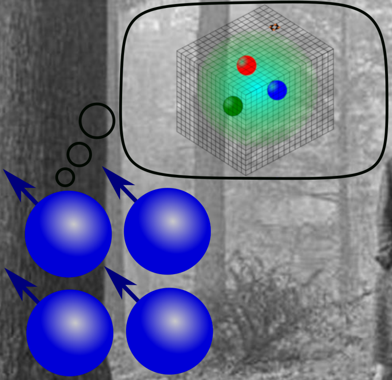
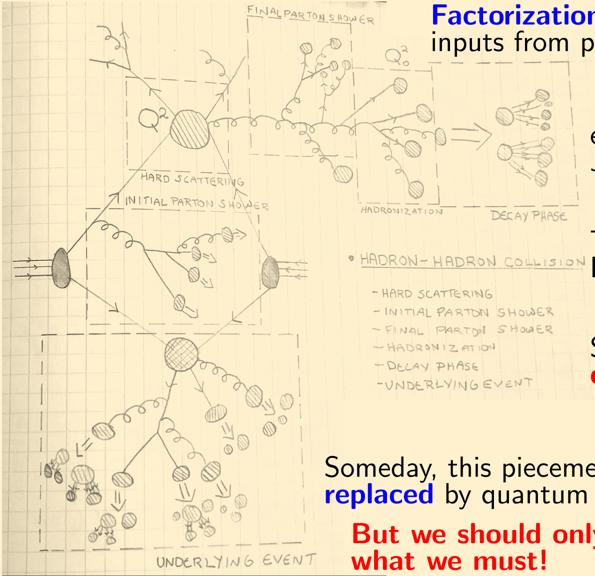
The Future of Quantum Simulations

Hank Lamm



Fermilab

Particle collisions require quantum advantage



Factorization separates non-perturbative inputs from perturbative calculations

e.g. PDF, TMD, Jet Functions[1]

This is an **assumption**! It gets $\mathcal{O}(\alpha)$ corrections

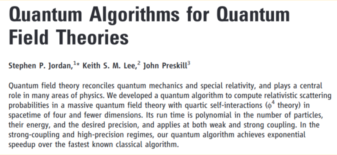
Showering based on **classical** models.

Someday, this piecemeal approach could be **replaced** by quantum simulation.

But we should only "quantumize" what we must!

[1] Bauer, C. W., M. Freytsis, and B. Nachman. In: (Feb. 2021). arXiv: 2102.05044 [hep-ph].

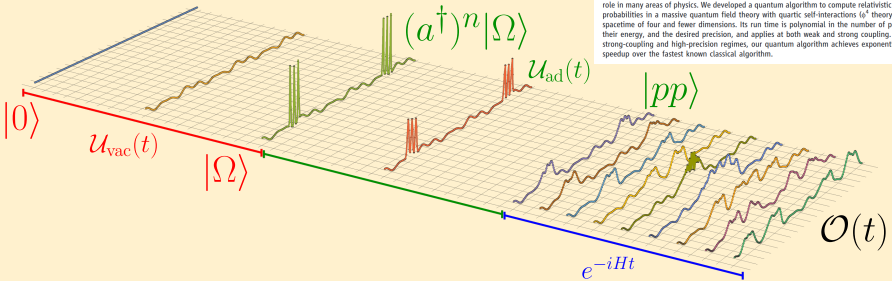
What might a galactic algorithm look like?



Quantum Algorithms for Quantum Field Theories

Stephen P. Jordan,[1*] Keith S. M. Lee,[2] John Preskill[3]

Quantum field theory reconciles quantum mechanics and special relativity, and plays a central role in many areas of physics. We developed a quantum algorithm to compute relativistic scattering probabilities in a massive quantum field theory with quartic self-interactions (ϕ^4 theory) in spacetime of four and fewer dimensions. Its run time is polynomial in the number of particles, their energy, and the desired precision, and applies at both weak and strong coupling. In the strong-coupling and high-precision regimes, our quantum algorithm achieves exponential speedup over the fastest known classical algorithm.



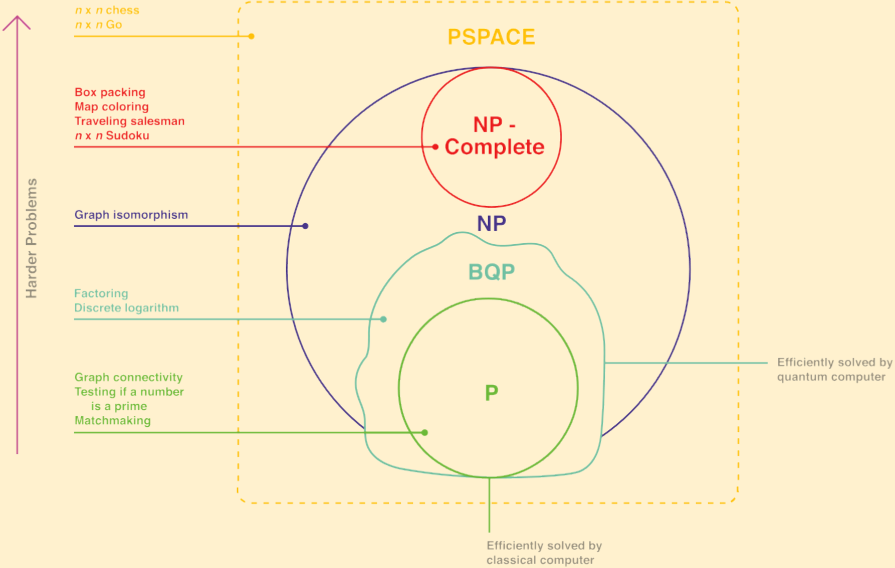
Vacuum Prep+**Adiabatic evolution**+**Trotterization**+Measurements[2]

Example: $|\langle p\bar{p}|U(t)|\pi\pi\pi\pi\rangle|^2$ needs $\mathcal{O}(10^7)$ **logical qubits**

$$\approx \left(\frac{3\text{ fm}}{0.05\text{ fm}}\right)^3 \times (3\text{ links} \times 11\text{ qubits} + 3\text{ colors} \times 2\text{ flavors} \times 2\text{ spins} \times 1\text{ qubit})$$

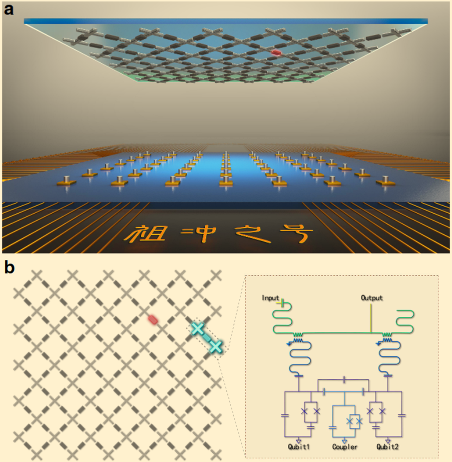
[2] Jordan, S. P., K. S. M. Lee, and J. Preskill. In: *Science* 336 (2012). arXiv: 1111.3633 [quant-ph].

Fundamentally, physics needs quantum computers.



Credit: Scott Aaronson

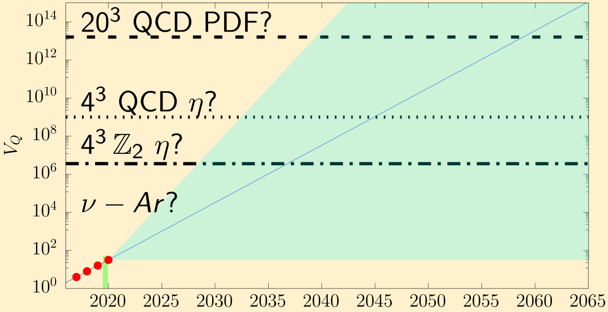
What is the state of QC? Nasty, brutish and short

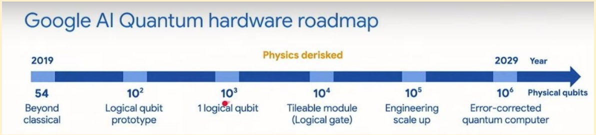


24 cycles of gates with **60** qubits[3]

[3] Zhu, Q. et al. 2021. arXiv: 2109.03494 [quant-ph].

Where could we be when EIC runs?





So ahead of the curve, the curve becomes a sphere

(1970s) Formulate th…

(1980s) Reac…

(1990s) … …cts

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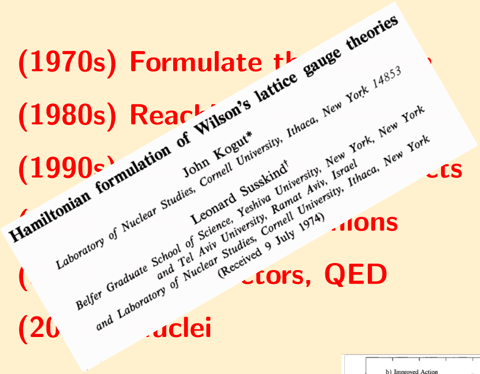
(20… …uclei


Hamiltonian formulation of Wilson's lattice gauge theories

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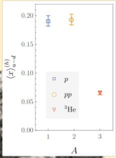
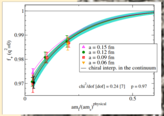
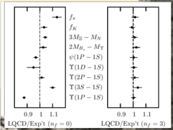
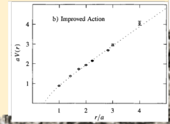
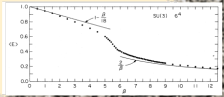
(Received 9 July 1974)

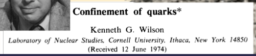











Confinement of quarks*

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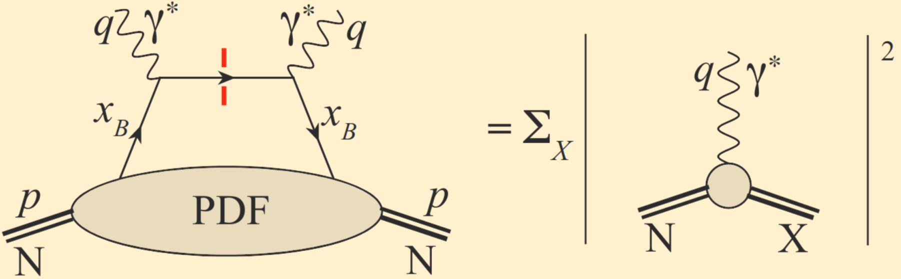
(Received 12 June 1974)

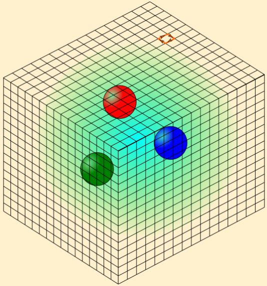
Cheaper: Response functions for nuclei[4]



Today:**Triton with 4q and $O(10)$ gates**
2030?:ν-**Ar with 4kq and 10^8 gates**

[4] Roggero, A. and J. Carlson. In: *Phys. Rev. C* 100 (2019). arXiv: 1804.01505 [quant-ph], Roggero, A., A. C. Y. Li, J. Carlson, R. Gupta, and G. N. Perdue. In: *Phys. Rev. D* 101 (2020). arXiv: 1911.06368 [quant-ph], Roggero, A. In: *Phys. Rev. A* 102 (2020). arXiv: 2004.04889 [quant-ph].

What will it take for practical quantum advantage?



$$N_q \propto N_{dof} \left(\frac{L}{a}\right)^d \text{ \& } N_g \propto (N_q)^\kappa \left(\frac{T}{a_t}\right)$$

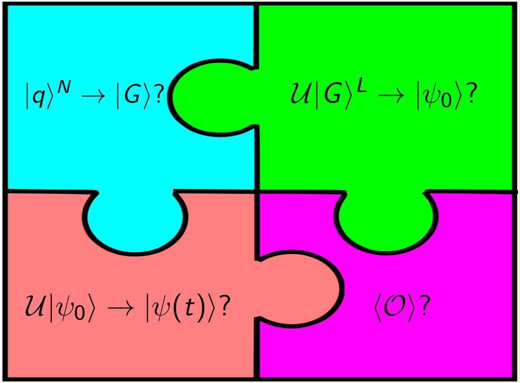
- **Hadron scattering**: $L, T = O(10)$ **fm,** $a, a_t = O(0.1)$ **fm**
- **Response funcs.**[5]: $L = O(1)$ **fm**, $T = O(10)$ fm, $a, a_t = O(0.1)$ fm
- **Transport coefficients**[6]: $L, T = O(1)$ **fm,** $a, a_t = O(1)$ **fm**

[5] **Lamm, H.**, S. Lawrence, and Y. Yamauchi. In: *Phys. Rev. Res.* 2 (2020). arXiv: 1908.10439 [hep-lat].

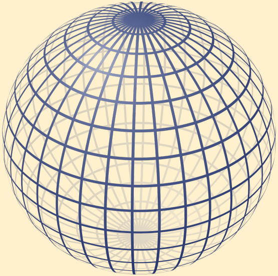
[6] Cohen, T. D., **H. Lamm**, S. Lawrence, and Y. Yamauchi. In: (Apr. 2021). arXiv: 2104.02024 [hep-lat].

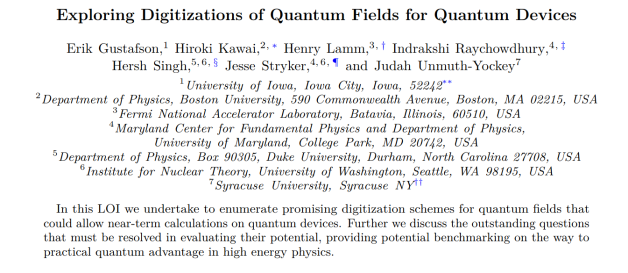
What “champagne problems” need to be solved?

- **Digitize**: How are bosons represented as registers?
- **Initalize**: How can registers be set to a state?
- **Propagate**: How can gates evolve states?
- **Evaluate**: How can observables be computed?



How do I digitize a gluon?





Exploring Digitizations of Quantum Fields for Quantum Devices

Erik Gustafson,[1] Hiroki Kawai,[2,*] Henry Lamm,[3,†] Indrakshi Raychowdhury,[4,‡] Hersh Singh,[5,6,§] Jesse Stryker,[4,6,¶] and Judah Unmuth-Yockey[7]

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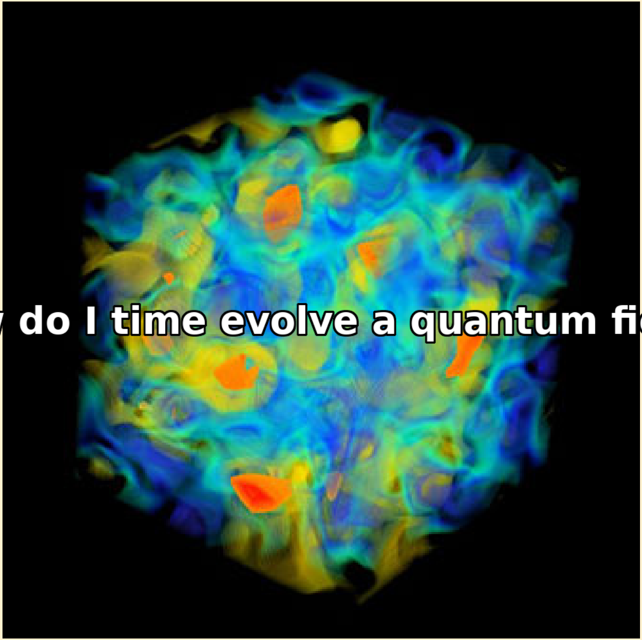
[2] *Department of Physics, Boston University, 590 Commonwealth Avenue, Boston, MA 02215, USA*
[3] *Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*
[4] *Maryland Center for Fundamental Physics and Department of Physics, University of Maryland, College Park, MD 20742, USA*
[5] *Department of Physics, Box 90305, Duke University, Durham, North Carolina 27708, USA*
[6] *Institute for Nuclear Theory, University of Washington, Seattle, WA 98195, USA*
[7] *Syracuse University, Syracuse NY*[††]

In this LOI we undertake to enumerate promising digitization schemes for quantum fields that could allow near-term calculations on quantum devices. Further we discuss the outstanding questions that must be resolved in evaluating their potential, providing potential benchmarking on the way to practical quantum advantage in high energy physics.

Combination of **Hamiltonian**, **Basis**, and **Truncation**

What qualities make a GOOD scheme?

- What **quantum resources** are required to get physical point?
- What symmetries are being **broken** in digitization?
- Can the scheme be simulated **classically**?

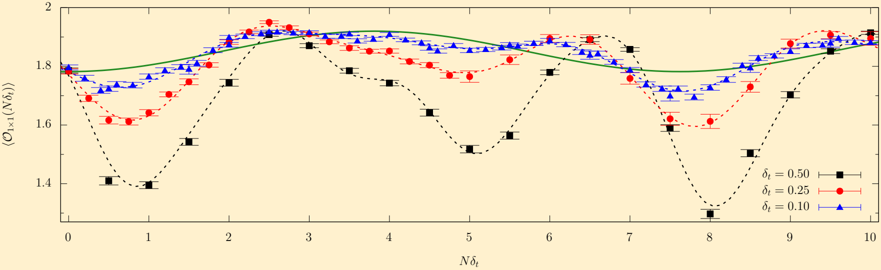


How do I time evolve a quantum field?

What is trotterization?

$$\mathcal{U}(t) = e^{-iHt} \approx \left(e^{-i\delta t \frac{H_V}{2}} e^{-i\delta t H_K} e^{-i\delta t \frac{H_V}{2}} \right)^{\frac{t}{\delta t}}$$

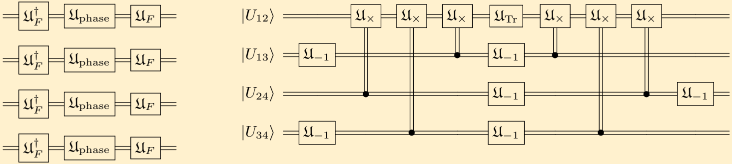
$$\approx \exp\left\{ -it \left(H_K + H_V + \frac{\delta t^2}{24} (2[H_K, [H_K, H_V]] - [H_V, [H_V, H_K]]) \right) \right\}$$



- Introduces **higher dimension operators**

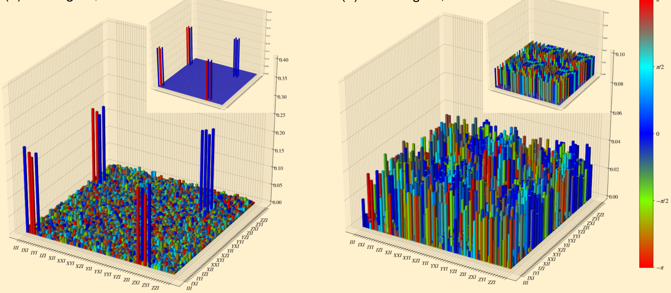
What low-level primatives are required for LGT?

How do we build $U_K = e^{iH_K}$ **and** $U_V = e^{iH_V}$?



D_4 gates have $\geq 80\%$ fidelity[7]

(a) Trace gate, $f = 0.857$ (b) Fourier gate, $f = 0.920$



[7] Alam, M. S., S. Hadfield, **H. Lamm**, and A. C. Y. Li. In: (Aug. 2021). arXiv: 2108.13305 [quant-ph].

It's time to go

So many things to do!...and lots can be done before the machine exists

- Digitizing SU(3)
  - **Spectroscopy** for approximations
  - Explicit **circuits**
- Reducing the errors
  - e.g. Finite volume, finite a, a_t, decimation errors, fidelity to obtain **realisitic** resource estimates
- Algorithms for **state prep, smearing**
- Investigate desirable properties
  - **PDF?, Viscosity?**
- **Actual** simulations of toy models
  - $\mathbb{Z}_2$ & $\mathbb{D}_4$