SFB

FoQuS

Foundations and Applications of Quantum Science

42nd SFB meeting
12-13 July 2018, Innsbruck

Contents

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14:25 (20’+5’)	Wolfgang Lechner, University of Innsbruck *Programmable Superpositions of Ising Configurations*
14:50	Poster flash talks (1’ and 1 slide each)
15:05	Coffee Break and Poster Session
16:00 (45’+10’)	Tom Stace, University of Queensland *Foliated Quantum Codes*
17:30	SFB-bus to the dinner location at the *ad hoc* bus stop (previously *Hötting West*) (see directions on page 12)
19:00	Dinner at the *Arzleralm* (see directions on page 12)

Friday, July 13th	
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10:45	Coffee Break and Poster Session

11:30 (20’+5’)	Michael Rader, University of Innsbruck *Finite Correlation Length Scaling in Lorentz-Invariant Gapless iPEPS Wave Functions*
11:55 (20’+5’)	Davide Orsucci, University of Innsbruck *Quantum algorithms for linear systems of equations inspired by adiabatic quantum computing*
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12:45	End of SFB meeting

Talks

Thursday, July 12th

13:30

Hybrid Quantum-Classical Simulations for Lattice Models and Self-Validation

Christian Kokail and Christine Maier, IQOQI Innsbruck

In this talk I will present recent theoretical and experimental advances of hybrid quantum-classical simulations for lattice gauge theories, using the Innsbruck 20-Qubit ion trap quantum simulator as a quantum processing unit (QPU). The essential features of our approach are a stochastic optimisation algorithm and symmetry-protecting quantum circuits for constructing entangled variational states. Furthermore we were able to equip our quantum simulator with a self-validation routine, based on measuring error bars on the final ground state energy.

14:00

Degenerate Fermi-Fermi mixture of dysprosium and potassium

Cornee Ravensbergen, IQOQI Innsbruck

We report on the realization of a double degenerate mixture of fermionic 161Dy and fermionic 40K. Both samples are polarized in their absolute ground state. We perform evaporative cooling of dysprosium atoms, where thermalization at low temperatures occurs through dipolar scattering, and we sympathetically cool potassium atoms. The final temperature of both species in the mixture is about $0.35\,T_{\mathrm{F}}$, while we reach below $0.1\,T_{\mathrm{F}}$ for Dy alone. We describe the trapping and cooling methods, in particular the evaporation sequence, for both species together and dysprosium alone. By analyzing the cross-thermalization of the two species we are able to provide an estimate of the inter-species s-wave scattering length. The properties of the Dy-K mixture make it a very promising candidate to explore the physics of strongly interacting mass-imbalanced Fermi-Fermi mixtures.

14:25

Programmable Superpositions of Ising Configurations

Wolfgang Lechner, University of Innsbruck

I will present a protocol to prepare superpositions of bit strings with deterministic programmable squared amplitudes using $O(N^2)$ qubits. The bit strings are encoded in the degenerate ground states of a lattice-gauge representation of an all-to-all connected Ising spin model. An analytical effective model allows one to determine the parameter to induce controlled diabetic transitions and tune the amplitudes of the final superposition.

[1] L. M. Sieberer, W. Lechner, Phys. Rev. A **97**, 052329 (2018).

16:00, Invited talk

Foliated Quantum Codes

Tom Stace, University of Queensland

We show how to construct a large class of quantum error correcting codes, known as CSS codes, from highly entangled cluster states. This becomes a primitive in a protocol that foliates a series of such cluster states into a much larger cluster state, implementing foliated quantum error correction. We exemplify this construction with several familiar quantum error correction codes, and propose a generic method for decoding foliated codes. We numerically evaluate the error-correction performance of a family of finite-rate CSS codes known as turbo codes, finding that it performs well over moderate depth foliations. Foliated codes have applications for quantum repeaters and fault-tolerant measurement-based quantum computation.

Friday, July 13th

09:30

Interacting Rydberg Ions

Gerard Higgins, Stockholm University

Systems of trapped ions and systems of ultracold Rydberg atoms are used at the forefront of quantum physics research and they make strong contenders as platforms for quantum technologies. Trapped Rydberg ions are a new hybrid technology which has both the exquisite control of trapped ion systems and the strong interactions of Rydberg atoms. We coherently excite two trapped strontium ions to Rydberg states using ultraviolet laser light. Microwave radiation is used to introduce large electric dipole moments to the Rydberg ions. We have observed strong dipole-dipole interactions (1 MHz) between two Rydberg ions. Next we will use Rydberg interactions to carry out a fast (1 μs) two-qubit gate. Such gates may allow fast quantum gates to be carried out in large systems of trapped ions

09:55

Counterfactual communication using a programmable nanophotonic waveguide

Teodor Strömberg, University of Vienna

Counterfactual communication is a uniquely quantum communication scheme, in which the quantum Zeno effect is used to exchange information between two parties in such a way that the information carrying particles propagate in the opposite direction of the message being transmitted. Previous theoretical proposals and subsequent experiments have not only relied on post-selection, but also left a problematic weak trace of the photon, calling into question the counterfactuality of information exchange [1, 2]. In this work, we experimentally implement a protocol proposed by Arvidsson-Shukur et al. [3] which eliminates both the weak trace and the need for post-selection. The implementation hinges both on the precision with which one can control the splitting ratio of 2-by-2 couplers, as well as high interferometric visibility, making it a task ideally suited for integrated photonics. Our experiment is carried out in a silicon-on-insulator waveguide, consisting of 88 cascaded Mach-Zehnder interferometers (MZIs), each equipped with two thermo-optic phase shifters, giving full control over the local unitary transformation performed by the MZIs.

[1] H. Salih, Z.-H. Li, M. Al-Amri, and M. S. Zubairy, Phys. Rev. Lett. **110**, 170502 (2013).
[2] Y. Cao, Y.-H. Li, Z. Cao, J. Yin, Y.-A. Chen, H.-L. Yin, T.-Y. Chen, X. Ma, C.-Z. Peng, and J.-W. Pan, PNAS **114**, 4920 (2017).
[3] D. R. M. Arvidsson-Shukur and C. H. W. Barnes, Phys. Rev. A **94**, 062303 (2016).
[4] N. C. Harris *et al.*, Nature Photonics **11.7**, 447 (2017).

10:20

Relaxation to a Phase-Locked Equilibrium State in a One-Dimensional Bosonic Josephson Junction

Marine Pigneur, Atominstitut TU Wien

We present an experimental study on the nonequilibrium tunnel dynamics of two coupled one-dimensional Bose-Einstein quasicondensates deep in the Josephson regime. Josephson oscillations are initiated by splitting a single one-dimensional condensate and imprinting a relative phase between the superfluids. Regardless of the initial state and experimental parameters, the dynamics of the relative phase and atom number imbalance shows a relaxation to a phase-locked steady state. The latter is characterized by a high phase coherence and reduced fluctuations with respect to the initial state. We propose an empirical model based on the analogy with the anharmonic oscillator to describe the effect of various experimental parameters. A microscopic theory compatible with our observations is still missing.

[1] M. Pigneur, T. Berrada, M. Bonneau, T. Schumm, E. Demler, and Jörg Schmiedmayer Phys. Rev. Lett. **120**, 173601 (2018).

11:30

Finite Correlation Length Scaling in Lorentz-Invariant Gapless iPEPS Wave Functions

Michael Rader, University of Innsbruck

It is an open question how well tensor network states in the form of an infinite projected entangled pair states (iPEPS) tensor network can approximate gapless quantum states of matter. Here we address this issue for two different physical scenarios: i) a conformally invariant (2+1)d quantum critical point in the incarnation of the transverse field Ising model on the square lattice and ii) spontaneously broken continuous symmetries with gapless Goldstone modes exemplified by the $S = 1/2$ antiferromagnetic Heisenberg and XY models on the square lattice. We find that the energetically best wave functions display *finite* correlation lengths and we introduce a powerful finite correlation length scaling framework for the analysis of such finite-D iPEPS states. The framework is important i) to understand the mild limitations of the finite-D iPEPS manifold in representing Lorentz-invariant, gapless many body quantum states and ii) to put forward a practical scheme in which the finite correlation length $\xi(D)$ combined with field theory inspired formulae can be used to extrapolate the data to infinite correlation length, i.e. to the thermodynamic limit. The finite correlation length scaling framework opens the way for further exploration of quantum matter with an (expected) Lorentz-invariant, massless low-energy description, with many applications ranging from condensed matter to high-energy physics.

[1] Michael Rader and Andreas M. Läuchli,
arXiv:1803.08566, accepted for publication in Phys. Rev. X.

11:55

Quantum algorithms for linear systems of equations inspired by adiabatic quantum computing

Davide Orsucci, University of Innsbruck

I present the results given in arXiv:1805.10549. Here two quantum algorithms are developed, based on evolution randomization, a simple variant of adiabatic quantum computing, to prepare a quantum state $|x\rangle$ that is proportional to the solution of the linear system of equations $A\vec{x} = \vec{b}$. The time complexities of the algorithms are nearly of order κ^2 and κ, respectively, and linear in $1/\epsilon$, where κ is the condition number of A and ϵ is the precision. The first algorithm aims at preparing the ground states of the Hamiltonians while the second algorithm aims at preparing excited states. The algorithms are simple: they are not obtained using equivalences between the gate model and adiabatic quantum computing, they do not use phase estimation, and they do not use variable-time amplitude amplification. Numerical simulations and experimental demonstrations validate the results.

12:20

Unified view of quantum correlations in quantum information and quantum optics

Farid Shahandeh, University of Innsbruck

Determining whether the correlations between two systems are quantum or classical is fundamental to our understanding of the physical world and our ability to use such correlations for technological applications. Here, we pose the quantum-classical separation problem from a computational perspective and try to provide a consistent solution to it. We ask “what do we infer about quantumness of correlations from the supremacy of collaborative quantum computations?”. We investigate the answer to this question within both continuous variable domain (i.e., bosonic systems) and discrete variable domain and find that a separation between classical and quantum correlations is possible from computational viewpoint. Within both regimes, we show that the global coherence of the input quantum states to the computational models provide the necessary and necessary-and-sufficient resources for the collaborative quantum advantage, respectively. We show that our generalized definition of quantum correlations properly and consistently unifies the standard classifications of quantum optics and quantum information. As such, Bell nonlocality, entanglement, discord, and global phase-space nonclassicality are only manifestations of net global coherence.

Posters

Enhanced entanglement criterion via symmetric informationally complete measurements

Ali Asadian, Atominstitut TU Wien

We show that a special type of measurements, called symmetric informationally complete positive operator-valued measures (SIC POVMs), provide a stronger entanglement detection criterion than the computable cross-norm or realignment criterion based on local orthogonal observables. As an illustration, we demonstrate the enhanced entanglement detection power in simple systems of qubit and qutrit pairs. This observation highlights the significance of SIC POVMs for entanglement detection.

Solid-state electron spin lifetime limited by phononic vacuum modes

Thomas Astner, Atominstitut TU Wien

In the solid state environment, the most fundamental process by which an excited spin ensemble transfers energy to the surrounding is governed by longitudinal relaxation processes. These processes are usually driven by spin-phonon interaction. Here we show a method to study the longitudinal spin-lattice relaxation of large ensembles of Nitrogen Vacancy spins in diamond. Our experiment is based on a cavity quantum electrodynamics where we use a 3D lumped element resonator. The spin ensemble is in the strong coupling regime and in the experiment we measure the spin-lattice relaxation below the single phonon limit. There quantum fluctuations become important and provide the ultimate upper bound for T1. Remarkably, we find that the low phononic density of states at the NV transition frequency enables the spin polarization to survive over macroscopic timescales of up to 8h. Astner *et. al.*, Nature Mat. **17**, 313 (2018).

Towards EPR Pairs

Kahan Dare, IQOQI Vienna

Renyi entropies and OTOCs from statistical correlations of randomized measurements

Andreas Elben, University of Innsbruck, IQOQI Innsbruck

In this poster, we discuss statistical correlations of randomized measurements as a new measurement tool to access properties of quantum systems beyond standard observables. From a unified point of view, we present first the protocol and recent experimental results on measuring in a trapped ion quantum simulator the 2nd order Renyi entropy of arbitrary (reduced) quantum states in a 10-qubit system - a size inaccessible with state-of-the-art quantum state tomography. We demonstrate the overall coherence of this system, and the generation of bipartite entanglement under quenched time-evolution governed by a long-range interacting spin-spin Hamiltonian, with and without controlled disorder. Secondly, we propose, based on the same ingredients, a new protocol to access out-of-time ordered correlators (OTOCs), characterizing spreading of information (scrambling) in quantum many body systems. Uniquely, our protocol does not require the implementation of time-reversed evolution and/or additional ancillas.

Robust preparation of logical basis states in planar codes

Matthias Englbrecht, University of Innsbruck

A central task associated with any quantum error correcting code is the preparation of logical basis states (codewords). We analyze the known preparation scheme of syndrome measurement and Pauli correction for planar codes in the presence of coherent errors. The main result is an efficient simulation procedure for the measurement of either plaquette or site operators based on planar matchgate tensor networks with runtime $O((D_1 D_2)^5)$ for codes of size $D_1 \times D_2$. For large enough codes of the shape $D_1 \times (D_1 - 1)$ numerical results based on this algorithm suggest a robustness of the preparation process to translation invariant coherent errors up to a certain threshold.

A Hidden bridge between Quantum Experiments and Graphs

Xuemei Gu, IQOQI Vienna

In this work we explore a hidden bridge between graphs and general linear optical quantum experiments with the probabilistic photon source. We uncover and identify a multiphoton quantum interference for a special-purpose quantum computation, where the experimental results is remarkably hard to calculate in a classical computer. In addition, we show a general restrictions on creating certain classes of quantum entanglement. By using the graph description, one can understand quantum protocols in a graphical way. These results open the door for designing and understanding novel state-of-the-art photonic quantum experiments.

Designing regular atomic arrays as *free-space* photonic quantum link

Pierre-Olivier Guimond, IQOQI Innsbruck

We present the design of a free-space interface between light and single atoms, where the aim is to connect atoms as qubits using photons propagating in free space. This is obtained by coupling each qubit in a laser-assisted process to an array of atomic emitters with subwavelength spacings. Using lasers to control the phases in these couplings, the atomic arrays are engineered to emit and absorb photons propagating only in a single paraxial gaussian mode of the radiation field. With this interface, deterministic and probabilistic protocols for *on-chip* quantum communication can be realized efficiently between two trapped distant atomic qubits. We present an effective quantum optical model and demonstrate how the success probability for quantum state transfer, limited by diffraction, depends on the number of atoms and their geometric arrangement. Even for as few as a hundred atoms in total, the state of the first qubit can be transferred to the second one with high probability for separation lengths of a few dozen wavelengths. Finally, we discuss experimental considerations in the implementation of this model based on laser-assisted Rydberg interactions.

A hybrid quantum-classical learning agent

Arne Hamann, University of Innsbruck

Quantizing the agent and the environment (QQ-learning) can give a quadratic speedup in learning complexity [1]. We investigate what happens, if only limited coherent interactions with the environment are possible. For this, we introduce a hybrid quantum-classical learning agent, which combines QQ-learning with Projective Simulation.

[1] V. Dunjko, J. M. Taylor, and H. J. Briegel., Phys. Rev. Lett. **117**, 130501 (2016).

Novel source of high-dimensional entanglement

Jaroslav Kysela, University of Vienna

High-dimensional entanglement is a key ingredient in many quantum-information protocols. For photonic systems, when more than two-dimensional quantum states are required, the orbital angular momentum (OAM) of light is often the preferred degree of freedom. So far, preparation of an arbitrary high-dimensionally entangled state in the OAM was rather difficult. Only recently, a novel concept of generation of such states was introduced [Phys. Rev. Lett. **118**, 080401 (2017)]. We present an experimental setup utilizing this concept where a bipartite three-dimensional maximally entangled state is created in the OAM of photons. The setup allows for straightforward adjustment of local phases as well as magnitudes of individual terms in a coherent superposition. Our scheme can be generalized also for other degrees of freedom.

Machine learning agent learns to create quantum experiments

Alexey Melnikov, University of Innsbruck

How useful can machine learning be in a quantum laboratory? Here we raise the question of the potential of intelligent machines in the context of scientific research. We investigate this question by using the projective simulation model, a physics-oriented approach to artificial intelligence. In our approach, the projective simulation system is challenged to design complex photonic quantum experiments that produce high-dimensional entangled multiphoton states, which are of high interest in modern quantum experiments. The artificial intelligence system learns to create a variety of entangled states, in number surpassing the best previously studied automated approaches, and improves the efficiency of their realization. In the process, the system autonomously (re)discovers experimental techniques which are only now becoming standard in modern quantum optical experiments - a trait which was not explicitly demanded from the system but emerged through the process of learning. Such features highlight the possibility that machines could have a significantly more creative role in future research.

Experimental investigation of the William-Searles-Evans equality

Markus Rademacher, University of Vienna

Several experiments with stochastic systems that are mechanically driven out of equilibrium have shown that certain fluctuation theorems provide a proper description of their statistics. Fluctuation theorems for continuous thermal driving far from equilibrium still lack experimental investigation. Here we investigate thermal driving of levitated nanoparticles. We show that the observed statistics is consistent with the William-Searles-Evans fluctuation theorem.

Experimental resource-efficient entanglement detection

Valeria Saggio, University of Vienna

Verification of quantum entanglement represents a crucial tool in the quantum information field. This problem is essential for practical implementation of quantum technologies, and many efforts [1-4] have been done so far to reliably certify its presence. However, the detection protocols that are commonly used still require many experimental runs, meaning repeated measurements on a large ensemble of identically prepared copies of a quantum state, and this turns out to be impractical when dealing with large entangled systems. Here we show that it is possible to detect entanglement with more than 99% confidence with no more than 33 copies for a 6-qubit H-shaped cluster state experimentally generated by using three single-photon pairs at telecom wavelength, demonstrating a dramatic cut in the number of measurements that these states would normally require to claim the presence of entanglement. This work applies the theory recently developed by A. Dimić *et al.* [5], according to which for a broad variety of large entangled states only a few copies of a quantum state suffice to detect entanglement with high confidence. The central point is to infer the presence of entanglement simply from the ability of the quantum state to answer certain binary tasks. This entails a significant reduction of resources needed for the verification problem and provides an easy end efficient tool to certify entanglement in large-scale systems.

[1] M. Horodecki, P. Horodecki, and R. Horodecki, Physics Letters A **223**, 1 (1996).
[2] O. Gühne and N. Lütkenhaus, in Journal of Physics Conference Series, Journal of Physics Conference Series, Vol. 67 p. 012004, (2007).
[3] Z. Wang, S. Singh, and M. Navascues, Phys. Rev. Lett. **118**, 230401 (2017).
[4] L. Pezzé and A. Smerzi, Phys. Rev. Lett. **102**, 100401 (2009).
[5] A. Dimić and B. Dakić, npj Quantum Information, **4**, 11 (2018).

Tuning single-photon sources for telecom multi-photon experiments

Peter Schiansky, University of Vienna

Multi-photon state generation is of great interest for near-future quantum simulation and quantum computation experiments. To-date spontaneous parametric down-conversion (SPDC) is still the most promising process, even though two major impediments still exist: accidental photon noise (caused by the probabilistic non-linear process) and imperfect single-photon purity (arising from spectral entanglement between the photon pairs). This poster presents how we overcome these difficulties by implementing a passive temporal

multiplexing scheme and carefully optimizing the spectral properties of the down-converted photons.
The optimizations are performed on two pico-second pulsed sources, based on periodically-poled KTP crystals. They operate in the telecom-wavelength regime favourable for long-distance transmission using optical fibers. The sources spectral properties are determined using superconducting nanowire single photon detectors (SNSPDs) and detectorindependent single-photon scanning monochromators (one of which was in-house built). Increasing the brightness of SPDC sources by raising the pump power leads to a degradation of the interference visibility due to higher-order emissions. This hindrance is overcome by implementing a passive temporal multiplexing scheme which allows us to increase the pump power (and thus the brightness) while keeping the photon pair creation probability per pulse (and thus the higher-order emission probability) low.
Optimizing the crystal temperature, the pumps temporal pulse-width and its central wavelength, we achieve high single-photon purities and interference visibilities. In addition, we study the effect of narrow-band spectral filters - on two out of four, and on all four photons - which open up the possibility to tune the photons purity from 0.89 ± 0.03 up to a maximum of 0.97 ± 0.03, with varying impact on the brightness.

Wave-matter interferometer with Bose-Einstein condensates

Tiantian Zhang, Atominstitut TU Wien

Our experimental setup features an atom chip enabling delicate manipulations of elongated Bose-Einstein condensate (BEC) and a sensitive light sheet imaging system capable of detecting single atoms with high fidelity. Here we present several exciting experiments that have been or are currently being conducted. One is the experimental realization is the matter-wave interferometer for trapped BECs using a tunable radio-frequency dressed double well. In a second one we study phase locking in tunnel coupled one-dimensional (1D) superfluids. In a third one we use optimal control of motional states to demonstrate a Ramsey interferometer with the ground and first transverse excited state of a BEC trapped inside an anharmonic potential. Building on our Twin Atom Beam experiment we are currently working towards the next-step: creating entangled twin atomic beams emitted from BECs into a double well. Furthermore we developed methods to quantify the entanglement and test a violation of Bell's inequality.

Directions

To/From the venue

Train connections

→ *Innsbruck, Thursday, 07/12/2018*

Wien Hbf 07:55 – Innsbruck Hbf 12:44 (RJ 662)

Wien Hbf 08:30 – Salzburg Hbf 10:52 (RJ 262) +
Salzburg Hbf 10:56 – Innsbruck Hbf 12:44 (RJ 662)

→ *Vienna, Friday, 07/13/2018*

Innsbruck Hbf 14:17 – Wien Hbf 18:30 (RJ 165/565)
Innsbruck Hbf 15:14 – Wien Hbf 19:30 (RJ 869)
Innsbruck Hbf 16:17 – Wien Hbf 20:30 (RJ 167)

From *Innsbruck Hauptbahnhof*, take *tram #3* from platform *C* towards *Innsbruck Technik* and get off at *Innsbruck Technik*. The tram runs every 10mins, the ride takes ∼17mins.

Alternatively, you can take the *O-bus*, or *OE-bus*, towards *Innsbruck Technik/Innsbruck Allerheiligen* which runs irregulary during rush hours from platform *C*.

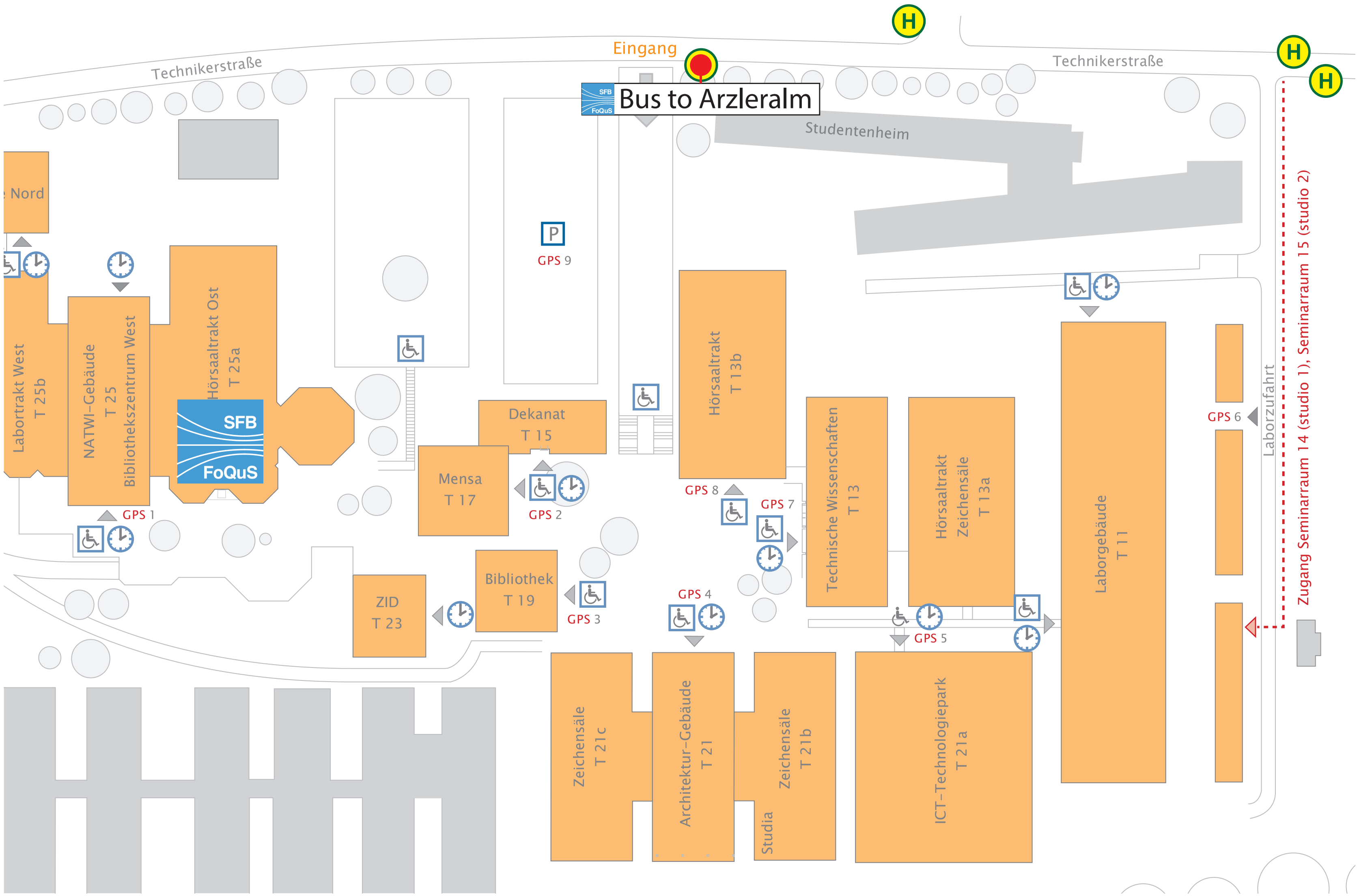
Please find more connections and timetables at http://fahrplan.vvt.at.

To the meeting's dinner

The meeting's dinner will take place at the *Arzler Alm*, at an altitude of 1.067m above the roofs of Innsbruck. The starting point for the walk will be the parking lot of the *Nordkettenbahn*. Time required: 40min, difference in altitude: app. 200m, length: ∼4km.

We will arrange a shuttle bus from the University to the lower terminus of the Nordkettenbahn (Hungerburg Bahn). Please be at the *ad hoc* bus stop as indicated on the campus map at the latest at 17:30. You can take several paths to hike up, like the *Waldsteig* no. 218 (40min) or the *Rosnerweg* (Arzler Alm Weg, 60min). All paths are signposted.

Campus area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Labortrakt West
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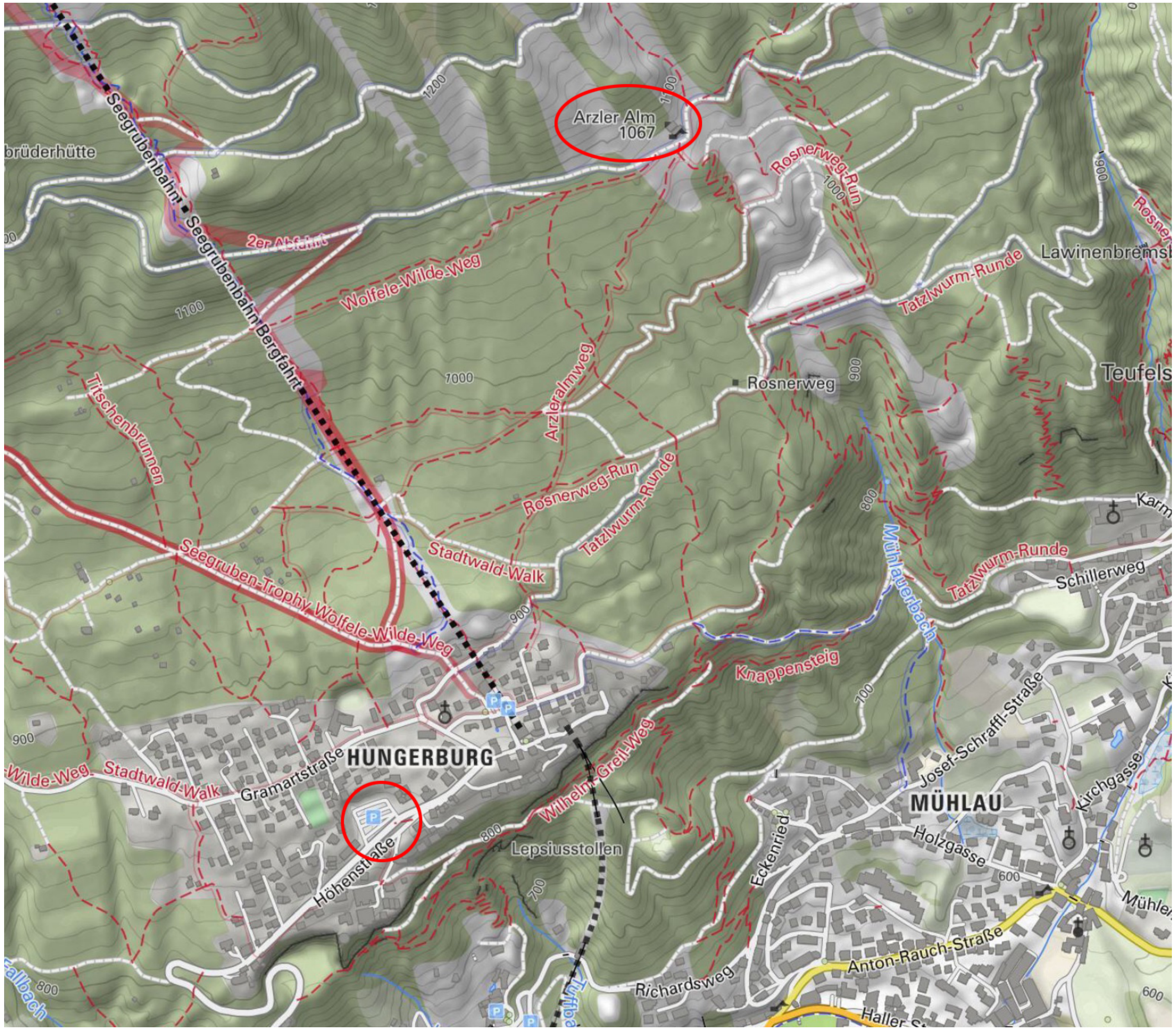
Hungerburg/Arzler Alm area



Contact

Organization:

Michaela Palz
SFB-Office
c/o Institute of Experimental Physics
University of Innsbruck
Technikerstraße 25
6020 Innsbruck, Austria

phone: +43-512-507-52515
fax: +43-512-507-52493
email: sfb-foqus@uibk.ac.at
http://www.uibk.ac.at/foqus

Scientific organizers:

Andreas Läuchli (andreas.laeuchli@uibk.ac.at)
Thomas Lang (thomas.lang@uibk.ac.at)