Note on proposed organization of program

When discussing our ideas for our program to be presented below, we felt that the community would be best served by our program if there is a team of organizers that combines broad expertise in the many areas that we plan to address. The team we have assembled consists of

Miguel Arratia (UC Riverside, US)
Daniel de Florian (Univ. of San Martín, Argentina)
Renee Fatemi* (University of Kentucky, US)
Thomas Gehrmann (Univ. of Zürich, Switzerland)
Zhong-Bo Kang (UC Los Angeles, US)
Huey-Wen Lin* (Michigan State Univ., US)
Matthew Sievert (New Mexico State Univ., US)
Werner Vogelsang** (Univ. of Tübingen, Germany)

(* = formal organizer, ** = lead). It seems to us that having this large and diverse organizing team will provide the best avenues for attracting the key EIC scientists who we would like to have at the INT, for shaping the scientific content of the program, and hence for making best use of the valuable INT resources. All of the organizers will be actively engaged in setting up and running the program. They will also each spend significant amounts of time at the program.

Individual family and workplace commitments are evidently very hard to forecast on a two-year time scale. Having this larger group of fully committed collaborators will be of much benefit for the program: We expect that at least two, ideally three, members of the team will be in residence at INT at any given time, allowing to cover the full topical diversity of the program at all times. In this respect, although the three "formal" organizers will make every effort to be at the INT for several weeks, we regard **all organizers as playing equal roles in running the program**, so that full organizational presence is guaranteed throughout the program, though not necessarily always by the formal organizers. We hope that this approach is acceptable for the INT. All this said, both Gehrmann and Vogelsang are currently planning to take sabbatical leave from their home universities during part of 2025, which would especially allow them to be at the INT for an extended period of time. Full confirmation is still outstanding.

Scientific motivations and impact for nuclear physics

The Electron-Ion Collider (EIC) to be constructed at Brookhaven National Laboratory over the coming decade will be the most powerful tool thus far for exploring the inner structure of matter and the forces that hold matter together. It will provide images of protons and nuclei at their deepest level, and with unprecedented precision.

With EIC construction now forthcoming, and with planning for ePIC, the project detector, well underway, we believe it is timely to review the status of the theory for ep and eA collisions at the EIC, to take stock of what has been achieved, to identify outstanding problems, and to forge new collaborations and alliances that will tackle them. A program at the Institute for Nuclear Theory would provide the ideal venue and setting to facilitate such a task. As the exchange among theorists and experimentalists will be particularly important, we plan to bring together the leading theorists and experimentalists interested in QCD precision studies at the EIC. We expect that the program will identify the topics for future work, bundle the activities of the field, and will also serve to generate additional new ideas for further measurements at the EIC. This goes hand in hand with development of the plans for ePIC and possibly a second EIC detector. Finally, we also hope to attract scientists not currently deeply engaged in EIC physics.

The **impact of our program on the broader nuclear community** would be tremendous. The program would address the outstanding theory issues at the EIC, with emphasis also on EIC phenomenology, and in close connection to the planned measurements and the foreseen machine and detection capabilities at the EIC. Below we present a list of key topics that our program would address, along with a brief discussion of progress that we hope can be achieved through the program. We note that many of these topics also featured in the recent theoretical White Paper *The case for an EIC Theory Alliance: Theoretical Challenges of the EIC* (arXiv:2305.14572). We expect our program to provide important input to the community effort toward such an Alliance in forthcoming years.

Precision theory for hard scattering at the EIC

Precision will play a fundamental role in the analysis of the data generated by the EIC and it will be necessary that the most advanced theoretical calculations are available. A similar situation was observed at the LHC, where, after two decades, second order (next-to-next-to leading order, NNLO) perturbative QCD calculations became the state-of-the-art for all benchmark processes, allowing predictions for differential distributions at a precision level of a few percent. First steps are now being taken to go to even higher perturbative orders for selected high-precision observables. The EIC will produce experimental measurements of a statistical quality that is comparable to – or even better than – what is obtained at the LHC, thereby challenging precision theory to a new level.

One of the most important goals of this workshop is to bring together experts in the field in order to extend the tools developed for the LHC to the EIC. A fundamental objective will be to extend the methods developed at NNLO and beyond in the case of unpolarized collisions to polarized collisions. That includes for example the computation of virtual (helicity) amplitudes, the (spin-dependent) generalization of the NNLO subtraction terms and the proper treatment of heavy quark masses.

Compared to the LHC, the EIC offers novel types of precision observables, going across the different topical areas of the planned program: measurements in new kinematical regions (e.g. small-x or transition to photoproduction), semi-inclusive production of identified hadrons, and multi-differential transverse-momentum dependent processes. Each of these poses novel types of challenges to precision theory, and the combination of experts from different subfields we hope to assemble for our INT program will provide a forum to identify these challenges and to devise strategies to address them. We also expect the program to provide important impulses for ongoing LHC precision studies.

Factorization and resummation

The systematic separation of long-distance and short-distance QCD phenomena forms the backbone for our ability to treat strong interactions. For numerous observables relevant at the EIC, this factorization has been established and will be exploited. Research in recent years has shown, however, that in some cases – notably when small transverse momenta of final states are relevant – factorization is expected to be broken, at least in regards to the universality of the involved nonperturbative pieces that normally accompanies factorization. Such breaking effects turn out to be particularly prominent when spins of hadrons or partons are taken into account. Their detailed exploration is one of the goals for our program. We plan to collect observables that are currently believed to break factorization, to determine the origins of the breaking effects in perturbation theory, and to study their impact on the EIC program.

Where applicable, factorization also implies a resummation of systematically-enhanced perturbative corrections to all orders in perturbation theory. Applications range from DGLAP evolution to small-x evolution and to threshold and transverse momentum resummation. Each of these play central roles for EIC precision physics. Not only do resummations offer information on higher orders in perturbation theory and hence serve as benchmarks for full, say, NNLO calculations, they are often also crucial for phenomenology. As part of our program, we plan to have detailed discussions on various aspects of resummation. We also plan on developing resummed phenomenological predictions for further EIC observables, among them cross sections and spin asymmetries with jet final states.

Parton distributions and the interplay of EIC and LHC

The EIC, as a machine designed to study nucleon and nuclear structure, will complement all the information about parton distributions obtained from previous colliders and especially the LHC, adding the unique characteristics of DIS to the subject. We foresee that experts on parton distribution functions (PDFs) participating in the workshop will analyze the interplay of both colliders and how they could complement each other in global precision analysis of parton densities. This will help to further develop key observables for PDF extractions at the EIC and the ensuing detection requirements and strategies. We expect to also compare various techniques on the determination of PDF uncertainties in global analyses. Additionally, photon-proton scattering through ultraperipheral collisions in heavy-ion colliders like at RHIC and the LHC can provide a shared interest to engage heavy-ion physicists in EIC science through this program.

In addition to unpolarized ep and eA physics, a prime goal of the EIC is to obtain vastly improved knowledge on spin-dependent parton distributions and hence on the spin structure of the nucleon. For our program, we expect collaboration among the leaders of the most advanced analyses of the spin structure of the nucleon towards code comparisons and agreements (e.g., in the spirit of the Les Houches accords) on clear standards for spin dependent PDFs, for instance regarding the treatment of heavy flavors. Another avenue for progress during the program will be on "fully" global analyses which now have become very topical in the PDF commmunity. Here one aims at analyzing unpolarized and polarized PDFs simultaneously (and possibly along with fragmentation functions (FFs) as well), in order to remove biases. Finally, another direction we would hope our program to start will be analyses of polarized PDFs and FFs at NNLO. Here, a goal would be to discuss and lay out the basic NNLO framework.

PDFs: Lattice QCD meets phenomenology

Using first-principles operator definitions of PDFs, one can use lattice gauge theory to compute PDF-related quantities. Until quite recently, this method was mostly confined to the computation of fixed moments of the PDFs. A potential breakthrough has come from new techniques that allow for direct computations of the x-dependence of PDFs. The main idea is that a PDF-like distribution may be formulated at large momentum P_z (rather than at large light-cone momentum), where it is computable on the lattice. This distribution has the same infrared (collinear) physics as a standard PDF, to which it is related just by a matching factor that is calculable perturbatively.

We anticipate that on EIC time scales this approach will have matured and will provide unique complementary insights into nucleon and nuclear structure that are perhaps not accessible in experiment. Discussion of the new opportunities provided by the lattice is therefore an important component of the program we envisage. We foresee three topics that will be addressed specifically: (1) the interplay of PDF extractions from phenomenology (see previous section) with those computed on the lattice. Here an outcome of our workshop could be a framework that allows for inclusion of lattice data in global PDF analyses, fostering dialogue and further improving our knowledge of PDFs; (2) comparison of various methods proposed for the computation of the x-dependence of PDFs. Some of these methods are presently being used for exploratory studies. By the time of our program, it is expected to be possible to confront early results and to weigh advantages of the various approaches; (3) discussion of perturbative matching calculations. Here it is of particular benefit that the program would bring together lattice experts with experts on high-order calculations in QCD perturbation theory, and we expect that new collaborations would be forged.

Jets and semi-inclusive reactions

In recent years, the semi-inclusive DIS (SIDIS) process $\ell p \to \ell h X$, with h a specific hadron observed in the final state, has become an increasingly important probe of PDFs and FFs, complementing DIS which has been the prime source of such information for several decades. In SIDIS one exploits correlations between the type of observed hadron and the flavor of a parton entering the hard scattering. The SIDIS reaction is expected to play an outstanding role at the EIC. It will therefore also feature prominently in our program.

Goals for our program will be to initiate precision QCD calculations for SIDIS in terms of higher orders in perturbation theory, both at fixed order and including resummation. We will also address power corrections about which very little is known so far in the case of SIDIS. Central to our efforts on SIDIS will also be to arrive at a general understanding of the process over the vast range in energies from present studies at the Jefferson Laboratory to future EIC measurements. Only with this understanding can successful use of future EIC data be expected. For our program we also plan to develop techniques towards NNLO extraction of fragmentation functions from SIDIS data.

There is a close relation between semi-inclusive observables and jet production cross sections. Recent years have seen remarkable progress for jet physics at the EIC. Apart from the general use of jets as precision probes of the nucleon and of nuclei, it has also been recognized that the substructure of jets may offer most valuable insights into the formation of QCD final states, a topic that is so central to our knowledge and understanding of the theory. Jet studies at the EIC, especially when compared with precision jet physics at the LHC, have the promise to provide new clues on the hadronization of QCD partons exiting from a hard collision. A number of new ideas were also presented in recent years regarding the interplay between the production of jets and heavy quarks. These include the flavor-tagging of jets, the use of charmed jets as a probe for strangeness in both unpolarized and polarized scattering and the study of lepton-jet correlations for nuclear tomography at the EIC.

We intend to address all these exciting applications of EIC jet physics at our program. For this topic in particular, we foresee a strong collaboration between theoretical and experimental colleagues that will lead to a more precise elaboration of the various concepts in a practical way. We expect that studies based on EIC simulated data will start during the time of this workshop.

Small-x physics in the EIC era

At high energies (or small x), gluon densities in hadrons grow quickly, resulting in a large parton occupation number. At sufficiently small x, this growth is expected to lead to a novel high-density regime of nuclear matter, controlled by non-linear QCD effects. Hadrons in this small-x regime are characterized by saturated, classical gluon fields, rather than the usual partonic description. Because these high-density effects are enhanced in nuclei, the EIC presents an ideal opportunity to search for signals of this novel regime of QCD. Recent theoretical developments have extended calculations based on the semi-classical Color-Glass Condensate (CGC) effective field theory to NLO precision, making precision small-x theory an important component of our program.

High-energy collider experiments have measured unexpected phenomena that may point to a gluon-saturated state, but competing mechanisms that do not evoke gluon saturation make a clean discovery challenging. The prospects at the EIC are much better, even compared to previous electron-proton collisions at HERA, thanks to the ability to collide electrons with large ions, where the saturation scale Q_s is enhanced by the mass number: $Q_s^2 \propto A^{1/3}$. The experimental discovery and in-depth quantification of gluon saturation will require comprehensive analyses and a new era of theoretical developments aiming to push the precision of the CGC framework to the standards of collinear perturbative QCD. Enhancing the present theoretical framework in this direction will be a goal for our program. We feel that in this respect the program would offer an opportunity not to be missed, since it will bring together leading experts on precision saturation physics, precision collinear QCD, and global analyses.

Quantifying the characteristics of gluon saturation at the EIC will need an in-depth energy, Q^2 and mass number dependence scan on a number of quantities including atomic number and momentum fraction x. Critical measurements that can help us in the discovery of a gluon saturated state can be classified into three main groups: structure functions, exclusive reactions, and semi-inclusive reactions. Of special value will also again be jet final states, among them back-to-back correlations with the outgoing lepton or another jet. Our program will take stock of the present state of the art on these topics, connecting the theoretical studies to the EIC machine and detector capabilities. An ideal outcome of our program would be to establish a set of “smoking-gun” signatures of saturated gluons at the EIC.

Nucleon and nuclear tomography

Semi-inclusive DIS is characterized by two natural momentum scales: the large momentum transfer carried by the virtual photon, and the momentum of the produced hadrons perpendicular to the direction of the momentum transfer, which prefers a small value sensitive to the motion of confined partons. Theoretical advances over the past decade have led to a rigorous framework that expresses this motion in terms of transverse-momentum dependent parton distributions (TMDs). TMDs carry information on correlations between parton momentum and spin, or spin of the parent nucleon. These correlations can arise from spin-orbit coupling among the partons, about which rather little is known to date. TMDs thus allow us to probe the full three-dimensional tomography of the proton, going beyond the information contained in conventional parton distributions.

TMD physics with nucleons and nuclei at the EIC will be a central topic in our program. In fact, TMDs reach out to virtually all aspects of our program that we have described so far: (1) their study and phenomenology involve a deep understanding of factorization issues; (2) scale evolution of TMDs is a direct counterpart to transverse-momentum resummation in perturbative QCD; (3) when the transverse momentum of the observed hadron increases, TMDs need to be “matched” to fixed-order collinear-factorized cross sections (an area that is currently not well understood); TMDs are related to ordinary PDFs in ways that appear obvious at first sight but turn out to be highly nontrivial when a deeper analysis is made; (4) at small x, TMDs must be similarly “matched” onto the semi-classical degrees of freedom of the CGC (an area of active research); (5) the recent progress on the lattice mentioned earlier also allows for computations of TMDs.

For each of these topics just described, open theoretical issues remain. We are confident that important progress would be made at our program, again thanks to the unique combination of experts to be gathered. We expect, in particular, to tackle the matching of TMD cross sections to collinear-factorized ones, and to discuss the interplay of phenomenological and lattice TMD studies and its impact on nucleon tomography.

A complementary approach to imaging of nucleons (and nuclei) is offered by the generalized parton distributions (GPDs). Both TMDs and GPDs may be viewed as descendants of the nucleon's Wigner functions. GPDs provide access to the spatial structure of hadrons and may be probed in novel off-forward scattering processes. Such reactions will play a crucial role at the EIC and will be reviewed during our program. We will address the recent progress and future prospects, which includes the QCD analysis of off-forward reactions, lattice calculations of GPDs, and the use of advanced mathematical methods and AI/ML for GPD extraction in global analyses. We will also discuss the possibilities of accessing the Wigner functions at the EIC.

Artificial intelligence enhanced design

The EIC community has embraced Artificial intelligence (AI) algorithms and techniques and is incorporating them into all aspects of design and development, ranging from accelerator and detector optimization, streaming data acquisition and the advancement of simulation and reconstruction tools. AI assisted design for an EIC detector was first demonstrated by Cisbani (JINST 15 (2020) 05, P05009) in the design of a dual-radiator Ring Imaging Cerenkov (dRICH) Detector used to identify and differentiate charged particles such as pions, Kaons and protons. The authors were able to demonstrate significant improvement in pion/Kaon separation via the application of Bayesian Optimization tools. Although developed for the dRICH, this approach is general and could easily be applied to any EIC detector design.

The upcoming two years will be an intense period of EIC detector design, and the INT program is well timed to bring together experts to discuss novel AI techniques employed in this process. Simulation and reconstruction tools will develop in parallel as they are an integral part of the design evaluation. This program will take stock of the landscape of AI techniques being used in the EIC design process and define new areas of opportunity as the community transitions from the design to the construction and commissioning phase.