University of Zurich$^{\text{UZH}}$

Department of Physics

Annual Report and Highlights 2021

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Zurich$^{\text{UZH}}$

Department of Physics

Annual Report and Highlights 2021

Winterthurerstrasse 190, CH-8057 Zurich, Switzerland

Preface

Thomas Gehrmann, Department Head

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

https://www.physik.uzh.ch/en/research.html

In 2021, our department was very happy to welcome three new research groups. Marc Janoschek holds a joint professorship appointment with the Paul-Scherrer-Institut (PSI), where he uses the state-of-the-art neutron, muon and photon facilities to probe quantum phenomena in bulk materials. Cristina Botta obtained an assistant professorship on the SNSF Prima programme, with a research group on the CMS experiment at CERN focusing on physics studies beyond the Standard Model and assuming important responsibilities in the upgrade of the CMS level-1 trigger system. Peter Stoffer obtained an assistant professorship on the SNSF Eccellenza programme, with a research programme in theoretical particle physics, especially focussing on low-energy precision physics and in close collaboration with ongoing experimental flavour physics activities at our department and at PSI.

The past year was again marked by the ongoing Covid-19 pandemic, which required the department members at all level to meet fastly changing boundary conditions in research and teaching with a lot of creativity, initiative and determination. Especially the experience gained with novel teaching

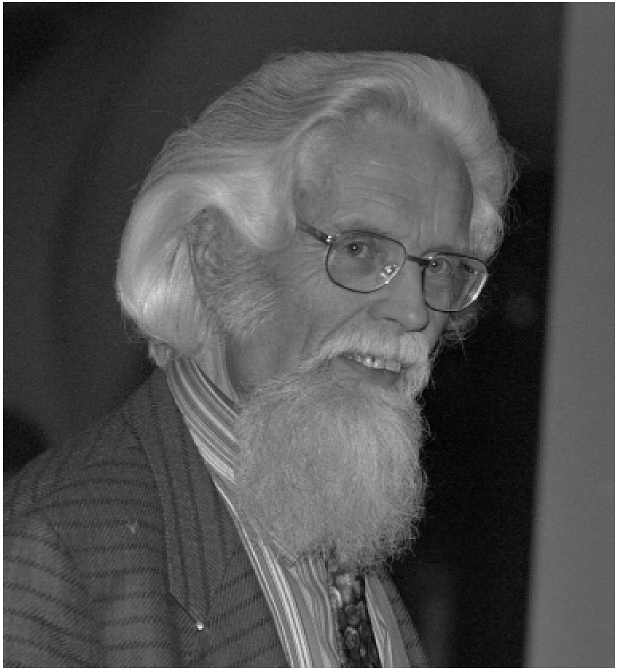
Impressions of the new chemistry building at Campus Irchel.

formats will remain in use once we are back to normal campus life.

Our department participated very actively in the Scientifica, the Zurich Science Days held in September 2021 and hosted for the first time also at Campus Irchel and on Höngerberg. Our researchers contributed with a lecture on LISA, a tour to XENOSCOPE, a science booth on the XENON and the LHC experiments, a physics show with lots of demonstration experiments and a theatre featuring 'three black holes at a bar'. The Science Exploratorium UZH was officially opened in November 2020 but first visitors were only allowed to enter in March due to the pandemic situation. Presently there are three exhibits from our institute on superconductors, search for Dark Matter and the CMS experiment, new exhibits are in planning. Guided tours for school classes and the general public are available at this new exhibit space at campus Irchel and help to increase the visibility of researchers and interest for the research. The opening of the UZI-5 buildings in 2021 mainly affected other departments on campus, but offers us access to new spaces especially for teaching and seminars.

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 in- dividual highlights with pride, we thankfully acknowledge the continued support from the Kanton Zürich, the Swiss National Science Foundation, the European Commission, and others who have made this fundamental research possible.

Prof. em. Roland Engfer, 1934 – 2021



Prof. em. Dr. Roland Engfer was Professor for Experimental Physics at our institute from 1975 until his retirement in 2001. Roland Engfer was an expert for rare and forbidden muon decays.

Roland Engfer studied and habilitated at the Technical University of Darmstadt under Professor Peter Brix. At that time, his research interest was in muonic atoms. These are exotic atoms with a negatively charged muon, forming a hydrogen-like system with the nucleus. Spectroscopy of exotic atoms teaches us how charges and magnetic moments are distributed in the atomic nucleus. He then worked as a researcher at CERN in Geneva and at the Paul Scherrer Institute (PSI, formerly the Swiss Institute for Nuclear Research SIN), as well as a lecturer at ETH Zurich. In 1975, Roland Engfer was appointed full professor of experimental physics at the University of Zurich as a successor of Hans H. Staub.

His research group in Zurich performed experiments at the Paul Scherrer Institute. The group first focused on particle emission following negative pion capture in nuclei but soon moved on to study rare and forbidden muon decays as a leading member of the SINDRUM I and II collaborations. Many new endevours are ongoing, not only at PSI, but most of the observed limits on lepton flavour number violation still stand. Roland Engfer thus became an internationally well regarded expert on exotic atoms and was a member of many international research commissions.

For many years Roland Engfer enthusiastically taught classical and modern physics to university students. As a stimulating lecturer, he inspired the students with his exciting lectures and original experiments. In doing so, he succeeded in conveying to the audience his fascination for the exploration of fundamental physics questions. Roland Engfer was a passionate cyclist, he rode his bike to the Irchel Campus every day, demonstrated biomechanics on the lecture hall stairs with his mountain bike and successfully fought for more bike stands as chairman of the University of Zurich Operations Committee. Also his experience as a mountaineer directly entered into his lessons; while rappelling in the lecture hall, friction, energy conservation and heat generation could be explained very vividly.

Roland Engfer was director of the Physics Institute of the University of Zurich from 1993 to 1999.

Statistical Data

202
personnel

- professors: 24
- associated professors: 11
- senior researchers: 17
- postdoctoral researchers: 51
- PhD students: 71
- engineers and technicians: 22
- administration: 6
- \+ research assistants

420
students

~80
new students

249 bachelor	33 BSc degrees
74 master	23 MSc degrees
97 PhD	12 PhD degrees

13
SNF prof.
and ERC grants

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

316
publications

291	peer reviewed papers
21	conference proceedings
4	books & others

259
conference and
workshop
contributions

103	talks at conferences
89	seminar and other talks
38	posters
29	outreach

Outreach

Awards

- Vera Hiu-Sze Wu: Dectris prize
- Kenny Choo: SPS thesis award
- Marino Missiroli and Cristina Botta: CMS award
- Karin von Arx: UZH Alumni FAN Award

Videos

- YouTube channel: demonstration experiments
- How particle physics works – The Anomalies strike back https://youtu.be/COXu8ntdTFU

Others

- Scientifica 2021 – Synthetic naturally
- Open Day of the institute
- Long Night of Museums
- Science & Nature Festival

Teaching

bachelor
3
major options

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

4
master
programs

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

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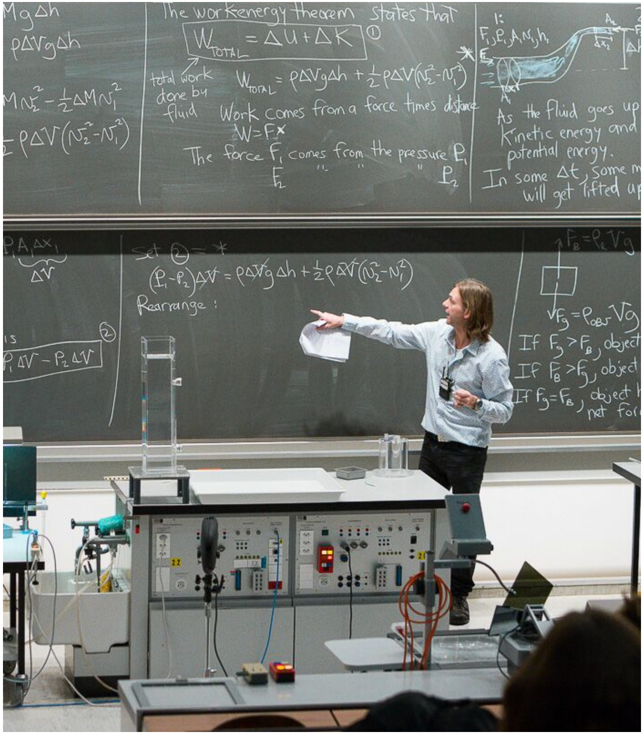
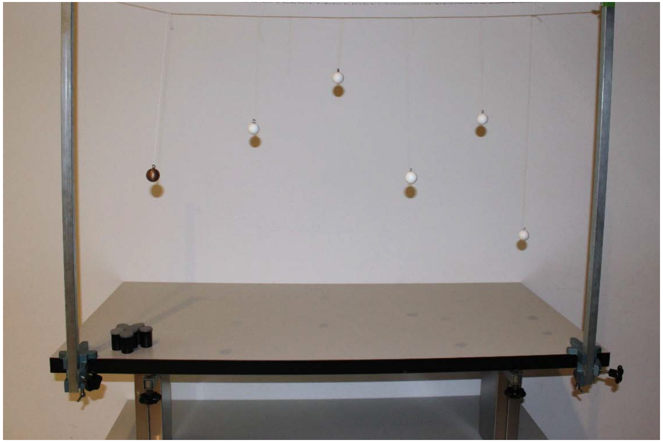
service lectures
1412
students

550	medicine
600	biology & biomedicine
170	chemistry
80	teacher
12	minors

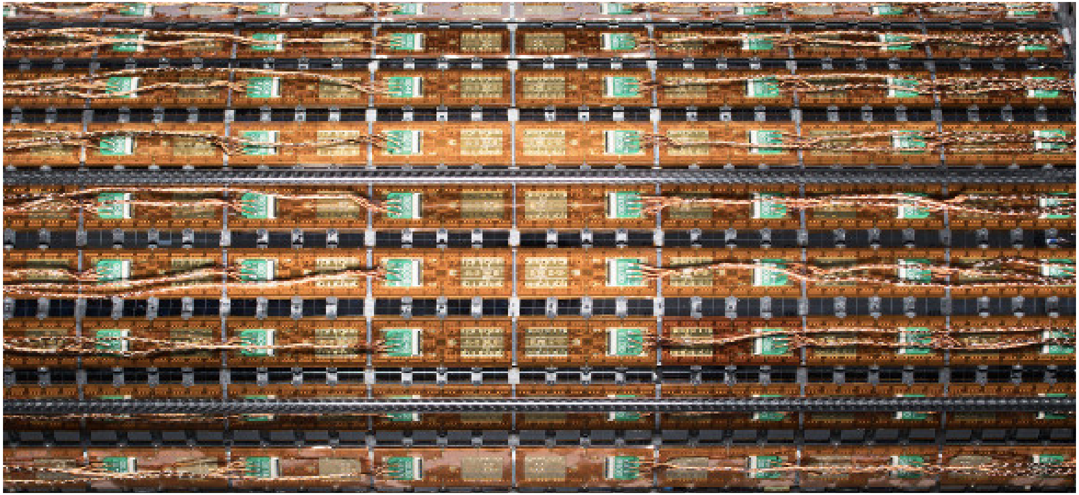


A visual experiment for resonance using pendulums of different length

To demonstrate the different aspects of resonance, i.e. its frequency dependence as well as the phase lag between excitation and response, we have developed a visual demonstration based on several coupled pendulums of different length. Due to the dependence on length of the Eigenfrequency of a pendulum, the different pendulums will respond with different amplitudes on the excitation provided by a heavier leading pendulum. As can be seen in the figure, the coupled pendulum of the same length will show a large resonant amplitude, while the other pendulums have greatly decreased amplitudes. Due to the direct visual accessibility of the different pendulums, the difference in phase of the excitation pendulum with the resonant pendulum can also be easily observed.



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

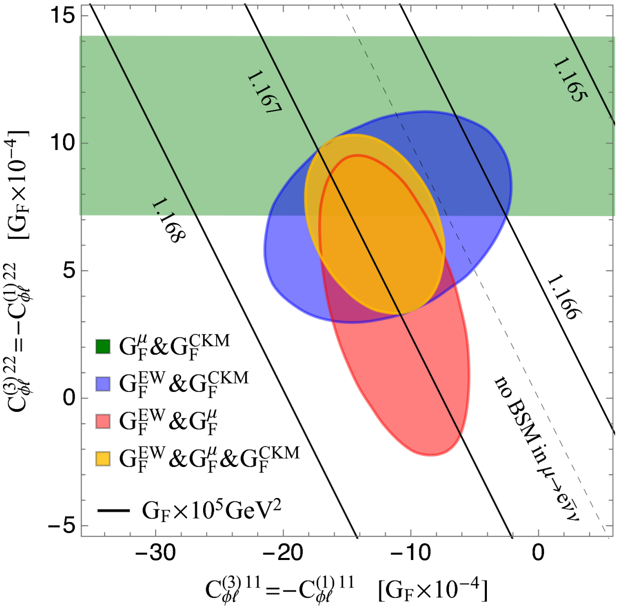
Hints for New Sources of Lepton Flavour Universality Violation

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, leading to different masses for particles of different flavour. Furthermore, all SM gauge interactions treat leptons in the same way; i.e. they respect lepton flavour universality (LFU) and the only source of LFU violation are the couplings of the Higgs.

However, several experiments found hints for deviations from lepton flavour universality in different observables [1], causing considerable interest within the theoretical community.

One of these observables is a precision measurements of a property of the muon called “anomalous magnetic moment”. Here we studied possible explanations in detail [2].

Furthermore, there exist discrepancies between different ways of determining elements of the aforementioned CKM



Example of the complementarity between the Fermi constant G_F determinations from muon decay (G_F^μ), CKM unitarity (G_F^{CKM}), and the global EW fit (G_F^{EM}) in case of $C_{\Phi\ell}^{(3)ii} = C_{\Phi\ell}^{(1)ii}$, corresponding to modifications of neutrino couplings to gauge bosons. Here, we show the preferred 1σ regions obtained by requiring that two or all three G_F determinations agree. The contour lines show the value of the Fermi constant extracted from muon decay once BSM effects are taken into account (from [1]).

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, possibly also related to muons [3].

Highlighted Publications:

1. Hints of lepton flavor universality violations,
   A. Crivellin and M. Hoferichter,
   Science **374** (2021) no.6571, 1051
   arXiv:2111.12739 [hep-ph]
2. Consequences of chirally enhanced explanations of
   $(g-2)$ for $h\to\mu\mu$ and $Z\to\mu\mu$,
   A. Crivellin and M. Hoferichter,
   JHEP **07** (2021), 135
   arXiv:2104.03202 [hep-ph]
3. Fermi Constant from Muon Decay Versus Electroweak
   Fits and Cabibbo-Kobayashi-Maskawa Unitarity,
   A. Crivellin, M. Hoferichter and C. A. Manzari,
   Phys. Rev. Lett. **127** (2021) no.7, 071801
   arXiv:2102.02825 [hep-ph]

Particle Physics Theory: Beyond the Standard Model

Prof. Gino Isidori

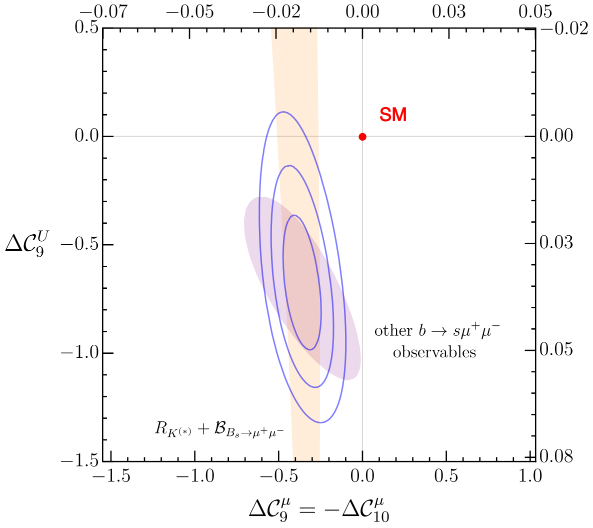
The Standard Model of fundamental interactions describes the nature of the basic constituents of matter, the so-called quarks and leptons, and the forces through which they interact. This Theory is very successful in laboratory experiments over a wide range of energies. However, it fails in explaining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

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 has been the main research activity of our group in the last five years. This research comprises three main directions: 1) the investigation of the consistency of the “anomalous” results with other data; 2) the construction of models able to describe the new data in terms of new interactions; 3) the analysis of the predictions of these new interactions for future experiments. In 2021 new experimental results by the LHCb experiment have strengthened the evidence of the anomalies. Motivated by these new results we have shown



Global fit of observables in $b \to s\ell^+\ell^-$ decays exhibiting deviations from the SM predictions.

how to obtain a conservative estimate of the overall significance of the anomalies irrespective of the hypotheses about the nature of physics beyond the SM. At the same time, we have refined the theoretical model developed in the last five years which provides a good description of all available data. This model is based on the hypothesis of a new force-mediator called “leptoquark”, transforming quarks into leptons and vice versa. We also developed general theoretical tools for the interpretation of new type of data expected by the LHCb collaboration in the next few years, which could provide a decisive test of this hypothesis.

Highlighted Publications:

1. Reading the footprints of the B-meson flavor anomalies, C. Cornella, D. A. Faroughy, J. Fuentes-Martin, G. Isidori and M. Neubert,
   JHEP **08** (2021), 050, arXiv:2103.16558 [hep-ph]
2. On the significance of new physics in $b \to s\ell^+\ell^-$ decays, G. Isidori, D. Lancierini, P. Owen and N. Serra,
   Phys. Lett. B **822** (2021), 136644,
   arXiv:2104.05631 [hep-ph]
3. The LFU ratio R_π in the Standard Model and beyond,
   M. Bordone, C. Cornella, G. Isidori and M. König,
   Eur. Phys. J. C **81** (2021) no.9, 850,
   arXiv:2101.11626 [hep-ph]

Particle Physics Theory: Precision Calculations

Prof. Thomas Gehrmann

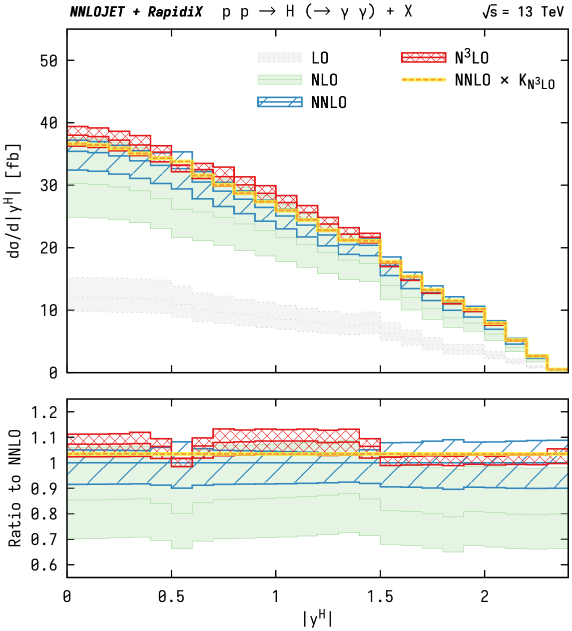
Our research group focuses on precision calculations for collider observables within the Standard Model and their application in the interpretation of experimental data. We develop novel techniques and computer algebra tools that enable analytical calculations in perturbative quantum field theory and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

Ultimate precision for fiducial Higgs cross sections

To address the fundamental nature of the Higgs boson and to measure its properties, it is of paramount importance to understand theoretically the features of its production and decay to a degree that rivals or surpasses the precision achieved by the experimental measurements. Predictions for fiducial cross sections that include realistic selection cuts on the final-state decay products of the Higgs boson will allow to compare theoretical predictions directly to experimental observations. To prepare for Higgs boson studies at per-cent level precision with future HL-LHC data, our group is currently developing methods and tools to perform fully differential calculations of fiducial cross sections that QCD corrections expanded up to third order (N3LO) in perturbation theory.

Fully differential predictions at higher orders in perturbation theory require special treatment for the cancellation of infrared singularities that appear at the intermediate stages of the calculation. The Projection-to-Born method accomplishes this through a special projection operation that allows matching an inclusive calculation to a differential calculation at one order lower but with an additional real emission. As a first application of this method to Higgs boson production at the LHC, we have focused on the di-photon decay mode of the Higgs boson. Combining the second-order (next-to-next-to-leading order, NNLO) QCD calculation of fully differential



Higgs boson rapidity distribution from di-photon final states at LO, NLO, NNLO and N3LO (newly computed, red) in perturbation theory, compared to approximate N3LO prediction (orange).

Higgs-boson-plus-jet production with the inclusive N3LO Higgs boson rapidity distribution, we obtain fully differential N3LO Higgs production cross sections.

The fiducial cross section in the di-photon decay mode is defined through cuts on the photon transverse momenta and rapidities as well as by isolation requirements on the photons. This setup induces a highly non-trivial interplay between the final-state photons and QCD emissions leading to kinematical features in the resulting distributions, seen prominently in the Higgs boson rapidity distribution in the fiducial di-photon channel (figure). We observe for example that in the central region of the rapidity distribution N3LO corrections are larger than expected from the inclusive correction factor, and that the corrections are not uniform in rapidity. Similar features are also observed in other kinematical distributions. Our results will enable a new level of quantitative precision for the study of the di-photon decay mode of the Higgs boson, and can possibly be extended to other channels.

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

Highlighted Publications:

1. Fully Differential Higgs Boson Production to Third Order in QCD, X. Chen *et al.*, Phys. Rev. Lett. 127 (2021) 072002.

Particle Physics Theory: Standard Model and Higgs Physics at Colliders

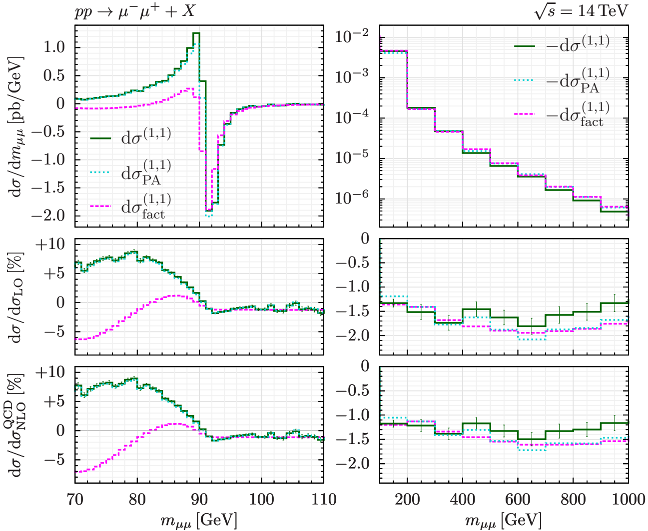
Prof. Massimiliano Grazzini

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 and jet production, to Higgs boson studies within and beyond the Standard Model.

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

Mixed strong-electroweak corrections to the Drell-Yan process

The Drell-Yan (DY) process is the most classic hard-scattering process at hadron colliders. It corresponds to the inclusive production of a lepton pair through an intermediate vector boson. It provides large production rates and clean experimental signatures, given the presence of at least one lepton with large transverse momentum in the final state. Historically, it offered the first application of parton model ideas beyond deep inelastic scattering and led to the discovery of the W and Z bosons at CERN SpS. The DY process was one of the first hadronic reactions for which radiative corrections in the strong and EW couplings α_S and α were computed. Radiative corrections for an on-shell vector boson are now known even at the third order in the strong coupling, at least for the inclusive cross section. Since the high-precision determination of EW parameters requires control over the kinematical distributions at very high accuracy, the attention has recently turned to the mixed QCD-EW corrections. The mixed corrections are exactly known for an on-shell vector boson. Beyond the on-shell limit, the most relevant results have been obtained in the *pole* approxi-



Complete $\mathcal{O}(\alpha_s\alpha)$ correction to the differential cross section $d\sigma^{(1,1)}$ in the dimuon invariant mass compared to the corresponding result in the pole approximation and to the factorised approximation $d\sigma^{(1,1)}_{\text{fact}}$. The top panels show the absolute predictions, while the central (bottom) panels display the $\mathcal{O}(\alpha_s\alpha)$ correction normalized to the LO (NLO QCD) result. For the full result the ratios also display our estimate of the numerical uncertainties.

mation, which is based on a systematic expansion of the cross section in the resonant region, so as to split the radiative corrections into well-defined gauge-invariant contributions.

Given the relevance of mixed QCD-EW corrections for precision studies of DY production and for an accurate measurement of the W mass, it is important to go beyond these approximations. Recently our group has presented the first complete computation of the mixed QCD-EW corrections for the neutral-current DY process [1].

The required tree-level and one-loop scattering amplitudes are computed with the Openloops and Recola generators, finding complete agreement. The two-loop virtual amplitude is computed by using semi-analytical techniques. Even when all the amplitudes have been computed, the completion of the calculation is highly non trivial. Indeed, double-real, real-virtual and purely virtual contributions are separately infrared divergent, and a method to handle and cancel infrared singularities has to be worked out. In our work we use a formulation of the q_T subtraction formalism derived from the second order QCD computation of heavy-quark production through an appropriate abelianisation procedure. The same method has been applied to the charged-current DY process [2].

1. Mixed Strong-Electroweak Corrections to the Drell-Yan Process, R. Bonciani *et al.*, Phys. Rev. Lett. **128** (2022) no. 1, 012002
2. Mixed Strong-Electroweak Corrections to the Drell-Yan Process, L. Buonocore *et al.*, Phys. Rev. D **103** (2021), 114012

Particle Physics Theory: Automated Simulations for high-energy colliders

Prof. Stefano Pozzorini

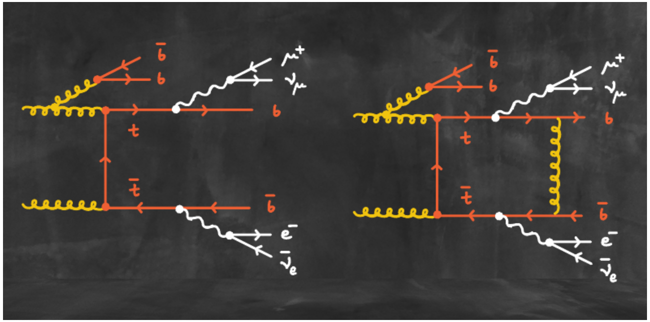
Our research deals with the development of automated methods for precision simulations of scattering processes in quantum-field theory. The OpenLoops program, developed in our group, is one of the most widely used tools for the calculation of scattering amplitudes at the LHC. OpenLoops is applicable 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

New algorithm for challenging multi-particle calculations

Recently we have developed a new algorithm for the calculation of first-order quantum effects in non-trivial multiparticle processes. Scattering processes can be described in terms of so-called Feynman diagrams, which encode the different quantum states that occur in the transition between the initial and final states of particle collisions. In this picture, first-order quantum effects correspond to "one-loop" diagrams that involve the exchange of virtual quanta with one unconstrained momentum and require the calculation of so-called one-loop integrals. The number of one-loop diagrams and the complexity of the associated integrals grow very fast with the number of scattering particles. For this reason, the preparation of precise predictions for scattering processes with more than four final-state particles can be very challenging. In particular, the required computing time can become prohibitively large. Moreover, the evaluation of one-



Examples of lowest-order (left) and one-loop (right) Feynman diagrams contributing to $t\bar{t}b\bar{b}$ *production at the LHC. This process can be initiated by various combinations of gluons, quarks and anti-quarks, and the depicted diagrams belong to the gluon–gluon channel, which involves more than 200'000 different one-loop diagrams. The orange curly lines represent gluons, the mediators of strong interactions, while red lines stand for top and bottom quarks or anti-quarks. White lines correspond to the weakly interacting particles that arise in top-quark decays:* W*-bosons, neutrinos and charged leptons.*

loop integrals can be jeopardised by large numerical instabilities.

To address these challenges we have developed a new algorithm, dubbed OTTER, that makes it possible to evaluate arbitrary one-loop integrals with unprecedented speed and numerical stability. This new tool will be made publicly available as part of a forthcoming release of the OPENLOOPS program, while its first applications have already appeared. Recently, together with collaborators at Würzburg and Cambridge University, the OTTER algorithm has been employed for the first full calculation of the first-order corrections to $t\bar{t}b\bar{b}$ production and decay [1] at the LHC. The precise theoretical understanding of this process plays a key role to test Higgs-boson interactions with heavy quarks, and the calculation at hand provides the first full quantum description of the $2 \to 8$ process that involves the production and decay of the top-antitop quark system. The OTTER algorithm has played a key role in enabling this highly non-trivial calculation, which involves several quark/gluon-initiated subprocesses with up to 200'000 one-loop diagrams.

The technical features of OTTER render it ideally suited also for high-precision calculations at the second order in perturbation theory, and this new algorithm is going to be a key building block for the automation of second-order calculations within the OPENLOOPS framework.

Highlighted Publications:

1. Full NLO QCD corrections to off-shell ttbb production,
   A. Denner, J-N. Lang, M. Pellen,
   Phys. Rev. D **104** (2021) no.5, 056018

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. The Paul Scherrer Institut (PSI) has obtained numerous lasting results with pions, muons and neutrons in the past decades and an overview has been compiled as a SciPost proceedings.

Using the world's most intense muon beam at PSI allows to look for tiny differences to the Standard Model or for extremely rare decays. Our group provides theory support for such experiments by computing higher-order corrections in Quantum Electrodynamics (QED) to scattering and decay processes and by systematically analysing the impact of experimental bounds on scenarios of physics beyond the Standard Model. These calculations are also adapted to experiments performed at other facilities with lepton beams.

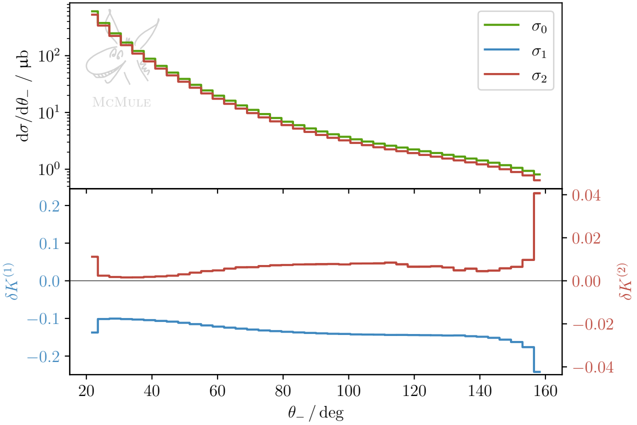
https://www.physik.uzh.ch/g/signer

Bhabha scattering at NNLO

Our group has set up McMule (Monte Carlo for MUons and other LEptons), a generic framework for higher-order QED calculations of scattering and decay processes involving leptons (`https://gitlab.com/mule-tools/mcmule`). 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.

After the implementation of several processes at next-to-leading order (NLO), recently we have calculated the photonic NNLO corrections to Bhabha (electron-positron) scattering. Currently, we treat Bhabha scattering as a pure QED process, restricting application to the low-energy domain, where the effect of the Z boson is negligible.

In QED it is important to keep the fermion masses at their physical value, rather than setting them to zero. This



Differential cross section $d\sigma/d\theta_-$ for Bhabha scattering at $\sqrt{s} =$ 1020 MeV, where θ_- is the scattering angle in the centre-of-mass frame of the outgoing electron. The relative NLO and NNLO corrections $\delta K^{(1)}$ and $\delta K^{(2)}$ are shown in the lower panel.

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.

Since the massive two-loop amplitudes for Bhabha scattering are not yet available, we had to apply 'massification'. This is a method that allows to obtain the dominant terms of the massive amplitudes from their massless counterpart. All terms that are not polynomially suppressed by the (small) mass are recovered. For the one-loop amplitudes we use OpenLoops. In addition we apply next-to-soft stabilisation, a method to use the analytic form of the soft limit to sufficient precision in order to guarantee a numerically reliable phase-space integration.

As a first application we have studied the impact of the full NNLO corrections for Bhabha scattering at $\sqrt{s} =$ 1020 MeV, compared to an earlier calculations with the code Babayaga, where the NNLO corrections are approximated through a parton-shower algorithm. The additional contributions of our calculation modify the NNLO coefficient by about 15%, in line with expectations. This amounts to a change of 0.07% for the total cross section. While this is a small correction, including corrections of this size is important when using Bhabha scattering as luminosity measurement for future electron-positron colliders.

Highlighted Publications:

1. Particle Physics at PSI, A. Signer, K. Kirch and C. Hoffman, SciPost Phys. Proc. **5** (2021)
2. Bhabha scattering at NNLO with next-to-soft stabilisation, P. Banerjee *et al.*, Phys. Lett. B **820** (2021) 136547

Effective Field Theories at the Precision Frontier

Prof. Peter Stoffer

The research of our group is focused on indirect searches for physics beyond the Standard Model and the theoretical challenges at the precision frontier: these concern the model-independent description of non-perturbative effects due to the strong interaction at low energies as well as higher-order perturbative effects that can be described within effective field theories.
Our current research activity is mainly motivated by experimental progress at the low-energy precision frontier, such as searches for CP- or lepton-flavor-violating observables and the improved measurement of the muon anomalous magnetic moment.

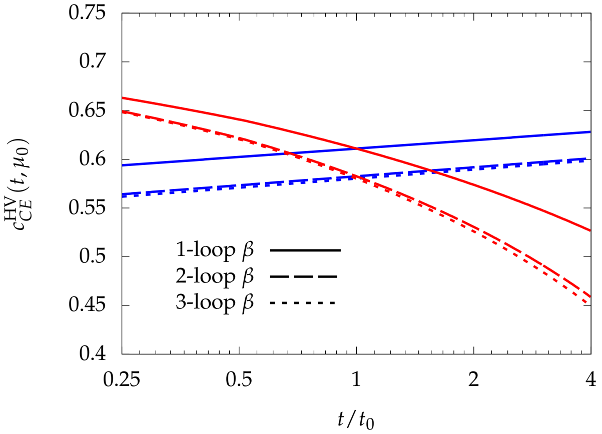
https://www.physik.uzh.ch/g/stoffer

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

CP and lepton-flavor violation

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

We recently worked out the one-loop matching for the dimension-five quark-dipole operators between the MS scheme used in EFTs and a gradient-flow scheme that can be implemented with lattice QCD. This calculation will enable the use of future lattice-QCD input for an accurate determina-



Scale dependence of the matching coefficient for the dipole operator between the MS-HV and gradient-flow scheme at an $\overline{\mathrm{MS}}$ *scale of 3 GeV. The calculated one-loop effect amounts to a correction of about* -40%.

tion of the dipole-operator contribution to the neutron EDM, which encodes effects beyond the SM.

Anomalous magnetic moment of the muon

The current SM prediction of the anomalous magnetic moment of the muon differs from the experimental value by 4.2σ. The theoretical uncertainty is dominated by hadronic contributions, i.e., effects due to the strong interaction, in particular hadronic vacuum polarization and hadronic light-by-light scattering. We are working on reducing these uncertainties using dispersion relations, which are based on the fundamental principles of unitarity and analyticity. In recent work, we analyzed the contribution of scalar resonances. On the other hand, within an EFT framework we worked out the potential contribution of heavy physics beyond the SM to one-loop accuracy, including renormalization-group and matching effects.

Highlighted Publications:

1. One-loop matching for quark dipole operators in a gradient-flow scheme, E. Mereghetti, C. J. Monahan, M. D. Rizik, A. Shindler, P. Stoffer, arXiv:2111.11449 [hep-lat], submitted to JHEP
2. A dispersive estimate of scalar contributions to hadronic light-by-light scattering, I. Danilkin, M. Hoferichter, P. Stoffer, Phys. Lett. B **820**, 136502 (2021), [arXiv:2105.01666 [hep-ph]]
3. Effective field theory interpretation of lepton magnetic and electric dipole moments, J. Aebischer, W. Dekens, E. E. Jenkins, A. V. Manohar, D. Sengupta, P. Stoffer, JHEP **07**, 107 (2021), [arXiv:2102.08954 [hep-ph]]

CMS Experiment

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

The CMS (Compact Muon Solenoid) experiment at CERN measures properties of the fundamental particles and their interactions, and can uncover new forces and particles. CMS surrounds one of the interaction points at the Large Hadron Collider (LHC), which when colliding protons produces an energy density comparable to that of the universe one ten- billionth of a second after it started. The CMS detector is used to determine the energy and direction of the energy and directions of the particles emerging from the LHC collisions of protons and heavy ions. In 2012, with 10 fb^{-1}, CMS discovered the Higgs boson, proving the mechanism on how particles acquire mass. The current dataset of 150 fb^{1} allows CMS to make precise measurements and searches for new physics. CMS is also focused on detector refurbishment for the data-taking period of 2022 to 2025, and upgrades needed for the high-luminosity run of the LHC from 2029 to 2038.

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

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

A leap forward in 2021 is the first observation of standard model triple J/Ψ production [1]. Most physics processes at the LHC occur when one parton, a quark or gluon, from each colliding proton interacts. Instead, in this new measurement, the dominant production mechanisms are when two (74% of the time) or three (20%) partons from each proton interact. This is the first time that the simultaneous production of three particles has been observed at the LHC. The process creates three J/Ψ mesons, each decaying to two muons, producing the spectacular signature of six muons (Fig. 1).

The discovery of the Higgs boson in 2012 has created more questions than answers, as its low mass is contradictory to theoretical expectations unless some new physics processes

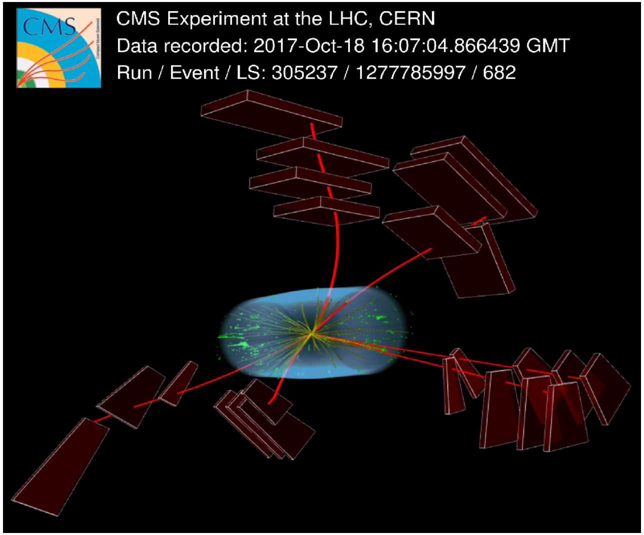


Fig. 1: In 2021, the UZH CMS group produced the first observation of the simultaneous production of three heavy particles. Shown is a Candidate event in which three J/Ψ *particles are produced. Each* J/Ψ *decays to two muons (red lines), which are observed in the tracker and dedicated muon chambers (red blocks).*

can stabilize it. A possible solution is a model where a new heavy particle couples strongly to the Higgs boson and other standard model bosons. In 2021, the CMS group searched for such a particle, and placed the most stringent bounds on its cross section as a function of its mass [2], up to 4.6 TeV, more than 25 times larger than the heaviest particle known.

Our group is performing searches for new particles that decay into weakly interacting massive particles (WIMPs) that could compose the dark matter of our universe. Our new search considers WIMPs produced in a compressed mass spectrum, meaning that the new particles have similar masses, such that when they decay into WIMPs and standard model particles, the detected particles have low momenta (Fig. 2). A compressed mass spectrum could be the reason why the LHC has not discovered dark matter yet. Searches for compressed particlesare experimentally challenging due to the very low momentum of the the observable particles, and therefore special reconstruction techniques are required. We make use of the identification of muons and electrons, with “soft" transverse momentum down to 3 and 5 GeV, respectively. In 2021, we used these techniques to produce new results extending the search for the supersymmetric partners of the Higgs boson [3]. The UZH CMS group also develops new tools for data analysis techniques inspired on modern methods of machine learning. In 2021, we created a pethod for point cloud information and applied it to jet-tagging of highly-boosted particles [4].

CMS will double its current dataset during the period of 2022 to 2025. UZH has played a major role in upgrading the pixel detector in 2017 to cope with the higher data rate and to provide better detector resolution [5]. The inner most pixel detector layer is subject to extremely high data rates and irradiation levels, and an improved inner layer was installed in June 2021 to mitigate these [6] (Fig. 3). Currently we are working on the testing and calibration of the detector to ensure a successful operation during the upcoming data-taking period.

CMS will collect more than 20 times the current data set during the period of 2029 to 2038. 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 billion pixels, and is capable of making 40 million measurements per second. In 2021, we carried out tests on prototype sensor modules integrated with the disk electronics and the pixel detector readout chain. 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. Using a new type of particle detector called an LGAD, we were able to measure a timing resolution of less than 40 picoseconds ($40 \cdot 10^{-12}$ s) in our lab, as well as demonstrate its high hit efficiency. Such a technology could greatly improve the physics potential of CMS in later upgrades.

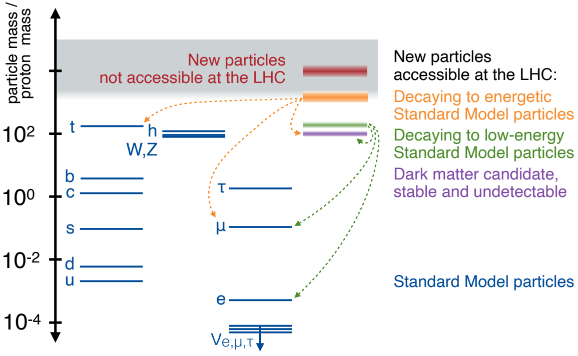


Fig. 2: A theory for dark matter in a compressed spectrum of new particles. New particles in yellow or green decay to standard model particles in blue and dark matter in purple. The mass difference between the new particle and its decay particles is small enough that the standard model particles are difficult to observe.

With the upcoming HL-LHC project, the CMS L1 Trigger, instrumented by custom hardware processor boards, needs to be redesigned to face the challenge of the high luminosity. The UZH group is involved in the design of a completely novel approach: the inclusion of tracking and high-granularity calorimeter information, together with a longer latency and a flexible and modular architecture, enables real-time state-of-the-art offline techniques, such as a global event reconstruction. The UZH group performed developments of new algorithms, implemented firmware, and emulated software to facilitate the performance studies of the proposed L1 trigger system. We have also played a major role in the Technical Design Report for the L1 trigger upgrade [7].

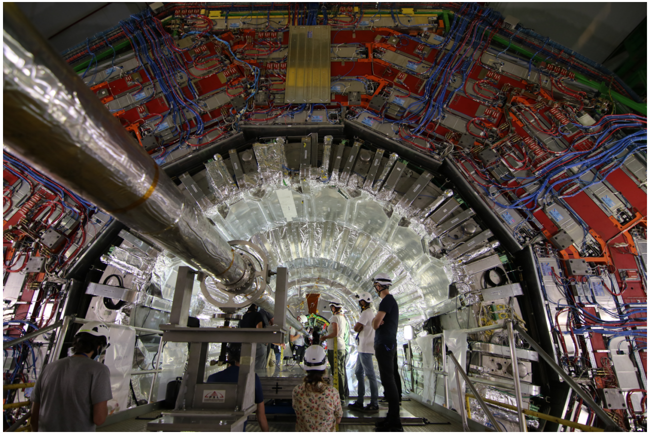


Fig. 3: After collecting data in 2017 and 2018, the CMS pixel detector inner layers were replaced in 2021 with new detectors designed to have better irradiation tolerance and higher rate capabilities for the data-taking period 2022 to 2025.

Highlighted Publications:

1. Observation of triple J/Ψ meson production in ...
   CMS Collab., https://cds.cern.ch/record/2790122
2. Search for a heavy vector resonance decaying to a Z ...
   CMS Collab., https://arxiv.org/abs/2102.08198
3. Search for supersymmetry in final states with two ...
   CMS Collab., https://arxiv.org/abs/2111.06296
4. Point cloud transformers ..., V. Mikuni and F. Canelli,
   https://iopscience.iop.org/article/10.1088/2632-2153/ac07f6
5. The CMS Phase-1 Pixel Detector Upgrade,
   CMS Tracker Group, https://inspirehep.net/literature/1838384
6. CMS Phase-1 pixel detector refurbishment ...
   L. Noethe, https://cds.cern.ch/record/2797711
7. The Phase-2 Upgrade of the CMS Level-1 Trigger,
   CMS Collab.,
   https://cds.cern.ch/record/2714892/files/CMS-TDR-021.pdf

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

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 contribute to an ongoing major uphgrade of the detector for 2023 and are involved in studies for future upgrades of the experiment.

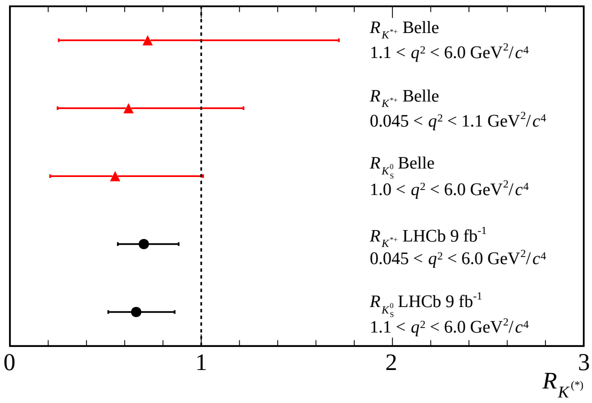
https://www.physik.uzh.ch/r/lhcb

New measurements strengthen hints of lepton universality violation

A distinctive feature of the Standard Model (SM) is the concept of lepton universality, whereby the charged leptons (electron, muon and tauon) have identical interaction strengths to the gauge bosons. 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.

Last year a high precision measurement of R_K was reported, for which the UZH group had a major role [2]. The measurement deviated from the SM prediction by 3.1 standard deviations (p-value $\sim 0.1\%$), constituting the first evidence of lepton universality violation from a single measurement. The discovery threshold in particle physics is 5.0 standard deviations and so more independent measurements, sensitive to the same physics are needed.

At the end of last year, LHCb reported two new lepton universality tests in the decays $B^+ \to K^{*+} K \ell^+ \ell^-$ with $K^{*+} \to K^0_s \pi^+$ and $B^0 \to K^0_s \ell^+ \ell^-$, where ℓ denotes either an electron or muon and K^{*+} and K^0 are mesons containing a strange quark [3]. These decays result in K^0_s mesons,



Comparison of the measurements of R_{K_s} and $R_{K^{*+}}$. Although the measurements are compataible with the Standard Model, they have values in the same direction as previous deviations [2].

which have a large lifetime and typically travel 2 meters in the experiment before decaying. This results in a lower statistical sensitivity compared to the previous measurement of R_K, but nevertheless provides an independent test of the underlying physics.

As for other lepton universality analyses, one of the main challenges is to control for the different detector response of electrons and muons. 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 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 ratios R_{K_s} and $R_{K^{*+}}$ were measured with the full run1-run2 dataset and were both found to be consistent with the Standard Model at the level 1.5 standard deviations. The results are shown alongside previous measurements made by the Belle and BaBar experiments. Interestingly, the central values of both these measurements are below the Standard Model predictions, which is in the same direction as previous, more precise, results which show deviations from the SM.

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. Tests of lepton universality using $B^0 \to K_S^0\ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$ decays, LHCb Collab., arXiv:2110.09501

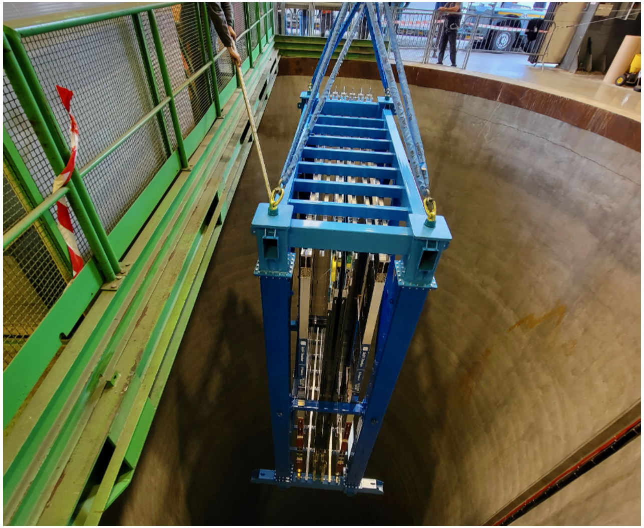
LHCb Experiment – Upgrade

Prof. Nicola Serra, PD Dr. Olaf Steinkamp

Since the end of the data taking in 2018, the LHCb detector has been undergoing a major upgrade. The goal is to accumulate five times more data in the next running periods of the LHC in order to increase the precision of previous measurements and to further extend the rich physics programme of LHCb.

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

All the front-end electronics have been changed to read out the full detector at the collider collision rate of 40MHz. Also, the average number of pp collisions will be multiplied by five, which makes track reconstruction more challenging and increases radiation damage. This implied that the full tracking system of LHCb had to be replaced. Our group is involved in the installation of one of the three new sub-detectors, the Upstream Tracker, as part of a large international effort to make the LHCb Upgrade detector ready to start recording very exciting new data sets for physics analysis in 2023.



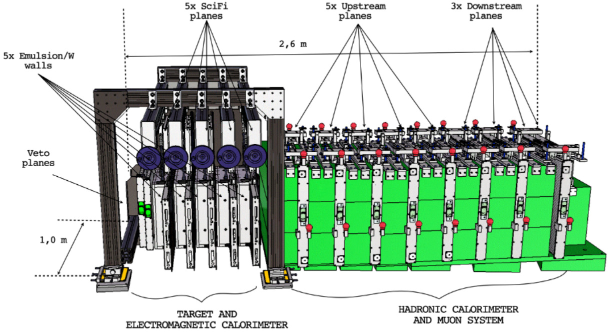
Lowering of part of the Scintillating Fibre detector into the LHCb cavern (Photo: Blake Leverington).

SND@LHC

Prof. Nicola Serra

SND@LHC is a compact experiment to exploit the high flux of energetic neutrinos of all three flavours from the LHC. It covers the pseudo-rapidity range of $7.2 < \eta < 8.4$, so far unexplored, in which a large fraction of neutrinos originate from charmed-hadron decays. Thus, neutrinos probe heavy-flavour production in a region that is not accessible to the other LHC experiments.

The UZH is a founding member of SND@LHC, and has spearheaded the design and construction of the veto and muon systems. The veto system aims at rejecting charged particles, mostly muons coming from ATLAS interaction point. It is located upstream of the target region and comprises two parallel planes of stacked scintillating bars read out on both ends by silicon photomultipliers. Downstream of the target region lies the hadronic calorimeter and muon system. Besides identifying muons it will serve together with the SciFi as a sampling hadronic calorimeter, enabling measurement of the energy of hadronic jets. The muon system comprises eight layers of scintillating planes interleaved between layers of iron slabs, which will act as passive material.



The experiment was approved in March 2021. Designs for the veto and muon systems were finalised in June, while construction was completed in the fall. Installation is nearly complete and the first physics runs will begin in June 2022.

Future Circular Collider (FCC)

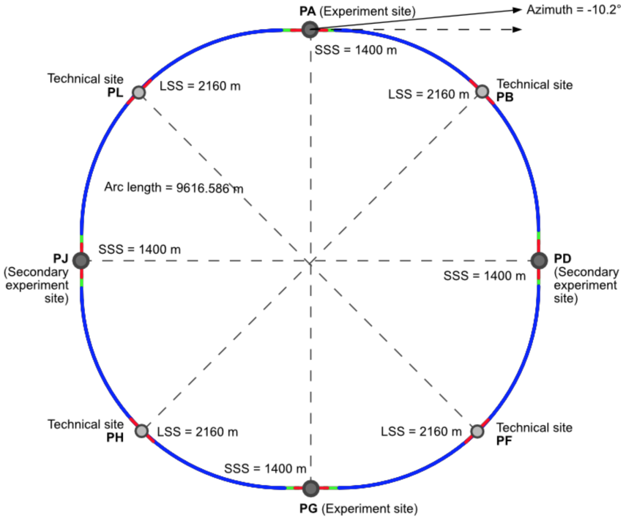
Prof. Florencia Canelli

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

In June 2021, the CERN Council endorsed the FCC feasibility study [2,3] with a budget of 100 MCHF to investigate the viability of the colliders and related infrastructure for the next Update of the European Strategy for Particle Physics in 2026. At the same time, our group started a collaboration with Vrije Universiteit Brussel (Belgium) to develop tracking detectors and algorithms for the FCC-ee.

A precise determination of the interaction vertices is crucial for the success of the FCC-ee physics program. Our group therefore develops state-of-the-art silicon sensors optimized for the Vertex detector at the FCC-ee. They feature a single point spatial resolution of a few microns while adding only a minimal amount of material to the detector. This enables a reliable determination of the jet flavour and to discriminate the decaying particles over a wide range of momentum, paving the way for flavour physics and precise Higgs coupling studies. In addition to this, our group implements modern analysis techniques, currently used at the LHC, into the FCC analysis framework and simulates the vertex detector performance to evaluate the potential physics reach of the FCC-ee.

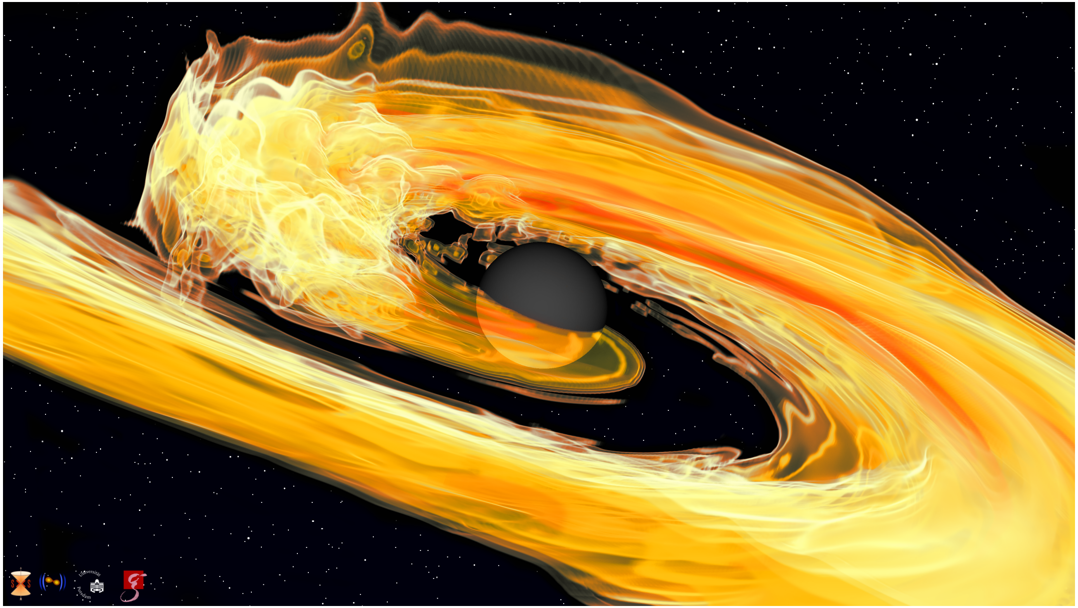


New FCC-ee baseline layout with four collision sites and circumference of 91.2 km. Source: J. Gutleber et al. https://indico.cern.ch/event/1065778

Highlighted Publications:

1. Future Circular Collider - European Strategy Update Documents,
   M. Benedikt et al., CERN-ACC-2019-0003 (2019)
2. Organisational structure of the FCC feasibility study,
   CERN, CERN/3566 (2021)
3. Main deliverables and timeline of the FCC feasibility study,
   CERN, CERN/3588 (2021)

Cosmology, Astro- and Astroparticle Physics



Astrophysics and General Relativity

Prof. Philippe Jetzer

LIGO (Laser Interferometer Gravitational-Wave Observatory) consists of two Earth-bounded instruments together with Virgo aimed to detect gravitational waves in the frequency range from about 10 to 1000 Hz. In 2015 the first gravitational wave signal has been detected. Since then about 90 events have been found. Our group has made important contributions to the analysis of LIGO/Virgo data and in the modelling of more accurate gravitational waveforms. The latter results will be used in LIGO/Virgo and for the future LISA mission and the Einstein Telescope project.

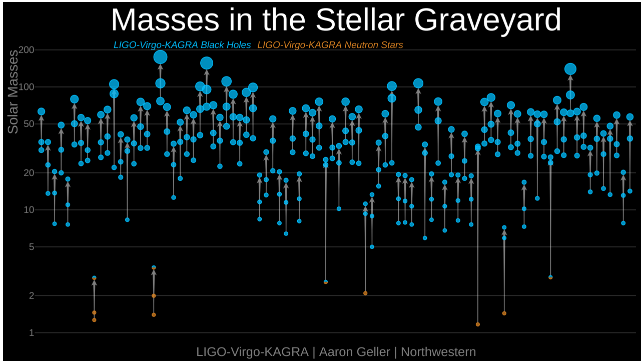
https://www.physik.uzh.ch/g/jetzer

Highlights

The work of the group is focused on the topic of gravitational waves in the framework of the LIGO Scientific Collaboration and for the future space mission LISA, since our group is involved in both these international collaborations. In the following we briefly describe some results published in 2021, besides all the works appeared in the framework of the LIGO/Virgo and LISA Pathfinder collaborations.

S. Tiwari, M. Ebersold and E. Hamilton developed a method to distinguish between binary-black-hole and neutron-star-black-hole systems by studying the effect of tidal disruption on the non-linear memory of the gravitational wave signal. This method is complementary to other methods of distinguishing these sources and is of particular relevance in cases where the observation of an electromagnetic counterpart from a neutron-star black-hole merger is unlikely. It will be most useful for observations made by third generation gravitational wave detectors, such as Einstein Telescope and Cosmic Explorer.

E. Hamilton and collaborators produced a model of the gravitational waves emitted by binary-black-hole systems in which the spins are oriented in an arbitrary direction. This is the first such model applicable to the complete inspiral-



Black holes of all shapes and sizes in the new gravitational-wave catalog (https://www.ligo.org/science/Publication-O3bCatalog/)

merger-ringdown signal where the spin effects have been tuned to numerical relativity. This model will be particularly relevant for the next observing run of the LIGO-Virgo-Kagra collaboration as we anticipate detecting a number of spinning binaries.

S. Tiwari and D. Lopez led the analysis and paper writing of the search for short duration generic transients for the LIGO-Virgo-Kagra collaborations.

A. Boitier, S. Tiwari and P. Jetzer derived a generic expression for the pulse redshift, the main observable for the Pulsar Timing Array (PTA) experiment for detection of gravitational waves for all possible polarizations induced by modifications of general relativity. In particular, we provided a generic expression of the overlap reduction function for PTA without using the short wavelength approximation for tensorial polarization. We derived a series expansion to calculate the integral exactly and investigated the behavior of the series for short wavelength values via numerical evaluation of the analytical series.

Highlighted Publications:

1. Leveraging gravitational-wave memory to distinguish neutron star-black hole binaries from black hole binaries,
   Phys. Rev. D**104** (2021), 123024, arXiv:2110.11171
2. Model of gravitational waves from precessing black-hole binaries through merger and ringdown,
   Phys. Rev. D**104** (2021), 124027, arXiv:2107.08876
3. All-sky search for short gravitational-wave bursts in the third Advanced LIGO and Advanced Virgo run,
   Phys. Rev. D**104** (2021), 122004, arXiv:2107.03701
4. Analytic series expansion of the overlap reduction function for gravitational wave search with pulsar timing arrays,
   Phys. Rev. D**103** (2021), 064044, arxiv:2011.13405

Theoretical Astrophysics

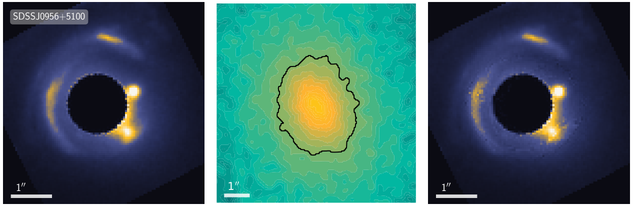
Prof. Prasenjit Saha

Our research has been on diverse astrophysical phenomena involving light and gravity, especially multiple-image gravitational lenses, but also spacecraft ranging as gravitational-wave sensors.

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

Galaxies that create multiple mirages of background galaxies through gravitational lensing have long been understood as a probe of dark matter and indeed the process of galaxy formation. As part of our long-running research in this area, we have now shown that it is possible to find simulated galaxies arising in galaxy-formation simulations that are plausible matches to observed lensing galaxies (see Figure).

In other work we explored the possibility of detecting the strongest LISA gravitational-wave events separately using spacecraft ranging, which would greatly improve sky localization compared to LISA alone.



The left panel shows four gravitationally-lensed images of a background galaxy. (The lensing galaxy itself has been cut out.) The middle panel shows a simulated candidate for the lensing galaxy, while the right panel shows the simulated lensed image.

Highlighted Publications:

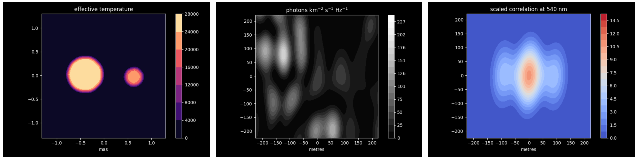
1. A new strategy for matching observed and simulated lensing galaxies, P. Denzel, S. Mukherjee, P. Saha, MNRAS **506**, 1815–1831 (2021)
2. Searching for gravitational waves via Doppler tracking by future missions to Uranus and Neptune, D. Soyuer, L. Zwick, D. J. D'Orazio, P. Saha, MNRAS **503**, L73–L79 (2021)

CTA – Cherenkov Telescope Array

Prof. Prasenjit Saha

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

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



Simulated interferometry of a binary star (Spica). The left panel shows the effective temperature, the middle panel its (not directly observable) interference fringes, while the right panel shows the observable auto-correlation of the fringes.

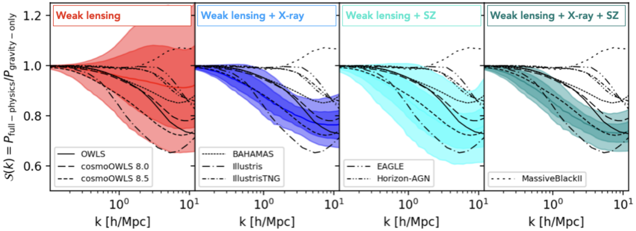
Highlighted Publications:
Radius measurement in binary stars: simulations of intensity interferometry,
K.N. Rai, S. Basak, P. Saha, MNRAS 507, 2813–2824 (2021)

Theoretical Astrophysics

Prof. Aurel Schneider (Institute for Computational Science)

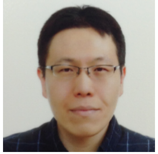
Research interests lie within the fields of cosmology and theoretical astrophysics, working on nonlinear structure formation as well as the astrophysical aspects of different dark matter models.

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



The observed shapes of galaxies contain information about the underlying matter distribution via the weak-lensing (light-deviation) effect. We use observations from the Kilo-Degree Survey (KiDS) to investigate how much the weak-lensing signal is affected by the black-hole driven ejection of gas from galaxy clusters. This so-called baryonic feedback effect consists of a very serious systematic for cosmological surveys (threatening their success in constraining fundamental physics). In our recent work, we show that the uncertainties from baryonic feedback can be overcome with the help of additional data from the distribution of gas around galaxy clusters (obtained via X-ray and kinematic Sunyaev-Zeldovich observations). Combining direct gas and weak-lensing observations, we find that baryonic feedback effects lead to a 20-30 percent suppression of the matter power spectrum, which is more than predicted by most simulations. The results are illustrated in the Figure , where the black lines show the results from various simulations, while the coloured bands indicate our constraints from observations.

Constraining baryonic feedback and cosmology...
Aurel Schneider *et al.* arXiv:2110.02228



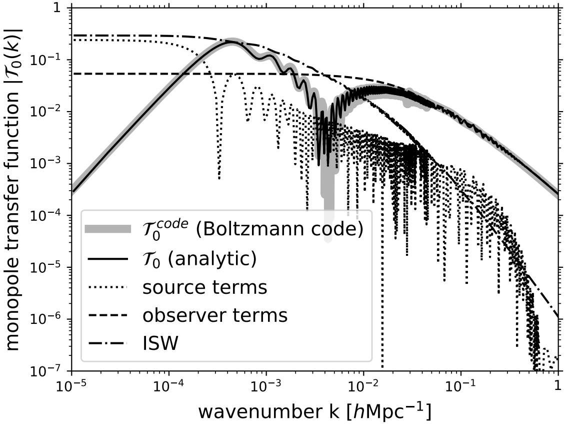
Theoretical Cosmology

Prof. Jaiyul Yoo (Institute for Computational Science)

The group is interested in large-scale structures of the Universe and focuses on developing gauge-invariant relativistic descriptions of the cosmological observables, performing numerical computations for their predictions in Einstein gravity or modified gravity theories.

https://www.ics.uzh.ch

In the standard model, the monopole fluctuation of the observed cosmic microwave background (CMB) temperature anisotropies is gauge dependent, and its power is infinite due to the infrared divergences, while the observations show the contrary. Here we resolved the theoretical issues associated with the infrared divergences and computed the finite monopole power. By recognizing that the background CMB temperature is in fact one of the fundamental cosmological parameters, we removed the ambiguity in defining the hypersurface and showed that the monopole fluctuation can be unambiguously defined and measured. Adopting simple approximations for the anisotropy formation, we derive a gauge-invariant analytical expression for the observed CMB temperature anisotropies to study the CMB monopole fluctuation and the cancellation of the uniform gravitational potential contributions on large scales.

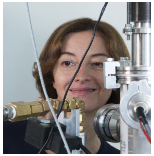


Gauge-invariant calculations (solid) show that all contributions to the CMB (dashed) are needed to cancel the infrared divergences.

Physical Review D **103**, 063516 (2021)

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.

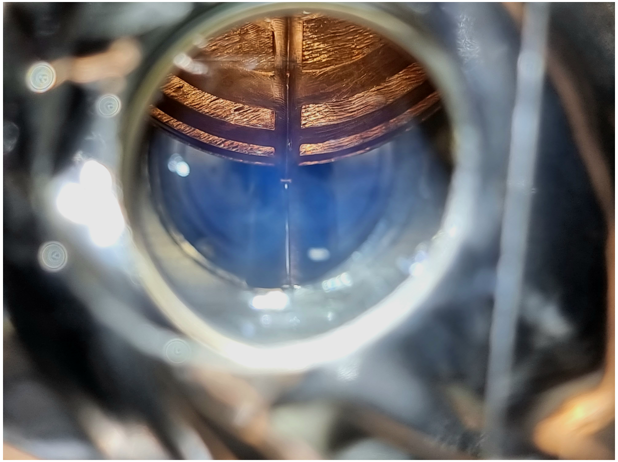
We are members of the **GERDA** and **LEGEND experiments**, which look for the **neutrinoless double beta decay of ^{76}Ge** in high-purity Ge crystals immersed in liquid argon, with an unprecedented sensitivity.

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

Highlight: Xenoscope

The DARWIN observatory is a proposed next-generation experiment to search for particle dark matter and other rare interactions. It will operate a 50 t liquid xenon detector, with 40 t in the time projection chamber (TPC). When a particle interacts with the liquid xenon target in a TPC, both scintillation and ionisation are produced. The scintillation photons are collected by arrays of photosensors, whereas the electrons produced from the ionisation process are drifted across the length of the TPC by an applied electric field. The electrons are then amplified via electroluminescence and collected as photons at the top of the detector. Achieving such an electron drift for the DARWIN TPC requires both high xenon purity to minimise electron capture along the anticipated 2.6 m length of the detector as well as the application of high voltage, on the order of -50 kV. To this end, a full-scale demonstrator in the vertical dimension, Xenoscope, was constructed in the assembly hall of the University of Zurich.

The design and construction of the facility infrastructure,



Liquefaction of xenon gas at -100 C and ∼2 bar, as viewed in Xenoscope during the system commissioning phase.

including the cryostat, cryogenic and purification systems, the xenon storage and recuperation system, as well as the slow control system, were completed in 2021, resulting in a technical design report published in the Journal of Instrumentation [1]. The publication details the system design and operation as well as the successful commissioning of the cryogenics and purification systems. Shown in Figure is the liquefaction of xenon as seen through a viewport in the system during the commissioning run. We demonstrated the nominal operational reach of Xenoscope and benchmarked the components of the systems, demonstrating reliable and continuous operation over 40 days.

Following the commissioning phase, a 50 cm purity monitor was designed, constructed, and installed inside the cryostat in order to benchmark the survival probability of electrons in the xenon. The purity monitor will be succeeded by a 1 m drift TPC, then followed by the full 2.6 m tall detector. In the future, the facility will also be a platform for testing several key technologies necessary to the realisation of the proposed DARWIN experiment.

Highlighted Publications:

1. Design and construction of Xenoscope – a full-scale vertical demonstrator for the DARWIN observatory,
   L. Baudis et al, JINST **16** (2021) P08052
2. A measurement of the mean electronic excitation energy of liquid xenon,
   L. Baudis, P. Sanchez-Lucas, K. Thieme,
   Eur. Phys. J. C **81** (2021) 1060
3. Calibration of the GERDA experiment
   GERDA collaboration (M. Agostini et al.),
   Eur. Phys. J. C **81** (2021) 8

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.

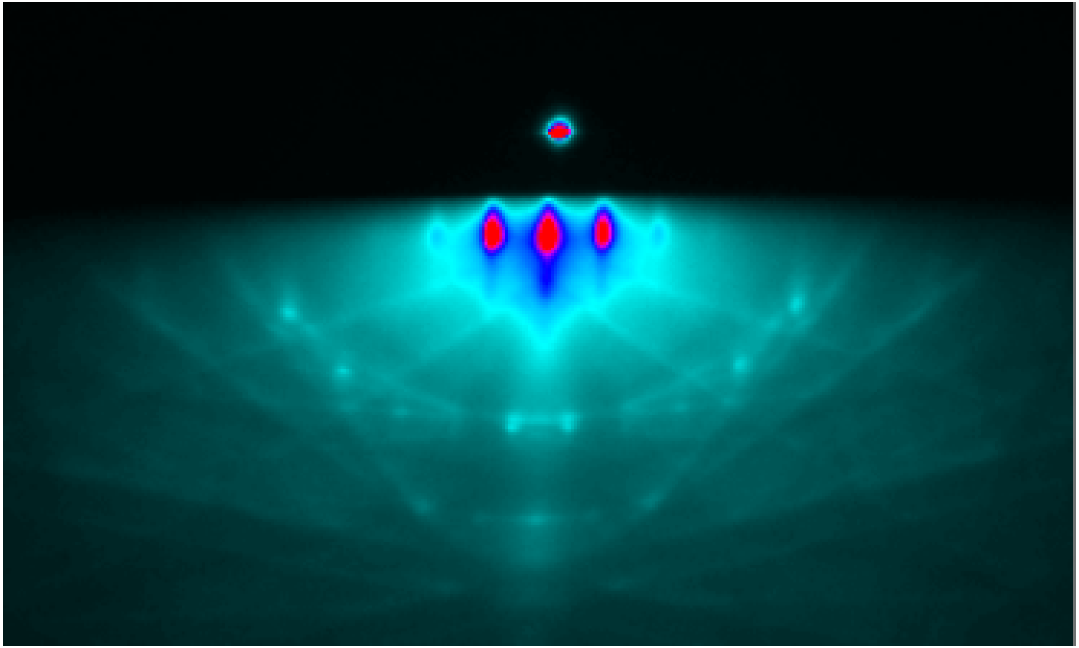
https://www.physik.uzh.ch/r/damic

Our group helped found the DAMIC experiment in 2008. For DAMIC-M, we have built mechanical components and a detector control and safety system for a prototype that has successfully collected data at the end of 2021. We have also developed and tested analog to digital electronics for the readout.

The new prototype DAMIC experiment, being installed in the Modane underground laboratory in France in November 2021. Shown are the copper box housing the CCD detectors, as well as lead and polyethylene shielding.

The copper box hosting the CCDs, top lead shield and in-vacuum electronics being inserted in the copper vacuum vessel.

Condensed Matter Physics



Condensed matter theory

Prof. Titus Neupert

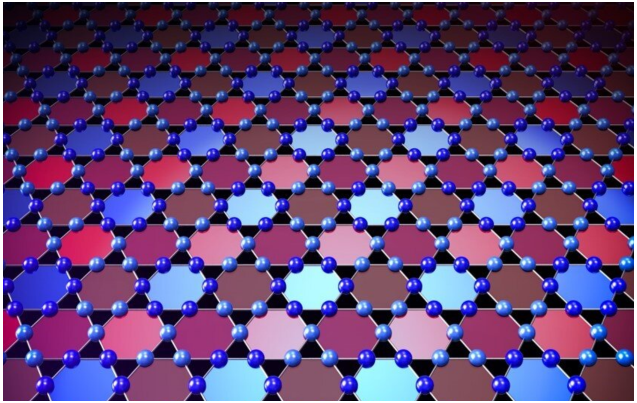
We study **topological phases of quantum matter** with numerical and analytical tools. Topological electronic states are characterized universal and robust phenomena, such as the Hall conductivity in the integer quantum Hall effect, that are of fundamental interest or promise applications in future electronics.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

Superconductivity and charge order in kagome compounds

Condensed matter physics is to a large extent concerned with the classification and characterization of all possible phases that many electrons can form in a crystal. The richness of such phases and their interplay comes with ever new surprises. Yet, there are certain materials in which physicists expect more interesting phases than in others, simply from their crystal lattice structure. A long-studied example is the kagome lattice, formed by corner sharing-triangles. Electronic states on the kagome lattice are strongly frustrated, meaning that simply ordered classical states are degenerate and a quantum-mechanical superposition is favored.

In 2021 we studied in intense collaborations with experimental groups from Princeton University and the Paul Scherrer Institute a new class of kagome lattice materials that harbor types of electronic order which were likely never probed before. The three compounds AV_3Sb_5 (A=K, Rb, Cs) all show charge order when cooled to 70–90 K and, at much lower temperature, superconductivity. In a charge ordered phase, electrons spontaneously modulate their density, thereby breaking some symmetries of the system. The symmetry breaking we found in the kagome metals is remarkable for two



Kagome lattice with a modulation of 2×2 *unit cells originating from unconventional charge order.*

reasons: (i) not only do the electrons break lattice symmetries, but they also break time-reversal symmetry by forming small loop currents on the lattice scale that generate magnetic fluxes; (ii) in contrast to previously observed charge orders, the electron-hole pairs attain a nonvanishing relative angular momentum in this state. To appreciate the importance of the latter, one should contrast charge orders with superconductors, in which electrons from particle-particle pairs. For them, higher-angular momentum states (e.g., d-wave superconductors such as the cuprates) are common. In contrast, charge orders are commonly implicitly considered to be of s-wave type and the higher angular momentum we found is a noteworthy exception. It is enabled by the unique electronic structure of the kagome lattice and relies on a sublattice interference mechanism through which certain electron waves become insensitive to the usually dominating local Coulomb repulsion.

Our findings were flanked by a flurry of research activities on these kagome metals. Their combination of quantum correlations, lattice frustration, and topological properties make them a unique material class to understand the interplay of these phenomena. A question that is largely open at this point is the nature of their superconducting phase. We have contrasted several scenarios in a theoretical study, but further experimental work is needed to differentiate between them.

Highlighted Publications:

1. Analysis of Charge Order in the Kagome Metal AV_3Sb_5 (A=K, Rb, Cs),
   Denner, M.M., *et al.*, Phys. Rev. Lett. **127**, 217601 (2021)
2. Unconventional chiral charge order in kagome superconductor KV_3Sb_5, Jiang, Y.-X., *et al.*, Nature Materials 20, 1353–1357 (2021)
3. Charge order and superconductivity in kagome materials, Neupert, T. *et al.*, Nature Physics, `https://doi.org/10.1038/s41567-021-01404-y` (2021)

Superconductivity and Magnetism

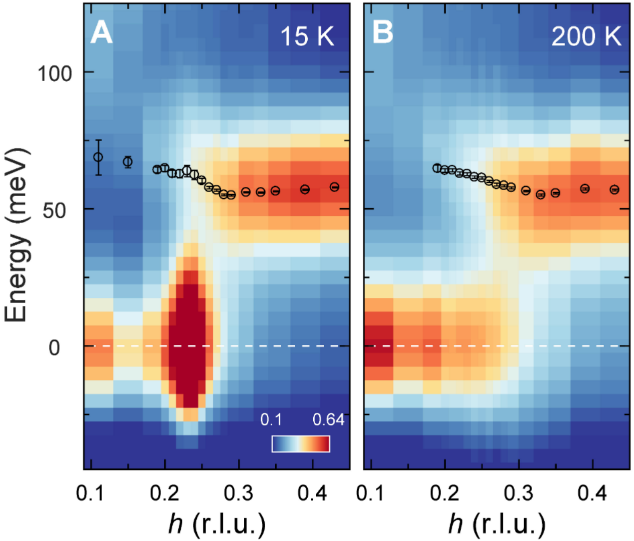
Professor Johan Chang

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

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

Charge order lock-in by electron-phonon coupling

Charge order is universal to all hole-doped cuprates. Yet, the driving interactions remain an unsolved problem. Electron-electron interaction is widely believed to be essential, whereas the role of electron-phonon interaction is unclear. Using ultrahigh-resolution resonant inelastic x-ray scattering (RIXS), we studied the in-plane bond-stretching phonon mode in stripe-ordered cuprate $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$. Phonon softening and lifetime shortening are found around the charge ordering wave vector, manifesting a significant electron-phonon coupling. In addition to these self-energy effects, the coupling strength is probed by its proportionality to the RIXS cross section. We find an enhancement of the electron-phonon coupling around the charge-stripe ordering wave vector at low temperature. Our study thus suggests that, in addition to electronic correlations, electron-phonon coupling contributes substantially to the emergence of long-range charge-stripe order in cuprates.



Temperature evolution of charge-stripe order and bond stretching phonon mode in $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$ probed by RIXS.

Unconventional Transverse Transport

As exemplified by the growing interest in the quantum anomalous Hall effect, the research on topology as an organizing principle of quantum matter is greatly enriched from the interplay with magnetism. Combining electrical and thermoelectrical transport, we studied the magnetic Weyl semimetal $EuCd_2As_2$. Unconventional contribution to the anomalous Hall and anomalous Nernst effects were observed both above and below the magnetic transition temperature of $EuCd_2As_2$, indicating the existence of significant Berry curvature. $EuCd_2As_2$ represents a rare case in which this unconventional transverse transport emerges both above and below the magnetic transition temperature in the same material. The transport properties evolve with temperature and field in the antiferromagnetic phase in a different manner than in the paramagnetic phase, suggesting different mechanisms to their origin. Our results indicate $EuCd_2As_2$ is a fertile playground for investigating the interplay between magnetism and topology, and potentially a plethora of topologically nontrivial phases rooted in this interplay.

Highlighted Publications:

- Charge Order Lock-in by Electron-Phonon Coupling in $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$
  Qisi Wang *et al.*, Science Advances **7**, 27 (2021)
- Unconventional Transverse Transport above and below the Magnetic Transition Temperature in Weyl Semimetal $EuCd_2As_2$
  Y. Xu *et al.*, Physical Review Letters **126**, 076602 (2021)
- Electronic reconstruction forming a C_2-symmetric Dirac semimetal in $Ca_3Ru_2O_7$
  M. Horio *et al.*, npj Quantum Materials **6**, 29 (2021)

Oxide Interface Physics

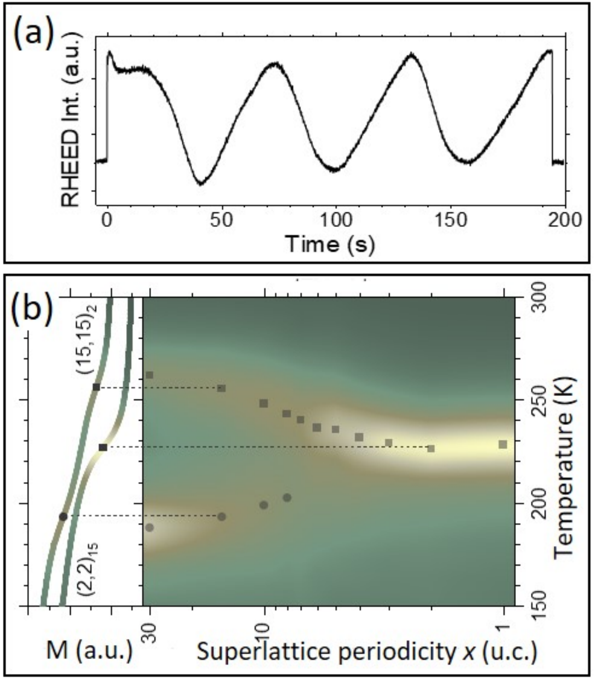
Prof. Marta Gibert

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.

In order to track atomic layer growth in situ, we have assembled a new custom-built RF magnetron sputtering setup featuring Reflection High Energy Electron Diffraction (RHEED). The presence of magnets in magnetron sputtering hampers the use of RHEED in conventional sputtering designs. Therefore, a unique design with the two sputter guns facing each other in order to compensate the magnetic fields was here required. The vacuum components for this new system were constructed by the mechanical workshop of the department. The electronics workshop contributed to the control electronics. This advanced tool enables us to grow complex oxide thin films



(a) Intensity of the specular RHEED spot during the sputter growth of 3 unit cells of Nd_2NiMnO_6*. (b) The left panel shows representative M(T) SQUID measurements for a* $(2,2)_{15}$ *and* $(15,15)_2$ *superlattice. The right panel shows the derivative dM/dT for all investigated periodicities x in a color scale. The discrete points indicate the magnetic transitions identified by local maxima in dM/dT.*

with atomic precision through real-time monitoring of the intensity of the specular RHEED spot. Each oscillation corresponds to the growth of one unit cell (u.c.), Fig. (a).

Currently, we are focusing on the growth of the double perovskites La_2NiMnO_6 and Nd_2NiMnO_6 which exhibit the rare combination of insulating behavior and ferromagnetism with respective magnetic transitions at 280 K and 200 K. Using the atomic precision of our new setup, we grow superlattices of the two materials with a fixed total thickness of 60 u.c.. They feature stacks of x u.c. of La_2NiMnO_6 and Nd_2NiMnO_6, respectively, which is repeated y times; denoted as $(x,x)_y$. We investigate the interplay between the two ferromagnetic constituents by in-house SQUID magnetometry as function of superlattice periodicity, Fig. (c). Field cooling experiments reveal a single transition for superlattices with small periodicities, suggesting that it is energetically favorable for the system to avoid splitting up into ferro- and paramagnetic layers. On the other hand, for superlattices of large periodicity we clearly identify two transitions with an intermediary temperature range where only the La_2NiMnO_6 experiences ferromagnetism. We identify a minimum of $x = 8$ u.c. for the appearance of two separate para- to ferromagnetic transitions.

1. Ferromagnetic insulating epitaxially strained ...
   G. De Luca *et al.*, APL Materials 9, 081111 (2021).

Low dimensional systems

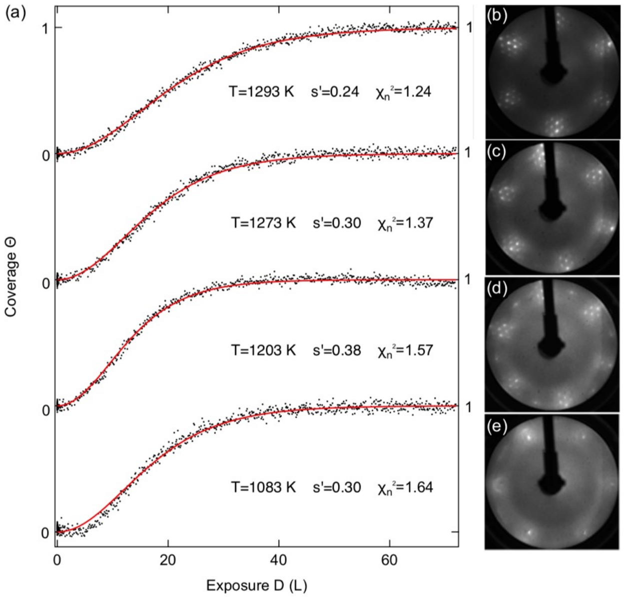
Prof. Thomas Greber

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 x-ray absorption and a sub-Kelvin superconducting quantum interference device. In the 2D materials activity we grow highest quality boron nitride on substrates up to the four inch wafer scale with chemical vapour deposition and subsequent exfoliation and device implementation. For these purposes we use a dedicated clean room, optical microscopy, ink jet printing and surface science tools such as low energy electron diffraction, photoemission and scanning tunnelling microscopy. At the Swiss Light Source we perform photoemission and x-ray absorption spectroscopy.

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

Wafer scale single layer *h*-BN on Pt(111)

Hexagonal boron nitride is considered as key material for the exploration and exploitation of two dimensional materials. Large scale single layer material may be grown by chemical vapour deposition of precursor molecules on hot transition metal surfaces like platinum. These surfaces act as catalysts for the decomposition of the precursors and their incorporation into the two-dimensional skin that forms. The growth process starts from *h*-BN nuclei and their merging into macroscopic sheets of material. The product is used as electrochemical electrode, template for supramolecular structures, as an ultimately thin membrane on a metal. The single layers can be exfoliated and transferred on arbitrary substrates. On insulators they may be used as single photon emitters. Furthermore, the *h*-BN/Pt(111) substrates serve as templates for the growth of insulating multilayer boron nitride with a low dielectric constant as it is needed for fast electronics and spintronics in next generation integrated circuits.



Growth kinetics and correlation to LEED patterns: (a) h-BN coverage on Pt(111) vs. borazine exposure. Black dots, data, red lines, tanh^2 fits with effective sticking parameters s'. A value χ_n^2 of 1 indicates a perfect fit of the model. (b-e) LEED patterns (Electron energy E=100 eV). (b) T=1293 K, (c) T=1273 K, (d) T=1203 K; note the minority phase 30 degrees away from the high symmetry direction, (e) T=1083 K growth temperature.

We optimised the growth of low-defect monolayer h-BN on 2 inch Pt(111)/sapphire wafers. The growth kinetics were monitored in situ with photoelectron yield measurements. They follow a tanh^2 law. The quality of h-BN/Pt(111) is studied with scanning low energy electron diffraction (LEED). The data indicate a strong dependence of the epitaxy on the growth temperature. [1].

The project is a collaboration with the Interuniversity Microelectronics Centre (IMEC) in Leuven where the Pt thin film substrates were produced. This activity is supported by the European Future and Emerging Technology flagship graphene.

Highlighted Publications:

1. Wafer-scale, epitaxial growth of single layer hexagonal boron nitride on Pt(111),
   A. Hemmi *et al.*, J. Phys. Mater. **4**, 044012 (2021)
2. Precise measurement of angles between two magnetic moments and their configurational stability in single-molecule magnets,
   R. Westerström *et al.*, Phys. Rev. B **104**, 224401 (2021)
3. Ferromagnetic insulating epitaxially strained La2NiMnO6 thin films grown by sputter deposition,
   G. De Luca *et al.*, APL Materials **9**, 081111 (2021)

Correlated Quantum Matter

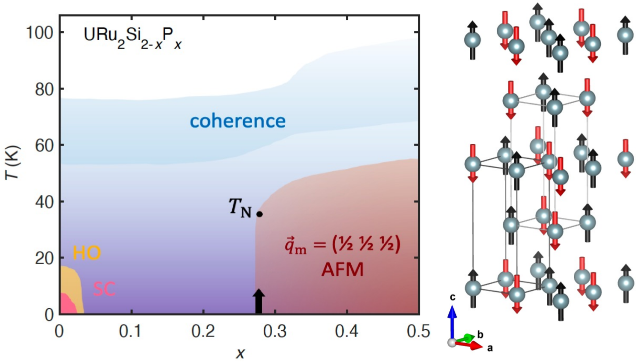
Prof. Marc Janoschek

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

Highlighted result

Strongly correlated electron materials are generally characterized by rich phase diagrams with energetically nearly-degenerate states that exhibit exotic physics. A formidable example is the heavy fermion material URu_2Si_2 for which a particularly abundant phase diagram has been revealed in the quest to understand the salient electronic properties of its unusual hidden order (HO) state. Here a large body of work has established that HO is markedly different from conventional spin or charge orders frequently found in strongly-correlated metals. Most notably, although the onset of the HO is marked by a second-order symmetry breaking phase transition visible in the heat capacity at $T_0 = 17.5$ K, the symmetry of its order parameter remains elusive.

In URu_2Si_2 strong electronic correlations arise due to the hybridization of localized uranium f electrons with the conduction electrons. In turn, unraveling the conundrum of HO requires a better understanding of the underlying duality of the itinerant and localized degrees of freedom. An impressive collection of studies has demonstrated that the HO state exists in close proximity to magnetic phases, which can be accessed by tuning via various control parameters including high magnetic fields, pressure and strain, as well as chemical substitu-



Phase diagram of URu$_2$Si$_{2-x}$P$_x$ (Left) featuring hidden order (HO), unconventional superconductivity (SC) and antiferromagnetic order (AFM) resolved by our neutron diffraction experiments (right).

tion, either on the uranium ruthenium site. The challenge in interpreting the consequences of doping f or d electrons is to disentangle the effects of varying the hybridization (e.g. by varying the degree of delocalization and spin-orbit coupling of the ligand), of the local environment (by variation of bond lengths and angles) and the variation of the Fermi surface.

A new substitution series is thought to address this issue, where it has been suggested from bulk measurements that (Si,P) weakens p–f hybridization, but affects the spacing and orientation of d-ligands only weakly. To test this microscopically, we carried out neutron diffraction to probe the order parameter of the new antiferromagnetic phase that is induced in URu$_2$Si$_{2-x}$P$_x$. This undertaking represents a major experimental challenge as the largest crystals of URu$_2$Si$_{2-x}$P$_x$ have a mass of only $\approx 0.5\,\text{mg}$ and dimensions of $0.8 \times 0.8 \times 0.05\,\text{mm}^3$. We overcome the issue by using the latest generation time-of-flight neutron diffractometer WISH, which combines high-brilliance neutron moderators with highly optimized focusing neutron guides to enable experiments on single crystals with dimensions of $\sim$ 1,mm and less. Our study reveals a simple c-axis colinear antiferromagnetic structure with localized magnetic moments (see Figure). Through comparisons with other tuning studies, we are able to delineate the mechanisms by which silicon-to-phosphorus substitution affects the system. In particular, both the localization of itinerant $5f$ electrons as well as the magnetic ground state appear to be a consequence of the increase in chemical potential. Further, enhanced exchange interactions are induced by chemical pressure and lead to magnetic order, in which an increase in inter-layer spacing may play a special role.

Highlighted Publications:

1. Collinear antiferromagnetic order in URu$_2$Si$_{2-x}$P$_x$ revealed by neutron diffraction
   M. C. Rahn *et al.*
   Phys. Rev. B 103, 214403 (2021)

Quantum Matter

Prof. Fabian Natterer

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

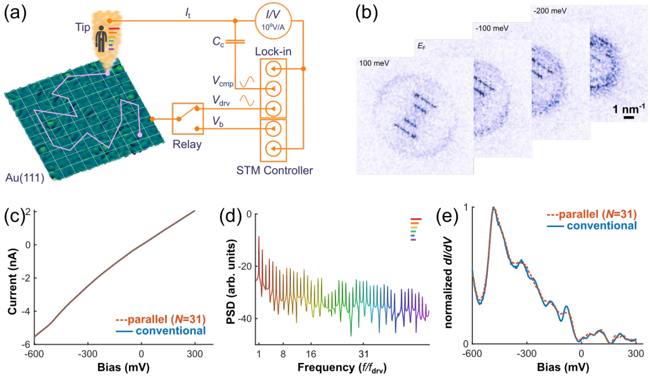
https://www.physik.uzh.ch/g/natterer

Fast Spectroscopic Mapping of two-Dimensional Quantum Materials

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 utilize compressed sensing and parallel spectroscopy. While the former enables the measurement of fewer locations, the latter speeds up the LDOS recording. In combination, we achieve three orders of magnitude faster mapping, which reduces a weeklong measurement to few minutes. Our fast mapping enables previously inconceivable measurement protocols, such as high momentum or energy resolution maps, or accessing the energy-dependent decay length. We plan to use our fast mapping schemes to explore the vast parameter space formed by temperature and uniaxial strain in the study of quantum materials near their critical points.

Scanning Probe Microscopy based ESR

Our second main project 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 sig-



Fast spectroscopic mapping of two dimensional quantum materials. Using the route of a traveling salesperson, we visit only a fraction of the usual measurement locations at which we measure the local density of states with a parallel spectroscopy technique. From the application of compressive sensing, we reconstruct the sparse information content in the Fourier domain, which is related to the bandstructure of the material. Our 1000-fold faster mapping scheme enables previously cumbersome measurement protocols, such as the exploration of a large parameter space in the discovery of quantum materials.

natures at the atomic scale. We pursue two complementary routes of electrical and optical readout to achieve universal quantum sensing with atomic resolution as an alternative to nitrogen vacancy centers whose spatial resolution plateaus at 5 nm. Our sensor will illuminate the atomic-scale origin and properties of radicals, artificially built quantum matter, and noncolinear magnetic structures.

Highlighted Publications:

1. Sparse sampling for fast quasiparticle-interference mapping,
   J. Oppliger and F. D. Natterer,
   Physical Review Research **2**, 023117 (2020),
   https://doi.org/10.1103/PhysRevResearch.2.023117
2. Fast spectroscopic mapping of two-dimensional quantum materials,
   B. Zengin, J. Oppliger, D. Liu, L. Niggli, T. Kurosawa, F. D. Natterer,
   Physical Review Research 3, L042025 (2021),
   arXiv:2102.00054

Surface physics

Prof. Jürg Osterwalder

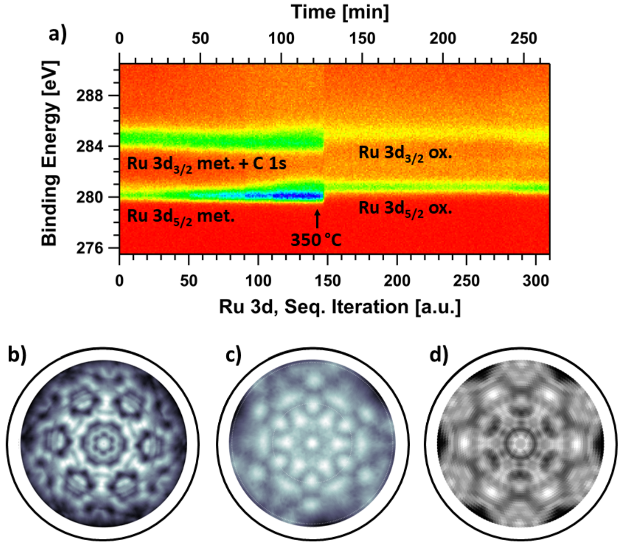
We study **model catalysts** based on single-crystalline oxide surfaces that are prepared under ultra-high vacuum conditions and characterize them in terms of structure, electronic structure, as well as photoexcited electron dynamics. Our laboratory is equipped with a toolbox of **surface science** methods and a laser system that can be used to investigate such phenomena at the **atomic and molecular level** and at the **femtosecond time scale**. Moreover, the group operates an endstation for **ambient-pressure XPS** at the Swiss Light Source at PSI, where catalysts can be studied under conditions close to the relevant pressure regime. Specific systems include a Cu_2O catalyst underneath a monolayer of hexagonal boron nitride for studying **catalysis in confined spaces**, stable **single-atom catalysts** on Fe_3O_4 that minimize the need for precious metals, and **carbon nanodots** on TiO_2 as an efficient photosensitizer for **solar water splitting**.

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

Real-time observation of the autocatalytic oxidation of ruthenium metal by near-ambient pressure XPS

Carbon monoxide is a toxic by-product of many combustion processes and needs to be removed from the exhaust gas via oxidation to CO_2. The rate limiting step in the CO oxidation reaction is the dissociation of O_2 molecules that requires a catalyst, typically a platinum group metal. Among these, ruthenium is the exception, as it is the oxide (RuO_2) that is a very efficient catalyst, far superior to Ru metal or other platinum group metals.

When Ru metal is exposed to a mixture of CO and air, a thin RuO_2 layer is formed at the surface, thus activating the catalyst. This process is autocatalytically enhanced: small RuO_2 nuclei that form during a sluggish induction phase promote oxygen dissociation that feeds and accelerates the oxide growth. We have studied this process with ambient pressure x-ray photoelectron spectroscopy (APXPS) at the ISS beamline of the Swiss Light Source, using a single crystalline Ru(0001) sample.



Autocatalytic oxidation of Ru(0001): (a) Evolution of Ru 3d XPS spectra as a function of time and temperature presented as a heat map (red/blue corresponding to minimum/maximum intensity). Up to iteration 140 the Ru(0001) sample was gradually heated to a temperature of 350° C, where it remained constant up to iteration 210. After a subsequent increase to 400° C, it was cooled down to room temperature. (b) XPD pattern of the Ru 3d core level from the clean Ru(0001) surface. (c) Same, after the oxidation reaction. In (d) the multiple scattering simulation of the latter is shown, using a model cluster representing three domains of RuO_2(110), each rotated by 120° with respect to the other.

Panel (a) shows the evolution of the Ru 3d core level spectrum as a function of time while the Ru(0001) sample is gradually heated under an oxygen partial pressure of 1×10^{-2} mbar. After a 6-minute induction time at a constant temperature of 350°C, the binding energies switch within one single iteration (42 s) to a fully oxidized spectrum. The spectra measured during the induction period support the existence of an O-Ru-O trilayer structure at the surface as an intermediate phase before rapid oxide formation. The latter consists of three rotated domains of RuO_2 with (110) orientation, as evidenced by x-ray photoelectron diffraction (XPD) patterns (panels (b)-(d)).

Highlighted Publications:

1. Thermal oxidation of Ru(0001) to RuO_2(110) studied with ambient pressure x-ray photoelectron spectroscopy, J. T. Diulus *et al.*,
   J. Phys. D: Appl. Phys. **54**, 244001 (2021)
2. Factors influencing surface carbon contamination in ambient pressure x-ray photoelectron spectroscopy,
   N. Comini *et al.*, J. Vac. Sci. Technol. A **39**, 043203 (2021)
3. Charge carrier dynamics and self-trapping on Sb_2S_3(100), L. Grad *et al.*,
   Phys. Rev. Materials **5**, 075401 (2021)

Phase Transitions, Materials and Applications

Prof. Andreas Schilling

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

We are structuring thin superconducting films at the FIRST Center for Micro- and Nanoscience at ETHZ and are using them both for basic research and applications. While the physics of thin-film superconductors is a fascinating research topic by itself, corresponding nanostructures may serve as ultrafast single-photon detectors in the infrared, visible and X-ray range.

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

Size dependent transition to superconductivity and superconductor-to-insulator transition in narrow micro-bridges

We have investigated a series of superconducting bridges based on homogeneous amorphous WSi and MoSi films, with bridge widths w ranging from 2µm to 1000 µm and film thicknesses d from 4-6 nm and 100 nm. Upon decreasing the bridge widths below the respective Pearl lengths $\Lambda = 2\lambda^2/d$, which can be substantially larger than the London penetration depth λ, we observe in all cases distinct changes in the characteristics of the resistivity in an external magnetic field B. Near the critical temperature T_c, the resistivity curves $R(B,T)$ separate for each of the films at a well-defined and field-dependent temperature, resulting in a dramatic suppression of the resistivity and a sharpening of the transitions with decreasing bridge width w (Fig. 1). As the interaction between vortices can change from long-range to an exponentially weak and short-range interaction as soon as the characteristic length scale of the su-

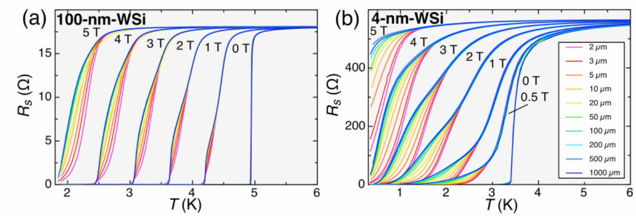


Fig. 1: Sheet resistance $R_s(B, T)$ for micro-bridges of amorphous WSi.

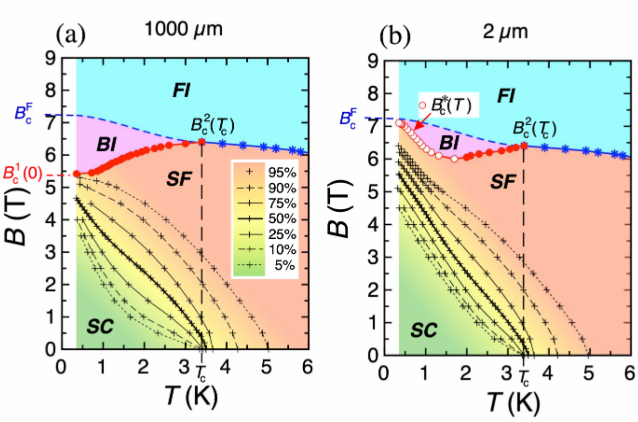


Fig. 2: The sequential superconductor (SC)-Bose insulator (BI)-Fermi insulator (FI) quantum-phase transitions for very wide (a) and narrow (b) 4 nm thin WSi bridges.

perconducting system is smaller than Λ, the vortices most likely become prone to pinning in the narrow bridges, which explains the decrease in resistance near T_c. In the low-temperature limit, the corresponding resistivity curves and magnetic phase diagrams dramatically change as well (Fig. 2 and movies on weblinks 1 and 2 for 4 nm thin WSi). In very wide films (Fig. 2 a), a sequential superconductor-to-Bose insulator-to-Fermi insulator quantum-phase transition takes place. By limiting their size w smaller than Λ, however, the superconducting state recovers and re-enters the originally Bose-insulating state as a consequence of the increased disorder (Fig. 2b). As a consequence, one observes a direct superconductor-to-Fermi insulator transition. In the narrow films, the critical exponent products associated with the phase transitions diverge along the corresponding phase boundaries with increasing magnetic field, which is a hallmark of a quantum-Griffiths singularity.

Highlighted Publications:

1. Size dependent nature of the magnetic-field ...,
   X. Zhang et al., Communications Physics 4, 100 (2021)
2. Physical properties of amorphous MoSi films ...,
   X. Zhang et al., Supercond. Sci. Technol. 34, 095003 (2021)

Coherent Diffraction Imaging

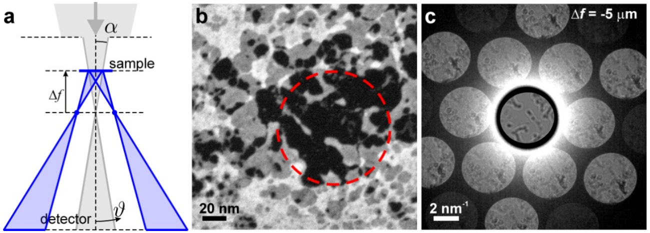
PD. Tatiana Latychevskaia (Paul Scherrer Institut)

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

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

Our current activities include:

1. Experimental convergent beam electron diffraction of two-dimensional materials (graphene, boron nitride, transition metal dichalcogenide (TMD) materials, etc) and nano-scaled objects such as individual macromolecules [1];
2. Light optical experiments for design and testing novel imaging techniques (holography, coherent diffraction imaging, ptychography, quantum optics imaging techniques, etc);
3. Theoretical and numerical study of wave-matter interaction at atomic scale: effects of wave coherence, multiple scattering, etc. Simulations of electron and X-ray wave scattering and wave propagation in various materials;
4. Developing algorithms for high-resolution (atomic-resolution) and three-dimensional reconstruction of

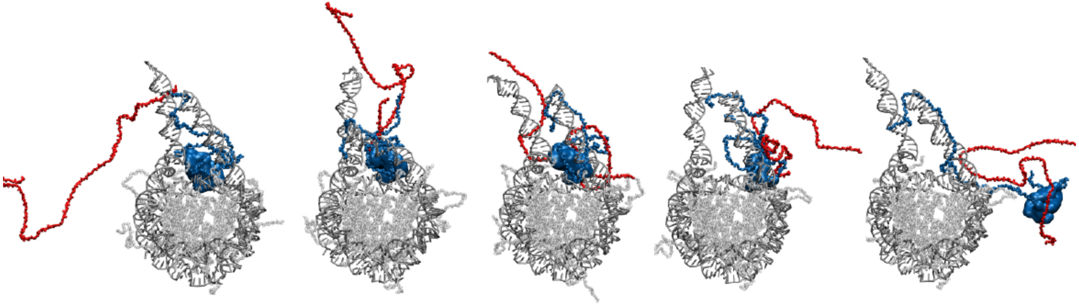


Convergent beam electron diffraction (CBED) of graphene with adsorbates: (a) experimental scheme, (b) high-angle annular dark field image of the sample, and (c) CBED pattern [1].

samples' structures from their diffraction patterns using iterative phase retrieval, machine learning etc [2, 3].

1. Holographic convergent electron beam diffraction (CBED) imaging of two-dimensional crystals,
   T. Latychevskaia, S. Haigh and K. Novoselov,
   Surf. Rev. Lett. **28**(8), 2140001 (2021)
2. Three-dimensional structure from single two-dimensional diffraction intensity measurement,
   T. Latychevskaia, Phys. Rev. Lett. 127 (6), 063601 (2021)
   doi:10.1103/PhysRevLett.127.063601
3. Phase retrieval methods applied to coherent imaging,
   T. Latychevskaia, Advances in Imaging and Electron Physics 218 1 62 (2021) doi:10.1016/bs.aiep.2021.04.001

Bio and Medical Physics



Disordered and biological soft matter

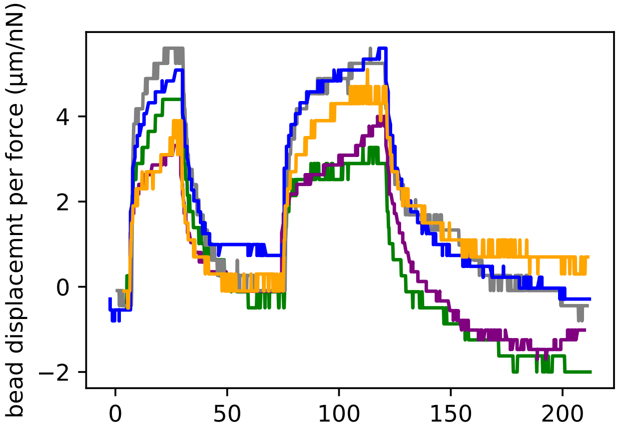
Prof. Christof Aegerter

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

In-vivo force determination of MyosinII waves in Drosophila embryos

The mechanical properties and the forces involved during tissue morphogenesis have been the focus of much research in the last years. Absolute values of forces during tissue closure events have not yet been measured. This is also true for a common force producing mechanism involving MyosinII waves that result in pulsed cell surface contractions. Our patented magnetic tweezer, CAARMA, integrated into a spinning disc confocal microscope, provides a powerful explorative tool for quantitatively measuring forces during tissue morphogenesis. Here, we used this tool to quantify the *in vivo* force production of MyosinII waves that we observed at the dorsal surface of the yolk cell in stage 13 *Drosophila melanogaster* embryos. In addition to providing for the first time quantitative values on an active Myosin-driven force, we elucidated the dynamics of the MyosinII waves by measuring their periodicity in both absence and presence of external perturbations, and we characterised the mechanical properties of the dorsal yolk cell surface.



Bead traces of pulling experiments on the yolk cell cortex in five different embryos (different colours are different embryos).

As an example, the relaxation dynamics displayed by the pull-and-release experiments on the cortex of the yolk cells showed that the elastic cortex restructures on a timescale of about 10 seconds at stage 13. This suggests that the cortex behaves elastically if deformed on a timescale shorter than 10 seconds, while it shows viscous deformation on larger timescales. Dividing the viscosity of the yolk cytoplasm by the characteristic time of cortex relaxation, we obtained a value of E =1.9±0.4 Pa for the elastic modulus of the cortex. This defines a solid-like behaviour of the yolk cell cortex during the dorsal closure stages 13/14, compared to its soft structure during the cellularization stage. We believe that the design and the approach we have established here can be applied widely to different cell types and development stages in Drosophila embryos as well as in other organisms, indicating that it will be a useful tool for analysing a wide range of cell/embryo functions affected by cytoskeletal forces and importantly also for modelling purposes.

Highlighted Publications:

1. Influence of hydrodynamic stress on ray bifurcation and regeneration in zebrafish,
   P. Dagenais, S. Blanchoud, D. Pury, C. Pfefferli, T. Aegerter-Wilmsen, C.M. Aegerter, and A.Jazwinska,
   Journal of Exp. Biol. **224**, jeb242309 (2021)
2. Clean carbon cycle via high-performing and low-cost solar-driven production of freshwater,
   V. Mazzone, M. Bonifazi, C.M. Aegerter, A.M. Cruz, A. Frattalocchi,
   Advanced Sustainable Systems **5**, 202100217 (2021)
3. In-vivo force measurements of MyosinII waves at the yolk surface during Drosophila dorsal closure,
   L.Selvaggi, M. Ackermann, L. Pasakarnis, D. Brunner, and C.M. Aegerter,
   Biophysical Journal **121** (2022)

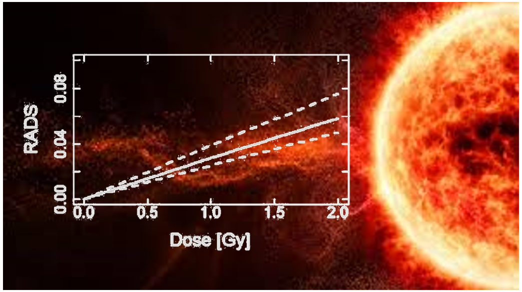
Medical Physics and Radiation Research

Prof. Uwe Schneider (Hirslanden)

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.

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

Currently we are developing an alternative approach for the radiation health risk assessment of astronauts. The new quantity, Radiation Attributed Decrease of Survival (RADS), representing the cumulative decrease in the unknown survival curve of astronauts, forms the basis for this approach (shown in the figure). We are also working on a compact nanodosimetric detector, which can be used to quantify the e biological effects of radiation. Additional research is conducted in the application of highly heterogeneous dose distributions to cancer patients.



RADS cancer risks for male astronauts, calculated for an age at exposure of 40 years, an attained age of 65 years (1 Gy is a typical dose for a Mars exploration) using a mixed ERR and EAR model.

1. A bespoke health risk assessment methodology for the radiation protection of astronauts, L. Walsh *et al.* Radiat Environ Biophys. 2021 May;60(2):213-231
2. A Novel Analytical Population Tumor Control Probability Model ..., S. Radonic *et al*, Int J Radiat Oncol Biol Phys. 2021 Aug 1;110(5):1530-1537

Medical Physics

Prof. Jan Unkelbach (University Hospital Zurich)

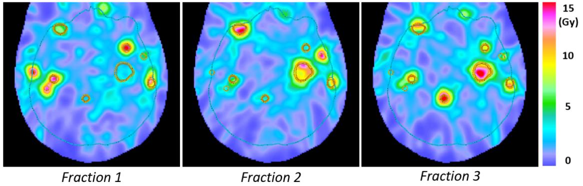
Radiotherapy is one of the mainstays of cancer treatment and a highly technology-driven field of medicine. In our research group, we contribute to the further development of radiotherapy technology by applying concepts from physics, mathematics, statistics, and machine learning to problems in medical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

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

We focus on three areas of research:

1) Radiotherapy treatment planning: We work on mathematical optimization methods to optimally combine x-ray and proton beams [2], and to optimally distribute radiation dose over multiple treatment days (see Figure).

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 [1].



Our work on Spatiotemporal fractionation, illustrated for a patient with many brain metastases treated in 3 fractions.

3) Adaptive radiotherapy: Our department is the first in Switzerland to install a MR-Linac, a combination of MRI scanner and radiotherapy device. This allows to acquire images of a patient during treatment and irradiate moving tumors (e.g. in the lung) more precisely.

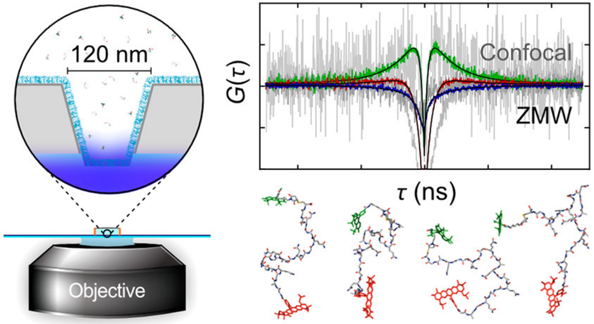
1. A hidden Markov model for lymphatic tumor ...
   R. Ludwig *et al.*, Scientific Reports, 11(1):p1-17, 2021
2. Combined proton-photon treatment for breast cancer,
   L. Marc *et al.* Phys. Med. Biol., 66(23): 235002, 2021

Molecular Biophysics

Prof. Ben Schuler (Department of Biochemistry)

We study fundamental aspects that govern the structure, dynamics, and functions of biomolecules, especially proteins, the nanomachines of life. Towards this goal, we integrate information on nanoscopic distances, forces, and dynamics from advanced single-molecule laser spectroscopy with other physical and biochemical methods, often in close combination with theory and simulations.

https://schuler.bioc.uzh.ch



Single-Molecule Fluorescence Spectroscopy of Biomolecules

A main technical advance in 2021 was the development of a new technique based on nanophotonics that allows us to probe previously inaccessible nanosecond motion in proteins [1] (see Figure). An important discovery was a new mechanism of protein interactions that is involved in how DNA is regulated [2].

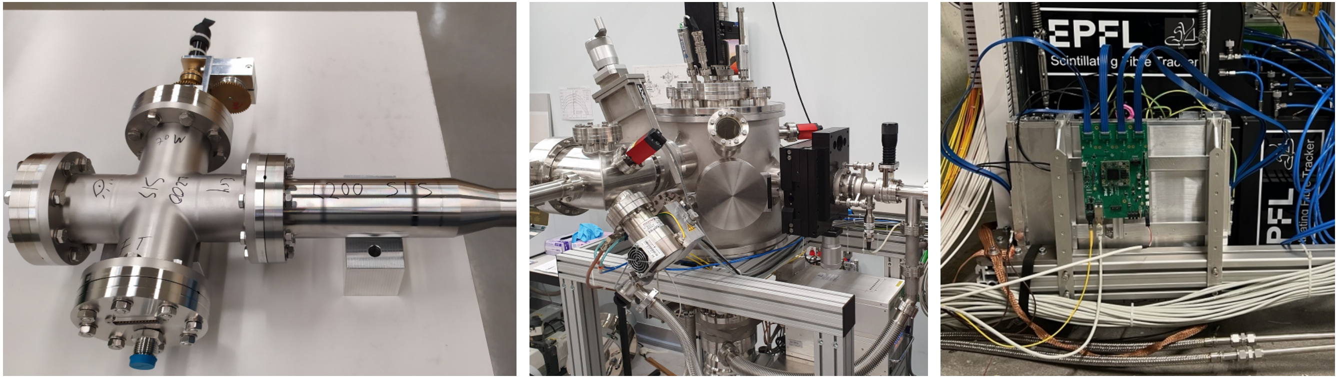
1. Single-molecule detection of ultrafast biomolecular dynamics with nanophotonics,
   M. F. Nüesch *et al.*, J. Am. Chem. Soc. **144**, 52 56
2. Release of linker histone from the nucleosome driven by polyelectrolyte competition with a disordered protein, P. O. Heidarsson *et al.*, Nat. Chem. https://doi.org/10.1038/s41557-021-00839-3

Workshops

Mechanical Workshop

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

https://werkstatt.physik.uzh.ch/werkstatt.html

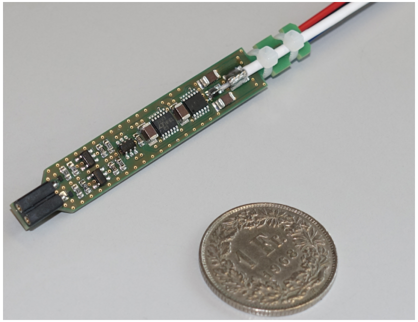


The three photograph are examples for work done in our workshop: (left) upgrade of the calibration system of the LEGEND-200 experiment for the group Baudis; (middle) the new Sputter-System for the group Gibert, here the complete vacuum system was completely produced in the mechanical workshop; (right) the VETO system of the SND experiment for the group Serra.

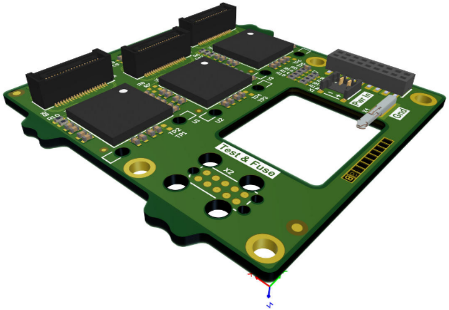
Electronics Workshop

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 PortCard for the CMS group.

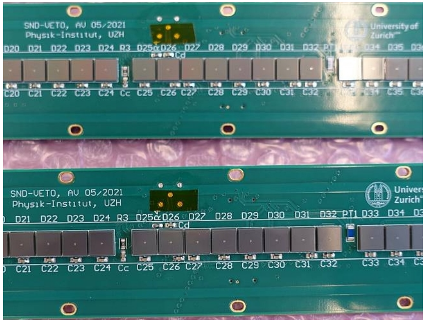
The PortCard (middle figure) has three chips that each combine the data from up to seven sensor modules of the CMS tracker endcap pixel detector (TEPX) - a large-area pixel disk system - and converts them into an optical signal. The challenge in developing the board was the high integration density and the fast signals of up to 10.24 Gbit/s.



Active differential probe with 1 GHz bandwidth.



Layout for the PortCard of the CMS Pixel (TEPX) detector (groups Botta, Caminada, Canelli, Kilminster).



Printed circuit board with silicon PMTs for readout of scintillators of the SND Veto Station (group Serra).

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