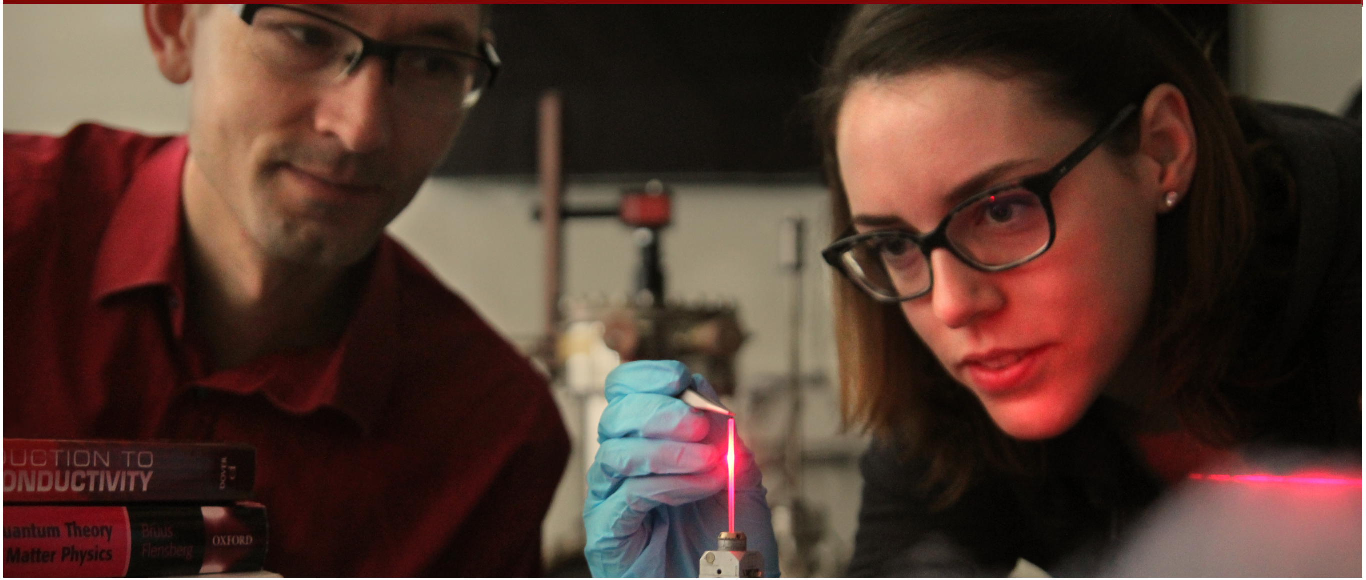
University of Zurich[UZH]

Department of Physics

Annual Report and Highlights 2019



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Department of Physics

Annual Report and Highlights 2019

Winterthurerstrasse 190, CH-8057 Zurich, Switzerland

Preface

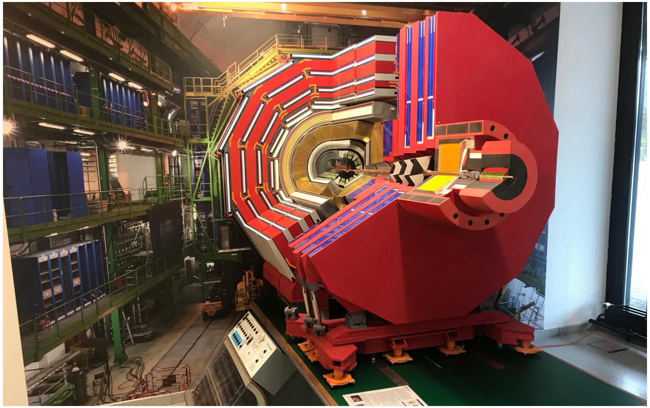
Jürg Osterwalder, Department Head

With a total of 22 research groups, the Department of Physics of the University of Zurich covers a variety of subfields of physics. Experimental activities include particle and astroparticle physics, hard and soft condensed matter physics, surface physics and nanoscience, as well as the physics of biological systems. Theoretical groups work on precision calculations of processes in quantum chromodynamics and new theories beyond the standard model of particle physics, astrophysics and general relativity, as well as topological concepts in condensed matter physics. Other physics-related groups from within the Faculty of Science and beyond are affiliated to our department, and our home page gives links to their research. Together, we can offer a broad and high quality spectrum of lecture courses as well as Bachelor, Master and semester projects to our students. The infrastructure department consisting of excellent mechanical and electronics workshops as well as efficient IT and administrative support teams complete our attractive research environment.
https://www.physik.uzh.ch/en/research.html

The arrival of Andreas Crivellin in January 2019 brought yet another SNF professorship to the department. His research is situated in the field of theoretical particle physics and focuses mainly on flavour physics beyond the Standard Model. With his co-affiliation with the Paul Scherrer Institute, he strengthens further our already strong interchange with this national research institution. Moreover, we welcomed Cristina Botta as the first PRIMA fellow, supported by one of the well funded grants of the SNF aimed at excellent women researchers who show a high potential for obtaining a professorship. Several members of the department won international recognition and awards, most notably Gino Isidori with his ERC Advanced Grant, Laura Baudis with a Visiting Miller Professorship Award of the UC Berkeley, Marta Gibert with the International Workshop on Oxide Electronics Prize and Titus Neupert with the Klung-Wilhelmy Wissenschafts-Preis.

End of October, the department was shaken by the tragic news that Alexey Soluyanov has passed away in St. Petersburg, Russia. Within a bit more than a year he had already built a strong research activity in theoretical condensed matter physics at our department (see next pages). Thankfully, with the help of Titus Neupert and with the unbureaucratic compliancy of the SNF, solutions could be found for all team members to continue with their projects.

In late August, the Swiss Physical Society Meeting, together with the Meeting of the Austrian Physical Society, took place on Irchel Campus, with Johan Chang acting as the local coordinator. Our institute contributed to the Scientifica 2019 event with a short opening talk on dark matter by Laura Baudis, a show on the magic of physics by Christof Aegerter and a booth concentrating on the topics of antimatter and dark matter. The two Poster Days in November, one for the students and one for the alumni, were again a great success. An impressive number of students showed up and involved the members of the research groups in lively discussions about the presented research posters. A less pleasing incident occurred in October: the laser cutter in the big assembly hall of the mechanical workshop caught fire during operation, which triggered the fire alarm. Most of the physics building was evacuated due to extensive smoke emission, but the fire brigade had the situation soon under control and nobody got harmed. Thanks go to Reto Meier for reacting fast and considerate, and to the university for covering with minimal delay the damage to the prototype DARWIN dark matter detector that was being under construction near the fire.



In spring 2020 the Faculty of Sciences will open the new Science Exploratorium within the space of the current Museum of Anthropology on the Irchel Campus. The model of the CMS detector at CERN's LHC, acquired by the Department of Physics, is the first exhibit of this new showcase for the wide range of research carried out within our faculty.

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

The legacy of a topological pioneer - Alexey Soluyanov

Prof. Dr. Alexey Soluyanov, SNF professor for theoretical solid-state physics at our department, passed away in October 2019 after bravely fighting a hard struggle against cancer. He will be remembered as an inspiring colleague, mentor, and friend. His discoveries in topological condensed matter physics were visionary.

The University of Zurich has lost in Alexey Soluyanov one of the world's leading experts in theoretical solid-states physics. His contributions to the field of topological states of matter have been both foundational and groundbreaking. His work has lead to a deeper understanding of the band theory of crystalline materials, so-called topological insulators. In addition to this fundamental work, he has predicted multiple classes of semimetals, which were experimentally discovered shortly thereafter. Furthermore, he developed two software packages, which have simplified the discovery of new exotic quantum materials. They became the standard way to identify topological materials in theoretical calculations. In a separate line of research, Soluyanov also contributed to Microsoft's effort to build a quantum computing by identifying the best possible material ingredients for its hardware basis.

Alexey Soluyanov studied physics in the great tradition of the Russian school, in his birth-town of St. Petersburg at the University of St. Petersburg, Russia. He earned his PhD in 2012 under David Vanderbilt at Rutgers University, USA. After that he worked at ETH Zurich, first as a postdoc and then as a senior scientist. Starting in 2018 he has been leading his own research group at our department.

Alexey Soluyanov has left a lasting mark on the active field of topological materials with his farsightedness and his outstanding physical intuition. From early in his career, he has served as the advisor to the very successful theses projects of several doctoral students. Thus, beyond his passing, his work and passion endures.

https://www.physik.uzh.ch/en/groups/neupert/Events/Soluyanov-Symposium/Obituary-Alexey-Soluyanov.html

Statistical Data 2019

189 personnel

- professors: 20
- associated professors: 10
- senior researchers: 23
- postdoctoral researchers: 44
- PhD students: 69
- engineers and technicians: 25
- administration: 6
- + research assistants

307 students

~55 new students

179 bachelor	11 BSc degrees
43 master	19 MSc degrees
116 PhD	18 PhD degrees

10 SNF prof. and ERC grants

- 39 SNF or EU research grants
- 6 fellowships
- 34 UZH and other grants

417 publications

- 362 peer reviewed papers
- 38 conference proceedings
- 17 books & others

418 conference and workshop contributions

- 140 invited talks
- 180 seminar and other talks
- 57 posters
- 41 outreach

Outreach

Awards

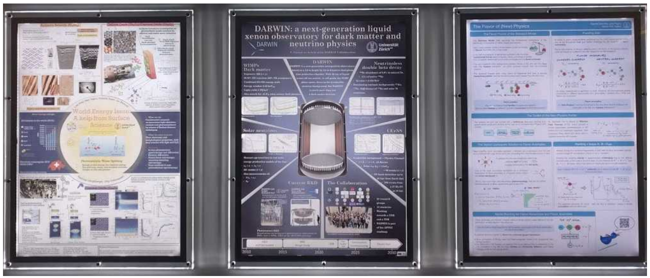
- Marta Gibert: iWOE prize for excellency in research
- Titus Neupert: Klung-Wilhelmy-Wissenschafts-Prize
- Frank Schindler: Special prize of the Mercator Award jury
- Karin von Arx: Dectris prize for best experimental master thesis
- Denys Suter: SNF & Innosuisse Proof of Concept Grant
- Annual poster award of the Department of Physics for members of the groups Osterwalder, Baudis and Isidori

Conferences and Workshops in Zurich

- Zurich Phenomenology Workshop
- Standard model @ LHC
- Strontium Ruthenate:
  25 Years of a Puzzling Superconductor
- SPS joint annual meeting Swiss Physical Society
  and the Austrian Physical Society

Others

- Scientifica 2019: Science fiction – Science Facts
- Schrödinger Colloquium:
  M. Massimi, S. Stevenson, Ch. K. Jung, R. Renner
- Pint of Science Festivals
- Masterclass in particle physics
- How Particle Physics works: Episode II (video)
- Open Day of the institute



Teaching

bachelor **3** major options

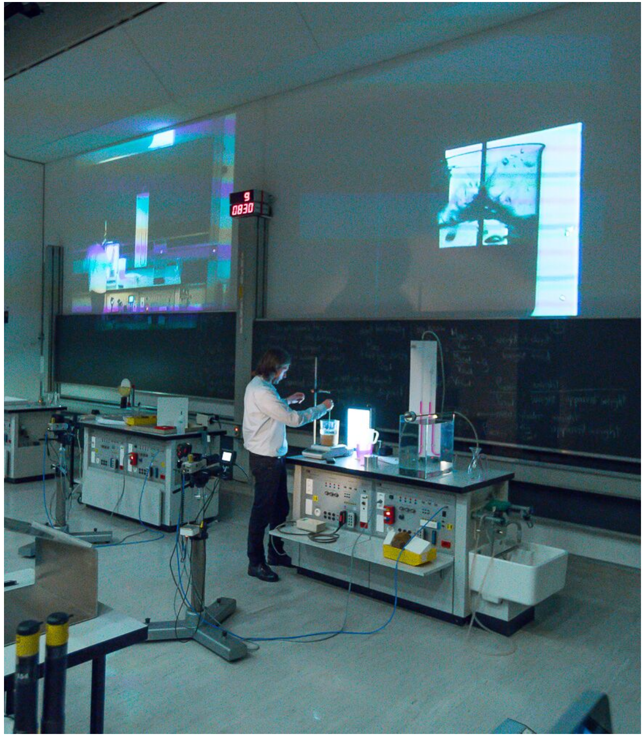
- 180 ECTS physics
- 150 ECTS physics/30 ECTS minor
- 120 ECTS physics/60 ECTS minor

4 master programs

- particle physics
- condensed matter
- astrophysics & cosmology
- bio- & medical physics

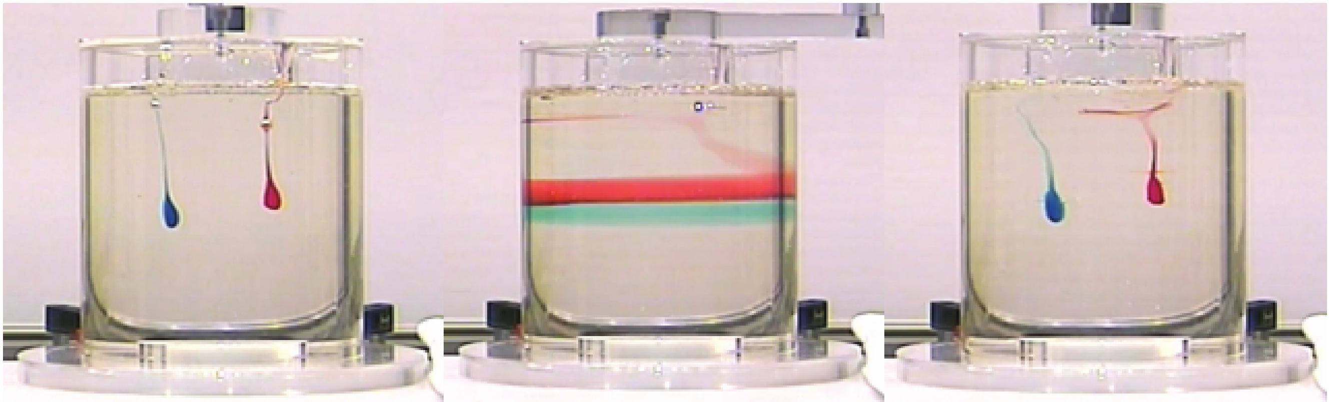
service lectures **1166** students

532	medicine
389	biology & biomedicine
170	chemistry
60	teacher
15	minors

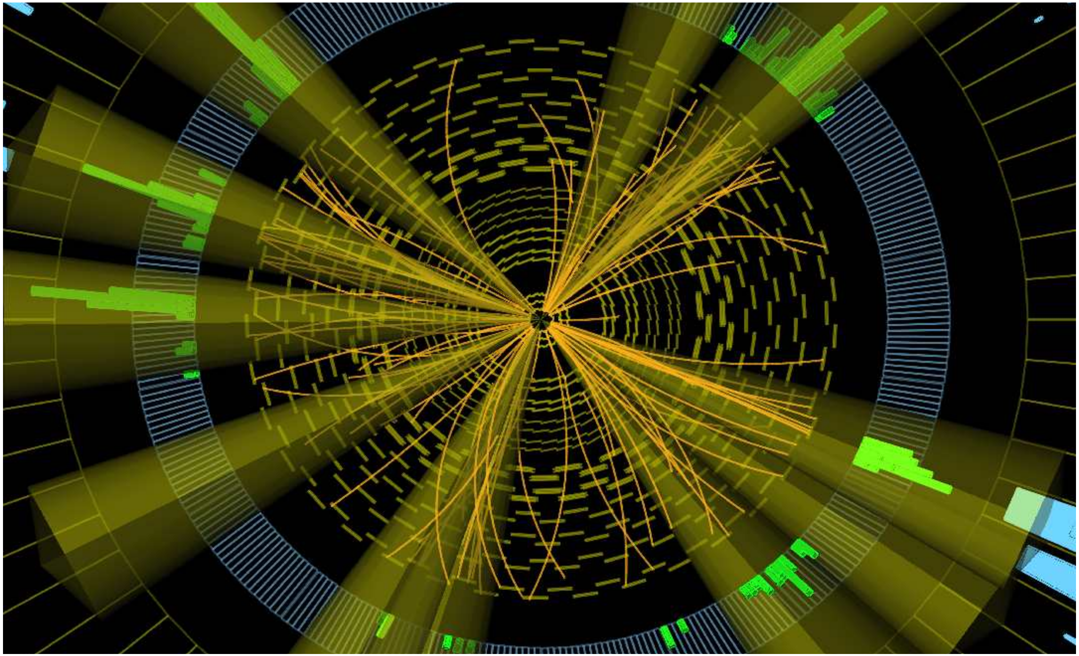


A demonstration to visualize time-reversal symmetry in laminar flow

In highly viscous flows, the low Reynolds number leads to laminar flows that are completely time-reversible. This is because in the low Reynolds number regime inertial dynamics can be neglected and forces are proportional to velocities rather than accelerations. To illustrate this, we have created a Taylor-Couette cell consisting of a rotating inner cylinder and a stationary outside cylinder, where highly viscous corn syrup is placed between the cylinders. With two coloured drops introduced into the liquid (left), it is then sheared continuously until the colours seem to be well mixed (middle). After shearing the liquid in the opposite direction for the same distance, the initial drops are recovered (right), showing the reversibility of the process. Interestingly, the dynamical law at the basis of this counter-intuitive effect is the Aristotelian dynamics still commonly present in many students. Thus, this demonstration can also be used to show the fallibility of this concept.



Physics of Fundamental Interactions and Particles



Particle Physics Theory: Flavour beyond the Standard Model

Prof. Andreas Crivellin

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

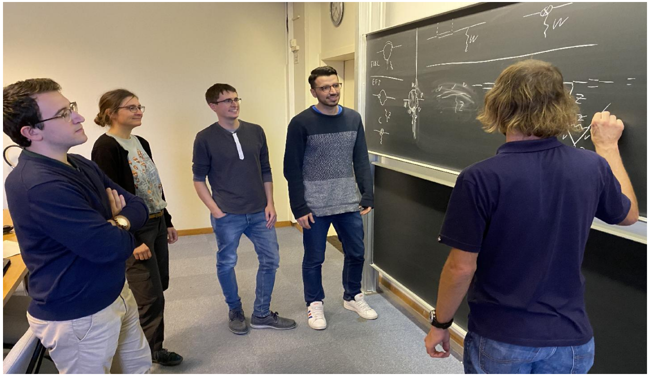
https://www.psi.ch/en/ltp-crivellin

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

One of the predictions of the SM is that quarks and leptons appear in three generations (or families), called flavours, which only differ in their couplings to the Higgs, leading to different masses for particles of different flavour.

All SM gauge interactions treat leptons in the same way; i.e. they respect lepton flavour universality and the only source of charge-parity (CP) violation – the violation of the symmetry between matter and antimatter – in the SM is the single phase in the CKM matrix, which describes the mixing between quarks of different flavours.

However, several experiments found hints for deviations from lepton flavour universality and also for CP violation beyond the SM. These experimental results caused considerable interest within the theoretical community. Concerning the violation of lepton flavour universality, we found that models with particles called “scalar leptoquarks” can explain



Members of Andreas Crivellins' group at a blackboard discussion.

these hints for new physics both in the decay of heavy B mesons and in precision measurements of a property of the muon lepton called "anomalous magnetic moment" [1].

Furthermore, there exist significant discrepancies between different ways of determining elements of the aforementioned CKM matrix. In particular, the CKM element determined from nuclear beta decay does not agree with the one from kaon decays. Here, we pointed out that this tension can also be explained in terms of lepton flavour universality violating physics beyond the SM since beta decays involve only electrons while the best data from kaon decays is related to muons [2].

Concerning CP violation, we pointed out the complementarity between low-energy precision experiments and high-energy searches at the LHC [3]. Furthermore, we showed that the hints for additional sources of CP violation in kaon and B decays can be explained within a consistent framework involving a flavour symmetry. In fact, a model involving a new gauge boson can explain CP violating data well and even lead at the same time to the lepton flavour universality violation as described above [4].

Highlighted Publications:

1. "Flavor Phenomenology of the Leptoquark Singlet-Triplet Model," A. Crivellin, D. Müller and F. Saturnino, arXiv:1912.04224 [hep-ph].
2. "Global Fit to Modified Neutrino Couplings and the Cabibbo-Angle Anomaly," A. M. Coutinho, A. Crivellin and C. A. Manzari, arXiv:1912.08823 [hep-ph].
3. "CP Violation in Higgs-Gauge Interactions: From Tabletop Experiments to the LHC," V. Cirigliano, A. Crivellin, W. Dekens, J. de Vries, M. Hoferichter and E. Mereghetti, Phys. Rev. Lett. **123** (2019) no.5, 051801
4. "Z' models with less-minimal flavour violation," L. Calibbi, A. Crivellin, F. Kirk, C. A. Manzari and L. Vernazza, arXiv:1910.00014 [hep-ph]

Particle Physics Theory: Beyond the Standard Model

Prof. Gino Isidori

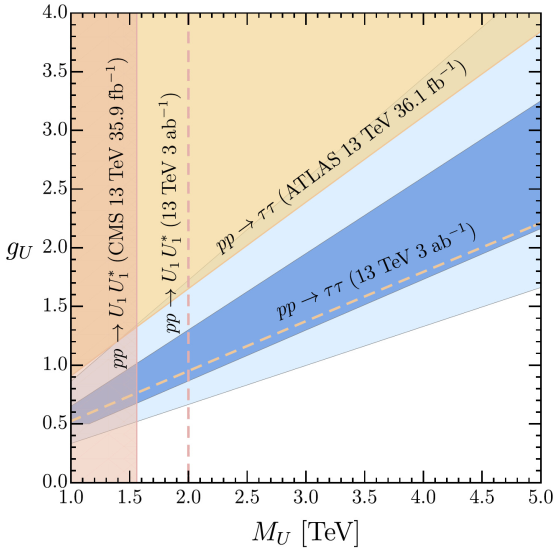
The Standard Model of fundamental interactions describes the nature of the basic constituents of matter, the so-called quarks and leptons, and the forces through which they interact. This Theory is very successful in laboratory experiments over a wide range of energies. However, it fails in explaining 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 three 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 the past years we showed that there is no inconsistency between the anomalies reported by LHCb experiment and other data, provided the hypothetical



Experimental constraints on leptoquark mass (horizontal axes) and coupling (vertical axes) from present and future searches at colliders. The blue and light-blue regions denotes the parameter region preferred by the B-physics anomalies at 1 and 2 sigma, respectively.

"new force" responsible for the anomalies has a peculiar strength on the different families of quarks and leptons: maximal for the third generation, weaker for particles of the second generation, and super-weak for those of the first generation. We also built an explicit model where such new force appears as a result of a unified description of quarks and leptons, i.e. in a model where quarks and leptons are two manifestations of the same fundamental field. In such model the new force, acting between quarks and leptons, is mediated by the exchange of a new hypothetical particle called "leptoquark". In 2019 we devoted quite a lot of attention to investigate the properties of this new particle: we clarified his properties, we explained why it has not been observed yet, and how it could possibly manifest itself in future experiments.

Highlighted Publications:

1. Revisiting the vector leptoquark explanation of B-physics anomalies,
   C. Cornella, J. Fuentes-Martín, G. Isidori,
   JHEP **1907** (2019) 168
2. High-p_T signatures in vector-leptoquark models,
   M.J. Baker, J. Fuentes-Martín, G. Isidori and M. König,
   Eur. Phys. J. C **79** (2019) 334
3. Vector Leptoquarks Beyond Tree Level,
   J. Fuentes-Martín, G. Isidori, M. König, N. Selimović,
   Phys. Rev. D **101** (2020) 035024

Particle Physics Theory: Precision Calculations

Prof. Thomas Gehrmann

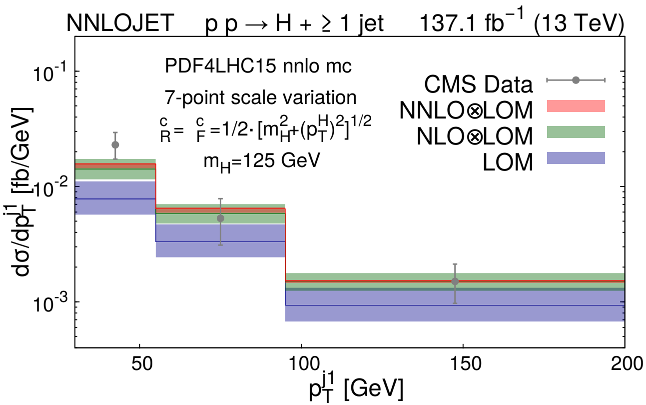
Our research group focuses on precision calculations for collider observables within the Standard Model and their application in the interpretation of experimental data. We develop novel techniques and computer algebra tools that enable analytical calculations in perturbative quantum field theory and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

Theory predictions for Higgs boson production and decay

With the increased statistics and excellent performance of the experiments at the Large Hadron Collider (LHC), precision studies of the production and decay of the Higgs boson are now becoming reality. A key observable is in particular the production of the Higgs boson in association with a hadronic jet, which is mediated at the quantum level through a top quark loop. It is probing the interaction of the Higgs boson with Standard Model particles and possible new states, reaching higher energy scales than in inclusive Higgs boson production. The measurement of Higgs-plus-jet production is performed in specific Higgs decay modes, each which different kinematical restrictions and background processes.

To confront these LHC precision data with theory predictions of commensurate accuracy requires the computation of higher order corrections in QCD, taking into account the kinematical definition of the final state under consideration. Our group has pioneered the antenna subtraction method for second-order (next-to-next-to-leading order, NNLO) QCD corrections, and is developing a numerical code, NNLOJET, for NNLO-accurate predictions of collider observables. Using this framework, we computed Higgs boson observables in the decay mode to four charged leptons. This mode offers a very clean experimental reconstruction of the Higgs boson; its theoretical description is however challenging due to the high dimensionality of the decay phase space, which com-



Transverse momentum distribution of the leading jet in events with a Higgs boson decaying into four leptons, computed with fiducial cuts for this final state as used in the CMS measurement, whose data are superimposed. Predictions at leading order (blue), next-to-leading order (green) and NNLO (red), all corrected for leading top quark mass effects, demonstrate the convergence of the perturbative series. Bands on the theory predictions estimate their uncertainty through the variation of renormalization and factorization scales.

bines with lepton identification and isolation cuts.

An example of our results is shown in the figure, displaying the transverse momentum distribution of the leading jet in events with a Higgs boson decaying into four leptons, compared to recent data from the CMS experiment. The newly computed corrections lead to residual uncertainties on the theory predictions at a level of below five per cent, which are ready to be confronted with future high-luminosity LHC data. Our study uncovered a subtle interplay between lepton isolation and event selection cuts, resulting in sizable QCD corrections to the acceptance factors that are used in the experimental extraction of the cross sections.

Our recent results on precision Higgs physics also include the transverse momentum spectrum of the Higgs boson, obtained by combining fixed-order predictions with resummation of large logarithmic corrections, and the third-order (N3LO) QCD corrections to the Higgs boson rapidity distribution.

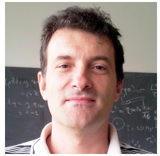
Highlighted Publications:

1. Fiducial cross sections for the four-lepton decay mode in Higgs-plus-jet production up to NNLO QCD, X. Chen, T. Gehrmann, E.W.N. Glover, A. Huss, JHEP 1907 (2019) 052

2. Higgs boson production at the LHC using the q_T subtraction formalism at N3LO QCD, L. Cieri, X. Chen, T. Gehrmann, E.W.N. Glover, A. Huss, JHEP **1902** (2019) 096

3. Precise QCD description of the Higgs boson transverse momentum spectrum, X. Chen *et al.*, Phys. Lett. B**788** (2019) 425

Particle Physics Theory: Standard Model and Higgs Physics at Colliders



Prof. Massimiliano Grazzini

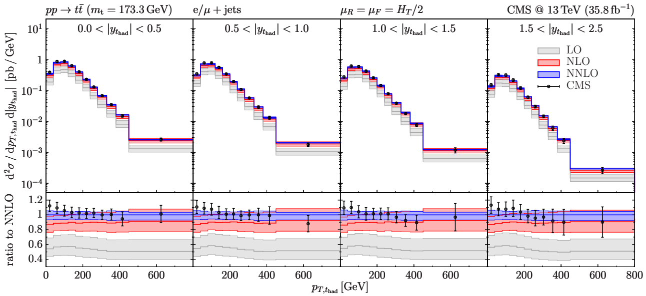
Our research activity is focused on the phenomenology of particle physics at high-energy colliders. We perform accurate theoretical calculations for benchmark processes at the Large Hadron Collider and we make their results fully available to the community. We strive to develop flexible numerical tools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

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

Precise predictions for top quark production

The top quark is the heaviest known elementary particle and it is expected to play a special role in electroweak symmetry breaking. Studies of top-quark production and decay are central in the LHC physics programme, allowing us to precisely test the Standard Model and, at the same time, opening a window on possible physics beyond the Standard Model. At hadron colliders, the main source of top-quark events is top-quark pair production. The proton-proton collisions at the LHC supply a huge number of top-quark pairs, thereby offering an excellent environment for physics studies. At the same time, top-quark pair production is a crucial background to Higgs studies and new-physics searches. For the above reasons, accurate theoretical predictions for this process are needed, and this implies including higher-order radiative corrections.

We have completed a new computation of the top-pair production cross section that includes perturbative corrections at next-to-next-to-leading order (NNLO) in Quantum Chromo Dynamics (QCD). The calculation is obtained by combining tree level and one-loop scattering amplitudes gen-



Double-differential cross sections as a function of the transverse momentum ($p_{T,t_{had}}$)of the hadronically decaying top quark in four rapidity ($y_{t_{had}}$) intervals. The CMS data are compared to the QCD predictions at LO, NLO and NNLO. The central value of the renormalisation and factorisation scales is fixed to $H_T/2$, where H_T is the sum of the transverse masses of the top and anti-top quarks [2].

erated with OpenLoops, an automated tool also developed in Zurich, with two-loop amplitudes that are available in numerical form. The various contributions are separately divergent, and a method is required to handle and cancel infrared singularities appearing at intermediate stages of the computation. In our group we have carried out several NNLO calculations for final states involving Higgs and vector bosons, which do not carry colour charge, but top-quark production is a more complicated process due to the additional soft radiation from the top-quark pair. By using advanced numerical techniques to carry out the phase space integrations, we have assembled all the above ingredients to compute the NNLO cross section. Our calculation is implemented in the general purpose numerical program MATRIX, which can already produce analogous results for all the relevant diboson production processes, fully accounting for their leptonic decays. We have presented results for single and double differential distributions of the top quarks and compared them to available data from the CMS collaboration. The extension of MATRIX to top-quark production paves the way to new and more accurate Monte Carlo simulations for this process, as it happened for Higgs and vector boson production.

Highlighted Publications:

1. Top-quark pair hadroproduction at next-to-next-to-leading order in QCD,
   S. Catani *et al*, Phys.Rev. D**99** (2019) no.5, 051501
2. Top-quark pair production at the LHC: Fully differential QCD predictions at NNLO
   S. Catani *et al*, JHEP **1907** (2019) 100
3. NNLO QCD+NLO EW with MATRIX+OpenLoops: precise predictions for vector-boson pair production,
   S. Kallweit *et al*, JHEP **2002** (2020) 087

Particle Physics Theory: Automated Simulations for Collider Physics

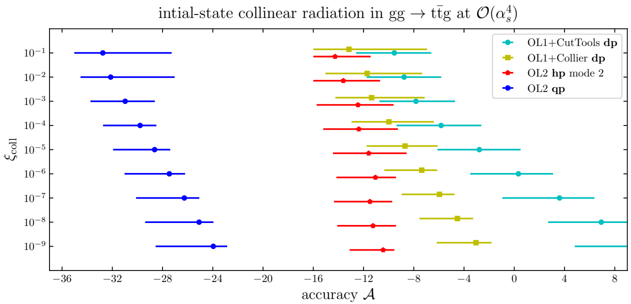
Prof. Stefano Pozzorini

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

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

OpenLoops 2

Recently we have released a new version of the OpenLoops program [1] that implements various new techniques and enables a broad spectrum of new applications. One of the main novelties is an entirely new method for the construction of scattering amplitudes at one loop and their reduction to a family of well known integrals. Such one-loop amplitudes belong to the most fundamental building blocks that are required for precision calculations of scattering processes at particle colliders. In particular, the theoretical interpretation of the measurements carried out at CERN's Large Hadron Collider (LHC) requires the calculation of one-loop scattering amplitudes for a large variety of scattering processes. The complexity of one-loop amplitudes grows extremely fast with the number of scattering particles, and for many of the nontrivial processes that are routinely probed at the LHC one-loop calculations can be still extremely CPU intensive. In



High-precision (NNLO) calculations require the evaluation of one-loop scattering amplitudes in regions where the final-state momenta become soft (small energy) of collinear (small angular separation). The plot illustrates the numerical stability of various one-loop tools for the process $gg \to t\bar{t}g$ (see [1]). In the collinear limit, $\xi_{\rm coll} \to 0$, standard one-loop reduction algorithms feature severe instabilities that can reach the level of 10^{-3} in Collier (yellow) and even 10^{8} in CutTools (turquoise). In contrast, the new on-the-fly reduction techniques implemented in OPENLOOPS 2 *(OL2, red curve) guarantee a level of numerical stability better than 10^{-10} even in the deeply collinear regime.*

OPENLOOPS 2 we have implemented a new method, dubbed on-the-fly reduction, that permits to tame the complexity of multi-particle calculations in a very efficient way. This algorithm implements new sophisticated techniques that guarantee a stable evaluation also in kinematic regions with soft and collinear particles. Such regions play a crucial role in high-precision (NNLO) calculations and are notoriously very challenging (see Figure). The other main novelty in OPENLOOPS 2 is the extension of one-loop calculations from QCD—the theory of strong interactions—to the full Standard Model of particle physics, including electroweak, Yukawa and Higgs interactions. Besides increasing the physics content of the predictions in a very significant way, the inclusion of electroweak effects is a key prerequisite for the theoretical description of high-precision measurements. Moreover it plays a very important role for a variety of measurements and searches at the high-energy frontier. In OPENLOOPS 2 the above mentioned features are implemented in the form of public libraries that cover more than two-thousand independent hard scattering processes. Such libraries can be easily exploited through various multipurpose simulation programs that are interfaced to OPENLOOPS, such as MATRIX, SHERPA, POWHEG and HERWIG.

Highlighted Publications:

1. OPENLOOPS 2, F. Buccioni *et al.*, Eur. Phys. J. C **79** (2019) no.10, 866
2. NLO QCD predictions for $t\bar{t}b\bar{b}$ production in association with a light jet at the LHC, F. Buccioni *et al.*, JHEP **1912** (2019) 015
3. Extracting the Top-Quark Width from Nonresonant Production, C. Herwig, T. Ježo and B. Nachman, Phys. Rev. Lett. **122** (2019) no.23, 231803

High-intensity low-energy particle physics

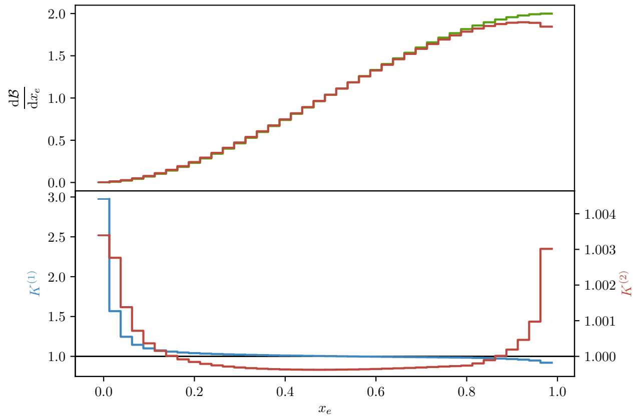
Prof. Adrian Signer

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

Fully differential muon decay including mass effects

Our group is in the process of setting up a generic framework for higher-order QED calculations of scattering and decay processes involving leptons. This framework properly treats infrared singularities when combining loop amplitudes and allows to obtain fully differential cross sections at any order in QED perturbation theory with massive fermions. The long-term goal is to provide a library of relevant processes with sufficient precision, typically at next-to-next-to leading order (NNLO) in the perturbative expansion.

After the implementation of several processes at next-to-leading order (NLO), recently we have implemented the muon decay $\mu \to e\nu\bar{\nu}$ at NNLO. In QED it is important to keep the fermion masses at their physical value, rather than setting them to zero. This allows to compute contributions with large mass logarithms, 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



The normalised energy fraction x_e of the electron in the muon decay $\mu \to e\nu\bar{\nu}$, with experimental cuts adapted to the MEG experiment at PSI. In the upper panel the LO result (green) is compared to the NNLO result (red). In the lower panel, the NLO and NNLO correction factors are shown as $K^{(1)}$ (blue, left scale) and $K^{(2)}$ (red, right scale). The corrections are large at the end points, partly due to logarithms mentioned in the text.

these logarithms cancel.

Keeping finite fermion masses makes the analytic computation of two-loop amplitudes much more demanding, and in fact often impossible. In the case of the muon decay we were able to analytically compute the two-loop amplitude including all mass effects. For more complicated processes, we have developed a method called 'massification' that extracts the leading fermion-mass terms of two-loop amplitudes from the corresponding amplitudes with massless fermions. This method, as well as the treatment of infrared singularities, has been tested in the muon decay. To do so we compared the fully massive with the massified computation. We also compared to already available inclusive calculations.

The analytic results of two-loop amplitudes are often expressed in terms of so-called generalised polylogarithms (GPL). These GPL depend on the kinematic variables of the process and need to be evaluated numerically repeatedly in the Monte Carlo code. To facilitate this we have implemented a fast numerical evaluation of GPL in Fortran. This code is an intrinsic part of the Monte Carlo framework, and will be essential in the implementation of further processes.

Highlighted Publications:

1. Small-mass effects in heavy-to-light form factors, T. Engel, C. Gnendiger, A. Signer, and Y. Ulrich, JHEP **1902** (2019) 118
2. A subtraction scheme for massive QED, T. Engel, A. Signer, and Y. Ulrich, JHEP **2001** (2020) 085
3. *handyG* - rapid numerical evaluation of generalised polylogarithms in Fortran, L. Naterop, A. Signer and Y. Ulrich, arXiv:1909.01656

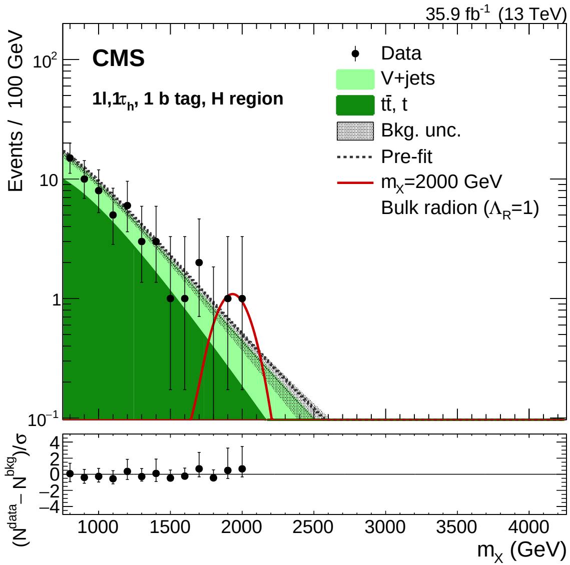
CMS Experiment

Prof. Florencia Canelli, Prof. Ben Kilminster


The CMS (Compact Muon Solenoid) experiment at CERN measures properties of the fundamental particles and their interactions, and can uncover new forces and particles. CMS surrounds one of the interaction points at the Large Hadron Collider (LHC), which produces an energy density comparable to that of the universe one ten-billionth of a second after it started. Detectors are used to determine the energy and direction of emerging particles. By reconstructing these particles, the particles and their interactions can be deciphered. In 2012, CMS discovered the Higgs boson, thus proving how particles acquire mass. By 2018, CMS recorded a record dataset of 150 fb^{-1}, allowing more precise measurements and searches for new physics. CMS is now focused on physics analyses, detector maintenance and upgrade activities, and pushing forward the Phase-2 upgrades and infrastructure needed for the high-luminosity run of the LHC envisioned to start in 2027.

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 undergo measurements of the heaviest fundamental particle known, the top quark, which is as heavy as a gold atom. In 2019, we have measured the simultaneous production of a pair of top quarks with a pair of b quarks in the challenging all-jets channel [1]. A good knowledge of this production is crucial in order to gain insight into other very rare processes containing top quarks. A new search for a massive particle that would decay to quarks in a region previously unaccessible was developed using a special data-taking technique, known as "data scouting" [2]. We continued our program of searching for new, heavy particles that would represent new forces. In three separate publications, we present searches that probe higher masses than previously achieved, in their decays to combinations of Higgs, W, and



A new search for heavy particles that decay to Higgs bosons. The new particles could be heavy excitations of the graviton that would be possible if our universe had extra dimensions [3].

Z bosons, as well as other standard model particles [3,4,5]. These searches probe models in which a new mass scale of physics is introduced to explain the theoretically anomalous observed Higgs boson mass. We have now a research program searching for new physics with tau leptons, and in 2019, we published a search for a low-mass $\tau\tau$ resonance [6].

CMS will collect more than 20 times the current data set during the period of 2026 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 2019, we produced a prototype of the detector with lightweight mechanical and electrical components. 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 10^{-12} s) in our lab. Such a technology could greatly improve the physics potential of CMS in later upgrades.

Highlighted Publications:

1. CMS Collab., arxiv.org:1909.05306, accepted by Phys. Lett. B
2. CMS Collab., arxiv.org:1911.03761, submitted to Phys. Lett. B
3. CMS Collab., JHEP **01** (2019) 051
4. CMS Collab., Phys. Lett. B **798** (2019) 134952
5. CMS Collab., Eur. Phys. J. C **79** (2019) 564
6. CMS Collab., JHEP **05** (2019) 210

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 are also involved in the preparation of a major upgrade of the detector for 2019/2020.

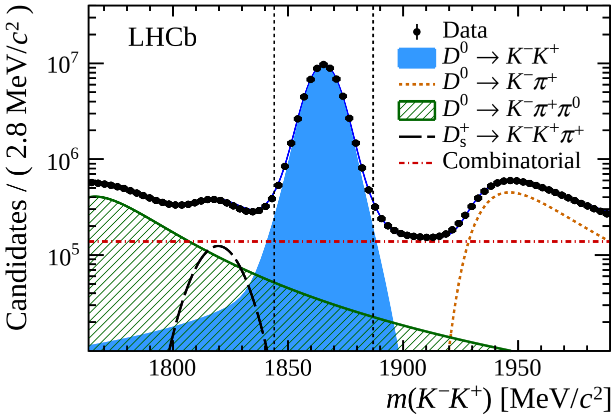
https://www.physik.uzh.ch/r/lhcb

Observation of *CP* violation in charm

Everything we see around us is the result of a triumph of matter over antimatter in the early stages of the universe. A necessary condition for this so-called baryon asymmetry is Charge-parity violation (*CPV*), whereby the laws of physics change under the reversal of particle electric charge and the inversion of spatial coordinates. The Standard Model of particle physics (SM) includes *CPV* through an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. However, the size of *CPV* in the SM appears to be too small to account for the observed matter-antimatter asymmetry, suggesting the existence of sources of *CPV* beyond the SM.

While *CPV* with strange and beauty quarks is well established, the observation of *CPV* in the charm sector had not been achieved, despite decades of experimental searches. The size of *CPV* in charm decays is expected to be very small in the SM, with asymmetries typically of the order of $10^{-4} - 10^{-3}$. The uncertainties however are large due to the presence of low-energy strong-interaction effects.

At peak luminosity, the LHC produces approximately one million charm hadrons per second. This huge production rate allows for very precise searches for CPV. The LHCb collaboration performed a search for *CPV* in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, using the full Run 2 dataset collected be-



Left: Invariant-mass distributions of $D^0 \to K^-K^+$ candidates with the fit results overlaid. The various components included in the fit model are indicated in the legend (from [2]).

tween 2015-2018 [2]. The idea is to compare the rate of D^0 decay with the corresponding $\bar{D}^0$ decay, and calculate the asymmetry, A_{CP} from these two.

Experimentally, it is easier to determine ΔA_{CP}, the difference in CP asymmetries between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays, where many systematic uncertainties cancel.

The combination with the Run 1 analyses gives $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$. The significance of the deviation from zero corresponds to 5.3 standard deviations and is the first observation of CPV in the decay of charm hadrons. The result is consistent with, although at the upper end of the SM expectations. The upgraded LHCb detector will allow for each larger charm-hadron samples to be collected in order to study different decays which can shed light on the origin of the CPV. The figure shows the invariant-mass distribution of $D^0 \to K^-K^+$ candidates with fit results overlaid.

Highlighted Publications:

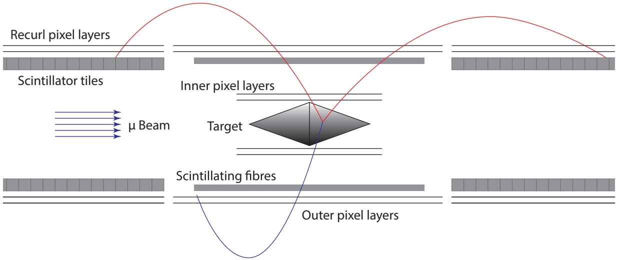
1. All LHCb publications:
   http://lhcb.web.cern.ch/lhcb/
2. Observation of CP Violation in Charm Decays,
   LHCb collab., Phys. Rev. Lett. **122** (2019) no.21, 211803
3. Search for lepton-universality violation in
   $B^+ \to K^+\ell^+\ell^-$ decays,
   LHCb collab., Phys. Rev. Lett. **122** (2019) no.19, 191801
4. Test of lepton universality with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays, LHCb collab., arXiv:1912.08139
5. Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$, LHCb collab., Phys. Rev. Lett. **122** (2019) no.22, 222001

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

Prof. Nicola Serra, PD Dr. Olaf Steinkamp

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

The conservation of lepton flavour, where the number of leptons in an interaction of a particular flavour is conserved, is a key symmetry in the Standard Model. Although lepton flavour violation has already been observed in neutrino oscillations, it has never been seen in charged leptons. The incredibly high intensity muon beam at PSI, Villigen offers a unique opportunity to probe lepton flavour violating decays such as $\mu^+ \rightarrow e^+e^-e^+$ and is expected to be sensitive to one $\mu^+ \rightarrow e^+e^-e^+$ decay in every 10^{16} muon decays, around 1000 times more sensitive than previous limits. The design is currently being finalised with data taking foreseen in the next two years.



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

Highlighted Publication:

1. Research Proposal for an Experiment to Search for the Decay $\mu^+ \rightarrow e^+e^-e^+$, Mu3e Collaboration, arXiv:1301.6113

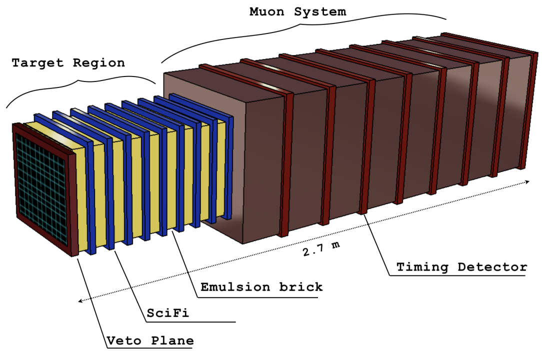
SHiP - Search for Hidden Particles

Prof. Nicola Serra

The **SHiP (Search for Hidden Particles)** experiment is a proposed beam dump target experiment at CERN. Its aim is to search for very weakly interacting long living particles, in particular for sterile neutrinos.

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

Our group is involved in the development of the official simulation software, in the estimation of neutrino interactions which mimic the signal we are looking for and also has a leading role in the design of the SHiP veto timing detector. We are also involved in the measurement of charm production from 400 GeV protons and we are among the main proponents of a Letter of Interest [2] sent to the LHC committee to build and operate a detector that, for the first time, will measure the process $pp \to \nu X$ at the LHC and search for feebly interacting particles in an unexplored domain.

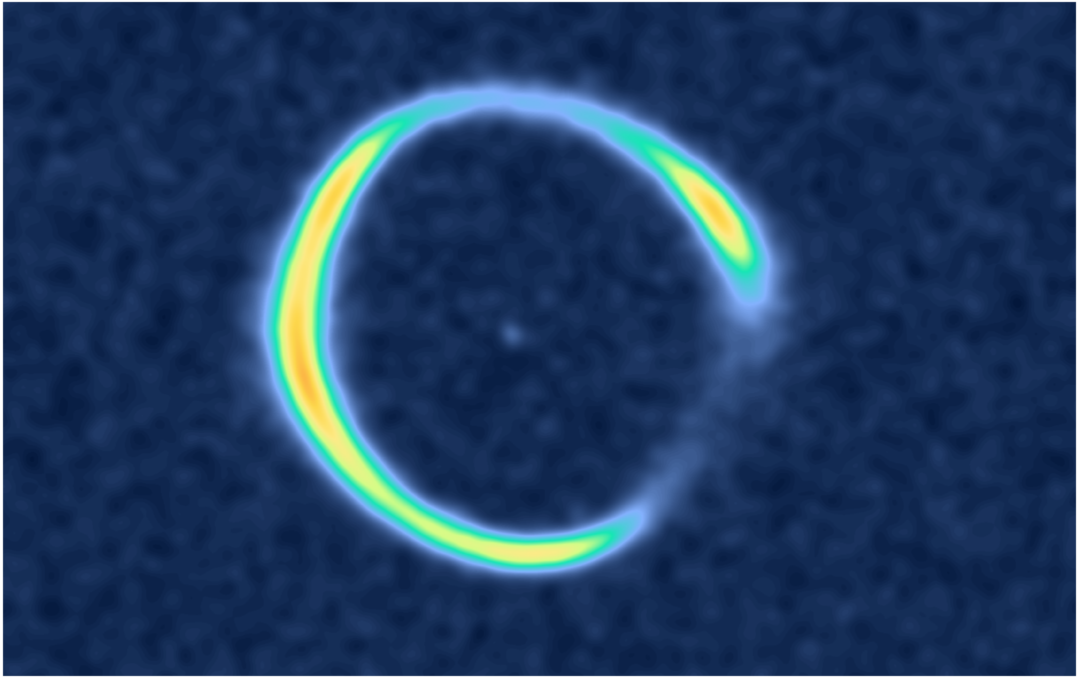


Schematic view of the neutrino detector for the SND@LHC project.

Highlighted Publications:

1. SHiP Experiment, Comprehensive Design Study, Report, SHiP Collaboration https://cds.cern.ch/record/2709550/files/LHCC-I-035.pdf
2. SND@LHC, SHiP Collaboration, https://cds.cern.ch/record/2704147/files/SPSC-SR-263.pdf

Cosmology, Astro- and Astroparticle Physics



Astrophysics and General Relativity

Prof. Philippe Jetzer, Prof. Prasenjit Saha

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

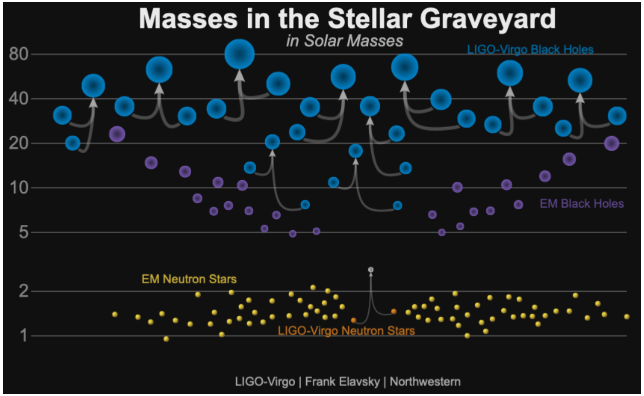
https://www.physik.uzh.ch/g/jetzer

Highlights

The work of the group is focused on the topic of gravitational waves and this both for use with LIGO/Virgo and for the future space mission LISA. Indeed, our group is involved in these collaborations. In the following we briefly describe two main results published in 2019.

In a paper Maria Haney and collaborators derived analytic expressions that provide Fourier domain gravitational wave (GW) response function for compact binaries inspiraling along moderately eccentric orbits. These expressions include amplitude corrections to the two GW polarization states that are accurate to the first postNewtonian (PN) order. Additionally, the fully 3PN accurate GW phase evolution incorporates eccentricity effects up to sixth order at each PN order. Further, a prescription to incorporate analytically the effects of 3PN accurate periastron advance in the GW phase evolution has been developed. The this way computed ready-to-use templates for compact binaries are useful to model moderately eccentric compact binary coalescences.

Michael Ebersold, Yannick Boetzel and collaborators computed the nonlinear memory contributions to the gravitational-wave amplitudes for compact binaries in eccentric orbits at the third post-Newtonian (3PN) order in general relativity. These contributions are hereditary in nature as they are sourced by gravitational waves emitted during



Merging of black holes observed by LIGO and Virgo (blue); masses of black holes detected through electromagnetic observations (purple); neutron stars measured with electromagnetic observations (yellow); and the masses of the neutron stars that merged in the event GW170817, which were detected in gravitational waves (orange). The figure is based on the observations during the first two runs from the LIGO Collaboration.
Figure from LIGO Collaboration, LIGO-Virgo, Frank Elavsky, Northwestern University

the binary's entire dynamical past. Combining these with already available instantaneous and tail contributions they got the complete 3PN accurate gravitational waveform.

Philipp Denzel, together with Saha and other collaborators, studied the effectiveness of different modelling strategies in strong gravitational lensing. The conclusion from this work is that while modelling is becoming increasingly good at reproducing the observables, the non-uniqueness of these models is larger than previously thought.

In a new research direction Saha and collaborators have begun studying future astronomical applications of Hanbury Brown and Twiss interferometry, which shows some promise of imaging at optical wavelengths at resolutions of $\sim 10^{-10}$ radians, which is comparable to the Event Horizon Telescope.

Highlighted Publications:

1. Ready-to-use Fourier domain templates for compact binaries inspiraling along moderately eccentric orbits, S. Tiwari, G. Achamveedu, M. Haney, P. Hemantakumar, Phys.Rev. D**99** (2019), 124008, arXiv:1905.07956.
2. Gravitational-wave amplitudes for compact binaries in eccentric orbits at the third post-Newtonian order: Memory contributions, M. Ebersold, Y. Boetzel, G. Faye, Ch. K. Mishra, B. R. Iyer, Ph. Jetzer, Phys.Rev. D**100** (2019), 084043, arXiv:1906.06263.
3. Lessons from a blind study of simulated lenses: image reconstructions do not always reproduce true convergence, P. Denzel, S. Mukherjee, J. P. Coles, P. Saha, arXiv:1910.10157

Astroparticle Physics Experiments

Prof. Laura Baudis

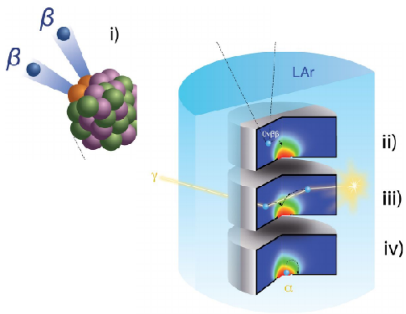
We study the composition of **dark matter** in the Universe and the **fundamental nature of neutrinos**. We build and operate ultra low-background experiments to detect dark matter particles, to search for the neutrinoless double beta decay, a rare nuclear process which only occurs if neutrinos are Majorana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

Searches for the neutrinoless double beta decay of ^{76}Ge in GERDA with a sensitivity on the half-life of $T_{1/2}^{0\nu\beta\beta} > 1 \times 10^{26}$ y

Neutrinos are the only fundamental fermions without electric charge and as a consequence, they might be Majorana particles, hence identical to their antiparticles. Majorana neutrinos would lead to nuclear decays that violate lepton number conservation and are therefore forbidden in the SM of particle physics. The so-called neutrinoless double beta ($0\nu\beta\beta$) decay simultaneously transforms two neutrons inside a nucleus into two protons with an emission of two electrons (see Figure). The two electrons together carry the available decay energy ($Q_{\beta\beta}$) and the resulting monoenergetic signal is the expected experimental signature.

The Germanium Detector Array (GERDA) experiment searches for the $0\nu\beta\beta$ decay $^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2e^-$ with $Q_{\beta\beta} = 2039.061 \pm 0.007$ keV by deploying High-Purity Germanium (HPGe) detectors enriched up to 87% in ^{76}Ge. The experiment is located underground at the Laboratori Nazionali del Gran Sasso (LNGS), at a depth of $\sim$3500 mwe. The HPGe



(i) Artist's view of the $0\nu\beta\beta$ decay of a nucleus by an emission of 2 e^-. (ii to iv) Three BEGe detectors immersed in LAr. Events from $0\nu\beta\beta$ decays deposit energy within a few m^3 in a single detector, while events with coincident LAr scintillation light or with multiple interactions in the Ge detector are classified as background events.

detector array, made of 37 enriched coaxial and Broad Energy Germanium (BEGe) diodes, is operated inside a 64 m^3 liquid argon (LAr) cryostat, which provides cooling and a high-purity, active shield against background radiation. The cryostat is inside a water tank instrumented with photomultipliers to detect Cherenkov light from muons passing through, and thus reduces the muon-induced background to negligible levels. Weekly calibrations of the Ge diodes with ^{228}Th sources are performed to monitor the energy scale and resolution, as well as to define and monitor the analysis selection criteria. The energy resolution (at FWHM) at $Q_{\beta\beta}$ is 3.6±0.1 keV for the coaxial detectors and 3.0±0.1 keV for the BEGe detectors. We have scrutinised a total of 82.4 kg·y of exposure for a $0\nu\beta\beta$ signal. Events with a reconstructed energy of $Q_{\beta\beta} \pm 25$ keV were blinded until the data selection was fixed. GERDA reached an unprecedented low background rate of $\sim 6\times10^{-4}$ events/(keV kg y) and thus operated in a background-free regime such that the expected number of background events is <1 in the energy region of interest at the given exposure. No signal was observed, and the derived lower half-life limit is $T_{1/2} > 0.9 \times 10^{26}$ y (90% C.L.). The $T_{1/2}$ sensitivity, assuming no signal, is 1.1×10^{26} y. Combining the latter with those from other $0\nu\beta\beta$ decay searches yields a sensitivity to the effective Majorana neutrino mass in the range 0.07 to 0.16 eV [1].

Highlighted Publications:

1. Probing Majorana neutrinos with double-beta decay, GERDA Collab., Science, Sept 05, 2019
2. Light Dark Matter Search with Ionization Signals in XENON1T, XENON Collab., Phys. Rev. Lett. **123** (2019) 251801
3. First results on the scalar WIMP-pion coupling, using the XENON1T experiment, XENON Collab., Phys.Rev.Lett. **122** (2019) 071301

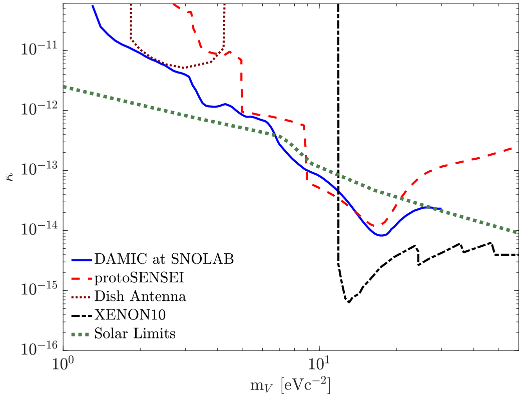
DAMIC Experiment

Prof. Ben Kilminster

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

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

Our group helped found the DAMIC experiment in 2008. For DAMIC-M, we are currently developing a calibration system based on a radioactive isotope, electronics for digitizing the data, imaging software, the control and safety system, and a prototype of the detector with a vacuum interfacing cabling system.



Results from DAMIC at SNOLAB, showing sensitivity to electromagneticnic interactions of hidden dark matter with mass between 1 and 10 eV. The blue line shows the interaction rate to which DAMIC-M can probe as a function of dark matter mass.

1. Constraints on Light Dark Matter Particles..., DAMIC Collab., Phys.Rev.Lett. **123** (2019) no.18, 181802.


CTA – Cherenkov Telescope Array

Prof. Florencia Canelli, Prof. em. Ueli Straumann

With more than 100 telescopes located in the northern and southern hemispheres, the Cherenkov Telescope Array (CTA) will extend the currently observable very high gamma ray spectrum by several orders of magnitude.

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

The CTA group at UZH has designed essential elements, including the mirror segment actuator system (AMC), light sensor electronics, safety and power control and mechanics for one of the proposed cameras (FlashCam), and contributes to calibration software development.

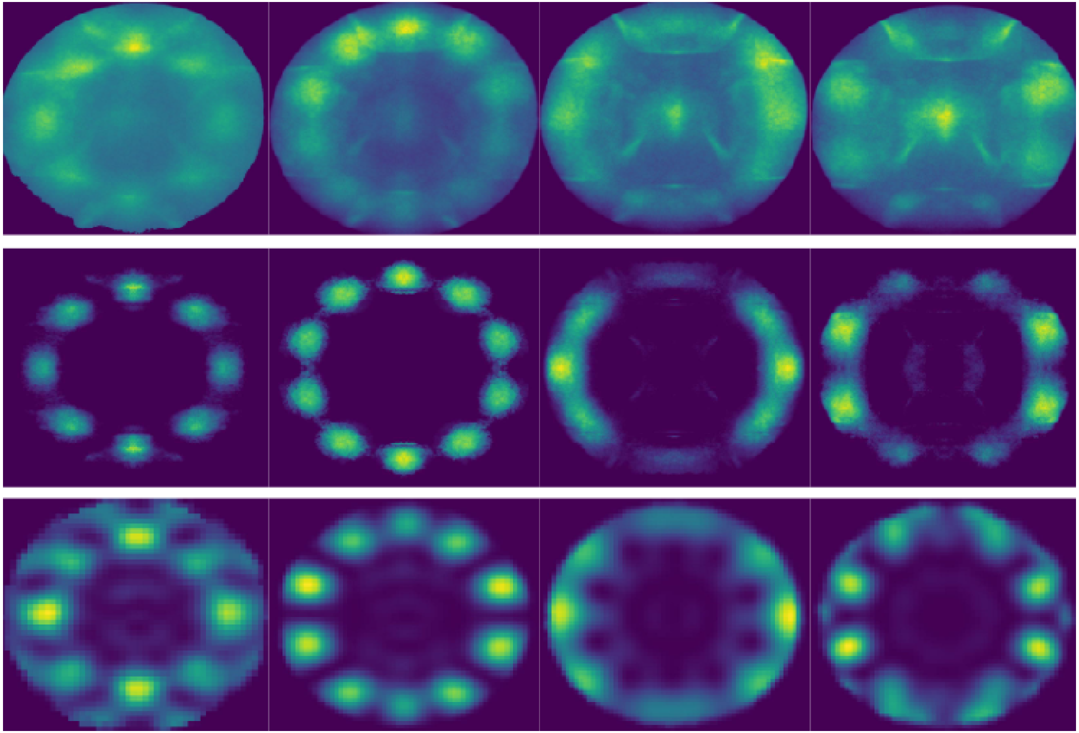
CTA will search for new very high energy gamma emitters. It will have a great potential for exploring fundamental frontiers in physics including the extragalactic background light, hypothetical dark matter annihilation signals, and the study of the charged cosmic ray acceleration processes. In 2019, one of the first FlashCam cameras was successfully installed at the HESS site (a currently operational Cherenkov Telescope experiment) and has been performing well.

FlashCam cameras installed at the HESS site in Namibia.

Highlighted Publications:

1. Potential for measuring the longitudinal and lateral profile of muons in TeV air showers with IACTs, A. Mitchell *et al*, Astroparticle Physics **111** 23-34 (2019)

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.

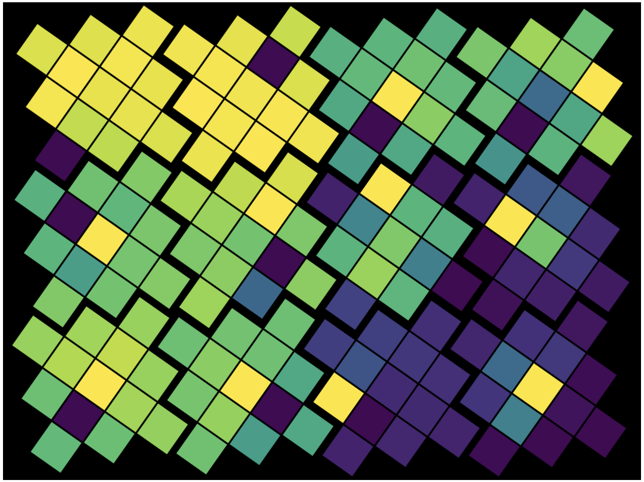
https://www.physik.uzh.ch/g/neupert

Machine learning meets condensed matter physics

Deep learning is everywhere in science and technology. Recently, it also starts to enjoy applications in quantum matter research. In 2019, a growing number of activities in our group were focused on these artificial intelligence techniques.

Most immediate is the use of neural networks to analyze various forms of experimental data or to aid experiments. As an example, Pascal Vecsei studied in his bachelor thesis how machine learning can be used to deduce the space group of a crystal based on powder x-ray diffraction curves. This is a challenging task which usually takes the experience of a crystallographer. We used a neural network for the classification of the crystal structures into one of the 230 space groups of nonmagnetic materials with the help of theoretically computed test data. When used on real data of rather low quality, the algorithm identified the correct space group more than half of the time. If the algorithm is also allowed to flag bad datasets, its accuracy on the good ones goes up to 80%.

A completely different application of machine learning is explored by the group members Kenny Choo and Nikita Astrakhantsev, who use neural networks as compressed representations of complex many-body wave functions. The underlying problem is that even for relatively small



Neural networks can be used efficiently as a compressed representation of complex quantum many-body states, that could otherwise not be stored on any computer memory. Shown is a color scale representation of some of the weights of a neural network quantum state that approximates to high accuracy the ground state of the Heisenberg model on the square lattice.

quantum many-body systems it is not possible to store the exact quantum state in any available computer memory. One has to resort to compressed representations, and neural networks provide an opportunity for this. In a collaboration led by the Flatiron Institute in New York, Kenny Choo co-developed a software package called Netket (www.netket.org) that allows to perform computations with these neural network quantum states. We applied this new methodology to the J1-J2 spin-1/2 Heisenberg model on the square lattice, a classic frustrated problem in quantum magnetism. We found that the neural network quantum states outperform other techniques almost everywhere in the phase diagram. Going forward, we want to employ this new methodology to solve very challenging quantum many-body problems, such as three-dimensional frustrated magnets.

Alongside these research activities, we also co-organized a symposium entitled "Artificial Intelligence and the Scientific Method" in September 2019, which brought together high-profile scientist from a diverse set of fields that use machine learning for their research.

Highlighted Publications:

1. Neural network based classification of crystal symmetries from x-ray diffraction patterns,
   Vecsei, P.M. *et al.*, Phys. Rev. B **99**, 245120 (2019)
2. NetKet: A machine learning toolkit for many-body quantum systems,
   Carleo, G., *et al.*, SoftwareX **10**, 100311 (2019)
3. Study of the Two-Dimensional Frustrated J1-J2 Model with Neural Network Quantum States,
   Kenny Choo, *et al.*, Phys. Rev. B **100**, 125124 (2019)

Superconductivity and Magnetism

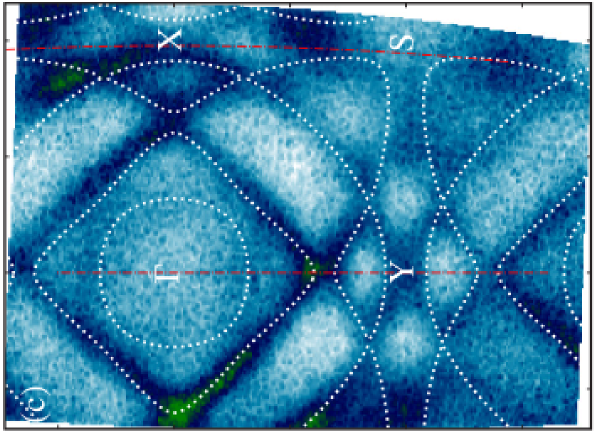
Prof. Johan Chang

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

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

Orbitally selective Fermi liquid breakdown.

Correlated metals are typically classified either as Fermi liquids or non-Fermi liquids depending on whether or not resistivity scales with temperature squared. There is, however, transport evidence suggesting that some materials are hybrids of these two metal classes. This mixed regime is of particular interest as it provides insight into how Fermi liquids break down and the nature of non-Fermi-liquid quasiparticles. In this context, multiorbital metallic systems in conjunction with strong Hund's coupling and electron correlations are of great conceptual importance. Using photoemission spectroscopy, we demonstrated that $Ca_{1.8}Sr_{0.2}RuO_4$ is neither a standard Hunds metal nor representing orbital-selective Mott physics. In fact, the thermally excited state constitutes an example of a hybrid metal.



Fermi surface of $Ca_{1.8}Sr_{0.2}RuO_4$ recorded using angle resolved photoemission spectroscopy.

Parental control of Mott-insulating La_2CuO_4.

An outstanding challenge in high-temperature superconductivity is to understand the optimal conditions for superconductivity: which microscopic parameters drive the change in T_c and how can we tune them? We demonstrated, by a combination of x-ray absorption and resonant inelastic x-ray scattering spectroscopy, how the Coulomb and magnetic-exchange interaction of La_2CuO_4 thin films can be enhanced by compressive strain. Our experiments and theoretical calculations establish that the substrate producing the largest T_c under doping also generates the largest nearest-neighbour hopping integral, Coulomb and magnetic-exchange interaction. We hence suggest optimising the parent Mott state as a strategy for enhancing the superconducting transition temperature in cuprates.

Highlighted Publications:

1. Strain-engineering Mott-insulating La_2CuO_4,
   O. Ivashko *et al.*, Nature Communications **10**, 786 (2019)
2. Orbitally selective breakdown of Fermi liquid quasiparticles in $Ca_{1.8}Sr_{0.2}RuO_4$,
   D. Sutter *et al.*, Physical Review B **99**, 121115(R) (2019)
3. Band structure of overdoped cuprate superconductors: Density functional theory matching experiments,
   K. P. Kramer *et al.*, Physical Review B **99**, 224509 (2019)

Oxide Interface Physics

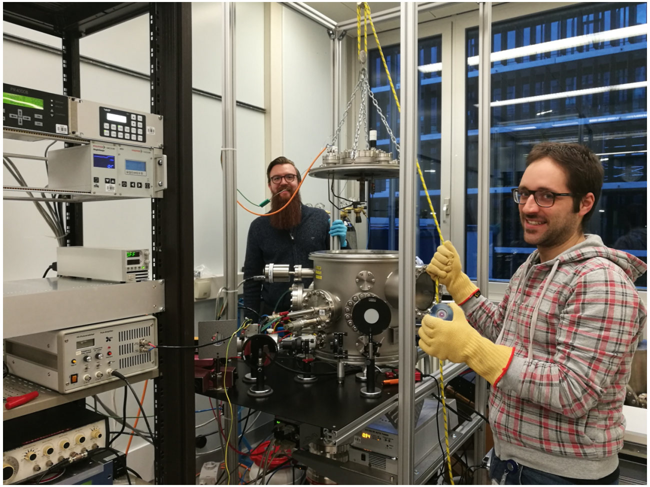
Prof. Marta Gibert

Complex-oxide heterostructures, consisting of layers of different oxide compounds stacked one on top of another with atomic precision, are of interest because the many routes they offer for the manipulation of the physical properties of these materials and the engineering of novel functionalities. Reduced dimensionalities and structural and electronic couplings originating at the interfaces have led to some of the most interesting findings.
In our group, we focus on the study of interface physics phenomena in complex oxides. Our research encompasses from the growth of high quality oxide heterostructures to the detailed study of their structural and electronic properties, both in the laboratory and also in large scale facilities.

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, multiferroicity, 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. These compounds often crystallize in rather similar crystalline structures enabling the generation of artificially layered structures (i.e. thin films, superlattices) as a means to tailor their properties. In our group, we grow high-quality oxide heterostructures by off-axis radiofrequency magnetron sputtering.

During the last year, our research has mainly focused on the family of double-perovskite compounds A_2NiMnO$_6$ (A being a rare earth cation), which is characterized by an insulating ferromagnetic behaviour. Ferromagnetism is often accompanied by metallicity, and thus ferromagnetic insulators are scarce compounds but of high interest in fields such



Jonathan Spring and Gabriele De Luca growing a La_2NiMnO_6 thin film by off-axis rf magnetron sputtering.

as spintronics. We have been extensively studying the end member La_2NiMnO_6, which displays high Curie temperature (T_c~280K). A rock-salt arrangement of the corner-sharing NiO_6 and MnO_6 building blocks of the double-perovskite structure is key for such magnetic behaviour. A variety of tools (x-ray diffraction, atomic force microscopy (AFM), SQUID-magnetometry, x-ray absorption spectroscopy (XAS), transmission electron microscopy (TEM), etc.) has been used to prove the long-range order of the Ni^{2+} and Mn^{4+} cations and to show that the bulk-like magnetic properties are achieved in our thin films.

The magnetism of the La_2NiMnO_6 films has been investigated as function of the epitaxial strain by synthesizing the layers on different substrates and as function of thickness by growing films down to only few unit cells (u.c). La_2NiMnO_6 films as thin as 2 nm (5 u.c.) are found to still exhibit a ferromagnetic behaviour with T_c~200K. We are now investigating the origin of such thickness-driven reduction of the magnetic properties in order to overcome it. To that aim, special emphasis is given to understand the role of interfacial phenomena (strain, coupling of oxygen octahedral rotations, polar discontinuity, etc.) in ultrathin epitaxial La_2NiMnO_6 layers.

Low dimensional systems

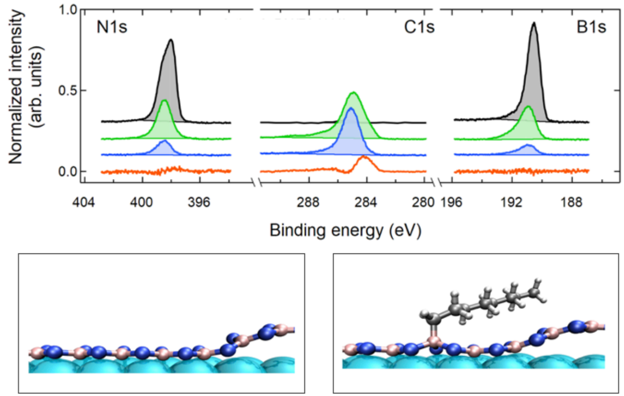
Prof. Thomas Greber

We study objects like **zero dimensional endofullerene** molecules and **two dimensional (2D) boron nitride** layers in view of their functionality as nano-materials.
Single molecule magnetism is the focus in the fullerene research, where we apply bulk sensitive x-ray absorption and a sub-Kelvin superconducting quantum interference device for the investigation of the materials that are obtained from collaborations with synthesis groups.
In the 2D materials activity we aim to grow highest quality boron nitride on substrates with chemical vapour deposition methods and subsequent exfoliation. For this purposes we use a clean room, optical microscopy, transmission electron microscopy and surface science methods such as low energy electron diffraction, photoemission and scanning tunneling microscopy for our investigations.

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

Catalyst Proximity-Induced Functionalization of h−BN

A single layer boron nitride realises a membrane that separates two regions. Still, such membranes allow chemical interaction across the layer. As we showed this year [1] one layer of h−BN on rhodium does not suppress the catalytic action of the rhodium substrate, which is reminiscent to proximity effects as they are observed in magnetic interfaces or in superconductors. We investigated with high resolution x-ray photoelectron spectroscopy (XPS) the interaction tetraoctylammonium (TOA) ions with h−BN/Rh(111). While the electrochemical process enables the large scale exfoliation of single layer h−BN, the underlying mechanism was not understood. XPS before and after TOA treatment in the liquid phase and density functional theory detailed a picture where the proximity of the substrate on which h−BN was grown is essential for the processes at work. The results as summarised in the Figure indicate that TOA may dissociate and that part of the resulting octyl radicals bind on the top face of h−BN but do not intercalate between the interface of h−BN and



Experimental XPS spectra of nitrogen, carbon and boron on h-BN/Rh(111) before (black) and after TOA treatment at normal emission (green), and at 84° grazing emission (blue). The differences between green and blue are depicted in orange. The photon energy is 850 eV, and all signals are normalised with their corresponding photoemission cross sections. The grazing angle data are scaled with a factor of 5.7 such that the carbon peak heights coincide. Bottom panels: Cross-sectional views of structures from XPS calculations before and after TOA treatment. The octyl radicals bind to a boron atom (pink) in the h−BN nanomesh pores.

rhodium. This functionalization scheme realises $h-$BN Janus membranes with two distinct faces which may become of use for biasing the transport direction of ions across such membranes.

Due to the required kinetic energy and resolution of the photoelectrons the XPS experiments were performed at the photoemission and atomic resolution laboratory (PEARL) beamline at the Swiss Light Source of the Paul Scherrer Institut.

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

Highlighted Publications:

1. Catalyst Proximity-Induced Functionalization of $h-$BN with Quat Derivatives
   A. Hemmi *et al.*, Nano Letters **19**, 5998 (2019)
2. Circular dichroism and angular deviation in x-ray absorption spectra of $Dy_2ScN@C_{80}$ single-molecule magnets on *h*-BN/Rh(111)
   T. Greber *et al.*, Phys. Rev. Mat., **3**, 014409 (2019)
3. Production and processing of graphene and related materials
   C. Backes *et al.*, 2D Mater., **7**, 022001 (2020)

Quantum Matter

Prof. Fabian Natterer

Our research investigates how matter receives her properties from the interaction between individual atoms. We especially focus on artificially built quantum matter that we assemble from scratch, one atom at a time. Our scanning tunneling microscope hereby serves as a tool for the construction of atomic structures and the characterization of its emergent properties. We use this knowledge to steer interesting quantum behavior, such as magnetic monopole excitations. We furthermore study 2D van der Waal materials and develop new measurement protocols for advanced scanning probe microscopy investigations, such as electron spin resonance and compressed sensing for quasiparticle interference mapping.

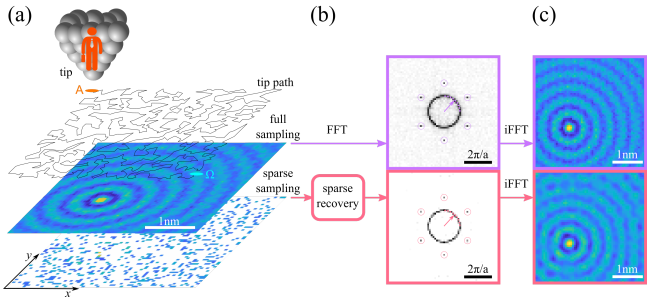
https://www.physik.uzh.ch/g/natterer

Scanning Probe Microscopy based ESR

One of our main projects is the development of Scanning Probe Microscopy based Electron Spin Resonance (ESR) and pump-probe methods to investigate the dynamics of single atom magnets. Using pulsed ESR, we gain control over the quantum phase of an atomic qubit that serves as a powerful quantum sensor for magnetic signatures at the atomic scale, such as in our artificially built quantum matter. Pump-probe methods yield insight into the lifetime of magnetic states, which defines the limits for data conservation and quantum manipulation.

Compressed sensing methods

The introduction of compressed sensing (CS) methods for scanning probe measurements is our second major project. Compressed sensing can fundamentally speed up measurements (ten to hundred-fold), because it removes data redundancies and requires only the mea-



Measure smarter, not harder, it the guiding principle behind our compressive sensing methods. The sparsely sampled LDOS allows perfect reconstruction of the QPI information with only a fraction of the usual measurements.

surement of a fraction of the full dataset. The applicability of CS is given for any data that is sparse in some represation domain. This is the case in many quasiparticle interference (QPI) measurements, where the number of wavevectors is typically significantly smaller than the number of data points. Traditional QPI may take up to hundreds of hours, whereas CS can retrieve the same information in a fraction of this time. The shorter measurement time allows us to better use our resources to improve the spectroscopic resolution which may help identify finer band-structure details of exotic 2D materials.

Highlighted Publications:

1. Sparse Sampling for Fast Quasiparticle Interference Mapping
   J. Oppliger and F.D. Natterer, arXiv 1908.01903 (2019)
2. Waveform-sequencing for scanning tunneling microscopy based pump-probe spectroscopy and pulsed-ESR,
   F.D. Natterer, arXiv 1902.05609 (2019)
3. Quantum state manipulation of single atom magnets using the hyperfine interaction
   P. Forrester *et al.*,arXiv 1903.00242 (2019)

Surface physics

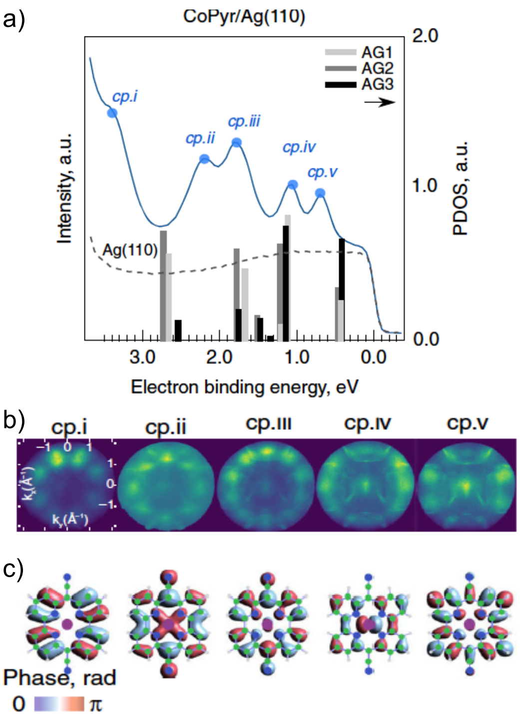
Prof. Jürg Osterwalder

We study processes at surfaces such as molecule adsorption and self assembly, charge and energy transport as well as fundamental aspects of **light-matter interaction** and associated electronic and atomic dynamics. Our laboratory is equipped with a toolbox of surface science methods for the preparation and characterization of clean single-crystalline surfaces that can be used to investigate such phenomena **at the atomic and molecular level**. Specific research projects include the structure and function of adsorbed catalyst molecules on semiconductor surfaces that serve as model electrodes in water splitting devices, as well as the measurement of molecular orbitals of adsorbed donor-acceptor dyads and their charge-transfer dynamics by **orbital tomography**. Finally, we push the development of new experimental techniques, most recently ambient-pressure XPS at **solid-liquid interfaces** at the Swiss Light Source at PSI.

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

Identifying molecular orbitals of adsorbed molecules by angle-resolved photoelectron spectroscopy

Valence electrons in molecules form delocalized molecular orbitals (MOs) which determine their physical properties and chemical reactivity. The energies of the MOs are sensitive to the local environment of the molecule such that, for instance, the ordering of the binding energies can change when molecules are adsorbed on a metal surface. UV excited photoelectron spectroscopy (UPS) can measure the energy distribution of MOs, but for the assignment of a measured energy level to a particular molecular orbital, one needs to go one step further. The angular distribution of the photoelectron intensity of a particular peak in the UPS spectrum carries the signature of the associated MO. Under certain conditions, it has been demonstrated that the MO can be directly reconstructed from the angular distribution map via a Fourier transform method including iterative phase retreaval algorithms, an approach termed *orbital tomography*.



a) UV photoelectron spectrum of a monolayer of Co-pyrphyrin molecules on an Ag(110) surface. b) Photoelectron angular distribution maps from molecular orbitals as denoted in a). c) Phased isosurfaces of corresponding molecular orbital amplitudes.

One condition necessary for this approach to work is that all molecules within the macroscopic probing area on the sample are adsorbed in a single orientation. However, adsorbed molecules often arrange themselves in domains with different orientations. In a collaboration with the Department of Chemistry of UZH we studied the system of Co-pyrphyrin on the Ag(110) surface. MOs were calculated via density functional theory and Fourier transformed in order to obtain their angular distribution maps. Superpositions of these maps with different orientations could be fitted to the measured maps for an unambiguous identification of five different MOs.

Highlighted Publications:

1. Comparative study of different anchoring of organometallic dyes on ultrathin alumina,
   W.-D. Zabka *et al.*, J. Phys. Chem. C **123**, 36 (2019)
2. Polarization-sensitive reconstruction of transient local THz fields at dielectric interfaces,
   K. Waltar *et al.*, Optica **6**, 1431 (2019)
3. Combined orbital tomography study of multi-configurational molecular adsorbate systems,
   P. Kliuiev *et al.*, Nature Commun. **10**, 5255 (2019)
4. Sb_2Se_3(100): A strongly anisotropic surface,
   R. Totani *et al.*, Phys. Rev. Materials **3**, 125404 (2019)

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.

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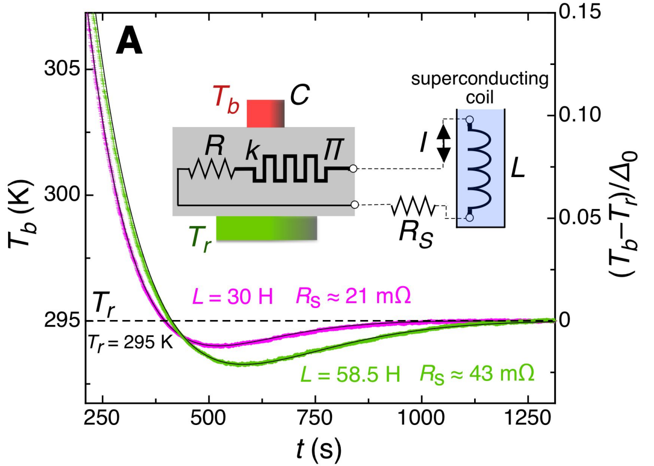
Design and implementation of a "thermal inductor"

Heat currents and electrical currents can both be described with the same mathematical formalism. The electric analogue to a heat current is the electric current; heat corresponds to charge, and temperature to voltage; an electric capacitor is equivalent to a heat capacity, and electric conductivity corresponds to thermal conductivity. However, no thermal analogue to an inductor has been reported up to present. It has been argued that its existence would violate the second law of thermodynamics, because a corresponding thermal LC circuit could carry an oscillating heat current where the temperature difference between two bodies perpetually changes its sign, and heat would temporarily flow form the colder to the warmer object. We have shown already in 2011 that a Peltier element, switched in series with an electric inductor and connected with a heat capacity, behaves like a thermal LC circuit with certain a "thermal inductance". When operated entirely passively, only over-damped temperature oscillations were expected at that time. A detailed analysis of the circuit



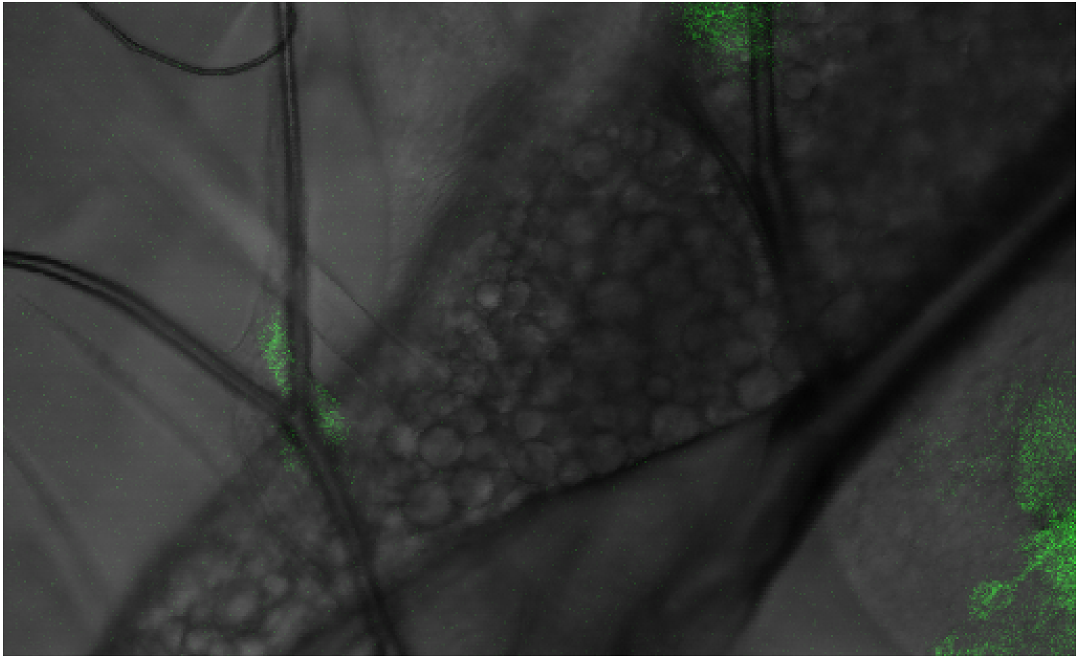
Temperature undershoot during the first cycle of a damped temperature oscillation, starting from 100 °C at t = 0.

showed, however, that a careful choice of superconducting inductors (L) and efficient Peltier elements (Π) allows for true temperature oscillations. In a typical experiment, an object (C) is initially heated and then connected to one side of the Peltier element, with a heat bath held at ambient temperature (T_r) on its other side. After a while, the temperature T_b of the object indeed dropped below that of the thermal bath. The maximum temperature difference to ambient temperature reached only 2 °C, however, which was mainly limited by the performance of the commercial Peltier element. Under the same conditions, a cooling from 100 °C down to -47 °C could be theoretically achieved, which would require the use of an ideal Peltier element with maximum possible efficiency. In theory, large amounts of a hot material could be cooled well below room temperature in this way, without any energy consumption or moving parts, and the passive thermal circuit could be used as often as desired. Most remarkably, heat is directed directly from the cold to the warm object for some time in such experiments, without being temporarily stored as magnetic energy in the electric inductor, and the process, which passes through a series of quasi-equilibrium states, still obeys the second law of thermodynamics. To prove this, we showed that entropy of the whole system is strictly monotonically increasing with time. Finally, we identified a very general thermodynamic limit for the maximum possible cooling effect that can occur during any thermal oscillation cycle without external work done on a system.

Highlighted Publications:

1. Heat flowing from cold to hot without external intervention by using a “thermal inductor”,
   A. Schilling, X. Zhang, and O. Bossen,
   Science Advances 5, eaat9953 (2019)
   Popular summary:
   https://www.youtube.com/watch?v=4Vi8k-p4COY

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 the production of colouration due to scattering rather than pigmentation in photonic glasses and natural systems.

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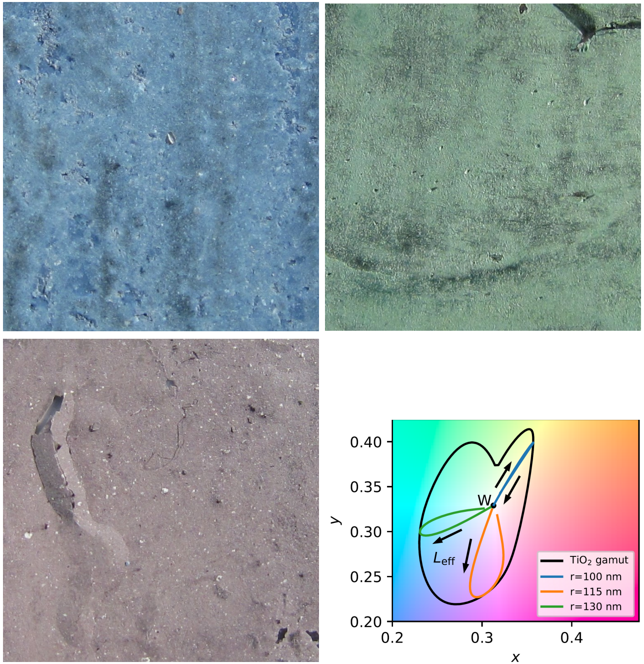
Structural colours using photonic glasses

Many colours in nature are not due to pigmentation, but rather intricate nano-structures of low-index biological materials. This can give rise to very striking blues, such as in morpho butterflies, but also yellows and greens, such as in peacock's or duck's feathers. While photonic glasses can give rise to such colours, these are highly specific on the incident angle, while the natural example given above show the same colouration over very wide angles. Based on a model describing the scattering of individual particles as well as the effects of disordered packing in a photonic glass, we have created a model that can describe the colouration of photonic glasses made of almost monodisperse particles depending solely on the particle size and refractive index as well as their packing fraction.

We have tested this using polystyrene nano-particles of different sizes, where the obtained broad range colours



Images of structural colours using polysterene photonic glasses of different particle radii. Top left: mean radius of 196 nm giving a blue colour, Top right: mean radius of 236 nm giving green, Bottom left: mean radius of 250 nm giving red. The model describing the colouration of a photonic glass shows the range of possible colours using TiO_2 nano-particles with a refractive index of 2 is able to give the entire spectrum of colours (bottom right).

visible in the figure on the left are in good agreement with the expectations from the model. In addition, the model predicts that all shades of colours can be created using a high enough refractive index of the particle, as indicated by the bottom right panel of the figure for amorphous TiO_2 with a refractive index of 2. This shows that photonic glasses can be used as non-pigmented colouration for all kinds of colours in a simple and well understood manner.

Highlighted Publications:

1. Disentangling geometrical, visco-elastic and hyper-elastic effects in force-displacement relationships of folded biological tissues,
   F. Atzeni, F. Lanfranconi and C.M. Aegerter,
   Europ. Phys. J. E **42**, 47 (2019).
2. The Structural Colors of Photonic Glasses,
   L. Schertel, L. Siedentop, J.-M. Meijer, P. Keim, C.M. Aegerter, G.J. Aubry, and G. Maret,
   Adv. Opt. Materials **7**, 1900442 (2019).
3. Scattering lens for structured illumination microscopy,
   A. Malavalli and C.M. Aegerter,
   OSA Continuum **2**, 2997 (2019)

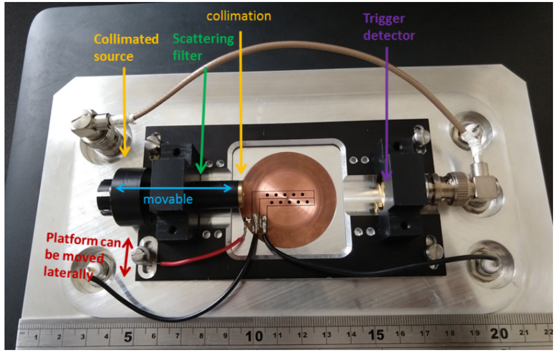
Medical Physics and Radiation Research

Prof. Uwe Schneider

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

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

Currently we are developing a compact nanodosimetric detector (see figure) which can be used to quantify the number of ionizations in DNA, the so called cluster size distribution. For the purpose of relating the measurements to biological effects in patients we are developing a novel radiation action model. Additional research is conducted in the application of highly heterogeneous dose distributions to cancer patients. We are also developing novel radiation risk models for astronauts.



Highlighted Publications:

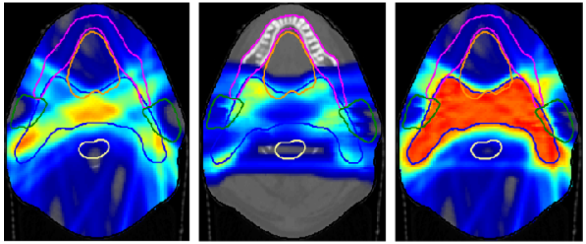
1. Track event theory: A cell survival and RBE model consistent with nanodosimetry, U. Schneider *et al.*, Radiat. Prot. Dosimetry **183**(1-2):17, 2019
2. Research plans in Europe for radiation health hazard assessment in exploratory space missions, L. Walsh *et al.*, Life Sciences in Space Research **21** 73, 2019

Medical Physics

Prof. Jan Unkelbach

Over the past 20 years, research in medical physics has improved the accuracy of radiotherapy for treating cancer patients tremendously. This includes the development of intensity-modulated radiotherapy with high-energy x-rays (IMRT) and protons (IMPT), which allows the delivery of highly conformal dose distributions to complex shaped tumors. More recently, the development of image guided adaptive radiotherapy has provided means to correct for geometric changes and organ motion over the course of therapy. The medical physics group contributes to these technological advances of radiotherapy.
https://www.physik.uzh.ch/g/unkelbach

We focus on three areas of research:
1) Treatment planning for IMRT and IMPT: In particular, we investigate treatments that combine x-rays and protons (see Figure).
2) Target delineation and outcome prediction: Here, we focus on quantitative analysis of medical images such as MRI, CT



Optimal combination (right) of x-rays (left) and protons (middle) to irradiate a tumor located in the oral cavity (blue contour) while minimizing radiation to the salivary glands (green contour). Ref: Fabiano et al., Radio. Onc. **145***:p81-87, 2020*

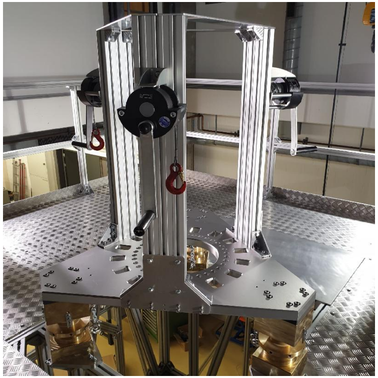
and PET, with the goal of precisely defining the region to be irradiated and predicting the patient's response to treatment.
3) Adaptive radiotherapy: Our department is the first in Switzerland to install a MR-Linac, a combination of MRI scanner and radiotherapy device. MR images of a patient can be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

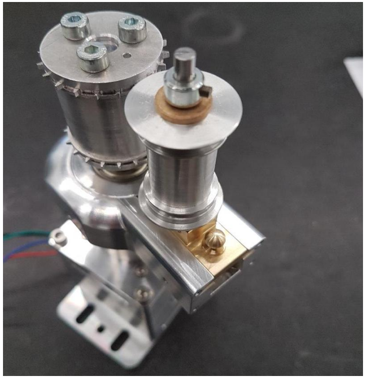
Workshops

Mechanical Workshop

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

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



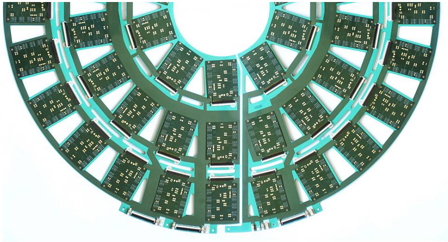


The three photograph are examples for work done in our workshop: prototype of the DARWIN Demonstrator for the group Baudis (left), a digitizer for old films for the department of film studies UZH (middle) and a vibration damping table for the group Natterer (right).

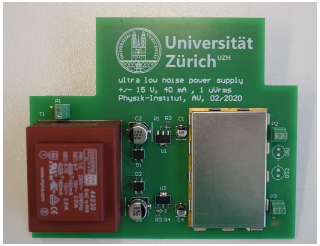
Electronics Workshop

Besides maintenance work for the existing laboratory infrastructure the **electronics workshop** continuously supports the groups of our institute with technical advice, prototypes and new developments for ongoing projects. Besides many ongoing and newly developed projects for the research groups of our institute we developed the steering electronics for an anaesthesia gun that was built in the mechanical workshop. The motorised turnable and tiltable gun that works with compressed air is equipped with a CCD camera, a motion detector, a laser pointer and IR lighting. It will be used for remotely narcotise wild animals.

Case with the control electronics for an anaesthetic gun.

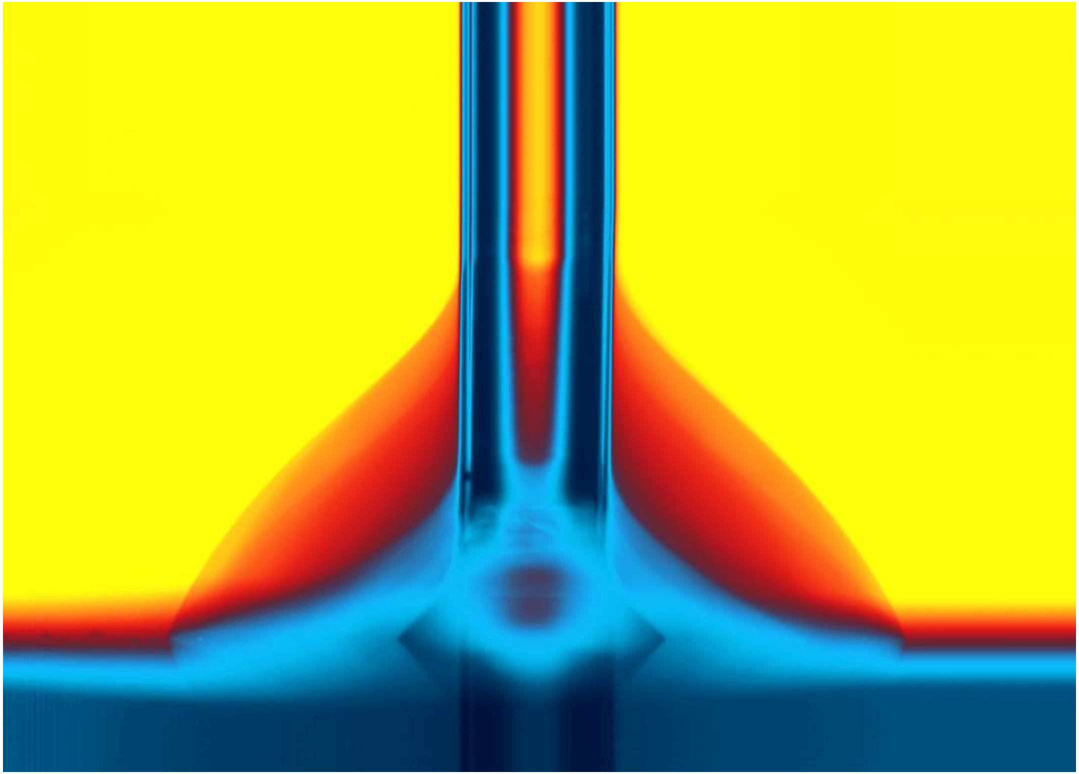


Design of the printed circuit board for the CMS Pixel Endcap Upgrade.



Bipolar 15V power supply with extremely low noise (<1uVrms).

Personnel



Personnel, January – December 2019

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Denise Caneve
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Regina Schmid
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Bruno Lussi
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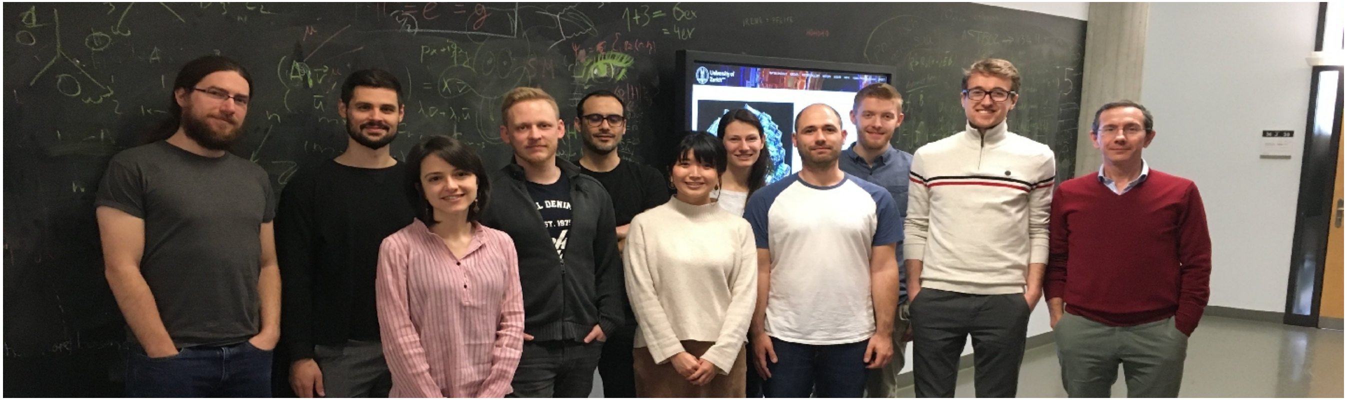

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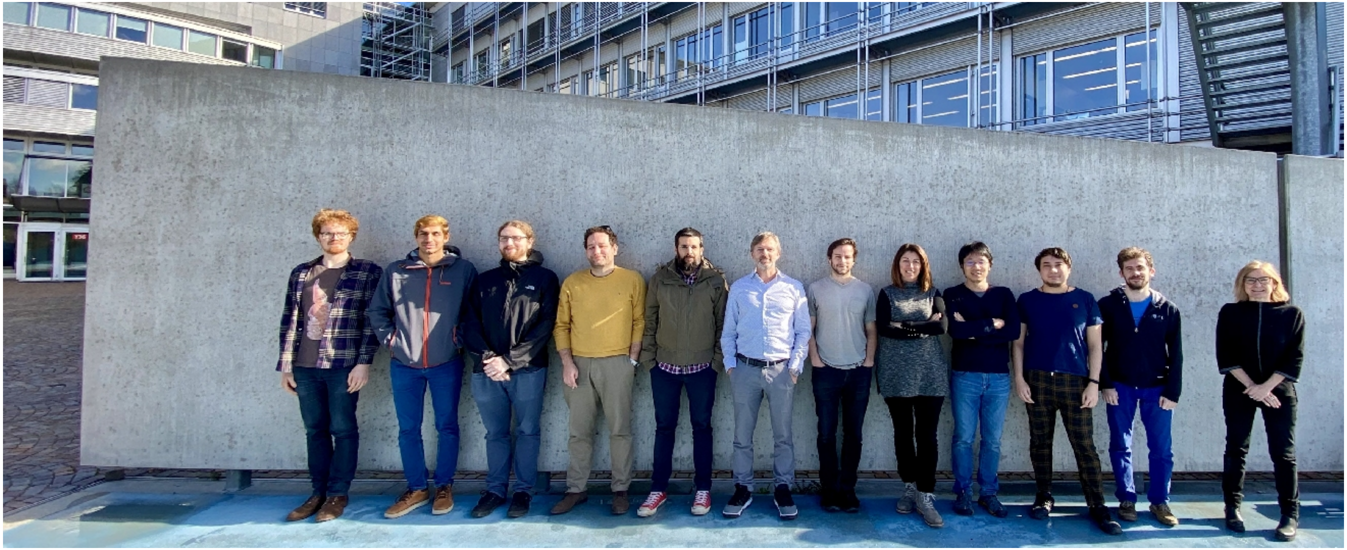

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