# Quantum Measurement Theory: Foundations and Applications

741. WE-Heraeus-Seminar

10 - 13 July 2022

HYBRID
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

# Introduction

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## Aims and scope of the 741. WE-Heraeus-Seminar:

The theory of quantum measurements provides an operationally motivated framework for the description of dynamical processes in quantum mechanics. The latter can originate, on the one hand, from the dynamics of an open quantum system that is interacting with its environment or, on the other hand, from measurements on the system itself leading to an altered post-measurement state. As such processes are ubiquitous in the description of any physical system, the theory of quantum measurements provides an important cornerstone of the foundations of quantum mechanics.

This WE-Heraeus-Seminar covers several aspects of the theory of quantum measurements ranging from the description of open quantum systems, over the compatibility properties of general quantum measurements, to applications, such as the certification and quantification of features that have been identified as resources for applications in quantum information theory.

The purpose of the seminar is to bring together young and more experienced researchers working on these closely related topics and to offer a platform for discussions among them. At the same time, we aim to give young researchers an overview of this fast developing field of research by listening to inspiring talks presented by experts in their respective domains.

## Scientific Organizers:

Dr. Andreas Ketterer — Fraunhofer-Institut für Angewandte Festkörperphysik (IAF), Freiburg
E-mail: andreas.ketterer@iaf.fraunhofer.de

Dr. Roope Uola — Université de Genève, Switzerland
E-mail: roope.uola@unige.ch

# Introduction

## Administrative Organization:


Dr. Stefan Jorda
Mojca Peklaj

Wilhelm und Else Heraeus-Stiftung
Kurt-Blaum-Platz 1
63450 Hanau, Germany

Phone +49 6181 92325-18
Fax +49 6181 92325-15
E-mail peklaj@we-heraeus-stiftung.de
Internet: www.we-heraeus-stiftung.de


## Venue :

Physikzentrum
Hauptstraße 5
53604 Bad Honnef, Germany

Conference Phone +49 2224 9010-120

Phone +49 2224 9010-113 or -114 or -117
Fax +49 2224 9010-130
E-mail gomer@pbh.de
Internet: www.pbh.de

Taxi Phone +49 2224 2222

## Registration:

Mojca Peklaj (WE Heraeus Foundation)
at the Physikzentrum, Reception Office
Sunday (16:00 h - 18:00 hrs) and Monday morning

# Program

# Program *(CEST)*

## Sunday, 10 July 2022

| | | |
|---|---|---|
| 16:00 – 18:00 | REGISTRATION | |
| 18:00 – 19:30 | *BUFFET SUPPER and informal get-together* | |
| | **Start of the Scientific Program** | |
| 19:30 – 20:30 | Otfried Gühne | **Entanglement in Quantum Networks** |
| 20:30 – 21:30 | **Discussions** | |

## Monday, 11 July 2022

| | | |
|---|---|---|
| 08:00 | *BREAKFAST* | |
| 09:00 – 10:00 | Joseph Renes | **Belief Propagation Decoding by Passing Quantum Messages: How to Perform an Optimal Measurement** |
| 10:00 – 10:30 | Benoit Vermersch | **Probing the Entanglement Structure of Quantum States via Partial-Transpose Moments** |
| 10:30 – 11:00 | *COFFEE BREAK* | |
| 11:00 – 12:00 | Sarah Croke | **Non-Locality in Quantum Measurements** |
| 12:00 – 12:30 | Michal Oszmaniec | **Implementation of Quantum Measurements Using Classical Resources and only a Single Ancillary Qubit** |
| 12:30 – 12:40 | **Conference Photo (outside at the main entrance)** | |
| 12:40 – 14:00 | *LUNCH / DISCUSSIONS* | |

# Program *(CEST)*

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|---|---|---|
| 14:00 – 15:00 | Reinhard Werner | **Compatibility of Quasi-free Bosonic Channels** |
| 15:00 – 15:30 | Victoria Wright | **Contextuality in Composite Systems: The Role of Entanglement in the Kochen-Specker Theorem** |
| 15:30 – 16:00 | *COFFEE BREAK* | |
| 16:00 – 16:30 | **Discussions** | |
| 16:30 – 17:00 | **Poster Flash Talks** | |
| 17:00 – 19:00 | **Poster Session 1** | |
| 19:00 | *HERAEUS DINNER* at the Physikzentrum<br>(cold & warm buffet, with complimentary drinks) | |

# Program *(CEST)*

## Tuesday, 12 July 2022

| | | |
|---|---|---|
| 08:00 | *BREAKFAST* | |
| 09:00 – 09:30 | Máté Farkas | **Mutually Unbiased Measurements** |
| 09:30 – 10:00 | Erkka Haapasalo | **Strategies for Joint Quantum Measurements: Sequential and Parallel Schemes** |
| 10:00 – 10:30 | Costantino Budroni | **Ticking-Clock Performance Enhanced by Nonclassical Temporal Correlations** |
| 10:30 – 11:00 | *COFFEE BREAK* | |
| 11:00 – 12:00 | Andreas Winter | **Hidden Markov Models: Classical and Quantum Mechanisms, and Beyond** |
| 12:00 – 12:30 | Glaucia Murta | **Towards Optimal Device-independent Cryptography with Multipartite Nonlocality** |
| 12:30 – 14:00 | *LUNCH / DISCUSSIONS* | |
| 14:00 – 15:00 | Dagmar Bruss | **On Resource Theories for Sets of Quantum Measurements** |
| 15:00 – 15:30 | René Schwonnek | **The Interrelation of Preparation and Measurement Uncertainty** |
| 15:30 – 16:00 | *COFFEE BREAK* | |
| 16:00 – 16:30 | **Discussions** | |
| 16:30 – 17:30 | **Freetime** | |
| 17:30 – 18:00 | **Poster Flash Talks** | |
| 18:00 – 19:30 | DINNER | |
| 19:30 – 21:30 | **Poster Session 2** | |

# Program *(CEST)*

## Wednesday, 13 July 2022

| | | |
|---|---|---|
| 08:00 | *BREAKFAST* | |
| 09:00 – 09:30 | Daniel McNulty | **Estimating Quantum Hamiltonians via Joint Measurements of Noisy Non-Commuting Observables** |
| 09:30 – 10:00 | Nikolai Miklin | **Device-independent Quantification of Measurement Incompatibility** |
| 10:00 – 10:30 | Andrea Smirne | **Non-Classicality of Multi-Time Measurements in Markovian and Non-Markovian Quantum Processes** |
| 10:30 – 11:00 | *COFFEE BREAK* | |
| 11:00 – 12:00 | Marcus Huber | **The Thermodynamics of Quantum Measurements** |
| 12:00 – 12:30 | Armin Tavakoli | **Quantum Measurements in Entanglement-assisted Communications** |
| 12:30 – 12:40 | Organizers | **Closing Remarks** |
| 12:40 | *LUNCH / DISCUSSIONS* | |

End of seminar and departure

# Posters

# Poster Session 1: Monday, 11 July, 17:00 h (CEST)

| | | |
|---|---|---|
| 1 | Konstantin Beyer | **Joint Measurability in Non-equilibrium Quantum Thermodynamics** |
| 2 | Some Sankar Bhattacharya | **Quantum Theory is Exclusive: A Distributed Computing Setup** |
| 3 | Jan Lennart Bönsel | **Spin Squeezing Inequalities Meet Randomized Measurements** |
| 4 | Giacomo Carrara | **Genuine Multipartite Entanglement is not a Precondition for Secure Conference Key Agreement** |
| 5 | Thomas Cope | **Average Dimensionality of Quantum Measurements** |
| 6 | Pedro Cruz | **Testing Complementarity on a Transmon Quantum Processor** |
| 7 | Bruna Gabrielly de Moraes Araújo | **Local Quantum Overlapping Tomography** |
| 8 | Sophia Denker | **Constructing Entanglement Witnesses Based on the Schmidt Decomposition of Operators** |
| 9 | Sébastien Designolle | **Quantifying Masurement Incompatibility of Mutually Unbiased Bases** |
| 10 | Tran Duc (Online) | **Quantum Nonlocality on the Quantum Circuit** |
| 11 | Sophie Egelhaaf | **Multipartite High-Dimensional Quantum Steering** |
| 12 | Regina Finsterhoelzl | **Benchmarking Quantum Error Correcting Codes on Near-term Devices** |

# Poster Session 1: Monday, 11 July, 17:00 h (CEST)

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|---|---|---|
| **13** | Mariami Gachechiladze | **Quantum Bell Inequalities from Information Causality - Tight for Macroscopic Locality** |
| **14** | Alexander Geng | **A Robust Quantum Image Edge Detector for Noisy Superconducting Quantum Processors** |
| **15** | Satoya Imai | **Work Fluctuations and Entanglement in Quantum Batteries** |
| **16** | Benjamin Jones | **High-dimensional Measurement Incompatibility and Steering** |
| **17** | Hermann Kampermann | **POVM Based Coherence** |
| **18** | Matthias Kleinmann | **Dynamic Theories in Phase Space: The Case of the Hydrogen Atom** |
| **19** | Tulja Varun Kondra | **Entanglement Catalysis for Quantum States and Noisy Channels** |
| **20** | Tristan Kraft | **Transformations in Quantum networks via local operations assisted by finitely many rounds of classical communication** |
| **21** | Kimmo Luoma | **Non-Markovian Quantum Dynamics in Strongly Coupled Multimode Cavities Conditioned on Continuous Measurement** |
| **22** | Andrea Matic | **Radiological Image Classification Using Hybrid Quantum-classical Convolutional Neural Networks** |
| **23** | Somayeh Mehrabankar | **Two-mode Gaussian States as Resource of Secure Quantum Teleportation in Open Systems** |
| **24** | Arindam Mitra (Online) | **Compatibility of Quantum Instruments** |

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|---|---|---|
| **25** | Andrey Moskalenko<br>(Online) | **Electro-optic Sampling of Quantum Fields: Back Action and Weak Measurement Regime** |

# Poster Session 2: Tuesday, 12 July, 19:30 h (CEST)

| | | |
|---|---|---|
| **1** | Moein Naseri | **Entanglement and Coherence in Bernstein-Vazirani Algorithm** |
| **2** | Ties-Albrecht Ohst | **Nearly Optimal Separability Certification of Quantum States** |
| **3** | Neha Pathania (Online) | **Quantum Coherence as an Entanglement Measure** |
| **4** | Tushita Prasad | **1/n Expansion of the Regularised Coherent Information of a Noisy Quantum Channel** |
| **5** | Maria Quadeer | **Typical Measurement Bases for State Tomography** |
| **6** | Muthuganesan Rajendran | **Asymmetry-induced Nonclassical Correlation** |
| **7** | Moritz Ferdinand Richter | **Quantum Frames, Distance Measures and Non-Markovianity** |
| **8** | Salwa Shaglel | **Estimating the Entangling Power of a Two-qubit Gate from Measurement Data: Artificial Neural Networks and Randomized Measurements versus Standard Tomography Methods** |
| **9** | Markus Sifft | **Quantum Polyspectra – Grand Unified Theory of Continuous Quantum Measurements** |
| **10** | Abdallah Slaoui (Online) | **A Comparative Study between Local Quantum Fisher Information and Local Quantum Uncertainty** |
| **11** | Hector Spencer-Wood | **Measurement Disturbance Tradeoffs in Unsupervised Quantum Classification** |
| **12** | Philipp Stammer | **Theory of Entanglement and Measurement in High Harmonic Generation** |

# Poster Session 2: Tuesday, 12 July, 19:30 h (CEST)

| | | |
|---|---|---|
| **13** | Jonathan Steinberg | **Optimising Shadow Tomography with Generalised Measurements** |
| **14** | Nidhin Sudarsanan Ragini | **Labeling of Quantum Observables and Process Measurements** |
| **15** | Jacopo Surace | **State Retrieval Beyond Bayes' Retrodiction and Reverse Processes** |
| **16** | Konrad Szymanski | **Entanglement Detection with Arbitrary Observables** |
| **17** | Philip Taranto | **Operational Characterisation of Quantum Memory Effects via Multi-Time Probing Schemes** |
| **18** | Lucas Tendick | **Distance-based Resource Quantification for Sets of Quantum Measurements** |
| **19** | Lauritz van Luijk | **The Classical Limit** |
| **20** | Isadora Veeren | **Entropic Uncertainty Relations and the Quantum-to-Classical transition** |
| **21** | Vadim Vorobyov | **On Measurement Efficiency in a Room Temperature Weak Measurement Apparatus Based on Single NV Center in Diamond with Weakly Coupled Nuclear Spin** |
| **22** | Lisa Weinbrenner | **Average Waiting Times for Entanglement Links in Multiplexed Quantum Networks** |
| **23** | Nikolai Wyderka | **Detecting Bound Entanglement Using Randomized Measurements in Two-qudit Systems** |
| **24** | Zhen-Peng Xu | **Quantum State-independent Certification** |

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|---|---|---|
| **25** | Mario Ziman | **Measurements of Quantum Memory Devices** |

# Abstracts of Lectures

(in alphabetical order)

# On resource theories for sets of quantum measurements

Lucas Tendick, Martin Kliesch, Hermann Kampermann, and Dagmar Bruß

Institute for Theoretical Physics, Heinrich-Heine-University Düsseldorf, Germany

Certain quantum information processing tasks, such as demonstrating the violation of a Bell inequality, require non-vanishing resources in both quantum states and measurements. While resource theories for quantum states have already been widely studied [1], much less is known about resource quantification for quantum measurements, in particular for sets of quantum measurements.

Here, we introduce distance-based quantifiers for resource theories of sets of measurements [2]. This allows us to establish a hierarchy between different resource theories that resembles an analogous hierarchy for states [3]. Furthermore, we derive general analytical bounds on the incompatibility of sets of measurements, that take a particularly elegant form in the case of projective measurements in mutually unbiased bases. Our approach provides a general framework to quantify the resources of sets of measurements, and to evaluate their power for quantum information processing tasks.

## References

[1] E. Chitambar and G. Gour, Rev. Mod. Phys. **91**, 025001 (2019).

[2] L. Tendick, M. Kliesch, H. Kampermann, and D. Bruß, arXiv:2205.08546.

[3] A. Streltsov, H. Kampermann, S. Wolk, M. Gessner, and D. Bruß, New J. Phys. **20**, 053058 (2018).

# Ticking-clock performance enhanced by nonclassical temporal correlations

**Costantino Budroni**[1,2], **Giuseppe Vitagliano**[2], **Mischa P. Woods**[3]
**Lucas B. Vieira**[2]

*[1]Faculty of Physics, University of Vienna, Vienna, Austria*
*[2] Institute for Quantum Optics and Quantum Information (IQOQI), Vienna, Austria*
*[2] ETH, Zurich, Switzerland*

We investigate the role of nonclassical temporal correlations in enhancing the performance of ticking clocks in a discrete-time scenario. We show that the problem of optimal models for ticking clocks is related to the violation of Leggett-Garg-type temporal inequalities formulated in terms of, possibly invasive, sequential measurements, but on a system with a bounded memory capacity. Ticking clocks inspire the derivation of a family of temporal inequalities showing a gap between classical and quantum correlations, despite involving no input. We show that quantum ticking-clock models achieving accuracy beyond the classical bound are also those violating Leggett-Garg-type temporal inequalities for finite sequences and we investigate their continuous-time limit. Interestingly, we show that optimal classical clock models in the discrete-time scenario do not have a well-defined continuous-time limit, a feature that is absent in quantum models.
Finally, we extend our investigation to the generation of arbitrary output sequences, not necessarily related to clock models. Here, the clock sequence seems to play a special role providing an upper bound for the output probability of all sequences, when the system memory is not enough to produce the sequence deterministically. This suggest a nontrivial universal upper bound for all the sequences generated by classical systems, which is not present in the quantum case.

## References

[1] C. Budroni, G. Vitagliano, M. P. Woods, Phys. Rev. Research **3**, 033051 (2021)
[2] L. B. Vieira and C. Budroni, Quantum **6**, 623 (2022)

# Non-locality in quantum measurements

**S. Croke**

*University of Glasgow, Glasgow, UK*

One notion of non-locality in quantum theory is the fact that information may be encoded in a composite system in such a way that it is not accessible through local measurements, even with the assistance of classical communication. Thus, contrary to the classical case, there exists information in quantum many body systems which cannot be accessed locally. Interestingly, the relationship between measurement non-locality and entanglement (perhaps a more well-known manifestation of quantum non-locality) is not straight-forward; the absence of entanglement is not enough to ensure the local accessibility of information, and conversely the *presence* of entanglement does not imply the local *in*accessibility of information. In the talk I'll give a tutorial type overview of some of the early surprising results illustrating this, and time permitting discuss two related topics that I've been interested in recently: multi-partite subspaces in which *all* information can provably be accessed locally; and an application of a local measurement scheme for distinguishing multi-partite entangled states to the problem of preparing arbitrary initial states in a quantum computational register.

# Mutually unbiased measurements

**M. Farkas[1], A. Tavakoli[2], D. Rosset[3], J-D. Bancal[4], J. Kaniewski[5], M. Prat Colomer[1], L. Mortimer[1], I. Frérot[6], A. Acín[1] and A. Nayak[7]**

*[1] ICFO, Barcelona, Spain, [2] IQOQI Vienna, Austria*
*[3] University of Geneva, Switzerland, [4] Universite Paris-Saclay, France*
*[5] University of Warsaw, Poland, [6] Univeriste Grenoble Alpes, France*
*[7] Univeristy of Waterloo, Canada*

Mutually unbiased bases (MUBs) are widely useful measurements in quantum information, used in state determination, quantum cryptography, quantum communication and other tasks. In this work we introduce a generalisation of MUBs that we call mutually unbiased measurements (MUMs). MUMs are defined through a complementarity property: if a measurement yields a definite outcome on a quantum state then a measurement unbiased to it yields a uniformly random outcome on the same state. MUMs are the same as MUBs whenever the Hilbert space dimension matches the outcome number. In general, MUMs admit the same incompatibility robustness and the same entropic uncertainty relations as MUBs. We characterise MUMs via block matrices that we call Hadamard matrices of unitaries. We show that a pair of MUMs is a direct sum of MUBs if and only if all blocks of the corresponding Hadamard matrix commute. Using this characterisation, we show that there exist MUMs that are not direct sums of MUBs, and we give explicit constructions through a correspondence with quaternionic Hadamard matrices. We further show that there exist MUMs that cannot be mapped to MUBs via any completely positive unital map.
We introduce a family of Bell inequalities whose maximal violation certify precisely the MUM property. Due to the fact that there exist unitarily inequivalent MUBs, this result also implies that the quantum correlation maximally violating these Bell inequalities is in general an extremal point but not a self-test, the first example of such a correlation. We further show that the maximal violation cerifies log(d) bits of device-independent secret key. Then, we generalise the inequalities to an arbitrary number of MUMs (instead of two) and by numerically optimising these inequalities in a fixed dimension we tackle the long-standing problem of the number of MUBs in composite dimensions, known as Zauner's conjecture.

## References

[1] A Tavakoli *et al.*, Science Advances **7**, eabc3847 (2021)
[2] M. Prat Colomer *et al.*, arXiv:2203.09429 (2022)
[3] M. Farkas, J. Kaniewski and A. Nayak, arXiv:2204.11886 (2022)

# Entanglement in Quantum Networks

**O. Gühne**[1], **K. Hansenne**[1], **Z.-P. Xu**[1], **T. Kraft**[2]

[1]*Universität Siegen, Germany*
[2]*Universität Innsbruck, Austria*

Quantum networks are promising tools for the implementation of long-range quantum communication. The characterization of quantum correlations in networks and their usefulness for information processing is therefore central for the progress of the field, but so far only results for small basic network structures or pure quantum states are known. In my talk I will introduce notions of network entanglement and study their properties. Specifically, I will provide an analytical approach to characterize correlations in large network structures with arbitrary topologies. As examples, I show that entangled quantum states with a bosonic or fermionic symmetry can not be generated in networks; moreover, cluster and graph states are not accessible. The methods can also be used to design certification methods for the functionality of specific links in a network and have implications for the design of future network structures.

## Reference

[1] K. Hansenne, Z.P. Xu, T. Kraft, O. Gühne, Nature Comm. 13, 496 (2022)

# Strategies for joint quantum measurements: sequential and parallel schemes

Erkka Haapasalo

Centre for Quantum Technologies, National University of Singapore

**ABSTRACT:** Unlike classical measurements, different quantum measurements cannot always be performed simultaneously. Despite this *incompatibility* of quantum measurement devices, in order to carry out informative measurements, we need to measure incompatible observables, described by *positive-operator-valued measures (POVMs),* at least approximately simultaneously; examples include informationally complete approximate joint measurements of position and momentum. One way is to measure one of the POVMs, or its approximation first, followed by a *retrieving measurement* of the second POVM. Whenever the two POVMs are jointly measurable, there is always such a successful retrieving strategy which recovers the target POVMs as margins of the resulting joint POVM. Another strategy is carrying out the POVMs in a parallel fashion: we first approximately clone or broadcast the state and then measure the target POVMs separately on the margins of the broadcasted state. This method is not always successful but a broad range of joint measurements can still be reached using this strategy. This talk studies these strategies and the related concept of non-disturbance, the resources needed for the retrieving measurements in the sequential scheme, and the conditions for the existence of a parallel joint measurement strategy. In an interesting class of examples, the latter setting leads into easily checked conditions involving matrix inequalities.

# The thermodynamics of quantum measurements

**Marcus Huber**[1 2]

*[1]Atominstitut, TU Wien, Vienna, Austria*
*[2] IQOQI Vienna, ÖAW, Austria*

Quantum measurements and thermodynamics often seem at odds with one another. Quantum theories of thermodynamics usually ignore measurements or just push them to the classical domain, never resolving their thermodynamics. From a thermodynamic perspective, the measurement postulates seem to contradict all thermodynamics laws. Salvaging thermodynamic consistency is harder, the more laws are taken into account [1]. Of course, the measurement postulates are just convenient fiction, idealized principles that can be well approximated, given sufficient resources. I will present an insight into thermodynamic irreversibility as the origin of measurement irreversibility [2], and the resources required to well approximate quantum measurements [3].

## References

[1] Y. Guryanova, N. Friis, M. Huber, Quantum 4, 222 (2020)
[2] E. Schwarzhans, F. Binder, M.Huber, M. Lock, *work in progress*
[3] P. Taranto, F. Bakhshinezhad, A. Bluhm, R. Silva, N. Friis, M. P. E. Lock, G. Vitagliano, F. C. Binder, T. Debarba, E. Schwarzhans, F. Clivaz, M. Huber, https://arxiv.org/abs/2106.05151

# Estimating Quantum Hamiltonians via Joint Measurements of Noisy Non-Commuting Observables

Daniel McNulty,* Filip Maciejewski,† and Michał Oszmaniec‡
*Center for Theoretical Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warszawa, Poland*

Measurement incompatibility, one of the defining non-classical features of quantum theory, limits an observer's ability to measure certain physical properties of a system simultaneously. This is a major issue for variational quantum algorithms, which constitute one of the leading candidates for attaining quantum speedups in near-term quantum computers. Algorithms of this type require a quantum computer to estimate the expectation values of a quantum many-body Hamiltonian, encoding, for example, a molecular system relevant for quantum chemistry. Estimating these expectation values involve measuring large collections of incompatible observables, leading to a significant computation burden on the scheme. In this talk we introduce a novel approach to reduce this burden, based on the repeated implementation of a single joint measurement that can be performed locally and whose marginals yield noisy versions of the target set of incompatible ones. We compare this strategy to the classical shadow formalism, another estimation approach useful for predicting many properties of a quantum system with as few measurements as possible. We formulate some basic connections between the two approaches, showing that joint measurements can be used to construct classical shadows and, conversely, the shadow protocol defines a joint measurement. Finally, we study the effects of noise on our measurement strategy, and show that a modified optimal joint measurement can provide significant improvements in performance when compared with noisy classical shadows.

*Electronic address: dmcnulty@cft.edu.pl
†Electronic address: filip.b.maciejewski@gmail.com
‡Electronic address: oszmaniec@cft.edu.pl

# Device-independent quantification of measurement incompatibility

**Shin-Liang Chen[1,2], Nikolai Miklin[3], Costantino Budroni[4,5], and Yueh-Nan Chen[2]**

*[1] Freie Universität Berlin, Berlin, Germany*
*[2] National Cheng Kung University, Tainan, Taiwan*
*[3] University of Gdańsk, Gdańsk, Poland*
*[4] University of Vienna, Vienna, Austria*
*[5] Institute for Quantum Optics and Quantum Information (IQOQI), Vienna, Austria*

The most accurate concept encapsulating the usefulness of quantum measurements in information processing tasks is measurement incompatibility. The previous and more widely known concepts such as non-commutativity or Heisenberg uncertainty are generalized by this notion. Qualitatively, in Bell's tests, incompatibility is known to be a necessary property for displaying nonlocality. The quantitative link, however, remained largely unexplored until recently.

In this work, we present a framework that establishes this first direct and quantitative link between Bell nonlocality and the incompatibility of measurements. This is accomplished by a map that we refer to as "measurement moment matrices" and which is formulated using semi-definite programming. The latter is an efficient tool for which many algorithms have been developed and more importantly, a certificate for the optimal solution can be provided. Our method offers a systematic way of addressing questions such as: “How incompatible the underlying measurements have to be in order to observe a certain quantum violation of a Bell inequality?” Previously, the answers to this question were known only in special cases where measurements could be identified uniquely (up to isometry) for maximum violation of some Bell inequalities. We provide an example of one of these cases in our manuscript and show that our method is capable of recovering the analytical solution to numerical accuracy. Additionally, we apply our method to previsuoly unconsidered scenarios. Finally, we show that our method straightforwardly generalizes to include constraints on the system's dimension (semi-device-independent approach) and on projective measurements, providing improved bounds on incompatibility quantifiers, and to include the prepare-and-measure scenario.

# Towards optimal device-independent cryptography with multipartite nonlocality

**F. Grasselli[1] , G. Murta[1] , H. Kampermann[1] , and D. Bruß[1]**

[1]*Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, Düsseldorf D-40225, Germany*

Multiparty quantum cryptography based on distributed entanglement will find its natural application in the upcoming quantum networks. The security of many multipartite device-independent (DI) protocols, such as DI conference key agreement and randomness expansion, relies on the violation of a Bell inequality to ensure the privacy of the parties outcomes with respect to an eavesdropper. More specifically, the secret key and randomness rates are determined by the von Neumann entropy of the parties' outcomes conditioned on the eavesdropper's quantum side information. In this talk, I will present analytical bounds for the privacy of the parties' outcomes given the violation of a multipartite Bell inequality. As an application of these bounds for the tripartite scenario, we obtain a DI conference key agreement protocol and a DI randomness expansion protocol with the currently best known rates. Our bounds rely on general results of independent interest such as a drastic simplification of the quantum setup of an N-partite Bell scenario, and an upper bound on the violation of a multipartite Bell inequalities by an arbitrary N-qubit state.

## References

[1] F. Grasselli, G. Murta, H. Kampermann, and D. Bruß, PRX Quantum **2**, 010308 (2021)
[2] F. Grasselli, G. Murta, H. Kampermann, and D. Bruß, *in preparation* (2022)

# Implementation of quantum measurements using classical resources and only a single ancillary qubit

**Tanmay Singal[1,2]. Filip Maciejewski [1] and Michal Oszmaniec[1]**

[1] *Center for Theoretical Physics PAS, Warsaw, Polandy*

[2] *Budapest University of Science and Technology, Budapes, Hungary*

We propose a scheme to implement general quantum measurements, also known as Positive Operator Valued Measures (POVMs) in dimension \$d\$ using only classical resources and a single ancillary qubit. Our method is based on probabilistic implementation of d-outcome measurements which is followed by postselection of some of the received outcomes. We conjecture that success probability of our scheme is larger than a constant independent of d for all POVMs in dimension d. Crucially, this conjecture implies the possibility of realizing arbitrary nonadaptive quantum measurement protocol on d-dimensional system using a single auxiliary qubit with only a constant overhead in sampling complexity. We show that the conjecture holds for typical rank-one Haar-random POVMs in arbitrary dimensions. Furthermore, we carry out extensive numerical computations showing success probability above a constant for a variety of extremal POVMs, including SIC-POVMs in dimension up to 1299. Finally, we argue that our scheme can be favorable for experimental realization of POVMs, as noise compounding in circuits required by our scheme is typically substantially lower than in the standard scheme that directly uses Naimark's dilation theorem.

## References

[1] T. Singal, f. Maciejewski, M Oszmaniec, arXiv:2104.05612, accepted for publication in NPJ Quantum Information

# Belief propagation decoding by passing quantum messages: How to perform an optimal measurement

**Christophe Piveteau and Joseph M. Renes**

*Institute for Theoretical Physics, ETH Zürich, Switzerland*

Recently, one of us proposed a quantum algorithm called belief propagation with quantum messages (BPQM) for decoding classical data encoded using a binary linear code with tree Tanner graph that is transmitted over a pure-state CQ channel [Renes, NJP 19 072001 (2017)]. This algorithm presents a genuine quantum counterpart to decoding based on classical belief propagation, which has found wide success in classical coding theory when used in conjunction with LDPC or Turbo codes. More recently Rengaswamy et al. [npj Quantum Information 7 97 (2021)] numerically observed that, for a small example code, BPQM implements the optimal decoder for determining the entire input codeword. Here we significantly expand the understanding, formalism, and applicability of the BPQM algorithm with the following contributions. First, we prove analytically that BPQM realizes optimal decoding for any binary linear code with tree Tanner graph. We also provide the first formal description of the BPQM algorithm in full detail and without any ambiguity. In so doing, we identify a key flaw overlooked in the original algorithm and subsequent works which implies quantum circuit realizations will be exponentially large in the code size. Although BPQM passes quantum messages, other information required by the algorithm is processed globally. We remedy this problem by formulating a truly message-passing algorithm which approximates BPQM and has circuit complexity $O(\text{poly}\, n, \text{polylog}\, 1/\epsilon)$, where $n$ is the code length and $\epsilon$ is the approximation error. Finally, we also propose a novel method for extending BPQM to factor graphs containing cycles by making use of approximate cloning. We show some promising numerical results that indicate that BPQM on factor graphs with cycles can significantly outperform the best possible classical decoder.

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# The interrelation of preparation and measurement uncertainty

**L. van Luijk[1], R. Schwonnek[1] , and R.F. Werner[1]**

[1]*Institut für Theoretische Physik, Leibniz Universität Hannover, Germany*

There is a broad consensus that the concept of 'the uncertainty within a set observables' comes in at least two flavours: preparation uncertainty and measurement uncertainty.
A preparation uncertainty describes the inability of preparing a common dispersion free state. It is present when observables share no eigenstates. In contrary a measurement uncertainty refers to situations, similar to the famous γ-ray microscope, in which no error free joint measurement can be constructed. Hence, it is present when observables are incompatible.
Even though these two types refer to operationally very different settings they can both be put on a common ground: By borrowing concepts from the field of optimal transport theory, we provide constructions for operational meaningful quantities that serve as measures of preparation or as measures for measurement uncertainty. These constructions are based on the concept of a cost function and stem from a generalization of the Wasserstein-Kantorovich–Rubinstein distance to POVMs.
As a central result, it can be shown that preparation uncertainty puts a lower bound on measurement uncertainty, whenever we consider projective measurements in finite dimensions. A generalization to more general operator algebras is possible if all observables admit a so-called amenable trace. Furthermore, this estimate becomes an equality in the special case of observables with common group covariant symmetries.
By a suitable choice of the parameters that enter our construction, we can recover many well-known measures for preparation uncertainty, like variances and entropies. Based on this we can now also provide their natural correspondences (that can be understood as incompatibility measures) in the realm of measurement uncertainty.
We apply this construction to different measures for information distance. This will result in a whole 'Zoo' of information theoretic incompatibility measures. We will put some clarification on the structure of this 'Zoo' and outline connections to existing preparation uncertainty relations that can be bounded by a Maassen and Uffink like constant.

# Non-classicality of multi-time measurements in Markovian and non-Markovian quantum processes

**S. Milz[1,2], D. Egloff[3,4], P. Taranto[2], T. Theurer[3], M.B. Plenio[3], <u>A. Smirne[3,5,6]</u>, and S.F. Huelga[3]**

*[1]School of Physics and Astronomy, Monash University, Victoria, Australia*
*[2]IQOQI, Austrian Academy of Sciences, Vienna, Austria*
*[3]Institute of Theoretical Physics and IQST, Universität Ulm, Ulm, Germany*
*[4]Institute of Theoretical Physics, Technical University Dresden, Dresden, Germany*
*[5]Dipartimento di Fisica "Aldo Pontremoli", Università degli Studi di Milano, Milan, Italy*
*[6] Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Milan, Italy*

More than a century after the inception of quantum theory, the question of which traits and phenomena are fundamentally quantum remains under active investigation. As a significant example, quantum coherence is indeed a basic element of quantum mechanics, but the mere presence of coherences in the quantum description of a physical phenomenon does not rule out the existence of an alternative classical description, as widely debated with regard to possible quantum effects in biological systems [1]. In this talk, I will discuss definite criteria to determine when and to what extent non-classicality can be unambiguously linked to specific features of the evolution of an open quantum system and its interaction with the environment. I will consider an open system that is undergoing sequential projective measurements of one observable at different times, and exploit the Kolmogorov consistency conditions to discriminate the resulting multi-time statistics from the statistics of any classical process, in the same spirit as the Leggett-Garg inequalities [2]. In the Markovian case, the multi-time statistics cannot be accounted for by means of any classical process if and only if the dynamics generates coherences (with respect to the measured observable) and subsequently turns them into populations [3]. On the other hand, such a direct connection between quantum coherence and non-classicality cannot be extended to general non-Markovian processes, where, instead, non-classicality is related to the quantum discord between the measured system and its environment [4]. The approach presented here is fully operational, since it relies on the observed multi-time probability distributions, and it thus directly applies to detect and quantify non-classicality of quantum experimental platforms [5].

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# Quantum Measurements in Entanglement-assisted Communications

**A. Tavakoli**[1]

*IQOQI Vienna & TU Vienna, Austria*

Entanglement can be used to boost communication beyond classical limitations. For long, it has been standard to employ measurements for some Bell inequality test and then use the nonlocal data to boost transmissions over classical channels, and to use entangled measurements to boost transmissions over quantum channels. Here, we revisit the role of quantum measurements for transmitting information, and find that both the classical case and the quantum case are richer than previously established. In the classical case, we show that the relationship between nonlocality and communication is more intricate, requiring adaptive measurement models. In the quantum case, we show that entangled measurements in fact are not necessary to optimally boost quantum communication.

# Probing the entanglement structure of quantum states via partial-transpose moments.

**B. Vermersch[1,2]**

*[1]Univ. Grenoble Alpes, CNRS, LPMMC, 38000 Grenoble, France*
*[2]Institute for Theoretical Physics, University of Innsbruck, Innsbruck A-6020, Austria*
*[3]Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Innsbruck A-6020, Austria*

I will discuss our works on partial-transpose (PT) moments, which are entanglement quantities that can be measured experimentally in existing quantum technologies using randomized measurements.
After a brief introduction on randomized measurements, I will first present the p3-PPT condition that has been experimentally used to detect mixed-state entanglement in a trapped-ion quantum system. I will then show that PT moments can also be used to reveal the entanglement structure of many-body quantum states.

# Hidden Markov models: classical and quantum mechanisms, and beyond

**A. Winter**[1,2]

*[1]ICREA, Pg. Lluís Companys 23, 08010 Barcelona, Spain*
*[2]Universitat Autònoma de Barcelona, Departament de Física, Grup d'Informació Quàntica, 08193 Bellaterra (Barcelona), Spain*

A fundamental problem of inference is that of the observation of a long (ideally infinite) stationary time series of events, generated by a hidden Markov chain. What can we say about the internal structure of the hidden Markov model, aka the latent variables? If the system generating the observations is classical, we are looking to reconstruct the "hidden" Markov chain from its "visible" image.
Here, we are studying the case that the hidden system is quantum mechanical, giving rise to a special class of finitely correlated states, which we call *quantum hidden Markov models*; and even more generally, a general probabilistic theory (GPT). The latter case is entirely described in terms of the rank of the so-called Hankel matrix of the process, and an associated canonical vector space with associated positive cone preserved under the hidden dynamics of the model. For the quantum case, we describe the structure of the possible GPTs via semidefinite representable (SDR) cones. It turns out that these GPTs are all finitely presented operator systems, i.e. induced subspaces of quotients of B(H) for a finite-dimensional Hilbert space H. Unlike operator systems, for which complete positivity can be very hard to decide, the SDR models come with a subset of the completely positive maps, which is itself an SDR cone [1].
I will also describe the first known example of a process generated via a finite-dimensional GPT as the hidden system, which however cannot be reproduced by any quantum hidden Markov model with finite state space [2]. Processes generated via a finite-dimensional GPT which cannot be reproduced by a classical hidden Markov chain had been known before [1,3].

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# Contextuality in composite systems: the role of entanglement in the Kochen-Specker theorem

**V. J. Wright**[1] **and Ravi Kunjwal**[2]

[1]*ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Spain*

Email: victoria.wright@icfo.eu

[2] *Centre for Quantum Information and Communication, Ecole polytechnique de Bruxelles, CP 165, Université libre de Bruxelles, 1050 Brussels, Belgium*

The Kochen-Specker (KS) theorem reveals the nonclassicality of single quantum systems. In contrast, Bell's theorem and entanglement concern the nonclassicality of composite quantum systems. Accordingly, unlike incompatibility, entanglement and Bell non-locality are not necessary to demonstrate KS-contextuality. However, in this work we find that logical proofs of the KS theorem for multiqubit systems require entangled measurements. In particular, measurements demonstrating nonlocality without entanglement are insufficient for these proofs. This result also implies that proving Gleason's theorem on a multiqubit system necessarily requires entangled projections, a result originally due to Wallach [Contemp Math, 305: 291-298 (2002)]. We proceed to show that in multiqubit systems statistical proofs of the KS theorem using unentangled measurements require not only entangled states, but states that can violate a Bell inequality using local projective measurements. Thus, we arrive at the statement that multiqubit KS-contextuality requires both nonlocality and entanglement.

# Abstracts of Posters

(in alphabetical order)

# Local quantum overlapping tomography

**Bruna G. M. Araújo**[1,2] , **Marcio M. Taddei**[1],**Daniel Cavalcanti**[1,3], **Antonio Acín**[1,4]

*[1]ICFO - Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860, Castelldefels, Barcelona, Spain*
*[2] Department of Physics, Universitat Autonoma de Barcelona, Campus UAB, Bellaterra, 08193 Barcelona, Spain*
*[3] Bitflow, Piquer 23, Barcelona, 08004 Spain*
*[4] ICREA - Institucio Catalana de Recerca i Estudis Avanc¸ats, Lluis Companys 23, 08010 Barcelona, Spain*

Reconstructing the full quantum state of a many-body system requires the estimation of a number of parameters that grows exponentially with system size. Nevertheless, there are situations in which one is only interested in a subset of these parameters and a full reconstruction is not needed.

A paradigmatic example is a scenario where one aims at determining all the reduced states only up to a given size. Overlapping tomography provides constructions to address this problem with a number of product measurements much smaller than what is obtained when performing independent tomography of each reduced state. There are however many relevant physical systems with a natural notion of locality where one is mostly interested in the reduced states of neighboring particles. In this work, we study this form of local overlapping tomography.

First of all, we show that, contrary to its full version, the number of product measurements needed for local overlapping tomography does not grow with system size. Then, we present strategies for qubit and fermionic systems in selected lattice geometries. The developed methods find a natural application in the estimation of many-body systems prepared in current quantum simulators or quantum computing devices, where interactions are often local.

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# Joint measurability in non-equilibrium quantum thermodynamics

**K. Beyer[1], R. Uola[2], K. Luoma[3] and W. Strunz[1]**

[1]*Institut für Theoretische Physik, Technische Universität Dresden, Germany*
[2]*Department of Applied Physics, University of Geneva, Switzerland*
[3]*Turku Center for Quantum Physics, University of Turku, Finland*

The two-point measurement (TPM) scheme is one of the standard approaches to define work in non-equilibrium quantum thermodynamics. The energy of a closed system is measured projectively at the beginning and at the end of the protocol. The work for a single run is then given by the energy difference. The measurement statistics for an initial Gibbs state fulfills the Jarzynski equality and allows us to determine the free energy difference. On the other hand, for initial states with coherences the projective TPM scheme does not yield the correct average work because the first measurement is inherently disturbing. It is well known that a projective TPM scheme cannot be replaced by a single work measurement that reproduces both the TPM statistics for diagonal input states and the correct average work for arbitrary states. However, projective measurements are an idealization. Therefore, we extend the scenario to less disturbing unsharp energy measurements and show that the no-go theorem does not apply if the (unsharp) energies at the beginning and at the end of the protocol can be measured jointly for any intermediate unitary evolution. In such a case the average work and the free energy difference can be determined with the same measurement setup.

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# Quantum theory is exclusive: a distributed computing setup

Sutapa Saha[2], Tamal Guha[3], Some Sankar Bhattacharya[1], and Manik Banik[4]

[1]*Physics and Applied Mathematics Unit, Indian Statistical Institute, 203 B.T. Road, Kolkata-700108, India.*
[2]*QICi Quantum Information and Computation Initiative, Department of Computer Science, The University of Hong Kong, Pokfulam Road, Hong Kong.*
[3]*International Centre for Theory of Quantum Technologies (ICTQT), University of Gdańsk, Bazynskiego 8, 80-309 Gdansk, Poland.*
[4]*S.N. Bose National Center for Basic Sciences, Block JD, Sector III, Salt Lake, Kolkata-700098, India.*

*Contact e-mail: some.bhattacharya@ug.edu.pl*

The framework of distributed computing, whose constituents are the several spatially separated input-output servers, has immense importance in distant data manipulation. The most challenging part for such a setting is to optimize the use of information transmission lines among these distant servers. In this work, we have modeled such a physically motivated distributed computing setup for which quantum communication outperforms its classical counterpart, in terms of a limited usage of perfect transmission lines. Moreover, a broader class of communication entities, which allow state-effect description more exotic than quantum and are described within the framework of general probability theory, also fails to meet the strength of quantum theory. The computational strength of quantum communication further justified in terms of a stronger version of this task, namely the delayed-choice distributed computation. The proposed task thus provides a new approach to operationally single out quantum theory in the theory-space and hence promises a novel perspective towards the axiomatic derivation of Hilbert space quantum mechanics.

# Spin squeezing inequalities meet randomized measurements

**J. L. Bönsel[1], S. Imai[1], Y.-C. Liu[1] and O. Gühne[1]**

*[1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen,*
*Walter-Flex-Straße 3, 57068 Siegen, Germany*
*E-mail: jan.boensel@uni-siegen.de*

Due to the recent advances in quantum control, large quantum systems containing thousands of atoms can nowadays be prepared in the lab. Here, the characterization of quantum correlations is of special interest. For systems where the individual atoms are difficult to address, the measurement of collective angular momentum observables and the evaluation of the corresponding spin squeezing inequalities are a possibility to characterize entanglement and its usefulness for metrology.

In this contribution, we first study the number of quantum state samples that are necessary to verify entanglement with a certain confidence. For this purpose, we compare different estimators of spin squeezing parameters. We characterize the probability that the estimators deviate from their mean using simulations as well as analytical bounds derived from concentration inequalities, like Cantelli's and Hoeffding's inequality. Second, we analyse if it is possible to obtain a good estimate from fewer measurements made only on a randomly chosen subset of the atoms.

# Genuine multipartite entanglement is not a precondition for secure conference key agreement

**G. Carrara[1], H. Kampermann[1], D. Bruß[1] and G. Murta[1]**

*[1] Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstr. 1, D-40225 Düsseldorf, Germany*

Entanglement is an important resource in quantum cryptography and it is known to be necessary to guarantee security in a bipartite quantum key distribution scenario. We will focus on protocols that utilize the distribution of multipartite states followed by local measurements to generate a common secret key shared among all the parties. In the more complex multipartite scenario, where different classes of entanglement can be defined, we investigate the type of correlations in the shared state that can lead to a non-zero secret key rate in this scenario. After showing that all partitions of the system must exhibit entanglement in order to achieve a non-zero key rate, we prove that a non-zero secret key can be extracted also from states that are not *genuinely multipartite entangled* (GME). We investigate different classes of non-GME states that can be successfully used in a multipartite quantum key distribution protocol. We analyze the performance of the protocol in the presence of noise and compare it to a scenario where the parties establish a common secret with only bipartite resources.

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# Average Dimensionality of Quantum Measurements

**T. Cope[1] and R. Uola[2]**

*[1]Leibniz Universität, Hannover, Germany*
*[2] University of Geneva, Geneva, Switzerland*

We introduce a measure of average dimensionality (or coherence) for high-dimensional sets of quantum measurements. Operationally it corresponds to the average quantum memory required to compress an arbitrary state, so that the measurement statistics of the set can be later reproduced. We show how symmetry of the measurements can be used to simplify the measure, and evaluate it for pairs of mutually unbiased bases in prime dimension. For an arbitrary number of qubit measurements, the calculation reduces to a semidefinite program.

In the full work, this concept is extended to quantum channels and steering assemblages, and for the latter the asymptotic behavior is also described.

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# Testing complementarity on a transmon quantum processor

**Pedro M. Q. Cruz**[1,2] **and J. Fernández-Rossier**[1]

[1] *QuantaLab, International Iberian Nanotechnology Laboratory (INL), 715-330 Braga, Portugal*
[2] *Faculdade de Ciências da Universidade do Porto, 4169-007 Porto, Portugal*

We propose quantum circuits to test interferometric complementarity using symmetric two-way interferometers coupled to a which-path detector. First, we consider the two-qubit setup in which the controlled transfer of path information to the detector subsystem depletes interference on the probed subspace, testing the visibility-distinguishability tradeoff via minimum-error state discrimination measurements. Next, we consider the quantum eraser setup, in which reading out path information in the right basis recovers an interference pattern. These experiments are then carried out in an IBM superconducting transmon processor. A detailed analysis of the results is provided. Despite finding good agreement with theory at a coarse level, we also identify small but persistent systematic deviations preventing the observation of full particlelike and wavelike statistics. We understand them by carefully modeling two-qubit gates, showing that even small coherent errors in their implementation preclude the observation of Bohr's strong formulation of complementarity.

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# Constructing entanglement witnesses based on the Schmidt decomposition of operators

**S. Denker[1], C. Zhang[2], A. Asadian[3] and O. Gühne[1]**

*[1] Naturwissenschaftlich-Technische Fakultät, Universität Siegen, 57068 Siegen, Germany*
*[2] School of Physical Science and Technology, Ningbo University, Ningbo, 315211, China*
*[3] Department of Physics, Institute for Advanced Studies in Basic Sciences (IASBS), Gava Zang, Zanjan, 45137-66731, Iran*

Characterizing entanglement is an important issue in quantum information, as entanglement is considered to be a resource for quantum key distribution or quantum metrology. One useful tool to detect and quantify entanglement are witness operators. A standard way to design entanglement witnesses for two or more particles is based on the fidelity of a pure quantum state; in mathematical terms this construction relies on the Schmidt decomposition of vectors [1]. In this contribution, we present a method to build entanglement witnesses based on the Schmidt decomposition of operators. Our scheme works for the bipartite and the multipartite case and is found to be strictly stronger than the concept of fidelity-based witnesses. We discuss various examples and demonstrate that our approach can also be used to quantify quantum correlations as well as characterize the dimensionality of entanglement.

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# Quantifying measurement incompatibility of mutually unbiased bases

Sebastien Designolle

*University of Geneva*
*Chemin de Pinchat 22, 1211 Geneva 4, Switzerland*

Quantum measurements based on mutually unbiased bases are commonly used in quantum information processing, as they are generally viewed as being maximally incompatible and complementary. We quantify precisely the degree of incompatibility of mutually unbiased bases (MUB) using the notion of noise robustness. Specifically, for sets of $k$ MUB in dimension d, we provide upper and lower bounds on this quantity. Notably, we get a tight bound in several cases, in particular for complete sets of $k = d + 1$ MUB (given d is a prime power). Moreover, we prove the existence of sets of $k$ MUB that are operationally inequivalent, as they feature different noise robustness. Finally, we discuss applications of our results for Einstein-Podolsky-Rosen steering.

# Quantum nonlocality on the quantum circuit

**Duc Minh Tran**[1], **Van-Duy Nguyen**[2], **Bin Ho Le**[3], **Hung Quoc Nguyen**[1]

[1]*Nano and Energy Center, Hanoi University of Science, Vietnam National University;*
[2]*Phenikaa Institute for Advanced Study, Phenikaa University;*
[3]*Ho Chi Minh City Institute of Physics, VAST, Ho Chi Minh City 70000, Vietnam*

Quantum nonlocality is a peculiar relation of quantum observables that differentiates the classical and quantum worlds. Meanwhile, the development of quantum computers gives us a powerful tool to simulate quantum physics. In this work, we show how quantum circuits - quantum computing's natural language - can be used to construct Hardy's nonlocal states and test them out. We build circuits for *n*-particle states with non-vanishing nonlocal probability as *n* grows, then run them on IBMQ real device and Qiskit simulator. The results show agreement with theoretical predictions of quantum mechanics.

# Multipartite High-dimensional Quantum Steering

**S.Egelhaaf[1] and R.Uola[1]**

*[1]Department of Applied Physics, University of Geneva, Geneva, Switzerland*
*email: sophie.egelhaaf@unige.ch*

Bipartite low dimensional entanglement has been studied extensively. However, many findings cannot be extrapolated to multiple parties and moreover, increasing the dimensions of the systems adds complexity to the entanglement structure.
We are interested in characterising the degree of high-dimensional entanglement, specifically focusing on various multipartite quantum steering scenarios. One such example is a triangle network with only one trusted party, or more generally a line network with some trusted parties. We investigate what can be deduced about the strength of entanglement between the different nodes of the network in such scenarios. We are especially interested in entanglement dimensionality, i.e. the question of how many degrees of freedom can be certified to be entangled, for which we provide analytical bounds.

# Benchmarking quantum error correcting codes on near-term devices

Regina Finsterhoelzl and Guido Burkard

Department of Physics, University of Konstanz, Germany

regina.finsterhoelzl@uni-konstanz.de

Abstract

We evaluate the performance of small error-correcting codes making use of stabilizer measurements which we implement on hardware platforms of very different connectivity and coherence: On the superconducting IBM Q system One and on a spintronic quantum register consisting of a color center in diamond. Taking the hardware-specific errors and connectivity into account, we investigate the dependence of the resulting logical error rate on the platform features such as the native gates, the native connectivity, gate times and coherence times. We investigate different recovery schemes for the encoded quantum state based upon the classical information obtained by the measurement outcome. Using a standard error model parametrized for the given hardware, we simulate the performance and benchmark these predictions with experimental results when running the code on the IBM quantum device. The results indicate that for small codes using postprocessing, IBMs hexagonal layout proves advantageous, yet for larger codes using unitary correction schemes the star-like connectivity of the color centers enables lower error rates.

# Quantum Bell inequalities from Information Causality - tight for Macroscopic Locality

**M. Gachechiladze** [1] , **B. Bąk** [2], **M. Pawłowski** [3], **N. Miklin** [4]

[1] *TU Darmstadt, Darmstadt, Germany*
[2] *University of Warsaw, Warsaw, Poland*
[3] *University of Gdansk, Gdansk, Poland*
[3] *Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany*

In a Bell test, the set of observed probability distributions complying with the principle of local realism is fully characterized by Bell inequalities. Quantum theory allows for a violation of these inequalities, which is famously regarded as Bell nonlocality. However, finding the maximal degree of this violation is, in general, an undecidable problem. Consequently, no algorithm can be used to derive quantum analogs of Bell inequalities, which would characterize the set of probability distributions allowed by quantum theory. Here we present a family of inequalities, which approximate the set of quantum correlations in Bell scenarios where the number of settings or outcomes can be arbitrary. We derive these inequalities from the principle of Information Causality, and thus, we do not assume the formalism of quantum mechanics. Moreover, we identify a subspace in the correlation space for which the derived inequalities give the necessary and sufficient conditions for the principle of Macroscopic Locality. As a result, we show that in this subspace, the principle of Information Causality is strictly stronger than the principle of Macroscopic Locality.

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# A robust quantum image edge detector for noisy superconducting quantum processors

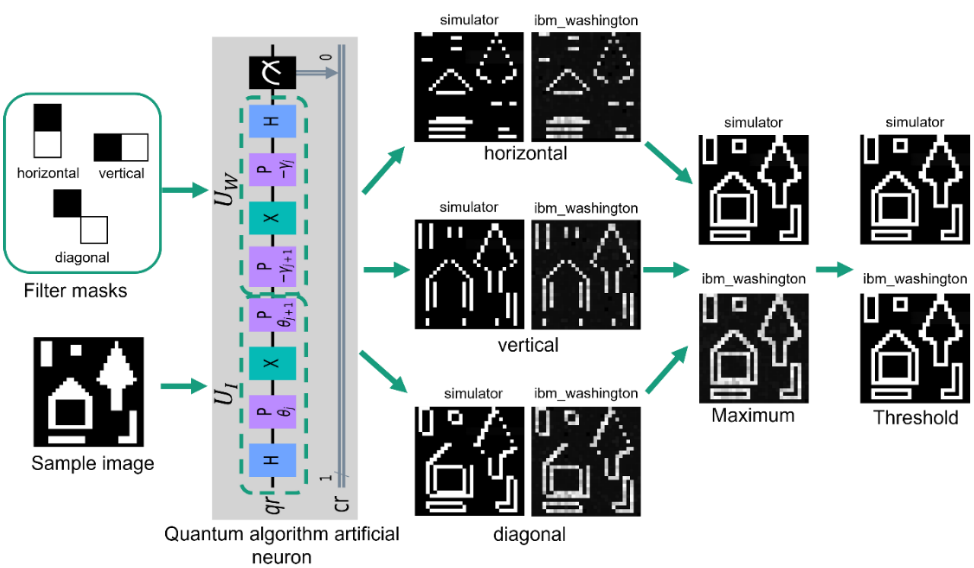
**Alexander Geng[1,2], Ali Moghiseh[1], Claudia Redenbach[2], Katja Schladitz[1]**

**[1] Fraunhofer Institute for Industrial Mathematics ITWM, Fraunhofer-Platz 1, Kaiserslautern, 67663, Germany.**

**[2] University of Kaiserslautern, Gottlieb-Daimler-Straße 47, Kaiserslautern, 67663, Germany.**

Edges are image locations where the gray value intensity changes suddenly. They are among the most important features to understand and segment an image. Edge detection is a standard task in digital image processing, solved for example using filtering techniques. However, the amount of data to be processed grows rapidly and pushes even supercomputers to their limits. Quantum computing promises exponentially lower memory usage in terms of the number of qubits compared to the number of classical bits. In this contribution, we propose a hybrid method for quantum edge detection. It is motivated by classical filtering and makes use of a quantum artificial neuron algorithm. We use three filter masks highlighting horizontal, vertical, and diagonal edges. For each of the three directions, we build a quantum circuit, measure them, and classically reassemble the partial results. We evaluate our method on superconducting quantum computers of the current noisy intermediate-scale quantum era. For that, we compare six variants of the method to reduce the number of circuits and thus the time required for the quantum edge detection. We process the three directions and several pixels in one circuit using mid-circuit measurements, reset operations, and parallel execution. Taking advantage of robustness and scalability of our method on real quantum processors, we can practically detect edges in images considerably larger than reached before.

We report on our paper published in the journal of Quantum Machine Intelligence [1].




*Scheme for edge detection of a* $30 \times 30$ *sample image by using one-dimensional filter masks, 'qasm_simulator' and backend 'ibm_washington' (executed on December, 22 2021) with 50 shots, and ToolIP for post-processing.*

[1] Geng, A., Moghiseh, A., Redenbach, C., Schladitz, K.: A hybrid quantum image edge detector for the NISQ era. Quantum Machine Intelligence 4 (2022), https://doi.org/10.1007/s42484-022-00071-3.

# Work fluctuations and entanglement in quantum batteries

**Satoya Imai**, **Otfried Gühne, and Stefan Nimmrichter**

*Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Str. 3, D-57068 Siegen, Germany*

We consider quantum batteries given by composite interacting quantum systems in terms of the thermodynamic work cost of local random unitary processes. We characterize quantum correlations by monitoring the average energy change and its fluctuations in the high-dimensional bipartite systems. We derive a hierarchy of bounds on high-dimensional entanglement (the so-called Schmidt number) from the work fluctuations and thereby show that larger work fluctuations can verify the presence of stronger entanglement in the system. Finally, we develop two-point measurement protocols with noisy detectors that can estimate work fluctuations, showing that the dimensionality of entanglement can be probed in this manner.

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# High-dimensional measurement incompatibility and steering

**Benjamin Jones[1], Roope Uola[2], Marie Ioannou[2], Sébastien Designolle[2], Pavel Sekatski[2], Thomas Cope[3] and Nicolas Brunner[2]**

[1] *University of Bristol, Bristol, BS8 1TL, UK*
[2] *University of Geneva, 1211 Geneva, Switzerland*
[3] *Leibniz Universität Hannover, Appelstr. 2, 30167 Hannover, Germany*

We investigate the compression of quantum information with respect to a given set *M* of high-dimensional measurements. This leads to a notion of simulability, where we demand that the statistics obtained from *M* and an arbitrary quantum state *ρ* are recovered exactly by first compressing *ρ* into a lower dimensional space, followed by some quantum measurements. A full quantum compression is possible if and only if the set *M* is jointly measurable [1]. Our notion of simulability can thus be seen as a quantification of measurement incompatibility in terms of dimension. We discuss links with high-dimensional steering [2], and show that many known connections generalise in terms of dimension, where the case of dimension 1 recovers previous results. As a tool for our work we make use of generalised channel-state duality [3], and we also introduce *n-partially incompatibility breaking channels*, motivated as an incompatibility analogue to *n-partially entanglement breaking channels* [4].

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# POVM based coherence

**F. Bischof[1], H. Kampermann[1] and D. Bruß[1]**

[1] *Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Germany*

In the usual resource theory of quantum coherence its magnitude is related to the off-diagonal density operator elements with respect to a fixed orthonormal basis. Incoherent quantum states are diagonal in this basis. In this work, we motivate and characterize the resource theory of quantum coherence based on positive operator valued measure (POVM) which covers the usual resource theory of coherence as a special case. We establish POVM-based coherence measures and POVM-incoherent operations. Examples are presented to discuss features which only occur in this generalized framework.

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# Dynamical theories in phase-space: The case of the hydrogen atom

**M. Plávala and M. Kleinmann**

*Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Siegen, Germany*

The successful description of the hydrogen atom is a hallmark of quantum theory. But how specific is this to quantum theory? We develop an alternative toy theory that can mimic many key features of the quantum hydrogen atom: Its stability, energy spectrum, the Bohr radius, quantum numbers, excitation of the electron by light, and Rutherford scattering. At the heart of the theory is a spectral decomposition of the energy observable into phase-space functions that predicts the probability distribution of the energy. This is in complete analogy to an energy measurement in quantum theory. For the dynamic properties, we develop a theory of time-evolution for generalized probabilistic theories in phase space on the basis of a generalization of the Moyal bracket. The corresponding equations of motion allow us to establish an analog to the Ehrenfest theorem while otherwise the dynamics can be significantly more general than in quantum theory: For example, neither the measurement of energy nor the energy eigenstates need to be constant in time. Still, the time-evolution enables us to predict the behavior of the hydrogen atom under a time-dependent electric field as well as the scattering behavior of a charged particle.

# Entanglement catalysis for quantum states and noisy channels

Chandan Datta, Tulja Varun Kondra, Marek Miller and Alexander Streltsov
*Centre for Quantum Optical Technologies, Centre of New Technologies,*
*University of Warsaw, Banacha 2c, 02-097 Warsaw, Poland*

**Abstract**

Many applications of the emerging quantum technologies, such as quantum teleportation and quantum key distribution, require singlets, maximally entangled states of two quantum bits [1]. It is thus of utmost importance to develop optimal procedures for establishing singlets between remote parties. As has been shown very recently, singlets can be obtained from other quantum states by using a quantum catalyst, an entangled quantum system which is not changed in the procedure[2]. In this work we take this idea further, investigating properties of entanglement catalysis and its role for quantum communication. For transformations between bipartite pure states, we prove the existence of a universal catalyst, which can enable all possible transformations in this setup. We demonstrate the advantage of catalysis in asymptotic settings, going beyond the typical assumption of independent and identically distributed systems. We further develop methods to estimate the number of singlets which can be established via a noisy quantum channel when assisted by entangled catalysts. For various types of quantum channels our results lead to optimal protocols, allowing to establish the maximal number of singlets with a single use of the channel.

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# Transformations in quantum networks via local operations assisted by finitely many rounds of classical communication

**C. Spee[1] and T. Kraft[1]**

[1]*Institute for Theoretical Physics, University of Innsbruck, Innsbruck, Austria*

Recent advances have led towards first prototypes of a quantum internet in which entanglement is distributed by sources producing bipartite entangled states with high fidelities. This raises the question which states can be generated in quantum networks based on bipartite sources using local operations and classical communication. In this work we study state transformations under finite rounds of local operations and classical communication in networks based on maximally entangled two-qubit states. We first derive the symmetries for arbitrary network structures as these determine which transformations are possible. Then we show that contrary to tree graphs for which it has already been shown that any state within the same entanglement class can be reached there exist states which can be reached probabilistically but not deterministically if the network contains a cycle. Furthermore, we provide a systematic way to determine states which are not reachable in networks consisting of a cycle. Moreover, we provide a complete characterization of the states which can be reached in a cycle network with a protocol where each party measures only once and each step of the protocol results in a deterministic transformation. Finally, we present an example which cannot be reached with such a simple protocol [1].

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# Non-Markovian Quantum Dynamics in Strongly Coupled Multimode Cavities Conditioned on Continuous Measurement

**V. Link[1] , K. Müller[1], R. G. Lena[2], K. Luoma[3], F. Damanet[4], W. T. Strunz[1], and A. J. Daley[2]**

[1]Institut für Theoretische Physik, Technische Universität Dresden, Dresden D-01062, Germany
[2]Department of Physics and SUPA, University of Strathclyde, Glasgow G4 0NG, United Kingdom
[3]Department of Physics and Astronomy, University of Turku, Turku FI-20014, Finland
[4]Department of Physics and CESAM, University of Liège, Liège B-4000, Belgium

An important challenge in non-Markovian open quantum systems is to understand what information we gain from continuous measurement of an output field. For example, atoms in multimode cavity QED systems provide an exciting platform to study many-body phenomena in regimes where the atoms are strongly coupled amongst themselves and with the cavity, but the strong coupling makes it complicated to infer the conditioned state of the atoms from the output light. In this work we address this problem, describing the reduced atomic state via a conditioned hierarchy of equations of motion, which provides an exact conditioned reduced description under monitoring (and continuous feedback). We utilize this formalism to study how different monitoring for modes of a multimode cavity affects our information gain for an atomic state, and to improve spin squeezing via measurement and feedback in a strong coupling regime. This work opens opportunities to understand continuous monitoring of non-Markovian open quantum systems, both on a practical and fundamental level.

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# Radiological image classification using hybrid quantum-classical convolutional neural networks

**A. Matic[1], M. Monnet[1], J. M. Lorenz[1], B. Schachtner[2] and T. Messerer[1]**

[1]*Fraunhofer IKS, Munich, Germany*
[2] *LMU Munich, Department of Radiology, Munich, Germany*

Artificial Intelligence receives widespread attention in the field of medical imaging, in which it can support radiologists in the diagnosis of diseases. In such safety-critical applications it is crucial that the decision process of the applied algorithm is comprehensible and reliable. For this purpose, the training of machine learning algorithms usually requires large training datasets. However, medical image data is complex and often only available in small numbers. Medical image classification could be improved with quantum-computing assisted algorithms: They may result in a faster and more precise training process, especially in situations with little training data.
In a joint project between the Fraunhofer Institute for Cognitive Systems and the hospital of the Ludwig-Maximilians-University Munich, we investigated the performance of hybrid quantum-classical convolutional neural networks for different radiological classification tasks. These include breast cancer identification in 2D ultrasound images and the analysis of 3D computer tomography images to identify malign lesions in the lung. In this contribution we will present the latest results of our studies, in which we tested various data encoding techniques and quantum circuit designs. Furthermore, we compared the performance of these quantum-assisted approaches to fully classical algorithms. The results show a promising performance of hybrid quantum-classical convolutional neural networks, which encourages to perform further studies into this direction in the future.

**Two-mode Gaussian states as resource of secure quantum teleportation in open systems**

**D. Afshar[1], F. Abbasnezhad, S. Mehrabankar and A. Isar[2]**

[1] *Department of Physics, Faculty of Science, Shahid Chamran University of Ahvaz, Ahvaz, Iran*

[2] *Department of Theoretical Physics, National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*

For secure quantum teleportation (SQT) of coherent states two conditions are necessary to be fulfilled: Gaussian-state resources with two-way steering and teleportation fidelity higher than 2/3. We investigate and compare squeezed thermal states and squeezed vacuum states as initial resource states for SQT in an open quantum system, consisting of two uncoupled harmonic oscillators interacting with a thermal environment. The evolution of the open system is obtained in terms of the covariance matrix, by using the Gorini-Kossakowski-Lindblad-Sudarshan master equation [1-3]. The SQT conditions are satisfied in a longer period of time in the case of initial squeezed vacuum states, therefore these states are better resource states for SQT than squeezed thermal states. We show that the admissible time for SQT decreases by increasing temperature, dissipation coefficient and average number of thermal photons, while for greater values of the squeezing parameter, SQT conditions are satisfied in a longer period of time.

*Keywords*: Quantum teleportation, steering, fidelity, open systems, Gaussian states

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# Compatibility of quantum instruments

**Arindam Mitra[1,2] and Máté Farkas[3]**

[1] *Optics and Quantum Information Group, The Institute of Mathematical Sciences, C. I. T. Campus, Taramani, Chennai 600113, India.*
[2] *Homi Bhabha National Institute, Training School Complex, Anushaktinagar, Mumbai 400094, India.*
[3] *ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Spain.*

Incompatibility of quantum devices is a useful resource in various quantum information theoretical tasks, and it is at the heart of some fundamental features of quantum theory. While the incompatibility of measurements and quantum channels is well studied, the incompatibility of quantum instruments has not been explored in much detail. In this work [1], we revise a notion of instrument compatibility that exists in the literature [2,3,4]. We call that notion as traditional compatibility. Then, we introduce the notion of parallel compatibility and show that these two notions are inequivalent [1]. We then argue that the notion of traditional compatibility is conceptually incomplete and prove that, while parallel compatibility captures both measurement and channel compatibility, traditional compatibility captures measurement compatibility, but does not capture channel compatibility [1]. Hence, we propose parallel compatibility as the conceptually complete definition of the compatibility of quantum instruments [1].

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# Electro-optic sampling of quantum fields: back action and weak measurement regime

**T.L.M. Guedes[1], I. Vakulchyk[2,3], D.V. Seletskiy[4], A. Leitenstorfer, A.S. Moskalenko[5] and Guido Burkard[1]**

[1] *Department of Physics and Center for Applied Photonics, University of Konstanz, Konstanz, Germany*
[2] *Center for Theoretical Physics of Complex Systems, Institute for Basic Science (IBS), Republic of Korea*
[3] *Basic Science Program, Korea University of Science and Technology (UST), Daejeon, Republic of Korea*
[4] *Department of Engineering Physics, Polytechnique Montréal, Montréal, Canada*
[5] *Department of Physics, KAIST, Daejeon, Republic of Korea*

Electro-optic sampling of quantum fields has recently been proposed and experimentally implemented as a nonlinearity-based quantum-optical technique. In contrast to the conventionally used homodyne detection, this approach allows for sampling of the quantum statistics of electromagnetic-field states with a true subcycle (below the cycle of optical oscillation) temporal resolution. It enabled measurements of the electric-field fluctuations and its correlations in the electromagnetic vacuum extending over multi-THz (mid-infrared) and THz frequency ranges [1-3]. Further, it can be also applied to track subcycle-resolved quantum statistics of ultrabroadband few-cycle squeezed vacuum states [4]. Until recently one key problem has remained unresolved in the analysis of such measurements: the characterization of the back action of the measurement process on the sampled quantum field and its influence on the detected signals themselves. The possibility to characterize and evade the effect of back action is crucial for future applications of electro-optic sampling in the quantum domain. In our contribution, we develop a nonlinear-quantum-optical theory capable of addressing the intriguing problem of back action in quantum electro-optic sampling and identify the weak-measurement regime when its effect on the detected signals can be effectively evaded [5]. The results might pave the way for the development of future quantum electro-optic sampling schemes with post-selection capabilities, bearing high promises for the ultrafast metrology of quantum fields and ultrafast quantum spectroscopy, studying formation of entanglement, underpinning macroscopic properties of correlated and quantum matter.

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# Entanglement and Coherence in Bernstein-Vazirani Algorithm

**<u>Moein Naseri</u>, Tulja Varun Kondra, Suchetana Goswami, Marco Fellous-Asiani and Alexander Streltsov**

*Center for Quantum Optical Technologies, Center of New Technologies, University of Warsaw, Banacha 2c, 02-097 Warsaw, Poland*

Quantum algorithms allow to outperform their classical counterparts in various tasks, most prominent example being Shor's algorithm for efficient prime factorization on a quantum computer. It is clear that one of the reasons for the speedup is the superposition principle of quantum mechanics, which allows a quantum processor to be in a superposition of different states at the same time. While such superposition can lead to entanglement across different qubits of the processors, there also exists quantum algorithms which outperform classical ones using superpositions of individual qubits without entangling them. As an example, the Bernstein-Vazirani algorithm allows one to determine a bit string encoded into an oracle. While the classical version of the algorithm requires multiple calls of the oracle to learn the bit string, a single query of the oracle is enough in the quantum case. In this Letter, we analyze in detail the quantum resources in the Bernstein-Vazirani algorithm. For this, we introduce and study its probabilistic version, where the goal is to guess the bit string after a single call of the oracle. We show that in the absence of entanglement, the performance of the algorithm is directly related to the amount of quantum coherence in the initial state. We further demonstrate that a large amount of entanglement in the initial state prevents the algorithm from achieving optimal performance. We also apply our methods to quantum computation with mixed states, proving that pseudopure states achieve optimal performance for a given purity in the Bernstein-Vazirani algorithm. We further investigate quantum resources in the one clean qubit model, showing that the model can exhibit speedup over any known classical algorithm even with arbitrary little amount of multipartite entanglement, general quantum correlations, and coherence.

# Nearly optimal separability certification of quantum states

**Ties-Albrecht Ohst[1], Chau Nguyen[1], Otfried Gühne[1] and Xiao-Dong Yu[2]**

*[1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen*
*[2] Department of Physics, Shadong University, Jinan, China*
*E-mail: ties-albrecht.ohst@uni-siegen.de*

Entanglement describes the possibility of local parties sharing a joint global system state that cannot be expressed as a probabilistic mixture of locally prepared states. The question on whether some given state is entangled or separable, on the contrary, is generically difficult to answer.
We present an algorithm for the quantum separability problem for intermediate dimensions with evidence of being nearly optimal. The basic idea of our considerations can in general be described by a systematic search for separable decompositions of a given state by polytope approximations to a local system.
As a benchmark we can compute the separability thresholds for known bound entangled states of two coupled qutrits with an accuracy that has not been achieved before. Also, for bi-partite systems of higher dimension we can certify the separability of states reliably which follows from the comparison with data by known entanglement criteria. For three coupled qubit systems, our ideas allow for an efficient distinction between different separability classes that lie at the heart of the theory of multi-partite entanglement. We developed an algorithm for the search among all fully bi-separable states to find the one whose entanglement robustness is as large as possible. Quite interestingly, the obtained states show a deep connection to the post measurement states in the teleportation protocol. This outcome could raise a connection between entanglement quantification and the shape of post-measurement states for non-local measurements.

# Quantum Coherence as an Entanglement Measure

**Neha Pathania[1] and Tabish Qureshi[2]**

*1Centre for Theoretical Physics, Jamia Millia Islamia, Delhi, India*

*2 Centre for Theoretical Physics, Jamia Millia Islamia, Delhi, India*

Quantifying entanglement is a work in progress which is important for the active field of quantum information and computation. We have proposed a measure of bipartite pure state entanglement named "Entanglement Coherence", which is essentially the normalized coherence of the entangled state in its Schmidt basis. Its value is 1 for maximally entangled states and 0 for separable states, irrespective of the dimensionality of the Hilbert space. So, a maximally entangled state is also the one which is maximally coherent in its Schmidt basis. Quantum Entanglement and Quantum Coherence are thus intimately connected.
We also found out that our measure is closely related to the unified entropy of the reduced state of one of the sub-systems. Additionally, we have shown an interesting relation between entanglement coherence and the Wigner -Yanase skew information of the reduced density operator of one of the subsystems.

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## 1/n expansion of the regularised coherent information of a noisy quantum channel

**Rochus Klesse[1] and Tushita Prasad[2]**

[1]*University of Cologne, Cologne, Germany*
[2]*International Center for Theory of Quantum Technologies ,Gdansk, Poland*

One of the biggest open problems in quantum information theory has been to find an efficient method to evaluate the quantum capacity of a general noisy quantum channel[1]. Computing the quantum capacity entails maximizing coherent information over the input quantum states of the channel $\Lambda^{\otimes n}$[2]. This is an extremely hard problem involving optimization of the coherent information over increasing number of channel uses [3] and no satisfactory solution exists till date. In our work, we consider $n \gg 1$ regime and for certain chosen trial states, we attempt to calculate the regularized coherent information. We finally examine if we can obtain any improvements in the regularized coherent information in the $n \gg 1$ region.

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# Typical measurement bases for state tomography

**Maria Quadeer**

*School of Physical and Mathematical Sciences,*
*Nanyang Technological University, 21 Nanyang Link #04-01, Singapore 637371.*

We are interested in exploring Haar random (typical) measurement bases for state tomography which also arise in the context of ensemble state distinction problem. It has been shown [1] that measuring any two low-rank quantum states in a random orthonormal basis results in two probability distributions that have a total variational distance of at least a universal constant times the Frobenius distance between the two states with high probability. Mutually Unbiased Bases (MUBs) were shown to be optimal for state tomography of large but finite ensembles and a construction for such a maximal set of *d+1* MUBs for prime power dimensions was given in Ref. [2]. Whether such a maximal set exists for non-prime power dimensions is an open question. The smallest example of a non-prime power dimension is 6, and it is not clear if there are more than 4 MUBs in this dimension when the maximal number is 7 [3]. This means that the question of optimal measurements remains open for such dimensions and implies that it is possible that a maximal set of optimal measurements may not be mutually unbiased. We want to estimate density matrices using Monte Carlo sampling to generate global Haar random unitaries (algorithm by Diaconis and Shahshahani as discussed in Ref. [4])—defining typical measurement bases. An estimate/estimator of a quantum state is a function from the set of measurement outcomes to the set of density matrices. We want to use the Bayes estimator since a. it is optimal for Bregman divergences (e.g. relative entropy and Hilbert-Schmidt distance)—minimises the average risk, b. has a closed form expression—is the mean with respect to the posterior distribution given a prior distribution over the set of density matrices, c. it fits an algorithmic framework due to the Bayes update rule, and d. the optimality is independent of the measurement procedure (discussion in Ref. [5]). If we assume that the states come from a finite ensemble, the integral in the Bayes estimate reduces to a finite sum and can be evaluated numerically. This, by definition, constitutes an incoherent/single-shot measurement scheme. With this set-up, we would like to compare Bayes estimates from random orthonormal bases to that of MUBs for smaller prime power dimensions and use that as a benchmark to first explore the smallest non-prime power dimension of 6.

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# Asymmetry-induced nonclassical correlation

**R. Muthuganesan[1] and V. K. Chandrasekar[2]**

[1] *Department of Physics, FNSPE,* Czech Technical University in Prague, Břehová 7, 115 19 Praha 1-Staré Město, *Czech Republic*

[2] *Department of Physics, Centre for Nonlinear Science & Engineering, School of Electrical & Electronics Engineering, SASTRA Deemed University, Thanjavur-613 401, Tamil Nadu, India*

In quantum resource theory (QRT), asymmetry recognized as a valid resource for the advantage of various quantum information processing. We establish the resource theory of asymmetry using quantum Fisher information (QFI). By defining the average Fisher information as a measure of asymmetry, we show that the discrepancy of bipartite global and local asymmetries naturally induces the nonclassical correlation between the subsystems. This measure satisfies all the necessary axioms of a faithful measure of bipartite quantum correlation. As an illustration, we have studied the proposed measure for an arbitrary pure state, a class of separable states and Bell diagonal state.

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# Quantum Frames, Distance Measures and Non-Markovianity

**M.F.Richter[1] and H.-P. Breuer[1]**

[1]*Institute of Physics, University of Freiburg, Freiburg, Germany*

**Quantum Frames, Distance Measures and Non-Markovianity** — ·Moritz Ferdinand Richter and Heinz-Peter Breuer — Institute of Physics, University of Freiburg, Hermann-Herder-Straße 3, D-79104, Germany

Based on Informationally Complete Positive Operator Valued Measures (IC-POVM) the poster will introduce a decomposition of generally mixed quantum states - given by their density operators - in a fixed set of pure quantum states, i.e. rank-one projection operators (quantum frame). This decomposition allows a vector like representation for arbitrary quantum states which can be linearly related to probability distribution generated by the IC-POVM - underlying the quantum frame - applied to quantum states at hand. Both the probability distribution and the quantum frame decomposition can be used to define certain distance measures for quantum states which provide a lower and upper bound for the trace distance between quantum states. Further, we will extend these results to coherent states which are indeed a continuous quantum frame on continuous variable (CV) systems like quantum harmonic oscillators, where decomposition and measurement distributions are given by the celebrated Glauber-Sudarshan-P-function and the Husimi-Q-function, respectively. We also discuss applications of these distances to witness non-Markovianity in CV systems. [1]

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# Estimating the entangling power of a two-qubit gate from measurement data: artificial neural networks and randomized measurements versus standard tomography methods

**Salwa Shaglel**

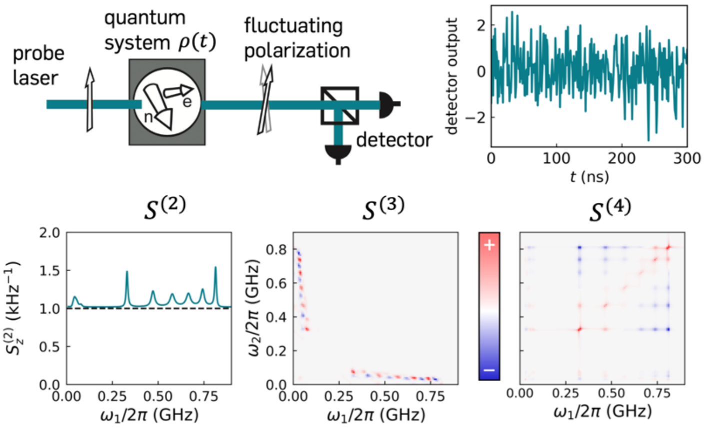
*Universität Siegen, Siegen, Germany*
*Email: salwa.shaglel@student.uni-siegen.de*

Quantum logic gates are the building blocks of quantum circuits and algorithms, where the generation of entanglement is essential to perform quantum computations. The amount of entanglement that a unitary quantum gate can produce from product states can be quantified by the so-called entangling power, which is a function of the gate's unitary or Choi matrix representation. In this thesis, I introduce two efficient approaches to the practical problem of estimating the entangling power of an unknown two-qubit gate from measurement data. The first approach is using a deep neural network trained with noisy data simulating the outcomes of prepare-and-measure experiments on random gates. The training data is restricted to 48 measurement settings, which is significantly less than the 256 dimensions of the ambient space of 16×16 Choi matrices and very close to the minimum number of settings that guarantees the recovery of a two-qubit unitary gate using the compressed sensing technique at an acceptable error rate. The second approach to determine the entangling power is based on the second moments of correlation functions obtained from locally randomized measurements. The two approaches do not make any prior assumptions about the quantum gate, and they also avoid the need for standard reconstruction tools based on full quantum process tomography, which is prone to systematic errors.

# Quantum Polyspectra – Grand Unified Theory of Continuous Quantum Measurements

**M. Sifft[1] and D. Hägele[1]**

[1]*Ruhr University Bochum, Faculty of Physics and Astronomy, Exp. Phy. VI, Germany*
*E-mail: markus.sifft@rub.de*




Quantum polyspectra are introduced as a completely general and uncompromising approach to the evaluation of continuous quantum measurements. Their applications include quantum transport and spin noise spectroscopy (see figure) and bear prospects for circuit quantum electrodynamics, quantum sensing, and quantum measurements in general. Quantum polyspectra (bottom row) are a higher-order generalization of 2nd-order power spectra and can be directly calculated from the stochastic detector output (see figure). They are evaluated via analytic quantum polyspectra that follow rigorously from the stochastic master equation [1]. Automatic fitting of analytic to measured higher-order polyspectra gives access to system parameters. Hence, quantum polyspectra are a most direct link between measurement and theory.

The quantum polyspectra approach can handle coherent quantum dynamics, environmental damping, and measurement backaction covering the limiting cases of weak measurements dominated by Gaussian noise, strong measurements resulting in quantum jumps, and detector clicks of single photon sampling [2]. The quantum polyspectra approach was in the case of quantum transport shown to be a powerful alternative to traditional methods like the full-counting statistics recovering electron tunneling rates and spin relaxation rates even in the presence of strong background noise [3]. Quantum polyspectra thus constitute a general unifying approach to the strong and weak regime of quantum measurements with possible applications in diverse fields as nano-electronics, circuit quantum electrodynamics, spin noise spectroscopy, or quantum optics.

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# Dynamics of non-classical correlations based on quantum uncertainty under decoherence effect

**A. Slaoui**[1,3], M. Daoud[2] and R. Ahl Laamara[1,3]

*1-LPHE-MS, Faculty of Sciences, Mohammed V University of Rabat, Morocco.*
*2-Department of Physics, Faculty of Sciences, University Hassan II, Casablanca, Morocco.*
*3-Centre of Physics and Mathematics (CPM), CNESTEN, Rabat, Morocco.*

*abdallah.slaoui@um5s.net.ma*

We employ the concepts of local quantum uncertainty and geometric quantum discord based on the trace norm to investigate the environmental effects on quantum correlations of two bipartite quantum systems. The first one concerns a two-qubit system coupled with two independent bosonic reservoirs. We show that the trace discord exhibits frozen phenomenon contrarily to local quantum uncertainty. The second scenario deals with a two-level system, initially prepared in a separable state, interacting with a quantized electromagnetic radiation. Our results show that there exists an exchange of quantum correlations between the two-level system and its surrounding which is responsible for the revival phenomenon of non-classical correlations.

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# Measurement disturbance tradeoffs in unsupervised quantum classification

**H. Spencer-Wood[1], J. Jeffers[2] and S. Croke[1]**

*[1]University of Glasgow, Glasgow, Scotland*
*[2] University of Strathclyde, Glasgow, Scotland*
*Email: h.spencer-wood.1@research.gla.ac.uk*

We consider measurement disturbance tradeoffs in quantum machine learning protocols which seek to learn about quantum data. We study the simplest example of a binary classification task, in the unsupervised regime. Specifically, we investigate how a classification of two qubits, that can each be in one of two unknown states, affects our ability to perform a subsequent classification on three qubits when a third is added. Surprisingly, we find a range of strategies in which a non-trivial first classification does not affect the success rate of the second classification. There is, however, a non-trivial measurement disturbance tradeoff between the success rate of the first and second classifications, and we fully characterise this tradeoff analytically.

# Theory of entanglement and measurement in high harmonic generation

**P. Stammer**[1]

[1]*ICFO, Barcelona, Spain*

Quantum information science and intense laser matter interaction are two apparently unrelated fields. However, the recent developments of the quantum optical description of the intense laser driven process of high harmonic generation allow to conceive new light engineering protocols [1,2]. Here, we introduce the notion of quantum information theory to intense laser driven processes by providing the quantum mechanical description of measurement protocols for high harmonic generation in atoms [3]. We explicitly evaluate conditioning experiments on individual optical field modes, and provide the corresponding quantum operation for coherent states. The associated positive operator-valued measures are obtained, and give rise to the quantum theory of measurement for the generation of high dimensional entangled states, and coherent state superposition with controllable non-classical features on the attosecond timescale.

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# Optimizing shadow tomography with generalized measurements

**H. C. Nguyen[1], J. L. Bönsel[1], J. Steinberg[1] and O. Gühne[1]**

*[1]Naturwissenschaftlich–Technische Fakultät, Universität Siegen*
*E-mail: steinberg@physik.uni-siegen.de*

Advances in quantum technology require scalable techniques to efficiently extract information from a quantum system, such as expectation values of observables or its entropy. Traditional tomography is limited to a handful of qubits and shadow tomography has been suggested as a scalable replacement for larger systems. Shadow tomography is conventionally analyzed based on outcomes of ideal projective measurements on the system upon application of randomized unitaries. Here, we suggest that shadow tomography can be much more straightforwardly formulated for generalized measurements, or positive operator valued measures. Based on the idea of the least-square estimator, shadow tomography with generalized measurements is both more general and simpler than the traditional formulation with randomization of unitaries. In particular, this formulation allows us to analyze theoretical aspects of shadow tomography in detail. For example, we provide a detailed study of the implication of symmetries in shadow tomography. Shadow tomography with generalized measurements is also indispensable in realistic implementation of quantum mechanical measurements, when noise is unavoidable. Moreover, we also demonstrate how the optimization of measurements for shadow tomography tailored toward a particular set of observables can be carried out.

# Labeling of quantum observables and process measurements

Nidhin Sudarsanan Ragini, Sk Sazim, Michal Sedlák, Mário Ziman

*Institute of Physics, Slovak Academy of Sciences, Dúbravská cesta 9, Bratislava 84511, Slovakia*

We identify a particular class of discrimination problems for observables (positive operator-valued measures), in which observables with identical range but permuted effects are involved, as the labeling problem for these observables. Consequently, we identify the set of observables those can be "labeled" perfectly and, study the minimum-error scenario as well as the unambiguous scenario for labeling. This notion is extended and studied for process POVMs [1,2,3], objects that can be considered as generalized versions of observables, which describe test procedures for testing quantum channels with one time step.

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# Reverse processes and state retrieval beyond Bayes' retrodiction


## Jacopo Surace and Matteo Scandi

*ICFO - Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, Castelldefels (Barcelona), 08860, Spain*



Reversible operations of a physical system are bijective mapping between input and outputs. They are called reversible for a well defined notion of reverse operation exists: it consists in the inversion of the direction of the element-wise mapping from the space of the outputs to the space of inputs. In quantum mechanics reversible operations are given by unitary operations, while for classical stochastic processes these are permutations. Whenever the bijectivity between the space of inputs and outputs is lost, the standard definition of reverse operation does no longer apply and one is forced defining a notion of generalised reversion. In general, associating to a physical process its intuitive reverse can result to be a quite ambiguous task. It is a standard choice to define the reverse process using Bayes' theorem, but, in general, this choice is not optimal. In this work we explore whether it is possible to characterise an optimal reverse map building from the concept of state retrieval maps. In doing so, we propose a set of principles that state retrieval maps should satisfy. We find out that the Bayes inspired reverse is just one case in a whole class of possible choices, which can be optimised to give a map retrieving the initial state more precisely than the Bayes rule. Our analysis has the advantage of naturally extending to the quantum regime. In fact, we find a class of reverse transformations containing the Petz recovery map as a particular case, corroborating its interpretation as quantum analogue of the Bayes retrieval. Finally, we present numerical evidences that by adding a single extra axiom one can isolate the usual reverse process derived from Bayes' theorem.


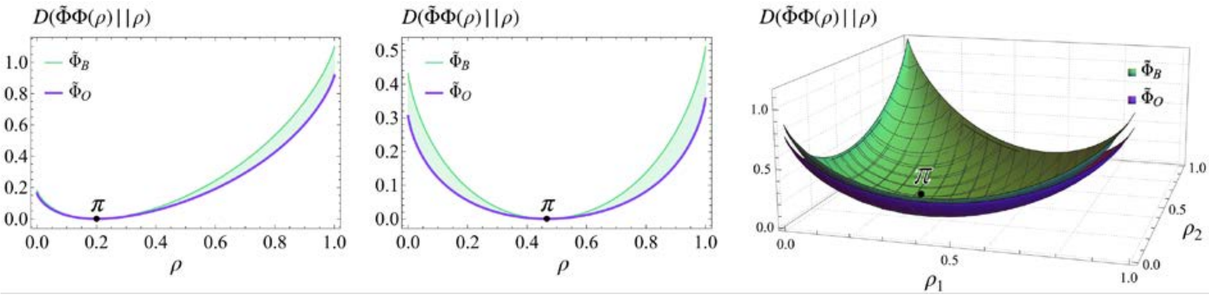


Figure 1. Relative entropy between a distribution and its evolution forwards and backwards. In the first two plots we consider probability vectors $\rho = [\rho, 1 - \rho]$ of length two, while in the third plot we consider probability vectors $\rho = [\rho_1, \rho_2, 1 - \rho_1 - \rho_2]$ of length three. In all of the plots the map $\Phi$ and the prior distribution $\pi$ are chosen at random. As it can be seen, the optimal map $\Phi_O$ outperforms the Bayes retrodiction $\Phi_B$ in retrieving the original distribution in the whole space.

The pre-print of the work can be found at https://arxiv.org/abs/2201.09899.

# Entanglement detection with arbitrary observables

**K. Szymański**[1]

[1] *Universität Siegen, Siegen, Germany*

Here I show a novel way of constructing certified entanglement and Schmidt rank witnesses from any multipartite observable, based on the geometric properties of the set of density operators. Most important here is the structure of projections of the set of quantum states (called the numerical ranges). Given any Hermitian operator X acting on a qubit-qudit system, maximal and minimal expectation values of X among separable states are determined from a particular 4-dimensional projection defined by X. This procedure is then recursively extended to the case of multiple qubits. This case has found use in the numerical analysis of random observables. Schmidt rank witnesses of bipartite system are constructed similarly, with projections of the set of separable states serving as the basis of calculation.

# Operational Characterisation of Quantum Memory Effects via Multi-Time Probing Schemes

**P. Taranto**[1]

[1]*Atominstitut, Technische Universität Wien, 1020 Vienna, Austria*

Understanding complex processes and their correlations in time is of paramount importance for the development of near-term technologies that operate under realistic conditions. Capturing the complete multi-time statistics defining a stochastic process lies at the heart of any proper treatment of memory effects. This is well-understood in classical theory, where a single (multi-time) joint probability distribution completely characterizes a process at hand. However, attempting to generalise this notion to quantum mechanics is problematic: due to measurement invasiveness, observing realisations of a quantum process is necessarily disturbing, breaking and implicit – and crucial – assumption of the classical setting. This special role of the measurement in quantum mechanics has led to a plethora of different (and inconsistent) definitions of memory properties of quantum processes. Importantly, the problem at hand here is one of formalism rather than anything fundamental: it can be circumvented by separating experimental interventions from the underlying process, enabling an unambiguous definition of the process itself and allowing for a consistent description of quantum stochastic processes in the presence of measurement invasiveness. In this contribution, I will demonstrate how taking such an operational perspective can provide a clear understanding of the length [1], structure [2], and strength [3] of (multi-time) memory effects in complex open quantum processes [4]. In particular, the contribution will focus on the dependence of these properties on the types of measurements that are performed, and will lay out that such dependence – while predominately genuine to the quantum case – is, at its hear, a direct consequence of measurement invasiveness and therefore also present in generalisations of classical physics and potential post-quantum theories.

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# Distance-based resource quantification for sets of quantum measurements

**<u>L. Tendick</u>[1], M. Kliesch[1], H. Kampermann[1], and D. Bruß[1]**

[1] *Institute for Theoretical Physics at Heinrich Heine University Düsseldorf, Düsseldorf, Germany*

The advantage that quantum systems provide for certain quantum information processing tasks over their classical counterparts can be quantified within the general framework of resource theories. Certain distance functions between quantum states have successfully been used to quantify resources like entanglement and coherence. Perhaps surprisingly, such a distance-based approach has not been adopted to study resources of quantum measurements, where other geometric quantifiers are used instead. Here, we define distance functions between sets of quantum measurements and show that they naturally induce resource monotones for convex resource theories of measurements. By focusing on a distance based on the diamond norm, we establish a hierarchy of measurement resources and derive analytical bounds on the incompatibility of any set of measurements. We show that these bounds are tight for certain projective measurements based on mutually unbiased bases and identify scenarios where different measurement resources attain the same value when quantified by our resource monotone. Our results provide a general framework to compare distance-based resources for sets of measurements and allow us to obtain limitations on Bell-type experiments.

# The Classical Limit

**Reinhard F. Werner** [1], **Lauritz van Luijk**[1] **and Alexander Stottmeister**[1]

[1] *Leibniz Universität Hannover, Institut für Theoretische Physik, Hanover, Germany*

The problem of understanding the classical limit of quantum theory is as old as the theory itself. A rigorous approach to the classical limit based on inductive systems of operator algebras is presented. For $\hbar$-dependent observables (resp. states) we define a notion of “convergence in the classical limit” and give a definition of the classical limit, which is a function (resp. probability measure) on phase space. Convergence is in norm in the sense that observables (or states) that are equal up to an error that vanishes in norm as $\hbar \to 0$ have the same limit. A product of convergent observables converges to the product of functions on phase space and $(i/\hbar)$ times a commutator of convergent observables converges to the Poisson bracket.

For a large class of unbounded Hamiltonians, we show that the $\hbar$-wise applied quantum dynamics preserves convergence convergent observables and states and that the classical limit the classical Hamiltonian dynamics of the limits [2]. We consider the classical limit of instruments and make precise the intuition that “near” the classical limit measurement becomes possible with arbitrarily small disturbance of the system [2]. By alternating between phase space measurements and dynamics, it follows that for small $\hbar$ the measured “path” is already close to the path of the classical limit which follows the classical Hamiltonian dynamics.

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# Entropic Uncertainty Relations and the Quantum-to-Classical transition

**I. Veeren[1] and F. de Melo[1]**

*[1]Centro Brasileiro de Pesquisas Físicas,*
*Rua Dr. Xavier Sigaud 150, Rio de Janeiro, Rj, Brazil*

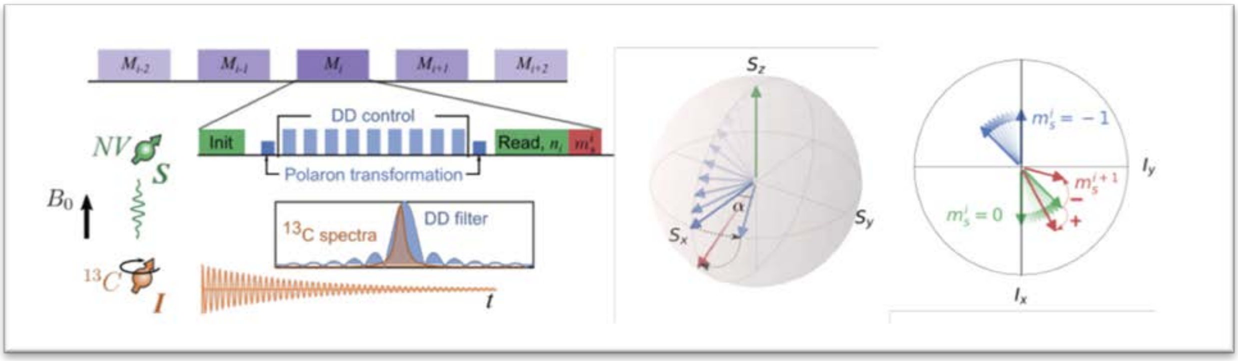
Our knowledge of quantum mechanics can satisfactorily describe simple, microscopic systems, but is yet to explain the macroscopic everyday phenomena we observe. Here we aim to shed some light on the quantum-to-classical transition as seen through the analysis of uncertainty relations. We employ entropic uncertainty relations to show that it is only by the inclusion of imprecision in our model of macroscopic measurements that we can prepare a system with two simultaneously well-defined quantities, even if their associated observables do not commute. We also establish how the precision of measurements must increase in order to keep quantum properties, a desirable feature for large quantum computers.

## On measurement efficiency in a room temperature weak measurement apparatus based on single NV center in diamond with weakly coupled nuclear spin

**Vadim Vorobyov**, Jörg Wrachtrup

3rd Physical Institute, University of Stuttgart, Germany

Mesoscopic quantum detectors amplify weak signatures of quantum objects signals to a readable macroscopic value, capable of overcoming thermal noise and being robustly detected [1]. A quantum limited detector imposes no additional technical noise on top of the amplified signal, apart form the fundamental noise, given by the quantum mechanical laws. In this work we analyse on the example of the single electron spin in diamond, how this scenario applies to a realistic weak measurement setting of a weakly coupled nuclear spin. The nuclear spin is sequentially weakly probed with electron spin, which is then readout with a single shot technique [2]. The decay of the nuclear spin state additional to the quantum backaction is extracted, as well as the information gained from the measurement. The result shows an 50% quantum efficiency of the detection in the optimal scenario [3].

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# Average waiting times for entanglement links in multiplexed quantum networks

**L. Weinbrenner[1], L. Vandré[1] and O. Gühne[1]**

[1]*University of Siegen, Siegen, Germany*

In quantum communication protocols using noisy channels, the error probability typically scales exponentially with the length of the channel. To reach long-distance entanglement distribution, one can use quantum repeaters. These schemes involve first a generation of elementary bipartite entanglement links between two nodes and then measurements to combine the elementary links to a long-distance link.

Since the generation of an elementary link is probabilistic and quantum memories have a limited storage time, the generation of a long-distance link is probabilistic, too [1]. One possibility to speed up the generation of a long-distance link is a multiplexed system, in which there is more than one elementary link between two nodes [2]. In this contribution, we will present estimates and bounds on waiting times in such a system. Our results rely on an analytical treatment of the underlying stochastic process, as well as numerical investigations using the matrix product state formalism.

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# Detecting bound entanglement using randomized measurements in two-qudit systems

**N. Wyderka[1], A. Ketterer[2], S. Imai[3] and O. Gühne[3]**

[1]*Institut für Theoretische Physik III, Heinrich-Heine-Universität, Universitätsstr. 1, D-40225 Düsseldorf*
[2] *Fraunhofer Institute for Applied Solid States Physics IAF, Tullastr. 72, D-79108, Freiburg*
[3] *Department Physik, Universität Siegen, Walter-Flex-Str. 3, D-57068 Siegen*

Characterization of qubit systems using random local measurement settings has recently received increasing attention, as it allows for detection of entanglement even when no shared reference frame or a good characterization of the measurement devices is available.
Here, we extend this framework to the setting of d by d-dimensional systems by establishing a correspondence between the moments of the distribution of random measurement results and the singular values of the correlation matrix of the state. Furthermore, we characterize the set of separable states in the landscape of the first two non-vanishing moments of the distributions, where we show that a wide range of entangled states, including weakly entangled states with positive partial transpose, are detectable.

# Quantum state-independent certification

**Zhen-Peng Xu[1], Debashis Saha[2, 3], Kishor Bharti[4, 5] and Adán Cabello[6,7]**

*[1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany*
*[2]S. N. Bose National Centre for Basic Sciences,Block JD, Sector III, Salt Lake, Kolkata 700098, India*
*[3]Center for Theoretical Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warsaw, Poland*
*[4]Centre for Quantum Technologies, National University of Singapore*
*[5]Joint Center for Quantum Information and Computer Science and Joint Quantum Institute, NIST/University of Maryland, College Park, Maryland 20742, USA*
*[6]Departamento de Física Aplicada II, Universidad de Sevilla, E-41012 Sevilla, Spain*
*[7]Instituto Carlos I de Física Teórica y Computacional, Universidad de Sevilla, E-41012 Sevilla, Spain*

Here, we address the problem of certifying quantum measurements using sources of which all we know is that they produce full-rank states (e.g., thermal states and maximally mixed states). Standard quantum self-testing methods cannot be applied to this problem as they require states producing boundary points in the set of quantum correlations. However, we show that some state-independent contextuality (SI-C) sets of measurements, which reveal contextuality for any initial quantum state, are unique up to isometries and can be certified from the statistics of experiments with sequential measurements on arbitrary states of full rank.We show that this “full-rank state-independent certification” (FRSIC) is possible in any finite dimension $d \geq 3$ and is robust against experimental imperfections. We also prove that a necessary and sufficient condition for Bell self-testing some SI-C sets is that they can be certified via FRSIC. This connects Bell self-testing and certification methods with sequential measurements and leads to a unified framework for certifying quantum systems with minimal assumptions.

# Process estimation in the presence of time-invariant memory effects

**Tomáš Rybár and Mário Ziman**

*RCQI, Institute of Physics, Slovak Academy of Sciences,*
*Dúbravská cesta 9 84511 Bratislava, Slovakia*

Any repeated use of a fixed experimental instrument is subject to memory effects. We design an estimation method uncovering the details of the underlying interaction between the system and the internal memory without having any experimental access to memory degrees of freedom. In such case, by definition, any memoryless quantum process tomography (QPT) fails because the observed data sequences do not satisfy the elementary condition of statistical independence. However, we show that the randomness implemented in certain QPT schemes is sufficient to guarantee the emergence of observable "statistical" patterns containing complete information on the memory channels. We demonstrate the algorithm in detail for the case of qubit memory channels with two-dimensional memory. Interestingly, we find that for the arbitrary estimation method, the memory channels generated by controlled unitary interactions are indistinguishable from memoryless unitary channels.