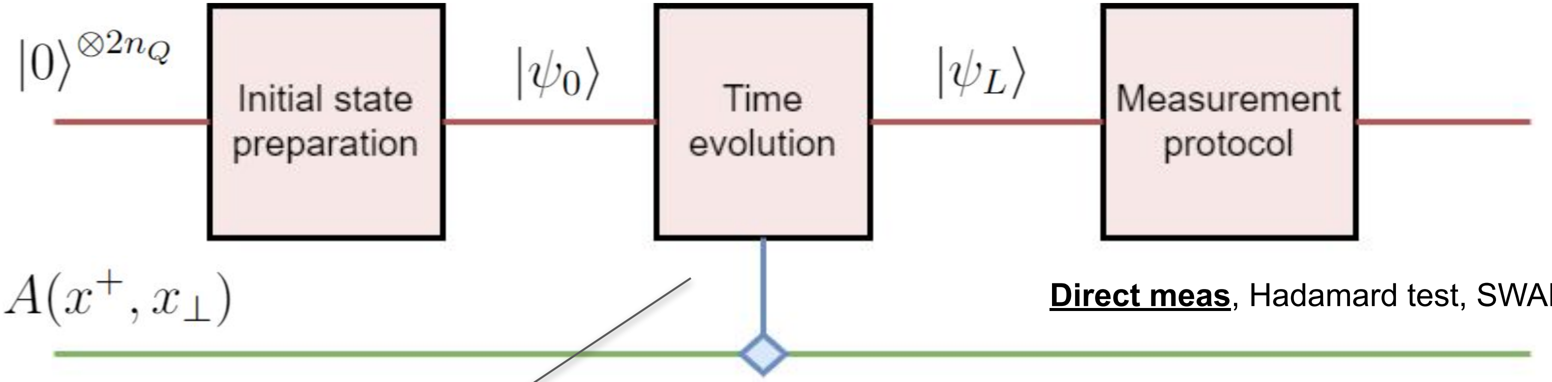
*static, non-dynamical*

$$(m_g^2 - \nabla_\perp^2)\mathcal{A}_a^-(\vec{x}_\perp, x^+) = \rho_a(\vec{x}_\perp, x^+)$$

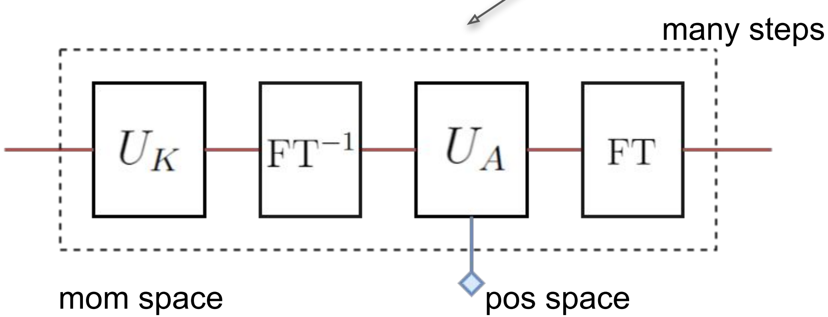
The correlation is achieved by using a local Gaussian distribution

Here, we are interested in the jet evolution using quantum simulation.

# Quantum simulation




**Direct meas**, Hadamard test, SWAP test, etc




**Quantum FT allows convenient simulation in the respective basis**

$$U_K(\delta x^+)\,|\boldsymbol{p}\rangle = \exp(-i\delta x^+ p_\perp^2/p^+)\,|\boldsymbol{p}\rangle$$

$$U_A(x^+, \delta x^+)\,|\boldsymbol{x}\rangle = \exp(-ig\delta x^+ A(x^+, \boldsymbol{x})\cdot T)\,|\boldsymbol{x}\rangle$$

# Field evolution

$$A(x)\cdot T = \sum_{a=X,Y,Z} A^a\sigma^a/2$$

*simplest colorful case, with two colors, SU(2)*

$$\exp(-ig\delta x^+ A(x)\cdot T) = \exp\left\{-ig\delta x^+(A^X\otimes\sigma^X + A^Y\otimes\sigma^Y + A^Z\otimes\sigma^Z)\right\}$$

Implementations:

$$e^{ia(\hat{n}\cdot\vec{\sigma})} = I\cos a + i(\hat{n}\cdot\vec{\sigma})\sin a$$

- Exact method using property of the *exponential of a Pauli vector*
- Exponent matrix approximation
- **Linear-order, allows for separation of color and pos space** (circuit modularization)
- **higher orders**

$$\exp\left(-iA(x)\sigma^Z\right)|\boldsymbol{x}\rangle|c\rangle = \begin{cases} e^{-iA(x)}|\boldsymbol{x}\rangle|c\rangle \ , \text{ if } c=0 \\ e^{+iA(x)}|\boldsymbol{x}\rangle|c\rangle \ , \text{ if } c=1 \end{cases}$$

# Basis space encoding

**Basis space encoding**

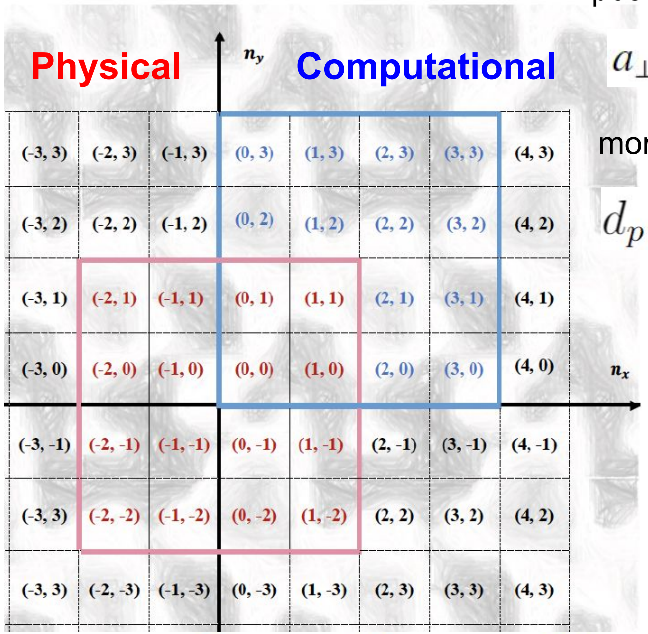
Here, we have 2D momentum/position space + 1D color space

$$n_{tot} = (2N_\perp)^2 N_c$$

For SU(2), $Nc$ = 2,

$$\text{state} = |q_{2n_Q}...q_1\rangle\,|q_0\rangle$$
$$= |n_x, n_y\rangle\,|c\rangle$$
$$= |k_x, k_y\rangle\,|c\rangle \qquad c = 1, 2$$

**Periodical Lattice**




$$O(n_x, n_y) = O(n_x + i2N_\perp, n_y + j2N_\perp)$$

pos lattice spacing

$$a_\perp = L_\perp / N_\perp$$

mom lattice spacing

$$d_p = \pi / L_\perp$$

# Simulation parameters:

- We study both evolutions with and without color, initial state: $(p_x, p_y) = (0, 0)$
- Duration of static medium: $L_\eta = 50\,\mathrm{GeV}^{-1} \approx 10\,\mathrm{fm}$
- 5 field configurations
- Two sets of lattice grids, 32 X 32 (10 qubits) and 64 X 64 (12 qubits)
- Fix $g = 1$, physical IR regulator $m_g = 0.8\,\mathrm{GeV}(\ll Q_s)$
- Selected values of saturation scales $Q_s$

$$g^2\tilde{\mu} = \sqrt{\frac{2\pi Q_s^2}{C_F L_\eta}}$$

$$\lambda_{IR} = \frac{\pi}{N_\perp a_\perp} \ll m_g \ll Q_s \ll \lambda_{UV} = \frac{\pi}{a_\perp}$$

range coverage cond

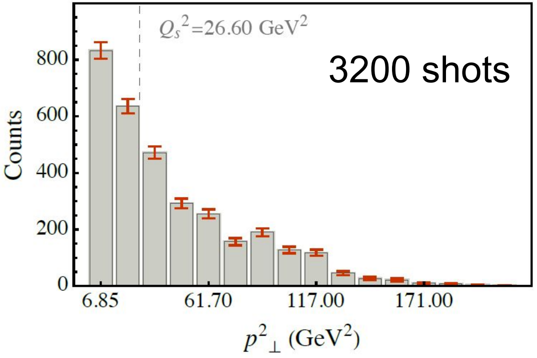
$$a_\perp^2 Q_s^2 < \frac{4\pi^2}{3}\left[\log\left(\frac{1}{a_\perp^2 m_g^2/\pi^2} + 1\right) - \frac{1}{1 + a_\perp^2 m_g^2/\pi^2}\right]^{-1}$$

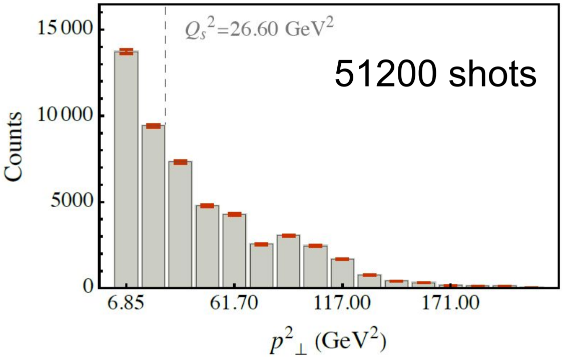
broadening coverage cond

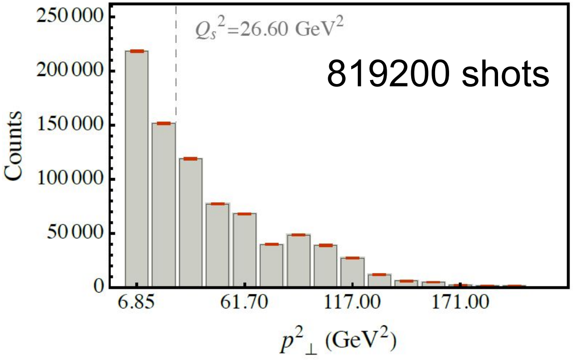
# Event simulations

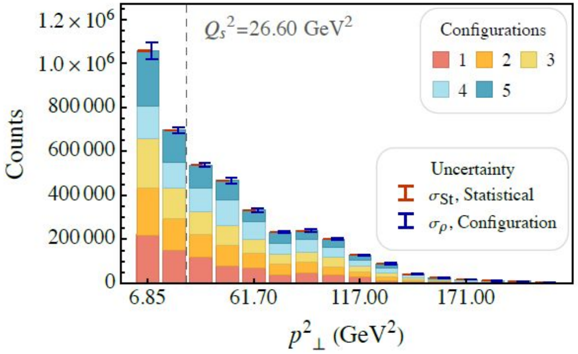
**Measurement (collapse) of quantum state**

**sampling noise** statistical uncertainty

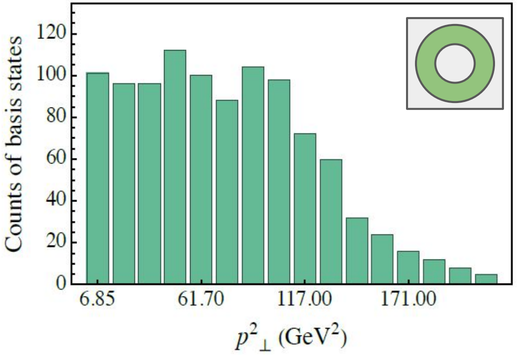



configuration uncertainty

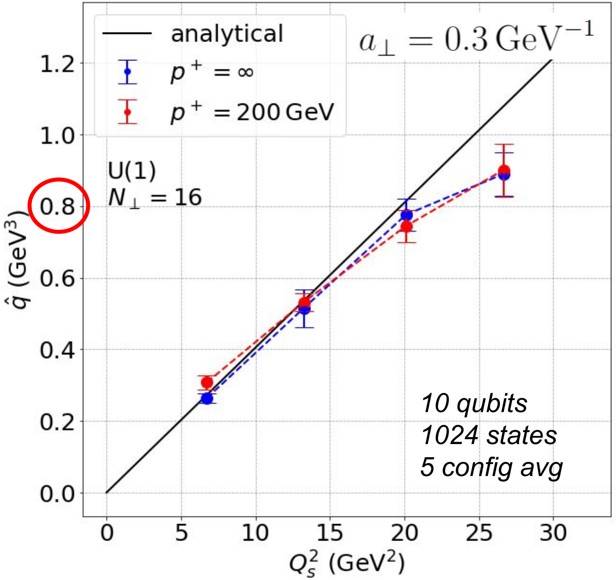


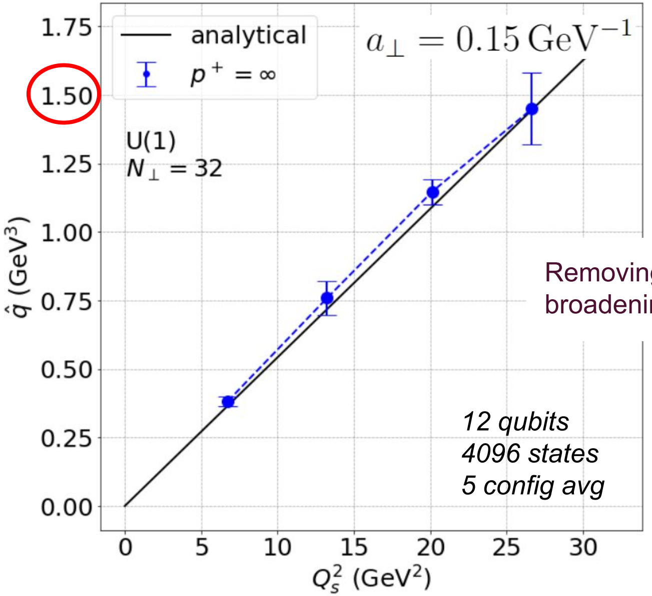

number of basis states

# Numerical results, colorless U(1) case

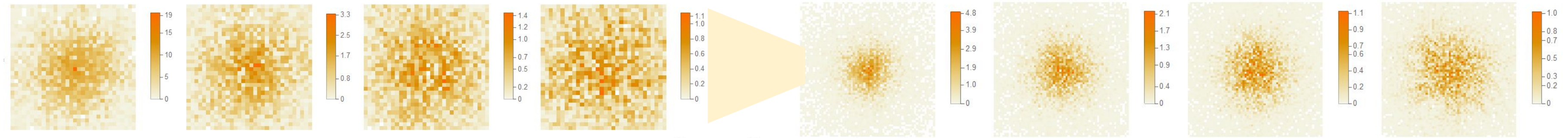
819200 shots
quantum simulation

$$\hat{q} = \langle \boldsymbol{p}_\perp^2 \rangle / L_\eta$$



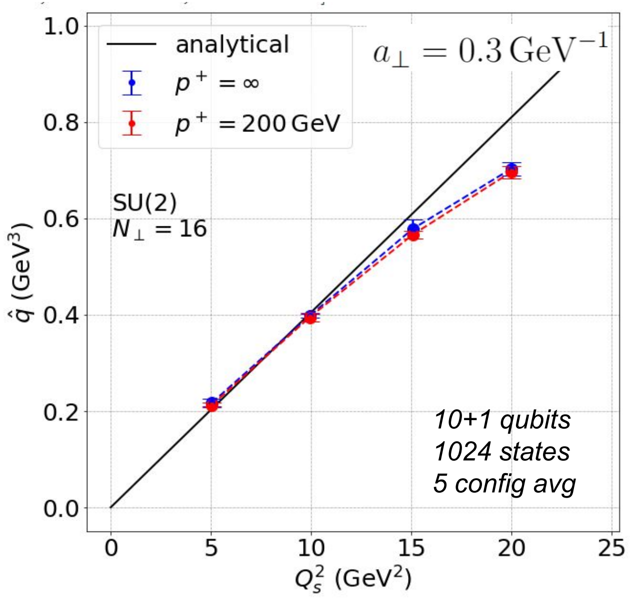

Removing cutoff, mom broadening increases

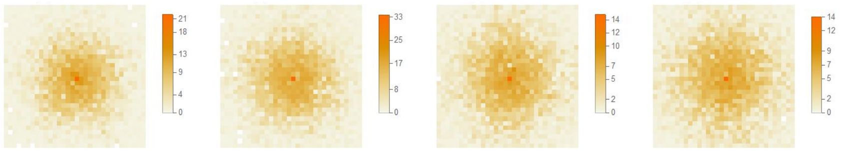


$$p_\perp = [-\pi/a_\perp, \pi/a_\perp]$$

# Numerical results, colorful SU(2) case

819200 shots
quantum simulation



See Li's talk (06/14)

Analytical

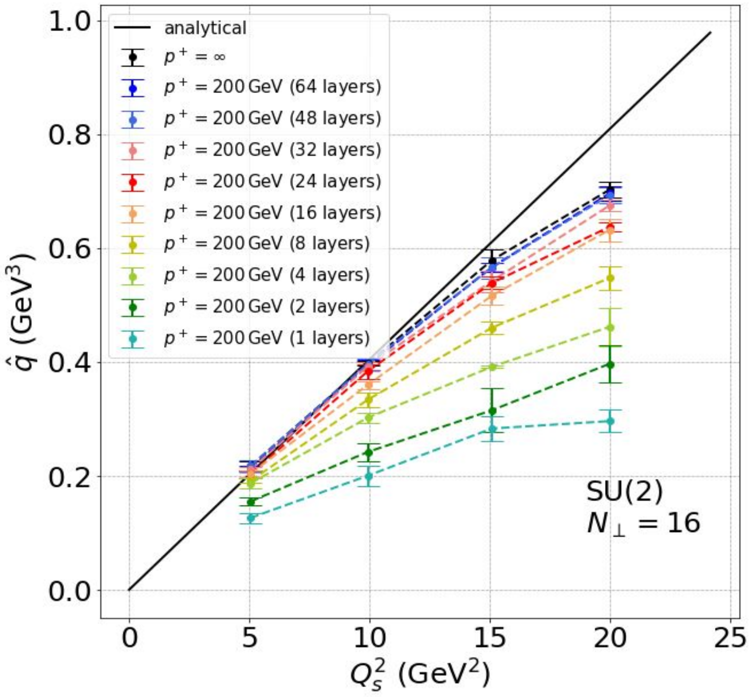
$$\hat{q} = \frac{g^4}{4\pi} C_F \tilde{\mu}^2 \left\{ \log\left(1 + \frac{\frac{\pi^2}{a_\perp^2}}{m_g^2}\right) - \frac{1}{1 + \frac{a_\perp^2 m_g^2}{\pi^2}} \right\}$$

identical curve for U(1) and SU(2)

Simulation

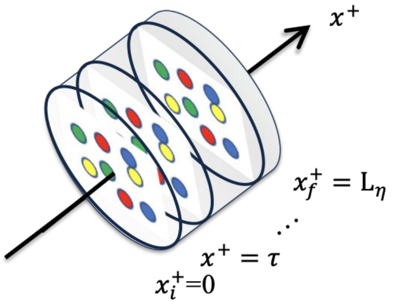
$$\hat{q} = \langle \boldsymbol{p}_\perp^2 \rangle / L_\eta$$

# Static field layers

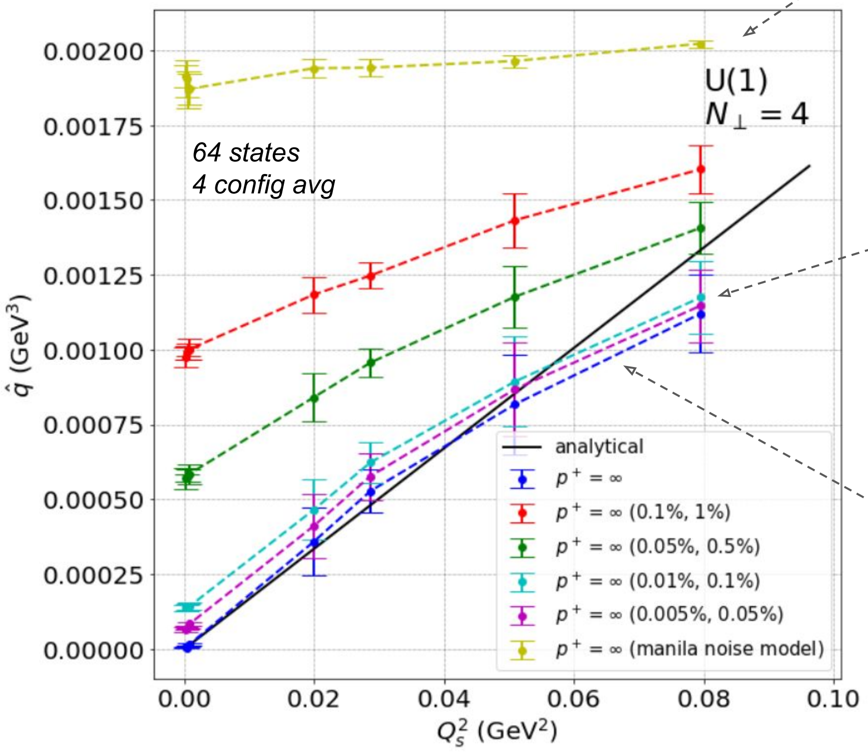



As layer increases, the correlation condition is approximately satisfied

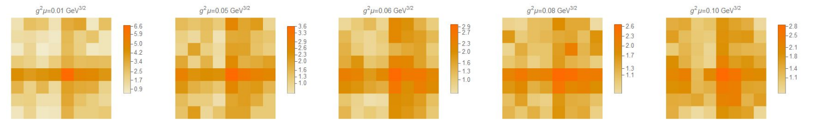
$$\langle\langle \rho_a(n^x, n^y, n_\tau)\rho_b(n'^x, n'^y, n'_\tau)\rangle\rangle = g^2\tilde{\mu}^2\delta_{ab}\frac{\delta_{n^x,n'^x}\delta_{n^y,n'^y}}{a_\perp^2}\frac{\delta_{n_\tau,n'_\tau}}{\tau}$$



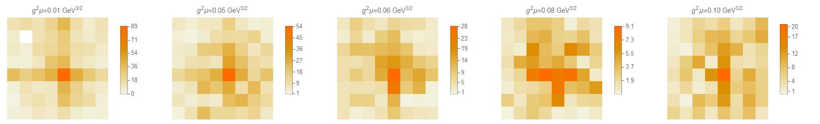

# In reality



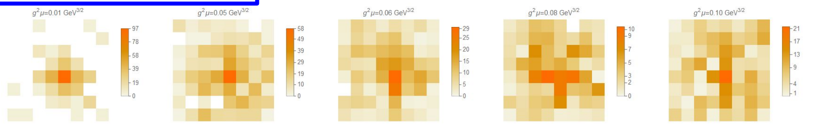

noise model using IBMQ manila



customized noise model with errors (0.01% for 1-qubit gates)



exact simulation



# Future plans

- Incorporate multiple Fock sectors, for example, to study gluon absorption and emission $|\psi\rangle = c_1|q\rangle + c_2|qg\rangle + c_3|qgg\rangle + \cdots$

  Li, Lappi, Zhao, 2107.02225 (2021)

- Simulation-friendly implementation of the potential fields on the quantum circuit, for example, polynomial-time discretization method, approximation is well-controlled

  Kassal, Jordan, Love, Mohseni, Aspuru-Guzik, 0801.2986 (2008)

- Investigate the effect of other medium and initial states, etc

  Barencoa, Ekerta, Suominenb, Torma, 9601018 (1996)

- Approximate QFT might help runtime on NISQ QCs

- Adding more colors, SU(3), to simulate a realistic QCD

$$\lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \equiv \tilde{\lambda}^1$$

*Thank you very much!*

Sainadh, 1309.2736 (2013)