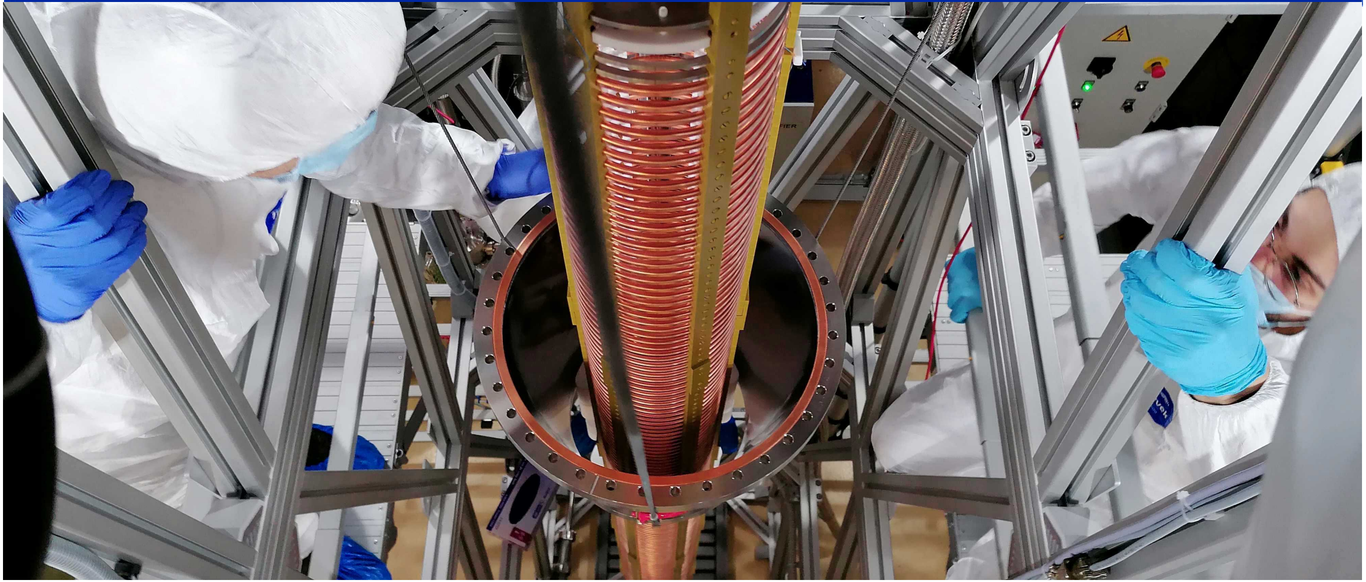
University of
Zurich^UZH

Department of Physics

Annual Report and Highlights 2022



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Department of Physics

Annual Report and Highlights 2022

Winterthurerstrasse 190, CH-8057 Zurich, Switzerland

Preface

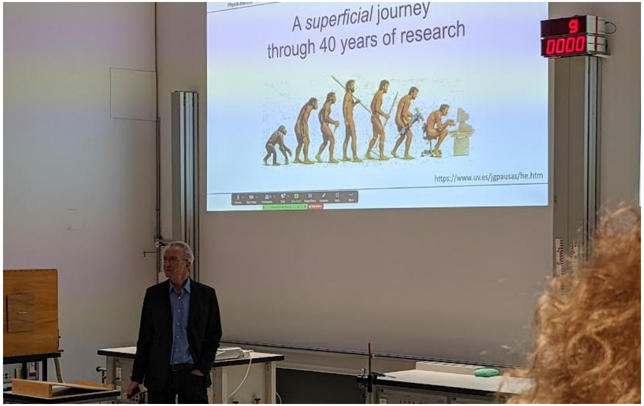
Thomas Gehrmann, Department Head

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

The year 2022 marked the successful commissioning of the Xenoscope demonstrator, seen on the report's frontpage. This accomplishment by the experimental astroparticle group of Laura Baudis, with substantial support from our mechanical and electronics workshops, marks an important step towards the DARWIN project, a large-scale detector for dark matter searches at unprecedented sensitivity.

Following almost three decades of world-class research activity in experimental condensed matter and surface physics at our department, our colleague Jürg Osterwalder retired at the end of the spring semester 2022. With a combination of curiosity, common sense, determination and good humour, he shaped and led his thriving research group. The same skills enabled him to successfully manage the Physik-Institut as director from 2016 to 2021 and to guide the Swiss science policy as member of the research council of the Swiss National Science Foundation. His lively lectures were filled with spectacular demonstration experiments, often demanding his all-out involvement, and gaining him a celebrity status especially among the medical students.



Farewell lecture of Jürg Osterwalder.

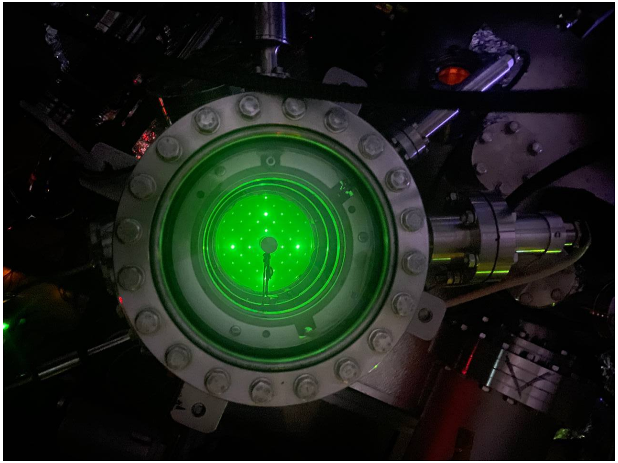
After two years of limited on-site activities due to the Covid-pandemic, our department was very happy to return to normal on-site operations in research, teaching and student supervision in 2022. Many of us gained substantial experience on novel teaching formats and on remote collaborative work during the past years. While parts of these formats were only emergency substitutes for in-person interactions, others proved to be very effective and well-appreciated, leading to innovative improvements especially of teaching methods and student interaction.

Our department made substantial contributions to community-building and outreach events. Researchers from our department initiated and co-organised the "Women in Physics Career Symposium" as a satellite event to the annual meeting of the Swiss Physical Society (SPS) in Fribourg. The symposium attracted 75 participants from all career stages and launched a mentoring program for early-career female physicists in Switzerland. The tenth anniversary of the discovery of the Higgs boson was celebrated with an informative walk through the Irchelpark. Marking the 100th anniversary of the award of the Physics Nobel Prize to UZH-alumnus Albert Einstein, we organised an exhibition in the Irchel Lichthof. Highlighting the stages of Einstein's career and explaining his major scientific accomplishments, the display was very well received by students and academics from all faculties. A new exhibition on the LHCb experiment was opened in the Science Pavilion UZH, joining the already present three exhibits from our institute on superconductors, search for Dark Matter and the CMS experiment. Finally, our institute organised an open day and contributed to the Long Night of the Museums and the Science & Nature Festival.

This booklet aims to 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.

Retirement - Jürg Osterwalder, Emeritus since August 2022

Ask which instrument you play, and I tell you who you are. This mantra of Katrina Krimsky reminds of approaches to personalities like graphology or astrology – Jürg is a fish – still, it might contain a grain or two of truth. Besides the question of which instrument you play, it is also important how good you play it, whether you like solos or whether you are part of an orchestra or a band. As we know, at least since June 3, Jürg plays banjo, an instrument where you pluck mostly five strings that are resonating via a membrane spanned across a cavity. The origins of the banjo are in the United States of America, a country that Jürg likes a lot, where he spent his time as a postdoc, his two sabbaticals and where he became a fellow of the American Physical Society. Plucking persons and then letting them evolve is one of his ways to manage, where he likes to listen to the tones that evolve from the resonator that makes the triggered vibrations audible, even if they are gentle. With this attitude he led and shaped the surface physics group from 1994 to 2022, and the Physik-Institut as a director from 2016 to 2021. Sixteen semesters he served as a member of the research council division II of the Swiss National Science Foundation and five of those as the president. Physics for medical students was one of his favorite lectures that he liked to give, condense and perfect to high standards. His science was based on the detection of electrons and learning from them all they can tell if they are excited in condensed matter: energy, momentum and spin. His way of recording and displaying photoelectron diffraction data in two dimensional maps was eye-opening and as well applied for the direct measurement and visualisation of Fermi surfaces. His development of methods around the photoelectric effect was coupled with his will to contribute step by step to the solution of problems such as the storage of hydrogen in metals or the conversion of light energy into chemical bonds. When we asked him on what he will do after emeritation, he smiled and said more will come, may be, I will program an app on a mobile phone. Such down to earth projects are typical for him, he makes use of his skills and insights and likes to see his work to work.



A low-energy electron diffraction (LEED) image taken at 60 eV on a freshly prepared Fe_3O_4(001) surface represents the diffraction spots of the $(\sqrt{2}) \times \sqrt{2})$-R45 reconstruction. Image: Mert Taskin, 2021.

Prof. em. Ernst Brun, 1927 – 2022

Prof. em. Dr. Ernst Brun was Professor for Experimental Physics at our institute from 1958 until his retirement in 1992.

Ernst Brun studied physics at the University of Zurich and received his doctorate in 1954 under Professor H.H. Staub with a thesis on magnetic nuclear moments using nuclear magnetic resonance. He developed new experimental methods - dynamic nuclear polarization - to amplify nuclear magnetic resonance signals and thus was able to detect very weak signals. After a research stay in the USA, he was appointed associate professor of experimental physics at the University of Zurich in 1958. In 1963 he was promoted to full professor.

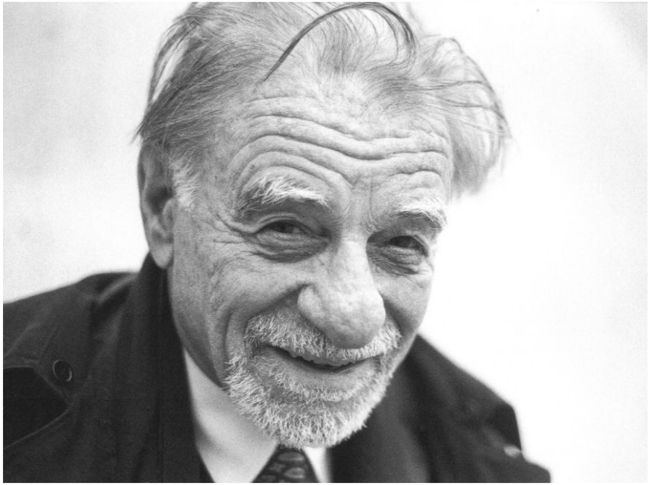
Brun initially worked on nuclear magnetic resonance (NMR) and its applications to the structural analysis of minerals. His close collaboration with crystallographers in Switzerland and abroad stemmed from this period. Later, he focused his diverse scientific activities on the study of complex nonlinear systems using NMR and laser methods, which led to the discovery of the NMR laser (Raser) in his research group. He also made increasing use of extensive simulation calculations based on spin dynamics and spin thermodynamics, as exemplified by the development of the Raser: It started with the observation of non-linearities in the signal strengths of the nuclei at strong negative polarization. Based on model calculations with extended Bloch equations, he postulated that a nuclear spin system should spontaneously emit coherent radio frequency radiation when the degree of polarization reaches a certain threshold. Following extensive experiments, he finally succeeded in realising experimentally this nuclear resonance laser or Raser. He interpreted the spontaneous transitions of the disordered system to a coherently radiating highly ordered state and the complex transient processes occurring in the process with theories of phase transitions and with chaos theoretical principles (chaos and order). The insights gained were often of a very general nature and can be applied to many areas of the natural sciences.

Ernst Brun's research was characterized by curiosity and enthusiasm. He successfully transferred this permanently to his colleagues. He was open to many new ideas, which he discussed critically, thus pursuing new paths with conviction, both mentally and materially.

In addition to his profound special lectures, Ernst Brun taught medical students for many years as a great and dedicated teacher in lectures that remained in the memory of many former students. In doing so, he succeeded in conveying to his audience the fascination of researching fundamental physical questions, and in introducing physics as a basic subject to the future natural scientists.

Ernst Brun served as Dean of the Philosophical Faculty II (today Faculty of Mathematics and Natural Sciences) from 1970 to 1972 and as Director of the Physik-Institut of the University of Zurich from 1972 to 1992. He was a charismatic and very people-oriented institute director who emphasised a collaborative management style. Important decisions were taken together with the people concerned and were presented and discussed at institute meetings. In this way, he made a significant impact in ensuring that no one felt advantaged or disadvantaged and that a good atmosphere was created throughout the institute. The welfare of all was always more important to him than personal success or honours. The Physics Institute under the leadership of Ernst Brun was marked by unity with a sense of community, which was shaped and fostered by his extraordinary personality.

Prof. em. K. Alex Müller, 1927 - 2023



Prof. Dr. Dr. h.c. mult. K. Alex Müller, IBM Fellow, Nobel Prize Winner in Physics 1987, was Professor for Experimental Physics at our institute from 1970 until his retirement in 1994.
K. Alex Müller's scientific career path started with the studies of physics at ETH Zurich where he was intensely influenced by Prof. Wolfgang Pauli. His diploma work was supervised by Prof. G. Busch, who was also the supervisor of his PhD thesis which dealt with the paramagnetic resonance in the newly synthesized double perovskite $SrTiO_3$.

K. Alex Müller started his professional life as head of the magnetic resonance group at the Battelle Memorial Institute in Geneva. Upon the recommendation of Prof. E. Brun he did his habilitation at the University of Zurich in 1962. In view of his high scientific impact, the IBM Zurich Research Laboratory offered him in 1963 the position of a researcher where he was promoted to a group leader of the physics department in 1971, a position that he held until 1985. During this time his research focused on $SrTiO_3$ and related perovskites with emphasis on their chemical binding, their ferroelectric and soft-mode properties, and later on their critical and multicritical phenomena at their phase transitions. His enormous successes in this field made him to one of the world leading experts in the research on ferroelectricity and structural phase transitions. In addition, his intimate knowledge of perovskites paved his way to superconductivity in this material class. In 1970 he was appointed as titular professor of the University of Zurich. A decisive moment in his career occurred in 1982 when he was nominated as IBM fellow. This enabled him to decide freely and independently about his further research areas - a milestone on his way to the Nobel prize.

During a sabbatical leave starting in 1979 at IBM Yorktown Height (USA) K. Alex Müller paid for the first time attention to superconductivity and gained profound knowledge in this field. He was especially interested in oxide superconductors which were rare at that time. Theoretical ideas as developed by Prof. Harry Thomas and his group at the University of Basel gave him the impulse to concentrate on complex oxides with Jahn-Teller centers. Such ions provide a source of strong and unconventional electron-phonon interactions including polaron and bipolaron formation. Together with J. Georg Bednorz he started in 1983 a new research project concentrating on superconductivity in oxide Jahn-Teller systems. In 1986 they achieved the breakthrough with the discovery of cuprate high-temperature superconductors (HTSs), which only a year later in 1987 was honored with the Nobel prize in physics for both. In the same year, but before their nomination, K. Alex Müller was promoted to a full professor at the University of Zurich.

After the Nobel prize K. Alex Müller continued his work on cuprate HTSs by focusing on their pairing mechanism. Since his original concept for the discovery was based on a polaronic or bipolaronic mechanism, he initiated a project on isotope effects in cuprate HTSs where novel and unexpected isotope effects were discovered which confirmed his starting concept that the charge carriers in these superconductors are strongly coupled to the lattice, *i.e.* that local lattice effects and inhomogeneity are relevant for superconductivity in cuprates. This notion is and was in strong contrast to the widely accepted conviction that the paring mechanism in the cuprates is of purely electronic origin.

Besides of his ingenious scientific achievements and engagements he was also a dedicated and inspiring teacher with profound interest in the students and their life. He attended the seminars at the Physik-Institut with deep scientific interest and was known for his perceptive and subtle questions and contributions. Up to an old age he stayed in close contact with the Physik-Institut and vividly took part in the social life.

Statistical Data

202
personnel

professors: 25
affiliated professors: 10
senior researchers: 17
postdoctoral researchers: 46
PhD students: 75
engineers and technicians: 22
administration: 8
+ research assistants

420
students

~80
new students

220 bachelor	31 BSc degrees
98 master	18 MSc degrees
97 PhD	18 PhD degrees

11
SNF prof.
and ERC grants

35	SNF or EU research grants
7	fellowships
45	UZH and other grants

304
publications

282	peer reviewed papers
19	conference proceedings
3	books & others

433
conference and
workshop
contributions

207	talks at conferences
123	seminar and other talks
66	posters
37	outreach

Outreach

Awards

- Jens Oppliger: Dectris prize
- David Urwyler: Soluyanov prize
- Yuta Takahashi: CMS young researcher prize
- Sevda Esen: LHCb early career award
- Michael Denner: SPS General Physics Award
- Laura Baudis: Charpak Ritz Prize

Events

- Connecting Women in Physics
- Open Day of the Institute
- Long Night of Museums
- Science & Nature Festival
- Exhibition: 100 years nobel prize of Albert Einstein
- Higgs@10: educative walk through the Irchel park

Others

- New exhibition on LHCb in the Science Pavilion UZH

Dance your Science: illustrating proton-proton collisions 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

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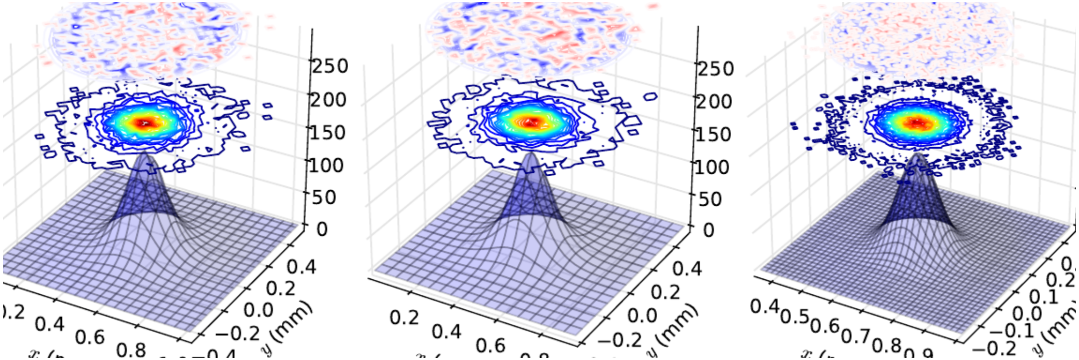
service lectures
1457
students

550	medicine
650	biology & biomedicine
160	chemistry
70	teacher
27	minors

A practical demonstration of the lens-maker equation by simple means

Describing the combined influence of refractive index contrast and boundary curvature on the properties of a lens is demonstrated by a glass inside a rectangular container that both can be filled with water. If both the glass and the container are empty (left most picture), the arrows behind the glass are undisturbed. If the glass is filled with water, it acts as a focusing lens and creates an inverted, real image of the arrow. Filling the container as well removes the curved interface, such that again an undisturbed image is obtained. Finally, filling the container, while leaving the glass empty results in the glass acting as a defocusing lens, producing a reduced, virtual image of the arrow.

Physics of Fundamental Interactions and Particles



Resolution-corrected fitted shapes of the two beams and of the luminous region at LHCb (arXiv:2211.12405).

Particle Physics Theory: Flavour beyond the Standard Model

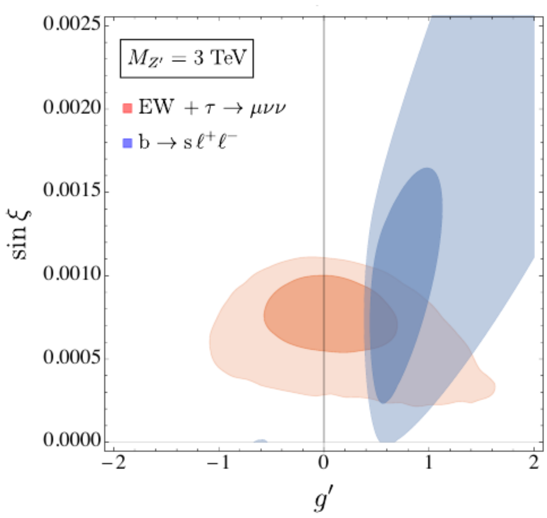
Prof. Andreas Crivellin

The Standard Model (SM) of particle physics describes the fundamental constituents and interactions of Nature. Matter consists of quarks and leptons (fermions) which interact via the exchange of force particles (gauge bosons). The SM has been tested to a very good 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.

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

Direct and Indirect Hints for Physics Beyond the Standard Model

The Large Hadron Collider (LHC) at CERN recently found several hints for so far unknown particles. This includes new strongly interacting particles that decay into quarks, resulting in signatures called "jets" at the LHC [1]. Also indirect test of the SM show signs of new physics, including the measurement of the *W* boson mass which is predicted very precisely within the SM. Here, we pointed out that this measurement could be explained by new heavy quarks, leading to exotic decays of the top quark [2]. Furthermore, there might be a connection of the *W* mass to the tensions observed in decays quark bound states containing a heavy bottom quark [3].



Global fit to EW precision observables, neutrino trident production, LEP bounds on 4-lepton contact interactions and $\tau \to \mu\nu\nu$ data (orange) and $b \to s\ell^+\ell^-$ data (blue) in the $g\prime - sin\xi$ plane for $m_{Z\prime} = 3$ TeV. One can see that both regions overlap nicely and that a non-zero value of the mixing angle is preferred (from [3]).

Highlighted Publications:

1. Consistency and Interpretation of the LHC (Di-)Di-Jet Excess,
   A. Crivellin, C. A. Manzari, B. Mellado, S. E. Dahbi and A. K. Swain,
   arXiv:2208.12254 [hep-ph]
2. Large t→cZ as a sign of vectorlike quarks in light of the W mass,
   A. Crivellin, M. Kirk, T. Kitahara and F. Mescia,
   Phys. Rev. D **106** (2022) no.3, L031704
   doi:10.1103/PhysRevD.106.L031704
   arXiv:2204.05962 [hep-ph] fig
3. Unified explanation of the anomalies in semileptonic B decays and the W mass,
   M. Algueró, J. Matias, A. Crivellin and C. A. Manzari,
   Phys. Rev. D **106** (2022) no.3, 033005
   doi:10.1103/PhysRevD.106.033005
   arXiv:2201.08170 [hep-ph]

Particle Physics Theory: Beyond the Standard Model

Prof. Gino Isidori

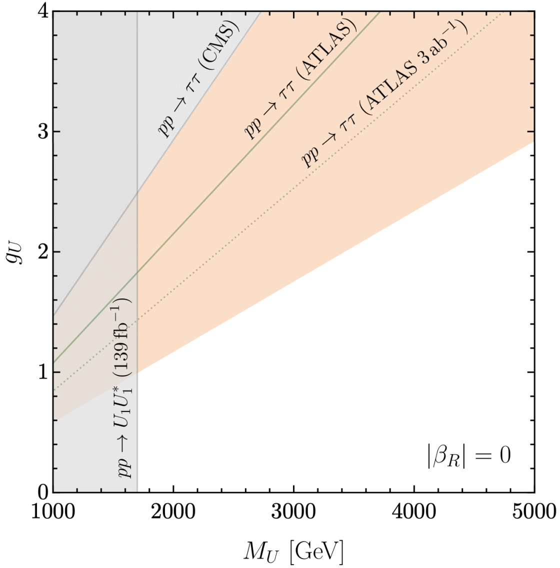
The Standard Model of fundamental interactions describes the nature of the basic constituents of matter, the so-called quarks and leptons, and the forces through which they interact. This Theory is very successful in laboratory experiments over a wide range of energies. However, it fails in explaining 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



Preferred region for mass and couplings (in orange) of a new particle (the leptoquark) predicted assuming quark and leptons are different manifestations of the same underlying field. The gray areas denote the current exclusion bounds from high-energy experiments, the green lines indicate their future sensitivity.

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 second and third directions. First, we improved the theoretical description of radiative corrections in rare B-meson decays. Applying these results to the analysis of current data from the LHCb experiment, we were able to place stringent constraints on the parameter space of a motivated SM extension. The latter is based on the interesting hypothesis that quarks and leptons are two manifestations of the same underlying field. We also made accurate predictions for processes occurring at high energies that will be measured in the coming years by ATLAS and CMS, showing that these future measurements could verify or disprove the validity of this hypothesis.

Highlighted Publications:

1. Flavor hierarchies, flavor anomalies, and Higgs mass from a warped extra dimension, J. Fuentes-Martin *et al.*, Phys. Lett. B **834** (2022) 137382, arXiv:2203.01952
2. Semi-inclusive Lepton Flavor Universality ratio in $b \to s\ell\ell$ transitions, M. Ardu, G. Isidori, and M. Pesut, Phys. Rev. D **106** (2022) 093008, arXiv:2207.12420
3. QED in $B \to K\ell\ell$ LFU ratios: theory versus experiment, a Monte Carlo study, G. Isidori, D. Lancierini, S. Nabeebaccus, R. Zwicky, JHEP **10** (2022), 146, arXiv:2205.08635

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.

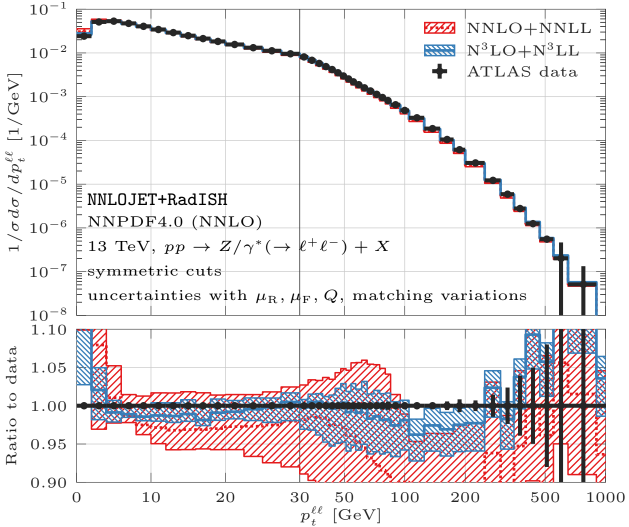
https://www.physik.uzh.ch/g/gehrmann

Fiducial cross sections in Drell-Yan type proceeses

The production of lepton pairs (Drell–Yan process) at hadron colliders is mediated through on-shell and off-shell electroweak vector boson production. It is a fundamental benchmark for the study of strong interactions and the extraction of electro-weak parameters. The outstanding precision of the LHC demands very accurate theoretical predictions with a full account of fiducial experimental cuts.

Predictions for fiducial cross sections that include realistic selection cuts on the leptons and on hadronic activity in the event allow to compare theoretical predictions directly to experimental observations. Our group is currently developing methods and tools to perform fully differential calculations of fiducial cross sections with QCD corrections expanded up to third order (N3LO) in perturbation theory.

Fully differential predictions at higher orders in perturbation theory require special treatment for the cancellation of infrared singularities that appear at the intermediate stages of the calculation. The q_T-subtraction method exploits the fact that the most singular phase space configurations are associated with the small transverse momentum q_T region of the lepton pair. They can be isolated numerically by an artificial q_T cut. The below-cut region is well-understood from resummation, and can be obtained in analytical form. We extended the q_T-subtraction method to N3LO in QCD



Fiducial $p_T^{\ell\ell}$ distribution at N3LO+N3LL (blue, solid) and NNLO+NNLL (red, dotted) compared to LHC data.

by computing the below-cut contribution to this order, and matching it to a numerical calculation of the above-cut contribution, which corresponds to Drell-Yan-plus-jet production at second-order (next-to-next-to-leading order, NNLO). A particular strength of the method is that its predictions can be combined with all-order resummation of large logarithmic corrections to all orders in perturbation theory in a straightforward manner.

An example application is the transverse momentum distribution of the lepton pair (figure), which we computed to N3LO matched to resummation at the third logarithmic order (N3LL). Our results provide an excellent description of the data across the spectrum and are accurate to the one percent level as required for precision phenomenology. The implementation of our results into a parton-level event generator allows to compute any distribution in the lepton kinematics, such as for example the transverse mass distribution relevant to the *W* boson mass determination.

Computing more complex final states to N3LO in QCD will however require substantial advances in concepts, algorithms and techniques for perturbative calculations. The major challenges associated with this endeavour are being addressed by our group in the framework of the ERC Advanced Grant 'Theory of Particle Collider Processes at Ultimate Precision (TOPUP)'.

Highlighted Publications:

1. Dilepton Rapidity Distribution in Drell-Yan Production to Third Order in QCD,
   X. Chen *et al.*, Phys. Rev. Lett. **128** (2022) 052001.
2. Third-Order Fiducial Predictions for Drell-Yan Production at the LHC,
   X. Chen *et al.*, Phys. Rev. Lett. **128** (2022) 252001.

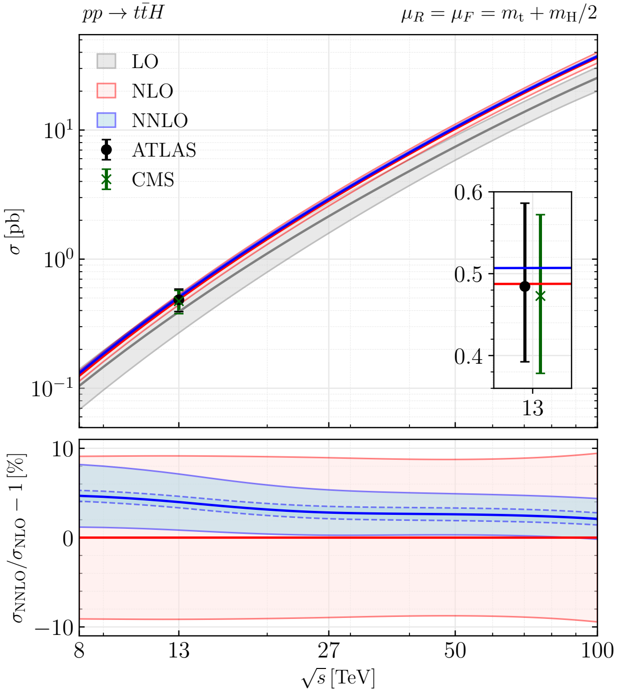
Particle Physics Theory: Standard Model and Higgs Physics at Colliders

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 make their results fully available to the community. We strive to 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

Hadroproduction of a heavy-quark pair in association with a massive boson

Processes characterised by a $2 \rightarrow 3$ reaction at Born level are the current frontier for perturbative computations at the next-to-next-to-leading order (NNLO) in QCD. Recently our group has presented two (almost) exact computations of the NNLO QCD corrections for the associated production of a Higgs boson with a top-antitop quark pair [1] and for the hadroproduction of a W boson in association with a massive bottom quark-antiquark pair [2]. The associated production of a Higgs boson with a $t\bar{t}$ pair is a crucial process at the LHC since it allows for a direct measurement of the top-quark Yukawa coupling. At present ATLAS and CMS measure the signal strength in this channel to an accuracy of $O(20\%)$, but at the end of the High-Luminosity phase the uncertainties are expected to go down to the $\mathcal{O}(2\%)$ level. Current theory predictions are characterised by $\mathcal{O}(10\%)$ uncertainties. Therefore, in order to match the expected experimental accuracy, the inclusion of NNLO QCD corrections is mandatory. In our work [1] the calculation of the NNLO QCD corrections is complete except for the finite part of the two-loop virtual amplitude, estimated with a soft Higgs boson approximation. Our approximation allows us to control the NNLO $t\bar{t}H$ cross



LO, NLO and NNLO cross sections with their perturbative uncertainties as functions of the centre-of-mass energy. The experimental results from ATLAS and CMS at $\sqrt{s} = 13$ TeV are also shown.

section to better than 1%, reducing the QCD perturbative uncertainties to few-percent level all over a wide range of collider energies (see figure).

The hadroproduction of a W boson in association with a $b\bar{b}$ pair constitutes one of the main backgrounds for WH and single-top production. The current predictions include NLO QCD corrections which were found to be very large. In order to avoid the ambiguities related to the use of flavored jet algorithms, massive bottom quarks have to be considered. In our work we compute the NNLO corrections by retaining the exact dependence on the b-quark mass in all the contributions but the two-loop virtual amplitude. The finite part of the two-loop virtual amplitude is reconstructed starting from the massless result and it includes mass effects up to power-suppressed terms. NNLO corrections to inclusive and fiducial cross sections are sizeable and the perturbative series starts to converge only if these corrections are included.

Order	$\sigma_{\rm inc}$[fb]	$\sigma_{\rm fid}^{binI}$[fb]	$\sigma_{\rm fid}^{binII}$[fb]
LO	$18.270(2)^{+28\%}_{-20.0\%}$	$35.49(1)^{+25\%}_{-18\%}$	$8.627(1)^{+25\%}_{-18\%}$
NLO	$60.851(7)^{+31.0\%}_{-21\%}$	$137.20(5)^{+34\%}_{-23\%}$	$37.24(1)^{+38\%}_{-24\%}$
NNLO	$85.23(9)^{+15\%}_{-14\%}$	$201.0(8)^{+17\%}_{-16\%}$	$50.5(1)^{+21\%}_{-18\%}$

1. $t\bar{t}H$ production in NNLO QCD S. Catani *et al.*, Phys. Rev. Lett. **130** (2023) no.11, 111902 doi:10.1103/PhysRevLett.130.111902
2. Associated production of a W boson and massive bottom quarks at next-to-next-to-leading order in QCD L. Buonocore *et al.*, arXiv:2212.04954

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.

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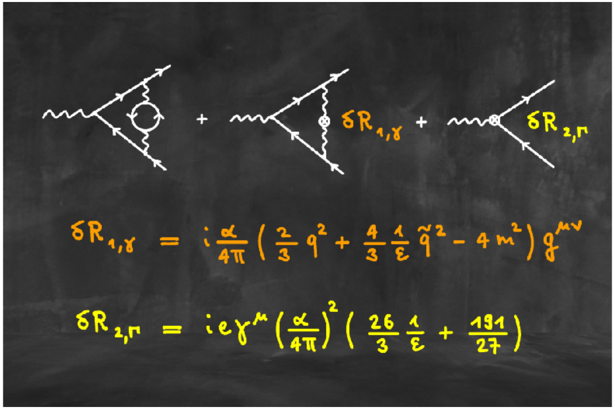
Rational terms of scattering amplitudes at two loops

Recently we did an important step forward towards the extension of the OpenLoops algorithm from first-order to second-order quantum corrections. Such corrections involve the exchange of virtual quanta with one or two unconstrained momenta, which gives rise to so-called one- and two-loop integrals. Due to the presence of ultraviolet singularities, loop integrals are typically evaluated in $D = 4 - \epsilon$ space-time dimensions, where ϵ is as infinitesimally small parameter. In this way the singularities assume the form of $1/\epsilon$ poles and can be canceled through the so-called renormalisation procedure. Finally, physical predictions are obtained by setting $\epsilon \to 0$. In this limit, the interplay of $1/\epsilon$ poles with infinitesimally small terms of order ϵ gives rise to subtle contributions, which are known as rational terms and play an important role for the automation of loop calculations.

So far automated algorithms exist only at one loop. In this case the most powerful approach turned out to be the com-



Example of Feynman diagrams describing second-order quantum correction to the interaction of photons (wavy lines) with electrons and positrons (solid lines). Two-loop diagrams (left) can be computed using numerical tools in $D = 4$ dimensions, while missing contributions in $D = 4 - \epsilon$ dimensions are reconstructed by means of one-loop (orange) and two-loop (yellow) rational counterterms. This approach is applicable to any scattering process.

bination of numerical algorithms in $D = 4$ dimensions together with special techniques for the reconstruction of the missing rational terms. In the recent few years, as a basis for automated two-loop algorithms, we have developed a fully-fledged theoretical framework to control rational terms at two loops.

In this approach, the standard procedure for the subtraction of ultraviolet singularities is supplemented by rational counterterms, which represent universal corrections to the Feynman rules that control the fundamental interactions of elementary particles and their propagation in the vacuum. Such rational counterterms can be determined for any theoretical model and, once available, they can be used to reconstruct the missing rational parts for any scattering process at two loops.

In [1] we have addressed the non-trivial problem of deriving the two-loop rational counterterms for theories that feature spontaneous symmetry breaking—also known as spontaneous symmetry breaking. To this end, we have presented a new method that makes it possible to carry out all calculations in the symmetric phase of the theory at hand. The high efficiency of this approach opens the door to the determination of two-loop rational counterterms for the full Standard Model of particle physics. As a first application we have derived all rational terms in the Standard Model at second order in the strong coupling constant.

These results provide an important building block for a new generation of automated algorithms for precision calculations at high-energy colliders.

1. Two-loop rational terms for spontaneously broken theories, J.-N. Lang, S. Pozzorini, H. Zhang, M. Zoller, JHEP **01** (2022) 105

High-intensity low-energy particle physics

Prof. Adrian Signer

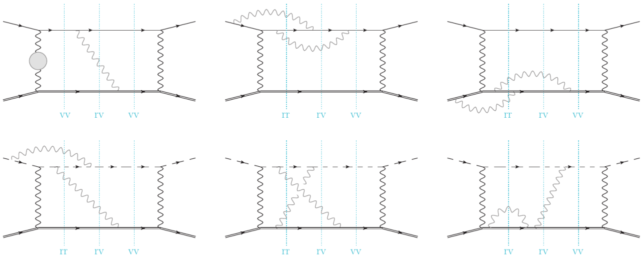
Particle physics at low energy but high intensity provides an alternative road towards a better understanding of the fundamental constituents of matter and their interactions. Using the world's most intense muon beam at PSI allows to look for tiny differences to the Standard Model or for extremely rare 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

Muon-electron scattering at NNLO

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`.

After the implementation of several processes at next-to-leading order (NLO), recently we have calculated the complete NNLO corrections to Møller and muon-electron scattering. The latter process is important in connection with the planned MUonE experiment that aims at an independent determination of the leading hadronic contributions to the anomalous magnetic moment of the muon.

In QED it is important to keep the fermion masses at their physical value, rather than setting them to zero. This allows to compute contributions with large mass logarithms,



Representative contributions to the squared amplitude for muon-electron scattering, resulting in double-real (rr), real-virtual (rv), and double-virtual (vv) contributions.

which often produce the dominant part of the corrections in QED. This is in contrast to similar calculations in the context of Quantum Chromodynamics, where observables are typically more inclusive such that these logarithms cancel.

A reliable numerical evaluation in particular of the real-virtual contribution relies on OpenLoops, in combination with a sufficiently precise approximation of the matrix element in the delicate soft and collinear regions. To this end, we extended the Low-Burnett-Kroll theorem and the collinear approximation to one-loop amplitudes, where a photon is emitted from a massive fermion line. We have derived a universal structure for these limiting behaviours and use them to ensure a numerically stable evaluation of the real-virtual corrections.

Highlighted Publications:

1. Møller scattering at NNLO,
   P. Banerjee *et al.*, Phys. Rev. D **105** (2022) no.3, 3
   doi:10.1103/PhysRevD.105.L031904
2. Muon-electron scattering at NNLO,
   A. Broggio *et al.*, JHEP **01** (2023), 112
   doi:10.1007/JHEP01(2023)112
3. Universal structure of radiative QED amplitudes at one loop,
   T. Engel, A. Signer and Y. Ulrich,
   JHEP **04** (2022), 097 doi:10.1007/JHEP04(2022)097

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.

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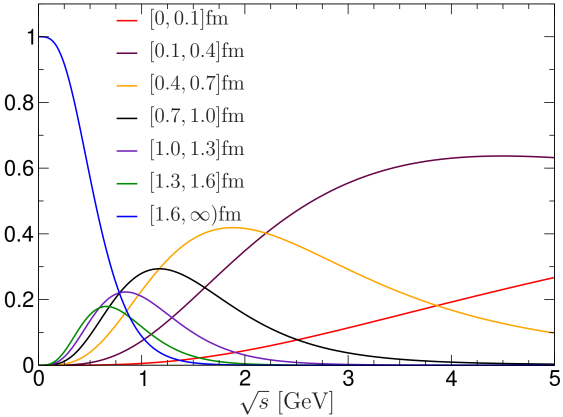
Despite its success, the Standard Model (SM) of particle physics fails to explain certain observations, such as the baryon asymmetry in the universe, dark matter, or neutrino masses. Our group is interested in indirect searches for physics beyond the SM, conducted in low-energy experiments at very high 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 one-loop matching between the MS scheme used in EFTs and a gradient-flow scheme that can be implemented with lattice QCD. We recently obtained the results for all dimension-five operators and we are extending this work to the CP-odd dimension-six oper-



Weight functions in center-of-mass energy for different Euclidean-time windows for the hadronic vacuum polarization contribution to the anomalous magnetic moment of the muon (from Ref.[2]).

ators. The results will enable the use of future lattice-QCD input for an accurate determination of the EFT contributions to the neutron EDM, which encode effects beyond the SM.

Anomalous magnetic moment of the muon

The 4.2σ discrepancy between the SM prediction of the anomalous magnetic moment of the muon and the experimental value is challenged by a conflict between data-driven and recent lattice-QCD evaluations of hadronic vacuum polarization. In order to scrutinize these different discrepancies, we have provided data-driven evaluations of Euclidean window quantities, which can be compared to lattice-QCD computations, and we have investigated isospin-breaking effects in the two-pion contribution, revealing systematic differences between different e^+e^- experiments.

In order to further reduce non-perturbative uncertainties, we are extending the dispersive framework for hadronic light-by-light scattering, enabling the inclusion of higher-spin resonances.

Highlighted Publications:

1. Isospin-breaking effects in the two-pion contribution to hadronic vacuum polarization,
   G. Colangelo, M. Hoferichter, B. Kubis, P. Stoffer,
   [2208.08993 [hep-ph]], JHEP **10** (2022) 032
2. Data-driven evaluations of Euclidean windows to scrutinize hadronic vacuum polarization, G. Colangelo et al., [2205.12963 [hep-ph]], PLB **833** (2022) 137313
3. One-loop matching for quark dipole operators in a gradient-flow scheme,
   E. Mereghetti, C. J. Monahan, M. D. Rizik, A. Shindler, P. Stoffer,
   [arXiv:2111.11449 [hep-lat]], JHEP **04** (2022) 050

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 t

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.

2022 marks the 10th anniversary of the discovery of the Higgs boson. UZH researchers on the CMS experiment were heavily involved in a 10-year anniversary paper published in Nature, in which CMS measurements over the previous 10 years were combined into a single review paper, demonstrating our improved understanding of this fascinating particle that explains how particles acquire mass (see Fig. 1) [1].

UZH members have also been involved in several of the analyses that were combined in this review, including the observation of the Higgs boson interacting with third-generation particles: b quarks, top quarks, and tau leptons. The current dataset

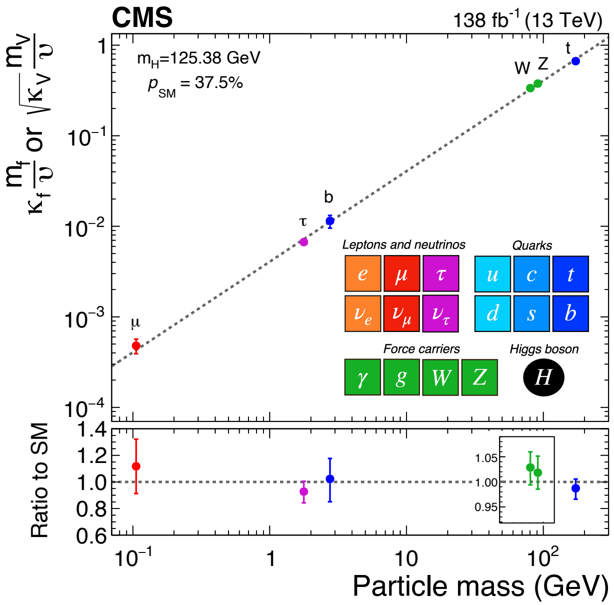


Fig 1: This plot shows that the Higgs boson interacts with both matter and force particles, with masses ranging over three orders of magnitude, according to predictions of the standard model [1].

of 150 fb^{-1} allows CMS to make precise measurements and searches for new physics.

In 2022, the UZH CMS group observed the production of tau leptons for the first time in PbPb collisions at the LHC. The tau leptons are produced by photons surrounding the high electromagnetic field of the Pb ions (see Fig. 2). 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 $(g\text{-}2)_\tau$ could be determined. So far, this result agrees with the SM, however, large deviations have been observed in the measurement of $(g\text{-}2)_\mu$, and it could be that such deviations could be even larger for the τ lepton. This result was accepted by PRL with the editor’s choice distinction [2].

In 2022, the UZH CMS group found an unexpected excess when searching for leptoquarks that interact strongly with third-generation particles (see Fig. 3). The excess was observed in events in which two tau leptons are produced. Such an excess is predicted by models from the Isidori group (see p.18). This was the first LHC analysis to search for non-resonant production of leptoquarks, such that the leptoquarks are exchanged rather than produced. Due to the large

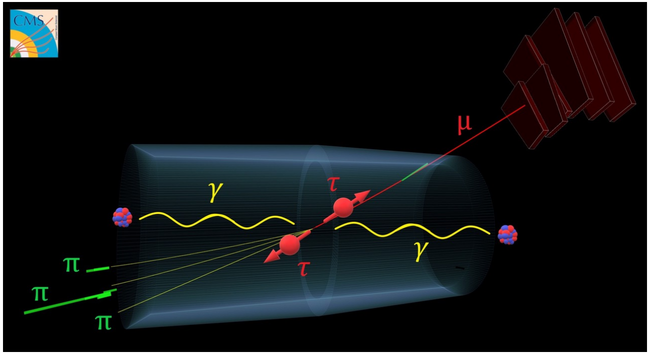


Fig. 2: In this sketch, two photons are exchanged from Pb ions, producing two tau leptons. The only observable particles in this interaction are the 3 pions from one tau lepton decay and the muon from the other tau decay [2].

deviation of 3.4 standard deviations, investigations are ongoing in CMS to determine if new physics is responsible [3]. Meanwhile, another UZH analysis, searching for a new type of particle called a vector-like lepton, also found a 2.8 standard deviation excess that is also consistent with the same models from the Isidori group [5]. Follow-up studies in other final states that would also be expected are ongoing.

The UZH CMS group produced a new type of analysis to search for the effects of new physics interactions by studying their off-shell effects through the use of the effective field theory (EFT) approach. The analysis focuses on new interactions that could couple top quarks with leptons, bosons, or quarks. Twenty-six extensions of the standard model are tested in how they would modify these events with top quarks. No significant modifications are currently observed, however, with future HL-LHC datasets that are ten times larger, deviations could become apparent. The search is explained in a manuscript that is currently being reviewed by the collaboration [4].

Many of the UZH measurements use tau leptons to probe for new physics. To do this, it is important to be able to identify tau leptons with high efficiency and low fake rate, and reconstructed with excellent energy resolution. UZH members helped develop and validate a new tau algorithm, known as DeepTau, that makes use of deep neural networks to identify tau leptons with up to a 30% reduction in fakes (other particles being misidentified as tau leptons) as compared to previous approaches for tau identification. A description of the new algorithm can be found in JINST **17** (2022) P0702.

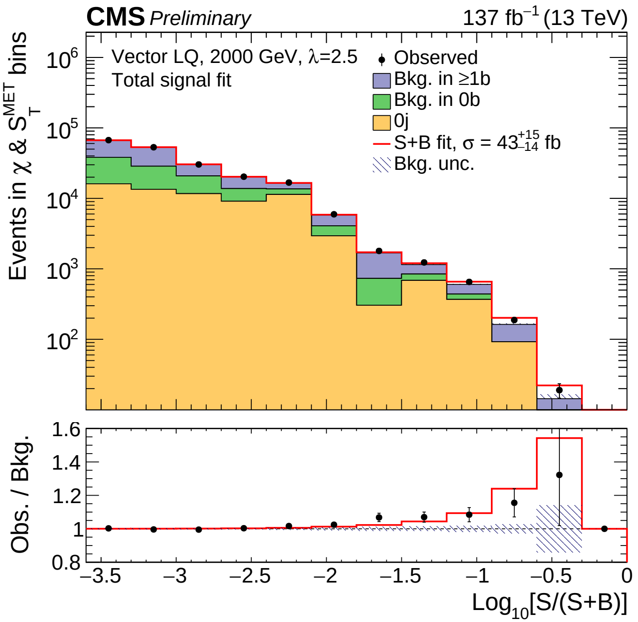


Fig. 3: The excess in data compared to the prediction is apparent at high values of the signal discriminant. Also shown is the expectation for a leptoquark signal in red.

Highlighted Publications:

1. A portrait of the Higgs boson by the CMS experiment ten years after the discovery
   CMS Collab., Nature **607**, 60–68 (2022),
   https://doi.org/10.1038/s41586-022-04892-x
2. Observation of τ lepton pair production in ultraperipheral lead-lead collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
   CMS Collab., https://arxiv.org/abs/2206.05192, accepted by PRL
3. The search for a third-generation leptoquark coupling to a τ lepton and a b quark through single, pair and nonresonant production at $\sqrt{s} = 13$ TeV, CMS Collab., https://inspirehep.net/literature/2110188
4. Search for new physics in top quark production with additional leptons in the context of effective field theory using 138fb^{-}1 of proton-proton collisions at $\sqrt{s} = 13$ TeV, CMS Collaboration., https://inspirehep.net/literature/2642353
5. Search for pair-produced vector-like leptons in final states with third-generation leptons and at least three b quark jets in proton-proton collisions at $\sqrt{s} = 13$ TeV
   CMS Collab., https://inspirehep.net/literature/2139823

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

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

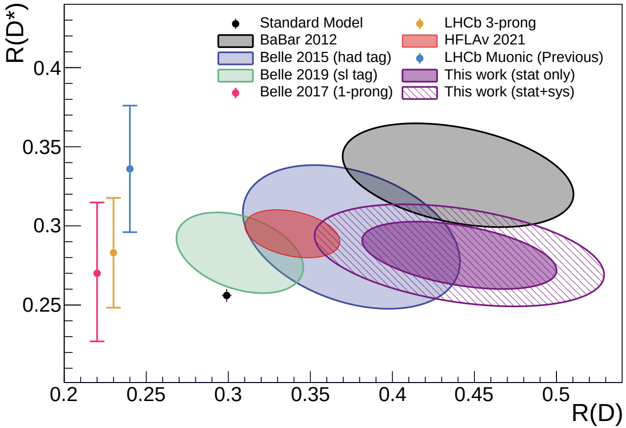
New LHCb measurements test behaviour of the third generation

Of the constraints on new physics, those from quark flavour physics, such as CP violation and mixing measurements, are particularly stringent with mass scale sensitivity up to 1000 TeV. The fact that the flavour sector has been consistent with the Standard Model (SM) therefore suggests that new physics is too heavy to solve the hierarchy problem.

However, this mass scale sensitivity assumes that new physics couples equally to the three generations of fermions. If the flavour structure of new physics is non-trivial, such a hierarchical coupling to the three generations, then the largest sensitivity is in decays involving third generation fermions such as the beauty quark and τ lepton.

The decays $b \to c\tau\nu_\tau$ are particularly interesting in this regard as they contain three third generation fermions and the decay rate can be reliably predicted in the SM due to their semileptonic nature. The LHCb collaboration has recently presented a new test of these decays by comparing the decay rate of transitions involving the τ lepton and the muon via so-called lepton universality ratios, $R(D)$ and $R(D^*)$.

The latest result from the LHCb collaboration measures the $R(D^0)$ ratio for the first time, which compares the $B \to D\tau\nu_\tau$ and $B \to D\mu\nu_\mu$ decay rates. This particular observable



Measurements of R(D) and $R(D^*)$ *along with the SM prediction shown in black. The single measurements of* $R(D^*)$ *are shown as the coloured data points whereas the joint measurements including* $R(D)$ *are shown as ellipses.*

is more complicated than existing LHCb measurements as the D meson is a ground state particle, meaning that there is much more background from excited states such as D^* mesons.

The τ lepton is reconstructed via the decay $\tau \to \mu\nu_\mu\nu_\tau$, meaning that the muonic and tauonic decays have the same final state which cancels systematic uncertainties associated with the efficiency. The main challenge is therefore to control for the background, as it cannot be easily distinguished from signal due to the presence of multiple neutrinos in the final state. The analysis is performed by fitting a three-dimensional distribution of kinematic variables which discriminate the signal from the background. Such variables include the energy of the final state lepton and the mass of the system of missing particles. Isolation criteria against additional particles is crucial to reduce the background. This criteria is extensively used to create control samples which are vital to verify that the background is under control.

The results of the new measurement is shown in the figure, along with previous results. The measurement is shown as a purple ellipse, and is around two standard deviations from the prediction based on the Standard Model shown in black. The combination of results, shown in red, is around three standard deviations from the SM. The discrepancy from the SM hints to towards new particles at the TeV scale which preferentially couple to third generation fermions. Clarifying this situation is of the main goals at UZH group in the future.

Highlighted Publications:

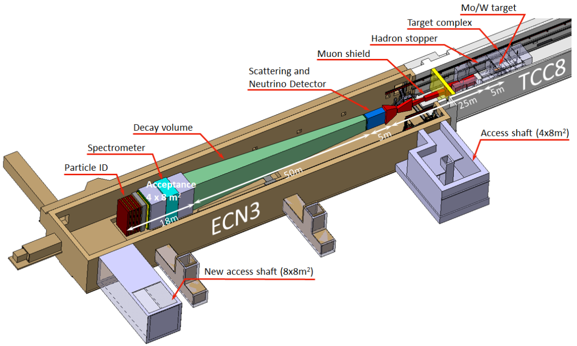
1. All LHCb publications: lhcb.web.cern.ch/lhcb/
2. Measurement of the ratios of branching fractions $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$,
   LHCb Collab., arXiv:2302.02886

SHiP

Prof. Nicola Serra

Our group is one of the main proponents of the SHiP (Search for Hidden Particles) experiment, which is a beam dump experiment at the SPS of CERN aiming to search for Feebly Interacting Particles (FIPs). These particles are predicted by several extensions of the Standard Model explaining Dark Matter.

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



Possible implementation of SHiP at the ECN3 experimental area.

SHiP implementation at ECN3

While there are some anomalies in flavour physics from the Standard Model, it is not clear yet if this is a genuine sign of physics beyond the Standard Model and no new particles have been observed in direct detection experiments (ALTAS and CMS). For these reasons, models predicting FIPs to explain Dark Matter are now attracting large attention in the particle physics community. For this reason, now CERN is considering a possible implementation of SHiP at the ECN3 experimental area, shown in the Figure, for which there is competition with another alternative proposal. A dedicated task force has been created at CERN to evaluate the feasibility and physics case of the different proposals. The result of the process will be known by the end of 2023. Prof. Serra is coordinating the physics studies of the SHiP experiment and the group is playing a crucial role in this area.

SND@LHC

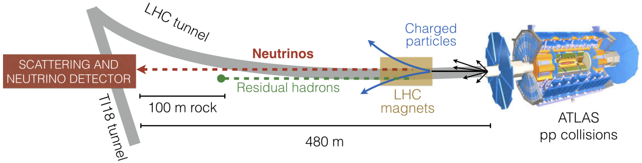
Prof. Nicola Serra

The 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 detector is located in the tunnel, $\sim 480\,\text{m}$ away from the interaction region of the ATLAS experiment (see Figure), and covers the forward pseudo-rapidity region $7.2 < \eta < 8.4$, where neutrinos are mostly produced from charmed hadrons. Measuring neutrinos at these unprecedented energies and rapidities provides crucial constraints on the production of heavy flavours, and in turn to the parton density function of the gluon at very small x values ($x < 10^{-6}$), currently limited by large theoretical uncertainties. These improved constraints are an essential benchmark for the realisation of Future Colliders and the understanding of astrophysical neutrino sources.

Our group is deeply involved in the experiment since its early days, initially contributing to preparing the experiment proposals and coordinating calibration test beams. It has also designed and built the detector's hadronic calorimeter and muon system.

With the start of Run3, the group has taken a leading role in analysing the first collected data, intending to perform the first observation of collider neutrinos at the LHC. The analysis results have been recently presented at the *57th Rencontres de Moriond - 2023*, and a dedicated publication will soon appear.



Location of the SND@LHC experiment in the LHC complex.

Future Circular Collider (FCC)

Prof. Florencia Canelli

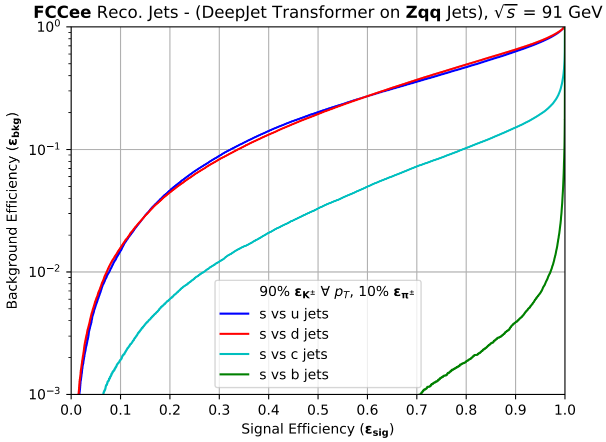
The goal of the Future Circular Collider (FCC) is to greatly push the intensity and energy frontiers of particle colliders and lay the foundations for a new research infrastructure that can succeed the LHC and serve the worldwide physics community for the rest of the 21st century. In the first stage, the FCC-ee, would collide e^+e^- pairs in unprecedented numbers at energies between 90 and 365 GeV.

Since 2021, our group is developing tracking detectors and algorithms for the FCC-ee in collaboration with the Vrije Universiteit Brussel (Belgium), informing the FCC feasibility study ending in 2025.

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

The successful identification of hadronic final states is an essential ingredient in exploiting the physics potential of collider experiments. At the FCC-ee the clean environment which is free of effects such as QCD ISR and PDFs, means that the identification of jet flavour (*flavour tagging*) is much more straightforward than at the (HL-)LHC, and is thus expected to improve considerably. Strange quark jet discrimination, for instance, would enable the first ever study of the $Z \to ss$ production, rare Higgs boson decays and the strange Yukawa coupling, CKM matrix elements via W decays, and BSM physics scenarios such as FCNCs. We have implemented a multiclassifier neural network using a transformer-based architecture [1] for flavour tagging at the FCC-ee [2]. Using a transformer architecture means that the network is highly parallelizable during training, which is of utmost importance when evaluating different potential detector configurations. The network has achieved state-of-the-art strange quark discrimination (see figure) and we will use it as a springboard to evaluate the feasibility of novel physics measurements and the required detector performance.

The most crucial element of FCC-ee experiments for flavour tagging is the innermost vertex detector. To provide the best possible position and momentum resolution, the



Strange jet classification performance of DeepJetTransformer on 1M $Z \to qq$ *events at 91 GeV center of mass energy.*

amount of material in the vertex detector has to be limited to the absolute minimum. We aim to achieve this using ultrathin Monolithic Active Pixel Sensors (MAPS) developed in the 65nm process. We are working together with the ALICE ITS3 collaboration, IPHC Strasbourg and other partners to test two kinds of test structures of such pixel sensors (APTS and CE-65). This work includes calibrating the sensors at the UZH lab and studying them at test beam facilities to discern which pixel structure best suits the FCC-ee requirements.

Our group also works on implementing one of the proposed vertex detector designs in full simulation using the common key4hep/DD4hep software frameworks to study its performance. We will also compare the performance a detector designed in above mentioned 65 nm technology.

Highlighted Publications:

1. Attention is all you need, A. Vaswani, et al., https://arxiv.org/abs/1706.03762 (1017)
2. Jet-Flavour Tagging at FCC-ee, K. Gautam, https://arxiv.org/pdf/2210.10322.pdf
3. Future Circular Collider - European Strategy Update Documents, M. Benedikt et al., CERN-ACC-2019-0003 (2019)
4. Main deliverables and timeline of the FCC feasibility study, CERN, CERN/3588 (2021)

Cosmology, Astro- and Astroparticle Physics

The XENONnT experiment at LNGS

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 about 90 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 will be used in LIGO/Virgo and for the future LISA mission and the Einstein Telescope project.

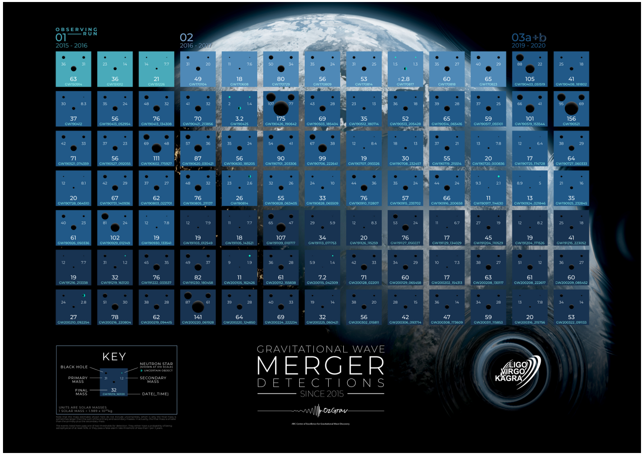
https://www.physik.uzh.ch/g/jetzer

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 these international collaborations. In the following we briefly describe some results published in 2022, besides all the works appeared in the framework of the LIGO/Virgo, LISA Pathfinder and LISA collaborations.

P. Jetzer being co-chair of the LISA Fundamental Physics Working Group (FPWG) coordinated the writing of the LISA Fundamental Physics *white paper*. This paper provides the briefest of reviews to then delineate avenues for future research directions and to discuss connections between the FPWG, other working groups and the consortium work package teams.

Dense astrophysical environments like globular clusters and galactic nuclei can host hyperbolic encounters of black holes which can lead to gravitational-wave driven capture. There are several astrophysical models which predict a fraction of binary black hole mergers to come from these radiation-driven capture scenarios. M. Ebersold, S. Tiwari and collaborators studied the sensitivity of a search toward gravitational-wave driven capture events for the third observing run of LIGO and Virgo.

Neutron stars are known to show accelerated spin-up of their rotational frequency called a glitch. A glitch in an



Gravitational-wave merger detections since 2015. Credit: Carl Knox, OzGrav, Swinburne University of Technology.

isolated neutron star can excite the fundamental (f)-mode oscillations which can lead to gravitational wave generation. This gravitational wave signal associated with stellar fluid oscillations has a damping time of 10 - 200 ms and occurs at the frequency range between 2.2 - 2.8 kHz for the equation of state and mass range considered in the work of D. Lopez, S. Tiwari and collaborators. Electromagnetic observations of pulsars (and hence pulsar glitches) require the pulsar to be oriented so that the jet is pointed toward the detector, but this is not a requirement for gravitational wave emission which is more isotropic and not jetlike. Hence, gravitational wave observations have the potential to uncover nearby neutron stars where the jet is not pointed towards the Earth. The prospects of finding glitching neutron stars using a generic all-sky search for short-duration gravitational wave transients have been studies in this work. The prospects of localizing the direction in the sky of these sources with gravitational waves alone, which can facilitate electromagnetic follow-up, is discussed as well.

Highlighted Publications:

1. New horizons for fundamental physics with LISA,
   K. G. Arun *et al.*,
   Living Rev. Rel. 25 (2022) 1, 4, arXiv:2205.01597.
2. Observational limits on the rate of radiation-driven binary black hole capture events, S. Tiwari *et al.*,
   Phys. Rev. D106 (2022), 104014, arXiv:2208.07762.
3. Prospects for detecting and localizing short-duration transient gravitational waves from glitching neutron stars without electromagnetic counterparts,
   E. Hamilton *et al.*,
   Phys. Rev. D106 (2022), 103037, arXiv:2206.14515.

Theoretical Astrophysics

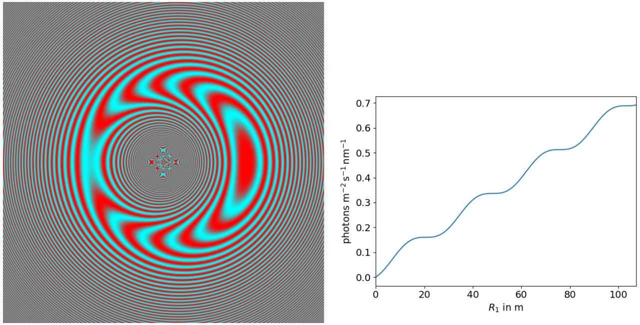
Prof. Prasenjit Saha

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 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 in this area, and recently have contributed to a very futuristic applications of gravitational lensing, namely the so-called solar gravity lens (see Figure).

In other work we have studied the sensitivity of deep-space spacecraft to local dark matter.



Simulations of the view from a spacecraft at 600 au, through the solar gravitational field. Left panel: interferences fringes. Right panel: photon flux at $1\,\mathrm{nm}$ *from a uniform-brightness disc of radius* R_1 *at 1.3 pc emitting* $1\,\mathrm{W\,m^{-2}\,nm^{-1}}$.

Highlighted Publications:

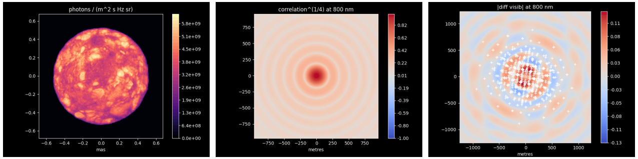
1. Optical properties of the solar gravity lens,
   S. Engeli, P. Saha, MNRAS **516**, 4679–4683 (2022)
2. Prospects for a local detection of dark matter with future missions to Uranus and Neptune,
   L. Zwick, D. Soyuer, J. Bucko, A&A **664**, A188 (2022)

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



Simulations of intensity interferometry with the Cherenkov Telescope Array. The left panel shows a fictitious image of Proxima Centauri (a spoof) which however mimics convection cells on the stellar surface. The middle panel shows the interferometric signal of a uniform disk. The right panel shows the interferometric signature of the surface structure, and representative sampling by the CTA.

Highlighted Publications: Simulations of astrometric planet detection in Alpha Centauri by intensity interferometry,
K. N. Rai, S. Sarangi, P. Saha, S. Basak,
MNRAS **516**, 2864–2875 (2022)

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.

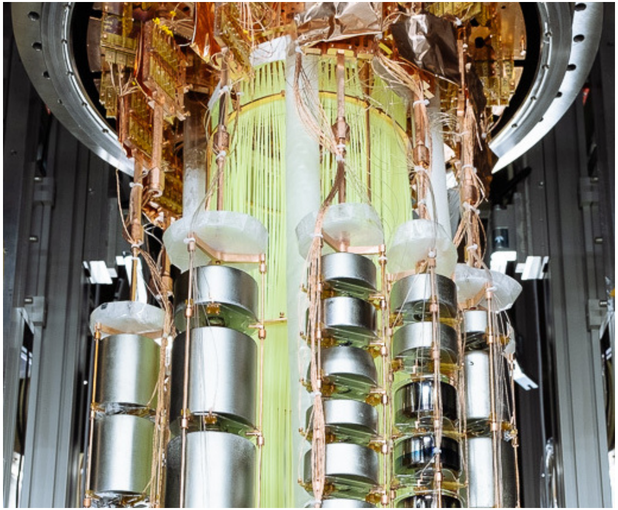
We are members of the **XENON collaboration**, which operates **xenon time projection chambers** to search for rare interactions such as from dark matter, and we lead the **DARWIN collaboration**, with the goal of building a 50 t liquid xenon observatory to address fundamental questions in astroparticle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

The LEGEND experiment aims to probe the neutrinoless double beta decay of ^{76}Ge with a half-life sensitivity beyond $T^{0\nu}_{1/2} > 10^{27}$ y. Based on the very successful GERDA concept, it employs enriched, high-purity detectors operated directly in liquid argon (LAr). An observation of this hypothetical, ultra-rare process could shed light on the imbalance between matter and antimatter in our Universe and on the nature of neutrinos, i.e. whether they are their own antiparticles. Located underground at the Laboratori Nazionali del Gran Sasso, the first phase of the project, LEGEND-200, operates an array of around 200 kg of high-purity germanium detectors isotopically enriched to 90% in ^{76}Ge. The array is submersed in a 64 m^3 cryostat filled with LAr. To collect the vacuum ultraviolet scintillation light from LAr, the volume around the Ge detector arrays is instrumented with wavelength-shifting fibres, which are coated with the WLS compound tetraphenyl butadiene (TPB). The TPB absorbs the VUV light and shifts it to the visible region. The cryostat is surrounded by a 590 m^3



A partial view of the LEGEND-200 high-purity germanium detector array and with the optical fibres and cold electronics.

water tank, acting as a water Cherenkov veto against cosmic muons and also as passive shielding against external radiation coming from the laboratory walls. In the next stage of the project, LEGEND-1000, more than 1000 kg of detector material will be operated, with a sensitivity goal of $T_{1/2}^{0\nu} > 10^{28}$ y.

The stability of the energy response, the energy resolution, and the pulse shape performance of the high-purity Ge detectors must be regularly calibrated with ^{228}Th sources, which emit several gamma-rays in the vicinity of the Q-value of the decay. The source insertion systems were designed and built at UZH, while the custom-made, low neutron emission sources were produced by our collaborators at Los Alamos, New Mexico, following our previous design for GERDA. Our group lead the characterisation measurement and the consecutive analysis of the neutron flux emitted by the ^{228}Th sources, a crucial parameter for their deployment in LEGEND-200. Source-induced neutrons could activate the ^{76}Ge, and the subsequent beta-decay of ^{77}Ge could mimic a signal in the region of interest. Our work revealed only a negligible expected contribution to the background, which will not affect the sensitivity of the experiment [1]. LEGEND-200 recently started its first science run, and the radioactive sources are regularly deployed in the vicinity of the detector array using our source-insertion systems.

Highlighted Publications:

1. Calibration sources for the LEGEND-200 experiment,
   L. Baudis *et al.*,JINST **18** (2022) P02001
2. Search for New Physics in Electronic Recoil Data from XENONnT,
   XENON Collab., Phys. Rev. Lett. **129** (2022) 161805
3. A next-generation liquid xenon observatory for dark matter and neutrino physics,
   J. Aalbers et al., J.Phys.G 50 (2023) 1, 013001

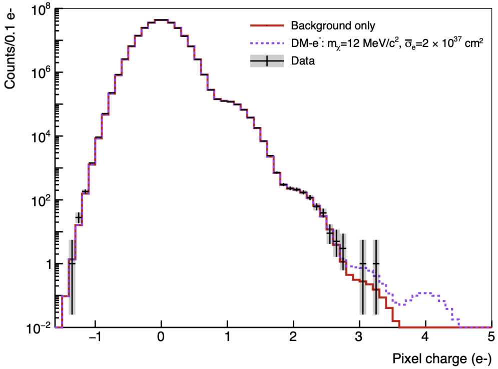
DAMIC Experiment

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 mechanical components, detector control and safety systems, and readout electronics for the next phase, DAMIC-M. In 2022, we collected data with a prototype DAMIC-M detector, and tested unexplored dark matter candidate parameters. The UZH group is also working on new methods of detecting dark matter by measuring the radiation damage caused by nuclear interactions on CCDs.



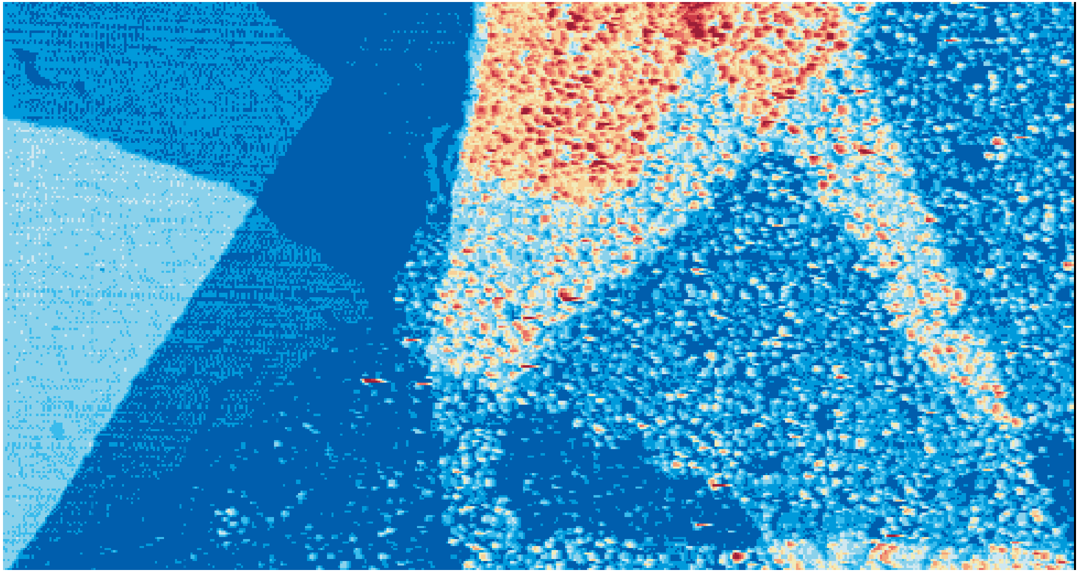
The very good resolution of the CCD detectors allows a dark matter signal that only produces a few electrons to be observed above background. This allows new constraints on the existence of DM with masses between 1 and 1000 MeV/c^2.

The dismantled prototype DAMIC-M experiment, showing layers of polyethylene, lead, and copper shielding. The CCDs are housed in the copper cryostat, with some components produced by UZH.

Highlighted Publications:

1. First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons, DAMIC-M collaboration, https://inspirehep.net/literature/2629764 , accepted by PRL.
2. Analysis of radiation damage in silicon charge-coupled
   devices used for dark matter searches
   Steven J. Lee for the DAMIC-M Collaboration
   14th International Workshop on the Identification of Dark Matter 2022.

Condensed Matter Physics



Tunneling microscopy image of a multilayer boron nitride on a platinum surface. 90x180 nm^2 (Data HY. Cun)

Condensed matter theory

Prof. Titus Neupert

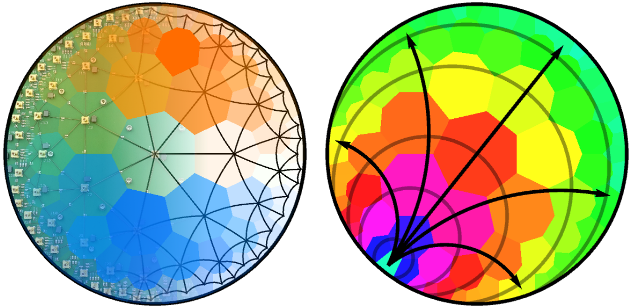
We study **topological phases of quantum matter** with numerical and analytical tools. Topological electronic states are characterized universal and robust phenomena, such as the Hall conductivity in the integer quantum Hall effect, that are of fundamental interest or promise applications in future electronics. 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

Hyperbolic space in the lab

General relativity teaches us that curved spaces are a reality. In condensed matter physics this insight is of little consequence as the scales of gravitation and electrodynamics are too different. Yet, curved spaces make an appearance in other forms — for instance to solve strongly interacting conformal field theories via their holographic correspondence with anti de-Sitter spaces or when compactifying condensed matter models into a finite curved system such as a sphere. However, little is known about how the curvature of space affects common concepts in condensed matter physics, such as band structures of crystal lattices, symmetry breaking phases or topological order.

The condensed matter theory group committed to shed light on these questions through a series of projects, led in particular by Tomas Bzdušek and Patrick Lenggenhager. The specific subject of study were lattice discretizations of homogeneous two-dimensional hyperbolic space, i.e., a sheet with constant negative curvature. In contrast to the positive curvature cousin, the sphere, this space is infinite and cannot be embedded in three-dimensional space, i.e., our observable world. This fact impedes experimental studies of hy-



Left: Overlay of the hyperbolic lattice electrical circuit and a measurement of one of its lowest eigenmodes. Right: Measurement of a wave packet propagating on the hyperbolic lattice, showing the curved geodesics.

perbolic lattices — almost! In a fruitful collaboration with the electronic workshop of the Department of Physics and the group of Ronny Thomale at Ludwig-Maximilians Universität Würzburg, the researchers were able to realize and measure a hyperbolic lattice on a circuit board, where nodes are coupled by capacitors and inductors. The unique opportunity that electric circuits offer is a decoupling between the physical distance of two nodes and the strength with which they interact. The latter is solely determined by the characteristics of the circuit element that connects them. This way, a Poincaré projection of hyperbolic lattice with about one hundred nodes could be mapped on a circuit board. The eigenmodes of the circuit were measured experimentally. They are in some sense analogous to the vibration modes of a "hyperbolic drum", which are distinctly reordered compared to the Euclidean case as a result of the negative curvature. Furthermore, the project studied the wave propagation on the hyperbolic lattice, which follows the curved-space geodesics.

Another project of purely theoretical nature proposed a way to construct topological band structures in hyperbolic space. This was the master thesis of David Urwyler, who received the first edition of the Soluyanov Prize for the best theoretical master thesis for his work for his thesis. Meanwhile the exploration of other aspects of hyperbolic quantum matter is ongoing.

Highlighted Publications:

1. Simulating hyperbolic space on a circuit board;
   P. M. Lenggenhager *et al.*,
   Nature Communications **13**, 4373 (2022)
2. Hyperbolic Topological Band Insulators,
   D. M. Urwyler *et al.*Phys. Rev. Lett. 129, 246402 (2022)
3. Hyperbolic Matter in Electrical Circuits with Tunable Complex Phases,
   A. Chen *et al.* arXiv:2205.05106, accepted in Nature Communications

Superconductivity and Magnetism

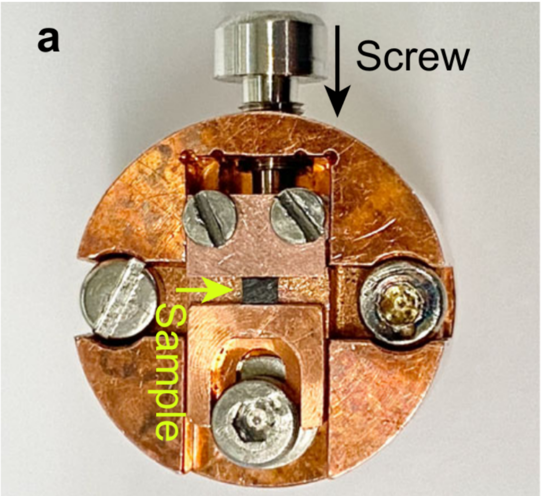
Professor Johan Chang

We investigate **quantum matter phases emerging from strong electronic interactions**. High-temperature superconductivity, strange metals, density-wave instabilities and electronic driven metal-insulator transitions are studied by synchrotron and laboratory based experimental techniques. At international synchrotrons, we are carrying out angle-resolved photo-emission spectroscopy (ARPES) and resonant inelastic x-ray scattering (RIXS) to reveal electronic structures and properties of correlated electron systems. Quantum phase transitions tuned by magnetic field or hydrostatic pressure are furthermore explored by high-energy x-ray diffraction. Within our laboratory, similar themes are probed by electrical and thermo-electrical transport measurements. 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/g/chang

A hallmark of quantum matter is complex phase diagrams reflecting numerous broken symmetries. Strikingly, despite distinct underlying microscopic interactions, phase diagrams are remarkably similar across a large range of material classes. For example, unconventional superconductivity is often found in the vicinity of magnetic quantum critical points around which competing electronic phases emerge. Their respective broken symmetries are often subtle and difficult to reveal experimentally. The difficulty stems from the challenge to lift electronic domain degeneration.

To make progress our team designed and produced with our in house workshop uniaxial pressure cells for x-ray diffraction. Difference designs were developed for respectively resonant (see Figure) and non-resonant x-ray diffraction. It let us to solve a long standing problem about the symmetry of charge stripe order in high temperature cuprate superconductors.



Custom sample holder for the application of uniaxial pressure.

Charge stripe order proven

We investigated the charge order in $La_{1.88}Sr_{0.12}CuO_4$ via x-ray diffraction with uniaxial pressure as a domain-selective stimulus to establish the unidirectional nature of the CDW unambiguously. A fivefold enhancement of the CDW amplitude is found when homogeneous superconductivity is partially suppressed by magnetic field. This field-induced state provides an ideal search environment for a putative pair-density-wave state.

Inducing a stripe order rotation

From a strong-coupling perspective, transverse stripe fluctuations are realized in the form of dynamic "kinks"—sideways shifting stripe sections. In recent work, we show how modest uniaxial pressure tuning reorganizes directional kink alignment. We find that in $La_{1.88}Sr_{0.12}CuO_4$ transverse kink ordering results in a rotation of stripe order away from the crystal axis. Application of mild uniaxial pressure changes the ordering pattern and pins the stripe order to the crystal axis. This reordering occurs at a much weaker pressure than that to detwin the stripe domains and suggests a rather weak transverse stripe stiffness. Weak spatial stiffness and transverse quantum fluctuations are likely key prerequisites for stripes to coexist with superconductivity.

Highlighted Publications:

- Unveiling Unequivocal Charge Stripe Order in a Prototypical Cuprate Superconductor,
  J. Choi *et al.*, Physical Review Letters 128, 207002 (2022)
- Uniaxial pressure induced stripe order rotation in $La_{1.88}Sr_{0.12}CuO_4$,
  Q. Wang *et al.*, Nature Communications 13, 1795 (2022)
- Crystal symmetry of stripe-ordered $La_{1.88}Sr_{0.12}CuO_4$,
  R. Frison *et al.*, Physical Review B 105, 224113 (2022)

Oxide Interface Physics

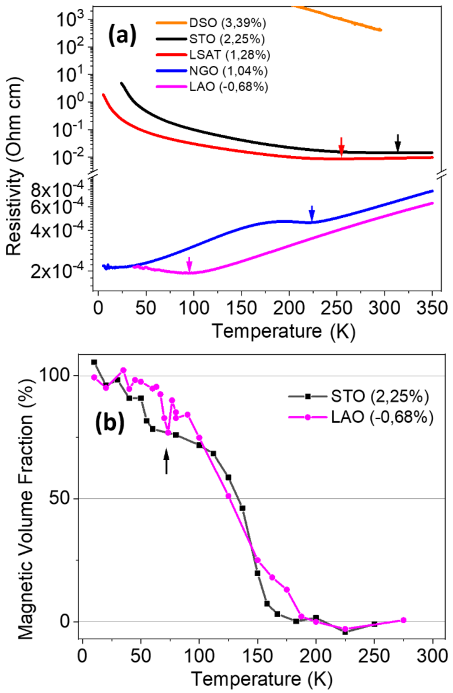
Prof. Marta Gibert

In our group, we grow transition metal oxide heterostructures (i.e. thin films, superlattices) and we investigate their functionalities. We especially focus on the study of the electronic and magnetic properties resulting from reduced dimensionalities and reconstructions occurring at oxide interfaces. Our goal is to understand the subtle atomic-scale structural and electronic mechanisms controlling interface physics in complex oxides. This knowledge is key for the rational design of materials with tailored properties. The atomic-scale precise oxide layers are grown by off-axis rf magnetron sputtering.

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

Transition metal oxides are a fascinating and widely studied class of materials displaying a broad spectrum of physical properties (i.e. metal-insulator transitions, magnetism, superconductivity, etc.), which makes them highly attractive candidates for 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. Furthermore, the possibility of creating thin films and heterostructures, thus imposing strain and low dimensionality, allows these functionalities to be tuned even more and meta-stable phases to be stabilized. The investigation of these types of materials has already proven to be successful. As an example, we recently showed that nickelate films as thin as 2 u.c. (0.8nm) are still ferromagnetic [1].

Currently, our group is studying the $SrCrO_3$ (SCO) compound which is suggested to be an antiferromagnetic metal, an unusual combination of properties. The goal of our investigation is to grow and characterize epitaxial SCO thin films to address its debated physical properties. The difficulties in synthesising this material are explained by the need to stabilize the rare Cr+4 ionized state. Therefore, the growth of SCO thin film by RF magnetron sputtering requires a very low but finite amount of oxygen since an excess or the absence of oxygen leads to un-



(a) Resistivity measurements of 25 uc (10 nm) thick $SrCrO_3$ thin films as a function of temperature and strain. The arrows indicate an upturn in resistivity. (b) Muon spin relaxation measurements for two differently strained SCO samples. The arrow indicates a dip in magnetic volume fraction, possibly caused by a spin reorientation.

wanted structures or poor growth quality. In order to successfully grow SCO film, the existing growth chamber has been modified to allow a very low and precise amount of oxygen (ratio Oxygen-to-Argon: 1/10000) to be injected. In this manner, high-quality SCO films were grown on a variety of substrates imposing compressive and tensile strain. Transport measurements have revealed a metallic phase down to 100K in low-strain films, whereas increasing tensile strain induces a metal-to-insulator transition. Muon spin relaxation measurements revealed a strain-independent magnetic phase at temperatures below 150K. This phase can be associated with an antiferromagnetic spin ordering as no ferromagnetism could be detected. These findings are the first indication of the coexistence of an antiferromagnetic and metallic phase on SCO films. Further magnetoresistance and Hall-effect measurements are ongoing to complete the characterization of SCO films.

1. Top-Layer Engineering Reshapes Charge Transfer at Polar Oxide Interfaces
   G. De Luca *et al.*, Adv. Materials 2022, **34**, 2203071 (2022).

Low dimensional systems

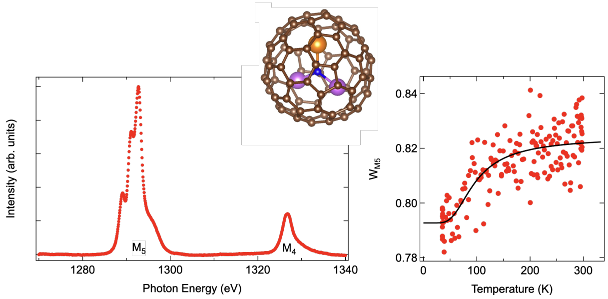
Prof. Thomas Greber

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 2D materials, we grow 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

Orientation of endohedral clusters

Endohedral fullerenes are small atomic clusters encapsulated by a fullerene carbon shell. For the case of $DySc_2N@C_{80}$ Dy turns out to display as a single magnetic ion. At low temperatures Dy^{3+} may maintain the orientation of the magnetic moment for hours. The orientation follows the ligand field and thus the Dy-N bond axis. Given this single-molecule magnet behavior, it is vital to know the Dy-N bond axis orientation in space. This orientation can be obtained from resonant x-ray absorption spectroscopy (XAS) experiments and comparison to multiplet calculations for different Dy-N orientations relative to the x-ray polarisation vector. The figure shows XAS data of $DySc_2N@C_{80}$ on a platinum surface. The spectral weight of the Dy M_5 edge depends on temperature. Since multiplet theory predicts different weights of the Dy M_5 edge as a function of the angle between the x-ray incidence and the Dy-N axis this indicates that the experiment is sensitive to the endohedral orientation, which is isotropic at room temperature and which shows a tendency of Dy-N axis



X-ray absorption spectrum at the Dy $M_{4,5}$ *edge of* $DySc_2N@C_{80}$ *on a Pt(111) surface (left). The spectral weight of the* M_5 *edge* W_{M5} *depends on the temperature and indicates the onset of endohedral rotation at about 90 K. The solid line is a thermodynamic model that describes the endohedral motion (right panel). The inset depicts one endohedral fullerene molecule with a diameter of 1.1 nm. Dysprosium yellow, nitrogen blue. Data R. Sagehashi et al.*

orientation parallel to the surface at low temperature. This shows that x-ray absorption experiments allow highly sensitive in-operando studies of the orientation of endohedral clusters.

The experiments were performed at the photoemission and atomic resolution laboratory (PEARL) bending magnet beamline at the Swiss Light Source. The project is a collaboration with the Institut für Festkörper- und Werkstoffforschung IFW in Dresden, the Chiba University, and the Paul Scherrer Institut in Villigen.

Highlighted Publications:

1. The Winner Takes It All: Carbon Supersedes Hexagonal Boron Nitride with Graphene on Transition Metals at High Temperatures
   A. Hemmi *et al.*, Small **18**, 2205184 (2022)
2. X-ray absorption measurements at a bending magnet beamline with an Everhart-Thornley detector: A monolayer of $Ho_3N@C_{80}$ on graphene
   W. C. Lee *et al.*, J. Vac. Sci. Technol. A **40**, 053205 (2022)
3. Synthesis of a magnetic π-extended carbon nanosolenoid with Riemann surfaces
   J. Wang *et al.*, Nature Comm. **13**, 1239 (2022)

Correlated Quantum Matter

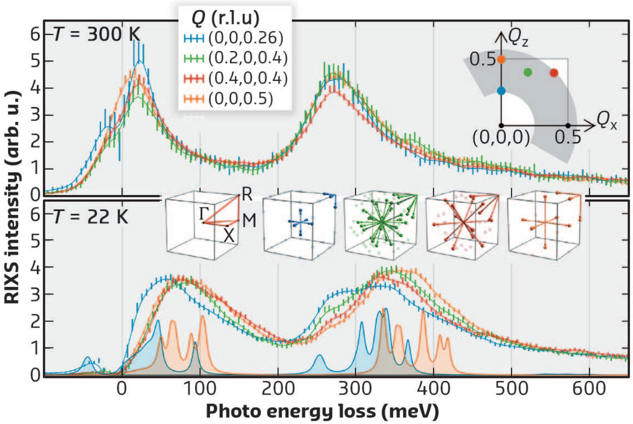
Prof. Marc Janoschek

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

New insights on the Kondo Lattice Problem

Effective low-energy models are a corner stone of solid state physics and have been instrumental in the qualitative understanding of collective electronic behavior in quantum materials. For example, the Kondo model—an iconic example of an effective low-energy model—was key to shedding light on the entanglement of localized and itinerant electronic degrees of freedom in strongly correlated metals. The interplay of these two opposing limits of electronic behavior is a reoccurring theme found at the heart of many quantum matter states ranging from unconventional superconductivity to correlated topological states of matter.

Despite the success of the Kondo lattice model, recent state-of-the-art electronic structure calculations indicate that quantitative and material-specific modelling of quantum matter states can only be achieved if high-energy degrees of freedom such as crystal field and spin-orbit interactions are included. Experimentally, however, it remained unclear how local high-energy degrees of freedom are incorporated into a collective electronic state. To overcome this challenge we employed resonant inelastic x-ray scattering (RIXS) on the prototypical Kondo lattice material $CePd_3$ to elucidate the role of all relevant energy scales. We find that even spin-orbit ex-



Emergent Kondo coherence in $CePd_3$. At room temperature (top), the RIXS response is isotropic. The momentum dependence at low temperature (bottom) showcases the incorporation crystal field and spin-orbit states into the coherent metallic state.

cited states at 500 meV develop a pronounced momentum-dependence at low temperature signaling their incorporation into the underlying coherent metallic state (see Figure). Our study demonstrates how localized electronic degrees of freedom endow correlated metals with novel properties.

Emergent magnon Landau levels in a skyrmion lattice

An electrically charged particle moving perpendicular to an applied magnetic field experiences a Lorentz force. In quantum mechanics, the resulting circular motion is quantized in discrete energy values known as Landau levels. In a two-dimensional electron gas, this quantum Hall effect is characterized by the formation of topological electronic bands with a finite Chern number. An analogy to the quantum Hall effect should also exist in the spin channel; for example, when the spin of a moving particle adiabatically follows the local magnetization of a topological spin texture, such as a skyrmion lattice, the inherent geometrical properties give rise to an emergent magnetic field, B_{em}, and an emergent Lorentz force. However, to date, probing the associated magnon Landau levels is a formidable experimental challenge as they are separated by energies on the order of 10 μeV. Using a novel state-of-the-art neutron spectroscopy method—so called MIEZE (modulated intensity with zero effort)— we resolve magnon Landau levels in the prototypical skyrmion lattice material MnSi for the first time.

Highlighted Publications:

1. Topological magnon band structure of emergent Landau levels in a skyrmion lattice,
   T. Weber, *et al.*, Science 375, 6584 (2022)
2. Kondo quasiparticle dynamics observed by resonant inelastic x-ray scattering,
   M. C. Rahn, *et al.*, Nat. Comm. **13**, 6129 (2022)

Quantum Matter

Prof. Fabian Natterer

Our group investigates the properties of low-dimensional quantum materials. We explore how materials receive their properties from the interaction between individual atoms and molecules that we control with atomic precision. We also study how to tune a material's electronic structure by the application of strain, doping, temperature, and magnetic fields. We spatially map the material's electronic structure using customized scanning probe microscopy techniques, such as electron spin resonance, pump-probe spectroscopy, and fast quasiparticle interference imaging.

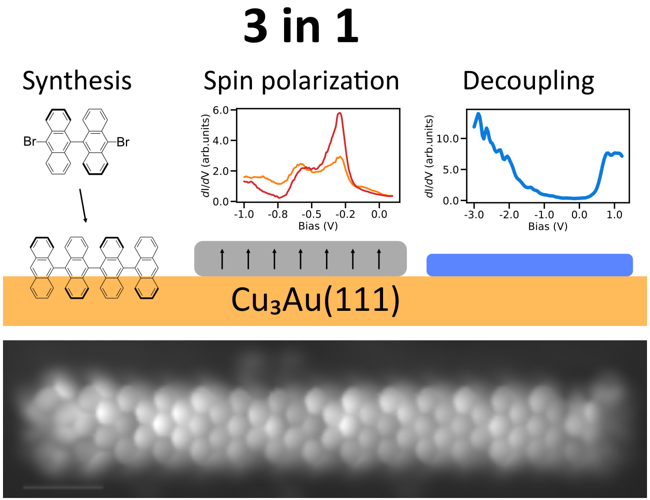
https://www.physik.uzh.ch/g/natterer

A versatile platform for graphene nanoribbon synthesis, electronic decoupling, and spin polarization

We demonstrate how to obtain spin-polarized sensitivity, electronic decoupling, and efficient Ullman coupling on the same platform Cu3Au for the advanced study of open shell hydrocarbon and magnetic molecules. This work is a key component for our goal to realize a universal quantum sensor in which we intend to connect a molecular magnetometer to the tip of our scanning tunneling microscope. By mapping how the local environment modifies the magnetic structure of the molecule-on-tip using STM based electron spin resonance, we can identify the magnitude and coordinates of local moments with atomic resolution. In addition to sensing via electrical current, we also built an optical readout scheme for electro-luminescence measurements. Our sensor on-tip concept will illuminate the atomic-scale origin and properties of radicals, quantum matter by design, and noncolinear magnetic structures.

Electronic Structure Mapping of 2D Materials

We infer the band structure of two dimensional quantum materials with quasiparticle interference imaging (QPI). QPI works by measuring the point spectroscopy (local density



The combination of spin-polarization, electronic decoupling, and synthesis of carbon based molecules, enables the study of open-shell systems in their pristine form. The decoupling improves the spin-relaxation times with potential access to exploit the coherent properties of free radicals for advanced quantum sensing applications.

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 recording. In combination, we achieve three orders of magnitude faster mapping, which reduces a week-long measurement to few minutes. Our fast mapping enables previously inconceivable measurement protocols, such as studying a material near and across a critical point to which we tune it via a customized uniaxial strain cell. To make our measurements even more efficient, we use adaptive sparse sampling concepts that enable prior-free measurements and provide the experimenter with immediate feedback to the electronic structure and quality of their measurements.

Highlighted Publications:

1. A. Cahlík *et al.*,
   A versatile platform for graphene nanoribbon synthesis, electronic decoupling, and spin polarized measurements,
   Nanoscale Adv. (2023), doi:10.1039/D2NA00668E.1.
2. J. Oppliger *et al.*,
   Adaptive Sparse Sampling for Quasiparticle Interference Imaging,
   MethodsX. 9, 101784 (2022).

Phase Transitions, Materials and Applications

Prof. Andreas Schilling

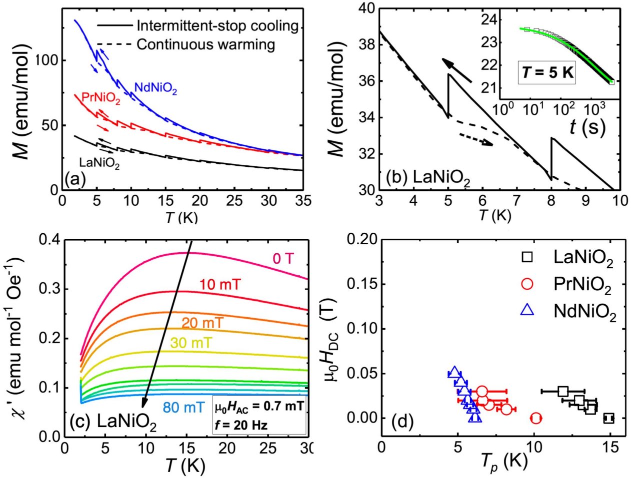
We are interested in selected topics in materials research, spanning the entire spectrum from **searching new materials**, their **characterization**, and corresponding **applications**. We have been particularly active in **superconductivity, magnetism and thermodynamics**. Our laboratory is equipped with modern furnaces for material synthesis, various ^{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. While the physics of thin-film superconductors is a fascinating research topic by itself, corresponding nanostructures may serve as ultrafast single-photon detectors in the infrared, visible and X-ray range.

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

Universal spin-glass behavior in bulk $LaNiO_2$, $PrNiO_2$ and $NdNiO_2$

Motivated by the recent discovery of superconductivity in doped infinite-layer nickelate thin films, we have synthesized and studied bulk samples of the so-called "parent compounds" RNiO$_2$ (R = La, Pr, Nd). The synthesis of these compounds with a square-planar arrangement of the Ni-O atoms is achieved by topochemical reduction of RNiO3 grown under high oxygen pressure, to RNiO$_2$. In Fig. (a) we show evidence for the spin-glass behaviour of all RNiO$_2$ samples provided by the presence of a distinct magnetic memory effect. Memory-effect measurements were performed using two different protocols, an "intermittent stop cooling process" (ISC-process) followed by a continuous warming process. At first, the sample is cooled in a magnetic field of 5 mT with intermittent stops at certain temperatures where the external field was switched off for 80 min and then switched back, followed by a further cooling down. At 1.8 K, the samples were



Magnetic memory effect [(a) and (b)], field dependence of the peak in the AC susceptibility of LaNiO$_2$ (c), and resulting spin-freezing temperatures of RNiO$_2$ (d).

warmed continuously to room temperature. The resulting magnetization data show distinct features at the previous stopping temperatures, and therefore reflect the magnetic history of the previous ISC-process. Furthermore, the magnetic-field dependence of the AC susceptibility χ (shown in Fig. (c) for LaNiO$_2$ as an example), reveals that the peaks in χ are significantly suppressed with increasing DC magnetic field and may even vanish in moderate fields of the order of 1 T or even less. The corresponding peak temperatures, and along with them most likely the spin freezing temperatures, decrease rapidly as it is usually observed in spin glasses (Fig. (d)).

Based on all our collected data, we suggest that the universal spin glass behaviour in bulk RNiO$_2$ compounds may be due to off-stoichiometric oxygen or even to an intrinsic magnetic frustration, rather than to impurities or weak crystallization. They exhibit a similarly slow spin dynamics as Pr$_4$Ni$_3$O$_8$ that we had studied last year, although with an almost one-order-of magnitude lower spin-freezing temperature.

Highlighted Publications:

1. Universal spin-glass behavior in bulk LaNiO$_2$, PrNiO$_2$ and NdNiO$_2$,
   H. Lin *et al.*, New. J. Phys. **24**, 013022 (2022)
2. Suppression of the transition to superconductivity in crystal/glass high-entropy alloy nanocomposites,
   X. Zhang *et al.*, Commun. Phys. **5**, 282 (2022)

Coherent Diffraction Imaging

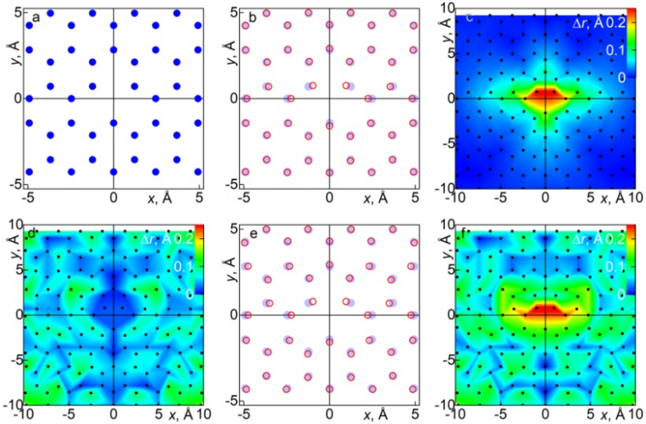
PD. Tatiana Latychevskaia (Paul Scherrer Institut)

We develop lens-less imaging methods towards high-resolution and three-dimensional imaging of nano-scaled objects, two-dimensional materials (graphene, TMDs, etc) and macromolecules. Coherent diffraction imaging (CDI) 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

Our current activities include:

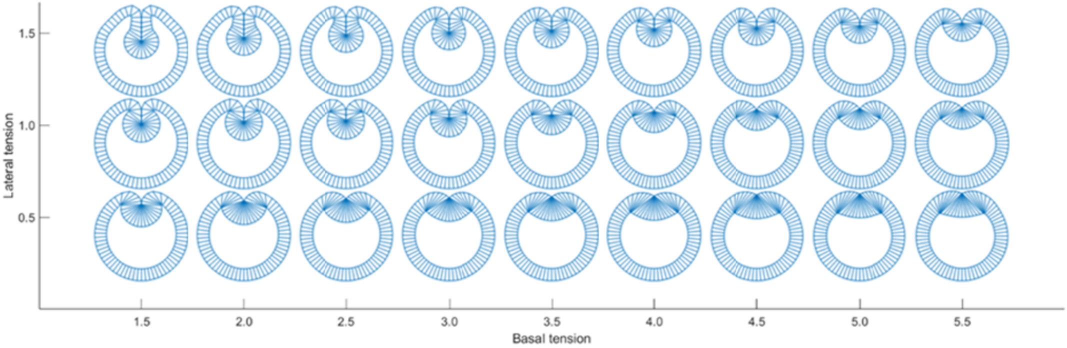
1. Convergent beam electron diffraction (CBED) of two-dimensional materials (graphene) and nano-scaled objects such as individual macromolecules [1];
2. Light optical experiments for design and testing novel imaging techniques (holography, coherent diffraction imaging, ptychography, etc) [2];
3. Theoretical study and simulations of wave-matter interaction at atomic scale: effects of the probing wave coherence, multiple scattering, etc [3];
4. Developing novel imaging techniques for high-resolution (atomic-resolution) and three-dimensional reconstruction of samples' structures from their diffraction patterns [4];



Atomic displacements in graphene with a single defect reconstructed by iterative phase retrieval from a convergent electron beam diffraction (CBED) pattern. (a) Positions of atoms in a lattice without relaxation, also shown as blue circles in (b) and (e). (b) Relaxed positions of atoms (red circles). (c) - (d) Difference between the atomic positions in the relaxed lattice and (c) lattice without relaxation, (d) the reconstructed lattice. (e) Reconstructed positions of the atoms around a defect (red circles). (f) Difference between the atomic positions in the lattice without relaxation and the reconstructed lattice [1].

1. Imaging defects in two-dimensional crystals by convergent beam electron diffraction,
   T. Latychevskaia, P. Huang, and K. S. Novoselov,
   Phys. Rev. B **105** 184113 (2022)
   doi:10.1103/PhysRevB.105.184113
2. Fourier Transform Holography: A lensless imaging technique, its principles and applications,
   S. Mustafi, and T. Latychevskaia, Photonics **10** (2), 153 (2023) doi:10.3390/photonics10020153
3. Potentials of individual atoms by convergent beam electron diffraction,
   T. Latychevskaia *et al.*, Carbon **201** 244–250 (2023) doi:10.1016/j.carbon.2022.09.003
4. Low-dose shift- and rotation-invariant diffraction recognition imaging,
   T. Latychevskaia, and A. Kohli, Sci. Rep. **12** (1), 11202 (2022) doi:10.1038/s41598-022-15486-y

Bio and Medical Physics



Simulation of basal and lateral tension in Drosophila embryo (from http://dx.doi.org/10.2139/ssrn.4100997)

Disordered and biological soft matter

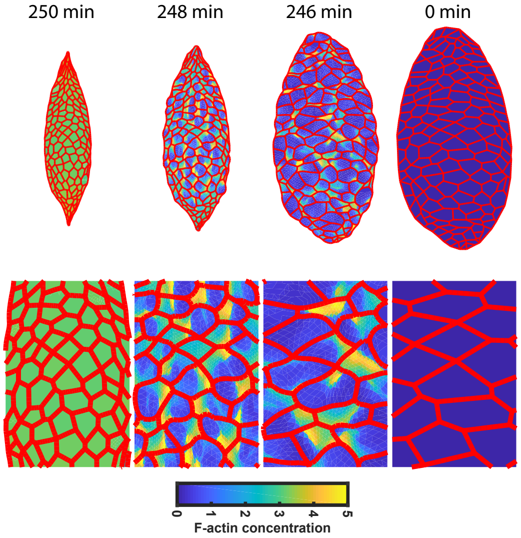
Prof. Christof Aegerter

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 the regeneration of zebrafish fins or the process of dorsal closure in drosophila embryos. 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 Dorsal Closure in Drosophila embryos

Tissue morphogenesis integrates cell type-specific biochemistry and architecture, cellular force generation and mechanisms to coordinate these forces amongst neighbouring cells and tissues. Here, we use finite element-based modelling to explore the interconnections at these multiple biological scales in the developmental process of dorsal closure, where pulsed actomyosin contractility in adjacent Amnioserosa (AS) cells powers the closure of an epidermis opening. We cross the different scales by modelling the biochemical regulations as well as the visco-elastic tissue properties in the same finite element framework, with cells distributions based on direct observations in vivo. Furthermore, we base the input of our biochemical regulation model on in vivo observations by our collaborators, for instance implementing F-actin nucleation periodicity that is independent of MyoII activity. Given these few and well established regulatory mechanisms, our model can reproduce several emergent properties of the dorsal closure process, such as the tissue closure or the arrest of cell pul-



Snapshots of the simulation at different times showing both the contraction of the AS tissue as well as the increase in F-actin concentration during the process of dorsal closure.

sations. This questions the previously proposed role of Dpp-mediated regulation of the patterned actomyosin dynamics in the AS tissue, suggesting them to be emergent. Moreover, the model also shows how depleting MyoII activity can under certain conditions nevertheless indirectly affect oscillatory F-actin behaviour without the need for biochemical feedback. The model further predicts that the mechanical properties of the surrounding epidermis tissue feed back on the shaping and patterning of the AS tissue again showing, how multiple scales interact to produce the observed final process. Finally, our model's parameter space can reproduce mutant phenotypes and provides predictions for their underlying cause due to the identification of the different parameters with biological processes. Our modelling approach thus reveals several unappreciated mechanistic properties of tissue morphogenesis and lays the ground for an experimental investigation of these identified causes by developmental biologists.

Highlighted Publications:

1. In-vivo force measurements of MyosinII waves the yolk surface during Drosophila dorsal closure,
   L.Selvaggi *et al.*,Biophysical Journal **121** (2022),
   https://doi.org/10.1016/j.bpj.2021.12.038
2. Mechanochemical modelling of dorsal closure emergent cell behaviour and tissue morphogenesis,
   F. Atzeni *et al.*, bioRxiv 2020.01.20.912725,
   https://doi.org/10.1101/2020.01.20.912725
3. Stochastic Resonance in Noisy Optical Resonators Modeled Through Coupled-Mode Theory,
   V. Mazzone and C.M. Aegerter, Communications in Nonlinear Science and Numerical Simulation (2022),
   http://dx.doi.org/10.2139/ssrn.4312925

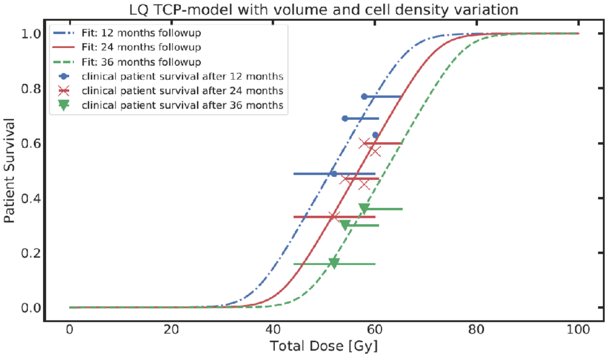
Medical Physics and Radiation Research

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

Tumor control probability (TPC) models based on Poisson statistics characterize the distribution of surviving clonogens, thus enabling the calculation of the TCP for individuals. To mathematically describe clinically observed survival data of patient cohorts it is necessary to extend the model. This is typically done by using an empirical logistic model. We developed an analytical population TCP model by establishing a mechanistic link between the Poisson statistics based individual and the logistic TCP model. This link can be used to determine the radiobiological parameters of patient specific TCP models from published fits of logistic models to cohorts of patients.



Fitting clinical patient survival with extended TCP population model incorporating tumour volume and cell density variations within a patient population.

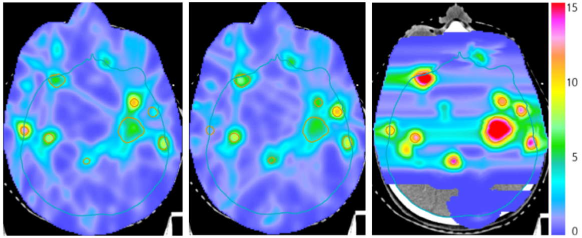
Tumour volume distribution can yield information on ...
U. Schneider, J. Besserer *et al.*
Z Med Phys. 2022 Jun 9:S0939-3889(21)00053-2

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. Our research group contributes to the 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.
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.
3) Adaptive radiotherapy: The MR-Linac, a combination of MRI scanner and radiotherapy device allows MR imaging of a patient during treatment. We work on innovative concepts to use the technology, e.g. MR-only workflows [1] and the concept of adaptive fractionation [2].



Combined proton-photon radiotherapy for a patient with many brain metastases treated with one proton fraction (right panel) and two photon fractions. The superior proton dose distribution is exploited by delivering larger doses.

1. M. Lapaeva *et al.*, Phys Imaging Radiat Oncol. 2022 Nov 28;24:173-179
2. Y. Pérez Haas *et al.* Phys. Med. Biol., 19;68(3), 2023

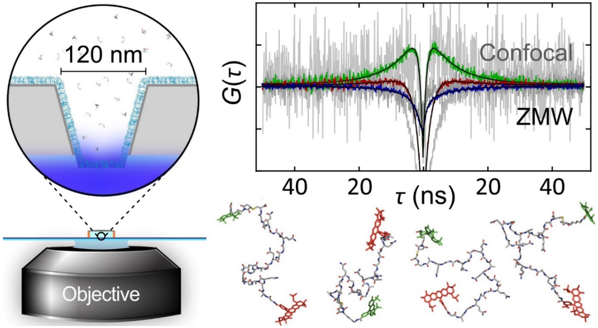
Molecular Biophysics

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

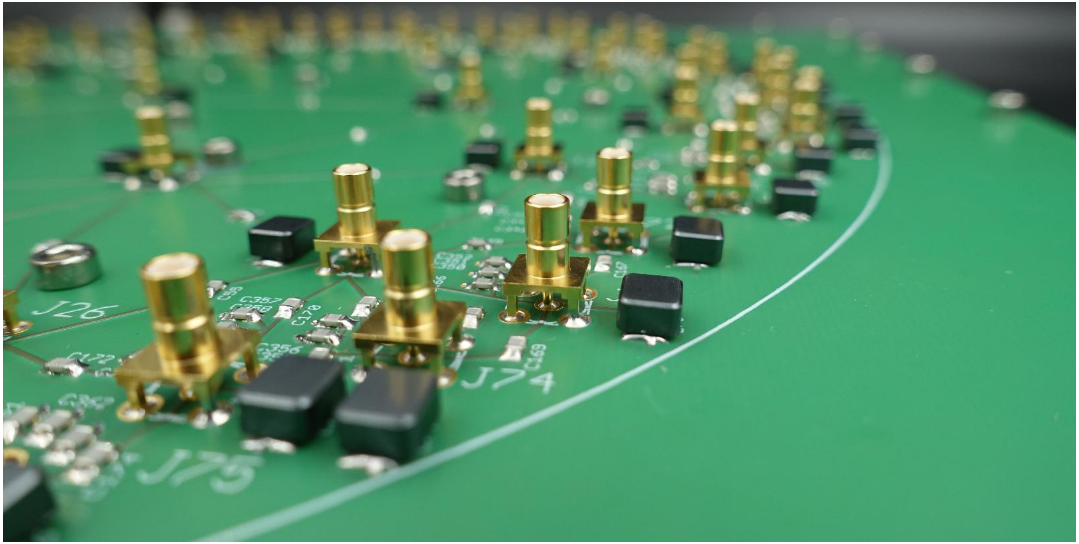
We recently started employing nanophotonics to enhance the fluorescence emission of single molecules, which allows us to probe previously inaccessible nanosecond motion in proteins and directly compare to molecular dynamics simulations [1] (see Figure). An interesting discovery was a new molecular mechanism of protein interactions that is important for regulating DNA [2].



Zero-mode waveguides nanofabricated in thin aluminium layers enhance fluorescence emission to a level that ultrafast motions within proteins become detectable with nanosecond correlation spectroscopy. Snapshots from computer simulations illustrate some of the myriad molecular configurations.

1. Single-molecule detection of ultrafast biomol. ...
   M. F. Nüesch *et al.*, J. Am. Chem. Soc. **144**, 52-56
2. Release of linker histone from the nucleosome ...
   P. O. Heidarsson *et al.*, Nat. Chem. **14**, 224-231

Workshops

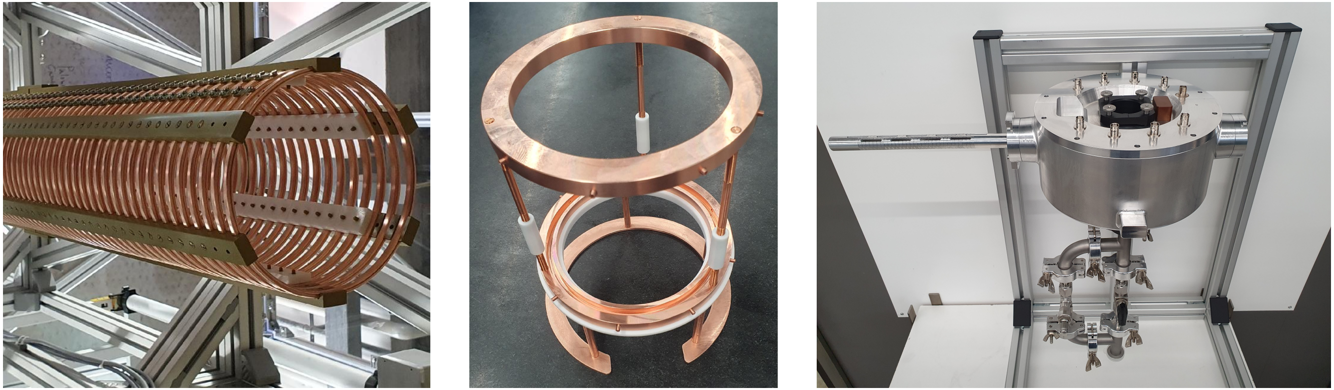


Circuit that simulates the dynamics of wave propagation in a hyperbolic space.

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.

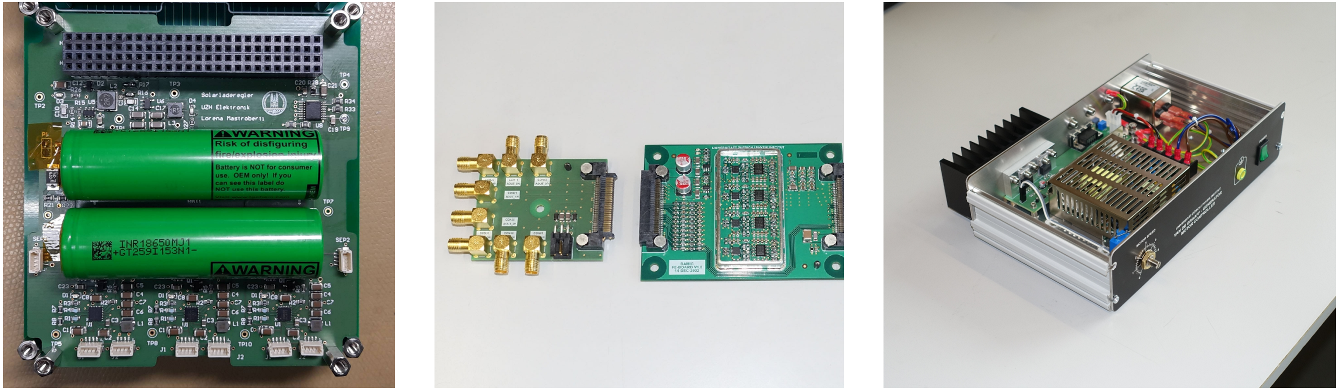
https://werkstatt.physik.uzh.ch



The three photograph are examples for work done in our workshop: (left) the TPC for the DARWIN demonstrator (group Baudis); (middle) the GATOR screening facility to verify the quantum mechanical Pauli principle (group Baudis); (right) the nanodosimeter that is used for the measurement of individual ionizations to quantify biological damage caused by radiation (group Schneider).

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 frontend board for DAMIC-M with adapters and four AC-coupled signal amplifiers for the processing of the CCD signals (middle figure). The local control of the power supply of the amplifiers as well as various low pass filters for the control signals and supply voltages of the CCD are also on the board.



Left: 6-channel solar-powered battery charge controller for a potential mini-satellite application. This was the final practial work of the apprentice Lorena Mastroberti. Middle: frontend board for DAMIC-M. Right: Drivers for the Van De Graaff generators used in a lecture hall experiment. Load changes, which are caused by the charge shifts, can be visualized directly by the motor speed.

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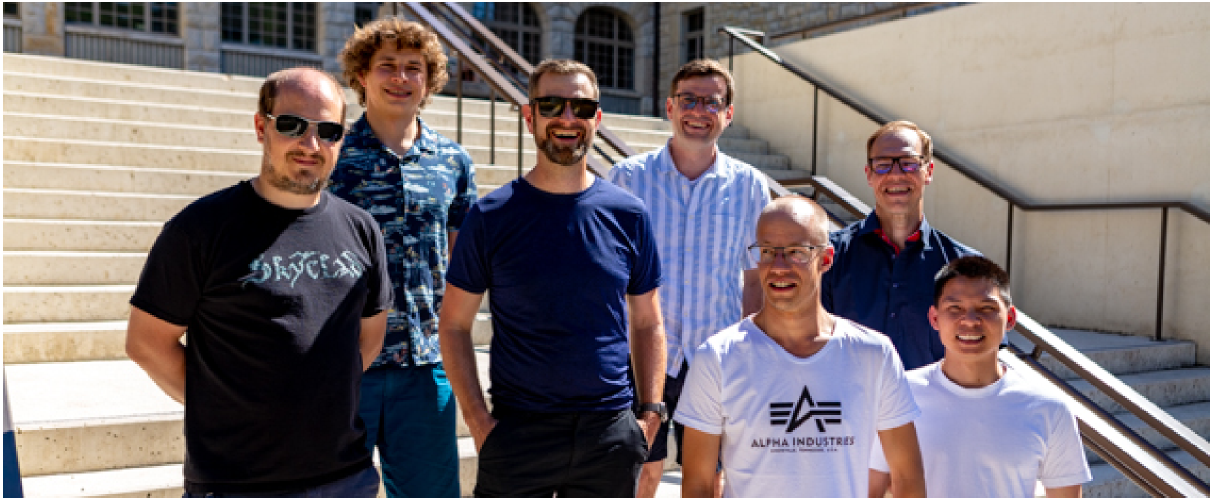

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Prof. Dr. Peter Stoffer


FEHLMANN
PICOMAX
USZ
Synthetic CT generation using generative adversarial networks for MR-only radiotherapy

University of Zurich
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Front: Assembly of the DARWIN demonstrator Xenoscope in the assembly hall of the physics department