Summary of the session on parton propagation and fragmentation

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Nuclear targets can be used as space-time analyzers of the propagation and fragmentation of high-energy partons. The DIS process is particularly important because the kinematics of the event is largely under control, the nuclear density is well known and static in time, and the multiplicity in the final state is low, allowing precise measurements.

In DIS a quark is scattered by a virtual photon. This quark will rescatter on nuclear gluons, and emit gluons by QCD *bremsstrahlung* in the nuclear medium therefore losing energy compared to the same process on a proton target this process is called *energy loss* and leads to attenuation in the production of high-energy hadrons `[Majumder],[Vitev]`. If the quark energy is low enough, the fragmentation into an observed hadron has a chance to start inside the nucleus, which allows to probe its space-time development and therefore open a window into the dynamics of color confinement; this process is generally referred to as *prehadron absorption* and leads as well to hadron attenuation `[Gallmeister]`.

On the other hand, if the parton lifetime and energy loss mechanism were under theoretical control, the partons created in the hard scattering could be used as a colored probe of the gluon distribution in a nucleus, in analogy with electron scattering measuring the charge density of nucleons inside a nucleus `[Majumder]`. Understanding the space-time evolution of parton propagation and fragmentation is also important in connection with other fields, e.g., to correctly interpret hadron attenuation in the Quark-Gluon Plasma created in Heavy-Ion Collisions, where the medium is unknown and rapidly expanding, and in neutrino experiments, which use nuclear targets to increase the cross section.

The main experimental tool is the measurement of the nuclear modification of high-energy hadron production through which different information can be extracted. The first experiments carried out at SLAC and by the EMC collaboration have been reviewed by `P. Di Nezza`, together with the high-quality and abundant HERMES collaboration data on single and dihadron attenuation at HERA. The preliminary data analyzed by the JLab CLAS collaboration have been reviewed by `T. Mineeva`. However, the phenomenological and theoretical analysis of these data has not yet been able to determine the typical quark life-time and therefore to determine in which kinematic conditions the energy loss process dominates over prehadron absorption.

In the following, we discuss the physics measurements and simulation tools discussed at the workshop. References are given to the presented talks, see `http://www.phy.anl.gov/mep/EIC-NUC2010/program.html`, or to comments offered during discussion time. We also recommend the review articles [1, 2].

Physics measurements

- **Hadronization in cold nuclear matter**
  The high energy provided by EIC ($s \sim 1000$ GeV^2) provides a chance to isolate *quark energy loss* in cold nuclear medium. Indeed, the parton life-time is proportional to its energy, and this can be large enough that the fragmentation process starts completely outside the nuclear target. With prehadronic interactions suppressed, we have the possibility to study partonic energy loss, which is a perturbatively calculable process, and test the available calculations based on different sets of approximations.

  EIC can also cover the low parton energy range, where hadronization is expected to start inside the medium. The clean DIS experimental environment is ideal to test in detail the available *prehadron absorption* models, such as the the Lund string based model implemented in the GiBUU Monte Carlo simulation `[Gallmeister]`, and microscopic descriptions of parton fragmentation, such as the Nambu-Jona Lasinio model presented by `W. Bentz`.

  Parton propagation and fragmentation studies at EIC are in fact a whole program. Observables like multiplicity ratios and transverse momentum broadening of single inclusive hadrons, can be accessed and can extend tremendously the kinematic range in ν, Q^2 ant p_t^2 of existing experiments, and so link medium to high energies [Dupré]. The high EIC luminosity will allow one to produce multi-dimensional measurements and to access di-hadron [DiNezza] and photon-hadron correlations [Vitev],[Majumder], which have been much less studied so far but are very promising in advancing our understanding.

Very importantly, the high energy of the EIC allows studying to previously unavailable classes of observables in nuclear DIS: heavy flavors [Dupré] and jets [Vitev],[Accardi], which we discuss in more detail below.

- **Heavy flavors**
  The large mass of the charm and bottom quarks allow in principle to address quark fragmentation in perturbative QCD, and are also responsible for the predicted reduced energy loss compare to light flavors. However, the latter has not been observed in measurements of heavy flavor attenuation in the QGP produced at RHIC. Due to the little understood properties of the QGP and the richness of interactions that can take place there, many explanation based on different physics processes have been proposed for the larger than expected attenuation. Measurements in DIS at the EIC offer the unique possibility of reducing the number of physical mechanisms at play, and study heavy quark propagation and fragmentation in a known medium.

  Of course heavy quarks detection is not simple and requires high level detectors, especially a vertex determination with precision of less than 100 μm. Moreover, high luminosity may be necessary for a successful measurement campaign: simulations show that a luminosity of few 10^{33} cm^{-2}s^{-1} gives reasonable statistic for good measurements involving charmed mesons; however, a similar precision for bottom quarks requires few 10^{34} cm^{-2}s^{-1} [Dupré].

- **Jets**
  EIC will allow for the first time to study jets in e+A collisions (preliminary results from the SLAC fixed-target E665 experiment exist [3, 4], but were not finalized to the best of our knowledge). A jet is a collimated group of hadrons originating from the hadronization of an en-

ergetic parton produced in a hard collision. It is defined by a jet reconstruction algorithm, and depends on a "jet parameter", typically a jet cone in the azimuthal angle and rapidity variables. Energy loss typically broadens the angular distribution of particles inside the jet. Therefore variations of the jet cone introduce one further variable by which parton energy loss models can be constrained `[Vitev]`.

Jet production in DIS is dominated by single jet production initiated by leading-order photon-quark scattering. Once single jet nuclear modifications have been understood and well modeled, one can look at di-jet production, to which both quarks and gluons contribute, to measure the nuclear modification of the gluon distribution. This would give a very important alternative method to measure nuclear gluons compared to F_L measurements. Preliminary work by G.Soyez indicates that values of the gluon fractional momentum x as low as $\sim 10^{-2}$ can be accessed at the EIC in e+p collisions `[Accardi]`. More detailed simulations including energy loss effects are needed to map out in detail the range and precision of gluon measurements, and the required luminosity.

- **Nuclear structure**
  The interaction of a colored probe (the scattered parton) with the nuclear medium can be used as a tool to explore the nuclear structure. With the basic formalism under control one can use colored partons as a probe of the nuclear gluon PDFs and GPDs `[Majumder]`, the saturation scale `[Mineeva]`, and the nucleon TMDs `[Avakyan]`.

- **Target fragmentation**
  Furthermore, EIC will give us a chance to look at a less studied channel, target fragmentation, because of the collider mode which, compared to fixed target experiments, boosts the hadrons produced in the target hemisphere to energy and angles large enough to be experimentally resolved. In particular we discussed detecting nucleons ejected from the nuclei: these give access to the other side of the process, observing the particles that received energy from the scattered partons as opposed to observing particles that lost that energy. On the one hand correlations of these nucleons with leading hadrons will provide more detailed information on the propagation and fragmentation of a parton `[comment by M.Strikman]`; on the other hand, they can be used to determine the centrality of the photon-nucleus scattering, giving a further handle

on the amount of matter traversed and thus the possibility of exploring the shadowing mechanism and enhancing the saturation scale in small-x studies. `K. Gallmeister` indicated that nucleons in the target region can be studied using the GiBUU Monte-Carlo generator.

- **Bose-Einstein Correlations**
  Though not discussed in the workshop, an interesting possibility to study nuclear modifications of the hadronization processes is in principle offered by the measurement of Bose-Einstein Correlations between the produced hadrons. This could enable us to extract the source size of an excited color string, possibly gain information on the tension in the string, and determine any nuclear dependence. Preliminary investigations are underway `[Gilfoyle]`.

Monte Carlo simulations

The "Parton Propagation and Fragmentation" working group is currently working on several Monte Carlo simulations to address the discussed observables `[Dupré]`. More information, references and links are available on the PPF working group wiki, `https://eic.jlab.org/wiki/index.php/EA_ppf`

- **PyQM.** The "Pythia Quenching Model[1]" is an energy-loss simulation based on Pythia `[Dupré]`. The partons created in the hard scattering are allowed to lose energy according to the Salgado-Wiedemann quenching weights, and then fed into the Lund string fragmentation Pythia module. The goal is to determine if the Lund string fragmentation leads to observable differences compared to using Fragmentation Functions to describe leading hadron attenuation (as implemented e.g. in PQM, see below). We discussed issues regarding the p_T-broadening simulation, which leads to too low results compared to the transport coefficient $\hat{q} \approx 0.4$ GeV^2 required for reproducing HERMES attenuation data.

- **Q-Pythia extension to DIS.** Q-Pythia is an energy loss simulation by Armesto, Cunqueiro and Salgado based on medium-modified DGLAP evolution equations. Currently, only energy loss in the QGP

[1]Warning: the name may change in the future.

is implemented, and we are working on implementing energy loss in the cold nuclear target. Pursuing this simulation is likely to have a very big pay-off: it will allow to study jet nuclear modifications, the effects of medium modified DGLAP evolution on hadron observables, and compare this to the BDMPS energy loss formalism in the integrated PQM simulation, and the forthcoming implementation of the Higher-Twist energy loss formalism.

  - **PQM.** The "Parton Quenching Model" is a simulation by Dainese, Loizides and Paic, which uses Pythia as a parton level generator, and then applies the Salgado-Wiedemann quenching weights to determine the parton energy loss before using Fragmentation Functions to determine single hadron attenuation. It has been integrated in Q-Pythia in the AliceROOT framework by C.Loizides, who will help us making it available stand-alone.
  - **PyQM integration.** It will be interesting to integrate PyQM in Q-Pythia, to provide a direct comparison between hadronization performed according to the Lund string model and using Fragmentation Functions.
  - **Higher-Twist energy loss.** We are currently studying how to implement in Q-Pythia the Higher-Twist energy loss formalism, recently extended to include a resummation of all higher-twist contributions `[Majumder]`. The (optimistic) time scale for this project is at least 6 months.

- **GiBUU.** This is (among other things) a simulation of nuclear modifications of hadron production in DIS based on the Lund string model and BUU coupled-channel transport equation for the (pre)hadrons, and completely neglects energy loss. It has been extensively tested on HERMES and EMC data, and is ready to use at the EIC energy `[Gallmeister]`. It will be interesting to implement the few variations in the space-time prehadron production schemes available on the market and investigate possible observable differences.

References

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[2] A. Majumder and M. Van Leeuwen, arXiv:1002.2206 [hep-ph].

[3] C. W. Salgado [E665 Collaboration], "Jet Production In Muon Scattering At Fermilab E665," presented 23rd International Symposium on Ultra-High Energy Multiparticle Phenomena, Aspen, CO, 12-17 Sep 1993.

[4] H. L. Melanson [E665 Collaboration], "Jet Production In Deep Inelastic Muon Scattering At 490-Gev," presented at 28th Rencontres de Morion, Les Arcs, France, 20-27 Mar 1993.