

2026年新物理前沿与交叉科学研讨会
(NPhiS 2026)



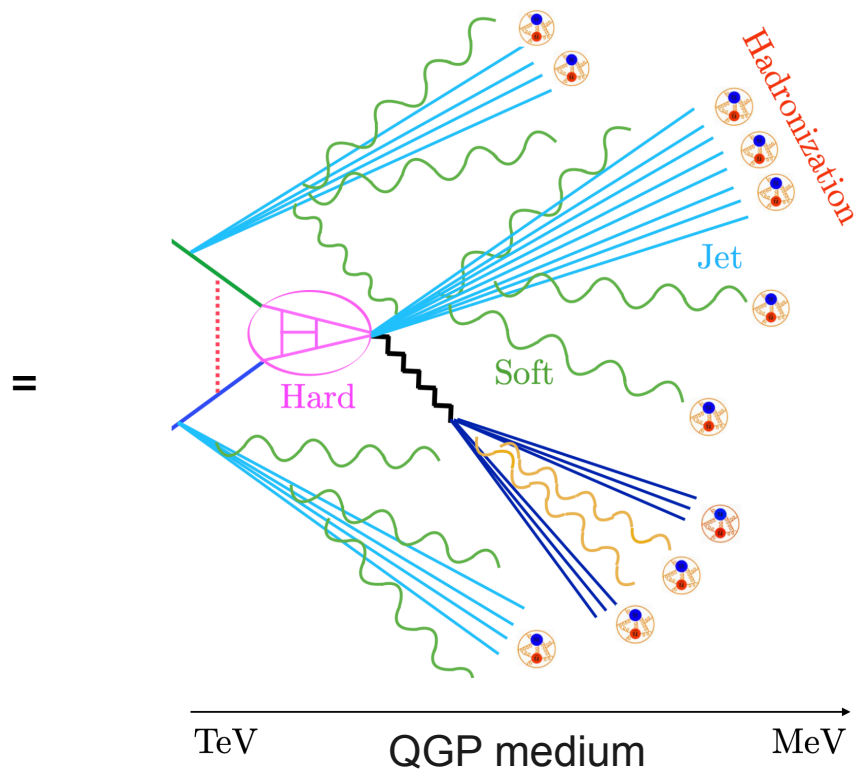
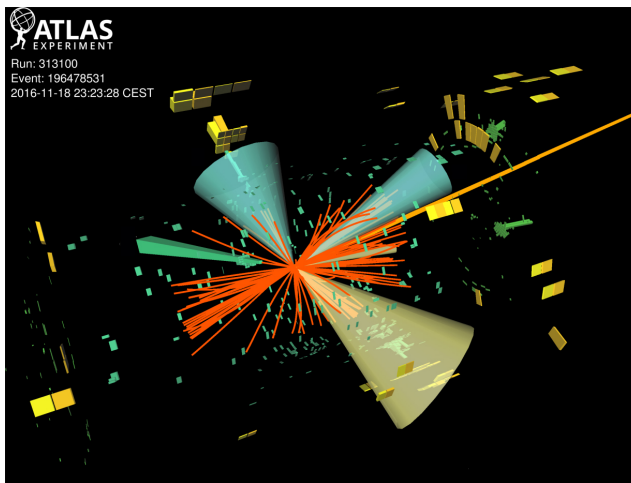
華中師範大學
CENTRAL CHINA NORMAL UNIVERSITY

Quantum simulation of QCD on the light front

—— Focus on Real-time dynamics of Jets in Heavy-ion collisions

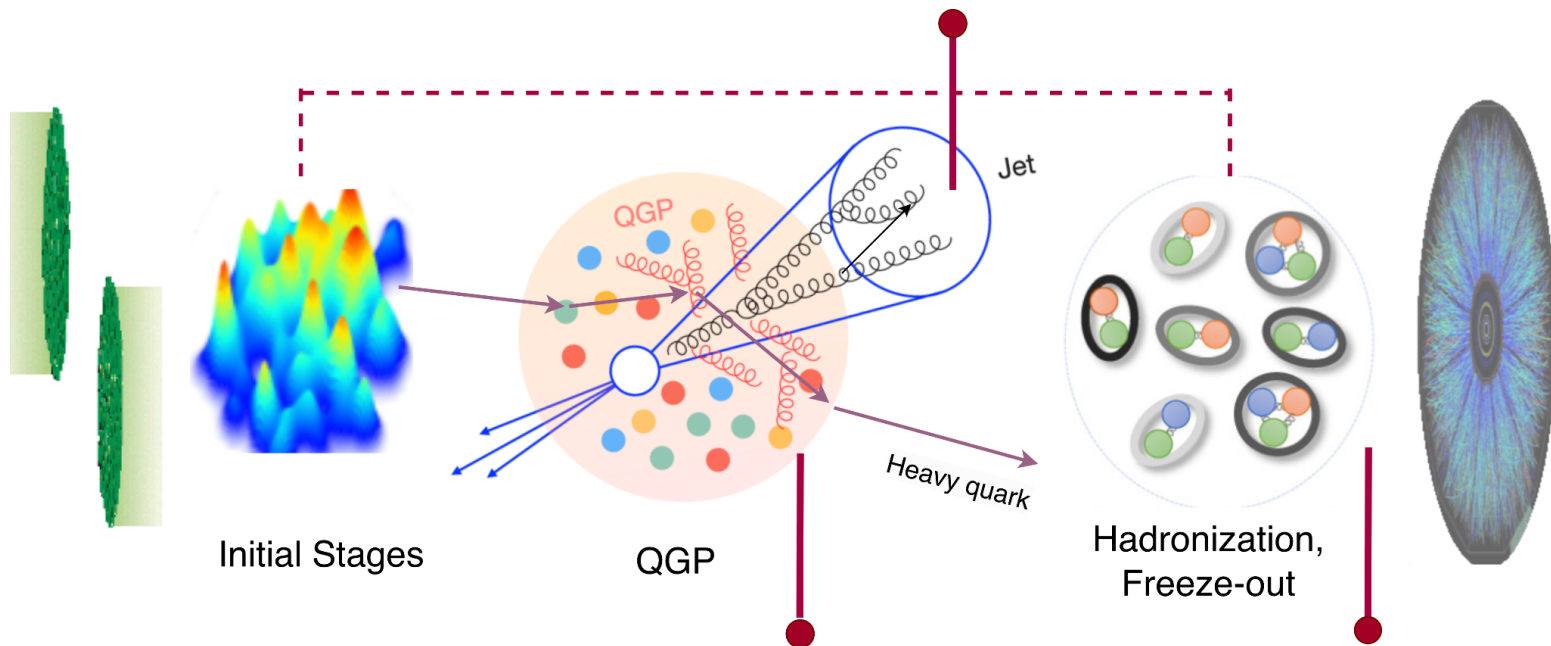
Wenyang Qian (钱文扬)
华中师范大学粒子物理研究所
2026.5.18

High-Energy Physics (HEP) scenario



High-Energy Physics (HEP) scenario

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



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

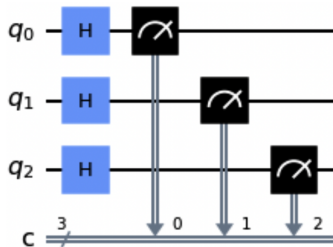
How hadrons form dynamically from deconfined matter?



ALICE



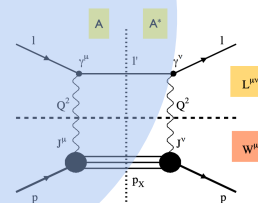
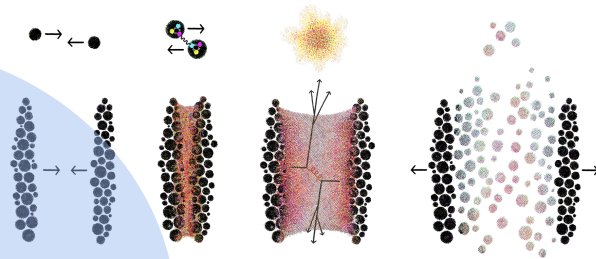
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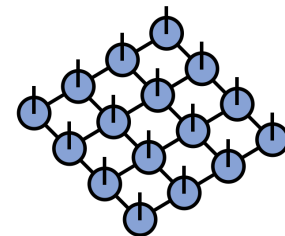
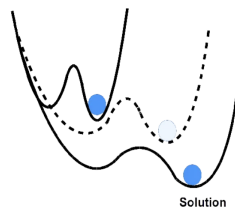
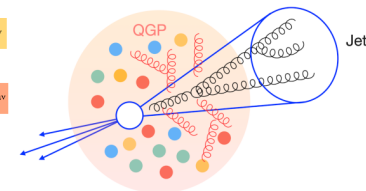
Experiments

Theory

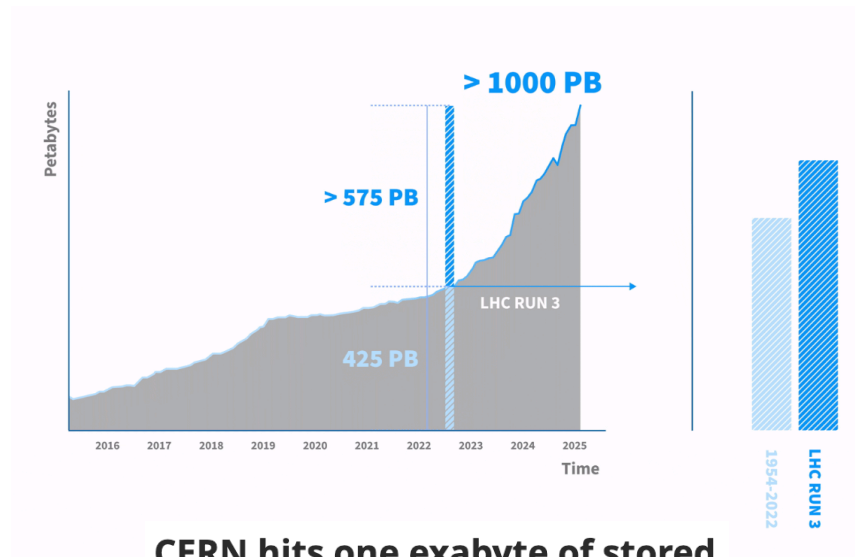
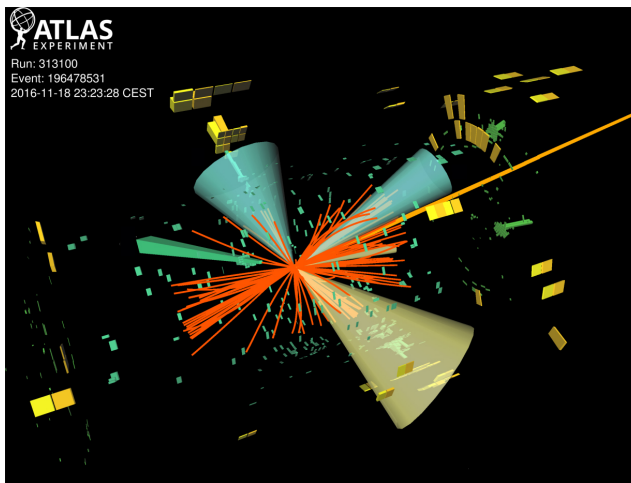
Quantum Computing (QC)



...



Experimental motivations for QC



CERN hits one exabyte of stored experimental data from the LHC

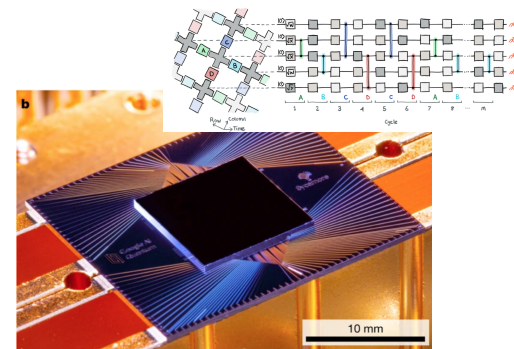
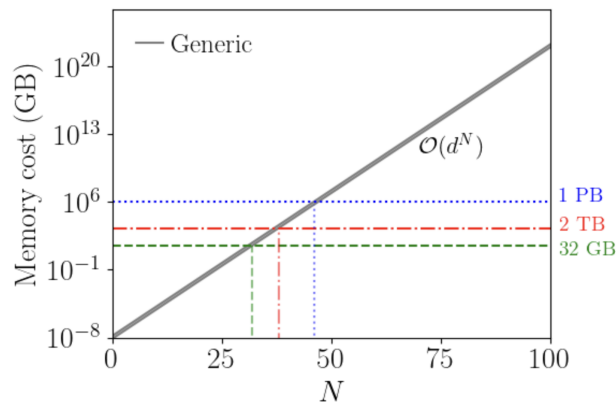
Excess data, quantum search speedup, optimization

See Hideki Okawa's review talk on Sunday

Theoretical motivations for QC

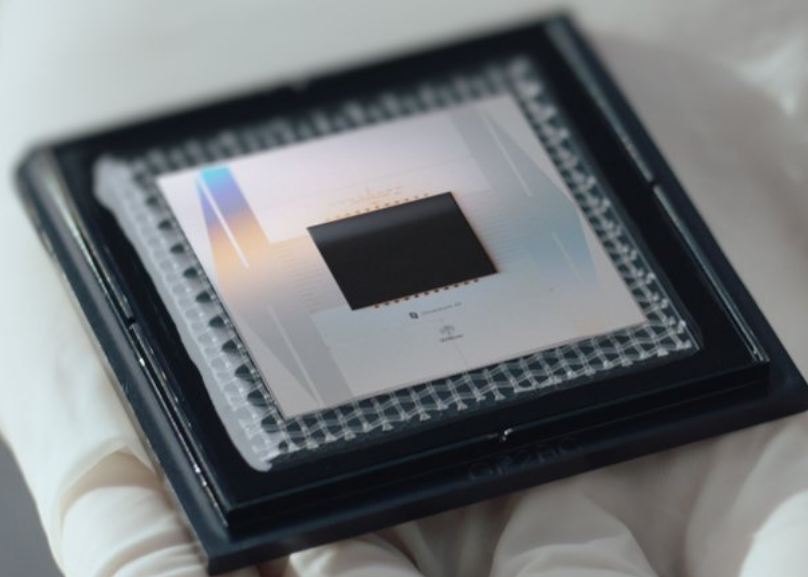
- Real-time correlator are prevented by the intrinsic sign problem with Euclidean lattice
- Hilbert space dimensionality grows exponentially (with particles), quickly surpassing classical resources
- Classically hard, real-time evolution are most natural on quantum computers

$$\begin{aligned}\langle \mathcal{O} \rangle &= \frac{\int \mathcal{D}\phi e^{-iS_I} \mathcal{O} e^{-S_R}}{\int \mathcal{D}\phi e^{-iS_I} e^{-S_R}} \\ &= \frac{\langle \mathcal{O} e^{-iS_I} \rangle_{S_R}}{\langle e^{-iS_I} \rangle_{S_R}}\end{aligned}$$



"Willow performed a standard benchmark computation in under 5 minutes that would take one of today's fastest supercomputers 10 septillion (that is, 10^{25}) years — a number that vastly exceeds the age of the Universe."
— Google, 2024

This is not a faster computer but new computational paradigm.



nature



HOLOGRAPHIC WORMHOLE

A step towards investigating quantum gravity using quantum computers

Carbon conundrum
EU climate plan

Integrated circuit
Global supply chain

The beak that was
Cretaceous bird fossil

Ecologists battle invasive
coconut palms

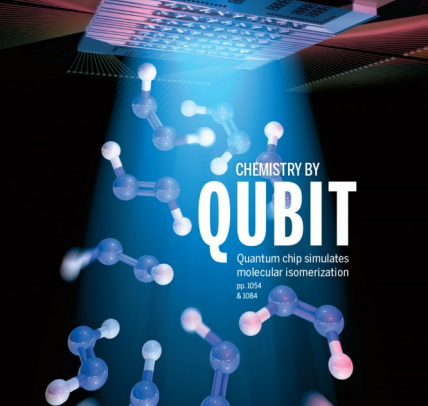
Digital health transformation
in India

Uncovering the origin of
Earth's water

Science

\$15
28 AUGUST 2020
ISSN 0036-8075

AAAS



CHEMISTRY BY QUBIT

Quantum chip simulates molecular isomerization

pp. 1054 & 1064

nature

outlook
lighting



HIGH FIDELITY

Silicon qubits cross key error-correction threshold for quantum computing

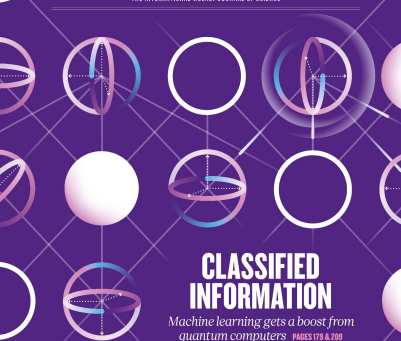
Coronavirus
Counting the global

Pregnancy health
Cell-free RNA in blood

Precision dating
Detailed timelines for

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE



CLASSIFIED INFORMATION

Machine learning gets a boost from quantum computers

CELL BIOLOGY
THE SECRET LIFE OF THE CELL
Insight into how cells drive cellular processes
PAGES 16

BIOTECHNOLOGY
REWRITING THE GENOME
How CRISPR-Cas9 can drive cellular processes
PAGES 16 & 17

MEDICAL RESEARCH
MALARIA TRANSMISSION
A possible role for mosquito resistance in malaria
PAGES 16 & 17

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0028-0836/22/0000

nature

outline
Cover vaccines



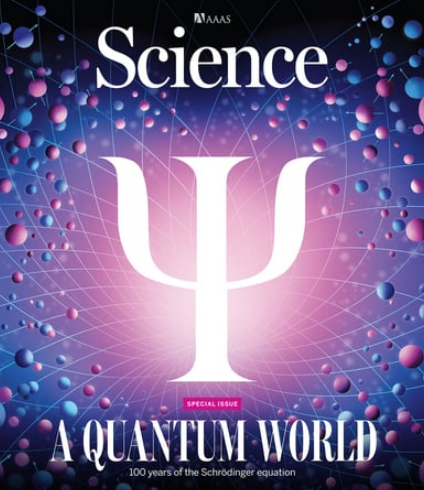
QUBIT QUOTA

Code cuts overhead for quantum error correction by 90%

Wooden ideal
The European wood

Liquid assets
A new way to use

Continental drift
Tracking the ancient



Science

Ψ

SPECIAL ISSUE

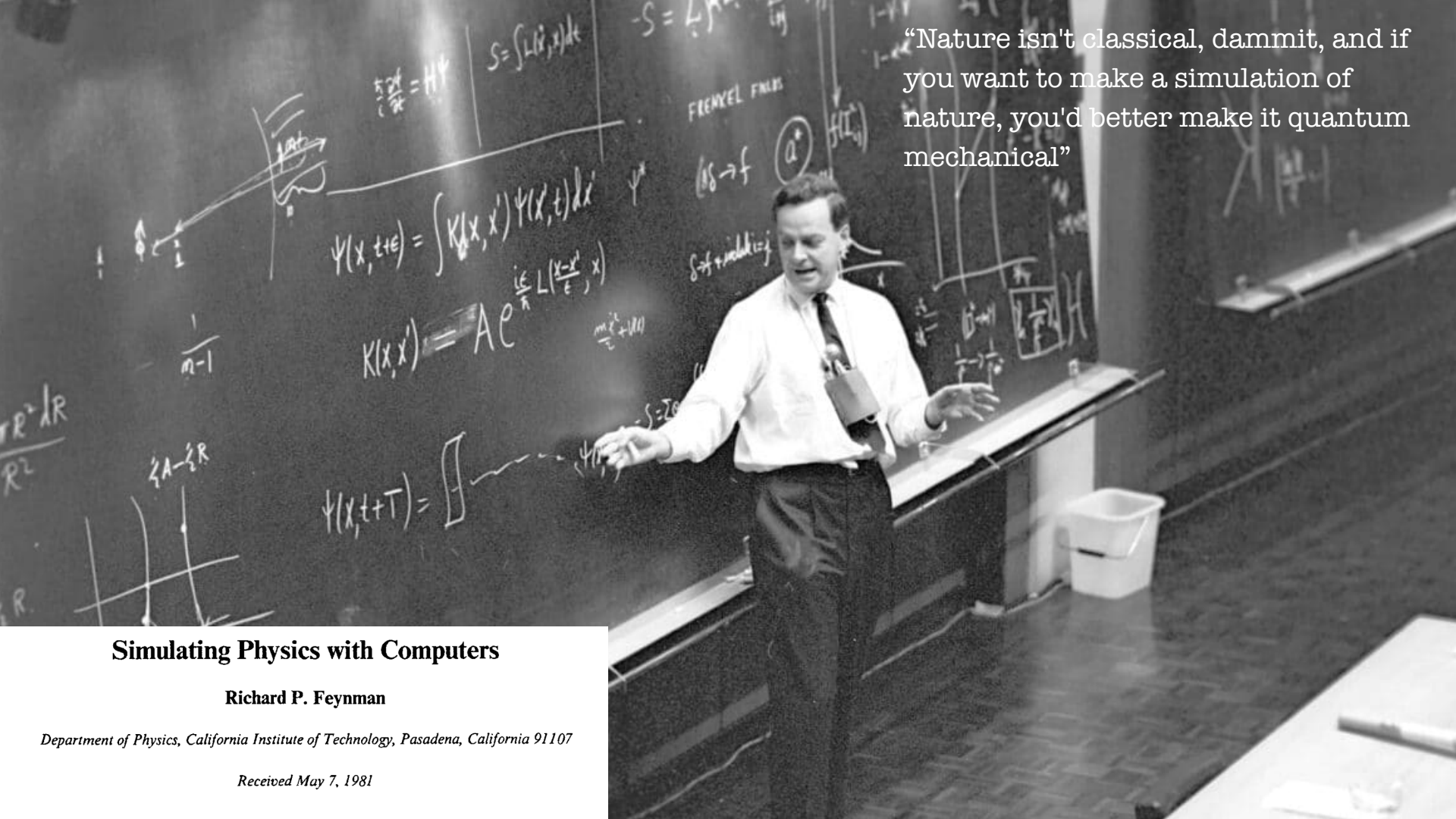
A QUANTUM WORLD

100 years of the Schrödinger equation

Can fixing the brain's plumbing
system ease dementia? P. 16

Wildlife crime standards
reform in China P. 33

Antimicrobial resistance
pre- and postantibiotic era P. 33



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

Simulating Physics with Computers

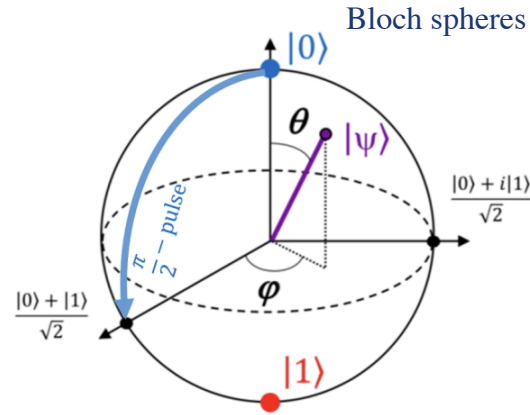
Richard P. Feynman

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

Received May 7, 1981

Quantum computing basics

- States via Quantum bit = qubit



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

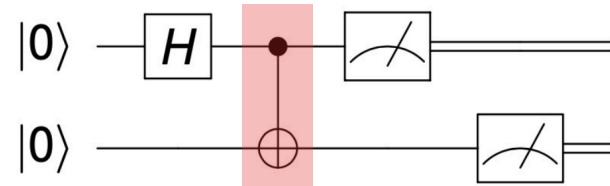
$$|\alpha|^2 + |\beta|^2 = 1$$

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

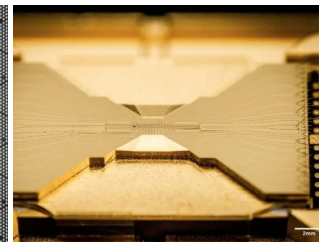
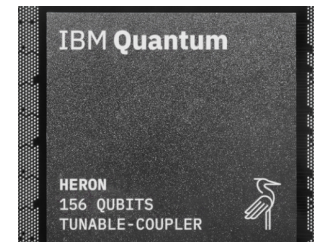
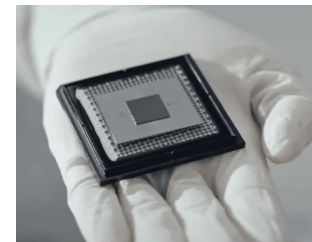
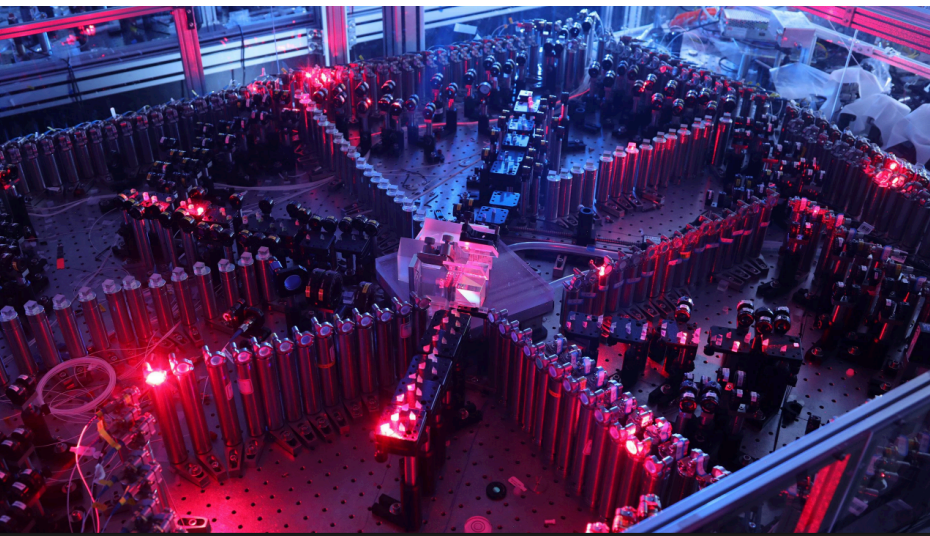
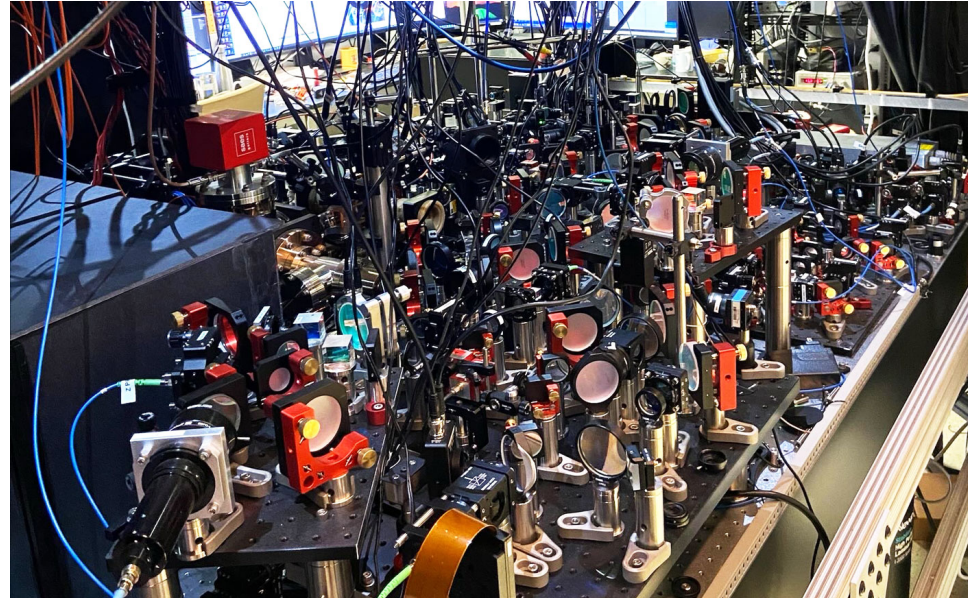
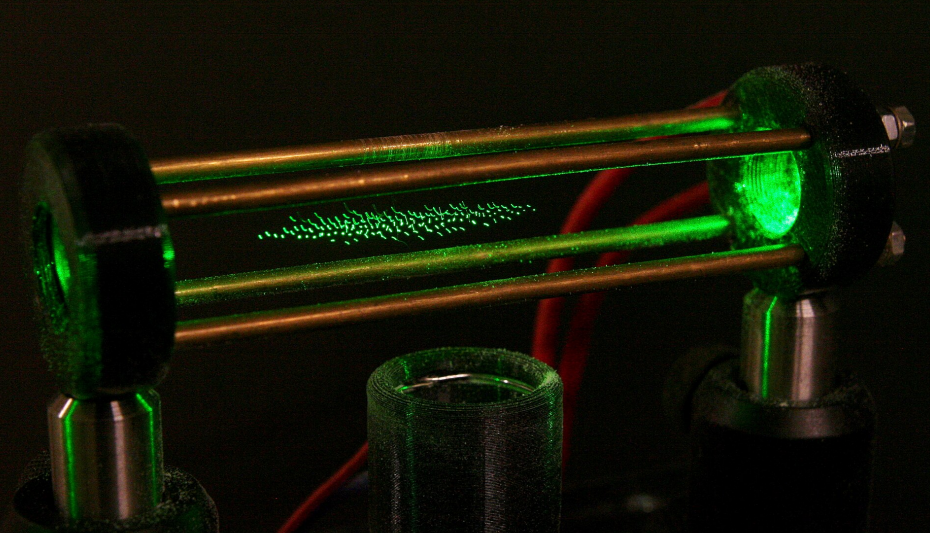


- Quantum operations via unitary quantum gate on qubits

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



=> truly empowers quantum computing



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



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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Philosophenweg 16, D-69120 Heidelberg, Germany

Michal P. Heller[†]

Max Planck Institute for Gravitational Physics (Albert Einstein Institute),
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Aleksas Mazeliauskas[‡]

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

Raju Venugopalan[§]

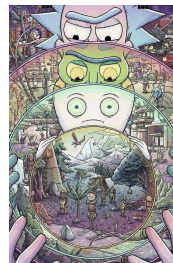
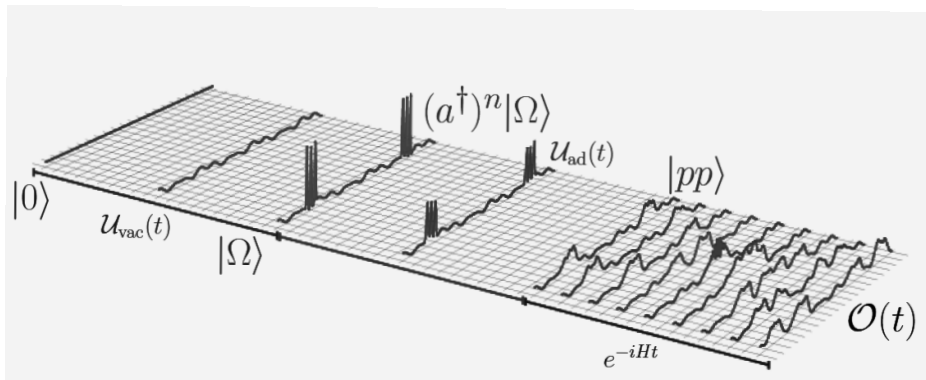
Physics Department, Brookhaven National Laboratory,
Upton, New York 11973-5000, USA

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



Season 2, Episode 6

Prototypical task

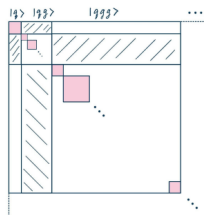
Quantum simulation of quantum field theory = perform “**ideal experiments**” on quantum computer

- Prepare initial state in quantum computer (**hadron structures**)
- Evolve state forward in time using Hamiltonian, for some specified time interval
- Measure observables by simulating measurement performed in idealized lab (**scattering problems**)

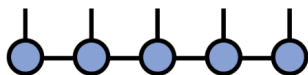
Jordan, Lee, & Preskill,
1111.3633, 1401.7115, 1703.00454

Quantum Information Science (QIS) toolkit

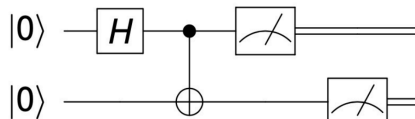
Hamiltonian methods



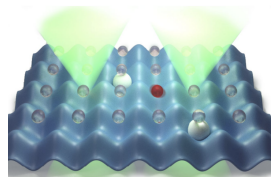
tensor network



quantum circuit



analog computation



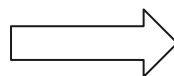
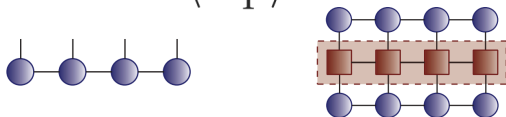
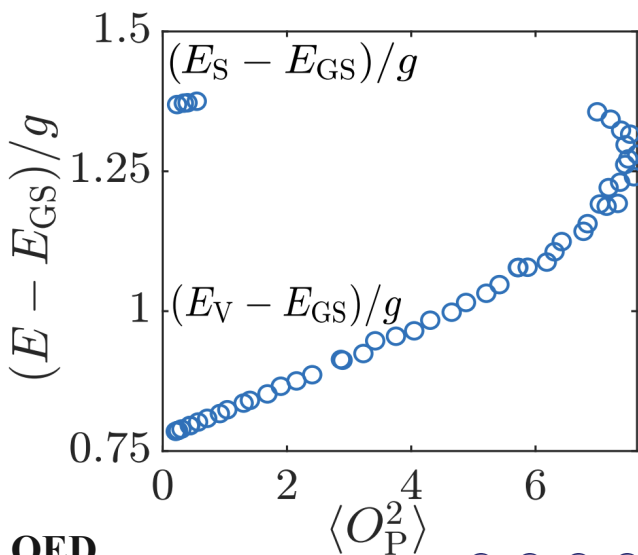
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Hadronic structure in HEP via QIS to LGT

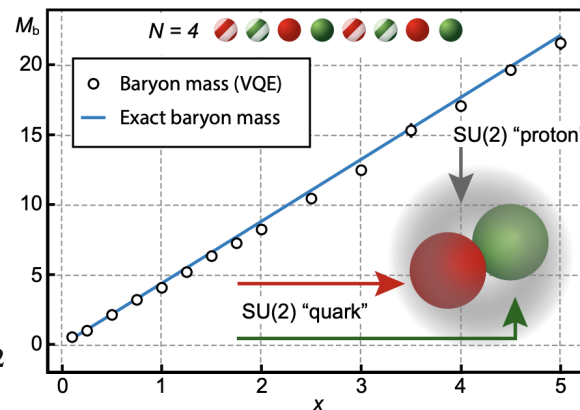
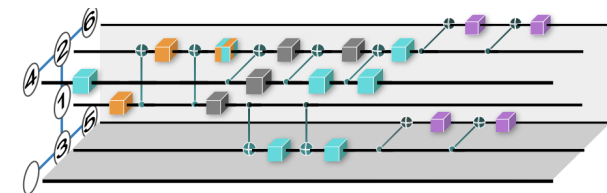
Quantum information science has emerged as one of the best tools to understand lattice gauge theory

Papaefstathiou et al, 2402.18429

Banuls et al, 1305.3765



QCD_2



...

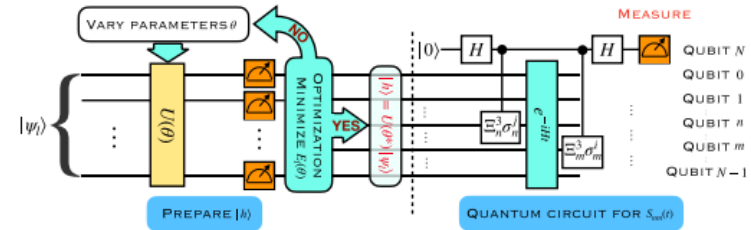
Real-time correlation in HEP via QIS to LGT

Parton distribution function (PDF), amplitudes (PDA), hadronic tensors evaluated from as real-time correlators from hadronic states

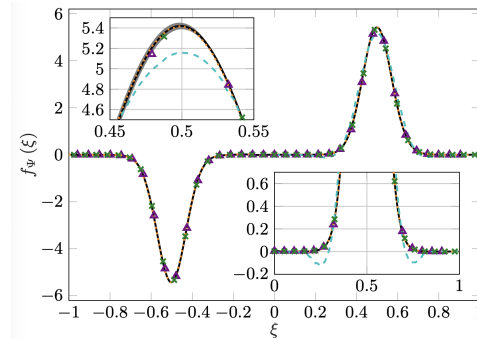
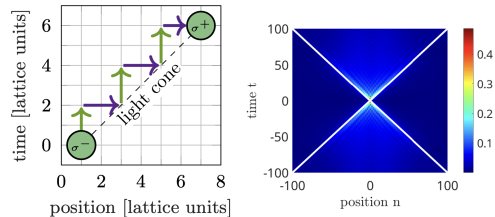
$$f_{q/h}(x) = \int_{-\infty}^{\infty} \frac{dt}{4\pi} e^{-itx\vec{n} \cdot \vec{P}} \langle h(\vec{P}) | \bar{\psi}(t\vec{n}) W(t\vec{n} \leftarrow \vec{0}) \vec{n} \cdot \vec{\gamma} \psi(\vec{0}) | h(\vec{P}) \rangle$$

Also see:

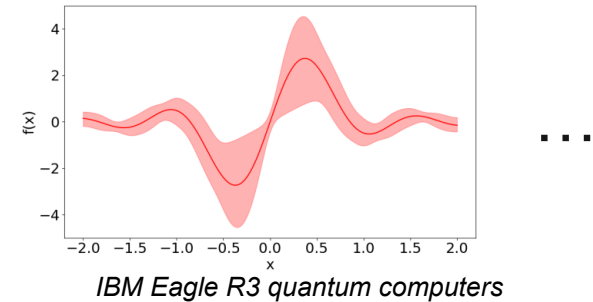
Lamm et al, 1908.10439
Mueller, Tarasov, Venugopalan, 1908.07051
Li et al, 2106.03865; 2207.13258
Kang, Moran, Nguyen, WQ, 2501.09738
Ikeda, Kang, Kharzeev, WQ, 2512.18062



Banuls et al, 2504.07508; 2409.16996

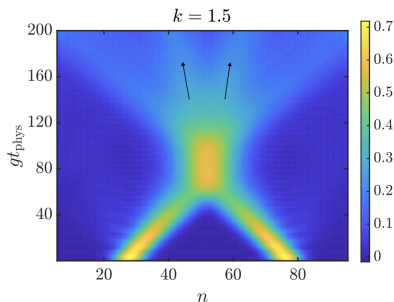


Chen et al, 2506.16829

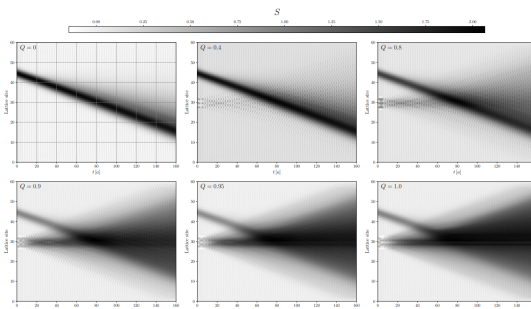


Real-time scattering in HEP via QIS to LGT

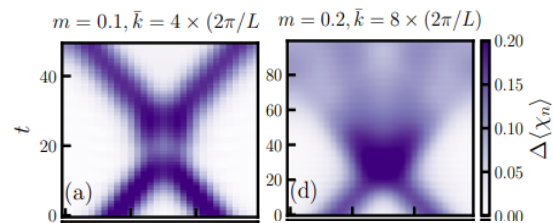
Recently there is also surge of studies in real-time scattering for HEP through lattice gauge theory



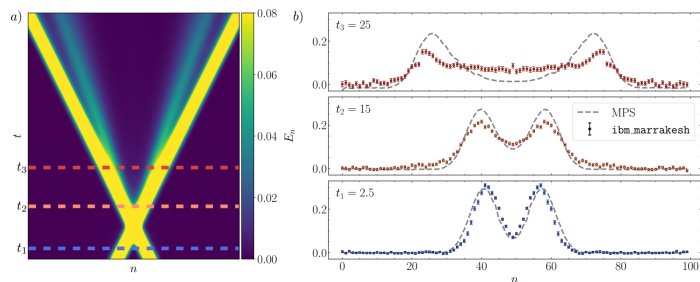
Bañuls et al, 2402.18429



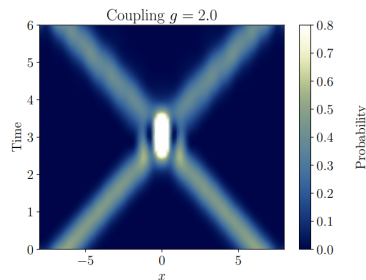
Barata and Rico, 2502.17558



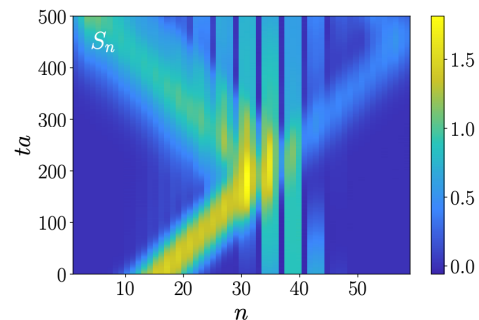
Chai et al, 2505.21240



Farrell et al, 2505.03111



Ingoldsby et al, 2505.03878



Barata, Hormaza, Kang, WQ, 2511.00154

(3+1)D Light-front QCD Hamiltonian + Classical background field

Li et al, 2002.09757; 2107.02225; 2305.12490 ...

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

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

McLerran and Venugopalan, 9309289 (1993)

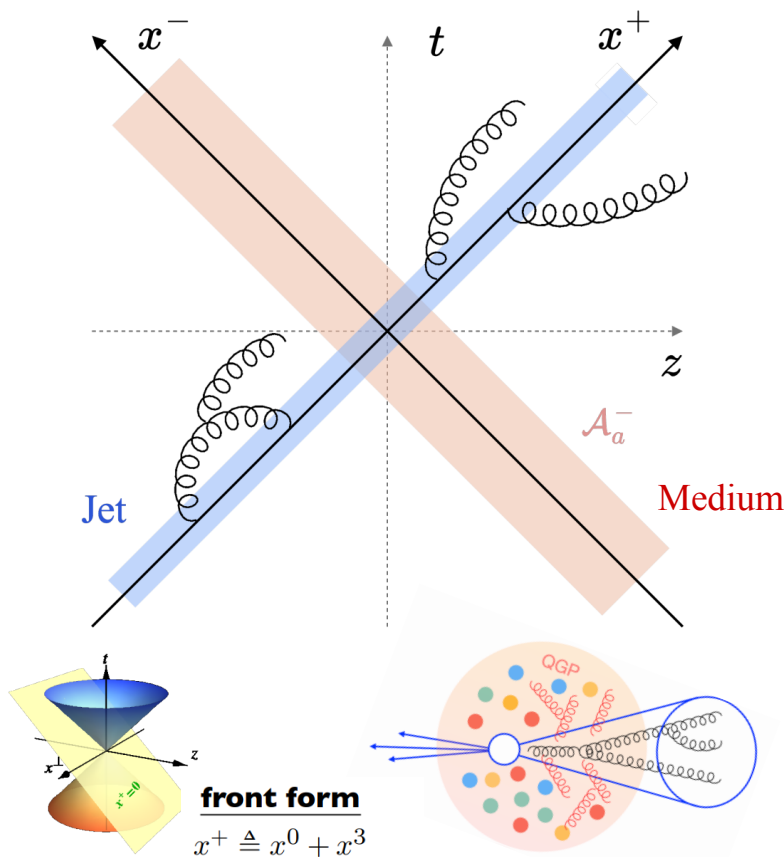
The light-front QCD Hamiltonian in $|q\rangle + |qg\rangle$ Fock space

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

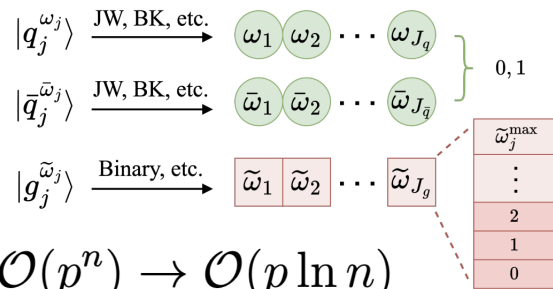
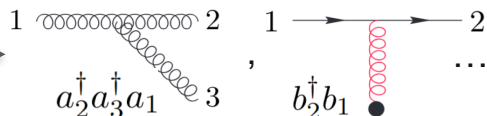
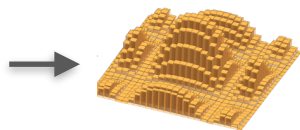
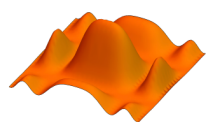
Fock sector	$ q\rangle$	$ qg\rangle$
$\langle q $		
$\langle qg $		

quark
 gluon

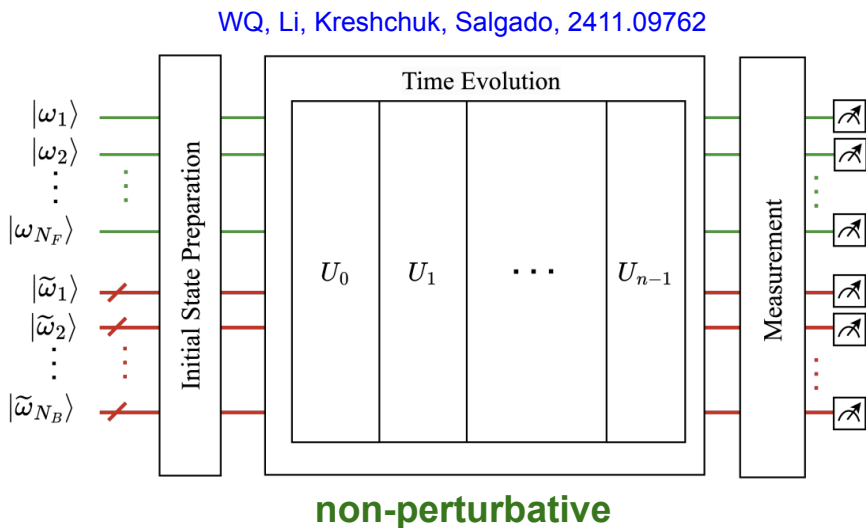
gluon from the background field



Quantum simulation of QCD on the qubits



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



=

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

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

Also see:

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

...

Efficient & universal framework to simulate (3+1)d QCD jet evolution in **medium** in **real-time**!

Extracting physical observable: jet quenching parameter

First qhat calculation on QC

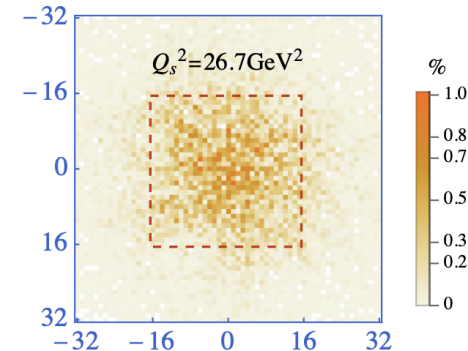
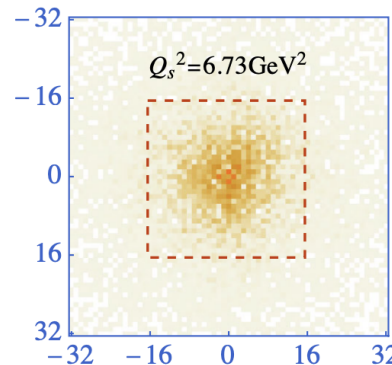
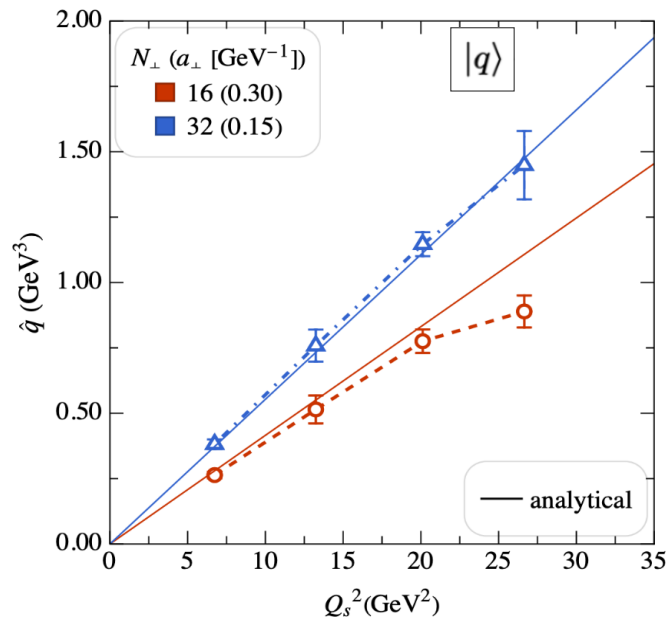
Barata, Du, Li, WQ, Salgado, 2208.06750

Jet quenching parameter:

$$\hat{q} = \frac{\Delta \langle p_{\perp}^2(x^+) \rangle}{\Delta x^+} = \langle p_{\perp}^2 \rangle / L_{\eta}$$

Eikonal analytical:

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



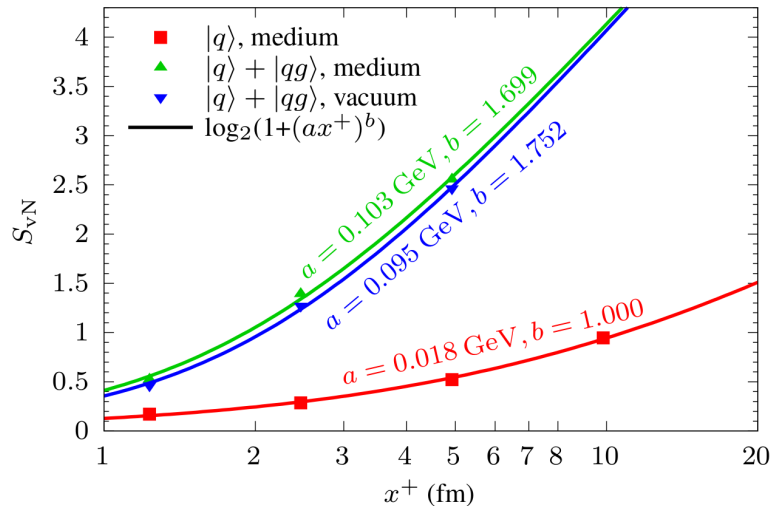
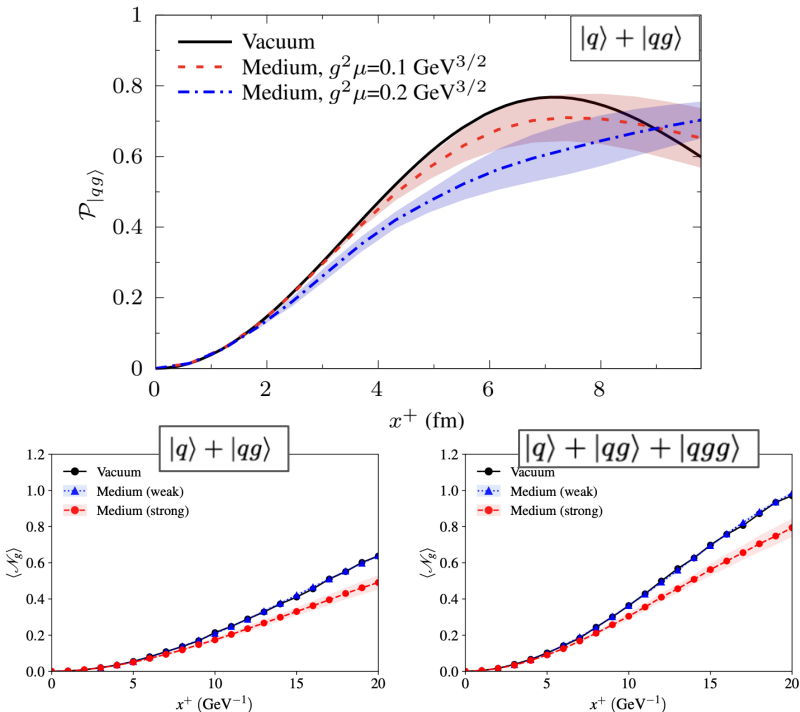
Dynamical observable: gluon production and entropy growth

Barata, Du, Li, WQ, Salgado, 2307.01792

Gluon production in strong & weak mediums
(error from stochastic medium)

Entropy expansion linear in Fock $|q\rangle$ and power-law in Fock $|q\rangle + |qg\rangle$ with radiation

Verified in leading $|q\rangle$ with classical calc, Barata et al, 2305.10476



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

Summary and future prospects

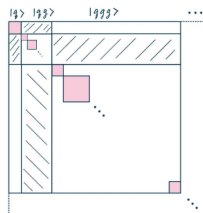
We discuss **Quantum Information Science** as a new tool that could help us understand HEP theory.

We talk about various application of quantum simulation, esp LGT and Light-front Hamiltonian.

Quantum simulation of QCD (jet) on the light front is a universal & scalable framework.

**For limitation of the talk, I apologize to have left out many interesting directions such as parton shower, thermalization, non-equilibrium dynamics, etc*

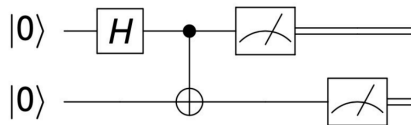
Hamiltonian methods



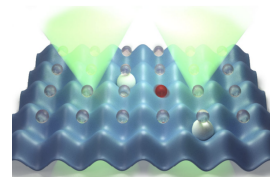
tensor network



quantum circuit

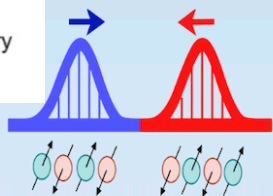


analog computation ...





Central China
Center for Nuclear Theory
华中核理论中心



QIS - HENP

C3NT Workshop:

Quantum Information Science in High Energy Nuclear Physics

June 15 - June 19, 2026

Central China Normal University, Wuhan, China

Workshop Webpage indico.ihep.ac.cn/event/27301/



We cordially invite interested researchers to participate in our upcoming C3NT International workshop – Quantum Information Science in High-Energy Nuclear Physics (QIS-HENP). This workshop aims to bring together experts in the field of quantum information science to explore innovative applications in high-energy physics and nuclear physics.

Organizing Committee

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Thank you!



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