

中国物理学会高能物理分会第十二届
全国会员代表大会暨学术年会



Institute of Particle Physics
粒子物理研究所

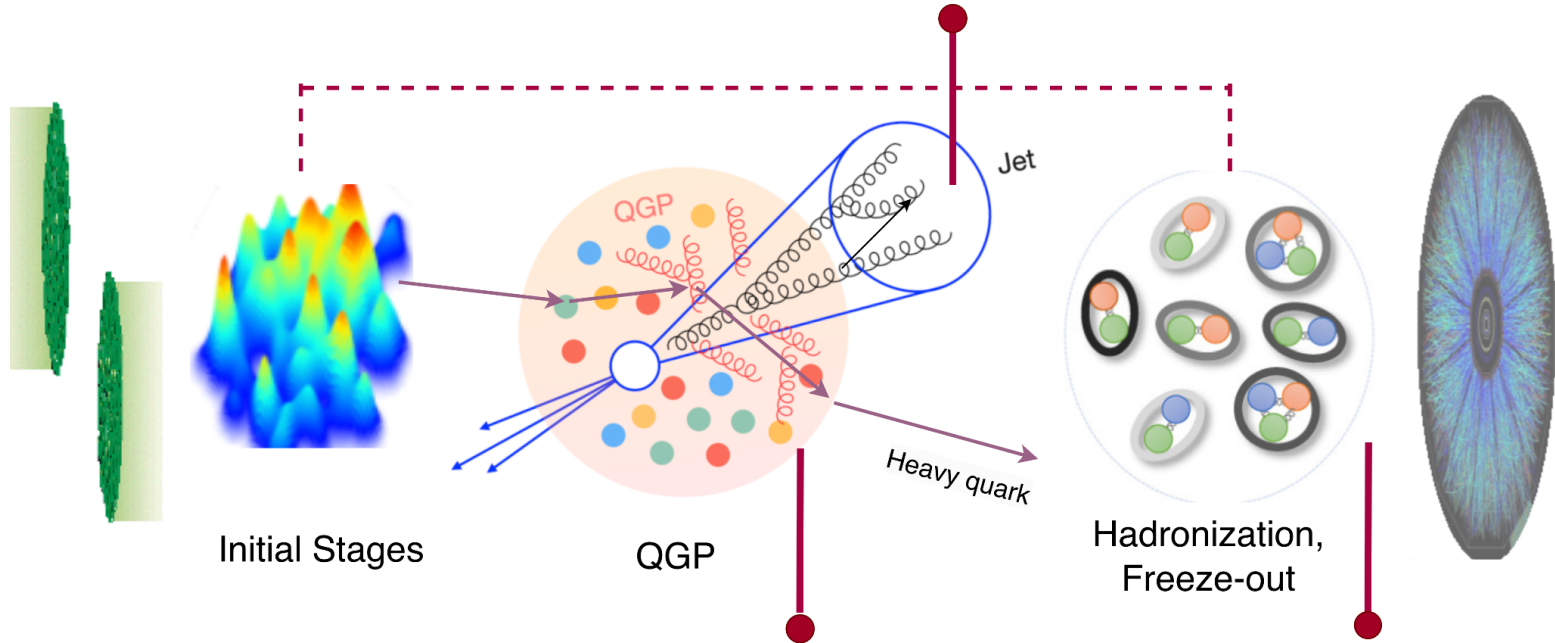


A first step towards -

Quantum Simulation of Hadronization in Relativistic Heavy-Ion Collisions

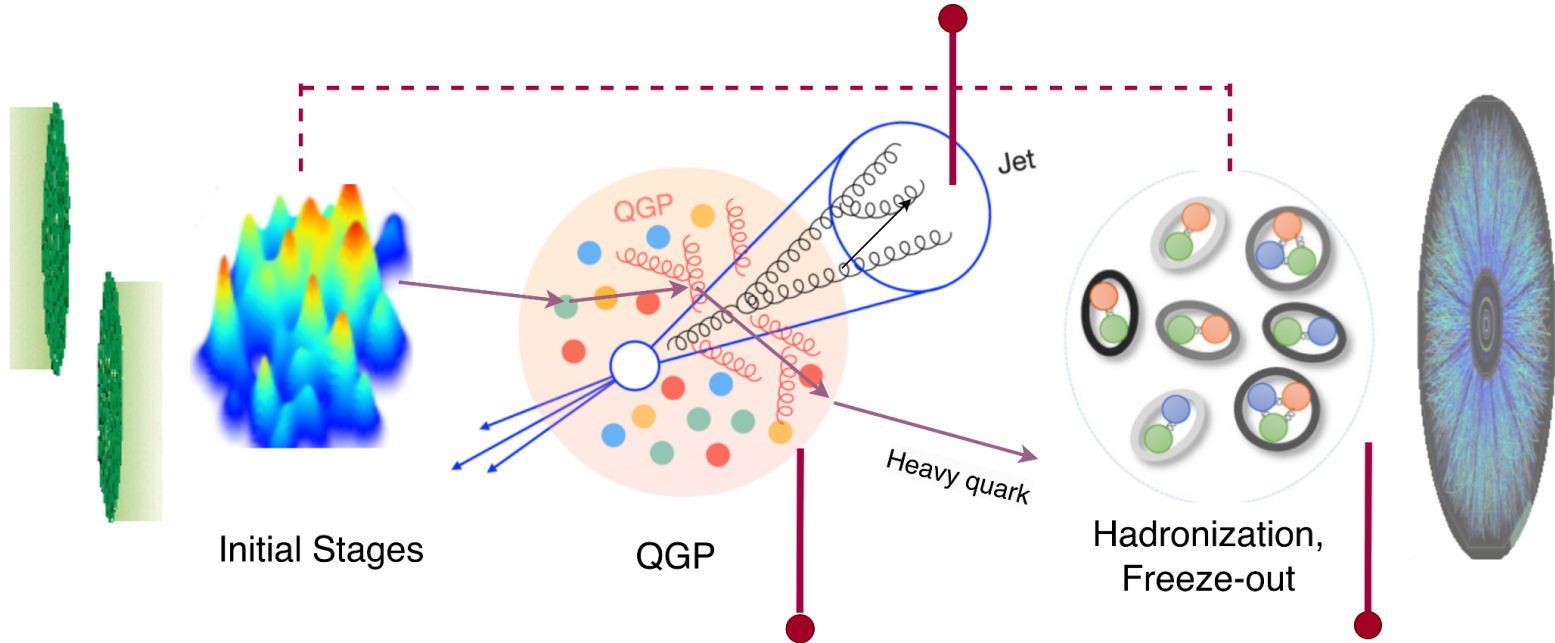
Wenyang Qian (钱文扬)
华中师范大学粒子物理研究所
广州, 2026.7.16

Relativistic heavy-ion collision scenario



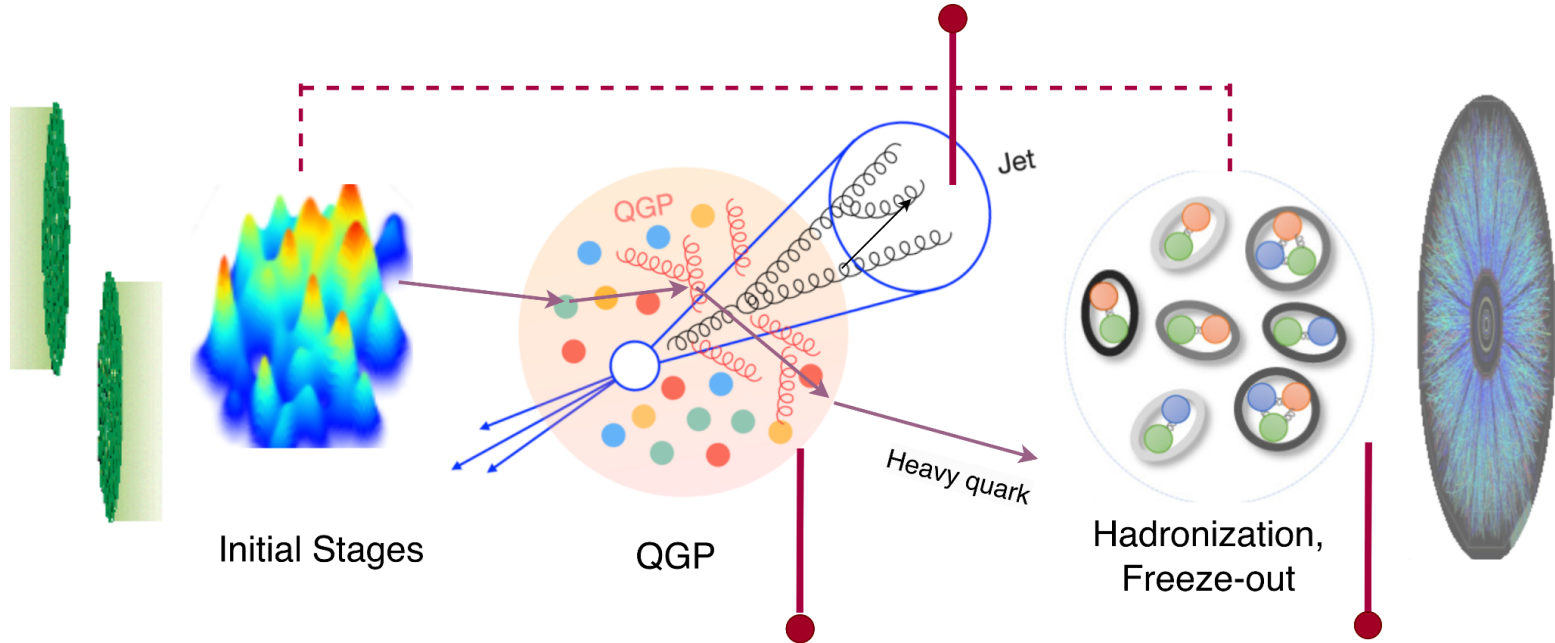
Relativistic heavy-ion collision scenario

How does the medium affect real-time evolution and color coherence?



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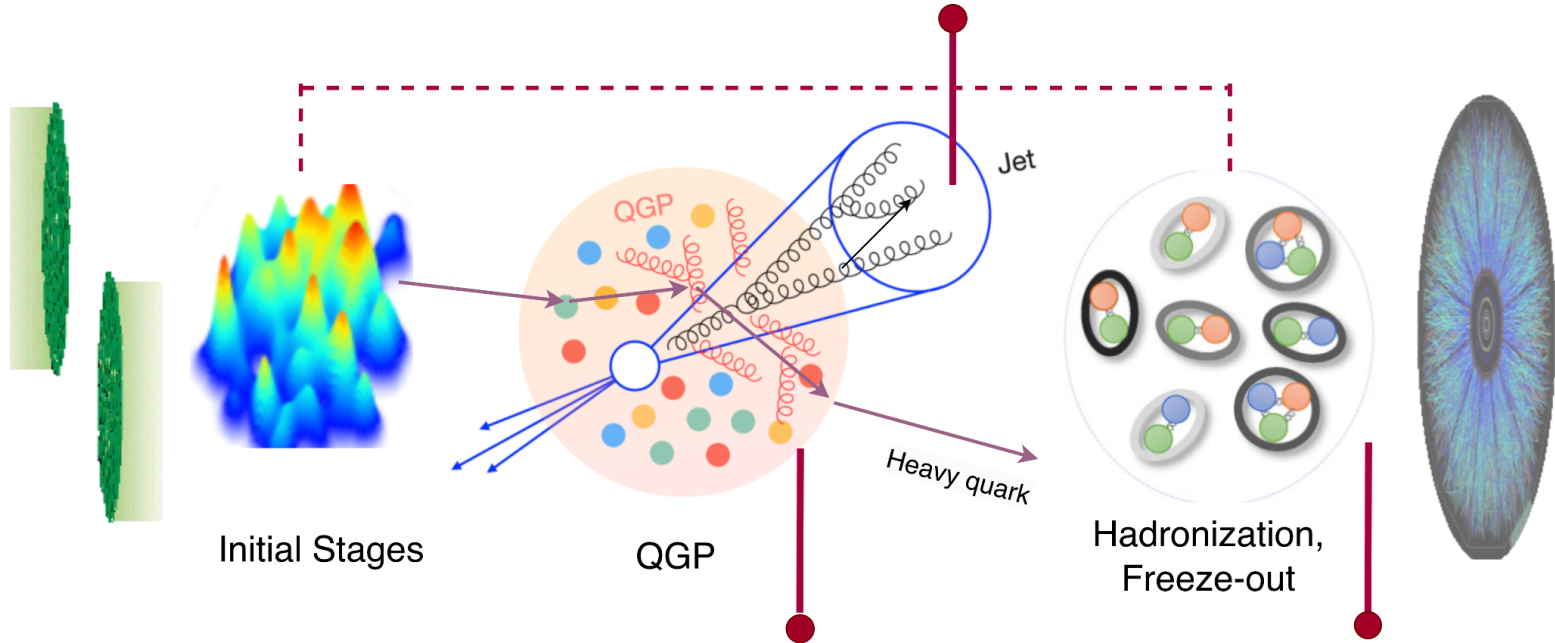
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How does coherent color field (Glasma) decohere into QGP?

Relativistic heavy-ion collision scenario

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How does coherent color field (Glasma) decohere into QGP?

How hadrons form dynamically from deconfined matter?

Classical approaches to Hadronization

Hadronization is the dynamical realization of color confinement — the essential, non-perturbative link between microscopic parton dynamics and the hadronic observables measured in detectors.

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- Excellent phenomenological fits to data

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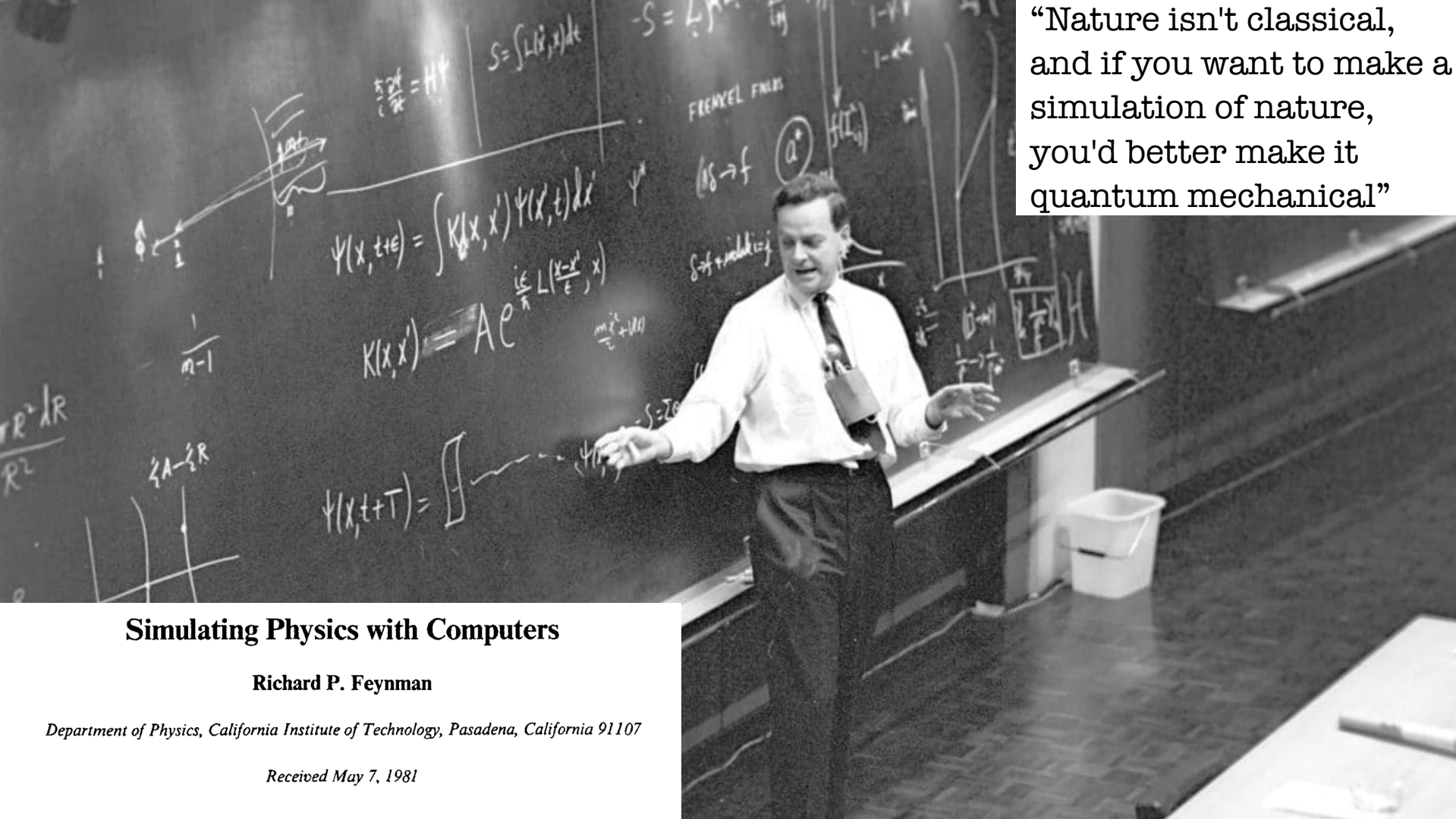
Statistical black box

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First-principles static hadron spectra, non-perturbative

Sign problem, hard to
access real-time dynamics

“Nature isn't classical,
and if you want to make a
simulation of nature,
you'd better make it
quantum mechanical”



Simulating Physics with Computers

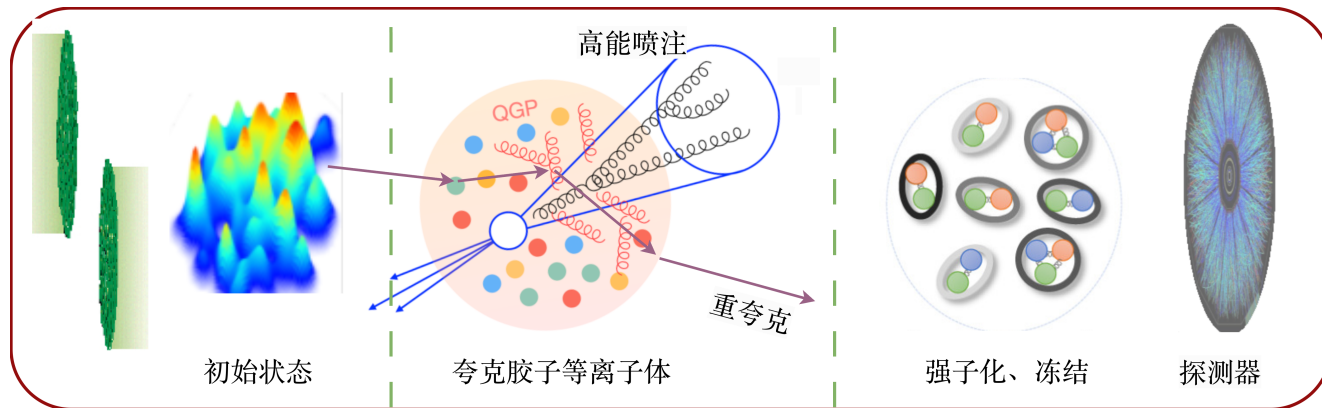
Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

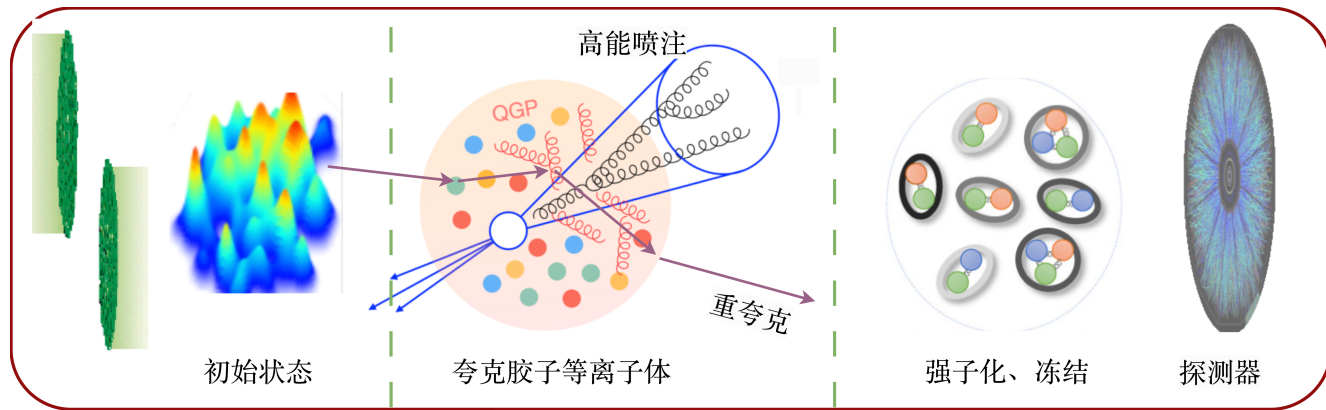
Quantum Computing = simulating one system with another

Target



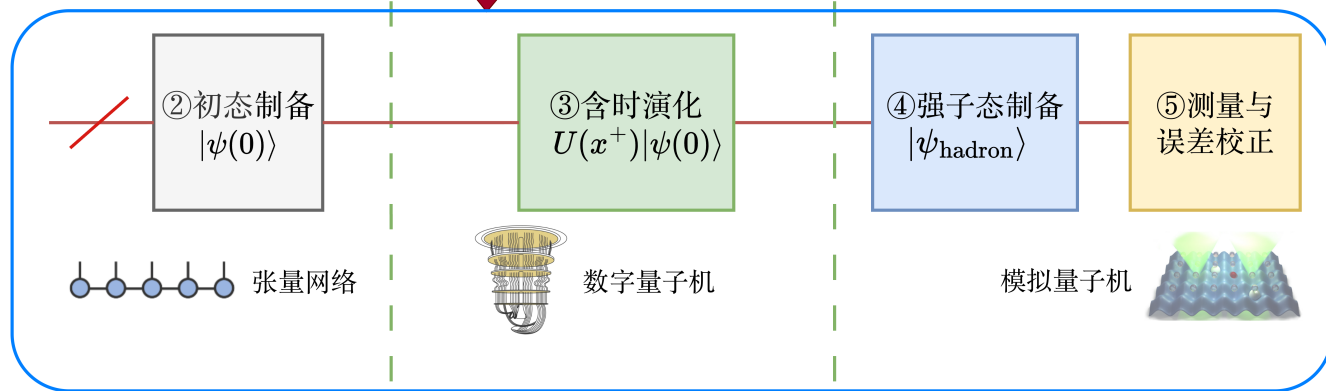
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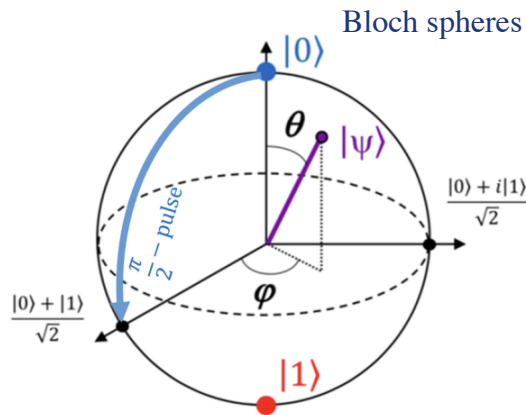
① 量子比特的映射

QIS



Building blocks for quantum computing

- States via Quantum bit = qubit



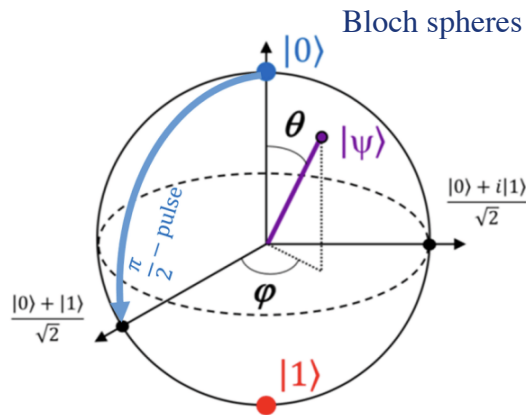
$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

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

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Building blocks for quantum computing

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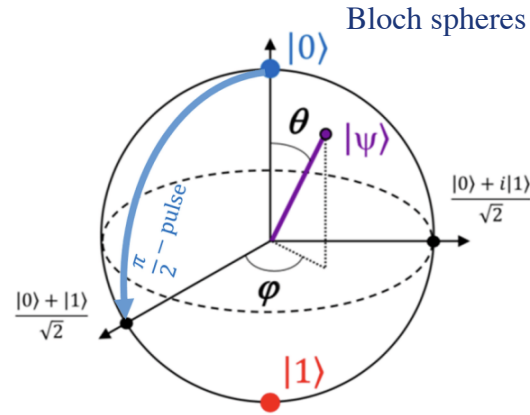
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- Operations via **unitary** matrices = quantum gate on qubits => free from sign problems

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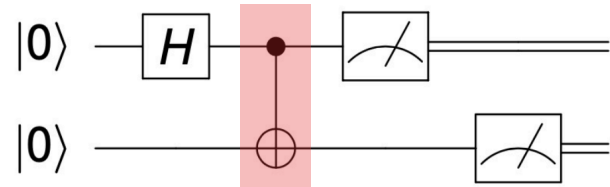
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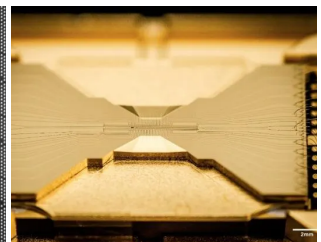
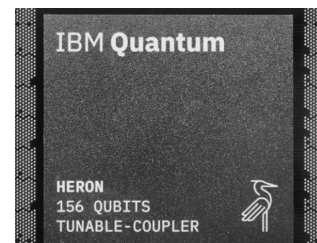
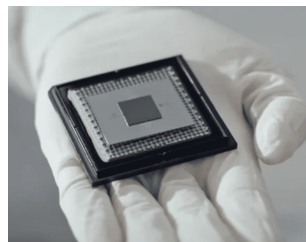
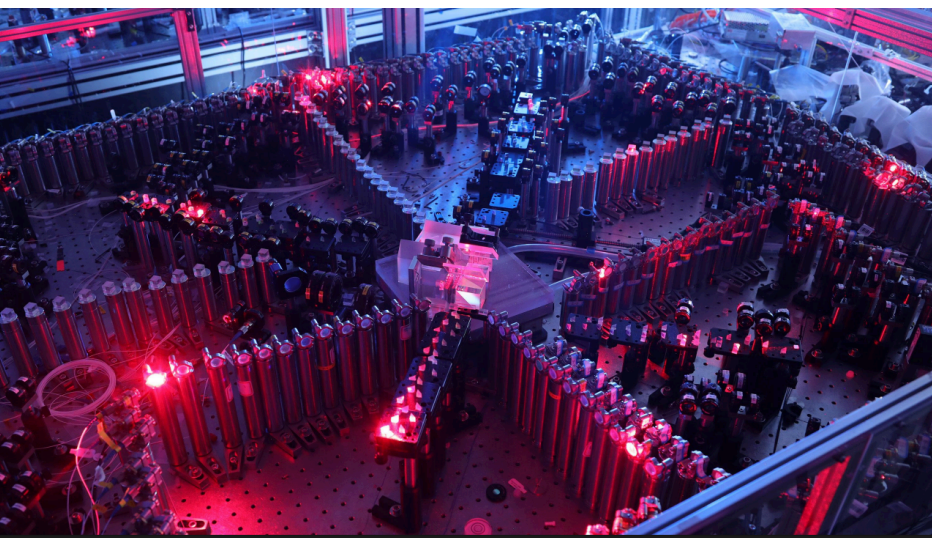
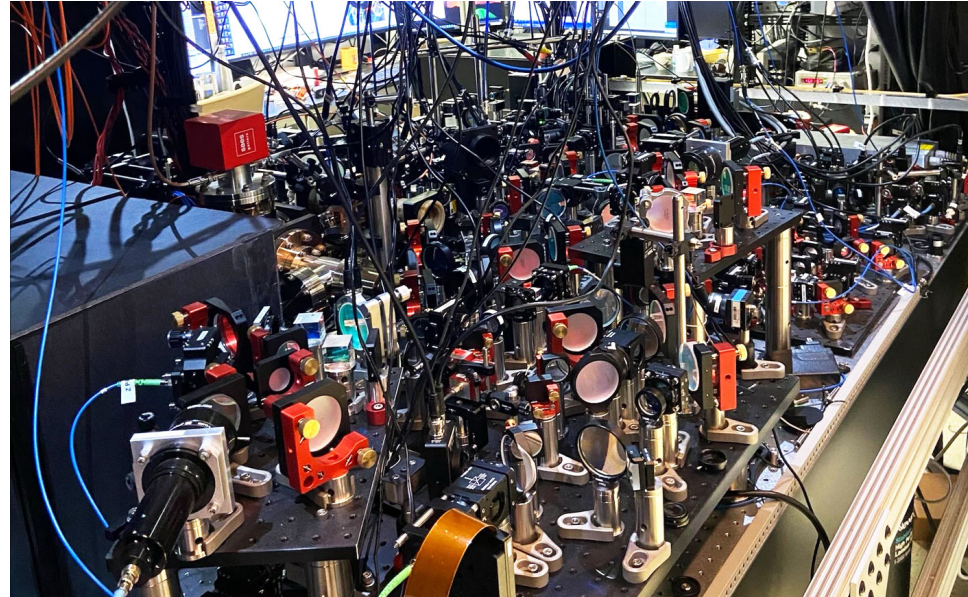
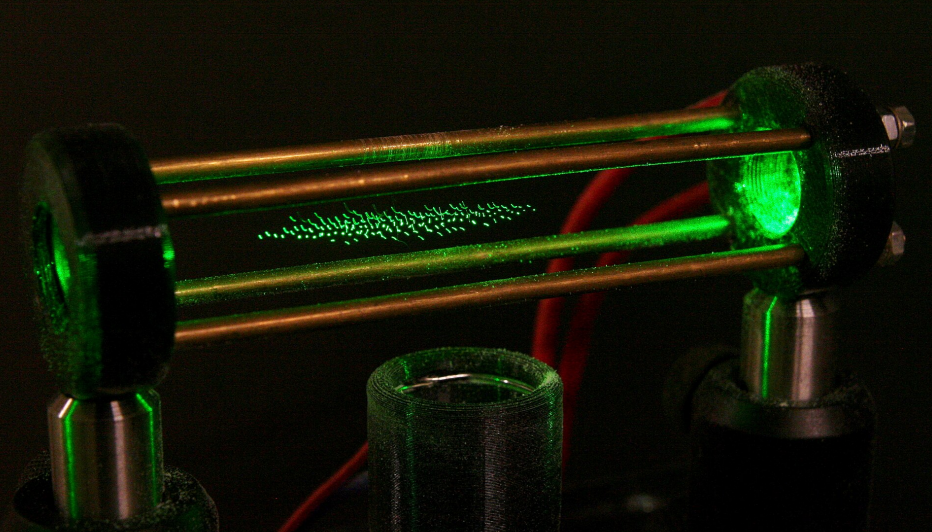
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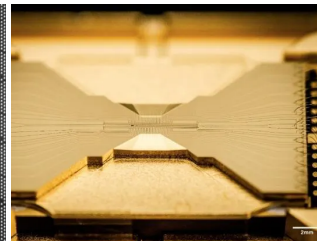
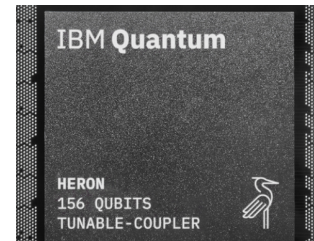
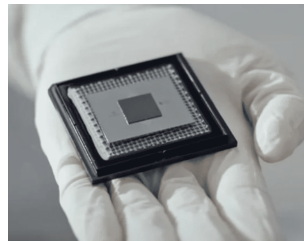
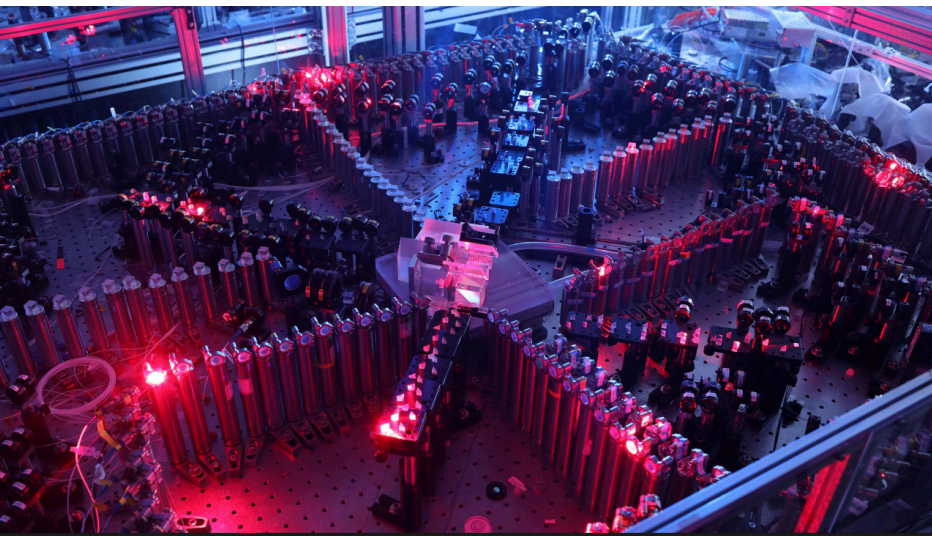
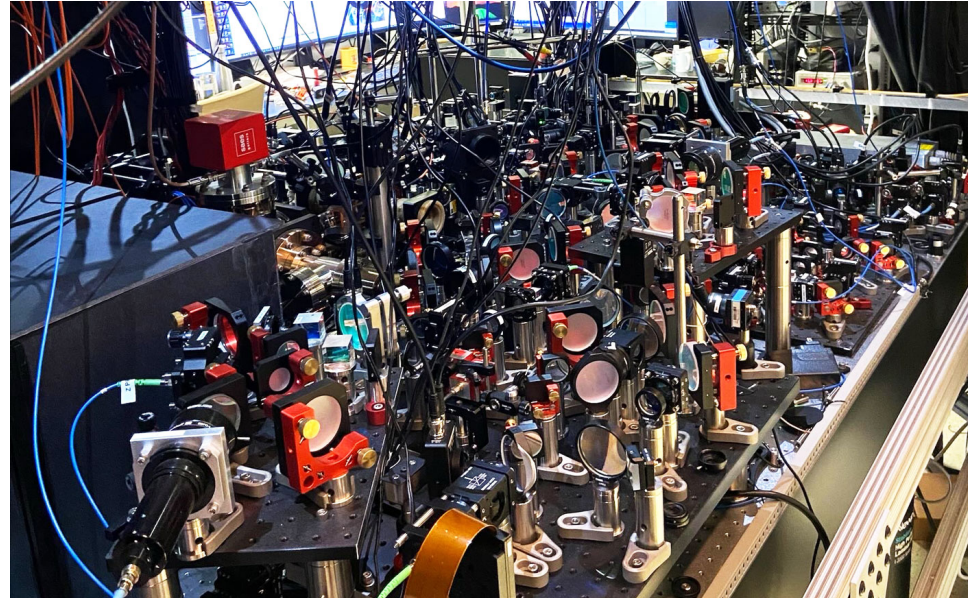
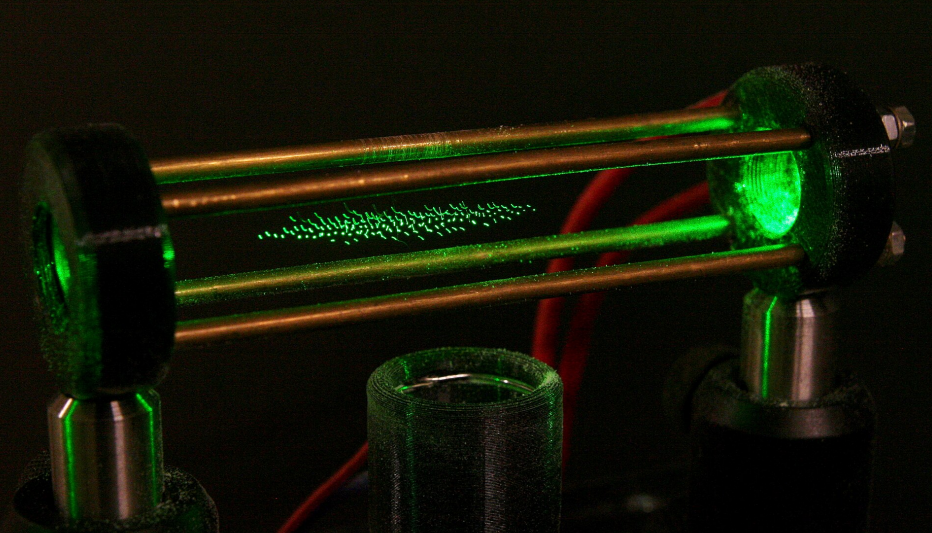
- Operations via **unitary** matrices = quantum gate on qubits => free from sign problems

- Three QM concepts:
superposition, measurement, **entanglement**



=> truly empowers quantum computing





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



Towards quantum advantage: Quantum simulation for HEP

PRX QUANTUM 4, 027001 (2023)

Roadmap

Quantum Simulation for High-Energy Physics

Christian W. Bauer,^{1,*} Zohreh Davoudi^{2,†} A. Baha Balantekin,³ Tanmoy Bhattacharya,⁴ Marcela Carena,^{5,6,7,8} Wibe A. de Jong,¹ Patrick Draper,⁹ Aida El-Khadra,⁹ Nate Gemelke,¹⁰ Masanori Hanada,¹¹ Dmitri Kharzeev,^{12,13} Henry Lamm,⁵ Ying-Ying Li,^{14,15} Junyu Liu^{16,17} Mikhail Lukin,¹⁸ Yannick Meurice,¹⁹ Christopher Monroe,^{20,21,22,23} Benjamin Nachman,¹ Guido Pagano,²⁴ John Preskill,²⁵ Enrico Rinaldi,^{26,27,28} Alessandro Roggero,^{29,30} David I. Santiago,^{31,32} Martin J. Savage,³³ Irfan Siddiqi,^{31,32,34} George Siopsis,³⁵ David Van Zanten,⁵ Nathan Wiebe,^{36,37} Yukari Yamauchi,² Kübra Yeter-Aydeniz,³⁸ and Silvia Zorzetti⁶

Eur. Phys. J. D (2020) 74: 165
<https://doi.org/10.1140/epjd/e2020-100571-8>

THE EUROPEAN
PHYSICAL JOURNAL D

Colloquium

Simulating lattice gauge theories within quantum technologies

Mari Carmen Bañuls^{1,2}, Rainer Blatt^{3,4}, Jacopo Catani^{5,6,7}, Alessio Celi^{3,8}, Juan Ignacio Cirac^{1,2}, Marcello Dalmonte^{9,10}, Leonardo Fallani^{5,6,7}, Karl Jansen¹¹, Maciej Lewenstein^{8,12,13}, Simone Montangero^{14,15,a}, Christine A. Muschik³, Benni Reznik¹⁶, Enrique Rico^{17,18}, Luca Tagliacozzo¹⁹, Karel Van Acoleyen²⁰, Frank Verstraete^{20,21}, Uwe-Jens Wiese²², Matthew Wingate²³, Jakub Zakrzewski^{24,25}, and Peter Zoller³

PRX QUANTUM 5, 037001 (2024)

Roadmap

Quantum Computing for High-Energy Physics: State of the Art and Challenges

Alberto Di Meglio^{1,*} Karl Jansen,^{2,3,†} Ivano Tavernelli,^{4,‡} Constantia Alexandrou^{3,5} Srinivasan Arunachalam,⁶ Christian W. Bauer,⁷ Kerstin Borras^{8,9} Stefano Carrazza^{1,10} Arianna Crippa^{2,11} Vincent Croft¹² Roland de Putter,⁶ Andrea Delgado¹³ Vedran Dunjko¹² Daniel J. Egger⁴ Elias Fernández-Combarro¹⁴ Elina Fuchs^{1,15,16} Lena Funcke¹⁷ Daniel González-Cuadra^{18,19} Michele Grossi¹ Jad C. Halimeh^{20,21} Zoë Holmes²² Stefan Kühn² Denis Lacroix²³ Randy Lewis²⁴ Donatella Lucchesi^{1,25} Miriam Lucio Martinez,^{26,27} Federico Meloni⁸ Antonio Mezzacapo,⁶ Simone Montangero^{1,25} Lento Nagano²⁸ Vincent R. Pascuzzi⁶ Voica Radescu,²⁹ Enrique Rico Ortega^{30,31,32,33} Alessandro Roggero^{34,35} Julian Schuhmacher⁴ Joao Seixas^{36,37,38} Pietro Silvi^{1,25} Panagiotis Spentzouris³⁹ Francesco Tacchino⁴ Kristan Temme,⁶ Koji Terashi²⁸ Jordi Tura^{12,40} Cenk Tüysüz^{2,11} Sofia Vallecorsa¹ Uwe-Jens Wiese,⁴¹ Shinjae Yoo⁴² and Jinglei Zhang^{43,44}

REVIEWS OF MODERN PHYSICS, VOLUME 93, JULY–SEPTEMBER 2021

QCD thermalization: *Ab initio* approaches and interdisciplinary connections

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Institute for Theoretical Physics, Heidelberg University,
Philosophenweg 16, D-69120 Heidelberg, Germany

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Max Planck Institute for Gravitational Physics (Albert Einstein Institute),
Am Mühlenberg 1, D-14476 Potsdam, Germany

Aleksas Mazeliauskas[‡]

Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland

Raju Venugopalan[§]

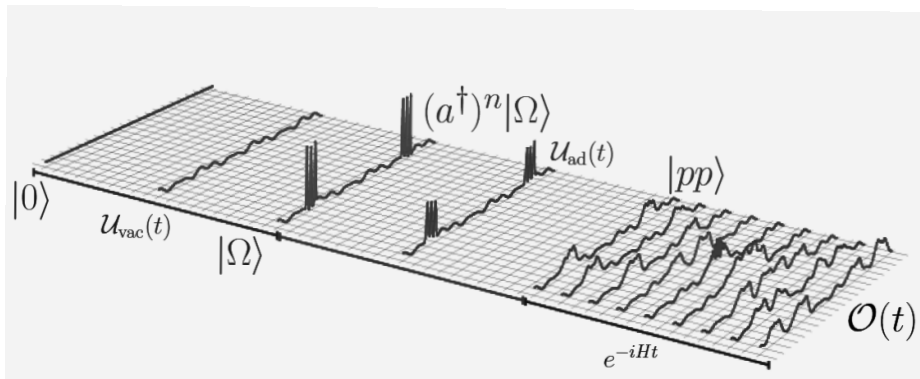
Physics Department, Brookhaven National Laboratory,
Upton, New York 11973-5000, USA

Prototypical task

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

- 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

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

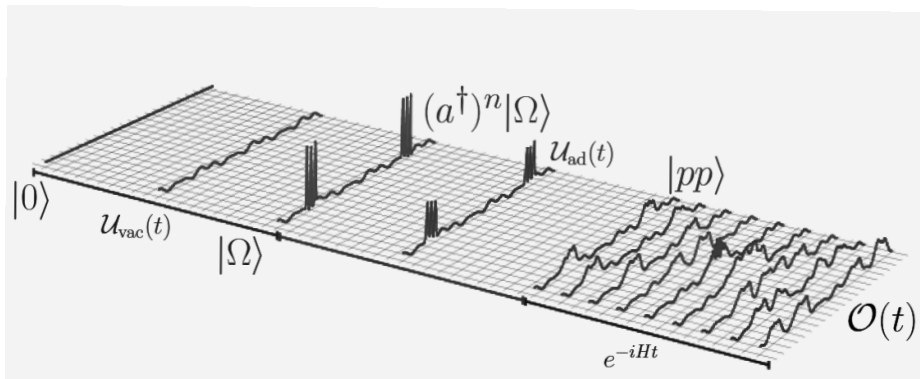


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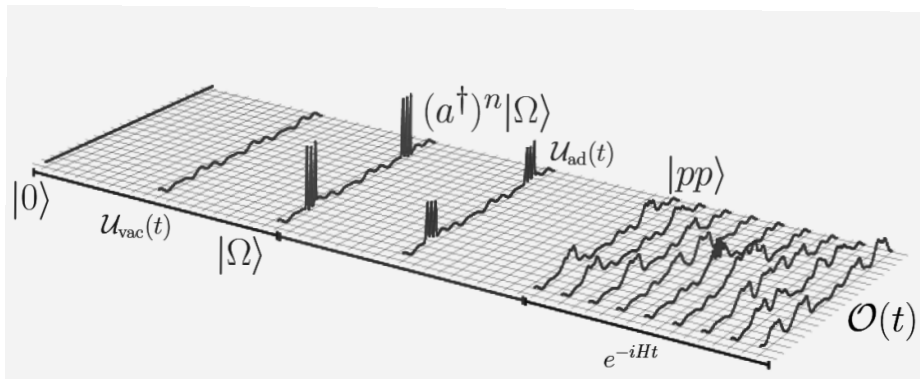
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Quantum simulation of quantum field theory = perform “**ideal experiments**” on quantum computer

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1111.3633, 1401.7115, 1703.00454
- Evolve state forward in time using Hamiltonian, for some specified time interval **(Scattering)**
- Measure observables by simulating measurement performed in idealized lab



QIS approach to Hadronization

1. Direct calculation of parton fragmentation functions (FFs) from first principles

[Li, Xing, Zhang, 2406.05683](#)

$$D_q^h(z) = z^{d-3} \int \frac{dy^-}{4\pi} e^{-iy^- p^+ / z} \text{Tr} \left\{ \langle \Omega | \psi(y^-) \sum_X |h, X\rangle \langle h, X| \bar{\psi}(0) | \Omega \rangle \gamma^+ \right\}$$

See related works:

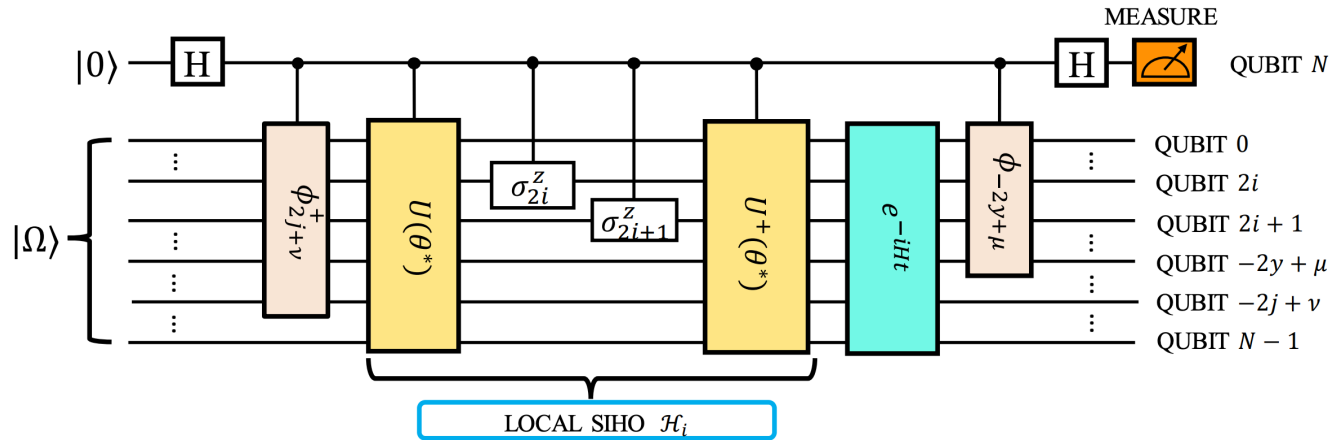
[Lamm et al, 1908.10439](#), [Li et al, 2106.03865](#); [2207.13258](#), [Kang, Moran, Nguyen, WQ, 2501.09738](#), [Ikeda, Kang, Kharzeev, WQ, 2512.18062](#), [Banuls et al, 2504.07508](#); [2409.16996](#), [Chen et al, 2506.16829](#), ...

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QIS approach to Hadronization

2. Replacing Markovian process with analog quantum simulator, “QuPyth” evolves the whole string as a single coherent state and measures entropy/multiplicity at the end

[Senseman, Ozzello, Heitritter, Meurice, Mrenna, 2212.02476](#)

$$H = \frac{\Omega}{2} \sum_j (|g_j\rangle \langle r_j| + |r_j\rangle \langle g_j|) - \Delta \sum_j n_j$$

string breaking electric field term

$$+ \sum_{j < k} V_{jk} n_j n_k$$

Experimentally feasible in 1D & 2D
see Lukin's group

[Gonzalez-Cuadra et al, 2410.16558](#)

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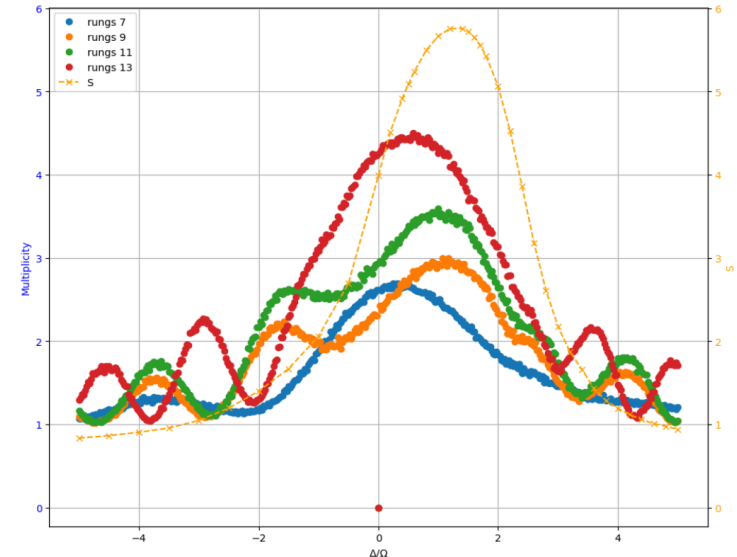
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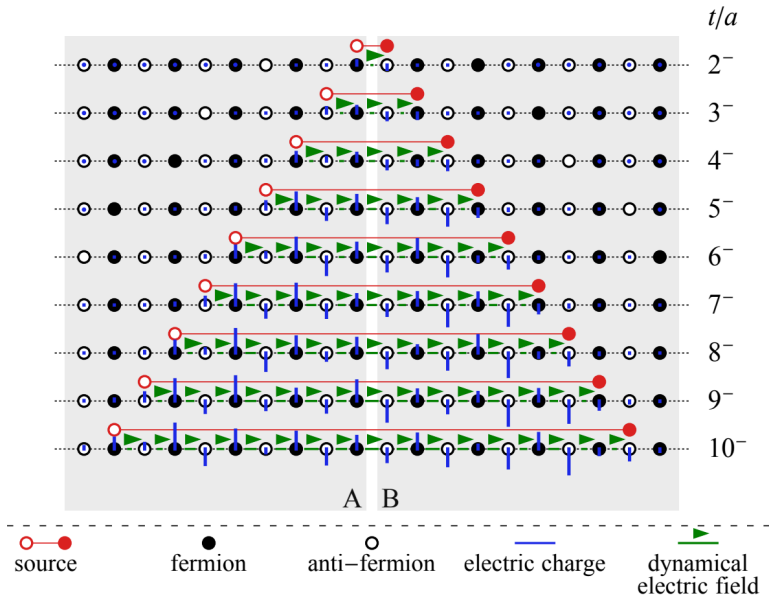
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QIS approach to Hadronization

3. Schwinger model with auxiliary fields to study real-time entanglement entropy as signal to hadronization

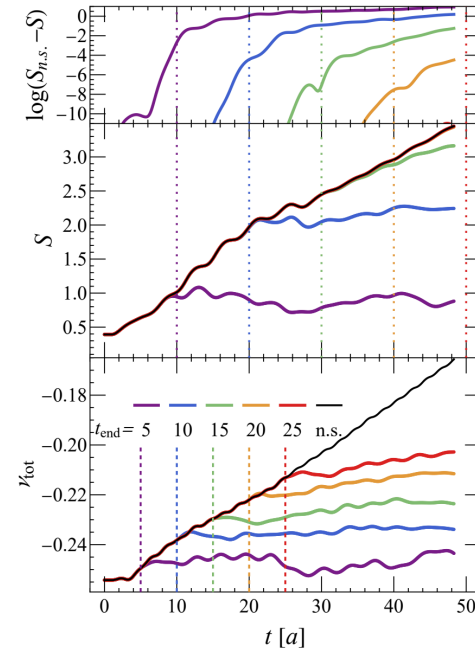
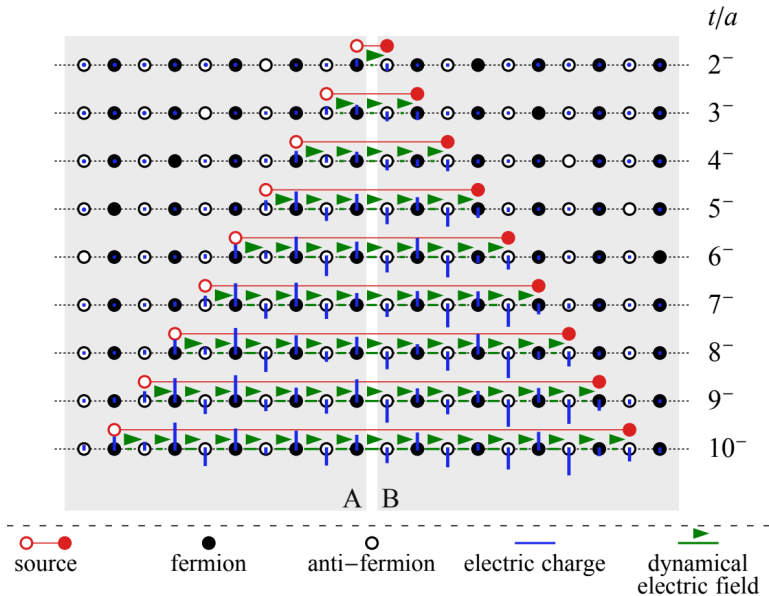
Florio, Frenklakh, Ikeda, Kharzeev, Korepin, Shi, Yu, 2301.11991, 2404.00087



QIS approach to Hadronization

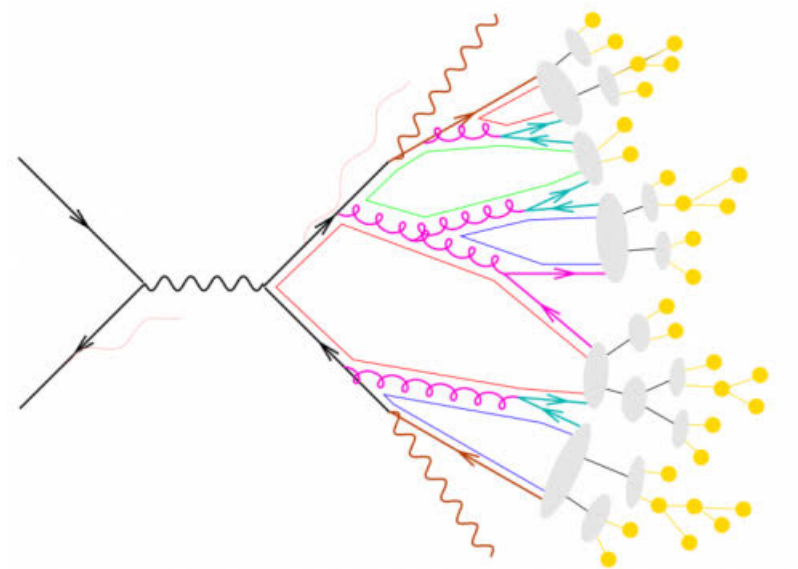
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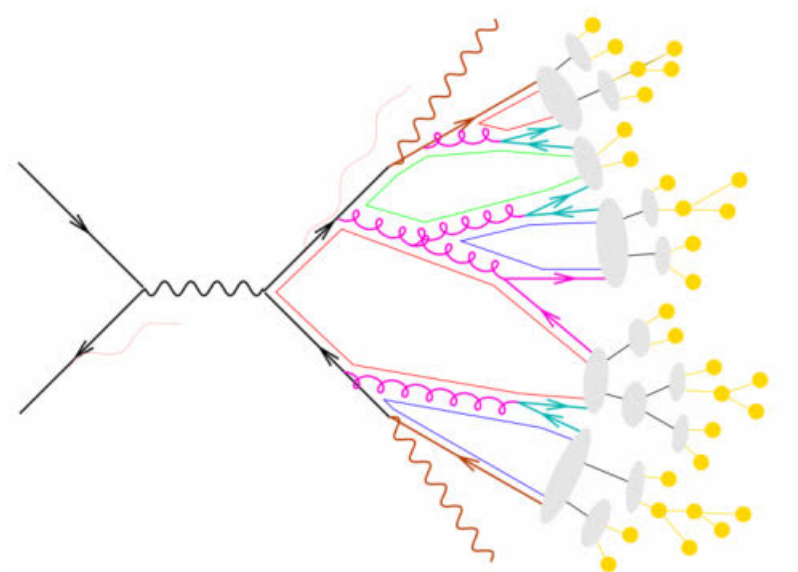
QIS approach to Hadronization

4. Could we simulate the real-time evolution of **jets** and measure its final probability to physical **hadron states**?



QIS approach to Hadronization

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$$| \langle \psi_h | \psi(x^+) \rangle |^2$$

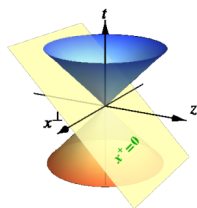
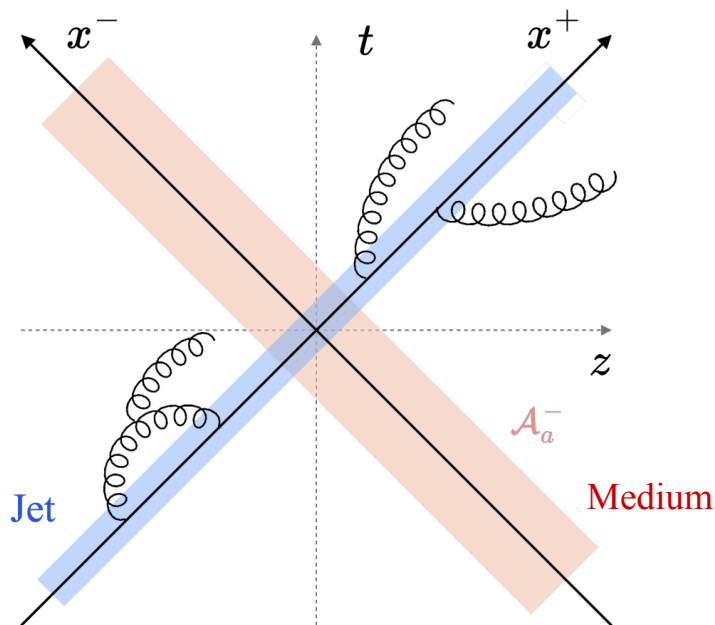
Jet: Light-front QCD Hamiltonian

Li et al, 2002.09757; 2107.02225; 2305.12490 ...
See Meijian's talk

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

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

Classical background field,
McLerran, Venugopalan, 9309289 (1993)



front form

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

Jet: Light-front QCD Hamiltonian

Li et al, 2002.09757; 2107.02225; 2305.12490 ...
See Meijian's talk

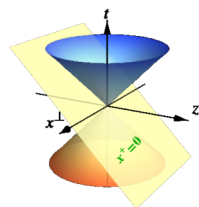
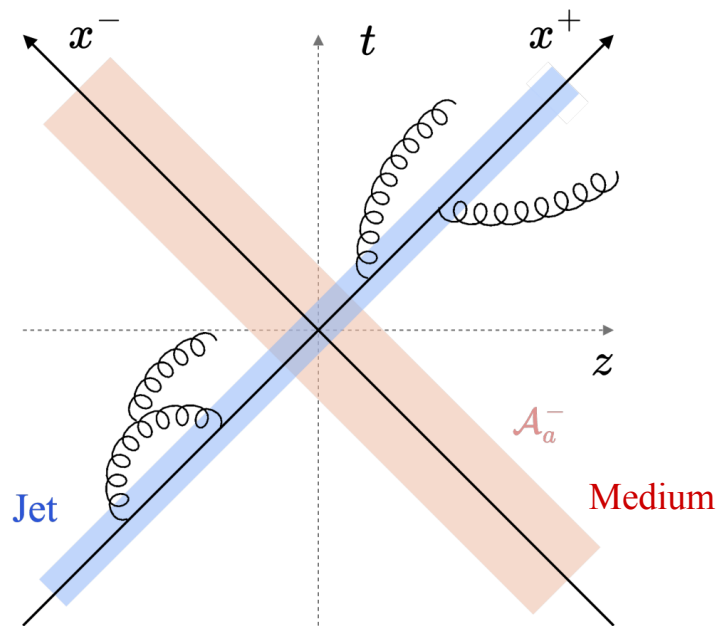
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$$D^\mu \equiv \partial_\mu + ig(A^\mu + \mathcal{A}^\mu)$$

Classical background field,
McLerran, Venugopalan, 9309289 (1993)

For example, in $|q\rangle + |qg\rangle$ Fock sector

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

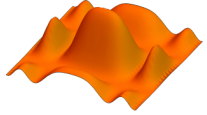


front form

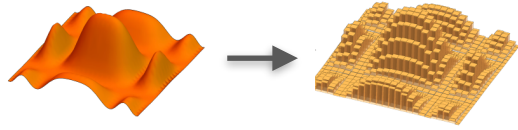
$$x^+ \triangleq x^0 + x^3$$

Fock sector	$ q\rangle$	$ qg\rangle$
$\langle q $		
$\langle qg $		

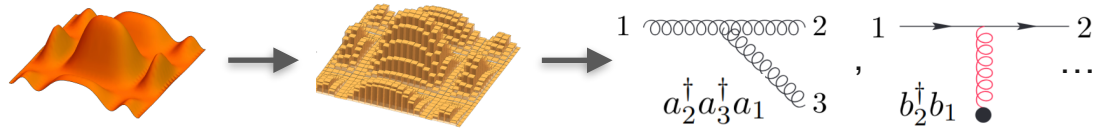
Jet: Quantum simulation



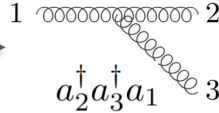
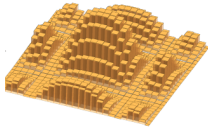
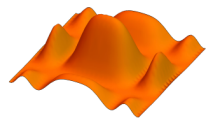
Jet: Quantum simulation



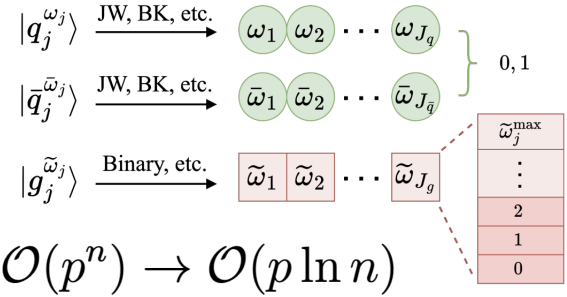
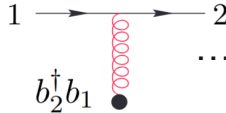
Jet: Quantum simulation



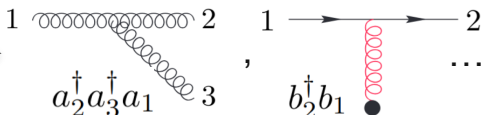
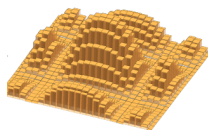
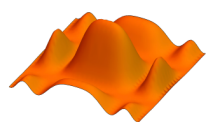
Jet: Quantum simulation



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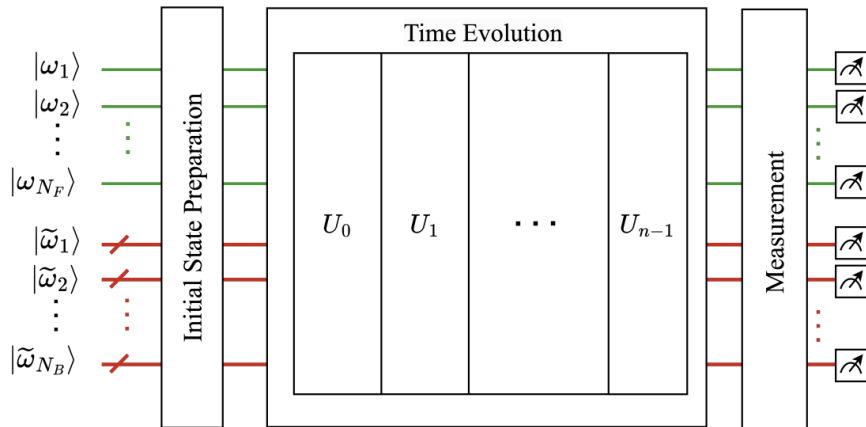
Jet: Quantum simulation



$$\begin{aligned}
 |q_j^{\omega_j}\rangle &\xrightarrow{\text{JW, BK, etc.}} \omega_1 \omega_2 \dots \omega_{J_q} \\
 |\bar{q}_j^{\bar{\omega}_j}\rangle &\xrightarrow{\text{JW, BK, etc.}} \bar{\omega}_1 \bar{\omega}_2 \dots \bar{\omega}_{J_{\bar{q}}} \\
 |g_j^{\tilde{\omega}_j}\rangle &\xrightarrow{\text{Binary, etc.}} \tilde{\omega}_1 \tilde{\omega}_2 \dots \tilde{\omega}_{J_g}
 \end{aligned}
 \left. \vphantom{\begin{aligned} |q_j^{\omega_j}\rangle \\ |\bar{q}_j^{\bar{\omega}_j}\rangle \\ |g_j^{\tilde{\omega}_j}\rangle \end{aligned}} \right\} 0, 1$$

$\tilde{\omega}_j^{\max}$
$\vdots$
2
1
0

$$\mathcal{O}(p^n) \rightarrow \mathcal{O}(p \ln n)$$

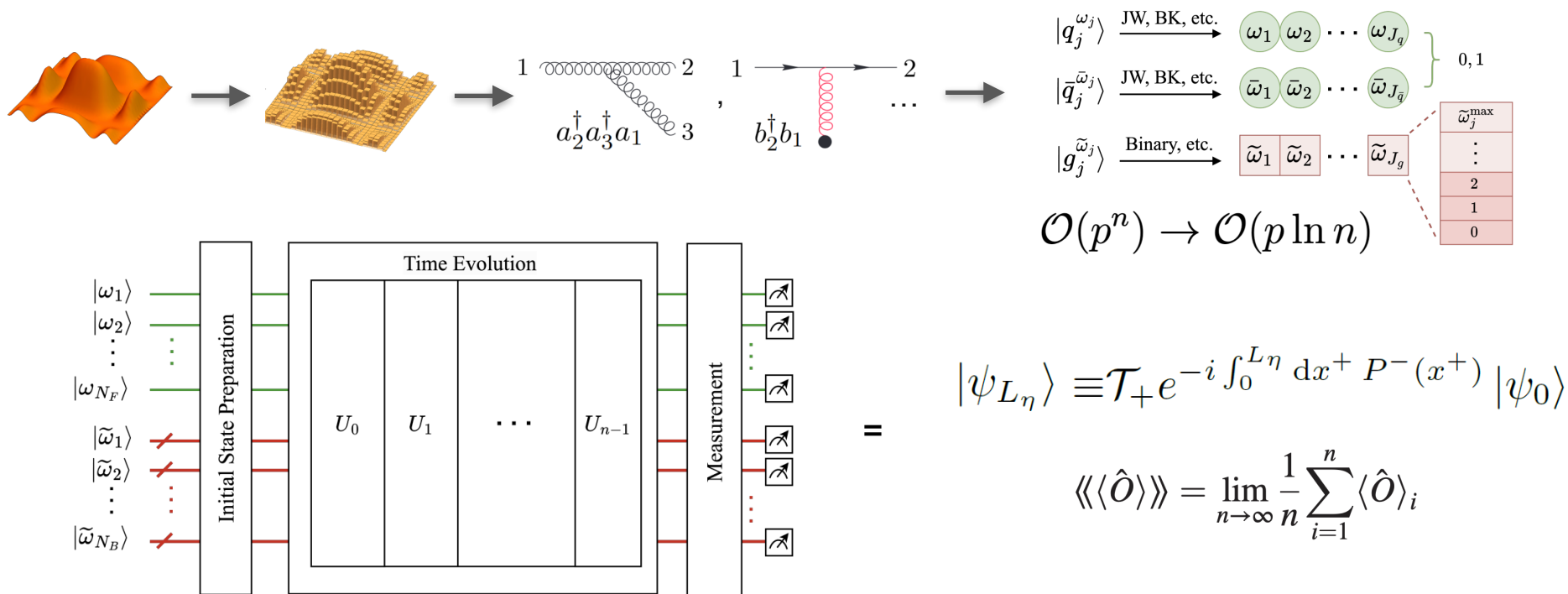


=

$$|\psi_{L_\eta}\rangle \equiv \mathcal{T}_+ e^{-i \int_0^{L_\eta} dx^+ P^-(x^+)} |\psi_0\rangle$$

$$\langle\langle \hat{O} \rangle\rangle = \lim_{n \rightarrow \infty} \frac{1}{n} \sum_{i=1}^n \langle \hat{O} \rangle_i$$

Jet: Quantum simulation



Efficient quantum simulation framework for (3+1)d jet evolution in medium

See refs:

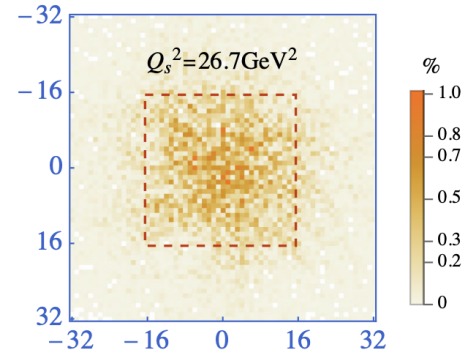
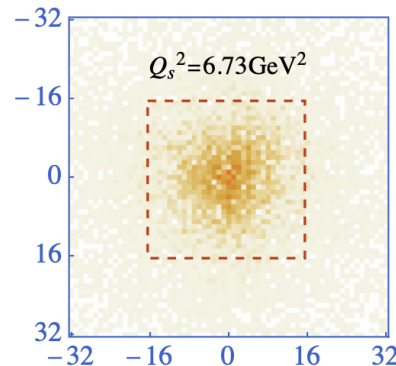
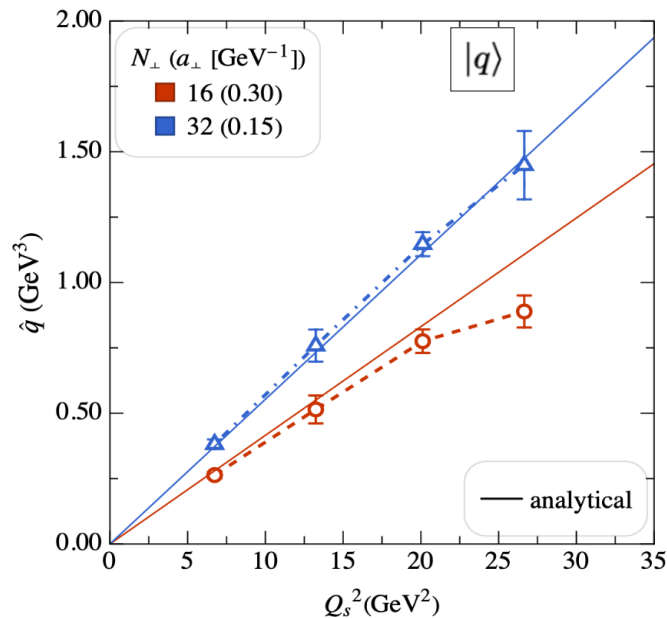
WQ, Li, Kreshchuk, Salgado, 2411.09762, Barata, Salgado, 2104.04661, Barata, Du, Li, WQ, Salgado, 2208.06750; 2307.01792, Wu et al, 2404.00819 (IMP), Castro et al, 2502.03431 (LIP), Barata, Li, Qian, Salgado, Silva, 2604.11616, ...

Jet: observables

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

Jet: observables

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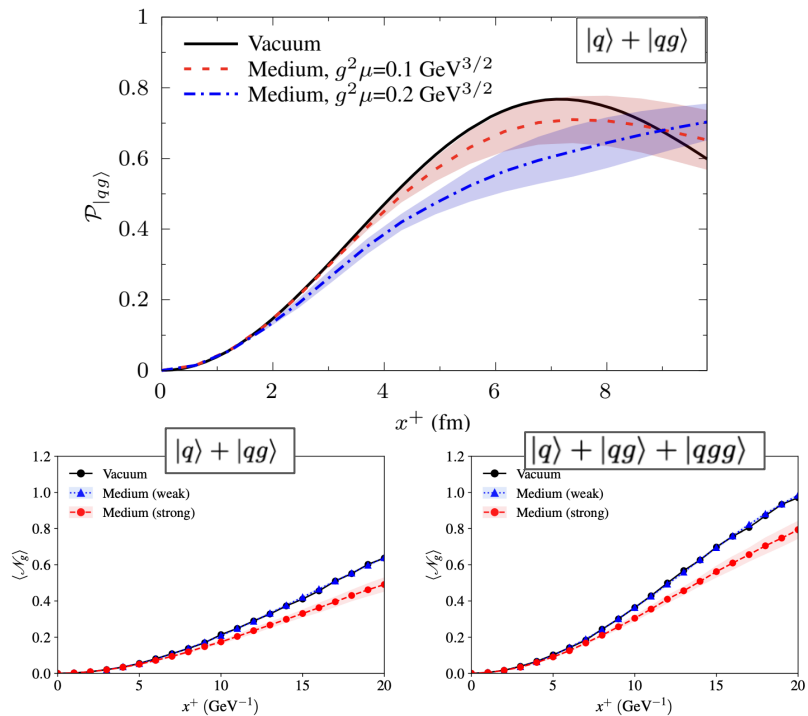
$$Q_s^2 \equiv C_F \frac{g^4 \mu^2 L_{\eta}}{2\pi}$$

First calculation on quantum circuit

Barata, Du, Li, WQ, Salgado, 2208.06750

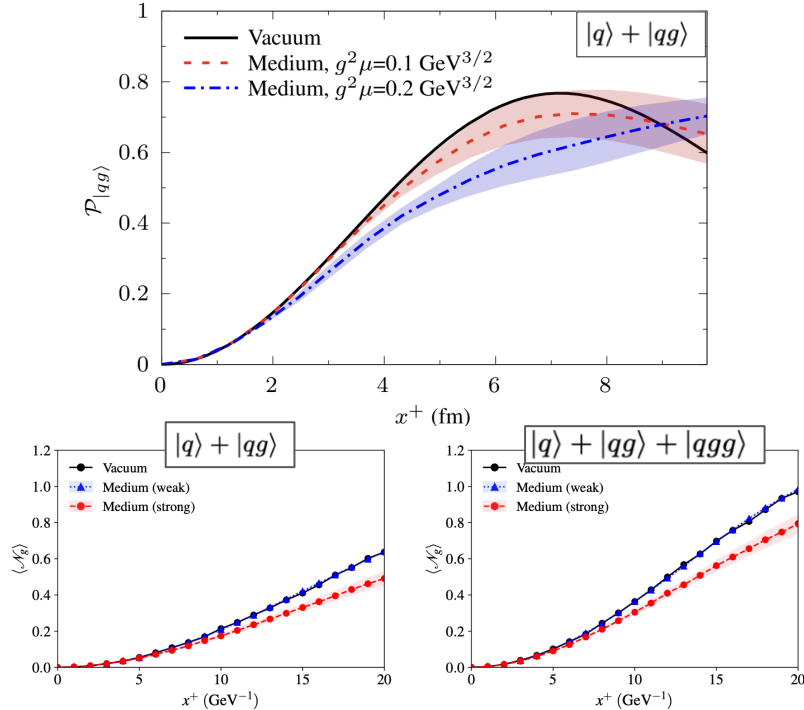
Jet: observables

Gluon production in strong & weak mediums

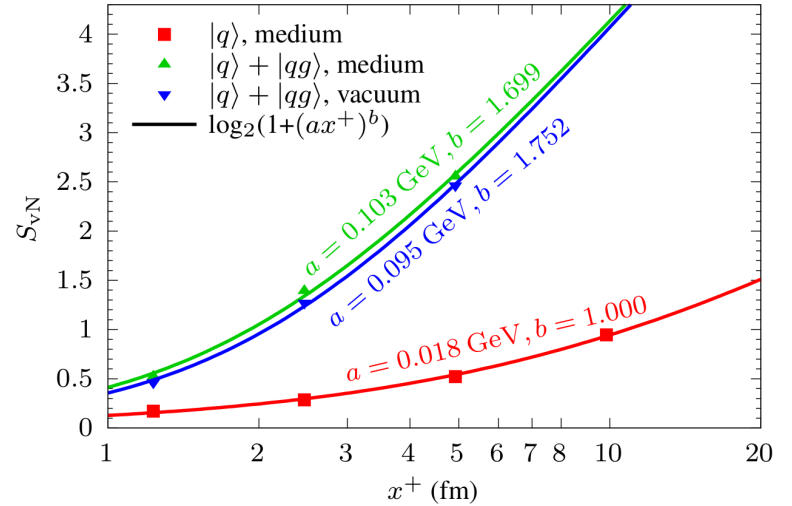


Jet: observables

Gluon production in strong & weak mediums



Entropy expansion with radiation



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

Hadrons: prepared on circuit

See Xingyu's talk on VQA

Solving hadron structures on light-front is natural with variational quantum algo: $|\psi(\vec{\theta})\rangle \equiv \hat{U}(\vec{\theta}) |\psi_0\rangle$

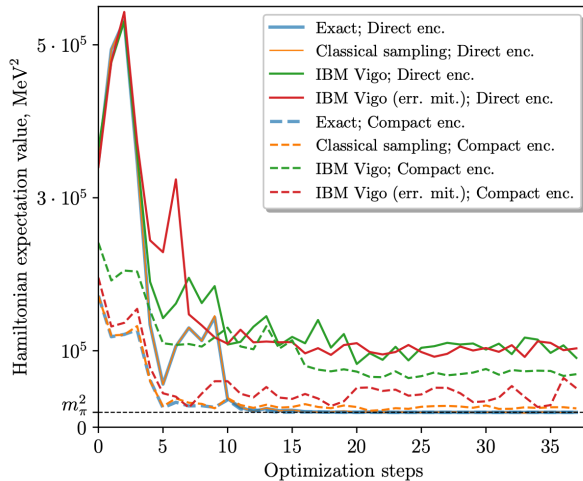
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Kreshuchuk et al, 2011.13443, 2009.07885, 2002.04016
Atas et al, 2102.08920

Ground states



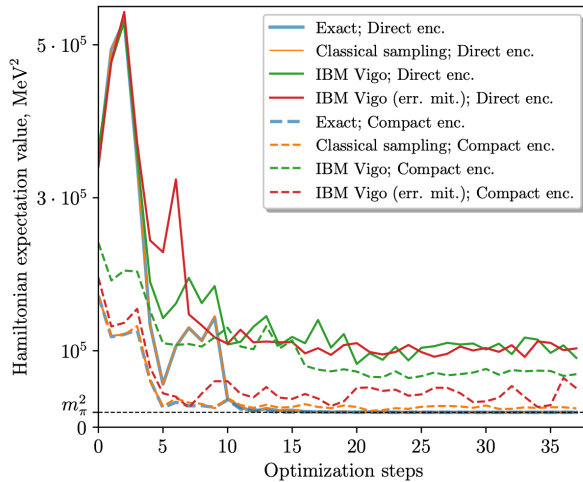
Hadrons: prepared on circuit

See Xingyu's talk on VQA

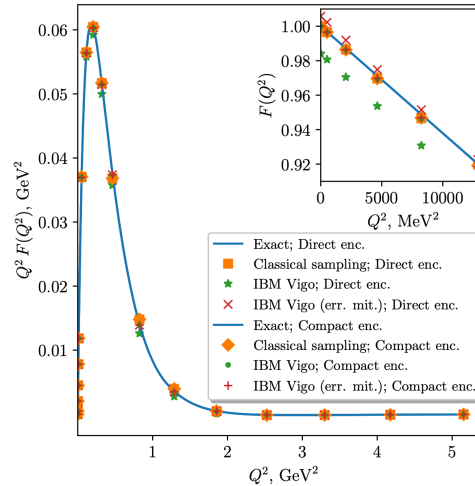
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Ground states



Hadronic observables



Hadrons: prepared on circuit

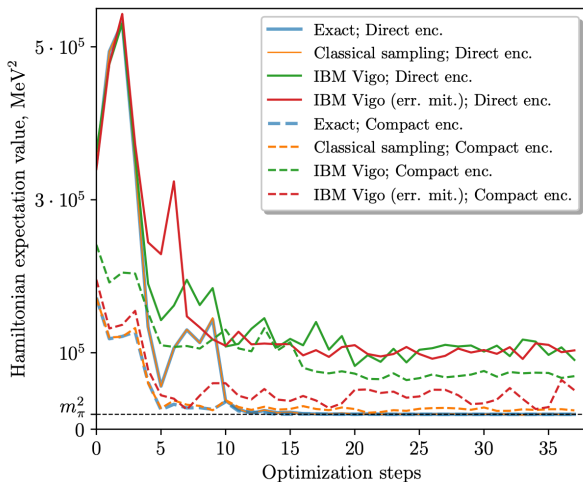
See Xingyu's talk on VQA

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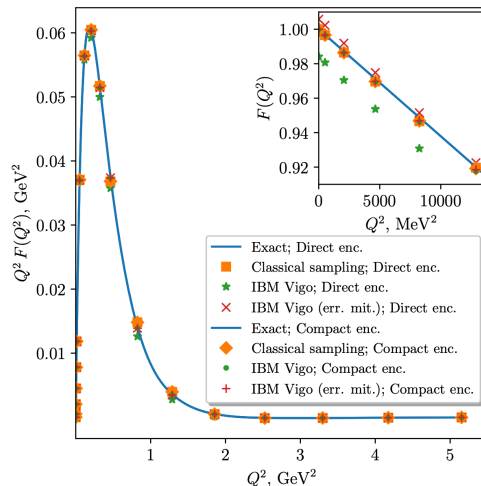
Kreshuchuk et al, 2011.13443, 2009.07885, 2002.04016
Atas et al, 2102.08920

Qian et al, 2112.01927

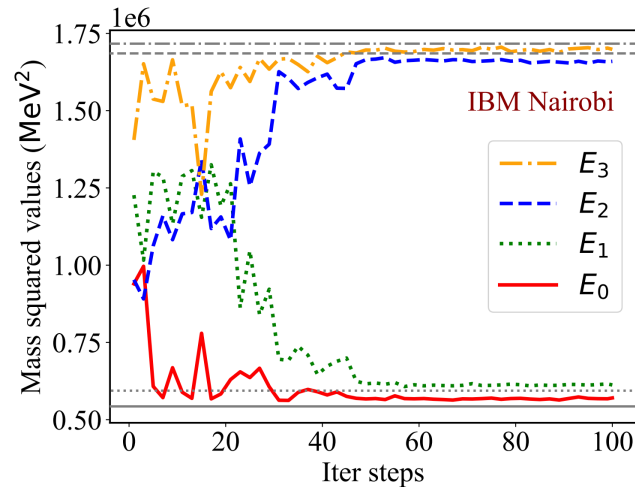
Ground states



Hadronic observables



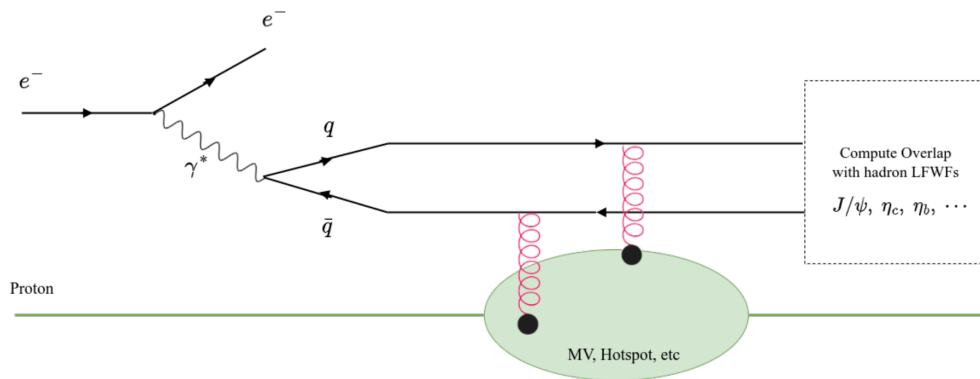
Excited states



Vector meson production in DIS

As first step...

$$\gamma^* + p \rightarrow X + p$$

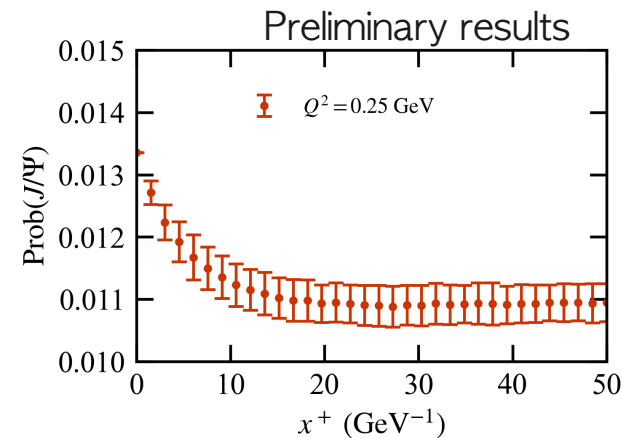
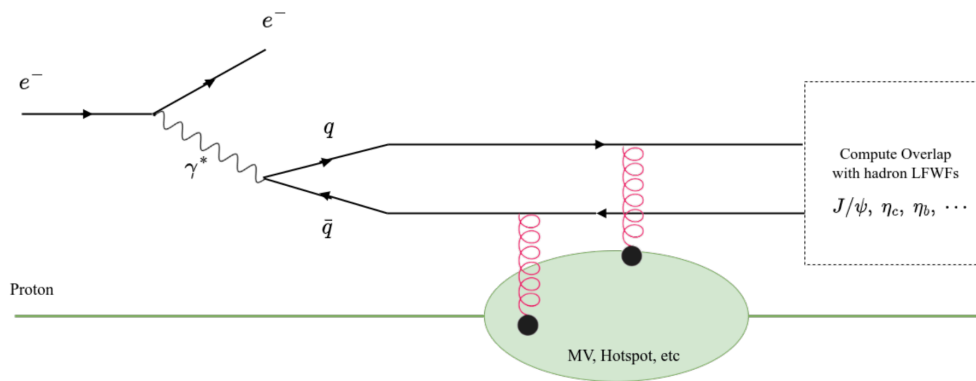


Vector meson production in DIS

Cao, Li, Li, Qian, 2608.XXXX

As first step...

$$\gamma^* + p \rightarrow X + p$$

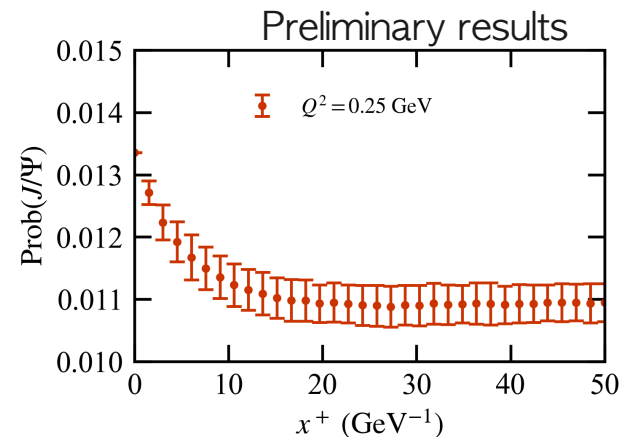
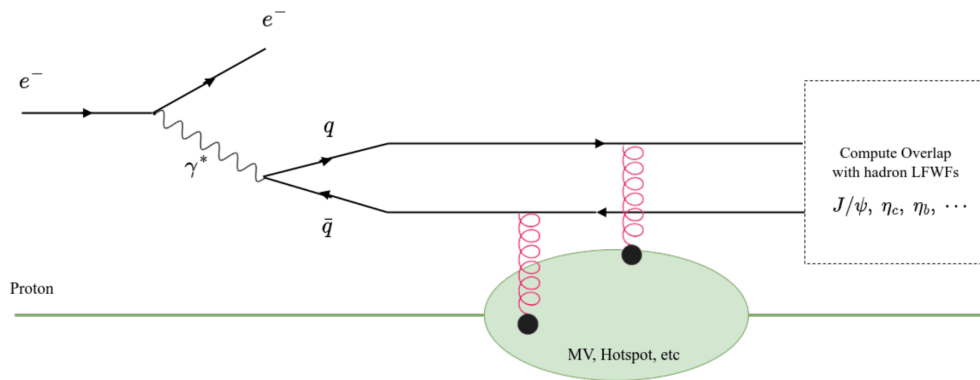


Vector meson production in DIS

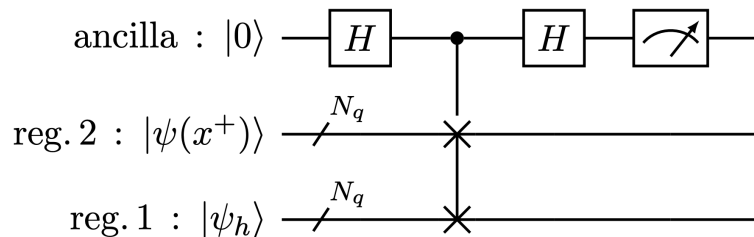
Cao, Li, Li, Qian, 2608.XXXX

As first step...

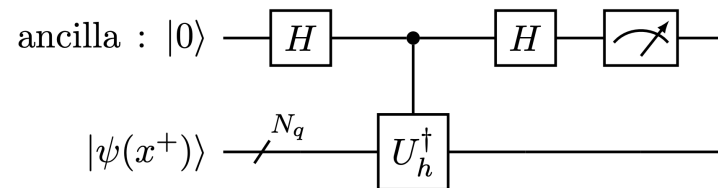
$$\gamma^* + p \rightarrow X + p$$



Swap test



Hadamard test



Summary and Outlook

- Quantum computing as a new tool is useful to help us understand HICs.
- Several quantum simulation proposals are available to interpret hadronization differently.
- Quantum simulation on the light front may be a scalable framework connect real-time dynamics and hadronic states.

Thanks for your attention!