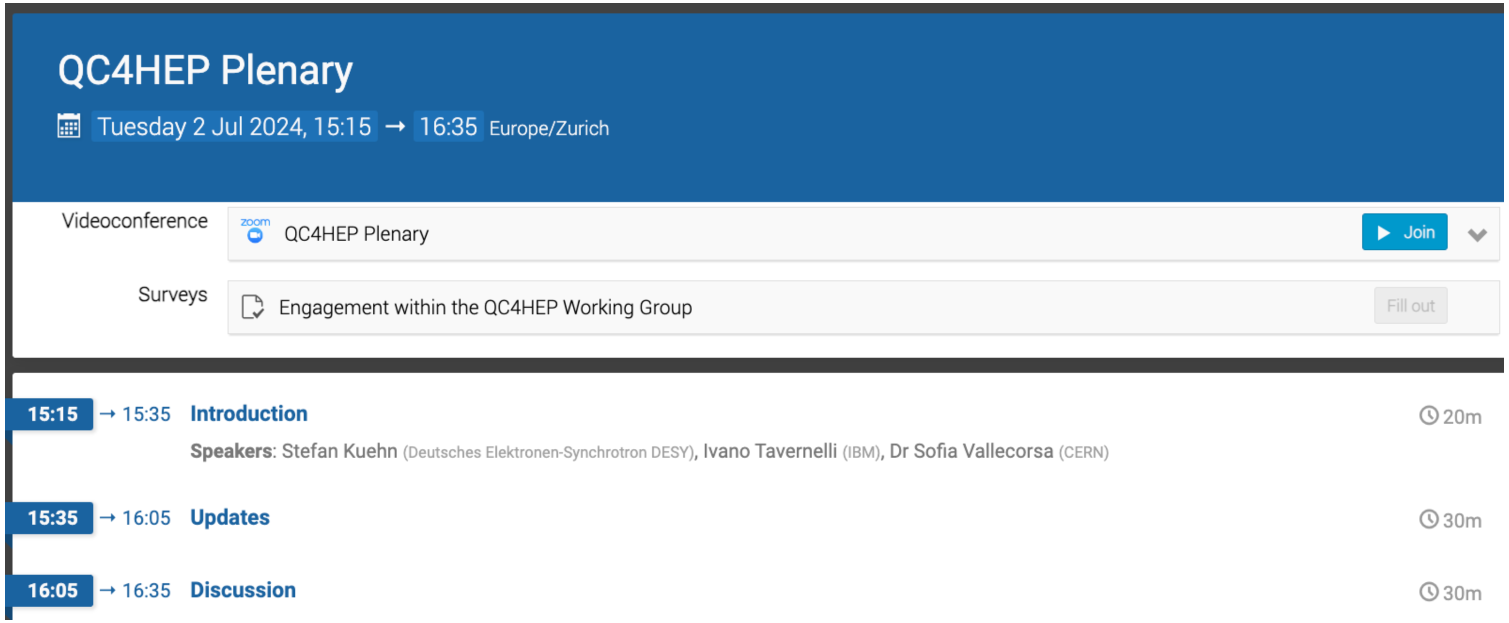
QC4HEP WG virtual meeting – July 2nd 2024

QC4HEP Box folder:
https://ibm.ent.box.com/folder/271639845223



Steering Committee members:

Sofia Vallecorsa – Alberto di Meglio (CERN)
Stefan Kühn - Karl Jansen (DESY)
Ivano Tavernelli (IBM Quantum)

Martin Savage (U Washington)
Andrea Delgado (ORNL)

AGENDA

- Welcome
- QC4HEP timeline
- High level overview
  - Organisational structure and interactions
  - Welcome new members
- Work streams updates:
  - Experiments
  - Theory
- Research Highlights 2023- 2024 (until June)
- Demonstrations
- Next steps

Info in Box folder: https://ibm.ent.box.com/folder/271639845223

QC4HEP Timelines

Kick start

1st On site Workshop
Nov 13-14
Supported by IBM Quantum

- Forming QC4HEP WG
- Group structure definition
  - Theory
  - Experiment

IBM Quantum Summit

Project exploration/ white paper

White paper Org:
- Use case identification for IBM HW (100x100)
- Resource Estimation

Bi-weekly Editorial meetings

Arxiv submission July 6
https://arxiv.org/abs/2307.03236

Prep for 2nd workshop

PRX

2nd On site Workshop – Nov 17
Supported by IBM Quantum
- Assign leads and co leads

Technical Enablement Workshop

IBM Quantum Summit Practitioner Forum

Project definition

Individual Projects Kick start
- Theory: weekly meetings
  - Real Time Evolution
  - Low Dimensional LGT and QLM
  - Neutrino Oscillations
- Experiments
  - Jet Reconstructions
  - BSM
  - Simulation

In presence meeting in Cyprus (Theory)

IBM Partner Forum
- Demo
- overview

PRX accepted

Virtual Meeting
Defining next steps

3rd On site Me

Nov 2022 | Jan 2023 | Jul 2023 | Aug 2023 | Nov 2023 | Dec 2023 | Jan 2024 | May 2024 | Jul 2024 | Jan 2025

List of Participating Institutions

1. Albert Einstein Center for Fundamental Physics, University of Bern
2. Brookhaven National Lab
3. CERN
4. DESY HH
5. DESY Zeuthen
6. RWTH Aachen University
7. EPFL
8. Fermilab
9. IBM
10. IJCLab-Orsay
11. INFN
12. INFN-TIFPA and University of Trento
13. Ikerbasque & UPV/EHU
14. LIP - Laboratorio de Instrumentação e Física Experimental de Partículas (PT)
15. Lawrence Berkeley National Lab. (US)
16. Leiden University
17. Ludwig Maximilian University of Munich
18. Maastricht University
19. Northeastern University
20. Oak Ridge National Laboratory
21. Padova University
22. TUM, Bayerische Akademie der Wissenschaften
23. U Lisboa
24. U Maastricht
25. U Waterloo
26. Uni Hannover
27. Universidad de Oviedo (ES)
28. Universita e INFN, Padova (IT)
29. University of Bonn
30. University of Cyprus and The Cyprus Institute
31. University of Geneva / CERN| Switzerland
32. University of Hannover
33. University of Innsbruck, IQOQI
34. University of Tokyo
35. University of Trento
36. University of Washington
37. Wits
38. York University

List of Participants

Experiments

#	Name	Affiliation
1	Alberto Di Meglio	CERN
2	Andrea Delgado	Oak Ridge National Laboratory
3	Bruce Melado	Wits
4	Concezio Bozzi	CERN
5	Davide Nicotra	Maastricht University
6	Donatella Lucchesi	Universita e INFN, Padova (IT)
7	Elias Fernández-Combarro	Universidad de Oviedo (ES)
8	Elina Fuchs	CERN
9	Enrique Rico Ortega	Ikerbasque & UPV/EHU
10	Federico Meloni	Deutsches Elektronen-Synchrotron (DE)
11	Francesco Pederiva	INFN-TIFPA and University of Trento
12	Joao Seixas	LIP - Laboratorio de Instrumentação e Física Experimental de...
13	Kerstin Borras	DESY / RWTH Aachen University
14	Koji Terashi	University of Tokyo
15	Kristan Temme	IBM Quantum
16	Lento Nagano	University of Tokyo
17	Michele Grossi	CERN
18	Miriam Lucio Martines	Maastricht University
19	Oriel Orphee Moira Kiss	University of Geneva / CERN| Switzerland
20	Panagiotis Spentzouris	Fermilab
21	Sofia Vallecorsa	CERN
22	Srinivasan Arunachalam	IBM Quantum
23	Vedran Dunjko	Leiden University
24	Vincent Croft	Leiden University / CERN
25	Vincent Pascuzzi	IBM Quantum
26	Voica Radescu	IBM Quantum
27	Yacine Haddad	Northeastern University
28	Yasser Omar	U Lisboa
29	Zoe Holmes	EPFL

Theory

#	Name	Affiliation
1	Alessandro Roggero	University of Trento
2	Alexander Stottmeister	University of Hannover
3	Andreas Juttner	CERN, U, Southampton
4	Antonio Mezzacapo	IBM
5	Arianna Crippa	DESY Zeuthen
6	Cenk Tüysüz	DESY
7	Christian Walter Bauer	Lawrence Berkeley National Lab. (US)
8	Constantia Alexandrou	University of Cyprus and The Cyprus Institute
9	Daniel González Cuadra	University of Innsbruck, IQOQI
10	Denis LACROIX	IJCLab-Orsay
11	Derek Wang	IBM
12	Enrique Rico Ortega	Ikerbasque & UPV/EHU
13	Francesco Tacchino	IBM Research
14	Giuseppe Carleo	EPFL
15	Ivano Tavernelli	IBM Research - Zurich
16	Jad C. Halimeh	Ludwig Maximilian University of Munich
17	Jeffrey Cohn	IBM
18	Jienglei Zhang	U Waterloo
19	Joe Gibbs	Surrey
20	Julian Schuhmacher	IBM Quantum, IBM Research - Zurich
21	Karl Jansen	DESY / Center of Quantum Technologies and Applications (C...
22	Khadijeh Najafi	IBM
23	Klaus Liegener	TUM, Bayerische Akademie der Wissenschaften
24	Kristan Temme	IBM Quantum
25	Lena Funcke	University of Bonn
26	Lucia Valor	TUM, Bayerische Akademie der Wissenschaften
27	Mario Motta	IBM
28	Martin Savage	University of Washington
29	Meifeng Lin	Brookhaven National Laboratory
30	Randy Lewis	York University
31	Shinjae Yoo	Brookhaven National Lab
32	Simone Montangero	Padova University
33	Stefan Filipp	TUM, Bayerische Akademie der Wissenschaften
34	Stefan Kühn	DESY Zeuthen
35	Stefano Carrazza	INFN
36	Tobias Osborne	Uni Hannover
37	Uwe-Jens Wiese	Albert Einstein Center for Fundamental Physics, University of...
38	Zoe Holmes	EPFL

active

NEW

inactive

New members from IBM HEP taskforce :
- Declan Millar (IBM UK)
- Luciana Henaut (IBM UK)

New members

Recent members of the WG

- Martin Savage, Institute for Nuclear Theory, University of Washington
- Bruce Mellado - University of the Witwatersrand
- Stefan Filipp, Lucia Valor – TU Munich
- Alexander Stottmeister – Uni Hannover
- Tobias Osborne - Uni Hannover
- Joe Gibbs – U. Surrey
- Mario Motta – IBM
- Jeffrey Cohn – IBM
- With the precious help of a number of PhD and master students

Onboarding new members

Process:

- A short proposal (max 1 page):
- Explain contribution to which stream
- Outline the added value (what expertise is brought in)
- Resources (how many hours able to dedicate to this effort)
- Proposal is reviewed by Steering Committee and group stream leads/co-leads
- Proposal voted during the Project Coordinators meetings

Organization of the QC4HEP WG

Organization of the HEP WG:

Research Steering Committee

and

sub-teams

Scientific Steering Committee (not final):

CERN:	Sofia Vallecorsa
DESY:	Stefan Kühn
IBM:	Ivano Tavernelli
ORNL:	Andrea Delgado
U Washington:	Martin Savage

New from July 2024

IBM scientific coordinator: Ivano Tavernelli

IBM administrator: Voica Radescu

Tasks of the SteerCo (among others):

1. Structuring the groups and identify the research areas of interest
2. Interact with the sub-team coordinators
3. Help with the organization of the main assemblies (1 in June and 1 in November)
4. Coordinate adhesion of new members to the WG: The sub-team coordinators will submit their suggestions for extensions/additions to the steering committee.

Organization of the HEP WG:

Research Steering Committee

and

sub-teams

Scientific Steering Committee (not final):

CERN:	Sofia Vallecorsa
DESY:	Stefan Kühn
IBM:	Ivano Tavernelli
ORNL:	Andrea Delgado
U Washington:	Martin Savage

New from July 2024

IBM scientific coordinator: Ivano Tavernelli

IBM administrator: Voica Radescu

Two main research areas

Theory

Status: *operative*

Experiments

Status: *in preparation*

Organization of the HEP WG

Structure:

Theory

Status: *operative*

← **Two main research Areas** →

Experiments

Status: *in preparation*

Theory - main groups

1. *Real-time evolution,*
2. *Quantum Link Models*
3. *Neutrino physics*
4. *....*

← **Groups** →

Experiments - main groups:

1. *Jet Reconstruction*
2. *Beyond SM (BSM) and*
3. *Anomaly Detection*
4. *.....*

Groups of 2-3 institutions working together on a speficic topic defined in the groups

Teams include students

← **Teams** →

Groups of 2-3 institutions working together on a speficic topic defined in the groups.

Teams include students

Organization of the HEP WG:

Theory - 3 main groups

1. *Real-time evolution, low dimensional LGT*
   Jad, Stefan, Karl
2. *Quantum Link Models*
   Uwe
3. *Neutrino physics*
   Alessandro

Experiments - 3 main groups:

1. *Jet Reconstruction*
   Donatella, Miriam
2. *Beyond SM (BSM) and Anomaly Detection*
   Michele, Yacine
3. *Simulations*
   Vincent Croft, Vincent Pascuzzi

Coordination

- Each group has a **coordinator** (and a **co-coordinator).**
- Coordinators are organizing the research projects and propose possible **additional members** to the Steering Committee.
- For any kind of advise/support ask the Steering Commeetee members

Each group is organized in teams

- Each group can split in **teams** working on different sub-projects.
- We expect **self-organization** of the activities (in case of questions contact the SteerCo)
- Team meetings will occure **regularly** and are decalated (allow members to follow more than one group)

Organization of the HEP WG:

Theory Group:

Real Time evolution and Low Dimensional LGT merged with QLM

Coordinators: Karl Jansen, Ivano Tavernelli, Jad Hallimeh, Uwe Wiese

Neutrino Oscillations

Coordinators: Alessandro Roggero, Denis Lacroix

Theory

Current topics (until June 2024)

Group event: one meeting a month in the form of seminars & discussions to trigger new projects and ideas

1. Real-time evolution & low dimensional LGT
   - Fermionic scattering (wp): biweekly meeting. - Stefan
   - Meson scattering (PYP-model): biweekly meeting - Jad
   - 2+1 D QED: biweekly meeting - Karl
2. Quantum Link Models
   - Hevy-hex model: biweekly meeting - Uwe
3. Neutrino physics
   - Neutrino oscillations (dynamics): biweekly meeting - Alessandro

We expect new projects triggered by the new QC4HEP members

Organization of the HEP WG:

Experiments Group:

Jet Reconstruction

Coordinators: Donatella Luchessi and Miriam Lucio Martinez

BSM

Coordinators: Yacine Haddad and Michele Grossi

Simulation

Coordinators: Vincent Croft and Vincent Pascuzzi

Mailing List:

https://e-groups.cern.ch/e-groups/EgroupsSearch.do

E-group name: qc4hep-exp

Experiments

Current topics

1. Reconstruction and pattern recognition
   - Jet reconstruction, Jet tagging, Jet substructure studies
   - Track reconstruction
2. Beyond the Standard Model searches
   - Anomaly detection
   - Classification
3. Simulation
   - Detectors (primarily calorimeter simulation)
   - Event generators and parton showers

Re-organize approach to collaboration (discussion forum).

Merge sub-tasks.

Highlights 2023- June 2024

Papers

Bibtex file of the papers available on Overleaf: https://www.overleaf.com/project/637ce463a5aa95851b3d6ee2

File name: QC4HEP.bib

Please keep it updated!!!

```
@article{DiMeglio2023,
  title={Quantum computing for high-energy physics: state of the art and challenges. Summary of the QC4HEP working group},
  author={Di Meglio, Alberto and Jansen, Karl and Tavernelli, Ivano and Alexandrou, Constantia and Arunachalam, Srinivasan and Bauer, Christian W and Borras, Kerstin and Carrazza, Stefano and Crippa, Arianna and Croft, Vincent and others},
  journal={arXiv:2307.03236},
  year={2023},
  volume = {{}},
  pages = {{}},
  doi = {10.48550/arXiv.2307.03236}
}
```

Please include acknowledgment to the QC4HEP working group; this will help us tracing publications. Thanks.

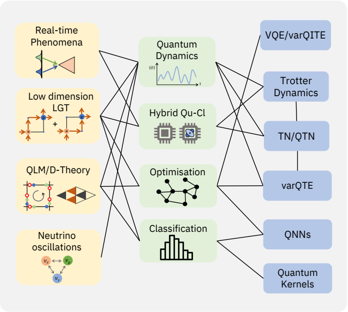
Results and papers

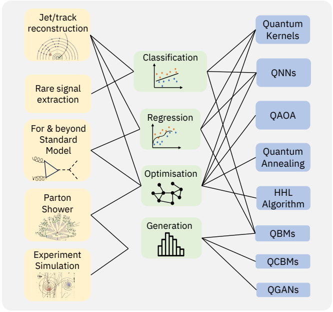
Remember to acknowledge the QC4HEP working group in the section “Acknowledgements”

RESEARCH

Quantum Computing for High-Energy Physics State of the Art and Challenges Summary of the QC4HEP Working Group

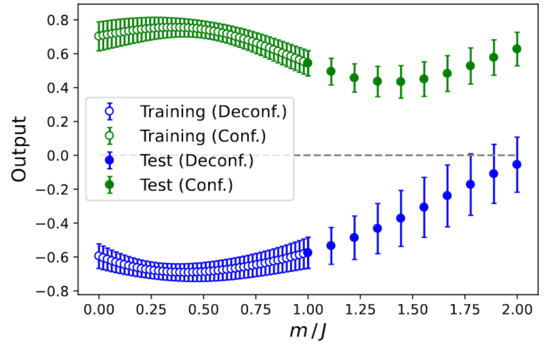
Alberto Di Meglio[8*], Karl Jansen[5], Ivano Tavernelli[3], Constantia Alexandrou[1], Srinivasan Arunachalam[3], Christian W Bauer[4], Kerstin Borras[5,6], Stefano Carrazza[7,8], Arianna Crippa[5,29], Vincent Croft[9], Roland de Putter[3], Andrea Delgado[10], Vedran Dunjko[9], Elias Fernández-Combarro[11], Elina Fuchs[8], Lena Funcke[12], Jay Gambetta[3], Daniel González Cuadra[13,14], Michele Grossi[8], Zoe Holmes[15], Stefan Kühn[5,2], Denis Lacroix[16], Randy Lewis[17], Donatella Lucchesi[18], Miriam Lucio Martinez[19], Federico Meloni[5], Antonio Mezzacapo[3], Simone Montangero[20], Lento Nagano[21], Voica Radescu[3], Enrique Rico Ortega[22], Alessandro Roggero[23,24], Julian Schuhmacher[3], Joao Seixas[25], Pietro Silvi[20], Panagiotis Spentzouris[26], Francesco Tacchino[3], Kristan Temme[3], Koji Terashi[21], Jordi Tura[9], Cenk Tüysüz[5,29], Sofia Vallecorsa[8], Uwe-Jens Wiese[27] and Jinglei Zhang[28]





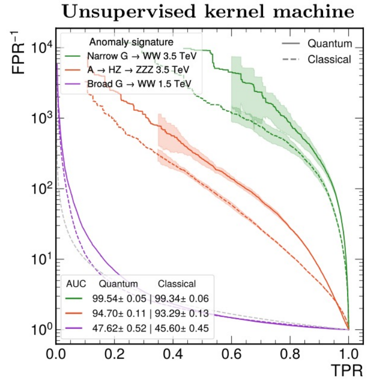
Quantum data learning for quantum simulations in high-energy physics

Lento Nagano,[1,*] Alexander Miessen,[2,3,†] Tamiya Onodera,[4,‡]
Ivano Tavernelli,[2,§] Francesco Tacchino,[2,¶] and Koji Terashi[1,**]
[1]*International Center for Elementary Particle Physics (ICEPP), The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2]*IBM Quantum, IBM Research – Zurich, 8803 Rüschlikon, Switzerland*
[3]*Institute for Computational Science, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*
[4]*IBM Quantum, IBM Research-Tokyo, 19-21 Nihonbashi Hakozaki-cho, Chuo-ku, Tokyo, 103-8510, Japan*
(Dated: July 3, 2023)



Quantum anomaly detection in the latent space of proton collision events at the LHC

Kinga Anna Woźniak*,[1,2] Vasilis Belis*†,[3] Ema Puljak*,[1,4] Panagiotis Barkoutsos,[5] Günther Dissertori,[3] Michele Grossi,[1] Maurizio Pierini,[1] Florentin Reiter,[6] Ivano Tavernelli,[5] and Sofia Vallecorsa[1]
[1]*European Organization for Nuclear Research (CERN), CH-1211 Geneva, Switzerland*
[2]*Faculty of Computer Science, University of Vienna, Austria**
[3]*Institute for Particle Physics and Astrophysics, ETH Zurich, 8093 Zurich, Switzerland†*
[4]*Departamento de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain**
[5]*IBM Quantum, IBM Research – Zurich, 8803 Rüschlikon, Switzerland*
[6]*Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland.*
(Dated: March 7, 2023)



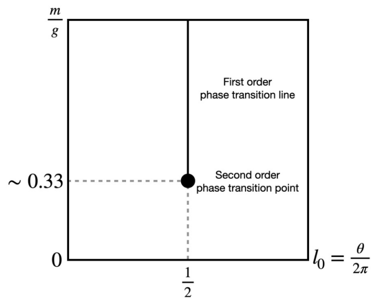
Papers

First-Order Phase Transition of the Schwinger Model with a Digital Quantum Computer

Takis Angelides,[1,2] Pranay Naredi,[3] Arianna Crippa,[1,2] Karl Jansen,[2,3] Stefan Kühn,[2] Ivano Tavernelli,[4] and Derek S. Wang[5]

[1] *Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Germany*
[2] *Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany*
[3] *Computation-Based Science and Technology Research Center, The Cyprus Institute, 20 Kavafi Street, 2121 Nicosia, Cyprus*
[4] *IBM Research Europe – Zurich, Säumerstrasse 4, 8803 Rüschlikon, Switzerland*
[5] *IBM Quantum, IBM T.J. Watson Research Center, Yorktown Heights, NY 10598, USA*

(Dated: October 12, 2023)



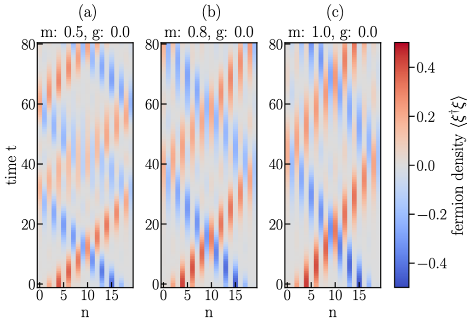
Entanglement production from scattering of fermionic wave packets: a quantum computing approach

Yahui Chai,[1] Arianna Crippa,[1] Karl Jansen,[1,2] Stefan Kühn,[1] Vincent R. Pascuzzi,[3] Francesco Tacchino,[3] and Ivano Tavernelli[3]

[1] *CQTA, Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany*
[2] *Computation-Based Science and Technology Research Center, The Cyprus Institute, 20 Kavafi Street, 2121 Nicosia, Cyprus*
[3] *IBM*

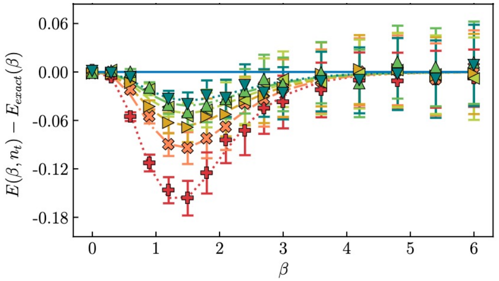
(Dated: October 12, 2023)

We propose a method to prepare two wave packets with opposite momenta on top of the interacting ground state of a fermionic Hamiltonian. Our method is based on Givens rotation, which can be used to create arbitrary fermionic states. Using our technique, we explore the scattering of wave packets in the lattice Thirring model.



Collective neutrino oscillations with a quantum computer

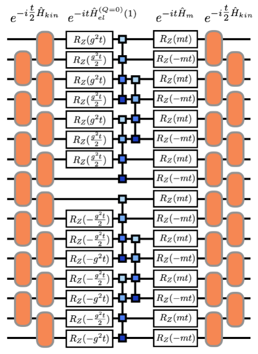
Jeffry Cohn, Mario Motta, Alessandro Roggero,o, I.T. et al



Papers

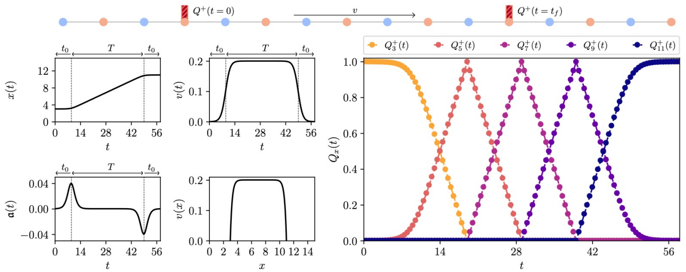
Quantum Simulations of Hadron Dynamics in the Schwinger Model using 112 Qubits

Roland C. Farrell[1,*] Marc Illa[1,†] Anthony N. Ciavarella[1,2,‡] and Martin J. Savage[1,§]
[1]InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, WA 98195, USA.
[2]Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
(Dated: January 17, 2024)



Steps Toward Quantum Simulations of Hadronization and Energy-Loss in Dense Matter

Roland C. Farrell[1,2,*] Marc Illa[1,†] and Martin J. Savage[1,‡]
[1]InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, WA 98195, USA.
[2]Albert Einstein Center for Fundamental Physics, Institut für Theoretische Physik, Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
(Dated: May 13, 2024)



arXiv > hep-lat > arXiv:2401.14570

Search...

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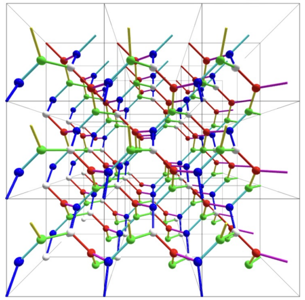
High Energy Physics – Lattice

[Submitted on 25 Jan 2024]

From square plaquettes to triamond lattices for SU(2) gauge theory

Ali H. Z. Kavaki, Randy Lewis

Lattice gauge theory should be able to address significant new scientific questions when implemented on quantum computers. In practice, error-mitigation techniques have already allowed encouraging progress on small lattices. In this work we focus on a truncated version of SU(2) gauge theory, which is a familiar non-Abelian step toward quantum chromodynamics. First, we demonstrate effective error mitigation for imaginary time evolution on a lattice having two square plaquettes, obtaining the ground state using an IBM quantum computer and observing that this would have been impossible without error mitigation. Then we propose the triamond lattice as an expedient approach to lattice gauge theories in three spatial dimensions, deriving the Hamiltonian and obtaining energy eigenvalues and eigenstates from a noiseless simulator for a three-dimensional unit cell.



Papers

IBM **Quantum**

arXiv > cs > arXiv:2406.06150

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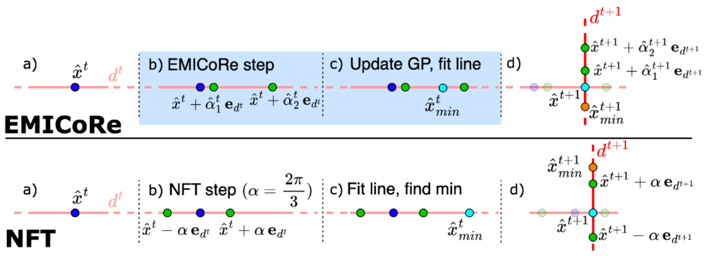
Computer Science > Machine Learning

[Submitted on 10 Jun 2024]

Physics-Informed Bayesian Optimization of Variational Quantum Circuits

Kim A. Nicoli, Christopher J. Anders, Lena Funcke, Tobias Hartung, Karl Jansen, Stefan Kühn, Klaus-Robert Müller, Paolo Stornati, Pan Kessel, Shinichi Nakajima

In this paper, we propose a novel and powerful method to harness Bayesian optimization for Variational Quantum Eigensolvers (VQEs) -- a hybrid quantum-classical protocol used to approximate the ground state of a quantum Hamiltonian. Specifically, we derive a VQE-kernel which incorporates important prior information about quantum circuits: the kernel feature map of the VQE-kernel exactly matches the known functional form of the VQE's objective function and thereby significantly reduces the posterior uncertainty. Moreover, we propose a novel acquisition function for Bayesian optimization called Expected Maximum Improvement over Confident Regions (EMICoRe) which can actively exploit the inductive bias of the VQE-kernel by treating



arXiv > hep-lat > arXiv:2404.17545

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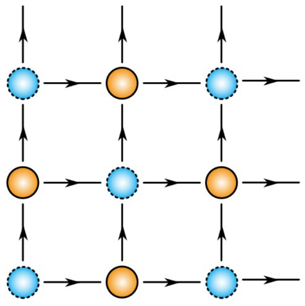
High Energy Physics - Lattice

[Submitted on 26 Apr 2024 (v1), last revised 12 Jun 2024 (this version, v2)]

Towards determining the (2+1)-dimensional Quantum Electrodynamics running coupling with Monte Carlo and quantum computing methods

Arianna Crippa, Simone Romiti, Lena Funcke, Karl Jansen, Stefan Kühn, Paolo Stornati, Carsten Urbach

In this paper, we examine a compact $U(1)$ lattice gauge theory in $(2+1)$ dimensions and present a strategy for studying the running coupling and extracting the non-perturbative Λ-parameter. To this end, we combine Monte Carlo simulations and quantum computing, where the former can be used to determine the numerical value of the lattice spacing a, and the latter allows for reaching the perturbative regime at very small values of the bare coupling and, correspondingly, small values of a. The methodology involves a series of sequential steps (i.e., the step scaling function) to bridge results from small lattice spacings to



arXiv > quant-ph > arXiv:2401.10293

Search...

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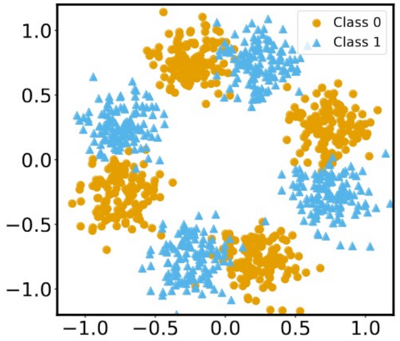
Quantum Physics

[Submitted on 17 Jan 2024]

Symmetry breaking in geometric quantum machine learning in the presence of noise

Cenk Tüysüz, Su Yeon Chang, Maria Demidik, Karl Jansen, Sofia Vallecorsa, Michele Grossi

Geometric quantum machine learning based on equivariant quantum neural networks (EQNN) recently appeared as a promising direction in quantum machine learning. Despite the encouraging progress, the studies are still limited to theory, and the role of hardware noise in EQNN training has never been explored. This work studies the behavior of EQNN models in the presence of noise. We show that certain EQNN models can preserve equivariance under Pauli channels, while this is not possible under the amplitude damping channel. We claim that the symmetry breaking grows linearly in the number of layers and noise strength. We support our claims with numerical data from simulations as well as hardware up to 64 qubits. Furthermore, we provide strategies to enhance the symmetry protection of EQNN models in the presence of noise.



Papers

Quantum Physics

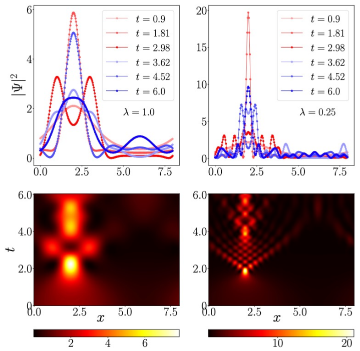
arXiv:2307.06032

[Submitted on 12 Jul 2023 (v1), last revised 26 Jan 2024 (this version, v3)]

From Vlasov-Poisson to Schrödinger-Poisson: dark matter simulation with a quantum variational time evolution algorithm

Luca Cappelli, Francesco Tacchino, Giuseppe Murante, Stefano Borgani, Ivano Tavernelli

Cosmological simulations describing the evolution of density perturbations of a self-gravitating collisionless Dark Matter (DM) fluid in an expanding background, provide a powerful tool to follow the formation of cosmic structures over wide dynamic ranges. The most widely adopted approach, based on the N-body discretization of the collisionless Vlasov-Poisson (VP) equations, is hampered by an unfavorable scaling when simulating the wide range of scales needed to cover at the same time the formation of single galaxies and of the largest cosmic structures. The dynamics described by the VP equations is limited by the rapid increase of the number of resolution elements which is required to simulate an ever growing range of scales. Recent studies showed an interesting mapping of the 6-



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Quantum Physics

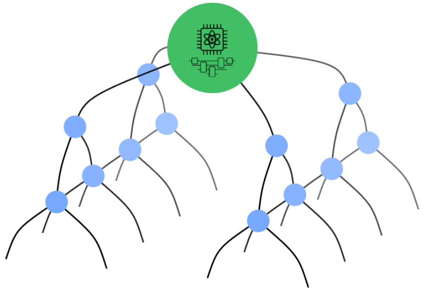
arXiv:2404.05784

[Submitted on 8 Apr 2024]

Hybrid Tree Tensor Networks for quantum simulation

Julian Schuhmacher, Marco Ballarin, Alberto Baiardi, Giuseppe Magnifico, Francesco Tacchino, Simone Montangero, Ivano Tavernelli

Hybrid Tensor Networks (hTN) offer a promising solution for encoding variational quantum states beyond the capabilities of efficient classical methods or noisy quantum computers alone. However, their practical usefulness and many operational aspects of hTN-based algorithms, like the optimization of hTNs, the generalization of standard contraction rules to an hybrid setting, and the design of application-oriented architectures have not been thoroughly investigated yet. In this work, we introduce a novel algorithm to perform ground state optimizations with hybrid Tree Tensor Networks (hTTNs), discussing its advantages and roadblocks, and identifying a set of promising applications. We benchmark our approach on two paradigmatic models, namely the Ising model at the critical point and the Toric code Hamiltonian. In both cases, we successfully demonstrate that hTTNs can improve upon classical equivalents with equal bond dimension in the classical part.



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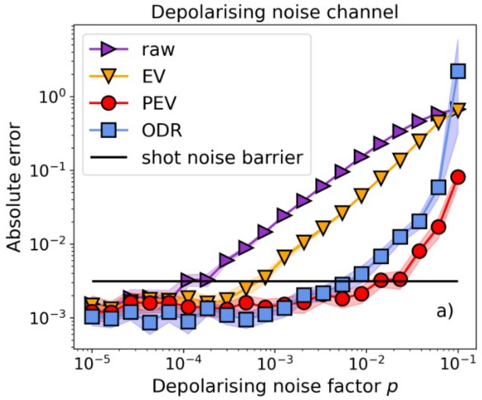
arXiv:2401.13048

[Submitted on 23 Jan 2024]

Quantum error mitigation for Fourier moment computation

Oriel Kiss, Michele Grossi, Alessandro Roggero

Hamiltonian moments in Fourier space - expectation values of the unitary evolution operator under a Hamiltonian at different times - provide a convenient framework to understand quantum systems. They offer insights into the energy distribution, higher-order dynamics, response functions, correlation information and physical properties. This paper focuses on the computation of Fourier moments within the context of a nuclear effective field theory on superconducting quantum hardware. The study integrates echo verification and noise renormalization into Hadamard tests using control reversal gates. These techniques, combined with purification and error suppression methods, effectively address quantum hardware decoherence. The analysis, conducted using noise models, reveals a significant reduction in noise strength by two orders of magnitude. Moreover, quantum circuits involving up to 266 CNOT gates over five qubits demonstrate high accuracy under these methodologies when run on IBM superconducting quantum devices.



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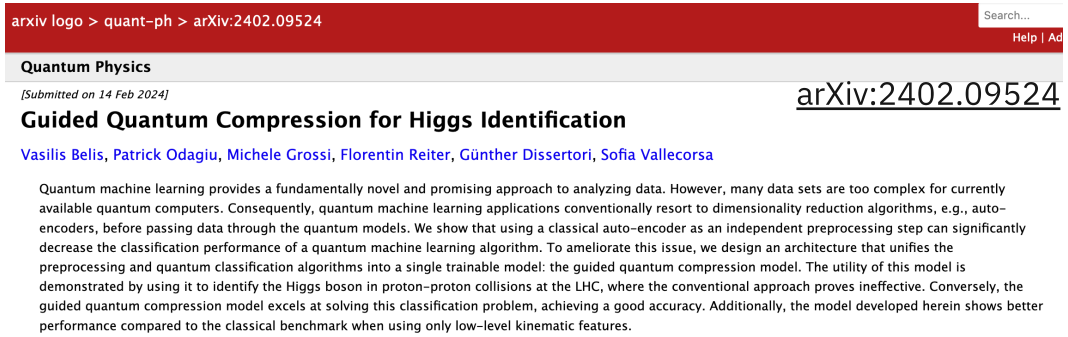
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Quantum Physics

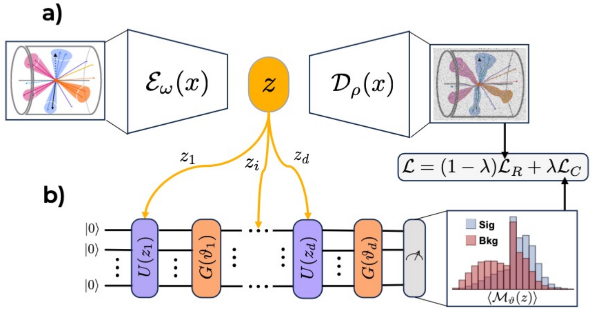
[Submitted on 14 Feb 2024]

arXiv:2402.09524

Guided Quantum Compression for Higgs Identification

Vasilis Belis, Patrick Odagiu, Michele Grossi, Florentin Reiter, Günther Dissertori, Sofia Vallecorsa

Quantum machine learning provides a fundamentally novel and promising approach to analyzing data. However, many data sets are too complex for currently available quantum computers. Consequently, quantum machine learning applications conventionally resort to dimensionality reduction algorithms, e.g., auto-encoders, before passing data through the quantum models. We show that using a classical auto-encoder as an independent preprocessing step can significantly decrease the classification performance of a quantum machine learning algorithm. To ameliorate this issue, we design an architecture that unifies the preprocessing and quantum classification algorithms into a single trainable model: the guided quantum compression model. The utility of this model is demonstrated by using it to identify the Higgs boson in proton-proton collisions at the LHC, where the conventional approach proves ineffective. Conversely, the guided quantum compression model excels at solving this classification problem, achieving a good accuracy. Additionally, the model developed herein shows better performance compared to the classical benchmark when using only low-level kinematic features.



Demonstrations 2023

DEMOs

Year 2024

4 propositions for the Summit

2 with DESY

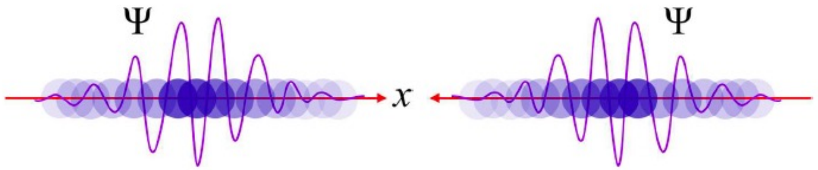
1 with CERN

1 with Algorithmiq

Fermion- anti-fermion collision - DESY

(presented in Aug, 7 th (2023))

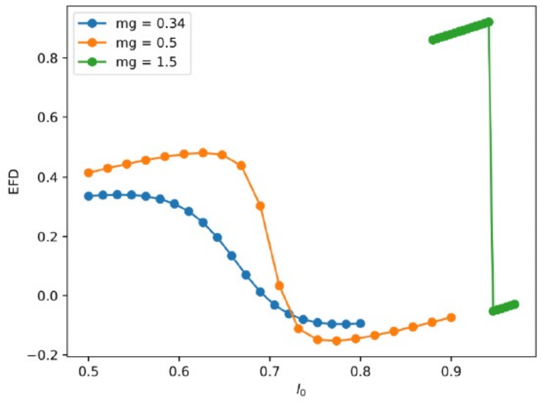
Planning to send the circuit by Oct, 17



Phase transitions in the SW model- DESY

Presented to Will Kirby and team – Sep 22

Possible extention to a 32+ qubit HW calculation (in the agenda for the meeting with Karl for tomorrow, 13th Oct)

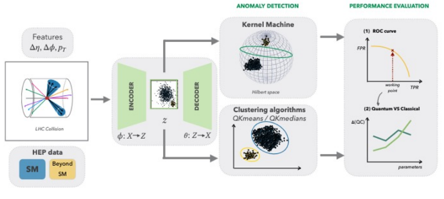


Anomaly detections with CERN

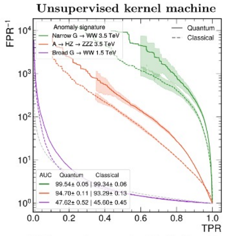
(presented in Aug, 24th)

Anomaly detections with unsupervised quantum classifiers (CERN)

Preliminary QC simulations with up to 16 qubits show that under specific correlation of the input data the quantum classifier can outperform the best classical algorithm.



Classical-quantum pipeline. LHC collision data (simulation) are passed through an autoencoder for dimensionality reduction followed by the quantum anomaly detection models: unsupervised quantum kernel machine and clustering algorithms\ (QK-means/QK-medians). Each jet contains 100 particles, each particle is described by three features (Δη, Δφ, pT) where Δ represents a distance from the jet axis. Hence, a dijet collision event is described by 300 features. The quantum models are trained on Standard Model data and learn to recognise anomalies in unseen data. All models are evaluated by calculating the Receiver Operating Characteristic (ROC) curve and metrics appropriate for anomaly detection tasks and are compared to their classical counterparts.



ROCS curves for unsupervised classification of two anomalies:
Higgs particles generation (red) and Graviton decay (green and violet)

DEMOs

2024

IBM partner forum

Milan, Italy

Symmetry breaking in geometric quantum machine learning in the presence of noise (DESY – Cenk Tüysüz)

Geometric QML incorporates inductive biases to ansatz design

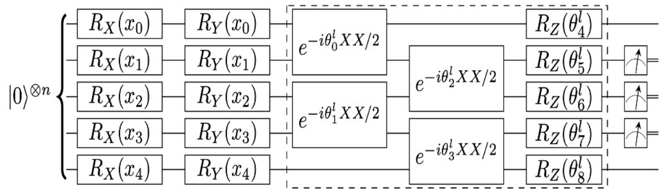
This can lead to:

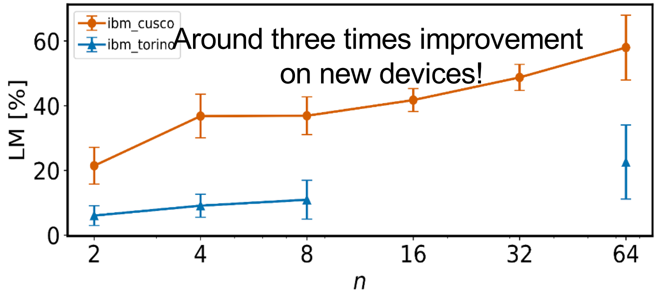
- Less parameters / shorter circuits (no BPs)
- Overparameterization
- Better generalization

Can current noisy devices execute such circuits and preserve the built-in symmetries?

- Depolarizing-like channels do not significantly impact Geometric QML.
- Non-unital channels break the symmetry approximately linearly in depth and noise strength.

$\mathcal{Z}_2$ symmetric QML model:





Planned DEMOS for 2024

1. Quantum Link Model
2. Particle scattering - the Thirring Model
3. Particle scattering – mesons
4. Neutrino's oscillations

Next Steps

Plans for 2024

1. Organize new subgroup teams
   - Experiments: tbd
   - Theory :

     Theory groups should meet virtually every 3 months

     Set calender invitation (possibly now)

2. Prepare for the demonstrations (see cover slide in appendices)

3. Extend the network
   - Select new potential candidates and projects
   - Propose them to the Steering Committee

4. Plan new steps

WG meeting

Year 2024

Virtual meeting

July 2nd 2024

Steering Committee Meetings

Bimonthly meeting (every 2 months)

Starting date: Tuesday September 10, 3 or 4 pm CET (**to be confirmed**)

In person meeting

At CERN on January 2025 (**QT4HEP** 20th Jan)

Appendix A: Slides for demo

Access to IBM Quantum HW:

- IBM Quantum Open Plan [10min/user/month]
- Demo qualification [next slides]
- Through IBM Quantum Premium Plan through our QICs.

Cover slide: Particle scattering on a digital quantum device

From a 2023 demo
Numbers are not updated

- Number of circuits (including error mitigation overhead): tbd – simple Trotter dynamics (depth size independent). [~50 (time steps) x O(10^3) twirling instances x O(10^2) shots per instance]
- QASM files for circuits ready: yes
- Depths: 4*N+10, if light cone → O(3N+8)
- Number of qubits: N=30-40
- Capabilities required: Zero-noise-extrapolation (ZNE)
- Comments on classical hardness: this is a **real time evolution** problem which is very hard for classical simulations. In particular with the linear growth of entanglement in the time evolution the bond dimension in a tensor network approach will grow exponentially which can be avoided by a quantum computation leading to a real quantum advantage eventually, especially when systems with a non-trivial interaction are considered. Here we propose a first experiment on 20 qubits which can demonstrate that this is a **realistic application** with a very large potential for future quantum simulations.
- Classical simulations performed: By the group of S. Montangero, *Phys.Rev.D* 104 (2021) 11, 114501 e-Print: 2105.03445
- Community of interest: High energy physics, condensed matter physics
- Partner org(s): DESY and IBM

Slide content (for demo)

1. 2-3 slides to introduce the problem, its relevance for the community, its hardness for classical approaches (classical computing).
2. Description of the systems: Hamiltonian, observables, etc
3. Description of the quantum approach: Quantum algorithm, circuits, state preparation, observables, etc
4. Descrition of the resources: Circuits, measurments, and error mitigation strategy (or strategies)
5. Preliminary results – classical simulations (up to the equivalent of ca. 12-14 quanits), including QASM type calculations and noisy simulations)
6. Preliminary results – quantum experiments (up to ca. 10-24 qubits)
7. Description of the expected results and impact

Appendix – to be cleaned

Organization of the HEP WG:

Theory Group:

Real Time evolution and Low Dimensional LGT merged with QLM

Coordinators: Karl Jansen, Ivano Tavernelli, Jad Hallimeh, Uwe Wiese

Neutrino Oscillations

Coordinators: Alessandro Roggero, Denis Lacroix

Organization – Theory evolution

Nov 2023

```
--- Groups

6. Real time evolution
        Coordinator: Karl (confirmed)
        Co-coordinator: Ivano (confirmed), Jad (new)

        Idea here is to study dynamics

        Members:
        - Lena Funcke
        - Lento Nagano
        - Zoe Holmes
        - Donatella -- we need to ask
        - Derek Wang
        - Stefan Kühn
        - Vincent Pascuzzi
        - Meifeng Lin -- we need to get in touch and check
        - Jad C. Halimeh
        - Enrique Rico Ortega
        - Ivano Tavernelli
        - Antonio Mezzacapo -- we need to ask
        - Uwe-Jens Wiese
        - Francesco Tacchino

        Meeting: 12th January 3.30pm, link to be sent by Karl

7. Low dimensional LGT - 8. QLM ---> merged
        Coordinator: Jad (new)
        Co-coordinator: Uwe (new), Karl (new)

        Idea here is to study more "static" properties (e.g., phases)

        Uwe added
        Meeting: 26th January 3.30pm, link to be sent by Jad

        Members:
        - Lena Funcke
        - Lento Nagano
        - Jinglei Zhang
        - Randy Lewis
        - Zoe Holmes
        - Donatella -- we need to ask
        - Derek Wang
        - Stefan Kühn
        - Vincent Pascuzzi
        - Meifeng Lin -- we need to get in touch and check
        - Jad C. Halimeh
        - Enrique Rico Ortega
        - Ivano Tavernelli
        - Antonio Mezzacapo -- we need to ask
        - Uwe-Jens Wiese
        - Francesco Tacchino

9. Neutrinos
        Coordinator: Alessandro (confirmed)
        Co-coordinator: Denis (confirmed)

        These are mostly real time studies.

        Meeting: 19th January 5pm, link to be sent by Alessandro

        Members:
        - Vincent Croft
        - Denis Lacroix
        - Antonio Mezzacapo
        - Mario Motta
        - Jeff Cohn
        - Michele Grossi
        - Derek Wang
        - Francesco Tacchino
        - Ivano Tavernelli
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July 2024

Team 1: Low-dimensional field theories, quantum link models and real-time dynamics

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Team 2: Neutrino oscillations