Christian Bauer Theory Group Leader PI Quantum Computing Physics Division LBNL

Christian Bauer QCD and Quantum Computing: First-principles simulation of non-perturbative physics

CMS Run/Event 262548/458269

CMS Run/Event 262548/458269

All computational Problems

Solvable by classical computer

All computational Problems

BERKELEY

QCD and Quantum Computing: First-principles simulation of non-perturbative physics Christian Bauer

Solvable by classical computer

All computational Problems

Solvable by quantum computer

Solvable by classical computer

All computational Problems

Solvable by quantum computer

Interesting problems lie here

Solvable by classical computer

Solvable by

Researcher Claims to Crack RSA-2048 With **Quantum Computer**
As Ed Gerck Readies Research Paper, Security Experts Say They Want to See Proof

 \mathbf{p}

All computational Problems

here

Simulating Physics with Computers

Richard P. Feynman

 \mathbf{p} externant of Physics, California Institute of Technology, Pasadena, California \ldots and \ldots simulation for \ldots \ldots \ldots \ldots

Received May 7, 1981

BERKELEY LAB

QCD and Quantum Computing: First-principles simulation of non-perturbative physics Christian Bauer

Solvable by classical computer

Solvable by

ther Claims to Crack RSA-2048 With Im Computer
lies Research Paper, Security Experts Say They Want to See Proof

All computational Problems

here

Solvable by assical computer

All computational Problems

Solvable by

ther Claims to Crack RSA-2048 With **Im Computer**

lies Research Paper, Security Experts Say They Want to See Proof

here

There are many HEP problems of this kind collider physics, neutrino physics, cosmology, early universe physics, quantum gravity etc

Recent review: CWB, Z Davoudi et al, Quantum Simulation for HEP (2204.03381)

Simulating Physics with Computers

Richard P. Feynman

 \mathbf{p} externant of Physics, California Institute of Technology, Pasadena, California \ldots and \ldots simulation for \ldots \ldots \ldots \ldots

Received May 7, 1981

 $e^{iS[\phi_j(x_i))} \rightarrow e^{-S[\phi_j(x_i))}$ Requires positive definite integrand, imaginary time

Standard approach to nonperturbative simulations: Lattice Gauge Theory, which performs path integral using Monte-Carlo integration

Can answer many static questions, but calculating dynamics requires real time, not imaginary time

Instead of doing Monte-Carlo simulation of path integral, can try to do time evolution using Schrödinger equation

$\langle X(T) | U(T, -$

Discretizing position x and digitizing field value $\phi(x)$ turn continuous (QFT) problem into discrete (QM) problem

$$
-T\big)\big|pp(-T)\bigg\|^2
$$

All elements in this expression in terms of fields $\phi(x)$ Both position x and field $\phi(x)$ are continuous

Go back to the S matrix elements mentioned before

 $\langle X(T) | U(T, -T) | pp(-T) \rangle$ 2

Basic idea is to map the infinite Hilbert space of QFT on a finite dimensional HS making this a QM problem

1. Create an initial state vector at time (-T) of two proton wave packets 2. Evolve this state forward in time from to time T using the Hamiltonian

-
- of the full interacting field theory
- 3. Perform a measurement of the state

3 basic steps:

Christian Bauer

QCD and Quantum Computing: First-principles simulation of non-perturbative physics

Christian Bauer

QCD and Quantum Computing: First-principles simulation of non-perturbative physics

Christian Bauer

QCD and Quantum Computing: First-principles simulation of non-perturbative physics

To yield finite-dimensional Hilbert space, have field configurations sample position and field values at discrete points

To yield finite-dimensional Hilbert space, have field configurations sample position and field values at discrete points

This complexity is completely unmanageable for classical computers, which explains why this has not been pursued

Quantum Algorithms for Quantum Field Theories

Stephen P. Jordan, ¹* Keith S. M. Lee, ² John Preskill³

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. Science 336 (2012) 1130

QCD and Quantum Computing: First-principles simulation of non-perturbative physics Christian Bauer T Chris
AB GREET CONDER GREEN WARD WATER COMPUTING: First-print Chris[.]
Chris computers was first possible was first possible was first possible was first possible. $Bauer$ so officiation of non-pertangalive priyoles

from this distribution. The asymptotic scaling

of the algorithm is given in Eq. 9 and Table 1. The

simulated scattering processes closely match ex-

Solvable by classical computer

Solvable by quantum computer

Time evolution in quantum field theories

All computational Problems

Quantum computers put first principles calculations of scattering cross sections (and other observables) in realm of possibility

Obtain results on realistic machines (with noise)

Quantum Simulations Research

Find Theory Formulation for SU(3)

Find efficient Quantum algorithms

Identify the right questions to address

Obtain results on realistic machines (with noise)

Quantum Simulations Research

Find efficient Quantum algorithms

Identify the right questions to address

Find Theory Formulation for SU(3)

Quantum Simulations Research

Identify the right questions to address

There are many energy scales that are present in LHC events, and all need to be accounted for in an adequate description

Energy of colliding protons

Scale of electroweak gauge bosons

Mass of the proton

Mass of the pion, the lightest hadron

Field configurations corresonding to given energy have wavelength

l ∼ 1/*E*

There are many energy scales that are present in LHC events, and all need to be accounted for in an adequate description

The largest and smallest energy scales set maximum and minimum wavelength of field configurations that need to be considered

The largest and smallest energy scales set maximum and minimum wavelength of field configurations that need to be considered

The largest and smallest energy scales set maximum and minimum wavelength of field configurations that need to be considered

The largest and smallest energy scales set maximum and minimum wavelength of field configurations that need to be considered

<u>,,,,,,,,</u>

Christian Bauer

សារសារសារសិលា

 0000

Runn

SURGIA

E ANNEVIRONALE

CONTENTIONS OF THE AUTHORITY OF THE AUTHORITY

alleelleele

Nature Reviews, Sherpa Collaboration

Christian Bauer

Remaining question: What exactly do we compute in perturbation theory and using quantum computing? Answer requires effective field theory (SCET for collider physics)

1. Use SCET to write observable in terms of matrix elements of long distance operators and

2. Use perturbation theory to compute matching

- matching coefficients
- coefficients
- matrix elements

3. Use quantum computer to compute long distance

Simulating Collider Physics on Quantum Computers Using Effective Field Theories

Christian W. Bauer \bullet and Benjamin Nachman \bullet [†]

Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

Marat Freytsis[‡]

NHETC, Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08854, USA and Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

(Received 18 May 2021; accepted 12 October 2021; published 18 November 2021)

Simulating the full dynamics of a quantum field theory over a wide range of energies requires exceptionally large quantum computing resources. Yet for many observables in particle physics, perturbative techniques are sufficient to accurately model all but a constrained range of energies within the validity of the theory. We demonstrate that effective field theories (EFTs) provide an efficient mechanism to separate the high energy dynamics that is easily calculated by traditional perturbation theory from the dynamics at low energy and show how quantum algorithms can be used to simulate the dynamics of the low energy EFT from first principles. As an explicit example we calculate the expectation values of vacuum-to-vacuum and vacuum-to-one-particle transitions in the presence of a time-ordered product of two Wilson lines in scalar field theory, an object closely related to those arising in EFTs of the standard model of particle physics. Calculations are performed using simulations of a quantum computer as well as measurements using the IBMQ Manhattan machine.

DOI: 10.1103/PhysRevLett.127.212001

QCD and Quantum Computing: First-principles simulation of non-perturbative physics **Christian Bauer** Christian Bauer $L_{\rm H}$ center-of-mass energy, the number of $\sigma_{\rm H}$ and $\sigma_{\rm H}$ and $\sigma_{\rm H}$ nd Quantum Computing: First-principles simulation of non-perturbative physics 37 \mathbf{f} wilson line for 3 lattice sites and ¹ models and ¹ models per sites and ¹

It is well well known that the set of the se simulate the time evolution of \sim The main technique involves disretizing the spatial degrees of freedom by introducing a lattice [2–4], and digitizing the field values at a given lattice point \mathbf{v} uncountably infinite dimensional Hilbert space of standard \Box finnel contract efficiently where no denotes the dimensionality of the dimensionality of the Hilbert space of the Hilbert sp for a given lattice point, N is the total number of lattice points in each spatial direction, and d represents the number Soft matrix elements \mathcal{L} discretization and finite volume of space introduces introduced intro \blacksquare in and \blacksquare and \blacksquare and \blacksquare (expectation values of Wilson continuum. In particular, one finds \overline{a} Nδx δx ≲ E ≲ lines) can be computed efficiently on quantum described is directly proportional to the number of lattice \mathbf{r} sites per dimension. In principal \mathbf{r} dynamics of the Large Hadron Collinder (LHC), one would computers

Can ontain results that agree with theory expectations from quantum hardware

Quantum Simulations Research

Find Theory Formulation for SU(3)

There are many different parts of the theory that need to be worked out when formulating a Hamiltonian lattice gauge theory

- 1. How to formulate a lattice theory that reproduces SU(3) in the limit of vanishing lattice spacing
	- Whether to add any additional expansions in the theory
- 2. What basis to choose for the Hilbert space
- 3. How to implement gauge invariance
- 4. How to truncate the theory (how to choose a discrete set of field values)

Goal is a Hamiltonian Lattice theory that reproduces QCD in continuum limit

A Trailhead for Quantum Simulation of SU(3) Yang-Mills Lattice Gauge Theory in the Local Multiplet Basis

Anthony Ciavarella,^{1,*} Natalie Klco,^{2,†} and Martin J. Savage^{1,‡} ¹*InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, WA 98195, USA California Institute of Technology, Pasadena CA 91125, USA* (Dated: February 23, 2021 - 1:41)

²*Institute for Quantum Information and Matter (IQIM) and Walter Burke Institute for Theoretical Physics,*

QCD and Quantum Computing: First-principles simulation of non-perturbative physics extending Christian Bauer integration. Christian Bauer connectivity,int
International
International \mathfrak{h} n aue
Bi ula
C Plaquettesti:
inc Ch
|-First 8 6 6 6 6 6 6 6 6 6 6 6 6 7 6 6 6 6 7 6 6 7 7 8 6 6 7 7 8 6 7 7 8 6 7 7 8 7 7 8 7 7 8 7 7 8 7 7 8 7 7 8 7 7 8 Truncationn
C าtเ \cup l Ω CD and (an
an

on qubit degrees of freedom. This paper considers the implications of representing SU(3) Yang-Mills

I.

II.

III.

 $\overline{}$ is a lattice of irreducible representations in a global basis of projected glob

IV.

\mathbf{V}^* aintiminations in the quantum simulations in the quantum simulation of gauge field \mathbf{V}^* states in the Hilbert space to be unphysical—theoretically benign, but experimentally dicult to Phys.Rev.D 103 (2021) 9 $t = t + \sqrt{2 \cdot t + 1}$ with the Hilbert space and modifying the field the fi $arXiv:2101.10227v2$

Part 1: What lattice Hamiltonian to use in the without truncation.

$\frac{1}{2}$ in this case the Koqut-Susskind Hamiltonian is used In this case the Kogut-Susskind Hamiltonian is used

directions using a cubic lattice of sites and defining link variables connecting adjacent sites of this underlying grid.

QCD and Quantum Computing: First-principles simulation of non-perturbative physics Christian Bauer Christian Bauer
Quantum Computing: First-principles simulation of non-perturbative ation of non-perturbative physics 41

In this case a basis in representation of SU(3) was chosen in which electric Hamiltonian is diagonal n representation of SU(3) was cho: *this case a basis in representation of SU(3) was chosen in which electric* ˆ is 2*a^d*² acio n r ˆ (*b*) *|* rese aadar Ur
taninn id $\overline{1/2}$ diagona h chosen ìk
 In which **h** elec i
Li

where *g* is the strong coupling constant, *a* is the lattice spacing between adjacent sites, and *d* is the number of

Part 2: How to represent basis to choose for Hilbert space spatial dimensions. In the irrep basis of tensor indices that are labeled by (*p, q*), the number of (fundamental, anti-fundamental) indices with total dimension s_{scat} over the more contribution is a sum over the chromo-electric contributions, as first discussed by s_{scat} Kogut and Susskind [58],

$$
\sum_{b} |\hat{\mathbf{E}}^{(b)}|^2 |p, q\rangle = \frac{p^2 + q^2 + pq + 3p + 3q}{3} |p, q\rangle
$$

$$
\dim(p, q) = \frac{(p+1)(q+1)(p+q+2)}{2}
$$

$$
|\hat{\mathbf{E}}^{(b)}|^2 |p, q\rangle = \frac{p^2 + q^2 + pq + 3p + 3q}{3} |p, q\rangle
$$

$$
\dim(p, q) = \frac{(p+1)(q+1)(p+q+2)}{2}
$$

QCD and Quantum Computing: First-principles simulation of non-perturbative physics Christian Bauer *|*E *|* ² *[|]p, q*ⁱ ⁼ *p*² + *q*² + *pq* + 3*p* + 3*q* ation of non-perturbative physics 42

QCD and Quantum Computing: First-principles simulation of non-perturbative physics **COLAGE CAP COLAGE COLLUCTURE ISL-DITIONES SITTUICITY OF THE MULTIPLE INTO ACT ACT COLLUCTURE IN A COLLUCTURE OF COLLUCTURE OF COLLUCTURE INTERNATIONAL COLLUCTURE OF COLLUCTURE INTO A COLLUCTURE INTO A COLLUCTURE OF THE CO**

$$
\overline{\mathbf{Q}}_\ell,d\rangle_\Gamma\,\ket{\mathbf{C}_1,a,b}\ket{\mathbf{Q}_\ell,c,d}\ket{\mathbf{R}_t,g,h}
$$

Part 3: How to implement gauge invariance **EVECT of EQS** equation of Fig. 1, an example of In the standard formulation of Hamiltonian lattice gauge theory [58], wavefunctions carry Clebsch-Gordon (CG)

In this case gauge invariance is implemented by requiring that representations satisfy Gauss' law, therefore putting restrictions on each plaquette factors at each vertex with the electric of each provided in the early contation of the notation of ϵ

Part 4: How to truncate the theory total angular momentum *^j* value of the link state by *[±]*¹

QCD and Quantum Computing: First-principles simulation of non-perturbative physics **Christian Bauer Christian Bauer Christian multiplets are directions are directions are directions are directions of the form of the form of the form of the form** α application of the fundamental representation. The link Hilbert space can be captured through the connectivity of a single constrained hexagonal lattice of quantum states (lower-left panel) or through a pair of correlated one dimensional lattices

S In this case theory is truncated by the maximum allowed p and q values of the representation at each link

All details in place \Rightarrow theoretical framework. Now needs to work out efficient quantum algorithms and get results from hardware

Christian Bauer

BERKELEY LAB SERKELEY LAB COD And Quantum Computing: First-principles simulation of non-perturbative physics 45 45 45 45 45 1789

-
- Paper presented above was first (and essentially still only one) that could do real SU(3) calculations on quantum hardware
	- Results could be obtained on a 3x2 lattice

Paper presented above was first (and essentially still only one) that could do real SU(3) calculations on quantum hardware Fig. 12. Two middle qubits were used to store the state of the system and, when the measurement error mitigation

H • H eⁱ↵*Z*^ˆ *H • H eⁱZ*^ˆ *.* (43)

QCD and Quantum Computing: First-principles simulation of non-perturbative physics Christian Bauer FIG. 12. The (trivial-) vacuum-to-vacuum persistence probability *[|]*h00*[|] ^U*ˆ(*t*) *[|]*00i*[|]* field (right panel) of the two panels of the two participates in the two parameters of the color particle system in the color particle system of the color particle is a 1st-order of 1st-order in the 3 and 3. Evolution is a Trotterinan in Eq. (39). Points correspond to \mathbf{P} , \mathbf{P} , \mathbf{P} , \mathbf{P} , \mathbf{P} , \mathbf{P}

2.0 Electric Energy Electric Energy 1.5 1.0 0.5 0.0 0.0 0.5 1.0 1.5 2.0 2.5 3.0 Time

Results could be obtained on a 3x2 lattice

 \overline{X} All details in place \Rightarrow theoretical framework. Now needs to work out efficient quantum algorithms and get results from hardware

We very recently realized that adding an additional expansion can lead to dramatic simplifications in the lattice theory

- 1. How to formulate a lattice theory that reproduces SU(3) in the limit of vanishing lattice spacing
	- Whether to add any additional expansions in the theory
- 2. What basis to choose for the Hilbert space
- 3. How to implement gauge invariance
- 4. How to truncate the theory (how to choose a discrete set of field values)

A $1/N_c$ expansion in QCD is quite standard in many classical applications. Can it help in quantum simulation?

-
- Gives dramatic simplifications on the size of the allowed Hilbert space and dramatically simplifies interactions

Results obtained on 8x8 lattice (25 times more plaquettes than previous best)

A $1/N_c$ expansion in QCD is quite standard in many classical applications. Can it help in quantum simulation?

I believe that this opens the door for quantum simulation of QCD through a systematic expansion, where higher order effects can be included as computing hardware roves

-
- Gives dramatic simplifications on the size of the allowed Hilbert space and dramatically simplifies interactions
- Results obtained on 8x8 lattice (25 times more plaquettes than previous best)

Quantum computers open the door to perform currenty unattainable simulations

- Using Effective Field Theories takes best advantage of quantum hardware
- This will open door for exploring the most fundamental forces of the universe

QCD and Quantum Computing: First-principles simulation of non-perturbative physics Christian Bauer

QCD and Quantum Computing: First-principles simulation of non-perturbative physics Christian Bauer

