Hadron Physics Opportunities in Europe

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Abstract

On November 20 and November 21 this working group has met in order to discuss and summarize future Hadron Physics Opportunities in Europe. The work of this working group is based on the Long Range Plan of the Nuclear Physics European Collaboration Committee from November 27, 2017 (NuPECC is an Expert Committee of the European Science Foundation). Furthermore it is based on a series of four strategy workshops organized in common by the German committee for Hadron and Nuclear Physics (KHuK), the German committee for elementary particle physics (KET) and the German committee for astro-particle physics (KAT) between January 2017 and May 2018. The document discusses experimental and theory activities for the understanding of the structure and excitation spectrum of hadrons in the non-perturbative regime of QCD.

The meeting featured short presentations on existing and planned future experiments at CERN, at GSI/FAIR, and other facilities. The meeting concluded with an open 4-hour discussion of the priorities in the field. The following text is not endorsed officially by any of the experimental collaborations and facilities mentioned, but summarizes the consensus view of the scientific community on the priorities of the field, as expressed by the participants of the meeting.

Introduction

Hadron physics is concerned with the study of the underlying structure and interactions of nuclear matter at the most fundamental level, that of quarks and gluons, which is described by the theory of Quantum Chromo Dynamics (QCD). The theoretical description of the strong interaction has given rise to some of the most influential ideas in quantum field theory. In addition, QCD is one of the pillars of the Standard Model (SM) of particle physics. It is of fundamental importance for quantum field theory (QFT) as such due to its rich phenomenology. While QCD is well tested in the perturbative region, it becomes a strongly coupled theory in the non-perturbative region where many aspects await a better understanding.

Strict factorization proofs allow to split QCD calculations into perturbative (pQCD) and non-perturbative parts. The latter is primarily constrained by experimental data. In recent years theory has made substantial progress so that in some cases it can be analyzed by sophisticated techniques like Lattice QCD (LQCD) and all order pQCD resummation, in other cases effective field theory (EFT) has proven efficient.

All high-energy accelerators probe perturbative and non-perturbative aspects of QCD with the emphasis shifting towards the latter for lower energies. As no single theoretical technique can answer all questions, a balanced effort is needed. Similarly, no single accelerator can sufficiently cover the important probes nor the necessary kinematic ranges and reaction classes. A balanced experimental effort involving different particle beams and different energy scales is needed.

The advent of high luminosity accelerators requires an increasing control of systematic uncertainties to a level that competes with the statistical uncertainties. This constitutes an unprecedented experimental and theoretical challenge. Some of the key physics questions to be addressed with this high level of accuracy are:

- Hadrons are relativistic, strongly coupled, many particle quantum states which was recently highlighted by the discovery of many unexpected - possibly four quark - bound states. What is their structure and how can it be understood within QCD?
- The strong force between hadrons in general can be described most efficiently using effective degrees of freedom and effective interactions. How can their properties be derived from hadron physics experiments? Can they derived directly from theory, either directly from QCD or from intermediate EFTs?
- Many cosmological and astrophysical events probe aspects of hadron and nuclear physics, e.g., reactions in the early universe like QCD and nuclear physics dominated phases of the Big Bang, neutron star mergers creating gravitational waves, or element synthesis in supernovae. How can additional experimental input and improved theoretical methods lead to a more precise understanding of such events?
- What are the fundamental symmetries governing our world and how can they be tested by methods developed for hadron physics, e.g. by searches for

static electric dipole moments, parity violating electron scattering, dark photon search etc.?
- The sensitivity of many high energy and medium energy experiments searching for Beyond-standard-model (BSM) physics is depends critically on the precision of hadron and nuclear physics input. How can this precision be improved?

State of the art computing is indispensable to meet the challenges faced by present day hadron physics, be it continuously developing High Performance Computing (HPC) for experiments and theory, data management in large data infrastructures, machine learning applications in Big Data samples for event recognition in experiment, or analytic computer algebra methods. In all of these fields hadron physics contributes cutting-edge developments with impact on a very broad spectrum of applications not only in academia but also for industrial applications and modern life in general.

Running and approved Projects

The physics potential of the presently operating hadron physics experiments at CERN, ELSA, DAPHNE, GSI, MAMI, and PSI and in particular: ALICE, COMPASS, LHCb at CERN; HADES at GSI, CBM and PANDA at FAIR, BEPC-II, and SuperKEKB must be fully exploited.

These projects provide now, and for the medium-term, the important particle beams to access electromagnetic and hadronic probes, in scattering and annihilation channels. They will provide a rich, high-precision and high-statistics data set covering the excitation spectrum of hadrons made of light, medium and heavy quarks. Structure aspects of hadrons will be explored too.

Future Projects

1. **The full completion of the ESFRI flagship FAIR with its additional storage rings is of highest priority and strongly recommended.**
   It will allow for an efficient, parallel use of all ion and antiproton beams and increase the luminosity and energy range of the FAIR facility substantially.

2. **The second highest priority of the European hadron physics community is to participate significantly in the EIC (Electron Ion Collider) program.**
   The European groups working at JLAB and COMPASS provide a very valuable contribution to the R&D for the EIC project which is expected to have a worldwide dimension and representing an opportunity for a major step forward in the field of hadron physics. The goal of the Electron Ion Collider

(EIC) is to probe with precision the structure of nucleons and nuclei from quarks and gluons with very high luminosity. This enables to collect data with sufficient statistical precision even for differential cross sections depending on many variables like for the determination of Generalized Parton Distribution Functions (GPDs) or Transverse Momentum Dependent PDFs (TMDs). Parton Distribution Functions (PDFs), Generalized Parton Distribution Functions (GPDs) and Transverse Momentum Dependent PDFs (TMDs) together contain an enormous amount of information which reveals, e.g., the three dimensional structure of hadrons both in momentum and coordinate space and both, flavor and spin resolved. For nuclei the EIC has the potential to establish unambiguously saturation and many other nuclear effects.

3. **Research and Development for a future QCD facility based on the COMPASS experiment is recommended.**
   A future general-purpose facility is being proposed by the COMPASS Collaboration reinforced by several interested groups worldwide. It is described in detail in the Letter of Intent “New QCD facility at the M2 beam line of the CERN SPS”. A Proton radius measurement using muon-proton elastic scattering aims at an independent precision determination of the electric mean-square charge radius of the proton. Hard exclusive reactions initiated by a muon beam impinging on a transversely polarised target are used to extend our knowledge on the angular-momentum structure of the nucleon in terms of Generalized Parton Distributions (GPDs). The measurement of Drell-Yan and J/ψ charmonium production aims at the determination of the nearly unknown pion and kaon parton distribution functions (PDFs). Spectroscopy with a beam of secondary low-energy antiprotons from a production target will provide a complementary approach to investigation of so-called X, Y and Z narrow resonance–like signals parallel to the continued thorough investigation in e+e- collisions at Belle II and BESIII. The Kaon spectroscopy program aims at deepening of the understanding of the strangeness degree of freedom as accessed through the kaon excitation spectrum, and is also of interest in the context of CP violation in heavy-meson decays as studied at LHCb and Belle II. The study of the gluon distribution in the kaon via prompt-photon production aims at a better understanding the partonic structure of light mesons via the dominant hard gluon Compton scattering process in the range of x_g above 0.05 and for $Q^2 \sim p_T^2 > 7\ (\mathrm{GeV}/c)^2$. The main objective of low-energy tests of QCD using kaon-induced Primakoff reactions is the first measurement of the kaon polarisability.

4. **Research and development work for high intensity e+e- colliders at moderate energies (Super-Tau-Charm Factory, SuperKEKB Upgrade) is strongly recommended.**

5. **Research and development work for a fixed target program at the LHC is strongly recommended.**

   The installation of a polarized gas fixed target along the LHC, making use of the most energetic proton and ion beams, opens to an outstanding physics program for polarized and unpolarized hadron physics. The center of mass system lays in between the SPS and the RHIC energies. One of the most significant issues to be addressed is the limited understanding of the spin structure of the nucleon, like in the field of the Transverse-Momentum Dependent (TMD) distribution functions. The present knowledge of the Parton Distribution Functions (PDFs) still suffers from large uncertainties, and in many cases, the PDF uncertainties have become the limiting factor in the accuracy of the predictions for LHC measurements. These are two examples, where a fixed target program at LHC can substantially contribute.

Probing physics beyond the Standard Model with hadron physics methods

The full exploration of precision experiments for the search for physics beyond the standard model is strongly recommended.

The presently known fundamental interactions governing Nature and the Universe from the largest to the smallest distances display symmetries and symmetry breaking. High precision studies allow tests of our understanding of Nature that are complementary to experiments at the highest energies and sometimes offer higher sensitivities to new effects beyond the Standard Model (SM) of particle physics.

Nuclear and Hadron Physics has played a major role in finding and establishing the laws which govern the physics at the most fundamental level. One of the most notable examples is the maximal violation of spatial inversion symmetry, parity P, in the weak interaction. The search for new physics with precision experiments relies on the indirect effects of BSM physics arising from its contribution in quantum corrections. It is complementary to the direct searches at highest energies at LHC.

1. A new high-intensity muon beam at PSI would allow for the full exploitation of the Mu3e-experiment. The Beam Dump Experiment (BDX) at MESA can use the world largest electron flux on a beam dump, up to 10^{22} electrons on target per year for the search for dark matter. Other beam dump experiments like the NA64-Experiment at CERN offers interesting possibilities for dark matter search.
2. A precision measurement of the weak mixing angle at low energy scales with parity violating electron scattering, like the P2-experiment at MESA, can reach sensitivities for new physics up to 50 TeV and is complementary to the direct searches at LHC.

3. The search for an electric dipole moment of charged particles in storage rings can lead to a substantial increase of BSM sensitivity. Research and development for a storage ring experiment in Jülich is recommended.
4. The anomalous magnetic moment g-2 of the muon provides at this moment the only experimental hint of BSM physics. An important input to the search for BSM physics with the measurement of the muon anomalous moment is the precise knowledge of the leading order quantum corrections involving hadrons. The MUonE experiment has proposed an alternative way to access the hadronic corrections measuring the running of the electromagnetic coupling alpha(t) in the space-like region through the elastic scattering of high energetic muons colliding on electron target at rest at CERN. We recommend research and development for the MUonE experiment.

Theory

A strong theory program is essential both for strategic decisions and for the success of experiments. Substantial support is therefore mandatory.

The last decades have witnessed dramatic increase in the detail and resolution seen in nearly all subfields of experimental hadron physics. This provides both a significant challenge and real opportunity for theory.

To profit from increasingly precise data coming from experiment, all systematic uncertainties have to be understood at the same level of detail. This is a monumental task both for experimenters and for theorists, where calculations have already reached such high levels of complexity and detail that further significant progress requires substantial resources and work. A fine-tuned and carefully balanced effort connecting lattice QCD, perturbative QCD and effective field theory methods is essential; all these techniques need to work together to provide the detailed understanding of hadron physics needed to confront the precision experimental data.

- Recent experiments have revealed surprising new features about hadronic matter and its excitations, with new resonant structures observed in scattering experiments. A theoretical understanding, linking these discoveries directly to QCD is still very far from complete and will require new methods, better connections between theory techniques and substantial high-performance computing resources to complete this picture. Finding answers to these questions provides excellent training opportunities for the next generation of European hadron physics researchers.
- Constantly improving precision is driving investigations of ever-more detailed properties of hadron structure. The theoretical descriptions of these details, which include for example generalised parton distributions (GPDs), transverse momentum distributions (TMDs) and double parton distributions (DPDs) are now so complex and numerous that experimental data is not sufficient to

determine them all completely. Theory input, coming for example from lattice QCD must be developed in tandem with experimental tests of these connections. Improving this link requires a paradigm shift for the role of theory and without significant theory input physics experiments will be less able to understand the detail of internal hadron structure.

- To build the infrastructure to lead these research areas in Europe requires substantial improvements to the funding structures and dedicating support to theoretical hadron physics, including focused theory centres and a substantial improvement of the required computing infrastructure in all three fields of lattice QCD, perturbative QCD and effective field theory methods. All these areas have distinct requirements and resource needs. A new strategy should focus on exploiting the significant expertise in these areas in European to maximise the benefit and connection to experimental physics combined with training of the next generation of European expertise. Theory can provide a bridge between experiments and other research and industrial stakeholders in data sciences, high-performance computing and better links will lead to both commercial and training opportunities.

Advances in Technology

Research and development in accelerator and detector technologies, as well as in computing and software, are a prerequisite for all future projects.

Many of the topics and projects discussed above require substantial developments in the areas of accelerator, detector, computing and software technology. Examples in accelerator R&D are high field magnets, energy recovery structures and plasma wake field acceleration. Examples in detector R&D are extremely fast, radiation hard and cost-effective detectors with high granularity. Unprecedented data rates and volumes will require the exploitation of state of the art computer science methods to develop adequate computing concepts and innovative algorithms for data handling, reconstruction and analysis. Due to the very long time scales of many of the currently proposed projects, it will be essential to keep and further develop the technological expertise within the community.

Research Conditions - Promoting Young Scientists

The research conditions must guarantee the maintenance and further evolution of expertise during the long project lifetimes and be attractive for junior scientists.

An outstanding European research landscape in particle physics is the basis to ensure scientific progress and the attractiveness of the field. In order to guarantee the continuity and evolution of indispensable expertise in computing, software, detectors and accelerators, the personnel structures must be adapted to the long-term duration of projects. Young scientists are often the source of new ideas and have the cutting-edge competence in many areas. Their scientific and technical contributions should be given high visibility and they need promotion and predictable career prospects.

Outreach

The commitment of scientists to activities that create public awareness and support is crucial and must be recognized as beneficial to their career record. Inspiring the next generation through outreach activities is an indispensable task.

Outreach and science communication aim at communicating current research questions and results, thereby raising public awareness of the societal benefits of particle physics and enhancing the support by the general public. Outreach programs also create opportunities for young people to encounter role models and to obtain insight in the research process. Access to open data online or in masterclass programs enable participation of the public in scientific research. Scientists have the opportunities to share their enthusiasm in outreach and communication efforts worldwide.