

Fig. 66. – Centre-of-mass energy vs. luminosity of past, present, approved and proposed lepton-nucleus facilities and experiments. [AA] SLAC E665 still to be added -

neutral kaons, protons, and electrons, can be upgraded to include direct detection of higher-energy charged kaons as well. With the increased luminosity comes access to rarer hadrons whose attenuation in the nuclear medium has never before been explored.

Table XII lists hadrons accessible with CLAS12 that are stable over nuclear distance scales. Nuclear attenuation measurements can be performed for all of these hadrons, and transverse momentum broadening will be directly accessible for a number of the listed hadrons. Estimations for the CLAS12 geometric acceptances for these particles are plotted in Fig. 67. As can be seen, a systematic study of the mass dependence for two-quark systems is feasible for eight meson species with a range of masses spanning nearly 1 GeV/c². Further, new insights into the poorly-understood hadronisation mechanisms for baryons can be gained by studying the series of eight baryon species indicated in this table. While experimentally challenging, the baryon measurements have the potential to open up a completely new realm of studies of hadron formation for three-quark systems.

8.7.2. Other fixed target experiments: DIS and DY. – The ongoing fixed-target COMPASS experiment [393] with its up to 190 GeV muon beam, can covseler a much larger ν and Q^2 range than HERMES or JLab. In particular, due to the higher reach in ν , one can select partons hadronising outside the medium, and cleanly test parton energy loss models by studying the hadron p_T -broadening. Therefore, a $\mu + A$ experimental programme at COMPASS would be very desirable to improve our knowledge of the space-time evolution of hadronisation and anticipate some of the results expected at the future electron-ion colliders discussed in Sect. 8.7.4. At the same time the availability of a high-energy proton or pion beam would allow measuring nuclear modifications of DY processes and studying the interplay of initial state and final state parton energy loss within the same detector.

Dedicated high-statistics medium energy DY experiments have been proposed in [315] to precisely measure initial-state parton energy loss in nuclear targets. The authors considered using

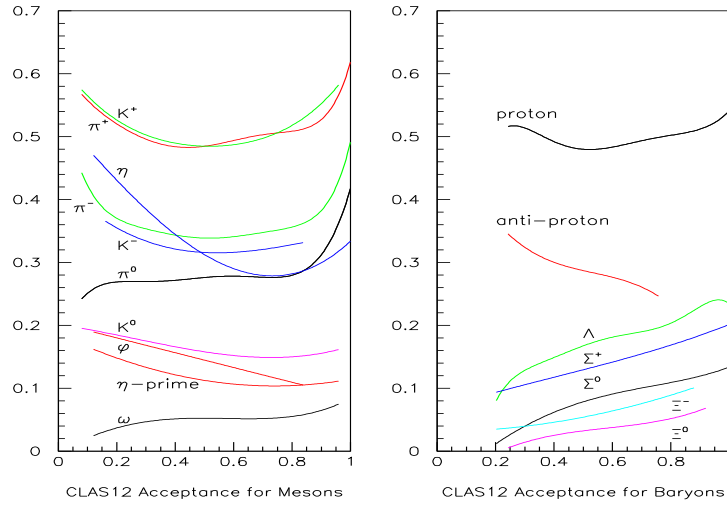


Fig. 67. – Acceptances for mesons and baryons in the CLAS12 experiment at the proposed 12-GeV JLab facility.

B is the lightest available nucleus. Indeed, the beam luminosity as well as part of the systematic errors cancel in the ratio. The A dependence of the ratio is analogous to the centrality dependence, but eliminates the large experimental uncertainties due to the determination of the centrality and to the normalization of the Cronin ratio. Moreover, without need of centrality cuts the statistics may be sufficient to probe the high- p_T region and test the mechanism underlying the Cronin effect.

8.7.4. Electron-ion colliders. – An electron-ion collider would significantly complement and add new dimensions to the experimental studies at fixed target facilities, by extending the range of accessible lepton, E_e , and ion, E_A , energies. Proposed designs for an electron-ion collider currently have a fairly wide range of luminosities and centre-of-mass energies, see Table XIII. The Electron-Ion Collider (EIC) is a proposed US-based facility, which would provide $E_e = 3 - 20$ GeV and $E_A = 15 - 100$ AGeV [46, 47]. There are currently two complementary conceptual proposals [47, 403]: (i) eRHIC would add an electron beam to the existing RHIC ion accelerator at BNL – the option of staging it, and first realise a lower energy version with $E_e = 2 - 4$ GeV, based on an energy recovery linear accelerator for the electron beam is being actively discussed [404, 405]; (ii) ELIC would add an ion accelerator to the CEBAF upgraded 12-GeV electron ring at Jefferson Lab [406, 407]. The eRHIC concept emphasises the energy range; the ELIC concept will reach up to 100 times more luminosity, but with lower maximum energy. In both cases polarized proton and light-ion beams will be available. The Large Hadron-electron Collider (LHeC) is a proposed upgrade of the LHC at CERN [408, 409], and will reach much higher energies than the EIC still with a good luminosity, but only with unpolarized hadron beams. Finally, the idea of building a low-energy electron-nucleon (ENC) collider at FAIR has recently been advanced [410]: the goal is to have a centre-of-mass energy between HERMES and COMPASS, but up to a factor 100 higher luminosity and polarized hadron beams. Here, we will focus on the EIC capabilities, but most of the discussed measurements will be in principle possible also at the LHeC and, with the exception of jet measurements, at the ENC.

The EIC will provide virtual photons with energies in the $\nu = 10 - 1600$ GeV range, large

	ENC	eRHIC			ELIC		LHeC	
		med	high	full	low	med		high
E_e [GeV]	3.3	3	20	30	3	4	11	70
E_A [GeV/A]	7.5	50	120	120	12	30	125	2750
\sqrt{s} [GeV]	10	24	98	120	12	22	74	880
\mathcal{L} [10^{33} cm $^{-2}$ s $^{-1}$]	0.44	0.5	1.0	0.2	6	40	100	1

TABLE XIII. – Beam energies E , center of mass energies \sqrt{s} , and luminosity \mathcal{L} , for $e + A$ collisions at the ENC, EIC (staged and full eRHIC and ELIC designs), and at the LHeC (ring-ring mode) proposed facilities.

Q^2 up to 1000 GeV 2 , and low $x \gtrsim 10^{-5}$. Its high luminosity will allow access to rare signals, multi-differential measurements, and dihadron and γ -hadron correlations. It will be able to cross-check HERMES and CLAS measurements, while offering many more channels and an extended kinematic range to study hadronisation inside the nucleus at low ν , as well as testing basic QCD processes such as non-Abelian parton energy loss and the space-time evolution of the DGLAP shower at high ν . EIC will be unique, compared to HERA (HERMES) and JLab (CLAS), in the following areas:

- At the large ν accessible at the EIC, hadrons will clearly be formed outside the nuclear medium, so that effects due to the propagation of the struck quark can be experimentally isolated. One will have new access to p_T -broadening studies, which can cleanly probe the parton radiative energy loss as predicted by pQCD at asymptotic energy. It will also be possible to study in detail the interplay of radiative and collisional parton energy loss, medium modifications of the DGLAP evolution, and test factorisation for the fragmentation functions.
- Heavier mesons like η and ϕ will be more abundantly produced than at HERMES/JLab. At both medium-low and large ν , comparing their quenching to that of their lighter π and K counterparts will provide important clues about parton propagation and hadronisation, see Sect. 8.2.
- The EIC excellent low- x coverage provides increased production of heavy flavour and quarkonia. In particular, it will be possible to study the heavy quarks energy loss through the B and D meson suppression. Theoretical mechanisms proposed to explain charmonium suppression in $p + A$ and $A + A$ collisions can be put to the test in a clean experimental environment by studying J/ψ , ψ' and χ spectra.
- The large Q^2 coverage will access a truly perturbative QCD regime, whose prediction can be more confidently tested against the data, in particular colour transparency effects and the Q^2 -dependence of the observables discussed in this review, like the hadron p_T -broadening.
- Baryon production through parton fragmentation will also be accessible, because of the collider mode and the accessible final-state invariant masses. This will allow studying baryon transport in cold QCD matter and the baryon anomalies observed in fixed target $e + A$ collisions at HERMES and in heavy-ion collisions at RHIC. The ability to identify a good variety of baryons, including the strange and charmed sector, will be a key to this programme.
- For the first time, jet physics in DIS with a nuclear target will be experimentally accessible. In particular, medium modifications of the jet shape, and the comparison of light-quark to

heavy-quark and gluon initiated jets will shed light on the mechanisms underlying parton energy loss. These studies can also be extended to dijet or γ -jet correlations.

In summary, the collider kinematics and associated detectors with excellent calorimetry, particle identification, vertex detection, and rapidity coverage will allow for a comprehensive programme to better understand how parton energy loss and fragmentation occur in cold QCD matter.

By contrast, the ENC will cover a smaller the $\nu = 10 - 50$ GeV range, which might or might not be sufficient to ensure hadronization outside the nuclear medium. The high luminosity and rather symmetric kinematics would however ensure the possibility of a rich hadronization program complementing and extending the HERMES results.

8.7.5. RHIC II. – In order to undertake extensive high-statistics studies of processes with low cross sections in $A + A$ collisions, an upgrade of the RHIC luminosity will be necessary as well as a comprehensive new detectors [411]. Key measurements will include two-particle correlations up to a p_T range where fragmentation can be safely tested and extended to include heavy identified hadrons. In addition, a comprehensive set of measurements of photon-jet correlations, and heavy-quark tagged jets can provide valuable information on parton energy loss and hadronisation mechanisms. The capabilities of the proposed new detector include: (i) excellent charged particle momentum resolution up to $p_T=40$ GeV/c in the central rapidity region, (ii) complete hadronic and electromagnetic calorimetry over a large phase space, (iii) particle identification up to large p_T (20 – 30 GeV/c) including hadron and lepton separation in the central and forward regions, and (iv) high rate detectors, data acquisition, and trigger capabilities.

8.7.6. LHC. – The possibility of colliding heavy nuclei with high luminosity at the Large Hadron Collider (LHC) offers a unique opportunity to investigate in detail the behaviour of strongly interacting matter under extreme conditions of density and temperature. The factor 30 increase in $\sqrt{s_{NN}}$ relative to RHIC corresponds to a huge increase in kinematic and statistical reach for hard probes, and new channels will become available [170] such as detailed jet studies (jet shapes, medium-modified fragmentation functions) [135].

ALICE: – The ALICE experiment was designed specifically to tackle as many measurements as possible in the high multiplicity environment of heavy-ion collisions. ALICE aims firstly at accumulating sufficient integrated luminosity in $Pb + Pb$ collisions at $\sqrt{s_{NN}} = 5.5$ TeV, as well as to carry out studies of $p + p$ and $p + A$ collisions in order to establish the benchmark processes under the same experimental conditions. ALICE can measure heavy-flavour production down to very low p_T because its unique low transverse-momentum cutoff for particle detection. This can be achieved by using inclusive large impact-parameter lepton detection, and by reconstructing exclusive charm-meson decays at relatively low p_T . As a result, the measurement of the total heavy flavour cross section will require a smaller extrapolation and will thus show improved precision. As discussed in 8.6 a very attractive methods to study hadron jets is to tag high energy hadrons or jets with prompt photons emitted opposite to the hadrons or jet directions. The combined use of the PHOTon Spectrometer (PHOS) – with excellent energy resolution although in a limited acceptance – and the ElectroMagnetic Calorimeter (EMCal) – about seven times larger in acceptance but with slightly worse resolution and coarser granularity – and the central tracking system for charged particles, will allow one to recover a large fraction of the jet energy, thus reducing sensitivity to the specific pattern of fragmentation, and to perform γ -hadron and γ -jet correlations measurements.

ATLAS: – ATLAS is the largest particle detector ever constructed, and its design, like CMS, is aimed at addressing a broad variety of physics processes [412]. The detector design has many