Quantum Technologies at DESY

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

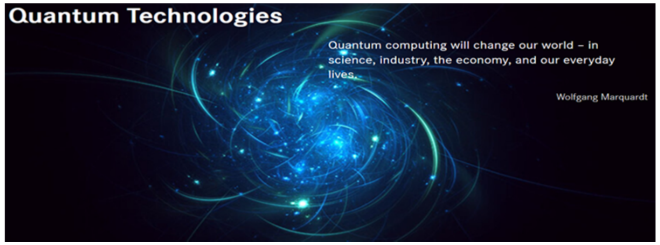
DESY Quantum Technology Task Force qt-task-force@desy.de
DESY, August 2020

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Quantum Technologies are the Future.

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

Source: Helmholtz



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
→ already pioneering work improves 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 connected institutes on campus:

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 assume a leading role in dedicated QT topics.

Quantum Technologies are the Future.

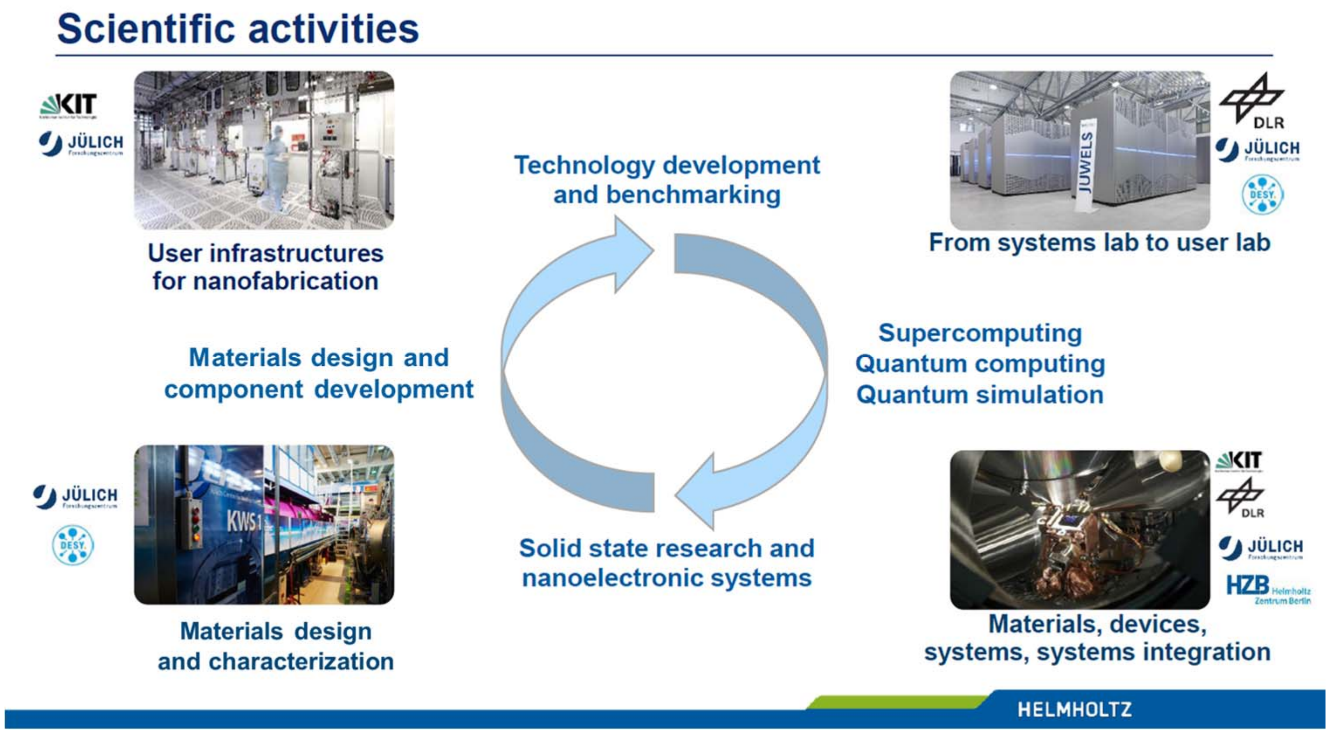
Quantum Technologies are one of the most ambitious technological goals of science today.

Helmholtz Association:

five primary active areas

- **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



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

Helmholtz Quantum Platform

Coordinate quantum technology activities within Helmholtz

Mandate and Tasks

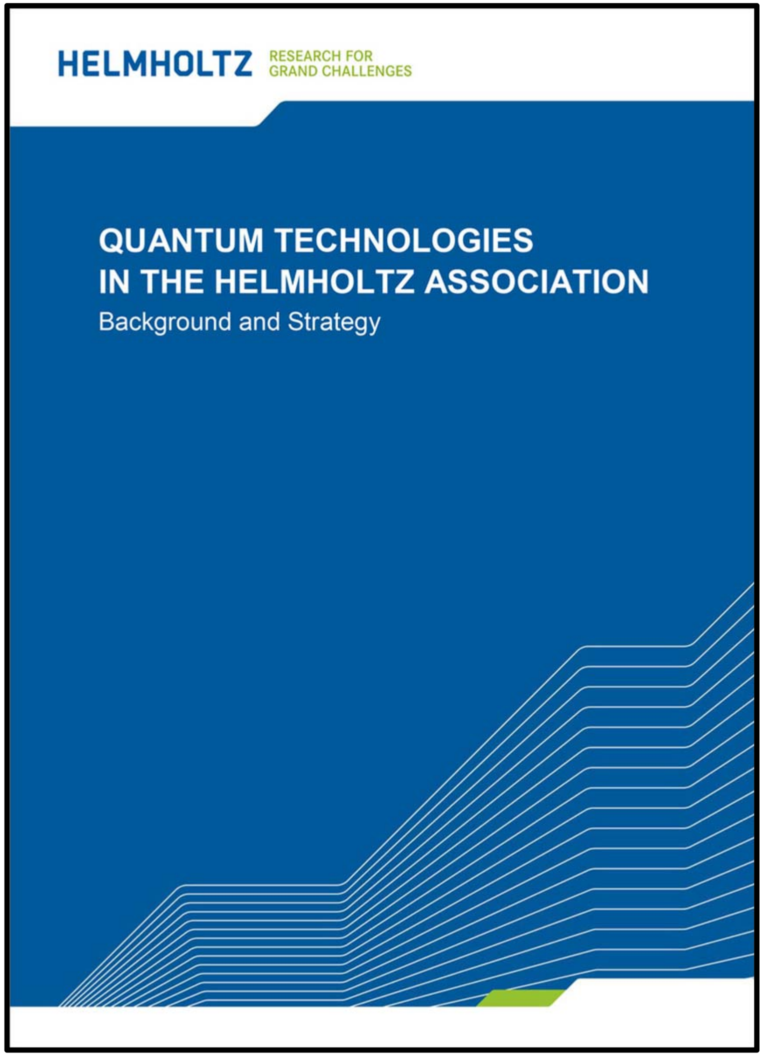
- Update the developed roadmap Quantum Technologies
- Link researchers and management
- Organize workshops
- Provide input for communication with government

Present members :
Tommaso Calarco, FZJ (spokesperson)
Georgy Astakhov, HZ Dresden, Wolfgang Ertmer, Institute for Quantumoptics, U Hannover
Karl Jansen, DESY, Christoph Marquardt, DLR, Oliver Rader, U Potsdam
Ferdinand Schmidt-Kaler, U Mainz, Thomas Stoehlker, HZ Jena
Wolfgang Wernsdorfer, KIT, Sabine Attinger, UFZ

QT in PoF:

- Cross – Cutting Activity , for example: MT DMA (ST-2) collaboration between Matter, Information and others (DESY, Jülich, DLR, HZDR, UFZ…)
- Quantum Materials are part of research in MML.
- Quantum Sensors are part of MT but likewise also in MU.

In general QTs are part of the enabling technologies and on the other hand part of applied technology in ambitious experiments.



https://www.helmholtz.de/fileadmin/user_upload/01_forschung/QT_in_the_Helmholtz_Association.pdf

Quantum Technologies at DESY and on Campus

Introduction

DESY and associated institutes have excellent competences in QT:

complementary activities presently concentrating in Particle and Astroparticle Physics and in Photon Science, all divisions and research areas on campus can greatly benefit, eg. computing for complex simulations, optimization challenges.

DESY and institutes on campus have unique facilities

→ unique profile to drive evolution of QT and to play a leading role on the various levels.

Presently three initial pillars for QT topics at DESY

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

The DESY QT Task Force

Mandate and Imminent Steps

Mandate: Evaluate the various topics of Quantum Technologies for DESY

- Assess and evaluate the opportunities for Quantum Technologies at DESY
- Identify running or planned QT activities on the whole DESY campus
  (Hamburg, Zeuthen, partner institutes and universities)
- Assess the importance of QT for all divisions at DESY,
  for example its relevance for PETRA IV, Particle Physics and beyond…
- Develop a vision for QT activities at DESY and cooperations with institutes on campus

Imminent Steps

- ➢ **collect feedback and identify interested colleagues by discussing QT in division**
- ➢ **organize a campus-wide workshop (21 / 22 Sep 2020)**
- ➢ **assess abilities, ambitions and opportunities**

The DESY QT Taskforce

Members

Present Members (reachable via email qt-task-force@desy.de)

- Martin Beye, Kerstin Borras, Volker Gülzow, Cigdem Issever, Karl Jansen, Dirk Krücker, Kai Rossnagel, Robin Santra, Hubert Simma, Steven Worm, Klaus Ehret (ex offcio)









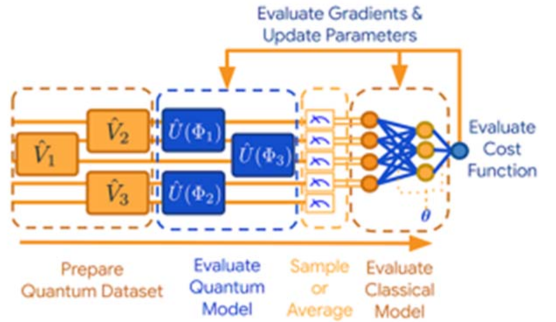


Activities in Particle and Astroparticle Physics Divisions

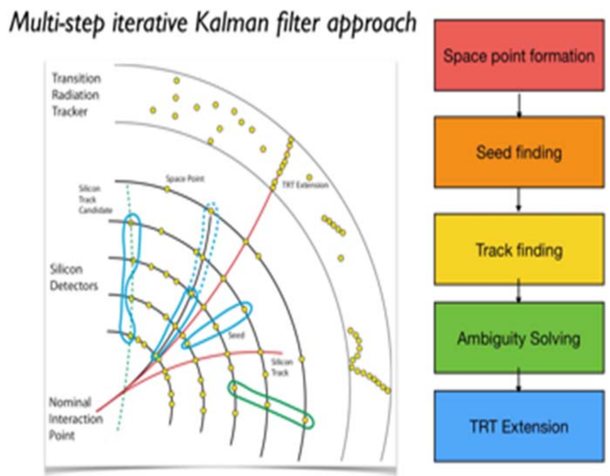
Quantum Computing and Quantum Sensors

Ongoing projects

- Develop algorithms and methods in Theoretical Particle Physics
  - Calculations in Lattice Gauge Theory → frequently demanded by companies to test their novel devices
  - Application to models in high energy and condensed matter physics and others for example flight gate assignment from DLR
  - Error mitigation in QC calculations (DASHH PhD)
- Quantum computing to cope with the vast amount of simulations (HL LHC)
  - Develop machine learning and tensor network methods for QC
    Q-GAN simulations for detectors (CERN Openlab Gentner PhD),
    Tracking, Anomaly detection, e.g. in Dark Matter search
- Explore, develop and apply quantum sensors and electronics in particle and astroparticle physics experiments and beyond,
  Establish contacts to other Helmholtz Centers and EU wide projects



Source: https://ai.googleblog.com/2020/03/announcing-tensorflow-quantum-open.html



CERN openlab

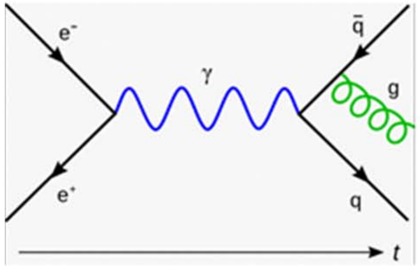
Theoretical Physics Pioneers Quantum Computing Application

Lattice Gauge Theory provides a perfect testbed

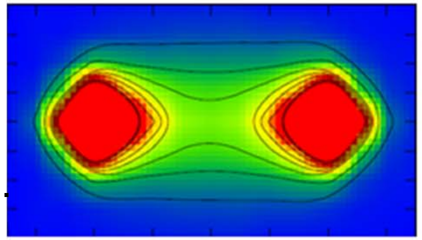
Lattice Gauge Theories

= study of gauge theory on a spacetime that has been discretized into a lattice.

In particle physics **non-perturbative process calculations** in continuous spacetime formally involve evaluating an infinite-dimensional path integral, which is **computationally intractable**. By working on a **discrete spacetime**, the path integral becomes finite-dimensional, and can be evaluated by stochastic simulation techniques such as the Monte Carlo method. When the size of the lattice is taken infinitely large and its sites infinitesimally close to each other, the **continuum gauge theory is recovered.**



Electron positron annihilation into a photon, production of a quark antiquark pair radiating a gluon



Meson composed of a quark and an antiquark

The $U(1)_{2+1}$ gauge theory Hamiltonian is

$$H = \frac{1}{2}\int d^2x \left[\vec{E}^2 + (\vec{\nabla} \times \vec{A})^2\right].$$

E is conjugate to A so $[A_j, E_{j'}] = i\delta_{jj'}$. Introduce the corresponding lattice variables $\theta = eaA$ and $L = \frac{a}{e}E$. We will use the compact version of the lattice theory so the A field is exponentiated. With

$$Z_P = e^{i(\theta_1+\theta_2+\theta_3-\theta_4)} = U_1 U_2 U_3^\dagger U_4^\dagger,$$

and $g^2 = e^2 a = 1/\sqrt{x}$ the lattice Hamiltonian can be written

$$H = \frac{g^2}{2a}\left[\sum_i L_i^2 - x\sum_P (Z_P + Z_P^\dagger)\right].$$

ICAL REVIEW D VOLUME 28, NUMBER 8 15 OCTOBER 1983

Compact U(1) in 2+1 dimensions: The finite-lattice Hamiltonian approach

A. C. Irving* and J. F. Owens
Physics Department, Florida State University, Tallahassee, Florida 32306

C. J. Hamer
Theoretical Physics Department, Institute for Advanced Studies, Australian National University, Canberra, Australian Capital Territory 2600

(Received 23 May 1983)

We have studied the mass spectrum and phase structure of compact electrodynamics in $D=2+1$ dimensions using the finite-lattice Hamiltonian approach. The numerical results are generally comparable to, but not significantly better than, available strong-coupling series results. Evidence for roughening of the "on-axis" string is found at $g^2 = e^2a \simeq 1.5$ while the vacuum and glueball sectors of the theory are smooth for all attainable g^2 ($\gtrsim 0.08$). Comparisons with results from applying weak-coupling approximations to the theory are also presented.

LETTER

doi:10.1038/nature18318

Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

Esteban A. Martinez[1]*, Christine A. Muschik[2,3]*, Philipp Schindler[1], Daniel Nigg[1], Alexander Erhard[1], Markus Heyl[2,4], Philipp Hauke[2,3], Marcello Dalmonte[2,3], Thomas Monz[1], Peter Zoller[2,3] & Rainer Blatt[1,2]

Gauge theories are fundamental to our understanding of interactions between the elementary constituents of matter as mediated by gauge bosons[1,2]. However, computing the real-time dynamics in gauge theories is a notorious challenge for classical computational methods. This has recently stimulated theoretical effort, using Feynman's idea of a quantum simulator[3,4], to devise schemes for simulating such theories on engineered quantum-mechanical devices, with the difficulty that gauge invariance and the associated local conservation laws (Gauss laws) need to be implemented[5–7]. Here we report the experimental demonstration of a digital quantum simulation of a lattice gauge theory, by realizing (1 + 1)-dimensional quantum electrodynamics (the Schwinger model[8,9]) on a few-qubit trapped-ion quantum computer. We are interested in the real-time evolution of the Schwinger mechanism[10,11], describing the instability of the bare vacuum due to quantum fluctuations, which manifests itself in the spontaneous creation of electron–positron pairs. To make efficient use of our quantum resources, we map the original problem to a spin model by eliminating the gauge fields[12] in favour of exotic long-range interactions, which can be directly and efficiently implemented on an ion trap architecture[13]. We explore the Schwinger mechanism of particle–antiparticle generation by monitoring the mass production and the vacuum persistence amplitude. Moreover, we track the real-time evolution of entanglement in the system, which illustrates how particle creation and entanglement generation are directly related. Our work represents a first step towards quantum simulation of high-energy theories using atomic physics experiments—the long-term intention is to extend this approach to real-time quantum

systems. In contrast, quantum simulations aim at the long-term goal of solving the specific yet fundamental class of problems that currently cannot be tackled by these classical techniques. The digital approach we employ here is based on the Hamiltonian formulation of gauge theories[9], and enables direct access to the system wavefunction. As we show below, this allows us to investigate entanglement generation during particle–antiparticle production, emphasizing a novel perspective on the dynamics of the Schwinger mechanism[2].

Digital quantum simulations described in the present work are conceptually different from, and fundamentally more challenging than, previously reported condensed-matter-motivated simulations of spin and Hubbard-type models[4,19,20]. In gauge theories, local symmetries lead to the introduction of dynamical gauge fields obeying a Gauss law[6]. Formally, this crucial feature is described by local symmetry generators $\{\hat{G}_i\}$ that commute with the Hamiltonian of the system $[\hat{H}, \hat{G}_i] = 0$ and restrict the dynamics to a subspace of physical states $|\Psi_{physical}\rangle$ which satisfy $\hat{G}_i|\Psi_{physical}\rangle = q_i|\Psi_{physical}\rangle$, where q_i are background charges. We will be interested in the case $q_i = 0$ for all i (see Methods). Realizing such a constrained dynamics on a quantum simulator is demanding and has been the focus of theoretical research[6,7,11,21–24]. Instead, to optimally use the finite resources represented by a few qubits of existing quantum hardware, we encode the gauge degrees of freedom in a long-range interaction between the fermions (electrons and positrons), which can be implemented efficiently on our experimental platform. This allows us to explore quantum simulation of coherent real-time

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Nature

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181 Citations

295 Altmetric

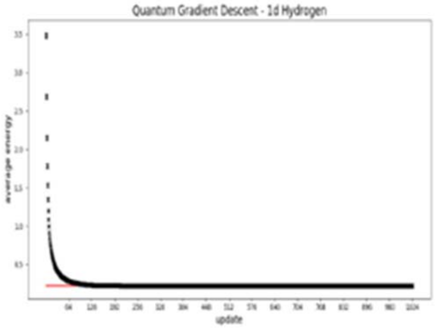
Quantum Computing for Particle Physics Theory

Lattice Gauge Theory Calculations

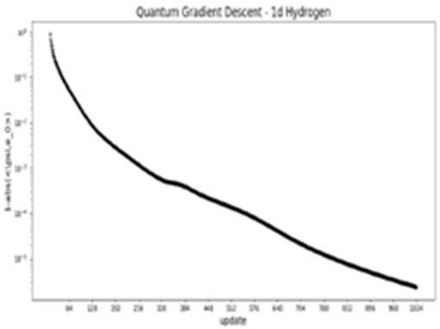
Example of a one dimensional Hydrogen atom

(T. Hartung, K.Jansen, arXiv:1808.06784, JMP)

Developing and testing new algorithms with QC simulators



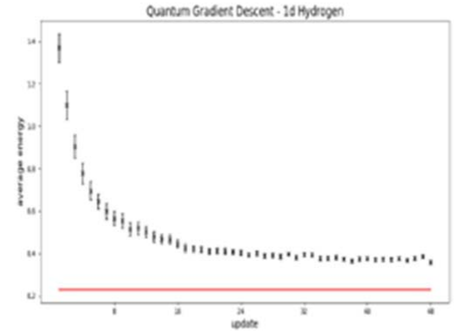
- average energy
  - simulator
  - no noise
  - 3 qubits
  - red line: exact result



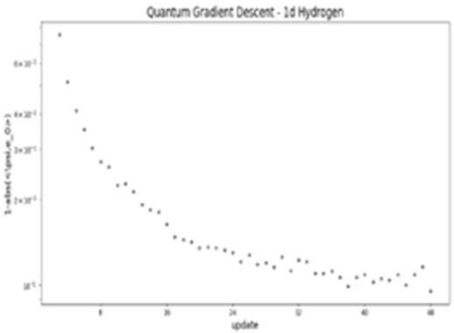
- distance to groundstate
- $|1 - \langle \Psi(j) | \Psi_0 \rangle|$

  Ψ_0 ground state wave function

Testing new hardware for QC Simulators, here Rigetti



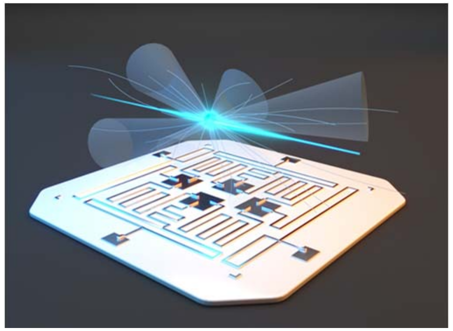
- average energy
  - 2 qubits
  - red line: exact result
  - 60% fidelity



- distance to groundstate
- 90% fidelity
- reaching machine precision

Quantum Computing for Particle Physics Theory

Projects published or in preparation



- Review on quantum computing for lattice gauge theories

  Simulating Lattice Gauge Theories within Quantum Technologies, M.C. Banuls et.al.
  https://arxiv.org/abs/1911.00003

- First papers of the calculations of the (1-dimensional) Hydrogen atom on Rigetti hardware

  Zeta-regularized vacuum expectation values from quantum computing simulations T. Hartung and K.Jansen
  https://inspirehep.net/literature/1768276, https://inspirehep.net/literature/1689146, https://arxiv.org/abs/1912.01276

- A new method to perform error mitigation, tested on IBMQ hardware.

  "Measurement Error Mitigation in Quantum Computers Through Classical Bit-Flip Correction"
  https://inspirehep.net/literature/1805462

- Pioneering work on simulations of a gauge theory for a Quantum Computer (to be realized)

  "A resource efficient approach for quantum and classical simulations of gauge theories in particle physics"
  https://inspirehep.net/literature/1802833

- In preparation

  Theoretical analysis of the expressivity of Quantum-Circuits
  Detailed protocol for the simulation of a 2+1 dimensional gauge theory for ultra-cold atoms

Quantum Computing for LHC Experiments

Cooperation of DESY-CMS with CERN Openlab

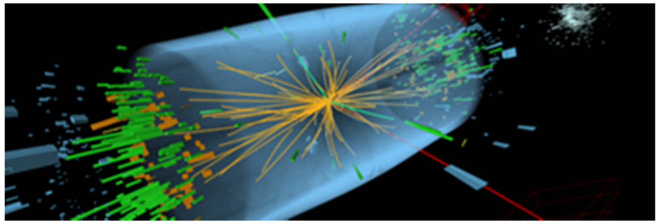
Massive need for simulation and smart reconstruction algorithms for HL-LHC and beyond:

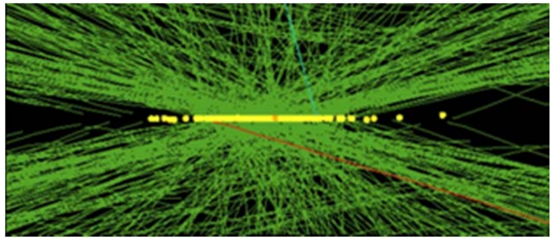
- **HL-LHC Phase II Upgrade:**
  event pile-up 40 → 200
  → novel fine granular detectors

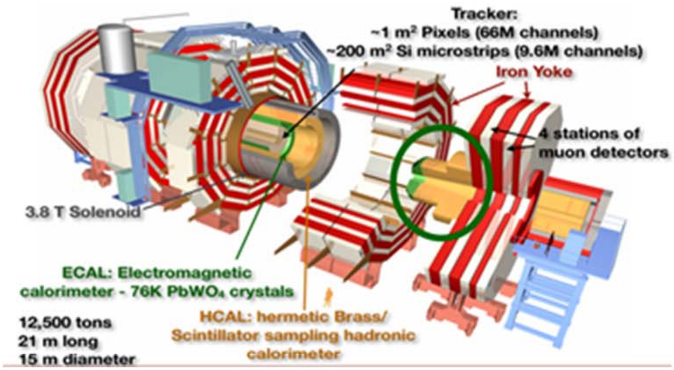
  CMS HGCal: 6 M channels in 5dim (space+energy+time)

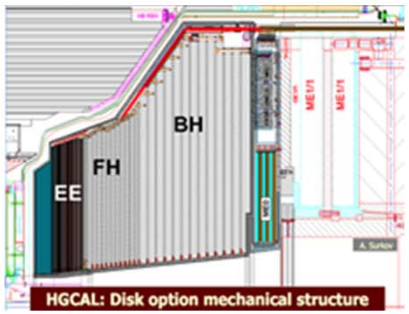
- **Investigate DL methods (like GANs) to produce fast simulation with high precision**
  → faster by 2-3 orders of magnitude
  particle flow (tracking), electromagnetic showers ongoing
  → start to address the complex simulation of hadronic showers

- **Investigate how to employ QC and Q-ML**

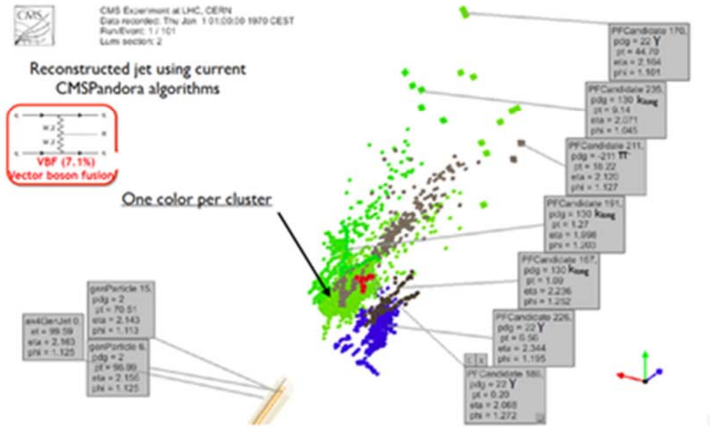








Higgs produced with VBF (Vector Boson Fusion)
Signal of VBF jets in the HGCal, no pile-up in the simulation!



Quantum Computing Application Examples

Published Projects

- Theoretical particle physics
  → variational quantum simulations of models in high energy physics

  Simulating Lattice Gauge Theories within Quantum Technologies, M.C. Banuls et.al.
  https://arxiv.org/abs/1911.00003

  Zeta-regularized vacuum expectation values from quantum computing simulations T. Hartung and K.Jansen
  https://arxiv.org/abs/1912.01276
- Experimental particle physics → quantum annealing

  A pattern recognition algorithm for quantum annealers, F. Babst et.al.
  https://arxiv.org/abs/1902.08324
- Astroparticle physics → quantum networks and quantum sensors

  Quantum-Assisted Telescope Arrays, E. T. Khabiboulline et.al.
  https://arxiv.org/abs/1809.03396
- Aerospace → Flight gate assignment

  Flight Gate Assignment with a Quantum Annealer, T. Stollenwerk et. al.
  https://arxiv.org/abs/1811.09465
- Computational Molecular Biology

  The prospects of quantum computing in computational molecular biology, Carlos Outeiral et al,
  https://arxiv.org/abs/2005.12792

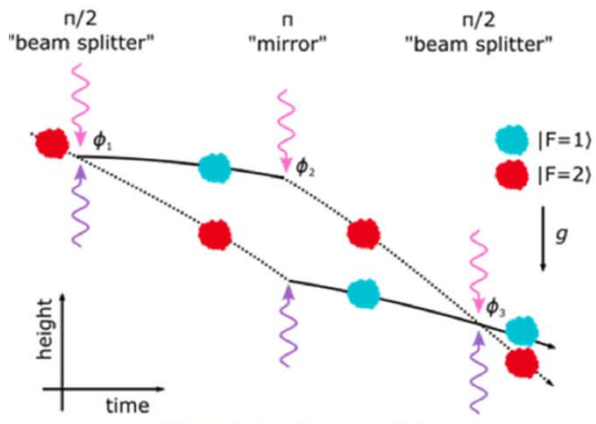
Quantum Sensors

Quantum sensors yield unprecedented sensitivity

Game-changing new technologies for Particle and Astroparticle experiments. Some examples include:

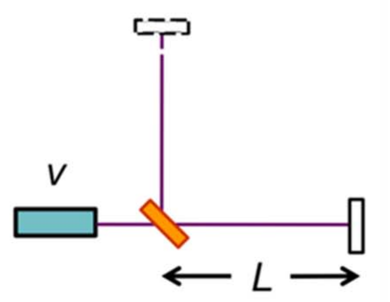
- **Particle:** New boson fields can be measured using optical atomic clocks (QSNET) or atom interferometry (MAGIS) → Matches DESY expertise in ultra-light Dark Matter searches.
- **Astroparticle:** Gravitational Wave physics relies on optical interferometry (Einstein Telescope) or possibly atom interferometry (AION).
- **Astronomy:** Ultra-low-noise electronics and quantum sensors needed for mm wavelengths. Quantum devices and DESY expertise could yield revolutionary high-resolution, high-speed spectrophotometers.

Important opportunity and enabler for new experiments



Atom Interferometry

Atomic Spectroscopy (clocks)



Laser Interferometry (cavities)

Quantum Sensors and the Search for Dark Matter

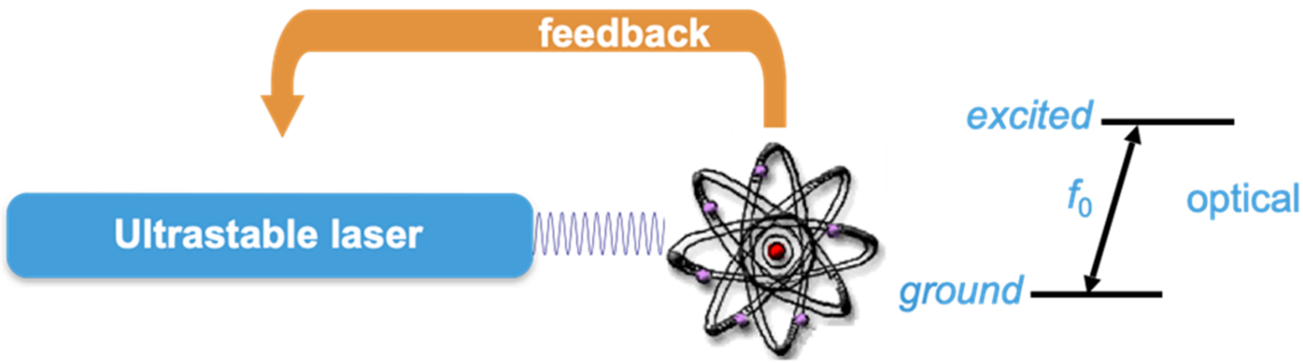
Search for Dark Matter by looking for spatial and temporal violations of fundamental constants (α, μ,…)

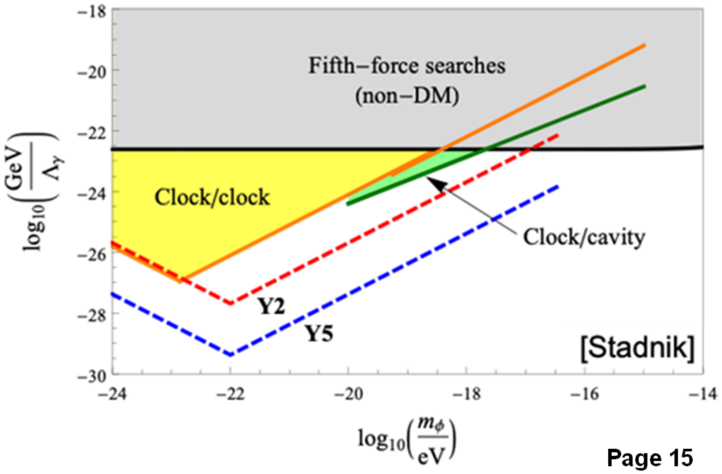
Quantum sensors enable a search for axion-like ultra-light Dark Matter (10^{-22} eV < m_{DM} < 10 eV)

New boson fields for Dark Matter can change fundamental constants into dynamic variables
For example: α = fine structure constant, and μ = proton to electron mass ratio, no longer constants

Optical atomic clocks as enabling technology

- Reaching precision of better than one second in the age of the Universe
- Electron transition frequency as timekeeping element: high-frequency mode-locked laser for optical transition
- Ultra-sensitive, e.g. to Dark Matter variations in fine structure constant α





Networking in Quantum Computing

Already existing links

- Member of European project **QTFLAG**
  → tensor network and quantum computing of lattice gauge theories
- **Helmholtz-TRIUMF Cooperation**
  → collaboration on Quantum Computing, Big Data, Computing Facilities
  TRIUMF: QC for nuclear and particle physics; quantum circuit design and optimization; open-source software;
  training activities in collaboration with Quantum BC: 2020 online lectures, TSI 2021: https://tsi.triumf.ca/2021/index.html
- Cooperation with Institute for Quantum Computing, **Waterloo, Canada**
  → Quantum computations of U(1) lattice gauge theories coupled to bosonic and fermionic matter
- **UK Quantum Technologies** for Fundamental Physics
  → new grant for joint work approved
- **HEIBRidS** graduate research school in Berlin
  → two PhD students working on development of variational quantum eigensolvers
- **DASHH** graduate research school in Hamburg
  → PhD working on error mitigation in Quantum Computer calculations
- DESY and **CERN Openlab**
  → PhD transferring GAN simulations to Quantum Computers
- **Berlin University Alliance** → Einstein Research Unit
- **Helmholtz International Fellow Award** for C. Alexandrou (Cyprus)
  → High Performance Computing, Quantum Computing

Explore opportunities for joint projects on campus and with associated institutes

Plans

Ongoing and planned activities

- Make use of *Noisy-Intermediate-State Quantum* (NISQ) device area
  → superconducting platforms are available
  → Python based simulator programs on your local machine
- Develop scalable and robust algorithms for problems in HEP
  → Knowledge transferable to chemistry, material science, aerospace, medicine, biology ...
- Connect machine learning, tensor networks and quantum computing
- Develop quantum sensors for HEP experiments
  → ultra light dark matter searches
  → tests of fundamental constants
- Explore one-way computing: collaboration of particle physics and photon science:
  → one-way computing with x-ray optics (R. Röhlsberger, K. Jansen)

Strategic Considerations in Photon Science Division

R&D towards a useful Quantum Computer

Requirements for R&D

- Controlled nanostructuring of materials: implementation of scalable quantum-computing systems (towards ~10^6 physical qubits, corresponding to ~10^3 logical qubits)
- Materials characterization: atomic structure, quantum-level structure, quantum dynamics (coherence properties, causes of errors, ...)
- Coherent control of qubits: implementation of one-qubit and two-qubit operators → set of universal quantum gates
- Readout → reliable measurement of the state of each qubit after running a quantum circuit

Examples of relevant expertise in Photon Science

- quantum materials → towards solid-state-based quantum technologies
- integrated optics → silicon photonics
- pure-state preparation and quantum control
- Moessbauer nuclei as quantum registers/memories
- quantum-dot technology
- coherent quantum dynamics of entangled states; decoherence
- nanoparticles and molecular spin-crossover systems → towards spin qubits
- coherent imaging → towards characterization of nano-structured qubit systems

FS organized a lecture series with renown QC experts and constructors → leading to intense discussion.

Aim for Quantum Technologies at DESY and the Campus

Quantum Technologies are the Future.

Employ competences and facilities at DESY and on campus to

- expand the expert role and combine crucial expertise
- drive the evolution
- **exploit QT to solve the challenges in our science ahead of us**

QT will change the way how we do our science and maximize the success in our research topics.

QT has an immense growth potential - upcoming Helmholtz and other funding opportunities from the government will be available for DESY and common projects with partners on campus.

QT needs to be placed into the daily research operation

→ leave the pioneering stage by expanding the contributing communities

→ establish joint projects across the divisions and on campus

A revolution is going on

the DESY campus is an excellent place to push it and exploit it !

Aim of the Workshop

Quantum Technologies are the Future.

- Inform all colleagues about the present status and future prospects
  → all relevant topics will be presented by excellent and renown experts
  → first contact with QC in a hands-on exercise
- collect feedback and interested colleagues in one QT community
- initiate thoughts about joined projects and prepare for the campus-wide workshop (21-22 Sep) to discuss common projects.

Tue 11. 8.	Tue 18.8.
	13:30 Hands-on Exercise Stefan Kühn
Session Leader: Karl Jansen 15:30 Introduction of QT at DESY and Campus Kerstin Borras	**Session Leader: Dirk Krücker** 15:00 ML with Quantum Computers Maria Schuld
16:00 Quantum-Inspired Optimization based on Digital Annealer Sebastian Engel, Andreas Rohnfelder (Fujitsu)	15:40 QT, esp QC Projects at CERN Openlab Alberto Di Meglio
Break 10 minutes	Break 10 minutes
Session Leader: Volker Gülzow 16:50 Introduction to Quantum Computing Martin Savage	**Session Leader: Steven Worm** 16:30 Quantum Sensors I Asimina Arvanitaki
17:30 Introduction to Error Mitigation Lena Funcke	17:10 Quantum Sensors II Dmitry Budker
18:10 Ensuing discussion (30 min)	17:50 Ensuing discussion (30)

Thank you

DESY QT Task Force reachable via **qt-task-force@desy.de**

Interested ?

Sign-up in this community email list **quantum-technologies@desy.de**