Quantum Computation for Jets in Heavy Ion Collisions

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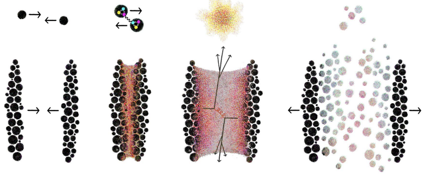
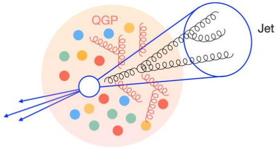
Sept 27, 2024

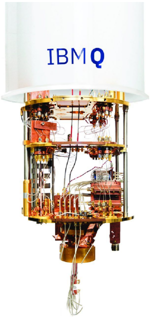


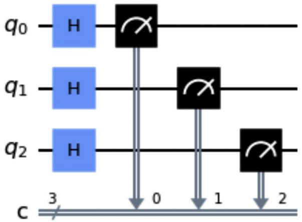


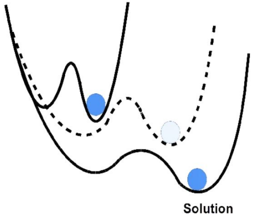
Experiments

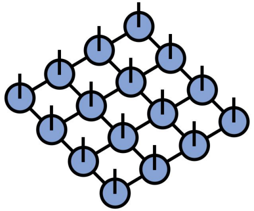
Theory
+
Phenomenology

New
Technology









1. Introduction to quantum computation

Quantum computing

Quantum computing (QC) is a rapidly-emerging technology that harnesses the laws of quantum mechanics to solve problems

Classical computing

- classical bit: 0, 1
- classical gates: logic gates
- deterministic

Quantum computing

- quantum bit (qubit): $|0\rangle = \begin{pmatrix}1\\0\end{pmatrix}, |1\rangle = \begin{pmatrix}0\\1\end{pmatrix}$
- quantum gates: **unitary operators**
- probabilistic (entanglement & superposition)

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$|\alpha|^2 + |\beta|^2 = 1$$

Quantum computing

Classical Hardware: laptop/supercomputer

Quantum Hardware: annealer/digital devices

FinisTerrae, CESGA

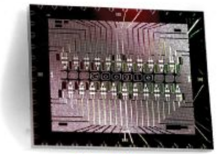
Qmio, CESGA

Key Difference:
multi-qubit states storing exponential phase information

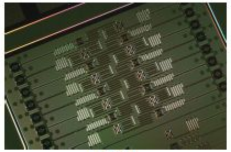
QC progress

We have really come a long way in past 40 years since Feynman! Feynman, “Simulating Physics with Computers” (1981)

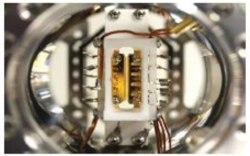
State-of-the-art: Noisy intermediate-scale quantum (NISQ) era = substantially imperfect and insufficient qubits. However, this can change fast!



Google

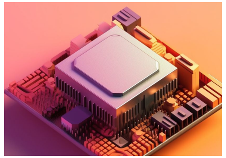


IBM



Rigetti

Intel



USTC

. . .

Qiskit

Cirq

XANADU

. . .

Optimist’s prediction:

Neven’s law = Double-exponential scaling

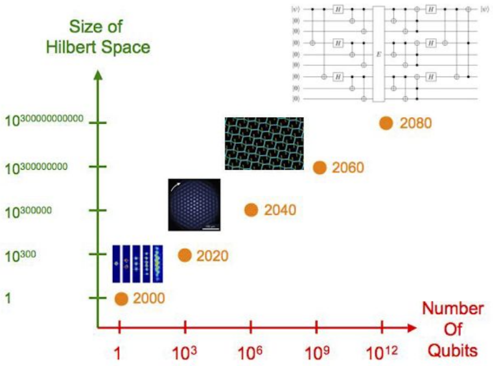
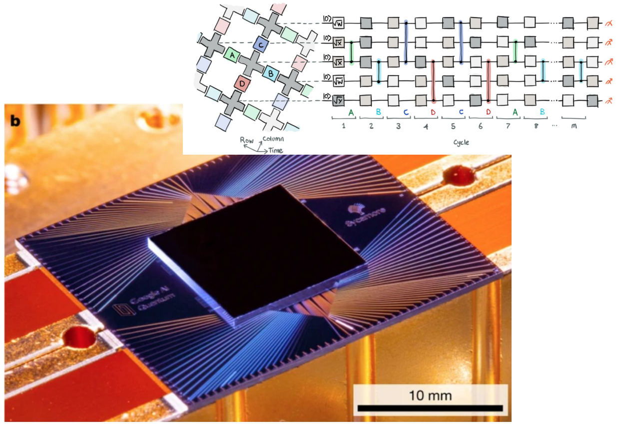


Chart: Quantum Pundit

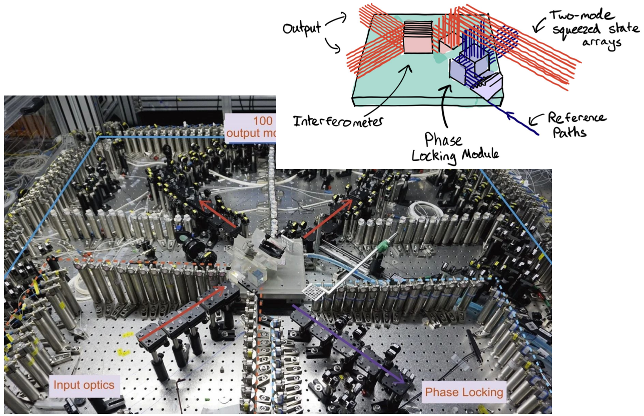
Quantum supremacy

Quantum supremacy = **anything** with a quantum device “cannot” be performed classically

Specific evidence for supremacy are found in sampling distributions!



random circuit 53 qubits, Google Quantum, 1910.11333



GBS 76 qubits, UTSC, 2012.01625
Schematic: Pennylane

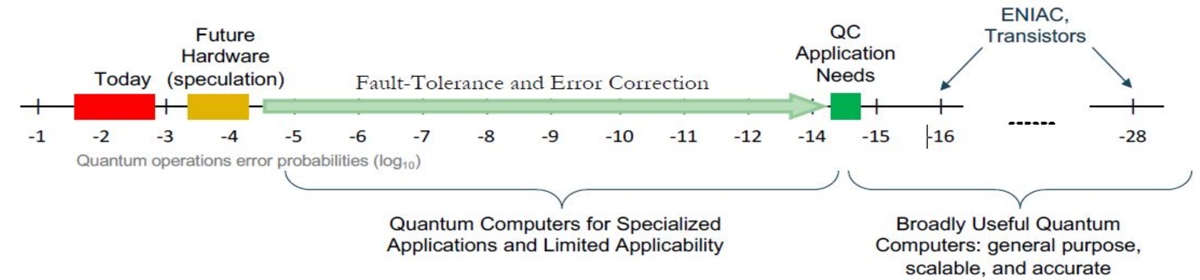
Quantum advantage = **sth useful** involving a quantum device “cannot” be performed classically

QC is Important

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

- Many problems are inherently quantum mechanical
- Complexity tamed with exponential book-keeping by nature in many-qubit state
- Quantum algorithms and complexity classes provide theoretical speedup

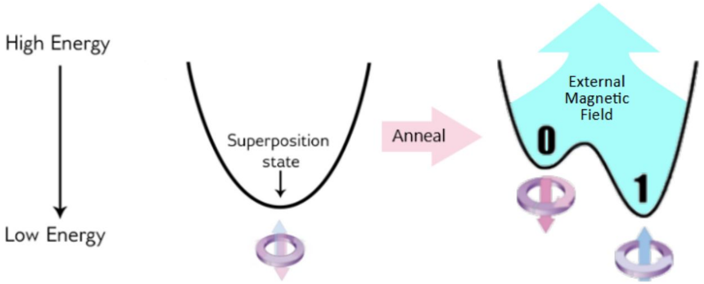
Simply a matter of time before QC revolutionizes the modern research (sth useful)



QC platforms

Analog quantum computers

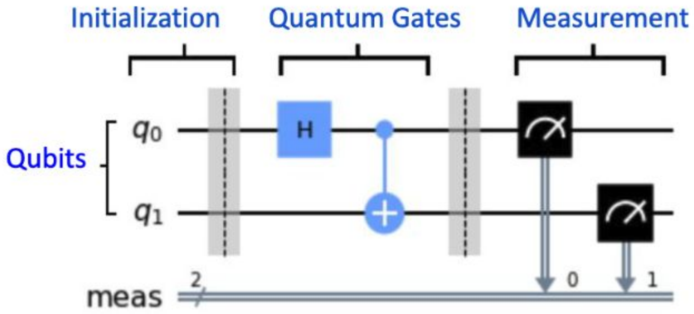
- Quantum annealing (Adiabatic QC)



- Successfully for optimization problems (~5000 qubits)
- Not an universal approach

Digital quantum computers

- Spin chain = qubits (lines) + unitary gates (operators)



- Ideal device for universal simulation
- Noisy, intermediate-scale (~100 qubits)

Schematic: D-Wave

Other useful platforms: Quantum Simulator, Tensor Networks, etc

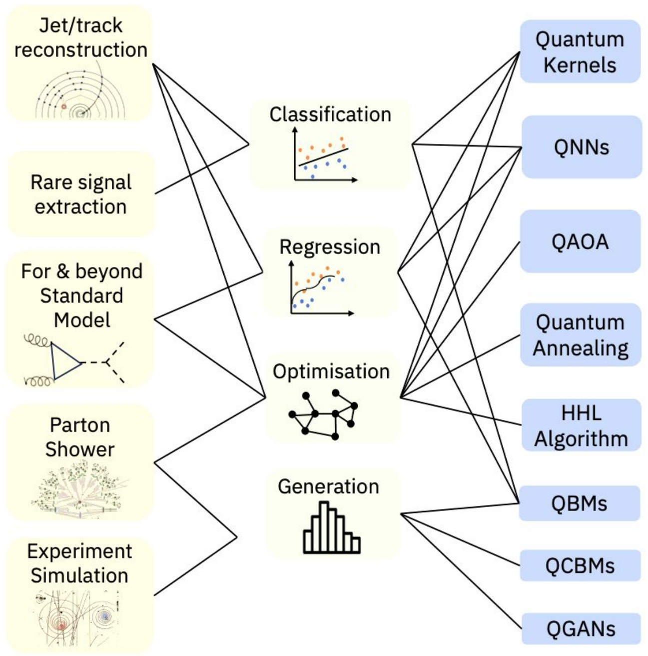
2. Quantum computing in heavy-ion collisions

[especially for jets]

QC for Experimental Physics

Several motivations:

- LHC Physics involves large data processing
- Quantum search algorithm provides theoretical speedup



See recent/comprehensive review:

Delgado et al 2203.08805
Di Meglio et al, 2307.03236

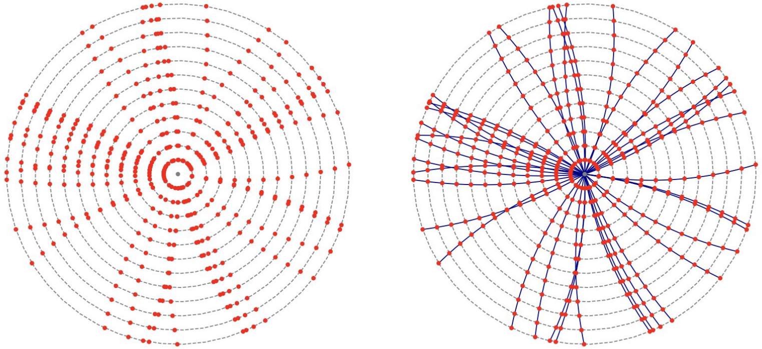
Tracking particles

Track reconstruction with Quadratic Unconstrained Binary Optimization (QUBO) using quantum annealing to High Luminosity LHC

Zlokapa1 et al, 1908.04475

Quantum speedup to recover charge particle trajectories using quantum search algorithm

Magano et al, 2104.11583



(a) Input. (b) Output.

Q-Search principle:
Grover, 9605043 (1996)
Brassard et al, 0005055 (2000)

Jet clustering

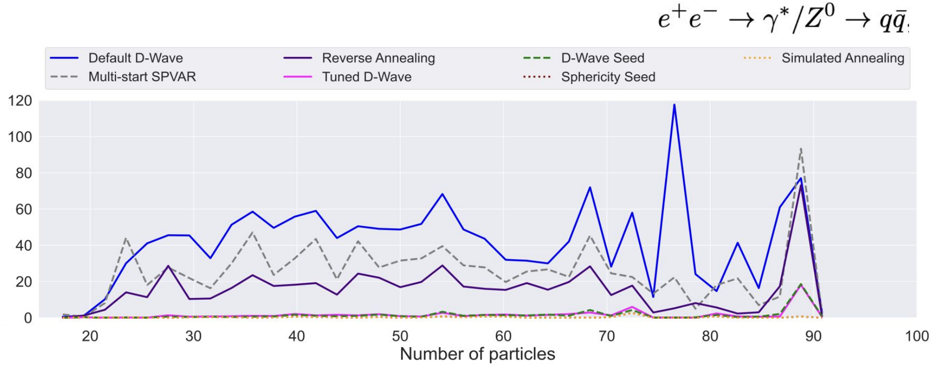
Digital quantum algorithm to tackle event reconstruction and jet clustering

Jet algorithm for thrust via

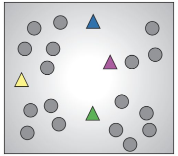
Wei et al, 1908.08949; Delgado, Thaler, 2205.02814

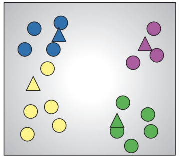
- QUBO formulation (quantum annealing)
- Grover search (digital)

$$T(\hat{n}) = \frac{\sum_{i=1}^{N} |\hat{n} \cdot \vec{p_i}|}{\sum_{i=1}^{N} |\vec{p_i}|}$$



Quantum k-means Pires et al, 2101.05618





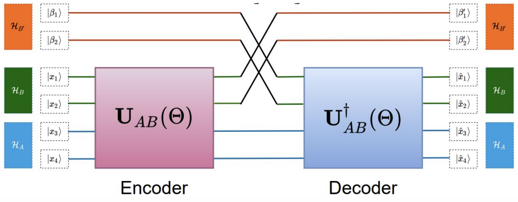
Quantum machine learning

Extending classical ML with quantum data encoding

Anomaly detection with parameterized circuits (PQC) and autoencoder

Alvi, Bauer, Nachman, 2206.08391
Ngairangbam, Spannowsky, Takeuchi, 2112.04958

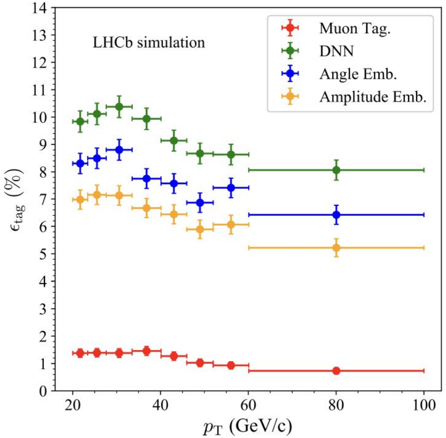
$pp \to H \to t\bar{t}$



Quantum Generative Adversarial Networks Chang et al, 2101.11132

B-jet charge tagging in LHCb simulation Gianelle et al, 2202.13943

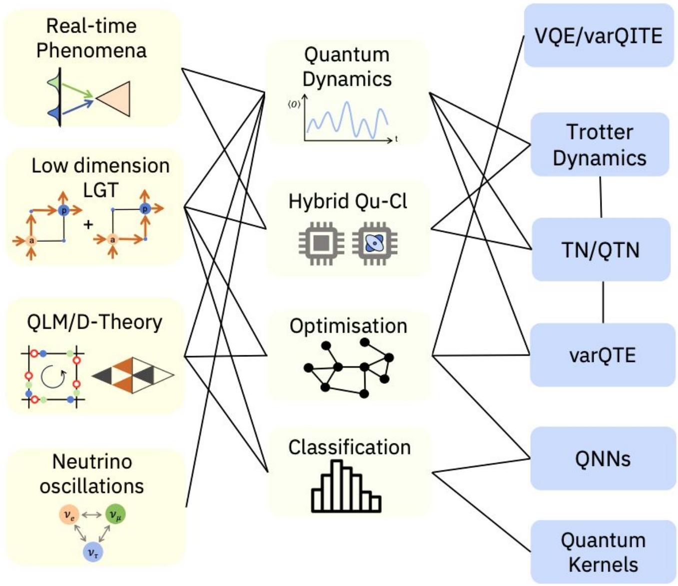
$$\epsilon_{\text{tag}} = \epsilon_{\text{eff}}(2a-1)^2$$



QC for Theories & Phenomenologies

Several motivations:

- Classical simulation encounters inherent problems and high problem complexity
- Quantum simulation algorithm provides an ultimate path to simulate quantum field theory



See recent/comprehensive review:

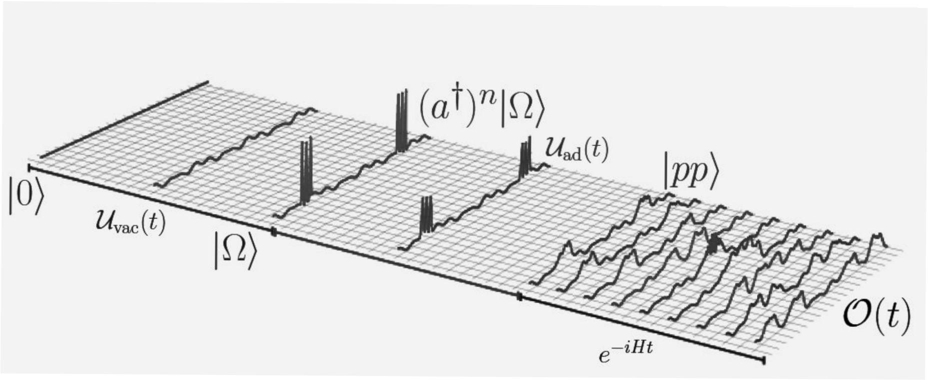
Bauer et al, 2204.03381
Di Meglio et al, 2307.03236

Prototypical task

Quantum simulation of quantum field theory = perform "**ideal experiments**" on quantum computer

Jordan, Lee, & Preskill,
1111.3633, 1401.7115, 1703.00454

- Prepare initial state in quantum computer
- Evolve state forward in time using Hamiltonian, for some specified time interval
- Measure observables by simulating measurement performed in idealized lab

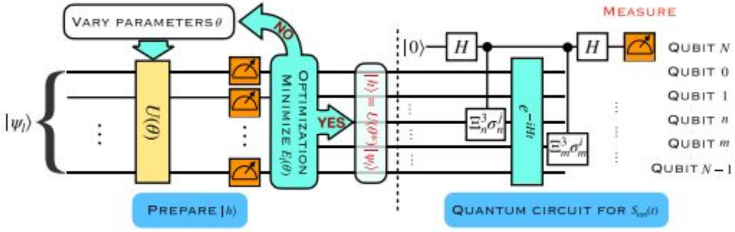


Extracting partonic functions

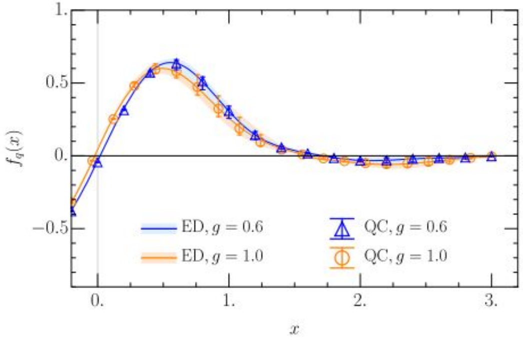
Quark parton distribution function (PDF) evaluated from flavored hadronic states

Lamm et al, 1908.10439
Mueller, Tarasov, Venugopalan, 1908.07051
Li et al, 2106.03865

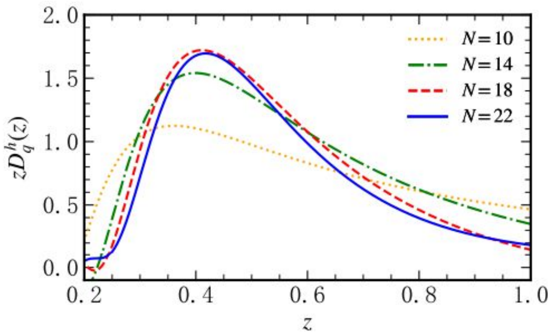
$$f_{q/h}(x) = \int \frac{dz}{4\pi} e^{-ixM_h z} \langle h|e^{iHt}\bar{\psi}(0,-z)e^{-iHt}\gamma^+\psi(0,0)|h\rangle$$



Hadron state preparation using Variational approaches (VQE)
Other methods include Adiabatic and Tensor Networks



Parton Fragmentation Functions



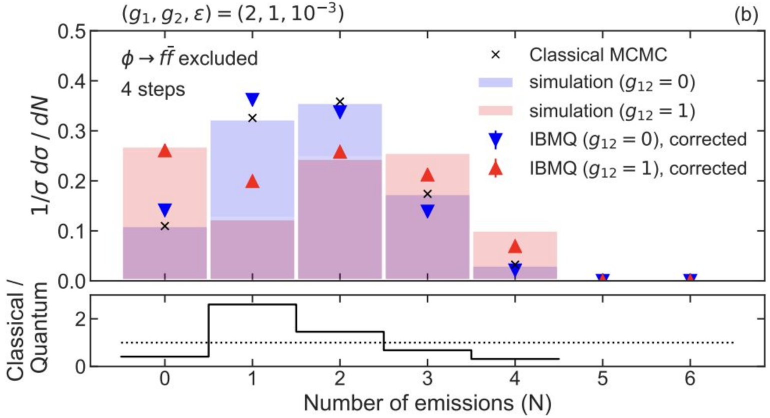
Li et al, 2406.05683

Simulating parton showers

Quantum algorithm for HEP simulation of parton shower to include quantum interference

Nachman et al, 1904.03196

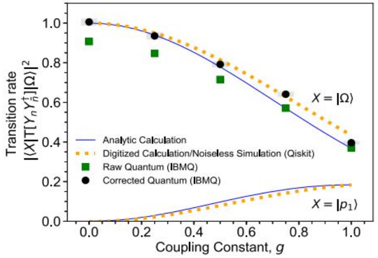
$$\mathcal{L} = \bar{f}_1(i\partial\!\!\!/ + m_1)f_1 + \bar{f}_2(i\partial\!\!\!/ + m_2)f_2 + (\partial_\mu \phi)^2 + g_1 \bar{f}_1 f_1 \phi + g_2 \bar{f}_2 f_2 \phi + g_{12}\left[\bar{f}_1 f_2 + \bar{f}_2 f_1\right]\phi$$



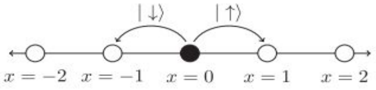
Simulating soft functions from EFT

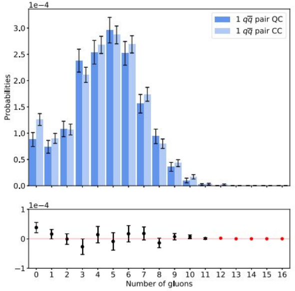
Bauer et al, 2102.05044

$$\sigma = H \otimes J_1 \otimes \dots \otimes J_n \otimes S.$$



Quantum walk approach to simulate parton showers

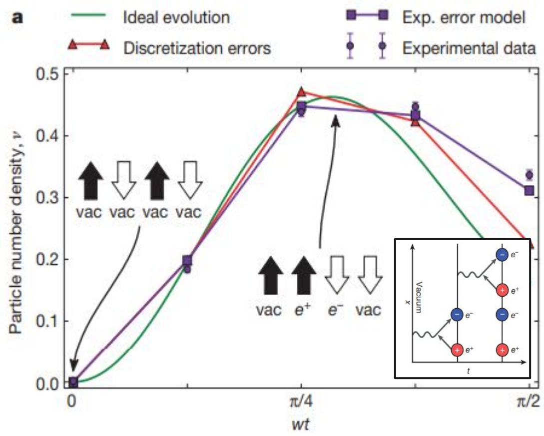




Williams et al, 2109.13975, 2207.10694

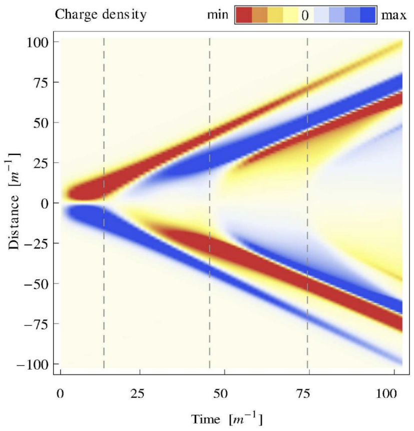
Pair production and more

Pair-production from vacuum

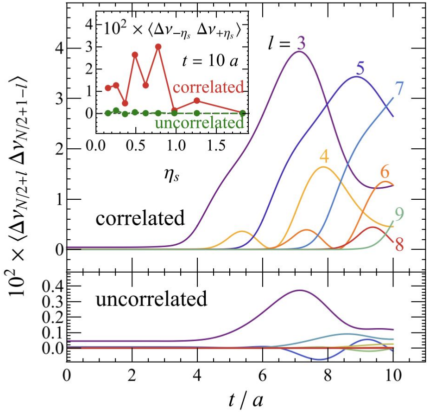


Martinez et al, 1605.04570

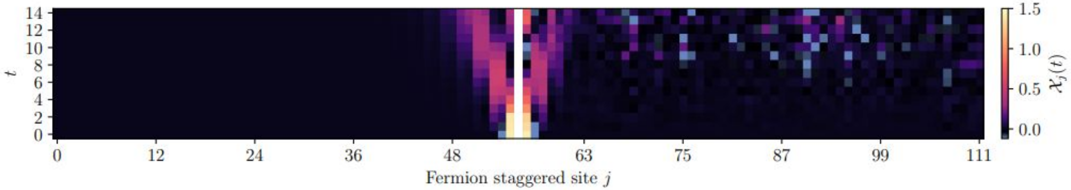
QCD string breaking and external source modification



Hebenstreit, Berges, Gelfand, 1307.4619
Kasper et al, 1506.01238



Florio et al, 2301.11991



Hadron state preparation and evolution on 112 qubits

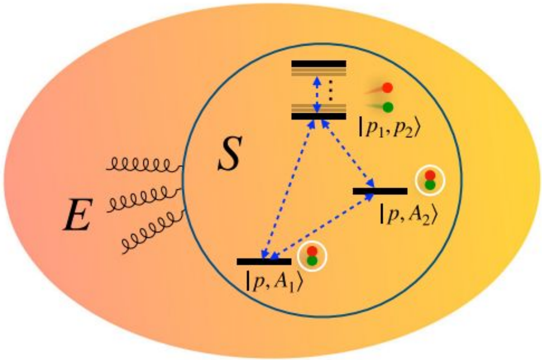
Farrell et al, 2401.08044

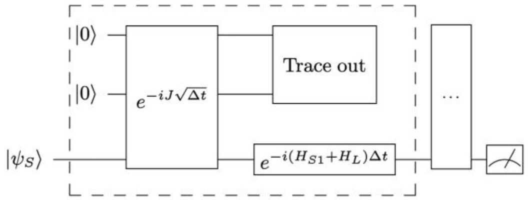
Non-equilibrium dynamics at finite temperature

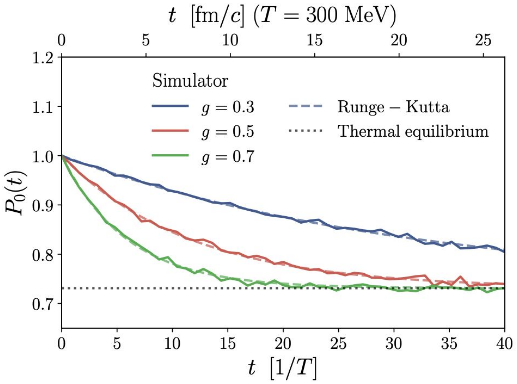
Simulating hard probes in QGP as open system via Lindblad equation — De Jong et al, 2010.03571, 2106.08394

Open quantum system formulation for quarkonia, jets, etc — Blaizot & Escobedo, 1711.10812, 1803.07996

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_S(t) = -i\left[H_{S1}(t) + H_L, \rho_S(t)\right] + \sum_{j=1}^{m}\left(L_j\rho_S(t)L_j^\dagger - \frac{1}{2}\{L_j^\dagger L_j, \rho_S(t)\}\right)$$







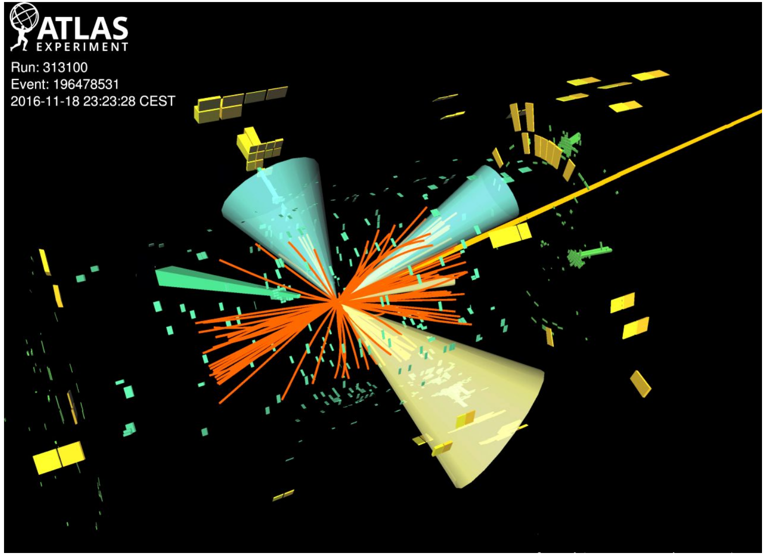
Cleve & Wang, 1612.09512

Alternative (equivalent) ways?

3. Quantum simulation of jets in heavy-ion collisions

[using Hamiltonian formalism]

Quantum jet simulation: Big picture



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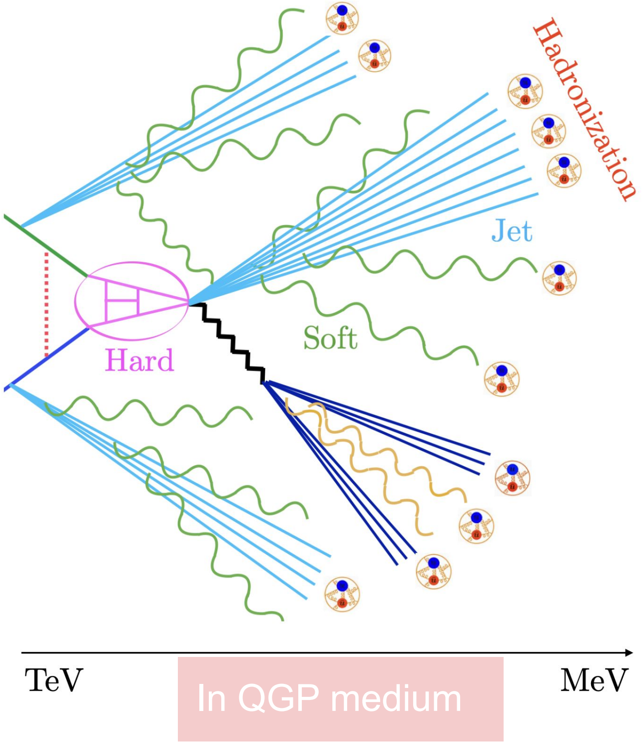
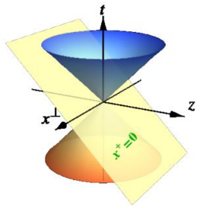


Quantum jet simulation: Method

Light-front QCD Hamiltonian + Classical background field

- First-principle method formulated in the front form
- Hamiltonian is used to study hadron structure and time evolution alike



front form

$x^+ \triangleq x^0 + x^3$

Natural to extend from classical simulation to quantum simulation

Classical simulation

Electron in laser field Zhao et al, 1303.3273

Ultrarelativistic quark-nucleus scattering Li et al, 2002.09757

Scattering and gluon emission in a color field Li, Lappi, Zhao, 2107.02225

Jet in Glasma field Li et al, 2305.12490

… See Lamas's talk (Wed 12:10)

Quantum simulation

Nuclear inelastic scattering Du et al, 2006.01369

Strategy to Jet quenching parameter Barata, Salgado, 2104.04661

Medium-induced QCD jet Barata et al, 2208.06750, 2307.01792; Yao, 2205.07902; Wu et al, 2404.00819

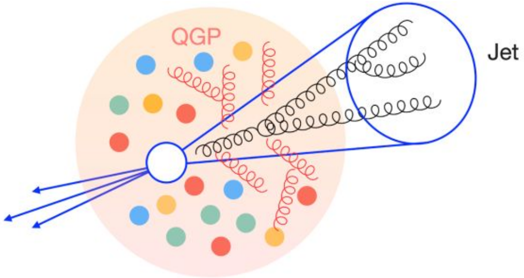
…

QCD Lagrangian

We start with the QCD lagrangian, with an external field

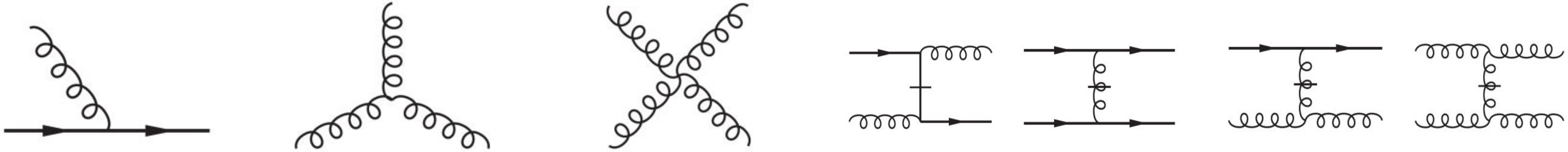
$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu}{}_a F^a_{\mu\nu} + \overline{\Psi}(i\gamma^\mu D_\mu - m_q)\Psi$$

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

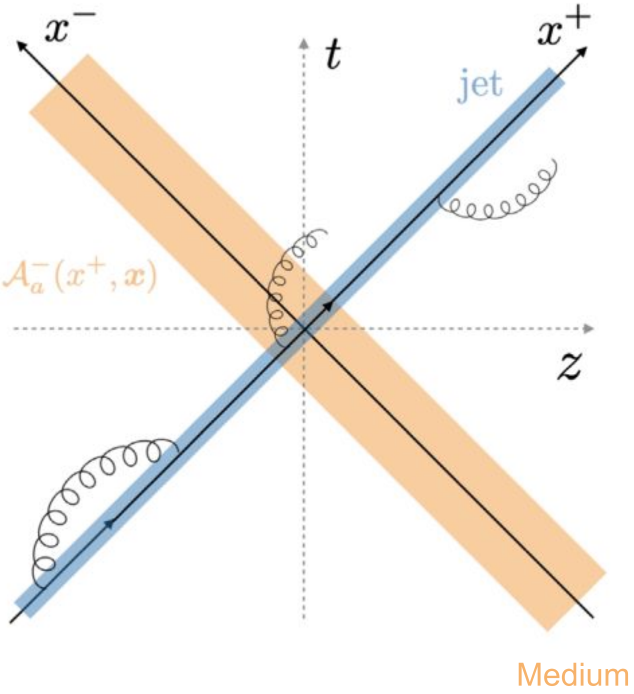


The light-front Hamiltonian is obtained by the canonical light-front quantization via the standard Legendre transformation,

For review: Brodsky, Pauli, Pinsky, 9705477



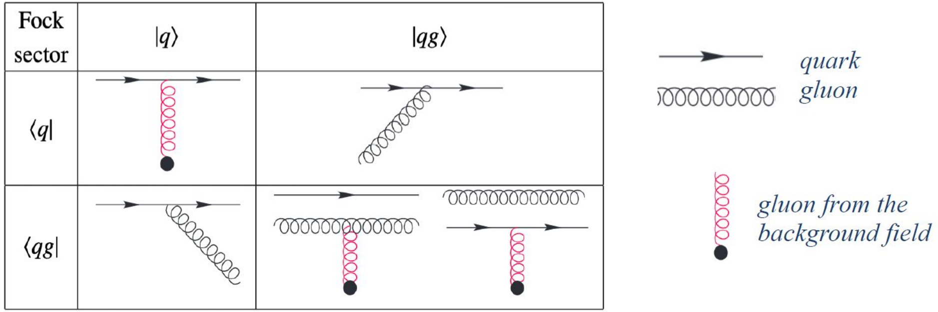
Physical setup



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

For example, light-front Hamiltonian in $|q\rangle + |qg\rangle$ Fock space

$$P^-(x^+) = P^-_{\mathrm{KE}} + V(x^+) = P^-_{\mathrm{KE}} + \left\{V_{qg} + V_{\mathcal{A}}(x^+)\right\}$$



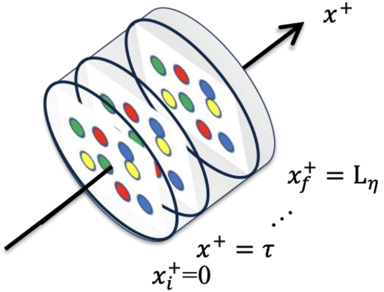
Medium and Evolution

Classical stochastic background field (to reduce problem complexity)

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

$$(m_g^2 - \nabla_\perp^2)\mathcal{A}_a^-(x^+,\boldsymbol{x}) = \rho_a(x^+,\boldsymbol{x}) \qquad Q_s^2 \equiv \frac{C_F g^4\mu^2 L_\eta}{2\pi}$$

saturation scales



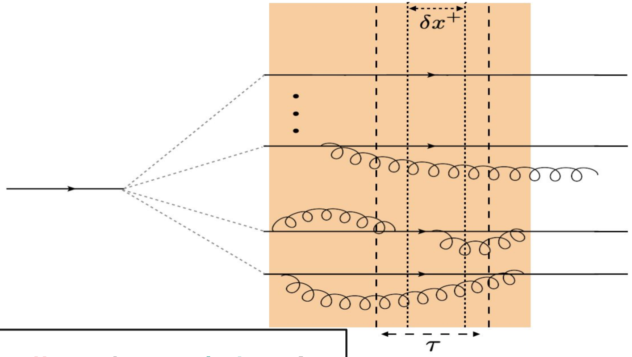
McLerran and Venugopalan, 9309289 (1993)

Jet probe evolution, decomposed as sequence of unitary operators

$$|\psi_{L_\eta}\rangle = U(L_\eta;0)\,|\psi_0\rangle \equiv \mathcal{T}_+ e^{-i\int_0^{L_\eta} \mathrm{d}x^+\, P^-(x^+)}\,|\psi_0\rangle$$

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

non-perturbative



Universal framework to simulate (3+1)-d QCD jet probe evolution in medium in real-time!

Qubit encoding of basis state

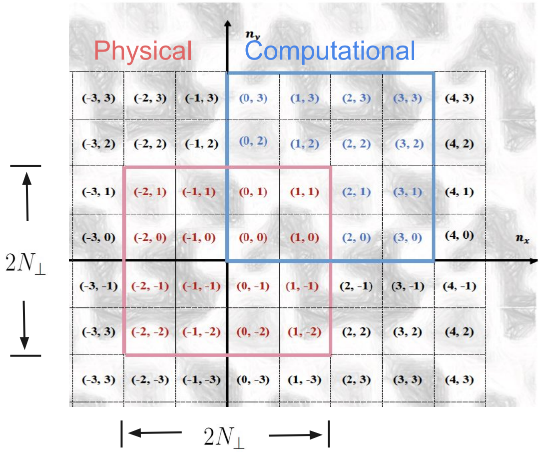
General QCD quantum state in single-particle basis: $\beta_l = \{p_l^+, p_l^x, p_l^y, c_l, \lambda_l\}, \text{ with } l = q, \bar{q}, g$

Qubit encoding on quantum registers with discretization

- Transverse momentum: $2N_\perp \times 2N_\perp$
- Longitudinal momentum: $\lceil K \rceil$

$$|\psi\rangle = |\zeta\rangle \otimes \underbrace{\Big(|g_x\rangle\, |g_y\rangle\, |c_g\rangle \Big)}_{|g\rangle} \otimes \underbrace{\Big(|q_x\rangle\, |q_y\rangle\, |c_q\rangle \Big)}_{|q\rangle}$$

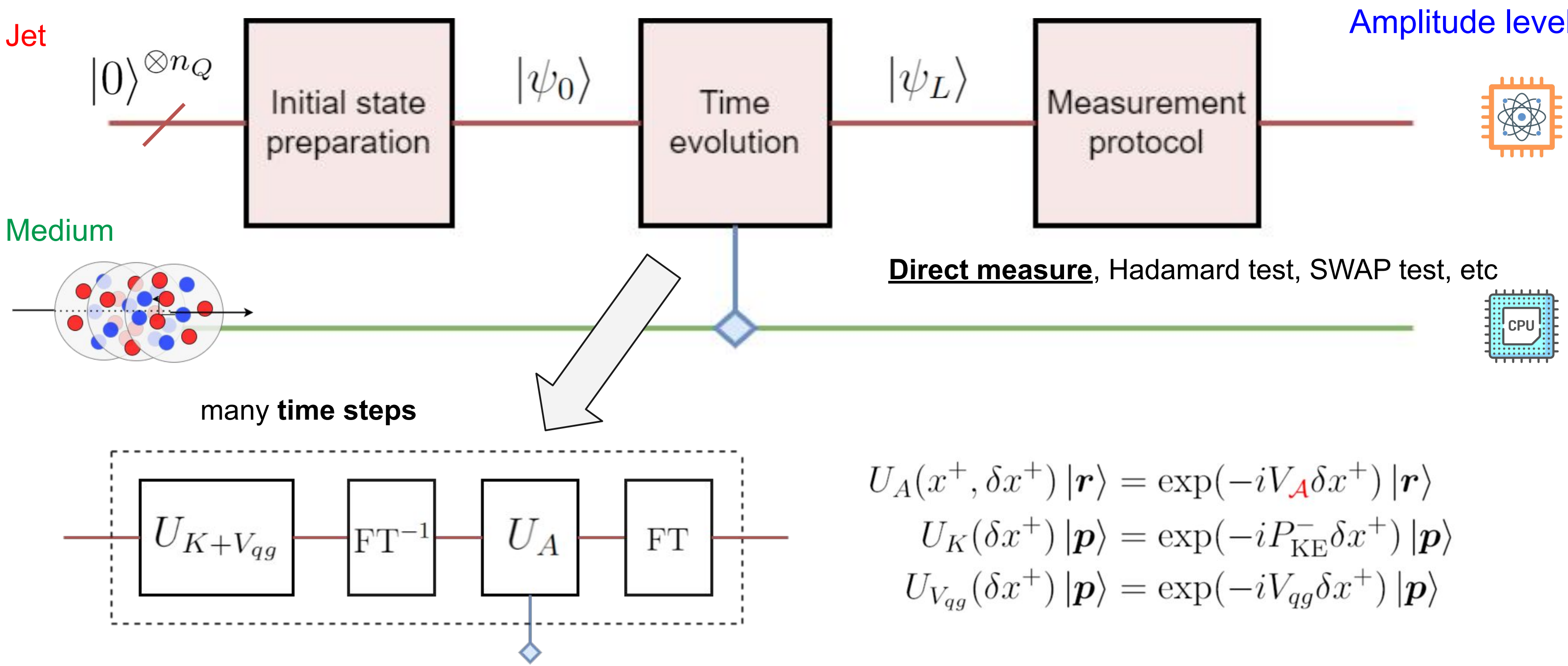
$$N_{\text{tot}} \sim \lceil K \rceil N_\perp^4 \rightarrow n_Q \sim 4 \log N_\perp + \log \lceil K \rceil$$



Logarithmic with momentum, Linear in Fock particles

Quantum simulation algorithm

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



Direct measure, Hadamard test, SWAP test, etc

$$U_A(x^+, \delta x^+)\,|\boldsymbol{r}\rangle = \exp(-iV_{\mathcal{A}}\delta x^+)\,|\boldsymbol{r}\rangle$$
$$U_K(\delta x^+)\,|\boldsymbol{p}\rangle = \exp(-iP^-_{\mathrm{KE}}\delta x^+)\,|\boldsymbol{p}\rangle$$
$$U_{V_{qg}}(\delta x^+)\,|\boldsymbol{p}\rangle = \exp(-iV_{qg}\delta x^+)\,|\boldsymbol{p}\rangle$$

FT allows efficient/sparse simulation in the respective basis

Sparse H => fewer pauli strings => less quantum gates

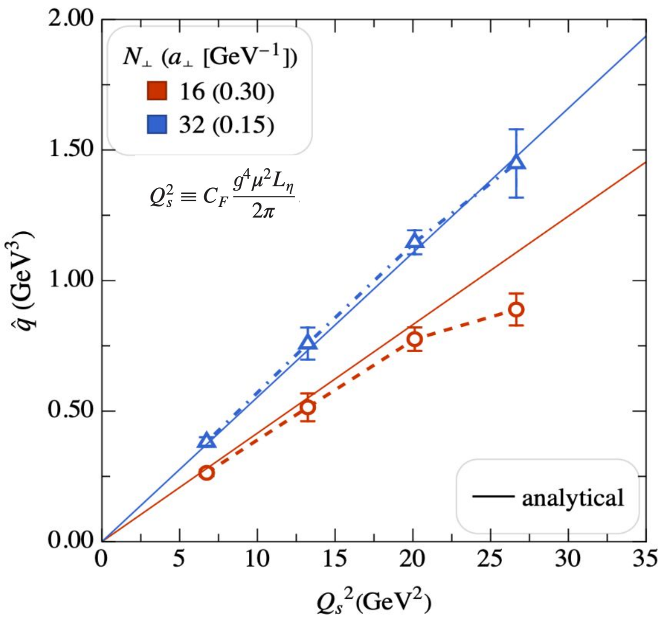
Extracting quenching parameter

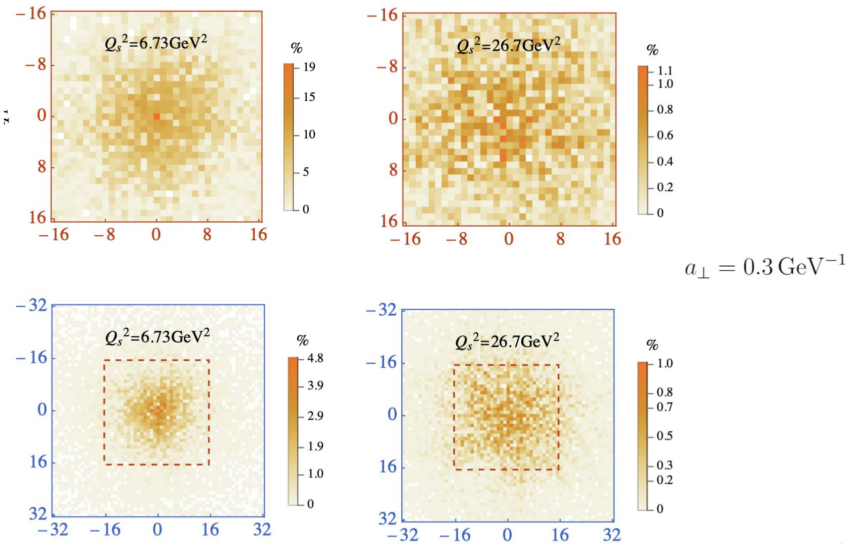
First quenching parameter calculation on QC

Barata, Du, Li, WQ, Salgado, 2208.06750

Jet quenching parameter: $\hat{q} = \frac{\Delta \langle p_\perp^2(x^+) \rangle}{\Delta x^+} = \langle \boldsymbol{p}_\perp^2 \rangle / L_\eta$

Eikonal analytical: $\sim Q_s^2 / L_\eta$





$a_\perp = 0.3\,\mathrm{GeV}^{-1}$

$a_\perp = 0.15\,\mathrm{GeV}^{-1}$

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

$(p_x, p_y) = (0, 0)$ $\quad L_\eta = 50\,\mathrm{GeV}^{-1} \approx 10\,\mathrm{fm}$

Similarly done for momentum broadening at finite p+

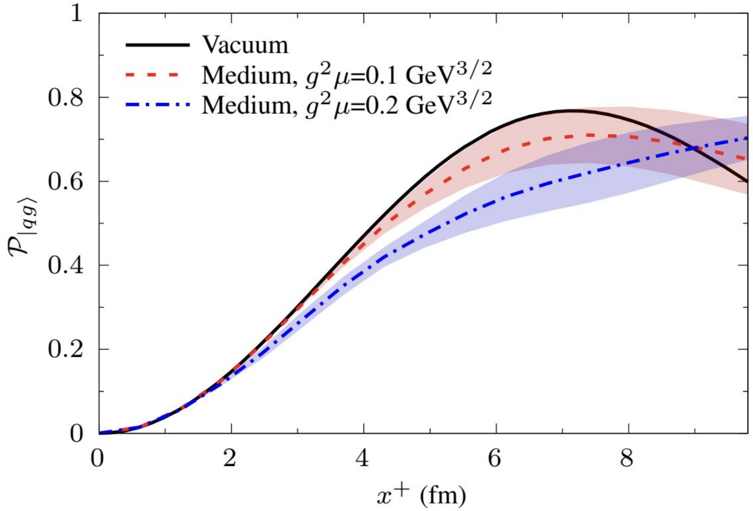
simulator, 10-12 qubits

Qiskit

Gluon production and entropy growth

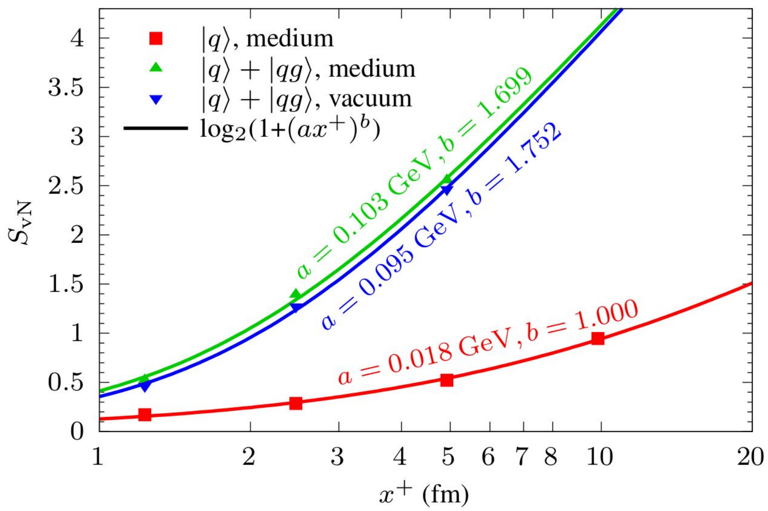
Barata, Du, Li, WQ, Salgado, 2307.01792

Gluon production in mediums
(error from stochastic medium)



Entropy expansion linear in Fock |q> and power-law in Fock |q> + |qg> with radiation

See Barata's talk (Tue 11:00)



$$S_{\rm vN}(x^+) = -{\rm Tr}[\rho(x^+)\log\rho(x^+)]$$

simulator, 9 qubits

Towards simulating many more particles

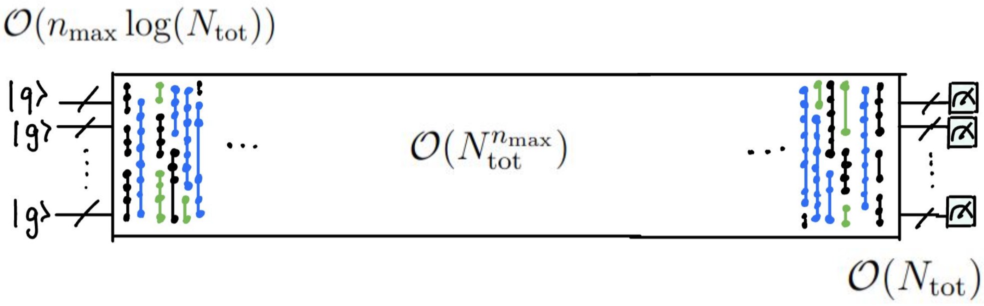
Go far beyond classical computations. But current setup is still expensive with increasing particle.

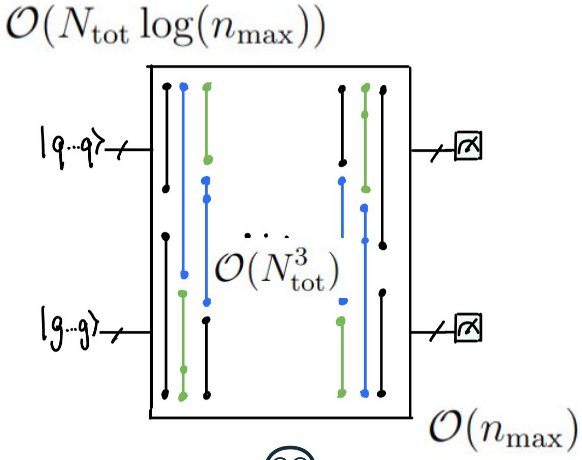
One potential solution: **Direct encoding** on the particle operators

Aspuru-Guzik et al, 0604193

- No need to evaluate Hamiltonian matrix to Pauli operators
- Shallow & sparse quantum circuits
- Particle exchange symmetry automatically satisfied

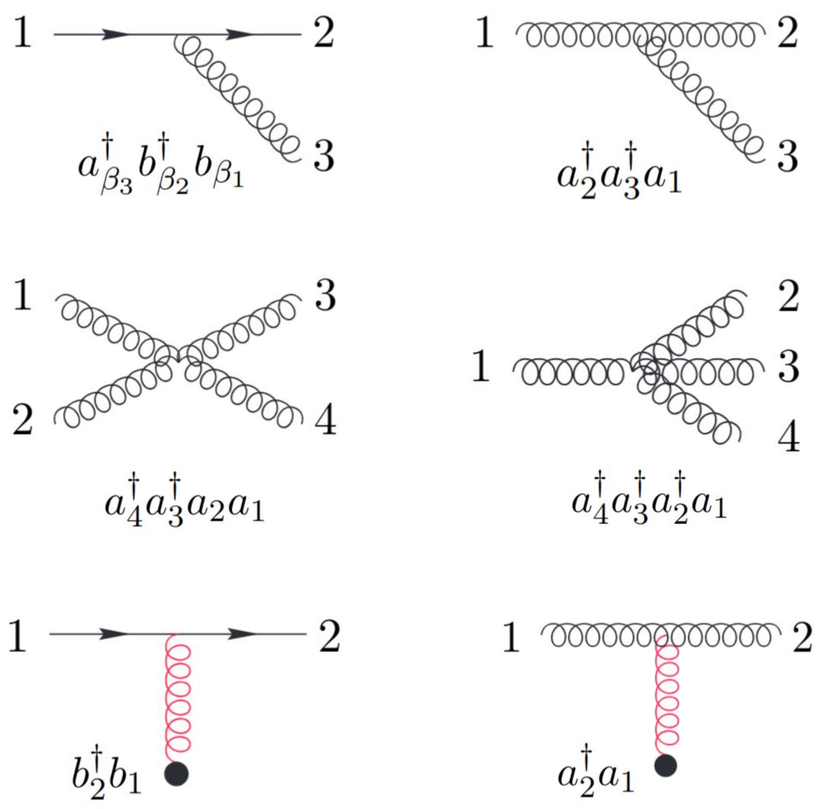
total modes $N_{\rm tot}$
gluon occupancy $n_{\rm max}$





Polynomial scaling

Qubit encoding of quantized operators



- QCD vertices are encoded into bosonic (a) and fermonic (b) creation/annihilation operators
- Jordan-Wigner encoding for fermions
  Standard binary encoding for bosons

Sawaya et al, 1909.12847

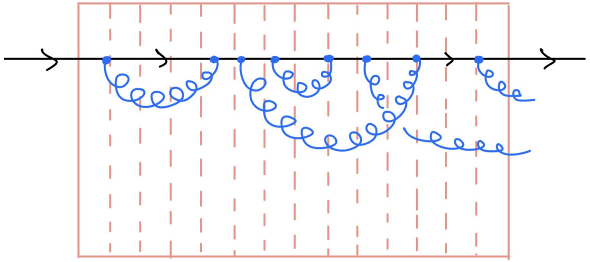
- Vertex coefficients are instantly computed

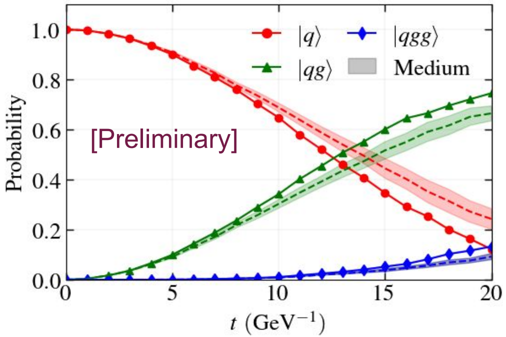
$$a^\dagger_4 a^\dagger_3 a^\dagger_2 a_1 \qquad g^2 \frac{1}{\sqrt{p_1^+ p_2^+ p_3^+ p_4^+ \Omega}} \delta^3_{p_1-p_2-p_3-p_4}$$

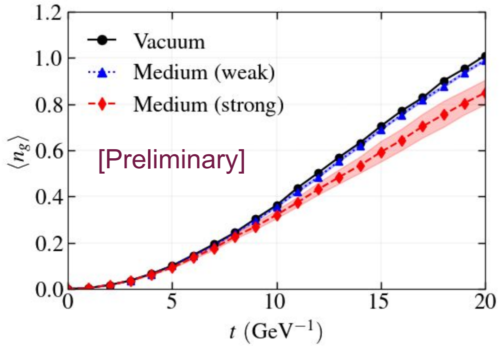
$$f^{aa_1a_2} f^{aa_3a_4} \delta_{\lambda_1,\lambda_3} \delta_{\lambda_2,-\lambda_4}$$

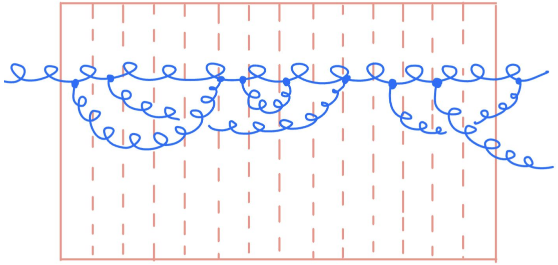
Quantum simulation of quark/gluon jet

Kreshchuk, Li, WQ, Salgado, to appear

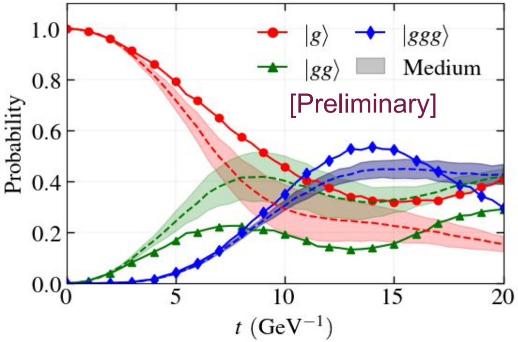


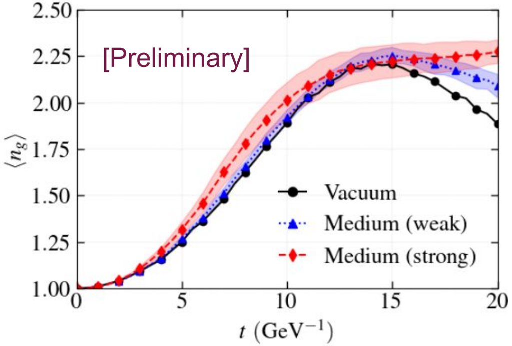






Medium

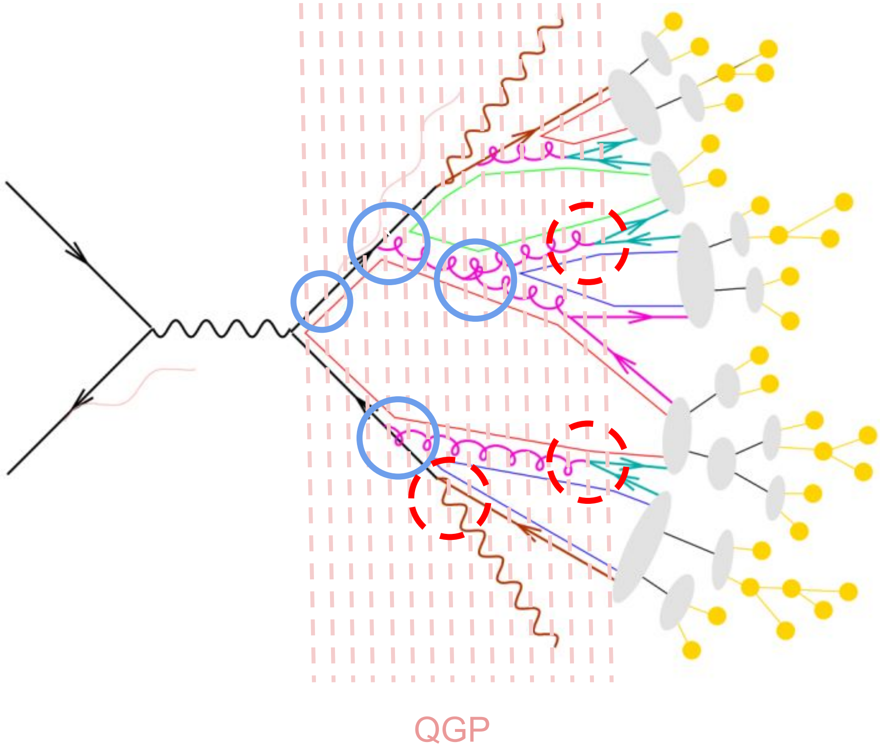




Qiskit simulator, 48/36 qubits

Quantum simulation of jet in HIC

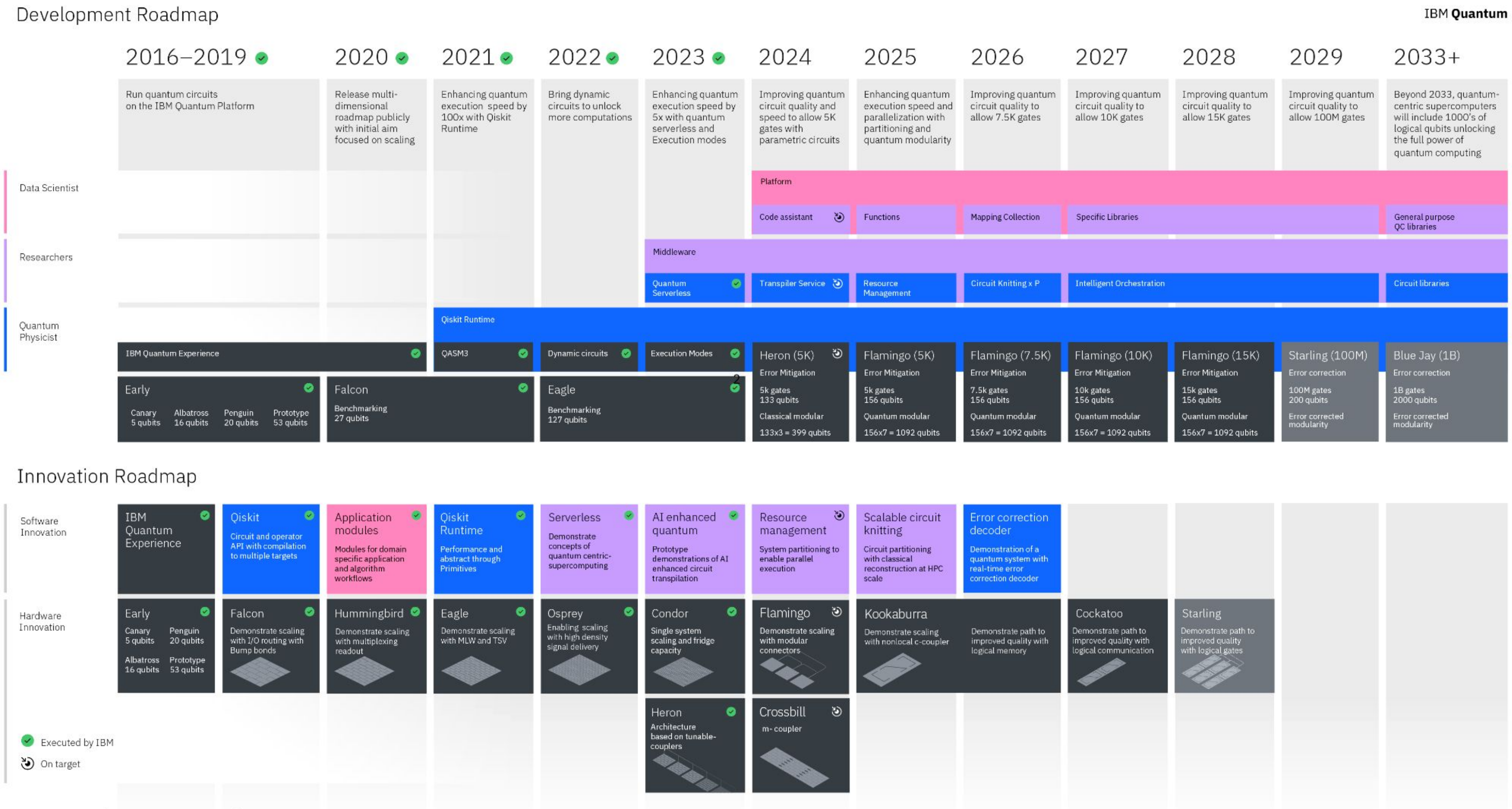
Full description requires much more but we will get there, together with hardware development in QC



Theoretical lab to simulate jet physics!

- Medium property
- Jet as fully quantum object
- Extract useful observable

Quantum technology is growing at fast pace



Fault-tolerant quantum simulation

We might have an ideal (useful) quantum computer in the next decade!

Most applications are Near-term such as VQE, it is also mindful to develop fault-tolerant quantum algorithms

- Block Encoding (quantum signal value transformation, etc)

Childs, Wiebe, 1202.5822
Gilyen et al, 1806.01838
App: Hardy et al, 2407.13819, …

- Quantum Eigenvalue Transformation for Unitary matrices

Dong, Lin, Tong, 2204.05955
App: Kane, Gomes, Kreshchuk, 2310.13757, …

…

Key insight: Quantum simulation needs not resemble physics process.

Use QC like a calculator!

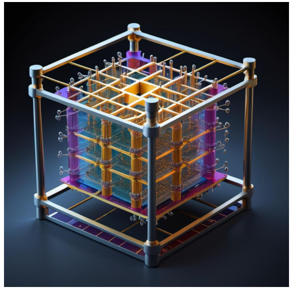
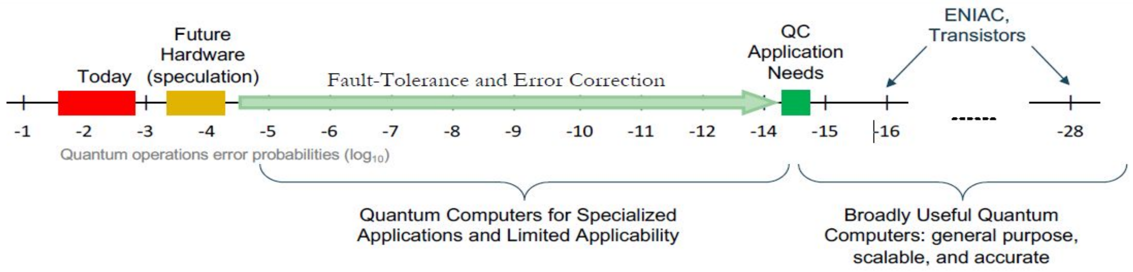


Image: ChatGPT

Lessons

- Quantum computing technology is available today and developing fast.
- Lots of quantum computing applications in experiment and theory for HIC, especially for jets.
- Quantum simulation of jets is promising using a universal & scalable Hamiltonian framework.
- We may be in reach of fault-tolerant quantum computing sooner than we expect.

Thanks for your attention!



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