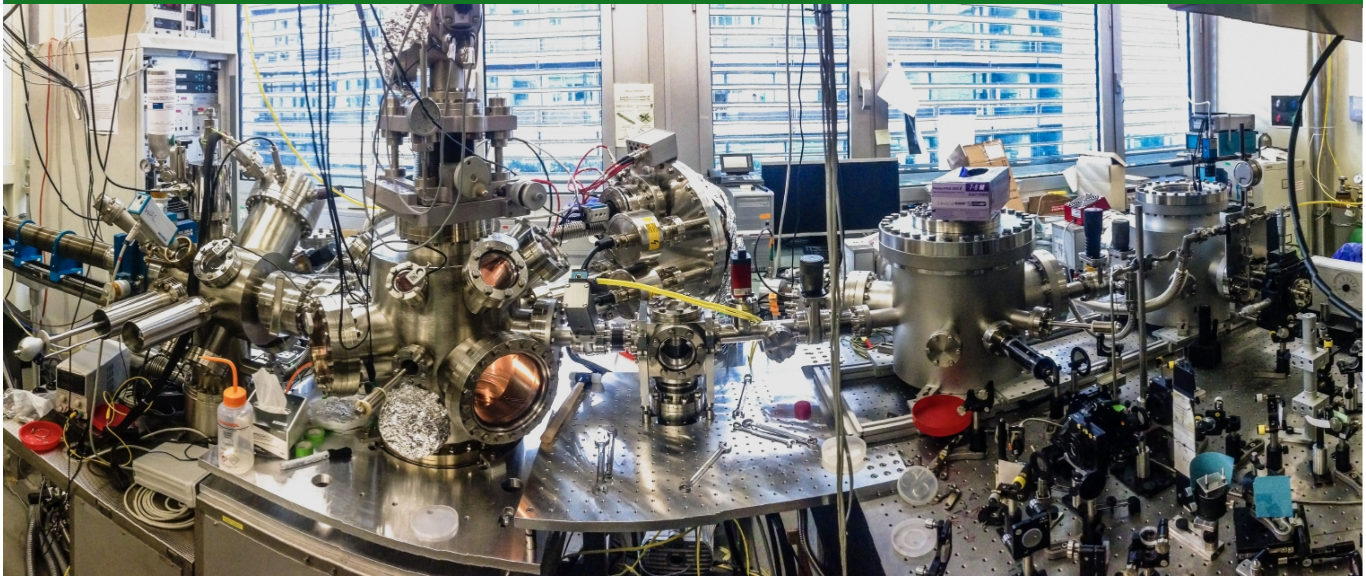
University of Zurich[UZH]

Department of Physics

Annual Report and Highlights 2020



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Department of Physics

Annual Report and Highlights 2020

Winterthurerstrasse 190, CH-8057 Zurich, Switzerland

Preface

Thomas Gehrmann, Department Head

With a total of 22 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 2020 posed an enormous set of challenges onto our department. With the Covid19-related lockdown in mid-March all teaching activities were moved to a purely online modus in record time, and most of the laboratory-based research was closed down for several months. Many of the department members showed a lot of creativity, initiative and determination to meet these challenges and to improvise solutions at all levels. These developments enabled us to start the fall term with hybrid courses combining classroom work with online elements, which was switched to an all-online format later on. It allowed many of us to experiment with novel teaching formats, several of which will remain in use once we are back to normal campus life.

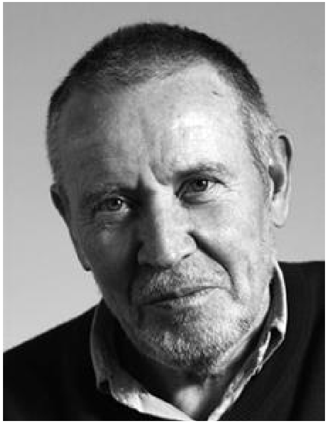
The physics department plays a very visible role in the newly designed 'Science Exploratorium' on Irchel Campus that was opened in November 2020, with large-scale exhibits of high-temperature superconductivity, of the dark matter search with the XENON experiment, and of elementary physics with the CMS experiment. A 1:10 scale model of CMS is one of the visual highlights of the Exploratorium, and the high-temperature superconductors allow for live demonstration experiments.

The physics department was evaluated by an external panel of experts during 2020, cumulating in an online site-visit in November. The diversity of our research portfolio was demonstrated through a line-up of video clips with lab visits and short introductions to ongoing projects. Preparing the evaluation helped the department to identify its strategic development priorities for the coming years. The experts' visit highlighted the performance and devotion of the department's members to common goals in research, training and teaching.

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

Exhibit on superconductors at the Science Exploratorium on the Irchel Campus.

Prof. em. Peter Truöl, 1939 – 2020



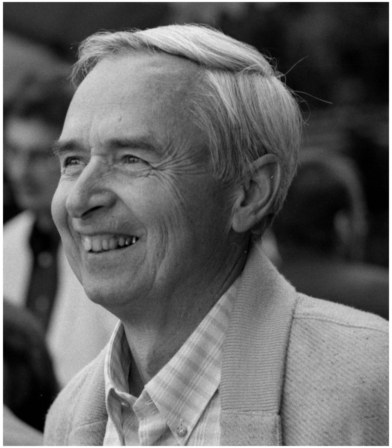
Prof. em. Dr. Peter Truöl was Professor for Elementary Particle Physics at our institute from 1971 to 2006. Here, he initiated the transition of experimental research from medium-energy to high-energy physics.

After studying physics, mathematics and chemistry in Göttingen and Zurich, Peter Truöl received his PhD under the supervision of Prof. Verena Meyer at the University of Zurich in 1967 with a thesis on the properties of the ^{10}B nucleus. He then continued his scientific research at the University of California, Berkeley, and soon afterwards became assistant professor at the University of California, Los Angeles. In 1971, he returned to Zurich for his habilitation. Here he introduced elementary particle physics to the curriculum of physics.

In 1988 Peter Truöl became full professor of experimental physics. His research group experimented in international research groups at accelerators in Berkeley, Los Alamos, Brookhaven, at PSI, at CERN and at DESY. In his scientific work, he was equally interested in the experimental aspects, the theoretical understanding and last but not least the linguistic quality of the publications.

Peter Truöl taught physics students in elementary particle physics for many years and gave the basic lectures for students of medicine and biology countless times. In doing so, he succeeded in conveying to his audience the fascination of researching fundamental physical questions and in making physics a basic subject for future scientists. Peter Truöl was Director of the Department of Physics of the University of Zurich from 1999 to 2003 and served as Dean of the Faculty of Mathematics and Natural Sciences from 2003 to 2006 and on the Board of Science Alumni from 2007 to 2012. After his retirement, he remained closely associated with current research projects in physics and the University of Zurich.

Prof. em. Günter Scharf, 1938 – 2020



Prof. em. Dr. Günter Robert Scharf was full professor of theoretical physics at the University of Zurich from 1970 to 2006. In particular, he was a capacity in mathematical physics.

Günter Scharf studied physics in Göttingen, Giessen and at ETH where he graduated in 1962. In 1965 Scharf received his doctorate under Prof. Armin Thellung at the Institute for Theoretical Physics at the University of Zurich. His dissertation on near-periodic potentials helped to establish his reputation as a mathematically precise theoretical physicist. In 1969 he was awarded his habilitation and in 1970 he was appointed professor of theoretical physics at the University of Zurich. In 2006 he was retired, but remained active as a researcher until shortly before his death.

Günter Scharf's work was characterised by mathematical clarity, fundamental physics questions and large range of topics. Thus, he often advanced some areas of theoretical physics off the tracks of general trends. These include above all his work on the renormalisation of gauge theories and on gravitation, in which he decisively developed the methodology of Epstein and Glaser. His studies on the linearised Boltzmann equation, the theory of lasers and spin waves in ferromagnetic materials were also influential.

Scharf's lectures were distinguished by clarity of terms and connections. His books on classical and quantised field theories impress with their clear and intuitive approach and have become standard works for many researchers.

Another, perhaps surprising side of Scharf was his relationship to applied physics. In recent years, he has worked with cardiologists and engineers to develop a novel system for the localisation of cardiac arrhythmias, from which a successful start-up company has emerged.

Statistical Data 2020

187
personnel

- professors: 19
- associated professors: 10
- senior researchers: 20
- postdoctoral researchers: 46
- PhD students: 70
- engineers and technicians: 23
- administration: 6
- + research assistants

370
students

~65
new students

190 bachelor	17 BSc degrees
68 master	12 MSc degrees
112 PhD	19 PhD degrees

11
SNF prof. and ERC grants

- 36 SNF or EU research grants
- 5 fellowships
- 34 UZH and other grants

355
publications

- 329 peer reviewed papers
- 18 conference proceedings
- 8 books & others

150
conference and workshop contributions

- 70 invited talks
- 46 seminar and other talks
- 9 posters
- 25 outreach

Outreach

Awards

- Jens Oppliger: UZH Semester award
- Claudio Andrea Manzari: Vito Volterra Prize for young researchers
- Claudio Andrea Manzari: LHCP2020 poster prize
- Frank Schindler: SPG Thesis award
- Stefan Hochrein: UZH Semester award
- Denys Sutter: Core Coaching grant from Innosuisse
- Nudzeim Selimovic: first prize on the Bosnian competition for best outreach video
- Laura Baudis: finalist at the Falling Walls and Berlin Science Week

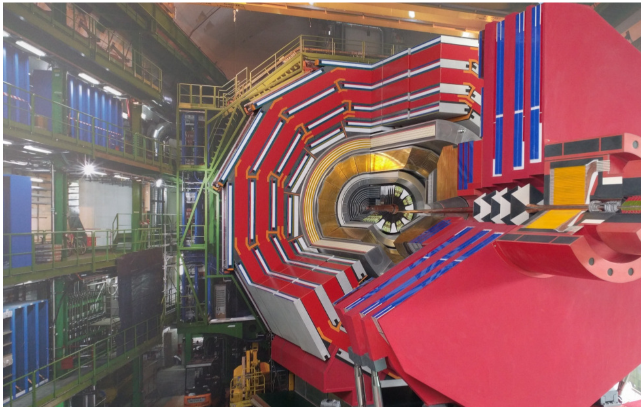
Videos

https://www.physik.uzh.ch/en/Videos-of-Research-Groups

- 26 Videos of the research groups
- Physics department in 5 minutes

Science Exploratorium UZH on Irchel Campus

The newly opened Science Exploratorium hosts several interactive stations that put a spotlight on selected research topics. The physics department contributed with an exhibit on superconductivity, a to-scale interactive replica of the CMS detector, and a recently decommissioned dark matter detector.

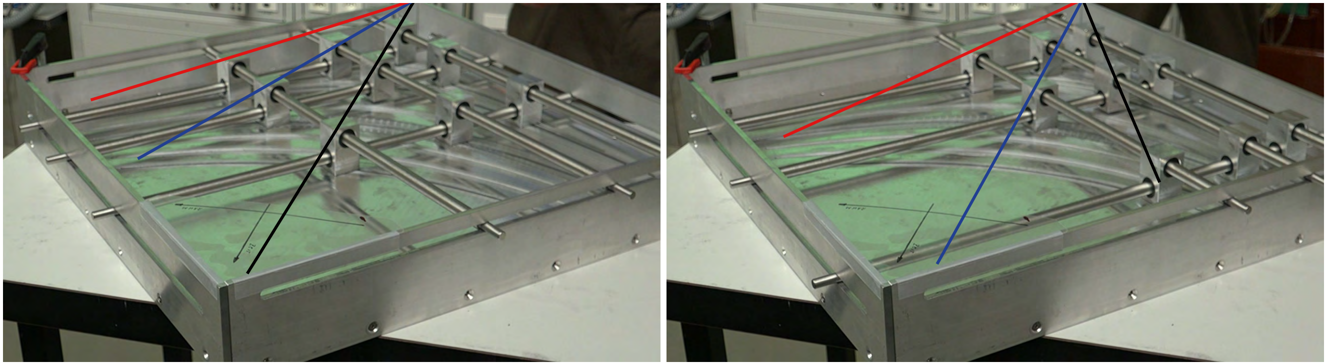


Teaching

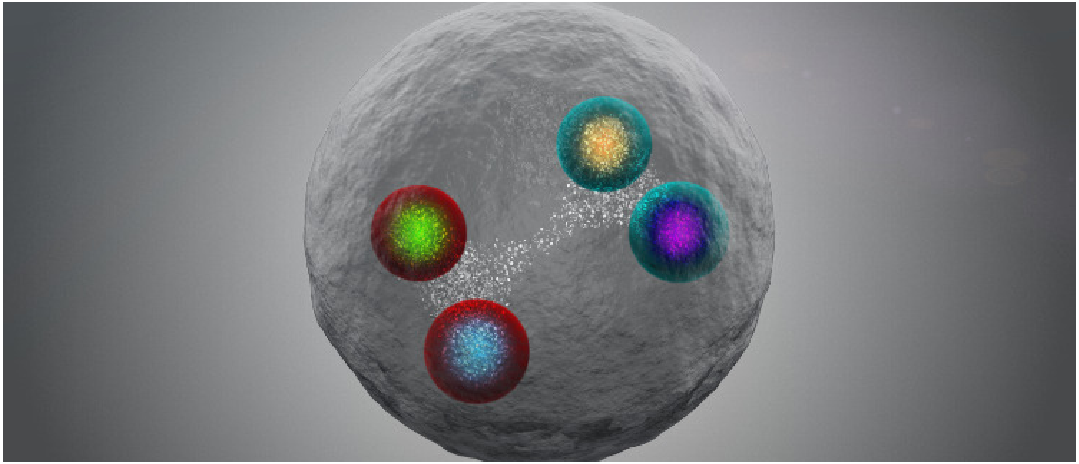
bachelor **3** major options	180 ECTS physics 150 ECTS physics/30 ECTS minor 120 ECTS physics/60 ECTS minor
4 master programs	particle physics condensed matter astrophysics & cosmology bio- & medical physics
service lectures **1342** students	570 medicine 500 biology & biomedicine 180 chemistry 80 teacher 12 minors

A mechanical implementation of Lorentz-transformations

In order to enable a more intuitive approach to special relativity, we have constructed a mechanical implementation of Lorentz-transformations, where the distortions of space-time are directly visualized. With the indicated space-time coordinates, the rest frame is along the vertical direction, indicated by the black line in the left figure. The mechanical implementation allows for a shift of a moving frame (blue line) to the new rest frame, see right figure. After this change of frame of reference, its effects on other coordinates can be directly inspected. As an example a third frame of referece indicated by the red line can be used for this. This e.g. allows for a direct demonstration of the effects of time-dilation and length contraction among others.



Physics of Fundamental Interactions and Particles



Particle Physics Theory: Flavour beyond the Standard Model

Prof. Andreas Crivellin

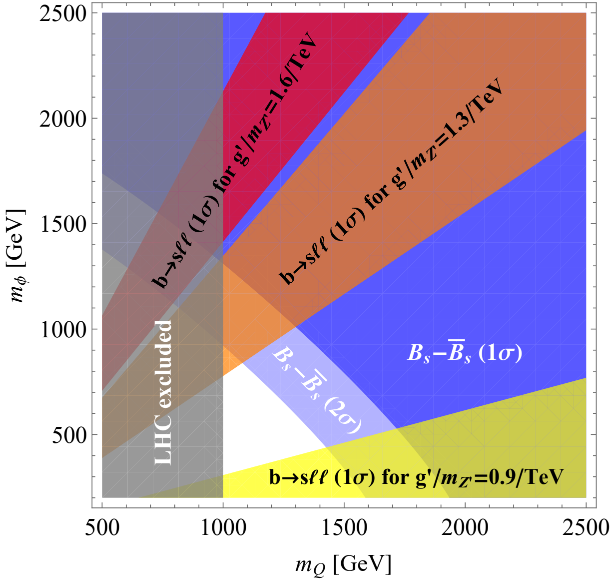
The Standard Model (SM) of particle physics describes the fundamental constituents and interactions of Nature. Matter consists of quarks and leptons (fermions) which interact via the exchange of force particles (gauge bosons). The SM has been tested to a very good accuracy, both in high-energy searches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

Hints for New Sources of CP- and Lepton Flavour Universality Violation

One of the predictions of the SM is that quarks and leptons appear in three generations (or families), called flavours, which only differ in their couplings to the Higgs boson, leading to different masses for particles of different flavour. The only source of flavour violation in the SM is the Cabibbo-Kobayashi-Maskawa (CKM) matrix and all SM gauge interactions treat leptons in the same way; i.e. they respect lepton flavour universality. However, several experiments found hints for deviations from lepton flavour universality, in particular in the decay of heavy B mesons (bound states involving a bottom quark).

These experimental results caused considerable interest within the theoretical community and various models for explaining them were proposed, including particles called leptoquarks (LQs). These hypothetical particles couple directly



Allowed regions in parameter space, showing that a combined explanation of the anomalies is possible.

quarks to leptons, unlike any particle in the SM. We examined the effects of LQ model in complementary observables [1]. In addition, there exist significant discrepancies between different ways of determining elements of the aforementioned CKM matrix. In particular, the CKM element determined from nuclear beta decay does not agree with the one from kaon decays. Here, we pointed out that this tension can also be explained in terms of lepton flavour universality violating physics beyond the SM as well, since beta decays involve only electrons while the best data from kaon decays is related to muons [2]. Furthermore, we investigated combined explanations of this anomaly together with the ones observed in B meson decays [3,4].

Highlighted Publications:

1. Leptoquarks in oblique corrections and Higgs signal strength: status and prospects,
   A. Crivellin, D. Müller and F. Saturnino, JHEP **11** (2020), 094 [arXiv:2006.10758 [hep-ph]]
2. β-Decays as Sensitive Probes of Lepton Flavor Universality,
   A. Crivellin and M. Hoferichter, Phys. Rev. Lett. **125** (2020) no.11, 111801
3. Explaining $b \to s\ell^+\ell^-$ and the Cabibbo Angle Anomaly with a Vector Triplet,
   B. Capdevila *et al.*, Phys. Rev. D **103** (2021), 015032
4. Combined Explanation of the $Z \to b\bar{b}$ Forward-Backward Asymmetry, the Cabibbo Angle Anomaly, $\tau \to \mu\nu\nu$ and $b \to s\ell^+\ell^-$ Data,
   A. Crivellin *et al.*, [arXiv:2010.14504 [hep-ph]]

Particle Physics Theory: Beyond the Standard Model

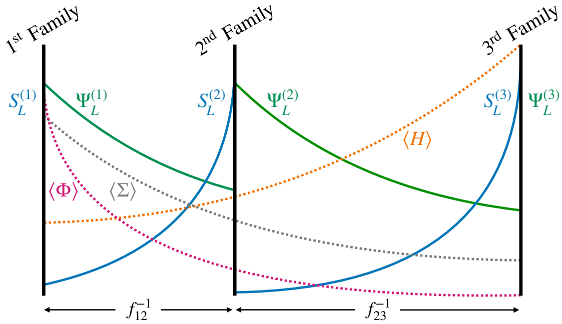
Prof. Gino Isidori

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

Flavour Anomalies and the origin of Flavour

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. Surprisingly enough, a series of precision measurements performed recently by the LHCb experiment at CERN seem to challenge this prediction. The theoretical investigation of these surprising results (denoted *flavour anomalies*) has been the main research activity of our group in the last four years. This research comprises four main directions: 1) the improvement of the SM predictions relevant to perform such precision studies; 2) the investigation of the consistency of the anomalous results with other data, using generic effective-theory approaches; 3) the construction of complete extensions of the SM able to describe the new data in terms of new particles and new symmetry principles; 4) the analysis of the predictions of these new interactions in view of future ex-



Schematic representation of the field profiles along the compact extra space-time dimension in the model proposed to explain the origin of the fermion hierarchies, neutrino masses, and the recent flavour anomalies.

periments. In the past year we worked mainly along the first and third direction. On the one hand, we improved the treatment of radiative corrections on rare decays within the SM. On the other hand, we developed an ambitious extension of the SM that addresses the flavour anomalies and, at the same time, provides a natural explanation for the smallness of neutrino masses. This model is based on the hypothesis of an extra compact space-time dimension. What we denote as *flavour* is nothing but a notable position along this extra dimension: the position where the geometry has a discontinuity (topological defect) and a given generation of fermion is localized. This model predicts a series of interesting phenomena, among which an anarchic spectrum on neutrinos, with average mass around 0.1 eV. It also predicts the existence of a new heavy particle called leptoquark, with mass of several TeV, which we identified in our previous studies as the best candidate to explain the flavour anomalies.

Highlighted Publications:

1. Flavour symmetries in the SMEFT,
   D. Faroughy, G. Isidori, F. Wilsch, K. Yamamoto,
   JHEP **08** (2020) 166, arXiv:2005.05366
2. Stability of the Higgs Sector in a Flavor-Inspired Multi-Scale Model,
   L. Allwicher, G. Isidori, A. E. Thomsen,
   JHEP **01** (2021) 191, arXiv:2011.01946
3. Flavor Non-universal Pati-Salam Unification and Neutrino Masses,
   J. Fuentes-Martin, G. Isidori, J. Pages, B. Stefanek,
   arXiv:2012.10492, submitted to Phys. Let. B

Particle Physics Theory: Precision Calculations

Prof. Thomas Gehrmann

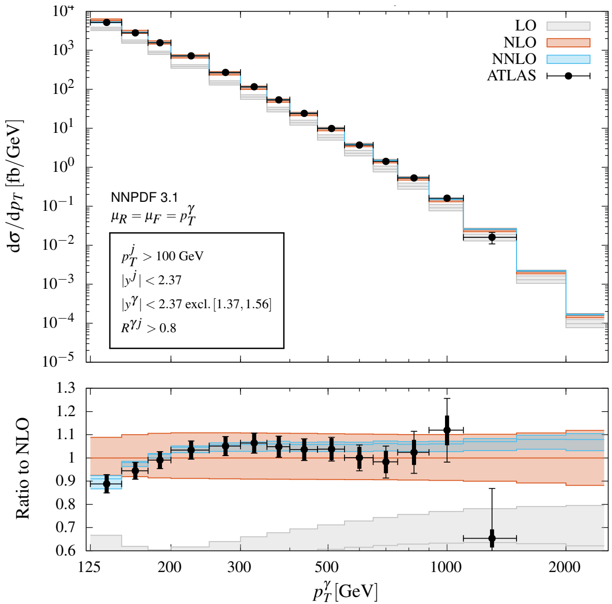
Our research group focuses on precision calculations for collider observables within the Standard Model and their application in the interpretation of experimental data. We develop novel techniques and computer algebra tools that enable analytical calculations in perturbative quantum field theory and 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

Precise theory predictions for isolated photons at the LHC

Photon production at large transverse momenta is a classical hadron collider observable. The underlying parton-level process is photon radiation off a quark produced in quark-gluon scattering, thereby offering high sensitivity to the gluon distribution in the proton. Its interpretation is however more involved than it appears at first sight. Highly energetic final state photons can also be produced as radiation in an ordinary jet production event or in the course of hadronization. To suppress these secondary contributions, an isolation procedure is applied in the experimental reconstruction of photon and photon+jet final states. This isolation procedure needs to accommodate the finite experimental resolution and must respect theory requirements on its infrared safety. It is typically accomplished by allowing only a limited amount of hadronic energy in a fixed-size cone around the photon direction.

Correspondingly, the theoretical description of isolated photon production processes must account for the isolation procedure applied in the experimental measurement. In our recent calculation of next-to-next-to-leading order (NNLO) QCD corrections to isolated photon, photon-plus-jet and di-photon final states, we employed the hybrid isolation prescription which combines the fixed cone isolation of the experimental measurement



Transverse momentum distribution of the photon in photon-plus-jet events, at LO, NLO and NNLO, compared to ATLAS 13 TeV data.

with a smaller inner cone with dynamical energy threshold that ensures infrared safety. Our calculation uses the antenna subtraction method to handle real radiation contributions and is implemented in the NNLOJET parton-level event generator framework.

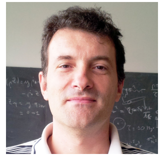
The next-to-leading order (NLO) corrections to isolated photon observables are often observed to be of comparable size to the leading-order predictions, thereby initially casting doubt on the convergence of perturbative series. With our newly derived NNLO corrections, we observe a stabilization of the predictions: the NNLO effects are typically below 10%, they lie within the uncertainty band of the previously known lower-order results. Most importantly, the NNLO corrections yield substantial improvements in the description of shapes of kinematical distributions, as illustrated in the figure. The residual uncertainty of the predictions at NNLO is typically below 5%, matching the quality of the LHC precision data.

Our newly derived NNLO corrections will enable precision studies with isolated photons, for example in determinations of the gluon distribution or in data-driven background estimates for rare processes in extreme kinematical regions.

Highlighted Publications:

1. Isolated photon and photon+jet production at NNLO QCD accuracy, X.Chen, T. Gehrmann, N. Glover, M. Höfer, A. Huss, JHEP **04** (2020) 166
2. Scale and isolation sensitivity of diphoton distributions at the LHC, T. Gehrmann, N. Glover, A. Huss, J. Whitehead, JHEP **01** (2021) 108

Particle Physics Theory: Standard Model and Higgs Physics at Colliders



Prof. Massimiliano Grazzini

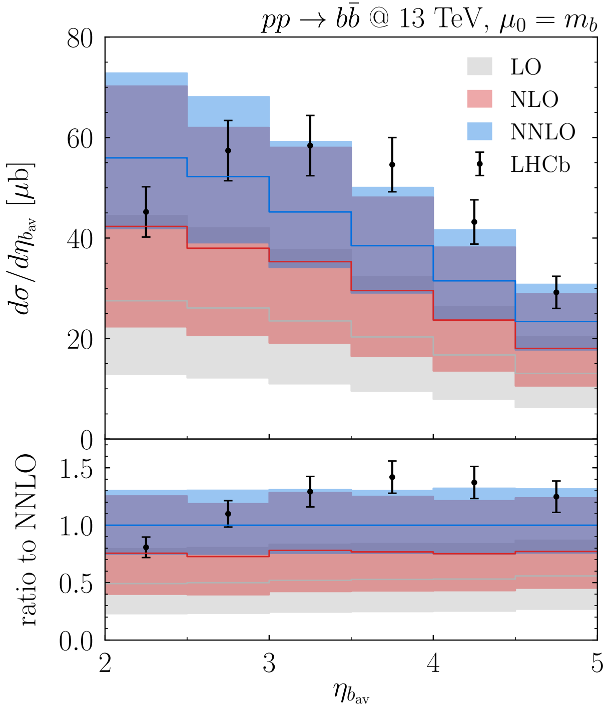
Our research activity is focused on the phenomenology of particle physics at high-energy colliders. We perform accurate theoretical calculations for benchmark processes at the Large Hadron Collider and we make their results fully available to the community. We strive to develop flexible numerical tools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

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

Precise predictions for bottom quark production

The production of bottom quarks has been extensively studied at hadron colliders. Early measurements were carried out at the CERN $Sp\bar{p}S$, and, later, at the Tevatron and at the LHC. From the theory viewpoint, heavy-quark production at hadron colliders is one of the most classic tests of perturbative Quantum Chromo Dynamics (QCD). The cross section to produce a pair of heavy quarks with mass m_Q is computable as a power series expansion in the QCD coupling $\alpha_S(\mu_R)$, where the renormalisation scale μ_R has to be chosen of the order of m_Q. In the case of the bottom quark the relatively low mass, $m_b \sim 4-5$ GeV, leads to a slow convergence of the perturbative expansion and, therefore, to large theoretical uncertainties. Up to very recently, the theoretical status for bottom-quark production was limited to the next-to-leading order (NLO) in perturbative QCD, with the inclusion of resummation effects at large transverse momenta.

We have completed a new computation of the bottom-quark production cross section that includes perturbative QCD corrections at next-to-next-to-leading order (NNLO). The calculation is obtained by combining tree level and one-



Pseudorapidity distribution for beauty production at the LHC for the scale choice $\mu_0 = m_b$, for centre of mass energy of 13 TeV. The theoretical predictions are compared with data from LHCb.

loop scattering amplitudes generated with OpenLoops, an automated tool also developed in Zurich, with two-loop amplitudes that are available in numerical form. The various contributions are separately divergent, and a method is required to handle and cancel infrared singularities appearing at intermediate stages of the computation. We have used the same method successfully applied by our group to the calculation of top-quark production. By using advanced numerical techniques to carry out the phase space integrations, we have assembled all the above ingredients to compute the NNLO cross section. The inclusion of NNLO corrections suggests a (slow) convergence of the perturbative series, with a significant reduction of perturbative uncertainties. We have presented several results for differential distributions for bottom quarks at the Tevatron and the LHC and compared them with available data. The inclusion of NNLO corrections generally improves the agreement with the data. More detailed data-theory comparisons will require the resummation of the logarithmically enhanced contribution at large transverse momenta and the inclusion of fragmentation effects.

1. Bottom-quark production at hadron colliders: fully differential predictions in NNLO QCD,
S. Catani *et al.*, arXiv:2010.11906
2. Top-quark pair hadroproduction at NNLO: differential predictions with the MSbar mass,
S. Catani *et al.*, arXiv:2005.00557

Particle Physics Theory: Automated Simulations for high-energy colliders

Prof. Stefano Pozzorini

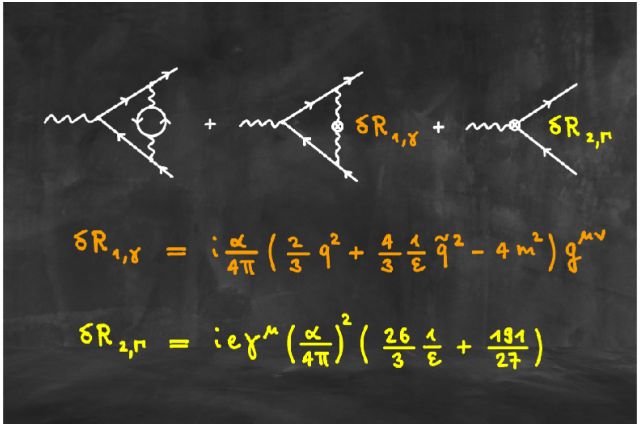
Our research deals with the development of automated methods for the simulation of scattering processes in quantum-field theory. The OpenLoops algorithm, developed in our group, is one of the most widely used programs for the calculation of scattering amplitudes at the LHC. This tool is applicable to arbitrary collider processes up to high particle multiplicity and can account for the full spectrum of first-order quantum effects induced by strong and electroweak interactions.

Currently, new automated methods for second-order quantum effects are under development. Our phenomenological interests include topics like the strong and electroweak interactions of heavy particles at the TeV scale, or theoretical challenges related to the extraction of rare Higgs-boson and dark-matter signals in background-dominated environments.

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

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 $D = 4 - \varepsilon$ space-time dimensions, where ε is as infinitesimally small parameter. In this way the singularities assume the form of $1/\varepsilon$ poles and can be canceled through the so-called renormalisation procedure. Finally, physical predictions are obtained by setting $\varepsilon \to 0$. In this limit, the interplay of $1/\varepsilon$ 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.



Example of Feynman diagrams describing second-order quantum corrections to the interaction of photons (wavy lines) with electrons and positrons (solid lines). Thanks to the technique of [1][2], two-loop diagrams (left) can be computed using numerical tools in $D = 4$ dimensions, while missing contributions in $D = 4 - \varepsilon$ dimensions are reconstructed by means of one-loop (orange) and two-loop (yellow) rational counterterms. This approach is applicable to any scattering process.

So far automated algorithms exist only at one loop. In this case the most powerful approach turned out to be the combination of numerical algorithms in $D = 4$ dimensions together with special techniques for the reconstruction of the missing rational terms. Recently, as a basis for automated two-loop algorithms, we have developed a fully-fledged theoretical framework for rational terms at two loops [1],[2].

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 reconstruct all missing rational parts when calculations are carried out in $D = 4$ dimensions. Rational counterterms can be computed for any theory using the algorithms presented in [1],[2] and, once available, they can be applied to any scattering process. Explicit results for all two-loop rational counterterms in quantum electrodynamics and quantum chromodynamics have been presented in [1],[2], and the determination of rational counterterms for the full Standard Model of Particle Physics is within reach. These results provide an important building block for a new generation of automated algorithms for precision calculations at high-energy colliders.

Highlighted Publications:

1. Rational Terms of UV Origin at Two Loops,
   S. Pozzorini, H. Zhang and M. F. Zoller, JHEP **05** (2020), 077
2. Two-Loop Rational Terms in Yang-Mills Theories,
   J. N. Lang, S. Pozzorini, H. Zhang and M. F. Zoller, JHEP **10** (2020), 016

High-intensity low-energy particle physics

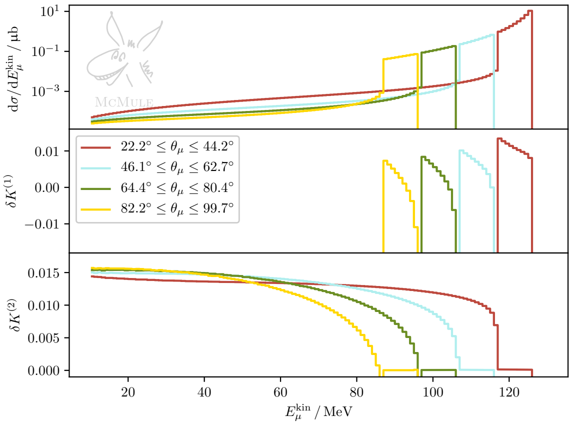
Prof. Adrian Signer

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 the Paul Scherrer Institut (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

Elastic lepton-proton scattering

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

After the implementation of several processes at next-to-leading order (NLO), recently we have implemented the dominant NNLO QED corrections for elastic muon-electron and electron-proton (or muon-proton) scattering, namely to corrections due to emission off the electron line. In QED it is important to keep the fermion masses at their physi-



Differential cross section $d\sigma/dE_\mu^{kin}$ for the MUSE experiment with incoming muons of momentum 210 MeV, at NNLO with relative NLO and NNLO corrections $\delta K^{(1)}$ and $\delta K^{(2)}$. Results are shown separately for different bands of the scattering angle θ_μ.

cal value, rather than setting them to zero. This allows to compute contributions with large mass logarithms, 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.

Very precise theoretical calculations are required for muon-electron scattering in connection with the proposed MUonE experiment which aims at an alternative determination of the leading hadronic contribution to the running of the electromagnetic coupling. Our group is contributing to this effort within the MUonE Theory Initiative and a theory summary based on a Workstop/Thinkstart event at UZH has been published. Our results for the dominant NNLO corrections have been validated by an independent computation of the Pavia group.

The MUSE experiment will measure lepton-proton scattering with $\mu^\pm$ and $e^\pm$ at PSI in the coming years. Measuring with muons and electrons of both charges in the same experimental set up will provide further insights to the proton radius puzzle and two-photon exchange contributions. We have adapted our muon-electron scattering calculation for this case and provide the most precise QED corrections to this process. As a next step, two-photon exchange contributions and radiative corrections from the proton line will be included as well.

Highlighted Publications:

1. Theory for muon-electron scattering @ 10 ppm: A report of the MUonE theory initiative, P. Banerjee *et al.*, Eur. Phys. J. C **80** (2020) no.6, 591, arXiv:2004.13663
2. QED at NNLO with McMule, P. Banerjee *et al.*, SciPost Phys. **9**, 027 (2020), arXiv:2007.01654

CMS Experiment

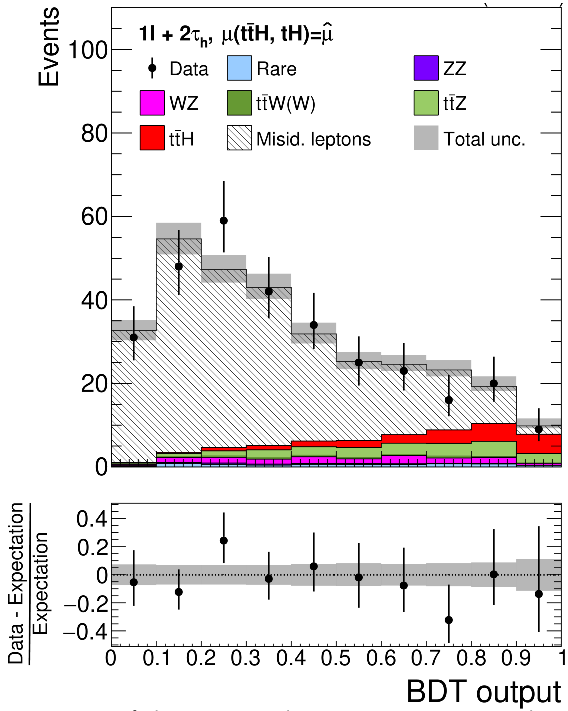
Prof. Lea Caminada, Prof. Florencia Canelli,
Prof. Ben Kilminster

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 produces an energy density comparable to that of the universe one ten billionth of a second after it started. Detectors are used to determine the energy and direction of emerging particles. By reconstructing these particles, the particles and their interactions can be deciphered. In 2012, CMS discovered the Higgs boson, thus proving how particles acquire mass. During Run 2 of the LHC, CMS collected a record dataset of 150 fb^{-1}, allowing more precise measurements and searches for new physics. CMS is also preparing for Run 3 in 2022, and building new detectors needed for the high-luminosity run of the LHC envisioned to start in 2027.

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

The CMS groups at UZH are strong in data analysis, focusing on the fundamental mysteries in particle physics. We are studying the Higgs boson, and also using it as a probe to look for new forces and particles. We undergo measurements of the heaviest fundamental particle known, the top quark, which is as heavy as a gold atom, and study its interactions with other particles. In 2020, we have continued our studies of the simultaneous production of a pair of top quarks with a Higgs boson in final states with multiple leptons [1] shown in Figure 1. We have created a method to classify quark and gluon jets and reduce pileup which would be crucial in the next runs of the LHC [2] and developed anomaly detection algorithms based on advanced machine learning techniques with the goal of improving our indirect searches for new physics [3] .

The LHC is the highest energy collider in the world, which allows us to search for new heavy particles that represent hitherto unknown forces. By using a new method that simultaneously searches for combinations of particles



Measurement of the Higgs production in association with a top quark pair [1].

that would lead to mass resonances from three particles, we achieve the best sensitivity yet for dijet searches for new particles such as Gravitons and additional copies of weak force carriers [4], such as the Z′.

We have also developed a new algorithm for identifying low-momentum tau leptons that will allow CMS to measure B hadron decays to tau leptons as compared to other charged leptons [5]. This will allow us to be competitive with LHCb in the search for lepton flavor universality violation, and search for indirect evidence of leptoquarks that couple more strongly to third-generation particles. Complementary to this, we are directly searching for TeV-scale third-generation leptoquarks in their decays to high momentum particles.

Highlighted Publications:

1. Measurement of the Higgs boson production rate in association with top quarks in final states ..., CMS Collab., arXiv:2011.03652, subm. to EPJC
2. ABCNet: an attention-based method for particle tagging,
   V. Mikuni, F. Canelli, Eur. Phys. J. Plus **135**, 463 (2020)
3. Unsupervised clustering for collider physics,
   V, Mikuni, F. Canelli, arXiv:2010.07106, subm. to PRD
4. A multi-dimensional search for new heavy resonances decaying to boosted WW, WZ or ZZ ..., CMS Collab., arXiv:1906.05977, Eur. Phys. J. C **80** (2020) 237
5. Performance of the low-p_T tau identification algorithm, CMS Collab., CERN-CMS-DP-2020-039

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

Collider detector development

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



The CMS detector includes a silicon pixel detector as the innermost part of the tracking system. The pixel detector provides 3-dimensional space points in the region closest to the interaction point that allow for high-precision tracking of charged particles and vertex reconstruction. This enables the measurement and search for particles that decay to b quarks and tau leptons, such as the Higgs boson, the top quark, and leptoquarks. Our groups are major contributors to the CMS pixel detector project. We helped build and operate the current pixel detector and are involved in the design and prototyping of a new, improved version with more tracking layers, less material, and higher data rates to be installed in 2026. Furthermore, we are developing and testing new pixel detector concepts for high-luminosity LHC (HL-LHC), future accelerators and other applications.

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

The current CMS pixel detector has 124 million readout channels and is capable of making 40 million measurements per second. The pixel detector has been installed in 2017 and collected collision data corresponding to an integrated luminosity of more than 150 fb^{-1} during Run 2 [1]. During the shutdown of the accelerator that is presently ongoing (2019-2022) the innermost layer of the barrel pixel detector is being replaced in order to maintain efficient and robust tracking in CMS during Run 3. The new innermost layer has been built at PSI and is fitted with the rest of the detector at CERN. We are contributing to the integration and the testing of the pixel detector as well as its re-installation into CMS and the commissioning in view of the next data-taking period (Figure 1).

CMS will collect more than 20 times the current data set during the period of 2027 to 2038 (called high-luminosity LHC). The UZH group will construct in Zurich an inner tracking detector for this period that will extend the tracking coverage. This Tracker Extended Pixel detector (TEPX) will be composed of a large-area disk system with more than

Half-disk electronics of the TEPX detector with 26 modules undergoing tests in a climate chamber. The CMS TEPX detector will consist of 1408 detector modules.

one billion pixels [2]. In 2020, we have produced first prototype modules and tested them integrated within the disk electronics and the pixel detector readout chain. A particular focus is on the verification and the characterization of the novel serial powering scheme. We studied detector sensor options that could dramatically reduce the cost of the detector, and measured the signal quality of detector modules in particle beams. Furthermore, we are prototyping lightweight mechanical structures and thin-walled cooling tubes to build the disk structures with minimal material.

We study new types of particle detectors called LGAD, and were able to measure a timing resolution of less than 40 picoseconds ($40{\cdot}10^{-12}$ s) in our lab. In order to use these sensors in the experiment, R&D for pixelated readout electronics with fast timing measurement is needed. We are evaluating the performance of different TDC (Time-to-Digital Converter) designs that have been produced in 110 nm CMOS technology and will test their performance when processing the signals from the LGAD sensor. The long-term focus is towards a possible use of disks with timing capabilities in later upgrades of the TEPX detector. Such a technology could greatly improve the physics potential of CMS during HL-LHC.

Highlighted Publications:

1. The CMS Phase-1 Pixel Detector Upgrade, Tracker Group of the CMS Collaboration, arXiv:2012.14304, JINST **16** P02027
2. The Phase-2 Upgrade of the CMS Tracker, CMS Collaboration, CMS-TDR-014

LHCb Experiment

Prof. Nicola Serra, PD Dr. 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 are also involved in the preparation of a major upgrade of the detector for 2019/2020.

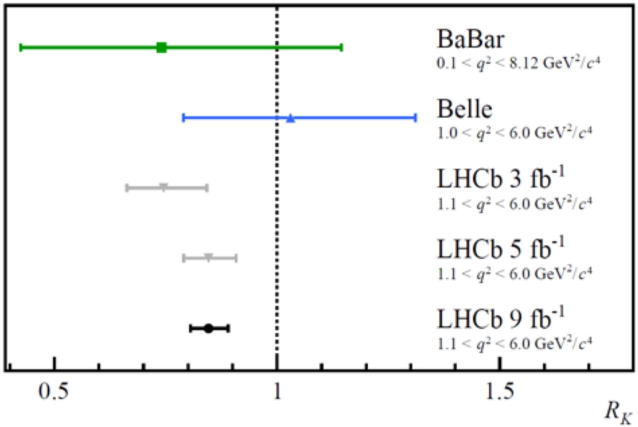
https://www.physik.uzh.ch/r/lhcb

Evidence for the violation of lepton universality in beauty quark decays

A distinctive feature of the Standard Model (SM) is the concept of lepton universality, whereby the charged leptons (electron, muon and τ-lepton) have identical interactions to the weak force. This accidental symmetry does not necessarily hold in theories beyond the SM. The LHCb group at UZH has a strong focus on testing lepton universality with beauty quark decays, whereby the behaviour of beauty quark decays into different lepton flavours is compared.

The group played a major role in a recent test of lepton universality, performed via a high precision measurement of the ratio R_K, which compares the decay probability of beauty quarks into electrons and muons. The SM prediction for R_K is unity with a theoretical uncertainty which is well below the experimental uncertainty. A deviation from unity would therefore be a indication of physics beyond the SM.

The experimental challenge lies in the fact that, while electrons and muons interact via the weak force in the same way, the small electron mass means it interacts with material much more than muons. For example, electrons radiate a significant number bremsstrahlung photons when traversing through the LHCb detector, which degrades the reconstruction efficiency and signal resolution compared to muons. The key



Comparison between R_K measurements. In addition to the new and the previous LHCb result, the measurements by the BaBar and Belle collaborations are shown [1].

to control this effect is to use the standard candle decays $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$, which are known have the same decay probability and can be used to calibrate and test electron reconstruction efficiencies. High precision tests with the J/ψ are compatible with lepton universality which provides a powerful cross-check on the experimental analysis.

The ratio R_K was measured with the full run1-run2 dataset and was found to deviate by 3.1 standard deviations (p-value $\sim$ 0.1%) from the SM prediction, constituting evidence for lepton universality violation in these decays. Interestingly, the decay probability of the electron decay is more consistent with SM predictions than the muons, suggesting that something is destructively interfering with the muonic decay and leaving the electronic decay untouched.

In particle physics, the gold standard for discovery is five standard deviations and so it is too early to conclude anything so far. However, this deviation agrees with a pattern of anomalies which have manifested themselves over the last decade. Fortunately the LHCb group at UZH is well placed to clarify the potential existence of new physics effects in these decays, with many related measurements upcoming soon.

Highlighted Publications:

1. All LHCb publications: lhcb.web.cern.ch/lhcb/
2. Test of lepton universality in beauty-quark decays, LHCb Collab., arXiv:2103.11769
3. Angular analysis of the $B^+ \to K^{\star +}\mu^+\mu^-$ decay, LHCb Collab., arXiv:2012.13241
4. Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$, LHCb Collab., arXiv:2103.01803

LHCb Experiment – Upgrades

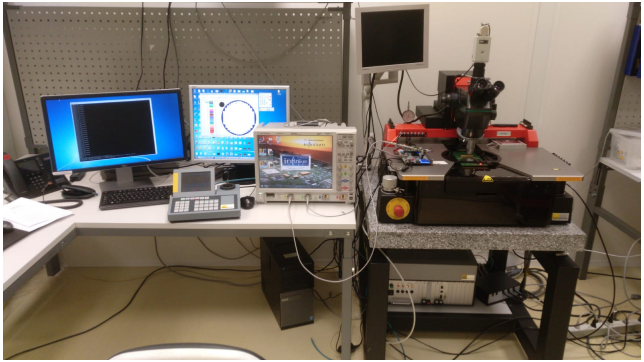
Prof. Nicola Serra, PD Dr. Olaf Steinkamp

The LHCb collaboration is making use of the ongoing long shutdown of the LHC accelerator for a comprehensive upgrade of the experiment. The goal of the upgrade is to collect data at five times higher proton-proton collision rate and with better efficiency when the LHC resumes operation in 2022. Studies for a second upgrade, that would allow for another significant increase in collision rate, are gaining momentum. Our group contributes to both upgrade efforts.

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

LHCb upgrade I

The contributions of our group to the LHCb detector are focussed on the so-called tracking system, a set of detectors that are employed to measure the trajectories and momenta of long-lived charged particles. The complete LHCb tracking system has to be replaced as part of the ongoing Upgrade I of the experiment. Detectors with finer granularity and better radiation hardness are needed to cope with the higher rate and density of charged particles that result from the increased proton-proton collision rate. Readout electronics have to be replaced to deal with higher trigger and data rates. Our group contributes to the development of the so-called "Upstream Tracker" (UT), a tracking station that is located in front of the LHCb spectrometer magnet and replaces the "Tracker Turicensis" which had been our main contribution to the original LHCb detector. In particular, we are responsible for quality assurance measurements of a newly developed front-end readout chip for the UT and for the development of the UT-specific firmware for the LHCb data-acquisition boards. We also contribute to the design, production and testing of various electronics boards for data taking and detector control. We plan to make significant contributions to the assembly and commissioning of the detector, which should take place at CERN in 2021.



Setup for quality assurance of front-end chips.

LHCb upgrade II

The upgraded LHCb detector has been designed to collect an integrated luminosity of about 50/fb over the next two periods of operation of the LHC. The LHCb collaboration then envisages a second comprehensive upgrade, which would allow to increase the proton-proton collision rate by another factor of five or more and collect an integrated luminosity of about 300/fb. Our group contributes to simulation studies to develop track reconstruction algorithms and understand the requirements for a tracking system for this Upgrade II. We also participate in the R&D effort to develop a novel silicon pixel detector that would allow to cover the regions of highest particle density in the tracking detectors downstream of the LHCb spectrometer magnet. The detector is based on the so-called HV-MAPS technology, Monolithic Active Pixel Sensors implemented in High-Voltage CMOS process. This technology offers a number of advantages in terms of complexity, cost and performance. It is being pioneered at the mu3e experiment at PSI, studies have also been performed for the upgrade of the ATLAS tracking system. R&D is needed to adapt this technology to the LHCb readout scheme and to demonstrate that it fulfills the requirements for Upgrade II. A first prototype sensor has been produced in 2020 and initial tests have been performed at a test beam at DESY. Further measurements at test beams and in laboratory setups, including tests of irradiated HV-MAPS detectors, as well as the submission of a second prototype are planned for 2021.

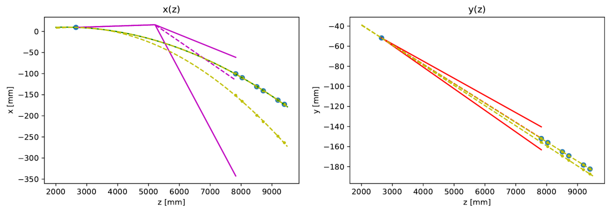


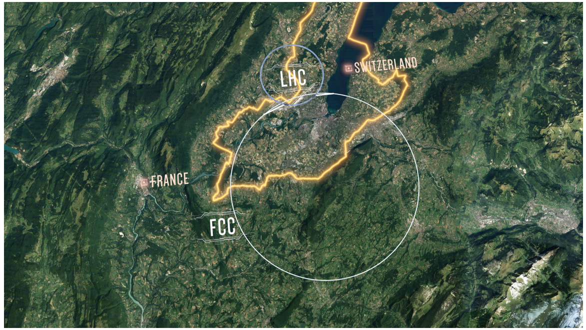
Illustration of a possible track finding algorithm in the bending plane (left) and non-bending plane (right) of the spectrometer magnet: true track (green line and dots); search window (purple resp. red lines), found track candidates (dashed yellow lines). In this example, the algorithm retrieves the correct track but also a wrong candidate.

Future Circular Collider (FCC)

Prof. Florencia Canelli

The goal of the Future Circular Collider Study (FCC) is to greatly push the energy and intensity frontiers of particle colliders and lay the foundations for a new research infrastructure that can succeed the LHC and serve the world-wide physics community for the rest of the 21st century. The FCC project envisions a staged approach, in which a new, 100-km tunnel is first used for electron-positron collisions (FCC-ee), after which the complex is upgraded to collide hadrons (FCC-hh), with the aim of reaching collision energies of 100 TeV, in the search for new physics [1].

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



Our group develops silicon sensor technologies for the Vertex detector with excellent precision, granularity and low mass, optimized for collisions at the FCC-ee. The measurement precision at the FCC-ee will depend on the detector technology: a vertex detector with fast read-out, low power consumption and single point spatial resolution of a few microns is required for Higgs sector definition and particle identification for flavour physics. During 2020, our group began the development of state-of-the-art tracking detectors, together with implementing modern analysis techniques currently used at the LHC, to evaluate the physics reach of the FCC-ee.

1. Future Circular Collider - European Strategy Update Documents, M. Benedikt et al., CERN-ACC-2019-0003 (2019)

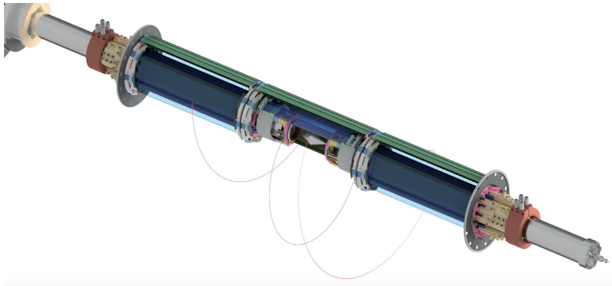


The $\mu^+ \to e^+e^-e^+$ experiment

Prof. Lea Caminada, Prof. Nicola Serra,
PD Dr. Olaf Steinkamp

The Mu3e experiment aims to search for the lepton flavour violating decay $\mu^+ \to e^+e^-e^+$. The experiment is currently finalising the design and is expected to start data taking in the next two years.

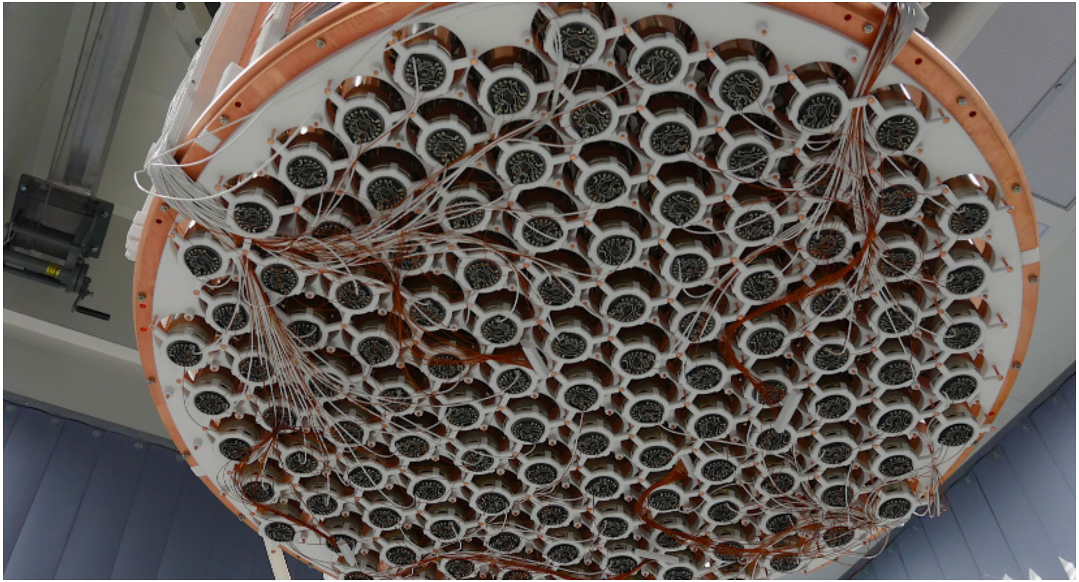
The conservation of lepton flavour, where the number of leptons in an interaction of a particular flavour is conserved, is a key symmetry in the Standard Model. Although lepton flavour violation has already been observed in neutrino oscillations, it has never been seen in charged leptons. The incredibly high intensity muon beam at PSI, Villigen offers a unique opportunity to probe lepton flavour violating decays such as $\mu^+ \to e^+e^-e^+$ and is expected to be sensitive to one $\mu^+ \to e^+e^-e^+$ decay in every 10^{16} muon decays, around 1000 times more sensitive than previous limits. We recently published the technical design report of the Mu3e experiment [1] and a first commissioning run is planned to take place this year.



Schematic of the Mu3e detector. Incoming muons are stopped in the target and decay. The resulting electrons are recorded in the pixel layers for spatial and scintillating fibre detector for time information.

1. Technical design of the phase I Mu3e experiment, K. Aandt *et. al.*, arxiv:2009.11690

Cosmology, Astro- and Astroparticle Physics



Astrophysics and General Relativity

Prof. Philippe Jetzer, Prof. Prasenjit Saha

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 many more events have been found. Our group has made important contributions to the analysis of LIGO/Virgo data and also 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

Highlights

The work of the group is focused on the topic of gravitational waves using LIGO/Virgo and the future space mission LISA. In the following we briefly describe some results published in 2020, besides all the works appeared in the framework of the LIGO/Virgo and LISA Pathfinder collaborations.

M. Haney, S. Tiwari and collaborators studied the performance of different search algorithms used in the LIGO/Virgo scientific collaboration to detect eccentric binary black holes. Indeed, several models for the formation of binary black holes predict that most of them are formed with a non-negligible eccentricity. This is an important issue which has to be investigated further also in view of LISA.

In a paper, including as co-authors S. Tiwari, M. Haney and P. Jetzer, a scenario for the merger of black holes in accretion discs of active galactic nuclei has been studied. The expected merging rate for such a scenario has been compared with the observed ones and turned out to be in good agreement. M. Ebersold and S. Tiwari presented in a paper the first results of the search for nonlinear memory effects from subsolar mass binary black hole mergers during the second observing run (O2) of the LIGO and Virgo detectors. No signal was detected as due to the memory effect, and thus this leads

Aerial view of the Virgo interferometer in Cascina, Italy (Image: Virgo/European Gravitational Observatory).

for the first time to an upper limit on the merging rate of very light black holes.

Still another aspect of gravitational waves was investigated by P. Saha and collaborators, who studied the possibility of resolving by optical intensity interferometry a system that LISA is expected to detect in gravitational waves. This could be an exceptional system for which gravitational-wave polarization could be predicted before it is observed.

Philipp Denzel, together with P. Saha and other collaborators, obtained a new estimate of the Hubble constant using gravitational-lensing time delays.

Highlighted Publications:

1. Impact of eccentricity on the gravitational wave searches for binary black holes: High mass case, Phys.Rev. D**102** (2020), 043005, arXiv:2005.14016
2. Binary black hole mergers in AGN accretion discs: gravitational wave rate density estimates, Astron.Astrophys. **638** (2020) A119, arXiv:2005.03571
3. Search for nonlinear memory from subsolar mass compact binary mergers, Phys. Rev. D 101 (2020), 104041, arXiv:2005.03306
4. Towards a polarization prediction for LISA via intensity interferometry, MNRAS **498** (2020) 4577–4589, arXiv:2008.11538
5. The Hubble constant from eight time-delay galaxy lenses, MNRAS **501** (2020), 784–801, arXiv:2007.14398

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.

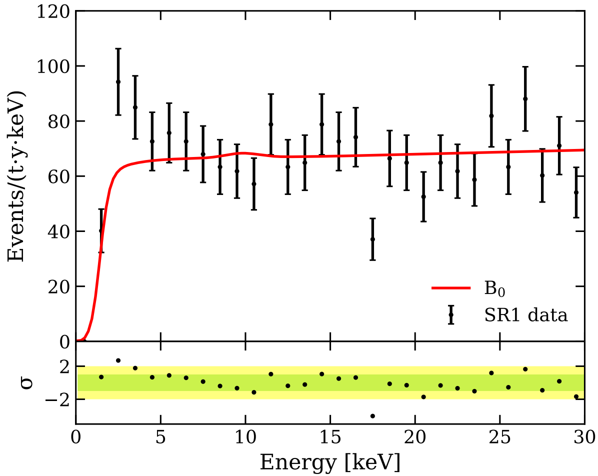
We are members of the **GERDA** and **LEGEND experiments**, which look for the **neutrinoless double beta decay of ^{76}Ge** in high-purity Ge crystals immersed in liquid argon, with an unprecedented sensitivity.

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

Highlight: Excess events in XENON1T

The XENON1T detector was mainly built to detect interactions of dark matter particles, and has placed the world's most stringent limits on the coherent elastic scattering of weakly interacting massive particles (WIMPs) with xenon nuclei. Due to its exceedingly low background, it is also sensitive to other physics channels and rare events. XENON1T, which was operated underground at Laboratori Nazionali del Gran Sasso, used 3.2 t of ultra-pure liquid xenon, of which 2 t were within the sensitive region of the time projection chamber (TPC): a cylindrical volume that is observed by 248 photomultiplier tubes. The TPC, made out of materials with ultra-low radioactivity levels, allowed for the measurement of the scintillation and ionisation signals induced by a particle interaction. It provided a calorimetric energy measurement, a 3D position reconstruction, and the scatter multiplicity of events.

The data recorded between February 2, 2017 and February 8, 2018, was also analysed to search for solar axions and to look for an enhancement of the neutrino magnetic moment



The XENON1T data (black markers) displaying an excess over the background model, B_0.

from solar neutrinos. If detected, the presence of solar axions would signify a solution to the strong CP problem, hence providing an answer to one of the biggest open questions in particle physics. Also of fundamental importance, an enhancement in the solar neutrino flux could allow to clarify its nature, be it Majorana or Dirac. The analysis also included a search for bosonic dark matter candidates, namely dark photons and axion-like particles.

From an unbinned likelihood fit, the data revealed a surprising excess of events as compared to the expected background model in the low-energy region, as shown in the Figure. The data can be interpreted as a solar axion signal, with a significance of 3.4σ above background, an enhancement in the neutrino magnetic moment favoured at 3.2σ above background, or bosonic dark matter with a mass of 2.3 keV and a local significance of 3.0σ over background. The excess may also be due to a trace amount of tritium in the detector which, if present, would be favoured over background with a significance of 3.2σ. Thus far the XENON collaboration is unable to confirm the nature of the excess, given the available data from the XENON1T experiment; however further clarification is anticipated from the upcoming XENONnT experiment which is currently under commissioning. These results were published and featured in Physical Review D in October 2020 [2]. They have generated great interest in the community, incurring thus far over 200 citations, and have further demonstrated the sensitivity of large xenon TPCs to new physics channels.

Highlighted Publications:

1. Final Results of GERDA on the Search for Neutrinoless Double-BetaDecay,
   GERDA Collab., Phys. Rev. Lett. **125** (2020) 252502
2. Observation of Excess Electronic Recoil Events in XENON1T,
   XENON Collab., Phys. Rev. D **102** (2020) 7, 072004

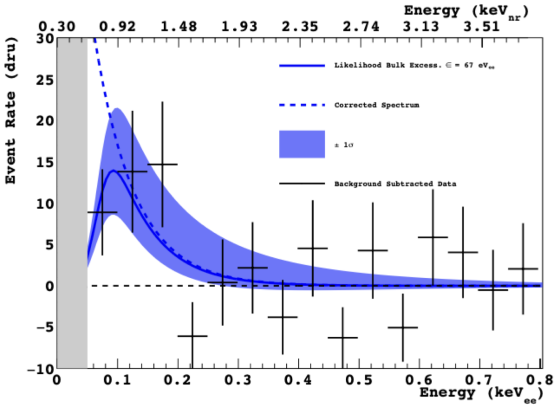
DAMIC Experiment

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. For DAMIC-M, we are currently developing a calibration system based on a radioactive isotope, electronics for digitizing the data, imaging software, the control and safety system, and a prototype of the detector with a vacuum interfacing cabling system.



In 2020, DAMIC@SNOLAB found an intriguing 3.4 standard deviation excess while searching for weakly interacting dark matter candidates. The background-subtracted data is shown in black crosses, with the fitted signal as a solid purple line [1].

1. Results on Low-Mass Weakly Interacting ..., DAMIC Collab., Phys. Rev. Lett. **125**, 241803 (2020)

CTA – Cherenkov Telescope Array

Prof. Prasenjit Saha

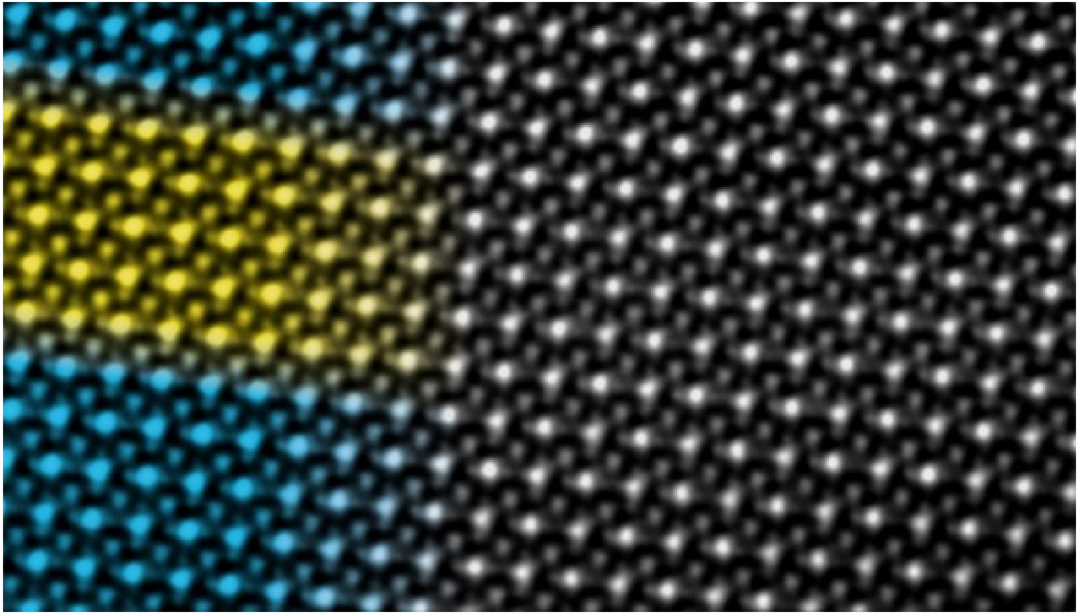
The Cherenkov Telescope Array (CTA) is a next generation facility for the detection of the most energetic gamma-rays from space, signatures of astrophysical particle acceleration. With more than 100 telescopes located in the northern and southern hemispheres, the Cherenkov Telescope Array (CTA) will extend the currently observable very high gamma ray spectrum by several orders of magnitude. The facility also has the potential to carry out optical intensity interferometry, which is the focus of current activity at UZH.

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

Located at the Fred Lawrence Whipple Observatory in Amado, AZ, the pSCT detected gamma-ray showers from the Crab Nebula in early 2020, proving the viability of the telescope design for gamma-ray astrophysics (Image: Amy C. Oliver, Center for Astrophysics | Harvard & Smithsonian).

CTA Homepage https://www.cta-observatory.org/

Condensed Matter Physics



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.

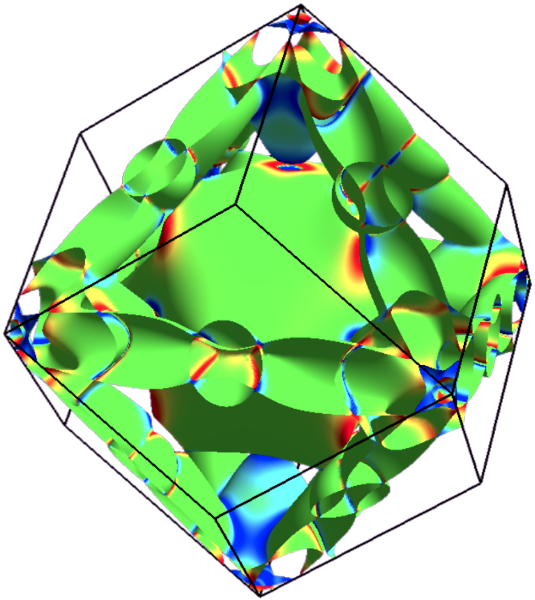
https://www.physik.uzh.ch/g/neupert

Numerical tools for first principles material modeling

Topology has become a major theme in studying quantum matter over the past decades. It is grounded in beautiful mathematical concepts and allows for the classification of phases of matter in a way that is complementary to the paradigm of symmetry breaking. Most excitingly, however, many of the theoretically conceived new phases have been found realized in actual materials over the past years. Their physics is often driven by spin-orbit coupling, with examples including two- and three-dimensional time-reversal symmetric topological insulators, Weyl and Dirac semimetals, and higher-order topological insulators. These discoveries were enabled by detailed predictions of first-principles calculations.

One thrust of our research, lead by Dr. Stepan Tsirkin, is to develop tools that allow to analyze the results of such calculations and further connect them to experimentally observable quantities. Two such tools have been released in 2020.

IrRep is a python tool that calculates the irreducible representation of Bloch eigenstates in the electronic band structure of a material. Along with the refinement of topological classifications came a renaissance of band theory. It has been realized that topological properties of a material can be ’read



Fermi surface of body centered cubic iron, colored by the Berry curvature computed using WannierBerri

off' its symmetry representations in many cases, leading to so-called symmetry-indicator topological invariants. Our IrRep code allows to extract the information needed for such an analysis based on the bandstructures computed with state-of-the-art density functional theory codes such as VASP, Quantum Espresso, or Abinit, as well as any other code that has an interface to the popular format of Wannier90.

WannierBerri is a code package that allows to compute very efficiently physical properties of materials that are related to their Berry curvature. Berry curvature, often characterized as a 'magnetic field in momentum space', is an intrinsic property of many materials, in particular spin-orbit coupled ones, and is intimately related to topological characteristics. For instance, a Weyl point is a monopole of diverging Berry curvature, leading to remarkable properties of Weyl semimetals. WannierBerri is capable of computing the intrinsic anomalous Hall and Nernst conductivities, the orbital magnetization, the nonlinear Hall effect, the gyrotropic magnetoelectric effect and many other response functions. Its capabilities are constantly expanding.

Highlighted Publications:

1. IrRep: symmetry eigenvalues and irreducible representations of ab initio band structures, M. Iraola *et al.*, arXiv:2009.01764
2. High performance Wannier interpolation of Berry curvature and related quantities with WannierBerri code, S.S. Tsirkin, npj Computational Materials 7, 33 (2021), https://www.nature.com/articles/s41524-021-00498-5
3. WannierBerri https://wannier-berri.org

Superconductivity and Magnetism

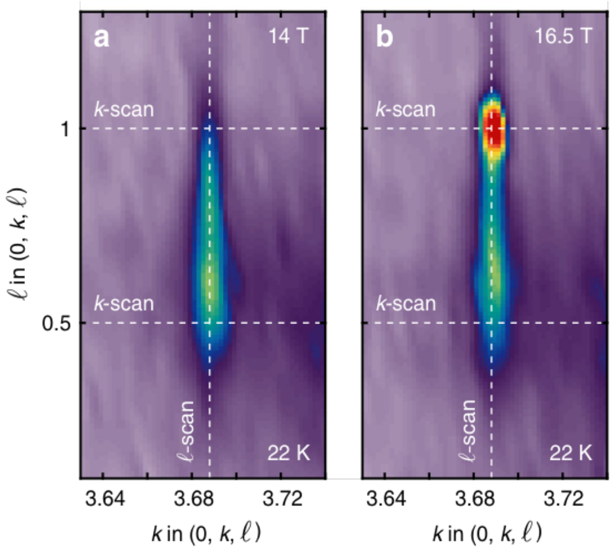
Prof. Johan Chang

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 single crystal synthesis through interdisciplinary collaborations with solid state chemists.

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

Two-flavor superconductivity

The charge density wave (CDW) in the high-temperature superconductor $YBa_2Cu_3O_{7x}$ (YBCO) has two different ordering tendencies differentiated by their *c*-axis correlations. These correspond to ferro- (F-CDW) and antiferro- (AF-CDW) couplings between CDWs in neighbouring CuO_2 bilayers. This discovery has prompted several fundamental questions: how does superconductivity adjust to two competing orders and are either of these orders responsible for the electronic reconstruction? With a x-ray diffraction study of $YBa_2Cu_3O_{6.67}$, we showed that regions with F-CDW correlations suppress superconductivity more strongly than those with AF-CDW correlations. This implies that an inhomogeneous superconducting state exists, in which some regions show a fragile form of superconductivity. By comparison of F-CDW and AF-CDW correlation lengths, it is concluded that F-CDW ordering is sufficiently long-range to modify the electronic structure. Our study thus suggests that F-CDW correlations impact both the superconducting and normal state properties of YBCO.



Charge density wave diffraction peaks in $YBa_2Cu_3O_{6.67}$ for temperatures and magnetic field as indicated.

High-temperature charge-stripe correlations.

Unconventional superconductivity is often associated with competing intertwined order parameters. For under-doped cuprate superconductors, the omnipresence of charge ordering has been established. By differentiating elastic from inelastic x-ray scattering signals of $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$, it is demonstrated that charge-stripe correlations precede both the structural low-temperature tetragonal phase and the transport-defined pseudogap onset. Likewise to other stripe-ordered compounds, the in-plane integrated intensity remains roughly temperature independent, so that our results are interpreted via a single scattering constituent. Due to this similarity, we provide a unifying picture for the charge-stripe ordering in La-based cuprates. As charge correlations in $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$ extend beyond the low-temperature tetragonal and pseudogap phase, their emergence heralds a spontaneous symmetry breaking in this compound.

Highlighted Publications:

1. Spatially inhomogeneous competition between superconductivity and the charge density wave in $YBa_2Cu_3O_{6.67}$
   J. Choi *et al.*, Nature Communications **11**, 990 (2020)
2. Oxide Fermi liquid universality revealed by electron spectroscopy
   M. Horio *et al.*, Physical Review B **102**, 245153 (2020)
3. High-Temperature Charge-Stripe Correlations in $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$
   Q. Wang *et al.*, Physical Review Letters **124**, 187002 (2020)

Oxide Interface Physics

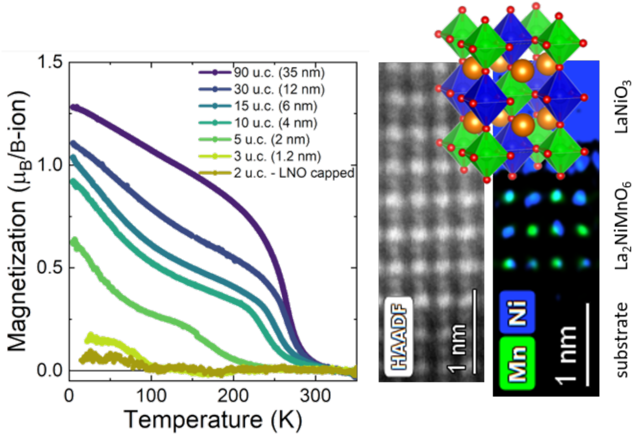
Prof. Marta Gibert

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 (TMOs) are an extensive class of compounds displaying a large variety of interesting 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. Especially attractive are not just the bulk compounds, but also the ability to create artificial layered materials by stacking different oxide compounds one on top of the other, i.e. in the so-called thin films and superlattice structure configurations.

As dimensionality is reduced, the effect of surfaces and interfaces starts to play a critical role in the behaviour of the electron system.[1] Polar/non-polar interfaces constitute a notable example, where a plethora of structural and electronic reconstructions occur leading to alterations of the respective bulk properties. This is the case of double-perovskite La_2NiMnO_6 thin films grown on (001)-oriented $SrTiO_3$ substrates. La_2NiMnO_6 is a ferromagnetic insulator with bulk Curie temperature $T_c \sim 280\,K$ provided that long-range order of Mn^{4+} - Ni^{2+} cations is achieved. By growing thin



Ferromagnetism is observed in double-perovskite La_2NiMnO_6 films as thin as 2-unit cells (0. 8nm) grown on $SrTiO_3$ substrates. By capping them with $LaNiO_3$, the undesired reconstructions associated with the polar discontinuity at film/substrate interface are overcome and the order of the Mn^{4+} - Ni^{2+} cations is recovered. © TEM - M. Rossell, EMPA.

films, we have shown that this is a very robust ferromagnetic behaviour independent of epitaxial strain.[2] Ferromagnetism is also observed in La_2NiMnO_6 films as thin as 2-unit cells (~0.8 nm), though both the Curie temperature and the saturation magnetization are reduced compared to the bulk counterpart (see figure). Detailed x-ray absorption spectroscopy (XAS) measurements, transmission electron microscopy (TEM) studies and first-principles calculations have revealed that the polar discontinuity is counteracted by the occurrence of electron-doping, oxygen vacancies formation and antisite disorder in the first 4-5 unit cells close to the substrate interface. Interestingly, by capping the film with $LaNiO_3$ layers, these interfacial reconstructions are overcome. As a result, $LaNiO_3$-capped 2-unit cells La_2NiMnO_6 films display $T_c \sim 80$ K, which corresponds to an increase of ~60 K with respect to the equivalent uncapped ones. The still existing difference to the bulk-T_c is attributed to the effect of dimensionality reduction. These results provide further understanding about the interplay between size reduction and fundamental physical properties in oxides thin films. At the same time, they open new venues of research by allowing to compensate the undesired effects often associated with interfacial polar discontinuities at oxides heterointerfaces through top-layer engineering while leaving the interface pristine.

Highlighted Publication:

1. Length scales of interfacial coupling between metal and insulator phases in oxides,
   C. Dominguez *et al.*, Nat. Mater. **19**, 1182 (2020)
2. Robust ferromagnetism in insulating La_2NiMnO_6 thin films,
   G. De Luca *et al.*, arXiv:2101.07530 (2020)

Low dimensional systems

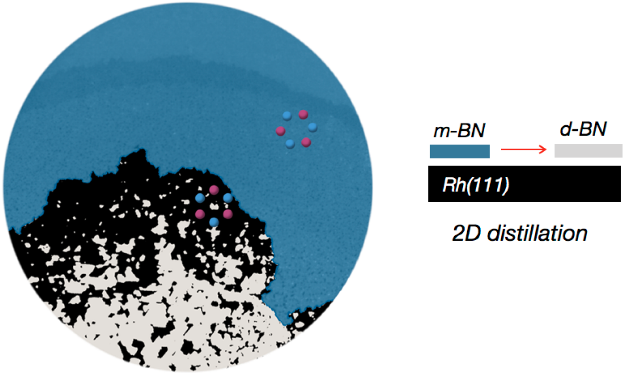
Prof. Thomas Greber

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 in the fullerene research, where we apply bulk sensitive x-ray absorption and a sub-Kelvin superconducting quantum interference device for the investigation of the materials that are obtained from collaborations with synthesis groups. In the 2D materials activity we aim to grow highest quality boron nitride on substrates up to the four inch wafer scale with chemical vapour deposition and subsequent exfoliation. For this purposes we use a dedicated clean room, optical microscopy, transmission electron microscopy and surface science tools such as low energy electron diffraction, photoemission and scanning tunneling microscopy.

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

Surface distillation of hexagonal boron nitride

Production of high-quality two-dimensional (2D) materials is critical to the full exploitation of their single layer properties and combination in hybrids. With respect to 2D electronic device performance hexagonal boron nitride (*h*-BN) is foreseen to become the key packaging material since it is atomically thin, impermeable, flat, transparent and chemically inert. Surface distillation is a new scheme to produce *h*-BN that is superior to material from chemical vapor deposition (CVD). Single layer CVD *h*-BN is delaminated from Rh(111) and transferred back to a clean Rh(111) surface. The twisting angle between BN and the new substrate yields metastable moiré structures (*m*-BN). Annealing above 1000 K leads to 2D distillation, i.e., catalyst-assisted BN sublimation from the edges of the transferred layer and subsequent condensation into superior quality *d*-BN. It is a low-cost way of high-quality 2D material production remote from CVD instrumentation [1]. The project is a collaboration with the Hong Kong University of Sci-



Illustrated frame from a movie of the 2D distillation process. Left: Colored LEEM image with a field of view of 23 μm at a process temperature of 910°C. The blue regions are covered with misaligned single layer boron nitride m-BN that has been back-transferred onto the Rh(111) substrate. The m-BN sublimates onto the Rh(111) substrate (black) where boron (pink) and nitrogen (light-blue) diffuse to the light grey regions where they condense into highly ordered d-BN, which is aligned to the substrate. The driving force for surface distillation is the lower chemical potential of d-BN. Right: Corresponding sketch of the 2D distillation process. (LEEM image Zichun Miao, HKUST).

ence and Technology (HKUST) where low energy electron microscopy (LEEM) experiments on our samples were performed (see Figure) and the UZH department of chemistry. The results lead to a joint UZH/HKUST patent application "A method for on-surface synthesis of a hexagonal boron nitride monolayer" that protects the production of single layer h-BN with high lattice quality. The method of surface distillation does not directly involve the use of precursor molecules from the gas phase, but the transfer of a single layer h-BN on a catalyst surface where this h-BN can be cleaned by mild thermal annealing leading to m-BN and further distilled to d-BN.

This activity is supported by the European Future and Emerging Technology flagship graphene.

Highlighted Publications:

1. High-Quality Hexagonal Boron Nitride from 2D Distillation
   H. Cun *et al.*, ACS Nano **15** 1351 (2020)
2. Gadolinium as an accelerator for reaching thermal equilibrium and its influence on the ground state of $Dy_2GdN@C_{80}$ single-molecule magnets
   A. Kostanyan *et al.*, Phys. Rev. B **103** 014404 (2021)
3. Sub-Kelvin hysteresis of the dilanthanide single-molecule magnet $Tb_2ScN@C_{80}$
   A. Kostanyan *et al.*, Phys. Rev. B **101** 134429 (2020)

Quantum Matter

Prof. Fabian Natterer

Our group investigates the properties of two dimensional quantum matter. We explore how materials receive their properties from the interaction between individual atoms that we can control with atomic precision. We furthermore study 2D van der Waal materials and develop new measurement protocols for advanced scanning probe microscopy investigations, such as electron spin resonance, nonlinear spectroscopy, and compressed sensing for quasiparticle interference imaging.

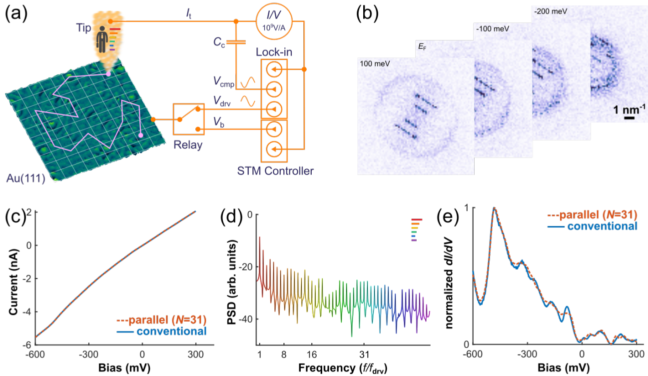
https://www.physik.uzh.ch/g/natterer

Fast Spectroscopic Mapping of Two Dimensional Material

The band structure of two dimensional quantum materials can be inferred from SPM measurements with quasiparticle interference imaging. It works by measuring the point spectroscopy (local density of states) at every topographic location. To speed up this traditionally slow technique, we introduce compressed sensing and nonlinear spectroscopy. While the former enables the measurement of fewer locations, the latter speeds up point spectroscopy. In combination, we achieve several orders of magnitude faster mapping. Measurements that would have lasted a week, can be done within minutes to few hours, enabling novel measurement concepts that were previously inconceivable. The time savings can be used to improve our spectroscopic resolution, to explore a vaster parameter space, or enable a faster measurement throughput, all promoting the discovery of novel quantum materials.

Scanning Probe Microscopy based ESR

Our second main projects is the development of novel spin sensors for electron spin resonance (ESR) with a scanning probe microscope. Our goal is to embed a molecular qubit into the SPM tip and use it as a detector for magnetic signatures at the atomic scale. This sensor will shed light on the spin texture of radicals, it can be used to scrutinize artificially



Combination of sparse sampling and parallel spectroscopy. (a) Experimental Setup. (b) QPI maps. (c) Point spectrum with nonlinearities that generate the harmonics shown in d. (d) Harmonics created by application of a harmonic drive that are used to measure the point spectrum much faster than conventionally. (e) Comparison of conductance obtained with conventional and parallel spectroscopy, showing great agreement at much faster pace.

built quantum matter and in the exploration of noncolinear magnetic structures. Our sensor would provide an alternative to nitrogen vacancy centers that have a limited spatial resolution.

Highlighted Publications:

1. Sparse sampling for fast quasiparticle-interference mapping, J. Oppliger and F. D. Natterer, Physical Review Research **2**, 023117 (2020)
2. Fast spectroscopic mapping of two-dimensional quantum materials, B. Zengin, J. Oppliger, D. Liu, L. Niggli, T. Kurosawa, F. D. Natterer, arXiv:2102.00054

Surface physics

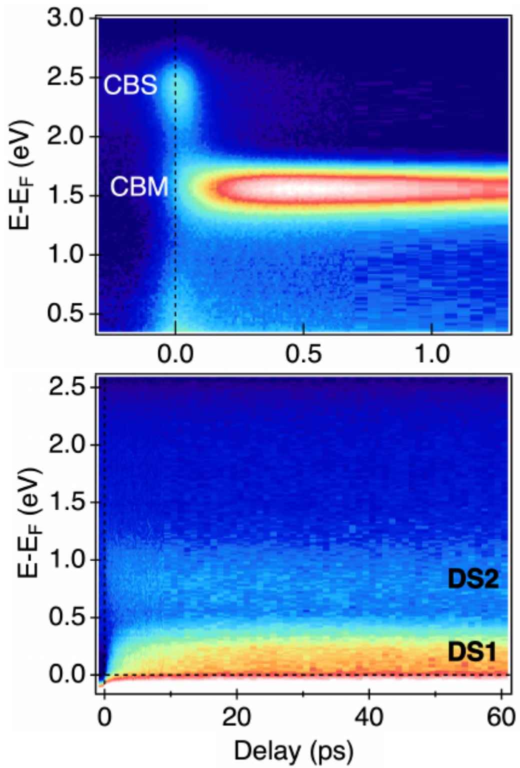
Prof. Jürg Osterwalder

We study processes at surfaces such as molecule adsorption and self assembly, charge and energy transport as well as fundamental aspects of **light-matter interaction** and associated electron dynamics. Our laboratory is equipped with a toolbox of surface science methods for the preparation and characterization of clean single-crystalline surfaces that can be used to investigate such phenomena **at the atomic and molecular level** and **at the femtosecond time scale**. Specific research projects include the structure and function of oxide semiconductor surfaces and interfaces that serve as model electrodes in water splitting devices, as well as the study of their interaction with small molecules at **solid-gas and solid-liquid interfaces**, using *in situ* **ambient pressure x-ray photoelectron spectroscopy** and x-ray absorption spectroscopy using our own endstation at the Swiss Light Source at PSI.

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

Carrier dynamics in a cuprous oxide photoelectrode

The direct splitting of water with solar light to form hydrogen gas as an energy carrier is a viable scenario for sustainable energy conversion and storage. Cuprous oxide (Cu_2O) is a promising material for use as a photocathode in photoelectrochemical cells for solar water splitting. It has a direct band gap of just the right size and a high absorbance for solar light, and it is Earth abundant and thus cheap. The relevant processes within the electrode involve the creation of electron-hole pairs, charge separation and transport to the surface. A downward band bending guides electrons through a protective layer to the surface, where a catalyst promotes the reduction of protons to form hydrogen molecules. The electron energy needs to exceed the redox potential for the water splitting reaction, and the transport within the conduction band of Cu_2O to the interface without energy loss is thus essential for an efficient device. Within the University Research Priority Program *LightChEC* we have studied these processes by means of time-resolved two-photon photoemission (2PPE).



2PPE spectra as a function of delay time after a pump laser pulse ($h\nu$ = 3 eV) has hit a $Cu_2O(111)$ sample. Data are shown for a defect-free surface (top), and for one on which a third of the surface oxygen atoms was missing (bottom).

Measurements on a defect-free $Cu_2O(111)$ surface show the ultrafast relaxation of photoexcited electrons (CBS) to the bottom of the conduction band minimum (CBM) with a decay time τ of 30 fs, where a strong population remains at the surface with τ = 10 ps. The same sample, but with a reconstructed surface missing one third of the oxygen atoms in the top layer, shows no trace of population in the conduction band. Instead, a long-lived occupation of defect states DS1 and DS2 is observed, with no decay measurable on a picosecond time scale. These results prove that surface and interface defects rather than bulk defects limit the performance of Cu_2O photocathodes.

Highlighted Publications:

1. Influence of surface defect density on the ultrafast hot carrier relaxation and transport in Cu_2O photoelectrodes
   L. Grad *et al.*, Scientific Reports **10**, 10686 (2020)
2. Dynamics of excited interlayer states in hexagonal boron nitride monolayers
   M. Hengsberger *et al.*, J. Phys. D: Appl. Phys. **53**, 203001 (2020)
3. Probing the solid-liquid interface with tender x rays: A new ambient-pressure x-ray photoelectron spectroscopy endstation at the Swiss Light Source
   Z. Novotny *et al.*, Rev. Sci. Instrum. **91**, 023103 (2020)

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 $^4He/^3He$ 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.

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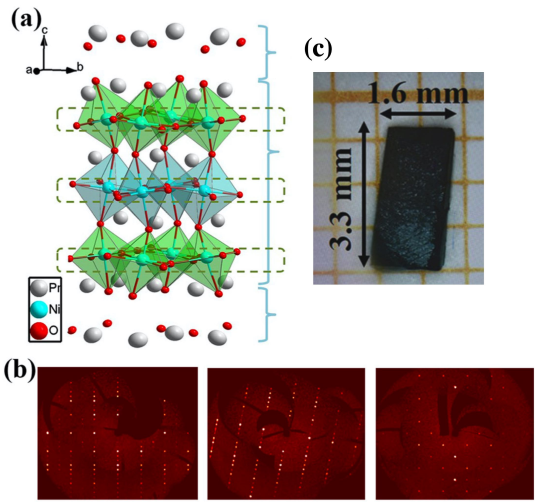
Infinite three-layer nickel-oxides as candidates for high-temperature superconductors

As a member of the Ruddlesden-Popper $Ln_{n+1}Ni_nO_{3n+1}$ series rare-earth-nickelates, $Pr_4Ni_3O_{10}$ consists of infinite quasi-two- dimensional perovskite-like Ni-O based layers (Fig. a). Although a metal-to-metal phase transition at $T_{pt} \approx 157$ K has been revealed by previous studies, a comprehensive study of physical properties associated with this transition has not yet been performed. We have grown single crystals of $Pr_4Ni_3O_{10}$ with an optical-image floating-zone furnace at high oxygen pressure in collaboration with PSI Villigen (Figs. b-c). The resistivity data indicate a metal-to-metal transition at T_{pt} within the $a-b$ plane and a metal-to-insulator-like transition along the c-axis upon cooling. The magneto-resistance (MR) is enhanced at T_{pt} and exhibits a sign change, which we attribute to a suppression of the first-order phase transition by a magnetic field.

We have furthermore successfully synthesized the series $Ln_{4-x}Ln'_xNi_3O_{10}$ (Ln and Ln$'$ = La, Pr and Nd). The



Crystal structure (a), Laue photographs (b), and a picture (c) of the grown $Pr_4Ni_3O_{10}$ single crystal

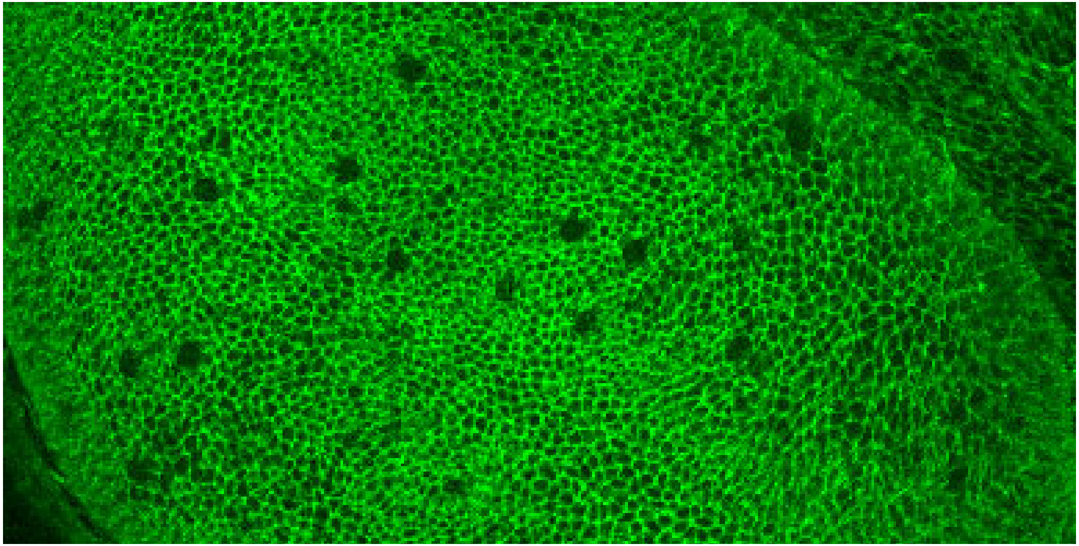
temperatures T_{pt} and the room-temperature resistivities vary systematically with the Goldschmidt tolerance factor t. With increasing t, the compounds become more conducting, which we attribute to a successively diminishing distortion of the NiO_6 octahedra which are responsible for the electron transport in these materials. While the bond lengths and Ni-O-Ni bond angles play a crucial role for the electronic structure, the magnetism of the Ln^{3+} ions is not a decisive factor.

We have synthesized $Pr_4Ni_3O_8$ by topotactic reduction of $Pr_4Ni_3O_{10}$. This compound features quasi-two-dimensional layers consisting of square-planar NiO_2 planes, in a similar way to the well-known T′-type cuprate superconductors. While $Pr_4Ni_3O_8$ is known to be metallic, little is known about the magnetic behaviour of this compound. A series of powder neutron diffraction, magnetization and μSR measurements on $Pr_4Ni_3O_8$ powders all show no evidence for long-range magnetic order in $Pr_4Ni_3O_8$. Our magnetization data clearly demonstrate a spin-glass behaviour with a freezing temperature $T_s \approx 68$ K and a distinct magnetic memory effect. The μSR data reveal two magnetic processes: a slowly-relaxing signal, resulting from paramagnetic fluctuations present at all temperatures, and a rapidly growing fast-relaxing signal due to the presence of short-range correlated regions in the glassy state below T_s.

Highlighted Publications:

1. Anisotropic character of the metal-to-metal transition in $Pr_4Ni_3O_{10}$, Sh. Huangfu *et al.*, Phys. Rev. B **101**, 104104 (2020)
2. Correlation between the tolerance factor and the phase transition in $Ln_{4-x}Ln'_xNi_3O_{10}$, Sh. Huangfu *et al.*, Phys. Rev. Research **2**, 033247 (2020)
3. Short-range magnetic interactions and spin-glass behaviour in the quasi-2D nickelate $Pr_4Ni_3O_8$, Sh. Huangfu *et al.*, Phys. Rev. B **102**, 054423 (2020)

Bio and Medical Physics



Disordered and biological soft matter

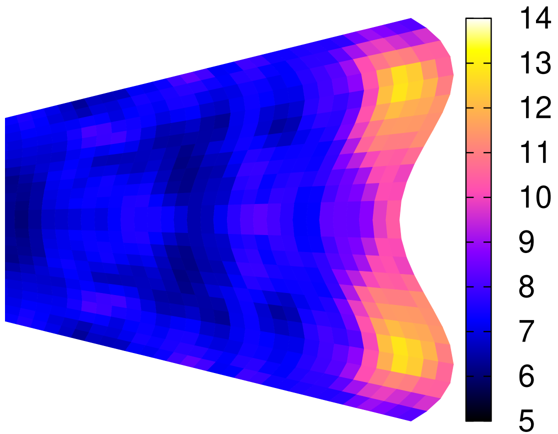
Prof. Christof Aegerter

We study the properties of disordered and heterogeneous systems out of equilibrium. This encompasses light transport in photonic glasses, imaging in turbid media, as well as the elastic properties of growing biological tissues and their influence on development, 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, however we also use computational modeling to guide these experiments. Our studies of light transport in disordered media have two main foci consisting of enabling imaging in turbid media, where we use wave-front shaping of the light to counter-act the effects of multiple scattering and optimisation of light absorbing materials for energy harvesting.

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

The influence of hydrodynamic forces on zebrafish fin regeneration

Zebrafish have the interesting property that they are able to regenerate their fins after amputation or injury. This regeneration is remarkably robust in that the final size and shape of the regenerate closely follows the original fin. Using changes in flow speeds during regeneration as well as flow changes due to different amputation geometries or biochemical treatments leading to narrower fins, we have however been able to show that this process also shows some plasticity driven by the hydrodynamic forces present from the water flows acting on the swimming fish during regeneration. To study this further, we have measured the full three-dimensional stress distribution on a fin using particle tracking velocimetry, which allows us to determine all components of the stress distribution. One such example for the proximodistal stress on the side of a fin is shown in the Figure.



Stress map of the absolute proximo-distal component, $|\sigma_{pd}|$, acting on the side of a fin-shaped flexible hydrofoil mimicking the elastic properties and geometry of a zebrafish caudal fin. Stress values in mPa are color-coded according to the depicted colourbar. Using such measurements on the spatial distribution of forces on differently sized and shaped fins, we are able to assess the possible influence of hydrodynamic forces during regenerative growth of zebrafish caudal fins..

Determining these force distributions for differently sized and shaped fins, we are then able to study the possible influence of these forces on growth and patterning of regenerating fins, where we find that the dorso-ventral stress component along the tip of the fin is fully consistent with acting as a growth activator during fin regeneration.

Highlighted Publications:

1. How shape and flapping rate affect the distribution of the fluid-force on a flexible hydrofoil
   P. Dagenais, and C.M. Aegerter,
   Journal of fluid mechanics **901**, 489 (2020)
2. Mechanochemical modelling of dorsal closure reveals emergent cell behaviour and tissue morphogenesis
   F. Atzeni, L. Pasykarnakis, G. Mosca, R.S. Smith, C.M. Aegerter, and D. Brunner,
   bioRxiv 2020.01.20.912725 (2020)
3. Hydrodynamic stress distributions on the surface of a flexible fin-like foil
   P. Dagenais, and C.M. Aegerter, PLoSOne **16**, e0244674 (2021)

Medical Physics and Radiation Research

Prof. Uwe Schneider

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

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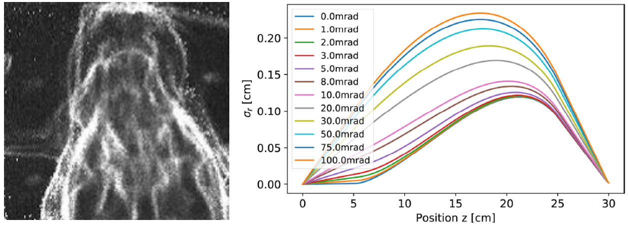


Proton radiography of the head of a dog on the left and spatial resolution which could be achieved with 200 MeV protons for different initial angular confusions (angular spread) on the right.

In 2020 one of the active research topics was the improvement of medical imaging with protons and Helium ions. In particular we were investigating the impact of air gaps for proton and Helium radiography and tomography, respectively. We are also developing novel radiation risk models for astronauts and a compact nanodosimetric detector which can be used to quantify the biological effectiveness of various radiations.

Highlighted Publications:

1. First Measurements of Ionization Cluster-Size Distributions with a Compact Nanodosimeter,
   Vasi F, Schneider U., Med Phys Lett. 2021 Jan 28
2. Investigation of the effect of air gap size on the spatial resolution in proton- and helium radio- and tomography ,
   Radonic S, Hälg RA, Schneider U., Z Med Phys. 2020 Jun 3; S0939-3889(20)30031-3

Medical Physics

Prof. Jan Unkelbach

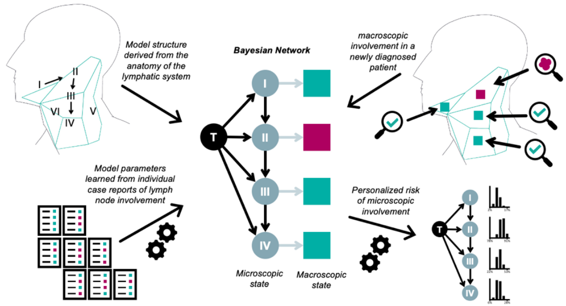
Radiotherapy is one of the mainstays of cancer treatment and a highly technology-driven field of medicine. In our research group, we contribute to the further development of radiotherapy technology by applying concepts from physics, mathematics, statistics, and machine learning to problems in medical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

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

We focus on three areas of research:

1) Radiotherapy treatment planning: We conduct research on mathematical optimization methods for radiotherapy planning to further improve treatment planning systems. In particular we investigate methods to optimally combine x-rays and protons.

2) Target delineation and outcome prediction: Here, we focus on quantitative 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.



Machine learning model of the lymphatic progression of cancer in the neck (from J. Unkelbach et al., *Radiotherapy & Oncology,* **153**:*p15-25, 2020)*

3) Adaptive radiotherapy: Our department is the first in Switzerland to install a MR-Linac, a combination of MRI scanner and radiotherapy device. MR images of a patient can be acquired during treatment such that moving tumors (e.g. in the lung) can be irradiated more precisely.

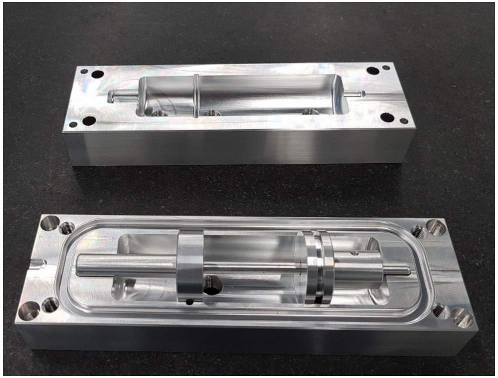
Workshops

Mechanical Workshop

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

http://www.physik.uzh.ch/groups/werkstatt

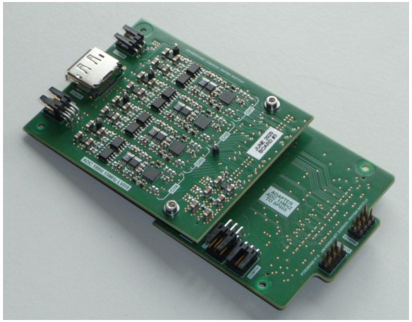




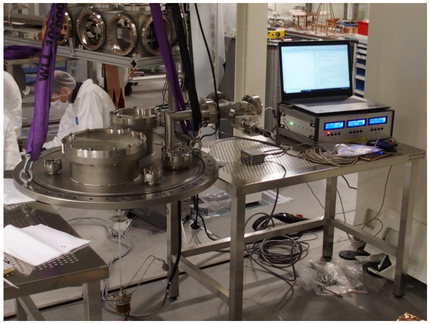
The three photograph are examples for work done in our workshop: copper flange for the Damic project of the group Kilminster (left), the Xenon experiment of the group Baudis in the MNF Exploratorium (middle) and coil potting mold for the group Chang (right).

Electronics Workshop

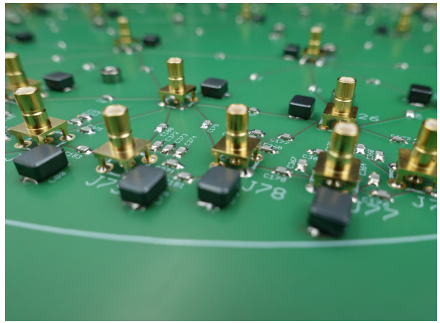
Besides maintenance work for the existing laboratory infrastructure the **electronics workshop** continuously supports the groups of our institute with technical advice, prototypes and new developments for ongoing projects. Besides many ongoing and newly developed projects for the research groups of our institute we developed the control cabinet for the DARWIN Demonstrator (group Baudis) that contains the power supply, safety circuits and slow control. Since it will be operated with voltages of up to 100 kV, a lot of effort had to be invested in personal safety.



4-channel ADC with 15Ms/s and 18-bit resolution for the DAMIC experiment (group Kilminster).

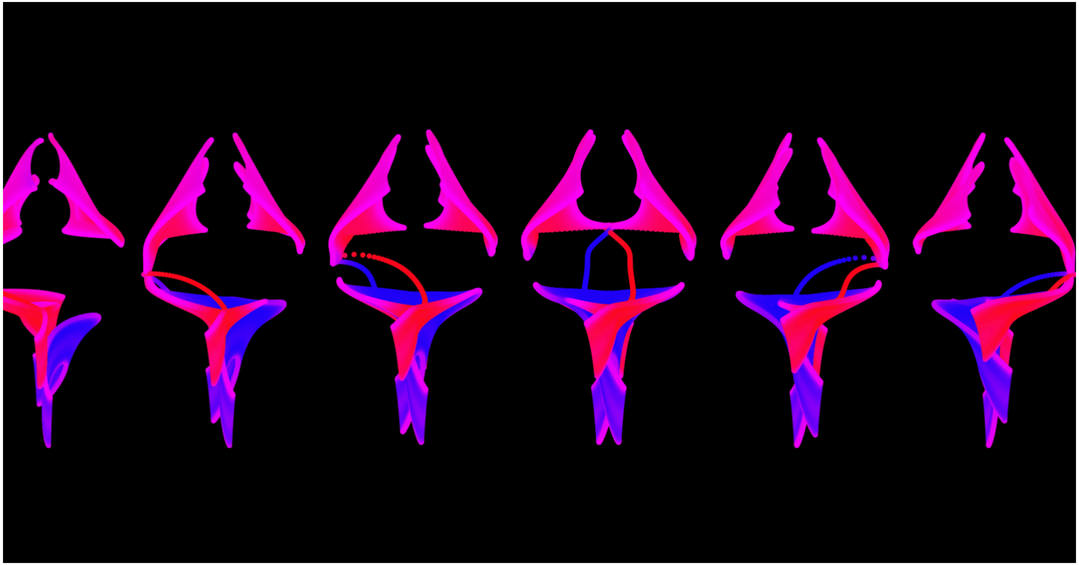


Test setup for the evaporation of the wavelength shifting reflectors for the LEGEND experiment (group Baudis).



Detail of a circuit that simulates the dynamics of wave propagation in a hyperbolic space (group Neupert).

Personnel



Personnel, January – December 2020

Secretariat
Gaby Aeppli
Denise Caneve
Brigitte Freund
Monika Röllin
Regina Schmid
Anna Troller

IT Coordination
Dr. Roland Bernet
Paul Käser

Lectures
Dr. Conrad Escher
Andreas James

Mechanical Workshop
Chris Albrecht
Gian Knüsel
Manuel Klokow
Bruno Lussi
Reto Maier
Brandon Markwalder
Noah Regensburger
Marcel Schaffner
Silvio Scherr
Stevan Vujmilovic

Electronics Workshop
Noah Ebner
Daniel Florin
Simon Karrer
Lorena Mastroberti
Dr. Achim Vollhardt
David Wolf

Group Christof Aegerter
Dr. Mirco Ackermann
Prof. Dr. Christof Aegerter
Dr. Marcella Bonifazi
Dominika Tworus
Dr. Valerio Mazzone
Dr. Lara Selvaggi

Group Laura Baudis
Prof. Dr. Laura Baudis
Yanina Biondi
Alexander Bismark
Adam Brown
Chiara Capelli
Dr. Michelle Galloway
Frédéric Girard
Lars Bjorn Iven
Dr. Junting Huang
Dr. Alessandro Manfredini
Dr. Neil McFadden
Yannick Müller
Ricardo Peres
Chloe Ransom
Gabriela Rodriguez Araujo
Kevin Thieme
Giovanni Volta
Dr. Shayne E. Reichard
Dr. Patricia Sanchez

Group Lea Caminada
Prof. Dr. Lea Caminada
Dr. Marino Missiroli
Lars Noethe

Group Florencia Canelli
Pascal Bärtschi
Daniel Brzhechko
Dr. Cristina Botta

Prof. Dr. Florencia Canelli
Dr. Kyle Cormier
Dr. Annapola de Cosa
Dr. Jaana Heikkilä
Sascha Liechti
Dr. Anna Macchiolo

Peter Meiring
Vinicius Mikuni
Dr. Alison Mitchell
Umberto Molinatti
Dr. Sergio Sanchez Cruz
Korbinian Schweiger

Weijie Jin
Dr. Sébastien Wertz
Dr. Adinda de Wit

Group Johan Chang
Dominik Biscette
Damian Bucher
Prof. Dr. Johan Chang
Dr. Jaewon Choi
Lakshmi Das
Dr. Ruggero Frison
Virginia Hernandez Leyva
Dr. Masafumi Horio
Kevin Kramer
Julia Küspert
Nehir Schmid
Dr. Tian Shang
Stefan Siegrist
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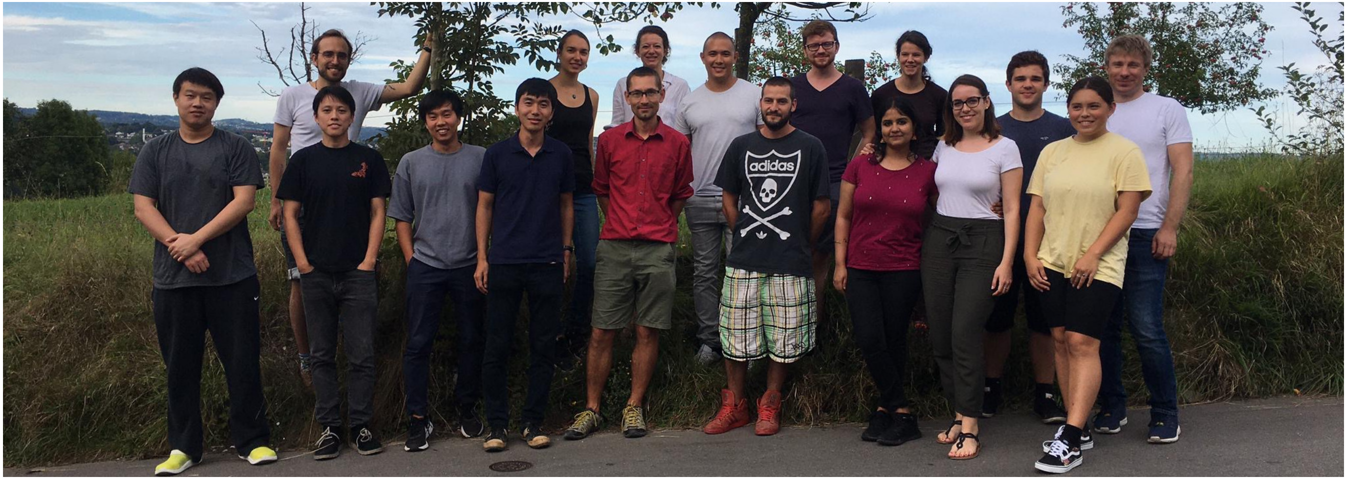
Karin von Arx
Dr. Qisi Wang
Catherine Witteveen
Dr. Yang Xu



Group Andreas Crivellin
Prof. Dr. Andreas Crivellin
Fiona Kirk
Claudio Manzari
Dario Müller
Dr. Marc Montull

Group Thomas Gehrmann
Dr. Xuan Chen
Prof. Dr. Thomas Gehrmann
Marius Höfer
Dr. Matthias Kerner
Matteo Marcoli
Jonathan Mo
Dr. Tiziano Peraro
Dr. Amedeo Primo
Robin Schürmann
Dr. Giovanni Stagnito
Dr. Tongzhi Yang

Group Marta Gibert
Simon Jöhr
Dr. Gabriele De Luca
Prof. Dr. Marta Gibert
Jonathan Spring

Group Massimiliano Grazzini
Luca Buonocore
Simone Devoto
Ignacio Fabre
Prof. Dr. Massimiliano Grazzini
Jürg Haag
Dr. Luca Rottoli
Chiara Savoini
Jeong Yeon Yook

Group Gino Isidori
Lukas Allwicher
Claudia Cornella
Dr. Darius Faroughy
Dr. Javier Fuentes-Martin
Prof. Dr. Gino Isidori
Dr. Matthias König
Dr. Javier Lizana
Prof. Dr. Matthias Neubert
Julie Pagès
Nudzeim Selimovic
Dr. Ben Stefanek
Dr. Olcyr Sumensari
Dr. Anders E. Thomson
Sokratis Trifinopoulos
Felix Wilsch
Dr. Kei Yamamoto

Group Marc Janoschek
Prof. Dr. Marc Janoschek
Simon Flury

Group Philippe Jetzer
Adrian Boitier
Michael Ebersold
Dr. Eleanor Hamilton
Dr. Maria Haney
Prof. Dr. Philippe Jetzer
Dr. Amir Khan
Dixena Lopez
Jan Ten Pierick
Prof. Dr. Prasenjit Saha
Dr. Shubhanshu Tiwari
Yumeng Xu

Group Ben Kilminster
Riccardo del Burgo
Marc Huwiler
Arash Jofrehei
Prof. Dr. Ben Kilminster
Steven Lee
Dr. Stefanos Leontsinis
Izaak Neutelings
Dr. Arne Reimers

Dr. Peter Robmann
Matias Senger
Dr. Yuta Takahashi
Dr. Stephan Wiederkehr

Group Fabian Natterer
Dr. Nicolas Bachellier
Danyang Liu
Prof. Dr. Fabian Natterer
Berk Zengin

Group Titus Neupert
Nikita Astrakhantsev
Dr. Bartholomew Andrews
Dr. Tomáš Bzdušek
Marta Brzezinska
Kenny Choo
Dr. Arkadiy Davydov
Michael Denner
Dr. Mark H. Fischer
Dr. Macei Koch-Janusz
Bastien Lapierre
Patrick Lenggenhager
Xiaoxiong Liu
Aleksandra Nelson
Prof. Dr. Titus Neupert
Frank Schindler
Anastasiia Skurativska
Dr. Luka Trifunovic

Dr. Stepan Tsirkin
Dr. Huaipiang Wang

Group Jürg Osterwalder & Thomas Greber
Dr. Sourav Banerjee
Jan Beckord
Nicolò Comini
Dr. Huanyao Cun
Dr. Trey Diulus
Lisa Grad
Prof. Dr. Thomas Greber
Christian Hanisch
Dr. Adrian Hemmi
Dr. Matthias Hengsberger
Thomas Kälin
Dr. Zbynek Novotny
Prof. Dr. Jürg Osterwalder
Mert Taskin

Group Prasenjit Saha
Philipp Denzel
Prof. Dr. Prasenjit Saha

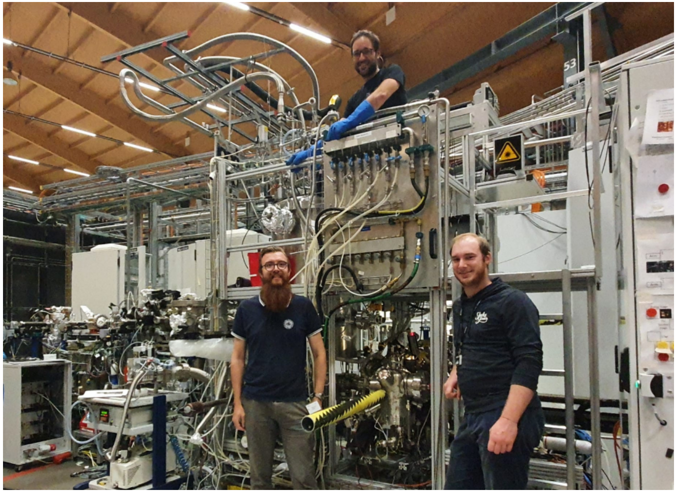
Group Stefano Pozzorini
Dr. Jean-Nicola Lang
Prof. Dr. Stefano Pozzorini
Hantian Zhang

Group Andreas Schilling
Shangxiong Huangfu
Dr. Hai Lin
Huanlong Liu
Prof. Dr. Andreas Schilling
Stefan Siegrist
Dr. Xiaofu Zhang
Dong Zhu

Group Nico Serra
Dr. Carlos Abellan Beteta
Michele Atzeni
Dr. Roland Bernet
Dr. Christopher Betancourt
Iaroslava Bezshyiko
Dr. Annarita Buonaura
Vadym Denysenko
Jonas Eschle
Dario De Simone
Martina Ferrillo
Dr. Julián García Pardiñas
Dr. Oliver Lantwin
Davide Lancierini
Dr. Abhijit Mathad
Dr. Andrea Mauri
Laura Meier-Villardita
Dr. Katharina Müller
Dr. Patrick Owen
Prof. Dr. Nicola Serra
Dr. Rafael Silva Coutinho
PD. Dr. Olaf Steinkamp
Zhenzi Wang
Andreas Weiden

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

Group Adrian Signer
Prof. Dr. Adrian Signer
Yannick Ulrich


53

University of Zurich
Department of Physics
Winterthurerstrasse 190
CH-8057 Zurich