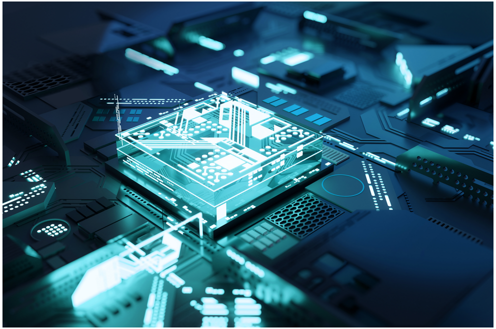
Quantum Computing: a future perspective for scientific computing

Quantum Computing

Karl Jansen

Cairns, The XVIth Quark Confinement and the Hadron Spectrum Conference, 19.8.2024

Overview

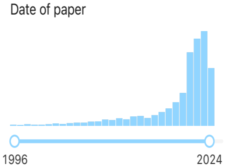


- Short intro to quantum computing
- Application to QED
  in 1+1, 2+1 and 3+1 dimensions
- Non-abelian gauge theories
- Real time dynamics
- PDFs
- Conclusion

Statistics

According to inspire, 4.8.24:

> *find t qubits:* since 2020 1,327 papers



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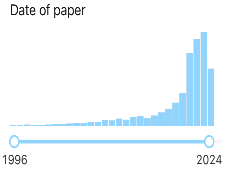
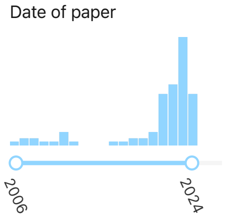


- *find t qudits* 107 papers



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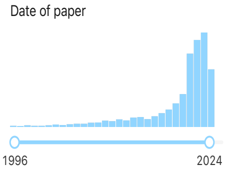

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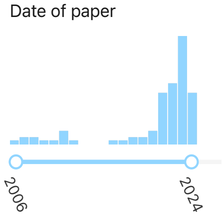
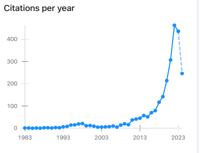
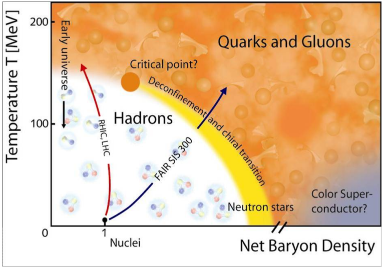


> Feynman's "Simulating physics with computers",
> $\rightarrow$ 2,521 citations



Where Monte Carlo fails

- Non-zero chemical potential
  - early universe
  - neutron stars, new phases, ...



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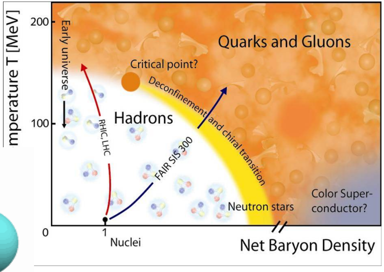
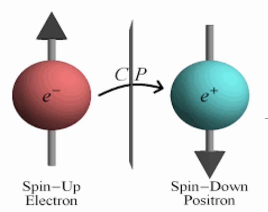
  - CP-violation
  - topological materials, ...





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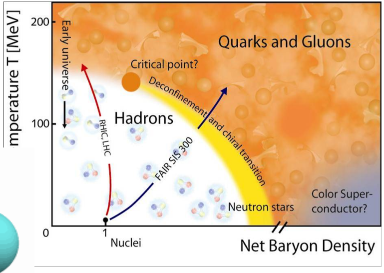
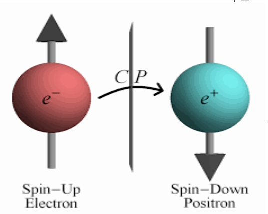
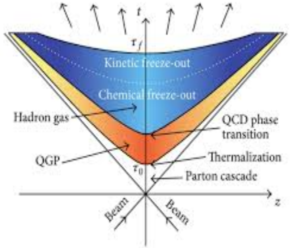
> Real time dynamics
  - heavy ion collisions, scattering
  - quenches, ...







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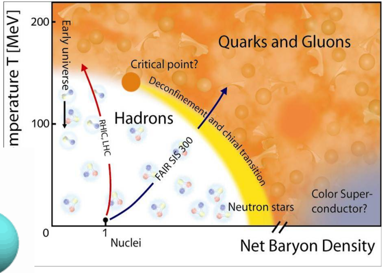
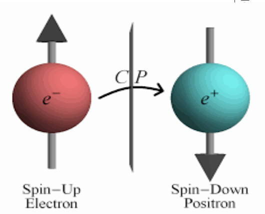
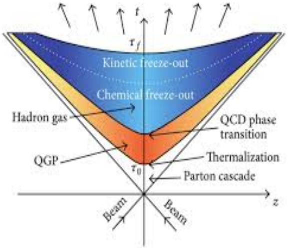
- Minkowski time observables, PDFs, S-matrix, ...







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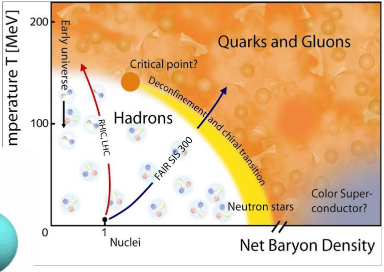
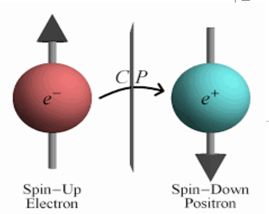
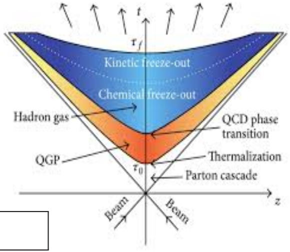






$\Rightarrow$ Hamiltonian formulation

A problem with Hamiltonian approach

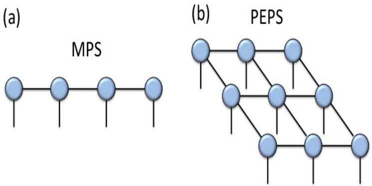
- determine wave function $|\Psi>$

$|\Psi>=\sum_{i_1,i_2,\cdots,i_N} C_{i_1,i_2,\cdots,i_N}|i_1 i_2\cdots i_N>$

$C_{i_1,i_2,\cdots,i_N}$ coefficient matrix with 2^N entries

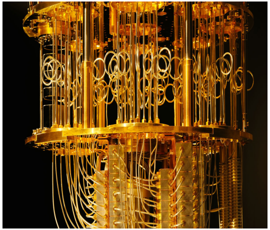
$\rightarrow$ problem scales exponentially

Two solutions for Hamiltonian approach



- Tensor Networks
  - gapped, local Hamiltonians
    $\rightarrow$ area law
    $\rightarrow$ very fast (exponential) convergence
  - costly: entanglement
    $\rightarrow$ phase transitions, (long) real time evolution

- Quantum Computing
  - conceptually clean path
  - noise, low number of qubits, ...



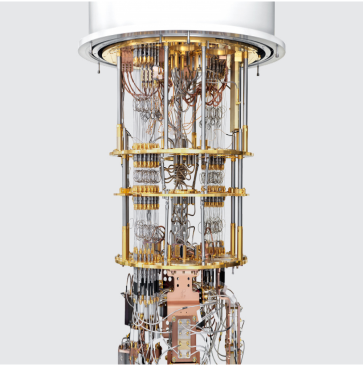
- **Here: focus on quantum computing Quantum Field Theories**

Quantum computer: from the outside

some qubit players

- Superconducting
  - fast, high fidelity, needs cooling
- Trapped ions
  - very high fidelity, no extreme cooling, slow
- Photonics
  - extremely fast, no cooling, noisy
- Neutral atoms
  - long coherence times, no cooling, ultrahigh vacuum
- Silicon Spin/Quantum dots
  - fast and good fidelity, very much in development
- analoque computing, adiabatic computing, ...

Quantum computer: from the inside (superconducting)



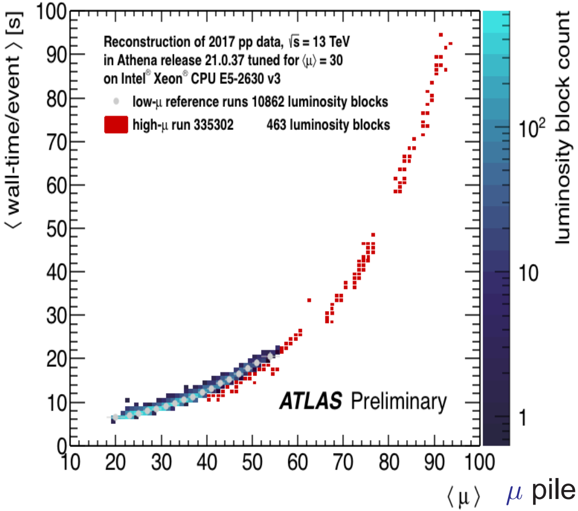
- Shielded to 50,000 times less than Earth's magnetic field
- In a high vacuum: pressure is 10 billion times lower than atmospheric pressure
- Cooled 180 times colder than interstellar space (0.015 Kelvin)
  → prevent quantum noise

- IBMQ: 433 qubits 2022, >1000 qubits 2023, >4000 qubits 2024

→ 10K to 100K error corrected, parallelized

- Google promise: 1.000.000 qubits 2030, 1000 qubits error corrected

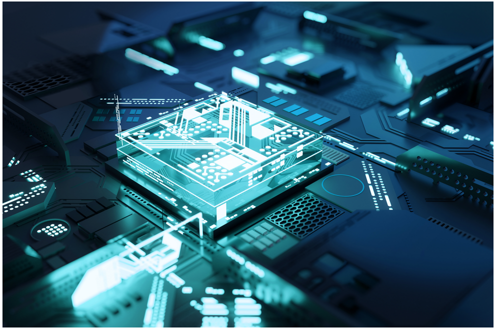
Computing challenge for High-Lumi LHC



μ pile up

- presently: event every 25 nano seconds (1 billion events per second)
- expected: values of $\mu \propto O(1000)$
- need: new algorithms and methods
- $\approx 99\%$ of data not considered
- see also talk by M. Yamazaki on *Quantum Parton Showers*

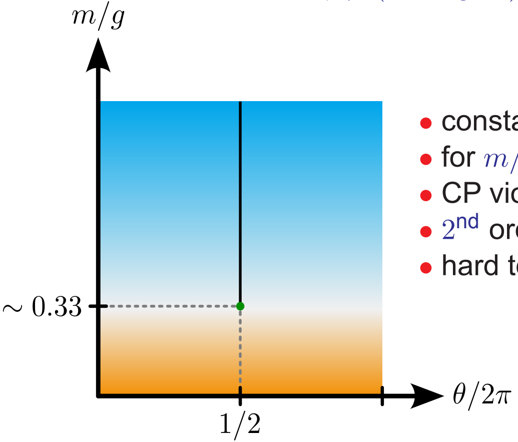
Overview



> Application to QED
in 1+1, 2+1 and 3+1 dimensions

Schwinger model in the continuum and phase diagram

$$\mathcal{H} = -i\bar{\psi}\gamma^1\left(\partial_1 - igA_1\right)\psi + m\bar{\psi}\psi + \frac{1}{2}\left(\dot{A}_1 + \frac{g\theta}{2\pi}\right)^2$$



- constant external electric field: θ
- for $m/g > 0.33$, 1^{st} order phase transition
- CP violating
- 2^{nd} order endpoint at $m/g = 0.33$
- hard to explore with Monte Carlo methods

Schwinger model on the lattice: Wilson fermions

(Takis Angelides, Arianna Crippa, Lena Funcke, Karl Jansen,
Stefan Kühn, Pranay Naredi, Ivano Tavernelli, Derek Wang, arxiv:2312.12831)

- Wilson Hamiltonian

$$H_W = \sum_{n=0}^{N-2} \left(\bar{\phi}_n \left(\frac{1 + i\gamma^1}{2a} \right) U_n \phi_{n+1} + \text{ h.c. } \right)$$
$$+ \sum_{n=0}^{N-1} \left(m_{\text{lat}} + \frac{1}{a} \right) \bar{\phi}_n \phi_n + \sum_{n=0}^{N-2} \frac{ag^2}{2} \left(L_n + l_0 \right)^2 , \quad U_\mu = e^{iagA_\mu}$$

- mass m_{lat}; coupling g; lattice spacing a; electric field $l_0 = \frac{\theta}{2\pi}$

- mass shift MS :
  $m_r/g = m_{\text{lat}}/g + \text{MS}\,(V, ag, l_0)$
  $\rightarrow$ needs to be determined non-perturbatively

Pauli representation through Jordan-Wigner transformation

- Jordan-Wigner transformation

$$\phi_{n,\alpha} \to \chi_{2n-\lfloor \frac{\alpha}{2} \rfloor + 1}$$

$$\chi_n = \prod_{k<n} (iZ_k)\sigma_n^-$$

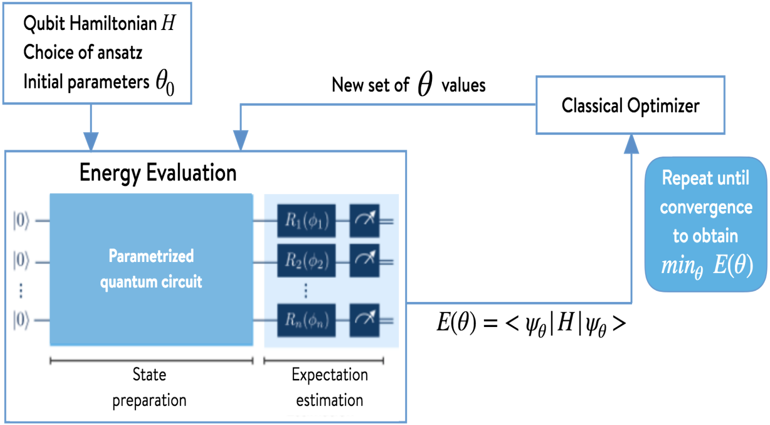
- (dimensionless) Wilson Hamiltonian, $x = 1/(ag)^2$
  $\to$ open boundary conditions: eliminate gauge fields

$$W_W = x \sum_{n=0}^{N-2} (X_{2n+2}X_{2n+3} + Y_{2n+2}Y_{2n+3}) +$$
$$\left(\frac{m_{\text{lat}}}{g}\sqrt{x} + x\right) \sum_{n=0}^{N-1} (X_{2n+1}X_{2n+2} + Y_{2n+1}Y_{2n+2}) + \sum_{n=0}^{N-2} \left(l_0 + \sum_{k=0}^{n} Q_k\right)^2$$

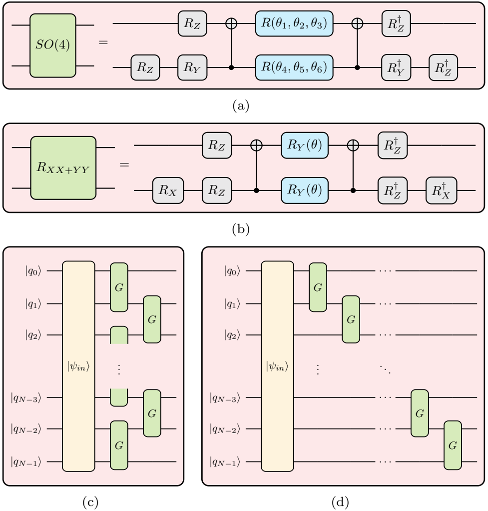
- see also talk by M. Honda based on *Digital Quantum Simulation for Spectroscopy of Schwinger Model*, D. Ghim and M. Honda, arxiv:2404.14788

Variational Quantum Eigensolver (VQE)

- a hybrid quantum/classical variational approach



The Ansatz

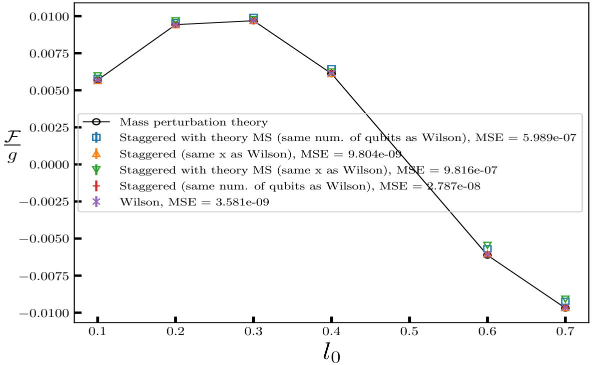


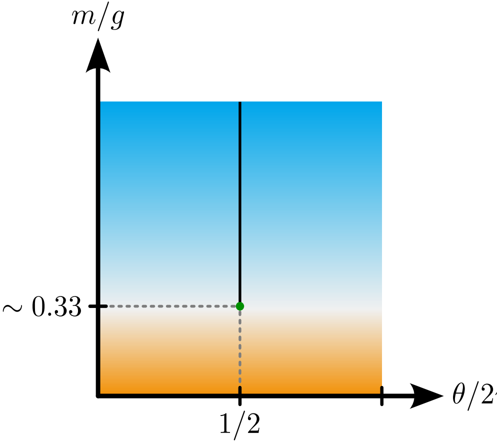
- decomposition of $SO(4)$ and R_{XX+YY} gates

- brick and ladder ansatz

Results: small mass

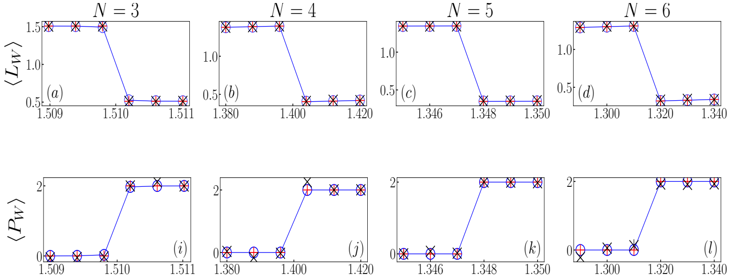
> results for $m_r/g = 0.01$ (remember: $x = 1/(ag)^2$)

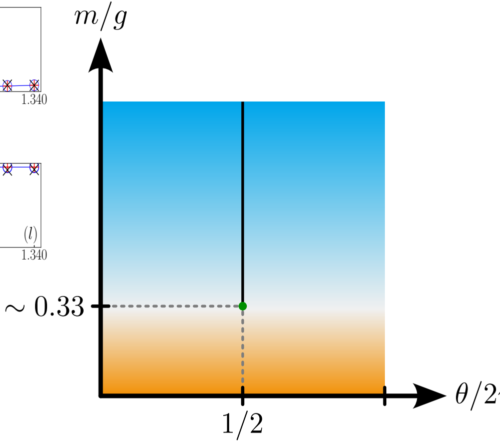




• blue circles: exact diagonalization, red pluses: exact simulations, black crosses: **IBM** quantum hardware

Results: large mass $m_r/g = 10$





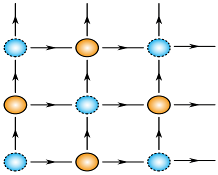
- including hardware results

The Hamiltonian of 2+1 dimensional QED

- fermionic matter fields on lattice sites

$$\hat{H}_{kin} = \frac{i}{2}\sum_{\vec{n}}\left(\phi^{\dagger}_{\vec{n}}\hat{U}_{\vec{n},x}\phi_{\vec{n}+x} - h.c.\right) - \frac{(-1)^{n_x+n_y}}{2}\sum_{\vec{n}}\left(\phi^{\dagger}_{\vec{n}}\hat{U}_{\vec{n},y}\phi_{\vec{n}+y} + \text{h.c.}\right)$$

$$\hat{H}_m = m\sum_{\vec{n}}(-1)^{n_x+n_y}\hat{\phi}^{\dagger}_{\vec{n}}\hat{\phi}_{\vec{n}}$$

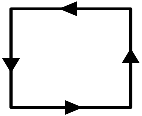


- set “bare” lattice spacing $a = 1$, physical $a = a(g)$
- electric field and plaquette operators

$$\hat{H}_E = \frac{g^2}{2}\sum_{\vec{n}}\left(\hat{E}^2_{\vec{n},x} + \hat{E}^2_{\vec{n},y}\right), \quad \hat{H}_B = -\frac{1}{2g^2}\sum_{\vec{n}}\left(\hat{P}_{\vec{n}} + \hat{P}^{\dagger}_{\vec{n}}\right)$$

- plaquette operator $\rightarrow$ magnetic effects

$$\hat{P}_{\vec{n}} = \hat{U}_{\vec{n},x}\hat{U}_{\vec{n}+x,y}\hat{U}^{\dagger}_{\vec{n}+y,x}\hat{U}^{\dagger}_{\vec{n},y}$$

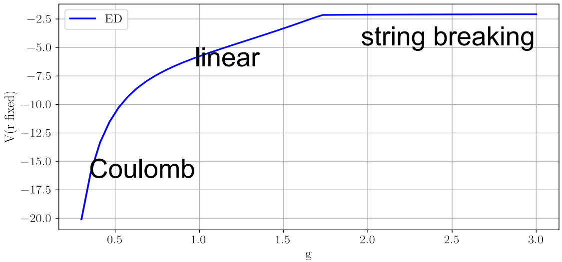


Static potential from a quantum computer

- static potential in 2+1-dimensional QED

$$V(r) = c_1 + c_2\alpha(r)\ln(r) + c_3\sigma r$$

  - $\alpha(r)$ running coupling
  - σ string tension
  - fixed distance in lattice units
  - lattice spacing $a \searrow$ when $g \searrow$ $\rightarrow$ physical distance becomes smaller



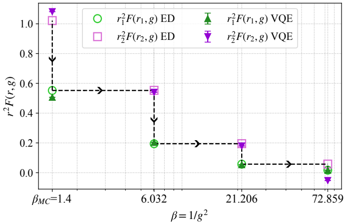
- flux configurations at different disctances $\rightarrow$ see talk by Enrico Rinaldi

Running coupling from MC and QC

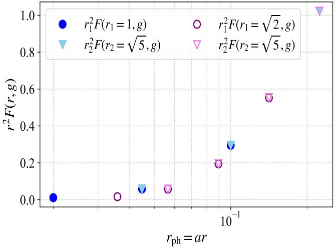
(A. Crippa, S. Romiti, L. Funcke, K. Jansen, S. Kühn, P. Stornati, C. Urbach, arXiv:2404.17545)

$\rightarrow$ see poster

- QC: step scaling at very small lattice spacing
- MC: provide value of lattice spacing



step scaling



"running" coupling

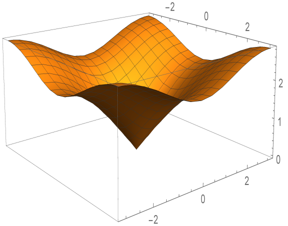
- *Simulating 2D lattice gauge theories on a qudit quantum computer*
  (M. Meth, J. Haase, J. Zhang, C. Edmunds, L. Postler, A. Steiner, A. Jena, L. Dellantonio, R. Blatt, P. Zoller, T. Monz, P. Schindler, C. Muschik, M. Ringbauer, arXiv:2310.12110)

Chern-Simons term in 2+1 dimensional QED

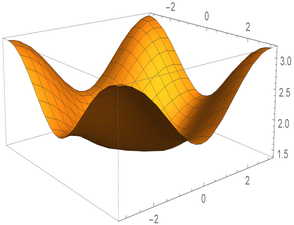
(C. Peng, C. Diamantini, L. Funcke, A. Hassan, K. Jansen, Stefan Kühn, D. Luo, P. Naredi, arxiv:2407.20225)

$$\hat{H} = \sum_{x \in \text{ sites}} \frac{e^2}{2a^2} \left[\left(\hat{p}_{x;1} - \frac{ka^2}{4\pi} \hat{A}_{x-\hat{2};2} \right)^2 + \left(\hat{p}_{x;2} + \frac{ka^2}{4\pi} \hat{A}_{x-\hat{1};1} \right)^2 \right] + \frac{1}{2e^2} \left(\Box \hat{A}_{x;1,2} \right)^2$$

- energy bands



pure Maxwell theory
massless photon



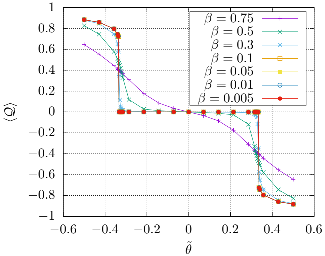
adding Chern-Simons term
topological mass generation

- opens door to investigate e.g. fermion/boson dualities, fractional quantum Hall effect, …

Topological term in 3+1 dimensional compact QED

(A. Kan, L. Funcke, S. Kühn, L. Dellantonio, J. Zhang, J Haase, C. Muschik, K. Jansen, arxiv:2105.06019)

$$\hat{H}_{\text{topo}} = \tilde{\theta}\hat{Q} = -i\frac{\theta}{\beta}\sum_{\vec{n}}\sum_{(i,j,k)\in\,\text{even}}\left(\hat{E}_{\vec{n}-\hat{i},i} + \hat{E}_{\vec{n},i}\right)\left(\hat{U}_{\vec{n},jk} - \hat{U}^{\dagger}_{\vec{n},jk}\right)$$

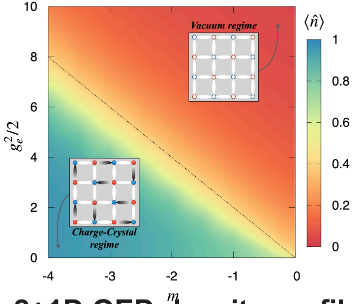


topological charge

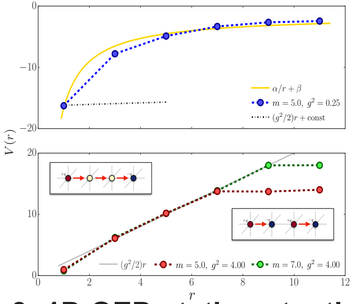
- 1st order phase transition for $\beta < 1$
- observe avoided level crossing

Higher dimension tensor network QED simulations

- 2+1 dimensional QED at finite density on up to 16 x 16 lattices
  (T. Felser, P. Silvi, M. Collura, S. Montangero, arxiv:1911.09693)
- 3+1 dimensional QED at finite charge density
  G. Magnifico, T. Felser, P. Silvi, S. Montangero, arxiv:2011.10658)



2+1D QED density profile



3+1D QED static potential

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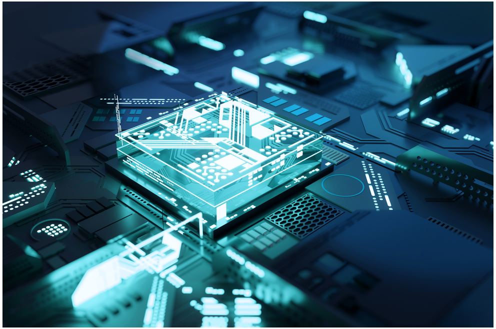


> Non-abelian gauge theories

Non-abelian lattice gauge theory

$$\hat{H} = \frac{1}{2a}\sum_{\vec{n}}\sum_{\alpha,\beta}\left(i\hat{\psi}_\alpha(\vec{n})^\dagger \hat{U}_{\alpha\beta}(\vec{n},i)\hat{\psi}_\beta(\vec{n}+\hat{i}) + (-1)^{\vec{n}}\hat{\psi}_\alpha(\vec{n})^\dagger \hat{U}_{\alpha\beta}(\vec{n},j)\hat{\psi}_\beta(\vec{n}+\hat{j}) + \text{ H.c. }\right)$$

$$+ m\sum_{\vec{n}}\sum_{\alpha}(-1)^{\vec{n}}\hat{\psi}^\dagger_\alpha(\vec{n})\hat{\psi}_\alpha(\vec{n})$$

$$+ \frac{g^2}{2a^{d-2}}\sum_{\vec{n},l}\sum_{b}\left[\hat{E}^b(\vec{n},l)\right]^2$$

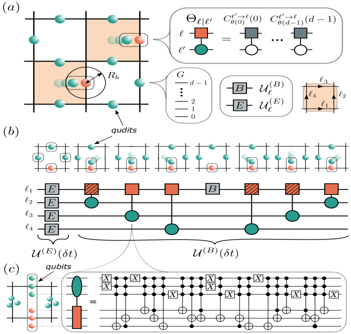
$$- \frac{1}{2a^{4-d}g^2}\sum_{\vec{n}}\sum_{\alpha,\beta,\gamma,\delta}\hat{U}_{\alpha\beta}(\vec{n},i)\hat{U}_{\beta\gamma}(\vec{n}+\hat{i},j)\hat{U}^\dagger_{\delta\gamma}(\vec{n}+\hat{j},i)\hat{U}^\dagger_{\alpha\delta}(\vec{n},j) + \text{ H.c.}$$

- Isn't it a nice Hamiltonian?

SU(2) LGT for qudit architecture

> quditing SU(2)

(D. González-Cuadra, T. Zache, J. Carrasco, B. Kraus, P. Zoller, arxiv:2203.15541)



- Rydberg atoms for qudits
- qudit circuit
- comparing to qubit circuit

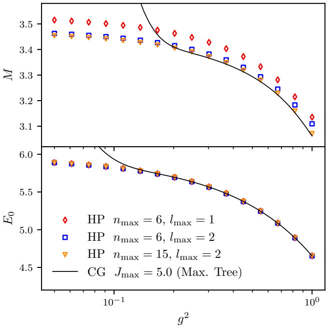
> promising realization of SU(2)

q-deformed Kogut-Susskind gauge theories

(T. Zache, D. González-Cuadra, P. Zoller, arXiv:2304.02527)

Non-abelian lattice gauge theory

- approach of SU(2) partitionings
- Hermite polynomial based operators
  (M. Garofalo, T. Hartung, T. Jakobs, K. Jansen,
  J. Ostmeyer, S. Romiti and C. Urbach, to appear)

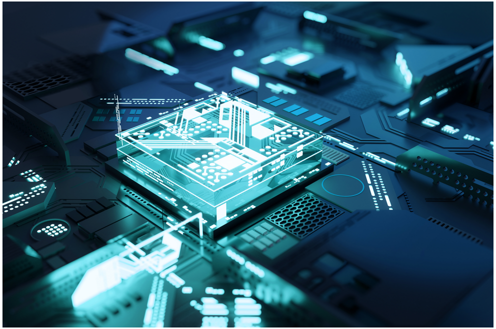


- E_0 ground state
- M mass gap
- solid curve:
  character expansion with electric operators
- data points:
  hermite polynomial based operators

Other approaches, non exhaustive examples ...

- Non-abelian gauge theories in optical lattices
  – L.Tagliacozzo, A.Celi, P.Orland, M. Mitchell, M. Lewenstein, Nature communications, 4(1):1–8, 2013
- Clebsch-Gordaning
  – N. Klco, M. Savage, and J. Stryker, Physical Review D, 101(7):074512
  – Sarmed Rahman, Randy Lewis, Emanuele Mendicelli, Sarah Powell, Phys. Rev. D 104, 034501 (2021)
- Integrating out gauge fields
  – Y. Atas, J. Haase, J. Zhang, V. Wei, S. Pfaendler, R. Lewis, and C. Muschik, arXiv:2207.03473
  – Y. Atas, J. Haase, J. Zhang, V. Wei, S. Pfaendler, R. Lewis, and C. Muschik, Nature communications, 12(1):1–11, 2021
- General quantum algorithm approach
  – Z. Davoudi, A. Shaw, J. R. Stryker, arXiv:2212.14030v2
- Highly-efficient quantum Fourier transformations for some nonabelian groups – E. Murairi, M. Alam, H. Lamm, S. Hadfield, E. Gustafson, arXiv:2408.00075

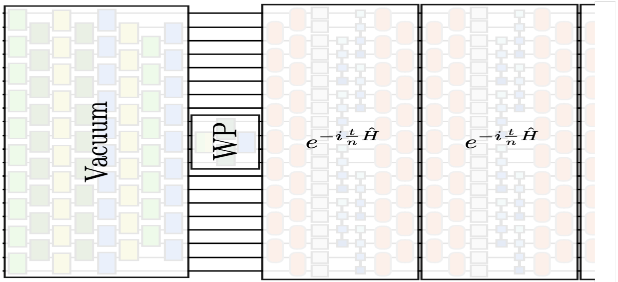
Overview



> Real time dynamics

real time dynamics

- Common scheme for real time dynamics
  - ground state preparation of considered model
  - generate hadron wavepacket on the ground state
  - real time evolution of the wave packet
  - measurement of relevant observables
- algorithms:
  VQE, Trotterization,
  Givens rotation, ...
- ansätze:
  brick, ladder,
  charge conservation, ...



Quantum Simulations of Hadron Dynamics in the Schwinger Model

(R. Farrell, M. Illa, A. Ciavarella, M. Savage, arXiv:2401.08044)

- ground state preparation:
  - use locality of interaction: effective Hamiltonian
  - Scalable Circuits-ADAPT-VQE (SC-ADAPT-VQE) algorithm: $\rightarrow$ define pool of operators

$$\{\hat{O}\}_{\text{vac}} = \left\{\hat{O}^V_{mh}(d), \hat{O}^S_{mh}(0,d), \hat{O}^S_{mh}(1,d)\right\}$$

$$\hat{O}^V_{mh}(d) \equiv i\left[\hat{\Theta}^V_m, \hat{\Theta}^V_h(d)\right] = \frac{1}{2}\sum_{n=0}^{2L-1-d}(-1)^n\left(\hat{X}_n\hat{Z}^{d-1}\hat{Y}_{n+d} - \hat{Y}_n\hat{Z}^{d-1}\hat{X}_{n+d}\right)$$

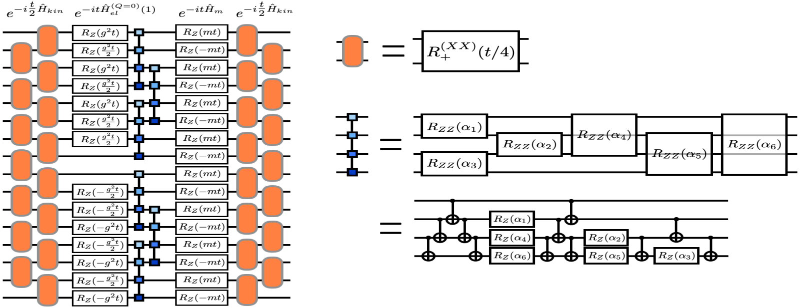
$$\hat{O}^S_{mh}(0,d) \equiv i\left[\hat{\Theta}^S_m(0), \hat{\Theta}^V_h(d)\right] = \frac{1}{4}\left(\hat{X}_0\hat{Z}^{d-1}\hat{Y}_d - \hat{Y}_0\hat{Z}^{d-1}\hat{X}_d - \hat{Y}_{2L-1-d}\hat{Z}^{d-1}\hat{X}_{2L-1} + \hat{X}_{2L-1-d}\hat{Z}^{d-1}\hat{Y}_{2L-1}\right)$$

$$\hat{O}^S_{mh}(1,d) \equiv i\left[\hat{\Theta}^S_m(1), \hat{\Theta}^S_h(d)\right] = \frac{1}{4}\left(\hat{Y}_1\hat{Z}^{d-1}\hat{X}_{d+1} - \hat{X}_1\hat{Z}^{d-1}\hat{Y}_{d+1} + \hat{Y}_{2L-2-d}\hat{Z}^{d-1}\hat{X}_{2L-2} - \hat{X}_{2L-2-d}\hat{Z}^{d-1}\hat{Y}_{2L-2}\right)$$

  - rank the operators, e.g. according to infidelity
  - perform all this on small lattices and extrapolate to large lattice
    $\rightarrow$ demonstrated on 100 qubits in
    (R. Farrell, M. Illa, A. Ciavarella, M. Savage, arXiv:2308.04481)

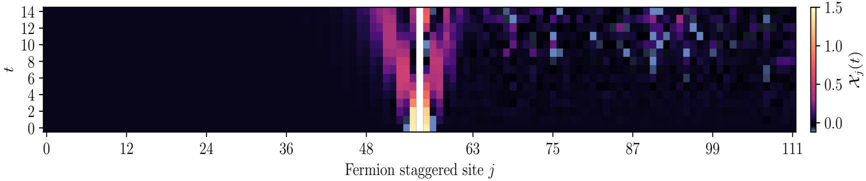
Quantum Simulations of Hadron Dynamics in the Schwinger Model

- generate hadron wavepacket on the the ground state
  $\rightarrow$ adiabatically evolving ground state
- real time evolution of the wave packet:
  $\rightarrow$ 2nd order trotterization



Quantum Simulations of Hadron Dynamics in the Schwinger Model on 112 qubits

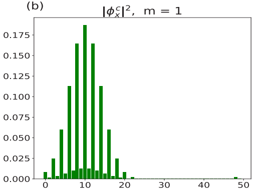
– measurement of relevant observables:
  → chiral condensate

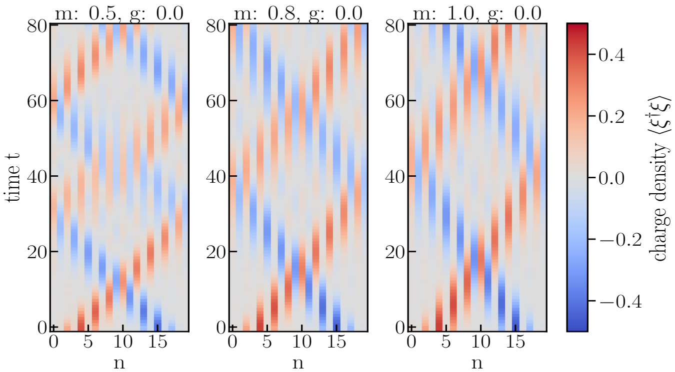


Scattering in the Thirring model

(Y. Chai, A. Crippa, K. Jansen, S. Kühn, I. Tavernelli, F. Tacchino, arxiv:2312.02272)

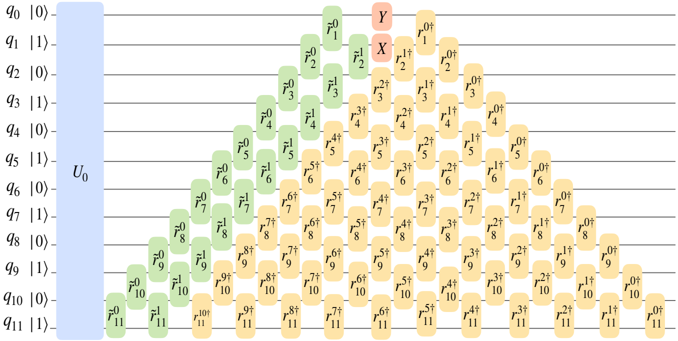
- Gaussian wave packets $\phi_k^{c(d)} = \frac{1}{\mathcal{N}_k^{c(d)}} e^{-ik\mu_n^{c(d)}} e^{-(k-\mu_k^{c(d)})^2/4\sigma_k^2}$
- time evolution: Givens rotation
- time evolution for free fermions: charge distribution



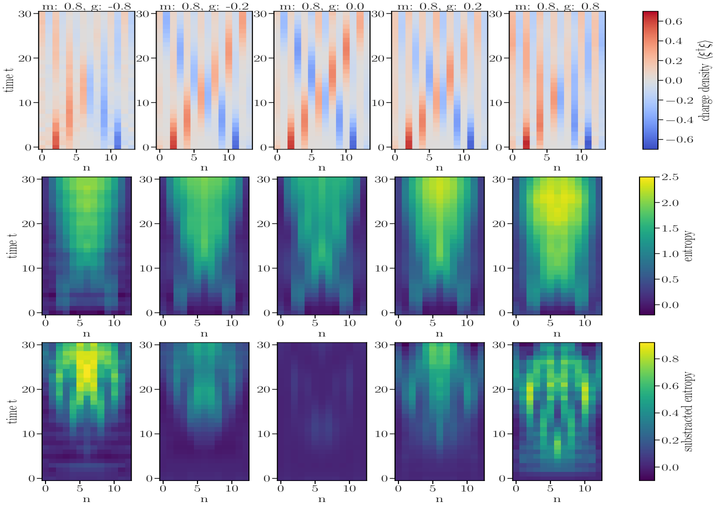


Quantum circuit

- blue box: vacuum preparation
- green and yellow boxes: wave packet preparation and time evolution

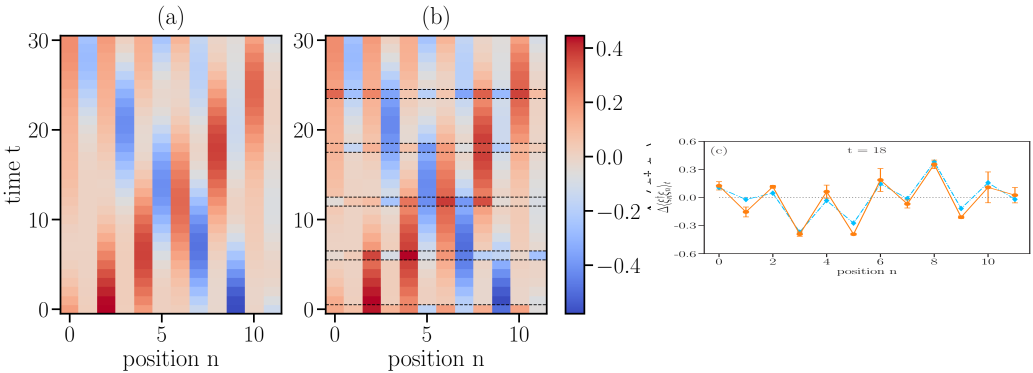


Interacting case



Hardware runs

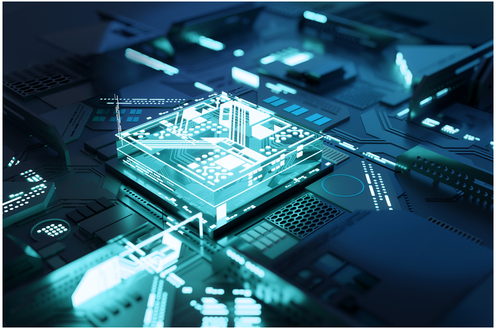
> Ideal versus hardware



Quantum computing real time evolution, not exhaustive

- *A Cold-Atom Particle Collider* (Guo-Xian Su, Jesse Osborne, Jad C. Halimeh, arxiv:2401.05489)
- *Meson Mass Sets Onset Time of Anomalous Dynamical Quantum Phase Transitions* (Jesse J. Osborne, Johannes Knaute, Ian P. McCulloch, Jad C. Halimeh, arxiv:2407.03394)
- *Quantum Computing Universal Thermalization Dynamics in a (2+1)D Lattice Gauge Theory* (Niklas Mueller, Tianyi Wang, Or Katz, Zohreh Davoudi, Marko Cetina, arxiv:2408.00069)
- *Simulating Meson Scattering on Spin Quantum Simulators* (Elizabeth R. Bennewitz, Brayden Ware, Alexander Schuckert, Alessio Lerose, Federica M. Surace, Ron Belyansky, William Morong, De Luo, Arinjoy De, Kate S. Collins, Or Katz, Christopher Monroe, Zohreh Davoudi, Alexey V. Gorshkov, arXiv:2403.07061v2)
- *Applying the noiseless extrapolation error mitigation protocol to calculate real-time quantum field theory scattering phase shifts* (Zachary Parks, Arnaud Carignan-Dugas, Erik Gustafson, Yannick Meurice, Patrick Dreher, arXiv:2212.05333)
- *Real-time chiral dynamics at finite temperature from quantum simulation* (Kazuki Ikeda, Zhong-Bo Kang, Dmitri E. Kharzeev, Wenyang Qian, Fanyi Zhao, arXiv:2407.21496)

Overview



> PDFs

Quantum computing parton distribution functions

(S. Grieninger, K. Ikeda, I. Zahed), arXiv:2404.05112v1)

> employing the Schwinger model Hamiltonian

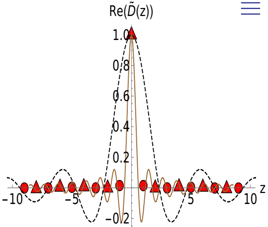
> parton distribution function from "time" evolution

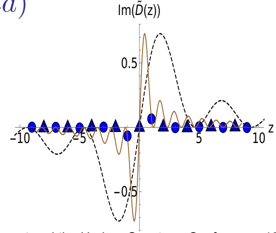
$$q_\eta(x,v) = \frac{1}{2}\int_{-\infty}^{+\infty} \frac{dz}{2\pi} e^{-iz\zeta m_\eta v} \left\langle \eta(0) \left| \bar{\psi}(0,z)[z,-z]\gamma^+\gamma^5 e^{-i2vz\mathbb{H}} \psi(0,-z) \right| \eta(0) \right\rangle$$

> staggered form on the lattice ($\zeta = 2x - 1$)

$$q_\eta(x,v) \rightarrow \frac{a}{4\pi} \sum_z e^{-iz\zeta m_\eta v} \left\langle \eta(0) \left| \left(\psi_e^\dagger(z) + \psi_o^\dagger(z) \right) e^{-i2vz\mathbb{H}} \left(\psi_e(-z) + \psi_o(-z) \right) \right| \eta(0) \right\rangle$$

$$\equiv \frac{1}{2\pi} \sum_{n=\text{even}} e^{-in\zeta a P(v)} D(na)$$

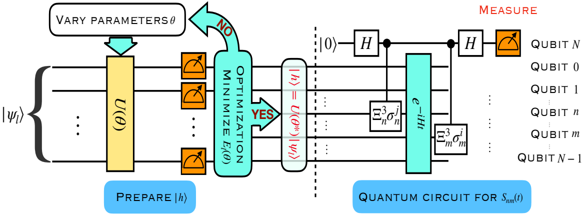




Quantum computing parton distribution functions

> related work

- *Parton Physics on a Quantum Computer*,
  (H. Lamm, S. Lawrence, Y. Yamauchi, arXiv:1908.10439)
- *Quantum Simulation of Light-Front Parton Correlators*,
  (M.G. Echevarria, I.L. Egusquiza, E. Rico, G. Schnell, arXiv:2011.01275v2)
- *Partonic collinear structure by quantum computing*,
  (T. Li, X. Guo, W. Kin Lai, X. Liu, E. Wang, H. Xing, D. Zhang, S. Zhu, arXiv:2106.03865)
- *work on distribution amplitudes*,
  (T. Li, X. Guo, W. Kin Lai, X. Liu, E. Wang, H. Xing, D. Zhang, S. Zhu, arXiv:2207.13258)



QC4HEP whitepaper, arXiv:2307.03236

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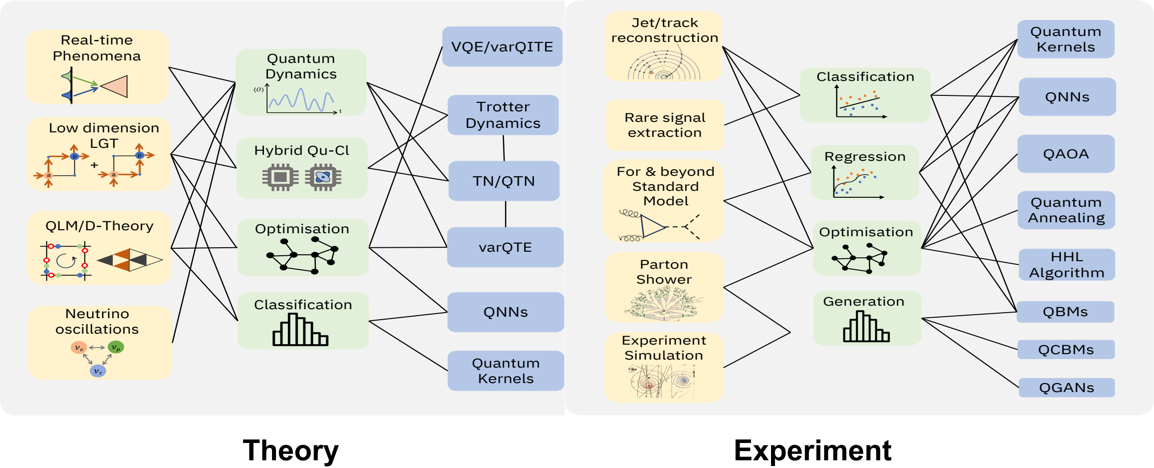
Abstract

Quantum computers offer an intriguing path for a paradigmatic change of computing in the natural sciences and beyond, with the potential for achieving a so-called quantum advantage, namely a significant (in some cases exponential) speed-up of numerical simulations. In particular, the high-energy physics community plays a pivotal role in accessing the power of quantum computing, since the field is a driving source for challenging computational problems. ...

Algorithms, methods and application for HEP



See also *Quantum Simulation for High-Energy Physics*, C. Bauer et.al., arxiv:2204.03381

QC for high energy, nuclear and condensed matter physics

Leaving the era of 1+1 dimensional toy models

- abelian and **non-abelian** pure gauge theories in **2 space** dimensions
- QED in 2+1 dimensions
- abelian **Higgs** model
- **topological** terms $\rightarrow$ CP-violation
- PDFs for simple models

- abelian and **non-abelian** gauge theories in **3 space** dimensions
- QED in 3+1 dimensions
- **non-abelian Higgs** model
- **topological** terms $\rightarrow$ topological materials

- SU(2) and SU(3) **'QCD' in 2+1 and 3+1 dimensions**
- QCD with topological term
- **chiral gauge** theories
- extensions of standard model
- non-zero **matter density**

QC for high energy, nuclear and condensed matter physics

Leaving the era of 1+1 dimensional toy models

Today

- real time simulation
  - → **thermalization**
  - → **scattering**
  - → **quenching**
- various **spin models**
- thermal field theory
- ...

- real time simulation
  → string breaking,
  formation of bound states
- collisions, **scattering**
- **non-perturbative** renormalization
- ...

- simulations of **heavy ion collisions**
- **quark gluon plasma**
- **nuclear** physics
- multi-Higgs models
- conformal field theories
- ...

⇒ **Completely new insight in condensed matter and high energy physics!**

Thank you!

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