Germany-U.S. Nuclear Theory Exchange Program for QCD Studies of Hadrons & Nuclei (GAUSTEQ): Final Report

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OVERVIEW

GAUSTEQ was a Germany-U.S. exchange program in nuclear theory whose purpose was to focus research efforts on QCD studies of hadrons and nuclei, centered around the current and future research programs of Jefferson Lab and the Gesellschaft für Schwerionenforschung (GSI) in Germany. GAUSTEQ provided travel support for theoretical physicists at US institutions conducting collaborative research with physicists in Germany. GSI (with its Darmstadt and Helmholtz Institute Mainz braches) served as the German "hub" for visits of U.S. physicists, while Jefferson Lab served as the corresponding "hub" for visits of German physicists visiting U.S. institutions through the reciprocal GUSTEHP (German-US Theory Exchange in Hadron Physics) program. GAUSTEQ was funded by the Office of Nuclear Physics of the U.S. Department of Energy, under Contract No.DE-SC0006758 and officially managed through Old Dominion University in Norfolk, Virginia. The program ran between 2011 and 2015.

ACHIEVEMENTS

The program funded a total of 19 visits by U.S. researchers to Germany between 2011 and 2015. The program facilitated the establishement of a number of collaborations between U.S.- and Germany-based physicists, which has thus far resulted in over 20 publications in refereed journals (see publication list below).

Among the highlights of the scientific achivements made possible by this program are the evaluation of nuclear spectra and observables of light nuclei with chiral $NN + NNN$ interactions; calculation of the spectrum from Coulomb dissociation of ^{22}C in PWIA; calculation of transverse momentum dependent parton distributions (TMDs) and generalized parton distributions (GPDs) in effective hadronic models; computation of the longitudinal-transverse double-spin asymmetry in $pp \to \gamma X$; computation of charmonia production in $\bar{p}A$ reactions; evaluation of the pion distribution amplitude in the Dyson-Schwinger equation framework; the first iterative Monte Carlo analysis of spin-dependent parton distribution functions; and others, as described in the summaries below.

The full list of visitors, host institutions and collaborators is listed in Table I. A permanent record of these and other details of the GAUSTEQ program can be found at the website `https://www.jlab.org/gausteq/`.

TABLE I: List of GAUSTEQ participants, institutions visited, and collaborators.

Participant	Institutions visited	Period	Collaborators
James Vary (Iowa State U)	Darmstadt, Bochum, GSI	07/01/12 – 08/18/12	R. Roth, K. Hebeler, S. Binder, A. Calci, J. Langhammer, A. Schwenk, H. Lenske, M. Dhar, E. Epelbaum
Peter Schweitzer (U Connecticut)	Bochum, Mainz	07/17/12 – 07/30/12	B. Pasquini, M. Vanderhaeghen
Pieter Maris (Iowa State U)	Darmstadt, GSI	07/18/12 – 08/01/12	R. Roth, A. Schwenk, T. Neff
Mark Strikman (Penn State U)	Mainz, Bochum, GSI Frankfurt	11/12/12 – 12/12/12	M. Bleicher, A. Gillitzer, A. Larionov
Chueng-Ryong Ji (NCSU)	DESY, Mainz, Bochum	02/27/13 – 03/17/13	B. Bakker, M. Polyakov, M. Vanderhaeghen
Daniel Phillips (Ohio U)	Mainz, Bonn, Bochum	06/19/13 – 07/03/13	V. Pascalutsa, H.-W. Hammer, H. Griesshammer, J. McGovern
Andreas Metz (Temple U)	Regensburg, GSI	06/02/13 – 07/05/13	A. Schäfer, J. Zhou, P. Braun-Munzinger
Fred Myhrer (U South Carolina)	Bochum, GSI	06/16/13 – 07/20/13	E. Epelbaum, V. Baru, A. Gasparyan, H. Krebs, M. Lutz
Ian Cloet (Argonne National Lab)	Regensburg, Darmstadt, FZ Jülich	07/14/13 – 07/29/13	J. Bloch, L. Chang, S. Schmidt
Daniel Phillips (Ohio U)	Darmstadt	06/07/14 – 06/12/14	H.-W. Hammer
Andreas Metz (Temple U)	Regensburg, Tübingen, Darmstadt	06/15/14 – 07/15/14	A. Schäfer, J. Zhou, W. Vogelsang, M. Schlegel, P. Hinderer
Ian Cloet (Argonne National Lab)	Mainz, FZ Jülich	06/24/14 – 07/11/14	V. Pascalutsa, S. Schmidt
James Vary (Iowa State U)	Darmstadt, Giessen, Bochum	07/03/14 – 07/15/14	R. Roth, K. Hebeler, S. Binder, A. Calci, J. Langhammer, E. Epelbaum, H. Krebs
Pieter Maris (Iowa State U)	Bochum, Darmstadt	07/13/14 – 07/31/14	E. Epelbaum, H. Krebs, R. Roth, K. Hebeler
Nobuo Sato (Jefferson Lab)	Mainz, Tübingen	11/13/14 – 12/05/14	W. Vogelsang, M. Stratmann
Chueng-Ryong Ji (NCSU)	Mainz, Bochum	03/01/15 – 03/15/15	N. Stefanis, B. Bakker, M. Vanderhaeghen
Igor Danilkin (Jefferson Lab)	Mainz	03/27/15 – 04/06/15	V. Pauk, P. Masjuan
Carl Carlson (William & Mary)	Mainz	06/10/15 – 07/08/15	M. Gorshteyn, M. Vanderhaeghen
Fred Myhrer (U South Carolina)	Bochum, Mainz	06/05/15 – 07/18/15	E. Epelbaum, V. Baru, H. Krebs, A. Gasparyan, S. Scherer

PUBLICATIONS

[1] P. Maris, J. P. Vary, A. Calci, J. Langhammer, S. Binder and R. Roth, *^{12}C properties with evolved chiral three-nucleon interactions*, Phys. Rev. C **90**, 014314 (2014) [arXiv:1405.1331 [nucl-th]].

[2] H. D. Potter, S. Fischer, P. Maris, J. P. Vary, S. Binder, A. Calci, J. Langhammer and R. Roth, *Ab Initio study of neutron drops with chiral Hamiltonians*, Phys. Lett. B **739**, 445 (2014) [arXiv:1406.1160 [nucl-th]].

[3] B. Pasquini and P. Schweitzer, *Pion transverse momentum dependent parton distributions in a light-front constituent approach, and the Boer-Mulders effect in the pion-induced Drell-Yan process*, Phys. Rev. D **90**, 014050 (2014) [arXiv:1406.2056 [hep-ph]].

[4] A. B. Larionov, M. Bleicher, A. Gillitzer and M. Strikman, *Charmonium production in antiproton-nucleus reactions at low energies*, Phys. Rev. C **87**, 054608 (2013) [arXiv:1303.0236 [nucl-th]].

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[6] A. B. Larionov, M. Strikman and M. Bleicher, *Determination of the structure of the $X(3872)$ in $\bar{p}A$ collisions*, Phys. Lett. B **749**, 35 (2015) [arXiv:1502.03311 [nucl-th]].

[7] A. B. Larionov, M. Strikman and M. Bleicher, *Test of the $X(3872)$ Structure in Antiproton-Nucleus Collisions*, arXiv:1512.05536 [nucl-th].

[8] A. B. Larionov, M. Strikman and M. Bleicher, *Color transparency in π^--induced dilepton production on nuclei*, arXiv:1601.00189 [nucl-th].

[9] B. L. G. Bakker and C.-R. Ji, *Nuclear chromodynamics: Novel nuclear phenomena predicted by QCD*, Prog. Part. Nucl. Phys. 74, 1 (2014).

[10] B. Acharya and D. Phillips, *Properties of Lithium-11 and Carbon-22 at leading order in halo effective field theory*, to appear in Proceedings of 21st International Conference on Few-body Problems in Physics, Chicago, IL, May 2015, arXiv:1508.02697 [nucl-th].

[11] K. Kanazawa, A. Metz, D. Pitonyak and M. Schlegel, *Longitudinaltransverse double-spin asymmetries in single-inclusive lepto-production of hadrons*, Phys. Lett. B **742**, 340 (2015) [arXiv:1411.6459 [hep-ph]].

[12] K. Kanazawa, A. Metz, D. Pitonyak and M. Schlegel, Single-spin asymmetries in the lepto-production of transversely polarized Λ hyperons, Phys. Lett. B **744**, 385 (2015) [arXiv:1503.02003 [hep-ph]]

[13] K. Kanazawa, Y. Koike, A. Metz, D. Pitonyak and M. Schlegel, *Operator constraints for twist-3 functions and Lorentz invariance properties of twist-3 observables*, arXiv:1512.07233 [hep-ph].

[14] M. G. Echevarria, A. Idilbi, K. Kanazawa, C. Lorce, A. Metz, B. Pasquini and M. Schlegel, *Proper definition and evolution of generalized transverse momentum distributions*, arXiv:1602.06953 [hep-ph].

[15] A. A. Filin, V. Baru, E. Epelbaum, H. Krebs, C. Hanhart and F. Myhrer, *Pion production in nucleon-nucleon collisions in chiral effective field theory with $\Delta(1232)$ degrees of freedom*, Phys. Rev. C **88**, 064003 (2013).

[16] V. Baru, E. Epelbaum, A. A. Filin, C. Hanhart, H. Krebs and F. Myhrer, *Threshold pion production in proton-proton collisions at NNLO in chiral EFT*, arXiv:1602.07333 [nucl-th].

[17] L. Chang, I. C. Cloet, J. J. Cobos-Martinez, C. D. Roberts, S. M. Schmidt and P. C. Tandy, *Imaging dynamical chiral symmetry breaking: pion wave function on the light front*, Phys. Rev. Lett. **110**, 132001 (2013).

[18] I. C. Cloet, L. Chang, C. D. Roberts, S. M. Schmidt and P. C. Tandy, *Pion distribution amplitude from lattice-QCD*, Phys. Rev. Lett. **111**, 092001 (2013).

[19] L. Chang, I. C. Cloet, C. D. Roberts, S. M. Schmidt and P. C. Tandy, *Pion electromagnetic form factor at spacelike momenta*, Phys. Rev. Lett. **111**, 141802 (2013).

[20] J. Segovia, C. Chen, I. C. Cloet, C. D. Roberts, S. M. Schmidt and S. Wan, *Elastic and Transition Form Factors of the $\Delta(1232)$*, Few Body Syst. **55**, 1 (2014).

[21] J. Segovia, L. Chang, I. C. Cloet, C. D. Roberts, S. M. Schmidt and H. S. Zong, *Distribution amplitudes of light-quark mesons from lattice QCD*, Phys. Lett. B **731**, 13 (2014).

[22] J. Segovia, I. C. Cloet, C. D. Roberts and S. M. Schmidt, *Nucleon and Δ elastic and transition form factors*, Few Body Syst. **55**, 1185 (2014).

[23] N. Sato, W. Melnitchouk, S. E. Kuhn, J. J. Ethier and A. Accardi, *Iterative Monte Carlo analysis of spin-dependent parton distributions*, arXiv:1601.07782 [hep-ph].

PARTICIPANTS' REPORTS

J. Vary and P. Maris

still to come

P. Schweitzer

During the stay in Mainz the PI discussed with the host Marc Vanderhaeghen and Barbara Pasquini (visitor from Pavia and long-term collaborator of the host) the opportunities of the experimental research programs at JLab and FAIR.

In the past results from non-perturbative calculations in light-cone constituent quark models were successfully applied to the description of observables on azimuthal spin asymmetries in semi-inclusive deep-inelastic scattering. The results of these calculations compare well to available data, and played important roles in proposals of new JLab experiments (to which the PI and B. Pasquini made contributions). While electron-nucleon scattering experiments provide important insights, crucial tests of the TMD factorization approach are only possible through combined studies of data from semi-inclusive DIS (e.g. at JLab) and the Drell-Yan process (e.g. at FAIR).

In the discussions in Mainz consensus was reached that presently the highest priority goal is the demonstration of the applicability of the light-cone constituent quark model to the description of Drell-Yan data sensitive to transverse parton momenta. Of particular interest in this context are data from pion-nucleon scattering on the so called violation of the Lam-Tung relation. These data are sensitive to the Boer-Mulders functions in the nucleon and pion.

During the stay in Mainz the PI and Barbara Pasquini focused on evolution of the results from the low initial scale of the model to experimentally relevant scales, and calculated relevant observables. The comparison of first numerical results to available data (from CERN, Fermilab) is encouraging. The paper resulting from this work appeared in Ref. [11]. The host, Marc Vanderhaeghen, does not appear as co-author of this work at this stage, although discussions with him in Mainz were valuable, highly stimulating, and critical for the completion of this work.

Once the applicability of the approach to the description of Drell-Yan processes is demonstrated (early in 2013 according to current estimates), numerous applications will emerge. In particular, the approach might be used to the description of observables in Drell-Yan from proton-antiproton collisions at FAIR. The PI will stay in contact with Barbara Pasquini and the host concerning further developments in this direction.

The successful research of the PI and Barbara Pasquini has lead in the past to publications and was incorporated in proposals of new JLab experiments. The research conducted in Mainz will demonstrate the applicability of the lightcone-constituent quark model to the description of Drell-Yan observables sensitive to transverse parton momenta. Once the approach has been shown to work, the next step will consist in making definite predictions for Drell-Yan observables in (unpolarized and polarized) proton-antiproton collisions at FAIR. In long-term this research will contribute to the demonstration that the same T-odd effects give rise to azimuthal (spin) observables in semi-inclusive deep-inelastic scattering (at JLab) and Drell-Yan (at FAIR).

M. Strikman

The discussions during the visit of Mark Strikman to Germany supported

by GAUSTEQ by now resulted in two lines of the research involving Alexei Larionov (FIAS, Frankfurt), Marcus Bleicher (Frankfurt U. & FIAS) and Albrecht Gillitzer (Julich, Forschungazentrum).

1) The production of charmonia in the antiproton-nucleus reactions at plab=310 GeV/c is studied within the Glauber model and the generalized eikonal approximation. The main reaction channel is charmonium formation in an antiproton-proton collision. The target mass dependence of the charmonium transparency ratio allows to determine the charmonium-nucleon cross section. The polarization effects in the production of \chi_c2 states was also evaluated. Such studies are complementary to the planned charmonium production studies at 12 GeV. We also suggested a method for determining the structure of X(3872) in the antiproton nucleus collisions.

2) We are currently working on the predictions for color transparency effects in 12 GeV JLab kinematics and and the complementary kinematics for the hadron induced reactions. The first results of the analysis which were released very recently focus on the effects of color transparency in the pion induced exclusive dilepton production. They are compared with analogous effects in the pion production in exclusive DIS which were first studied at 6 GeV and which will be studied at 12 GeV.

C.-R. Ji

In this review, we have discussed the novel QCD phenomena that go beyond what can be described in terms of the ordinary baryonmeson picture of nuclear physics. In particular, the three-nucleon short-range correlations (3N-SRCs) measured recently at JLab Hall C (E02-019) were significantly higher than the previous CLAS data and suggested that contributions from 3N-SRCs in heavy nuclei are larger than previously believed. If this difference between Hall C and CLAS is truly due to the Q^2 difference between these experiments, it might open a possibility to associate this difference with the dramatic increase of hidden color degrees of freedom in the nine-quark system compare to the six-quark system that we have discussed in this review. It will be interesting to test more details in the upcoming 12 GeV upgraded experiments in JLab.

D. R. Phillips

The (2013 and 2014) funding from GAUSTEQ was very useful. As a result I:

- Continued collaboration with Hans-Werner Hammer (which includes two students, one from Ohio, and one from Bonn). We are presently working to complete a paper of the spectrum from Coulomb dissociation of Carbon-22 in plane-wave impulse approximation. GAUSTEQ will be acknowledged in that publication. A preliminary version of these results was presented at the 21st International Conference on Few-body Problems in Physics in Chicago, IL in May 2015 and will be published in the proceedings [10]. This conference proceeding was refereed.

- Presented seminars on my research in Mainz, Bochum, and Darmstadt

- Discussed the feasibility and benefits of experiments on Compton scattering from Helium-3 with experimentalists at Mainz. As a result of those discussions I am working to produce a paper which updates earlier predictions for Compton scattering from Helium-3. GAUSTEQ will be acknowledged in that publication.

A. Metz

Here I very briefly summarize the main outcomes of my two research trips to Germany that were supported through the GAUSTEQ program. The trips took place in the years 2013 and 2014. The host institutions were the University of Darmstadt, University of Regensburg, and the University of Tuebingen.

1) Discussions with Marc Schlegel and Werner Vogelsang at the University of Tuebingen about single-inclusive hadron production in lepton-nucleon collisions, where NLO-corrections and higher-twist observables were considered. Recent data on this reaction have been published by the HERMES Collaboration and by the Hall-A Collaboration at Jefferson Lab. These discussions triggered activities that finally led to three papers (see Refs. [11,12,13] in the publication list).

With Marc Schlegel, I also spoke about a proper field-theoretic definition of generalized TMDs (GTMDs), which led to the publication in Ref.~[14].

2) In Regensburg I discussed with Andreas Schaefer and J. Zhou about a couple of topics. First, we spoke about the distribution of linearly polarized gluons at small values of Bjorken-x. In particular, we considered key processes in which this distribution could be measured. Theoretically the simplest one is the production of a lepton-pair with a back-to-back jet in pA collisions. The aim is to perform a dedicated phenomenological study with a focus on RHIC and LHC energies. The second topic deals with the scale dependence of 3-parton correlators. Several papers on this topic exist already, but there still is partial disagreement in the final evolution equations. I suggested to use the Burkardt sum rule as an independent check, since the ingredients in that sum rule have a close connection to 3-parton correlators. J. Zhou worked out all the details and presented them in Phys. Rev. D 92, 074016 (2015) [arXiv:1507.02819], "Note on the scale dependence of the Burkardt sum rule". (As he had done basically all the detailed work I declined authorship of that paper.)

3) At the GSI in Darmstadt I discussed with Peter Braun-Munzinger and his group the possibility to measure hyperon polarization in unpolarized pp and pA collisions at the LHC, and in particular with the ALICE detector. Various final states were considered, all of which should be accessible with ALICE. The discussion stimulated me to consider the calculation of pp -> Lambda X, where the Lambda is transversely polarized. Such a calculation could be performed based on some recent developments at Temple University.

F. Myhrer

Threshold pion production in proton-proton collisions at NNLO in chiral EFT

The reaction NN -> NN \pi is a useful tool to test chiral effective field theory at intermediate energies, understand mechanisms of the first inelastic channel in NN interactions and study charge symmetry breaking.

In the previous studies [Phys. Rev. C85, 054001 (2012) and Phys. Rev. C88, 064003 (2013)] we presented a complete calculation of the pion-production operator for s-wave pions up-to-and-including next-to-next-to-leading (NNLO) order in chiral effective field theory, which includes pions, nucleons and \Delta(1232) degrees of freedom. In the new work (see Publication list) we calculate observables for the pp -> d \pi^+ reaction by performing the convolution of the obtained operators with nuclear wave functions based on modern phenomenological and chiral potentials.

We show that the evaluated NNLO amplitudes give corrections to the
dominant leading order amplitudes as expected from dimensional analysis.
The result gives support to the counting scheme used to classify the
pion production operators, which is a precondition for a reliable
investigation of the chirally suppressed neutral pion production.
Due to cancellations, the explicit inclusion of the \Delta(1232)
is found to be important but smaller than expected.

I. Cloët

I received funds from GAUSTEQ to visit Germany in both 2013 and 2014.
These funds where primarily used to initiate and continue a
collaboration with Sebastian Schmidt, who is a director at
Forschungszentrum Julich. In addition, I was able to visit the
University of Regensburg, Technische Universitat Darmstadt and Johannes
Gutenberg-Universitat Mainz. As a new staff member at Argonne National
Laboratory, the GAUSTEQ proved extremely valuable, as it enabled me to
showcase my research and ANL to important members of the Germany hadron
physics community, and as such my reseacrh profile in Germany and Europe
more broadly has increased dramatically. My collaboration with Sebastian
Schmidt - which would not have been possible without funds from GAUSTEQ
- has been very fruitful and continues today.
Six publications resulted from this collaboration (see Publication List).

My collaboration with Sebastian Schmidt is ongoing and publications on
the application of the Dyson-Schwinger equations to pion and nucleon
transverse momentum dependent parton distribution functions will appear
this year.

N. Sato

A new global QCD analysis of spin-dependent PDFs has been performed by the JAM
(Jefferson Lab Angular Momentum) Collaboration, including all available data
on inclusive spin structure functions from CERN, SLAC, DESY and JLab.
In particular, we explore the impact of recent high-precision JLab data at
high x and low Q^2 on the determination of large-x PDFs and the extraction
of higher twist matrix elements.

For the analysis, a new fitting methodology called iterative Monte Carlo
technique has been developed. The methodology relies heavily on the fast
evaluation of the spin observables and my visit to the Tuebingen group
supported by GAUSTEQ founds was crucial for this end.

I. Danilkin

The topics discussed during the visit included (1) light-by-light sum rules,
(2) virtual photon-photon scattering, and (3) decays of light mesons and
hadron spectroscopy.

Two new projects were initiated with Prof. Marc Vanderhaeghen related to
light-by-light sum rules and the muon anomalous magnetic moment. The first
estimate of gamma gamma-> 4 pi (which is predominantly gamma gamma -> rho rho)
has been performed. Next step would be imposing virtuality on one of the photon.
In addition we discussed the application of the sum rules in the charmonium sector.

The projects are relevant both for JLab and FAIR experiments. In particular,
the light-by-light sum rules in charmonium sector can indicate to what extent
the lowest lying states saturate this sum rule and therefore can constrain the
contribution of the states above the charm threshold. This topic is relevant

for future PANDA experiment. The analysis of the muon anomalous magnetic moment will benefit from low energy experiments at JLab such as the eta radiative decay width from the Primakoff process (E-10-011).

C. Carlson

text to come