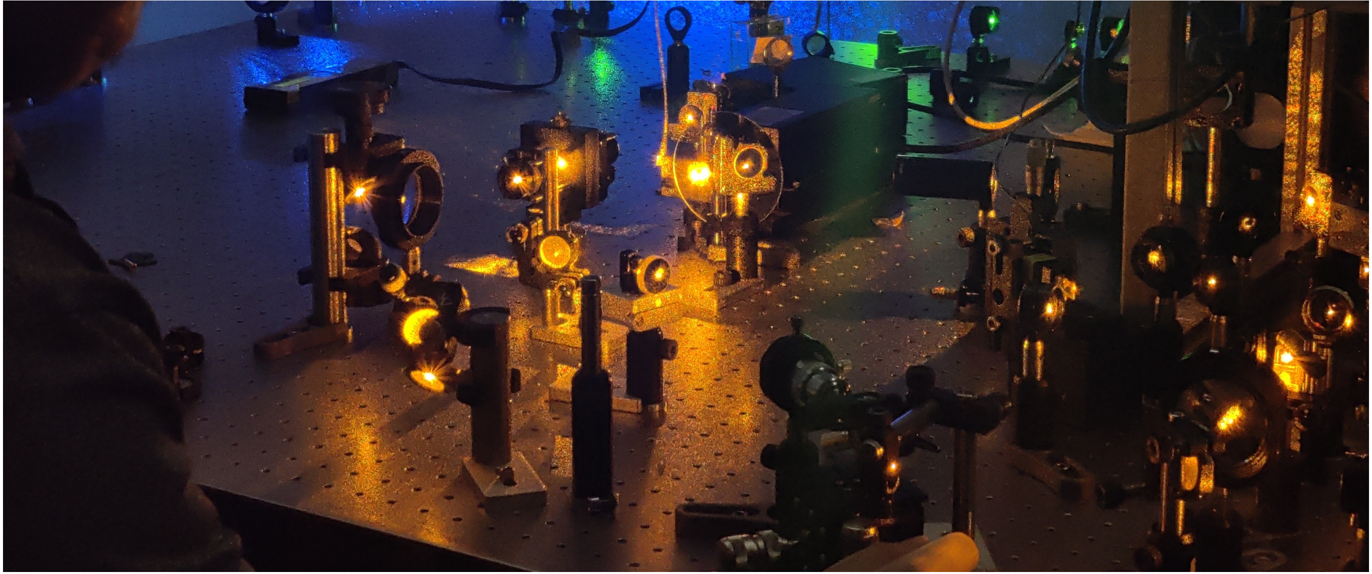
University of Zurich^UZH^

Department of Physics

Annual Report and Highlights 2023



University of Zurich^UZH

Department of Physics

Annual Report and Highlights 2023

Winterthurerstrasse 190, CH-8057 Zurich, Switzerland

Preface

Thomas Gehrmann, Department Head

With a total of 24 research groups, the Department of Physics of the University of Zurich covers a variety of subfields of physics. Experimental activities include particle and astroparticle physics, hard and soft condensed matter physics, surface physics and nanoscience, as well as the physics of biological systems. Theoretical groups work on precision calculations of processes in quantum chromodynamics and new theories beyond the standard model of particle physics, astrophysics and general relativity, as well as topological concepts in condensed matter physics. Other physics-related groups from within the Faculty of Science and beyond are affiliated to our department, and our home page gives links to their research. Together, we can offer a broad and high quality spectrum of lecture courses as well as Bachelor, Master and semester projects to our students. The infrastructure department consisting of excellent mechanical and electronics workshops. Efficient IT and administrative support teams complete our attractive research environment.
https://www.physik.uzh.ch/en/research.html

During the year 2023, the refurbishment of the laboratory building 56 of the Physik-Institut was completed. The new building offers state-of-the-art clean-room facilities and extra laboratory space for various groups. A major initial usage of the clean-room will be the assembly of the central silicon detectors for the high-luminosity phase of the CMS experiment at CERN. In the medium term, building 56 could become home to the planned DEMETER center, which is a joint initiative with colleagues at PSI to foster detector development for applications in various subfields of physics.

The start of the year was marked by the passing of our former colleague K. Alex Müller, who died on January 9, 2023 at age 95. The eminent physicist was awarded the 1987 Nobel Prize in Physics with J. Georg Bednorz for the discovery of high-temperature superconductivity. K. Alex Müller was both a professor at the University of Zurich and a fellow at the IBM Research Laboratory in Rüschlikon. In his honour, our department set up an exhibition on high-temperature superconductivity and its applications in Irchel Lichthof during the fall semester. The display was very well-received by stud-

NOBELPREIS 1987 FÜR K. ALEX MÜLLER UND J. GEORG BEDNORZ

K. Alex Müller (rechts) und J. Georg Bednorz, Bildarchiv der ETH-Bibliothek

THE NOBEL PRIZE IN PHYSICS 1987 WAS AWARDED JOINTLY TO J. GEORG BEDNORZ AND K. ALEXANDER MÜLLER «FOR THEIR IMPORTANT BREAK-THROUGH IN THE DISCOVERY OF SUPERCONDUCTIVITY IN CERAMIC MATERIALS»

(https://www.nobelprize.org/prizes/physics/1987)

Exhibition in the Lichthof at Irchel campus to honour Nobel Laureate K. Alex Müller.

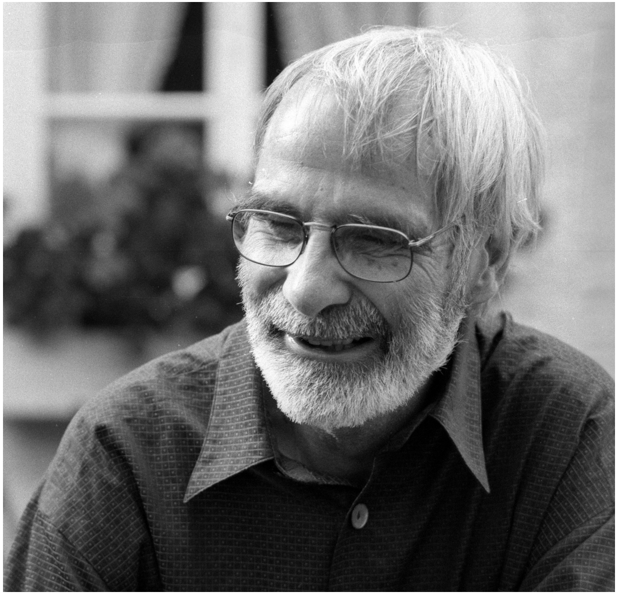
ents and academics from all faculties. We also co-organized a festive symposium that brought together friends and colleagues of K. Alex Müller, sharing recollections of their joint work and highlighting its lasting impact and present-day relevance.

In 2023, our department was very happy to welcome two new research groups in theoretical physics: Max Zoller and Tomáš Bzdušek both obtained SNSF Starting Grants and joined our institute as assistant professors. Max Zoller and his group perform precision calculations in particle theory, while Tomáš Bzdušek and his group investigate topological phases and related phenomena.

Our department made substantial contributions to community-building and outreach events such as our traditional hiking day or the christmas dinner for the members of our institute and various events for high-school students including specific workshops and the participation in the international masterclasses in particle physics. Finally, our institute organised an open day and contributed to the Scientifica 2023 with an exhibit on the basic building blocks of matter, with guided visits to the XENOSCOPE facility, a fun show on physical effects and with an astronomy theatre performance.

This booklet aims give a broad idea of the wide range of research pursued in our department and refers the more interested reader to the research websites. Presenting individual highlights with pride, we thankfully acknowledge the continued support from the Kanton Zürich, the Swiss National Science Foundation, the European Commission, and others who have made this fundamental research possible.

Prof. em. Dr. Franz Waldner, 1928 –2023



Prof. em. Dr. Franz Waldner was Professor for Experimental Physics at our institute from 1964 until his retirement in 1995.

After completing his training as a primary school teacher, Franz Waldner worked for three years before continuing his training as a secondary school teacher and teaching at this level for a short time. From 1955 he studied physics at the University of Zurich and obtained his doctorate in 1963 under Professor Ernst Brun with a thesis on "Paramagnetic electron resonance of Fe_3^+ in $MgAl_2O_4$". In 1964 Franz Waldner was appointed assistant professor and in 1979 full professor in experimental physics at the University of Zurich. In 1969 he spent a year at the Argonne National Laboratory (USA), where he was not only very curious to learn about new research approaches and a different institute culture, but also intensively engaged with American society.

Franz Waldner's research interests were very broad, ranging from electron spin resonance, crystallography, magnetism and superconductivity to complex non-linear systems and the movement of desert ants.

While still a student, he worked as an assistant in Hermann Wäffler's group and, among other things, carried out measurements of cosmic radiation on the Jungfraujoch. As an assistant professor, Franz Waldner set up the electron spin resonance (ESR) laboratory at the former Physics Institute, where the measurement of paramagnetic ions as probes in single crystals was started. In collaboration with the future Nobel laureate Professor K. Alex Müller and the crystallographer Professor Fritz Laves, ESR was used for the first time to determine the structure of solids, an essential basis for later studies of high-temperature superconductivity. Later, the ESR research group studied quasi-two-dimensional magnets in the form of layered structures. It was shown experimentally that the dimensionality essentially determines the critical dynamics. Very weakly damped spin waves could be excited at low dimensionality and used to study non-linear phenomena. This laid the foundation for his later research on superconductors, quantised lattice vibrations, spinors, skyrminons and solitons.

After his retirement, Franz Waldner continued to work intensively on scientific topics, mainly from a theoretical point of view and with the help of simulations. He regularly published the results. One of his latest publications, which appeared in 2018, describes a model with random perturbations that describes the search pattern of desert ants.

Franz Waldner's research was characterised by an incredible curiosity and interest. He successfully transferred this to his employees time and time again. He was open to many new ideas and willing to break new grounds. He is described as an internationally recognised and well-connected, modest scientist with a generous personality, to whom research and findings were more important than his own person.

In addition to his in-depth specialist lectures, Franz Waldner also taught first-year medical and physics students for many years. He understood how to present complex topics in a clear, didactically sophisticated and humorous way, and was not shy about going to a conference to demonstrate a soliton with a vector arrow.

Franz Waldner took great care of his doctoral and diploma students. He was always available to answer questions and for discussions and looked after the staff in his group with great commitment.

Even after his retirement, Franz Waldner remained very close to the Institute, taking an interest in current research topics and innovations in the workshop. He visited the institute on Open Days and joined the Christmas dinner, and even in his old age took part in the traditional Institute walk.

Statistical Data

179
personnel

professors: 23
affiliated professors: 10
senior researchers: 20
postdoctoral researchers: 40
PhD students: 67
engineers and technicians: 22
administration: 7
+ research assistants

391
students

~80
new students

197 bachelor	17 BSc degrees
79 master	29 MSc degrees
115 PhD	34 PhD degrees

13
SNF prof.
and ERC grants

37	SNF or EU research grants
6	fellowships
36	UZH and other grants

383
publications

360	peer reviewed papers
22	conference proceedings
1	books & others

356
conference and
workshop
contributions

198	talks at conferences
91	seminar and other talks
34	posters
33	outreach

Outreach

Awards

- Livio Redard-Jacot: Dectris prize
- Mohammad Alminawi: Soluyanov prize
- Adinda de Wit: Guido Altarelli Award

Events

- 2nd Women in Physics Career Event
- Open Day of the Institute
- Scientifica
- Symposium and Exhibition to commemorate Nobel Prize-Winning Physicist K. Alex Müller

Workshops & Visits

- Guided tours through the Science Pavilion UZH
- More than 30 Workshops in the Science Lab UZH

Scientifica – the Zurich Science Days

Booth on particle physics
Labtour to XENOSCOPE
Theatre on black holes
Physics show

Exhibition on gravitational waves in the Science Pavilion UZH.

Teaching

bachelor
3
major options

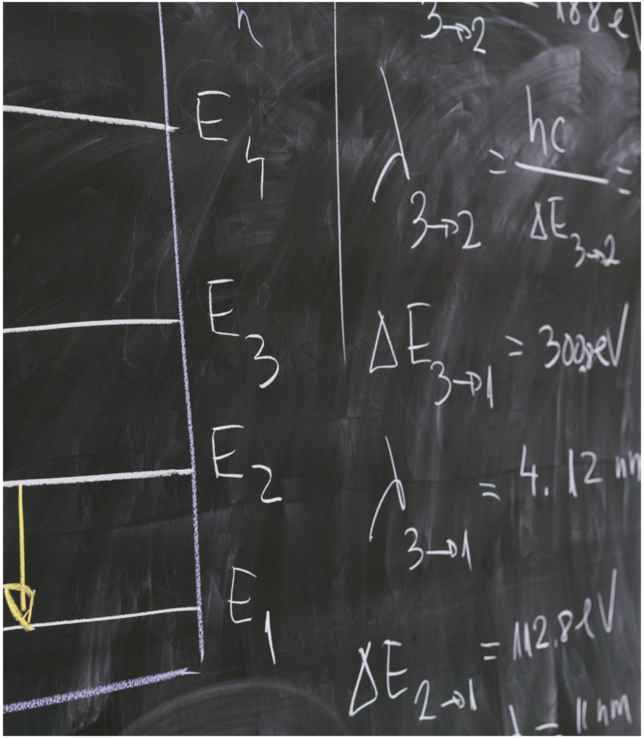
- 180 ECTS physics
- 150 ECTS physics/30 ECTS minor
- 120 ECTS physics/60 ECTS minor

4
master
programs

- particle physics
- condensed matter
- astro(particle) & cosmology
- bio- & medical physics

service lectures
1445
students

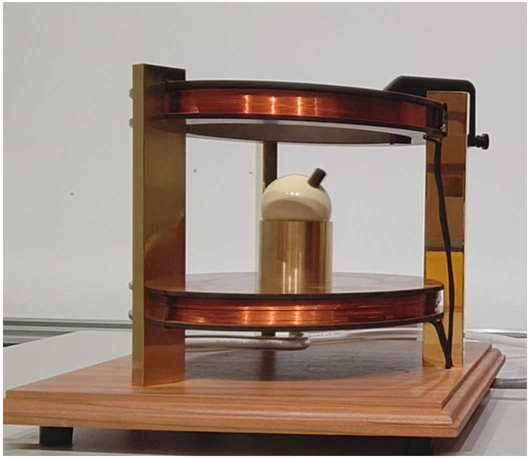
550	medicine
600	biology & biomedicine
150	chemistry
70	teacher
75	minors

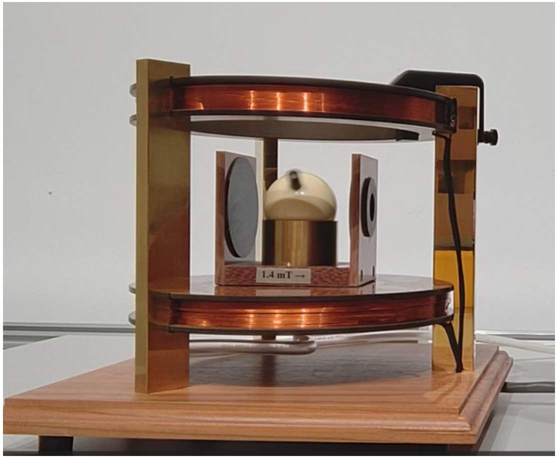


Demonstration experiments

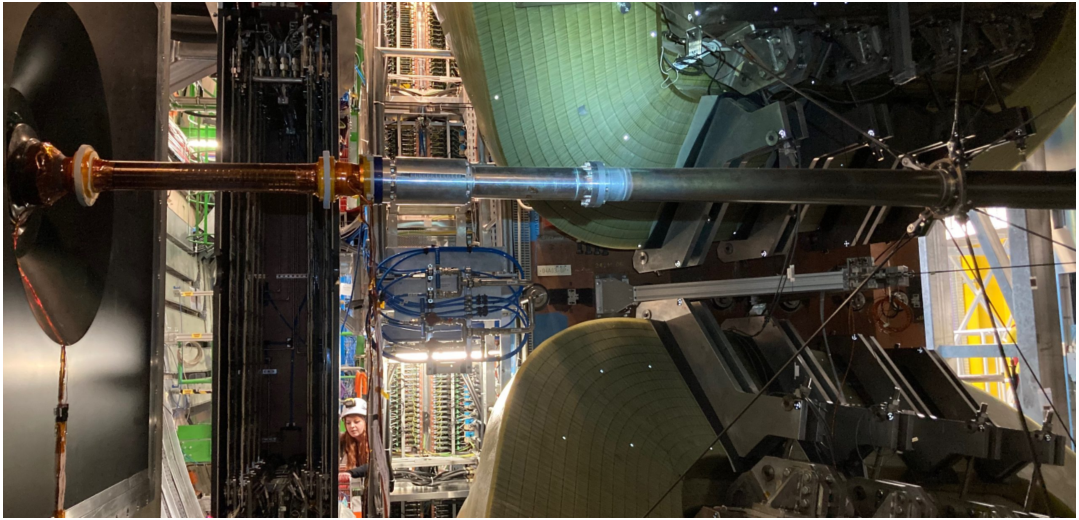
A macroscopic demonstration of magnetic spin resonance

Magnetic spin resonance is demonstrated by a spinning ball containing a magnet along the spin direction (black top). When the spinning ball is in a constant vertical field (left image), the spin precesses along the applied field at a constant angular frequency. By adding a second, horizontal field (right image), the precession direction changes. If the horizontal field is rotated at the original precession frequency, the spin precesses to the horizontal position. This corresponds to resonant absorption of electromagnetic radiation at the Larmor precession frequency. Using such a macroscopic demonstrator, the different concepts leading to magnetic spin resonance can be discussed one by one, giving a clear picture of the physical process at play.





Physics of Fundamental Interactions and Particles



Closing of the LHCb detector completes the LHCb Upgrade 1 (© 2022 CERN)

Particle Physics Theory: Beyond the Standard Model

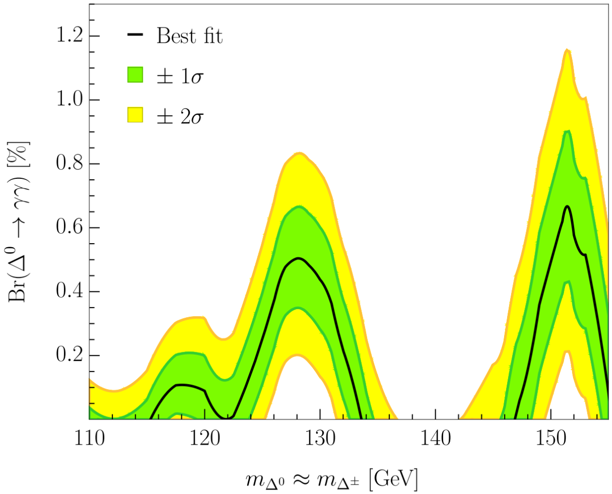
Prof. Andreas Crivellin

The Standard Model (SM) of particle physics describes Nature's fundamental constituents and interactions. Matter consists of quarks and leptons (fermions) which interact via the exchange of force particles (gauge bosons). The SM has been tested with high accuracy, both in high-energy searches at the Large Hadron Collider (LHC) at CERN and in low-energy precision experiments. However, it is well known that it cannot be the ultimate theory of nature since it fails to explain observations like Dark Matter, Dark Energy, neutrino masses or the presence of more matter than anti-matter in the Universe. The goal of our research is to construct and study models of physics beyond the SM both regarding their signatures in low-energy precision experiments and direct searches at the Large Hadron Collider (LHC).

https://www.psi.ch/en/ltp-crivellin

Direct and Indirect Hints for Physics Beyond the Standard Model

Significant tensions with the SM predictions were observed in many processes involving multiple leptons and missing energy, (possibly in conjunction with bottom quarks) at the LHC [1]. In particular, the differential top quark distributions ($pp \to tt \to WWbb \to e\mu bb$) measured by ATLAS indicate the presence of new Higgs bosons (>5sigma) [2]. These new scalars can also be searched for at the LHC in di-photon final states. Here, we showed that a Higgs triplet can explain the excesses in $\gamma\gamma$+X, where X can be missing energy, leptons and (bottom) quarks [3] (see Figure). In Ref. [4] we proposed a complete model which can account for the differential top quark distributions as well as for the di-photon excesses at the same time. This model predicts more new Higgs bosons which can be discovered with LHC run-3 data.



Statistical combination of the relevant channels for $\gamma\gamma + X$. Note that a non-zero branching ratio is preferred at both ≈127 GeV (3.6σ) and ≈ 151 GeV (3σ).

Highlighted Publications:

1. Anomalies in Particle Physics, A. Crivellin, B Mellado, arXiv 2309.03870
2. Uncovering New Higgses in the LHC Analyses of Differential $t\bar{t}$ Cross Sections, S. Banik, G. Coloretti, A. Crivellin, B. Mellada, arXiv 2309.03870
3. Explaining the $\gamma\gamma + X$ Excesses at ≈151.5 GeV via the Drell-Yan Production of a Higgs Triplet, S. Ashanujjaman, S. Banik, G. Coloretti, A. Crivellin, S. P. Maharathy, B. Mellado, arXiv 2402.00101
4. Combined Explanation of LHC Multi-Lepton, Di-Photon and Top-Quark Excesses, G. Coloretti, A. Crivellin, B. Mellado, arXiv 2312.17314

Particle Physics Theory: Precision Calculations

Prof. Thomas Gehrmann

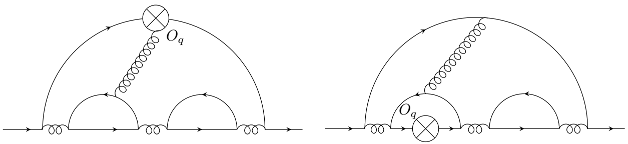
Our research group focuses on precision calculations for collider observables within the Standard Model and their application in the interpretation of experimental data. We develop novel techniques and computer algebra tools that enable analytical calculations in perturbative quantum field theory and help to unravel the underlying mathematical structures. We implement our results into numerical parton-level event generator programs, which are flexible tools that allow to take proper account of the details of experimental measurements, enabling precision theory to be directly confronted with the data.

https://www.physik.uzh.ch/g/gehrmann

Altarelli-Parisi splitting functions at three and four loops in QCD

The operator product expansion (OPE) provides an elegant method to separate short-distance from long-distance contributions in quantum field theory. Its early application to deeply inelastic lepton-nucleon scattering processes in quantum chromodynamics (QCD) successfully predicted the violation of Bjorken scaling, thereby enabling the development of the QCD-improved parton model. The anomalous dimensions of quark and gluon operators in the OPE are directly related to the Altarelli-Parisi splitting functions of the QCD-improved parton model.

Despite its early success and its computational simplicity, the OPE method has not played a significant role in this progress towards precision QCD for collider observables. Its applicability at higher loop orders is limited by the currently incomplete understanding of the renormalization of singlet quark and gluon operators, which involves the mixing with so-called gauge-variant (GV) operators, that are unphysical operators resulting from the gauge fixing in QCD. Although the existence of such operators has been known since the initial applications of the OPE in QCD, it has not been possible to determine the number and the form of these GV operators — or even only the renormalization counterterms that result from



Two example diagrams contributing to the operator matrix elements for the four-loop pure-singlet splitting functions.

them — beyond what is required for two-loop calculations.

We revisited the long-standing question of the renormalization of the quark and gluon operators, whose anomalous dimensions determine the scale evolution of parton distribution functions. In our work, we developed a new method to extract the Feynman rules for renormalization counterterms that result from GV operators through the computation of multi-leg operator matrix elements in general kinematics. We then applied our newly computed GV counterterm Feynman rules to rederive the three-loop anomalous dimensions of the unpolarized quark and gluon operators in a general covariant gauge using the OPE method. These three-loop anomalous dimensions or the corresponding splitting functions were previously computed with several other approaches (but always in Feynman gauge). Working in a general covariant gauge, we confirmed these earlier results and established for the first time the gauge-independence of the anomalous dimensions at three loops.

Based on these developments, we were able to derive several contributions to the four-loop splitting functions, thereby preparing the ground for their full computation, which is currently ongoing in the context of the ERC Advanced Grant project 'TOPUP – Theory for collider processes at ultimate precision'.

Highlighted Publications:

1. Renormalization of twist-two operators in covariant gauge to three loops in QCD,
   T. Gehrmann, A. von Manteuffel and T. Z. Yang,
   JHEP **04** (2023), 041.
2. Complete N_f^2 contributions to four-loop pure-singlet splitting functions,
   T. Gehrmann, A. von Manteuffel, V. Sotnikov and T. Z. Yang, JHEP **01** (2024) 029.

Particle Physics Theory: Standard Model and Higgs Physics at Colliders

Prof. Massimiliano Grazzini

Our research activity is focused on the phenomenology of particle physics at high-energy colliders. We perform accurate theoretical calculations for benchmark processes at the Large Hadron Collider and we strive to make their results fully available to the community. We develop flexible numerical tools that can be used to perform these calculations with the specific selection cuts used in the experimental analyses. Our projects span over a wide range of processes from vector-boson pair production to heavy-quark and jet production, to Higgs boson studies within and beyond the Standard Model.

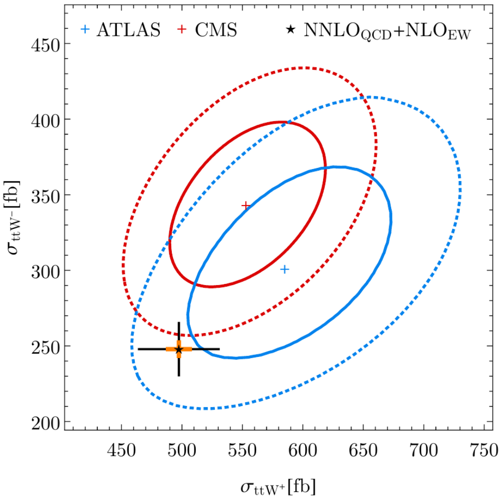
https://www.physik.uzh.ch/g/grazzini

Precise predictions for the associated production of a W boson with a top-antitop quark pair at the LHC

The final state of a $W^{\pm}$ boson produced together with a top-antitop pair represents one of the most massive Standard Model (SM) signatures accessible at the Large Hadron Collider (LHC). The leptonic decay of the top quarks and of the W boson lead to multi-lepton signatures relevant to a number of searches for physics beyond the Standard Model (BSM). In particular $t\bar{t}W$ production is one of the few SM processes providing an irreducible source of same-sign dilepton pairs.

Measurements of $t\bar{t}W$ production carried out by the ATLAS and CMS collaborations at the LHC led to rates consistently higher than the SM prediction. With this situation, it is clear that a precise knowledge of the $t\bar{t}W$ SM cross section for this process is of utmost importance. It has been indeed argued that the discrepancy with the data, which is at the $2-3\sigma$ level, could be explained by the missing next-to-next-to-leading order (NNLO) QCD corrections.

We have completed the first (almost exact) computation of $t\bar{t}W$ production at NNLO in QCD. While the required tree-level and one-loop scattering amplitudes can be evaluated with automated tools, the two-loop amplitude is still unknown. We estimate it by using two different approaches.



Comparison of our $\text{NNLO}_{\text{QCD}}+\text{NLO}_{\text{EW}}$ *result to the measurement performed by the CMS (red) and ATLAS (blue) collaborations at 68% (solid) and 95% (dashed) confidence level. We indicate in black and orange the scale and the approximation uncertainties, respectively, of the* $\text{NNLO}_{\text{QCD}}+\text{NLO}_{\text{EW}}$ *result.*

The first is based on a soft-W approximation, which allows us to extract the $t\bar{t}W$ amplitude from the known two-loop amplitudes for top-pair production. The second is obtained from the two-loop amplitudes for a W boson and four massless partons through a *massification* procedure, through which the approximate form of the mass dependent terms is reconstructed. Despite their distinct conceptual foundations and the fact that they are used in a regime where their validity is not granted, the two approximations give consistent results within their respective uncertainties, which is a strong check of our approach. The final NNLO result is obtained by taking the average of the two approximations and linearly combining their uncertainties. The full prediction is obtained by combining the NNLO QCD result with the complete NLO EW corrections.

In the figure we present our $\text{NNLO}_{\text{QCD}}+\text{NLO}_{\text{EW}}$ results with their perturbative uncertainties in the $\sigma_{t\bar{t}W^+} - \sigma_{t\bar{t}W^-}$-plane, together with the 68% and 95% confidence level regions obtained by the ATLAS and CMS collaborations. The subdominant uncertainties due to the approximation of the two-loop corrections are also shown. When comparing to the data, we observe an overlap between the $\text{NNLO}_{\text{QCD}}+\text{NLO}_{\text{EW}}$ uncertainty bands and the 1σ and 2σ contours of the ATLAS and CMS measurements, respectively.

1. Precise predictions for the associated production of a W boson with a top-antitop quark pair at the LHC, L. Buonocore *et al.*, arXiv:2306.16311, Phys.Rev.Lett. 131 (2023) 23, 231901.

Particle Physics Theory: Beyond the Standard Model

Prof. Gino Isidori

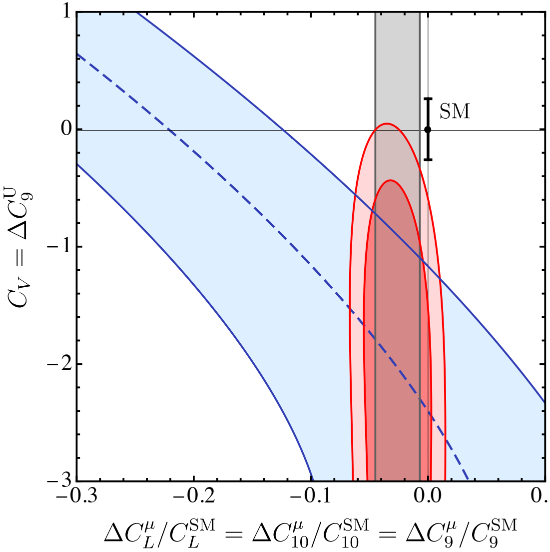
The Standard Model of fundamental interactions describes the nature of the basic constituents of matter, the so-called quarks and leptons, and the forces through which they interact. This theory is very successful in laboratory experiments over a wide range of energies. However, it fails in explaining cosmological phenomena such as dark matter and dark energy. It also leaves unanswered basic questions, such as why we observe three almost identical replicas of quarks and leptons, which differ only in their mass. Finally, it gives rise to conceptual problems when extrapolated to very high energies, where quantum effects in gravitational interactions become relevant. The goal of our research activity is to formulate extensions of this theory that can solve its open problems, identifying way to test the new hypotheses about fundamental interactions in future experiments.

https://www.physik.uzh.ch/g/isidori

Probing new interactions via flavour-changing transitions

One of the key predictions of the Standard Model (SM) is that quarks and leptons do appear in three replicas (denoted generations, or flavours) that behave exactly in the same manner under the known microscopic forces, and differ only in their mass (or better their interaction with the Higgs field). Why we have three almost identical replica of quarks and leptons, and which is the origin of their different interactions with the Higgs field is one of the big open questions in particle physics. The peculiar structure of quark and lepton masses, which exhibits a strongly hierarchical pattern, is very suggestive of some underlying new dynamics that we have not identified yet. The main goal of our research activity in the last few years is trying to understand the nature of this dynamics.

To achieve this main goal, we proceed along three complementary research directions: 1) we build explicit extensions of the SM that can explain the observed pattern of quark and lepton masses, possibly addressing also other short comings



Structure of the $b \to s\ell^+\ell^-$ transition, as extracted from different physical processes [1]. The blue band is derived from the inclusive decay $B \to X_s\mu^+\mu^-$ at large dilepton invariant mass. The dark and light red regions indicate the combined compatibility at 68% and 90% confidence level, respectively.

of the SM (in particular the instability of the Higgs sector); 2) we investigate the consistency of the new hypothesized interactions with current data, particularly on rare flavour-changing transitions; 3) we perform detailed predictions, according to the new hypotheses, in view of future experiments.

Over the past year, we have worked mainly along the first and second directions. On the model-building site, we have systematically analysed the hypothesis of flavour deconstruction, i.e. the idea that the apparent flavour universality of strong, weak and electromagnetic interactions is only an accidental low-energy property, resulting from an ultraviolet theory where gauge symmetries act differently on the different fermion families. Beside investigating the technical aspects of this hypothesis, we have shown that it explains well the observed pattern of quark and lepton masses and, at the same time, offers a general framework to construct models able to stabilise the Higgs sector.

Highlighted Publications:

1. Semi-inclusive $b \to s\ell^+\ell^-$ transitions at high q^2,
   G. Isidori, Z. Polonsky and A. Tinari,
   Phys. Rev. D108 (2023) 093008, arXiv:2305.03076.
2. Non-universal gauge interactions addressing the inescapable link between Higgs and flavour,
   J. Davighi and G. Isidori,
   JHEP **07** (2023) 147, arXiv:2303.01520.
3. Third-family quark-lepton Unification and electroweak precision tests, L. Allwicher *et al.*,
   JHEP **05** (2023) 179, arXiv:2302.11584.

Particle Physics Theory: Automated Simulations for high-energy colliders

Prof. Stefano Pozzorini

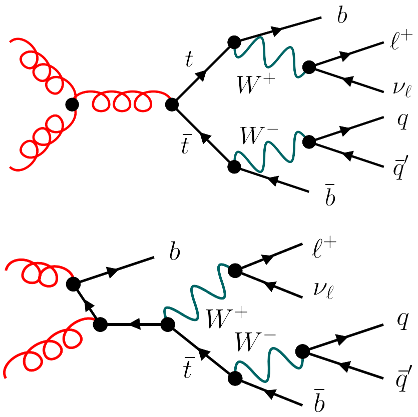
Our research deals with the development of automated methods for the simulation of scattering processes in quantum-field theory. The OpenLoops algorithm, developed in our group, is one of the most widely used programs for the calculation of scattering amplitudes at the LHC. This tool is applicable to arbitrary collider processes up to high particle multiplicity and can account for the full spectrum of first-order quantum effects induced by strong and electroweak interactions.
Currently, new automated methods for second-order quantum effects are under development. Our phenomenological interests include topics like the strong and electroweak interactions of heavy particles at the TeV scale, or theoretical challenges related to the extraction of rare Higgs-boson and dark-matter signals in background-dominated environments.

https://www.physik.uzh.ch/g/pozzorini

Precision simulation of top-quark pair production and decay

Since the first release of the OpenLoops program, our group was involved in the integration of our code into widely used Monte Carlo (MC) generators that support fully fledged simulations of proton–proton collisions at the LHC. In this context, one of the main objectives has been the precise theoretical description of multi-particle processes that involve the production of heavy unstable particles and their decays.

Together with the authors of the Powheg generator, we have pioneered the development of fully realistic precision simulations for the production and decay of top-quark ($t\bar{t}$) pairs. Top quarks are the heaviest known elementary particles. Due to their very short lifetime of 5×10^{-25} seconds, top quarks can be experimentally studied only through the detection of their decay products. Such decays involve the conversion of top quarks into bottom quarks (b) and W bosons, which subsequently decay into lepton–neutrino ($\ell\nu$) or light quark–anti-quark pairs ($q\bar{q}'$) (see Figure).



Examples of Feynman diagrams representing two top-production modes that yield identical final states involving a bottom–anti-bottom pair ($b\bar{b}$) a light quark–anti-quark pair ($q\bar{q}'$), a charged lepton ℓ^+ and a neutrino ν_ℓ. The $t\bar{t}$ mode (top) involves $t\bar{t}$ production with $t \to b\ell^+\nu_\ell$ and $\bar{t} \to \bar{b}q\bar{q}'$ decays. The tWb mode (bottom) involves only a single anti-top quark with $\bar{t} \to \bar{b}q\bar{q}'$ decay, while the $b\ell^+\nu_\ell$ system does not give rise to any top-quark resonance.

So far, the analysis of LHC data was largely based on MC simulations where the production of $t\bar{t}$ pairs and their decays are handled as separate processes. This approach relies on the assumption that $t\bar{t}$ pairs are produced on a time scale that is negligibly small as compared to the lifetime of top quarks. This is a reasonably good approximation. However, the increasing precision of LHC data calls for more accurate simulations, where the effects of the short life-time of top quarks are taken into account. To this end, we have developed a new kind of MC simulations where unstable top and anti-top quarks are handled as resonances with well-defined shapes and widths, as predicted by quantum-field theory. Technically, this was achieved by matching OPENLOOPS scattering amplitudes to parton showers in the “resonance-aware” POWHEG framework [1].

These new simulations account for various physics features that are usually neglected or handled in a simplified way. In particular, they guarantee a fully realistic description of top resonances, including quantum effects. Moreover, they provide a unified description of resonant $t\bar{t}$ production with non-resonant tWb production (see Figure), including the quantum interference between these two top-production mechanisms. These and other features of the new MC generator presented in [1] play an important role for precision measurements of the top-quark mass as well as for the accurate modelling of backgrounds to new-physics searches at the LHC.

Highlighted Publication:

1. Resonance-aware NLOPS matching for off-shell $t\bar{t}+$ tW production with semileptonic decays, T. Ježo, J. Lindert, St. Pozzorini, JHEP **10** (2023) 008

High-intensity low-energy particle physics

Prof. Adrian Signer

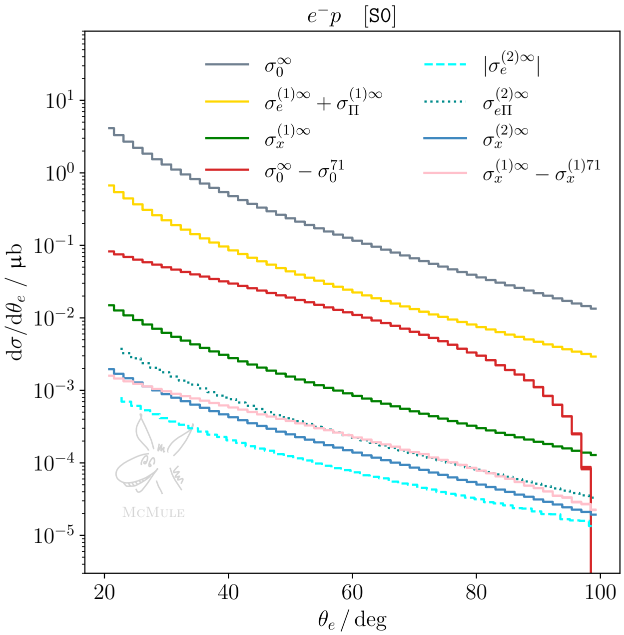
Particle physics at low energy but high intensity provides an alternative road towards a better understanding of the fundamental constituents of matter and their interactions. Using the world's most intense muon beam at PSI allows to look for tiny differences to the Standard Model or for extremely rare decays. Our group provides theory support for such experiments by computing higher-order corrections in Quantum Electrodynamics (QED) to scattering and decay processes and by systematically analysing the impact of experimental bounds on scenarios of physics beyond the Standard Model. These calculations are also adapted to experiments performed at other facilities with lepton beams.
https://www.physik.uzh.ch/g/signer

NNLO QED effects in lepton-proton scattering

Our group has set up McMule (Monte Carlo for MUons and other LEptons), a generic framework for higher-order QED calculations of scattering and decay processes involving leptons. This framework properly treats infrared singularities when combining loop amplitudes and allows to obtain fully differential cross sections at any order in QED perturbation theory with massive fermions. The long-term goal is to provide a library of relevant processes with sufficient precision, typically at next-to-next-to leading order (NNLO) in the perturbative expansion. The code is public and the current version is available at `https://gitlab.com/mule-tools/mcmule`.

Low-energy lepton-proton scattering has received renewed attention due to discrepancies in experimental data and the ongoing unclear situation regarding the proton-radius determination. Currently, the MUSE collaboration is taking data at PSI for electron-proton and muon-proton scattering with incoming lepton momenta between 100-200 MeV. With McMule we are providing a state-of-the-art theoretical description of these processes.

In the case of lepton-proton scattering an additional complication arises due to the fact that the proton is not point-



Various contributions to the differential cross section w.r.t. the scattering angle for electron-proton scattering with incoming electrons of 210 MeV momentum (see text for details).

like. For small momentum transfer, using dipole factors for the photon-proton interaction is a reasonable approximation. However, the form factors and potential additional hadronic effects do affect the predictions. In particular, the so called two-photon-exchange (TPE) contributions have received a lot of attention in the literature. Their impact on proton-radius extraction from scattering experiments has been widely discussed. What we have shown is that standard leptonic NNLO QED corrections, which we have computed, are as important as details of the TPE contributions.

This statement is illustrated in the figure, where various contributions to electron-proton scattering are plotted. Results for a pointlike proton are shown in grey (tree level), yellow (leptonic NLO), and green (TPE). The relative impact of going from a pointlike proton to including the form factor is shown in red (tree level) and pink (TPE). The various blue curves (dotted, solid, dashed) indicate NNLO leptonic corrections and three-point photon exchange (for a pointlike proton). As shown in the figure, they are of the same importance as detailed modifications of the TPE. Hence, NNLO QED effects need to be carefully considered when extracting the proton form factor or the proton radius from lepton-proton scattering experiments.

1. Impact of NNLO QED corrections on lepton-proton scattering at MUSE, T. Engel, F. Hagelstein, M. Rocco, V. Sharkovska, A. Signer and Y. Ulrich,
Eur. Phys. J. A **59** (2023) no.11, 253
doi:10.1140/epja/s10050-023-01153-x

Effective Field Theories at the Precision Frontier

Prof. Peter Stoffer

The research of our group is focused on indirect searches for physics beyond the Standard Model and the theoretical challenges at the precision frontier: these concern the model-independent description of non-perturbative effects due to the strong interaction at low energies as well as higher-order perturbative effects that can be described within effective field theories.

Our current research activity is mainly motivated by experimental progress at the low-energy precision frontier, such as searches for CP- or lepton-flavor-violating observables and the improved measurement of the muon anomalous magnetic moment.

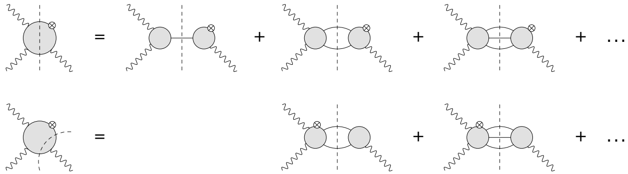
https://www.physik.uzh.ch/g/stoffer

Despite its success, the Standard Model (SM) of particle physics fails to explain certain observations, such as the baryon asymmetry in the universe, dark matter, or neutrino masses. Our group is interested in indirect searches for physics beyond the SM, conducted in low-energy experiments at very high precision. These observables pose interesting theoretical challenges concerning the model-independent description of effects beyond the SM, as well as non-perturbative effects due to the strong nuclear force.

CP and lepton-flavor violation

Beyond-the-SM sources of CP or lepton-flavor violation are probed up to very high scales by searches for electric dipole moments (EDMs) or lepton-flavor-violating decay processes, e.g., in the upcoming n2EDM and Mu3e experiments at PSI. We are interested in non-perturbative effects that affect these observables at low energies. Their description is based on effective field theories (EFTs) and usually requires input from lattice QCD.

Our group is working on the matching between the MS scheme used in EFTs and a gradient-flow scheme that can be implemented with lattice QCD. We recently obtained results for all dimension-six operators contributing to the neutron EDM. In order to reduce theoretical uncertainties, we are



The contribution of different intermediate states to the two discontinuities in the new dispersive formalism for hadronic light-by-light scattering (from Ref. [1]).

extending this work beyond one loop.

The results will enable the use of future lattice-QCD input for an accurate determination of contributions beyond the SM to the neutron EDM.

Anomalous magnetic moment of the muon

The theoretical prediction of the anomalous magnetic moment of the muon is currently affected by several puzzles that concern the determination of hadronic effects: there is a conflict between data-driven and recent lattice-QCD evaluations of hadronic vacuum polarization, but also between different e^+e^- experiments used as input in the data-driven determination. These different discrepancies need to be resolved in order to enable a meaningful comparison to the experimental measurement of the anomalous magnetic moment of the muon at Fermilab.

In order to reduce these non-perturbative uncertainties, we are extending the dispersive frameworks used for hadronic vacuum polarization and for hadronic light-by-light scattering.

Highlighted Publications:

1. Dispersion relations for hadronic light-by-light scattering in triangle kinematics,
   J. Lüdtke, M. Procura, P. Stoffer,
   JHEP **04**, 125 (2023), [arXiv:2302.12264 [hep-ph]]
2. One-loop matching of CP-odd four-quark operators to the gradient-flow scheme,
   J. Bühler, P. Stoffer, JHEP **08**, 194 (2023),
   [arXiv:2304.00985 [hep-lat]]
3. One-loop matching of the CP-odd three-gluon operator to the gradient flow,
   Ò. L. Crosas, C. J. Monahan, M. D. Rizik, A. Shindler, P. Stoffer, PLB **847**, 138301 (2023), [arXiv:2308.16221 [hep-lat]]

CMS Experiment

Prof. Cristina Botta, Prof. Lea Caminada, Prof. Florencia Canelli, Prof. Ben Kilminster




The CMS (Compact Muon Solenoid) experiment at CERN measures properties of the fundamental particles and their interactions, and can uncover new forces and particles. CMS surrounds one of the interaction points at the Large Hadron Collider (LHC), which when colliding protons produces an energy density comparable to that of the universe one ten- billionth of a second after it started. The CMS detector is used to determine the energy and direction of the energy and directions of the particles emerging from the LHC collisions of protons and heavy ions. In 2012, with 10 fb^{-1}, CMS discovered the Higgs boson, proving the mechanism on how particles acquire mass. CMS is also focused on detector refurbishment for the data-taking period of 2022 to 2025, and upgrades needed for the high-luminosity run of the LHC from 2029 to 2038.

https://www.physik.uzh.ch/r/cms

The CMS group at UZH is strong in data analysis, focusing on the fundamental mysteries remaining in particle physics. We are studying the Higgs boson, and also using it as a probe to look for new forces and particles. We are searching for dark matter in unexplored phase space, and we are measuring standard model processes that can elucidate rare phenomena.

In collisions at the LHC, the protons that collide are not fundamental particles, but are composed of quarks and gluons called partons. While most interactions involve the collision of one parton from each proton, double-parton interactions, in which two partons from each proton were first observed around 1990. In our 2023 paper [1], we have now observed for the first time, interactions in which 3 partons from each proton interact. The striking signature of this is the production of three J/ψ particles, each of which decays to two muons (Fig. 1). Such physics processes are hard to calculate theoretically, and provide insight into proton structure.

In 2023, the UZH CMS group published the first ob-

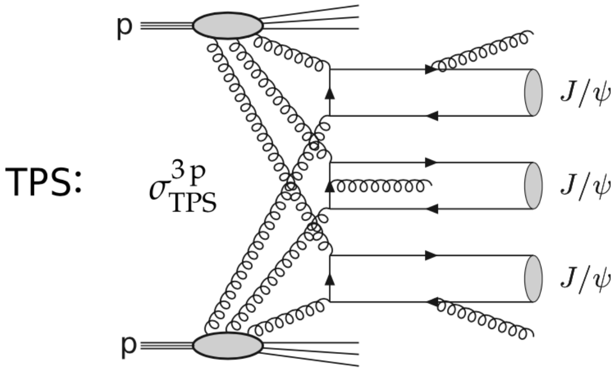


Fig 1: The triple parton scattering (TPS) of two protons at the LHC. The CMS experiment has recently observed this process for the first time, by measuring the muon pairs produced from the three J/ψ decays.

servation of the production of tau leptons for in PbPb collisions at the LHC. The tau leptons are produced by photons surrounding the high electromagnetic field of the Pb ions. Since these events are produced through the electromagnetic interaction, the events are extremely clean, allowing the group to measure the lowest energy tau leptons ever reconstructed by the CMS experiment. Using these events, a measurement of the anomalous magnetic moment of the tau lepton (g-2)τ could be determined. So far, this result agrees with the SM, however, large deviations have been observed in the measurement of (g-2)μ, and it could be that such deviations could be even larger for the τ lepton. This result was published by PRL with the editor's choice distinction [2].

Leveraging the recently observed ttH (multilepton) events, the UZH CMS group embarked on a study investigating the Lorentz structure of the top quark Yukawa interaction. Our focus was mainly on probing the potential existence of CP-violating terms within this coupling. Expanding upon previous analysis frameworks, the study introduced a novel event categorization based on kinematic properties. Events were categorized depending on their resemblance to the ttH signal under CP-odd or CP-even hypotheses or background. These results constrain $|f^{Htt}_{CP}|$ to less than 0.55 at 68% confidence level, in agreement with the standard model CP-even prediction of $|f^{Htt}_{CP}| = 0$ [3].

The UZH CMS group remains prominent in the study of the top quark and its interactions with a recent measurement of top quark pairs produced in association with b-quarks (ttbb) process. Enhancing the accuracy and precision of perturbative calculations in QCD for this process is vital, as they pose a notable limitation for measurements of the Higgs boson through the ttH(bb) process, as well other searches for new physics at the LHC. Measurements of the ttbb cross-section exceed the predicted rate by 30%, underscoring

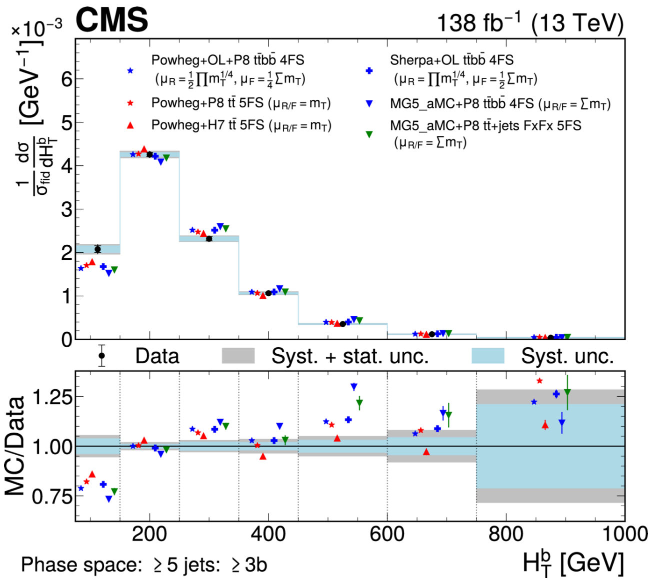


Fig. 2: Predicted and observed normalized differential cross sections in the ≥5 jets: ≥3b fiducial phase space for the HT of b jets.

the necessity for further experimental investigations to refine theoretical calculations. The UZH group spearheaded a new measurement of the differential ttbb cross-section, scrutinizing variables that could enhance the understanding of the diverse processes contributing to ttbb production (Fig. 2). The results of these studies represent the most comprehensive examinations of ttbb to date and are poised to reduce uncertainties in its modeling significantly. The differential cross-sections exhibit varying levels of agreement with theoretical predictions, with none of the tested generators simultaneously capturing the features of all measured distributions [4].

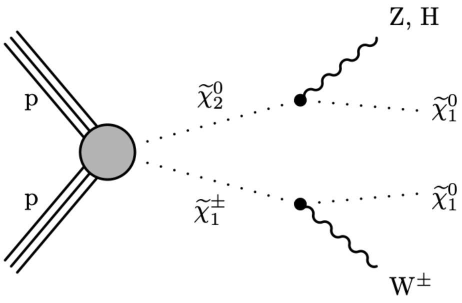


Fig. 3: Neutral and charged supersymmetric particles decaying to Standard Model bosons and a stable supersymmetric particle, which would be a candidate for dark matter.

In 2023, the UZH group remained involved in searches for BSM Physics caracterized by new states with mass-compressed spectra, foreseen by several Dark Matter models. These searches target final states with soft leptons and mod-

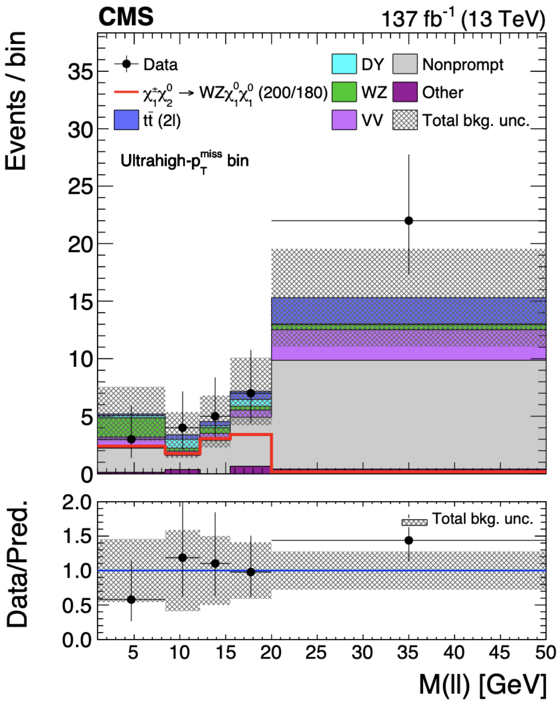


Fig. 4: This plot of the invariant mass of the charged leptons in CMS events compares data with a background model. The red line indicates what the presence of the supersymmetric signal shown in Figure 3 would add to the distribution.

erate missing transverse energy. In particular, the group developed and published the statistical combination of six CMS searches targeting electroweak-produced supersymmetry [5], as shown in Figs. 3 and 4.

Highlighted Publications:

1. Observation of triple J/ψ meson production in proton-proton collisions at $\sqrt{s)} = 13$ TeV, CMS collaboration, Nat. Phys. **19** (2023) 338.
2. Observation of $\tau\tau$ lepton pair production in ultraperipheral lead-lead collisions at $\sqrt{s_N N} = 5.02$ TeV, CMS collaboration, Phys. Rev. Lett. **131** (2023) 151803.
3. Search for CP violation in ttH and tH production in multilepton channels in proton-proton collisions at $\sqrt{s} = 13$ TeV, CMS collaboration, JHEP **07** (2023) 092.
4. Inclusive and differential cross section measurements of ttbb production in the lepton+jets channel at $\sqrt{s} = 13$ TeV, CMS collaboration, Submitted to the Journal of High Energy Physics, arXiv 2309.14442
5. Combined search for electroweak production of winos, binos, higgsinos, and sleptons in proton-proton collisions at $\sqrt{s} = 13$ TeV, CMS collaboration, Submitted to PRD, 2023, arXiv 2402.01888

More publications at: https://www.physik.uzh.ch/r/cms

Collider detector development

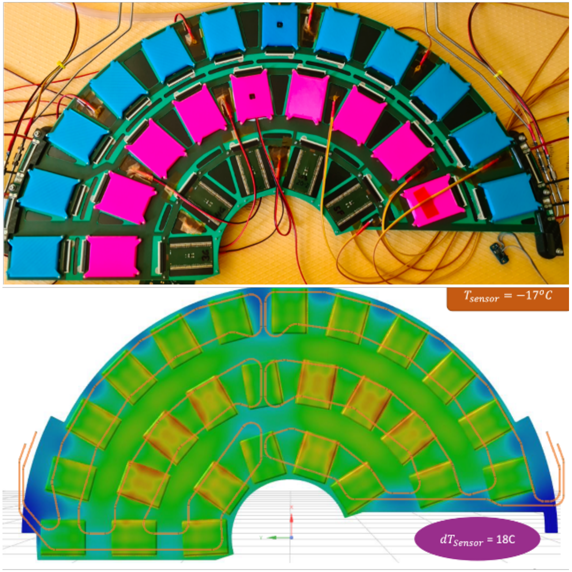
Prof. Lea Caminada, Prof. Florencia Canelli, Prof. Ben Kilminster

The CMS detector includes a silicon pixel detector as the innermost part of the tracking system. The pixel detector provides 3-dimensional space points in the region closest to the interaction point that allow for high-precision tracking of charged particles and vertex reconstruction. This enables the measurement and search for particles that decay to b quarks and tau leptons, such as the Higgs boson, the top quark, and leptoquarks. Our groups are major contributors to the CMS pixel detector project. We helped build and operate the current pixel detector and are involved in the design and prototyping of a new, improved version with more tracking layers, less material, and higher data rates to be installed in 2028 for high-luminosity LHC (HL-LHC). Furthermore, we are developing and testing new pixel detector concepts for future upgrades of CMS, future accelerators and other applications.

https://www.physik.uzh.ch/r/cms

In 2022, the UZH group replaced the innermost layer of the pixel detector in order to maintain efficient tracking during Run 3. The new layer has been successfully operated with the rest of the detector since 2022 and our groups contribute significantly to its operation and monitoring [1].

CMS will collect more than 20 times the current data set during the period of 2029 to 2041 (during HL-LHC). The UZH group together with PSI, will build an inner tracking detector for this period, that will extend the tracking coverage. This Tracker Extended Pixel detector (TEPX) will consist of a large-area disk system with more than one billion pixels [2]. At UZH, we have contributed to the module concept and we are developing the disk electronics, components of the pixel detector readout chain as well as lightweight mechanical structures and thin-walled cooling tubes to build the disk structures with minimal material. We tested prototype modules integrated with the disk electronics and characterized the performance of the novel serial powering scheme. In particular we studied the ther-



Measuring of the thermal behavior of the TEPX disc is key to a successful operation. Top: test setup with thermal loads; Bottom: simulated temperatures.

mal behavior of the disk and compared it to simulations. After the successful validation we are now moving towards production of the pixel modules and detector system.

We are studying new types of particle detectors called LGAD, that measure at the same time position and time of arrival of charged particles with high accuracy. We measured a timing resolution of less than 40 picoseconds ($40\cdot10^{-12}$ s) in our lab with different flavours of LGAD structures. In order to use these sensors in the experiment, R&D for pixelated readout electronics with fast timing is needed. We are evaluating the performance of different TDC (Time-to-Digital Converter) designs that have been produced in 110 nm CMOS technology and will test their performance when processing the signals from the LGAD sensor. The long-term focus is towards a possible use of disks with timing capabilities in later upgrades of the TEPX detector. Such a technology could greatly improve the physics potential of CMS during HL-LHC.

In 2023, the UZH group remained involved in the upgrade of the CMS L1 hardware Trigger for HL-LHC. We developed a new method to identify electrons in the harsh environment of 200 pile-up interactions based on a multivariate approach and makes use of novel tools to synthesize machine learning algorithms into FPGA's firmware [3].

1. Development of the CMS detector for the CERN LHC Run 3, CMS Collab., arXiv:2309.05466
2. The Phase-2 Upgrade of the CMS Tracker, CMS Collaboration, CMS-TDR-014
3. Electron Reconstruction and Identification in the CMS Phase-2 Level-1 Trigger, CMS collaboration, https://cds.cern.ch/record/2868782

LHCb Experiment

Prof. Nicola Serra, Prof. Olaf Steinkamp

LHCb is an experiment for **precision measurements** of observables in the decays of B mesons at the Large Hadron Collider (LHC) at CERN.
We play a leading role in measurements with B meson decays and in measurements of electroweak gauge boson production, and have made important contributions to the LHCb detector. We contribute to an ongoing major upgrade of the detector for 2023 and are involved in studies for future upgrades of the experiment.

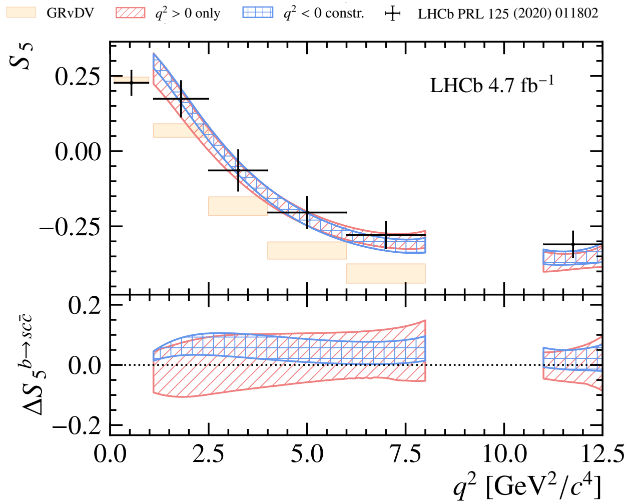
https://www.physik.uzh.ch/r/lhcb

A fresh look at a rare *B* decay

Rare $b \to s\mu^+\mu^-$ decays can only proceed through loop or box transitions and are therefore highly sensitive probes of new physics beyond the Standard Model (SM). Such new physics models include particles with masses up to 50 TeV, which is well beyond the maximum energy scale directly accessible at the LHC.

Over the last decade, several discrepancies have arisen in the behaviour of $b \to s\mu^+\mu^-$ when comparing to predictions based on the SM, many of which the our group has directly contributed to. The statistical significance of these discrepancies is large, but depends strongly on the uncertainties associated with the SM predictions, which rely on calculations of low-energy QCD (strong force). These calculations are notoriously difficult, and are therefore the main stumbling block in the way to interpreting deviations from the SM in this system.

A new analysis of the decay of the B^0 meson (bound state of a beauty quark and a down quark) to a K^{*0} meson (bound state of a strange quark and a down quark) and two muons has treated these QCD uncertainties in a new way by including them directly into the fit to data. By treating them directly in the measurement, the distribution of the data can help constrain the QCD parameters during the fit procedure which allows to potentially disentangle the contribution of new physics with QCD.



Projection of the forward-backward asymmetry (A_{FB}) as determined by the fresh analysis both with (blue) and without (red) theoretical constraints. Also shown in black are previous measurements which do not directly fit for QCD parameters and the SM predictions in yellow.

The data analysed was collected by the LHCb experiment, which is a detector specifically designed to study beauty decays. A full angular analysis of the decay was required to compare the helicity structure of the $B^0 \to K^{*0}\mu^+\mu^-$ decay with the SM prediction. An example observable is the forward-backward asymmetry of the positive muon with respect to the B^0 direction in the di-lepton rest frame (A_{FB}).

The main improvement for this analysis was to fit the distribution of the squared invariant mass of the di-lepton system (q^2) in addition to the angles describing the decay. A comparison of the results with the previous measurements is shown in the figure, and are displayed with and without including QCD predictions in the unphysical region ($q^2 < 0$). The SM predictions in yellow are also shown.

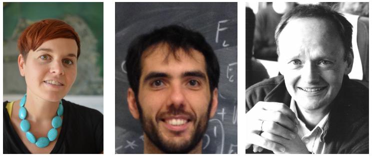
The new analysis agrees well with the older measurements, suggesting that no problems with the predictions have been found. However, the significance of the discrepancy with the SM predictions in the new analysis is reduced below two standard deviations, meaning that the interpretation is still unclear at this stage. New analyses with different decay modes and more data will be needed to clarify the situation in the future, for which the upgraded LHCb detector that has just been install will be key.

Highlighted Publications:

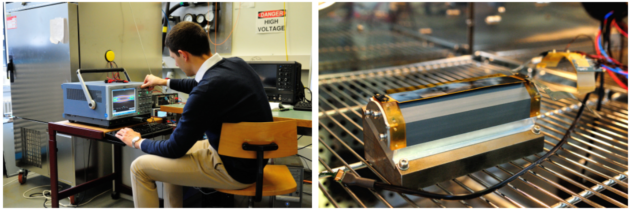
1. All LHCb publications: lhcb.web.cern.ch/lhcb/
2. Determination of short- and long-distance contributions in $B^0 \to K^{*0}\mu^+\mu^-$ decays,
   LHCb Collab., arXiv:2312.09102

The $\mu^+ \rightarrow e^+e^-e^+$ experiment

Profs. Lea Caminada, Nicola Serra, Olaf Steinkamp



The mu3e experiment at PSI aims at probing the Standard Model of particle physics by searching for the decay of positively charged muons to two positrons and an electron. The observation of this decay would falsify one of the central assumptions of the Standard Model and provide unequivocal proof of "new" physics. The measurement is challenging and requires the development of novel detector techniques, which are also of significant interest for experiments at future collider facilities.



Left: mu3e test stand in our lab; right: detail showing one of the first "ladders" of the mu3e vertex detector.

In a first phase of the experiment, the mue3 collaboration aims at exploiting existing muon beams at PSI to improve on the currently best upper limit by three orders of magnitude. The sensitivity of the experiment relies on efficient suppression of backgrounds, which necessitates precise measurements of the origins, momenta and production times of the low-energy positrons and electrons produced in decays of muons at rest. To match these requirements on measurement precision, the design of the detector incorporates a number of novel technologies. In particular, the reconstruction of the production vertices and trajectories of positrons and electrons relies on HV-MAPS, Monolithic Active Pixel Sensors produced in a commercial High-Voltage tolerant CMOS process. After an extensive R&D phase, the final version of HV-MAPS for mu3e has been produced and first detector modules have been assembled. Our group has joined this effort and already plays an important role in the assembly and testing of components for the vertex detector as well as in the development of the necessary quality assurance tools.

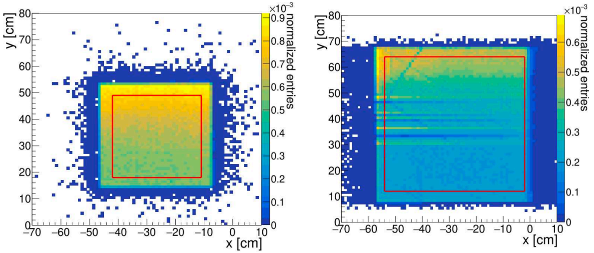
SND@LHC

Prof. Nicola Serra

SND@LHC is a recently approved and running experiment at the Large Hadron Collider (LHC) performing neutrino physics and searches for feebly interacting particles. It collects man-made neutrinos in the uncharted TeV energy scale from pp collision at the ATLAS interaction point.

The experiment is located 480 m downstream of ATLAS. The location permits the experiment of detecting the high flux of neutrinos in a very forward region ($\eta > 7$) in an unexplored energy region between 350 GeV and 10 TeV. The observation was performed using a data set of proton-proton (pp) collisions at a center-of-mass energy of 13.6 TeV collected in 2022 with an integrated luminosity of 36.8 fb^{-1} a total of 8 ν_μ interaction candidates were observed with an estimated background of 0.086 events, yielding a significance of about 7 standard deviation for the observed ν_μ signal.

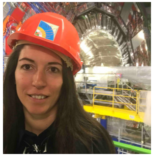
This year, the lower part of the VETO system acceptance will be greatly improved by digging a few centimeters into the ground and adding an extra layer of the VETO system built at UZH. This element will not only help to increase the vetoed area, but will also help in the analysis of electron neutrinos. The experiment is expected to collect an integrated luminosity of about 90 fb^{-1} in 2024. With this amount of data, new results are expected. Exciting times are ahead!



Muon flux: Distribution of muon tracks seen by the main tracking detector (left) and in the muon detector at the downstream side (right) at the most upstream detector plane. The distribution is normalized to the unit integral. The red border delimits the region considered for the muon flux measurement.

Future Circular Collider (FCC)

Prof. Florencia Canelli



The goal of the Future Circular Collider (FCC) is to greatly push the intensity and energy frontiers of particle colliders to answer fundamental questions about the universe by studying the properties of particles and forces at energies beyond what current colliders can achieve. The FCC will lay the foundations for a new research infrastructure succeeding the LHC and serving the world-wide physics community for the rest of the 21st century. The first stage, FCC-ee, will collide e^+e^- pairs in unprecedented numbers at energies between 90 and 365 GeV.

The UZH group specializes in developing advanced tracking detectors and algorithms tailored for the FCC project. Our primary objective is to provide critical insights to support the FCC Feasibility Study, slated for completion by 2025.

https://www.physik.uzh.ch/r/fcc

Accurate identification of hadronic final states is crucial for harnessing the physics potential of collider experiments. At the FCC-ee, the pristine experimental environment, devoid of effects such as QCD ISR and PDFs, simplifies flavor tagging significantly compared to the (HL-)LHC, promising substantial improvements. Specifically, discriminating strange quark jets opens avenues for groundbreaking studies, including $Z \to ss$ production, rare Higgs boson decays, investigation of strange Yukawa coupling, determination of CKM matrix elements through W decays. We have implemented a multiclassifier neural network built upon a transformer-based architecture and achieved state-of-the-art performance in strange quark discrimination at FCC-ee [1].

These results will be used to evaluate the feasibility of novel physics measurements and impose requirements on the detector design. Optimal flavor tagging requires that the innermost vertex detector at FCC-ee minimize the material to ensure optimal position and momentum resolution. The UZH strategy to reduce material involves the utilization of ultra-thin Monolithic Active Pixel Sensors (MAPS) fabricated using a cutting-edge 65nm process. Since autumn

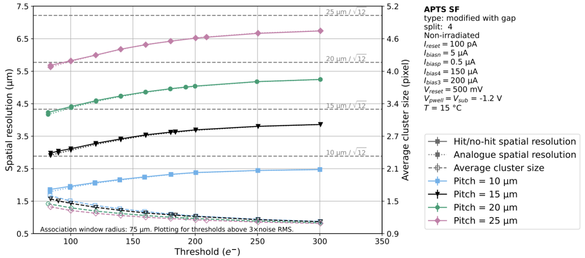


Fig 1. Spatial resolution of the APTS test structure with pixel pitches between 10 *and* 25 *μm in the 65 nm TPSCo CMOS process [2].*

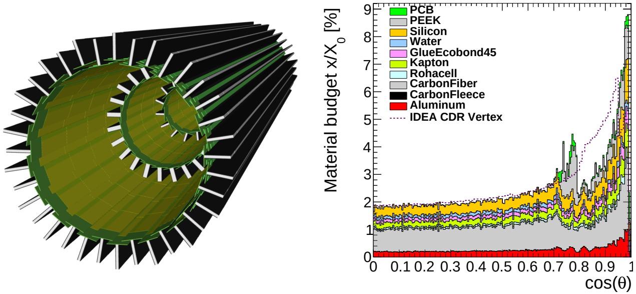


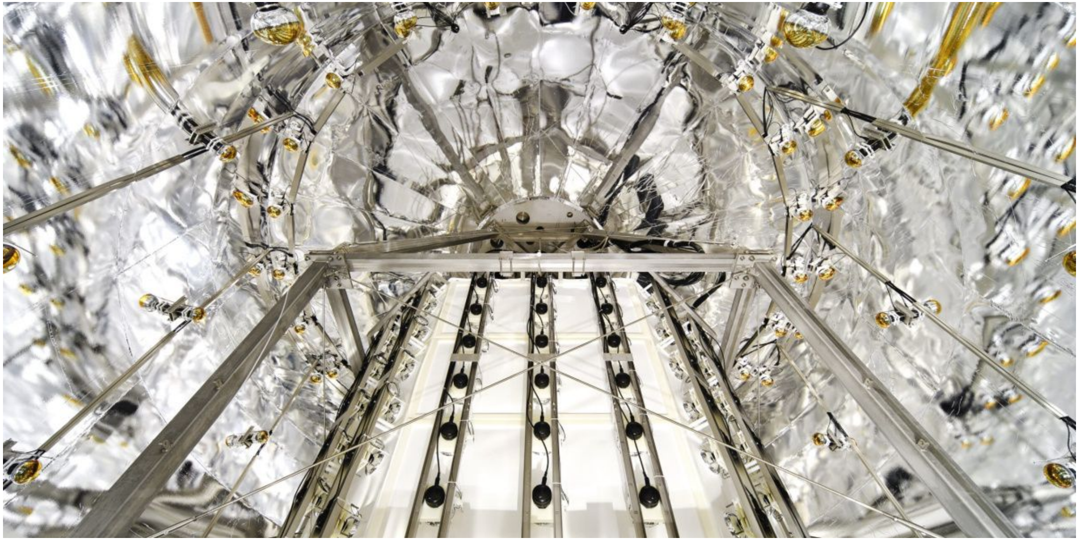
Fig 2. Full simulation geometry of the IDEA vertex inner barrel (left) and the resulting material budget for the whole vertex detector (right).

2022, we've collaborated with the ALICE ITS3 consortium, IPHC Strasbourg, and other partners to investigate two test structures for these pixel sensors: APTS and CE-65 [2]. Our current focus, led by two dedicated Ph.D. students, revolves around characterizing these sensors using a Fe-55 source and test beams at CERN PS and SPS and at DESY. Spatial resolutions down to 2.5 μm are achievable as shown in Fig. 1, with hit efficiencies $>$ 99% [3].

Our group also implemented one of the proposed vertex detector designs in full simulation using the key4hep framework common to all future colliders [3]. Employing realistic models of all detector components alongside innovative reconstruction algorithms is imperative for accurately assessing the physics potential of experiments at the FCC). Figure 2 shows the geometry of the first three layers and the resulting material budget of the vertex detector, which was included in the mid-term report of the Feasibility Study. The material is in line with the previous estimate, showing that the assumptions taken for the vertex detector in the CDR stage were realistic. In 2024, we will continue the CE-65 characterization and investigate ultra-light vertex detector designs.

1. Jet-Flavour Tagging at FCC-ee,
   K. Gautam, ICHEP2022, arXiv:2210.10322
2. Characterisation of analogue MAPS test structures implemented in a 65 nm CMOS imaging process,
   G. Aglieri Rinella et al., arXiv:2403.08952
3. Design and Performance of the IDEA Vertex Detector at FCC-ee in Full Simulation,
   A. Ilg, PoS(EPS-HEP2023), doi:10.22323/1.449.0600

Cosmology, Astro- and Astroparticle Physics



XENONnT inside the watertank (https://xenonexperiment.org/photos/)

Astrophysics and General Relativity

Prof. Philippe Jetzer

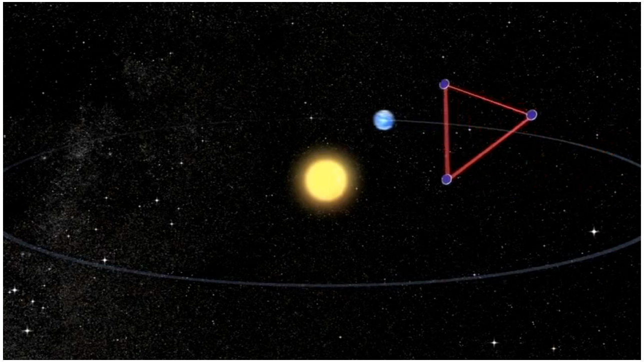
LIGO (Laser Interferometer Gravitational-Wave Observatory) consists of two Earth-bounded instruments together with Virgo aimed to detect gravitational waves in the frequency range from about 10 to 1000 Hz. In 2015 the first gravitational wave signal has been detected. Since then more than 100 events have been found. Our group has made important contributions to the analysis of LIGO/Virgo data and in the modelling of more accurate gravitational waveforms. The latter results are used in LIGO/Virgo data analysis and in future for the LISA mission and the Einstein Telescope project.

https://www.physik.uzh.ch/g/jetzer

The work of the group is focused on the topic of gravitational waves in the framework of the LIGO Scientific Collaboration and for the future space mission LISA, since our group is involved in both of these international collaborations. In the following we briefly describe some results published in 2023, besides all the works appeared in the framework of the LIGO/Virgo, LISA Pathfinder and LISA collaborations.

P. Jetzer as a member of the LISA Science Working Team of ESA was involved in the writing of the Definition Study Report for LISA. This report is an important contribution towards the so-called Mission Adoption of LISA, which was decided on 25 January 2024, and which marks the end of various study phases and the beginning of the construction of the satellites.

Gravitational wave detections offer insights into the astrophysical populations of black holes in the universe and their formation processes. Detections of binaries consisting of black holes lying outside the bulk distribution of the astrophysical population are particularly intriguing. In a study by Y. Xu and E. Hamilton, they investigated the detectability of precession and its potential degeneracy with eccentricity in some gravitational wave events. They found that eccentricity lower than 0.2 is insufficient to mimic precession in parameter estimation when assuming a quasicircular signal. Thus their results suggest that a certain degree of precession is nec-



LISA will consist of three spacecraft, millions of kilometres apart, following the Earth on its orbit around the sun. The spacecraft will send signals to each other and the interference patterns will enable scientists to reconstruct the gravitational waves in space. (Image: AEI, MILDE)

essary to produce evidence of high precession in parameter estimation, but it remains challenging to conclusively determine which effect is responsible for the high precession observed in events like GW190521.

E. Hamilton with L. London and M. Hannam found a simple formula for the effective ringdown frequencies of the gravitational-wave signal of a precessing black-hole binary in the coprecessing frame. This formula requires only knowledge of the quasi-normal mode frequencies of the system and the value of the precession angle β during ringdown. Such a formula will be useful in modeling precessing systems. They also provide a comprehensive description of the oscillations in the ringdown frequency in an inertial frame where the spin of the final black hole is orthogonal to the orbital plane. These oscillations arise due to the superposition of the prograde and retrograde frequencies.

Highlighted Publications:

1. Measurability of precession and eccentricity for heavy binary-black-hole mergers,
   Y. Xu, E. Hamilton, Phys. Rev. D107 (2023), 103049, arXiv:2211.09561.
2. Ringdown frequencies in black holes formed from precessing black-hole binaries,
   E. Hamilton, L. Londan, M. Hannam, Phys. Rev. D107 (2023), 104035, arXiv:2301.06558.

Theoretical Astrophysics

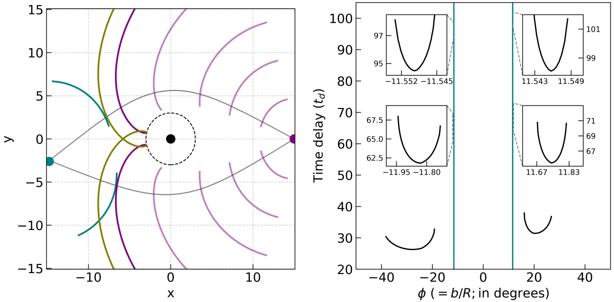
Prof. Prasenjit Saha

Our research has been on diverse astrophysical phenomena involving light and gravity, especially gravitational lenses, but also novel applications of spacecraft ranging.

https://www.physik.uzh.ch/g/saha

Galaxies and clusters that create multiple mirages of background galaxies through gravitational lensing have long been understood as a probe of dark matter and indeed the process of galaxy formation. We have continued our long-running research program in this area, and also studied less-explored regimes of lensing, such as strong gravitational fields.

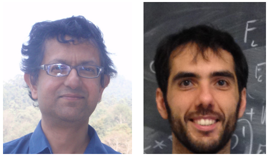
In other work we have continued our study of a future Uranus mission and similar spacecraft as a detector of long-period gravitational waves, in the gap between the LISA and PTA ranges.



Wavefronts and light travel times near a black hole, similar to those arising in the famous photon-ring images around the M87 black hole.

Highlighted Publications:

1. What are the parities of photon-ring images near a black hole?
   A. Meena, P. Saha, The Open Journal of Astrophysics, vol. 6, id. 50 (2023)



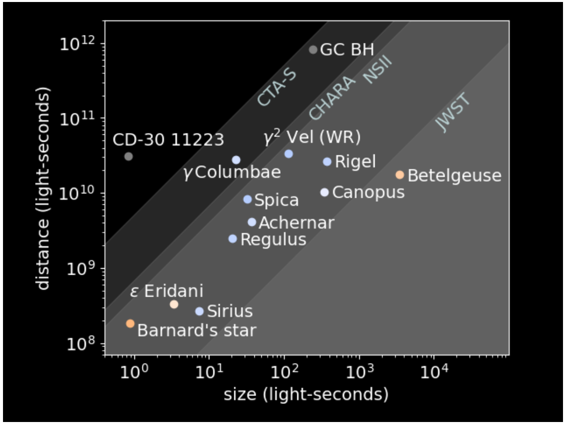
CTA – Cherenkov Telescope Array

Prof. Prasenjit Saha, Prof. Nico Serra

The Cherenkov Telescope Array (CTA) is a next-generation facility to observe high-energy sources in the Milky Way and beyond. It is designed especially for gamma-ray photons from 10 GeV to above 100 GeV, which it will detect indirectly, through optical Cherenkov showers in the atmosphere. Fortuitously, the facility will also have the capacity to operate in a completely different mode, as an optical intensity interferometer, which can image stellar-scale phenomena.

https://www.physik.uzh.ch/r/cta

We have continued our developmental simulation work on the CTA, as well as contributing to the precursor telescopes of MAGIC in intensity interferometry mode to resolve stars below the milli-arcsecond range.

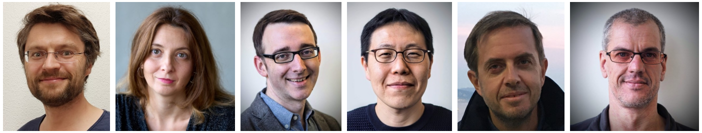


Indicative resolutions of the CTA in intensity interferometric mode, compared with other interferometric and standard telescopes.

Performance and first measurements of the MAGIC Stellar Intensity Interferometer,
MAGIC Collaboration, preprint arXiv:2402.04755

Theoretical Astrophysics

Institute for Astrophysics



As of January 2024 the Institute für Astrophysik has been established, gathering all groups working on theoretical and computational astrophysics and cosmology that were previously part of the Institute of Computational Science (ICS).

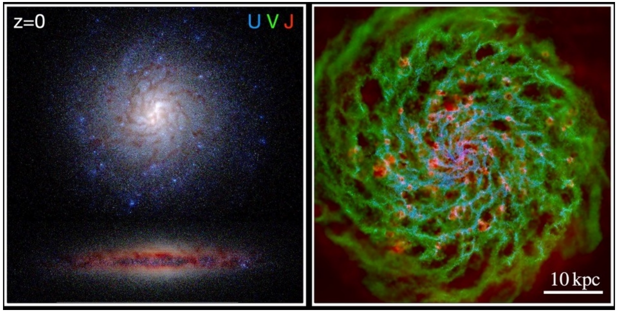
https://www.ics.uzh.ch/

In the field of planetary science, the group of Helled continued the efforts in preparing the science case for a Uranus mission, in characterizing exoplanets, and in simulating planet formation and evolution. We also continued our involvement in space missions including Juno, JWST, Ariel and Plato. The group of Helled and Stadel together also made progress in simulating giant impacts using a new hydrodynamical method for non-ideal fluids.

Cosmological probes are affected by fluctuations of wavelength larger than the horizon scales. This infrared sensitivity in cosmological probes is canceled in general relativity (GR). Yoo's group has quantified the general conditions for such cancellation in theory of gravity beyond GR. Research interests lie within the fields of cosmology and theoretical astrophysics, working on nonlinear structure formation as well as the astrophysical aspects of different dark matter models.

Collectively, groups at the institute made progress on one of the most active frontiers in astrophysics — the study of galaxies in the young Universe. In addition to being involved in various observational projects with JWST, we made advances in the numerical modeling of the physics of galaxy formation, including feedback from stars and supermassive black holes. The new state-of-the-art FIREBOX galaxy formation simulation in a full cosmological volume, designed and performed by the Feldmann group has marked a new milestone in this field. In addition, we are developing generative machine learning methods for applications with the Square Kilometer Array Observatory (Feldmann group), and for the modeling of gravitational wave sources (Mayer group).

The groups of Feldmann, Mayer and Schneider are deeply involved in SKACH, the Swiss SKA Consortium, and contributed to obtain longterm funding from the federal government to support swiss research in SKA. To



Visualization of the multiphase structure of the interstellar medium in one of many Milky Way like galaxy in FIREbox. (Left) Color composite image showing the stellar and dust components of the depicted galaxy in a face-on and edge-on view. (Right) Face-on, color composite image of the galaxy's molecular (blue), atomic (green), and ionized (red) hydrogen content.

gether with groups at EPFL, UniGE and ETH, they also recently joined the Millimeter Wave Array (MWA), an Australian radio-telescope facility precursor of SKA. The ICS also hosted the main international swiss-based SKA meeting.

The group of Mayer, together with the team of Prof. Ciorba at UniBasel, managed to begin production mode with the first Exascale particle-based simulation code in astrophysics and cosmology, SPH-EXA, whose development has been funded over the past 6 years through the Platform for Advanced Scientific Computing and the Swiss National Supercomputing Center. Owing to SPH-EXA, in October 2023 they were awarded the "EuroHPC Extreme Access Scale Award", the largest ever supercomputing time allocation in Europe across all disciplines of science and industry. With that they are running, on the LUMI supercomputer, simulations of the turbulent interstellar medium and star formation which can resolve for the first time the full turbulent cascade down to the scale pre-stellar core formation.

Team members in Mayer's group also made progress in the field of gravitational wave astrophysics, developing a new model for the origin of the first supermassive black holes in the early Universe, the dark collapse scenario, which generates a gravitational wave burst detectable with the Laser Interferometer Space Antenna (LISA), and showing how waveforms generated by in-spiraling massive black hole binaries can be altered in a detectable way by perturbations form matter surrounding the black holes.

1. Conditions for the absence of infrared sensitivity ...
   M. Magi, J. Yoo, Physics Letters B **864** 138204
2. Priorities in gravitational waveforms for future ..
   L. Zwick, P. R. Capelo, L. Mayer, MNRAS **521**, 4645
3. FIREbox: simulating galaxies at high dynamic range ...
   R. Feldmann et al, MNRAS **522**, 3831
4. Towards a new era in giant exoplanet characterisation,
   S. Müller, R. Helled, A& A **669** id.A24, 11

Astroparticle Physics Experiments

Prof. Laura Baudis

We study the composition of **dark matter** in the Universe and the **fundamental nature of neutrinos**. We build and operate ultra low-background experiments to detect dark matter particles, to search for the neutrinoless double beta decay, a rare nuclear process which only occurs if neutrinos are Majorana particles.

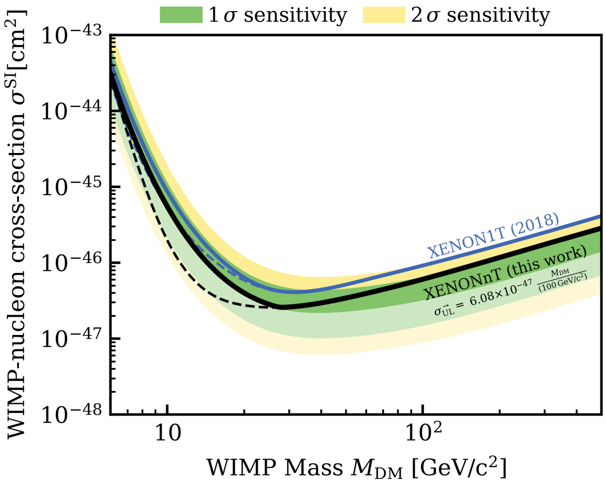
We are members of the **XENON collaboration**, which operates **xenon time projection chambers** to search for rare interactions such as from dark matter, and we lead the **DARWIN collaboration**, with the goal of building a 50 t liquid xenon observatory to address fundamental questions in astroparticle physics.

We are members of the **GERDA** and **LEGEND experiments**, which look for the **neutrinoless double beta decay of ^{76}Ge** in high-purity Ge crystals immersed in liquid argon, with an unprecedented sensitivity.

https://www.physik.uzh.ch/g/baudis

Highlight: First XENONnT Dark Matter Search with Nuclear Recoils

The XENONnT experiment was designed to detect the faint and rare interactions of hypothetical dark matter particles with ordinary matter. As a popular dark matter candidate, weakly interacting massive particles (WIMPs) are expected to scatter on nuclei. The corresponding nuclear recoil would have a low energy of only few keV and experimental results indicate that it would occur at a rate of less than one event per tonne of target material per year. XENONnT uses 5.9 tonnes of xenon in a dual-phase time projection chamber to measure these signals. The required low energy threshold is achieved by measuring scintillation signals in liquid and gaseous xenon with arrays of photomultiplier tubes. The UZH group was strongly involved in the sensor characterization and array assembly. The low background could be achieved by careful material selection, also with the Gator high-purity Germanium detector operated by the UZH group, as well as active background



Limits on the interaction cross-section of WIMPs with individual nucleons as a function of the WIMP mass as set by XENONnT in 2023 (black) and XENON1T in 2018 (blue). The dashed lines indicate the raw limits while the solid lines represent the limits constrained to the median sensitivity in order to prevent exclusion of parameter space beyond the experiment's sensitivity. The 68 % and 95 % confidence intervals of the simulated sensitivity are shown in green and yellow, respectively.

mitigation measures including a water Cherenkov neutron veto and online radon removal by cryogenic distillation. The first 95 days XENONnT science data were taken in the second half of 2021. In a blind analysis, no significant excess of nuclear recoil events attributable to WIMP dark matter was found. The collaboration thus placed a best upper limit of 2.58×10^{-47} cm^2 on the spin-independent WIMP-nucleon cross-section for a 28 GeV/c^2 WIMP at 90 % confidence level. Together with the LZ and PandaX-4T experiments, XENONnT places the most stringent constraints on WIMP interactions and significantly improves on the previously leading XENON1T results with data taken in a considerably shorter time. XENONnT continues to take data for its multi-year measurement campaign with the ultimate goal of detecting dark matter interactions.

Highlighted Publications:

1 First Dark Matter Search with Nuclear Recoils from the XENONnT Experiment,
XENON Collab., Phys. Rev. Lett. **131** (2023) 041003

2 Electron transport measurements in liquid xenon with Xenoscope, a large-scale DARWIN demonstrator,
L. Baudis et al., Eur. Phys. J. C 83, 717 (2023)

3 Final Results of GERDA on the Two-Neutrino Double-β Decay Half-Life of ^{76}Ge,
GERDA Collab., Phys. Rev. Lett. **131** (2023) 142501

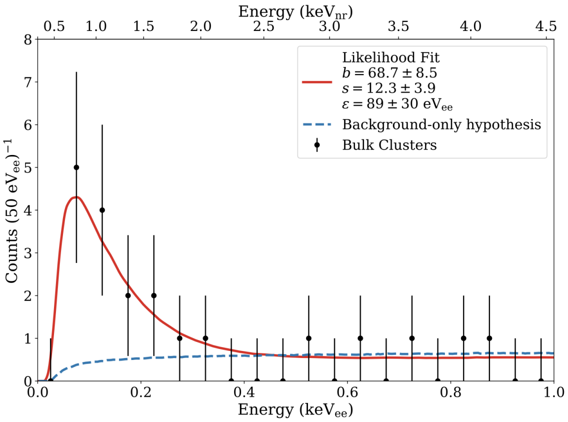
DAMIC Experiment

Prof. Ben Kilminster

DAMIC-M (Dark Matter in CCDs at Modane Underground Lab) is an experiment that searches for the dark matter gravitationally bound in our Milky Way through electrical signals produced from its collisions with silicon CCD detectors. This experiment represents a factor of 10 increase in mass, a factor of 10 decrease in the energy threshold, and a factor of 50 decrease in background rates, as compared to the current DAMIC experiment operating in SNOLAB.

https://www.physik.uzh.ch/r/damic

Our group helped found the DAMIC experiment in 2008. We are contributing readout electronics, mechanical components, and detector control and safety systems for the next phase, DAMIC-M. In 2023, DAMIC@SNOLAB took new data with improved skipper CCD readout, and confirmed a previously observed low-energy excess, now finding an excess with a significance of 5.4 Sigma. In order to understand the origin of the excess, the UZH group is pioneering a new technique to distinguish between dark matter particles causing nuclear recoils and those causing electronic recoils. We describe the characterization of the new scientific-grade CCDs in a new paper, and also describe a recent measurement with them, characterizing for the first time the Compton scattering process on valence electrons with energy levels below 100 eV. DAMIC-M has been operating a prototype detector, while the complete detector is being constructed. With this prototype, we produced a new search for the daily modulation of dark matter, and excluded previously unexplored regions of the allowed parameter space for low-mass, dark matter, which interacts electromagnetically with the detector.

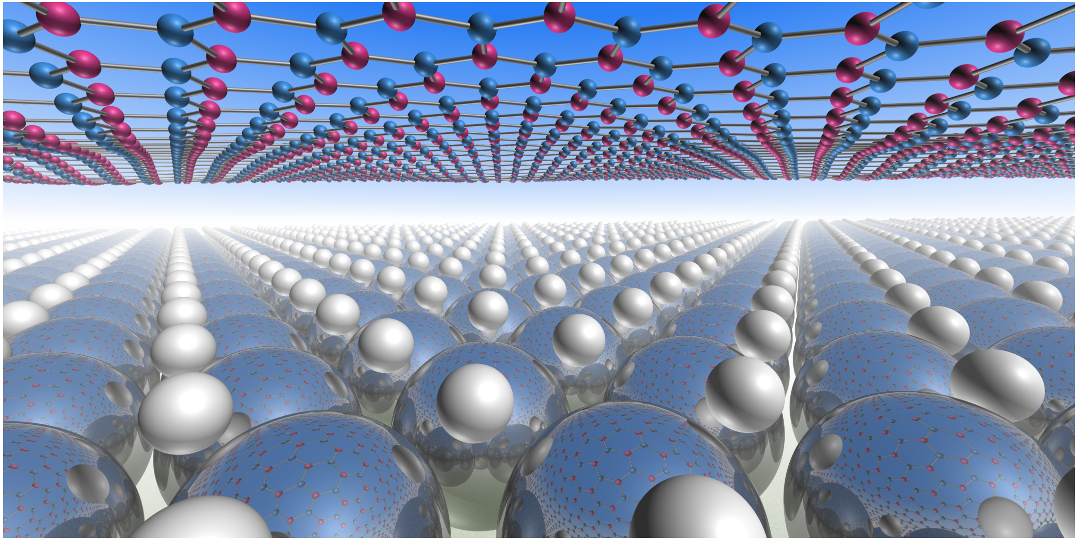


Data from DAMIC@SNOLAB (black points) show an excess above the background prediction (dashed blue line) that is consistent with a signal (solid red line) with a significance of 5.4 Sigma. The signal model is generically shown as a decaying exponential, taking into account the detector efficiency.

Highlighted Publications:

1. Confirmation of the spectral excess in DAMIC at SNOLAB with skipper CCDs, DAMIC, DAMIC-M, SENSEI collab., arXiv2306.01717, accepted by Phys. Rev. D.
2. Search for Daily Modulation of MeV Dark Matter Signals with DAMIC-M, DAMIC-M collaboration, arXiv2307.07251, Phys.Rev.Lett. **132** (2024) 10, 101006.
3. First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons, DAMIC-M collaboration, arXiv2302.02372, Phys.Rev.Lett. **130** (2023) 17, 171003.
4. Nuclear Recoil Identification in a Scientific Charge-Coupled Device, K.J.McGuire, A.Chavarria, N.Castello-Mor, S. Lee, B. Kilminster, et al., arXiv2309.07869, submitted to Phys.Rev.D.

Condensed Matter Physics



Artist's view of a single layer boron nitride before hydrogen-assisted exfoliation from the growth substrate. (A. P. Seitsonen)

Condensed matter theory

Prof. Titus Neupert

We study **topological phases of quantum matter** with numerical and analytical tools. Topological electronic states are characterized universal and robust phenomena, such as the Hall conductivity in the integer quantum Hall effect, that are of fundamental interest or promise applications in future electronics. We study and propose **concrete materials** to realize such topological effects, but are also interested in studying abstract models to understand what phases of matter can exist in principle.

Our numerical toolbox includes **neural network algorithms** to study strongly interacting quantum many-body systems. Furthermore, we work at the interface of **quantum computing** and condensed matter physics.

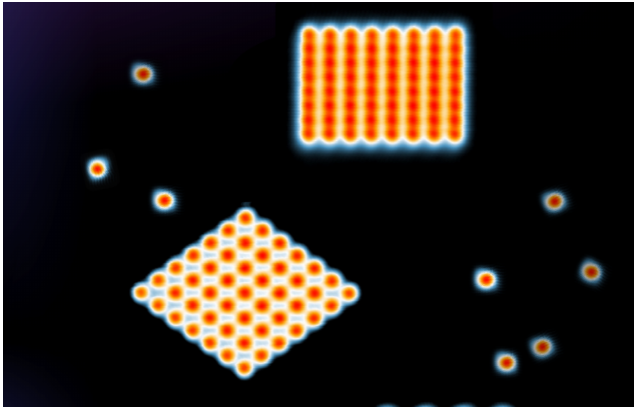
https://www.physik.uzh.ch/g/neupert

Building topological crystalline superconductors atom by atom

Two-dimensional superconductors are a highly sought-after phase of matter, and their fundamental characteristic is the presence of Majorana modes at their boundaries. While these phases are elusive in natural compounds, they may be realized by designing artificial quantum materials.

Our group has worked closely with researchers in the Sessi group at the Max Plank Institute of Microstructure Physics in Halle, Germany, to build a platform in which such exotic superconductivity can be found. The workhorse are so-called Shiba-states, which appear when a magnetic atom (in our case chromium) is added to the surface of a conventional superconductor (in our case niobium). The Shiba states are located near the magnetic adatom in the spectral gap of the superconductor. Adding several atoms next to each other will lead to a hybridization of their Shiba states. If a whole lattice of adatoms is formed, one can think of a "band structure" of Shiba states — all within the gap of the underlying superconductor and thus at very low energies. This band structure is by construction that of a superconductor and can be in different topological phases, depending on the design of the lattice.

By assembling the lattices of magnetic adatoms one by



Scanning tunneling microscopy image of some of the adatom structures that were created in our study. The individual chromium atoms, each of which hosts a Shiba state, are visible.

one, using scanning tunnelling microscopy techniques, it was possible to built different two dimensional structures, distinguished by the type of lattice in the bulk and termination geometry. Scanning tunnelling microscopy also allows to probe these structures with single-atom precision. The experimental measurements and theoretical predictions indicate that two of the structures host Majorana edge bands and corner Majorana modes, respectively, which are protected by the crystalline symmetries of the sample and termination geometry.

The corner Majorana modes are a manifestation of the concept of "higher-order topology" that was introduced by our group in 2018. Standard topological phases host special protected modes on their boundary (a surface for three-dimensional systems and an edge for two-dimensional systems). Higher-order topological phases exhibit such modes in lower-dimensional sections of the boundary (a hinge of a three-dimensional system and a corner for a two-dimensional system). So far, experiments have focused on realizing higher-order topology in three-dimensional semiconductors and two-dimensional metamaterial structures. Our study reports the first realization of higher-order topology in superconductors.

This work shows that Shiba lattices are a promising a platform to design topological phases in two dimensional superconductors.

1. Two-dimensional Shiba lattices as a possible platform for crystalline topological superconductivity,
   M. O. Soldini *et al.* Nature Physics 19, 1848–1854 (2023)
2. Evidence of a room-temperature quantum spin Hall edge state in a higher-order topological insulator,
   N. Shumiya *et al.* Nature Materials 21, 1111–1115 (2022)
3. Transport response of topological hinge modes in α-Bi_4Br_4, M. S. Hossain *et al.* arXiv:2312.09487,
   in press in Nature Physics

Theory of topological matter

Prof. Tomáš Bzdušek

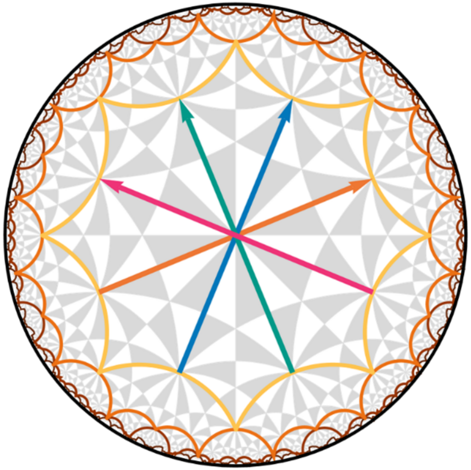
Our research focuses on **topological phases of classical and quantum matter**. Topological matter exhibits properties resilient against a broad range of perturbations, and include phenomena such as quantized Hall conductivity in semiconductor devices or spin-momentum-locked metallic states on the surface of topological insulators. We use diverse mathematical techniques and numerical approaches to extend the notion of topological invariants to a broader array of physical systems and to study their fingerprints in physical observables, and we propose prospective setups for realizing them in experiments. Besides conventional crystalline solids, we also explore dissipative and periodically driven systems, along with lattices that feature unique curved or aperiodic geometries.

https://www.physik.uzh.ch/g/bzdusek

Spectra and topology in hyperbolic lattices

Curved spaces constitute an essential ingredient of general relativity. As a theoretical tool, negatively curved anti-de Sitter spaces also arise by virtue of a holographic correspondence when describing certain strongly correlated conformal field theories. While curvature of space is not an essential ingredient of traditional condensed matter physics, recent experimental works with superconducting waveguide resonators and with electric-circuit networks made it possible to engineer classical and quantum Hamiltonians with emergent negative curvature. However, little is presently known about generalizations of common condensed matter physics notions, such as crystal symmetry, Bloch band theory, and topological order, to the realm of negatively curved spaces.

Our group conducted investigations aimed at providing the theoretical characterization of these recent experimental works. We studied the symmetry group of regular "$\{p, q\}$" hyperbolic lattices, where q regular p-gons meet at each vertex. Their spectral and quantum mechanical properties imply



Hyperbolic $\{8,3\}$ *lattice, drawn in the Poincaré disk projection. The indicated primitive unit cell (yellow) tiles the hyperbolic plane, with translation group generated by four primitive translation (colored arrows). The growing supercells (shades of brown) form a coherent sequence that facilitates an efficient computation of energy spectra.*

unique challenges, owing to the curvature-induced non-commutativity of hyperbolic translations, and practical approaches for efficient computations of their spectra have remained missing. In a work carried out with our former doctoral student Patrick Lenggenhager, we have developed an approach, based on constructing ever larger supercells as symmetric aggregates of smaller cells, that allows for computing hyperbolic spectra with an unprecedented level of detail. To make these tools available for the broader community, we have implemented the technique in a pair of complementary software packages, namely HyperCells for GAP and HyperBloch for Mathematica.

A particularly striking feature of hyperbolic lattices is the high dimension of their reciprocal space. In particular, topological invariants characterizing Euclidean crystals in arbitrarily high spatial dimension, such as the second Chern number describing non-linear quantum Hall state in four-dimensional space, can arise in two-dimensional hyperbolic lattice. By leveraging the supercell method, we currently investigate how these exotic topological states are constrained by crystalline symmetry, and how they manifest through bulk-boundary correspondence and in transport properties.

Highlighted Publications:

1. Non-Abelian Hyperbolic Band Theory from Supercells; P. M. Lenggenhager, J. Maciejko, and T. Bzdušek, Phys. Rev. Lett. **131**, 226401 (2023)
2. Symmetry and topology of hyperbolic Haldane models; A. Chen, Y. Guan, P. M. Lenggenhager, J. Maciejko, I. Boettcher, and T. Bzdušek,
   Phys. Rev. B **108**, 085114 (2023)

Superconductivity and Magnetism

Professor Johan Chang

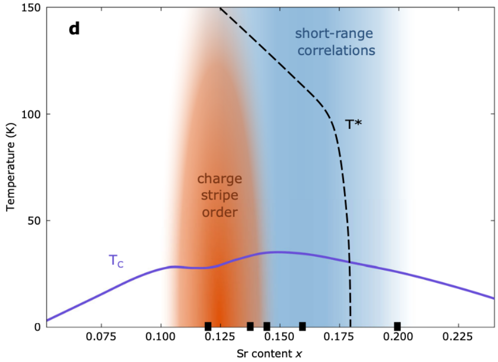
We investigate **quantum matter phases emerging from strong electronic interactions**. High-temperature superconductivity, strange metals, density-wave instabilities and electronic driven metal insulators metal-insulator transitions are studied by synchrotron techniques. Using angle-resolved photo-emission spectroscopy (ARPES) and resonant inelastic x-ray scattering (RIXS), we reveal electronic structures and properties of such correlated electron systems. Quantum phase transitions tuned by magnetic field, uniaxial or hydrostatic pressure are furthermore explored by high-energy x-ray diffraction. Our group also has technical initiatives to develop innovative and compact cryo-cooling methodology. Finally, we are involved in data science analysing x-ray scattering results using machine learning methodology.

https://www.physik.uzh.ch/chang

Hallmarks of quantum matter are complex phases emerging from electronic interactions. An experimental progress pathway is to study these phases with advanced spectroscopy techniques. Here, we provide two study examples using electron spectroscopy and resonant x-ray scattering on, respectively, a multi-orbital Mott insulator and a superconductivity charge order system.

Skin metal-insulator transition

Doped Mott insulators are the starting point for interesting physics such as high temperature superconductivity and quantum spin liquids. For multi-band Mott insulators, orbital selective ground states have been envisioned. However, orbital selective metals and Mott insulators have been difficult to realize experimentally. Using photoemission spectroscopy, we demonstrated how Ca_2RuO_4, upon alkali-metal surface doping, develops a single-band metal skin. Our dynamical mean field theory calculations reveal that homogeneous electron doping of Ca_2RuO_4 results in a multi-band metal. All together, our results provide evidence for an orbital-selective



Charge order phase diagram emerging from our resonant scattering experiments

Mott insulator breakdown, which is unachievable via simple electron doping. Supported by a cluster model and cluster perturbation theory calculations, we demonstrate a type of skin metal-insulator transition induced by surface dopants that orbital-selectively hybridize with the bulk Mott state and in turn produce coherent in-gap states.

Charge order and superconductivity

In high-temperature cuprate superconductors, stripe order refers broadly to a coupled spin and charge modulation with a commensuration of eight and four lattice units, respectively. How this stripe order evolves across optimal doping remains a controversial question. Here we carried out a systematic resonant inelastic x-ray scattering (RIXS) study of weak charge correlations in $La_{2-x}Sr_xCuO_4$ and $La_{1.8-x}Eu_{0.2}Sr_xCuO_4$. Our ultra high energy resolution experiments demonstrate the importance of the separation of inelastic and elastic scattering processes. Long-range temperature-dependent stripe order is only found below optimal doping. At higher doping, short-range temperature-independent correlations are present up to the highest doping measured. This transformation is distinct from and preempts the pseudogap critical doping. We argue that the doping and temperature-independent short-range correlations originate from unresolved electron–phonon coupling that broadly peaks at the stripe ordering vector.

Spin-off initiative

After winning the Swiss Innovation Award end of 2021, condenZero matured – in 2023 – to the level where the company could move to the Zurich-campus. The patent underlying the company technology went into the nationalization phase (accepted in China, pending decision in EU, USA, Canada). Three orders arrived in 2023 and Innosuisse awarded a "consolidation" innovation grant.

- Fate of charge order in overdoped La-based cuprates, K. von Arx *et al.*, npj Quantum Materials 8, 7 (2023)
- Orbital-selective metal skin induced by alkali-metal ... M. Horio *et al.*, Communications Physics 6, 323 (2023)

Oxide Interface Physics

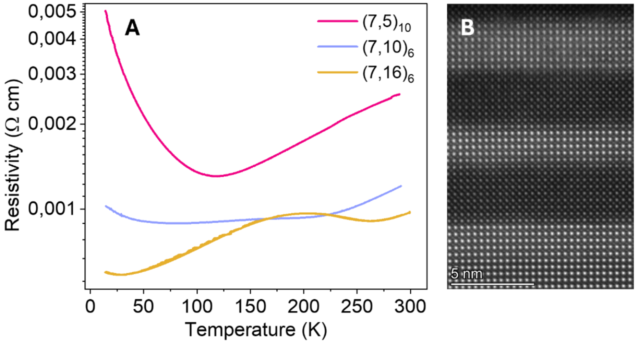
Prof. Marta Gibert

Our group is dedicated to the growth and investigation of transition metal oxide heterostructure (i.e. thin films, superlattices). The ability to create structures with sub-nm precision by off-axis rf magnetron sputtering allows us to tune the properties of these materials thanks to reduced dimensionality and interface reconstructions. Our goal is to understand the subtle atomic-scale structural and electronic mechanisms controlling interface physics in complex oxides, which is key for the rational design of materials with tailored properties.

https://www.physik.uzh.ch/g/gibert

Transition metal oxides are a fascinating and widely studied class of materials displaying a wide range of physical properties (i.e. metal-insulator transitions, magnetism, superconductivity, etc.) useful for the development of next-generation electronic devices. All these functionalities stem from strong electronic correlations and a complex interplay between the charge, orbital, spin and lattice degrees of freedom. The generation of thin films and heterostructures allows these functionalities to be tuned even further, i.e. by imposing epitaxial strain and lowering the dimensionality. For instance, we recently showed that B-site ordered double perovskite Nd_2NiMnO_6 films exhibit ferromagnetism even at ultralow thicknesses of only 3 unit cells (≈1.2 nm). Through a detailed x-ray magnetic circular dichroism study, we were able to distinguish the magnetic components into a strong ferromagnetic Ni/Mn sublattice and a paramagnetic Nd sublattice [1].

In Zurich, we continued the investigation of $SrCrO_3$ thin films. Transport measurements have revealed a metallic phase down to 100K for films grown under low strain with a strain-dependent metal-to-insulator transition. On the other hand, magnetic properties measurements revealed a strain-independent antiferromagnetic phase at temperatures below 150K. These findings prove the coexistence of an antiferromagnetic and metallic phase in $SrCrO_3$ films. The possible Fermi surface reconstruction occurring at the metal-insulator



SrCrO3/LaCrO3 (SCO/LCO) superlattices. A: Resistivity measurements as a function of superlattice periodicity. The legend indicates the number of LCO and SCO unit cells, respectively. The subscripted number indicates the number of period repetitions. Two transitions are observed for samples with thick SCO layers, whereas a unique transition occurs as SCO thickness is reduced to few unit cells. B: Scanning transmission electron microscopy image of a (7,10)6 superlattice (blue curve in panel A). In this image, only two periods are visible. The interfaces between SCO and LCO are well visible and the intermixing is low.

transition signalled by a change in charge carrier is currently being investigated using magnetoresistance measurements.

In parallel, we started the fabrication and investigation of superlattices alternating ultrathin layers of $SrCrO_3$ and $LaCrO_3$. In contrast to $SrCrO_3$, $LaCrO_3$ is known to be insulating and weakly ferromagnetic. As both materials stabilise with different oxidation states, a polar discontinuity occurs at the interfaces between $SrCrO_3$ and $LaCrO_3$ together with interfacial charge transfer. Scanning transmission electron microscopy measurements are used to investigate the microscopic atomic structure of the superlattices, revealing coherent and epitaxial growth and a low intermixing at the layer interface. The $SrCrO_3$/ $LaCrO_3$y superlattices have a rather small resistivity. They show a metallic behaviour with two resistivity upturns when the SCO layer is thicker than 16uc but only one when less than 5uc.

Highlighted Publication:

1. Paramagnetic Nd sublattice and thickness-dependent ferromagnetism in Nd_2NiMnO_6 double perovskite thin films,
   Jonathan Spring et al., Phys. Rev. Materials 7, 104407 (2023)

Low dimensional systems

Prof. Thomas Greber

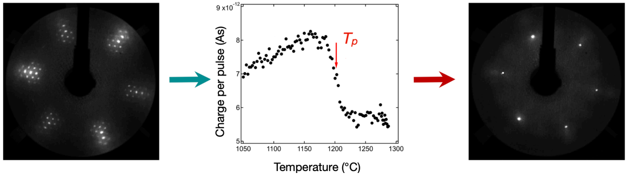
We study objects like **zero-dimensional endofullerene** molecules and **two-dimensional (2D) boron nitride** layers in view of their functionality as nano-materials. Single-molecule magnetism is the focus of the fullerene research, where we apply x-ray absorption and a sub-Kelvin superconducting quantum interference device. In the activity of the 2D materials, we grow the highest quality boron nitride on substrates up to the four-inch wafer scale with chemical vapor deposition, subsequent exfoliation, and implementation in devices. At UZH Irchel, we use a dedicated clean room, optical microscopy, inkjet printing, and surface science tools such as low-energy electron diffraction, photoemission, and scanning tunneling microscopy for these purposes. At the Swiss Light Source, we perform photoemission and x-ray absorption spectroscopy experiments.

https://www.physik.uzh.ch/g/greber

Stability of single layer *h*-BN on metals

High quality single layer hexagonal boron nitride may be grown on transition metals with chemical vapor deposition (CVD). These systems are used as templates for molecules, production of pores with nanometer size, functional electrodes in electrochemical cells, or as educts for the production of free standing boron nitride layers.

With density functional theory (DFT) we calculated the atomic adsorption energies of boron and nitrogen, BN dimers, $(BN)_3$ hexamers and *h*-BN with and without atomic vacancies for different transition metals. It turns out that the catalytic substrates lower the stability of the *h*-BN that is e.g. more stable on copper than on nickel. Importantly, defects, impurities like carbon or domain boundaries lower the stability of the systems. The over all stability may be quantified with pyrolysis experiments where the systems are heated at a given rate to high temperatures. The disintegration of the



Pyrolysis of h-BN on Pt(111). Low energy electron diffraction (LEED) pattern (E = 100 eV) prior (left) and after (right) pyrolysis. Center UV flash lamp photoemission signal during annealing with a heating rate of 10°C min^{-1}. A significant signal drop is observed after the temperature reached the pyrolysis temperature T_p of 1200°C (red arrow). Data: A. Hemmi et al., Small (2022).

h-BN is measured in the decrease of the photoelectron yield of a xenon flash lamp. For the case of *h*-BN on platinum the Figure shows high quality electron diffraction pattern of *h*-BN on Pt(111) before and clean Pt(111) after heating. The record pyrolysis temperature T_p of 1200 °C indicates highest quality boron nitride.

The pyrolysis temperature of *h*-BN on a given transition metal is a measure for its quality and can be correlated to the DFT results.

The calculations run at the at the Swiss National Supercomputing Centre (CSCS) in Lugano, and the experiments were performed in the Sinergia lab on the Irchel campus of the University of Zürich. The project was funded by the European Commission (European Union's Horizon 2020 research and innovation programme) under the Graphene Flagship.

Highlighted Publications:

1. Growing sp^2 materials on transition metals: calculated atomic adsorption energies of hydrogen, boron, carbon, nitrogen, and oxygen atoms, C_2 and BN dimers, C_6 and $(BN)_3$ hexamers, graphene and *h*-BN with and without atomic vacancies
   A. P. Seitsonen and T. Greber, Nanoscale Adv. **6**, 268 (2024)
2. Correlation of Work Function and Conformation of C_{80} Endofullerenes on *h*-BN/Ni(111)
   R. Stania *et al.*, Adv. Mater. Interfaces 2300935, (2023)
3. Inferring the Dy-N axis orientation in adsorbed $DySc_2N@C_{80}$ endofullerenes by linearly polarized x-ray absorption spectroscopy
   R. Sagehashi *et al.*, Phys. Rev. Mat. **7**, 086001 (2023)

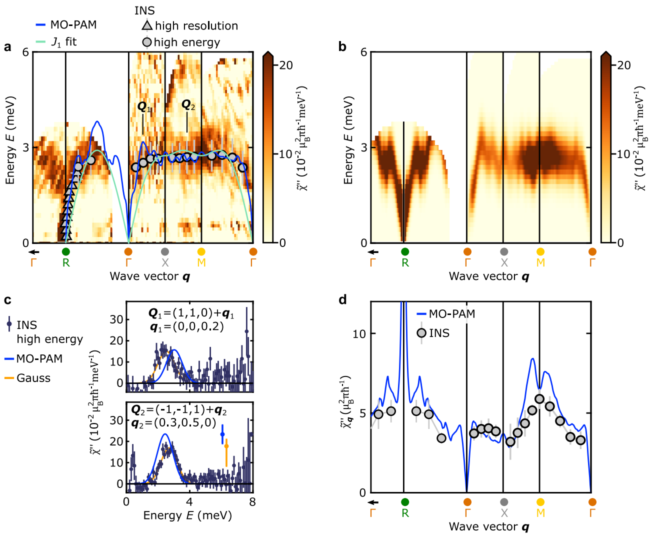
Correlated Quantum Matter

Prof. Marc Janoschek

Our research is centered on genuine quantum phenomena in bulk materials that arise due to collective electronic behavior. These electronic correlations strongly couple spin, charge and lattice degrees of freedom resulting in emergent and rich low-energy physics. We study materials in which such collective quantum phenomena at the atomic-scale are borne out in exotic and functional macroscopic properties. We tune the underlying quantum interactions via external control parameters (pressure, field, strain, crystal chemistry) to understand the properties of quantum materials. For this purpose, we probe quantum matter with state-of-the-art large-scale neutron, photon and muon experiments.
https://www.physik.uzh.ch/g/janoschek

A quantitative Kondo Lattice Model

Electrons at the border of localization generate exotic states of matter across all classes of strongly correlated electron materials and many other quantum materials with emergent functionality. The Kondo lattice model has been key in qualitatively demonstrating how a myriad of correlated quantum matter states emerge from the interplay of local and itinerant electrons. Beyond the strongly correlated electron materials for which this archetypal model was conceived, it applies to a growing list of novel quantum systems with potential for applications including the electronic transport through quantum dots, voltage-tunable magnetic moments in graphene, magnetism in twisted-bilayer graphene and in two-dimensional organometallic materials, the electronic structure in layered narrow-electronic-band materials, electronic resonances of Kagome metals, metallic spin liquid states, skyrmions in centrosymmetric magnets and fully tunable electronic quasiparticles in semiconductor moiré materials. Further, Kondo lattice models have been used to study flat-band materials and predict novel topological states such as topological superconductivity and quantum spin liquid states, including the highly sought-after fractional quasiparticles. Despite this continued relevance, quantitative predic-



Magnetic excitations in CeIn$_3$. (a) Calculated and (b) measured magnon dispersion and dynamic magnetic susceptibility in the antiferromagnetic state of CeIn$_3$ are in quantitative agreement. Panels (c) and (d) compare theory (blue lines) and experiment (circles) along energy and momentum transfer cuts, respectively.

tions for real materials based on Kondo lattice models remain a formidable computational hurdle.

Both for experiment and theory, the challenge in understanding real materials is the extreme energy resolution required to capture the inherently small energy scales that emerge in the renormalized electronic state arising from interplay of local and itinerant electrons. Notably, materials-specific theoretical investigations of emergent phenomena are often limited by the difficulty of validating low-energy effective models derived from complex high-energy input. Together with our theory collaborators from the University of Tennessee, Los Alamos, and RIKEN, we have demonstrated that for the prototypical strongly-correlated antiferromagnet CeIn$_3$ a multi-orbital periodic Anderson model embedded with input from ab initio bandstructure calculations can be reduced to a simple Kondo-Heisenberg model, which captures the magnetic interactions quantitatively. We validate this tractable Hamiltonian via high-resolution neutron spectroscopy that reproduces accurately the magnetic soft modes in CeIn$_3$ (see figure), which are believed to mediate unconventional superconductivity. Our study paves the way for a quantitative understanding of metallic quantum states such as unconventional superconductivity.

Highlighted Publications:

1. A microscopic Kondo lattice model for the heavy fermion antiferromagnet CeIn$_3$,
   W. S. Simeth, *et al.*, Nat. Comm.**14**, 8239 (2023)

Quantum Matter

Prof. Fabian Natterer

Our research group focuses on low-dimensional quantum materials. We explore how matter receives her properties from the interaction between individual atoms and molecules using atomically resolved scanning probe microscopy (SPM). By subjecting matter to extreme conditions - such as cryogenic temperatures, exposure to magnetic fields, or doping – we find control knobs that fine-tune material properties. Our investigations include measurements of the electronic structure using SPM enabled electron spin resonance, pump-probe spectroscopy, and fast quasiparticle interference imaging.

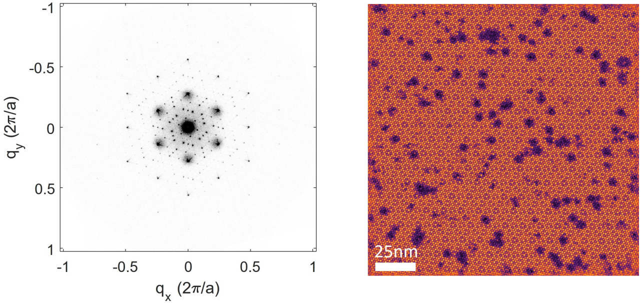
https://www.physik.uzh.ch/g/natterer

Electronic Structure Mapping of 2D Materials

We infer the band structure of two dimensional quantum materials using fast quasiparticle interference imaging (QPI). QPI works by measuring the point spectroscopy (local density of states) at every topographic location. To speed up this traditionally slow technique, we utilize compressed sensing and parallel spectroscopy. While the former enables the measurement of fewer locations, the latter speeds up the LDOS mapping. Using our fast QPI method, we investigate the van der Waals material 4Hb-TaS_2 that exhibits a superlattice of alternating layers with 1H and 1T coordination structures. The interaction between the two charge density waves (CDW) of the respective layers enhances the superconducting properties compared to pristine 2H-TaS_2. We identify a weakly dispersing band on the 1T surface and find domains with different orientations of the CDW, which change the observed long-wavelength Moiré patterns at the surface and the energy onset of the weakly dispersing band.

Superconducting tips for Josephson Junction STM

To enhance the energy resolution of our STM, we introduce a straightforward method to create superconducting tips made from Nb wires. The trick is to controllably break the Nb wires



Large scale quasiparticle interference map of 4Hb-TaS$_2$, measured in 2 days instead of 27 with our fast QPI technique, and showing the effect of Moiré patterns on the weakly dispersing bands close to the Fermi level.

in vacuum to expose fresh metal to the vacuum instead of ambient pressure that previously resulted in oxidized tips. These superconducting tips can be used for QPI mapping or represent one part of a Josephson junction. The latter act as the central component of a charge qubit that can be scanned along the surface and used to atomically map the presence of sources of decoherence or it provides insight into the pairing mechanism of low-dimensional superconductors via the emission of Josephson radiation.

Highlighted Publications:

1. Vacuum cleaving of superconducting niobium tips to optimize noise filtering and with adjustable gap size for scanning tunneling microscopy,
   Carolina A. Marques et al., MethodsX 11, 102483 (2023), DOI: 10.1016/j.mex.2023.102483

Phase Transitions, Materials and Applications

Prof. Andreas Schilling

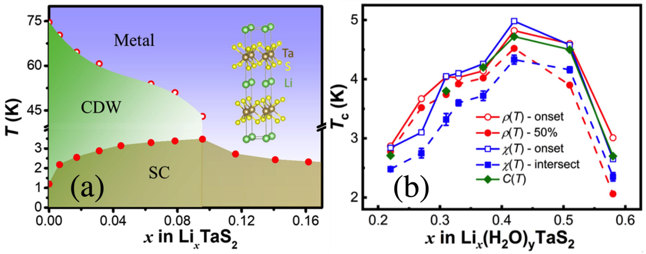
We are interested in selected topics in materials research, spanning the entire spectrum from **searching new materials**, their **characterization**, and corresponding **applications**. We have been particularly active in **superconductivity, magnetism and thermodynamics**. Our laboratory is equipped with modern furnaces for material synthesis, ^{4}He/^{3}He cryostats and a dilution cryostat, all with superconducting magnets.

We are structuring thin superconducting films at the FIRST Center for Micro- and Nanoscience at ETHZ and are using them both for basic research and applications. Corresponding nanostructures may serve as ultrafast single-photon detectors in the infrared, visible and X-ray range.

https://www.physik.uzh.ch/g/schilling

Superconductivity in un-hydrated and hydrated $Li_x(H_2O)_yTaS_2$

Layered transition-metal dichalcogenides (TMDs) have attracted increasing interest due to their relevance in understanding high-temperature superconductors. They can exhibit various quantum states such as metallic, Mott insulating, and a state with charge-density waves (CDWs). 2*H*-TaS_2 is a prominent representative member of the 2*H*-TMD family, in which both superconductivity and CDW can coexist. In bulk 2*H*-TaS_2, the incommensurate charge-density wave order has a transition temperature (T_{CDW}) of approximately 75 K. This state coexists with superconductivity as the temperature decreases below the superconducting transition temperature (T_c) of 0.8 K. Like in other transition metal dichalcogenides, this transition temperature can be tuned through chemical doping, intercalation, annealing, gating, and exfoliation or restacking. We have systematically studied the structural and physical properties of Li-intercalated Li_xTaS_2 and hydrated $Li_x(H_2O)_yTaS_2$ ($y \approx 0.86$).



Electronic phase diagrams of (a) un-hydrated Li_xTaS_2 and (b) hydrated $Li_x(H_2O)_yTaS_2$. Open circles in (a): CDW transition temperature T_{CDW}; filled circles: T_c. Inset: crystal structure of Li_xTaS_2.

In un-hydrated $\mathrm{Li}_x\mathrm{TaS}_2$, the CDW formation temperature is continuously suppressed by gradually increasing the lithium content x, and T_c increases with a maximum transition temperature $T_c = 3.5\,\mathrm{K}$ for $x = 0.096$ (see Fig. a). In contrast, there are no signs of a charge-density wave formation in hydrated $\mathrm{Li}_x(\mathrm{H}_2\mathrm{O})_y\mathrm{TaS}_2$, where the intercalation of water leads to a considerable expansion of the unit cell. There, the transition temperature to superconductivity also shows a dome-shaped dependence on the lithium content x, but with a maximum T_c of 4.6 K for a comparably high Li content ($x \approx 0.42$) (Fig. b).

This T_c value is larger than that of corresponding optimally doped 2H-TaS$_2$ without water or organic intercalants, which supports the scenario that a weakened interlayer coupling, resulting from a large interlayer spacing, may suppress the tendency of charge-density wave formation and thereby enhances superconductivity. At first glance, the dependence of T_c on the Li content x may be attributed to an associated charge-carrier doping. However, our Hall-effect data taken on $\mathrm{Li}_x\mathrm{TaS}_2$ suggest that the changes in the effective number of charge carriers is at least an order of magnitude larger than that inferred from the Li-content x alone. Therefore, the intercalation probably primarily weakens the CDW state and thus indirectly leads to a strong increase in the density of the mobile charge carriers, which in turn promotes superconductivity.

Highlighted Publications:

1. Superconductivity in hydrated $\mathrm{Li}_x(\mathrm{H}_2\mathrm{O})_y\mathrm{TaS}_2$
   H. Liu et al., J. Mater. Chem. C **11**, 3553 (2023).
2. Competing spin-glass and spin-fluctuation states in $\mathrm{Nd}_x\mathrm{Pr}_{4-x}\mathrm{Ni}_3\mathrm{O}_8$
   S. Huangfu et al., Phys. Rev. B **108**, 014410 (2023).

Coherent Diffraction Imaging

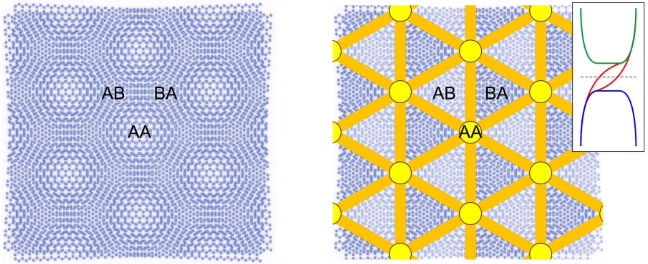
PD. Tatiana Latychevskaia (Paul Scherrer Institut)

We develop lens-less imaging methods towards high-resolution and three-dimensional imaging of nano-scaled objects, two-dimensional materials and macromolecules. Coherent diffraction imaging and holography are lens-less imaging techniques where the intensity of the wave diffracted by the sample is acquired by a detector in the far field. The phase distribution of the diffracted wave together with the sample structure is then reconstructed by applying numerical methods. Employing short wavelength radiation, such as electron or X-ray waves, in lens-less imaging techniques allows for imaging at atomic resolution.

https://www.psi.ch/en/lnb/people/tatiana-latychevskaia

Coherent imaging with low-energy electrons, quantitative analysis

Low-energy electrons (20 - 300 eV) hold the promise for low-dose, non-destructive, high-resolution imaging, but at the price of challenging data analysis. Recently, we quantitatively evaluated the properties of low-energy electrons when applied for coherent imaging [1]. Unlike electrons of energies typically employed in commercial transmission electron microscopes (20 - 300 keV), low-energy electrons (20 - 300 eV) introduce about 10 times larger phase shift into the probing electron waves. The maximal phase shift acquired by a 120 eV electron wave scattered by a carbon atom was theoretically estimated to be 5.03 radian and experimentally measured to be between 3 and 7.5 radian. Low-energy electrons diffract much stronger than high-energy electrons, the corresponding point spread function shows that only very thin objects of up to 3 Å in thickness can be imaged in focus. Thus, when imaging an object of finite thickness, such as a macromolecule, the obtained image will always be blurred due to the out-of-focus



Left: moiré pattern in twisted bilayer graphene (TBG) with indicated AA, AB and BA stacking regions. Right: topological channels (shown in orange) in TBG; the inset shows the band structure, the green and blue curves denote the conduction and valence bands, and the red lines show the topologically protected states formed in between the domains (inside the domain wall (DW) region) when the domains are gapped.

signal, which can be an explanation for the long-standing problem of limited resolution in low-energy electron holography of macromolecules. A simple method to quantitatively evaluate the absorption of a specimen from its in-line hologram without the need to reconstruct the hologram was presented.

Controlling topological states in bilayer graphene

Topological states are exciting physical objects with potential for use in quantum applications. In bilayer graphene, the topological states are hosted by the domain walls (DWs) that separate the AB and BA stacking of atoms. An example of topological channels in twisted bilayer graphene is shown in Figure 1 [2]. The DWs size can be changed by lithium intercalation, but the overall number of DWs is preserved; these processes were visualised by electron microscopy by Endo et al. (Nat. Nanotech. 18, 1154–1161 (2023)). We provided perspective for future directions for such lithium-intercalated systems: The electronic properties of such systems are yet to be characterised. Moreover, other 2D crystals and various intercalating atoms can be tried out. The observed differences in the speed of lithium intercalation and de-intercalation processes can be further investigated; such studies can help in understanding the lithium battery operation processes at the atomic level.

1. Coherent imaging with low-energy electrons, quantitative analysis,
   T. Latychevskaia, Ultramicroscopy 253 113807 (2023)
   https://doi.org/10.1016/j.ultramic.2023.113807
2. Controlling topological states in bilayer graphene,
   T. Latychevskaia, Nature Nanotechnology (2023)
   http://dx.doi.org/10.1038/s41565-023-01454-8

Advanced Materials for Advanced Lasers

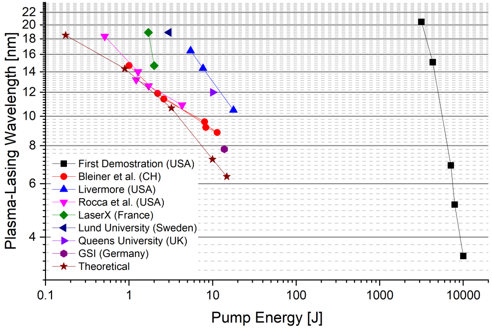
PD. Davide Bleiner (EMPA)

The group investigates materials and plasmas for enabling new laser concepts. In particular, a main challenge is the realization of compact X-ray lasers. These are complementary to accelerator beamlines or high harmonic generation beamlines. The level of footprint reduction influences the conceptual design. For lab-scale systems, either kiloampere discharges or terawatt laser pulses are used as pumps. For X-ray lasers on a chip, we are exploring 2D materials with resonant capabilities.

https://www.empa.ch/web/s502

Plasma Physics for Tabletop X-ray Lasers

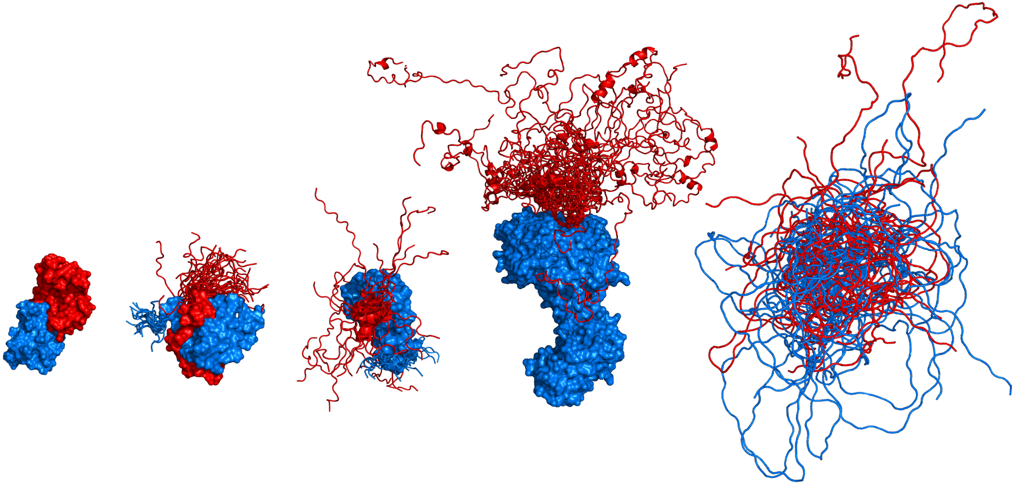
Plasmas of highly ionized atoms have electronic transition of higher energy than the neutral counterparts found in crystalline lattices. Henceforth, the use of plasmas as gain media permits to realize lasing action at higher transition energies. These are in the VUV down to the soft X-rays. Stimulated emission and amplification across a plasma is a single-pass process, without resonator.



The main challenge is that the plasma is not as homogeneous as a crystal medium. From the early days at Livermore National Laboratory with multi kJ pulses, the efficiency has dramatically grown to fit of a optical table in the lab. Typically, electrical discharges or laser-produced plasmas are used.

Tabletop beams for short wavelength spectrochemistry, D. Bleiner, Spectrochimica Acta Part B: Atomic Spectroscopy 181 (2021):105978.

Bio and Medical Physics



The spectrum of disorder in protein complexes (Schuler et al. 2020)

Disordered and biological soft matter

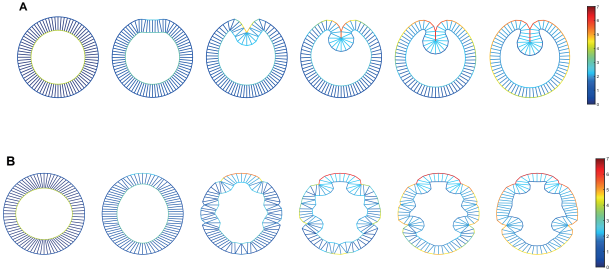
Prof. Christof Aegerter

We study the properties of disordered and heterogeneous systems out of equilibrium. This encompasses light transport in turbid media and photonic glasses, with applications in imaging, structural colours, light harvesting for energy and secure optical communication. A second focus of our activities is the study of the elastic properties of growing biological tissues and their influence on development and pattern formation, e.g. in embryonal development of drosophila, such as ventral furrow formation or dorsal closure. In all these fields our investigations are mainly experimental, developing the tools necessary, e.g. to study forces in tissues on the scale from nN to mN, however we also use computational modeling to guide these experiments.

https://www.physik.uzh.ch/g/aegerter

Modelling Ventral Furrow Formation in Drosophila embryos

The invagination of mesoderm during ventral furrow formation in the Drosophila embryo is part of the archetypal morphogenic process of gastrulation. This is one of the most fundamental processes during embryonal development, where the initial symmetry breaking of the embryonal shell takes place. To explore the roles of the active cellular forces and the regulation of these forces, we developed an integrated vertex model that gives a complete description of the process. In this, it combines the regulation of morphogen expression in a regulatory network with cell movements and the corresponding tissue mechanics. Finally, in order to take into account mechanical regulation of biological development, the regulatory network is influenced by the mechanical tensions, thus providing a mechanism for mechanical feedback. In our simulations, a successful furrow formation requires an apical tension gradient, decreased basal tension, and increased lateral tension, which corresponds to apical constriction, basal expansion, and apicobasal shortening respectively. These ten-



A) A simulation of normal invagination using the regulatory network to control the expression of twist determining the tensions in the cells. These tensions are colour coded using the scale shown on the right.
B) A simulation using the same regulatory network, however here, the embryo has been constantly deformed using an external compression. Such a deformation experimentally leads to the overexpression of twist and thus constricts invagination. This is also seen in the simulations shown here.

sions can be dynamically obtained from a regulation by the morphogen twist, which acts as a regulator of myosin, responsible of contractile tension in the cell boundaries.

Our regulatory equations can reproduce this dynamics of the apical tension gradient, basal tension decrease, and lateral tension increase, which are corresponding to apical constriction, basal expansion, and apico-basal shortening respectively. Then we integrated the regulation network and the vertex model. The results show that our integrated model is also able to form a closed ventral furrow although there are anomalous deformations in the intermediate states. Our model also replicates the ectopic *twist* expression induced by mechanical compression. The ectopic expression of *twist* prevents mesoderm invagination, which is consistent with experimental observations (see figure). Our model also predicts the ectopic invagination in presence of a locally applied external force gradient, which has not been verified in vivo.

1. An integrated vertex model of the mesoderm invagination during the embryonic development of Drosophila, J. Jiang and C.M. Aegerter
Journal of theoretical Biology **572**, 111581 (2023).

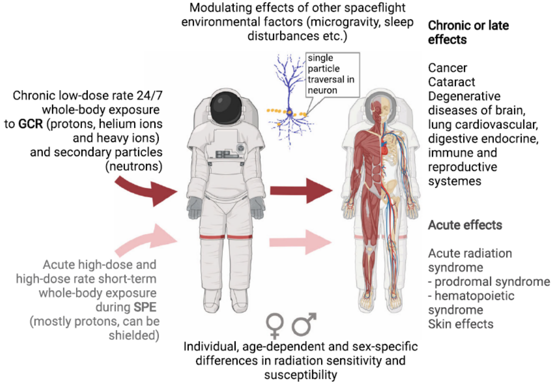
Medical Physics and Radiation Research

Prof. Uwe Schneider (Hirslanden)

We are conducting research and development in Medical Physics, Theoretical Biology and Medical Modelling. Our main topics are: Development of radio-biological models, space radiation research, Monte Carlo simulations and dosimetry for radiotherapy and imaging and the development of novel detector systems.

https://www.physik.uzh.ch/g/schneider

In 2023 our work was focused on Space Radiation Research (Figure). One project, in collaboration with CERN, is aiming on the development of a beam line to simulate high-LET irradiation of the cosmic galactic background for earth based material and biological experiments. In a second project, we are developing an European risk assessment software to assess organ dose equivalents for European astronauts. For Astronauts the probability of surviving cancer free a Mars swing-by mission until retirement age is being reduced by a range from 0.78% to 2.63%. It was found that the risks for females are higher than for males, and the risks at solar minimum are higher than at solar maximum.



Radiation exposure during space missions beyond low Earth orbit and health effects of space radiation (from [1]).

1. Towards sustainable human space exploration-priorities for radiation research to quantify and mitigate radiation risks.,
A. Fogtman et al., NPJ Microgravity. 2023 Jan 27;9(1):8.

Medical Physics

Prof. Jan Unkelbach (University Hospital Zurich)

Radiotherapy is one of the mainstays of cancer treatment and a highly technology-driven field of medicine. In our research group, we contribute to the further development of radiotherapy technology by applying concepts from physics, mathematics, statistics, and machine learning to problems in medical imaging and radiation oncology.

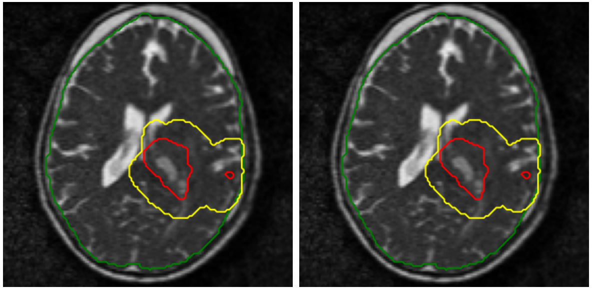
https://www.physik.uzh.ch/g/unkelbach

We focus on three areas of research:

1) Radiotherapy treatment planning: We work on mathematical optimization methods to optimally combine x-ray and proton beams, and to optimally distribute radiation dose over multiple treatment days and radiation modalities [1].

2) Target delineation and outcome prediction: Here, we focus on quantitative modeling of tumor progression and the analysis of medical images such as MRI, CT, and PET, with the goal of precisely defining the region to be irradiated and predicting the patient's response to treatment (see Figure).

3) Latest radiotherapy technology: We perform research on FLASH therapy and MR-guided therapy at the MR-Linac, a combination of MRI scanner and radiotherapy device allows MR imaging of a patient during treatment (see Figure).



MR-images of a brain tumor patient, showing tumor changes between the start (left) and the end (right) of treatment.

1. Spatiotemporal fractionation schemes for stereotactic radiosurgery of multiple brain metastases,
   N. Torelli, D. Papp, J. Unkelbach, Med Phys. 2023;50(8):5095-5114.

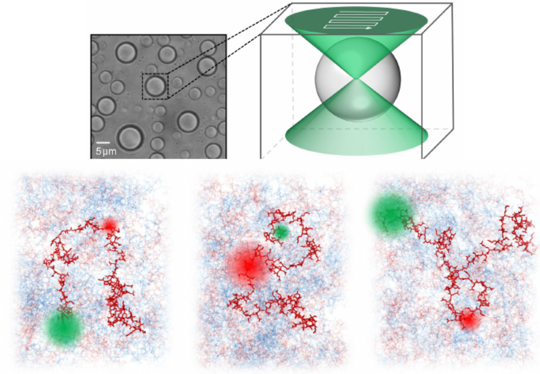
Molecular Biophysics

Prof. Ben Schuler (Department of Biochemistry)

We study the **structure, dynamics, and functions of biomolecules, especially proteins, the nanomachines of life**. Towards this goal, we develop and apply **single-molecule fluorescence and force spectroscopy**, often in close combination with theory and simulations. A particularly important tool is Förster resonance energy transfer (FRET), a spectroscopic nanoscale ruler.

https://schuler.bioc.uzh.ch

Two highlights were the development of a droplet-based microfluidic mixing device for the rapid triggering of biomolecular reactions [1], and the single-molecule study of nanoscopic dynamics within phase-separated droplets of biomolecular polyelectrolytes and their interpretation based on massive molecular dynamics simulations [2].

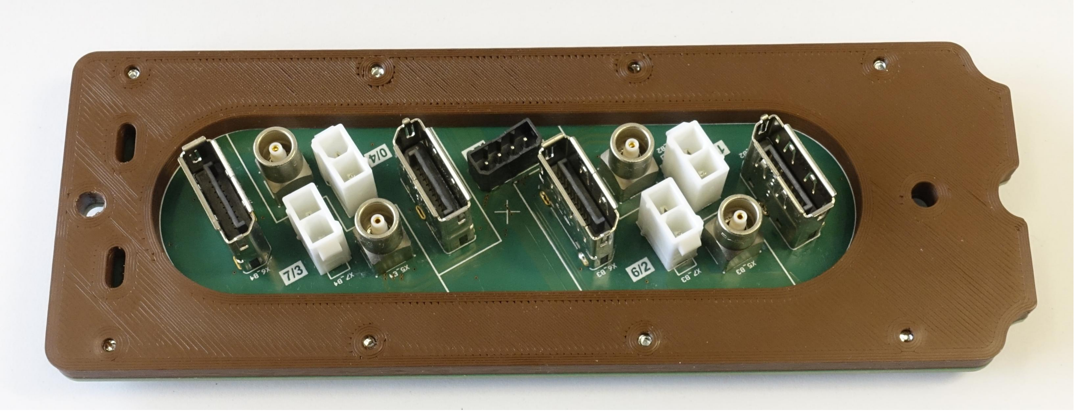


Confocal single-molecule FRET measurements in complex coacervates of highly charged protein molecules revealed polymer dynamics on sub-microsecond timescales. The snapshots at the bottom illustrate the behavior of fluorescently labeled molecules in a dense phase of protein.

1. Rapid droplet-based mixing for single-molecule spectroscopy, T. Yang *et al.*, Nat. Methods **20**, 1479–1482

2. Extreme dynamics in a biomolecular condensate, N. Galvanetto *et al.*, Nature **619**, 876-883

Workshops



Mechanical Workshop

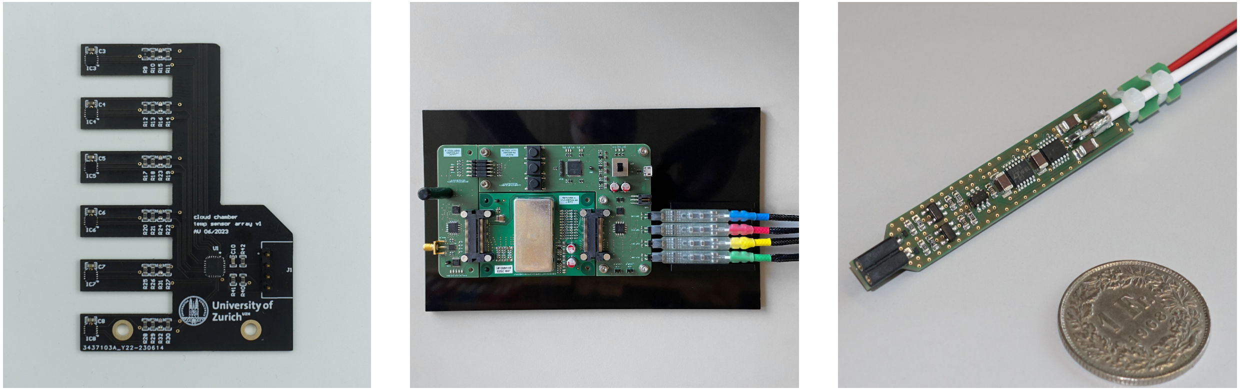
The **mechanical workshop** produces complex parts for all the experiments in house as well as for the large-scale astrophysics and particle physics experiments our groups are contributing to and helps to find solutions for technical problems. The high competence of the workshop is well appreciated also by other institutes of the university or external companies.

https://werkstatt.physik.uzh.ch

The three photographs are examples for work done in our workshop: (left) sample rod for NMR experiments in the PPMS under uniaxial pressure (group Janoschek); (middle) setup to measure the electrical contact resistance between two metal contacts (copper) at room temperature and at liquid nitrogen temperature as a function of axial pressure (group Natterer); (right) example of a complex component.

Electronics Workshop

Besides maintenance work for the existing laboratory infrastructure the **electronics workshop** continuously supports the groups of our institute with technical advice, prototypes and new developments for ongoing projects. Apart from many ongoing and newly developed projects for the research groups of our institute we designed a current pulser to deliver up to 12’000 A in a short pulse to allow a coil to generate a magnetic field of up to 50 T. The voltages and currents involved in this design required special precautions to provide human safety.



Left: 6-channel thermometer to measure the temperature gradient inside the cosmic ray cloud chamber. Middle: Semi-automatig testing jig for DAMIC-M frontend boards. An integrated microcontroller generates stimuli to check for connectivity and passive component values. Right: Active differential probe with a bandwidth of 1 GHz and interface to LeCroy oscilloscopes.

Personnel

Personnel, January – December 2023

Secretariat
Gaby Aeppli
Ewa Bolli
Denise Caneve
Markus Ehrle
Brigitte Freund
Frank Hitzemann
Parisa Rezaei Mianroodi
Monika Röllin
Regina Schmid
Anna Troller

IT Coordination
Dr. Roland Bernet
Paul Käser

Lectures
Ruth Bründler
Dr. Conrad Escher
Andreas James

Mechanical Workshop
Chris Albrecht
Manuel Klokow
Bruno Lussi
Reto Maier
Ryan Morf
Marcel Schaffner
Thomas Schär
Max Spörri
Stevan Vujmilovic

Electronics Workshop
Daniel Florin
Diego Loosli
Antonio Tejada
Dr. Achim Vollhardt
David Wolf

Group Christof Aegerter
Dr. Mirco Ackermann
Prof. Dr. Christof Aegerter
Dr. Valerio Mazzone
Dr. Lara Selvaggi

Group Laura Baudis
Ali Askin
Dr. Marta Babicz
Prof. Dr. Laura Baudis
Yanina Biondi
Alexander Bismark
Paloma Cimental Chavez
Dr. Ping-Jung Chiu
Dr. Jose Cuenca Garcia
Dr. Michelle Galloway
Frédéric Girard
Jonathan Franchi
Yannick Müller
Dr. Ricardo Peres
Francesco Piastra
Mariana Rajado Silva
Aravind Remesan Sreekala
Dr. Diego Ramirez
Gabriela Rodriguez Araujo
Dr. Christian Wittweg

Group Cristina Botta
Prof. Dr. Cristina Botta
Dr. Jaana Heikkilä
Peter Meiring

Group Tomáš Bzdušek
Zoltán Guba
Dr. Patrick Lenggenhager
Prof. Dr. Tomáš Bzdušek

Group Lea Caminada
Tiziano Bevilacqua
Prof. Dr. Lea Caminada
Dr. Marino Missiroli
Lars Noehte

Group Florencia Canelli
Pascal Bärtschi
Prof. Dr. Florencia Canelli
Giovanni Celotto
Dr. Kyle Cormier
Dr. Armin Ilg
Gautam Kunal
Sascha Liechti
Dr. Anna Macchiolo
Umberto Molinatti
Eduardo Ploerer
Dr. Sergio Sanchez Cruz
Fabian Stäger

Dr. Rafaella Tramantano
Weijie Jin
Dr. Adinda de Wit

Group Johan Chang
Dr. Izabela Bialo
Prof. Dr. Johan Chang
Changsheng Chen
Dr. Ola Forslund
Giordano Galati
Xunyang Hong
Dr. Chun Lin
Dr. Leonardo Martinelli
Dr. Kevin Kramer
Prof. Dr. Tohru Kurosawa
Julia Küspert
Jens Oppliger
Prof. Kaori Tanaka
Dr. Karin von Arx
Dr. Qisi Wang

Group Andreas Crivellin
Dr. Sumit Banik
Guglielmo Coloretti
Prof. Dr. Andreas Crivellin

Group Thomas Gehrmann
Dr. Piotr Bargiela
Souvik Bera
Leonardo Bonino
Oscar Braun-White
Dr. Xuan Chen
Dr. Vittorio Del Duca
Dr. Giulio Falcioni
Weijie Feng
Gaia Fontana
Prof. Dr. Thomas Gehrmann
Prof. Dr. Nigel Glover
Petr Jakubcik
Dr. Florian Larkowski
Markus Löchner
Matteo Marcoli
Dr. Robin Marzucca
Dr. Kay Schönwald
Dr. Vasily Sotnikov
Dr. Giovanni Stagnitto
Dr. Tongzhi Yang

Group Marta Gibert
Simon Jöhr
Prof. Dr. Marta Gibert
Jonathan Spring

Group Massimiliano Grazzini
Dr. Daniel Baranowski
Luca Buonocore
Paolo Garbarino
Prof. Dr. Massimiliano Grazzini
Flavio Guadagni
Jürg Haag
Dr. Stefan Kallweit
Dr. Luca Rottoli
Chiara Savoini

Group Thomas Greber
Jan Beckord
Nicolò Comini
Dr. Huanyao Cun
Kamil Dwinger
Prof. Dr. Thomas Greber
Dr. Adrian Hemmi
Dr. Matthias Hengsberger
Wei Chuang Lee
Mert Taskin
Lebin Yu

Group Gino Isidori
Dr. Jason Aebischer
Lukas Allwicher
Mohammad Alminawi
Sebastiano Covone
Dr. Joseph Davighi
Noemi Fabri
Prof. Dr. Gino Isidori
Dr. Javier Lizana
Sandro Mächler
Marko Pesut
Dr. Gioacchino Piazza
Dr. Emanuelle Pinsard
Dr. Zachary Polonsky
Dr. Davide Racco
Nudzeim Selimovic
Dr. Ben Stefanek
Arianna Tinari
Felix Wilsch

Group Marc Janoschek
Prof. Dr. Marc Janoschek
Dang Xuan Dang
Simon Flury
Jonas Philippe
Dr. Wolfgang Simeth
Dr. Danielle Yahne

Group Philippe Jetzer
Dr. Cecilio Garci'a Quiros
Dr. Eleanor Hamilton
Prof. Dr. Philippe Jetzer
Dixena Lopez
Simon Stähler
Dr. Shubhanshu Tiwari
Yumeng Xu

Group Ben Kilminster
Nicola Gadola
Marc Huwiler
Dr. Arash Jofrehei
Prof. Dr. Ben Kilminster
Anson Kwok
Steven Lee
Dr. Stefanos Leontsinis
Fanqiang Meng
Izaak Neutelings
Dr. Arne Reimers
Dr. Peter Robmann
Matias Senger
Eslam Shokr
Dr. Yuta Takahashi
Dr. Vagelis Gkougkousis

Group Fabian Natterer
Dr. Ales Cahlik
Ajla Karic
Danyang Liu
Dr. Carolina De Almeida Marques
Prof. Dr. Fabian Natterer
Berk Zengin

Group Titus Neupert
Dr. Nikita Astrakhantsev
Kouta Dagnino
Dr. Michael Denner
Dr. Mark H. Fischer
Sofie Castro Holbaek
Dr. Mikel Iraola
Dr. Macei Koch-Janusz
Bastien Lapierre
Xiaoxiong Liu
Bernhard Lüscher
Prof. Dr. Titus Neupert
Midori Pittini-Yamada
Martina Ondina Soldini
Dr. Maurizio Storni
Dr. Luka Trifunovic
Dr. Tarun Tummuru
Dr. Glenn Wagner
Dr. Songbo Zhang

Group Stefano Pozzorini
Nicolo Giraudo
Dr. Florian Herren
Lorenzo Mai
Prof. Dr. Stefano Pozzorini

Group Prasenjit Saha
Antonio del Rio
Prof. Dr. Prasenjit Saha

Group Andreas Schilling
Noah Brugger
Dr. Ilya Charaev
Dr. Hai Lin
Huanlong Liu
Prof. Dr. Andreas Schilling
Stefan Siegrist
Dong Zhu

Group Nico Serra
Dr. Carlos Abellan Beteta
Martin Andersson
Pasquale Andreola
Michele Atzeni
Dr. Violaine Bellée
Dr. Christopher Betancourt
Dr. Iaroslava Bezshyiko
Dr. Lariza Golinka-Bezshyiko
Dr. Annarita Buonaura
Dr. Daniel Craik
Dario De Simone
Jonas Eschle
Dr. Sevda Esen
Martina Ferrillo
Guillermo Hijano
Davide Lancierini
Dr. Thomas Lehéricy
Dr. Abhijit Mathad
Dr. Katharina Müller
Dr. Patrick Owen
Maria Pilar Peco Regales
Dr. Shah Rukh Qasim
Thomas Senger
Prof. Dr. Nicola Serra
Dr. William Sutcliffe
Dr. Gerardo Vasquez
Aleksander Terentev
Zhenzi Wang
Jie Wu

Group Uwe Schneider
Irina Kempf
Prof. Dr. Uwe Schneider
Dr. Linda Walsh

Group Adrian Signer
Prof. Dr. Adrian Signer

Group Olaf Steinkamp
Dr. Vadym Denysenko
Prof. Dr. Olaf Steinkamp

Group Peter Stoffer
Oscar Lara Crosas
Luca Naterop
Prof. Dr. Peter Stoffer
Dr. Jan-Niklas Toelstede

Group Max Zoller
Dr. Fabian Lange
Prof. Dr. Max Zoller

University of Zurich
Department of Physics
Winterthurerstr. 190
CH-8057 Zurich

Front: Alignment of wave-front shaping setup for imaging through turbid media.