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Synergies between a U.S.-based Electron-Ion Collider and the European research in Particle Physics

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Abstract

This document is submitted as input to the European Strategy for Particle Physics Update (ESPPU). The U.S.-based Electron-Ion Collider (EIC) project recently received strong endorsement by the U.S. National Academies of Sciences, Engineering, and Medicine, bringing its realization another step closer. A large group of European scientists is already involved in the EIC project. Currently, more than a quarter of the EIC User Group (consisting of over 800 scientists) is based in Europe. This European involvement is not only an important driver of the EIC, but can also be beneficial for a number of related ongoing and planned particle physics experiments at CERN. In this document, the connections between the scientific questions addressed at CERN and at the EIC are outlined, as well as the shared interest regarding detector R&D. The aim is to highlight how the synergies between the European Particle Physics research and the EIC project offer ample opportunities to foster progress at the forefront of collider physics.

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1 Introduction

A U.S.-based Electron-Ion Collider (EIC) has recently been endorsed by the U.S. National Academies of Sciences, Engineering, and Medicine (NAS) [1]. This brings the realization of such a collider another step closer, after its earlier recommendation in the 2015 Long-Range Plan for U.S. nuclear science of the Nuclear Science Advisory Committee *"as the highest priority for new facility construction following the completion of FRIB"* [2]. Given the substantial European interest and involvement in the EIC and its physics program, it seems appropriate to outline to the Panel of the European Strategy for Particle Physics Update (ESPPU) the current European involvement in the EIC endeavor and the mutual benefits for particle physics experiments at CERN and EIC experiments.

The general need for and uses of high-energy electron-proton and electron-ion collisions, often referred to as Deep Inelastic Scattering (DIS), are outlined in a separate document submitted to this Panel. Also, detailed accelerator (R&D) aspects of the U.S.-based EIC are outlined in a dedicated document. Here the focus will be on the EIC physics and detector R&D program, the synergies with present and planned CERN experiments, and outlining the European involvement in the EIC.

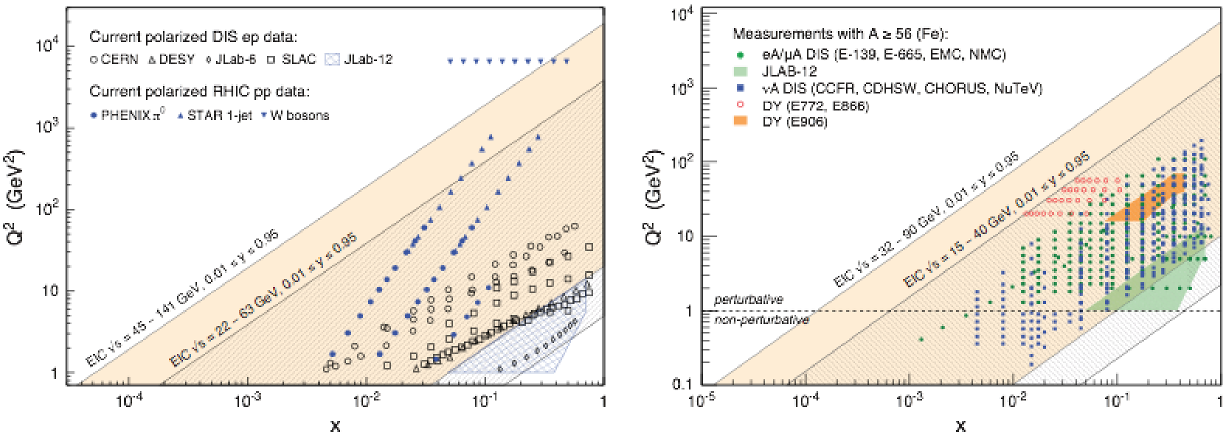

Figure 1: Left: the phase space in (x, Q^2) covered in polarized electron-proton DIS by two different setups for the EIC, in comparison with past and current DIS machines and RHIC (updated version of Ref. [3]). A center-of-mass energy in the range of 20-100 GeV is foreseen for the EIC, with 45 GeV having maximum luminosity and 140 GeV being the maximal energy after a possible future upgrade. Right: EIC kinematical reach for nuclei, compared to earlier nuclear DIS experiments.

The EIC is a machine that is unique compared to any previous DIS experiment because of the combined availability of high energy, high luminosity, ion versatility, and polarization. It is the first ever machine with the capability to collide highly polarized electrons on polarized protons and light ions, as well as on unpolarized heavier ions up to uranium. The EIC has a large reach in x and Q^2 (see Fig. 1). High energy scattering of polarized electrons and ions, including both longitudinally and transversely polarized light ions, is crucial to a full understanding of the quark-gluon structure and dynamics of baryons, mesons, and nuclei. Compared to the HERA collider at DESY, the EIC will have lower energy but much higher luminosity. It can conduct measurements that have never been feasible before. The NAS committee finds the scientific case for EIC compelling, unique, timely, and supported by the U.S. nuclear science community. According to the NAS report [1]: *"The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would advance accelerator science and technology in nuclear science; it would as well benefit other fields of accelerator-based science and society, from medicine through materials science to elementary particle physics."*

The location of the EIC is expected to be chosen after the U.S. Department of Energy has started its staged project approval process. Future users will, to a considerable extent, be international, in particular European. The interested scientists world-wide are organized in the EIC User Group (EICUG, web site `http://www.eicug.org/`) which is governed by three committees:

- the Institutional Board (IB), which is formed by a representative of each participating institution

- the elected Steering Committee (SC), which organizes the regular business of the EICUG, and has one specific European Representative and currently another European as one of the 4 "at-large" members
- the Election and Nominating Committee (ENC), which is charged to organize and conduct the elections of the SC members.

The configuration and detailed mission of each committee are regulated by a Charter that was formally approved by the EICUG in 2016. As of December 18, 2018, the EICUG consists of 837 scientists from 177 institutions of 30 countries in all world regions, with a large European involvement consisting of 237 scientists (28%) from 59 institutions. About 28% of the European scientists are working on theory. The composition of the EICUG is outlined in more detail in the addendum.

Since 1999, there have been many dedicated scientific meetings to shape the physics case for the EIC, most notably the yearly POETIC and EICUG meetings. In 2010 there was a ten-week program at the Institute of Nuclear Theory (INT) in Seattle that resulted in a 547-page document [4] detailing the science case. This was updated and condensed in the EIC white paper [3]. The NAS report summarizes the physics objectives as follows: *"An EIC can uniquely address three profound questions about nucleons - neutrons and protons - and how they are assembled to form the nuclei of atoms:*

- *How does the mass of the nucleon arise?*
- *How does the spin of the nucleon arise?*
- *What are the emergent properties of dense systems of gluons?"*

To answer these fundamental questions one needs to probe with high precision and high energy the quark and gluon structure of nucleons and nuclei. It is of great advantage to do this with a simple and well-known probe, such as the electron or the photon. The quark and gluon structure of nucleons is expressed theoretically in terms of parton distributions of various levels of detail and sophistication. For inclusive DIS, where one ignores details of the final state, the scattering process is described in terms of collinear (i.e., transverse-momentum integrated) Parton Density Functions (PDFs). When more aspects of the final state are measured, one can become sensitive to the three-dimensional momentum distributions (Transverse Momentum Dependent PDFs or TMDs). Exclusive and diffractive processes allow one to probe also transverse spatial distributions, given in terms of Generalized Parton Densities (GPDs). The information contained in TMDs and GPDs is truly complementary since the position of partons in a transverse plane is not Fourier conjugate to their transverse momentum. Hence, the combined investigation of PDFs, TMDs, and GPDs, will allow one to arrive at a more complete picture of how nucleons are composed at the level of quarks and gluons. These studies go far beyond global (and scale-dependent) observations like *"50% of the proton's momentum is carried by gluons"* or *"only about 30% of the proton's spin is carried by quarks"* (a well-known conclusion from the EMC, SMC, and later experiments). More specifically, the three major themes of the EIC physics program are:

- the flavor and spin structure of the proton
- three-dimensional structure of nucleons and nuclei in momentum and configuration space
- QCD in nuclei

In addition, the high luminosity and cleaner environment (with respect to hadron colliders) will enable precision studies in electroweak physics and some specific searches of physics beyond the Standard Model.

The EIC is expected to start operating toward the end of the 2020's. It will most likely run concurrently with LHC after its high-luminosity upgrade. Hence, it seems appropriate and timely to outline below how investigations at the EIC of each of the above topics could benefit CERN experiments and vice versa.

2 The flavor and spin structure of the proton

This topic centers around the accurate determination of collinear parton densities for both unpolarized and polarized protons (and neutrons and deuterons). The unpolarized collinear PDFs currently used for LHC studies are primarily determined by the HERA data and have an (NNLO) uncertainty of 2.4% for up quarks at $x = 0.5$ and $Q^2 = 100$

GeV, but 12% for down quarks, 140% for strange quarks and 34% for gluons [5]. The uncertainty quickly rises for all flavors at $x \gtrsim 0.6 - 0.7$ (see Ref. [6]).

It is important to constrain PDFs in the limit of large x over a wide range of Q^2 because they influence the production rate of high transverse momentum W and Z bosons and jets, as well as the possible production of new heavier partners that are predicted in several BSM extensions (see the DIS document for more details). LHC data will help to decrease these uncertainties, particularly after the high-luminosity upgrade [7], but for the search for BSM physics at the LHC it is essential that the employed PDFs are obtained from data that are insensitive to that BSM physics. Proposed future experiments at CERN, such as a fixed-target experiment [8] or the LHeC experiment (see the related document submitted to the ESPPU Panel), could provide such data with high precision. An overall 1% uncertainty in the PDFs would be the desired goal at the LHC to confront with theory [5]. High statistics data obtained with the EIC from neutral and charge currents in electroweak DIS would also help to reach a better precision at large x, especially for the EIC configuration with maximum center-of-mass energy of 140 GeV. For instance, a projection study shows that charged current DIS at the EIC would have very strong impact on the $x\bar{d} + x\bar{s}$ combination of quark distributions [6].

The EIC can measure various processes from which the contribution from different quark and antiquark flavors can be separately extracted over a very broad range in x. These processes include not only neutral and charged current electroweak DIS but also semi-inclusive DIS (SIDIS), where a hadron in the final state is identified. SIDIS at the EIC is particularly useful for a precise determination of the strange quark distribution [6]. Such analyses go hand in hand with the extraction of collinear fragmentation functions (FFs), where light flavor contributions can be individually tagged. Therefore, our knowledge of PDFs is influenced also by the accuracy at which FFs are known. The FFs are usually determined in B-factory experiments by measuring electron-positron collisions, but this yields only a limited knowledge of each individual flavor contribution, and the gluon channel is reachable only at subleading order. Ideally, one should extract FFs by performing a global fit to data of all available reactions, including hadron collider data. At present, this was done only by one group [9, 10]. More recently, the `NNPDF` collaboration found that hadron colliders data (`CDF, CMS, ALICE`) can significantly constrain the gluon FFs [11]. On the other hand, the (anti)strange FFs still suffer from large uncertainties, and this reflects in a large uncertainty on the (anti)strange PDFs as well. More generally, the limitations of the current SIDIS data hinder a complete flavor separation of unfavored channels. At the EIC, the high luminosity, combined with the large lever arm in the hard scale Q and the purposefully planned detector capabilities, will allow for very precise studies of the flavor dependence of FFs over a large phase space. Current studies on the projected relative error indicate that significant improvements can be achieved also for PDFs of light flavors over a wide range of low to medium x, particularly for the strange component [6]. Hence, combining inputs from the EIC, hadron colliders and B-factories, will allow to drastically reduce the uncertainties on FFs, and could make it possible also to reach the ultimate goal of a simultaneous extraction from data of both PDFs and FFs. Additionally, it could help in clarifying if the intrinsic flavor content of the proton (i.e., Fock components in its wave function) receives contributions also from charm [12].

The availability of polarized proton beams at the EIC allows to do a similar analysis for the polarized quark and gluon PDFs and thereby to shed further light on their contribution to the proton spin. In particular, the strange quark and gluon PDFs still have large uncertainties. Recent results obtained at RHIC give evidence that the gluon contribution is nonvanishing and positive, although the uncertainty is large because the result is very sensitive to the minimum attainable x ($x_{\min}$). With its unique capability of colliding longitudinally polarized electrons and protons, while spanning small x even below 10^{-4}, the EIC will drastically reduce this uncertainty (see Fig. 2). Both DIS and SIDIS data will be important here. The development of reliable and versatile Monte Carlo generators to analyze them is also of vital importance, as are the collaborations based on the European leadership in this field.

3 Three-dimensional structure of nucleons and nuclei in momentum and configuration space

One of the main topics to be studied with the EIC is that of transverse momenta and positions of quarks and gluons inside hadrons, as quantified by TMDs and GPDs, respectively. The ultimate aim of such studies is to gain much deeper insight into the dynamics of quarks and gluons in hadrons than what can be inferred from PDFs alone. TMDs and GPDs have been central to the investigations conducted earlier by the `HERMES` experiment at DESY and currently by the `COMPASS` experiment at CERN and at Jefferson Lab with both polarized and unpolarized targets. Quark TMDs are typically studied using SIDIS and in vector boson production in proton-proton collisions. Quark

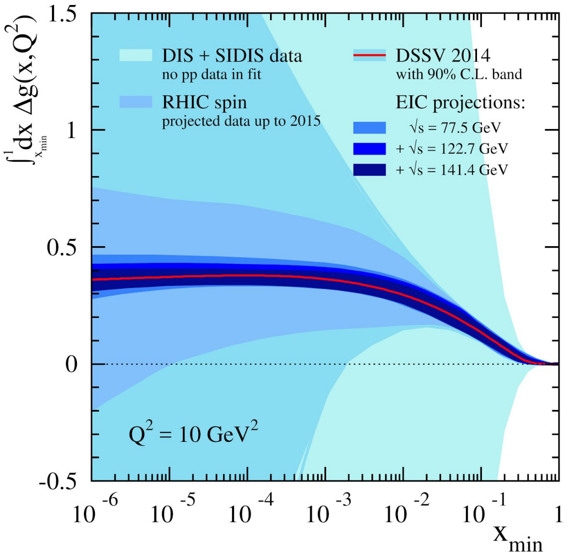

Figure 2: Integrated gluon helicity as a function of the attainable $x_{\min}$ for various EIC configurations [13].

GPDs are typically studied through the Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP) processes. Polarized light ions at the EIC (both longitudinal and transverse) are crucial for fully resolving the diverse spin-spatial and spin-momentum correlations of hadronic structure.

TMD factorization and evolution

Many critically important aspects of TMDs can be studied experimentally with the EIC. Apart from measuring the various TMDs for polarized and unpolarized quarks, gluons and/or hadrons, the TMD formalism itself needs thorough investigations.

First of all, TMD factorization, which allows for the theoretical description of particle spectra at small or intermediate transverse momentum, needs to be tested. A main objective is to demonstrate to what extent the TMDs are universal (like the collinear PDFs and FFs). Although the TMD for unpolarized quarks and hadrons is expected to be the same in SIDIS and Drell-Yan (DY), for some polarized cases there is a calculable process dependence. In 2015 and 2018 the `COMPASS` experiment acquired DY data with the objective of testing this (more specifically, determining the predicted overall sign difference between the SIDIS and DY measurements of the Sivers TMD effect) and the results so far are consistent with the expectations from the TMD formalism, although the uncertainties are still large. The same applies to the asymmetry measurements at RHIC in W production [14]. Furthermore, for gluon TMDs even the unpolarized case is expected to be non-universal. Hence, it is important to compare observables at the LHC, e.g., for quarkonium production [15], to related observables at the EIC. The specific predictions from the TMD formalism can be safely tested in a high Q^2 regime ($Q^2 \gg M_p^2$), in order to avoid complications from power suppressed quark-gluon correlation effects. Secondly, TMD evolution, i.e., the Q^2 dependence of the predictions, needs to be tested, as was done extensively for the scaling violations in DIS with HERA, showing that Altarelli-Parisi equations (DGLAP evolution) for collinear PDFs work over many orders of magnitude, but at the same time hinting at possible deviations at small x and moderate Q^2 [16]. Investigation of the latter regime is another objective of the EIC (covered in Sec. 4).

Transition between TMD and collinear frameworks

Besides testing its predictions, the limitations of the TMD formalism also need to be clarified. For this purpose proton-proton collisions, even unpolarized ones, are particularly useful. Currently, it is expected on theoretical grounds that azimuthal correlations in dijet production in $p-p$ collisions do not factorize [17]. The size of the factorization breaking effects is entirely unknown and can only be assessed from a comparison of high energy $p-p$ and $e-p$ collisions. The data from HERA on dijet production in $e-p$ collisions is too limited to do this already now. Recent studies of various dijet measurements at the EIC indicate that they are feasible [18, 19]. The same applies to D-meson pair production, which is another process of interest for TMD factorization breaking tests.

The TMD formalism applies to the region of low transverse momenta (much smaller than the large scale in the process). Therefore, sufficient momentum resolution is required in the full p_T range in order to test the limits of applicability and the transition to the collinear formalism that applies at large p_T. In many of the observables of interest, such as azimuthal correlations in the Drell-Yan process (studied by, e.g., `CMS` [20] and `ATLAS` [21]), the momentum resolution is currently too limited, but that will improve over time. The same applies to di-photon and quarkonium (pair) production. The transition region of intermediate p_T has recently attracted much attention from the theoretical point of view [22, 23]. Because of the additional degrees of freedom (observables differential in more variables) it is harder to reach the same level of precision as for observables calculable in collinear factorization. Nevertheless, at present NNLL expressions are available for a number of processes and more data, from LHC and other experiments, are needed to confront with theoretical predictions.

GPDs

GPDs enter collinear factorization expressions and are expected to be universal. While the associated theory has reached a high level of sophistication, progress on relevant measurements has been comparatively slow because the experiments require high statistics and excellent detector coverage. One is dealing with exclusive processes in this case. `HERA,` `COMPASS` and Jefferson Lab experiments have already obtained experimental information on some of the GPDs, but this is only the beginning when it comes to extractions of the GPDs with precision and in a sufficiently large kinematic domain. The capabilities of the EIC will open the way to a thorough exploration of GPD properties. In particular, the large Q^2 coverage will enable tests of GPD evolution and studies of power-suppressed higher-order correlations.

GPDs encode information about the spatial distribution of partons inside a hadron, correlated with their distribution in longitudinal momentum. The spatial distribution is obtained in a rather direct way by Fourier transforming the transverse momentum spectrum of the scattered hadron in suitable exclusive reactions like DVCS or DVMP. In an indirect manner, this distribution also influences the dynamics of $p-p$ as well as $p-A$ and $A-A$ collisions, namely in the context of multiparton interactions (MPI). In such interactions, several partons in the colliding hadrons take place in independent hard scatters, and the relative transverse distance between the partons is of crucial importance for this mechanism. Information on the spatial distribution of single partons from GPDs provides a quantitative baseline expectation, on top of which one can then attempt to assess correlation effects between different partons. In this sense, MPI and underlying events description will considerably benefit from a fully developed GPD picture.

Containing simultaneous information about longitudinal momentum and transverse position, GPDs give access to the orbital angular momentum carried by quarks and gluons. The most prominent (but not the only) expression of this is Ji's sum rule [24], which relates integrals over GPDs with the total (spin and orbital) angular momentum carried by a parton species in the proton. The detailed measurements that will become possible at the EIC will bring us much closer to a quantitative understanding of the role of orbital angular momentum and hence to the question of how the nucleon spin arises from its constituents at parton level. Moreover, GPDs will enable detailed studies of the spatial distribution (tomography) of several interesting observables like charge, pressure, energy and number densities.

TMDs and GPDs have been studied extensively. Various computer codes and tools, to a large extent developed by European groups, are available, such as for example `TMDlib` and `TMDplotter` (`https://tmdlib.hepforge.org/doxy/html/index.html/`) and for GPD model studies the package `PARTONS` (`https://arxiv.org/abs/1512.06174`). There are also proposals for future TMD and GPD studies at CERN. A proposal for *"a new QCD facility at the M2 beam line of the CERN SPS"* [25] has been presented to the Physics Beyond Collider (PBC) study group. Another initiative that is being put forward is that of a fixed-target program which would allow scattering of an LHC proton or lead beam on a polarized fixed-target. The physics case for such an experiment has been developed over recent years under the name "AFTER@LHC" [8] and a particular proposal for such a fixed-target experiment at `LHCb` is called "LHC-spin". There would of course be ample synergies between such experiments and the EIC as well.

4 QCD in nuclei

The EIC could be the first ever collider experiment for deeply inelastic scattering with nuclei, opening up a large new window of high atomic number A at small x and large Q^2 that has never before been experimentally accessed (see Fig. 1). Electron-ion collisions allow to study the internal structure of heavy ions in terms of elementary partonic constituents, quarks and gluons. In addition to a new understanding of QCD in large nuclei being a fundamental topic in itself, it is also complementary to the program of heavy-ion collisions at the LHC. Probing the partonic structure of the colliding nuclei by DIS experiments is important for understanding the production of both the matter that then becomes a quark-gluon plasma, and the jets and other hard probes that are used to explore its properties.

Nuclear PDFs
At the LHC kinematics, one is mostly sensitive to the region of relatively small x, where the nuclear PDFs are very poorly known since they are hardly constrained by any currently existing data. Studies of modifications to the structure of jets as they pass through deconfined QCD matter are becoming very sophisticated and will form an increasingly important part of the nuclear collision program at the LHC when it moves to higher luminosities. These studies will require a reduction of the large uncertainty of nuclear PDFs at small x, and the EIC will have a significant impact here [26]. In particular, one should note that accurate measurements of charm structure functions at the EIC would have an even larger effect than total cross section measurements, also improving the determination of the nuclear gluon PDF at large x (aiding the further study of the EMC effect and of (anti-) shadowing). Semi-inclusive DIS at large x in nuclei also provides a laboratory to study the energy loss of high-energy partons passing through ordinary, confined nuclear matter. Such measurements provide the comparison that is necessary to calibrate and check theoretical approaches to jet energy loss. Last but not least, the exclusive and inclusive measurements will give access to the GPDs and TMDs of nuclei, respectively.

Saturation phenomena
At high collision energies, or equivalently small x, the phase space available for emitting soft gluons is very large. Since every emitted gluon is itself a source of further radiation, a fast growing cascade is created that leads to a strong growth of the gluon distribution. Eventually unitarity is expected to be preserved due to the nonlinear interactions, i.e., gluon mergings, that start to play an important role, leading to the phenomenon of gluon saturation. Gluon saturation then controls the physics in DIS collisions in the small x limit at moderate Q^2. The gluons in the same regime are also responsible for the production of deconfined QCD matter – the quark-gluon plasma – in heavy ion collisions, studied at the LHC and in particular by the `ALICE` collaboration.

Since a high atomic number A also increases the gluon density at a given Q^2, gluon saturation is accessible in DIS experiments at lower energies with nuclei than with protons. The EIC will provide a versatile experimental program to investigate in detail this new regime of QCD. In order to fully understand this regime, it is important to simultaneously measure inclusive and semi-inclusive cross sections, inclusive diffraction (diffractive structure functions) and exclusive reactions, such as vector meson production and diffractive dijets. The EIC is being designed to be a facility that can perform this broad set of measurements that are necessary for a full picture of the gluonic structure of nuclei.

The small-x physics at the EIC is complemented by several measurements that are performed in hadron colliders (RHIC and LHC) to probe aspects of the same physics. Inclusive particle production and two-particle correlations in $p-p$ and $p-A$ collisions, especially at forward rapidities, directly probe the small-x gluons in nuclei. At CERN, these forward measurements are performed at `LHCb` and, especially with future instrumentation upgrades, at `CMS` and `ATLAS`. Furthermore, as mentioned, the small-x and high-A program at the EIC is very closely connected to studies of deconfined QCD matter in heavy-ion collisions. The correct interpretation of several aspects of heavy-ion collisions, such as the ridge, requires data from high-energy electron-ion experiments.

Initial conditions for Quark-Gluon Plasma studies
One of the most challenging problems in heavy-ion physics is to understand how the gluons and quarks from the colliding nuclei form a thermalized plasma. Data from $A - A$ collisions seems to be well described by models assuming a very quick formation of an equilibrated medium. It is, however, very difficult to get direct experimental access to the earliest stages of a heavy-ion collision, and the theoretical understanding of the thermalization process is still quite incomplete. Here, the picture of the small-x degrees of freedom in the nucleus obtained from electron-

ion collisions is crucial, as it provides the starting point – the initial condition – from which one evolves towards a deconfined matter.

In recent studies at the LHC, it has become clear that effects usually attributed to collective behavior in $A-A$ collisions, such as elliptic flow and the ridge, are also visible in $p-A$ and $p-p$ collisions. There is currently an intense debate in the field concerning the correct interpretation of these results. They have been explained either in terms of multiparticle correlations already present in the colliding protons or nuclei, or alternatively ones generated by collective interactions if deconfined QCD matter is present. For a resolution of the puzzle posed by these results, a baseline measurement of such initial state correlations in a more tractable collision system is essential. The ideal experiments for this are provided by $e-p$ and $e-A$ collisions.

UPCs

Besides being a source for many small-x gluons, ultra-relativistic heavy ions also form a source of strong electromagnetic fields, which can be probed in Ultra-Peripheral Collisions (UPCs) at high energies. This effectively leads to high-energy photon-ion scattering, where partons at small x are probed both in nuclei (in $A-A$ collisions) and protons (in $p-A$ collisions). Since in these collisions the photon is always quasi-real, one does not have the same ability to vary Q^2 as in DIS experiments, but on the other hand the higher collision energy gives access to smaller values of x than available at the EIC. To date, exclusive vector meson production in $\gamma-A$ collisions measured by `ALICE` [27] have been used to probe nuclear gluons at small x. The possibility to separately perform coherent (nucleus stays intact) and incoherent (nucleus breaks up into smaller color neutral fragments) measurements gives an additional handle on probing the nuclear geometry and its fluctuations, which are important features for understanding the initial state of $A-A$ collisions. Exclusive J/ψ and Υ productions in UPCs have been studied at `ALICE`, `LHCb` and `CMS`. The results (e.g., see Refs. [28, 29, 30]) are consistent with HERA measurements of the same process at lower energies, and can be used to constrain the x dependence in different theory calculations.

5 Electroweak physics and the search for physics beyond the Standard Model

Although not the main objective of the EIC, certain EW precision measurements, despite Q being well below M_W, can be done at the EIC thanks to the high luminosity. For example, precision determinations of the weak mixing angle $\sin^2\theta_W$ can be performed in collisions of polarized electrons and unpolarized deuterons (see Fig. 3). This measurement as a function of energy is of interest because deviations from the SM running would signal BSM physics. These modifications can not only affect the high energy part, but also the low energy one, e.g., through effects induced by “dark” Z bosons [31]. The EIC data is projected to be in the intermediate Q range, which is beyond the reach of fixed-target experiments. Apart from the weak mixing angle, the EIC can put further constraints on electron$\to\tau$ flavor violating transitions, improving on an earlier limit set by HERA and complementing the limits from τ decays at B-factories (see Ref. [4] for further discussion of these and related topics).

The EIC can contribute to reducing the uncertainties in the determination of the W mass from its p_T spectrum. Currently, the best determination of the W mass is deduced from a global electroweak fit [33] ($\delta M_W = 8$ MeV), but precise extractions of this SM parameter have been obtained also by fitting the transverse mass and momentum distributions of the W decay products in proton-proton collisions at `ATLAS` [34] and in proton-antiproton collisions at `D0` and `CDF` [35] ($\delta M_W \approx 20$ MeV). By introducing a flavor dependence in the intrinsic transverse momenta of the partons entering the collision, it was recently found that this nonperturbative effect (already observed in the `HERMES` data at low energy) has a statistically significant impact on the extracted values of the $W^\pm$ masses [36]. The details of this flavor dependence are best studied in SIDIS by looking at unintegrated multiplicities. In this way the measurements at the EIC will indirectly affect the accuracy level in the determination of the W mass, consequently influencing also searches of new BSM physics.

The Standard Model does not contain fundamental tensor interactions. However, loop effects and new interactions at the TeV scale can effectively generate such interactions that can be indirectly constrained either by data at the LHC or in hadronic decays at low energy (see, e.g., Ref. [37] and references therein). In the latter case, helicity-flip parameters in the neutron β-decay cross section can be combined with information on the isovector component of the nucleon tensor charge to put constraints on novel tensor interactions at the TeV scale. Information on the nucleon tensor charge can come from very precise lattice computations, in particular regarding

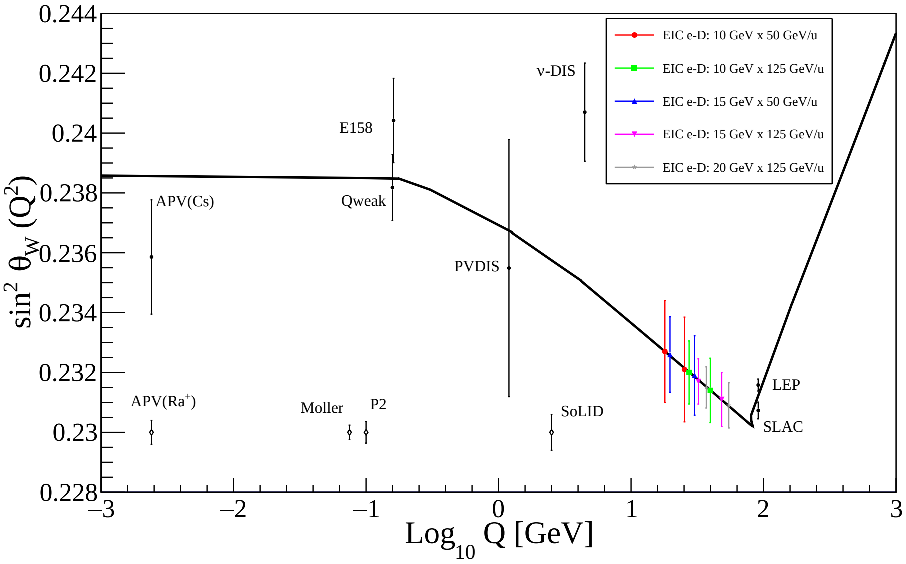

Figure 3: The dependence of $\sin^2\theta_W$ on Q calculated in the Standard Model (solid line) compared with existing data and projected fixed-target and EIC measurements. For the EIC projections 200 days of electron-deuteron running is assumed (with luminosity of 267 fb^{-1} per nucleon and electrons 80% polarized). QED and QCD radiative corrections and effects of detector smearing are taken into account [32].

its isovector component. But it can also be obtained from SIDIS (`HERMES, COMPASS`) or proton-proton collisions (RHIC) with transversely polarized hadrons by extracting the chiral-odd transversity distribution, whose first Mellin moment is the tensor charge. The EIC can significantly contribute in reducing the current uncertainty on the phenomenological extraction of the tensor charge by widely enlarging the covered x and Q^2 range.

6 Detector R&D

The ability to extract exciting physics at the EIC is intimately connected to the overall design of the experiments and to the performance of the required detectors incorporated appropriately into the interaction region of the collider. From the experimental point of view, the broad EIC physics program encompasses the study of inclusive and semi-inclusive reactions, as well as exclusive processes in the collision of electrons with protons or light to heavy nuclei over a wide range of center-of-mass energies. Consequently the requirements for the experimental apparatus are complex and challenging.

In all cases the unambiguous identification of the scattered electron and the precise measurement of its angle and energy is essential, since it determines the key kinematic variables (x, Q^2) of the interaction. This imposes many strong requirements on the detectors. Also needed to access the semi-inclusive processes: excellent hadron identification over a wide momentum and rapidity range, from 200 MeV/c to 10 GeV/c in the barrel region and up to 50 GeV/c in the forward (hadron going) region, with full 2π acceptance for tracking and momentum analysis and excellent vertex resolution by a low-mass vertex detector. In particular, the extremely wide phase-space range where hadron identification is needed is specific of experiments at the EIC and imposes the use, within the same setup, of diversified approaches for particle identification. Exclusive reactions require the capability to accurately track all particles with high spatial and momentum resolution. The identification of many key processes depends on the complete hermeticity of the setup, another characteristic aspect of experiments at the EIC resulting in the additional requirement of very forward detectors such as Roman pots, and large-acceptance zero-degree calorimetry to effectively detect neutrons from the breakup of nuclei. The entire experimental program will require the precise measurement of luminosity; polarized beams impose the need of highly accurate electron, proton, and light nucleus polarimetry.

The need for a largely diversified set of detector types is evident from this schematic analysis. Expertise and experience with the required subsystems is spread over many communities and continents. There are sectors where

U.S. physicists have the leadership, as is the case for proton beam polarimetry, thanks to the unique high-energy polarized proton beam at the RHIC collider. In other cases U.S. and European projects complement each other, as for instance in the development of DIRC detectors for hadron identification in the few GeV/c domain. State-of-the-art performance for many detector technologies was developed and achieved in various European projects. Examples are the large high-rate TPC with GEM readout and the light-mass vertex detector for `ALICE`, the gaseous RICH detectors of `LHCb`, the high-momentum hadron identification capabilities of `COMPASS` at the SPS, and the large-size gaseous trackers using MPGD technologies in various LHC experiments.

The examples mentioned above form a far from exhaustive list but illustrate the expertise and know-how available in the European community that can address the requirements of an EIC detector, especially when accompanied by European participation to the experimental effort. There is already a significant involvement of European physicists in the generic EIC detector R&D program in the U.S. (see `https://wiki.bnl.gov/conferences/index.php/EIC_R%25D`). Here, European groups from the University of Birmingham, GSI, INFN Genova, INFN Ferrara, INFN Roma, INFN Trieste and IPN Orsay already collaborate with U.S. groups in six R&D projects. They address calorimetry, particle identification by Cherenkov imaging techniques, silicon tracking and vertexing, development of simulation and analysis tools, and streaming read-out data acquisition. In this context, the recently approved INFN project, denominated `EIC-NET`, should be mentioned, which currently includes 45 physicists from 11 INFN groups. The project supports efforts for specific detector R&D including the corresponding domestic and international networking activity towards the formation of future collaborations at the EIC.

Given the European interest in the hadron physics exploration with the EIC, there is a considerable opportunity for contributions in the detector sector, presently via R&D activities and in the future through participation in detector constructions. Europe can provide a substantial contribution, thanks to its recognized leadership in several domains of detector technologies in high-energy physics. The CERN neutrino platform, created to foster and contribute to fundamental research in neutrino physics at particle accelerators worldwide, is a brilliant example of how the European support can contribute to progress in physics also outside Europe.

7 Conclusions

In this document for the ESPPU, we outline the European involvement in the U.S.-based Electron-Ion Collider (EIC) project, which recently received strong endorsement by the U.S. National Academies of Sciences, Engineering, and Medicine. More than a quarter of the EIC User Group consists of European scientists, indicating a large European interest in the EIC, in both its science case and its detector and accelerator development. Furthermore, this document reviews the large variety of mutual benefits for CERN and EIC experiments, ranging from the connections between the scientific questions addressed to the shared interest regarding detector R&D. We conclude that strengthening the ties between the particle physics community in Europe and the EIC project, would be very beneficial to all parties involved and could foster important progress in research at the forefront of collider physics.

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