Pion and Kaon Structure Functions at the EIC

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Abstract
We provide a summary of discussions at the week-long tele-workshop "Pion and Kaon Structure Functions at the EIC", held in June 2020 under the auspices of the Center for Frontiers in Nuclear Science. The presentations and attendant conversations provided a perspective on existing challenges and future opportunities as experiment, phenomenology, and theory reach toward the goals of revealing the origin and consequences of emergent hadronic mass using modern and planned facilities. The potential for discovery at modern and planned facilities was highlighted, with emphasis on the electron ion collider.

1 Executive Summary

The Lagrangian masses of the quarks deliver only ≈ 1% of the proton mass, m_p; and it is the emergence of the bulk of m_p and the (very probably) related mechanism of confinement that are the key unresolved issues in hadron physics. In addressing these issues, the potential of the EIC is enormous. It promises to enable a quantitative understanding of the structure of hadrons, such as the nucleon, pion, and kaon, in terms of quarks and gluons, thereby achieving key goals of modern physics. Recent synergistic advances in computation, experiment and theory reveal the prospects for a precise description of the one-dimensional structure of hadrons, exemplified by electromagnetic form factors and parton distribution functions (PDFs), and of constructing three-dimensional images of hadrons, as expressed in Generalized Parton Distributions (GPDs) and Transverse-Momentum-Dependent Distributions (TMDs). Hence, today, there is an unprecedented opportunity to chart the in-hadron distributions of, *inter alia*, mass, charge, magnetization, and angular momentum.

This workshop focused on evaluating recent progress toward a comprehensive program of pion and kaon structure studies at the Electron-Ion Collider (EIC) and identifying and developing new opportunities at the EIC and elsewhere. Its near-term goals included expansion of existing documentation, driving toward a significant new element in the EIC User Group Physics and

Detector Handbook, and developing contributions as part of the ongoing Yellow Report Initiative. The meeting gathered members of the academic and laboratory communities interested in recent experimental developments, new theoretical insights and rapid computational advances, as well as high-level phenomenology in the form of global structure function fitting frameworks. It also included discussions of new avenues, like machine learning and exascale computing.

The workshop is linked into the inSPIRE data base:

https://inspirehep.net/conferences/1816008?ui-citation-summary=true

and at the bottom-left of the inSPIRE page, under the "website" tag, one finds a link to the Zenodo site that hosts all presentations:

https://zenodo.org/communities/pieic-2020?page=1&size=20

All presentations are Open Access, are associated with a unique DOI, and can be cited using the toolbox at the bottom-right of the presentation's "view" page.

2 Future prospects and community identified needs

As guidance for the future of pion and kaon structure studies at the electron ion collider (EIC), the following items were advanced during the workshop:

- The case for pion and kaon structure function studies is strong. Pions and kaons – Nature's only known (pseudo-) Nambu-Goldstone modes – are fundamental to our existence. Yet, more than seventy years after their discovery, little is known about π and K structure
- There is a pressing need for a program of experiments that extend the exploration of hadron structure, moving beyond the fifty-year fascination with the nucleon and broadening the focus to include the pion and kaon
- Progress with hadron structure studies requires development of a rigorous phenomenological framework capable of reliably connecting experimental measurement and theoretical predictions to the fundamental elements of the Standard Model
- All understanding gained and lessons learnt during four decades of PDF phenomenology must be incorporated into future analyses. Regarding 1D PDFs, the issue of threshold (next-to-leading logarithm) resummation and its impact on the large-x behavior of extracted PDFs should be further explored; and concerning experiment and theory aimed at the hugely greater challenge of revealing the 3D structure of hadrons, there is great need for clear statements of all challenges faced and discussion of feasible approaches to overcoming them
- It is essential to identify the array of basic calculations and experiments whose mutual validation can justify the use of theory to infer information not directly accessible via experiment
- There is an urgent need to develop all arms of phenomenology and theory as soon as possible because Science is entering a new era, with facilities being built that can definitively expose pion and kaon structure experimentally

3 Summary of the Workshop Sessions

The workshop brought together a diverse mix of participants from 71 institutions and 15 countries. A considerable fraction of the 139 registered participants were early-career researchers (students, postdocs), highlighting the growing interest and importance of the themes covered in the workshop. (**Participant List** lists the registered participants.)

The main foci of the workshop were: (*i*) further expanding and strengthening the science case for pion and kaon structure studies at the EIC; and (*ii*) understanding the associated detector requirements and developing strategies to meet them. Synergies and areas of complementary potential with other facilities were also discussed. The main topics included:

a. Setting the stage
b. Experiments and methods
c. Large-x PDFs and resummation
d. PDA and PDF connections
e. Toward 3D meson structure

Within each topic, the presentations highlighted recent progress and opportunities. The workshop included 28 talks and 4 discussion sessions over four days. The program details are registered: https://indico.bnl.gov/e/PIEIC2020. A summary of the findings from each day is listed below.

3.a Setting the Stage

Studies of hadron structure, in one-dimension, via electromagnetic form factors and PDFs, and three-dimensions, through TMDs and GPDs, are entering a new era of discovery. We have seen the appearance of first results from the 12 GeV upgrade of CEBAF at Jefferson Lab (JLab), announcement of an EIC to be sited at BNL, steady progress toward exascale computing, continuing development of global analysis frameworks, and rapid progress in QCD theory. All this demands a coordinated effort, aimed at exploiting these developments and ensuring they can be combined synergistically to deliver, at last, a complete picture of the structure of hadrons.

New theoretical and computational techniques, developed and applied within the last five years, are yielding novel and much needed predictions for the x-dependence of the one-dimensional and three-dimensional measures of hadron structure. First, many of these predictions can be validated experimentally, through their correlations with measurable quantities, at existing, upgraded, and planned facilities. Second, predictions can augment the experimentally measurable quantities to provide a more faithful description of the internal structure of hadrons. However, realization of these opportunities can only be achieved with a rigorous, QCD-connected phenomenological framework. Now is the time to develop it.

3.b Experiments and methods

The experimental program of the 12 GeV upgrade of JLab represents a major advance in the international hadron-structure effort. Recent results from the PRad experiment, with its finding of a small proton charge radius, is proving vital in resolving the discrepancy between measurements in muonic hydrogen and hadron lamb-shift, and previous electron scattering results. The large-Q^2 behavior of pion, kaon and nucleon form factors will be measured, with the goal of exposing the emergence of quark and gluon degrees of freedom. The longitudinal structure of the proton and neutron will be revealed through experiments such as BONUS, aimed at delineating the *u*- and *d*-quark contributions to the large-*x* structure, whilst tagged DIS experiments will explore pion and kaon PDFs. Three-dimensional structure of the nucleon will be investigated through measurements of semi-inclusive deep-inelastic scattering (SIDIS), deeply virtual Compton Scattering (DVCS), and related processes, such as deeply virtual meson production (DVMP). This program, together with complementary activities at other new facilities worldwide, will reveal the valence quark contribution to the structure of hadrons.

Activities at the next experimental frontier are represented by the EIC, to be built at Brookhaven National Laboratory (BNL); the proposed AMBER@CERN, that will provide a complementary lens on hadron structure through the use of pion and kaon beams; and, potentially, the electron ion collider in China (EicC), which could both neatly fill a gap between JLab at 12 GeV and the EIC, and develop a powerful synergy with AMBER@CERN. These investments will greatly expand our understanding of the valence structure of hadrons and simultaneously extend that to the domains of glue and sea-quark dominance, revealing the "glue that binds us all". They will also open wide the door that leads to the ultimate understanding of the structure of the pion and kaon, the pseudo-Nambu-Goldstone modes whose existence and character are so crucial to the evolution of the vast bulk of visible matter. The opportunities here are exciting and ground-breaking. How do mass and confinement emerge from QCD and how are they related? What is the distribution of pressure, both of quarks and gluons, within a hadron? How do we construct three-dimensional images of the nucleon, not only for quarks but also for gluons? Can we derive a unified picture of hadrons, which encompasses not only the nucleon, but the pion and kaon?

Modern experimental developments have been matched by theoretical and computational advances. Calculations within the Dyson-Schwinger framework describe how the quarks acquire a momentum-dependent mass that give rise to the constituent-quarks and provide a framework for describing the inter-related mechanisms of chiral symmetry breaking and confinement. The physical insights afforded by these calculations are matched by increasingly precise calculations of key physical quantities, notably in the pion, where both the PDFs, describing longitudinal structure, and the quark distribution amplitudes, describing the behavior of the form factors at high momentum transfers, have now appeared. These methods are now being extended to the nucleons using Faddeev methods.

Lattice QCD calculations have advanced through the development and adoption of new theoretical ideas, algorithmic advances, and the march to the exascale era of leadership-class computing. Notable amongst the first is the development of methods to enable the extraction of x-dependent PDFs from Euclidean-space lattice calculations, characterized through the computation of quasi-PDFs, pseudo-PDFs, and “lattice cross sections”. The algorithmic and computational improvements have enabled the calculation of key measures of hadron structure, such as the nucleon's axial-vector charge, with controlled uncertainties, directly at the physical light-quark masses. First calculations of the unpolarized and polarized *x*-dependent PDFs have appeared at the physical light-quark masses, and these methods are now being applied to the calculation of GPDs and TMDs.

The final element of a triad of progress is the increasing effort aimed at the development of global analysis frameworks, exemplified by the JAM collaboration at Jefferson Lab, the multi-institutional CTEQ collaboration, and the NNPDF effort in Europe, which are exploiting ideas of machine learning and neural networks. The development of global fitting for the collinear PDFs is the culmination of nearly three decades of effort. Yet, important questions still remain, and the development of such frameworks for TMDs and for GPDs is key to capitalizing on the theoretical and experimental advances in 3D imaging.

Each of the elements described above is crucial to our understanding of the structure of hadrons, but that understanding can only proceed through a combined campaign of experiment, theory and global fitting.

3.c Large-x PDFs and Resummation

Recent efforts have re-emphasized the importance of including resummation in global analyses. Global PDF fit results with uncertainties have revealed the importance of new pion and kaon data. To access the full power of quark PDFs, pion and kaon structure function data at large *x*, covering a wide range in Q^2, are needed. To illustrate the power of the data from an EIC, projected pion structure functions, with uncertainties estimated by varying PDFs, could be of interest. Furthermore, flexible functional fitting forms should be evaluated and methods developed to minimize the degree of fitting bias in the global analyses.

3.d PDA and PDF

The Light Front Wave Function (LFWF) is the unifying object in studies of PDAs and PDFs. The mechanism of Emergent Hadron Mass (EHM) is encoded in every hadron LFWF. Experiments sensitive to differences in hadron LFWFs are thus also sensitive to EHM. Examples of such experimental quantities are PDAs and PDFs themselves. Owing to EHM, both show a broadening at experimentally accessible scales. The difference between the shapes of the pion and kaon PDAs is due to Higgs-induced modulations, via the *s*-quark current-mass, of EHM in these pseudo-Nambu-Goldstone modes. Notably, for the pion valence DF, numerous calculations within a diverse array of frameworks preserve the following relation: for a $J^{PC} = 0^{-+}$ meson, a vector-boson exchange interaction with ultraviolet power-law behavior $(\frac{1}{k^2})^n$ produces a valence-quark DF that behaves as $(1-x)^{2n}$ on $x \simeq 1$. Contemporary continuum theory indicates that this prediction could be validated with precise data and sound extraction on the domain $0.6 < x < 0.8$.

3.e Towards 3D meson structure

Ongoing theoretical studies are working to determine regions where it is theoretically *safe* to interpret measurements in terms of pion and kaon 3D structure functions, as well as to define domains that can be used to distinguish between different models and better understand backgrounds. On the experiment side, the development of EIC detector requirements is the focus of the Meson Structure Working Group (MSWG). For example, in connection with pion GPD studies, one must show that the Sullivan process dominates, and that the forward-going baryon and its decay products can be detected. These things affect detector design, *e.g*. requirements on electron calorimetry. Detector requirements based on recent studies by the MSWG were presented. For pion structure function measurements, the neutron detection efficiency with the planned Zero Degree Calorimeter (ZDC) is 100% for all energies. Lower energies require the ZDC to be at least 60cm × 60cm in active area in order to access a wider range of energies. For both pion and kaon structure function measurements, good ZDC angular resolution is required at all energies to achieve the required ($-t$) resolution. Higher energies require resolution of 1cm or better. For kaon structure function measurements, additional high-resolution/high-granularity EM calorimetry and tracking are needed before the ZDC. Studies have shown that good hadron calorimetry for good z resolution at large x is needed. There is a potentially interesting prospect for pion TMD studies. In general, much work remains to be done on developing sound theory predictions and developing the phenomenology connection between data and calculation.

4 Conclusion

This was the 3rd workshop in a series that began in 2017 following conversations during the 2016 International Nuclear Physics Conference. It is part of a wider effort that involves a worldwide community of scientists (experiment, phenomenology, theory) in joint activities at the world's leading accelerator facilities, and in organizing conferences and workshops at numerous international centers, *e.g*. Institute for Nonperturbative Physics (INP), Nanjing, China; Université Paris-Saclay, France; ECT*, Trento, Italy; CERN, Geneva, Switzerland; JLab, Newport News, USA; and CFNS, SUNY – Stony Brook, USA.

These coordinated efforts aim to address the challenge of explaining the origin and distribution of the vast bulk of visible mass in the Universe. Progress and insights have been delivered by an amalgam of experiment, phenomenology, and theory; and the continued exploitation of existing synergies is essential in order to capitalize on the extraordinary opportunities promised by new generation facilities. Discussions are continuing as the experimental opportunities and capacities evolve. They join high-energy nuclear and particle physicists, with the goal of consolidating and expanding the collaboration between experimentalists proposing new measurements, phenomenologists undertaking global data analyses, and hadron-structure theorists working to deliver Standard Model predictions for validation. In the coming year, conferences and workshops are planned, *e.g*. at CERN, Saclay, ECT*, and INP.

Appendix A – Participant List

Pion and Kaon Structure Functions at the EIC

First Name	Last Name	Affiliation
Maxim	Alexeev	University of Turin & INFN sez. Torino
Vladimirov	Alexey	Regensburg University
Sheren	Alsalmi	King Saud University
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