Collaborative Research Centre 110

Symmetries and the Emergence of Structure in Quantum Chromodynamics

Rheinische Friedrich–Wilhelms–Universität Bonn (Germany)

Ruhr-Universität Bochum (Germany)
Forschungszentrum Jülich (Germany)
Technische Universität München (Germany)
Institute of High Energy Physics, Beijing (China)
Peking University, Beijing (China)
Theoretical Physics Center for Science Facilities, Beijing (China)
Institute of Theoretical Physics, Beijing (China)

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Name of the spokesperson:	Prof. Dr. Dr. h.c. Ulf-G. Meißner
Official address of the spokesperson:	Helmholtz Institut für Strahlen- und Kernphysik Rheinische Friedrich-Wilhelms-Universität Bonn Nussallee 14-16 D-53115 Bonn Germany
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[1] FP stands for Funding Period

Contents

1 Summary / Zusammenfassung

1.1 English version

The theme of this CRC was the role of **symmetries and the emergence of structure in Quantum Chromodynamics (QCD)**. Here, the complex structures that are investigated include hadrons as well as nuclei, as these are different manifestations of the strong force. It was the great strength of this CRC that the fields of hadronic and nuclear physics are considered together, as it is now accepted world-wide. This CRC combined in a unique fashion various techniques to tackle these difficult strongly interacting many-particle problems, namely effective field theories (EFTs), lattice simulations and modeling.

We have made quite some progress in all the projects. We just list a few important findings in the different fields: In **hadron physics**, particular emphasis was put on the so-called exotic hadron states that are at the center of many experimental and theoretical investigations world-wide since 2003. Here, we developed EFTs for hadronic molecules and charmonia and systematically investigated the properties of such states, including their decays and production in various high-energy reactions. We also established the so-called two-pole structures in the spectrum of QCD, made substantial contributions to hadron reactions in lattice QCD, solved the so-called proton radius puzzle and developed a formalism to deal with three-particle final-states in hadronic decays. Furthermore, we made significant contributions to the light-by-light scattering part of the muon anomalous magnetic moment, improved our understanding of charmless B-meson decays and performed coupled-channel analyses in the light baryon sector to establish new baryon resonances. In **nuclear physics**, we developed the modern theory of nuclear forces based on chiral EFT to high precision, which has become a standard tool in nuclear structure calculations world-wide. Further, we developed the same machinery for baryon-baryon interactions which had a large impact on the strangeness nuclear physics community. We have established Nuclear Lattice EFT as a novel quantum many-body approach. We performed a number of groundbreaking investigations, such as the first ab initio calculation of alpha-alpha scattering, or we showed that nature is close to a quantum phase transition from a Bose-condensed gas of alpha-particles to a nuclear liquid. Furthermore, we obtained new insights into the equation of state of neutron matter relevant to the description of neutron stars and their properties.

Over the course of the three funding periods, the Sino-German as well as the collaborations between the German nodes intensified considerably, leading to many common publications and an intense exchange of researchers on all career levels. We had about 30 early career researchers that found a permanent position in academia. In addition, our outreach and education activities were extremely successful. In summary, **this CRC can be considered as a lighthouse of a large international collaboration**.

1.2 Deutsche Version

Das Hauptthema dieses Sonderforschungsbereichs war die Rolle der **Symmetrien und die Strukturentstehung in der Quantenchromodynamik (QCD)**. Die komplexen Strukturen, die hier untersucht wurden, beinhalten sowohl Hadronen als auch Atomkerne, beide sind verschiedene Manifestationen der starken Wechselwirkung. Es war die Stärke dieses SFBs, daß die Felder der Hadronen- und der Kernphysik zusammen betrachtet wurden, eine Vorgehensweise, die heutzutage weltweit akzeptiert wird. Zusätzlich verband dieser SFB in einzigartiger Weise verschiedene Techniken, nämlich effektive Feldtheorien (EFTn), Gittersimulationen und Modellierung, um komplexe Vielteilchenprobleme mit starker Wechselwirkung zu bewältigen.

In allen Teilprojekten haben wir beachtliche Fortschritte erzielt, von denen wir hier nur einige aufführen: In der **Hadronenphysik** haben wir insbesondere die exotischen Zustände, die seit 2003 im Fokus vieler experimenteller und theoretischer Untersuchungen stehen, untersucht. Wir haben EFTn für hadronische Moleküle und Quarkonia entwickelt, und ihre Eigenschaften systematisch untersucht. Weiterhin haben wir die sogenannten 2-Pol Strukturen etabliert, hadronische Reaktionen auf dem Gitter berechnet, das Proton Ladungsradius Rätsel gelöst, und einen Formalismus für 3-Teilchen-endzustände in hadronischen Zerfällen entwickelt. Weiterhin haben wir wesentlich zum Verständnis hadronischer Beiträge zur Muon (g-2) Anomalie und zu charmlosen B-Zerfällen beigetragen. Wir konnten weiterhin neue Baryon-Resonanzen im Sektor der leichten Quarks mit Hilfe von Analysen basierend auf gekoppelten Kanälen etablieren. In der **Kernphysik** haben wir die Theorie der Kernkräfte zu extrem hoher Präzision entwickelt, dies ist mittlerweile ein Standardwerkzeug in Kernstruktur Untersuchungen. In ähnlicher Weise haben wir EFTn für Baryon-Baryon Wechselwirkungen entwickelt, die nun wesentlich zur Kernphysik mit seltsamen Quarks beitragen. Wir haben die chirale EFT auf dem Gitter als ein neues Werkzeug der Kernphysik etabliert und einige bahnbrechende Untersuchungen durchgeführt, wie zum Beispiel die erste *ab initio* Rechnung zur ^{4}He-^{4}He Streuung. Darüberhinaus haben wir neue Einsichten in die Zustandsgleichung von Neutronenmaterie gewonnen, die von großer Bedeutung für die Berechnung von Neutronensternen und ihrer Eigenschaften sind.

Die deutsch-chinesischen als auch die Kollaborationen zwischen den deutschen Knoten haben sich im Lauf des SFB wesentlich vertieft, was zu einer ganzen Reihe gemeinsamer Publikationen sowie intensivem akademischen Austausch auf allen Karrierestufen führte. Etwa 30 unser Nachwuchswissenschaftler haben permanente Stellen in der akademischen Welt bekommen. Auch unsere Wissenschaftskommunikations- und Schulungsmassnahmen waren sehr erfolgreich. Zusammenfassend kann gesagt werden, daß dieser **SFB als ein Leuchtturm für eine große internationale Kollaboration betrachtet werden kann**.

2 Published Results

Here, we list some important papers and textbooks. All papers are available on `https://arxiv.org/` and are thus open access. For some of them, gold open access has been paid (like e.g. publications in *Nature*). Note that on `inspirehep` (July 1st, 2024) one finds 1459 papers with the DFG or the NSFC funding number and 1176 papers with the DFG and (in most, but not all, cases) the NSFC funding number. Only the latter ones appear in the following list.

2.1 Publications with scientific quality assurance

• Well cited review papers (note that [4] and [8] have already more than 1000 citations on inspirehep):

[1] N. Brambilla, S. Eidelman, P. Foka, S. Gardner, A. S. Kronfeld, M. G. Alford, R. Alkofer, M. Butenschoen, T. D. Cohen and J. Erdmenger, *et al.*, "QCD and Strongly Coupled Gauge Theories: Challenges and Perspectives," Eur. Phys. J. C **74** (2014) no.10, 2981 doi:10.1140/epjc/s10052-014-2981-5 [arXiv:1404.3723 [hep-ph]].

[2] M. V. Polyakov and P. Schweitzer, "Forces inside hadrons: pressure, surface tension, mechanical radius, and all that," Int. J. Mod. Phys. A **33** (2018) no.26, 1830025 doi:10.1142/S0217751X18300259 [arXiv:1805.06596 [hep-ph]].

[3] M. Freer, H. Horiuchi, Y. Kanada-En'yo, D. Lee and U.-G. Meißner, "Microscopic Clustering in Light Nuclei," Rev. Mod. Phys. **90** (2018) no.3, 035004 doi:10.1103/RevModPhys.90.035004 [arXiv:1705.06192 [nucl-th]].

[4] F. K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao and B. S. Zou, "Hadronic molecules," Rev. Mod. Phys. **90** (2018) no.1, 015004 [erratum: Rev. Mod. Phys. **94** (2022) no.2, 029901] doi:10.1103/RevModPhys.90.015004 [arXiv:1705.00141 [hep-ph]].

[5] E. Epelbaum, H. Krebs and P. Reinert, "High-precision nuclear forces from chiral EFT: State-of-the-art, challenges and outlook," Front. in Phys. **8** (2020), 98 doi:10.3389/fphy.2020.00098 [arXiv:1911.11875 [nucl-th]].

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[9] L. Gan, B. Kubis, E. Passemar and S. Tulin, "Precision tests of fundamental physics with η and η' mesons," Phys. Rept. **945** (2022), 1-105 doi:10.1016/j.physrep.2021.11.001 [arXiv:2007.00664 [hep-ph]].

[10] M. Mai, U.-G. Meißner and C. Urbach, "Towards a theory of hadron resonances," Phys. Rept. **1001** (2023), 1-66 doi:10.1016/j.physrep.2022.11.005 [arXiv:2206.01477 [hep-ph]].

• Highly cited / high impact papers (3 in Nature, 1 in Nature Commun.). Note that [21] and [14] are the most cited non-review papers on the LHCb pentaquarks and the $Z_c(3900)$, respectively.

[11] E. Epelbaum, H. Krebs, T. A. Lähde, D. Lee and U.-G. Meißner, "Structure and rotations of the Hoyle state," Phys. Rev. Lett. **109** (2012), 252501 doi:10.1103/PhysRevLett.109.252501 [arXiv:1208.1328 [nucl-th]].

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doi:10.1038/s41586-024-07422-z [arXiv:2210.17488 [nucl-th]].

We also published four textbooks with explicit mention of DFG support, that originate from various projects during the course of the CRC. PLs are underlined. These are:

T. A. Lähde and U.-G. Meißner, “Nuclear Lattice Effective Field Theory: An introduction,” Lect. Notes Phys. **957** (2019), 1-396 Springer, 2019, ISBN 978-3-030-14187-5, 978-3-030-14189-9, doi:10.1007/978-3-030-14189-9

U.-G. Meißner and A. Rusetsky, “Effective Field Theories,” Cambridge University Press, 2022, ISBN 978-1-108-68903-8, doi:10.1017/9781108689038

H. K. Dreiner, H. E. Haber and S. P. Martin, “From Spinors to Supersymmetry,” Cambridge University Press, 2023,
ISBN 978-1-139-04974-0, doi:10.1017/9781139049740

P. Bechtle, F. Bernlochner, H. Dreiner, C. Hanhart, J. Pretz, J. Jochum and K. Riebe, “Faszinierende Teilchenphysik: Von Quarks, Neutrinos und Higgs zu den Rätseln des Universums,” Springer, 2023, ISBN 978-3-662-67903-6, 978-3-662-67904-3, doi:10.1007/978-3-662-67904-3

3 Overview of Projects

Project Code	Title	Research area	Project leaders, institutions, locations	Duration
		A. Symmetries		
A.1	Flavor symmetries and final-state interactions in heavy hadron decays (FP 1); Flavor symmetries and final-state interactions in hadronic decays (FP 2,3)	Theoretical hadron physics	Prof. Dr. F.-K. Guo, ITP-CAS (FP 2,3); PD Dr. J. Haidenbauer (FP 1,2); PD Dr. B. Kubis, HISKP-UB; Prof. Dr. S. Paul, E31-TUM (FP 2,3); Prof. Dr. B.-S. Zou, IHEP-CAS (FP 1)	2012/2- 2024/1
A.2	Hadron-hadron scattering in lattice QCD (FP 1); Hadronic dynamics on the lattice (FP 2,3)	Theoretical hadron & nuclear physics	Prof. Dr. C. Liu, PKU; Prof. PhD T. Luu, FZJ (FP 3); Prof. Dr. C. Urbach, HISKP-UB;	2012/2- 2024/1
A.3	Universality and effective field theory for threshold states (FP 1); Effective field theory for threshold phenomena (FP 2,3)	Theoretical hadron physics	Prof. Dr. N. Brambilla, T30F-TUM; Prof. Dr. Y. Jia, IHEP-CAS Prof. Dr. H.-W. Hammer, HISKP-UB (FP 1)	2012/2- 2024/1
A.4	Hadronic parity violation	Theoretical nuclear physics	Prof. Dr. N. Kaiser, T39-TUM; Prof. Dr. S.-L. Zhu, PKU	2012/2- 2016/1
A.5	Quark mass dependence of heavy-light systems (FP 1); Quark mass dependence of hadronic observables (FP 2,3)	Theoretical hadron physics	Prof. Dr. F.-K. Guo, ITP-CAS; Prof. Dr. Dr. h.c. U.-G. Meißner, HISKP-UB Prof. Dr. P. Wang, IHEP-CAS (FP 1,2)	2012/2- 2024/1
A.7	Precision calculations in hadronic physics (FP 2); Precision calculations in hadronic physics and beyond the standard model physics (FP 3)	Theoretical particle & hadron physics	Prof. Dr. H. Dreiner, PI-UB; PD. Dr. B. Kubis, HISKP-UB (FP 2); Prof. Dr. C.-D. Lü, IHEP-CAS	2016/2- 2024/1
A.8	Charmless exclusive B decays	Theoretical particle & hadron physics	Prof. Dr. M. Beneke, T31-TUM; Prof. Dr. C.-D. Lü, IHEP-CAS	2016/2- 2024/1
A.9	EFT for nuclear electromagnetic currents: Foundations and applications	Theoretical nuclear physics	Prof. Dr. E. Epelbaum (FP 2); Prof. Dr. N. Kaiser, T39-TUM; Dr. H. Krebs, THTP-RUB	2016/2- 2024/1
A.10	Symmetry-violating hadronic interactions from lattice QCD	Theoretical hadron physics	Prof. PhD. T. Luu, FZJ; Dr. M. Petschlies, HISKP-UB; Prof. Dr. C. Urbach, HISKP-UB	2021/1- 2024/1
A.11	Hadronic transition form factors from analyticity	Theoretical hadron physics	PD Dr. B. Kubis, HISKP-UB; Dr. D. van Dyk, T31-TUM	2021/1- 2024/1

Project Code	Title	Research area	Project leaders, institutions, locations	Duration
B. Emergence of Structure				
B.1	Nucleon form factors (FP 1); Partonic structure of nucleons and nuclei (FP 2,3)	Theoretical hadron & nuclear physics	Prof. Dr. Y.-B. Dong, IHEP-CAS; Prof. Dr. H.-W. Hammer, HISKP-UB (FP 1); Prof. Dr. M. Polyakov, THTP-RUB (FP 2,3); Prof. Dr. E. Epelbaum, THTP-RUB (FP 3);	2012/2- 2024/1
B.2	Hadron spectroscopy	Theoretical hadron physics	Prof. Dr. Y. Chen, IHEP-CAS (FP 3); Prof. Dr. M. Huang, IHEP-CAS (FP 1,2); Prof. Dr. S.-L. Zhu, PKU; Prof. Dr. B.-S. Zou, ITP-CAS;	2012/2- 2024/1
B.3	Hadronic molecules with heavy meson loops	Theoretical hadron physics	Prof. Dr. F.-K. Guo, FZJ (FP 1); Prof. Dr. Ch. Hanhart, FZJ; Prof. Dr. Q. Wang, IHEP-CAS/SCNU (FP 2,3); Prof. Dr. Q. Zhao, IHEP-CAS;	2012/2- 2024/1
B.4	Boxed exotica (FP 1); Boxed hadrons (FP 2,3)	Theoretical hadron physics	Prof. Dr. C. Liu, PKU; PD Dr. A. Rusetsky, HISKP-UB;	2012/2- 2024/1
B.5	Exotic states from lattice QCD	Theoretical hadron physics	Prof. Dr. Y. Chen, IHEP-CAS; Prof. Dr. C. Urbach, HISKP-UB	2012/2- 2020/2
B.6	Hadronic systems with strange quarks (FP 1); Strangeness in hadronic and nuclear systems (FP 2); Strangeness in nuclear systems (FP 3)	Theoretical nuclear physics	Dr. A. Nogga, FZJ (FP 2,3); PD Dr. A. Rusetsky, HISKP-UB (FP 1,2) Prof. Dr. W. Weise, T39-TUM (FP 1); Prof. Dr. S.-G- Zhou, ITP-CAS (FP 2,3)	2012/2- 2024/1
B.7	Chiral dynamics of nuclei and hypernuclei (FP 1); Chiral symmetry in nuclear physics (FP 2,3)	Theoretical nuclear physics	Prof. Dr. E. Epelbaum, THTP-RUB (FP 2,3); Prof. Dr. N. Kaiser, T39-TUM; Prof. Dr. Dr. h.c. U.-G. Meißner, HISKP-UB (FP 1); Dr. A. Nogga, FZJ (FP 1) Prof. Dr. J. Meng, PKU (FP 2,3)	2012/2- 2024/1

Project Code	Title	Research area	Project leaders, institutions, locations	Duration
B.8	Quarkonium interactions in hadronic, nuclear and thermal matter (FP 1); Quarkonium interactions in hadronic and nuclear matter (FP 2,3)	Theoretical hadron & nuclear physics	Prof. Dr. Y. Jia, IHEP-CAS; Prof. Dr. A. Vairo, TUM; Prof. Dr. J.-X. Wang, IHEP-CAS (FP 1)	2012/2- 2024/1
B.9	Lattice nuclear physics	Theoretical hadron & nuclear physics	Prof. Dr. E. Epelbaum, THTP-RUB (FP 3); PD Dr. H. Krebs, THTP-RUB (FP 2); Prof. PhD. T. Luu, FZJ (FP 2); Prof. Dr. Dr. h.c. U.-G. Meißner, HISKP-UB	2016/2- 2024/1
B.10	Partial wave analysis	Phenomenological hadron physics	Prof. Dr. U. Thoma, HISKP-UB; Prof. Dr. U. Wiedner, EPI-RUB	2016/2- 2024/1
B.11	Coupled channel dynamics	Theoretical hadron physics	Dr. D. Rönchen, FZJ; Prof. Dr. B.-S. Zou, ITP-CAS	2016/2- 2024/1
B.12	Parton distribution functions on the lattice	Theoretical particle physics	Prof. Dr. X. Feng, PKU; Dr. F. Steffens, HISKP-UB	2021/1- 2024/1
Z. Administration & Outreach				
Z.1	Administration	Administration	Prof. Dr. Dr. h.c. U.-G. Meißner, HISKP-UB; Prof. Dr. C. Urbach, HISKP-UB (FP 2,3); Prof. Dr. W. Weise, T39-TUM (FP 1); Prof. Dr. B.-S. Zou, ITP-CAS	2012/2- 2024/1
Z.2	Outreach	Administration	Prof. Dr. H. Dreiner, PI-UB; Prof. Dr. Ch. Hanhart, FZJ	2012/2- 2024/1

UB – Rheinische Friedrich-Wilhelms-Universität Bonn; HISKP – Helmholtz-Institut für Strahlen– und Kernphysik; PI – Physikalisches Institut; RUB – Ruhr-Universität Bochum; EPI – Institut für Experimentalphysik I; THTP – Institut für Theoretische Hadronen- und Teilchenphysik; TUM – Technische Universität München; E18 – Physik Department E18; T30F – Physik Department T30F; T31 – Physik Department T31; T39 – Physik Department T39; FZJ – Forschungszentrum Jülich; IHEP – Institute of High Energy Physics Beijing; ITP – Institute of Theoretical Physics Beijing; CAS – Chinese Academy of Sciences Beijing; PKU – Peking University Beijing; SCNU – South China Normal University Guangzhou.

4 Research Achievements of the CRC

In 2012 with the discovery of the Higgs boson, the particle content of the so successful Standard Model (SM) of the strong, electromagnetic and weak interactions had been established. The most difficult part of the SM are certainly the strong interactions, described by Quantum Chromodynamics (QCD), as the strongly interacting fundamental particles, the quarks and gluons, can not be observed in isolation but only appear in color neutral states, such as hadrons and nuclei. This is called color

confinement, which constitutes one of the most challenging problems in all of theoretical physics.
The research within the CRC 110 was driven by two open questions within and beyond the SM, namely (i) what forms of strongly interacting particles and matter are generated by QCD? and (ii) how are the underlying symmetries manifested in the spectrum and interactions of QCD? In particular, precision calculations within the SM compared to accurate measurements allow one to eventually access traces of beyond the SM (BSM) physics. As outlined below, there has been made considerable progress towards an understanding of these topics, driven in part by close collaboration with experimental collaborations and also by timely response to the findings of new exotic hadronic states, like e.g. the pentaquarks discovered with the LHCb experiment at CERN in 2015. A worldwide unique feature of this CRC is the investigation of hadrons and nuclei as different manifestations of structure formation in QCD, employing state-of-the-art methods like stochastic simulations (lattice QCD and nuclear lattice effective field theory), effective field theories in various settings and more phenomenological modeling (coupled-channel analyses, quark models).

In more detail, the most significant progress in the various fields is:

Hadron physics

- A significant fraction of the observed exotic states reside close to two- (or three-)particle thresholds. Thus, they can be naturally explained as hadronic molecules. Besides from explaining many of these states and their properties, we have developed a complete theory for such states based on effective field theories, including their decays, lineshapes and production in high-energy collisions (either e^+e^- or $pp/\bar{p}p$ collisions or photoproduction). Here, we have very much profited from the nuclear physics knowledge present in the CRC.

- We have further developed EFTs for quarkonium studies, in particular for the so-called hybrid states including constituent gluons as well as the production of quarkonia in high-energy electron-positron and proton-proton collisions.

- We have established the role of triangle singularities in hadron physics. Such kinematical effects have profound implications on our understanding of the hadron spectrum. This can lead to the distortion of lineshapes as seen e.g. in the isospin-violating decays of the $\eta(1405/1475)$ state or lead to correlations between exotic states, such as the production of the $Z_c(3900)$ is found to be strongly correlated with the $Y(4260)$ and enhanced by the triangle singularity kinematics.

- Based on a combined analysis of lattice QCD and experimental data, we have established a new phenomenon in the hadron spectrum, the so-called two-pole structures. The notion "two-pole structure" refers to the fact that single states appearing in the *Review of Particle Physics* (RPP) are in fact two different states. This phenomenon was only known for the $\Lambda(1405)$ before, but could be established also for the $D_0^*(2300)$ and a few other states. In particular, we have provided improved K-matrix schemes including SU(3) symmetry for the lattice QCD practitioners to properly assess the two-pole phenomenom.

- In lattice QCD (LQCD), we have significantly contributed to the *ab initio* calculations of low-lying resonances and scattering processes, like e.g. the ρ-resonance in P-wave pion-pion scattering or the precise determinations of the S-wave scattering lengths a_0 and a_2 in $\pi\pi$ scattering, that serve as fine tests of the QCD chiral dynamics. Of particular significance are the methodological developments to deal with three-hadron final states and the first lattice calculation of a three-particle resonance based on a scalar field theory was performed.

- By combining a new EFT approach to radiative corrections and LQCD computations, we could contribute to resolving the puzzling status of the first-row unitarity of the CKM matrix. In particular, the hadronic uncertainty form the γW box diagram could be reduced by one order of magnitude and the prediction for $|V_{ud}|$ from pion β-decay could be improved considerably. Similarly, kaon and neutron decays can now be predicted much more precisely from LQCD.

- We have solved the so-called proton radius puzzle by performing high-precision analyses of electron-proton scattering data based on dispersion relations embodying the QCD strictures from analyticity and unitarity. This led to a very precise extraction of the proton charge radius that is perfectly consistent with the value extracted from the Lamb shift in muonic hydrogen and recent extractions from electronic hydrogen as well as low-energy ep scattering at JLab.
- Based on dispersion theoretical methods, we have developed a formalism to deal with three-particle final states in hadronic decays, embodying exact three-body unitarity. This has been applied to the decays of η and η' mesons with a number of predictions for signals of C and CP violations in the Dalitz plots of such decays as well as the search for BSM physics in B-meson decays. These methods have also been employed in collaboration with experimentalists from the COMPASS collaboration to find out the limitations of the often-used isobar approach to final-state interactions.
- We have made significant contributions to the light–by–light scattering contribution to the anomalous magnetic moment of the muon, $(g-2)_\mu$, that still shows deviations between the the theory predictions and the most precise measurements from Fermilab. Here, we have employed dispersion relations as well as lattice QCD, contributing very visibly to the so-called *Muon g-2 Theory Initiative*.
- In B-meson physics, we have made important progress in the understanding of charmless B-decays. Significant results have been obtained in (i) the computation of direct CP asymmetries in hadronic two-body decays of the B-meson, (ii) the rigorous theory of structure-dependent QED effects in B-meson decays, and (iii) predictions for radiative B-meson decays with loop and power corrections.
- We have improved the coupled-channel analysis of hadronic and photo-induced reactions to understand the baryon spectrum in the light quark sector, both within the theoretically well-founded Jülich-Bonn (JüBo) approach as well as the more phenomenological Bonn-Gatchina (BnGa) model. This allowed in particular to pin down the properties of a number of baryon resonances in the second and third resonance regions which have entered the RPP. We have also applied such approaches to better understand the pentaquarks, making predictions for such states in higher partial waves.

Nuclear physics

- We have made remarkable progress in the modern theory of nuclear forces by providing chiral effective field theory two-nucleon forces at N4LO+, which are more precise than any phenomenological parametrization. These forces have become a standard tool in nuclear structure research. There has also been significant progress in our understanding of three-nucleon forces and a number of high-precision computations in few-nucleon systems have been performed, such as the most precise extraction of the neutron charge radius from the analysis of electron scattering off the deuteron.
- We have made important contributions to strangeness nuclear physics, in particular by working out hyperon-nucleon interactions to NLO and NNLO in chiral effective field theory, as well as hyperon-hyperon interactions to NLO and constructing the leading three-baryon forces in this framework. These forces have become a benchmark in the community and allowed us to study e.g. charge-symmetry breaking in hypernuclear spectra as well as s- and p-shell hypernuclei

in the framework of the the Jacobi-No-Core-Shell-Model, that was also developed within this CRC.

- We have established Nuclear Lattice Effective Field Theory (NLEFT) as a novel quantum many-body approach, that allows for *ab initio* calculations in nuclear structure and reactions. During the course of the CRC, we performed a number of groundbreaking calculations, namely (i) the first *ab initio* calculation of alpha-alpha scattering, (ii) we showed that nature is close to a quantum phase transition from a Bose-condensed gas of alpha-particles to a nuclear liquid, (iii) we discussed the emergence of structure and duality in the carbon nucleus and (iv) developed wavefunction matching, a new quantum many-body tool that allows for calculations of systems that would otherwise be impossible owing to problems such as Monte Carlo sign cancellations.
- For larger nuclei, we developed effective field theories for triaxially deformed nuclei as well as for collective rotations and vibrations of triaxially deformed nuclei. Based on such approaches, we investigated static quadrupole moments of nuclear chiral doublet bands and the g-factor and static quadrupole moment for the wobbling mode in ^{133}La, adding to the toolbox of nuclear many-body theory.
- We obtained new insights into the equation of state of neutron matter relevant to the description of neutron stars and their properties. The main findings are (i) the behavior of hyperons in nuclear matter, (ii) constraints on the possible appearance of hyperons inside neutron stars based on the chiral EFT description of the hyperon-nucleon interactions (a major step towards a solution of the so-called “hyperon puzzle”) and (iii) constraints on a possible first-order phase transition inside neutron stars from a Bayesian analysis of recent new observational data.

A common theme in these research endeavors was the use of lattice field theory methods as well as effective field theories. This is most clearly seen in the single-baryon and few-nucleon sectors, where the chiral Lagrangian of QCD was utilized, on the one hand in a perturbative setting and one the other hand non-perturbatively in the few-nucleon sector. Also, lattice methods were used both in hadron and nuclear physics, where lattice QCD and NLEFT achieved different level of success on the nuclear side. In lattice QCD, the CRC enabled novel Sino-German collaborations, e.g. the Chinese PLs (Chuan Liu, Ying Chen, Xu Feng) used the configurations of the Extended Twisted Mass Collaboration in some of their contributions to projects **A.2** and **B.5**. This was not foreseen at the beginning of the CRC.

Another important thrust of this CRC was the understanding and interpretation of the so-called exotic states, which is one of the hottest topics in particle physics since 2003. Here, the collaboration did many groundbreaking and highly cited works and this also dynamically drove a number of projects beyond what was originally planned, e.g. **A.2**, **A.5**, **B.2** and **B.3**. We also made changes to the projects whenever necessary. For example, in FP 1 hadronic parity violation was investigated using chiral Lagrangians in **A.4** and many interesting results were obtained, but due to the lack of experimental data to fit the low-energy constants of the chiral effective Lagrangian, this project was terminated after the first period. However, with new theoretical developments in FP 2, that offered a different venue for calculating e.g. the weak pion-nucleon coupling constant, the topic was taken up again now in the framework of lattice QCD and first results on this difficult observable have been obtained within project **A.10** in FP 3.

It is also worth pointing out that the nuclear physics part, that was relatively small in the first funding period, was considerably boosted by adding Bochum as a node in FP 2 with the renowned PLs Evgeny Epelbaum and Hermann Krebs and also renowned PLs on the Chinese side, namely Jie Meng (Peking Univ.) and Shan-Gui Zou (ITP/CAS). This led to very visible works on nuclear forces in chiral EFT and collective excitations in nuclei (projects **A.8**, **B.7**) as well as improving the work on NLEFT in project **B.9**. This further led to new Sino-German collaborations, like on EFTs for triaxially deformed nuclei involving researchers from UB, TUM and PKU and also on strangeness nuclear physics between FZJ and ITP/CAS. Consequently, this also enhanced the insights into quantum many-body systems not foreseen at the start of the CRC.

Name	Position CRC	Award/Grant	Year
Andria Agadjanov	PhD student	Dr. Klaus Erkelenz Award	2016
Len Brandes	PhD student	Dr. Klaus Erkelenz Award	2022
Nora Brambilla	PL	Advanced Grant from the European Resarch Council	2024
Evgeny Epelbaum	PL	Fellow American Physical Society	2019
Evgeny Epelbaum	PL	Faddeev Medal	2021
Evgeny Epelbaum	PL	Advanced Grant from the European Resarch Council	2020
Evgeny Epelbaum	PL	CAS President's Fellowship for Distinguished Scientists	2023
Xu Feng	PL	National Science Fund for Distinguished Young Scholars	2021
Feng-Kun Guo	PL	The Thousand Talents Plan for Young Professionals Grant	2016
Feng-Kun Guo	PL	Hu Jimin Education and Science Award	2019
Feng-Kun Guo	PL	National Science Fund for Distinguished Young Scholars	2021
Bai-Long Hoid	PhD student	Panda Theory PhD Prize	2022
Yu Jia	PL	NSFC Outstanding Youth Grant	2017
Norbert Kaiser	PL	Dr. Klaus Erkelenz Award	2020
Ulf-G. Meißner	PL	CAS President's Fellowship for Visiting Scientists	2015
Ulf-G. Meißner	PL	Beller Lectureship, American Physical Society	2016
Ulf-G. Meißner	PL	Lise Meitner Prize of the European Physical Society	2016
Ulf-G. Meißner	PL	CAS President's Fellowship for Visiting Scientists	2017
Ulf-G. Meißner	PL	CAS President's Fellowship for Distinguished Scientists	2018
Ulf-G. Meißner	PL	Honorary Doctorate (Dr. h.c.) of the Ivane Javakhishvili Tbilisi State University, Georgia	2018
Ulf-G. Meißner	PL	Advanced Grant from the European Resarch Council	2021
Ulf-G. Meißner	PL	CAS President's Fellowship for Distinguished Scientists	2024
Jie Meng	PL	Humboldt Research Award	2022
Andreas Nogga	PL	Robert and Rene Glidden Visiting Professorship, U. Ohio, USA	2016
Andreas Nogga	PL	Peng Huanwu Visiting Professorship des ITP/CAS	2019
Johann Ostmeyer	student	Pinneapple Science Award in physics	2021
Stephan Paul	PL	Fellow of the Max-Planck Society, MPP, Germany	2019
Patrick Reinert	PhD student	Dr. Klaus Erkelenz Award	2019
Deborah Rönchen	PhD student, PL	Dr. Klaus Erkelenz Award	2014
Akaki Rusetsky	PL	CAS President's Fellowship for Visiting Scientists	2021
Akaki Rusetsky	PL	CAS President's Fellowship for Visiting Scientists	2024
Shihang Shen	postdoc	Dr. Klaus Erkelenz Award	2021
Carsten Urbach	PL	Pinneapple Science Award in physics	2021
Jordy de Vries	postdoc	VENI-grants for young talented physicists	2016
Qian Wang	postdoc, PL	The Excellent PHD Thesis of the Chinese Academy of Sciences	2015
Qian Wang	postdoc, PL	The Thousand Talents Plan for Young Professionals Grant	2017
Wei Wang	postdoc	The Thousand Talents Plan for Young Professionals Grant	2016
Wei Wang	postdoc	National Science Fund for Distinguished Young Scholars	2021
Qiang Zhao	PL	NSFC Outstanding Youth Grant	2016
Qiang Zhao	PL	Wu Youxun Prize by the Chinese Physics Society	2019
Shi-Lin Zhu	PL	Wang Ganchang Prize by the Chinese Physics Society	2019
Bing-Song Zou	PL	Humboldt Research Award	2023

Table 1: Recognition of CRC members through prizes and grants.

As is evident from this, there have been major developments in both hadron and nuclear physics and this CRC was one of the drivers, which is world-wide recognized. It is worth mentioning that from the research in this CRC, three ERC Advanced Grants emerged, namely for Prof. E. Epelbaum (2019, Nuclear Theory from First Principles), Prof. U.-G. Meißner (2021, Emergent Complexity from strong Interactions) and Prof. N. Brambilla (2024, Effective Field Theories to understand and predict the nature of the XYZ exotic hadrons). Further, two of the Chinese PLs were awarded the prestigious Humboldt research award, partly based on the work done in this CRC, namely Prof. J. Meng (2022) and Prof. B.-S. Zou (2023). Other indications are the various prizes, awards and grants bestowed upon CRC PLs, post-docs and students are (incompletely) listed in Tab. 1.

Quality-assurance or quality-enhancement also played an important role within this CRC. This could be achieved by attacking various problems from different angles or using different methods. One example are the pentaquarks from LHCb, which were considered in suitably tailored effective field theories, in one-boson exchange models and also within the JüBo coupled-channel approach. Another example is the production of quarkonia or the pertinent exotic states in electron-positron and proton-proton collisions, that were considered in two very different types of EFTs, namely NRQCD and pNRQCD as well as EFTs for the final-state hadron-hadron interactions. These differ in the treatment of the short-distance physics as well as underlying picture of the generated states. Using such methods and drawing from the nuclear physics knowledge in the CRC, it could also be shown that a number of statements in the literature concerning the hadroproduction of charmed exotica are simply incorrect. Needless to say that all obtained results have been published in refereed journals, which adds another layer of quality control.

Next, we discuss **data handling**. All results obtained in this CRC are freely available on the `arXiv` repository, see `https://arxiv.org/`. We also supply results in electronic form, as such as `Mathematica` notebooks or data files. Also, transition matrix elements calculated in the Jacobi-No-Core-Shell-model are made publicly available in HDF5 format, see
`https://jugit.fz-juelich.de/a.nogga/nucdensity`.
In some cases, the journals also require an explicit data storage, such as *Nature*, see e.g. the recent work on "wavefunction matching": All of the data produced in association with this work have been stored and are publicly available at
`https://drive.google.com/drive/folders/1MByuG6NMagcgmURe4py-kwr9vksnHCl4`.
Another example are the analysis results for the finite volume scattering investigation of the ρ meson and three pions are publicly available in the repositories
`https://github.com/HISKP-LQCD/Nf211-2pi-I1-scattering-data` and
`https://github.com/HISKP-LQCD/Nf2-3pi-I3-scattering-data`, respectively. At RUB, computer codes, which are made available for general public (e.g., the code for generating two-nucleon potentials from chiral EFT developed in the project **B.7**). Furthermore, all data sets generated and/or analyzed within the projects, which have results in scientific publications, are archived locally.

The fundamental data generated in lattice QCD simulations are so-called gauge configurations. Those generated in the CRC110 are going to be available on the International Lattice Data Grid (ILDG): the gauge configuration data is stored together with extensive meta data in order to follow the FAIR principles: they are findable via command line tools or a web interface, they can be accessed in different ways, the data is described by meta data to make it interoperable, and can be reused by other researchers. In the last two years we have also contributed to a refurbishment procedure of the file catalogue and the meta data server of ILDG. In addition, we have updated and modernised the schemata used to describe the data in particular to extend the supported data beyond gauge configurations. This process involved the community for instance at a special session organised at Lattice 2022 in Bonn organised as part of the CRC110 in cooperation with the PUNCH4NFDI consortium. This update is close to finished.

As a research institution, RUB transfers knowledge into the scientific community by providing research results that contribute to current scientific debates. Keeping research data available is important for traceability, scientific progress, the dissemination of scientific findings, and subsequent use. Therefore, RUB has centrally coordinated and sustainable research data management that implements guidelines of good scientific practice. These guidelines outline how research data is processed during its data life cycle to ensure traceability and accessibility. Further, Research Data Services have been established at RUB as a central contact and monitoring unit, whose team provides operational support in line with demand and guidelines, targeting a strategy to offer researchers storage options and tools that optimally fit their needs. The data experts also receive feedback on the usability of the proposed solutions and advise individual researchers.

At TUM, research data have been presented at numerous meetings and conferences. Publications have occurred in proceedings of various conferences. Peer reviewed publications are in progress and additional data will be presented as supplementary material. Computer codes are shared within the big international research collaborations (COMPASS and Belle 2) and follow their respective standards. Owing to the nature of the experimental data, user access requires deep knowledge and interactions with the respective collaborations. However, details of all analysis are available within the collaborations as thesis like write-ups including all details also documenting statistical methods used. PhD theses are publicly available. Raw experimental data are residing on large storage servers at international research centers (KEK, CERN).

4.1 Scientific Events and Science Communication

Meetings (conferences, workshops and schools) with contribution from the CRC110 (note that the participating PLs are not listed. Note further that we do not use a tabular format but an easier readable layout):

1. Micro-Workshop on Strangeness and Nuclear Physics,
   TU München, Germany, October 25-26, 2012,
   Sebastian König.
2. Workshop on Threshold Phenomena,
   IHEP, Beijing, China, April 27-28, 2013,
   Estia Eichten, Tom Mehen, Zhiqing Liu, Gang Li.
3. 9th International Workshop on Heavy Quarkonium 2013,
   IHEP, Beijing, China, April 22-26, 2013,
   Goffrey Bodwin, Roberto Mussa, Chengping Shen, Klaus Peters
4. Mini-Workshop on $B \to \pi\pi$ Semileptonic,
   Bonn, Germany, Feb. 21, 2014,
   Jochen Dingfelder, Xavier Virto, Alexander Khodjamirian, Danny van Dyk
5. Micro-Workshop on Strangeness and related topics,
   ECT*, Trento, Italy, Dec. 5-6, 2013,
   Maxim Mai, Avraham Gal.
6. First CRC 110 general meeting,
   Weihai, China, July 25-29, 2014,
   Chinese reviewers (Xin-nian Wang, Yuan-ning Gao, Chao-hsi Chang, Fan Wang, Zuo-tang Liang, Zhong-Zhou Ren), invited guests (Jie Meng, Shan-Gui Zhou, Cai-Dian Lv, Fei Huang, Yu-Qi Chen) as well as NSFC representatives (Wen-Cong Li and Hui-Hong Li) were also present.
7. 10th International Workshop on Heavy Quarkonium 2014,
   CERN, Switzerland, November 10-14, 2014,
   Joan Soto, Peter Petreczky, Simon Eidelman, Claudia Patrignani, Ramona Vogt, Eric Braaten.
8. Present Status of the Nuclear Interaction Theory,
   Kavli Institute for Theoretical Physics at the CAS, Beijing, China, August 25 to September 19, 2014,
   Dean Lee, Peter Ring, Ruprecht Machleidt, Heiko Herget, Achim Schwenk, Hiroshi Toki.
9. International Workshop on QCD Exotics,
   Jinan, China, June 8-12, 2015,
   Changzheng Yuan, Estia Eichten, Roman Mizyuk, Wei-Hong Liang.
10. Clustering effects of nucleons in nuclei and quarks in multi-quark states,
    Kavli Institute for Theoretical Physics at the CAS, Beijing, China, March 28 to April 22, 2016,
    Elena Santopinto, Emiko Hiyami, Hisashi Horiuchi, Peter Schuck. Gerd Röpke.
11. Advances in Effective Field Theories,
    Forschungszentrum Jülich, Germany from November 7-9, 2016,
    Johan Bijnens, Gilberto Colangelo, Dean Lee, Thomas Mannel, Martin Savage, Achim Schwenk, Wolfram Weise

12. 12th International Workshop on Heavy Quarkonium,
Peking University, Beijing, China, November 6-10, 2017,
Ahmed Ali, Antonio Pineda, Changzheng Yuan, Clara Peset, Geoffrey Bodwin, Jean-Marc Richard.
13. Summer School on Methods of Effective Field Theory & Lattice Field Theory,
Garching, Germany, June 26 to July 7, 2017,
Antonio Pich, Christian Lang, Alexei Bazazov, Guido Martinelli, Sinya Aoki.
14. Workshop on Partial Wave Analyses & Advanced Tools for Hadron Spectroscopy (PWA9/ATHOS4),
Bad Honnef, Germany, March 13 to 17, 2017,
Ian Aitchison, Peter Braun-Munzinger, Philip Cole, Simon Eidelman, Bachir Moussallam.
15. Workshop on Nuclear Dynamics and Threshold Phenomena,
Ruhr-Universität Bochum, April 5-7, 2017,
Arnoldas Deltuva, Serdar Elhatisari, Hans-Werner Hammer
16. Second General meeting of the CRC,
Peking University, China, August 29-31, 2017,
Chien Yeah Seng, Zhi-Hui Guo, Zheng Li Wang.
17. TRR110 workshop on Amplitudes for Three-Body States,
MIAPP, München, Germany, July 11-13, 2018,
Bachir Moussallam, Emilie Passemar, Ikaros Bigi, Jonas Rademacker, Patricia Magalhaes.
18. 13th International Workshop on Heavy Quarkonium,
Torino, Italy, May 13-17, 2019,
Andreas Kronfeld, Estia Eichten, Claudia Patrignani, Eric Braaten, Geoffrey Bodwin, Jianwei Qiu, Sara Collins.
19. Bethe Forum: Multihadron Dynamics in a Box,
Bonn, Germany, September 9-13, 2019,
Andrei Alexandru, Zohreh Davoudi, Takumi Doi, Maxwell Hansen, David Wilson.
20. 18th International Conference on Hadron Spectroscopy and Structure (HADRON2019),
Guilin, China, August 16-21, 2019,
Adam Szczepaniak, Alessandro Pilloni, Eulogio Oset, Jaroslava Hrtankova, Wei-Hong Liang.
21. 14th International Workshop on Heavy Quarkonium,
online, March 15-19, 2021,
Andreas Kronfeld, Estia Eichten, Eric Braaten, Geoffrey Bodwin, Christine Davies, Giulia Pancheri.
22. A Virtual Tribute to Quark Confinement and the Hadron Spectrum,
online, August 2-6, 2021,
Alexander Rothkopf, Aleksi Kurkela, Laura Tolos, Jens Oluf Andersen.
23. Third General CRC meeting 2022,
online, June 7-9, 2022,
only internal participants.
24. 39th International Symposium on Lattice Field Theory,
Bonn, Germany, August 8-13, 2022,
Aaron Meyer, Anna Hasenfratz, Francesca Cuteri, John Bulava, Lena Funcke.
25. Bethe Forum on Multihadron Dynamics in a Box - A.D. 2022,
Bonn, Germany, August 15 - 19, 2022,
Andrew Hanlon, Christopher Thomas, Fernando Romero-Lopez, Hartmut Wittig, Phiala Shanahan.
26. 15th International Workshop on Heavy Quarkonium,
GSI, Darmstadt, Germany, September 26-30, 2022,
Geoffrey Bodwin, Roberto Mussa, Antonio Polosa, Claudia Patrignani, Marc Wagner
27. The XVth Quark confinement and the Hadron spectrum conference,
Stavanger, Norway, August 1-6, 2022,
Alexander Rothkopf, Laura Tolos, Hagop Sazdjian, Gastao Krein.
28. Machine Learning approaches in Lattice QCD,
IAS, TU München, Germany, February 27 to March 3, 2023,
Gert Aarts, Andrzej J. Buras, Will Detmold, Christoph Lehner, Phiala Shanahan.
29. The 7th Meeting of the Low Energy Nucelar Physics International Collaboration (LENPIC2024),
HISKP, Bonn, Germany, March 11-13, 2024,
Pieter Maris, James Vary, Henryk Witala, Jacek Golak.
30. Final Meeting of the CRC110,
Universiätsclub Bonn, Bonn, Germany, June 3-5, 2024,
only internal participants.

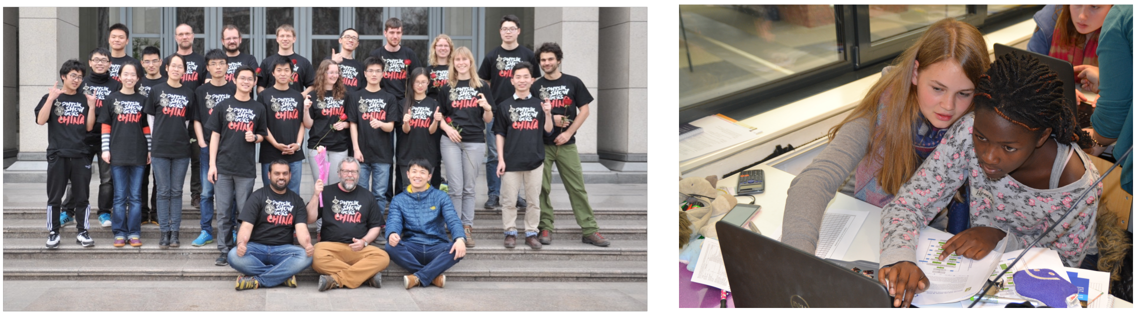

Figure 1: Left panel: The group participating in the Physics Show designed and performed in Beijing, 2016. Right panel: Two of the participants of the Schülerkademie 2015 working on their project on numerical simulations.

Next, we discuss **science communication and outreach**. In the 12 years of the CRC we have on the one hand further developed the already existing and successfully running Bonn physics show ("Physik Show") and on the other hand have created educational courses for high school students of grade 10 and older (age 16+), the so-called "Schülerakademie", and teachers, which we denoted "Lehrerfortbildung", respectively. In the following these efforts are briefly summarized.

The Bonn Physik Show was initiated in December 2001. It has since then been coordinated by Herbert K. Dreiner and Michael Kortmann. In the Physik Show the University of Bonn physics students develop, rehearse and perform an on-stage show typically involving about 25 live experiments, which are embedded to a play-like story. The shows are performed in front of a general audience, and depending on the show in front of kids aged 9-99 or 15-99. Based on the extensive existing experience, the funding within the CRC could trigger the development of a brand new show with special emphasis on particle physics. This was the first ever stage show on particle physics with live experiments and a full story-line. The text of the play as well as a full description of the experiments has been published on the arXiv, see `https://arxiv.org/abs/1607.07478`. This show has been performed in Oxford & London (2014); Padua & Trieste (2015); Copenhagen & Odense (2015); Bonn (2016); Valencia & Barcelona (2017); Bonn (2018); Staatstheater Mainz (2018); Lissabon & Madrid (2018); Amsterdam (2019); Aachen, Freiburg (2019).

We have separately using the funding of the CRC developed a worldwide first ever physics show musical with live experiments, live singing and a live orchestra. This show is also fully described in the arXiv publication: `https://arxiv.org/abs/2201.10968`. This show has been performed in Bonn: 3/2019 (1x), 7/2019 (1x), 2/2020 (1x), 8/2022 (2x); and in Tübingen 3/2023 (3x).

In 2016 with the experienced students we were able within the CRC 110 to travel to Beijing. It was not possible to import our experiments to China, so instead together with 7 Bonn physics students we taught the local students to develop a new show at Peking University using the collection of experiments they had themselves in their collection. We rehearsed the show with local students first in English and then with the help of a local professor they switched to Chinese. As far as we know, this was the first physics show ever in China. The participants of both sides in this activity are shown in the left panel of Fig. 1. A second visit in 2021 was cancelled due to the covid pandemic. We have received an invitation to return in March 2026 outside of the framework of the CRC.

The Physik Show was bestowed with two prizes of UB, on the one hand the "Lehrpreis der Fakultät" for Herbert K. Dreiner for his work and on the other hand the "Initiativpreis der Universitätsgesellschaft Bonn" for the students involved in it.

The Schülerakademie as well as the Lehrerfortbildung were created and further developed throughout the course of the CRC funding period. The first events were held in 2013, both in Jülich, and both have been repeated every second year until 2019. There was no program offered in 2021 due to Covid regulations. The final pair of programs were run in 2022. The high school student programs each ran for four days and were all presented at the Science College Overbach near Jülich. It provided the full infrastructure for the events and was thus ideal for our purposes.

The single day Lehrerfortbildung on the other hand visited all German nodes involved in the CRC, with Bonn being the only place where we were twice. In the Lehrerfortbildung, local professors and postdocs presented current topics in particle and nuclear physics as well as scientific computing and cosmology to bring the teachers up to date with current developments. Both kinds of programs are to our knowledge unique in Germany, since they put the focus on theoretical particle and nuclear physics in contrast to the many existing programs with an experimental focus.

For the Schülerakademie we developed three different projects for the students to work on in small groups, and then to jointly present on the last day: One project is on the concepts of quantum mechanics, one is on philosophical implications of certain insights from nuclear and particle physics, and one is on numerical simulations. The right panel of Fig. 1 shows two participants in the last project. Especially this one was very much improved over time and finally lead to a publication in Physics Education, where the project is worked out in detail and presented in modular form for direct applications, e.g. in special high school courses on physics.

All the different events were very well received by the target groups. The lecture halls where the Physik Show was performed were typically full, and the Schülerakademie overbooked, interestingly with very similar numbers of female and male participants. For the number of participants for the teachers we did not need to be restrictive and had usually over 20 participants. The feedback we have received for all activities has throughout been enthusiastically positive. Our outreach activities have been recognised by the Netzwerk Teilchenwelt, where the Forschungszentrum Jülich is now also affiliated. In particular the Schülerlabor of the Forschungszentrum Jülich is now directly connected to the network.

4.2 National and international collaboration

Here, we list the international collaborations, in which PLs of the CRC are involved and play a significant role:

1. The **Extended Twisted Mass Collaboration (ETMC)** is a lattice QCD collaboration that studies hadron structure and reactions including members from Cyprus, France, Germany, Italy, Poland, Switzerland, USA and China. Involved PLs: Carsten Urbach, Marcus Petschlies, Fernanda Steffens, Xu Feng, Chuan Liu.

2. The **Nuclear Lattice Effective Field Theory Collaboration (NLEFT)** deals with nuclei on a lattice based on nuclear forces from chiral EFT including members from Germany, USA, France, China and South Korea. Involved PLs: Ulf-G. Meißner, Evgeny Epelbaum, Hermann Krebs.

3. The **TUMQCD collaboration** is a lattice QCD collaboration that deals with hot and dense QCD matter and quarkonia including members from Germany and the USA. Involved PLs: Nora Brambilla, Antonio Vairo.

4. The **China Lattice QCD (CLQCD) Collaboration** is a lattice collaboration that deals with hadron structure and dynamics, especially involving charm quarks, with members from China. Involved PLs: Chuan Liu, Xu Feng, Ying Chen.

5. The **Low Energy Nuclear Physics International Collaboration (LENPIC)** aims to develop chiral effective field theory nucleon-nucleon and three-nucleon interactions to a high precision including members from Germany, Poland, USA, Canada and France. Involved PLs are Evgeny Epelbaum, Hermann Krebs, Ulf-G. Meißner.

6. The **Jülich-Bonn(-Washington) (JüBO)** collaboration develops a coupled-channel analysis of hadron- and photon-induced reactions in the light quark sector based on a theoretical well-founded approach including members from Germany, USA and China. Involved PLs are Deborah Rönchen, Ulf-G. Meißner, Bing-Song Zou.

7. The **Bonn-Gatchina (BnGa)** collaboration develops a coupled-channel analysis of hadron- and photon-induced reactions in the light quark sector based on a phenomenological model including members from Germany and Russia. Involved PLs are Ulrike Thoma.

8. The **Particle Data Group (PDG)** compiles all data relevant to particle physics and related areas and edits the *Review of Particle Physics* that appears bi-annually. The PDG group consists of members from many countries. Involved PLs are Christoph Hanhart, Ulrike Thoma, Ulf-G. Meißner, Herbert K. Dreiner, Shi-Lin Zhu.

9. The **Muon g-2 Theory Initiative** aims at improving the calculations of the hadronic contributions to the anomalous magnetic moment of the muon including members from Switzerland, Germany, France, USA, Japan. Involved PLs are Bastian Kubis.

Furthermore, some PLs are members of large international experimental collaborations such as:
– The Beijing Spectrometer III (**BES III**) is a particle physics experiment at the Beijing Electron–Positron Collider II (BEPC II) at the Institute of High-Energy Physics at Beijing (involved PLs are: Ulrich Wiedner, Ulrike Thoma, Bing-Song Zou, Qiang Zhao).
– The **CBELSA/TAPS** experiment at the Elektronen-Stretcher-Anlage (ELSA) in Bonn investigates photo-induced reactions on the proton and the deuteron, allowing also for single- and double-polarization set-ups (involved PS are: Ulrike Thoma, Ulrich Wiedner).
– **COMPASS** is a high-energy physics experiment at the Super Proton Synchrotron (SPS) at CERN. The purpose of this experiment is the study of hadron structure and hadron spectroscopy with high intensity muon and hadron beams (involved PLs are Stephan Paul, Ulrich Wiedner).
– The **CLAS** experiment at the Thomas Jefferson National Accelerator Facility at Newport News, Virginia, USA, performs photo- and electroproduction experiments off protons with multi-GeV beams (involved PS are: Deborah Rönchen).

5 Impact on Research Priorities and International Visibility

In **Bonn**, the CRC 110 had major impact on the development of the fields of hadron and nuclear physics. The rector of the University of Bonn, Prof. Dr. Dr. h.c. Michael Hoch, gave his assessment of the impact of the CRC 110 at the final meeting in June 2024. For the structural developments in Bonn, he listed three major achievements of this CRC:

1. The CRC 110 was instrumental in keeping the field of hadron and nuclear physics alive due to the extremely competitive environment in the department of physics & astronomy, which participates in a number of other CRCs (in the fields of quantum physics and astrophysics) as well as one cluster of excellence in light-matter interactions (ML4Q).

2. The CRC 110 was the seed of the new CRC 1639 NuMeriQS ”Numerical Methods for Dynamics and Structure Formation in Quantum Systems” (Speaker: Carsten Urbach), which brings together researchers from the University of Bonn, Forschungszentrum Jülich and the Max-Planck-Institut für Kohlenforschung (Mülheim, Germany).

3. The CRC 110 was also of prime importance for the excellence cluster initiative “Color meets flavor” (with U. Siegen, TU Dortmund, FZJ), which is presently in the final review stage. Here,

> the work on hadron physics and precision calculations within the CRC 110 is an important cornerstone for the cluster topic, namely the search for new phenomena in particle physics, combining weak and strong interaction investigations for all quark flavors at all energy scales.

In **Bochum**, the CRC 110 also had a significant impact on the development of the fields of hadron and nuclear physics as due to its success, the positions of Prof. Ulrich Wiedner (W3, experimental hadron physics) and of Prof. Maxim Polyakov (W2, theoretical hadron physics) could be kept in the respective fields and the following appointments were made: Prof. Mikhail Mikhasenko as the successor of Ulrich Wiedner and Prof. John Bulava as successor of Maxim Polyakov.

In **Munich**, no new positions were created at the professorial level. However, the collaboration of some experimental groups with theory at TUM and in Bonn was intensified or started, respectively, and due to the CRC, the activity in the field of tau physics has been significantly expanded. A small research group for tau physics was established at the Max-Planck Institut für Physik (MPP), and PhD students from the TUM were able to shape their academic profile and visibility as postdocs at MPP. So in summary, the CRC has further strengthened ties between theoretical physics and experimental physics on the level of data analysis and interpretation.

In **Jülich**, the work in the CRC on computational hadron and nuclear physics was essentially to keep the strong interaction theory institute (IKP-3) alive. This was formerly part of the IKP (Institut für Kernphysik), which was decided to be closed in 2018 (by the end of the running PoF period) by the board of directors of FZJ. However, the IKP-3 was also part of the Institute for Advanced Simulation since 2010 and this is now the strong interaction theory institute (IAS-4) at the FZJ.

The academic achievements of the CRC were made public in the many talks of PLs, postdocs and students at various national and international workshops and also made available on the CRC website `https://crc110.hiskp.uni-bonn.de/`. In addition, the list of prizes and awards compiled in Tab. 1 clearly shows the international recognition of the CRC.

6 Structural Impact of the Collaborative Research Centre

6.1 Staffing

As shown in Tab. 2, the number of PLs increased from 24 in FP 1 to 34 in FP 2 and finally 35 in FP 3. This was achieved by adding two new nodes (RUB on the German side and ITP/CAS on the Chinese side) in FP 2 as well as by increasing the number of PLs in Bonn in FP 2 and at TUM in FP 2 and FP 3.

	Bonn	FZJ	TUM	RUB	IHEP	ITP	PKU
FP1	7	3	4(1)	-	8(1)	-	2
FP2	8(1)	4(2)	5(1)	4	7(1)	3	3
FP3	8(2)	4(1)	6(1)	4	6(1)	3	4

Table 2: Project leaders at each node in the three funding periods. The number in the round brackets corresponds to the number of the female PLs.

Here, we give the developments of the PLs that entered or left the CRC in an easily readable form (not a table):

Bonn

- Prof. Hans-Werner Hammer (W2 at HISKP) left during FP 1 to the TU Darmstadt.
- Prof. Carsten Urbach moved from a non-tenured JProf. W1 position to a W2 Professor position at HISKP in FP 1.
- Prof. Thomas Luu from the Lawrence Livermore National Laboratory (USA) was hired as a W2 Professor at the HISKP within the Jülich model[2] in FP 1.
- Dr. Feng-Kun Guo, PL of projects **A.1** and **A.5** in Bonn in FP 1 returned to China as Associate Professor at the ITP/CAS (Beijing) for the second FP and was promoted to Full Professor in FP 3.
- Dr. Qiang Wang, PL of project **B.3** in Bonn in FP 2 returned to China as Full Professor at South China National University (Guangzhou) with association to the IHEP/CAS (Beijing).
- Dr. Marcus Petschlies (HISKP) became PL in FP 3 and did his Habilitation at Bonn University during FP 3.
- We also note that the position of Prof. Ulf-G. Meißner (W3) was secured to stay in the field of theoretical strong interaction physics due to the success of the CRC110.

Jülich

- Dr. Deborah Rönchen, who did her thesis at University of Bonn during the first funding period, became a PL in FP 2 and also became a permanent staff member at the Institute for Advanced Simulation (IAS-4) at the end of FP 2.
- PD Dr. Christoph Hanhart (IKP-3/IAS-4) became außerplanmäßiger Professor at University of Bonn in FP 1.

[2]The Jülich model means that a professor is appointed by a university (say UB) and then released from his duties at the university (except for teaching) to work at the FZJ. The position is also paid by the FZJ.

Bochum

- Prof. Maxim Polyakov deceased unexpectedly during FP 3. The German lead of project **B.1** was taken over by Prof. E. Epelbaum. Due to the CRC, the position stayed in the field of theoretical hadron physics and is now filled with Prof. John Bulava. His appointment, however, came too late to make him PL of the CRC in FP 3.

München

- Dr. Danny van Dyk, an Emmy-Noether group leader, was associated to the CRC in FP 2 and became PL in FP 3. He left the CRC during the last funding period as he took a permanent position (Ass. Prof.) at the Institute for Particle Physics Phenomenology, Durham, UK.
- PD Dr. Antonio Vairo was promoted to außerplanmäßiger Professor at the TUM in FP 2.

The large impact of the CRC on the Chinese nodes and generally on the field of hadron and nuclear physics in China was already reported by Prof. Zou to the NSFC in January 2024.

6.2 Researchers in early career phases

Concerning mentoring, all research groups involved in the CRC had weekly or bi-weekly group meetings, in which the students and postdocs shared the state of their work and discussed problems. While this is very conventional (at least in theoretical physics), it is by far the best method to guide students through their PhD work and to support postdocs. Further, the students and postdocs were sent to conferences and workshops to present their work to the community, which is also conventional but invaluable. This also holds for schools in fields related to the CRC, to which students were sent regularly.

A number of students and postdocs were involved in the outreach activities, the physics show, the student academy and the teacher education program. This gave them the opportunity to acquire additional skills like being able to explain complicated topics to a general audience. In addition, we had many Chinese students to come to one of the German nodes, either for an extended stay during their PhD time or performing their PhD in Germany. Some German students also spend 1 to 6 months at the Chinese nodes, this number was, however, considerably smaller than the one of Chinese students coming to Germany. Needless to say that many of the Chinese postdocs returned to China on faculty positions, for details see Tab. 3 below.

Furthermore, in Bonn and Jülich we had five PhD students, that were supervised by a Chinese and German colleague. This was possible due to MoUs between the Faculty of Mathematics and Natural Sciences (MNF) at Bonn University and the School of Physics, Peking University, the IHEP/CAS and the ITP/CAS, all signed in the years 2012-2014, when U.-G. Meißner was Dean of the MNF. These students and their supervisors were (see also Fig. 2):

Martin Cleven (Christoph Hanhart, Ulf-G. Meißner, Qiang Zhao) (PhD UB, 2013) [3],
Zhi Yang (Feng-Kun Guo, Ulf-G. Meißner) (PhD UB, 2016)
Menglin Du (Feng-Kun Guo, Ulf-G. Meißner) (PhD UB, 2017),
Ripunjay Acharya (Feng-Kun Guo, Ulf-G. Meißner) (PhD UB, 2019),
Thomas Vonk (Feng-Kun Guo, Ulf-G. Meißner) (PhD UB, 2022).

We intend to continue this successful student co-supervision.

Note that we did not include an RTG in this CRC since all the nodes have their own large-scale graduate schools, which offer many additional courses for the PhD students (Bonn-Cologne Graduate

[3] Note that the dissertation rules at UB require on advisor to be fully employed as "Universitätsprofessor" at Bonn.

Figure 2: Common PhD education. Left panel: Martin Cleven (on the "Doktorwagen" in front of the HISKP) with his two advisors Qiang Zhao (left) and Christoph Hanhart (right) in front. Right panel: Ripunjay Acharya being pulled around the HISKP by his two advisors Ulf-G. Meißner (left) and Feng-Kun Guo (right).

School in Physics and Astronomy (UB/FZJ), the RUB Research School at RUB and the Graduate School of the Technical University Munich). However, whenever required, we sent students to special courses, such as high-performance computing courses at the Jülich Supercomputing Centre (FZJ).

Duration of contract	**Number of contracts for doctoral researchers**		**Number of contracts for postdoctoral researchers**		**Number of researchers in total**
	male	**female**	**male**	**female**	
up to 12 months	8	2	5(2)	1	16(2)
up to 24 months	7	1	4(1)	1	13(1)
up to 36 months	6(2)	1	2(3)	0	9(5)
up to 48 months	13	1	9(4)	2(1)	25(5)

A number of explanations concerning this table are necessary:

(1) The third funding period only ran for 42 months, as FP 2 was prolonged by 6 months. We list here only the persons employed in FP 3.

(2) The number in the round brackets are persons not paid by the CRC but other funds that contributed significantly to different projects (CRC associates).

(3) The students with contracts of up to 24 months are spill-over from FP 2.

List of all doctoral degree completions sorted according to funding period, institution (UB/TUM/FZJ/RUB) and sex (F/M)

Here, we list all dissertations that were done at one of the German nodes. Note that the students that had a position at FZJ did their dissertation at UB, as only universities can grant this title in Germany. The 118 dissertations performed on the Chinese side (IHEP/CAS, ITP/CAS, Peking University) were already reported by Prof. Zou to the NSFC in January 2024.

Project	Surname, first name	Type of funding	Topic	Duration
Completed in first funding period: 2012/2 – 2016/1; UB [F]				
B.1	Lorenz, Ina [F] (UB)	CRC110	Theory and phenomenology of the nucleon electromagnetic form factors	02/2012– –08/2015
B.2	Rönchen, Deborah* [F] (FZJ)	UB	Baryon resonances in pion- and photon-induced hadronic reactions	–03/2014
B.7	Liebig, Susanna [F] (FZJ)	CRC110	Antisymmetrisation in a Jacobi-coordinate based no-core shell model approach	–04/2013
Completed in first funding period: 2012/2 – 2016/1; UB [M]				
A.1	Kang, Xian-Wei [M] (FZJ)	CRC110, FZJ	Chiral dynamics and final-state interactions in semileptonic B meson decay and antinucleon-nucleon scattering	–08/2014
A.3	Wilbring, Erik [M] (UB)	CRC110	Efimov effect in Pionless Effective Field Theory and its epplication to hadronic molecules	02/2012– –12/2015
A.3	Jansen, Max [M] (TU Darmstadt)	CRC110, TUD	Quark Mass Dependence of Hadronic Molecules	01/2013– –11/2016§
B.3	Cleven, Martin [M] (FZJ)	CRC110	Systematic study of hadronic molecules in the heavy quark sector	–12/2013
Completed in first funding period: 2012/2 – 2016/1; TUM [M]				
B.7	Petschauer, Stefan [M] (TUM)	CRC110	Baryonic forces and hyperons in nuclear matter from SU(3) chiral effective field theory	07/2012– –02/2016
Completed in second funding period: 2016/2 – 2020/2; UB [F]				
A.1	Niecknig (née Daub), Johanna [F] (UB)	CRC110	Final-state interactions in heavy-meson decays	09/2013– –07/2018
B.6	Le Thi, Hoai** [F] (FZJ)	CRC110	Jacobi no-core shell model for p-shell hypernuclei	01/2016– –04/2020
Completed in second funding period: 2016/2 – 2020/2; UB [M]				
A.1	Gülmez, Dilege [M] (UB)	CRC110, UB	Vector-meson interactions, dynamically generated molecules, and the hadron spectrum	12/2014– –07/2018
A.1	Niecknig, Franz [M] (UB)	CRC110	Dispersive analysis of charmed meson decays	01/2012– –07/2016
A.2	Werner, Markus [M] (UB)	CRC110	Hadron-hadron interactions from $N_f = 2+1+1$ Lattice QCD: The ρ-resonance	11/2014– –04/2019
A.2	Ueding, Martin [M] (UB)	CRC110	Three pion scattering at maximal isospin from Lattice QCD at physical mass	10/2017– –10/2020
A.5	Yang, Zhi [M] (UB)	CRC110, UB	Prompt Production of hadronic molecules and rescattering of final states in heavy hadron decays	09/2013– –07/2016
A.5	Du, Menglin [M] (UB)	CRC110, UB	Topics in chiral perturbation theory for charmed mesons	07/2014– –08/2017
A.5	Acharya, Ripunjay [M] (UB)	UB	Disconnected contributions to hadronic processes	09/2015– 12/2019
A.7	Wang, Zeren Simon (UB)	CRC110	Confronting the R-parity-violating MSSM with flavor observables and displaced vertices	10/2016– –06/2019
A.7/A.11	Hoid, Bai-Long [M] (UB)	CRC110	Taming hadronic effects at the precision frontier: from the muon anomaly to rare decays	12/2016– –11/2020
B.3	Ropertz, Stefan [M] (UB)	CRC110	Effects of light meson final state interactions in heavy meson decays	09/2016– –09/2020
B.4	Agadjanov, Dimitri [M] (UB)	CRC110	Exploring exotic states with twisted boundary conditions	07/2012– –09/2017
B.4	Agadjanov, Andria* [M] (UB)	CRC110	Hadronic electroweak processes in a finite volume	06/2012– –11/2017
B.5	Helmes, Christopher [M] (UB)	CRC110	$K-K$ and $\pi-K$ scattering lengths at maximal isospin from lattice QCD	05/2014– –03/2019
B.5	Jost, Christian [M] (UB)	CRC110	Pion-Pion Scattering from Lattice QCD	12/2013– –12/2017

Project	Surname, first name	Type of funding	Topic	Duration
B.9	Du, Dechuan [M] (FZJ)	FZJ	Nucleon-nucleon scattering process in Lattice Chiral Effective Field Theory approach up to next-to-next-to-next-to-leading order	10/2012– –01/2018
B.9	Klein, Nico [M] (UB)	CRC110	Few-body systems in Lattice Effective Field Theory	03/2014– –12/2018
B.9	Körber, Christopher [M] (FZJ)	CRC110	Nuclear lattice investigations of fundamental symmetries	11/2014– –03/2018
B.9	Wynen, Jan-Lukas [M] (FZJ)	CRC110	Strongly interacting few-body systems from lattice stochastic methods	12/2016– –06/2020
B.9	Stellin, Gianluca [M] (UB)	CRC110	Nuclear Physics in a finite volume: Investigation of two-particle and α-cluster systems	09/2016– –12/2020
Completed in second funding period: 2016/2 – 2020/2; TUM [F]				
B.7	Strohmeier, Susanne [F] (TUM)	CRC110	Nucleon-nucleon interaction with coupled nucleon-delta channels in Chiral Effective Field Theory	09/2016– –07/2020
B.8	Hwang, Sungmin [F] (TUM)	CRC110, TUM	Symmetries and determination of heavy quark potentials in effective string theory	07/2013– –01/2018
Completed in second funding period: 2016/2 – 2020/2; TUM [M]				
A.3	Martinez, Hector [M] (TUM)	CRC110, TUM	Phenomenology of the radiative $E1$ quarkonium decay	09/2011– –05/2017
A.8	Schwertfeger, Steffen [M]‡ (TUM)	CRC110	Exclusive B decays with photons	02/2015– –09/2016
B.7	Wellenhofer, Corbinian [M] (TUM)	CRC110	Isospin-asymmetry dependence of the nuclear equation of state in many-body perturbation theory	01/2013– –06/2017
B.7	Gerstung, Dominik [M] (TUM)	CRC110	Hyperons in nuclear matter and SU(3) chiral effective field theory	05/2017– –08/2020
B.8	Shtabovenko, Vladyslav [M] (TUM)	CRC110	Nonrelativistic effective field theories of QED and QCD: Applications and automatic calculations	10/2012– –05/2017
A.11	Gubernari, Nico [M] (TUM)	TUM	Applications of light-cone sum rules in flavour physics	09/2017– –09/2020
Completed in second funding period: 2016/2 – 2020/2; RUB [F]				
B.10	Kümmel, Miriam [F] (RUB)	RUB	Analysis of $J/\psi \to \phi\eta\eta$ at BESIII and Calibration of the Temperature Monitoring System for the PANDA Electromagnetic Calorimeter	10/2014– 04/2019
Completed in second funding period: 2016/2 – 2020/2; RUB [M]				
B.10	Leiber, Stephan [M] (RUB)	RUB	Analyse der Kanäle $J/\psi \to \omega\pi^+\pi^-$ bei BESIII und Entwicklungen für das Kühlsystem und die thermische Isolierung des PANDA-EMC	09/2013– 05/2018
B.10	Richter, Marvin [M] (RUB)	RUB	Analyse des $\pi^0\pi^0\pi^0$-Systems in Zwei-Photonen-Reaktionen bei BESIII	08/2015– 02/2019
B.10	Mustafa, Arber [M] (RUB)	RUB	Analyse der Systeme $\pi^+\pi^-\eta, \eta'\pi^0$ sowie $\pi^+\pi^-\pi^0$ in Zwei-Photonen-Reaktionen bei BESIII	08/2015– 01/2019
B.10	Schnier, Clausius [M] (RUB)	RUB	Analyse des Zerfalls $\eta_c \to \Pi^+\pi^-\eta$ bei BESIII und Entwicklung von Komponenten für das elektromagnetische Kalorimeter des PANDA - Experimentes	07/2014– 01/2019
Completed/started in third funding period: 2021/1 – 2024/1; UB [F]				
A.11	Schäfer, Hannah [F] (UB)	CRC110	Loop-induced form factors in the hadronic sector	01/2022–
Completed/started in third funding period: 2021/1 – 2024/1; UB [M]				
A.1	Isken, Tobias [M] (UB)	CRC110	Dispersion-theoretical analysis of $\pi\pi$ and $\pi\eta$ rescattering effects in strong three-body decays	12/2015– –09/2021

Project	Surname, first name	Type of funding	Topic	Duration
A.1	Niehus, Malwin [M] (UB)	BCGS-stipend, CRC110	Quark-mass dependence of pion scattering amplitudes	10/2017– –06/2022
A.1	Akdag, Hakan [M] (UB)	stipend Avicenna-Studienwerks	C and CP violation in light-meson decays	10/2020– –09/2023
A.1	Stamen, Dominik [M] (UB)	CRC110	Application of Khuri-Treiman equations in three-body decays and Primakoff reactions	08/2020–
A.2	Ostmeyer, Johann [M] (UB)	CRC110	The Hubbard Model on the honeycomb lattice with hybrid Monte Carlo	11/2018– –10/2021
A.5	Vonk, Thomas [M] (UB)	CRC110	Phenomenology of the QCD θ-angle and axions in nuclear and particle physics	05/2019– –04/2022
A.5	Severt, Daniel [M] (UB)	UB, CRC110	Baryon properties from chiral QCD	01/2019– –05/2023
A.10	Schlage, Nikolas [M] (UB)	CRC110	Hadronic Parity Violation from Lattice QCD	01/2021–
A.11	Holz, Simon [M] (UB)	CRC110	The quest for the η and η' transition form factors: A stroll on the precision frontier	10/2018– –09/2022
A.11	Zanke, Martin [M] (UB)	CRC110	Dispersively improved vector-meson-dominance approaches to precision observables	09/2020– –07/2024
A.11	Korte, Yannis [M] (UB)	stipend Hans-Böckler-Stiftung, CRC110	Dispersive analysis of $\gamma\gamma \to \pi\eta$ and its contribution to the magnetic moment of the muon	02/2018–
A.11	Kürten, Stephan [M] (TUM)	TUM, UB	Long-distance effects in rare B decays	11/2018–
B.3	von Detten, Leon [M] (FZJ)	CRC110	Two-pion exchange contributions for coupled-channel $B^{(*)}B^{(*)}$ and $\bar{B}^{(*)}B^{(*)}$ scattering	01/2021– –06/2024
B.3	Chacko, Jabez Tom [M] (FZJ)	CRC110	Towards a systematic study of $D, D^*, \bar{D}_1, \bar{D}_2$ scattering and exotic vector states	07/2021– –06/2024
B.11	Rawat, Shivam [M] (FZJ)	CRC110	Hyperon resonances in a dynamical coupled channel approach	01/2021–
Completed/started in third funding period: 2021/1 – 2024/1; TUM [M]				
A.1	Rabusov, Andrej [M] (TUM)	CRC110, TUM	Partial-Wave Analysis of $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ at Belle	03/2017– –09/2023
A.8	Toelstede, Jan [M] (TUM)	TUM	Electromagnetic and power-suppressed effects in exclusive B decays	10/2018– –06/2023
A.8	Finauri, Gael [M] (TUM)	TUM	Exclusive decays and factorization in Flavour Physics	02/2021– –09/2024
A.8	Qerimi, Grames [M] (TUM)	TUM	Effective field theory treatment of dark matter pairs evolving as an open quantum system in a dark thermal environment	01/2020–
A.8	Scirpa, Tommasco [M] (TUM)	TUM	Effective field theory treatment of double heavy exotic hadron systems	03/2022–
B.7	Brandes, Len** [M] (TUM)	CRC110, TUM	Inference of neutron star matter equation of state	03/2021– –06/2024
B.7	Doepper, Niklas [M] (TUM)	CRC110, TUM	Neutrino-indiced pion production off the proton in covariant chiral perturbation theory	04/2021–
B.7	Geiger, Maurus [M] (TUM)	CRC110, TUM	Density dependent nucleon-nucleon potentials from chiral N-forces	05/2021–
B.8	Vander Griend, Peter [M] (TUM)	CRC110	Theory and phenomenology of the out of equilibrium evolution of heavy probes in a Quark Gluon Plasma	02/2018– –09/2022

Project	Surname, first name	Type of funding	Topic	Duration
Completed/started in third funding period: 2021/1 – 2024/1; RUB [F]				
B.1	Panteleeva, Julia [F] (RUB)	CRC110, ERC	Studies of hadron interactions in the presence of external gravitational fields	09/2021–
Completed/started in third funding period: 2021/1 – 2024/1; RUB [M]				
A.9	Möller, Daniel [M] (RUB)	CRC110, MKW NRW, ERC,BMBF	Electromagnetic form factors of light nuclei in chiral effective field theory	04/2018– –04/2024
B.1	Son, Hyeon-Dong [M] (RUB)	CRC110	Parton quasi-distributions and energy-momentum tensor form factors for large N_c nucleons	10/2016– –07/2021
B.1	Alharazin, Herzallah Son [M] (RUB)	CRC110	Gravity-induced hadronic interactions at low energies	10/2021– –10/2024
B.7	Reinert, Patrick‡ [M] (RUB)	CRC110	Precision studies in the two-nucleon system using chiral effective field theory	01/2016– –10/2022
B.7	Springer, Victor [M] (RUB)	CRC110, ERC	Drei-Pion-Austausch Nukleon-Nukleon Potential in chiraler effektiver Feldtheorie	01/2021–
B.9	Bovermann, Lucas [M] (RUB)	CRC110	Nucleon-deuteron scattering on the lattice	11/2018–

* The PhD thesis of Deborah Rönchen was bestowed with the Dr. Klaus Erkelenz Preis in 2014.
* The PhD thesis of Andria Agadjanov was bestowed with the Dr. Klaus Erkelenz Preis in 2016.
† Her study was prolonged due to child birth.
§ In CRC110: 01/2013-04/2014; from 05/2014 at TU Darmstadt.
‡ Part of the work for his PhD thesis of was bestowed with the Dr. Klaus Erkelenz Preis in 2019.
** The work of her thesis and her work as post-doc was bestowed with the Dr. Klaus Erkelenz Preis in 2022.
** The PhD thesis of Len Brandes was bestowed with the Dr. Klaus Erkelenz Preis in 2023.

It is important to stress that the students who did not finish within the duration of FP 3 are put on other funds (Landesmittel, other third party funding) to finish their dissertations.

In Tab. 3, we list the PhD students and postdocs at the German nodes that stayed in academia, either on a permanent position or a high-level fellowship. Not listed are normal post-doc positions (that is PhD students, that moved to a postdoc position somewhere). All other PhD students obtained well-paid jobs in IT companies, banking, consulting, and federal or state agencies, because they have been trained to solve complex problems and use state-of-the-art IT methods.

Next, let us discuss how the CRC affected the **teaching portfolio within the institutions**. At Bonn, there was already a strong offer of particle and hadron physics topics in the MSc curriculum before the CRC. However, the PLs offered additional courses on more specialized topics like lattice field theory, effective field theories, chiral perturbation theory and so on as well as student seminars tailored to the topics of the CRC. At TUM, the PLs have included in their teaching of master courses in nuclear, particle and astrophysics the theoretical foundations for research topics conducted in the CRC. The research carried out within the CRC has considerably impacted the reaching portfolio at RUB and is being regularly discussed in various lectures including, e.g., Theoretical Hadron Physics, Introduction into Chiral Perturbation Theory, Introduction to Nuclear and Particle Physics I and II, Particle Detectors for Hadron Physics Experiments and in seminars such as e.g., Effective Field Theories, Current Topics in the Standard Model and Beyond, Detectors for Particle Physics and Experimental Methods in Nuclear and Particle Physics. Another important course, called Theoretical Minimum, was introduced and regularly offered by Prof. Maxim Polyakov, who deceased unexpectedly during FP 3. This course aims at training students interested in research on theoretical hadron physics in advanced mathematical methods. It was taken over by Dr. Jambul Gegelia (postdoc in project **B.1**), who has become a permanent staff member at RUB in 2022. Furthermore, all PLs involved in the CRC are very actively participating in the supervision of Bachelor, Master and PhD students.

Name	Position CRC	Position now	Institution
Yun-Hua Chen	postdoc	Assoc. Prof.	University of Science and Technology, Beijing, China
Qibo Chen	postdoc	Prof.	East China Normal University, Chian
Lingyun Dai	postdoc	Prof.	Hunan University, China
Danny van Dyk	PL TUM	Assis. Prof.	IPPP, Durham, United Kingdom
Menglin Du	PhD student	Assoc. Prof.	UESTC, Chengdu, China
Miguel Escobedo	postdoc	Lecturer	Barcelona University, Spain
Jambul Gegelia	postdoc	Staff member	TP II, Ruhr-University Bochum, Germany
Feng-Kun Guo	PL Bonn	Prof.	Institute of Theoretical Physics, CAS, China
Yuki Kamiya	postdoc	Assis. Prof.	Tohoku Universiuty, Sendai, Japan
Xianwei Kang	student	Assoc. Prof.	Beijing Normal University, China
Bartosz Kostrzewa	postdoc	Staff member	High Performance Computing & Analytics Lab, UB, Germany
Ning Li	postdoc	Assoc. Prof.	Sun Yat-sen University, China
Liuming Liu	postdoc	Prof.	Institute of Modern Physics, CAS, China
Xiao-Hai Liu	postdoc	Assoc. Prof.	Tianjin University, China
Bingnan Lyu	postdoc	Assoc. Prof.	Grad. School of Chinese Academy of Eng. Physics, China
Li Ma	postdoc	Lecturer	Beijing Jiaotong University, China
Maxim Mai	postdoc	Heisenberg fellow	Berne University, Switzerland
Johann Ostmeyer	PhD student	PL CRC 1639	Bonn Uinversity, Germany
Jing-Yi Pang	postdoc	Lecturer	University of Shanghai for Science and Technology, China
Deborah Rönchen	PhD student	Staff member	Institute for Advanced Simulation (IAS-4), FZJ, Germany
Shihang Shen	postdoc	Assoc. Prof.	Beihang University, China
Jaume Tarrús Castellà	postdoc	Subst. Prof.	Barcelona University, Spain
Keri Vos	postdoc	Assis. Prof.	Masstricht University, Netherlands
Jordy de Vries	postdoc	Assis. Prof.	Univ. Massachussetts at Amherst, USA
Qian Wang	PL Bonn	Prof.	South China Normal University, China
Wei Wang	postdoc	Prof.	Shanghai Jiaotong University, China
Jia-Jun Wu	postdoc	Assoc. Prof.	University of Chinese Academy of Sciences, China
Chuwen Xiao	postdoc	Prof.	Central South University, China
Xiaonu Xiong	postdoc	Prof.	Central South University, China
Zhi Yang	student	Assoc. Prof.	UESTC, Chengdu, China
Deliang Yao	postdoc	Prof.	Hunan University, China
Ji Yao	postdoc	Assis. Prof.	The Chinese Uniersity of Hong Kong, Shenzen, China

Table 3: The CRC as a career booster in academia.

6.3 Equal opportunities and work-life balance

All of the German nodes have large scale programs on equal opportunity and work-life balance, from which members of the CRC benefited. Here, we only list CRC specific measures.

The most significant equal opportunity measure was to increase the number of female PLs, because female PLs serve as role models for students and postdocs (it should be stated that such issues play no role on the Chinese side):

In FP 1, we had 2 female PLs (Prof. Nora Brambilla (TUM) and Prof. Mei Huang (IHEP/CAS)) together with 22 male PLs. On the German side, we had one female PL and 13 male PLs.

In FP 2, we could increase the number of female PLS to 5 by adding Dr. Qian Wang (UB), Prof. Ulrike Thoma (UB) and Dr. Deborah Rönchen (UB) together with 29 male PLs. On the German side, we had 4 female PLs and 17 male PLs.

In FP 3, we added Dr. Fernanda Steffens (UB) as PL, but also lost Prof. Mei Huang, who moved from the IHEP/CAS to UCAS and decided to leave the CRC as her work shifted to another topic not represented in the CRC. So we stayed with 5 female PLs together with 30 male PLs. On the German side, we had 4 female PLs and 18 male PLs.

During the course of the CRC, two female PLs (Deborah Rönchen, Qian Wang) and one postdoc (Keri Vos) obtained permanent positions in academia, see Tab. 3.

In FP 1, we organized together with the CRC 16 (Bonn, Bochum, Giessen) a 3-day workshop in a

Hotel in Remagen for our female students and postdocs on the topic “Time management, leadership strategies and networking” with an external coach. However, the feedback form the participants was absolutely non-enthusiastic, so we decided not to offer such type of event in the following funding periods.

Concerning work-life balance, we do not list the general strategies of the involved nodes here as they are given in the applications for the various funding periods. Within the CRC, from the beginning we made home office work possible whenever required, of course within the rules and regulations of the different nodes. This was also very helpful during the covid pandemic. It should, however, also be stated critically that the funds from the DFG for gender and family issues are difficult to spend. One example from FP 1 underlines this: To come to the general CRC meeting in Weihai (China), Profs. Nora Brambilla and Antonio Vairo from the TUM, who had a young kid at that time, wanted to fly a grandmother from Torino (Italy) to Munich so that she could take care of the child. This would have costed less than 200 €. However, we were denied to use the “Chancengleichheitsmittel” as a grandmother is not a certified care-taker. Thus, only Nora Brambilla could attend the meeting.

6.4 Research infrastructure

Beginning of June 2013 the GPU cluster QBiG started operation in the HISKP at Bonn. The hardware was entirely funded by the CRC 110, while the room and electricity where supplied by the University of Bonn. In its first stage of expansion it comprised a total of 48 K20m NVIDIA GPUs with an integrated peak performance of 56 TFlops in double precision and 168 TFlops in single precision. The 12 nodes were interconnected with a fast infiniband network for efficient parallel execution and a fast connection to 70 TByte of available RAID disk space. QBiG was subsequently expanded in the second and third funding period: QBiG II added five nodes with eight NVIDIA P100 GPUs each, and QBiG III another two nodes with eight A100 GPUs. Until end of 2023 QBiG was the largest GPU machine at UB. Slurm is used as queuing software, allowing the lattice researchers from the CRC access to the computing resources, which allowed to try novel ideas, seed new projects and amend computer resources obtained from the national supercomputer centres.
Of course, some of the work performed in the CRC helped to shape the high-performance computing activities at the FZJ and was pertinent to push the boundaries of these activities, e.g. through projects **A.2**, **A.11** and **B.9**.

6.5 Knowledge transfer

The scientific results have been proactively disseminated to specific target audiences by publishing them in peer-reviewed high-impact journals and presentations at international conferences. The PLs are also serving as members of scientific boards of various international conferences and workshops. All CRC nodes are also engaged in public outreach programs to take research and its results to general public. The PLs involved in the CRC participated in various activities of the corresponding faculties/universities along this line, which include girls’ and boys’ days, Saturday Morning Physics talks for the general public, training of school teachers, the students academy in Overbach as well as talks for general public in different settings at the various nodes. Thus, there was very visible transfer into society, in particular also through the many PhD students, that took jobs in IT companies, banking, consulting, other companies as well as state and federal agencies.

6.6 Internal collaboration and management

The CRC started relatively small, as collaborations between the nodes had either to be set-up or strengthened. In particular, to collaborate on a larger scale with our Chinese colleagues was demanding but turned out to work better than originally expected. Here, the use of online (video) exchanges was critical, but also the constant in-flow of well-trained Chinese PhD students and postdocs at the various German nodes. Also, our German PL Feng-Kun Guo returned to China after FP 1 and acted as an important contributor to the CRC in the following years. Since the collaboration worked well, we could extend it in FP 2 by including two new nodes (RUB, Germany and ITP/CAS, China) and also adding more nuclear physics projects, which gave a better balance between hadron and nuclear physics. In FP 3, we could further add projects and younger PLs (Xu Feng, Marcus Petschlies and Fernanda Steffens). Despite the covid pandemic, the collaborations could continue due to the earlier made experiences in FP 1 and FP 2. Since such a collaboration is like a living organism, whenever necessary, projects were terminated or split or combined as described earlier.

Concerning CRC internal meetings, we kept the number of general CRC meetings rather small (one per funding period plus the final meeting). Instead, we preferred smaller and more focused workshops, either devoted to a specific topic (like e.g. strangeness nuclear physics) or to an overarching topic (like e.g. threshold phenomena in hadron and nuclear physics). In addition, the CRC PLs were very active in contributing to or organizing international workshops and conferences, which could often be used parasitically for small CRC meetings. In addition, the above-mentioned co-supervision of a number of PhD students also helped in bringing a number of PLs closer. **Altogether, this CRC can be considered as a lighthouse of a large international collaboration.**

The management was relatively easy (with one exception to be discussed below) as the two spokesmen were already experienced in large scale collaborations. Prof. Meißner was the spokesperson of the CRC 16 “Subnuclear Structure of Matter” (UB, RUB, U. Giessen) in the second funding period from 2008 to 2012 and deputy speaker in the first and third FP. Prof. Zou was hired as the director of the ITP/CAS just at the beginning of the CRC, which was quite a challenge as the ITP is the only multi-field institute within the Chinese Academy of Sciences and thus under particular scrutiny. He did a very good job in consolidating and further expanding the ITP before stepping down in September 2017 and moving to Tsinghua University in 2024 to build up the nuclear theory group there. The main challenge was the typical phenomenon of any CRC, namely to keep everybody involved and make sure that the projects flourished by e.g. using lump sum money to supply additional students or postdocs in case of new and exciting developments, that required extra personal.

It is worth to mention one major hurdle that had to be overcome during FP 2. The NSFC terminated the contract with the DFG for co-funding CRCs in January 2016, just one month before the review for the second funding period in Beijing. I was informed on that issue by then DFG vice-president Prof. Dr. Michael Famulok. While the second FP was not in jeopardy (under the provision of a positive review), under this condition a third FP was not possible. Therefore, I started a 2.5 years long series of talks with NSFC presidents and other NSFC officials, the rector of PKU, the IHEP director and members of the CAS president’s office. Here, my Chinese co-spokesperson was helpful in arranging these meetings, but clearly he had to avoid direct confrontation with his funding agencies. Together, we prepared a two-page memo for the NSFC detailing all the successes of the CRC. On November $9^{\rm th}$, 2018, we were informed that we could apply for a third funding period. Only after this NSFC decision, the DFG also agreed to that. I must say that during these difficult times, I would have liked to have support from the DFG.