

90 Years of Einstein- Podolsky-Rosen Paradox: Foundations and Applications

851. WE-Heraeus-Seminar

07 – 10 April 2026

at the Physikzentrum Bad Honnef, Germany

**WILHELM UND ELSE
HERAEUS-STIFTUNG**



Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see <https://www.we-heraeus-stiftung.de>

Aims and scope of the 851. WE-Heraeus-Seminar:

The Einstein-Podolsky-Rosen (EPR) paradox, introduced in 1935, challenged the completeness of quantum mechanics and reshaped our understanding of reality and nonlocality. It inspired key breakthroughs in the field, including Schrödinger's concept of entanglement and Bell's theorem, which proved the incompatibility of quantum mechanics with both realism and locality.

Today, the EPR argument remains a cornerstone of quantum information science. As we celebrate the first 90 years of EPR, this seminar will examine the paradox from both theoretical and experimental perspectives, covering topics such as quantum correlations, entanglement, Bell nonlocality, and quantum measurement theory. It will also highlight the paradox's role in emerging quantum technologies, including quantum cryptography, secure communication, and metrology.

In addition to scientific discussions, the seminar will reflect on the historical and philosophical impact of the EPR argument, as well as experimental breakthroughs such as using EPR correlations for benchmarking quantum devices and ensuring high-security quantum key distribution.

This seminar will bring together leading experts, early-career researchers, and PhD students to explore the foundational significance, recent developments, and future directions of the EPR paradox. By fostering scientific exchange between senior and junior researchers, the event aims to inspire new research directions and collaborations. Contributed talks and poster sessions will provide a platform for young scientists to engage with leading experts, ensuring a dynamic and productive exchange of ideas.

Scientific Organizers:

Dr. Roope Uola

Uppsala University, Sweden

E-mail: roope.uola@physics.uu.se

Dr. Martin Renner

ICFO Barcelona, Spain

E-mail: martin.renner@icfo.eu

Dr. Ramona Wolf

Universität Siegen, Germany

E-mail: ramona.wolf@uibk.ac.at

Introduction

Administrative Organization:

Dr. Stefan Jorda
Elisabeth Nowotka

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

Phone +49 6181 92325-12
Fax +49 6181 92325-15
E-mail nowotka@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:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Tuesday (16:00 h – 21:00 h) and Wednesday
morning

Program

Program

Tuesday, 07 April 2026

16:00 – 20:00	Registration	
18:00	<i>BUFFET SUPPER and informal get-together</i>	
19:15 - 19:30	Scientific organizers	Welcome words
19:30 – 20:30	Christoph Lehner	The tangled tale of entanglement: New discoveries from Schrödinger's research notes
20:30	Discussions	

Wednesday, 08 April 2026

08:00	<i>BREAKFAST</i>	
08:50 – 09:00	Scientific organizers	Organizational information
09:00 – 09:45	Howard Wiseman	Jumping from EPR to Steering, and unfolding from Bohr to Discord: a history of asymmetric nonlocality
09:45 – 10:30	Marco Túlio Quintino	Understanding the relationship between measurement incompatibility, EPR steering, and Bell nonlocality
10:30 – 11:00	<i>COFFEE BREAK</i>	
11:00 – 11:45	Dagmar Bruß	Characterising entanglement and separability
11:45 – 12:30	Glauca Murta	High-dimensional advantages in quantum key distribution
12:30 – 14:00	<i>LUNCH</i>	

Program

Wednesday, 08 April 2026

14:45 – 15:30	Mehul Malik	Overcoming loss in Steering and Bell scenarios with high-dimensional entanglement
15:30 – 16:00	Nicola D'Alessandro	Block moment-matrix relaxations for constrained quantum correlations
16:00 – 16:30	<i>COFFEE BREAK</i>	
16:30 – 18:00	Poster session 1	
18:00	<i>DINNER</i>	
20:15	Discussions	

Program

Thursday, 09 April 2026

08:00	<i>BREAKFAST</i>	
09:00 – 09:45	Margaret Reid	The Einstein-Podolsky-Rosen paradox and weak elements of reality in a Q-based, objective-field interpretation of quantum mechanics
09:45 – 10:30	Pavel Sekatski	Detecting entanglement with minimal assumptions
10:30 – 11:00	<i>COFFEE BREAK</i>	
11:00 – 11:45	Otfried Gühne	Quantifying quantum correlations from the geometric perspective
11:45 – 12:30	Armin Tavakoli	Classical models for quantum theory
12:30 – 14:00	<i>LUNCH</i>	
15:45 – 15:30	Ana Costa	EPR and the notion of quantum irre realism
15:30 – 16:15	Adrian Kent	Could EPR yet be (partly) right?
16:15 – 16:45	<i>COFFEE BREAK</i>	
16:45 – 18:00	Poster session 2	
18:00	<i>HERAEUS DINNER</i> (social event with cold & warm buffet with complimentary drinks)	
20:15	Discussions	

Program

Friday, 10 April 2026

08:00	<i>BREAKFAST</i>	
09:00 – 09:45	Paul Skrzypczyk	Post-quantum steering
09:45 – 10:30	Ana Belén Sainz	Einstein-Podolsky-Rosen steering beyond quantum theory
10:30 – 11:00	<i>COFFEE BREAK</i>	
11:00 – 11:45	Eric Chitambar	Local models for quantum steering: from two parties to networks
11:45 – 12:30	Andreas Bluhm	Factorization of multimeters: a unified view on nonclassical quantum phenomena
12:30 – 12:45	Scientific organizers	Closing words
12:45	<i>LUNCH</i>	

End of the seminar and departure

NO DINNER for participants leaving on Saturday; however, a self-service breakfast will be provided on Saturday morning

Posters

Posters

Damiano Aliverti	Can we define correlation among identical particles?
Ida Åsljung	Testing entanglement in Higgs to ZZ^* decays at colliders
Gustavo Balvedi Pimentel	Optimal variant of a noncontextuality inequality for experimental implementations
Stefan Bäuml	Network quantum random number generation via entropy accumulation
Alexander Bernal	Operationally classical simulation of quantum states
Pawel Blasiak	Identical particles as a genuine non-local resource
Yasmin Bougammoura	Machine learning methods for entanglement detection in high-dimensional systems.
Polina Chernyshova	The hardest prior for state discrimination.
Gabriele Cobucci	Maximally non-projective measurements are not always symmetric informationally complete
Sophia Denker	Genuine multipartite high-dimensional entanglement and the partition rank
Sébastien Designolle	Most incompatible measurements and sum-of-squares optimisation
Ritu Dhaulakhandi	Security analysis for steering-based one-sided device-independent QKD
Lionel Jeevan Dmello	Probabilistic theories stable under teleportation
Maike Drieb-Schön	Bundling of bipartite entanglement

Posters

- Peter Drummond **Using EPR's logic to identify the element of reality of a homodyne measurement**
- Sophie Egelhaaf **Certifying components of quantum networks using the generalised Choi isomorphism**
- Adam Fredriksson **Generalization of the Schmidt sphere to qutrit-pairs and geometric two-qutrit Schmidt gates**
- Bohnishikha Ghosh **Towards parallel bell tests using high dimensional entanglement**
- Khanh Uyen Giang **Average-case certification of quantum gates via learning-assisted quantum system quizzing**
- Dmitry Grinko **Compatibility of binary qubit measurements**
- Jonas Hawellek **Entanglement-assisted communication: Bridging theory and practical application**
- Flavien Hirsch **Escaping bell: fight, flight, or freeze**
- Matty Hoban **Activation of postquantum steering**
- Joel Huber **Generalized dynamics in phase space: Quantum states require quantum time evolution**
- Pauli Jokinen **Generalised contextuality of continuous variable quantum theory can be revealed with a single projective measurement**
- Shishir Khandelwal **Simulating quantum instruments with projective measurements and quantum post-processing**
- Arturo Konderak **Local content for generalized qubit measurements**

Posters

Robin Krebs	Immanent inequalities and entanglement
Edwin Lobo	Generalized measurement incompatibility
Will Mccutcheon	Certifying high-dimensional quantum channels
Camiel Meijer	Towards information-theoretic principles to delimit signalling quantum correlations
Shintaro Minagawa	All star-incompatible measurements can certify steering-based randomness
Giorgio Minati	Randomness certification in the bilocal quantum network
Saheli Mukherjee	Detecting genuine multipartite entanglement using moments of positive maps
Ties-Albrecht Ohst	Structure of quantum measurements implementable with one round of classical communication
Sohyun Park	Can tachyons explain all possible non-local effects?
Wolfgang Paul	Stern-Gerlach, EPRB and Bell inequalities: An analysis using the quantum Hamilton equations of stochastic mechanics
Jef Pauwels	Symmetric localizable multiparty quantum measurements
Rick Perche	Useful qubits and state updates in relativistic quantum information
Martin Plávala	Existing experiments suffice to indirectly verify the quantum essence of gravity

Posters

- | | |
|--------------------------------|---|
| Emanuele Polino | Detection-loophole-free quantum steering in the simplest scenario |
| Lucas Porto | Measurement incompatibility and genuine multipartite steering |
| Alejandro Pozas-Kerstjens | When Einstein, Podolsky and Rosen distribute quantum states: A journey to the smallest possible demonstration of quantum nonlocality in networks |
| Albert Rico | Robust certification of high-dimensional quantum devices |
| Carles Roch i Carceller | The role of entanglement in energy-restricted communication and randomness generation |
| Abhyoudai Sajeevkumar Shaleena | Understanding Bell inequality violations in 2-2-d and 2-d-2 systems |
| Shubhayan Sarkar | Nonlocality beyond Bell: Operationally independent events can influence each other in quantum theory |
| Sebastian Schlösser | Genuinely high-dimensional teleportation |
| Mariana Storrer | Theory-independent context incompatibility |
| Lucas Tendick | Quantum correlations cannot be reproduced with a finite number of measurements in any no-signaling theory |
| William Townsend | Measurement incompatibility, extremal quantum decoherence, and minimal informationally complete measurements. |
| Nick von Selzam | On the dynamics of local hidden-variable models |

Posters

- Amanda Wei **Non-projective Bell state measurements**
- Lisa T. Weinbrenner **Superactivation and incompressibility of genuine multipartite entanglement**
- Lewis Wooltorton **Genuine multipartite entanglement is not necessary for standard device-independent conference key agreement**
- Nikolai Wyderka **Quantum network correlations require classical communication to be useful**
- Julius Alexander Zeiss **Approximating fixed size quantum correlations in polynomial time**
- Andrea Zingarofalo **Towards Bell tests with minimal sample complexity**

Abstracts of Talks

(in alphabetical order)

Factorization of multimeters: a unified view on nonclassical quantum phenomena

T. Achenbach¹, A. Bluhm², L. Leppäjärvi¹, I. Nechita³, and M. Plávala⁴

¹ *Faculty of Information Technology, University of Jyväskylä, Jyväskylä, Finland*

² *Univ. Grenoble Alpes, CNRS, Grenoble INP, LIG, Grenoble, France*

³ *Laboratoire de Physique Théorique, Univ. de Toulouse, CNRS, Toulouse, France*

⁴ *Institut für Theoretische Physik, Leibniz Universität Hannover, Hannover, Germany*

Quantum theory exhibits various nonclassical features, such as measurement incompatibility, contextuality, steering, and Bell nonlocality, which distinguish it from classical physics. These phenomena are often studied separately, but they possess deep interconnections. In this talk, we will present a unified mathematical framework based on commuting diagrams that unifies them. By representing collections of measurements (multimeters) as maps to the set of column-stochastic matrices, we will see that measurement compatibility and simulability correspond to specific factorizations of these maps through intermediate systems. We will apply this framework to put forward connections between different nonclassical notions and provide factorization-based characterizations for steering assemblages and Bell correlations. We will also investigate the symmetric n -extensions of multimeters and no-signaling behaviors and connect these extensions to a notion of n -wise compatibility and to the existence of n -wise local hidden variable models, respectively. This talk is based on [1].

References

- [1] T. Achenbach, A. Bluhm, L. Leppäjärvi, I. Nechita, and M. Plávala, arXiv preprint [arXiv:2504.19865](https://arxiv.org/abs/2504.19865) (2025)

Characterising entanglement and separability

T. V. Kondra, P. Barrios, J. Neumann, N. Wyderka,
H. Kampermann, and D. Bruß

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

While deep insights into the properties of entanglement have been acquired over the last ca 30 years, much less is known about the structure of separable states. However, global operations allow the creation of entanglement or non-locality from separability. In this sense even separable states may provide a resource. We investigate the limitations of entanglement extraction and point out the corresponding properties of separable states.

Local Models for Quantum Steering: From Two Parties to Networks

**Eric Chitambar¹, Samihr Hermes¹, Haeum Kim¹, Prince Yadav¹,
Yujie Zhang^{1,2}**

¹*University of Illinois Urbana-Champaign, Urbana, Illinois, USA*

²*The Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada*

This talk discusses local hidden state (LHS) models for quantum steering. I will begin by describing different approximations of the Bloch sphere and relate these approximations to the amount of shared randomness in LHS models for isotropic states. In the bipartite setting, we show that as the visibility of an isotropic state increases, more shared randomness is needed to construct an LHS model. We then turn to scenario of network quantum steering. While much less is known about the structure of local models in the network setting, I will describe one method for constructing network LHS models for independent isotropic states. Our findings show that network LHS models do not require as much shared randomness for simulating certain entangled measurements across isotropic states.

References

- [1] Zhang, Chitambar, Phys. Rev. Lett. **132**, 250201 (2024).
- [2] Zhang, Zhang, Chitambar Quantum 9, 1902 (2025).

EPR, quantum irrealism and the Bell inequality violations

Paulo H. B. Silva¹, Ana C. S. Costa¹, and Renato M. Angelo¹

¹Federal University of Paraná, Curitiba, Brazil

Bell inequality violations are known for having provided a profound disruption to classical models of the physical world. Yet, their meaning is still debatable nowadays. An important point under dispute in this context concerns the relevance of realism. While some believe that a Bell inequality violation implies the manifestation of nonlocal aspects, others defend that it is the notion of realism that should be abandoned. The purpose of the present work is to shed some light on the matter by employing a formal definition of (ir)realism [1]. Our strategy consists of (i)rephrasing Bell's assumption of local causality in terms of more primitive hypotheses and (ii) assessing where the fundamental difficulties emerge when using the quantum formalism. As a byproduct of our approach, the connections of (ir)realism with both quantum steering and entanglement are also discussed.

References

[1] A. L. O. Bilobran and R. M. Angelo, *Europhys. Lett.* 112, 40005 (2015)

Block moment-matrix relaxations for constrained quantum correlations

Nicola D’Alessandro,¹ Carles Roch i Carceller,¹ and Armin Tavakoli¹

¹*Physics Department and NanoLund, Lund University, Box 118, 22100 Lund, Sweden.*

Characterizing quantum correlations, that is deciding whether observed or hypothesized statistical relations among states, observables and measurement outcomes admit a physical realization, is a fundamental problem in quantum theory. This question underlies many central tasks in quantum information science, from entanglement detection and nonlocality certification to quantum steering and the study of constrained quantum systems. Because exact analytical characterizations are available only in exceptional cases, the last fifteen years have seen the rise of powerful numerical methods based on semidefinite programming (SDP) relaxations. Despite their success, such methods are usually tailored to specific scenarios and remain much better understood in settings with limited structure. By contrast, physically motivated constraints such as finite dimension, energy bounds, or algebraic restrictions on observables often make the characterization problem substantially harder, even though these features are essential in many realistic quantum settings.

Existing SDP methods for correlation problems share the idea that quantities capturing the structure of quantum correlations can be represented as entries of a positive semidefinite moment matrix. Our key observation is that the most general construction for such a semidefinite positive operator is $\Gamma = \sum_{u,v \in S_K(L)} |i_u\rangle\langle i_v| \otimes \Theta(uv^\dagger)$, where $L = \{O_1, \dots, O_n\}$ is a collection of bounded operators, $S_K(L)$ denotes the set of all products of length up to K formed from elements of L , and Θ is a positive map chosen so that the relevant correlations and constraints can be encoded in Γ while preserving the SDP structure. Algebraic and physical assumptions then translate into linear and semidefinite constraints on linear maps over the blocks of Γ , yielding an SDP outer approximation to the compatible correlation set. Increasing K defines a hierarchy of progressively tighter relaxations.

This methodology applies to a broad variety of constrained quantum-correlation problems. As an explicit construction, we present SDP relaxations for high-dimensional EPR steering, where Θ can be chosen as a partial trace so as to retain the information associated with the characterized Hilbert space while eliminating the uncharacterized degrees of freedom. This yields relaxations tailored to steering scenarios and enables enhanced high-dimensional steering detection, including entanglement-dimension certification and quantitative bounds on how closely the source approximates a maximally entangled state. To our knowledge, the latter is the first steering-compatible numerical method of this kind. For dimension certification, the approach offers two main advantages over previous techniques: its computational cost is independent of the certified entanglement dimension, making higher-dimensional certification accessible, while remaining highly accurate across a broad range of settings where analytical or numerical benchmarks are available.

More broadly, Table I illustrates the breadth of scenarios and structural constraints to which we adapted this methodology, highlighting its applicability well beyond steering.

Scenario	Main constraints	Contribution
EPR steering	Assemblage, Schmidt rank	Enhanced high-dimensional steering detection
Bipartite entanglement witness	Dimension, separability & fidelity	Making entanglement witnesses robust to errors
Prepare-and-measure	Fidelity in subspace	Characterising correlations from imperfect sources
Multipartite entanglement source	Schmidt-rank & fixed state	Enhanced multiparticle entanglement detection
Quantum preparation device	Subspace dimension & fixed state	Witnessing the dimension of quantum states
Uncertainty relations	Operator norm	Correcting uncertainty relations for calibration errors

TABLE I: The SDP relaxation methodology is used to address six different quantum information problems. The scenario for each problem is listed together with the main types of constraints required to address it and the corresponding contribution to the state of the art.

Quantifying quantum correlations from the geometric perspective

S. Denker¹, K. Goodenough¹, O. Gühne¹, S. Imai², A. Rico¹,
J. Steinberg¹, L. T. Weinbrenner¹, X.-D. Yu³

¹*Universität Siegen, Siegen, Germany*

²*University of Tsukuba, Tsukuba, Japan*

³*Shandong University, Jinan, China*

I present an overview on the geometric measure of entanglement, being a quantifier based on the distance of a state to the nearest separable state. Besides the physical application, this measure is also studied in mathematics as the so-called injective tensor norm. Then, I will discuss three recent results in some more detail. First, the identification of maximally entangled states with respect to this measure will be explained. Second, I will show how symmetries can be used to construct highly entangled subspaces. Finally, I will present a method to determine the measure by constructing hierarchies using multiple copies of a quantum state.

References

- [1] L. T. Weinbrenner, O. Gühne, EPL **151**, 68001 (2025).
- [2] J. Steinberg, O. Gühne, Phys. Rev. A **110**, 062428 (2024).
- [3] S. Denker, S. Imai, O. Gühne, arXiv:2506.15609.
- [4] L. T. Weinbrenner, A. Rico, K. Goodenough, X.-D. Yu, O. Gühne, arXiv:2601.23243.

Could EPR yet be (partly) right?

Adrian Kent

Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road,
Cambridge, CB3 0WA, United Kingdom.

and

Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, Ontario
N2L 2Y5, Canada.

EPR's premises are generally taken to be refuted by successive Bell experiments, culminating in "loophole-free" experiments from 2015 onwards. I review how definitive the refutation actually is, noting that there remains at least one significant loophole, the so-called "collapse locality loophole" [1,2,3], that could be closed by foreseeable experiments but currently remains open. I also discuss and motivate a weaker formulation of EPR's premises that appears attractive and unrefuted and illustrate its implications in a realist model based on hypothetical asymptotic late time measurement data [4].

[1] <http://arxiv.org/abs/quant-ph/0204104v3> Causal Quantum Theory and the Collapse Locality Loophole, Adrian Kent, Phys. Rev. A 72, 012107 (2005) DOI: 10.1103/PhysRevA.72.012107

[2] <http://arxiv.org/abs/1807.08791v3> Stronger Tests of the Collapse Locality Loophole in Bell Experiments, Adrian Kent, Phys. Rev. A 101, 012102 (2020) DOI: 10.1103/PhysRevA.101.012102

[3] <http://arxiv.org/abs/1807.09663v3> Testing Causal Quantum Theory Adrian Kent Proceedings of the Royal Society A 474 (2018) DOI: 10.1098/rspa.2018.0501 [

4] <http://arxiv.org/abs/1608.04805v3> Quantum Reality via Late Time Photodetection Adrian Kent Phys. Rev. A 96, 062121 (2017) DOI: 10.1103/PhysRevA.96.062121

The Tangled Tale of Entanglement: New Discoveries from Schrödinger's Research Notes

Christoph Lehner

Institut für Quantenoptik und Quanteninformation, Wien

Today, entanglement is commonly accepted as the most striking and characteristic phenomenon of quantum mechanics. But this realization was slow to emerge, in the early years of quantum mechanics, entanglement was just seen as a normal statistical correlation. Only with Einstein, Podolsky and Rosen's "Can quantum mechanical description of reality be considered complete?" (1935) and Schrödinger's "Die gegenwärtige Situation in der Quantenmechanik" (1936) did the phenomenon come into focus as a central and puzzling feature of quantum mechanics. However, not much has been known about the prehistory of these papers. Jos Uffink and me were able to trace the development of both Einstein's and Schrödinger's thought, using Schrödinger's correspondence and especially his extensive research notes. We especially found that they both got important input from Leo Szilard, who proposed in 1931 a thought experiment that is a direct precursor to the EPR experiment and a quantum mechanical state that is essentially identical to the EPR state.

High-Dimensional Advantages in Quantum Key Distribution

G. Murta¹

¹TU Wien, Vienna, Austria

High-dimensional entanglement offers increased information capacity and has also been shown to exhibit enhanced noise resilience. A natural question is whether this resilience translates into practical advantages for quantum communication tasks. In this talk, we review results demonstrating high-dimensional advantages in quantum key distribution (QKD) with characterized devices. We then discuss the challenges of establishing such advantages in fully adversarial, device-independent scenarios. Finally, we turn to the intermediate regime of one-sided device-independent QKD, where we show that leveraging high-dimensional quantum steering reveals clear advantages across different settings. We conclude with a discussion of the experimental prospects for realizing these advantages.

Understanding the relationship between measurement incompatibility, EPR steering, and Bell nonlocality

Marco Túlio Quintino

Sorbonne Université, CNRS, LIP6, F-75005 Paris, France

It follows that if a set of measurements $\{A_{a|x}\}$ is compatible (i.e., jointly measurable), it cannot lead to EPR steering. Indeed, if $\{A_{a|x}\}$ is compatible, the assemblage $\{\sigma_{a|x} := \text{tr}_A[(A_{a|x} \otimes \mathbb{1})\rho]\}$ admits a local hidden state model for any state ρ_{AB} . In Refs. [1, 2], it was shown that the converse relation also holds, i.e., if $\{A_{a|x}\}$ is incompatible, then there exists a state ρ_{AB} such that the assemblage $\{\sigma_{a|x} := \text{tr}_A[(A_{a|x} \otimes \mathbb{1})\rho]\}$ is steerable.

As in the EPR-steering case, compatible measurements cannot lead to Bell nonlocality. Ref. [3] shows that incompatible projective measurements can always lead to Bell nonlocality. Also, Ref. [4] shows that when considering a pair of dichotomic measurements, measurement incompatibility is sufficient for Bell nonlocality. However, in general, there exist incompatible measurements which cannot lead to Bell nonlocality [5, 6].

More recently, the relationship between measurement incompatibility and Bell nonlocality has been investigated in multipartite scenarios, where a close relationship between these concepts was obtained. Ref. [7] shows that, if $\{A_{a|x}\}$ is a set of qubit incompatibility measurements, then there exists a number of parties n , an n -party state ρ_n such that the probability distribution $p(a_1 a_2, \dots, a_n | x_1 x_2 \dots x_n) := \text{tr}[(A_{a_1|x_1} \otimes A_{a_2|x_2} \otimes \dots \otimes A_{a_n|x_n})\rho_n]$ is nonlocal.

In a recent work still to be published, every set of incompatibility measurements can lead to genuine multipartite EPR steering [8]. This result extends the result of Refs. [1, 2] to genuine multipartite EPR steering. Also, in this multipartite scenario, we present different sets of states that are not equivalent by SLOCC, but can lead to genuine multipartite EPR steering for any set of incompatible measurements.

This talk will combine the results mentioned above with a historical perspective on how our understanding of the relationship between measurement incompatibility, EPR steering, and Bell nonlocality evolved over the years. We will also discuss open questions and future directions in this area of research.

References

- [1] M. T. Quintino, T. Vértesi, and N. Brunner, Joint Measurability, Einstein-Podolsky-Rosen Steering, and Bell Nonlocality, *Phys. Rev. Lett.* **113**, 160402 (2014).
- [2] R. Uola, T. Moroder, and O. Gühne, Joint Measurability of Generalized Measurements Implies Classicality, *Phys. Rev. Lett.* **113**, 160403 (2014).
- [3] L. A. Khalfin and B. S. Tsirelson, Quantum and quasi-classical analogs of bell inequalities, Symposium on the Foundations of Modern Physics , 441–460 (1985).
- [4] M. M. Wolf, D. Perez-Garcia, and C. Fernandez, Measurements Incompatible in Quantum Theory Cannot Be Measured Jointly in Any Other No-Signaling Theory, *Phys. Rev. Lett.* **103**, 230402 (2009).
- [5] F. Hirsch, M. T. Quintino, and N. Brunner, Quantum measurement incompatibility does not imply Bell nonlocality, *Phys. Rev. A* **97**, 012129 (2018).
- [6] E. Bene and T. Vértesi, Measurement incompatibility does not give rise to Bell violation in general, *New Journal of Physics* **20**, 013021 (2018).
- [7] M. Plávala, O. Gühne, and M. T. Quintino, All Incompatible Measurements on Qubits Lead to Multipartite Bell Nonlocality, *Phys. Rev. Lett.* **134**, 200201 (2025).
- [8] D. Cavalcanti, P. Skrzypczyk, G. H. Aguilar, R. V. Nery, P. S. Ribeiro, and S. P. Walborn, Detection of entanglement in asymmetric quantum networks and multipartite quantum steering, *Nature Communications* **6**, 7941 (2015).

The Einstein-Podolsky-Rosen paradox and weak elements of reality in a Q-based, objective-field interpretation of quantum mechanics

M. D. Reid¹, C. McGuigan¹, C. Hatharasinghe¹, R-Y Teh¹, P. D. Drummond¹

¹*Swinburne University of Technology, Melbourne 3122, Australia*

The Einstein-Podolsky-Rosen (EPR) paradox was put forward in 1935 as an argument for the incompleteness of quantum mechanics [1]. The argument has been realized both in the original continuous-variable version and in the discrete version introduced by Bohm. The EPR argument is often considered unconvincing because it is based on a set of assumptions negated by the later work of Bell. However, a weaker set of assumptions (weak local realism) not negated by Bell's theorem can be used, which similarly imply the incompleteness of quantum mechanics [2].

In this paper, we analyze the EPR argument using a model of reality motivated by the Q function $Q(x,p)$ in quantum optics [3]. Solutions are obtained for amplitudes x and p using equivalent forward-backward stochastic simulations, in which the amplitude x is solved in the reverse-time direction. We consider both the measurement and generation of EPR correlations. Measurement is modelled as a direct amplification or else, in the spin version, by coupling to a macroscopic meter. Our conclusion is a model of reality in which both the EPR paradox and Bell violations are shown to be consistent with the three weak local realistic assumptions: (1) the existence of real properties (defined for the system after operations that fix measurement settings); (2) a partial locality implying no-signaling; (3) "elements of reality" that apply to the predictions of a system by a meter, once meter-settings are fixed. Despite the apparent retrocausality inherent the solutions, we identify a causal model in which observable quantities are governed by causal deterministic relations, thereby explaining why no retrocausality is observed macroscopically. We show how other paradoxes in quantum mechanics can be resolved. In particular, we examine the questions raised by Schrodinger about the EPR paradox in his essay of 1935 [4].

References

- [1] A. Einstein, B. Podolsky, and N. Rosen, *Phys. Rev.* **47**, 777 (1935)
- [2] J. Fulton, R.Y. Teh, and M.D. Reid, *Phys. Rev. A* **110**, 022218 (2024)
- [3] P.D. Drummond and M.D. Reid, *Phys. Rev. Research* **2**, 033266 (2020); M.D. Reid and P.D. Drummond, *Phys. Rev. A* **113**, 012210 (2026).
- [4] E. Schrodinger, *Die Naturwissenschaften*, **23**, 844 (1935). P. Colciaghi, Y. Li, P. Treutlein, and T. Zibold, *Physical Review X* **13**, 021031 (2023)

Einstein-Podolsky-Rosen steering beyond quantum theory

Ana Belen Sainz

International Centre for Theory of Quantum Technologies, University of Gdańsk, Poland

The discovery of postquantum nonlocality – the existence of nonlocal correlations stronger than any quantum correlations but nevertheless consistent with the no-signaling principle – has deepened our understanding of the foundations quantum theory. In this talk I discuss how the phenomenon of Einstein-Podolsky-Rosen steering can also be generalized beyond quantum theory [1-3]. We will consider a variety of steering scenarios, such as multipartite and Bob-with-Input. I will show how postquantum steering is a different phenomenon to Bell postquantum correlations [1-3,4], and argue how it goes beyond just being a mere mathematical curiosity [5]. I will also mention some recent results in the field of postquantum steering [3,6,7].

References

- [1] A. B. Sainz *et al*, Phys. Rev. Lett. **115**, 190403 (2015).
- [2] A. B. Sainz, M. J. Hoban, P. Skrzypczyk, and L. Aolita, Phys. Rev. Lett. **125**, 050404 (2020).
- [3] A. B. Sainz, in preparation.
- [4] A. B. Sainz *et al*, New J. Phys. **20**, 083040 (2018).
- [5] P. J. Cavalcanti *et al*, npj Quantum Inf. **8**, 76 (2022).
- [6] B. Zjawin, D. Schmid, M. J. Hoban, A. B. Sainz, Quantum **7**, 1134 (2023).
- [7] A. B. Sainz, P. Skrzypczyk and M. J. Hoban, New J. Phys. **27**, 124508 (2025).

Detecting entanglement with minimal assumptions

Pavel Sekatski¹

¹*Department of Applied Physics, University of Geneva*

Entanglement and Bell nonlocality are known to be inequivalent: there exist entangled states that admit a local hidden-variable model for all local measurements. This reveals a fundamental gap between the intrinsic resource content of entangled systems and its empirical consequences – correlations observable in a Bell test. A natural question is whether this gap can be closed by slightly modifying the causal structure of the standard Bell tests. I will present some recent ideas and results along these lines: (i) routed Bell tests, (ii) the local broadcasting scenario, (iii) many-copy and catalytic activation of Bell nonlocality.

- [1] P. Sekatski, J. Pauwels, E. P. Lobo, S. Pironio, N. Brunner, arXiv:2502.12241 (2025)
- [2] J. Bavaresco, N. Brunner, A. Girardin, P. Lipka-Bartosik, P. Sekatski, Phys. Rev. Lett. **135**, 220203 (2025)
- [3] P. Sekatski, J. Pauwels, arXiv:2512.15656 (2025)

Post-quantum steering

Paul Skrzypczyk¹

¹*H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, United Kingdom, UK*

In this talk I will introduce the topic of *post-quantum steering*, an idea that we introduced in a paper in 2015 [1]. In that paper, we were seeking a notion of steering beyond quantum mechanics, that was not equivalent to post-quantum nonlocality, i.e. was not just another simple manifestation of Popescu-Rohrlich (PR) or other nonlocal correlations. We showed that this does appear to exist: specifically, we showed that in a three-party setting, with two ‘steerers’, it is possible to find examples of steering of the third party which both could not occur in quantum theory, but also such that if we just looked at correlations (i.e. in a device-independent or Bell-type setting), then there would be a quantum explanation. After first introducing this concept, I will present recent results, where we show that if we consider a more general scenario, we can ‘activate’ the post-quantumness, such that it can be witnessed purely at the level of correlations. The main idea is to consider an additional party (i.e. a network scenario). We show that in such a scenario, building upon ideas from the study of quantum nonlocality, we can find a Bell-type inequality, and surpass the quantum (Tsirelson) bound, whenever we have post-quantum steering. This thus suggests that contrary to our original aim, it does not appear possible to find post-quantum steering which is genuinely distinct from post-quantum nonlocality.

References

- [1] A. B. Sainz, N. Brunner, D. Cavalcanti, P. Skrzypczyk, and T. Vértesi. *Phys. Rev. Lett.* **115**, 190403 (2015)
- [2] A. B. Sainz, P. Skrzypczyk and M. J. Hoban, *New J. Phys.* **27**, 124508 (2025)

Classical models for quantum theory

Armin Tavakoli, Lund University

Traditionally, quantum theory is compared with other hypothesized models through its statistical predictions. In this talk, I depart from this approach and instead ask if alternative models can explain the actual Hilbert space formalism of quantum theory. With focus on dimension, state classicality and measurement classicality, I propose a resource-theory perspective on these concepts, based on the limitations of the involved devices. This perspective has operational connections to the prepare-and-measure scenario and has links to established fundamental concepts. In particular, it reveals that many seemingly quantum devices can be reproduced by much simpler models.

Jumping from EPR to Steering, and unfolding from Bohr to Discord: a history of asymmetric nonlocality

H. M. Wiseman

*Quantum and Advanced Technologies Research Institute, Griffith University,
Yuggera Country, Brisbane, Queensland 4111, Australia*

Famously, the EPR paper [1] introduced, just over 90 years ago, an asymmetric type of nonlocality apparent in quantum mechanics. This was formalised by myself and others, in quantum information language, in 2007 [2]. The term we gave this phenomenon was “steering” (later “EPR-steering” [3]), one of the terms introduced by Schrödinger in his discussion of EPR in the same year as their paper [4]. What is less famous is my original motivation for wanting to formalise EPR-steering, which was rooted in the stochastic dynamics of open quantum systems, including “diese verdammte quantenspringerie” which Schrödinger (famously) complained about almost 100 years ago. (See, e.g., Ref. [5].) Returning to 90 or so years ago, Bohr (famously) responded [6] to the EPR paper. He objected to a key assumption in their argument, relating to disturbance, and replaced it with his own criterion. I have argued [7] (sadly, not at all famously) that implicit in Bohr’s criterion was the concept of Discord, another asymmetric type of nonlocality in quantum mechanics introduced in 2001 [8,9]. Finally, I will offer some simple reflections on the role of asymmetry in the thinking behind some of the works cited.

References

- [1] A. Einstein, B. Podolsky, N. Rosen, *Phys. Rev.* 47 (1935) 777.
- [2] H.M. Wiseman, S.J. Jones, A.C. Doherty, *Phys. Rev. Lett.* 98 (2007) 140402.
- [3] E. G. Cavalcanti, S.J. Jones, H.M. Wiseman, and M. D. Reid, *Phys. Rev. A* 80 (2009) 032112.
- [4] E. Schrödinger, *Proc. Cambridge Philos. Soc.* 31 (1935) 555.
- [5] M. Jammer, *The conceptual development of quantum mechanics 2e*, American Institute of Physics (1989). p.344.
- [6] N. Bohr, *Phys. Rev.* 48 (1935) 696.
- [7] H.M. Wiseman, *Annals of Physics* 338 (2013) 361–374.
- [8] L. Henderson, V. Vedral, *J. Phys. A* 34 (2001) 6899.
- [9] H. Ollivier, W.H. Zurek, *Phys. Rev. Lett.* 88 (2001) 017901.

Abstracts of Posters

(in alphabetical order)

Testing Entanglement in Higgs to ZZ^* decays at Colliders

I. Åsljung¹

¹*University of Oxford, Oxford, United Kingdom*

Recent years have seen growing interest in probing quantum entanglement at the high energies of collider experiments. Extending entanglement tests to new energy regimes enables studies of correlations between massive gauge bosons, probes the spin of virtual particles, and could potentially provide novel tools for tests of physics beyond the Standard Model¹.

This poster reviews proposals to test entanglement at the Large Hadron Collider, focusing on pairs of Z bosons produced in Higgs boson decays. Following the recent observation of quantum entanglement in top-quark pairs by ATLAS, these studies aim to extend such tests and could lead to the first observation of entanglement between massive spin-1 particles².

Due to their short lifetimes, and the design of general-purpose collider detectors, the spins of the Z bosons cannot be measured directly but are instead encoded in the angular distributions of their decay products. By analysing the leptonic final states (electrons and muons), the spin density matrix of the Z-boson pair can be reconstructed³. Entanglement can then be tested using various entanglement witnesses, such as the Peres-Horodecki criterion or by violation of a Bell inequality.

Given the active discussion surrounding the interpretation of entanglement tests at high energies, this poster also highlights the key assumptions and limitations inherent in this approach⁴⁻⁵.

References

- [1] A. J. Barr, M. Fabbrichesi, R. Floreanini, E. Gabrielli, L. Marzola, *Prog. Part. Nucl. Phys.* **139**, 104134 (2024)
- [2] ATLAS Collaboration, *Nature* **633**, 542-547 (2024)
- [3] J.A. Aguilar-Saavedra, A. Bernal, J.A. Casas, J.M. Moreno, *Phys. Rev. D* **107**, 016012 (2023)
- [4] C. Timpson, IntechOpen, doi:10.5772/intechopen.1002905 (2023)
- [5] P. Bechtle, C. Breuning, H. Dreiner, C. Duhr. arXiv:2507.15947 (2025)

Can We Define Correlation among Identical Particles?

D. Aliverti-Piuri¹, J. Liebert² and C. Schilling¹

¹*Ludwig-Maximilians-Universität, Munich, Germany*

²*Princeton University, Princeton, USA*

Quantum correlations such as entanglement underpin quantum computing, cryptography, and teleportation. For distinguishable particles, a well-established theory rests on tensor product Hilbert spaces. Zanardi and Werner extended this framework by identifying commuting subalgebras of the operator algebra of the total system as the key elements for defining subsystems [1,2]. Yet, adapting this to identical bosons or fermions is not straightforward, as their (anti)symmetrized Hilbert space is not a tensor product space. For example, two distant identical particles that have never interacted are physically uncorrelated, but their state $(|\phi\rangle \otimes |\psi\rangle \pm |\psi\rangle \otimes |\phi\rangle)/\sqrt{2}$ looks like the state of a Bell pair. Indeed, no approach towards identical-particle correlations has so far reproduced the full set of properties of distinguishable-particle correlations [3]. We argue that individual particles do not constitute proper subsystems in identical particle systems, and thus identical-particle correlation cannot be defined on the same footing as for distinguishable particles. More precisely, we show that the single-particle operator algebra cannot be embedded in the N-identical particle algebra in a way that respects some basic physically motivated constraints. For fermions, we extend this no-go result to subsystems of P particles out of N.

Correlations can be recovered for states where the N identical particles are confined to N non-overlapping regions or, more generally, N orthogonal subspaces of the single-particle space [4]. In fact, these states can be identified with states in the tensor product of the N subspaces. However, such states form a zero-measure subset of all states of N identical particles, leaving almost all identical-particle states without a well-defined notion of correlation among particles.

References

- [1] P. Zanardi, Phys. Rev. Lett. **87**, 077901 (2001)
- [2] R. Verch and R. F. Werner, Rev. Math. Phys. **17.5**, 545–576 (2005)
- [3] F. Benatti, R. Floreanini, F. Franchini, and U. Marzolino, Phys. Rep. **878**, 1-27 (2020)
- [4] F. Herbut and M. Vujicic, J. Phys. A: Math. Gen. **20**, 5555 (1987)

Network Quantum Random Number Generation via Entropy Accumulation

S. Bäuml¹ and N. Walk¹

¹*Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany*

In this ongoing work, we apply Entropy Accumulation to provide a rigorous security proof for device-independent quantum random number generation (QRNG) in a tripartite network setting. We further apply recent numerical frameworks to obtain better rates than previous results which were based on the min-entropy. Our setting is based on the work of Bowles et al. [1], where a tripartite setting of broadcast non-locality was introduced. In this setting, a bipartite nonlocal resource is transformed into a tripartite nonlocal resource using a broadcast channel. Further, a tripartite Bell inequality was introduced and it has been shown that in such a broadcast setting the robustness of certifiable randomness can be enhanced compared to a purely bipartite setting and there is an activation of non-locality for an isotropic state that does not exhibit standard Bell non-locality. An experiment has also been performed [2].

Whereas an experiment and a sketched security proof have been provided by Polino et al. [3], the setting is still lacking a thorough security proof as well as a numerical treatment that goes beyond computing the min-entropy. We here apply the numerical framework by Brown et al [4], which directly lower bounds the von Neumann entropy using non-commutative polynomial optimisation which can be lower bounded via the NPA hierarchy. This is then combined with the entropy accumulation theorem (EAT) to provide security against coherent attacks. We further consider the generalised Renyi entropy accumulation theorem (GREAT) [5], which in combination with non-commutative polynomial optimisation [6], promises even better rates and greatly simplified higher order terms.

References

- [1] Bowles, J., Hirsch, F., & Cavalcanti, D. (2021). *Quantum*, 5, 499.
- [2] Villegas-Aguilar, L., Polino, E., Ghafari, F., Quintino, M. T., Laverick, K. T., Berkman, I. R., ... & Pryde, G. J. (2024). *Nature Communications*, 15(1), 3112.
- [3] Polino, E., Villegas-Aguilar, L., Poderini, D., Walk, N., Ghafari, F., Quintino, M. T., ... & Slussarenko, S. (2024). *arXiv preprint arXiv:2412.16973*.
- [4] Brown, P., Fawzi, H., & Fawzi, O. (2024). *Quantum*, 8, 1445.
- [5] Arqand, A., Hahn, T. A., & Tan, E. Y. Z. (2025). *Physical Review X*, 15(4), 041013.
- [6] Hahn, T. A., Tan, E. Y. Z., & Brown, P. (2024). *arXiv preprint arXiv:2408.12313*.

Optimal variant of a noncontextuality inequality for experimental implementations

Gustavo Balvedi Pimentel¹ and Bárbara Lopes Amaral²

1. ICFO - The Institute of Photonic Sciences, Barcelona, Spain

2. USP - University of São Paulo, São Paulo, Brazil

Quantum contextuality results from the impossibility of explaining the probabilities of measurement outcomes in quantum systems using models that assume that observables have well-defined values prior to the measurement, and that these values do not depend on which other compatible measurements are performed simultaneously to the measurement [1]. Contextuality has been widely studied experimentally, but real tests often break the no-disturbance assumption, motivating alternative frameworks that work under such conditions. This work extends Renou et al. [2], who showed that variants of a Bell inequality, though equivalent under no-signaling, differ in experimental robustness. Their method uses the symmetry group of a Bell scenario to optimize such robustness. We generalize this approach to contextuality scenarios, employing group representation theory to optimize noncontextuality inequalities.

References

[1] KOCHEN, S., & SPECKER, E. P., *Journal of Mathematics and Mechanics*, 17(1), 59–87 (1967).

[2] RENO, M.O., ROSSET, D., MARTIN, A., GISIN, N., *Journal of Physics A: Mathematical and Theoretical*, Volume 50, Number 25 (2017).

Operationally classical simulation of quantum states

Gabriele Cobucci¹, Alexander Bernal¹, Martin J. Renner², Armin Tavakoli¹

¹*Physics Department and NanoLund, Lund University, Box 118, 22100 Lund, Sweden.*

²*ICFO - Institut de Ciències Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain.*

Abstract

A classical state-preparation device cannot generate states in relative superposition. In this poster, based on [1], we introduce classical models in which devices that are individually unable to generate states with relative superposition can be stochastically coordinated to simulate sets of quantum states. These models have natural operational interpretation in prepare-and-measure scenarios and they can account for many non-commuting quantum state sets. We develop systematic methods both for classically simulating quantum sets and for showing that no such simulation exists, thereby certifying quantum coherence. In particular, we determine the exact noise rates required to classically simulate the entire state space of quantum theory. We also reveal connections between the operational classicality of sets and the well-known fundamental concepts of joint measurability and Einstein-Podolsky-Rosen steering.

References

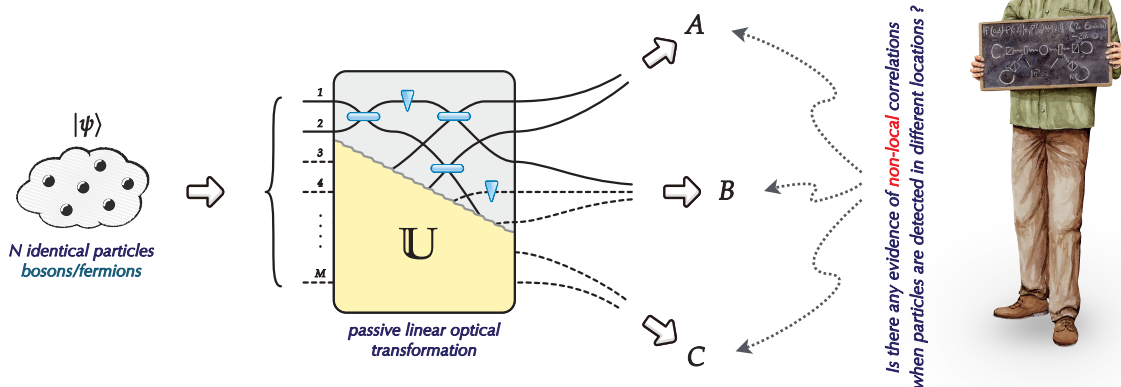
- [1] G. Cobucci, A. Bernal, M. J. Renner and A. Tavakoli, *Operationally classical simulation of quantum states*, *Nature Commun.* **17** (2026) 1104, [[2502.01440](#)].

Identical particles as a genuine non-local resource

Pawel Blasiak

Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland

Entanglement due to symmetrisation of the wave function in the second-quantised theory is ubiquitous, but at the same time it is severely constrained by the inability to address individual particles. So, can it nevertheless be turned into a useful, genuine resource of non-local correlations observed in the laboratory? We show that this is possible with very modest passive linear optical means for almost every state of identical particles.



Reference

P. Blasiak and M. Markiewicz

Identical particles as a genuine non-local resource

[npj Quantum Inf. 11 171 \(2025\)](#)

EurekAlert! (2025): [Nonlocality inherent in the nature of identical particles](#)

Machine learning methods for entanglement detection in high-dimensional systems

F. Anselmi¹, F. Benatti¹, M. Plávala² and Y. Bougammoura²

¹*University of Trieste, Trieste, Italy*

²*Leibniz University Hannover, Hannover, Germany*

The Positive under Partial Transposition criterion represents the first level of the hierarchy in a complete family of separability criteria based on the PPT symmetric extension of the quantum mixed state ρ . It holds for bipartite systems whose total dimension $d \leq 6$. For $d > 6$, there's no analytical criterium able to detect entanglement for any bipartite or multipartite state taken into consideration. The entanglement detection problem can be formulated as a numerical optimisation problem. This motivates the exploration of numerical methods - in particular, machine learning methods - to develop computational solutions towards this goal. First, we present results obtained by leveraging Automatic Differentiation as a tool to approximate a given state ρ_g through construction of a learnable state ρ . Although the order of magnitude of the resulting Loss function hints at the correlation state of the given state, it does not provide a robust separability criterium. Subsequently, we develop a deep learning method that given a quantum state ρ_e constructs the entanglement witness W using the state's PPT symmetric extension above mentioned. The latter shows a higher efficiency with respect to the computational resources used by the analogous SDP problem formulation.

The hardest prior for state discrimination.

Polina Chernyshova¹ and Marco Túlio Quintino¹

¹Sorbonne Université, CNRS, LIP6, F-75005 Paris, France

The quantum state discrimination task is a fundamental problem which arises frequently due to the innate difficulty of distinguishing between quantum states [1]. In the standard approach, one considers an ensemble of quantum states with their accompanying prior distribution, which is very often chosen uniform. In this work, instead of assuming a particular prior distribution, we minimize the probability of successfully discriminating over all distributions, thus considering the worst-case prior distribution, as in the minimax quantum state discrimination [2]. In this approach, two natural questions arise: 1 - what are sets of states for which the hardest prior is a uniform distribution; 2 - for which set of sets the hardest prior is close to a deterministic distribution?

Motivated by these questions, we show that the problem of discriminating a set of quantum states with the hardest prior can be formulated as a semidefinite program [3], and provide necessary and sufficient conditions for a prior distribution to be the hardest given a set of states in a formulation that allows us to study the corresponding optimal POVMs. Then, we present an explicit example of a set of states for which the hardest prior is arbitrarily close to a deterministic distribution, showing that the hardest prior can be very far from uniform. Finally, we prove that for sets of pure states which are group covariant, also known as geometrically uniform, the hardest prior is necessarily uniform.

References

- [1] Joonwoo Bae et al. “Quantum state discrimination and its applications”. In: *Journal of Physics A: Mathematical and Theoretical* 48.8 (Jan. 2015), p. 083001. ISSN: 1751-8121. DOI: 10.1088/1751-8113/48/8/083001. URL: <http://dx.doi.org/10.1088/1751-8113/48/8/083001>.
- [2] Giacomo Mauro D’Ariano et al. “Minimax quantum-state discrimination”. In: *Phys. Rev. A* 72.3, 032310 (Sept. 2005), p. 032310. DOI: 10.1103/PhysRevA.72.032310. arXiv: [quant-ph/0504048](https://arxiv.org/abs/quant-ph/0504048) [quant-ph].
- [3] Paul Skrzypczyk et al. *Semidefinite Programming in Quantum Information Science*. IOP Publishing, Mar. 2023. ISBN: 9780750333412. DOI: 10.1088/978-0-7503-3343-6. URL: <http://dx.doi.org/10.1088/978-0-7503-3343-6>.

Maximally non-projective measurements are not always symmetric informationally complete

Gabriele Cobucci,^{1,*} Raphael Brinster,^{2,*} Shishir Khandelwal,¹ Hermann Kampermann,² Dagmar Bruß,² Nikolai Wyderka,² and Armin Tavakoli¹

¹*Physics Department and NanoLund, Lund University, Box 118, 22100 Lund, Sweden.*

²*Institute for Theoretical Physics III, Heinrich Heine University Düsseldorf, D-40225 Düsseldorf, Germany*

(Dated: February 27, 2026)

While standard measurements in quantum theory are identified by complete sets of orthogonal projectors, it is well-established that a more general description of quantum measurements requires the use of positive operator-valued measures (POVMs). Since POVMs generally outperform projective measurements, but are experimentally more expensive to implement, it is practically relevant to ask whether it is possible to simulate POVMs using only projective measurements and classical resources.

This study was initiated in [1] and it led to the question of identifying which POVMs most strongly defy the limitations of standard projective measurements, being therefore the most difficult to simulate. For many years, it has been conjectured that this role would be filled by the symmetric informationally complete (SIC) POVMs. They are indeed the most natural candidates, given their broad relevance in quantum theory and the fact that they have been proven to be the most non-projective measurements for qubit systems.

In our work [2], we introduce a framework to systematically quantify simulability of POVMs in terms of projective measurements. We then use this approach to show that the conjecture is false: in general, SIC-POVMs are not the most non-projective measurements for dimensions higher than two. Our method relies on efficiently computable numerical techniques and enables us to answer a crucial follow-up question, namely to identify which measurements are the most non-projective. We solve this question for qutrit and ququart systems.

Our work resolves an important and long-standing open problem in quantum information theory and introduces a new technique to perform a systematic study of projective simulability of POVMs.

-
- [1] M. Ozmaniec, L. Guerini, P. Wittek, and A. Acín, Simulating positive-operator-valued measures with projective measurements, *Physical Review Letters* **119**, [10.1103/physrevlett.119.190501](https://doi.org/10.1103/physrevlett.119.190501) (2017).
[2] G. Cobucci, R. Brinster, S. Khandelwal, H. Kampermann, D. Bruß, N. Wyderka, and A. Tavakoli, Maximally nonprojective measurements are not always symmetric informationally complete, *Physical Review Letters* **136**, [10.1103/slt1-gfv6](https://doi.org/10.1103/slt1-gfv6) (2026).

* These authors contributed equally.

Characterising genuine multipartite high-dimensional entanglement with the partition rank

S. Denker¹, I. Settembre¹, R. Krebs² and O. Gühne¹

¹University of Siegen, Siegen, Germany

²Technical University Darmstadt, Darmstadt, Germany

Quantum entanglement is an important resource in quantum information and it has been demonstrated to bring advantages in several applications. In fact, these advantages are even higher when going to larger systems, i. e. increasing the number of particles, their local dimensions, or both. However, with increasing system size, the characterization and quantification of quantum entanglement become more intricate.

We introduce a new measure for the entanglement dimensionality of multiparticle states, based on the partition rank. The partition rank generalizes the slice rank known from mathematical literature and is given by the number of biseparable terms that are needed to decompose a multipartite quantum state [1]. This approach is a truly multipartite quantification as each term may be separable with respect to a different bipartition. We translate the problem of finding the closest states with a certain partition rank to the problem of finding the closest product state, which is known as the geometric measure of entanglement. This translation allows us to tackle this new problem with well-established methods. Along the way, we identify quantum states which are maximally entangled in the sense of our newly introduced entanglement measure, and we further show that our methods could contribute towards solving an open problem in mathematics, related to the partition rank.

References

- [1] E. Naslund, Journal of Combinatorial Theory Series A **174**, 105190 (2020)

Most incompatible measurements and sum-of-squares optimisation

Sébastien Designolle^{1,2}

¹*Zuse Institute Berlin, Takustraße 7, 14195 Berlin, Germany*

²*Inria, ENS de Lyon, UCBL, LIP, 69342, Lyon Cedex 07, France*

Measurement incompatibility, or joint measurability, is a cornerstone of quantum theory and a useful resource. For finite-dimensional systems, quantifying this resource and establishing universal bounds valid for all measurements is a long-standing problem. In this work, we exhibit analytical universal parent measurements giving access to bounds that beat the state of the art. In particular, we can show that, for relevant robustnesses, sets of anticommuting observables give rise to the most incompatible dichotomic measurements. We also formalise the construction of such universal parent measurements in the framework of sum-of-squares optimisation and obtain preliminary numerical results demonstrating the power of the method by improving on our own analytical values. All results find direct application for demonstrating genuine high-dimensional steering, that is, certifying the dimensionality of a quantum system in a one-sided device-independent manner.

References

- [1] T. Heinosaari, T. Miyadera, and M. Ziman, *J. Phys. A* **49**, 123001 (2016)
- [2] J. Bavaresco, M. T. Quintino, L. Guerini, T. O. Maciel, D. Cavalcanti, and M. T. Cunha, *Phys. Rev. A* **96**, 022110 (2017)
- [3] A. Bluhm and I. Nechita, *J. Math. Phys.* 59(11), 112202 (2018)
- [4] S. Designolle, M. Farkas, and J. Kaniewski, *New J. Phys.* **21**, 113053 (2019)
- [5] A. Bluhm and I. Nechita, *SIAM J. Appl. Algebra Geom.* **4**, 255–296 (2020)
- [6] A. Tavakoli, M. Farkas, D. Rosset, J.-D. Bancal, and J. Kaniewski, *Sci. Adv.* **7**, eabc3847 (2021)
- [7] A. Bluhm and I. Nechita, *Quantum* **6**, 656 (2022)
- [8] S. Designolle, *Phys. Rev. A* **105**, 032430 (2022)
- [9] A. Bluhm, E. Evert, I. Klep, V. Magron, and I. Nechita, arXiv:2512.17706 (2025)

Security Analysis for Steering-Based One-Sided Device-Independent QKD

Ritu Dhaulakhandi¹ and Ramona Wolf²

¹Universität Siegen, Siegen, Germany

²Universität Innsbruck, Innsbruck, Austria

One-sided device-independent quantum key distribution (1sDI-QKD) is a way for two people to share secret information securely, even if only one of them completely trusts their device. The security of the method relies on a quantum effect called steering, which confirms that the two parties really share entanglement. In this work, we introduce a way to prove the security of such setups. Our approach shows that the amount of steering observed in an experiment can be directly linked to the conditional entropy, i.e., how much information an eavesdropper could possibly gain. This makes it possible to calculate a clear limit on the eavesdropper's knowledge and shows that steering offers a practical and realistic path to achieving secure device-independent QKD.

References

- [1] R. Uola, A. C. S. Costa, H. C. Nguyen, and O. Gühne, *Rev. Mod. Phys.* **92** (1), 015001 (2020).
- [2] S. Pironio, A. Acín, N. Brunner, N. Gisin, S. Massar, and V. Scarani, *New J. Phys.* **11**, 045021 (2009).

Probabilistic theories stable under teleportation

Lionel J. Dmello, David Gross

Institute for Theoretical Physics, University of Cologne, Germany

A long-standing problem in the foundations of quantum mechanics is to identify a physical principle that explains why algebraically maximal violations of Bell inequalities can generally not be achieved in Nature. One recently proposed approach considers *iterated Bell tests* [1], where a Bell test is performed on a state that has undergone several rounds of entanglement swapping. Obtaining large violations in this scenario is more demanding, because it requires a theory to have both highly entangled states and highly entangled measurements. It has been conjectured that the maximal quantum mechanical Clauser-Horne-Shimony-Holt (CHSH)-value of $2\sqrt{2}$ might be optimal for any probabilistic theory which, like quantum mechanics, maintains its CHSH-value after an arbitrary number of rounds of entanglement swapping. However, in a previous paper [2], we have exhibited a first example of a probabilistic theory that can sustain a CHSH value of 4 in this setting. In this work, further investigating this property, we give a classification of all general probabilistic theories (GPTs) whose CHSH value is stable in the above sense. The problem reduces to a representation-theoretic condition that allows for exactly seven solutions. The GPT from our previous work showed some counter-intuitive features, e.g. that the local state space had a higher dimension than seemed necessary to realize CHSH tests. The classification shows that this is necessarily so. Along the way, we generalize the concept of *self-testing* to GPTs.

References

- [1] Mirjam Weilenmann and Roger Colbeck. “Self-Testing of Physical Theories, or, Is Quantum Theory Optimal with Respect to Some Information-Processing Task?” In: *Phys. Rev. Lett.* 125 (6 Aug. 2020), p. 060406.
- [2] Lionel J. Dmello, Laurens T. Ligthart, and David Gross. “Entanglement swapping in generalized probabilistic theories and iterated Clauser-Horne-Shimony-Holt games”. In: *Phys. Rev. A* 110 (2 Aug. 2024), p. 022225.

Bundling of bipartite entanglement [1]

Maike Drieb-Schön,¹ Florian Dreier,^{1,2} and Wolfgang Lechner^{1,2}

¹*Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria*

²*Parity Quantum Computing GmbH, A-6020 Innsbruck, Austria*

We investigate bipartite entanglement and prove that in constrained energy subspaces, the entanglement spectra of multiple bipartitions are the same across the whole subspace. We show that in quantum many-body systems the bipartite entanglement entropy is affected in such a way that it forms "bundles" under unitary time evolution. Leveraging the structure of the subspace, we present methods to verify whether the entanglement spectrum of two bipartitions is identical throughout the entire subspace. This previously unobserved equivalence in entanglement behavior has crucial practical consequences, as it considerably reduces the experimental effort needed to determine the total entanglement. To achieve this, we significantly depart from previous approaches by systematically establishing a connection between the structure of the subspace to which the system state is constrained and the spectra of the reduced density matrices of all subsystems. Our results are primarily mathematical and are numerically supported by application examples, including embeddings that inherently induce energetic constraints in quantum computational systems. In addition, we develop for such embedded systems an algorithm to verify whether two bipartitions yield the same entanglement spectrum, and we prove that, for the parity embedding, this algorithm runs in polynomial rather than exponential time.

REFERENCES

- [1] M. Drieb-Schön, F. Dreier, and W. Lechner, (2025), [arXiv:2512.16979](https://arxiv.org/abs/2512.16979) [quant-ph].

Using EPR's logic to identify the element of reality of a homodyne measurement

R. Y. Teh, M. Thenabadu, M. D. Reid, P.D. Drummond

Centre for Quantum Science and Technology Theory, Swinburne University of Technology, Melbourne 3122, Australia

Quantum mechanics is a statistical theory, which makes predictions about ensemble averages. Yet, any probabilistic theory must describe *some* objective reality, or else it is operationally meaningless. Stochastic Schrödinger equation methods can model objective experimental events at the observed, macroscopic level, through describing stochastic jumps or measured currents.

We validate this approach using Einstein, Podolsky and Rosen's argument. They used a no-signaling principle to define real events: "If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."

Our alternative logic is subtly different. We do *not* assume that changing measurement settings has no effect. Instead, we apply the argument only to macroscopic currents *after* the phase-angle or measurement setting is chosen. For measurements made after fixing measurement settings, there is no Bell counterexample, the no-signaling principle is valid, and the EPR argument is applicable.

Trajectories generated by the stochastic Schrödinger equation (SSE) were originally proposed as models for state reduction, and are now used to simulate the output measurements of quantum experiments. We show that the predicted homodyne current correlations change drastically with the stochastic method used. To obtain the physical unfiltered "element of reality", we prove that one must use a Stratonovich noise at large bandwidth, and verify this with an EPR argument. By comparison, homodyne current models with Ito stochastic noise give incorrect correlations.

Using this, we show how filtering dynamics and quantum noise reduction are complementary in modern quantum technology experiments, through simulations of a coherent Ising model with strong coupling. We also model a foundational gedanken-experiment originally proposed by Schrödinger, in which the choice of measuring either x or p at one causally separated site is delayed until after the prepared state has started to decay out of the interferometer for measurement.

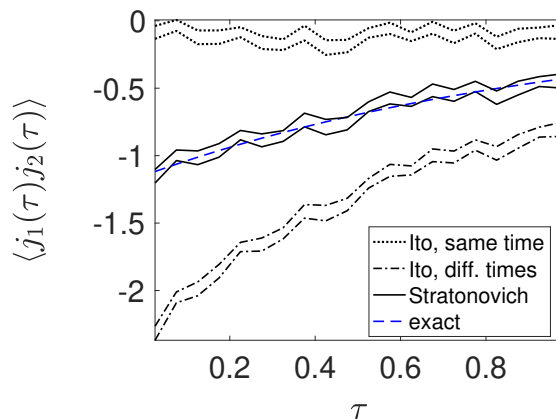


Figure 1: The homodyne current correlation $\langle j_1(\tau)j_2(\tau) \rangle$ for a damped EPR state. The blue dashed line is the exact solution, in agreement with the Stratonovich result.

Certifying components of quantum networks using the generalised Choi isomorphism

S. Egelhaaf^{1,2} and R. Uola^{1,3,4}

¹Department of Applied Physics, University of Geneva, 1205 Geneva, Switzerland

²Vienna University of Technology, Atominstitut & Vienna Center for Quantum Science and Technology (VCQ), Stadionallee 2, 1020 Vienna, Austria

³Department of Physics and Astronomy, Uppsala University, Box 516, 751 20 Uppsala, Sweden

⁴Nordita, KTH Royal Institute of Technology and Stockholm University, Hannes Alfvéns väg 12, 10691 Stockholm, Sweden

We propose a framework for network steering, facilitating the certification of quantum states and measurements. It is based on the Choi isomorphism, which maps states and measurements to quantum operations. This allows the expression of network steering as a set of local maps. We demonstrate the power of the approach by deriving explicit certification criteria for common convex geometric quantities for quantum states and measurements. We also discuss the benchmarking of entanglement dimensionality, thus, bringing the idea of high-dimensional steering to networks. In particular, the activation of high-dimensional steering is demonstrated. Furthermore, we introduce the concept of the Schmidt number for measurements, which we believe is relevant for the benchmarking of detectors.

Generalization of the Schmidt Sphere to Qutrit-Pairs and Geometric Two-Qutrit Schmidt Gates

Adam Fredriksson^{1,2} and Erik Sjöqvist²

¹*Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany*

²*Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden*

The Bloch sphere is a well-known geometrical representation of a single qubit, but it has no associated notion of entanglement. The Schmidt sphere [1] is a Bloch-like structure pertaining to qubit-pairs that provides a connection between geometry and bipartite entanglement. In this work, the Schmidt sphere is generalized to qutrit-pairs and the construction of geometric two-qubit Schmidt gates in Ref. [2], which is based on the Schmidt sphere, is subsequently generalized to qutrit-pairs for a particular set of maximally entangled two-qutrit states. Notably, the generalization of the gate construction required the derivation of a sum rule for geometric phases, and some of the constructed geometric two-qutrit Schmidt gates were found to be entangling.

References

- [1] E. Sjöqvist, Phys. Rev. A **62**, 022109 (2000)
- [2] M. Johansson Saarijärvi and E. Sjöqvist, Phys. Rev. A **109**, 042610 (2024)

Towards Parallel Bell Tests using High Dimensional Entanglement

D. Sabogal^{1,2}, S. Goel¹, B. Ghosh¹, N. Valencia¹, W. McCutcheon¹, N. Miklin³, A. Cabello^{4,5}, and M. Malik¹

¹Institute of Photonics and Quantum Sciences, Heriot-Watt University, Edinburgh, ²Tampere University, Tampere, Finland, ³Technical University of Darmstadt, Darmstadt, Germany, ⁴Departamento de Física Aplicada II, Universidad de Sevilla, Sevilla, Spain, ⁵Instituto Carlos I de Física Teórica y Computacional, Universidad de Sevilla, Sevilla, Spain

Bell tests constitute the sharpest experimental expression of the Einstein–Podolsky–Rosen paradox, revealing the incompatibility between quantum correlations and local-realistic descriptions of nature. Beyond their foundational role, Bell violations underpin a growing range of device-independent quantum information protocols. Given this dual significance, it is crucial to develop experimental Bell tests that close all relevant loopholes under realistic conditions.

In optical platforms, the dominant limitation is the detection loophole, governed by the detection efficiency η . If η does not exceed a critical threshold η_{C} , local hidden-variable models can reproduce apparent Bell violations, often forcing experiments to rely on the fair-sampling assumption. This challenge becomes particularly acute in long-distance implementations, where transmission losses render conventional loophole-free Bell tests impractical. Although theoretical advances—such as partially entangled states, high-dimensional Bell inequalities, and hyperentangled encodings—have progressively lowered η_{C} , scalable and experimentally feasible strategies remain an open problem.

Parallelized Bell tests provide a powerful conceptual shift: multiple Bell inequalities can be violated simultaneously using a single high-dimensional entangled system, rather than independent entangled pairs. Recent theory predicts that penalized N-product Bell inequalities enable an exponential reduction of the detection-efficiency requirement with the number of parallel tests [1].

We work towards the first experimental demonstration of parallelized Bell tests enabled by deliberately engineered multi-outcome measurements. Using a multi-plane light converter, we manipulate high-dimensionally entangled biphoton states generated via spontaneous parametric down-conversion. This platform allows multiple CHSH-type inequalities to be violated in parallel within a single bipartite system. Our results establish an experimentally viable route toward lowering detection-efficiency thresholds and advancing loophole-resistant tests of quantum nonlocality in high dimensions.

References

- [1] Phys. Rev. Lett. 129, 230403 (2022)

Average-Case Certification of Quantum Gates via Learning-Assisted Quantum System Quizzing

K. U. Giang¹ and M.Gachechiladze¹

¹*Department of Computer Science, Technical University of Darmstadt, Darmstadt, 64289 Germany*

Reliable certification of quantum processors remains a central challenge, as many existing methods do not guarantee that only a correctly functioning quantum device can pass the test, or rely on assumptions vulnerable to systematic state-preparation-and-measurement (SPAM) errors. Recently, [1] introduced quantum system quizzing, a certification framework in which a classical verifier tests quantum computations while remaining robust to SPAM errors, and derived worst-case performance bounds for single-qubit gates.

In this work, we extend this framework by combining machine learning techniques with optimal control to obtain average-case performance bounds under a broad class of realistic noise models. This approach yields tighter and more practically relevant guarantees for end users than worst-case analyses. We further develop a systematic comparison between our method and established certification and calibration protocols, including randomized benchmarking and gate set tomography. Our results demonstrate that the proposed approach achieves a favorable complexity scaling while providing meaningful certification guarantees, positioning it as a practical alternative for near-term quantum devices and paving the way toward fully classical, efficient, and autonomous calibration of quantum computers.

References

- [1] J. Nöller, *Quantum* **9**, 1825 (2025)

Compatibility of binary qubit measurements

D. Grinko^{1,2} and R. Uola^{3,4}

¹ *QuSoft, Amsterdam, The Netherlands*

² *Institute for Logic, Language and Computation, University of Amsterdam, Amsterdam, The Netherlands*

³ *Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden*

⁴ *Nordita, KTH Royal Institute of Technology and Stockholm University, Stockholm, Sweden*

Deciding which sets of quantum measurements allow a simultaneous readout is a central problem in quantum measurement theory. The problem is relevant not only from the foundational perspective but also has direct applications in quantum correlation problems fueled by incompatible measurements. Although central, only a few analytical criteria exist for deciding the incompatibility of general sets of measurements. This work approaches the problem through functions defined on the Boolean hypercube and their Fourier transformations. We show that this reformulation of the problem leads to a complete geometric characterisation of joint measurability of any finite set of unbiased binary qubit measurements and gives a necessary condition for the biased case. We discuss our results in the realm of quantum steering, where they translate into a family of steering inequalities. When certain unbiasedness conditions are fulfilled, these criteria are tight, hence fully characterizing the steering problem when the trusted party holds a qubit, and the untrusted party performs any finite number of binary measurements. We further discuss how our results point towards a second-order cone programming approach to measurement incompatibility and compare this to the predominantly used semi-definite-programming-based techniques. We use our approach to falsify an existing conjecture on measurement incompatibility of special sets of measurements.

References

- [1] D. Grinko and R. Uola, *Phys. Rev. Lett.* 135, 200201 (2025).

Entanglement-Assisted Communication: Bridging Theory and Practical Application

J. Hawellek¹

¹Institute for Communications Technology, Technische Universität Braunschweig, Braunschweig, Germany

In quantum information theory, it is well established that entanglement is a valuable resource, enhancing communication tasks not only regarding security aspects but also increasing communication rates. One approach involves entanglement to increase cooperation between communication parties, even though adhering to the no-communication theorem. For instance, cooperating transmitters in a multiple access channel, such as interfering wireless transmitters, perform better than working independently. This observation has also been validated for entanglement-assisted transmitters [1–3].

The pathway to implementing such systems involves significant engineering efforts, particularly in performing accurate and controllable measurements on entanglement resources, which are a crucial step in the encoding process. Furthermore, it is necessary to continue exploring the class of communication channels observing such an advantage. Current theoretical results are related to experiments that violate Bell inequalities, while their practical implications for communication tasks remain uncertain.

References

- [1] Leditzky, F., Alhejji, M. A., Levin, J. & Smith, G. Playing games with multiple access channels. *Nature Communications* **11**, 1497 (2020).
- [2] Seshadri, A., Leditzky, F., Siddhu, V. & Smith, G. On the Separation of Correlation-Assisted Sum Capacities of Multiple Access Channels. *IEEE Transactions on Information Theory* **69**, 5805–5844 (2023).
- [3] Pereg, U., Deppe, C. & Boche, H. The Multiple-Access Channel with Entangled Transmitters. In *Proc. of 2023 IEEE Global Communications Conference* 3173–3178 (2023).

Escaping Bell: fight, flight, or freeze

Flavien Hirsch, Ricardo Faleiro

Instituto de Telecomunicações, Instituto Superior Técnico, 1049-001 Lisbon, Portugal

Bell's theorem and its experimental validation showed that any empirically adequate theory using a classical framework must be nonlocal. This stark conclusion has inspired decades of attempts to "escape Bell," either by accepting the framework and dropping an assumption -forcing deep changes to the way we model Nature- or by rejecting the framework itself, in realist or instrumentalist forms.

I review these attempts and show how they can be sorted into 3 categories of attitude towards Bell's theorem: fight, flight, or freeze.

I will compare the strengths and weaknesses of these "families" of tentative escapes from Bell, and discuss possible implications on future physical theories.

Activation of Postquantum Steering

Ana Belén Sainz^{1,2}, Paul Skrzypczyk^{3,4}, and Matty J. Hoban⁵

¹International Centre for Theory of Quantum Technologies, University of Gdańsk, 80-309 Gdańsk, Poland

²Basic Research Community for Physics e.V., Germany

³H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom

⁴CIFAR Azrieli Global Scholars program, CIFAR, Toronto, Canada

⁵Quantum Group, Department of Computer Science, University of Oxford, Wolfson Building, Parks Road, Oxford, OX1 3QD, United Kingdom

There are possible physical theories that give greater violations of Bell's inequalities than the corresponding Tsirelson bound, termed post-quantum non-locality. Such theories do not violate special relativity, but could give an advantage in certain information processing tasks. There is another way in which entangled quantum states exhibit non-classical phenomena, with one notable example being Einstein–Podolsky–Rosen (EPR) steering; a violation of a bipartite Bell inequality implies EPR steering, but the converse is not necessarily true. The study of post-quantum EPR steering is more intricate, but it has been shown that it does not always imply post-quantum nonlocality in a conventional Bell test. In this work we show how to distribute resources in a larger network that individually do not demonstrate post-quantum non-locality but violate a Tsirelson bound for the network. That is, we show how to activate post-quantum steering so that it can now be witnessed as post-quantum correlations in a Bell scenario. One element of our work that may be of independent interest is we show how to self-test a bipartite quantum assemblage in a network, even assuming post-quantum resources. This work is based on reference [BSSH25]; see [ZHSS24] for extensions of this work.

References

- [BSSH25] Ana Belén Sainz, Paul Skrzypczyk, and Matty J Hoban. Activation of post-quantum steering. *New Journal of Physics*, 27(12):124508, 2025.
- [ZHSS24] Beata Zjawin, Matty J. Hoban, Paul Skrzypczyk, and Ana Belén Sainz. Activation of postquantumness in bipartite generalized Einstein-Podolsky-Rosen scenarios. *Phys. Rev. A*, 110:042212, 2024.

Generalized Dynamics in Phase Space: Quantum States Require Quantum Time Evolution

JOEL D. HUBER^{1,2}, MATTHIAS KLEINMANN^{1,2}

¹ Departement für Quantentechnologie, Universität Münster, Münster, Germany

² Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Siegen, Germany

Within the Hilbert space formulation of quantum mechanics, reversible dynamics is described by unitary time evolution and hence by the Schrödinger equation. We investigate how quantum dynamics can be altered while still yielding a consistent theory. For this, we use a phase-space formulation of quantum mechanics, which readily allows for modifications of quantum theory [1]. Specifically, in the Wigner–Weyl formalism, quantum states are described as quasi-probability densities over phase space, and quantum time evolution is governed by the Moyal bracket. To study deviations from this dynamics, we consider generalizations of the Moyal bracket and how they affect time evolution under anharmonic potentials. The effects on the momentum and position distributions are, at least in principle, experimentally accessible. We analyze which modifications correspond to consistent dynamics, meaning that the position and momentum distributions are valid probability densities for all times—in particular, they are required to be non-negative. Previously, it has been shown that an algebraic condition, specifically the Jacobi identity, uniquely singles out the Moyal bracket [2]. Here, we show that the operational positivity condition alone suffices to rule out modifications; in fact, we find that it is sufficient to only consider the ground state and the first excited state of the quantum mechanical harmonic oscillator. For Gaussian states, any time evolution in between classical and quantum dynamics is consistent, whereas the first excited state is only compatible with quantum evolution. In the case of ideal preparation of these states, phase space dynamics is strongly constrained, and quantum dynamics is found to be the only consistent reversible time-evolution, at least to the order that can be probed in a cubic potential.

References

[1] M. Plávala and M. Kleinmann, *Physical Review A* **108**, 052212 (2023).

[2] P. Fletcher, *Physics Letters B* **248**, 323 (1990).

Generalised contextuality of continuous variable quantum theory can be revealed with a single projective measurement

Pauli Jokinen,^{1,2} Mirjam Weilenmann,^{3,4} Martin Plávala,⁵
Juha-Pekka Pellonpää,⁶ Jukka Kiukas,⁷ and Roope Uola^{1,2}

¹*Department of Physics and Astronomy, Uppsala University, Box 516, 751 20 Uppsala, Sweden*

²*Nordita, KTH Royal Institute of Technology and Stockholm University, 10691 Stockholm, Sweden*

³*Inria, Télécom Paris - LTCI, Institut Polytechnique de Paris, 91120 Palaiseau, France*

⁴*Department of Applied Physics, University of Geneva, Switzerland*

⁵*Institut für Theoretische Physik, Leibniz Universität Hannover, 30167 Hannover, Germany*

⁶*Department of Physics and Astronomy, University of Turku, FI-20014 Turun yliopisto, Finland*

⁷*Department of Mathematics, Aberystwyth University, Aberystwyth SY23 3BZ, United Kingdom*

ABSTRACT

Generalized contextuality is a possible indicator of non-classical behaviour in quantum information theory. In finite-dimensional systems, this is justified by the fact that noncontextual theories can be embedded into some simplex, i.e. into a classical theory. We show that a direct application of the standard definition of generalized contextuality to continuous variable systems does not envelope the statistics of some basic measurements, such as the position observable. In other words, we construct families of fully classical, i.e. commuting, measurements that nevertheless can be used to show contextuality of quantum theory. To overcome the apparent disagreement between the two notions of classicality, that is commutativity and noncontextuality, we propose a modified definition of generalised contextuality for continuous-variable systems. The modified definition is

based on a physically-motivated approximation procedure, that uses only finite sets of measurement effects. We prove that in the limiting case this definition corresponds exactly to an extension of noncontextual models that benefits from non-constructive response functions. In the process, we discuss the extension of a known connection between contextuality and no-broadcasting to the continuous-variable scenario, and prove structural results regarding fixed points of infinite-dimensional entanglement breaking channels.

-
- [1] P. Jokinen, M. Weilenmann, M. Plávala, J.-P. Pellonpää, J. Kiukas, and R. Uola, (2026), [arXiv:2601.14067](https://arxiv.org/abs/2601.14067) [quant-ph].

Simulating quantum instruments with projective measurements and quantum post-processing

Shishir Khandelwal and Armin Tavakoli

Physics Department and NanoLund, Lund University, Sweden

Quantum instruments describe both the classical outcome and the updated state associated with a quantum measurement. We ask whether these processes can be simulated using only a natural subset of resources, namely projective measurements on the system and quantum processing of the post-measurement states. We show that the simulability of instruments can be connected to an entanglement classification problem. This leads to a computationally efficient necessary condition for simulation of generic instruments and to a complete characterisation for qubits. We use this to address relevant quantum information tasks, namely (i) the noise-tolerance of standard qubit unsharp measurements, (ii) non-projective advantages in information-disturbance trade-offs, and (iii) increased sequential Bell inequality violations under projective measurements. Moreover, we consider also d -dimensional Lüders instruments that correspond to weak versions of standard basis measurements and show that for large d these can permit scalable noise-advantages over projective implementations.

Reference:

Phys. Rev. Lett. 135, 040202 (2025)

Local content for Generalized Qubit Measurements

A. Konderak¹ and M. J. Renner²

¹ *Centrum Fizyki Teoretycznej PAN , Warsaw, Poland*

² *The Institute of Photonic Sciences, Castelldefels, Spain*

Full nonlocality is the strongest form of nonlocality that can be realized in nature. It can be shown that there are situations in which every single realization of an experiment cannot be obtained with a classical setting, while in the standard nonlocality, it is only the complete statistics that cannot be reproduced classically. Despite several examples of fully nonlocal statistics in the literature, achieved with fewer and fewer resources, it is still unclear whether full nonlocality can be obtained without maximally entangled states. In particular, it was proved that, for bipartite qubit systems, all partially entangled states have a local content, that is, it is not possible to extract fully nonlocal correlations. Nevertheless, this result has only been proved for von Neumann orthogonal measurements. We were able to prove that this result can be generalized to all generalized measurements. Furthermore, we were able to obtain examples of fully nonlocal correlations generated by partially entangled states in dimensions 3, proving that this result cannot be further generalized.

References

- [1] A. Konderak, M. J. Renner et al., in preparation (2026).
- [2] M. J. Renner, E. Lobo, A. Konderak, R. Augusiak, A. Acin, in preparation (2026).

Immanant inequalities and entanglement*

Albert Rico^{1,2}, Dmitri Grinko^{3,4,5}, Robin Krebs⁶, Lin Htoo Zaw⁷

¹GIQ - Quantum Information Group, Department of Physics, Autonomous University of Barcelona, Spain

²Theoretical Quantum Optics, University of Siegen, Germany

³QuSoft, Amsterdam, Netherlands

⁴Institute for Logic, Language and Computation, University of Amsterdam, Netherlands

⁵Korteweg-de Vries Institute for Mathematics, University of Amsterdam, Netherlands

⁶Quantum Computing, Technical University Darmstadt, Germany

⁷Centre for Quantum Technologies, National University of Singapore, Singapore

We investigate the representation-theoretical links between the areas of immanant inequalities and multipartite entanglement. Here, the problem of finding immanant inequalities can essentially be reduced to finding witnesses to the fully separable subset of the simplex of multipartite Werner states. This allows relaxations and other tools known from physics to be transferred to the difficult mathematical problem of finding immanant inequalities. Conversely, the mathematical literature puts heavy emphasis on immanant inequalities, which are valid for matrices of arbitrary size. This allows constructing witness families in arbitrarily high dimensions and parties. Such witnesses can then be (efficiently ?) applied in an experimental setting, using methods such as shadow tomography (?) and weak Schur sampling. Besides the immanant inequalities, which are related to full separability, we also study m -separability of multipartite Werner states, that is, specific types of biseparability where partitions are of bounded size.

This paper presents a tentatively complete characterization of all immanant inequalities for matrices of size 3 and 4 respectively. This is achieved by applying methods from convex geometry and various tools of entanglement theory to the remapped problem. New immanant inequalities related to *indecomposable* witnesses are found, and various immanant inequalities from mathematical literature are shown to relate to *decomposable* witnesses. This establishes the semidefinite programs obtained from the PPT relaxation as viable tool for deriving new immanant inequalities and simultaneously poses the question of the meaning of decomposability when viewed detached from an entanglement-theoretical interpretation.

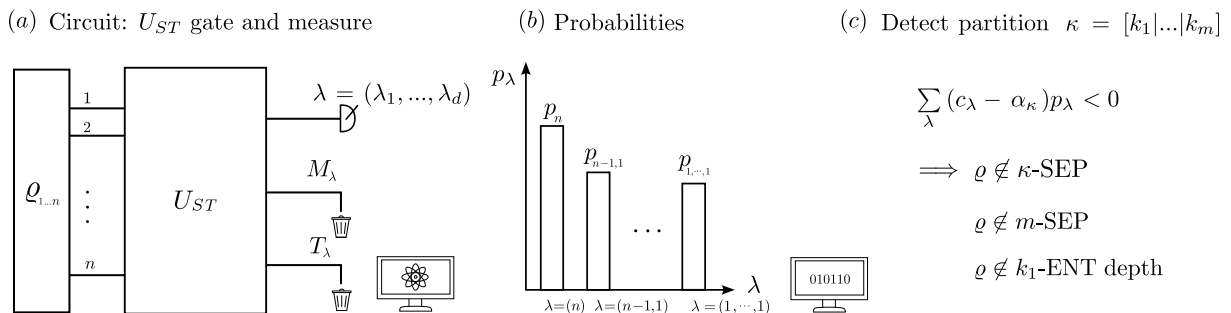


Figure 1: Practical entanglement detection: (a) We perform weak Schur sampling with an appropriate circuit, isolating irrep labels λ into a subsystem. (b) We tabulate measurement statistics, allowing inference of a statistical distribution over irreps (Young diagrams). (c) We apply viable witnesses for m -separability, or "translated" immanant inequalities.

*This contribution is based on "Detection of many-body entanglement partitions in a quantum computer", arXiv: 2511.13822

Generalized measurement incompatibility

Edwin Peter Lobo, Maria Balanzó-Juandó, Stefano Pironio

*Laboratoire d'Information Quantique, Université libre de Bruxelles (ULB),
Av. F. D. Roosevelt 50, 1050 Bruxelles, Belgium.*

Quantum measurements can be incompatible, i.e., they can fail to be jointly measurable. Incompatible measurements are essential for demonstrating nonclassicality in quantum theory, e.g., Bell nonlocality, quantum steering, Kochen-Specker contextuality all require incompatible measurements. In this work, we extend a generalized notion of measurement incompatibility called ‘partial joint measurability’ [1] and show that determining whether or not a set of measurements demonstrate generalized measurement incompatibility can be cast as an instance of semidefinite programming (SDP). We prove that in the setting of an untrusted measurement device, an adversary Eve— limited to classical side information (i.e., without access to quantum memory)— can perfectly guess the outcomes used for key-generation (in QKD protocols)/randomness extraction (in QRNG protocols) if, and only if, the set of measurements performed in the experiment are partially jointly measurable. This leads to two applications:

Firstly, our formalism gives us simple attacks for QKD and QRNG protocols that contradict some of the claims in literature. We identify the mistake that led to these incorrect results.

Secondly, our result implies that we can always extract randomness from the outcomes of an untrusted measurement device if the measurements performed are not partially jointly measurable. This lets us intelligently pick the measurements as well as the rounds from which to generate the key/randomness for QKD and QRNG protocols.

We also derive some tight analytical thresholds on detection losses and noise under which a set of qubit projective measurements become partially jointly measurable, which may be of independent interest.

References

- [1] Michele Masini, Marie Ioannou, Nicolas Brunner, Stefano Pironio, and Pavel Sekatski, *Quantum* **8**, 1574 (2024).

Absolute Schmidt number: characterization, detection, and resource-theoretic quantification

Bivas Mallick¹, Saheli Mukherjee¹, Nirman Ganguly², and A. S. Majumdar¹

¹ S. N. Bose National Centre for Basic Sciences, Block JD, Sector III, Salt Lake, Kolkata 700 106, India

² Department of Mathematics, Birla Institute of Technology and Science, Pilani, Hyderabad Campus, Jawahar Nagar, Kapra Mandal, Medchal District, Telangana 500078, India

The dimensionality of entanglement, quantified by the Schmidt number, is a valuable resource for a wide range of quantum information processing tasks. While the Schmidt number remains invariant under local unitaries, it can, in general, be increased through suitable global unitary operations. In this work, we introduce the notion of the absolute Schmidt number, referring to states whose Schmidt number cannot be increased by any global unitary transformation. We begin by providing a complete characterization of the set of states whose Schmidt number is invariant under all global unitaries. Due to the significant operational advantages offered by higher Schmidt-number states, a fundamental and important question concerns the identification of states that do not have the absolute Schmidt number property. To address this, we develop both witness-based and moment-based techniques to detect states whose Schmidt number can indeed be enhanced by global unitaries. Next, we investigate the resource-theoretic features of states that do not exhibit the absolute Schmidt number property. We introduce two quantitative measures, one based on Schmidt number witness and the other based on robustness, and we show that both satisfy all the requirements for a valid quantifier of nonabsolute Schmidt number. Finally, we extend our analysis to quantum channels by introducing a new class of channels that possess the absolute Schmidt number property. We also derive a necessary and sufficient condition for identifying when a channel has the absolute Schmidt number property, with our discussion confined to the class of covariant channels.

Certifying high-dimensional quantum channels

**Sophie Engineer^[1,2], Suraj Goel^[1], Sophie Egelhaaf^[3], Will
McCutcheon^[1], Vatshal Srivastav^[1], Saroch
Leedumrongwatthanakun^[1,4], Sabine Wollmann^[1], Benjamin D.M.
Jones^[2], Thomas Cope^[5], Nicolas Brunner^[3], Roope Uola^[3], Mehul
Malik^[1]**

[1] Institute of Photonics and Quantum Sciences, Heriot-Watt University, Edinburgh

[2] H. H. Wills Physics Laboratory and Department of Electrical & Electronic Engineering, University of Bristol, Bristol, United Kingdom,

[3] Department of Applied Physics, University of Geneva, Switzerland,

[4] Division of Physical Science, Faculty of Science, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand,

[5] Institut für Theoretische Physik, Leibniz Universität Hannover, 30167 Hannover, Germany

The use of high-dimensional systems for quantum communication opens interesting perspectives, such as increased information capacity and noise resilience. In this context, it is crucial to certify that a given quantum channel can reliably transmit high-dimensional quantum information. Here we develop efficient methods for the characterization of high-dimensional quantum channels. We first present a notion of dimensionality of quantum channels, and develop efficient certification methods for this quantity. We consider a simple prepare-and-measure setup, and provide witnesses for both a fully and a partially trusted scenario. In turn we apply these methods to a photonic experiment and certify dimensionalities up to 59 for a commercial graded-index multi-mode optical fiber. Moreover, we present extensive numerical simulations of the experiment, providing an accurate noise model for the fiber and exploring the potential of more sophisticated witnesses. Our work demonstrates the efficient characterization of high-dimensional quantum channels, a key ingredient for future quantum communication technologies.

References

[1] Phys. Rev. Research **7**, 033233 (2025)

Towards information-theoretic principles to delimit signalling quantum correlations

C. Meijer¹ camiel.meijer@lip6.fr and Jessica Bavaresco¹ jessica.bavaresco@lip6.fr

¹ Sorbonne Université, LIP6, 75005 Paris, France

Several physical and information-theoretic principles for delimiting quantum correlations have been proposed and studied over the years. Some prominent examples are non-trivial communication complexity, information causality, local orthogonality, the E-principle, and macroscopic locality. However, these all apply to non-signalling scenarios, while signalling correlations that arise in scenarios of quantum communication have garnered far less attention so far. Our work focuses on developing information-theoretic principles that are able to delimit the set of correlations that can be realised within signalling quantum theory. By this, we mean the correlations that can be created in a scenario as described by a process matrix, where two parties are each allowed to interact with a quantum state once and share both classical and quantum communication resources. This scenario allows for signalling correlations between the parties, which can happen in a definite or an indefinite causal order. This includes genuine two-way signalling correlations (non-causal correlations) that cannot be described as a probabilistic mixture of one-way signalling correlations with different signalling directions. While non-causal correlations can in principle be achieved in these signalling quantum scenarios, there are limitations to the set of correlations that can be produced even by process matrices.

First, we adapted the information-theoretic principle of trivial communication complexity, as defined for non-signalling cases, to the signalling/non-causal scenario. We were able to do so by constructing a new information-theoretic task based on the Guess Your Neighbour's Input (GYNI) game. The task consists of two players and a referee. The players are given a GYNI task to complete by the referee, and the quantity of interest is the average amount of rounds of the game needed for the players to successfully complete this task. Players that have access to deterministic, perfect two-way signalling correlations are able to complete the task in only a single round, regardless of the size of their input bit string. However, players sharing any other kind of correlations will require, on average, a number of rounds that scales with $\log(N)$, where N is the length of the input bit string, in order to win the game. Our task is intimately related to the ability of the parties to compute any function from two bit strings to two bit strings. Therefore, we present the trivialisation of this task as a motivation to exclude perfect two-way signalling correlations as a possible resource in a reasonable physical theory.

The trivialisation of this task is able to exclude a single point of the polytope of signalling correlations, but not any correlations that are arbitrary close to it. In order to strengthen our result, several approaches for broadening its scope were examined, with the goal of allowing one to exclude a volume in the polytope of signalling correlations instead of just a single point. We have been working on proving a conjecture stating that the total mutual information attainable in a signalling correlations scenario with indefinite causal order cannot exceed the total mutual information attainable in the causally ordered scenario. We know that this limit on the mutual information does not hold for perfect two-way signalling correlations, yet, it holds for all one-way signalling correlations. If we are able to prove that this conjecture holds for all non-causal quantum correlations, this might allow us to exclude a non-trivial volume of correlations, thereby potentially leading to another information-theoretic separation of quantum and post-quantum correlations, this time in signalling scenarios. This would provide a better physical intuition into what the limits of the quantum set are even in the presence of indefinite causal order.

All star-incompatible measurements can certify steering-based randomness

Shintaro Minagawa¹ and Ravi Kunjwal¹

¹Aix-Marseille University, CNRS, LIS, Marseille, France

Certifying that the randomness is unpredictable even to an attacker (Eve) is crucial. Device-independent (DI) randomness certification (e.g. [1]) is one of the representative methods, but its experimental requirements make implementations costly [2]. This has motivated the study of a more relaxed paradigm, one-sided device-independent (1SDI) randomness certification, where one party is trusted [3]. In this work, we identify a necessary and sufficient resource for quantum measurements to certify randomness in the 1SDI setup. We also provide a quantitative analysis of the quantum resource required for generating a certain level of certified randomness.

Contributions

- We show that *star-incompatibility* (originally $K_{1,m-1}(x^*)$ -incompatibility [4]) *i.e.*, the measurement setting of interest for the guessing probability of Eve is incompatible with at least one of the remaining measurement settings, is a necessary and sufficient resource for producing an assemblage with certified randomness.
- We provide a lower bound on the star-incompatibility weight, a measure of star-incompatibility we introduce, in terms of the optimal guessing probability of Eve. This gives a one-sided estimation of star-incompatibility from certified randomness.

Relation to prior work

Ref. [4] showed that assemblages that exhibit certified randomness must have a realization using **a** set of star-incompatible measurements. Our result shows the opposite direction, showing that **every** star-incompatible set of measurements can certify steering-based randomness. Moreover, we provide an inequality that lower bounds the necessary amount of star-incompatibility using the guessing probability, thereby addressing the task proposed in Ref. [4] of quantifying star-incompatibility through certified randomness.

References

- [1] R. Colbeck, Quantum and relativistic protocols for secure multi-party computation (2011), Ph.D. thesis, University of Cambridge (2006).
- [2] Y. Liu, et al., Nature **562**, 548 (2018).
- [3] E. Passaro, D. Cavalcanti, P. Skrzypczyk, and A. Acín, New Journal of Physics **17**, 113010 (2015).
- [4] Y. Li, Y. Xiang, J. Tura, and Q. He, Phys. Rev. Lett. **135**, 060201 (2025).

Randomness Certification in the Bilocal Quantum Network

Giorgio Minati¹, Giovanni Rodari¹, Emanuele Polino^{1, 2}, Francesco Andreoli³, Davide Poderini^{4, 5}, Rafael Chaves^{4, 6}, Gonzalo Carvacho¹, and Fabio Sciarrino¹

¹*Dipartimento di Fisica - Sapienza Università di Roma, P.le Aldo Moro 5, I-00185 Roma, Italy*

²*Centre for Quantum Dynamics and Centre for Quantum Computation and Communication Technology Griffith University Yuggera Country Brisbane Queensland 4111 Australia*

³*ICFO - Institut de Ciències Fotòniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Spain*

⁴*International Institute of Physics, Federal University of Rio Grande do Norte, 59078-970, Natal, Brazil*

⁵*Università degli Studi di Pavia, Dipartimento di Fisica, QUIT Group, via Bassi 6, 27100 Pavia, Italy*

⁶*School of Science and Technology, Federal University of Rio Grande do Norte, 59078-970, Natal, Brazil*

Device-independent randomness certification [1] plays a pivotal role in quantum information, driven both by its foundational implications, intimately linked to Bell nonlocality, and its potential applications in secure communication. While this task has been extensively investigated within the bipartite Bell scenario, it remains largely unexplored in quantum networks with multiple independent sources [2]. This is mainly due to the significantly more complex characterization of correlations among network nodes, despite the relevance of these scenarios for long-range communication and quantum key distribution. In this work [3], we address randomness certification within the entanglement-swapping network, modeled by a causal structure with two independent sources, i.e. the bilocal scenario [4]. Based on the scalar extension technique [5], we develop a numerical approach to quantify secure randomness against a potential eavesdropper. In particular, we explore different attacking strategies where the eavesdropper either has full access to the sources, enabling entangled measurements, or is constrained to separately attack the two sources. In both cases, we can certify up to 1.41 bits of randomness from the outer nodes of the network, surpassing the 1.23 bits achieved by violating the CHSH inequality. By exploring explicit eavesdropping strategies, we derive analytical upper bounds on the certifiable randomness and identify specific configurations capable of achieving the theoretical maximum of 4 bits. Finally, we benchmark our method using experimental data [6] applied to different attack scenarios, reporting the first-ever certification of randomness within a genuine quantum network. These findings provide valuable insights into the study of quantum networks, paving the way to advanced quantum protocols, such as long-range communication and quantum key distribution, critical for the implementation of the future quantum internet.

References

- [1] Pironio, S. et al. *Nature* 464, 1021–1024 (2010).
- [2] Tavakoli, A., et al. *Reports on Progress in Physics* 85, 56001 (2022).
- [3] Minati G. et al. *.Sci. Adv.* **12**, eaea8571(2026).
- [4] Branciard, C., et al. *Phys. Rev. A* 85, 032119 (2012).
- [5] Pozas-Kerstjens, A. et al. *Physical review letters* 123, 140503 (2019).
- [6] Carvacho, G. et al. *Nature communications* 8, 1–6 (2017).

Detecting genuine multipartite entanglement using moments of positive maps

Saheli Mukherjee¹, Bivas Mallick¹, Sahil Gopalkrishna Naik¹, Ananda G. Maity²,
and A. S. Majumdar¹

¹ S. N. Bose National Centre for Basic Sciences, Block JD, Sector III, Salt Lake, Kolkata 700
106, India

² School of Physical Sciences, Indian Institute of Technology Goa, Ponda 403401, Goa, India

Genuine multipartite entanglement (GME) represents the strongest form of entanglement in multipartite systems, providing significant advantages in various quantum information processing tasks. In this work, we propose an experimentally feasible scheme for detecting GME, based on the truncated moments of positive maps (namely the transposition and reduction maps). Our method avoids the need for full state tomography, making it scalable for larger systems. We provide illustrative examples of both pure and mixed states to demonstrate the efficacy of our formalism in detecting inequivalent classes of tripartite genuine entanglement. We further demonstrate the detection of quadripartite genuine entanglement, underscoring the effectiveness of our method in identifying entanglement beyond the tripartite case. Finally, we present a proposal for realising these moments in real experiments.

Structure of quantum measurements implementable with one round of classical communication

Arthur C. R. Dutra^{1,2}, Ties-A. Ohst^{1,3,4}, Hai-Chau Nguyen¹
and Otfried Gühne¹

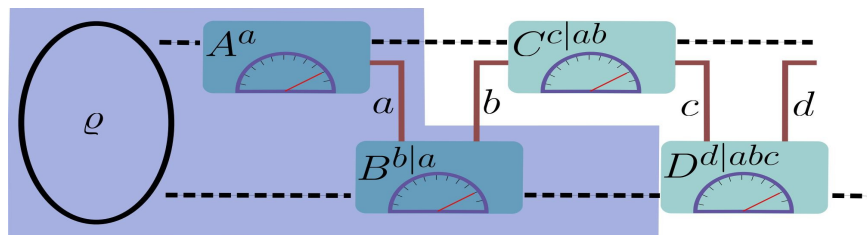
¹Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany

²Instituto de Matemática, Estatística e Computação Científica, Universidade Estadual de Campinas, Campinas, SP, Brazil

³Department of Physics and Astronomy, Uppsala University, 75120 Uppsala, Sweden

⁴Nordita, KTH Royal Institute of Technology and Stockholm University, 10691 Stockholm, Sweden

Measurements that can be implemented via local operations and classical communication (LOCC) constitute a class of operations that is available in future quantum networks in which parties share entangled resource states. In Reference [1], we characterise the different classes of measurements implementable with LOCC, where communication is restricted to a single round with a fixed direction. In particular, using the framework of constrained separability problems, we provide a complete characterisation of the class of LOCC measurements that require one round of classical communication with a limit on the transmitted information. Furthermore, we show how to distinguish between adaptive and non-adaptive measurement strategies. Using our techniques, we present examples where the success probability of state discrimination depends on the direction of communication as well as on the message size. We also discuss explicit instances of state ensembles where non-projective measurements provide an advantage and where adaptive measurement strategies lead to improved success rates when compared to all non-adaptive strategies.



References

- [1] Arthur C. R. Dutra, Ties-A. Ohst, Hai-Chau Nguyen, and Otfried Gühne
arXiv.2510.09381(2025)

Can tachyons explain all possible non-local effects?

Sohyun Park¹, Paul Skrzypczyk¹ and Sandu Popescu¹

¹H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, United Kingdom

One of the most counter-intuitive features of quantum mechanics is the existence of correlations between distant particles that are stronger than any classical model allows. Classically, reproducing such correlations would require faster-than-light communication, for example by exchanging *tachyons*. Yet, in a theory such as quantum mechanics, in which measurement outcomes are probabilistic, these so-called non-local correlations are consistent with special relativity, and this has motivated two complementary research programmes: studying the most general non-local phenomena compatible with relativity, and proposing underlying mechanisms that could generate them.

We focus on the second programme, in particular a model in which tachyons propagate forwards in time in a hidden absolute frame. Such a model can reproduce all quantum non-local correlations, and even non-signalling correlations beyond quantum mechanics (such as PR boxes), all of which are independent of the space-time relations between the parties' measurement events. One would therefore be tempted to think that such a tachyonic model could explain all non-local phenomena consistent with relativity. We show, however, that it fails for *jamming*: a non-local phenomenon in which a third party, the jammer, can affect correlations without changing local marginals by an action that is space-like separated from the measurement events, under specific space-time constraints. In a tachyonic model, varying the time at which the jammer acts would lead to a space-time point at which jamming must break down, which would allow the presumed "hidden" absolute frame to be exposed, thereby violating the principle of relativity. Since jamming itself is fully consistent with relativity, this contradiction implies that a tachyonic model cannot explain it, even with arbitrarily fast tachyons. Hence tachyonic models are not strong enough to explain all possible non-local effects that are consistent with relativity.

Stern-Gerlach, EPRB and Bell Inequalities: An Analysis Using the Quantum Hamilton Equations of Stochastic Mechanics

W. Paul¹, M. Beyer

¹Institut für Physik, Martin-Luther-Universität Halle-Wittenberg, 06099 Halle, Germany

We present an analysis of the quantum Hamilton equations of stochastic mechanics for a spinning particle, which describe the spin measurement in a Stern–Gerlach experiment. We show that this theory predicts a continuously changing orientation of the particles magnetic moment over the course of its motion across the Stern–Gerlach apparatus. The final measurement results agree with experiment and with predictions of the Pauli equation. Furthermore, the Einstein–Podolsky–Rosen–Bohm (EPRB) thought experiment is simulated, and the violation of Bells’s inequalities is reproduced within this stochastic approach. The origin of the violation of Bell’s inequalities is traced to the non-separability of the probability distribution for a particle pair in an entangled state. In the EPRB thought experiment, which is realizable in its strict form only in a computer simulation, this non-separability is induced by the requirement of angular momentum conservation, whereas in the original EPR thought experiment it arises from translational momentum conservation.

References

- [1] M. Beyer, W. Paul, Ann. Phys. (Berlin) **535**, 2200433 (2023)
- [2] M. Beyer, W. Paul, Found. Phys. **54**, 20 (2024)

Symmetric localizable multiparty quantum measurements

[arXiv.2509.01851](https://arxiv.org/abs/2509.01851)+.2509.01852

Jef Pauwels^{1,2}

Cyril Branciard³

Alejandro Pozas-Kerstjens¹

Nicolas Gisin^{1,2}

¹Department of Applied Physics, University of Geneva, 1211 Geneva, Switzerland

²Constructor University, 8759 Bremen, Germany

³Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France

Entangled joint measurements are far less understood than entangled states, especially beyond two parties and in higher dimensions. We study a highly structured family of multi-qubit joint measurements with tetrahedral symmetry, motivated by the two-qubit Elegant Joint Measurement (EJM), a canonical partially entangled basis that plays a central role in network nonlocality.

Our first contribution is a complete parametrization of all tetrahedrally symmetric “orbit” measurement bases: we identify the symmetry group, characterize exactly which fiducial states generate valid orthonormal bases under its action, and obtain a compact normal form for every admissible fiducial. This yields a simple and explicit description of a large family that includes the EJM as the smallest instance.

Our second contribution is an operational classification of which of these tetrahedral measurements can be implemented efficiently using only local operations, classical communication, and preshared entanglement. We show that the localization cost of any tetrahedral basis in our family reduces to a single ingredient in its normal form: a diagonal phase operation. Concretely, determining whether a measurement is localizable at a given finite “teleportation depth” can be reduced to placing that diagonal phase operation within the Clifford hierarchy, using the phase-polynomial formalism. This turns a hard, nonlocal implementation problem into a tractable algebraic one and enables explicit enumeration at low hierarchy levels.

As applications, we (i) analyze a previously studied one-parameter family that interpolates between the Bell measurement and the EJM, and determine how its localization cost increases along the family, and (ii) construct efficiently localizable EJM-type generalizations to three and four qubits with fully regular local tetrahedral geometry, revealing multiple inequivalent classes distinguished by genuine multipartite entanglement invariants. These results motivate an explicit conjecture for an n -qubit EJM family with predictable scaling of local Bloch-vector magnitudes and a fixed hierarchy placement.

Open directions include deriving a closed-form phase-polynomial description for the n -qubit EJM, proving optimal hierarchy placement, extending the framework beyond tetrahedral symmetry (and to qudits), and leveraging these measurement families in applications such as network nonlocality.

Useful Qubits and State Updates in Relativistic Quantum Information

Jose Polo-Gomez ^{1,2,3}, T. Rick Perche ⁴, Eduardo Martin-Martinez ^{2,3,5}

¹Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany

²Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada

³Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada

⁴Nordita, KTH Royal Institute of Technology and Stockholm University, Hannes Alfvén's väg 12, 23, SE-106 91 Stockholm, Sweden

⁵Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada

We address the longstanding challenge of consistently updating quantum states after selective measurements in a relativistic spacetime. Standard updates along the future lightcones preserve causality but break correlations between causally disconnected parties, whereas updates along the past lightcone either imply retrocausality or do not respect the causal propagation of information.

We introduce a minimal extension of multipartite states to encode subsystem-specific contextual information. This "polyperspective" formalism ensures causally consistent covariant state updates, preserves multipartite correlations, and respects conservation laws.

Reference: arXiv:2506.18906

Existing experiments suffice to indirectly verify the quantum essence of gravity

Martin Plávala

Institut für Theoretische Physik, Leibniz Universität Hannover, Hannover,
Germany

The gravity-mediated entanglement experiments employ concepts from quantum information to argue that if entanglement due to gravitational interaction is observed, then gravity cannot be described by a classical system. However, the proposed experiments remain beyond our current technological capability, with optimistic projections placing the experiment outside of short-term future. Here we argue that current matter-wave interferometers are sufficient to indirectly prove that gravitational interaction creates entanglement between two systems. Specifically, we prove that if we experimentally verify the Schrödinger equation for a single delocalized system interacting gravitationally with an external mass, then, under one of two reasonable assumptions, the time evolution of two delocalized systems will lead to gravity-mediated entanglement.

Title: Detection-loophole-free quantum steering in the simplest scenario

Authors: N. T Raveendranath 1, T. J. Baker 1,2, E. Polino 1, M. Haddara 1, L. K. Shalm 3, V. B. Verma 3, G. J. Pryde 1, S. Slussarenko¹, H. M. Wiseman 1, and N. Tischler 1,

1. Quantum and Advanced Technologies Research Institute, Griffith University, Yuggera Country, Brisbane, QLD 4111, Australia

2. Nanyang Quantum Hub, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371

3. National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA

Abstract: Quantum nonlocality, whether in the form of Bell nonlocality or Einstein–Podolsky–Rosen steering, is central to our understanding of quantum theory and underlies a range of emerging quantum technologies. Loophole-free demonstrations of quantum nonlocality, however, typically require resource-intensive experiments with high complexity, defined by the number of measurement settings and outcomes, and multiple highly efficient detectors.

In this work [1], we identify the fundamental efficiency and complexity thresholds for detection-loophole-free quantum steering using two-qubit entangled states. Our analysis provides the steering analogue of Eberhard’s seminal result for Bell nonlocality. We show that demonstrating detection-loophole-free quantum steering requires only a single photon detector on the untrusted side, with efficiency exceeding $1/X$, where $X \geq 2$ is the number of measurement settings on that side. Remarkably, this threshold applies to all pure entangled states, in contrast to analogous two-qubit Bell-nonlocality tests, which require almost unentangled states to be loss-tolerant.

We experimentally confirm these predictions in a minimal-complexity photonic implementation, employing $X = 2$ settings for the untrusted party and a single three-outcome measurement for the trusted party. Our detection-loophole-free experiment is able to demonstrate quantum steering, in the simplest configuration, with an efficiency equal to $(51.6 \pm 0.4)\%$, close to the fundamental limit of 0.5.

These results establish a new benchmark for the faithful realization of quantum nonlocality with minimal experimental resources and have direct implications for the development of secure quantum technologies.

References:

[1] R. T Raveendranath, T. J. Baker, E. Polino, M. Haddara, L. K. Shalm, V. B. Verma, G. J. Pryde, S. Slussarenko, H. M. Wiseman and N. Tischler, "Detection-loophole-free nonlocality in the simplest scenario." *arXiv preprint arXiv:2601.03817* (2026).

Measurement incompatibility and genuine multipartite steering

Lucas E. A. Porto¹, Lucas Tendick², Daniel Cavalcanti³,

Roope Uola⁴, Marco Túlio Quintino¹

¹*Sorbonne Université, CNRS, LIP6, Paris, France*

²*Inria Paris-Saclay, Bâtiment Alan Turing; CPHT, Ecole polytechnique, Institut Polytechnique de Paris; LIX, Ecole polytechnique, Institut Polytechnique de Paris, Paris, France*

³*Algorithmiq Ltd, Helsinki, Finland*

⁴*Department of Physics and Astronomy, Uppsala University, Uppsala; Nordita, KTH Royal Institute of Technology and Stockholm University, Stockholm, Sweden*

Measurement incompatibility and bipartite quantum steering are known to display a strong connection [1,2,3]. In the first place, for steerable correlations to be produced it is necessary that the steering party performs incompatible measurements on their share of the quantum system. Additionally, it is also known that every set of incompatible measurements can produce steering, in particular when applied to a share of a maximally entangled state. In this sense, measurement incompatibility is necessary and sufficient for bipartite quantum steering. However, despite such a close link between incompatibility and steering in bipartite scenarios, very few is known in scenarios with more than two parties, especially when the notion of *genuine* multipartite steering is considered [4]. This is precisely what we investigate in this work, showing that this strong connection extends only partially for the multipartite case. More precisely, we prove that in scenarios with a single uncharacterised party incompatibility is also necessary and sufficient for genuine multipartite steering, as in the bipartite case. In contrast, in scenarios with more than one uncharacterised party we show that this is not the case, by providing an explicit example of incompatible measurements that can never lead to genuine multipartite steering in these settings, which reflects the more complex nature of multipartite quantum systems. In order to obtain our main results, we introduce methods tailored for multipartite correlations, paving the way to understanding the role of measurement incompatibility beyond bipartite scenarios.

References

- [1] M. T. Quintino *et al.*, Phys. Rev. Lett. 113, 160402 (2014)
- [2] R. Uola *et al.*, Phys. Rev. Lett. 113, 160403 (2014)
- [3] R. Uola *et al.*, Phys. Rev. Lett. 115, 230402 (2015)
- [4] D. Cavalcanti *et al.*, Reports on Progress in Physics 80, 024001 (2017)

When Einstein, Podolsky and Rosen distribute quantum states: A journey to the smallest possible demonstration of quantum nonlocality in networks

Erwan Don^{1,2,3}, Jessica Bavaresco⁴, Patryk Lipka-Bartosik^{5,6}, Nicolas Gisin^{1,7}, Nicolas Brunner¹, and Alejandro Pozas-Kerstjens¹

¹*Department of Applied Physics University of Geneva, 1211 Geneva, Switzerland*

²*Institute for Complex Quantum Systems, Ulm University, 89069 Ulm, Germany*

³*Center for Integrated Quantum Science and Technology, Ulm-Stuttgart, Germany*

⁴*Sorbonne Université, CNRS, LIP6, F-75005 Paris, France*

⁵*Center for Theoretical Physics, Polish Academy of Sciences, Warsaw, Poland*

⁶*Institute of Theoretical Physics, Jagiellonian University, 30-348 Kraków, Poland*

⁷*Constructor University, Bremen, Germany*

Ninety years after EPR, and after many decades of studying quantum nonlocality in bipartite and "trivial" multipartite scenarios, the field is now showing interest in networks where multiple independent sources distribute physical systems to different sets of parties. The study of nonlocality in networks is resulting very fruitful, with many interesting results, especially at the foundational level. Yet, the need to take into account the independence of the sources makes understanding network correlations difficult in general. In this contribution, I will exemplify this difficulty by trying to answer the question "what is the simplest demonstration of quantum nonlocality in networks?" [1]. This will take us through a journey that begins at the very start of the field in 2012 [2] and ends by demonstrating that quantum nonlocality in the triangle network without inputs and with binary outcomes is possible. This demonstration refutes an 8-year-old conjecture [3], and I will argue that it constitutes a demonstration of nonlocality that, in a sense, is simpler than the traditional demonstration in the bipartite case.

References

[1] S. Boreiri, A. Girardin, B. Ulu, P. Lipka-Bartosik, N. Brunner, and P. Sekatski, Towards a minimal example of quantum nonlocality without inputs, *Phys. Rev. A* 107, 062413 (2023), arXiv:2207.08532.

[2] T. Fritz, Beyond Bell's theorem: correlation scenarios, *New J. Phys.* 14, 103001 (2012), arXiv:1206.5115.

[3] T. C. Fraser and E. Wolfe, Causal compatibility inequalities admitting quantum violations in the triangle structure, *Phys. Rev. A* 98, 022113 (2018), arXiv:1709.06242.

Robust certification of quantum devices

J. Fernández-Cano^{1,2}, A. Rico^{1,3}, A. Vallès^{1,2}, A. Sanpera¹, D. Viedma¹, V. Ahufinger^{1,2}, S. Sankar-Bhattacharya¹

¹UAB – Universitat Autònoma de Barcelona, Bellaterra, Spain

²ICFO - Institut de Ciències Fotòniques, Castelldefels, Spain

³Universität Siegen, Siegen, Germany

Certifying genuinely quantum behaviour from classically accessible data is essential for secure communication and scalable quantum technologies. While powerful certification methods such as Bell nonlocality and quantum steering exist, their implementation typically requires entanglement or additional structural assumptions, and experimental demonstrations remain largely confined to low-dimensional systems. In minimal prepare-and-measure scenarios, where a sender encodes information into quantum states and a receiver performs a single measurement, robust certification becomes particularly challenging, especially in the presence of noise and in higher-dimensional Hilbert spaces.

In this contribution [1] we propose, design, and experimentally implement a protocol that certifies quantumness between two distant parties without the need for preshared resources or measurement incompatibility. The experiments are carried out using the orbital angular momentum degrees of freedom of single photons, chosen for providing increased dimensionality that is scalable. We demonstrate the robustness of the protocol through rank-stability analysis of the observed correlations, which enables the certification of non-classicality even in the presence of noise. Our results provide a practical route to validating high-dimensional quantum communication systems and open new possibilities for secure and dimension-efficient quantum information processing.

References

- [1] J. Fernández-Cano, A. Rico, A. Vallès, A. Sanpera, D. Viedma, V. Ahufinger and S. Sankar-Bhattacharya, *Robust certification of quantum devices*, Soon on Arxiv (2026)

The role of entanglement in energy-restricted communication and randomness generation

Carles Roch i Carceller¹ and Armin Tavakoli¹

¹*Physics Department and NanoLund, Lund University, Box 118, 22100 Lund, Sweden*

A promising platform for semi-device-independent quantum information is prepare-and-measure experiments restricted only by a bound on the energy of the communication. Here, we investigate the role of shared entanglement in such scenarios. For classical communication, we derive a general correlation criterion for nonlocal resources and use it to show that entanglement can fail to be a resource in standard tasks. For quantum communication, we consider the basic primitive for energy-constrained communication, namely the probabilistic transmission of a bit, and show that the advantages of entanglement only can be unlocked by non-unitary encoding schemes that purposefully decohere the entangled state. We also find that these advantages can be increased by using entanglement of higher dimension than qubit. We leverage these insights to investigate the impact of entanglement for quantum random number generation, which is a standard application of these systems but whose security so far only has been established against classical side information. In the low-energy regime, our attacks on the protocol indicate that the security remains largely intact, thereby paving the way for strengthened security without more complex setups and with negligible performance reductions.

Understanding Bell inequality violations in $2-2-d$ and $2-d-2$ systems

Abhyoudai S. Shaleena¹, Michał Banacki^{1,2}, Paweł Horodecki^{1,3}

¹International Centre for Theory of Quantum Technologies (ICTQT), University of Gdańsk, ²Institute of Mathematics, Faculty of Mathematics, Physics and Informatics, University of Gdańsk, Poland, ³Faculty of Applied Physics and Mathematics, Gdańsk University of Technology, Gdańsk, Poland.

Motivated by the semi-analytical optimization of tight bounds for Bell inequalities in the tripartite case corresponding to the $4 \times 4 \times 2$ scenario with three qubit subsystems [1], we consider a similar task in a more complicated setting involving d -dimensional subsystems. In particular, using approaches based on the Schmidt decomposition and recent results for optimal violation of CHSH inequality [2], we provide a semi-analytical expression for values of maximal violation for certain tripartite Bell inequality in a case of $2 - 2 - d$ and $2 - d - 2$ dimensional subsystems. Specifically, the obtained results open the way to witnessing nonlocality for a certain family of states arising from a three-body decay beyond the qubit setting [3].

References

- [1] Horodecki, P., Sakurai, K., Shaleena, A.S. et al. Three-body non-locality in particle decays. *J. High Energ. Phys.* 2025, 160 (2025). [https://doi.org/10.1007/JHEP10\(2025\)160](https://doi.org/10.1007/JHEP10(2025)160).
- [2] Alexander Bernal, J. Alberto Casas, Jesús M. Moreno, *Maximal Clauser-Horne-Shimony-Holt violation for qubit-qudit states*, *Phys. Rev. A* 112, 042404 (2025).
- [3] K. Sakurai, A. S. Shaleena et al. (2026), work in progress.

Nonlocality beyond Bell: Operationally independent events can influence each other in quantum theory

Shubhayan Sarkar

Institute of Informatics, University of Gdansk, Wita Stwosza 57, 80-308 Gdansk, Poland

Nonlocality is one of the most fascinating aspects of quantum theory, encapsulating the absence of a local description for spatially separated quantum systems that can not communicate with each other. Discovered by Bell in 1964 and then experimentally observed in the last decades, the phenomenon of nonlocality clearly establishes the departure of the quantum world from classical physics. An equivalent way to understand it is that two quantum systems can be correlated in a stronger way than two classical systems. In this work, we pose an even more stringent inquiry: consider two systems that exhibit no correlation with each other, meaning they are mutually independent. The fundamental question we address is whether these two independent systems can influence each other in any manner. Equivalently, can one system exert an impact on its counterpart when there is no correlation and no communication between them? Drawing upon our classical understanding of the natural world, it can be logically deduced that in the absence of communication and with both systems being mutually independent, they cannot exert any influence on each other in any conceivable manner. We consider this viewpoint as a notion of classicality and term it “classical independence”. Here, we show that the notion of classical independence is violated in quantum theory, that is, two mutually independent quantum systems might affect each other if they are individually entangled with different quantum systems.

For our purpose, we consider the framework of quantum networks, in particular, the quantum bilocality scenario with weaker constraints on the network. We then derive a linear inequality inspired by Clauser-Horne-Shimony-Holt (CHSH) inequality. Restricting to operationally independent correlations, we find an upper bound for correlations that can be described in a classically independent way. We then find a set of quantum states and measurements that violate this bound. For a remark, just like the bilocality scenario, our setup is inspired by the phenomenon of entanglement swapping. In fact, one can also consider this work as probing the nature of nonclassicality that is violated in the entanglement swapping experiment. Furthermore, we find the maximum value of the inequality that can be attained in quantum theory. Interestingly, using the methods presented also allows us to certify the quantum states and measurements in a device-independent way from the maximal violation of the constructed inequality. Most of the recent works in network nonlocality point to the fact that observing genuine quantum nonlocality in networks requires non-linear inequalities, which additionally require the assumption that the sources generate independent and identically distributed random variables, commonly known as the i.i.d. assumption. We show here that one can also obtain linear inequalities to observe network nonlocality by considering weaker assumptions on the underlying hidden variable models. For more details, please refer to [1].

[1] Shubhayan Sarkar, Causal links between operationally independent events in quantum theory, [Phys. Rev. A \(Letter\) 109, L040202 \(2024\)](#).

Genuinely high-dimensional teleportation

P. Jokinen^{1,2}, S. Egelhaaf³, M. Storrer⁴, S. Schlösser^{1,2}, T. Ohst^{1,2} and R. Uola^{1,2}

¹*Uppsala University, Uppsala, Sweden*

²*Nordita, KTH Royal Institute of Technology and Stockholm University, Stockholm, Sweden*

³*University of Geneva, Geneva, Switzerland*

⁴*Federal University of Paraná, Curitiba, Brazil*

Quantum teleportation is a fundamental task that lies at the core of modern quantum information protocols. The vast majority of literature on quantum teleportation and related tasks, such as entanglement distribution in quantum networks, focuses on qubit systems. However, more recently, teleportation of qutrits has been demonstrated experimentally. Advances in high-dimensional photonics raise the question of how to certify genuinely high-dimensional teleportation. We argue that when the teleportation of a high-dimensional system can be simulated by means of teleporting systems of lower dimension, it is not genuinely high-dimensional. A formal definition of high-dimensional teleportation is proposed, based on the dimensionality of entanglement. We relate this definition to other notions of high-dimensional teleportation proposed in the literature. We show that in an ideal setting of perfect teleportation, the genuine teleportation dimension is equivalent to the operational notion of compression dimension. We discuss the scenario of imperfect teleportation and derive witnesses for the genuine dimensionality of teleportation, based on input-output correlations of the teleportation channel.

References

- Y.-H. Luo et al., Phys. Rev. Lett. 123, 070505 (2019)
- X.-M. Hu et al., Phys. Rev. Lett. 125, 230501 (2020)
- A. Bluhm et al., Ann. Henri Poincaré 19, 1891–1937 (2018)

Theory-Independent Context Incompatibility

M. Storrer¹, P. Lima², A. C. S. Costa¹, S. Pádua², R. M. Angelo¹

¹ *Department of Physics, Federal University of Paraná, Curitiba, Brazil*

² *Department of Physics, Federal University of Minas Gerais, Belo Horizonte, Brazil*

Measurement incompatibility lies at the core of quantum foundations and quantum information [1,2]. Initially linked to the uncertainty principle and the noncommutativity of observables, it was later generalized to positive-operator valued measurements (POVMs) and joint measurability. To probe its role beyond quantum theory and in the classical limit, the notion of *context incompatibility* was introduced [3], capturing state-dependent quantumness and decoherence-induced classical behavior while recovering measurement incompatibility in suitable regimes. However, these formulations remain largely confined to the quantum formalism, motivating theory-independent generalizations compatible with broader probabilistic frameworks [4]. In search of a broader notion of incompatibility—one that captures the classical limit, accommodates generalized measurements, applies to generic probabilistic theories, and recovers measurement incompatibility—we introduce the concept of *theory-independent context incompatibility* (TICI) [5]. Moreover, we present a figure of merit capable of quantifying the degree of violation of TICI, and we experimentally demonstrate, using a quantum optics platform, that quantum systems can exhibit pronounced degrees of violation. Besides yielding a concept that extends to generic probabilistic theories and retrieving the notion of measurement incompatibility in the quantum domain, our results offer a promising perspective on evaluating the role of incompatibility in the manifestation of non-local correlations.

References

- [1] T. Heinosaari, et al., J. Phys. A: Math. Theor. **49**, 123001 (2016)
- [2] O. Gühne, et al., Rev. Mod. Phys. **95**, 011003 (2023)
- [3] E. Martins, et al., Phys. Rev. A **102**, 050201 (2020)
- [4] G. M. D’Ariano, et al., Cambridge University Press, United Kingdom (2017)
- [5] M. Storrer, et al., Phys. Rev. A **113**, L010202 (2026)

Quantum correlations cannot be reproduced with a finite number of measurements in any no-signaling theory

Lucas Tendick*

Inria Paris-Saclay Palaiseau, France

*CPHT, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France and
LIX, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*

We show, for any finite $n \geq 2$, that there exist quantum correlations obtained from performing n dichotomic quantum measurements in a bipartite Bell scenario, which cannot be reproduced by mixtures of measurement devices with at most $(n - 1)$ incompatible measurements across different partitions in any no-signaling theory. That is, it requires any no-signaling theory an unbounded number of measurements to reproduce the predictions of quantum theory. We prove our results by showing that there exist linear Bell inequalities that have to be obeyed by any no-signaling theory involving only $(n - 1)$ -wise incompatible measurements and show explicitly how these can be violated in quantum theory. Finally, we discuss the relation of our work to previous works ruling out alternatives to quantum theory with some kind of bounded degree of freedom and consider the experimental verifiability of our results.

* lucas-amadeus.tendick@inria.fr

Measurement incompatibility, extremal quantum decoherence, and minimal informationally complete measurements.

D. McNulty¹, W. Townsend², J. Kiukas³, and J.-P. Pellonpää⁴

¹*Universita di Bari, Bari, Italy*

²*Aberystwyth university, Aberystwyth, United Kingdom*

³*Aberystwyth university, Aberystwyth, United Kingdom*

⁴*University of Turku, Turku, Finland*

We characterise the effect of extremal pure decoherence in open quantum systems in terms of (the loss of) quantum measurement incompatibility, in a specific analytically tractable setting. The basic idea [1] is that an incoherent observable (i.e. diagonal in a fixed incoherent basis) is incompatible with maximally coherent observables, but this incompatibility will typically be lost under Markovian (CP-divisible) pure decoherence at some unique point in time [1,2]. Each pure decoherence channel is described by the entry-wise multiplication by a unit-diagonal positive semidefinite matrix, and here we focus on reporting our new ongoing work on the extremal elements of this convex set of matrices.

The extremality condition has a well-known characterisation in terms of the dilation space of the decoherence channel, which (when suitably restricted) links mathematically with Minimal Informationally Complete (MIC) POVMs. In this highly constrained setting, the measurement incompatibility problem becomes analytically tractable, and we are able to study the interesting question of how the emergence of joint measurability under decoherence is related to the symmetry properties of the associated MIC. In particular, we consider the special role of Symmetric IC POVMs (commonly abbreviated as SIC-POVMs) in this context; given that the loss of measurement incompatibility is related to the emergence of classicality in open systems, and SIC-POVMs are typically regarded as “closest to classical” quantum measurements, our results provide an interesting view to the fundamental distinction between classical and quantum physics.

References

[1] J. Kiukas, P. Lahti, and J.-P. Pellonpää, Joint Measurability in Lindbladian Open Quantum Systems, *Open Syst. Inf. Dyn.* **30**, 2350013 (2023).

[2] J. Kiukas, D. McNulty, and J.-P. Pellonpää, Amount of quantum coherence needed for measurement incompatibility, *Phys. Rev. A* **105**, 012205 (2022).

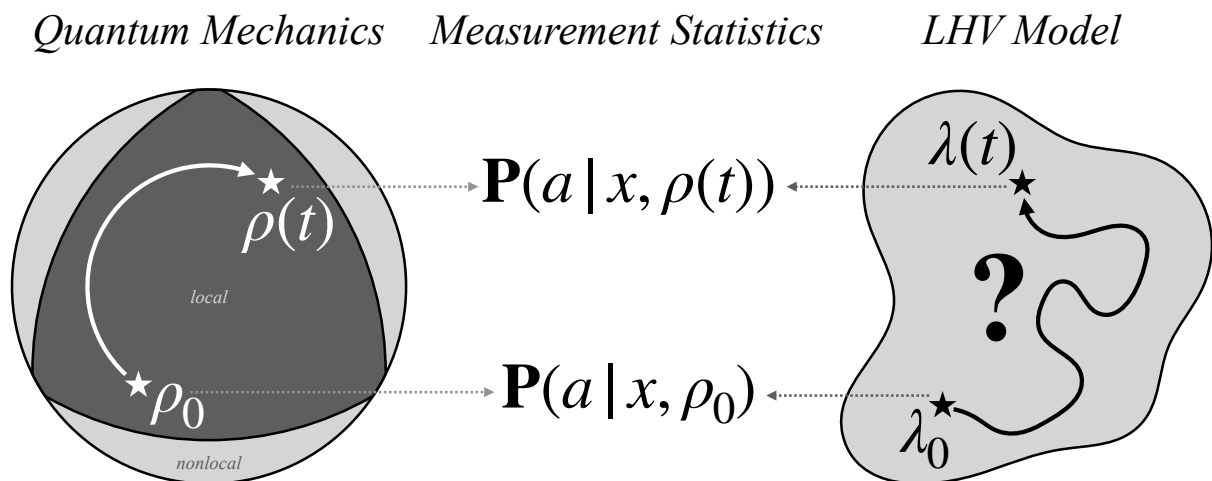
On the Dynamics of Local Hidden-Variable Models

N. von Selzam^{1,2} and F. Marquardt^{1,2}

¹Max Planck Institute for the Science of Light, Erlangen, Germany

²Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany

Bell nonlocality is an intriguing property of quantum mechanics with far-reaching consequences for information processing, philosophy, and our fundamental understanding of nature. However, standard Bell nonlocality is a statement about correlations at a fixed point in time only. It does not take into account dynamics, i.e., time evolution of those correlations. Consider a dynamic situation where the correlations remain local for all times. Then, at each moment in time, there exists a local hidden-variable (LHV) model reproducing the momentary correlations. Can the time evolution of the correlations then be captured by evolving the hidden variables? In this light, we define dynamical LHV models and motivate and discuss potential additional physical and mathematical assumptions. Based on a simple counterexample we conjecture that such LHV dynamics does *not* always exist. This is further substantiated by a rigorous no-go theorem. Our results suggest a new type of nonlocality: Even when the observed correlations are local at all times, their time evolution may nevertheless be incompatible with local hidden-variable dynamics.



References

- [1] N. von Selzam and F. Marquardt, arXiv:2512.16682 (2025)

Non-Projective Bell State Measurements

A. Wei^{1,2}, G. Cobucci³, A. Tavakoli³

¹*Inria, Université Paris Saclay, Palaiseau, France*

²*Nokia Bell Labs, Massy, France*

³*Lund University, Lund, Sweden*

The Bell-state measurement (BSM), the maximally entangled projective measurement on two qubits, has found extensive applications in quantum information theory. However, it is also known that non-projective measurements over single quantum systems have found useful applications in quantum cryptography, quantum tomography, among others. In this work we first propose how to appropriately generalize BSM to non-projective entangled measurements with more than four outcomes, and then study whether they exist in quantum theory. We observe that nonprojective BSMs can be defined systematically in terms of equiangular tight frames of maximally entangled states, i.e., a set of maximally entangled states, where every pair is equally, and in a sense maximally, distinguishable. We show that there exists a five-outcome BSM through an explicit construction and find that it admits a simple geometric representation. Then we prove that there exists no larger BSM on two qubits by showing that no six-outcome BSM is possible. We also determine the most distinguishable set of six equiangular maximally entangled states and show that it falls only somewhat short of forming a valid quantum measurement. Finally, we apply our constructed measurement to the task of entanglement-assisted quantum communication. Our results put forward natural forms of nonprojective joint measurements and provide insight into the geometry of entangled quantum states.

References

- [1] Wei A., Cobucci G., Tavakoli A., *Phys. Rev. A* **110**, 042206 (2024).

Superactivation and incompressibility of genuine multipartite entanglement

Lisa T. Weinbrenner¹, Klára Baksová², Sophia Denker¹, Simon Morelli², Xiao-Dong Yu³, Nicolai Friis² and Otfried Gühne¹

¹ *University of Siegen, Siegen, Germany*

² *University of Vienna, Vienna, Austria*

³ *Shandong University, Jinan, China*

E-Mail: lisa.weinbrenner@uni-siegen.de

Quantum correlations in the form of entanglement, quantum steering or Bell nonlocality are resources for various information-processing tasks, but their detailed quantification and characterization remain complicated. One counter-intuitive effect is the phenomenon of superactivation, meaning that two copies of a quantum state may exhibit forms of correlations which are absent on the single-copy level. We develop a systematic approach towards a full understanding of this phenomenon using the paradigm of genuine multipartite entanglement. We introduce systematic methods for studying superactivation of entanglement based on symmetries and generalized notions of multipartite distillability. With this, we present novel criteria for superactivation as well as a quantitative theory of it. Finally, we prove the existence of incompressible entanglement, meaning that there are quantum states for which superactivated multipartite entanglement cannot be reduced to the single-copy level.

References

- [1] L. T. Weinbrenner, K. Baksová, S. Denker, S. Morelli, X.-D. Yu, N. Friis, O. Gühne, arXiv:2412.18331

Genuine multipartite entanglement is not necessary for standard device-independent conference key agreement

Lewis Wooltorton¹, Peter Brown², Roger Colbeck³

¹*Inria, ENS de Lyon, LIP, 46 Allée d'Italie, 69364 Lyon Cedex 07, France*

²*Télécom Paris, Inria, LTCI, Institut Polytechnique de Paris, 19 Place Marguerite Perey,
91120 Palaiseau, France*

³*Department of Mathematics, King's College London, Strand, London, WC2R 2LS,
United Kingdom*

Conference key agreement aims to establish shared, private randomness among many separated parties in a network. Device-independent conference key agreement (DICKA) is a variant in which the source and the measurement devices used by each party need not be trusted. So far, DICKA protocols largely fall into two categories: those that rely on violating a joint Bell inequality using genuinely multi-partite entangled states, and those that concatenate many bipartite protocols. The question of whether a hybrid protocol exists, where a multi-partite Bell inequality can be violated using only bipartite entanglement, was asked by Grasselli *et al.* in [Quantum **7**, 980, (2023)]. We answer this question affirmatively, by constructing an asymptotically secure DICKA protocol achieving the same rate as bipartite protocol concatenation, yet relying on a single joint Bell violation. Our results prompt further discussion on the benefits of multi-partite entanglement for DICKA over its bipartite alternative, and we give an overview of different arguments for near-term devices.

The full version of this work can be found at [Phys. Rev. Lett. **135**, 220803, (2025)].

Quantum network correlations require classical communication to be useful

Justus Neumann¹, Tulja Varun Kondra¹, Kiara Hansenne^{2 3}, Lisa T. Weinbrenner², Hermann Kampermann¹, Otfried Gühne², Dagmar Bruß¹ and Nikolai Wyderka¹

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

² Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Str. 3, 57068 Siegen, Germany

³ Université Paris-Saclay, CEA, CNRS, Institut de Physique Théorique, 91191 Gif-sur-Yvette, France

Quantum networks connect systems at separate locations via quantum links, enabling a wide range of quantum information tasks between distant parties. We show that quantum networks relying on the long-distance distribution of bipartite entanglement, combined with local operations and shared randomness, cannot achieve strong enough quantum correlations to be useful for tasks like distributed computing. Specifically, we prove that these networks do not help in preparing resourceful quantum states such as Greenberger-Horne-Zeilinger states or cluster states, despite the free availability of long-distance entanglement. At an abstract level, our work points towards a fundamental difference between bipartite and multipartite entanglement. From a practical perspective, our results highlight the need for classical communication combined with quantum memories to fully harness the power of quantum networks.

[1] J. Neumann, T. V. Kondra, K. Hansenne, L. T. Weinbrenner, H. Kampermann, O. Gühne, D. Bruß and Nikolai Wyderka¹, arXiv:2503.09473 (2025)

Approximating fixed size quantum correlations in polynomial time

Julius A. Zeiss¹, Gereon Kossmann¹, Omar Fawzi², and Mario Berta³

¹ *Institute for Quantum Information, RWTH Aachen University, Aachen, Germany*

² *Univ Lyon, Inria, ENS Lyon, UCBL, LIP, Lyon, France*

³ *Department of Computing, Imperial College London, London, UK*

We show that ε -additive approximations of the optimal value of fixed-size two-player free games with fixed-dimensional entanglement assistance can be computed in time $\text{poly}(1/\varepsilon)$. This stands in contrast to previous analytic approaches, which focused on scaling with the number of questions and answers, but yielded only strict $\exp(1/\varepsilon)$ guarantees. Our main result is based on novel Bose-symmetric quantum de Finetti theorems tailored for constrained quantum separability problems. These results give rise to semidefinite programming (SDP) outer hierarchies for approximating the entangled value of such games. By employing representation-theoretic symmetry reduction techniques, we demonstrate that these SDPs can be formulated and solved with computational complexity $\text{poly}(1/\varepsilon)$, thereby enabling efficient ε -additive approximations. In addition, we introduce a measurement-based rounding scheme that translates the resulting outer bounds into certifiably good inner sequences of entangled strategies. These strategies can, for instance, serve as warm starts for see-saw optimization methods. We believe that our techniques are of independent interest for broader classes of constrained separability problems in quantum information theory.

Towards Bell Tests with Minimal Sample Complexity

Andrea Zingarofalo^{1,2}, Jean-Daniel Bancal², and Stefano Pironio¹

¹*Laboratoire d'Information Quantique, Université Libre de Bruxelles, 1050, Brussels, Belgium*

²*Université Paris-Saclay, CEA, CNRS, Institut de Physique Théorique, 91191, Gif-sur-Yvette, France*

Bell inequality violations provide a device-independent test of local causality, but real photonic experiments suffer from detection losses and finite statistics. Reliable certification therefore depends both on the quantum strategy and on the statistical protocol used to assign p-values or determine the number of experimental trials needed to reach a given confidence level.

Following Eberhard's formulation of Bell experiments with inefficient detectors [1] we study statistical methods for two-party photonic scenarios with losses and extend the analysis to the CGLMP inequality. We benchmark binomial tests, martingale-based inequalities (e.g. Azuma-Hoeffding), and the Prediction-Based Ratio (PBR) protocol introduced by Zhang, Glancy and Knill [2] and the nearly optimal bounds developed by Elkouss and Wehner [3].

We compare constrained and unconstrained PBR variants in terms of achievable p-values and minimum sample complexity. Our results show that when loss events are treated as additional outcomes, PBR-based strategies significantly outperform standard binomial methods.

Motivated by this, we investigate quantum strategies that maximize the statistical distance from the local set in lossy scenarios. In the CHSH case, we study measurement and state choices that maximize the minimum Kullback-Leibler divergence between quantum and local distributions, identifying candidate optimal strategies for experiments with imperfect detectors.

This work provides practical guidance for designing loophole-free photonic Bell experiments and for choosing optimal statistical certification methods under finite-data and loss constraints.

References

[1] P. H. Eberhard, *Phys. Rev. A* **47**, R747, (1993)

[2] Y. Zhang, S. Glancy, and E. Knill, *Phys. Rev. A* **84**, 062118, (2011)

[3] D. Elkouss and S. Wehner, *npj Quantum Inf.* **2**, 16026, (2016)