Quantum Technologies at DESY

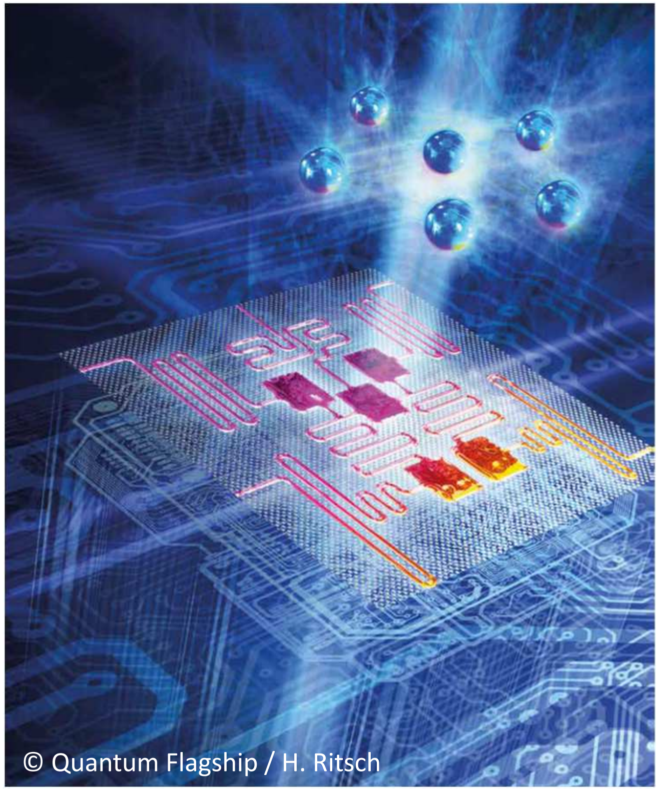
What are the present activities ? - What are the prospects ?

Prof. Dr. Kerstin Borras

Dr. Karl Jansen

DESY Quantum Technology Task Force

PRC Meeting 10 May 2022



HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Quantum Technologies are part of our Future.

Quantum Technologies are one of the most ambitious technological goals of science today.

Quantum Advantage: working on completely different principles than classic technology
→ potential to solve the challenges in our future projects
→ changing science research → maximizing the achievable success

Quantum Technologies demand for a rethinking of our methods
→ pioneering work improves already our classical methods.

Worldwide: several extensive research programs, dedicated centers, large-scale research,
supported by substantial funding programs on national, European and international level.

DESY and Campus Partners:
excellent scientific competences and facilities for R&D in QT
crucially complementary to the running research projects

cross-cutting activities like QT are in DESY's DNA
→ **unique pole position to drive the evolution and to play a leading role in dedicated QT topics**

→ **Quantum Technologies identified as a strategic direction**

Quantum Technologies identified as a strategic direction

Introduction

DESY established a cross-divisional Quantum Technology Task Force to

- identify running activities,
- develop a proposal to organize a structure that connects the divisions inside DESY and establish links to outside activities,
- identify opportunities for third party funds and submit applications,
- work closely with technology transfer for early industry connections.

Three initial pillars for Quantum Technology topics at DESY:

- **Development of quantum computing algorithms for applications**
- **Materials and photonics research and development towards novel quantum devices and a scalable and reliable quantum computer**
- **Quantum sensors as evolving/enabling and also applied technology**

Quantum Technologies in the Helmholtz Association.

Strategic Roadmap with many contributions from DESY.

Helmholtz Association: DESY's Funding Agency

five primary active research areas

https://www.helmholtz.de/en/research/quantum-technologies/

- **Quantum computing**
- **Simulation, numerical and ML methods**
- **Quantum sensors**
- **Quantum materials and basic research**
- **Quantum communication**

In addition, Helmholtz develops and operates powerful **infrastructures** for researching quantum technologies

DESY provided important and unique contributions to this roadmap of all Helmholtz Centers.

https://www.helmholtz.de/fileadmin/user_upload/04_mediathek/21_Quantum_Strategy_Brochure_WEB.pdf

Overarching Goal:

employ novel Quantum Technologies
to enhance and enable cutting-edge science in all divisions as well as to act as a national hub for solving the major challenges facing society, science and the economy
→ DESY wide organization with partners from the campus and the industry

DESY. QUANTUM
Quantum Technology Applications

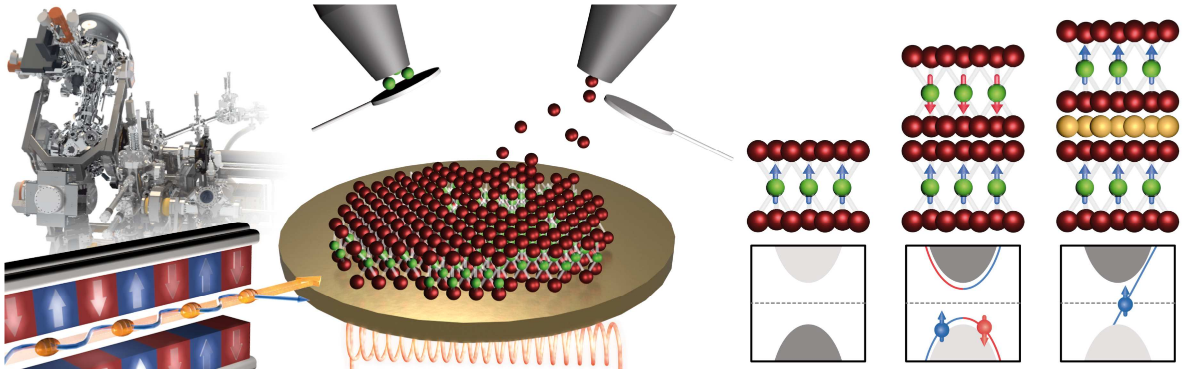
DESY. QUANTUM

Zeuthen		Hamburg
Quantum Simulations Algorithms & Methods Benchmarking	Knowledge & Technology Transfer	Photon Science for Quantum Materials and for Quantum Devices
Access to Quantum Computers	Training and Education	Quantum Machine Learning Quantum Simulations
Quantum Sensing	Outreach	Quantum Sensing

Quantum Materials

Find out and cure what causes problems in Quantum Computers and other Quantum Devices

- **From fundamental understanding of quantum phenomena in materials to the development of tailor-made materials for quantum technology devices, including innovative qubit systems.**
- **DESY light sources: uniquely powerful quantum tools - PETRA IV: ultimate multi-D quantum microscope**
  - **Precision spectroscopy on quantum materials and devices**
    study **n**ovel, complex quantum materials and devices with high resolution and highly selective X-ray spectroscopies
    → understand the atomic and electronic structure and connect to the functional properties
  - **Ultrafast spectroscopy on quantum materials → assess couplings and decoherence mechanisms**
    employed to study quantum materials at FLASH and EuXFEL
    → insights to coupling strengths and mechanisms of decoherence mechanisms
  - **X-ray quantum optics**
    employ nuclear resonant scattering
    to extend quantum optics to the hard X-ray range
    → explore the vastly different coupling strengths, photon energies, material parameters
    → improve the generalizability of underlying theories
    → potentially discover novel applications that require exotic parameter sets.



Quantum Materials Analytics Lab (in discussion)

Fast-reaction materials analytics laboratory.

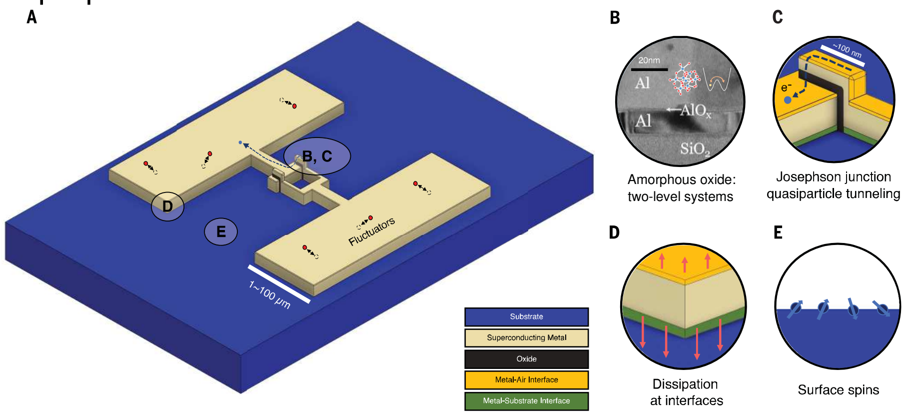
REVIEW

QUANTUM COMPUTING

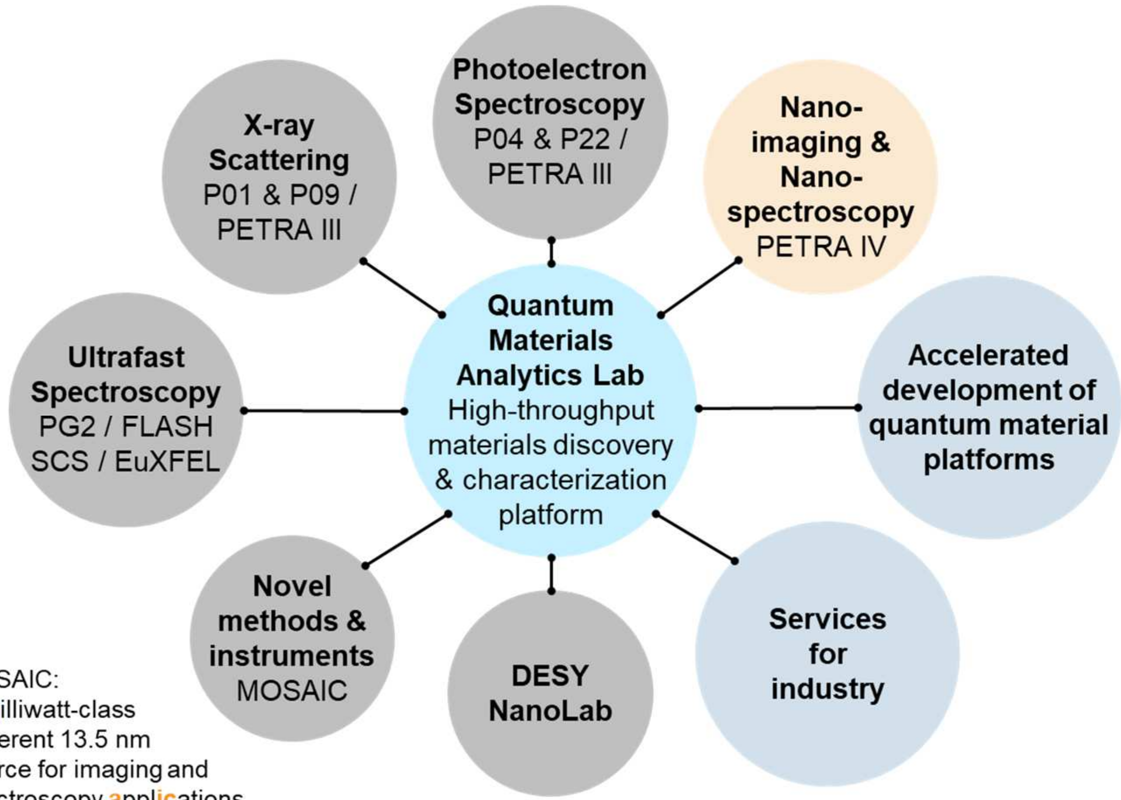
Materials challenges and opportunities for quantum computing hardware

It is important to develop …

- high-throughput methods for correlating qubit measurement with direct materials spectroscopy and characterization
- materials discovery pipelines that exploit directed, rational material searches in concert with high-throughput characterization approaches aimed at rapid screening for properties relevant to QIP



N. P. de Leon *et al.*, Science **372**, eabb2823 (2021)



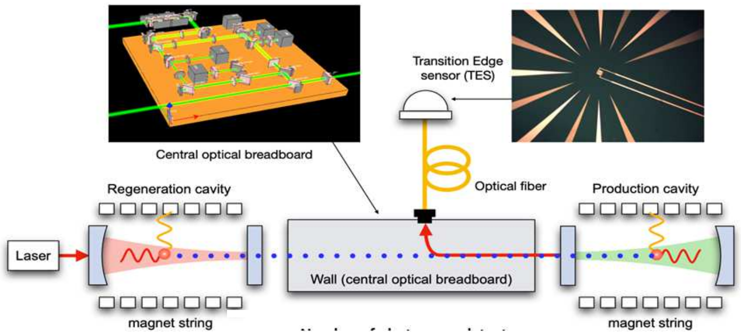
MOSAIC:
A milliwatt-class coherent 13.5 nm source for imaging and spectroscopy applications

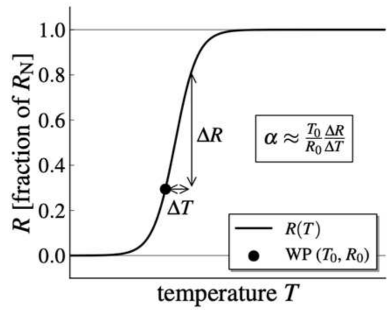
Quantum Sensing

Enabling technology for novel experiments and operation

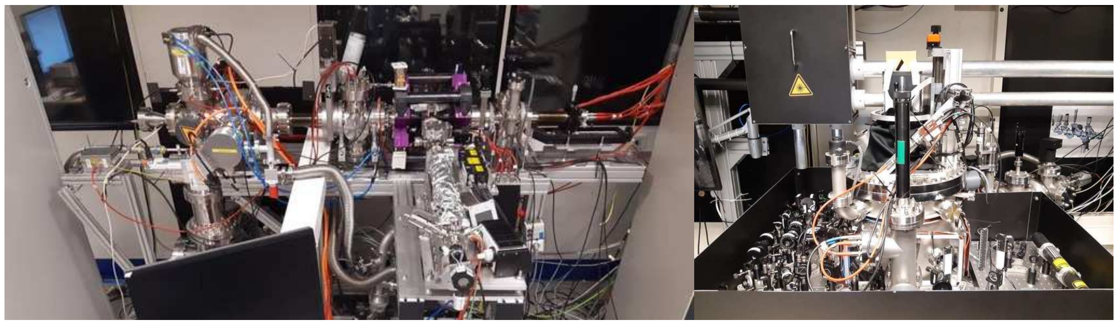
- **Explore, develop and apply quantum sensors and electronics in particle and astro-particle physics experiments and beyond**
- **Evolving and enabling technology → part of genuine detector R&D**
- **Applied in already operating experiments like ALPS II**

Transition-edge sensors (superconducting single-photon detectors) for ALPS II
(Axel Lindner)





Highly charged ion clocks as sensors for ultralight dark matter with QSNET
(Steven Worm)



Electron beam ion trap @ MPI Heidelberg, to be used for dark matter search @ DESY

Quantum Machine Learning

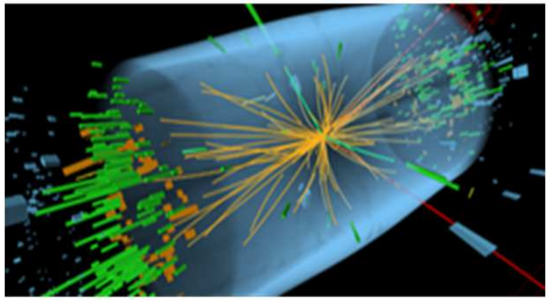
Early examples in Experimental Particle Physics

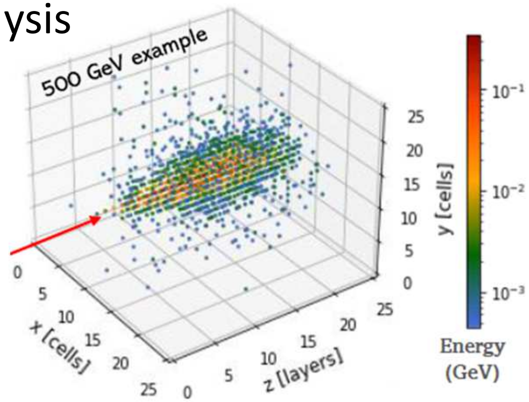
- **Quantum Maschine Learning lies at the intersection of**
  Quantum Computing and Maschine Learning

  → usually employed to analyze classical data in a hybrid mode

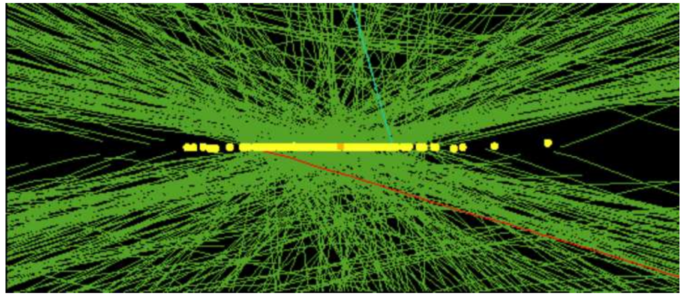
  - High Luminosity LHC (>2029) needs vast amount of simulations with 200 pile-up events, GRID Computing, Big Data Analysis

LHC (~20 pile-up events)



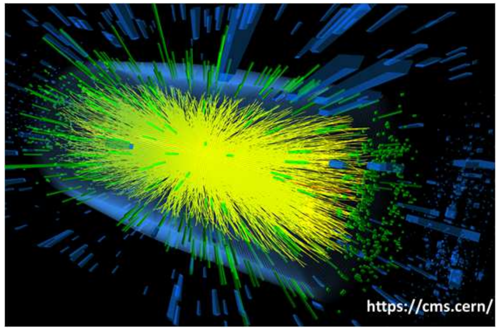


LHC (~140 pile-up events)



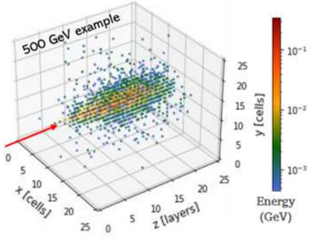
- **Develop machine learning and tensor network methods for QC**
  - Quantum GAN (Quantum Generative Adversarial Network) simulations for detectors (CERN Openlab with joint Gentner PhD Student)
  - Tracking with Quantum Computers for LUXE and ATLAS

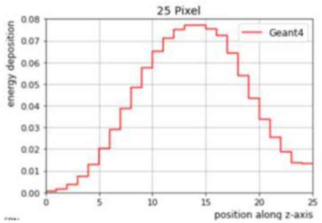
Quantum GANs in One Dimension

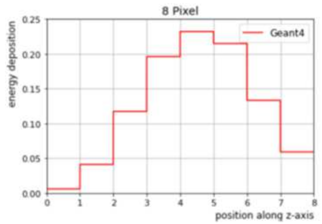


Quantum Generative Adversarial Network

- ➢ **Down sample 3D shower image → 8 pixels → 3 qubits**

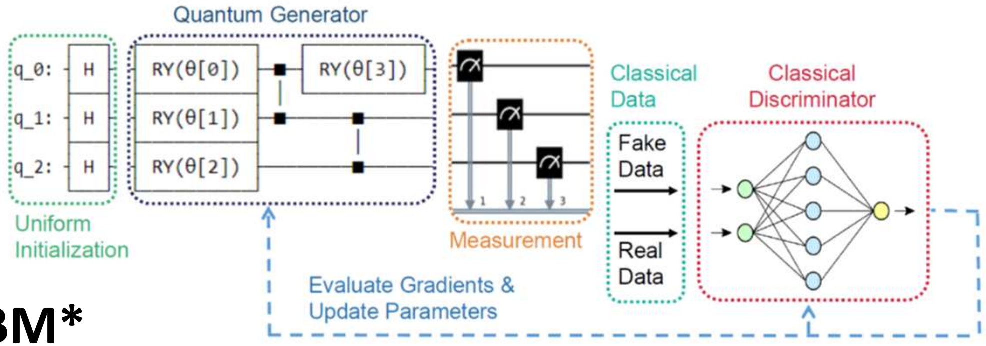




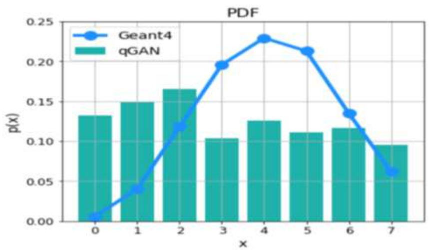


8 quantum states:
|000⟩, |001⟩, |010⟩, |011⟩,
|100⟩, |101⟩, |110⟩, |111⟩

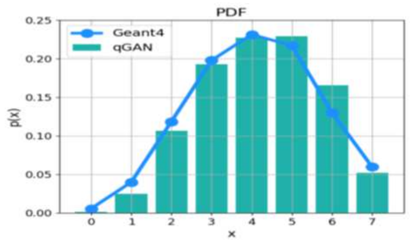
- ➢ **Use hybrid approach: quantum + classical**



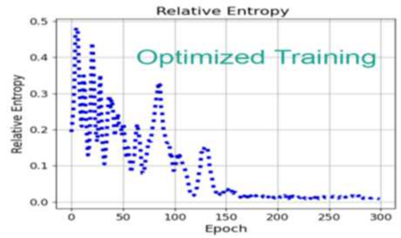
- ➢ **Employ a Quiskit qGAN model developed by IBM***



Uniform Initialization



Trained Model



* https://qiskit.org/documentation/machine-learning/tutorials/04_qgans_for_loading_random_distributions.html

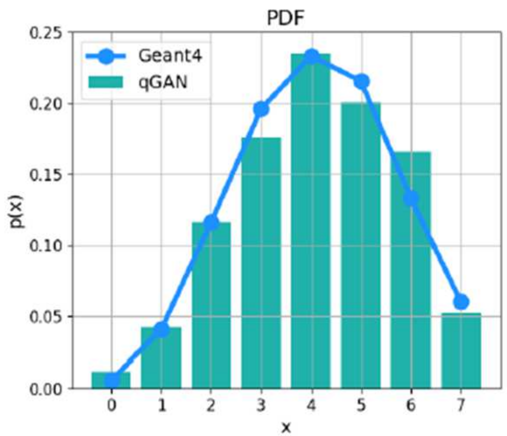
Quantum GAN in One Dimension with Noise

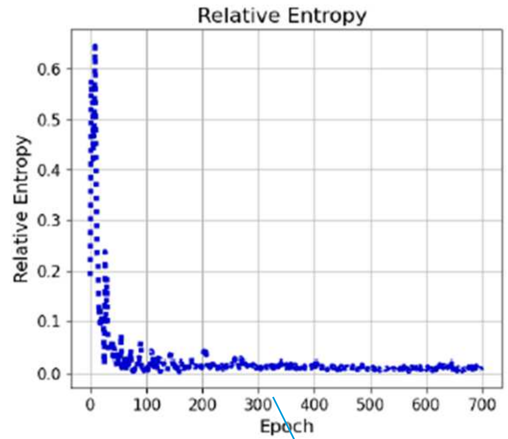
F. Rehm, S. Vallecorsa, K. Borras, D. Krücker http://symsim.jinr.ru/grid2021/363-368-paper-67.pdf

➢ Apply Readout Noise (model IBMq belem)

Qubit Number:	0	1	2
Readout Error:	3.6%	4.7%	9.6%

no decrease in accuracy
fast convergence

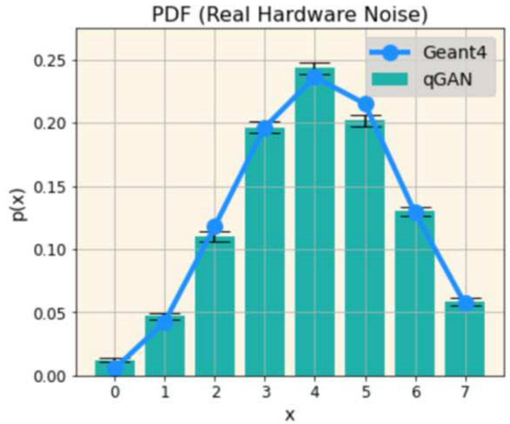


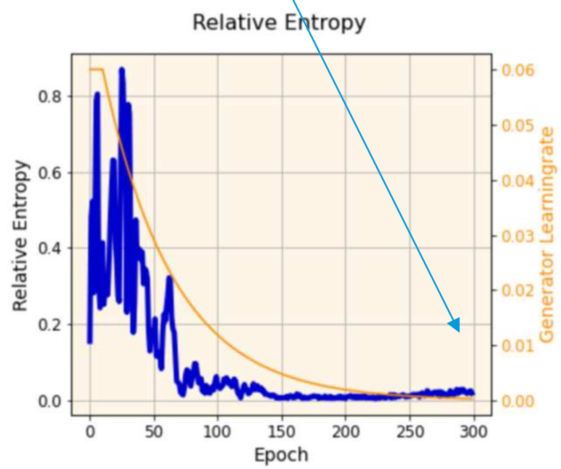


➢ Apply Full Noise (model IBMq manila)

Qubit Number	0	1	2	Average
Readout Error	2.34%	2.66%	2.05%	**2.35%**
CX-gate Error	1.11%		1.75%	**1.43%**

no decrease in accuracy
fast convergence



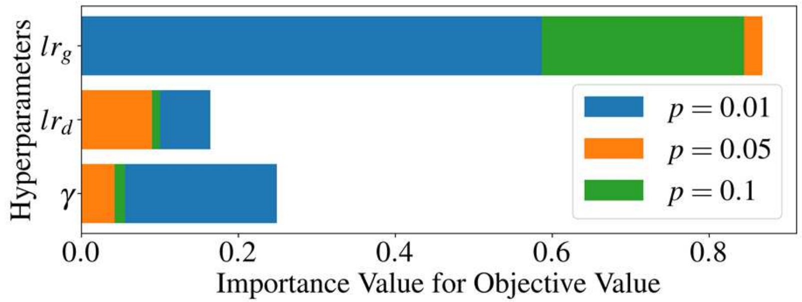


Impact of quantum noise on the training of Quantum GANs

K.Borras,S.Y.Chang,L.Funcke,M.Grossi,T.Hartung,K.Jansen, D.Kruecker,S.Kühn,F.Rehm, C.Tüysüz,S.Vallecorsa

https://arxiv.org/abs/2203.01007

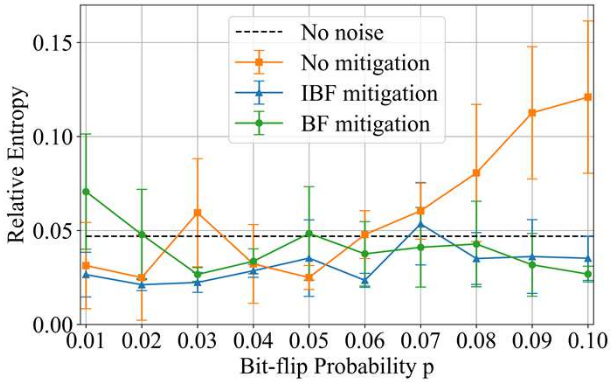
Detailed studies with noise and noise mitigation



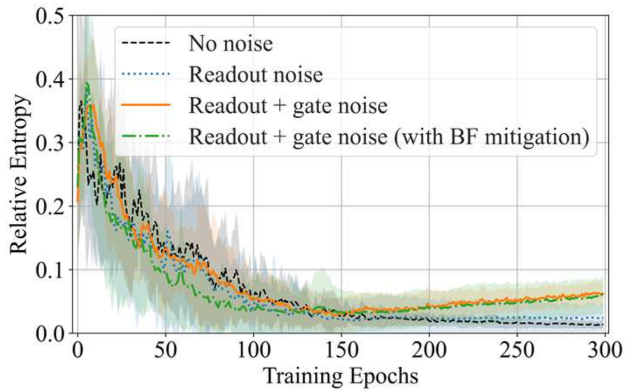
- **Importance of hyperparameters for different values of the bit-flip probability, p = {0.01, 0.05, 0.1}**
  - generator learning rate lrg, discriminator learning rate lrd, exponential decay rate γ for the learning layers

→ generator learning rate lrg has the highest impact → demonstrates the difficulty of training the quantum generator

- **Results without and with two different error mitigation methods**



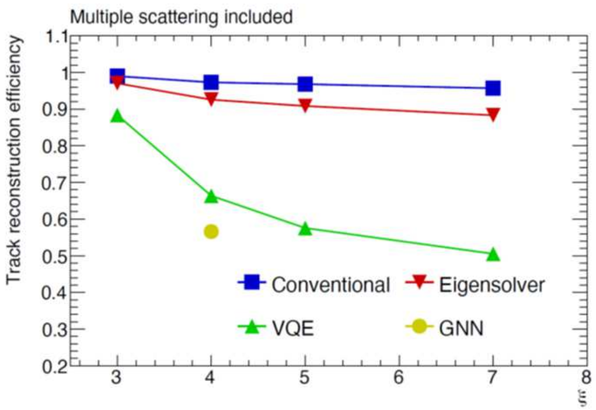
Error mitigation plays a crucial role for qGAN training in the presence of the large readout errors on current NISQ devices



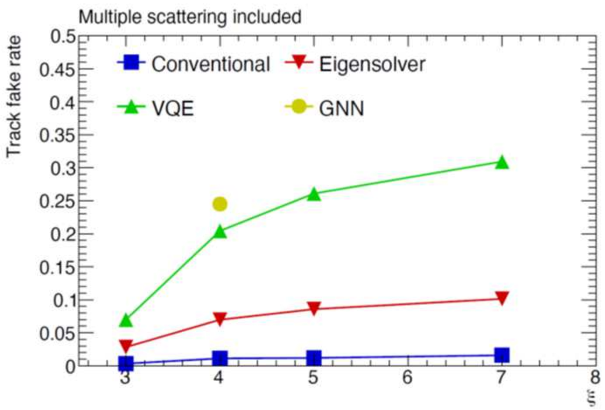
Average values quickly converge in the noise-free and readout-error only cases, but do not seem to converge when including two-qubit gate errors → reveal the critical effect of two-qubit gate errors on qGAN training with current NISQ devices.

Track Reconstruction with Quantum Computers at LUXE

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

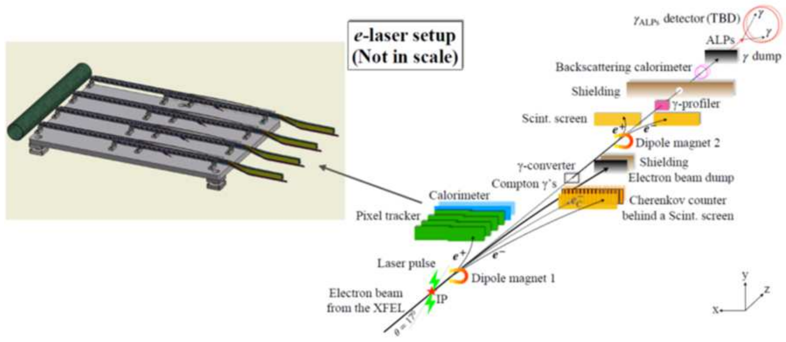


Track reconstruction efficiency as a function of the field intensity parameter ξ



Track fake rate as a function of the field intensity parameter ξ

LUXE EXPERIMENT SETUP



Very preliminary results , For example GNN is limited by the training dataset size

→ system with quantum approach and classical benchmarks is working

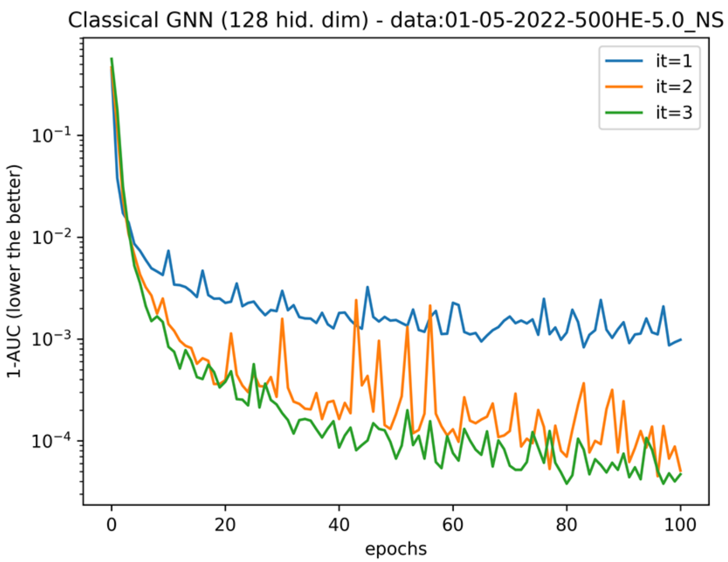
→ conventional tracking shows the performance that can be realistically achieved

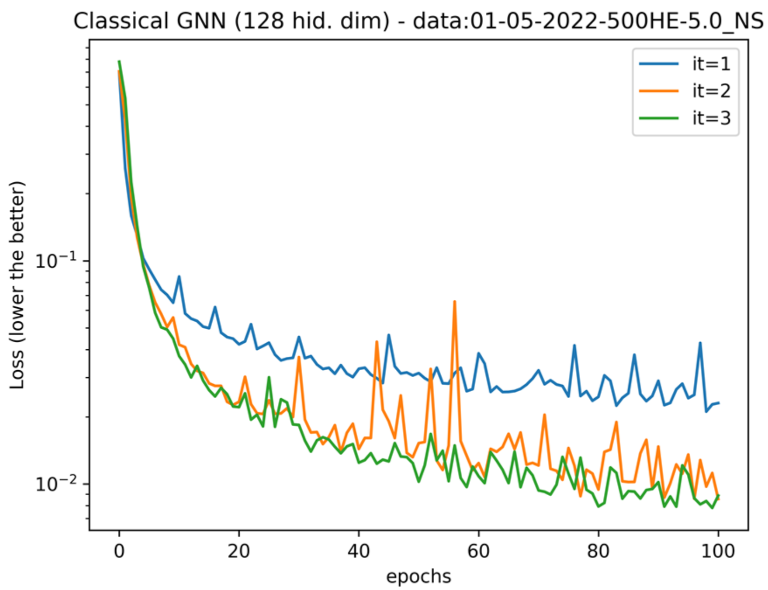
→ room for improvement for other tracking methods

→ further optimization studies in progress.

Track Reconstruction with Quantum Computers at LUXE

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

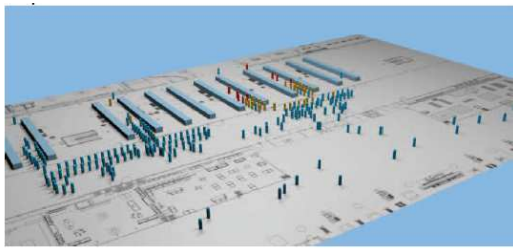




→ More training data → very good AUC and loss values

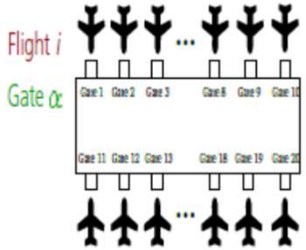
→ Promising results

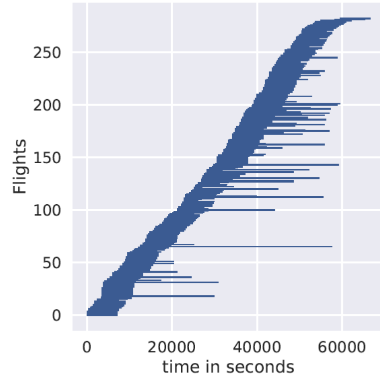
Quantum Computing in Theoretical Particle Physics



The Pioneers in Quantum Computing

- **Quantum Computers have the potential to solve problems that cannot be addressed with classical computers**
- **Develop algorithms and methods → focus on Variational Quantum Eigensolver**
  - Calculations in Lattice Gauge Theory
    → novel results for complex theoretical problems
    → frequently demanded by companies (IBM) to test their novel devices
  - Application to various models in high energy, condensed matter physics and others (flight gate assignment (DLR))
  - Error mitigation in Quantum Comptuer calculations (DASHH PhD with Prof. Matthias Riebisch, UHH)
  - Optimize Expressivity of Quantum Gate Circuits
    → lower noise





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

Task: find lowest energy ⇔ shortest path

Same mathematical description for problems in traffic, logistics, aerospace, ... tracking in particle physics

Example for Error Mitigation in VQS

Increase the Reliability for Quantum Computing Calculations

➢ **Model in Condensed Matter Physics: 1-Dimensional Heisenberg model**

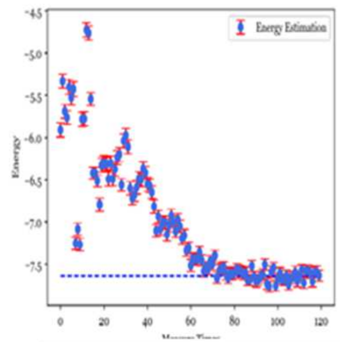
$$H = \sum_{i=1}^{N} \beta\left[\sigma_x(i)\sigma_x(i+1) + \sigma_y(i)\sigma_y(i+1) + \sigma_z(i)\sigma_z(i+1)\right] + J\sigma_z(i)$$

- Pauli matrices

$$\sigma^x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad , \quad \sigma^y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad , \quad \sigma^z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

- nearest neighbor interaction, tensor products
- Hamiltonian expressed in Pauli matrices → suitable for quantum computer
- shows phase transitions, critical behavior, non-trivial spectrum

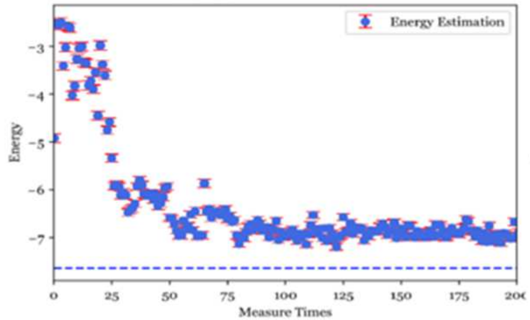
Measurement Error Mitigation in Quantum Computers Through Classical Bit-Flip Correction
L. Funcke, T. Hartung, S.Kühn, P. Stornati, X. Wang, K.Jansen, arxiv:2007.03663, under review in Phys. Rev. D

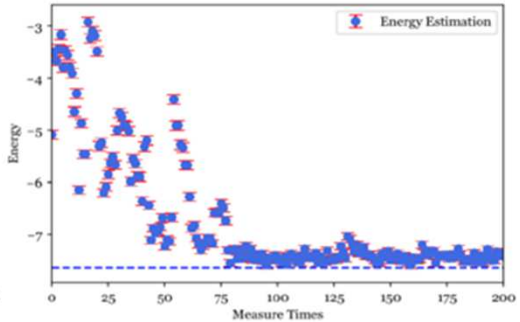


no noise:
reaching exact result very fast

full noise
cannot find
ground state

corrected
ok !





Towards gauge theories

QED in 2+1 dimensions

- lattice Hamiltonian, lattice spacing a, periodic boundary conditions

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

$$\hat{H}_E = \frac{g^2}{2}\sum_{\boldsymbol{n}}\left(\hat{E}^2_{\boldsymbol{n},\boldsymbol{e}_x} + \hat{E}^2_{\boldsymbol{n},\boldsymbol{e}_y}\right), \hat{H}_B = -\frac{1}{2g^2a^2}\sum_{\boldsymbol{n}}\left(\hat{P}_{\boldsymbol{n}} + \hat{P}^{\dagger}_{\boldsymbol{n}}\right)$$

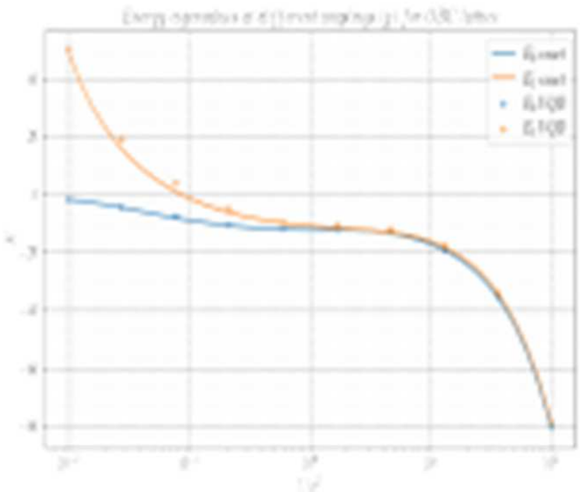
- electric field operator: $\hat{E}_{\boldsymbol{n},\boldsymbol{e}_\mu}\left|E_{\boldsymbol{n},\boldsymbol{e}_\mu}\right\rangle = E_{\boldsymbol{n},\boldsymbol{e}_\mu}\left|E_{\boldsymbol{n},\boldsymbol{e}_\mu}\right\rangle, \quad E_{\boldsymbol{n},\boldsymbol{e}_\mu} \in \mathbb{Z}$
- plaquette operator: $\hat{U}_{ij} = \hat{U}_{ij,e_x}\hat{U}_{ij+e_x,e_y}\hat{U}^{\dagger}_{ij+e_y,e_x}\hat{U}^{\dagger}_{ij,e_y}$
  → represented as lowering and raising operators, i.e. $\hat{U}_{ij}|e_{ij}\rangle = |e_{ij} - 1\rangle$
- "naive" continuum limit: $\hat{H} \xrightarrow[a\to 0]{} \int \mathrm{d}\boldsymbol{x}[E(\boldsymbol{x})^2 + B(\boldsymbol{x})^2]$
- Gauss law

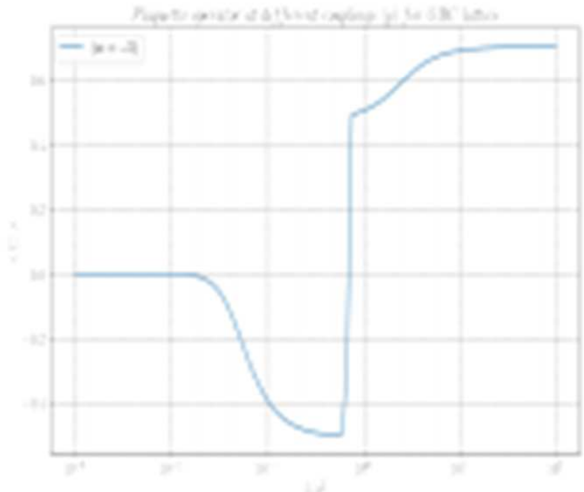
$$\left[\sum_{\mu=x,y}\left(\hat{E}_{n,e_\mu} - \hat{E}_{n-e_\mu,e_\mu}\right) - \hat{q}_n\right]|\Phi\rangle = 0\forall n \quad \Longleftrightarrow |\Phi\rangle \in \{\text{ physical states }\}$$

Results inaccessible for Markov chain Monte Carlo

First steps in quantum computing gauge theories

- Variational Quantum Computer Simulations (VQCS) of QED
  (Giuseppe Clemente, Arianna Crippa, Karl Jansen)





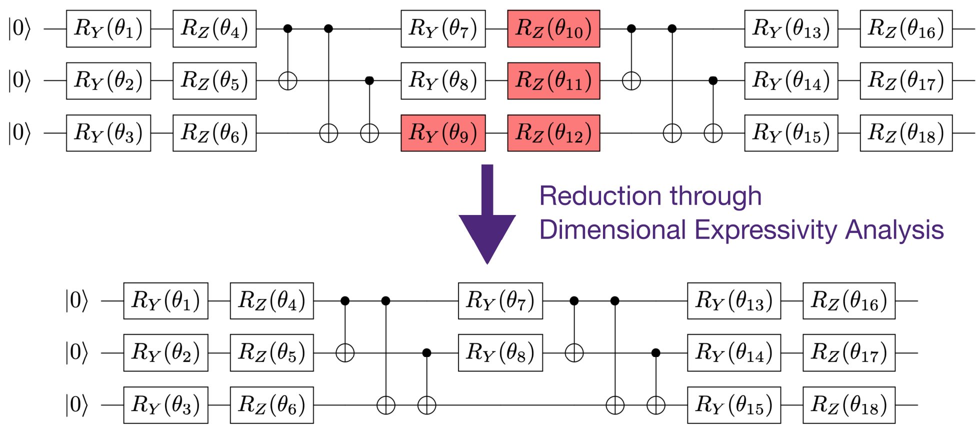
Particle mass $\Delta = E_1 - E_0$
$\rightarrow$ physical quantity

detecting a phase transition at negative mass
$\rightarrow$ not possible with Monte Carlo methods

Optimize Dimensional Expressivity of an Quantum Gate Circuit

Less gates → less noise.

- **Gate Operations are a source of noise in QC calculations.**
- **Develop algorithms and methods for Dimensional Expressivity Analysis**
  - generate as many/complicated states as possible with fewest number of gates
  - for non-parametric gates: algebraic techniques (commutator rules) to minimize gate count (no decrease in expressivity)
  - parametric gates: algebraic techniques become difficult (groups have infinitely many generators)
  - need a metric of expressivity



Dimensional Expressivity Analysis of Quantum Circuits
L. Funcke, T. Hartung, S. Kühn, P. Stornati, K.Jansen,
Quantum 5 (2021) 422

DESY. Quantum in Zeuthen

Specific Focus on Quantum Computing

DESY. QUANTUM | Center for Quantum Technology and Applications

- **Innovation-Funding from the state of Brandenburg:**
- **up to 15 Million Euros over 5 years**
- **focus topics**
  - provide access to quantum computer hardware
  - develop applications and use cases → enable quantum computations
  - benchmark, tests and verification of emerging hardware platforms
  - provide training in quantum computing
  - make new generation "quantum ready"
  - successful Helmholtz recruitment → leading sceintist
  - Employment of first permanent staff member

Summary

DESY's Competence in Quantum Technology

DESY develops a large variety of Quantum Computing Applications: VQS, Quantum-ML in simulation and reconstruction and more:

- useful for particle physics, condensed matter as well as optimization problems and simulations and reconstruction of detectors and arbitrary events
- algorithms can be generalized towards many interdisciplinary areas (logistic, scheduling and more)

DESY develops methods for efficient Quantum Computing:

- error mitigation, expressivity optimization, benchmark tests for QC hardware

DESY employs its unique photon source facilities:

- understand the working of Quantum Materials, shape and design tailor-made materials for Quantum devices like qubits and sensors

DESY studies and develops Quantum Sensors:

- apply and operate Quantum Sensors in new experiments, evolve and enable unprecedented precision for novel experiments to answer fundamental questions.

Any

Questions ?

More Information

DESY.

Present Cooperations in Science

National and International Collaborations

- **Develop algorithms and methods**
  - Perimeter Institute, University of Bath, Cyprus University and Cyprus institute, MIT Boston, Peking University
  - Hamburg University, Berlin University Alliance, Saarbrücken University, FZJ, MPG

- **Towards gauge theories**
  - Institute for Quantum Computing (Waterloo), IQOQI (Innsbruck), Autonoma University (Barcelona)
  - Ulm University

- **Experimental particle physics: track reconstruction, simulation with QGANs**
  - CERN Openlap, Fudan University, LBNL, ...

Present Cooperations with Industry Participation

National and International Collaborations

- **DLR → DESY in contact for participation in BMWI Funding for Industry QC Enabling**
  - Flight gate assignment problem
- **IBM:**
  - Noise Mitigation and Employment in Cooperation with QCRUISE (start-up), U Saarbrücken, TU Berlin, FZJ
  - Error Mitigation in Software Engineering Modelling, UHH
  - Grant Access for Industry through Brandenburg Funding
- **Rigetti:**
  - Error Mitigation Studies in Cooperation with Cyprus University and Institute, MIT
- **EU funded PhD Education Network of 9 EU Institutions – ENGAGE:**
  - NovaMechanics (Cyprus) and Goodyear (Akron, Ohio and Luxemburg) and the Delphi consortium of companies in the hydrocarbon energy sector (Netherlands) will host internships
- **Emerging Cooperation with Institute for High Performance Micro-Elelctronics in Frankfurt / Oder**