JENAA EXPRESSION OF INTEREST (EOI)

"Synergies between the Electron-Ion Collider and the Large Hadron Collider experiments"

Objectives:

To stimulate and strengthen collaboration among the European nuclear, particle and astroparticle physics communities, to mutually benefit from the many synergies between experiments at the planned U.S.-based Electron-Ion Collider (EIC) and the Large Hadron Collider (LHC) at CERN.

Context:

The Electron-Ion Collider (EIC) is a 4km-circumference particle collider to be constructed at Brookhaven National Laboratory. It will collide high-energy polarized electrons with polarized protons and atomic nuclei (up to Pb/U), at center of mass energies ranging from 20 to 140 GeV. Compared to the past HERA collider at DESY, the EIC will have lower energy but much higher luminosity (up to 10^{34} $cm^{-2}s^{-1}$ for ep collisions). The primary physics goals of the EIC are to explore how quarks and gluons build up the mass and spin of hadronic matter and the phenomenon of gluon saturation. There are many physics objectives that overlap with or complement those of LHC experiments, of which several examples will be given below. The EIC is expected to start operation around 2030 and run concurrently for about a decade with the LHC after its high-luminosity upgrade.

The EIC is now firmly on its path towards realization, with detector design and collaboration formation currently taking place. The EIC User Group continues to grow and currently has over 1200 members, of which about 30% are working in Europe. This large European involvement in the EIC was noted in the 2020 update of the European Strategy for Particle Physics. The synergies with neighbouring fields, especially with nuclear physics, were also noted. Currently, however, the interactions among EIC and LHC physicists lack structure, and this is what the present JENAS EoI is aimed at providing.

Activities:

- Workshops on the topics of this EoI and other community building activities
- Initiate articles directed to the communities represented by ECFA, NuPECC and APPEC that report and showcase results and activities that are of mutual interest
- Initiate ERC Synergy grant applications between the interested European parties

Topics of mutual interest include:

- The flavor and spin structure of the proton: PDFs
- Three-dimensional structure of nucleons and nuclei in momentum and configuration space (TMDs, GPDs, GTMDs) and their evolution
- QCD in nuclei: nuclear PDFs and gluon saturation phenomena
- Heavy Ion Collisions: Quark-Gluon Plasma studies & Ultra-Peripheral Collisions
- Diffractive processes and distributions
- Jet physics, Jet substructure
- Heavy flavor physics, quarkonia, exotic states
- Electroweak physics and beyond the Standard Model physics
- EFT studies, SMEFT
- Neutrino cross-sections at low and high-energy
- High energy cosmic rays and Dark Matter
- Detector R&D
- Computational physics, Monte Carlo simulations, machine learning techniques

Background:

In the 2020 update of the European Strategy for Particle Physics (ESPPU), NuPECC has been identified as the group to coordinate with CERN on topics of mutual interest on the boundary of nuclear and particle physics. In the deliberation document of the European Strategy Update it is stated that "Electron-proton colliders, such as LHeC or FCC-ep, with the option of including ion-targets, are also of interest to NuPECC, which is preparing a support statement for the participation of Europe in the Electron-Ion Collider in the United States." and "CERN should continue to coordinate with NuPECC on topics of mutual interest." NuPECC has issued its support statement as part of the input [1] for the ESPPU and NuPECC has since installed an EIC task-force. This taskforce, consisting of NuPECC members Dave Ireland, Eugenio Nappi, Franck Sabatié, in collaboration with Daniel Boer, the European Representative of the EIC User Group (EICUG) until 31-8-2021, has initiated this Expression of Interest. The idea was to identify and bring together the European physicists that are associated with NuPECC, ECFA and APPEC and have a common interest in the physics of the EIC and LHC. Synergies between the Electron-Ion Collider research and the European research in particle physics have been described in an input document for the ESPPU prepared by the EICUG [2]. A similar objective was part of the US Snowmass 2021 exercise that solicited Letters of Interest related to the future of high-energy physics in the U.S. The workshop "EIC opportunities for Snowmass" summarized these efforts and illustrated the extensive synergies. The present JENAS EoI has similar goals for the European community.

As mentioned before, the EICUG currently consists of over 1200 members of which about 30% are based in Europe. This includes experimental as well as theoretical physicists.

Besides the annual EICUG meeting that is regularly held in Europe, there are several other EIC related conferences regularly organized in Europe, e.g. the REF (Resummation, Evolution, Factorization) and POETIC (Physics Opportunities at an ElecTron-Ion-Collider) workshop series. In these meetings, and also in the various national meetings, there are also pp, pA and AA oriented talks. This is also the case for the annual DIS conference, which traditionally was focused on ep and eA collisions, but nowadays includes a considerable number of speakers from the LHC experiments. Conversely, in the LHC community meetings, such as in the PDF4LHC, LHC ElectroWeak, and LHC forward physics working groups, ep/eA oriented topics are frequently discussed. For the LHC heavy-ion collision community, the characterization of the initial state as determined by hadron structure plays an important role and is often discussed in dedicated conferences (*e.g.* Initial Stages) or sessions (at Hard Probes, Quark Matter) that cover the future EIC programme. Nevertheless, there is interest from both sides to increase and deepen such interactions, and to make them more structured. This is what this JENAS EoI aims to achieve.

Another aim of this activity is to explore and exploit synergies with astroparticle physics. The goal is to involve the APPEC community and stimulate progress in this direction, for instance by discussing which cross section measurements would be most beneficial for the study of cosmic rays (*e.g.* neutrino cross sections, antiproton production cross section, oxygen cross sections) and what can be learned from cosmic rays about cross sections at energies above the collider experiments.

[1] https://indico.cern.ch/event/765096/contributions/3295981/attachments/1785333/2906392/Nupecc_ESPP2018.pdf

[2] https://indico.cern.ch/event/765096/contributions/3295735/attachments/1785257/2906268/EICdocumentforESPPU.pdf

Examples of physics synergies among the EIC and LHC experiments:

The EIC is expected to start operation around 2030 and run concurrently for about a decade with the LHC after its high-luminosity upgrade (the HL-LHC is foreseen in Run 4). Although the Bjorken x range probed at EIC and the HL-LHC overlap to a large extent, the impact of the experiments at EIC and the HL-LHC will be quite complementary. For instance, the uncertainty on the gluon parton distribution function (PDF) for protons and for lead nuclei are expected to improve much due to the HL-LHC data, whereas the gluon PDFs for other heavy nuclei are expected to improve much due to EIC data. Simultaneous fits to data for the proton and for the various nuclei will be most beneficial for our understanding of the gluon content of protons and nuclei.

Improvements of proton PDFs with respect to existing fits will occur at EIC especially at large x and Q^2 for the light quark flavors, in particular the s-quark distribution. Knowing these distributions better at large x and Q^2 will assist in new physics searches at the LHC.

Global fits including both HL-LHC and EIC data will therefore be most helpful to improve the existing knowledge on the proton structure in terms of collinear PDFs. A similar conclusion is reached for studies of p_T spectra. Whereas at the LHC mostly large p_T values are probed, detailed measurements at low p_T will be possible at EIC. The full description of the p_T spectra requires combination with lower p_T values where collinear factorization descriptions need to match onto Transverse Momentum Dependent parton distribution (TMD) descriptions based on TMD factorization. See [3] for a recent illustration for Drell-Yan, where the TMD approaches (ArTeMiDe and PBTMD in CASCADE), thanks to a better understanding of the non-perturbative transverse dynamics of partons, are able to describe well the low p_T range for all invariant masses investigated. In this way the LHC data can provide valuable information about TMD evolution, which can be compared to complementary studies of TMDs and their evolution at the EIC. Furthermore, a joint global analysis of EIC and LHC data can provide a simultaneous extraction of collinear PDFs, TMDs and even Generalized Parton Densities (GPDs), something that is likely to be impossible with a single experiment.

At small x values gluon saturation effects are expected to show up, whose study is a major objective of the Focal upgrade at ALICE and the eA collisions at EIC. The latter will provide a crucial baseline (the initial conditions) for studies of the Quark-Gluon Plasma and its consequences at the LHC, such as pinpointing the origin of the observed elliptic flow in various reactions.

Fixed-target collisions measurements are being considered at the LHC, allowing one to explore new kinematic domains and also making use of unique probes. The recent upgrade of the LHCb detector includes a storage cell system (SMOG2) that provides access to unpolarized gas fixed-target collisions at high energy, while its polarized upgrade (LHCspin) is in the R&D phase. Similarly, in ALICE an unpolarized solid target system is under study. All this will complement and partially overlap with the EIC physics program, which also includes studies with polarized light nuclei.

Although not the main objective of the EIC, certain electroweak precision measurements can be done thanks to its very 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. This measurement as a function of energy is of interest because deviations from the SM running would signal BSM physics, such as the existence of ``dark'' Z bosons. Also EIC can put further constraints on flavor violating electron to tau transitions, complementing lepton flavor violation studies at LHC.

As final examples, we mention:

- EFT studies which show that EIC measurements can constrain particular directions in the SMEFT parameter space which are not accessible at the LHC
- Studies of jet substructure; for example, jets in eA can be used to probe cold nuclear matter in a way which complements the HL-LHC heavy ion program.

[3] "Measurement of mass dependence of the transverse momentum of Drell Yan lepton pairs in proton-proton collisions at 13 TeV", report CMS-PAS-SMP-20-003, https://cds.cern.ch/record/2764470/files/SMP-20-003-pas.pdf

Example of physics synergy of the collider experiments with astroparticle physics:

Particle production at high-x_F and in diffractive collisions is relevant for the formation of huge particle cascades (UHECR air showers). The modelling of such processes is limited by the available experimental constraints. Charm production cross sections are especially of interest, because the decays of produced D mesons give rise to neutrinos as a background to astrophysical neutrino searches. Nuclear PDF errors currently form the dominant theory error in the description of high-energy neutrino-nucleus cross sections. Improved knowledge on the required nuclear PDFs at very small x will come from both the LHC and EIC. In addition, cosmic rays will continue to provide valuable constraints on the total pp cross section at energies above collider energies, as they already did before the LHC era. Moreover, the observed over-abundance of muons in air showers above LHC energies deserves better understanding, possibly leading to new insights.

Examples of synergies on detector R&D:

The EIC design is based on an electron and a hadron storage ring and up to two interaction regions are foreseen. The high luminosity is ensured by frequent injection of polarized electron beams and strong cooling of the ion beams. A crossing angle of the two beams is necessary to avoid parasitic collisions due to short bunch spacing, to make space for machine elements, improve detection opportunities and reduce the detector background. The crab waist scheme ensures preserving the luminosity in spite of the large crossing angle: 25 mrad and 35 mrad for the 2 interaction regions, respectively. The design benefits from the ion accelerator complex with beam polarization capability already available from the RHIC complex, including multiple spin rotators and roman pots.

The EIC detectors pose challenging requirements concerning a variety of sub-detector systems and require up-to-date approaches for all the components of the experimental set-up. A large fraction of these needs partially or completely coincide with requirements for the experimental program at the LHC and its upgrades. The opportunities for synergy in this respect are recognized in the development of the ECFA Detector R&D Roadmap (https://indico.cern.ch/event/957057/), to be published in the fall of 2021.

Some specific examples of shared detector components and requirements:

- Tracking and vertexing using ultra-light silicon detectors is a must at EIC. The currently favoured (MAPS) technology is aligned with the needs for ALICE-3, such that a joint development programme is already in place.
- Tracking using Micro-Pattern Gaseous Detectors (MPGDs) such as Micromegas or GEMS nicely complements silicon detectors to cover larger areas. They are used in most LHC experiments already and are planned for both barrel and forward/backward tracking at the EIC.
- Particle identification in a wide momentum range is also essential at both EIC and LHC, *e.g.* for spectroscopy studies at LHCb or for the identification of low momentum hadrons at ALICE.
- Silicon detectors offering extremely high time resolution O(10 ps), such as LGAD or ARCADIA, are needed at the EIC (for time-of-flight applications) and the LH-LHC (for mitigating the 'pile-up' overlap of events).
- The development of novel ASICs for Front-End detector readout such as MPGDs, matching both the sensor characteristics and the needs of largely streaming-readout-based data acquisition systems.

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Additional support will be solicited through the Indico webpage to be set up, in a manner similar to other EoIs.