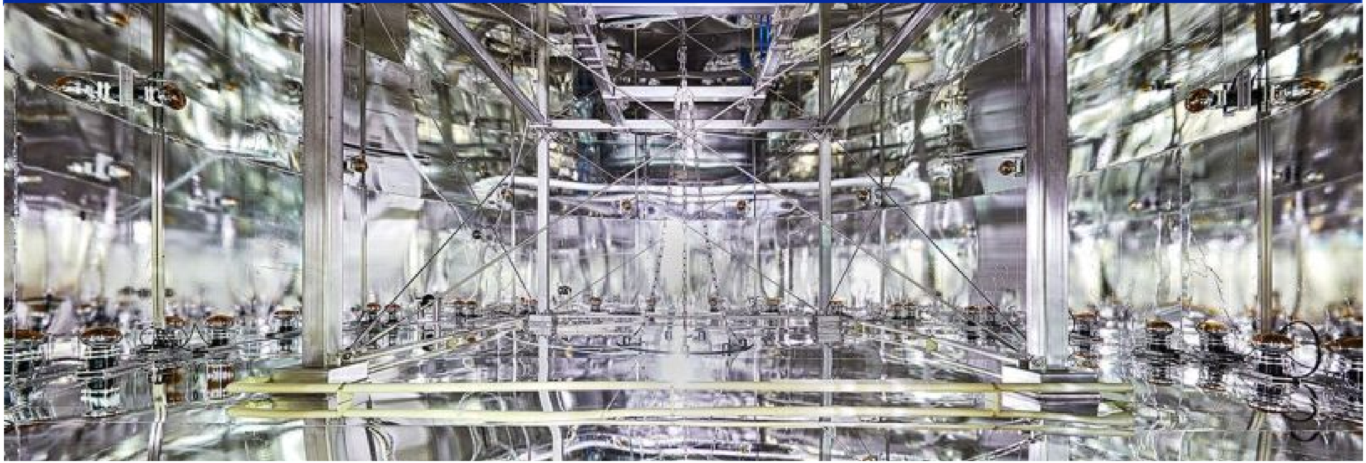
University of Zurich[UZH]

Department of Physics

Annual Report and Highlights 2018



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Department of Physics

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Winterthurerstrasse 190, CH-8057 Zurich, Switzerland

Preface

Jürg Osterwalder, Department Head

With a total of 21 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, and 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 and Bachelor, Master and semester projects to our students. The infrastructure department with the excellent mechanical and electronics workshops and the efficient IT and administrative support teams complete our attractive research environment.
https://www.physik.uzh.ch/en/research.html

Last year brought the arrival of three new SNF professors. Marta Gibert started in February by setting up a laboratory for the controlled layer-by-layer growth of transition metal oxides and for studying the physical properties of perovskite heterostructures. Alexey Soluyanov, who is interested in materials with non-trivial topology, followed in June. With his team, he will develop computational methods for simulating real materials with existing tensor network numerical approaches. Finally, Fabian Natterer joined in October and started preparations for a low-temperature scanning tunneling microscopy laboratory in the basement of our building. He will implement electron spin resonance excitation at the tunnel junction and study quantum matter at the atom-by-atom level.

On the other hand, 2018 saw the departure of Ueli Straumann into retirement - but not entirely. After handing over the LHCb activities at CERN into capable hands (page 21) he still held on to responsibilities in the CTA project (page 34) and helped the department overcome a teaching emergency in the fall semester. Likewise,

The year 2018 saw the rising of Building Y38 just behind our building, replacing the view on green forest and cosy residential houses with modern architecture for functional office and lab space for chemistry and the life sciences. The members of our department endured the construction with patience.

Tiziano Crudeli and Lucien Pauli retired last summer after having worked for 41 and 38 years in our department, respectively. Lucien was responsible for the lecture demonstration experiments and knew every trick to get them going. Tiziano solved all the problems that nobody else could solve - I wish he could have enjoyed his retirement longer.

In July the department lost one of its most prominent former faculty members. Verena Meyer was a pioneering woman, the first ever female full professor at UZH. She served terms as Dean of the Faculty of Sciences, as Vice President and President of the University. She was very active in science policy and was for many years the President of the Swiss Science Council, among many other services to the scientific community.

Previous subscribers to our scientific annual report will note that this years issue comes in a new, more compact format. The rationale behind this is to address a broader readership also outside the department. Refraining from condensing it down to the information content of a tweet, the present form should give a broad idea of the groups' research and refer the more interested reader to the research websites. Presenting individual highlights with pride, we thankfully acknowledge the continued support from the Kanton Zürich, the Swiss National Science Foundation, the European Commission, and others who have made this fundamental research possible.

Retirement - Ueli Straumann

Ueli Straumann studied experimental physics (1972-1979) at our institute, in those years located at the Schönberggasse. He graduated in 1983 with a thesis on "Pion capture in C-14, N-15 and C-13" under Prof. Peter Truöl using an experiment at SIN (nowadays PSI). During his time as a PhD student he also spent a year at Berkeley Lab in California as a visiting scientist working on an experiment to measure the η parameter of the muon decay. After his PhD Ueli joined the University of Mainz as a postdoc working at CERN on the ASTERIX experiment. The ASTERIX spectrometer has been used to study proton-antiproton interactions at rest in a hydrogen gas target, using antiprotons from the Low Energy Antiproton Ring (LEAR) at CERN.

1986 he returned to Zurich as a senior assistant where he built up the first lab courses on computing in experiments and started to work on the first level trigger of the H1 experiment at the electron-proton collider HERA in Hamburg. He contributed significantly to the successful running of the experiment first as the trigger coordinator and later as the technical coordinator.

In 1996 Ueli Straumann was appointed professor (C3) in Heidelberg where he started to work on the development of micropattern gas detectors (MSGC, GEM) and got involved in the LHCb experiment at CERN. Finally Ueli Straumann moved back to his home town in 1999 as he became a full professor for particle physics at our institute.

Ueli is a passionate physicist loving the experimental work in the lab as well as to develop new ideas and drive them forward from a sketch on a piece of paper to a working experiment with several hundred collaborators. In his time at UZH his group was largely involved in the high-energy experiments H1 at HERA and LHCb at LHC and in the past years the Cherenkov Telescope Array (CTA). The latter he shaped for two years as managing director commuting between Zurich, Heidelberg and Bologna in his favourite vehicle, the train.

Besides his duties as a group leader he was strongly involved in managing the institute and structuring the physics curriculum as institute director (2011 – 2016) and in the administration of the faculty as Dean of Studies (2013 – 2016). His open-door philosophy and his closeness to the students during the countless lectures he gave and his solve-a-problem-don't-create-one attitude made him a very popular teacher and mentor for the students and his own staff.

Statistical Data 2018

187
personnel

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

307
students

~55
new students

175 bachelor	16 BSc degrees
62 master	23 MSc degrees
70 PhD	25 PhD degrees

8
SNF prof. and ERC grants

- 35 SNF or EU research grants
- 5 SNF ambizione fellowships
- 19 UZH and other grants

342
publications

- 291 peer reviewed papers
- 30 conference proceedings
- 26 books & others

321
conference and workshop contributions

- 354 invited talks
- 39 seminar and other talks
- 44 posters
- 25 outreach

Outreach 2018

Conferences and Workshops in Zurich

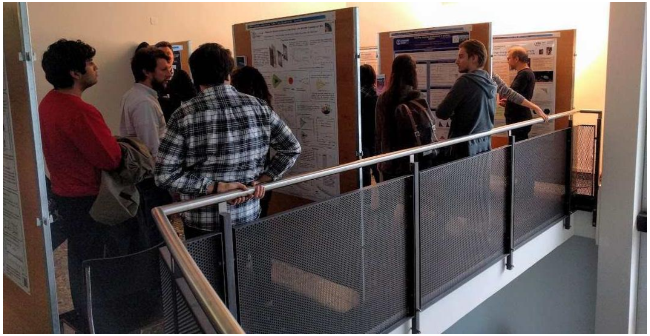
- Zurich Phenomenology Workshop
- 6th Beam Telescope and Test Beam Workshop
- Symposium on quantum matter
- International Workshop on the Interconnection between Particle Physics and Cosmology 2018
- Machine Learning for High Energy Physics

Others

- Symposium Joseph Fourier
- Einstein Ehrengast: talk from William D. Phillips
- Schrödinger Colloquium:
  K. Marvel, W. Hofmann, C. Macchiavello
- Verena Meyer Symposium
- Masterclass in particle physics
- How particle-physics works: hope and worries on the B-physics anomalies (video)
- Open Day of the institute

Awards

- CMS young researcher prize for Lea Caminada
- Dectris prize for best experimental master thesis: Chris Marentini
- UZH semester award for outstanding bachelor theses: Céline Nauer and Björn Salzmann
- Annual poster award of the Department of Physics for members of the groups Serra, Pozzorini and Aegerter



Teaching

bachelor 3 major options

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

4 master programs

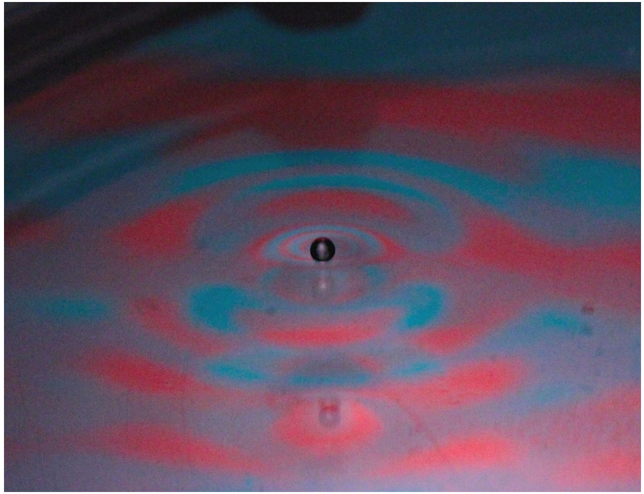
- particle physics
- condensed matter
- astrophysics & cosmology
- bio- & medical physics

service lectures 1034 students

475	medicine
190	biomedicine
226	biology
143	chemistry

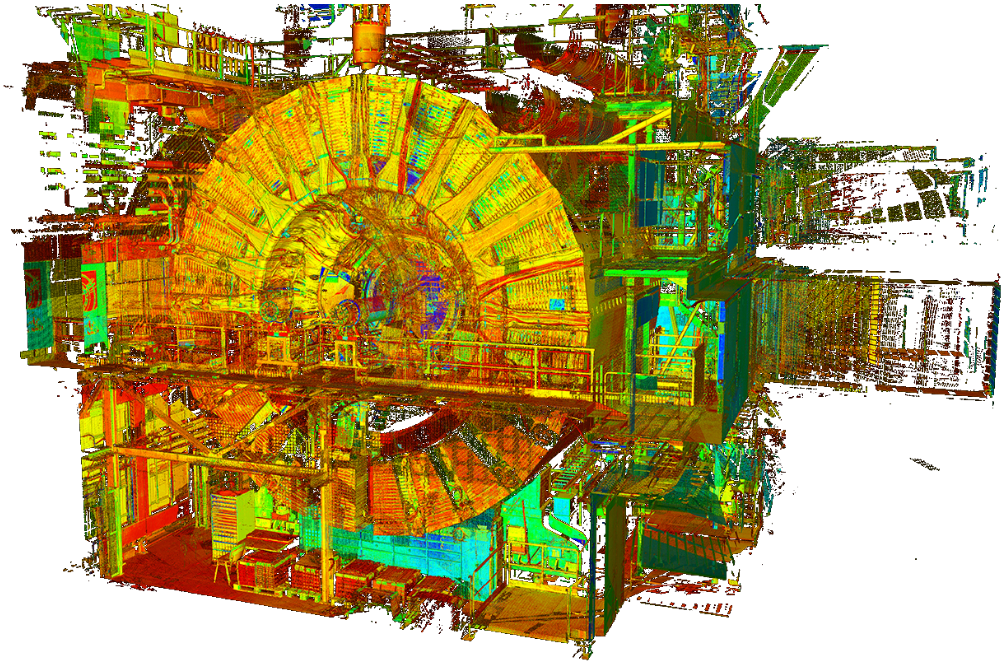
A new experiment to visualize wave-particle duality

Wave-particle duality is one of the most fundamental concepts in quantum mechanics and due to its inherent quantum nature notoriously difficult to visualise. Based on experiments by Yves Couder, ENS Paris, we have created a macroscopic visualisation of the phenomenon that captures many of the aspects of a quantum system. A bath of liquid is vibrated just below the onset of a surface wave instability. In that case, a drop of the same liquid will not coalesce with the bulk, but locally creates a surface wave that leads to a motion of the droplet reminiscent of a pilot-wave in Bohmian mechanics. Hence, the drop and the surface wave can only exist in tandem, creating an object that shows both particle and wave-like properties. For instance if the object is sent trough a slit, a definite track can be observed, whose statistics however show a diffraction pattern dictated by the properties of the surface waves.



A new experiment visualizes the wave-particle duality.

Physics of Fundamental Interactions and Particles



Particle Physics Theory: Beyond the Standard Model

Prof. Gino Isidori

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

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

Flavour Anomalies and the origin of fermion masses

One of the key predictions of the Standard Model (SM) is that quarks and leptons do appear in three replicas (denoted generations, or flavours) that behave exactly in the same manner under the known microscopic forces and differ only in their mass (or, more precisely, in their interaction with the Higgs field). Surprisingly enough, a series of precision measurements performed recently by the LHCb experiment at CERN seem to challenge this prediction: these measurements hint to a different behaviour of leptons belonging to different families that is not related to their mass.

These results have stimulated a lot of theoretical investigations. A first natural question to be addressed is the consistency of these “anomalous” results, so far observed only in the decays of B mesons (containing quarks of the 3rd generation), with the tight bounds on possible extensions of the SM derived by many past experiments. A theoretical study of our group has clarified that there is no inconsistency between

the recent B-physics anomalies and the past tight bounds, provided the hypothetical "new force" responsible for the anomalies is not universal not only in the lepton sector, but also when acting on quarks. More precisely, the strength of the new interaction should be maximal for quarks and leptons of the third generation, should become weaker for particles of the second generation, and must be super-weak for those of the first generation (this is why we do not experience it on ordinary matter). Interestingly enough, this hypothesis also explains the hierarchy of the different anomalies so far observed, and provides a hint that this new interaction may be the key towards a deeper understanding about the origin of particle masses. Encouraged by these observations, we have started a systematic investigation of realistic extensions of the SM aimed at this twofold goal: a phenomenological explanation of the recent anomalies, linked to a solution of the long-standing puzzle of quark and lepton masses. A promising line in this direction has lead us to an extended gauge group that unifies the interactions of quarks and lepton at high energies, i.e. a class of models where quarks and leptons are different states of the same fundamental particle, and where new force mediators called leptoquarks do appear. We are not yet in a position to draw definite conclusions about such models, but our studies have identified a series of precise predictions that could allow us to confirm or disproof them in the near future with the help of more experimental data.

Highlighted Publications:

1. A three-site gauge model for flavor hierarchies and flavor anomalies, M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, Phys. Lett. B **779** (2018) 317
2. Low-energy signatures of the PS^3 model: from B-physics anomalies to LFV, M. Bordone, C. Cornella, J. Fuentes-Martín, G. Isidori, JHEP **1810** (2018) 148
3. Leptonic WIMP coannihilation and the current dark matter search strategy, M.J. Baker and A. Thamm, JHEP **1810** (2018) 187

Particle Physics Theory: Standard Model and Higgs Physics at Colliders

Prof. Massimiliano Grazzini

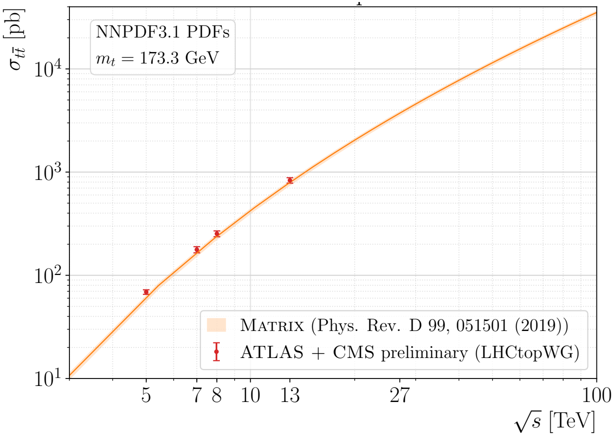
Our research activity is focused on the phenomenology of particle physics at high-energy colliders. We perform accurate theoretical calculations for benchmark processes at the Large Hadron Collider and we make their results fully available to the community. We strive to develop flexible numerical tools 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. Therefore, accurate theoretical predictions for this process are needed, which 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 generated with OpenLoops, an automated tool also developed



NNLO calculation of the top pair cross section as a function of the centre of mass energy [1].

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. Top-quark production is a more complicated process due to the additional soft radiation from the top-quark pair. To address this problem we have developed an extension of our methods to this process, and computed the missing soft contributions at NNLO. 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 result, which is the first independent confirmation of a landmark result obtained in 2013, is implemented in a fully differential parton level event generator that is able to compute fiducial cross sections and distributions for stable top quarks. The 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. 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. D99 (2019) no.5, 051501
2. ZZ production at the LHC: NLO QCD corrections to the loop-induced gluon fusion channel,
   M. Grazzini *et al*, JHEP **1903** (2019) 070
3. Higgs boson production at large transverse momentum within the SMEFT: analytical results,
   M. Grazzini *et al*, Eur.Phys.J. C**78** (2018) no.10, 808

Particle Physics Theory: Precision Calculations

Prof. Thomas Gehrmann

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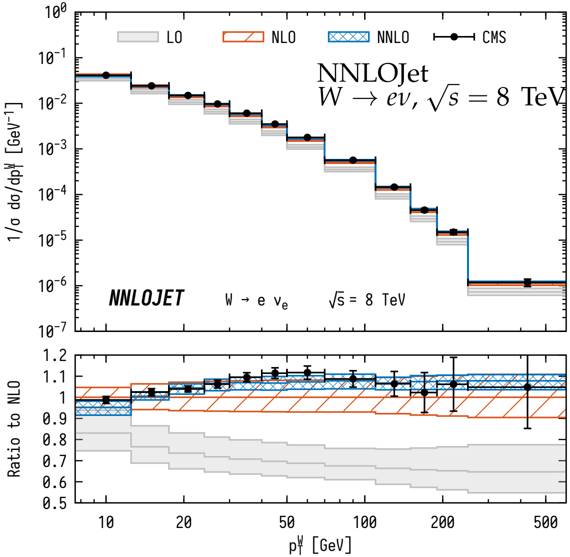
Our research group focuses on precision calculations for collider observables within the Standard Model and their application in the interpretation of experimental data. We develop novel techniques and computer algebra tools that enable analytical calculations in perturbative quantum field theory and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

The production of electroweak gauge bosons is one of the most prominent processes at hadron–hadron colliders such as the LHC. The gauge bosons are produced in abundance and their clean leptonic signature allows this class of processes to be measured with great precision. As a consequence, the production of $V = (W, Z)$ bosons is among the most important benchmark processes at hadron colliders and has a wide range of applications. The transverse-momentum (p_T^V) spectrum of the gauge bosons plays a particularly important role: this observable probes multiple aspects of the theory predictions and enables precision measurements of electroweak parameters. In particular, the ratio of the transverse momentum spectra in W and Z boson production is the key ingredient to the determination of the W-mass at hadron colliders.

To confront LHC precision data with theory predictions of matching accuracy requires the computation of higher order corrections in QCD. In the past years, 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 for the first time the NNLO corrections to the p_T^W distribution. Our theory predictions are at the level of fiducial cross sections, taking full account of the



Normalized p_T^W distribution in the electron-neutrino channel. Theory predictions (NNLOJet) at leading order (grey), next-to-leading order (orange) and next-to-next-to-leading order (blue) in perturbative QCD are compared to CMS data. The bands on the theory predictions estimate their uncertainty through the variation of renormalization and factorization scales. The lower frame displays the ratio to the previously available NLO theory.

experimental cuts on the lepton momentum and on missing transverse energy from the unobserved neutrino.

Comparing the newly computed NNLO predictions with experimental data from the CMS experiment (figure on the left), we observe a considerably improved description of the kinematical shape of the distribution, and a decrease in theory uncertainty, now comparable in magnitude to the experimental errors.

We performed similar studies for Z and Higgs boson production, combining fixed-order calculations with all-order resummations of large logarithmic corrections at low p_T^V.

Further recent calculations obtained in the NNLOJET framework include jet production observables in hadron-hadron and lepton-hadron collisions, which are of direct impact to the precise determination of the proton structure.

Highlighted Publications:

1. NNLO QCD Corrections to the transverse momentum distribution of weak gauge bosons,
   A. Gehrmann-De Ridder *et al*, Phys. Rev. Lett. **120** (2018) 122001
2. Fiducial distributions in Higgs and Drell-Yan production at N^{3}LL+NNLO,
   W. Bizon *et al*, JHEP **1812** (2018) 132
3. N^{3}LO corrections to jet production in deep inelastic scattering using the Projection-to-Born method,
   J. Currie *et al*, JHEP **1805** (2018) 209

Particle Physics Theory: Automated Simulations for Collider Physics

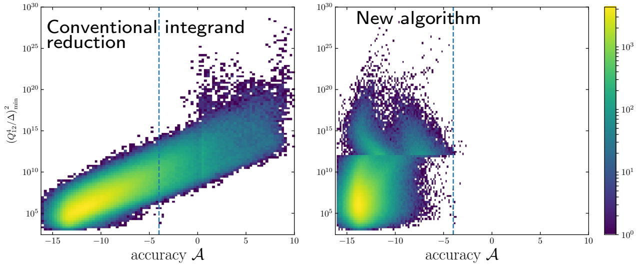
Prof. Stefano Pozzorini

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. It is applicable to arbitrary collider processes and can account for the full spectrum of first-order quantum effects induced by strong and electroweak interactions. Its reach in terms of process complexity outperforms traditional algorithms by more than two orders of magnitude. 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

A new way of constructing scattering amplitudes

Recently we have proposed and implemented in OpenLoops a novel method for the calculation of scattering amplitudes with first-order quantum effects. Such effects are described in terms of Feynman diagrams with one loop. Each Feynman diagram represents one of the possible intermediate states in a given scattering processes, and one-loop diagrams correspond to quantum fluctuations where extra intermediate particles and anti-particles are created and annihilated in a closed loop.

The number and complexity of one-loop diagrams grow 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 or simply unaffordable. This is due also to the occurrence of severe numerical instabilities that require to carry out certain parts of the calculations in quadruple precision, slowing down the codes in a dramatic way. Such instabilities



Correlation of the one-loop accuracy $\mathcal{A}$ of a $2 \to 4$ scattering amplitude with a critical kinematic variable Q_{12}. At small Q_{12} conventional algorithms (left) suffer from huge instabilities that can generate output several orders of magnitude away from the correct result, while the new OpenLoops algorithm (right) provides stable results in the whole phase space.

are related to the fact that loop amplitudes are typically constructed in terms of complex (high-rank) integrals, which are subsequently reduced to a relatively small set of well-know and simple (rank-zero) integrals.

In order to avoid the explosion of complexity at intermediate stages of the calculations, in [1] we have developed a new type of algorithm where fundamental operations associated with the construction and the reduction of loop amplitudes are interleaved in a way that minimises the complexity (rank) at all stages of the calculation.

The new algorithm, which is publicly available in the latest release of OpenLoops, features an unprecedented level of numerical stability and is amenable to one-loop calculations with up to 10^5 one-loop diagrams. This will benefit theoretical simulations based on a variety of multipurpose simulations programs that are interfaced to OpenLoops, such as Sherpa, Powheg and Matrix. As a first phenomenological application we have presented a study of $pp \to t\bar{t}b\bar{b}j$, a multi-particle process that plays a key role in measurements of the recently discovered process of Higgs-boson production in association with top-quark pairs. The new OpenLoops algorithm is also an optimal basis for the extension of automated methods beyond first order in perturbation theory.

Highlighted Publications:

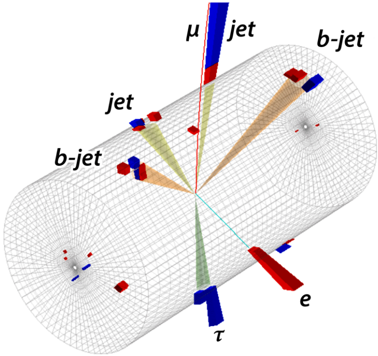
1. On-the-fly reduction of open loops, F. Buccioni, S. Pozzorini and M. Zoller, Eur. Phys. J. C**78** (2018) no.1, 70
2. New NLOPS predictions for $t\bar{t} + b$-jet production at the LHC, T. Ježo, J. M. Lindert, N. Moretti and S. Pozzorini, Eur.Phys.J. C**78** (2018) no.6, 502
3. A theoretical study of top-mass measurements at the LHC using NLO+PS generators of increasing accuracy, S. Ferrario Ravasio, T. Ježo, P. Nason and C. Oleari, Eur. Phys. J. C **78** (2018) no.6, 458

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, as well as differences between data and theory calculations that could mean discoveries of 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. The detector is used to determine the energy and direction of emerging particles. By reconstructing these particles, the forces and particles producing the interactions can be deciphered. In 2012, the CMS collaboration discovered the Higgs boson, and was thereby able to prove the mechanism for how particles acquire mass. CMS finished the Run 2 data taking period in 2018, achieving a record dataset of 150 fb^{-1} that allows more precise measurements and searches for new physics.
https://www.physik.uzh.ch/r/cms

The CMS group at UZH has strong analysis groups, 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 2018, we observed the simultaneous production of a Higgs boson with top quarks [1] and demonstrated for the first time that the Higgs boson couples to leptons [2]. Dark matter can be produced in LHC collisions, and would manifest itself as a momentum imbalance. In 2018, we explored the potential interaction of dark matter with heavy quarks [3]. To explain why the Higgs boson has an unnaturally light mass, we performed a search for the production of a new heavy particle decaying to a Higgs boson and a b quark [4]. Recent measurements point to certain anomalies which might indicate the existence of leptoquarks, new particles carrying quark and lepton properties that would cause a violation of lepton flavor universality. During 2018, we initiated new searches to directly detect such



An event candidate for the production of a top quark and antiquark in conjunction with a Higgs Boson in the CMS detector.

a leptoquark decay [5]. Finally, we also looked for heavy versions of gravitons decaying into standard model bosons [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 2018, we designed a prototype of the detector with lightweight mechanical, cooling, and powering, 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 about 40 picoseconds (40E-12 s) in our lab. Such a technology could greatly improve the physics potential of CMS in later upgrades.

Highlighted Publications:

1. Observation of $t\bar{t}H$ production,
   CMS Collab., Phys. Rev. Lett. **120** 231801;
2. Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector,
   CMS Collab., Phys. Lett. B **779**, 283 (2018)
3. Search for dark matter particles produced in association with a top quark pair at $\sqrt{s} = 13$ TeV,
   CMS Collab., Phys. Rev. Lett. **122** 011803
4. Search for single production of vector-like quarks decaying to a b quark and a Higgs boson,
   CMS Collab., JHEP **06** (2018) 031
5. Search for a singly produced third-generation scalar leptoquark decaying to a τ lepton and a bottom quark in proton-proton collisions at $\sqrt{s} = 13$ TeV,
   CMS Collab., JHEP **1807**, 115 (2018)
6. Search for massive resonances decaying into WW, WZ, ZZ, qW, and qZ with dijet final states at $\sqrt{s} = 13$ TeV,
   CMS Collab., Phys. Rev. D **97**, no. 7, 072006 (2018)

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

LHCb Experiment

Prof. Nicola Serra, PD Dr. Olaf Steinkamp

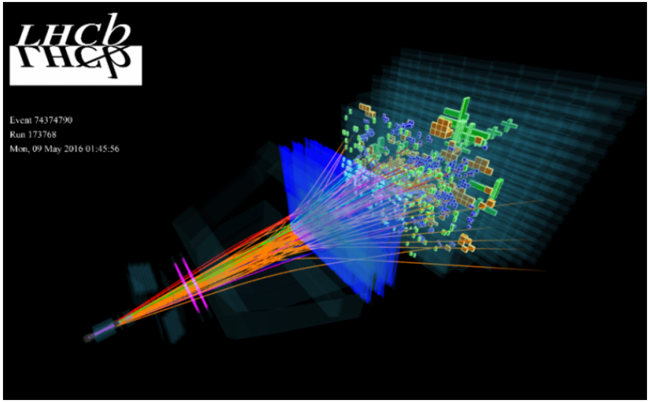
LHCb is an experiment for **precision measurements** of observables in the decays of B mesons at the Large Hadron Collider (LHC) at CERN.
We play a leading role in measurements with B meson decays and in measurements of electroweak gauge boson production, and have made important contributions to the LHCb detector. We are also involved in the preparation of a major upgrade of the detector for 2019/2020.

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

Tests of Lepton Flavour Universality

In the Standard Model (SM) of particle physics, each fermion is replicated three times into different flavours. For charged leptons, these three flavours are identical copies of each other, apart from different masses. For example, the muon is simply a heavier copy of the electron in the SM. This prediction is called lepton flavour universality (LFU), any violation of which would be a clear sign of physics beyond the Standard Model. Lepton universality has been well-tested in the decays of many different SM particles such as pions, kaons and gauge bosons and the measurements are consistent with the SM. The LHCb experiment has been testing LFU in decays of beauty quarks. These measurements are highly sensitive to New Physics particles which preferentially couple to the 2nd and 3rd lepton flavours.

The ratio R_K describes how often a B^+ meson decays to a charged kaon and either a muon and anti-muon pair or an electron and anti-electron pair. The decays involve the transformation of a beauty quark into a strange quark ($b \to s$), a process that is highly suppressed in the Standard Model and can be affected by the existence of new particles, which could have masses too high to be produced directly at the Large Hadron Collider. These decays are extremely rare, occurring at a rate of only one in two million B^+ meson decays.



Display of an event with in the LHCb detector.

The challenge in the experimental analysis is to control for the fact that electrons and muons interact very differently with the detector. Electrons are absorbed by the electromagnetic calorimeter and muons traverse through the calorimeter into the muon stations.

To minimise the influence of detector and other experimental effects, LHCb physicists used a "double ratio" method: what they measure is R_K divided by another ratio, $r_{J/\psi}$, the true value of which is known to be very close to 1 but which has similar sensitivity to detector effects to R_K. The double ratio method greatly reduces systematic uncertainties related to the different experimental treatment of muons and electrons, which largely cancel in the double ratio.

The result of the measurement is

$$R_K = 0.846^{+0.060}_{-0.054}(\text{stat})^{+0.016}_{-0.014}(\text{syst})[2],$$

which is consistent with the SM at the level of 2.5 standard deviations. The measurement does not confirm nor refute previous hints of lepton universality violation. The measurement is statistically limited and so will be improved with the full run-II dataset and the upcoming LHCb upgrade.

Highlighted Publications:

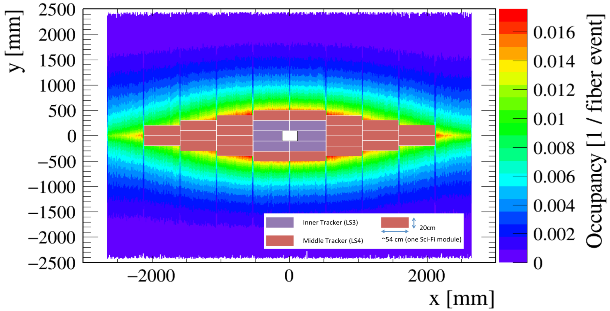
1. All LHCb publications:
   http://lhcb.web.cern.ch/lhcb/
2. Search for lepton-universality violation in
   $B^+ \to K^+\ell^+\ell^-$ decays,
   LHCb collab., Phys. Rev. Lett. **122** (2019) no.19, 191801
3. Measurement of antiproton production in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV,
   LHCb collab., Phys. Rev. Lett. **121** (2018) no.22, 222001
4. Measurement of the lifetime of the doubly charmed baryon Ξ_{cc}^{++},
   LHCb collab., Phys. Rev. Lett. **121** (2018) no.5, 052002
5. γ combination, LHCb collab.,
   https://cds.cern.ch/record/2319289

LHCb Experiment – Upgrades

Prof. Nicola Serra, PD Dr. Olaf Steinkamp

At the end of 2018, the LHCb experiment has collected a data sample corresponding to about 10/fb in proton-proton collisions. Even after analysing the full available data sample, most measurements will be limited by statistical uncertainties. To be able to further reduce uncertainties on a reasonable time scale will require to collect data at higher instantaneous luminosity and with higher efficiency. The LHCb collaboration has therefore decided to perform a comprehensive upgrade I of the experiment in 2019/2020 and to study an upgrade II around 2030.

Upgrade I of the LHCb experiment in 2019/2020 necessitates the replacement of the entire tracking system. Our group is involved in the replacement of the tracking station that was located upstream of the LHCb dipole magnet. The new Upstream Tracker is going to employ silicon microstrip detectors with finer granularity and better radiation hardness, and a new readout chip that is compatible with triggerless readout. Our group is involved in the testing of the readout chip and in the development of hardware and firmware for the detector control and readout. We also contribute to feasibility studies for upgrade II of the tracking system. We study algorithms for efficient and fast track reconstruction and we work towards the development of a new silicon pixel detector for the inner part of the tracking stations downstream of the LHCb magnet. A first version of this new detector could be installed in 2025.



Occupancy in the downstream tracking stations and possible layout of a new pixel detector for upgrade II of the LHCb detector.

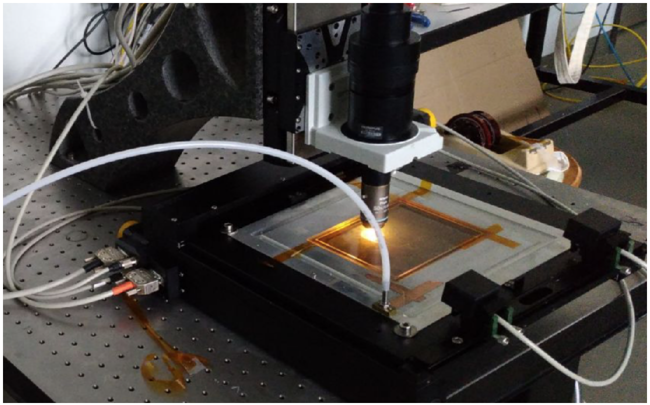
SHiP - Search for Hidden Particles

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.

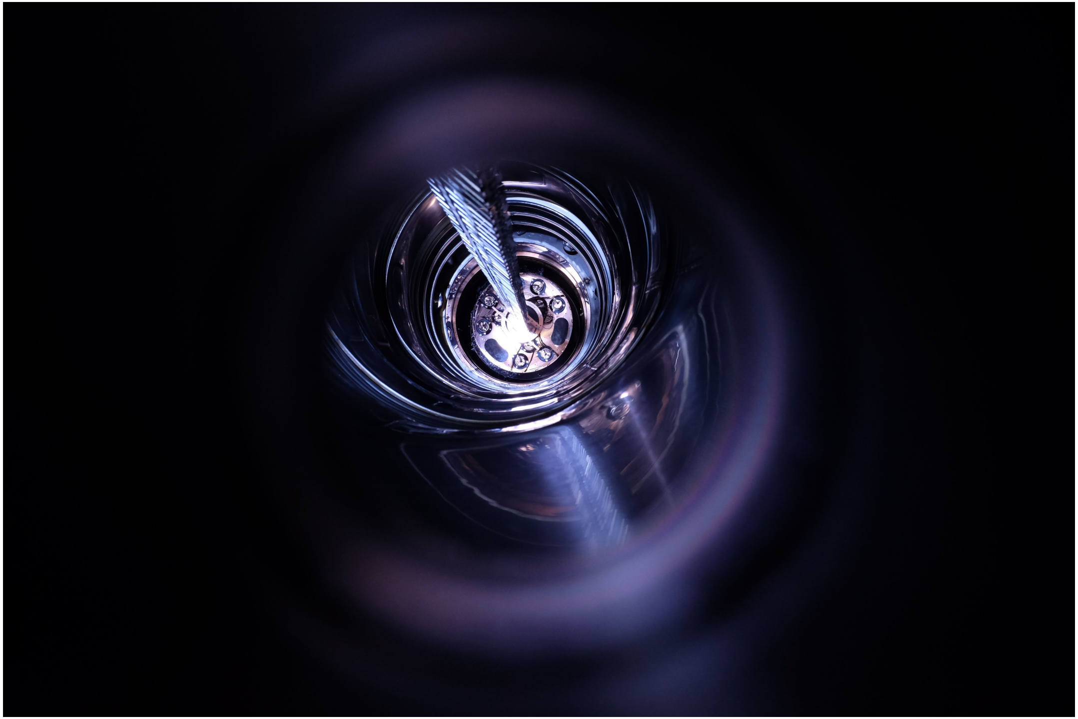
https://www.physik.uzh.ch/r/ship

Our group, featuring two new members, 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 which is critical for the SHiP experiment since hidden particles are mostly produced in the decay of charmed hadrons. A test run was conducted in July 2018 using nuclear emulsions films, alternated with layers of passive materials. Emulsion films have micrometric resolution, allowing us to resolve the proton interaction point and the vertex-decay location of the charmed hadron, a few hundred micrometers away. Our group is involved in the analysis of the data recorded in the emulsion films using an automated microscope for the emulsion scanning.



Microscope setup for the scanning of the emulsion films.

Cosmology, Astro- and Astroparticle Physics



Astrophysics and General Relativity

Prof. Philippe Jetzer

LIGO (Laser Interferometer Gravitational-Wave Observatory) consists of two Earth-bounded instruments together with VIRGO aimed to detect gravitational waves in the frequency range from about 10 to 1000 Hz. In 2015 the first gravitational wave signal has been detected. Since then 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.

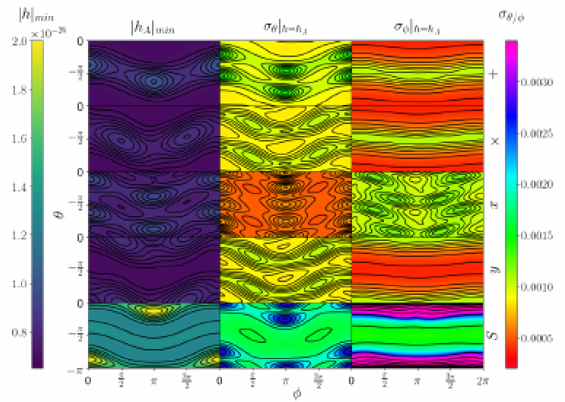
https://www.physik.uzh.ch/g/jetzer

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 three main results published in 2018.

In a paper, starting from first principles, Maria Haney and collaborators derived the third post-Newtonian (3PN) accurate Keplerian-type parametric solution to describe PN-accurate dynamics of non-spinning compact binaries in hyperbolic orbits [1]. Orbital elements and functions of the parametric solution were obtained in terms of the conserved orbital energy and angular momentum in both Arnowitt-Deser-Misner type and modified harmonic coordinates. Some elegant checks were discussed that include a modified analytic continuation prescription to obtain our independent hyperbolic parametric solution from its eccentric version. A prescription to model gravitational wave polarization states for hyperbolic compact binaries experiencing 3.5PN accurate orbital motion was presented that employs our 3PN-accurate parametric solution.

Yannick Boetzel and collaborators studied the inspiral waveforms for precessing binaries on eccentric orbits in the Fourier domain [2]. To achieve this, they used a small eccentricity expansion of the waveform amplitudes in order to



Sensitivity of Einstein Telescope, LIGO and DECIGO at 100 Hz towards the different polarizations in the left column. Standard deviation of the Θ and Φ angle for a GW with polarization A and amplitude of $h_A = 2.6 \cdot 10^{-26}$ in the middle and right column respectively. (from [3])

separate the periastron precession timescale from the orbital timescale, and used a shifted uniform asymptotic transformation to compute the Fourier transform in the presence of spin induced precession. They showed that the resulting waveforms can yield a median faithfulness above 0.993 when compared to an equivalent time domain waveform with an initial eccentricity of $e_0 \simeq 0.3$. When the spins are large, using a circular waveform can potentially lead to significant biases in the recovery of the parameters, even when the system has fully circularized, particularly when the accumulated number of cycles is large. This is an effect of the residual eccentricity present when the objects forming the binary have non vanishing spin components in the orbital plane.

In a paper Lionel Philippoz and Adrian Boîtier investigated the sensitivity to additional gravitational wave polarization modes of future detectors [3]. They first looked at the upcoming Einstein Telescope and its combination with existing or planned Earth-based detectors in the case of a stochastic gravitational wave background. They then studied its correlation with a possible future space-borne detector sensitive to high-frequencies, like DECIGO. Finally, they adapted those results for a single GW source and establish the sensitivity of the modes, as well as the localization on the sky.

Highlighted Publications:

1. Gravitational waves from compact binaries in post-Newtonian accurate hyperbolic orbits, G. Cho, A. Gopakumar, M. Haney, H. Mok, Phys.Rev. D**98** (2018) no.2 024039 arXiv:1807.02380
2. Fourier domain gravitational waveforms for precessing eccentric binaries , A. Klein, Y. Boetzel, A. Gopakumar, Ph. Jetzer, and L. de Vittori, Phys.Rev. D**98** (2018) no.10, 104043 arXiv:1801.08542
3. Gravitational wave polarization from combined Earth-space detectors, L. Philippoz, A. Boîtier, and Ph. Jetzer, Phys.Rev. D**98** (2018) no.4, 044025 arXiv:1807.09402

Theoretical Astrophysics

Prof. Prasenjit Saha

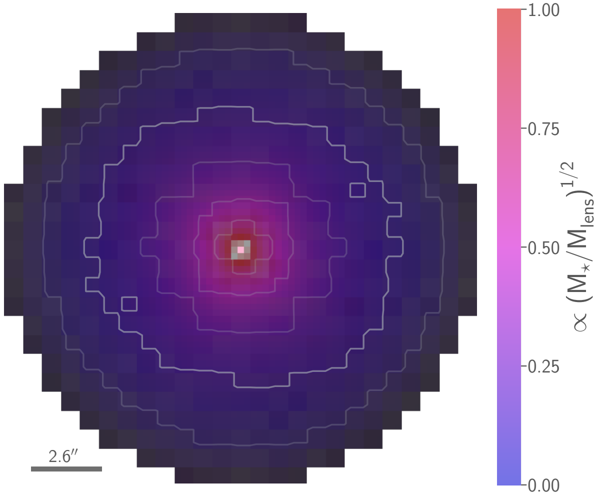
Light always takes the path of shortest travel time — except when it doesn't. According to Fermat's principle, light can also take paths that are maxima or saddle-points of the travel time, which can produce multiple images of the same object. In astronomy this phenomenon, known as strong gravitational lensing, can be caused by galaxies warping the spacetime around them. When observed, it offers a way to probe the otherwise invisible dark matter, which makes up most of the mass of a galaxy. Our research is on new ways of extracting the interesting information from the observables, and using it to help understand how galaxies work.

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

The dark halos of galaxies

An average cubic metre of the universe has about a quarter of an atom, and a little over an atomic mass in the form of dark matter. How then, did condensed matter like us form? The basic process is that small inhomogeneities created by quantum fluctuations grew through gravitational instability. The higher-density regions formed would have been predominantly dark matter, since there is more of it, but because gas unlike dark matter is dissipative, gas would fall into the deepest gravitational potential wells, and increase the density still further. The result: galaxies that are mainly ordinary matter in the inner regions, and almost entirely dark matter in the outer regions.

Our main research has been on mapping the distributions of ordinary matter and dark matter in galaxies using gravitational lensing. A special aspect of this work has been the collaboration with knowledgeable non-professional citizen scientists, four of whom have co-authored papers. This was possible because of a very creative software stack developed by



A reconstruction of the mass distribution in the galaxy J1434+522 from its lensing action on the light of a more distant galaxy. The red/blue scale represents the dark-matter fraction.

Rafael Küng and continued by Philipp Denzel. One interesting conclusion to emerge, which was previously known but only inferred indirectly, is that galaxies similar in mass to the Milky Way are the most efficient at turning their gas into stars.

Together with our collaborators, we are also exploring other exciting optical phenomena in astrophysics. Among them is the granularity in the gravitational field of a galaxy, due to individual stars. This can produce extreme magnification of background objects. If that background object is a quasar, our calculations indicate that the observed image contains tomographic information on the event-horizon scale.

Highlighted Publications:

1. Models of gravitational lens candidates from space warps CFHTLS,
   R. Küng *et al.*, MNRAS 474, 3700–3713 (2018)
2. Microlensing as a possible probe of event-horizon structure in quasars,
   M. Tomozeiu *et al.*, MNRAS 475, 1925–1936 (2018)

Astroparticle Physics Experiments

Prof. Laura Baudis

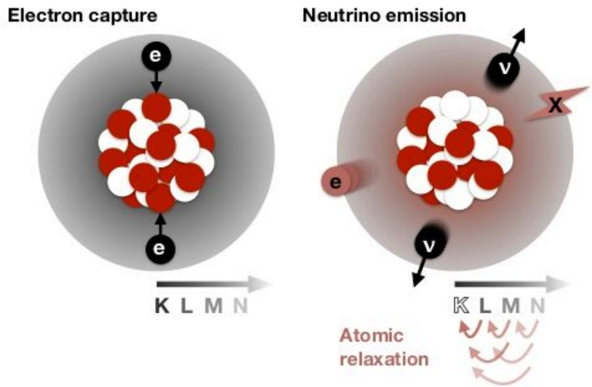
We study the composition of dark matter in the universe and the fundamental nature of neutrinos. We build and operate ultra low-background experiments to detect dark matter particles and to search for the neutrinoless double beta decay, a rare nuclear process which only occurs if neutrinos are Majorana particles.
We are leading 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 GERDA and the future LEGEND experiments, which look for the neutrinoless double beta decay of ^{76}Ge in high-purity Ge crystals immersed in liquid argon, with a sensitivity on the half-life of $T_{1/2}^{0\nu\beta\beta} > 1 \times 10^{26}$ y.

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

Double electron capture in ^{124}Xe with XENON1T

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

The data recorded between February 2, 2017 and February 8, 2018 as part of the dark matter search, was also analysed for the double electron capture (2νECEC) of ^{124}Xe with emis-



Schematics of the double electron capture in ^{124}Xe.

sion of two neutrinos. This is a very rare process that escaped detection for decades. Two protons in the ^{124}Xe nucleus simultaneously convert into neutrons by the absorption of two electrons, mostly from the K shell, and the emission of two electron neutrinos. After the electron capture, the filling of the vacancies results in a detectable cascade of X-rays and Auger electrons at 64.3 keV. The nuclear binding energy Q =2857 keV released in the process is carried away mostly by the two neutrinos, which are not seen within our detector.

During the analysis process, the XENON1T data in the energy region from 56 keV to 72 keV were blinded, thus inaccessible for analysis, and the energy scale around the expected signal at E_0 = (64.3±0.6) keV was calibrated using mono-energetic lines from injected sources such as ^{83m}Kr, from neutron-activated xenon isotopes as well as γ-rays from radioactive decays in detector materials. Upon unblinding, 126 events from 2νECEC were observed, which - taking into account the isotopic abundance of ^{124}Xe, the fiducial volume containing 1.5 t of natural xenon, and the measurement time, yields a half-life of $T_{1/2}^{2\nu ECEC} = 1.8 \times 10^{22}$ y, the longest half-life ever measured directly. This measurement demonstrates the sensitivity of large xenon TPCs to ultra-rare decays, and sets the stage for 0νECEC searches that can complement double-β-decay experiments in the search for Majorana neutrinos.

Highlighted Publications:

1. Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T
   XENON Collab., Nature Volume **568** Issue 7753 (2019)
2. Dark matter search results from a one ton-year exposure of XENON1T
   XENON Collab., Phys. Rev. Lett. **121** 111302 (2018)
3. Improved limit on neutrinoless double beta decay of ^{76}Ge from GERDA phase II
   GERDA Collab., Phys. Rev. Lett. **120** 132503 (2018)
4. A dual-phase xenon TPC for scintillation and ionisation yield measurements in liquid xenon
   L. Baudis *et al*, Eur.Phys.J. C**78** 351 (2018)

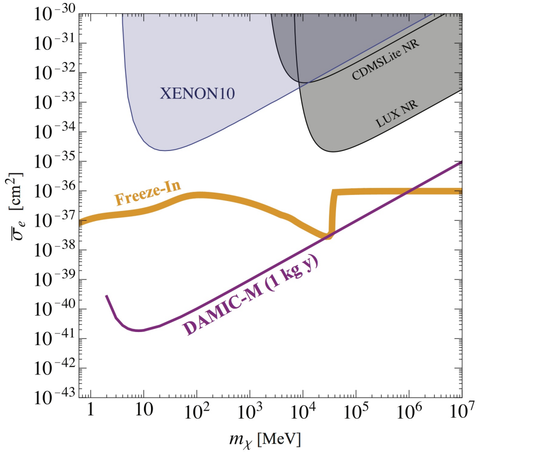
DAMIC Experiment

Prof. Ben Kilminster

33 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.



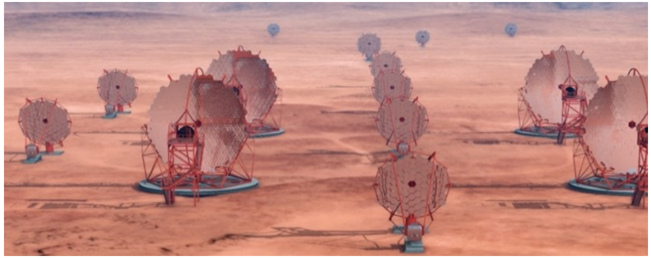
The DAMIC-M experiment tests scenarios of hidden dark matter for the first time. The x-axis is dark matter mass. The y-axis is a measure of the rate of dark matter interactions with matter. The purple line shows the rate down to which DAMIC-M can probe, which is below the theoretical prediction for a type of dark matter that freezes in during the formation of particles in the early universe. The shaded areas are the rates probed by previous experiments.


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



Simulated view of part of the CTA telescopes.

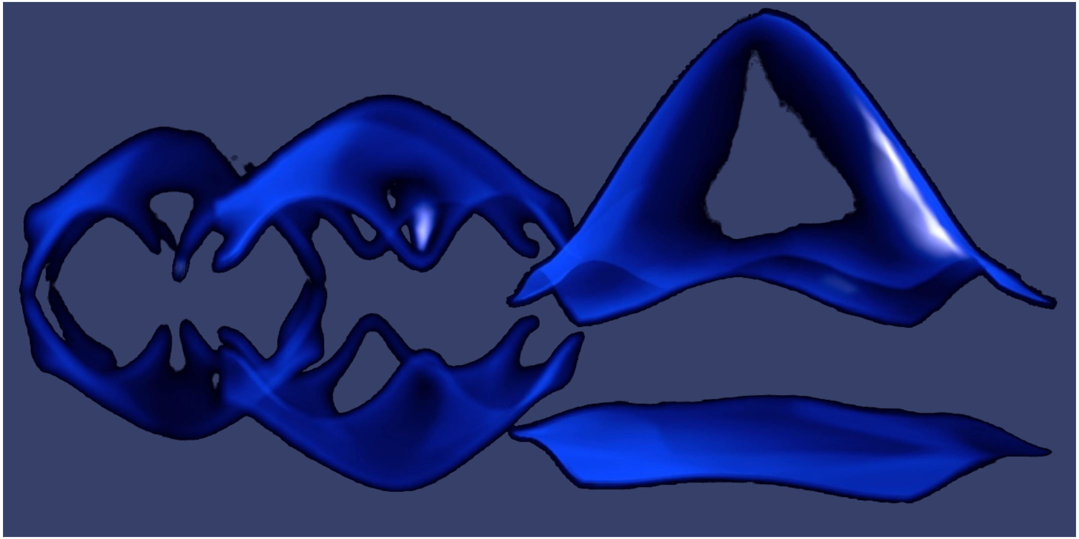
The CTA group at UZH has designed essential elements, including the mirror segment actuator system (AMC), light sensor electronics, safety and power control and mechanics for one of the proposed cameras (FlashCam), and contributes to calibration software development.

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.

Highlighted Publications:

1. Science with Cherenkov Telescope Array,
   The CTA consortium, World Scientific, March 2019,
   arXiv 1709.07997
2. 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

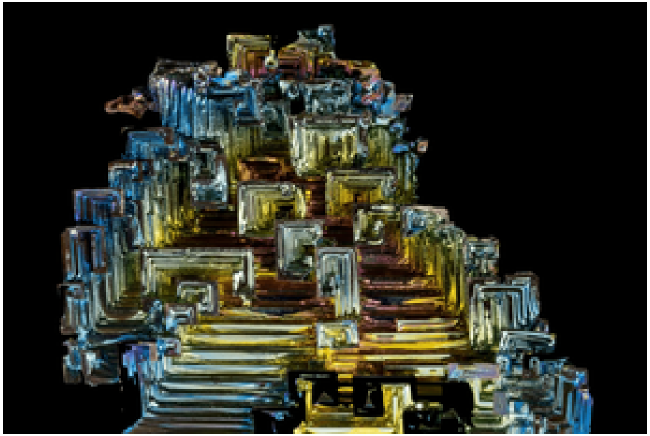
We study **topological phases of quantum matter** with numerical and analytical tools. Topological electronic states are characterized universal and robust phenomena, such as the Hall conductivity in the integer quantum Hall effect, that are of fundamental interest or promise applications in future electronics.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

Higher-order topology: Electrons living on the edge

Topology is a field of mathematics that fascinates physicists more and more in recent years. It is concerned with properties that are particularly robust against perturbations and deformations. For about ten years we know a class of materials called topological insulators, which are crystals that are insulators in the bulk but conduct electrical current on their surface. The conducting surfaces are topologically protected, which means that they cannot be brought into an insulating state easily.

Recently, we studied a new class of topological insulators which do not possess conducting states on the surface, but on the hinges of a crystal. We dubbed the new material class "higher-order topological insulators". The extraordinary robustness of the conducting hinges makes them particularly interesting: for instance, they cannot be removed by adding disorder or impurities. If a crystal imperfection gets in the way of the current of topological electrons, this



Bismuth is not only visually appealing but has also interesting electronic properties, as the group of Titus Neupert has uncovered in their recent work.

current is not stopped but simply flows around the impurity.

The crystal hinges do not have to be prepared in a special way in order to conduct current. If one breaks the crystal, one obtains new hinges that are automatically conducting in this topological way. Most exciting is the fact that theoretically the electric conduction happens without dissipation, i.e., without resistance. This property, which is otherwise known from superconductors at low temperatures, cannot be found in topological insulators with conducting surface states. One can think of the crystal hinges as forming a highway for electrons, on which they cannot make a U-turn.

One hope is that nanowires made of higher-order topological insulators may serve as current paths in electric circuits in the future. Furthermore, they may be combined with magnetic and superconducting elements to serve as quantum bits in future quantum computers. To make progress toward these visions, the new class of materials has to be thoroughly studied theoretically and experimentally. We theoretically proposed tin-telluride as a compound that should show these novel phenomena. Furthermore, in a collaboration with two experimental groups from Princeton and Paris, we were able to show that elementary bismuth is a higher-order topological insulator.

Highlighted Publications:

1. Higher-order topology in bismuth,
   F. Schindler *et al.*, Nature Physics 14, 918–924 (2018)
2. Topolectrical-circuit realization of topological corner modes,
   S. Imhof *et al.*, Nature Physics 14, 925–929 (2018)
3. Higher-order topological insulators,
   F. Schindler *et al.*, http://advances.sciencemag.org/content/4/6/eaat0346.full.pdf

Computational materials theory

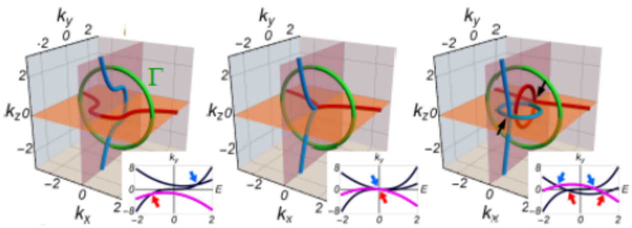
Prof. Alexey Soluyanov

Our research is aimed to prediction of materials that host topological phases. This is done by computing special kind of quantum numbers called topological invariants. These invariants contain information about the geometric properties of the wave functions that describe the state of material. In metals they describe topologically protected band degeneracies in the vicinity of the Fermi level that govern the excitations of topological metals and lead to transport properties not seen in ordinary metals. In topological insulators these invariants describe the metallic surface or edge states of materials with insulating bulk. Topological materials hold big promise for quantum technologies.

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

Novel topological phases in simple metals

We established a novel approach to uncover constraints put on the behavior of electronic bands in metals that have a PT-symmetry, that is the product of inversion and time reversal. These constraints are described by topological invariants, which unlike all the known to date cases form a non-Abelian group. The invariants describe nodal lines (paths in momentum space, along which two electronic energy bands are degenerate) and their non-Abelian nature uncovers the impossibility of interchanging two nodal lines described by different invariants from the group without forming other nodal lines, not present in the material before. We also made a material prediction for experimental verification of this theory. Elemental metal – scandium – hosts nodal lines below the Fermi level that under certain epitaxial strains interchange in exact accord with our theoretical prediction. As illustrated in the figure, blue and red nodal lines, formed by different bands, are pushed across each other by strain, but once interchanged both of them obtain additional nodal lines that form



Interchange of two nodal lines in momentum space: The red and blue nodal lines with different topological charges are separated from each other before the exchange (left), then under strain meet each other (central), and move across each other (right), forming two additional nodal lines enforced by non-Abelian topology that is tracked by a special invariant, computed on the green loop Γ.

ear-like loops, because the red and blue nodal lines have topological charges described by the non-commuting topological invariants from the non-Abelian group. The discovery of non-Abelian topological charges (invariants) allowed us to introduce a topological phase that goes beyond the classification schemes that were standard in the field of topological materials.

While non-Abelian topology is usually associated with a special kind of two-dimensional quasiparticles called non-Abelian anyons that unlike fermions and bosons obey fractional exchange statistics in coordinate space, this work provides the first illustration of non-Abelian topology in momentum space. Realization of non-Abelian anyons is only possible in the presence of strong interactions or superconductivity, and these quasiparticles are predicted to be the cornerstone of topological quantum computing. Non-Abelian nodal lines described in our work can be realized in the most simple crystalline metals, but still holds technological promises, due to the possibility to create topologically protected doublets on the ends of insulating quantum wires, which follows from our derivations. The detailed study of such wires and their properties is left for future work.

Highlighted Publications:

1. Beyond the tenfold way: Non-Abelian topology in noninteracting metals,
   Q. S. Wu, A. A. Soluyanov,
   T. Bzdusek, arXiv:1808:07469

2. Topological phonons and thermoelectricity in triple-point metals,
   S. Singh, Q. S. Wu, C. Yue, A. H. Romero,
   A. A. Soluyanov, Phys. Rev. Materials 2, 114204 (2018)

3. Automated construction of symmetrized Wannier-like tight-binding models from ab initio calculations,
   D. Gresch, Q. S. Wu, R. Hauselmann, M. Troyer,
   A. A. Soluyanov, Phys. Rev. Materials 2, 103805 (2018)

Surface physics

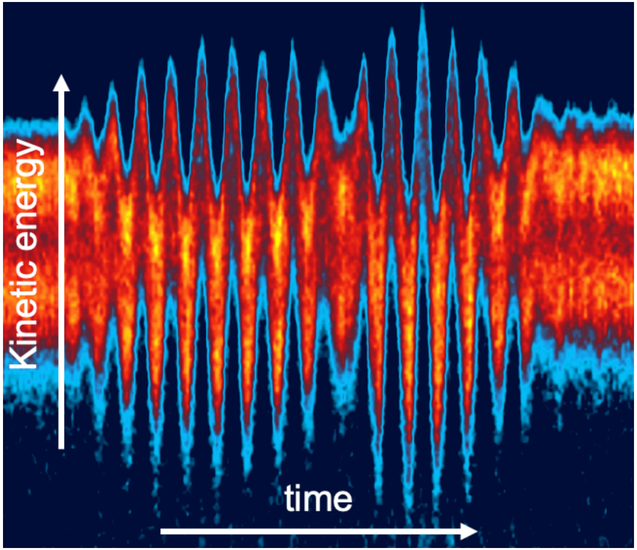
Prof. Jürg Osterwalder

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 x-ray Photoelectron Spectroscopy (XPS) at **solid-liquid interfaces** at the Swiss Light Source at PSI.

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

Measuring local fields of ultrashort terahertz pulses at surfaces

The oscillating electric fields of intense terahertz (THz) pulses can be used to excite specific low-frequency modes in condensed matter or drive confined alternating currents in nanostructured arrays, paving the way for a new class of optoelectronic devices. The strong interaction leads to strong modifications of the THz fields in the vicinity of surfaces and interfaces. Our group has developed a method that measures these local fields by exciting photoelectrons at the surface with extreme ultraviolet radiation (XUV) pulses and by observing the effect that the THz field has on their kinetic energy and momentum. Varying the temporal delay between the XUV and THz pulses leads to photoelectron streaking traces as shown in the figure. Here, the kinetic energy of the electrons is periodically modulated by the acceleration/deceleration in the oscillating THz field component perpendicular to the surface. The energy oscillations are thus a direct consequence of the interaction of the electron with the THz standing-wave field that builds up close to



Electrons dance in the rhythm of the electrical field within a terahertz pulse after being photoemitted by an extreme ultraviolet pulse. The color code represents the measured photoemission intensity of platinum valence levels (yellow = high).

the surface during the THz pulse duration of a few picoseconds. In our method, we further exploit the two-dimensional detection system of our spectrometer that measures the kinetic energy and the polar emission angle of the photoelectrons concurrently. From the latter we can extract also the THz field component parallel to the surface.

Our motivation for this study was to explore the idea that strong THz fields might induce chemical reactions at surfaces and thus enhance the activity of a catalyst. As a case study we selected carbon monoxide molecules on a platinum surface. One can expect the THz field to couple to the electrical dipole moment of adsorbed CO molecules, thus inducing molecular motion and chemical dynamics. For these experiments, we had to bring our angle-resolved photoelectron spectrometer to the FLASH free-electron laser at DESY in Hamburg, where XUV light and THz radiation is available at the same beamline, produced by two consecutive undulators. Our measurements showed that the THz fields at the surface were too weak to induce any structural dynamics.

Highlighted Publications:

1. Functionalization and passivation of ultrathin alumina films of defined thickness with self-assembled monolayers,
   W.-D. Zabka *et al.*, J. Phys.: Condens. Matter **30**, 424002 (2018)
2. Algorithms and image formation in orbital tomography, P. Kliuiev *et al.*, Phys. Rev. B **98**, 085426 (2018)
3. Polarization-sensitive pulse reconstruction by momentum-resolved photoelectron streaking,
   K. Waltar *et al.*, Opt. Express **26**, 8364-8374 (2018)

Low dimensional systems

Prof. Thomas Greber

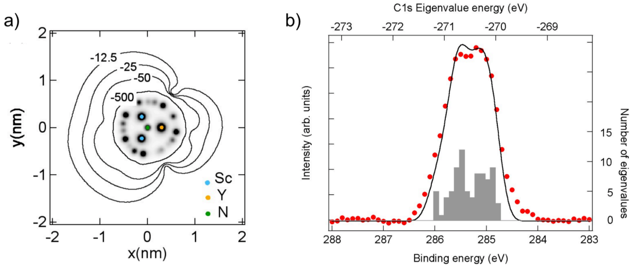
We study objects like **zero dimensional endofullerenes** and **two dimensional (2D) boron nitride** in view of their functionality as nano-materials.
Single molecule magnetism is the focus in the fullerene research, where we apply bulk sensitive x-ray absorption and a sub-Kelvin superconducting quantum interference device to the materials that we obtain from collaborations with synthesis groups.
In the 2D activity we aim to **grow highest quality boron nitride** on substrates with chemical vapour deposition methods and subsequent **exfoliation** of single layers. 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.

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

Electrostatic Interaction across a Single-Layer Carbon

Low dimensional systems like single layer boron nitride or fullerenes, both realise membranes that separate two regions. Though these ultimately thin single layer membranes allow chemical interaction across the membrane. For example, electrons may easily tunnel across single layer boron nitride, or the carbon cage of a fullerene molecule does not realize a Faraday cage that completely shields the electrostatic field of the endohedral unit [1]. This is reminiscent to proximity effects as observed in magnetic interfaces or in superconductors. It is a manifestation of physics at the nanometer scale and may possibly be exploited in future nanodevices. In the case of magnetic endofullerenes electrostatic control will open new possibilities of addressing the spin information inside the molecules.

Specifically, we investigated the single molecule magnet $TbSc_2N@C_{80}$ [1]. Over all, the molecule is neutral and has a very small dipole moment. The $TbSc_2N$ endohedral unit transfers six electrons on the carbon cage. The resulting



Electrostatic potential of a C_{80} endohedral fullerene. (a) Calculation of the potential of $YSc_2N@C_{80}$ on a plane comprising the endohedral cluster and the carbon shell (contour units meV). (b) High resolution x-ray photoelectron spectroscopy from the carbon shell of $TbSc_2N@C_{80}$ (red dots) and comparison to the calculated C1s eigenvalues that mainly reflect the electrostatic potential at the 80 carbon sites (grey bars and black line) (from [1]).

discrete charge distribution causes an electrostatic potential that is not spherical and thus not constant outside the molecule. The figure above shows the calculated electrostatic potential. As expected, it falls off rapidly but has a significant non-isotropic component outside the carbon cage. The potential in the immediate vicinity of the cage may not be measured easily, though it can be inferred from the potential at the positions of the carbon atoms. The potential variation on the carbon cage is reflected in the electron binding energies as they are measured with photoemission. We could establish the correlation between the calculated C1s eigenvalues and the measured C1s core level binding energies. Due to the high requirements to the energy resolution the experiments were performed at the photoemission and atomic resolution laboratory (PEARL) beamline at the Swiss Light Source.

Highlighted Publications:

1. Electrostatic interaction across a single-layer carbon shell
   R. Stania *et al.*, J. Phys. Chem. Lett. **9** 3586 (2018)
2. Remote doping of graphene on SiO_2 with 5 keV x-rays in air
   B. Salzmann *et al.*, J. Vac. Sci. Technol. A **36** 020603 (2018)
3. Centimeter-sized single-orientation monolayer hexagonal boron nitride with or without nanovoids
   H. Cun *et al.*, Nano Letters **18** 1205 (2018)
4. Orbital insight from an upright molecule
   T. Greber, Nature **558** 525 (2018)

Phase Transitions, Materials and Applications

Prof. Andreas Schilling

We are interested in selected topics in materials research, spanning the entire spectrum from searching new materials, their characterization, and corresponding applications. We have been particularly active in superconductivity, magnetism and thermodynamics. Our laboratory is equipped with modern furnaces for material synthesis, various 4He 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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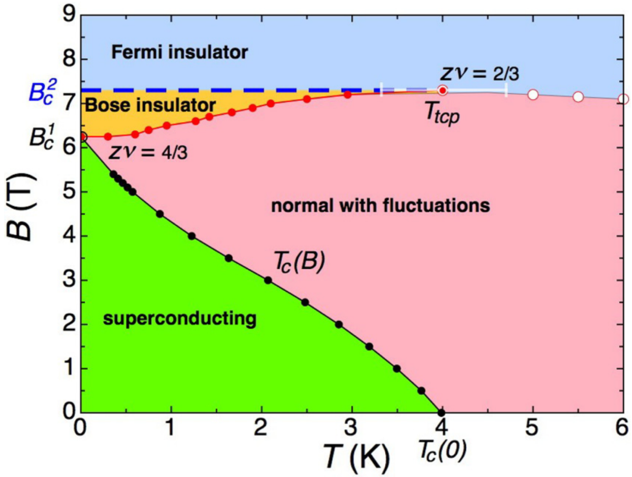
The advantages of amorphous WSi

We have been working with ultrafast superconducting nanowire single-photon detectors since more than a decade, with the aim to detect single photons in the visible, in the infrared, and even in the X-ray range. In the early stages, efforts concentrated on the deposition of high-quality crystalline or granular superconducting thin films. We realized later on that very homogeneous superconducting films can be easily obtained with amorphous superconductors. Due to their uniformly amorphous nature on a microscopic scale, an electrical current is naturally homogeneously distributed in such films, which makes them perfectly suitable for the research on superconductivity in nanostructures. They are also very suitable for device fabrication because constriction effects can be essentially neglected. Indeed, the highest detection efficiency so far was obtained in 4-nm-thick amorphous WSi films. These amorphous superconductors are very robust against chemical degradation, and can also be deposited on a variety of substrates, even on glass or photon resists.



Sketch of the superconductor-to-insulator transition the magnetic phase diagram of an amorphous 5nm thin WSi film.

Magnetic phase diagram of amorphous WSi thin films

In general, a zero-temperature magnetic-field-driven superconductor to insulator transition (SIT) is expected to occur in quasi-two-dimensional superconductors when the applied magnetic field crosses a certain critical field. A fundamental question is whether this transition is due to the localization of Cooper pairs or due to their destruction of. We have addressed this question by studying the SIT in an amorphous WSi film with a thickness of ≈ 5 nm. Transport measurements revealed the localization of Cooper pairs at a quantum critical field B_c^1 (Bose insulator), with a product of the correlation length and dynamical exponents $z\nu \sim 4/3$ near the quantum critical point. Beyond B_c^1, superconducting fluctuations still persist at finite temperatures. Above a second critical field $B_c^2 > B_c^1$, the Cooper pairs are destroyed and the film becomes a Fermi insulator. The different phases all merge at a tricritical point at finite temperatures with $z\nu = 2/3$. These results suggest a sequential superconductor to Bose insulator to Fermi insulator phase transition, which differs from the conventional scenario involving a single quantum critical point.

Highlighted Publications:

1. Tuning the orbital-lattice fluctuations in the mixed spin-dimer system $Ba_{3-x}Sr_xCr_2O_8$,
   A. Gazizulina *et al.*, Phys. Rev. B **98** 144115 (2018)

2. Sequential superconductor-Bose insulator-Fermi insulator phase transitions in quasi-2D α-WSi,
   X. Zhang and A. Schilling, Phys. Rev. B **97** 214524 (2018)

3. Superconducting fluctuations and characteristic time scales in amorphous WSi,
   X. Zhang *et al.*, Phys. Rev. B **97** 174502 (2018)

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.

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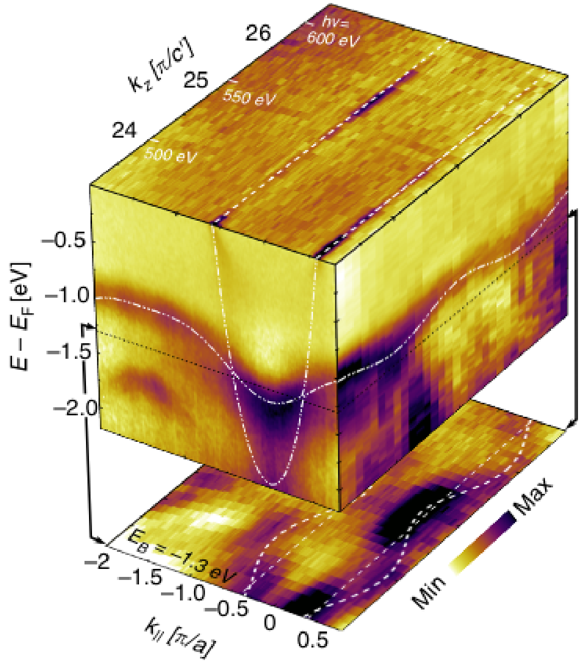
Distilling Electrons for Superconductivity

The minimal ingredients to explain the essential physics of layered copper-oxide (cuprates) materials remain heavily debated. Identifying the factors that limit the transition temperature T_c of high-temperature cuprate superconductivity is a crucial step towards revealing the design principles underlying the pairing mechanism. It may also provide an explanation for the dramatic variation of T_c across the known single-layer compounds. Although superconductivity is certainly promoted within the copper-oxide layers, the out-of-plane apical oxygen position may play an important role in defining T_c. It has, for example, been predicted that apical oxygen distance influences T_c in at least two different ways. First, the apical oxygen distance d_A to the copper-oxide plane controls the charge transfer gap between the oxygen and copper sites which, in turn, suppresses superconductivity. Second, Fermi-level orbital hybridisation, controlled by d_A, impedes superconductivity. For the latter scenario, no double orbital electronic structure has been observed. In the quest to disentangle



Three-dimensional band structure of the high-temperature superconductor $La_{2-x}Sr_xCuO_4$ measured by angle-resolved photoemission spectroscopy.

these causal relation between d_A and T_c, it is therefore imperative to experimentally reveal the orbital character of the cuprate band structure. We have performed direct ultraviolet and soft-x-ray ARPES measurements of the electronic structure of La-based single-layer compounds. A double orbital electronic band structure with direct hybridisation has been identified.

Highlighted Publications:

1. Spin-orbital excitations in Ca_2RuO_4 revealed by resonant inelastic x-ray scattering
   L. Das *et al.*, Physical Review X **8** 11048 (2018)
2. Direct observation of orbital hybridisation in a cuprate superconductor,
   C.E. Matt *et al.*, Nature Communications **9** 972 (2018)
3. Two-dimensional type-II dirac fermions in layered oxides,
   M. Horio *et al.*, Nature Communications **9** 3252 (2018)
4. Three-dimensional fermi surface of overdoped La-based cuprates,
   M. Horio *et al.*, Physical Review Letters **121** 77004 (2018)

Oxide Interface Physics

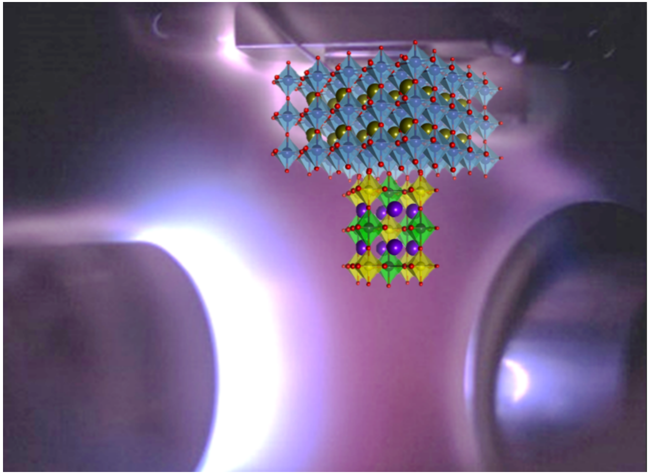
Prof. Marta Gibert

Epitaxial heterostructures allow for multiple strategies to manipulate the interplay between the different degrees of freedom in transition metal oxides. Reduced dimensionalities and interfacial structural and electronic couplings are key to tune the properties of these materials and even allow the engineering of novel functionalities.
In our group, we focus on the study of oxide interface physics phenomena. Our research encompasses from the growth of high quality oxide heterostructures to detailed studies 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 showing an incredible variety of physical properties such as metal-insulator transitions, exotic magnetism, multiferroicity, superconductivity and many more. This places them as interesting candidates for next generation electronic devices. All these unique properties stem from strong electronic correlations and a complex interplay between the charge, orbital, spin and lattice degrees of freedom.

These materials often crystallise in rather similar structures made of simple building blocks consisting of a transition metal (B) embedded in an oxygen octahedral cage in the perovskite ABO_3 structure. As a result, and thanks to the advances in growth techniques, it is today possible to stack layers of different TMO compounds one on top of the other (just like *lego*-blocks) with atomic scale precision. These new artificially layered structures are very interesting because they allow not only the bulk functionalities to be further tuned, but also because they often pave the way to novel electronic properties completely different to those of the parent compounds. Landmark examples include the emergence of conductivity at the interface between insulators or ferromagnetism between antiferromagnets. This flourishing research field is called **oxide interface engineering**.



Plasma during the growth (upside down) of a La_2NiMnO_6 thin film by off-axis rf sputtering. The double-perovskite-film/perovskite-substrate heterostructure is sketched.

In our group, we study the structure-property relation in TMOs when grown into atomically-engineered layered heterostructures (i.e. thin films or superlattices). To that aim, we have built up an off-axis rf-magnetron sputtering deposition system which allows high quality oxide heterostructures to be generated. During this first year at UZH, in addition to study the perovskite nickelates, we have started developing a new research line focused on double-perovskite $A_2BB'O_6$ structure films, where the ordered rock-salt like arrangement of corner-sharing BO_6 and $B'O_6$ units allow for an additional knob to control the functionalities of TMOs.

Special attention has been given to La_2NiMnO_6, an insulator ferromagnet with almost room temperature transition temperature ($T_c \sim 280$ K) in bulk. Ferromagnetic insulators are rare in nature, given that ferromagnetism is often accompanied by metallicity. However, ferromagnetic insulators are needed for a variety of devices in fields such as spintronics. We have showed that long-range order of Mn^{+4}-Ni^{+2} cations and the magnetic properties of bulk can be achieved in films of only few nanometres thickness. Careful optimization of the growth conditions and detailed characterization through a variety of techniques (x-ray diffraction, atomic force microscopy, SQUID-magnetometry, absorption spectroscopy, etc.) is key to our research.

Highlighted Publication:

1. Rare-earth nickelates $RNiO_3$: thin films and heterostructures,
   S. Catalano, M. Gibert, *et al.*
   J. Reports on Progress in Physics **81** 046501 (2018)

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 quantum point interference mapping.

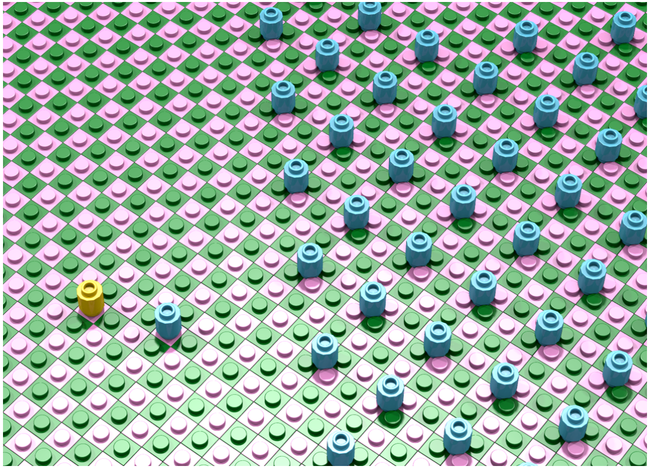
https://www.physik.uzh.ch/g/natterer

Scanning Pulse Microscope

One of our main projects is the development of pulsed electron spin resonance (ESR) and pump-probe methods for the scanning tunneling microscope 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 other project. Compressed sensing can significantly speed up measurement times (ten to hundred-fold), since only a subset of data needs to be recorded provided the information content is sparse. This is the case in many quantum point interference (QPI) measurements, where the number of wavevectors is typically significantly smaller than the number of data points. Traditional QPI may take up to



Understanding the interaction between two atoms is the first step towards building artificial quantum matter.

hundreds of hours, whereas CS can retrieve the same information in a fraction of this time. The shorter measurement time allows us to reinvest time to improve our spectroscopic resolution which may help identify more band-structure details of exotic 2D materials.

Highlighted Publications:

1. Upgrade of a low-temperature scanning tunneling microscope for electron-spin resonance,
   F. Natterer *et al.*, Review of Scientific Instruments **90**, 013706 (2019), arXiv 1810.03887
2. Thermal and magnetic-field stability of Holmium single-atom magnets,
   F. Natterer *et al.*, Physical Review Letters **121**, 027201 (2018), arXiv 1712.07871
3. Antiferromagnetic MnNi tips for spin-polarized scanning probe microscopy,
   P. Forrester *et al.*, Review of Scientific Instruments **89**, 123706 (2018), arXiv 1807.00364
4. Waveform-sequencing for scanning tunneling microscopy based pump-probe spectroscopy and pulsed-ESR,
   F. Natterer, arXiv 1902.05609 (2019)
5. A quantum pathway to overcome the trilemma of magnetic data storage,
   P. Forrester *et al.*, arXiv 1903.00242 (2019)

Disordered and biological soft matter

Prof. Christof Aegerter

We study the properties of disordered and heterogeneous systems out of equilibrium. This encompasses **light transport in turbid substances**, the dynamics of levitated foams as well as the elastic properties of growing biological tissues, such as *Drosophila* embryos and wing discs and their influence on development.

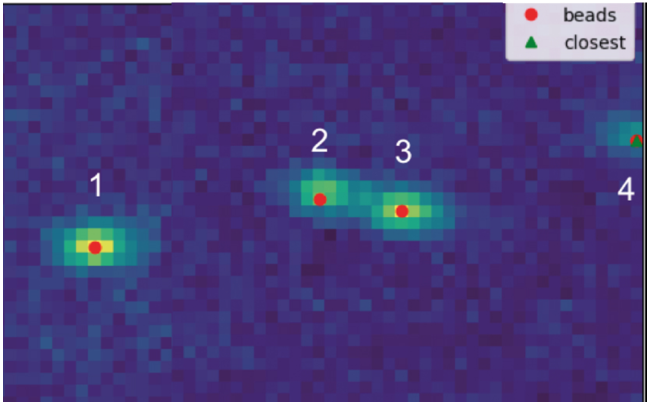
In all these fields our investigations are mainly experimental, however we also use computational modeling to guide these experiments.

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.

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

Imaging behind turbid media: Extending the field of view

Turbid media, such as fog, milk or white paint are detrimental to imaging because light passing through them is multiply scattered and hence directional information is lost. Due to the wave nature of light, it is however possible to obtain information about the scattering process encoded in the spatial interference (speckle) pattern formed behind the turbid medium. Using this knowledge and adjusting the incoming wave-front accordingly using a spatial light modulator, it is possible to create a focused laser beam even behind thick layers of white paint. In this, the disorder inherent in the multiple scattering is actually used to create the focus via constructive interference akin to the use of destructive interference in noise cancelling headphones.



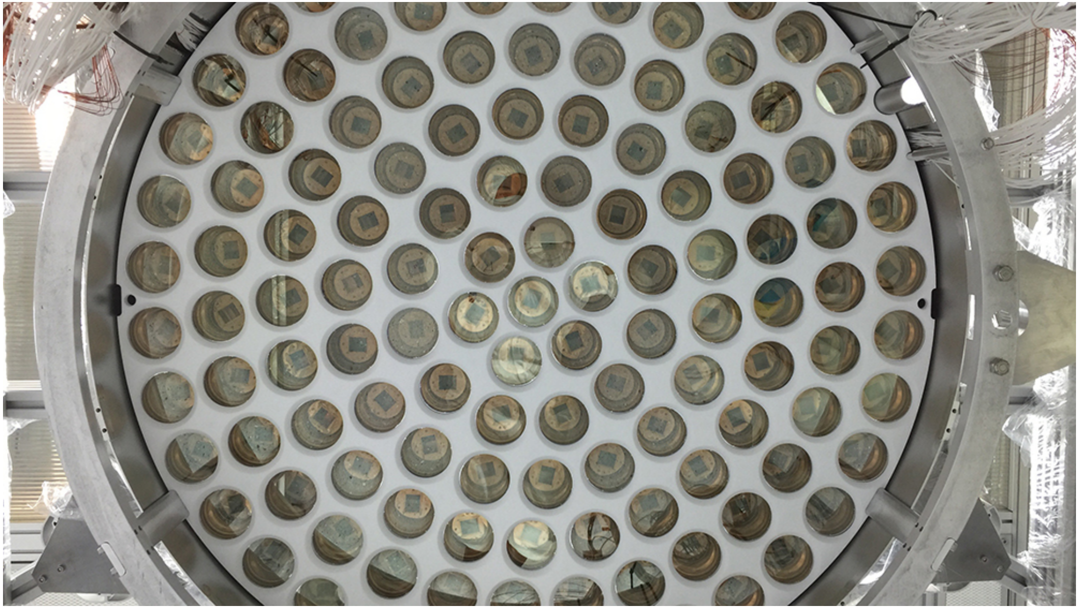
Imaging of fluorescent particles behind a layer of white paint, where the field of view is extended in excess of the theoretically possible range dictated by the optical memory effect.

A scanning of this focus is possible due to the optical memory effect, which prescribes that a shift over an angular range given by the ratio of the wavelength to the thickness can be achieved. Using this method, we have previously shown that diffraction limited imaging of fluorescent particles is possible even behind layers of white paint much thicker than the mean free path. The applicability of this is however limited due to the limited field of view of the imaging implied by the range of the memory effect. Using an iterative approach, we have now shown that this limitation can be overcome, which is shown in the Figure on the left side, where an image of fluorescent particles is shown over a field of view exceeding the memory effect range by a factor of three. Hence microscopy behind turbid media comes into the realm of being technically feasible.

Highlighted Publications:

1. Introductory Physics for Biological Scientists,
   C.M. Aegerter,
   published with Cambridge University Press (2018)
   ISBN: 9781108525862
2. Dynamic generation of light sheets behind turbid media,
   J. Schneider and C.M. Aegerter,
   J. Europ. Opt Soc. **14**, 7 (2018).
3. Enhanced field of view scattered light fluorescence microscopy,
   S. Scheibler, A. Malavalli, M. Ackermann and C.M. Aegerter,
   OSA Continuum **2**, 1468 (2019).

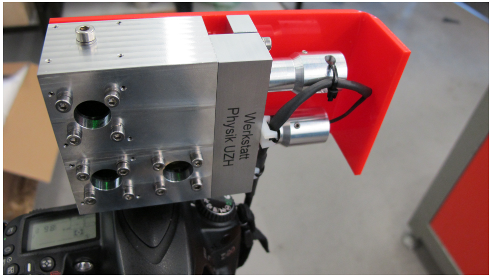
Workshops

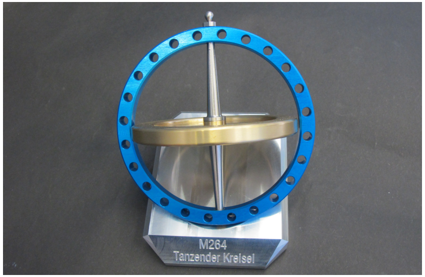


Mechanical Workshop

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



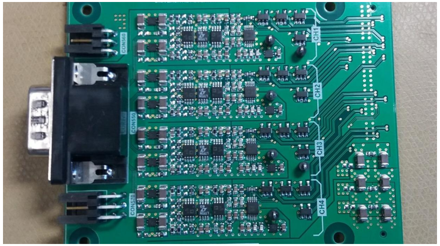


The three photograph are examples for work done in our workshop for external institutes (left: anatomy institute), research groups (middle, group Chang) and education (right).

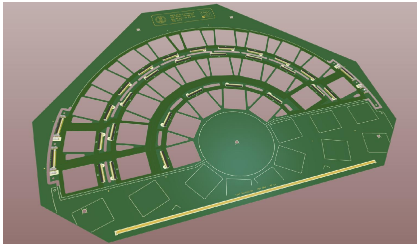
Electronics Workshop

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.

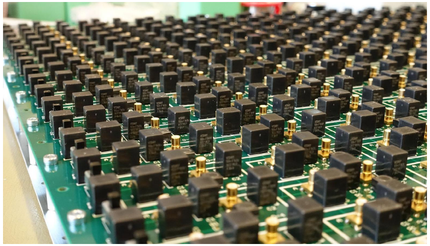
Our projects in 2018 included the development of a 4 GHz preamplifier for fast oscilloscopes, a programmable fast pulse generator with <100ps rise-/fall time, and a SALT128TB testboard for the UT detector of LHCb the design of low-temperature high frequency printed circuit boards, silicon photomultiplier testboards as well as documentation and testing of the FlashCam for CTA.



First prototype boards for the 20 bit, 1.5MS/s ADC for DAMIC-M.

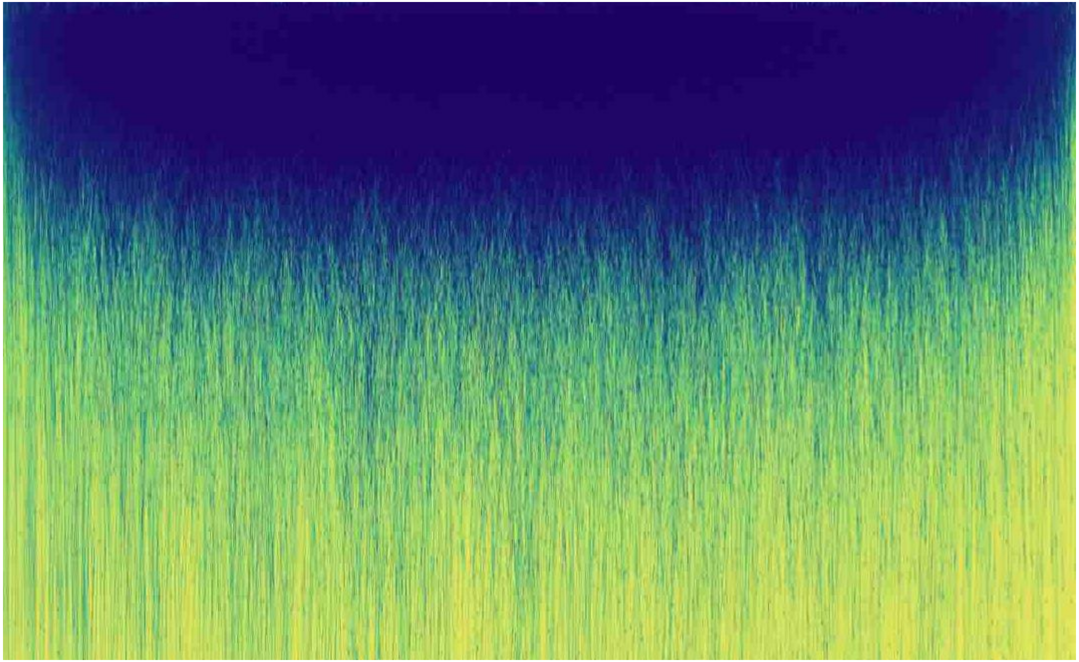


Printed circuit board for power supply and data connections for the silicon sensors for the CMS TEPX detector.



Close-up view of a two-dimensional grid of resonant circuits to model lattice band structures.

Personnel



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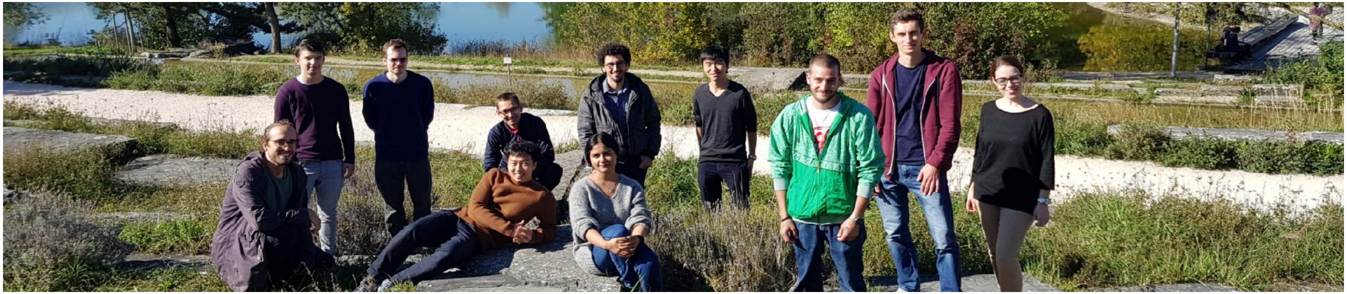

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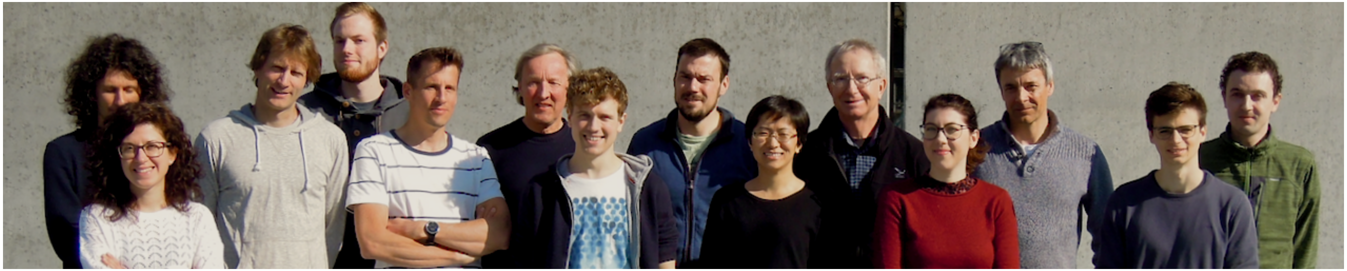

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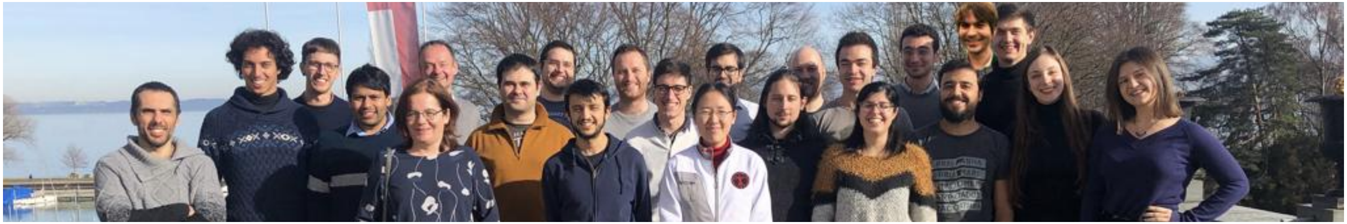
Djordje Pantic
Prof. Dr. Alexey Soluyanov



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