# Symposium Quantum Correlations Beyond Entanglement (SYQE)

jointly organized by
the Quantum Optics and Photonics Division (Q) and
the Theoretical and Mathematical Physics Division (MP)

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Quantum correlations in composite systems can entail non-classical behaviour, without necessarily involving entanglement. Recently, the analysis of this phenomenon has found a lot of interest, both theoretically and experimentally. It concerns fundamental properties of quantum states, and questions about the role of quantumness as resource for quantum information processing, such as quantum algorithms, quantum communication, and precision measurements.

## Overview of Invited Talks and Sessions

(Lecture rooms: Audimax and Kinosaal)

### Invited Talks

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| SYQE 1.1 | Tue | 14:00–14:30 | Audimax | **The role of quantum discord in quantum information theory** — •Alexander Streltsov |
| SYQE 1.2 | Tue | 14:30–15:00 | Audimax | **Experimental entanglement distribution by separable states** — •Roman Schnabel, C.E. Vollmer, D. Schulze, T. Eberle, V. Händchen, J. Fiurasek |
| SYQE 1.3 | Tue | 15:00–15:30 | Audimax | **Quantum computing with black-box quantum subroutines** — Jayne Thompson, Mile Gu, •Kavan Modi, Vlatko Vedral |
| SYQE 1.4 | Tue | 15:30–16:00 | Audimax | **Quantum metrology embraced for the worst** — •Gerardo Adesso |
| SYQE 2.1 | Tue | 16:30–17:00 | Kinosaal | **The arrow of time and correlations in quantum physics** — •Vlatko Vedral |
| SYQE 2.2 | Tue | 17:00–17:30 | Kinosaal | **Quantum correlations on indefinite causal structures** — •Caslav Brukner |
| SYQE 2.3 | Tue | 17:30–18:00 | Kinosaal | **Zero-error classical channel capacity and simulation cost assisted by quantum non-signalling correlations** — •Andreas Winter |
| SYQE 2.4 | Tue | 18:00–18:30 | Kinosaal | **The quantum marginal problem** — •Matthias Christandl |

### Sessions

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| SYQE 1.1–1.4 | Tue | 14:00–16:00 | Audimax | **Quantum Correlations Beyond Entanglement I** |
| SYQE 2.1–2.4 | Tue | 16:30–18:30 | Kinosaal | **Quantum Correlations Beyond Entanglement II** |

## SYQE 1: Quantum Correlations Beyond Entanglement I

Time: Tuesday 14:00–16:00 Location: Audimax

**Invited Talk** SYQE 1.1 Tue 14:00 Audimax
**The role of quantum discord in quantum information theory** — •Alexander Streltsov — ICFO - The Institute of Photonic Sciences, Castelldefels, Spain

Quantum correlations beyond entanglement - in particular represented by quantum discord - have become a major research field in the last few years. In this talk we report on the role of quantum discord in several fundamental tasks in quantum information theory. Starting with the role of quantum discord in the quantum measurement process, we will also discuss its role in the tasks of information sharing and entanglement distribution. Finally, we will also show the limits of these results and present possible ways to go beyond these limits.

**Invited Talk** SYQE 1.2 Tue 14:30 Audimax
**Experimental entanglement distribution by separable states** — •Roman Schnabel[1], C.E. Vollmer[1], D. Schulze[1], T. Eberle[1], V. Händchen[1], and J. Fiurasek[2] — [1]Institut für Gravitationsphysik (Albert-Einstein-Institut), Leibniz Universität Hannover — [2]Department of Optics, Palacky University, Olomouc, Czech Republic

Distribution of entanglement between macroscopically separated parties is crucial for future quantum information networks. Surprisingly, it has been theoretically shown [1,2] that two distant systems can be entangled by sending a third system that is not entangled with either of them. Here, we experimentally distribute entanglement and successfully prove that our transmitted light beam is indeed not entangled with the parties' local systems. Our work [3], as well as related work by other groups [4,5], demonstrates an unexpected variant of entanglement distribution [6] and improves the understanding necessary to engineer multipartite quantum networks in noisy environments.

[1] T. S. Cubitt, F. Verstraete, W. Dür, J. I. Cirac, Phys. Rev. Lett. 91, 037902 (2003).

[2] L. Mista, N. Korolkova, Phys. Rev. A 77, 050302 (2008).

[3] C. E. Vollmer, D. Schulze, T. Eberle, V. Händchen, J. Fiurasek, R. Schnabel, Phys. Rev. Lett. 111, 230505 (2013).

[4] A. Fedrizzi, M. Zuppardo, G. G. Gillett, M. A. Broome, M. de Almeida, M. Paternostro, A. G. White, T. Paterek, Phys. Rev. Lett. 111, 230504 (2013).

[5] C. Peuntinger, V. Chille, L. Mista, N. Korolkova, M. Förtsch, J. Korger, C. Marquardt, G. Leuchs, Phys. Rev. Lett. 111, 230506 (2013).

[6] C. Silberhorn, Viewpoint: Sharing Entanglement without Sending It, Physics 6, 132 (2013).

**Invited Talk** SYQE 1.3 Tue 15:00 Audimax
**Quantum computing with black-box quantum subroutines** — Jayne Thompson[1], Mile Gu[2,1], •Kavan Modi[3], and Vlatko Vedral[4,1,5] — [1]Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, 117543 Singapore, Singapore — [2]Center for Quantum Information, Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing, China — [3]School of Physics, Monash University, Clayton, Victoria 3800, Australia — [4]Department of Physics, University of Oxford, Clarendon Laboratory, Oxford, OX1 3PU, United Kingdom — [5]Department of Physics, National University of Singapore, 2 Science Drive 3, 117551 Singapore, Singapore

In classical computation a subroutine is treated as a black box and we do not need to know its exact physical implementation to use it. A complex problem can be decomposed into smaller problems using such modularity. We show that quantum mechanically applying an unknown quantum process as a subroutine is impossible, and this restricts computation models such as DQC1 from operating on unknown inputs. We present a method to avoid this situation for certain computational problems and apply to a modular version of Shor's factoring algorithm. We examine how quantum entanglement and discord fare in this implementation. In this way we are able to study the role of discord in Shor's factoring algorithm.

**Invited Talk** SYQE 1.4 Tue 15:30 Audimax
**Quantum metrology embraced for the worst** — •Gerardo Adesso — School of Mathematical Sciences, University of Nottingham, Nottingham NG7 2RD (UK)

Quantum metrology exploits quantum mechanical laws to improve the precision in estimating technologically relevant parameters such as phase, frequency, or magnetic fields. Probe states are usually tailored on the particular dynamics whose parameters are being estimated. Here we consider a novel framework where quantum estimation is performed in an interferometric configuration, using bipartite probe states prepared without full knowledge of the generating Hamiltonian. We introduce a figure of merit for the scheme, given by the worst case precision over a suitable class of Hamiltonians, and prove that it amounts exactly to a measure of quantum discord for the input probe. We demonstrate the superiority of discordant probes over classically correlated ones in a highly controllable metrology experiment with room temperature nuclear magnetic resonance, one of the paradigmatic testbeds for quantum information processing. We thus provide a rigorous operational interpretation of discord, shedding light on its potential for quantum technology.

## SYQE 2: Quantum Correlations Beyond Entanglement II

Time: Tuesday 16:30–18:30 Location: Kinosaal

**Invited Talk** SYQE 2.1 Tue 16:30 Kinosaal
**The arrow of time and correlations in quantum physics** — •Vlatko Vedral — University of Oxford — National University of Singapore

We discuss the arrow of time in terms of the increase of correlations between the system and its environment. Here we show that the existence of the arrow of time, based on deleting correlations, requires a strict absence of initial correlation between the system and the environment. We discuss our work in relation to other approaches addressing the same problem of entropy increase and emphasize similarities and differences. In particular, we comment on the link between initial correlations between the system and the environment and the resulting non complete positivity of the reduced state evolution.

**Invited Talk** SYQE 2.2 Tue 17:00 Kinosaal
**Quantum correlations on indefinite causal structures** — •Caslav Brukner — Faculty of Physics, University of Vienna, Austria — Institute for Quantum Optics and Quantum Infromation, Austrian Academy of Sciences, Austria

In quantum physics it is standardly assumed that the background time or definite causal structure exists such that every operation is either in the future, in the past or space-like separated from any other operation. I will present a framework that assumes that operations in local laboratories are described by quantum theory (i.e. are completely-positive maps), but where no reference is made to any causal relations between the operations in the laboratories. Remarkably, the framework allows for correlations that are not causally ordered (i.e. one cannot say that one operations is before or after the other), as demonstrated by the violation of "causal inequality". I will show that the violation of the inequality is upper bounded by a bound (analogous to the "Tsirelson's bound") that is lower than what is algebraically possible and discuss interferometric experiments involving "superpositions of quantum circuits with definite causal structures".

**Invited Talk** SYQE 2.3 Tue 17:30 Kinosaal
**Zero-error classical channel capacity and simulation cost assisted by quantum non-signalling correlations** — •Andreas Winter — Universitat Autonoma de Barcelona

We describe quantum non-signalling correlations as two-input and two-output completely positive and trace preserving maps with linear constraints determining non-signalling. We then study the one-shot zero-error classical capacity of a quantum channel assisted by quantum non-

signalling correlations, and the reverse problem of simulation. Both lead to simple semidefinite programmings (SDPs) whose solutions can be given in terms of the conditional min-entropies and depend only on the Kraus operator space of the channel. In particular, we show that the asymptotic zero-error classical simulation cost is precisely the conditional min-entropy of the Choi-Jamiolkowski matrix of the given channel. The asymptotic zero-error classical capacity is given by the regularization of a sequence of SDPs, and generally has no simple form. Interestingly, for the class of classical-quantum channels, we show that the asymptotic capacity is reduced to the solution of a rather simple SDP, which coincides with a quantum version of the fractional packing number suggested by Aram Harrow. This further gives an operational interpretation of the celebrated Lovasz number of a classical graph as the zero-error classical capacity of the graph assisted by quantum non-signalling correlations.

**Invited Talk** SYQE 2.4 Tue 18:00 Kinosaal
**The quantum marginal problem** — •Matthias Christandl — ETH Zurich

Given a set of local density matrices, are they compatible? That is, could they arise from a joint global state? This question is known as the quantum marginal problem and is of importance in many aspects of quantum theory ranging from quantum chemistry (here known as the N-representability problem) to quantum information theory. In this talk, I will give an overview over recent progress on this problem and highlight some unexpected relations of this problem to the representation theory of the symmetric group and of Lie groups as well as the P versus NP conjecture of computational complexity.