

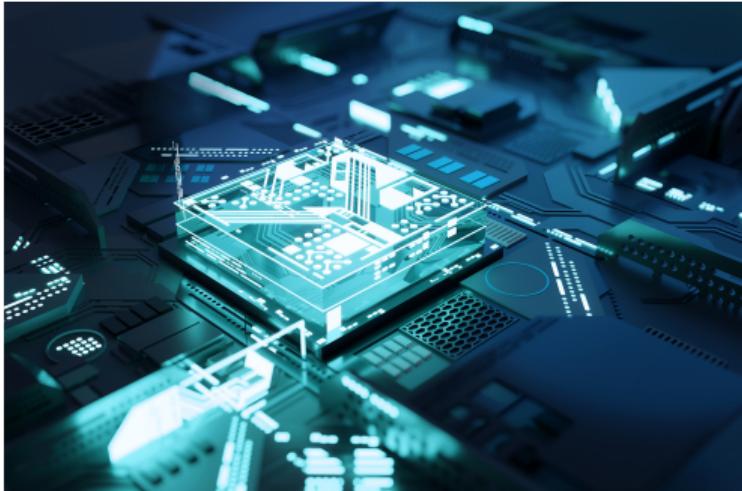
Quanten Computing: a future perspective for high energy physics

HEP challenges

Karl Jansen

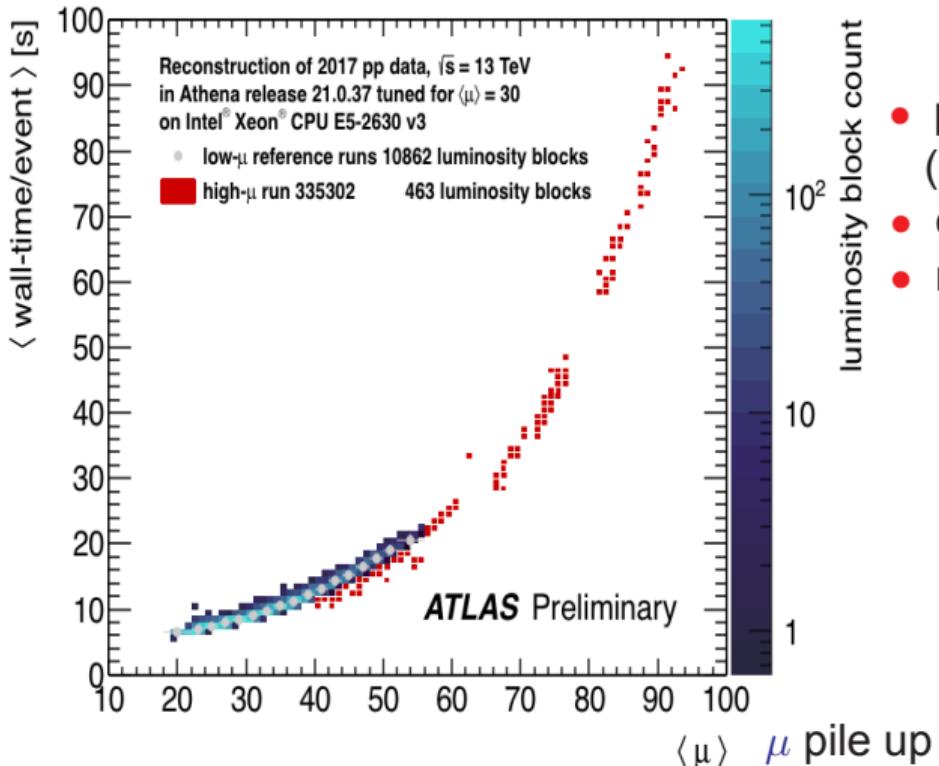
QCMB Conference, Orsay, 23.11.2022

Overview



- > Challenges in HEP experiment and theory
- > Applications
 - Classical optimization
 - Quantum machine learning
 - Theoretical models
 - Error mitigation and expressivity
- > Conclusion

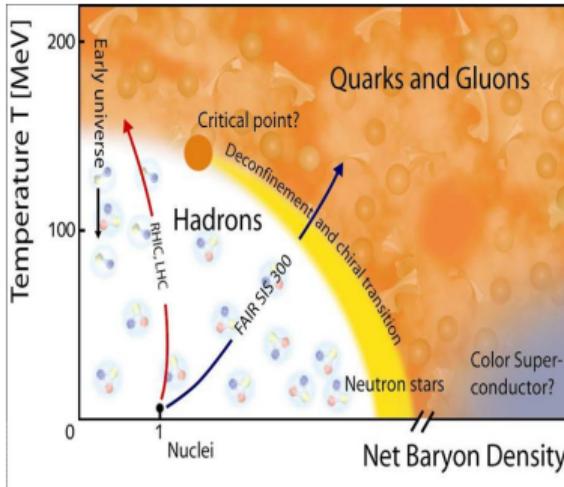
Computing challenge for High-Lumi LHC



- presently: event every 25 nano seconds (1 billion events per second)
- expected: values of $\mu O(1000)$
- need: new algorithms and methods

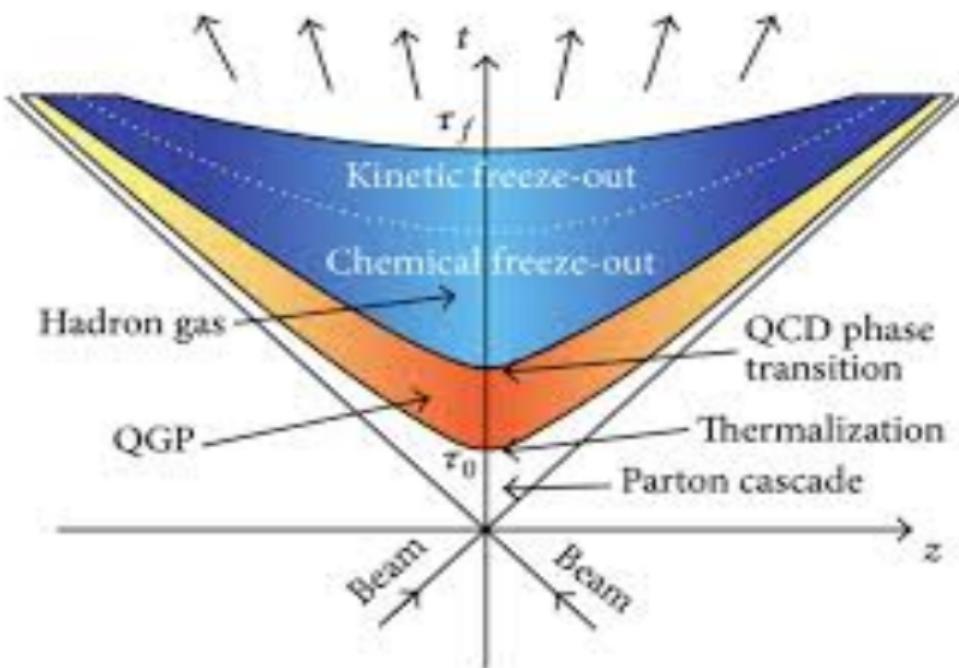
Understanding the early universe

- > Markov Chain Monte Carlo: only zero baryon density accessible
 - understanding of phase transitions?
 - early universe
 - heavy ion experiments
 - exotic regions of PD
- > do not understand origin of todays universe



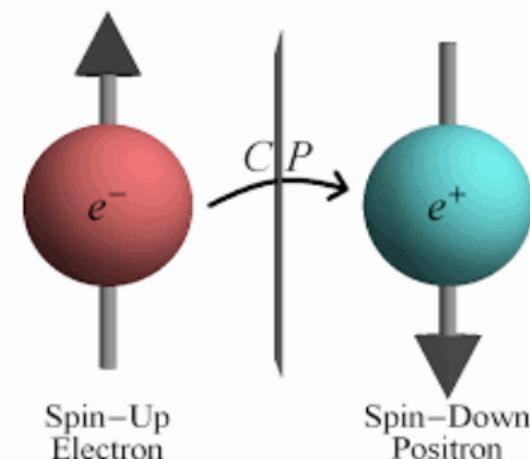
Real time evolution

- > Markov Chain Monte Carlo: only thermal equilibrium accessible
 - no real time simulation
- > understand real time processes in heavy ion collisions
 - complicated sequence of transitions
- > standard way: linearize equations plus small fluctuations
- > do we really understand the involved transitions?



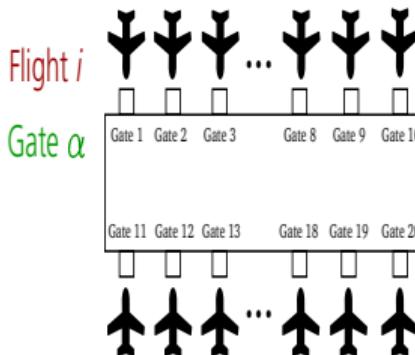
Topological terms

- > topological term leads to complex action
red → infamous sign problem
- > QCD: CP violation: $i\theta\epsilon_{\mu\nu\rho\delta}F_{\mu\nu}F_{\rho\delta}$
- > condensed matter: topological insulators, ...



Quantum computing the flight gate assignment problem

- > A classical optimization problem: flight gate assignment
(Y. Chai, L. Funcke, T. Hartung, S. Kühn, T. Stollenwerk, P. Stornati, K. Jansen)
- > Find shortest path between connecting flights
- > Different incoming and outgoing flights need to be assigned to gates
 - find optimal assignment
- > Classical optimization problem
 - quantum advantage?



Quantum computing the flight gate assignment problem

- > binary variables encoding gates and flights

$$x_{i\alpha} = \begin{cases} 1, & \text{if flight } i \in F \text{ is assigned to gate } \alpha \in G \\ 0, & \text{otherwise} \end{cases}$$

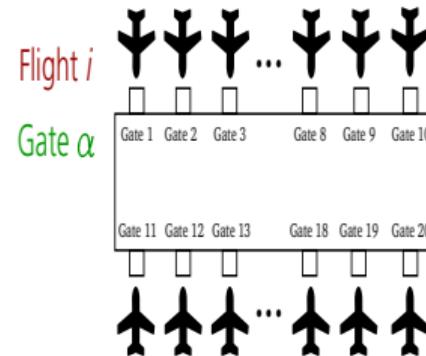
$x \in \{0, 1\}^{F \otimes G} \rightarrow x$ binary variable $\rightarrow x \in \{-1, 1\}$

eigenstate of third Pauli matrix σ_z

- > leads to mathematical description of Hamiltonian

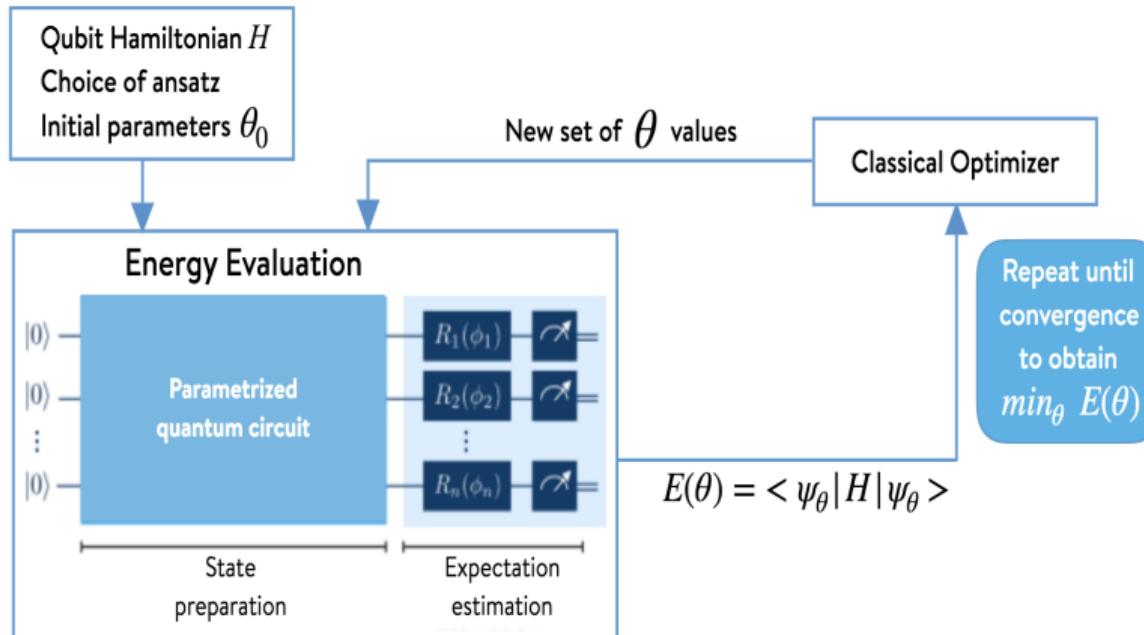
$$H = \sum_{j=1}^n Q_{jj} \sigma_j^z + \sum_{\substack{j,k=1 \\ j < k}}^n Q_{jk} \sigma_j^z \otimes \sigma_k^z$$

- > Task: find lowest energy \Leftrightarrow shortest path
- > Same mathematical description for problems in **traffic, logistics, particle tracking,**



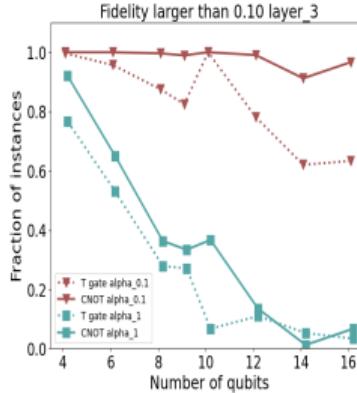
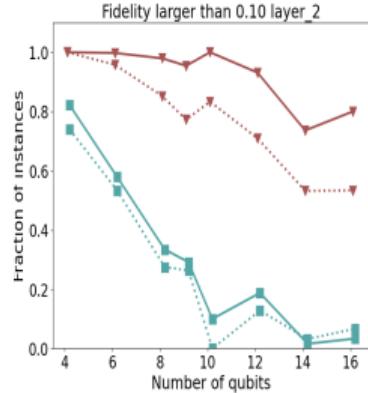
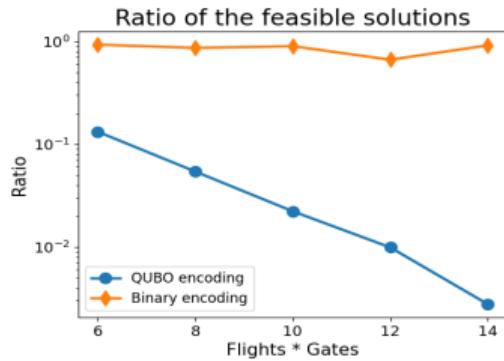
Variational Quantum Eigensolver (VQE)

- > a hybrid quantum/classical variational approach



Quantum computing the flight gate assignment problem

- > Started with QUBO implementation
- > Implementation of various improvements
 - using binary encoding
 - reformulation of Hamiltonian through projectors
 - Using Conditional Value at Risk (CVaR)
- > see indications of improvement through entanglement



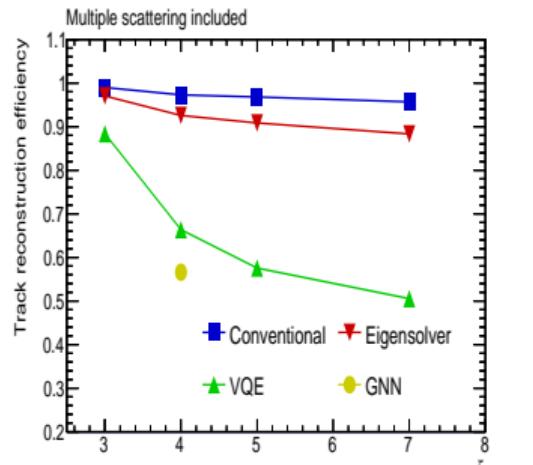
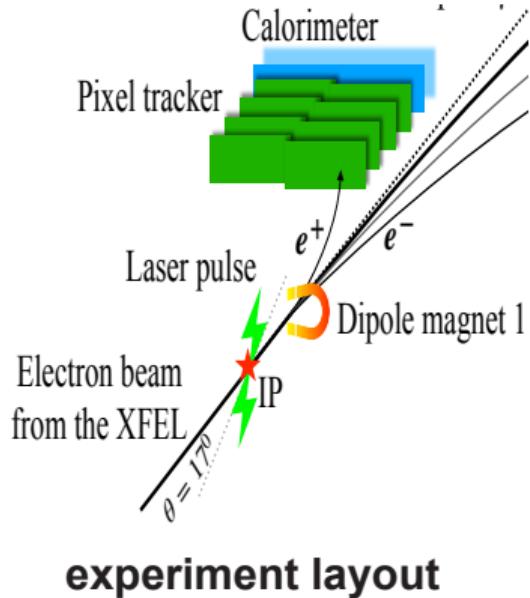
Feasible ratio

role of entanglement

Particle tracking at LASER und XFEL Experiment (LuXE)

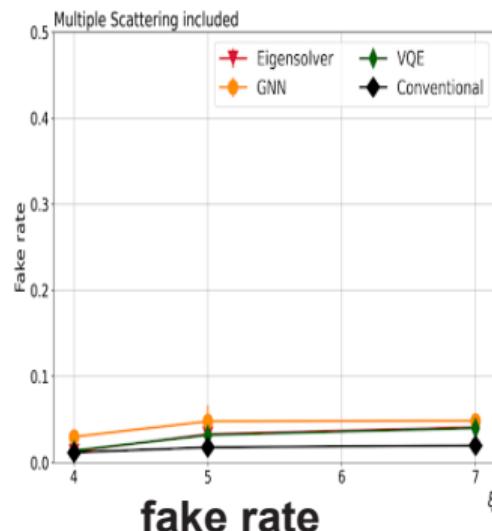
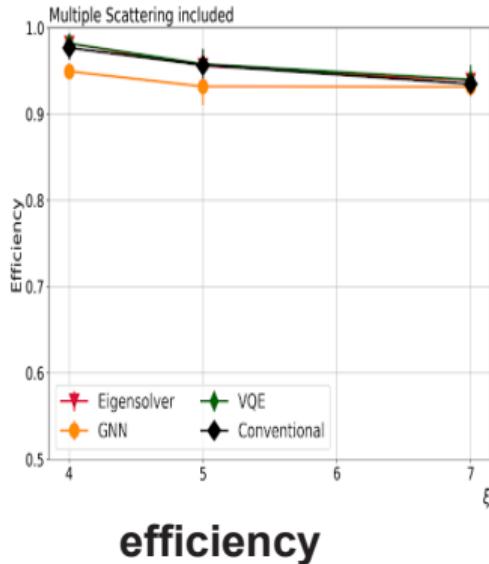
- > using Ising Hamiltonian for particle tracking

(L. Funcke, T. Hartung, B. Heinemann, K. Jansen, A. Kropf, S. Kühn, F. Meloni, D. Spataro, C. Tüysüz, Y. Yap, arxiv:2202.06874)



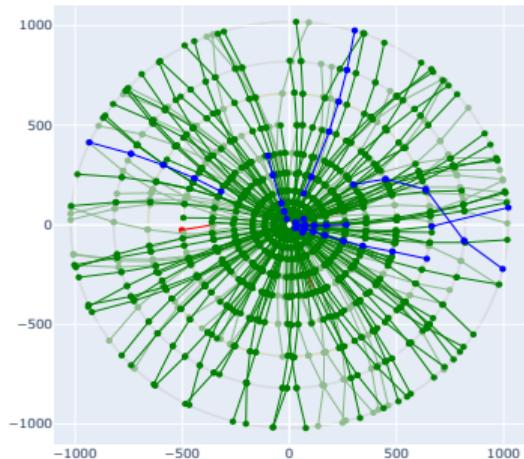
Particle tracking at LASER und XFEL Experiment (LuXE)

- > using FGA Ising Hamiltonian for particle tracking
(L. Funcke, T. Hartung, B. Heinemann, K. Jansen, A. Kropf, S. Kühn, F. Meloni, D. Spataro, C. Tüysüz, Y. Yap, arxiv:2202.06874)



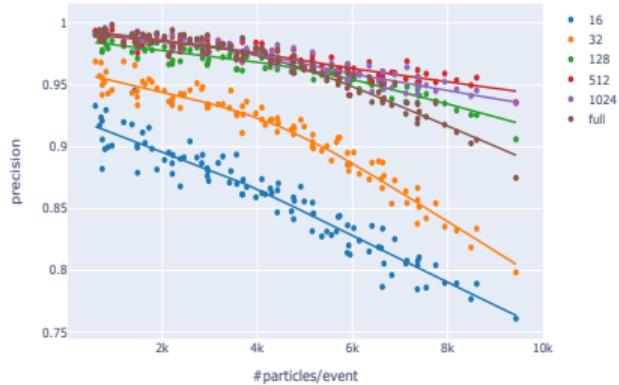
Particle Track Reconstruction in an ATLAS-like Detector

(Cigdem Issever, Karl Jansen, Teng Jian Khoo, Stefan Kühn,
Tim Schwägerl, Cenk Tüysüz, Hannsjörg Weber, in preparation)
➤ using again Ising Hamiltonian for particle tracking



event

Precision, simulated annealing, slices of increasing size in r-z-plane

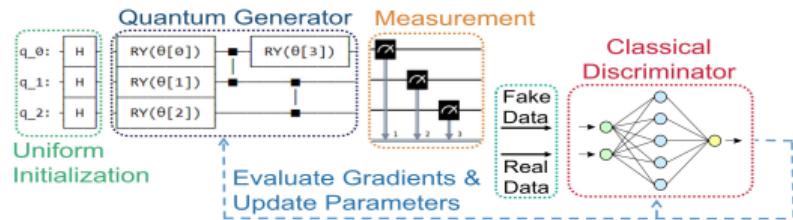


precision success probability

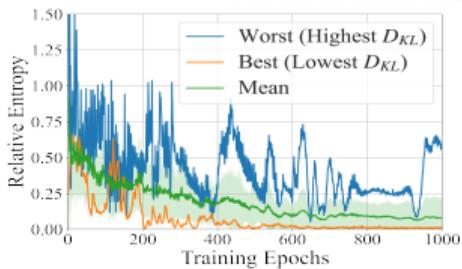
Quantum machine learning

> using Quantum Generative Adversarial Networks

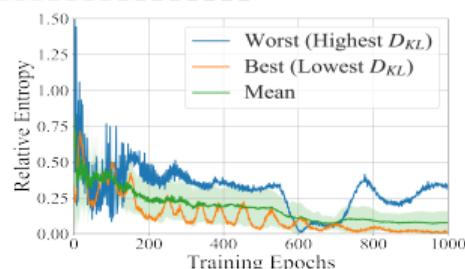
(K. Borras, S.Y. Chang, L. Funcke, M. Grossi, T. Hartung, K.J., D. Kruecker, S. Kühn, F. Rehm, C. Tüysüz, S. Vallecorsa, arxiv:2203.01007)



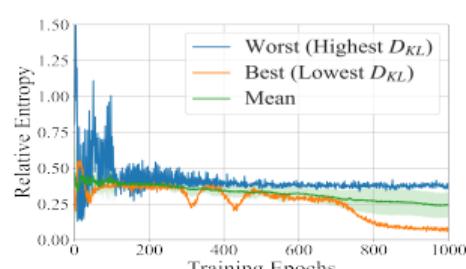
qgan model



bit-flip probability $p=0.01$



$p=0.05$



$p=0.1$

BMBF project "Noise in Quantum Algorithms (NiQ)" → cooperation with IBM Zürich

Quantum computing the Heisenberg model

- > 1-dimensional Heisenberg model

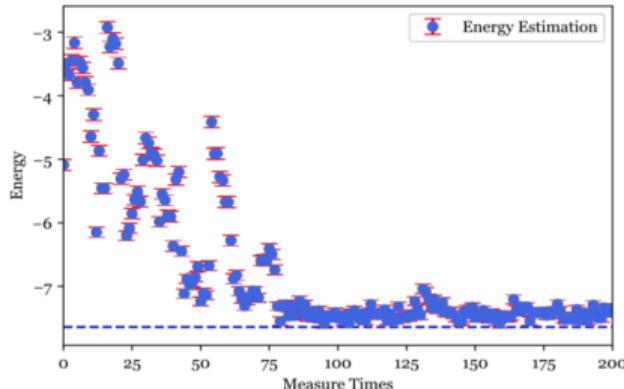
Heisenberg, W. *Zur Theorie des Ferromagnetismus.* Z. Physik 49, 619–636 (1928)

$$H = \sum_{i=1}^N \beta [\sigma_x(i) \otimes \sigma_x(i+1) + \sigma_y(i) \otimes \sigma_y(i+1) + \sigma_z(i) \otimes \sigma_z(i+1)] + J\sigma_z(i)$$

- > microscopic description of magnetism
- > phase transition from un-magnetized to magnetized phase
- > mathematical structure typical for models in **Lattice Gauge Theories** (LGT)
- > very flexible: can use $N = 2$ or $N = 1000$ lattice sites
 - can be studied **already now** on quantum computers

Quantum computing the Heisenberg model

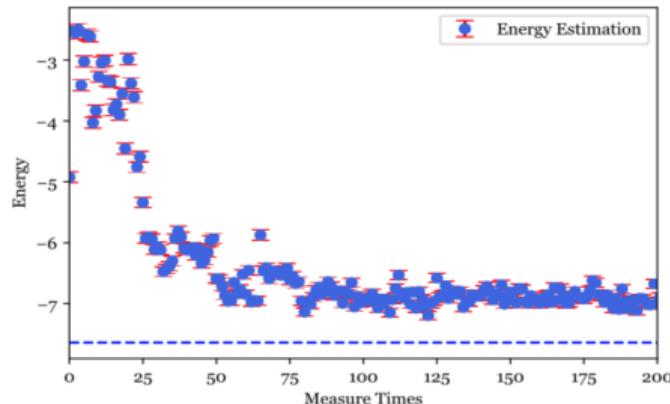
- > Quantum computing the lowest physical energy using 3 qubits
- > Using the exact simulation on laptop
- > dashed line exact result



- exact simulation
- find correct result

Quantum computing the Heisenberg model

- > Quantum computing the lowest physical energy using 3 qubits
- > On quantum computer: exist **quantum noise**
 - ⇒ add noise model

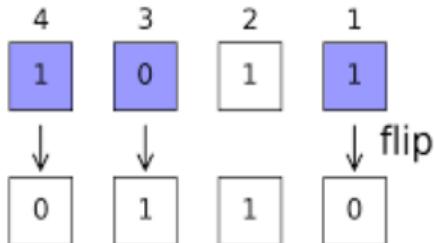


- noisy simulation
- fail to find correct result

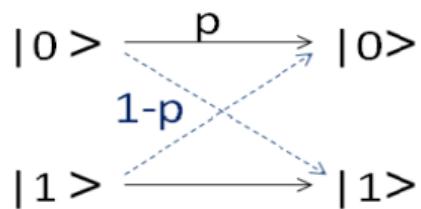
Readout error mitigation

(L. Funcke, T. Hartung, S. Kühn, P. Stornati, X. Wang, K. Jansen, arxiv:2007.03663, to appear in PRA)

- > Quantum computers are noisy: bit-flips in readout process



- > bit-flips occur with certain probabilities
- > erroneous measurements through bit-flips
- > often dominating error $O(10\%)$



Correcting readout errors: Pauli Z operator

- > Hamiltonian: simply Z operator
- > energy of random state $|\psi\rangle = c_1|0\rangle + c_2|1\rangle$; $E_Z = \langle 0|c_1^*Zc_1|0\rangle + \langle 1|c_2^*Zc_2|1\rangle$
- > possible measurement outcomes for bit-flip probability p

Outcome	Measured Energy	Probability
No bit flips	$E_Z = + c_1 ^2 - c_2 ^2$	$(1-p)^2$
$0 \rightarrow 1, 1 \rightarrow 1$	$E_1 = - c_1 ^2 - c_2 ^2$	$p(1-p)$
$0 \rightarrow 0, 1 \rightarrow 0$	$E_2 = + c_1 ^2 + c_2 ^2 = -E_1$	$(1-p)p$
$0 \rightarrow 1, 1 \rightarrow 0$	$E_3 = - c_1 ^2 + c_2 ^2 = -E_Z$	p^2

→ noisy result \tilde{E}_Z

$$\tilde{E}_Z = (1-p)^2 E_Z + 2p(1-p)(E_1 + E_2) + p^2 E_3 = (1-2p)E_Z .$$

→ invert: obtain exact result E_Z

- > need knowledge of p → calibration of qubit readout error

Correcting readout errors: ZZ operator

- > bit-flip probabilities for an operator O_q for qubit q , $\gamma(O_q)$

$$\gamma(O_q) := \left\{ \begin{array}{ll} 1 - p_{q,0} - p_{q,1} & \text{for } O_q = Z_q \\ p_{q,1} - p_{q,0} & \text{for } O_q = \mathbb{1}_q. \end{array} \right\}$$

$p_{q,0}$ ($p_{q,1}$) probability of bit-flip from zero (one) to one (zero) on qubit q

- > inverting noisy measurements

$$\begin{aligned} Z_2 \otimes Z_1 = & \frac{1}{\gamma(Z_2)\gamma(Z_1)} \mathbb{E}(Z_2^n \otimes Z_1^n) - \frac{\gamma(\mathbb{1}_1)}{\gamma(Z_2)\gamma(Z_1)} \mathbb{E}(Z_2^n) \otimes \mathbb{1}_1 \\ & - \frac{\gamma(\mathbb{1}_2)}{\gamma(Z_2)\gamma(Z_1)} \mathbb{1}_2 \otimes \mathbb{E}(Z_1^n) + \frac{\gamma(\mathbb{1}_2)\gamma(\mathbb{1}_1)}{\gamma(Z_2)\gamma(Z_1)} \mathbb{1}_2 \otimes \mathbb{1}_1. \end{aligned}$$

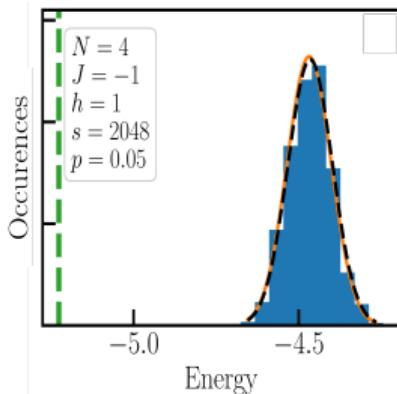
\mathbb{E} expectation value in the number of experiments performed

- > measurements of noisy operators $Z_1, Z_2, Z_1 \otimes Z_2 \rightarrow$ exact result
- > factorization of expectation values: $\mathbb{E}(\tilde{Z}_Q \dots \tilde{Z}_1) = \mathbb{E}\tilde{Z}_Q \dots \mathbb{E}\tilde{Z}_1$

Measurement histogram

- > Energy histogram for transversal Ising model

$$\mathcal{H}_{\text{TI}} = J \sum_{i=1}^N Z_i Z_{i+1} + h \sum_{i=1}^N X_i$$



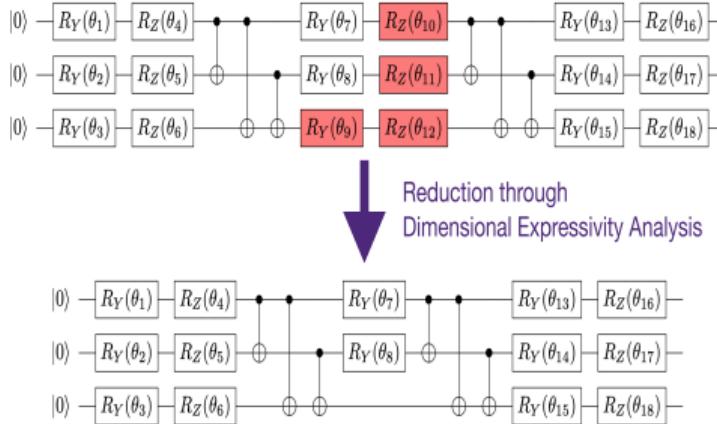
- dashed green line: true ground state energy
- solid orange line: prediction
- dashed black line: fit to data
- $N_{\text{qubit}} = 4, J = -1, h = 1, n_{\text{shots}} = 2048$ with $p = 0.05$

Quantum circuit expressivity

- > dimensional expressivity analysis (DEA)
(L. Funcke, T. Hartung, S. Kühn, P. Stornati, K. Jansen, Quantum 5 (2021) 422)
- > Idea: consider quantum circuit as operator acting on state space
 - circuit is a map of parameter space to state space
 - leads to a Jacobian
- > reachable states by quantum circuit is submanifold
- > expressivity: dimension of this submanifold
- > in practise: determine the row echelon form (Gaussian elimination) of Jacobian
 - determine linear dependencies from eigenvalues

Quantum circuit expressivity

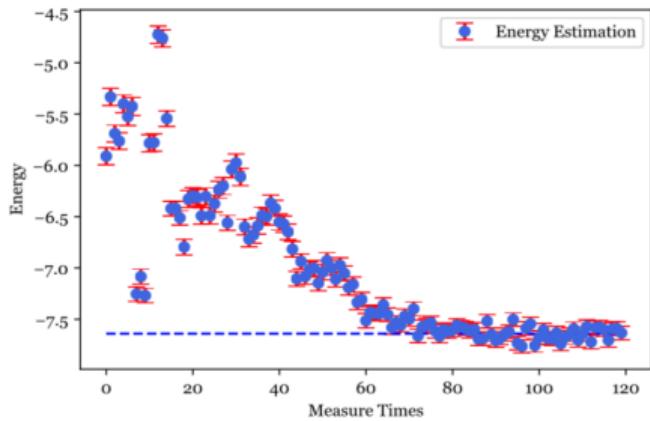
- > example: IBM's EfficientSU2 2-local circuit `|EfficientSU2(3, reps=N=1)|`



- > DEA allows to eliminate gates
 - leads to minimal, but maximally expressive circuit
 - reduction of noise
- > analysis can be performed efficiently

Quantum computing the Heisenberg model

- > Mitigate quantum noise through analytical method on minimal, but maximally expressive circuit



- error mitigated noisy simulation
- find correct result

- > develop new methods from basic research (LGT)

2+1-dimensional quantum electrodynamics

- > lattice Hamiltonian, lattice spacing a , periodic boundary conditions

$$\hat{H}_{\text{gauge}} = \hat{H}_E + \hat{H}_B$$

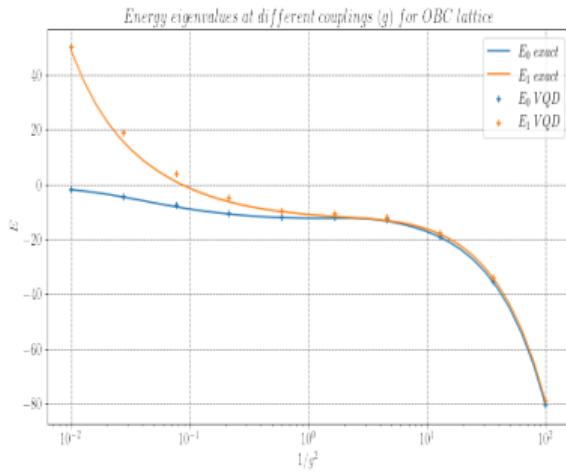
$$\hat{H}_E = \frac{g^2}{2} \sum_{\mathbf{n}} \left(\hat{E}_{\mathbf{n}, e_x}^2 + \hat{E}_{\mathbf{n}, e_y}^2 \right), \quad \hat{H}_B = -\frac{1}{2g^2 a^2} \sum_{\mathbf{n}} \left(\hat{P}_{\mathbf{n}} + \hat{P}_{\mathbf{n}}^\dagger \right)$$

- > electric field operator: $\hat{E}_{\mathbf{n}, e_\mu} |E_{\mathbf{n}, e_\mu}\rangle = E_{\mathbf{n}, e_\mu} |E_{\mathbf{n}, e_\mu}\rangle$, $E_{\mathbf{n}, e_\mu} \in \mathbb{Z}$
- > plaquette operator: $\hat{U}_{ij} = \hat{U}_{ij, e_x} \hat{U}_{ij+e_x, e_y} \hat{U}_{ij+e_y, e_x}^\dagger \hat{U}_{ij, e_y}^\dagger$
→ represented as lowering and raising operators, i.e. $\hat{U}_{ij} |e_{ij}\rangle = |e_{ij} - 1\rangle$
- > Gauss law

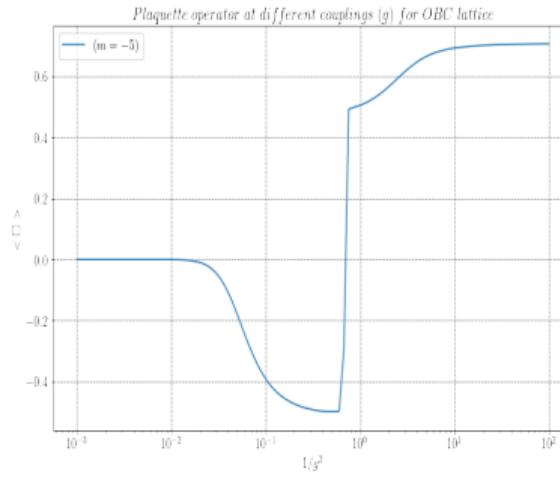
$$\left[\sum_{\mu=x,y} \left(\hat{E}_{\mathbf{n}, e_\mu} - \hat{E}_{\mathbf{n}-e_\mu, e_\mu} \right) - \hat{q}_n \right] |\Phi\rangle = 0 \forall n \iff |\Phi\rangle \in \{ \text{physical states} \}$$

Quantum computing 2+1-dimensional quantum electrodynamics

- > Variational Quantum Computer Simulations (VQCS) of QED
(G. Clemente, A. Crippa, K. Jansen, arxiv:2206.12454)



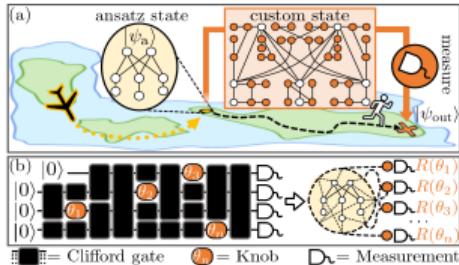
Particle mass $\Delta = E_1 - E_0$
→ physical quantity



detecting a phase transition at negative mass
→ not possible with Monte Carlo methods

One-way computing

- > A measurement-based variational quantum eigensolver
(R. Ferguson, L. Dellantonio, A. Al Balushi, W.Dür, C. Muschik, K.J., **Phys.Rev.Lett.** 126)
- > quantum computation of the Schwinger model with cluster states



- > extension: Schwinger model with chemical potential
(L. Funcke, T. Harting, S. Kühn, M. Pleinert, S. Schuster, J. von Zanthier, K.J.)
- > ongoing work: matrix product states, VQE and one-way computing
→ hard to treat with MC methods

Center for Quantum Technologies and Applications at DESY (Zeuthen place)

- > Innovation funding from state of Brandenburg
 - > focus activities
 - DESY has become an IBM Quantum hub
 - provide access to quantum computer hardware
 - develop applications of uses case for industry and academia, e.g. particle physics
 - develop algorithms and methods
 - benchmark, test and verify emerging quantum computers
 - provide training in quantum computing
 - include quantum sensing
- ⇒ **DESY is becoming quantum ready**



Center for
Quantum Technology
and Applications

DESY QUANTUM.

Quantum Technology Applications

Zeuthen

Quantum Simulations
Algorithms & Methods
Benchmarking

Access to Quantum
Computers

Quantum Sensing



Knowledge & Technology
Transfer
Training and Education

Outreach

Hamburg

Photon Science
for Quantum Materials and
for Quantum Devices

Quantum Machine Learning
Quantum Simulations

Quantum Sensing

Summary and outlook

- > It took 40 years to start realizing Feynman's vision of using quantum computers
- > Quantum computing offers the fascinating possibility
 - to address applications very hard or not accessible to classical computers
 - to show a quantum advantage to solve problems
- > Presently: we research the second quantum revolution
- > For quantum computing
 - identify and evaluate applications for quantum computers
 - develop quantum algorithms and methods
- > Midterm: employ quantum computations for solving problems
 - most probably through hybrid quantum/classical algorithms
- > Long term: routinely use quantum computers in daily life



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Contact

DESY. Deutsches
Elektronen-Synchrotron
www.desy.de

Karl Jansen
 0000-0002-1574-7591
Center for Quantum Technologies and Applications
karl.jansen@desy.de
+49-33762-77286