

# Some aspects of impact of the Electron Ion Collider on particle physics at the Energy Frontier

S.V. Chekanov, S. Magill

<sup>a</sup> *HEP Division, Argonne National Laboratory, 9700 S. Cass Avenue, Lemont, IL 60439, USA.*

---

## Abstract

This overview describes several science cases at the Electron-Ion-Collider (EIC) experiment which are traditional to general particle physics. It has an emphasis on connections between future measurements at the EIC and the physics topics explored at high-energy frontier colliders. It covers several selected topics, such as parton density functions, multi-quarks states, correlations of final-state particles, precision QCD measurements and forward jet physics. We will discuss possible EIC measurements that can improve previous experimental results obtained at high-energy (HEP) experiments.

*Keywords:* EIC, DIS, HEP

---

## 1. Introduction

The Electron-Ion-Collider (EIC) [1, 2] is a proposed collider experiment to study the structure of building blocks of matter - the nucleus and the nucleons (protons and neutrons). This future experiment will collide beams of spin-polarized electrons with intense beams of both polarized nucleons and unpolarized nuclei. The EIC is a flagship nuclear science facility, however, many goals of this project are aligned with high-energy physics (HEP) that also studies the structure of the nucleons at their deepest level. In particular, EIC can revolutionize our understanding of quantum chromodynamics, a theory that is important for almost all physics processes studied at the energy frontier.

This contribution describes science cases at the EIC experiment which are traditional to general particle physics, with a particular emphasis on the connections to the physics at the energy frontier studied in previous circular colliders, such as the Large Electron-Positron Collider (LEP), the Hadron-Electron Ring Accelerator (HERA), the Large Hadron Collider (LHC) and the Tevatron experiments at the Fermi National Accelerator Laboratory (Fermilab). The paper describes a number of possible measurements related to parton density functions (PDF), multi-quarks states, precision QCD measurements and forward jet physics. In addition to rather traditional topics, such as perturbative QCD, hadronic jets and PDFs, a significant area of research at the energy frontier is soft (i.e. non-perturbative) phenomena, and their interplay with the hard QCD. Therefore, this report also covers various not-well understood soft effects encountered in  $ep$  and  $pp$  collision experiments, that can be verified and further studied at the EIC experiment.

---

*Email addresses:* [chekanov@anl.gov](mailto:chekanov@anl.gov) (S.V. Chekanov), [srm@anl.gov](mailto:srm@anl.gov) (S. Magill)

## 2. Parton distributions functions

The knowledge of parton density functions (PDF) has a crucial impact on future collider program of HEP. The EIC is expected to supersede the previous fixed-target deep-inelastic scattering (DIS) experiments that currently dominate the constraints on high- $x$  PDFs. The EIC will help constraining PDF dependence of HEP observables at moderate and large  $x$ , including the Higgs and electroweak sectors like  $M_W$  and  $\sin^2 \theta_W$ . The effect of measured PDF at EIC show substantial sensitivity to the total Higgs production cross section at the LHC [3].

Recent re-analysis of HERA data [4] with the focus on high- $x$  regions of the proton PDF indicated that the uncertainties on the current PDFs are underestimated. At the value of  $x$  larger than 0.5 (and  $525 < Q^2 < 9500 \text{ GeV}^2$ ), such uncertainties could be significantly larger than currently thought. The EIC experiment can clarify this question by providing high-precision data for  $x > 0.5$  in the region of  $10 < Q^2 < 1000 \text{ GeV}^2$ , i.e. with an overlap in the  $(Q^2 - x)$  kinematic plane with the HERA data at low  $Q^2$  studied in [4].

## 3. Beauty and charm production

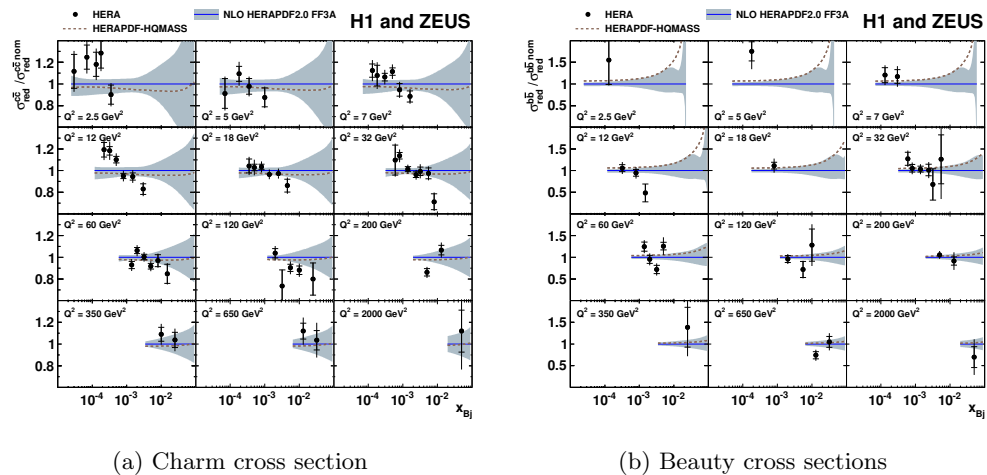


Figure 1: Ratio of reduced charm (top) and beauty (bottom) cross sections, as a function of  $x$  for given values of  $Q^2$ , to the NLO FFNS predictions using HERAPDF-HQMASS (dash lines) with respect to the reference cross sections  $\sigma$  compared, based on HERA-APDF2.0 FF3A (solid lines with uncertainty bands). From Ref.[5].

Measurements of cross sections in particle physics provide an important testing ground for calculations of the QCD matrix elements and our understanding of PDFs. The studies of open charm and beauty production in neutral current (NC) deep inelastic scattering (DIS) by H1 and ZEUS [5] show the consistency of experimental data with theoretical calculations performed at the next-to-leading (NLO) and the approximate next-to-next-to-leading-order QCD predictions based on different flavor schemes.

However, the data on beauty production have significant experimental uncertainties that can be reduced at the EIC. Figure 1 illustrates that the uncertainties on charm (beauty) cross sections at low  $Q^2$  are at the level of 20% (50%). Data at high  $x$  at  $2.5 < Q^2 < 60 \text{ GeV}^2$  are not available. This is precisely where the theory has large theoretical uncertainties, and where the EIC can provide valuable data for testing such predictions.

Even for the given level of uncertainties, a recent QCD analysis [5] reveals some tensions at the level of  $3 \sigma$  in describing simultaneously the inclusive and the heavy-flavour HERA DIS data. This can also be resolved at the EIC.

The EIC experiment can also provide new data on photoproduction of  $b$ -mesons. Fig. 2 shows the  $d\sigma/dp_T^b$  cross section for  $b$ -photoproduction compared to NLO QCD in the massive-quark scheme. The measurements are somewhat above the theory at low transverse momenta, but they are still consistent with the predictions. No data in the region below 5 GeV are available, i.e. near the bottom-quark mass of about 4.2 GeV. This is the kinematic region where theoretical calculations should treat the heavy quark as a massive quark, and should include careful estimation of high-order QCD corrections. The EIC data can fill this gap in terms of low- $p_T$  data.

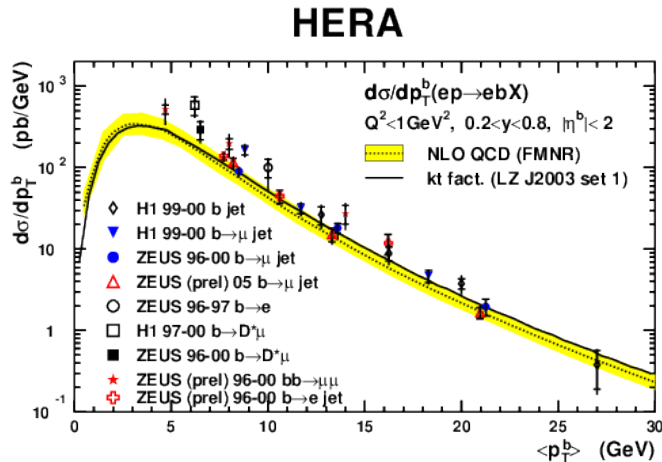


Figure 2: A summary of HERA data on beauty photoproduction cross-section  $d\sigma/dp_T^b$  compared to NLO QCD in the massive scheme and a  $k_T$  factorisation calculation (see [6] and referenced herein).

## 4. Fragmentation

Fragmentation functions parameterize the transfer of the quark's energy to a given hadron. In this section we will discuss several effects that have been observed in the past, and which can be further investigated at the EIC.

### 4.0.1. Charm fragmentation functions

Measurements of fragmentation functions and their comparison with  $e^+e^-$  experiments provide a measure of the universality of charm fragmentation, and can further

constrain its form. At HERA, charm fragmentation functions measured using the  $D^*$  production are significantly limited by available statistics [7]. Figure 3 shows the  $D^*$  fragmentation function versus the ratio of the momentum of the  $D^*$  meson and the maximum attainable momentum at the relevant beam energy. Such results indicate that the precision in the  $ep$  collision measurements is a factor 5 smaller than that in  $e^+e^-$  experiments. The EIC is expected to improve the precision of such measurements.

It is interesting to note that the normalized differential cross sections in the kinematic-threshold region cannot be well described [8] by the NLO QCD calculations in the fixed-flavor number scheme using the independent fragmentation of charm quarks to  $D^*\pm$ . This indicates the need for realistic QCD calculations in all kinematic regions of the  $D^*\pm$  measurements.

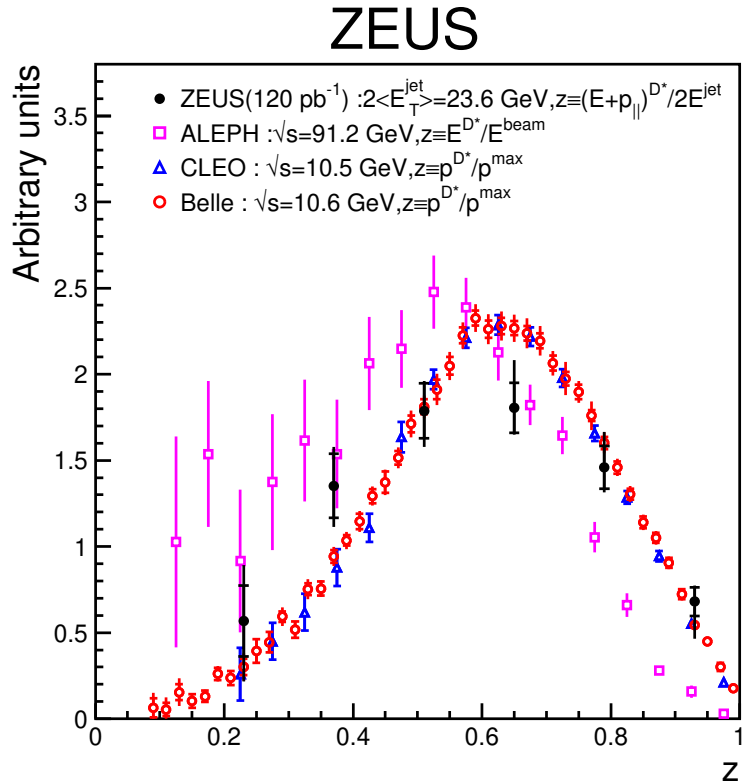


Figure 3:  $D^*$  fragmentation function measured [7] at HERA compared to measurements of  $e^+e^-$  experiments. The fragmentation function is measured versus the ratio of the momentum of the  $D^*$  meson and the maximum momentum at the relevant beam energy.

#### 4.0.2. Compound states

Production of baryonic states in fragmentation is typically described by various phenomenological models. Beyond multi-quark states, the production of nucleus of atoms in collider experiments, such as deuterons, which are composed of one proton and one neutron, cannot be calculated from first principles. According to physical cosmology, deuterium is expected to be produced in the first minutes that followed

the Big Bang. Studies of deuterons and more complex states in colliding experiments may shed light on the dynamic mechanism of the production of deuterium in the early universe.

Coalescence models are typically used to explain the production of deuterons after the hadronization step in particle colliding experiments, but they can only be used for a handy parameterization of observations, rather than for quantitative predictions. First observation of (anti)deuterons in DIS events of  $ep$  collisions was reported at HERA [9] with a puzzling observation of an excess of the deuteron rate over that of antideuterons in the central fragmentation region where the contribution from incoming protons should be negligible. Another interesting observation is related to the measured parameter  $B_2$ , reflecting the spatial size of the fragmentation region emitting the particles. In DIS, it is significantly larger than for heavy-ion experiments, but lower than for  $pp$  and  $pA$ .

The EIC experiment can improve the existing measurements due to the advanced particle identification in the regions of large  $p_T/M$  and due to the large statistics of event samples.

## 5. Short and long-range correlations

Historically, short- and long-range correlations were an active area of studies of various collective effects in HEP.

Short-range correlations of final-state particles are sensitive to interdependence between particles as the phase-space separations between them decrease. The correlations are related to fluctuations of particle densities in small rapidity windows, and are often interpreted as a manifestation of “intermittency” in particle density that exhibits “self-similarity” with respect to the size of the phase-space volume [10]. Such local fluctuations have been intensively studied in  $e^+e^-$ ,  $ep$ ,  $pp$ ,  $AA$ ,  $\mu p$ , and  $hA$  collisions (for a review see [11]). Their strength depends on parton-evolution dynamics, Bose-Einstein correlations (to be discussed later), resonance decays and other effects. Generally, short-range correlations and fluctuations can be reproduced by QCD-based Monte Carlo models with various degrees of success [11]. An advanced two-track resolution (i.e. the ability to distinguish two nearby track) combined with a large event sample can improve such measurements at small phase-space regions (in rapidity, angular variable etc.) that were not accessible by the previous experiments.

Long-range correlations in the Breit frame [12] of  $ep$  collisions (the so-called current-target correlations), to the first-order perturbative QCD, can be used to extract the behavior of the boson-gluon fusion rates as a function of the Bjorken variable  $x$  [13]. Such rates, in turn, depend on the gluon density inside the proton. The measurements do not require explicit reconstruction of jets, therefore, they are well suited for relatively low  $Q^2$  events to be collected at the EIC where jet reconstruction has significant uncertainties. The studies performed by the ZEUS collaboration [14] show that the correlation are large and negative. They are thus very different from those measured in  $e^+e^-$ , where small and positive forward-backward correlations have been observed. Some popular Monte Carlo simulations fail to describe the long-range correlations in the Breit frame of  $ep$  collisions.

The long-range correlations in the Breit frame can also be viewed [15] as a tool for high-precision measurements of the polarized gluon distribution function  $\Delta G$ . Multiplicity correlations between current and target regions in the Breit frame of DIS events are particularly sensitive to  $\Delta G$  for polarized beams. It is important to emphasize again that this approach is well suited for a low  $Q^2$  and small transverse momenta of jets, i.e. in the regions where dijet reconstruction suffers from large hadronization corrections and various instrumental effects, i.e. in the EIC collision environment.

Recently, a significant attention has been directed toward long-range (large pseudorapidity gap) particle correlations that can arise from collective phenomena in high-energy collisions. For example, such correlations can originate from the formation of a hot, strongly interacting quark gluon plasma with nearly ideal hydrodynamic behavior. The long-range correlations were observed in  $pA$  and  $AA$  at the Relativistic Heavy Ion Collider (RHIC) and the LHC. Surprisingly,  $pp$  collisions at the LHC also indicate this type of correlations (see [16] for the recent results). However, the long-range correlations are absent in DIS  $ep$  collision events, as recently studied in two-particle azimuthal correlations at HERA [17]. Therefore, the kind of collective behavior recently observed at RHIC and the LHC energies in high-multiplicity hadronic collisions does not exist in  $ep$  collisions.

The EIC experiment can contribute to a better understanding of this effect due to the unique opportunity of measuring the long-range correlations in both  $ep$  and  $eA$  collision using the same instrumental environment and the same kinematic ranges. The collectivity effect has never been explored in  $eA$  collisions. A reduced systematic when comparing two different processes using the same instrumental apparatus may shed light on the evolution of the multi-particle production mechanism.

## 6. Bose-Einstein correlations

Bose-Einstein (BE) corrections play a significant role in short-range correlations between identical particles. The BE effect has been extensively studied in heavy-ion,  $e^+e^-$ ,  $pp$ ,  $p\bar{p}$  and  $ep$  collisions. These correlations are known to reflect the spatial dimensions of the production source from which the identical bosons originate. The results [18, 19] from the HERA experiments indicate that the production source radii in  $ep$  DIS are similar to those in  $e^+e^-$ , but disagree with the source size in relativistic heavy-ion collisions where the radii depend on the atomic number  $A$ . It has been also found that the source of identical particles has an elongated shape [19], consistent with the expectations of the Lund model [20]. In  $ep$  collisions, the average size of the production source is typically smaller than 0.8 fm, but it can be as large as 1 fm in the longitudinal direction. For  $pp$  collisions, BE correlations have a larger radius (up to 3 fm) [21, 22, 23] than for  $ep$  and  $p\bar{p}$  collisions. The EIC experiment is expected to update such measurements with a better precision and reduced systematics.

## 7. Instanton-induced processes

Searches for instanton-induced processes in DIS was one of the well-established studies at HERA. Such studies can bring a better understanding of tunnelling transitions between topologically different vacua. Instanton processes are a direct prediction of

the Standard Model, but such processes have not been experimentally observed so far despite significant efforts to find such processes in  $ep$  and  $pp$  collisions (see the recent overviews [24, 25]).

Recently, the H1 collaboration has updated their searches for instanton-induced events [26] using HERA II data, setting the upper limits on the cross section for instanton-induced processes between 1.5 pb and 6 pb at 95% confidence level.

The reason why searches for such events in DIS may be more attractive than in  $pp$  collisions is because of a relatively clean, gluon rich environment compared to  $pp$  collisions, and because of several sophisticated theoretical predictions, implemented in Monte Carlo simulations, are available for DIS (see references in [26]). It was argued [25] that, although the instanton cross sections are very large at hadron colliders, experimental sensitivity to instantons is limited due to the trigger criteria that is necessary to reduce the event rate. DIS events also have independent kinematic scale, such as highly virtual momentum scale  $Q$ . This can make searches for instantons easier at EIC compared to  $pp$  collisions at the LHC.

Observations of instantons in particle collisions, a direct consequence of QCD, would be a major breakthrough in modern physics. The EIC experiment, in terms of accumulated integrated luminosity, should have a sensitivity to instanton-induced events at least a factor 10 better compared to HERA [25]. In the case if no evidence for such events will be found, experimental limits will be set at the level of a few tens of femtobarn ( $fb$ ), which may reshape the way we understand the tunnelling transitions between topologically different vacua.

## 8. Particle spectroscopy

The contribution of the EIC to the particle spectroscopy is a special topic that needs to be discussed. This topic is so broad that we will only illustrate one measurement. It has been previously extensively conducted in  $ep$  [27], heavy-ion collisions [28] and two-photon collisions in  $e^+e^-$  experiments [29].

Studies of the rich mass spectra of  $K_0^S K_0^S$  touch several important areas that have been forming the core of particle physics in the past decades, such as the production of  $f_0$ ,  $f_2$  mesons and their branching ratios, formation of possible glueballs or tetraquarks and their contributions to the meson spectra (for a review see [30]) and heavy flavour physics (such as the studies of branching fraction of the decay of  $B^0$  [28]).

Figure 4 illustrates typical invariant masses of the  $K_S^0$  pairs in  $ep$  and  $pp$  collisions. The measurements are severely limited by the available statistics and, therefore, it can be improved at the EIC with advanced tracking systems and a high-efficient secondary vertex finding algorithm.

The  $K_S^0 K_S^0$  pairs provide a clean sample of well-identified particle pairs that can also be used for searches of the CP violating processes in charmonium decays [31], such as  $J/\psi \rightarrow K_S^0 K_S^0$  or  $v(2S) \rightarrow K_S^0 K_S^0$ . Similarly, the BaBar collaboration searched for the CP-violating asymmetries for  $B$  decays into charmless two-body final states [32], i.e.  $B^0 \rightarrow K_S^0 K_S^0$ . The experimental upper limit on the branching fraction for such decays are typically of the order of  $10^{-6}$ , and is approaching the upper range of the current theoretical estimates.

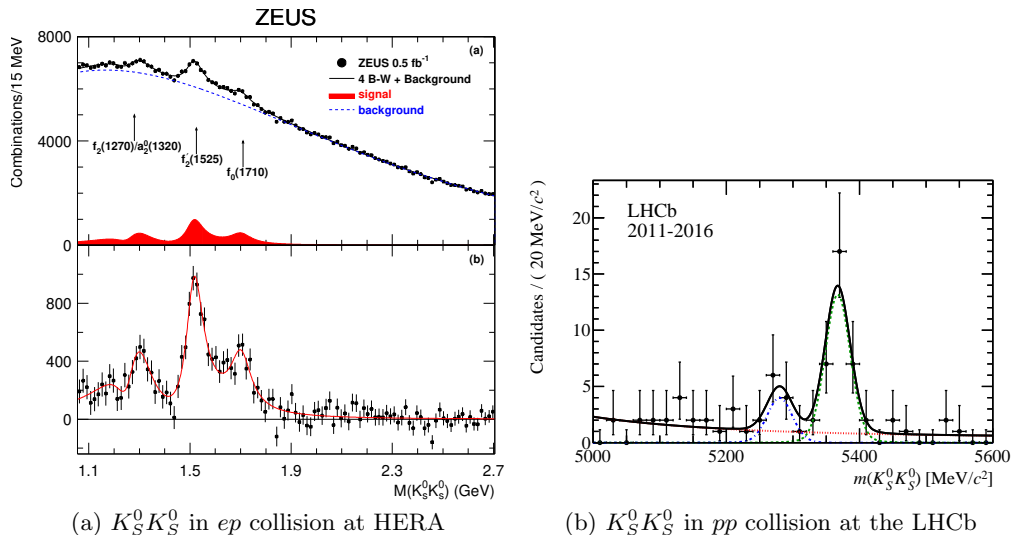


Figure 4: Invariant-mass distributions of  $K_S^0 K_S^0$  in  $ep$  collision at ZEUS [27] and the LHCb [28]

The EIC can further improve these measurements. The expected number of  $J/\psi$  at the EIC for  $100 \text{ fb}^{-1}$  is in the range  $(20 - 70) \times 10^6$  for  $y > 0.001$ , depending on the CM energy planned for the EIC. This was estimated [33] using a leading-order Monte Carlo simulation for all decay channels. This statistics is in direct competition with BES data [31].

## 9. Search for Lepton Flavour Violation

Lepton flavour violation studies in the previous HERA experiments [34, 35] focused on the processes  $ep \rightarrow lX$ , where  $l$  is a  $\mu$  or  $\tau$ . The main feature of such events is the presence of an isolated  $\mu/\tau$  with high transverse momentum, which is balanced by that of a jet in the transverse plane. An observation of such processes would be an indication for a signal of new physics beyond the Standard Model. A typical model that explains such events would be a leptoquark (LQ) particle that couples directly to leptons and quarks. Therefore, events like  $ep \rightarrow l\mu$ , can be explained by the exchange of leptoquarks.

The HERA studies indicate that the reconstructed leptoquark mass in the  $\mu$  and  $\tau$  channels agree well with the SM prediction (see Fig. 1 of [35]). However, the signal region contains only 10 events, therefore, such a comparison with the theory is statistically limited. The EIC experiment is expected to improve such measurements.

## 10. Multiquark states

The integrated luminosity expected at the EIC will be sufficient to probe particle production in significant details, and can answer the questions related to the dynamics of multiquark state formation. Composite particles can be either mesons (formed of quark–antiquark pairs) or baryons (formed of three quarks). Particles with a larger



number of quarks are called pentaquarks. It should be noted that neither the quark model nor the QCD exclude the existence of such non-conventional hadrons.

The LHCb experiment at the LHC reported several particles in the mass range of 4300 – 4500 GeV decaying to a proton and a  $J/\psi$ . Such particles can be interpreted as charmonium pentaquarks. More recently, the LHCb experiment made an observation [36] of a narrow structure around 6.9 GeV in the di- $J/\psi$  invariant mass, matching the lineshape of a resonance. If it is confirmed, it can be interpreted as a tetraquark state. The observation was obtained using 34,000  $J/\psi$  pairs.

With a total cross section of about 10 nb at the EIC, the total number of produced  $J/\psi$  particles for  $250 \text{ fb}^{-1}$  of integrated luminosity, the number of produced  $J/\psi$  particles will be around 2.5 billion. Even after taking into account branching ratio and acceptance correction, the statistics of reconstructed will be competitive to that of the LHCb.

An observation of lighter pentaquarks with strange quarks can lead to a more complete picture of the QCD dynamics leading to such states. However, experimentally, searches for light pentaquarks in the LHC data is more challenging than searches for heavy pentaquarks due to the complex collision environment at the LHC and due to high rates of light particles from fragmentation.

Search for strange and light charm pentaquarks was a significant part of the scientific program at HERA. An evidence for strange pentaquarks near the mass 1.5 GeV, initially reported by ZEUS using HERAI data [37], was not confirmed using HERAII runs [38]. The statistics for  $K_S$  mesons and  $K_S - p$  combinations for HERA II was smaller than for HERAI, although some improvements in proton identification at HERA II were introduced using the microvertex detector, which could led to a higher purity for identified protons. Searches by the H1 collaboration [39] using a similar statistics for  $K_S - p$  combinations as in ZEUS did not confirm the ZEUS observation from HERAI. The results for strange pentaquarks from fixed-target experiments are typically mixed, i.e. had either positive or negative signals [40]. Therefore, the question of the existence of strange pentaquarks is still open and represents an active area of studies. The observation of lightest pentaquarks with strange quarks can be a significant discovery that can clarify the dynamics of multi-quarks states.

As for the strange pentaquarks, a light charm pentaquark can shed light on the dynamics of pentaquarks states. An evidence [41] for light charmed pentaquarks at around 3.1 GeV, first reported by H1, was not conformed by ZEUS data [42].

The main lesson for these searches of light pentaquarks in  $ep$  collider experiments is that evidences at a  $3 \sigma$  level should always be confronted with the studies using alternative detector designs (ZEUS vs H1). Although the attempts to exclude the HERAI observations using HERAII data is pointing to the absence of the light pentaquarks, a firm conclusion can only be made using a statistics that is significantly larger than that achieved at the HERA collider. The EIC experiment has a significant potential to contribute to the searches for light pentaquarks.

## 11. Forward physics and BFKL

One of the most significant findings of the experiments in DIS at HERA (ZEUS, H1) is the steep rise of the gluon density in the proton as the parton momentum fraction,

$x$ , decreases (see Fig. 5) [6].

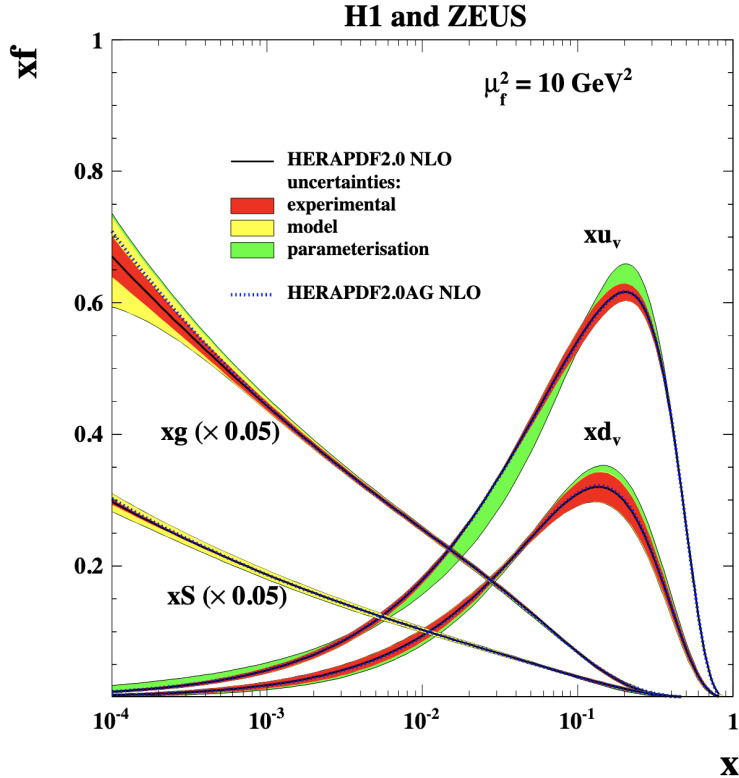


Figure 5: HERA H1 and ZEUS combined PDFs.

Before HERA, there were many PDFs that exhibited the full range of the (then unknown) gluon density from flat to steeply rising at low  $x$ . One consequence of a steeply rising gluon density is that at some point, gluons will completely fill the proton, which, if unchecked reaches a limit known as the unitarity bound, expressed as:

$$\alpha_s(x, Q^2)xg(x, Q^2)/Q^2 = \pi R^2. \quad (1)$$

There must be some mechanism to stop or slow the gluon rise in order not to violate the unitarity limit as  $x$  decreases. As the gluon density saturates the proton, the unitarity limit can hold if gluons interact with each other, reducing the overall gluon density. One particularly interesting idea of how this might manifest itself is for saturation effects to take place initially in small regions of the proton - so-called Hot Spots as described by A. H. Mueller in [43]. No evidence was found for these regions of extreme QCD effects at HERA, but the use of large A nuclear targets at the EIC present an opportunity to revisit the “hot spot” saturation condition again.

Recently, some aspects of the BFKL evolution have been discussed in [44]. Jet measurements at HERA show that the cross sections increase steeply towards small  $x$ , but the predictions obtained from DGLAP parton shower simulations fall below the measurements. Some experimental limitations for forward jets measurements at HERA are illustrated in Fig. 6 [45]. The figure shows the prediction of the three MC models.

The cross sections are measured in two intervals of rapidity distance ( $Y$ ),  $2.0 \leq Y < 4.0$  and  $4.0 \leq Y \leq 5.75$ . The model with the key CCFM shows the CASCADE Monte Carlo generator that implement the Ciafaloni-Catani-Fiorani-Marchesini (CCFM) evolution that unifies the DGLAP and BFKL approaches. shows a better agreement with the data compared to DGLAP based simulations and the Colour Dipole Model (CDM) (see the corresponding references in [45]).

On the experimental side, it is clear that the forward-jet measurements suffer from the lack of statistics and a significant (4%) hadronic energy scale uncertainty that gives rise to the dominant uncertainty of 7% to 12% for the measured cross sections. The EIC experiment can make a unique contribution to such measurements if jet energy scale uncertainties will be reduced to a percent level.

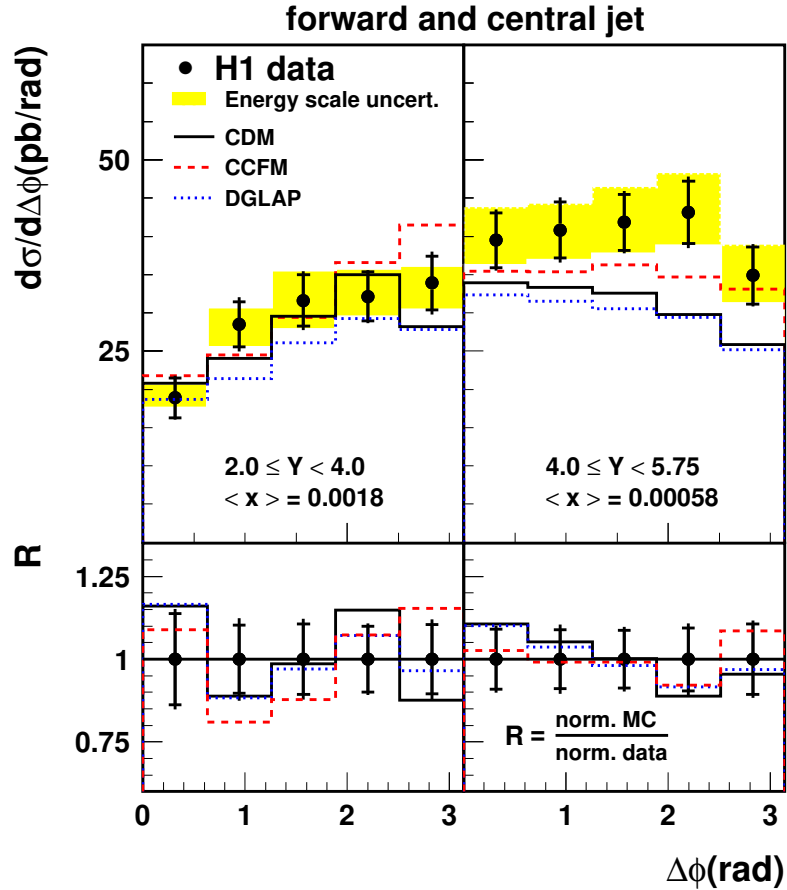


Figure 6: Forward and central jet cross sections as a function of the azimuthal angle difference  $\Delta\phi$  between the most forward jet and the scattered positron in two intervals of the rapidity distance (reproduced from [45]).

## 12. Summary

In conclusion, the EIC experiment offers unique opportunities to extend many physics measurements performed in the previous circular colliders. This paper provides a snapshot of several not-well understood physics effects encountered in such HEP experiments in the past, that can be verified and further studied at the EIC with a high precision. We believe that innovations in the accelerator and detector designs of the EIC, together with substantial theoretical progress in soft and hard QCD, could have a significant impact on understanding of particle physics in the next two decades.

## Acknowledgments

The submitted manuscript has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory (“Argonne”). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357. The U.S. Government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan. <http://energy.gov/downloads/doe-public-access-plan>. Argonne National Laboratory’s work was funded by the U.S. Department of Energy, Office of High Energy Physics under contract DE-AC02-06CH11357.

## References

- [1] A. Accardi, et al., Electron Ion Collider: The Next QCD Frontier: Understanding the glue that binds us all, *Eur. Phys. J. A* 52 (9) (2016) 268. [arXiv:1212.1701](#), [doi:10.1140/epja/i2016-16268-9](#).
- [2] E.-C. Aschenauer, S. Fazio, J. Lee, H. Mäntysaari, B. Page, B. Schenke, T. Ullrich, R. Venugopalan, P. Zurita, The electron-ion collider: Assessing the energy dependence of key measurements, *Reports on Progress in Physics* 82. [doi:10.1088/1361-6633/aaf216](#).
- [3] T. Hobbs, B.-T. Wang, P. M. Nadolsky, F. I. Olness, Collinear PDFs in the era of HL-LHC, LHeC, and EIC, *PoS DIS2019* (2019) 247. [arXiv:1907.00988](#), [doi:10.22323/1.352.0247](#).
- [4] ZEUS Collaboration, I. Abt, et al., Study of proton parton distribution functions at high  $x$  using ZEUS data [arXiv:2003.08742](#).
- [5] H1, ZEUS Collaboration, H. Abramowicz, et al., Combination and QCD analysis of charm and beauty production cross-section measurements in deep inelastic  $ep$  scattering at HERA, *Eur. Phys. J. C* 78 (6) (2018) 473. [arXiv:1804.01019](#), [doi:10.1140/epjc/s10052-018-5848-3](#).
- [6] M. Klein, R. Yoshida, [Collider physics at heracl](#), *Progress in Particle and Nuclear Physics* 61 (2) (2008) 343–393. [doi:10.1016/j.pnpnp.2008.05.002](#). URL <http://dx.doi.org/10.1016/j.pnpnp.2008.05.002>
- [7] ZEUS Collaboration, S. Chekanov, et al., Measurement of the charm fragmentation function in  $D^*$  photoproduction at HERA, *JHEP* 04 (2009) 082. [arXiv:0901.1210](#), [doi:10.1088/1126-6708/2009/04/082](#).
- [8] H1 Collaboration, F. Aaron, et al., Study of Charm Fragmentation into  $D^{*+}$ -Mesons in Deep-Inelastic Scattering at HERA, *Eur. Phys. J. C* 59 (2009) 589–606. [arXiv:0808.1003](#), [doi:10.1140/epjc/s10052-008-0792-2](#).
- [9] ZEUS Collaboration, S. Chekanov, et al., Measurement of (anti)deuteron and (anti)proton production in DIS at HERA, *Nucl. Phys. B* 786 (2007) 181–205. [arXiv:0705.3770](#), [doi:10.1016/j.nuclphysb.2007.06.022](#).
- [10] A. Bialas, R. Peschanski, Study of levy stability in relativistic heavy-ion collisions, *Nuclear Physics B* 273 (1986) 703–718.
- [11] W. Kittel, E. A. De Wolf, *Soft Multihadron Dynamics*, Book. World Scientific, 1995.
- [12] R. P. Feynman, *Photon-hadron interactions*, W. A. Benjamin Reading, Mass, 1972.
- [13] S. V. Chekanov, [Long-range correlations in deep-inelastic scattering](#), *Journal of Physics G: Nuclear and Particle Physics* 25 (1) (1999) 59–67. [doi:10.1088/0954-3899/25/1/006](#). URL <http://dx.doi.org/10.1088/0954-3899/25/1/006>

- [14] ZEUS Collaboration, J. Breitweg et al., Angular and current-target correlations in deep inelastic scattering at hera, The European Physical Journal C 12 (1) (2000) 53–68. [doi:10.1007/s100529900245](https://doi.org/10.1007/s100529900245).
- [15] I. Akushevich, S. Chekanov, Current target correlations as a probe of  $\Delta G / G$  in polarized deep inelastic scattering, Phys. Lett. B 462 (1999) 329–334. [arXiv: hep-ph/9908270](https://arxiv.org/abs/hep-ph/9908270), [doi:10.1016/S0370-2693\(99\)00933-8](https://doi.org/10.1016/S0370-2693(99)00933-8).
- [16] CMS Collaboration, A. M. Sirunyan, et al., Studies of charm and beauty hadron long-range correlations in pp and pPb collisions at LHC energies, Phys. Lett. B 813 (2021) 136036. [arXiv:2009.07065](https://arxiv.org/abs/2009.07065), [doi:10.1016/j.physletb.2020.136036](https://doi.org/10.1016/j.physletb.2020.136036).
- [17] H1 Collaboration, I. Abt, et al., [Two-particle azimuthal correlations as a probe of collective behaviour in deep inelastic ep scattering at hera](https://arxiv.org/abs/2004.07001), Journal of High Energy Physics 2020 (4). [doi:10.1007/jhep04\(2020\)070](https://doi.org/10.1007/jhep04(2020)070).  
URL [http://dx.doi.org/10.1007/JHEP04\(2020\)070](http://dx.doi.org/10.1007/JHEP04(2020)070)
- [18] H1 Collaboration, C. Adloff, et al., Bose-Einstein correlations in deep inelastic e p scattering at HERA, Z. Phys. C 75 (1997) 437–451. [arXiv:hep-ex/9705001](https://arxiv.org/abs/hep-ex/9705001), [doi:10.1007/s002880050486](https://doi.org/10.1007/s002880050486).
- [19] ZEUS Collaboration, S. Chekanov, et al., [Bose–einstein correlations in one and two dimensions in deep inelastic scattering](https://arxiv.org/abs/hep-ex/0312068), Physics Letters B 583 (3-4) (2004) 231–246. [doi:10.1016/j.physletb.2003.12.068](https://doi.org/10.1016/j.physletb.2003.12.068).  
URL <http://dx.doi.org/10.1016/j.physletb.2003.12.068>
- [20] B. Andersson, G. Gustafson, G. Ingelman, T. Sjostrand, Parton Fragmentation and String Dynamics, Phys. Rept. 97 (1983) 31–145. [doi:10.1016/0370-1573\(83\)90080-7](https://doi.org/10.1016/0370-1573(83)90080-7).
- [21] CMS Collaboration, A. M. Sirunyan, et al., Bose-Einstein correlations in  $pp$ ,  $pPb$ , and  $PbPb$  collisions at  $\sqrt{s_{NN}} = 0.9 - 7$  TeV, Phys. Rev. C 97 (6) (2018) 064912. [arXiv:1712.07198](https://arxiv.org/abs/1712.07198), [doi:10.1103/PhysRevC.97.064912](https://doi.org/10.1103/PhysRevC.97.064912).
- [22] CMS Collaboration, A. M. Sirunyan, et al., Bose-Einstein correlations of charged hadrons in proton-proton collisions at  $\sqrt{s} = 13$  TeV, Journal of High Energy Physics 2020 (3). [doi:10.1007/jhep03\(2020\)014](https://doi.org/10.1007/jhep03(2020)014).
- [23] ATLAS Collaboration, G. Aad, et al., [Two-particle bose–einstein correlations in pp collisions at 0.9 and 7 tev measured with the atlas detector](https://arxiv.org/abs/1505.04795), The European Physical Journal C 75 (10). [doi:10.1140/epjc/s10052-015-3644-x](https://doi.org/10.1140/epjc/s10052-015-3644-x).  
URL <http://dx.doi.org/10.1140/epjc/s10052-015-3644-x>
- [24] V. V. Khoze, F. Krauss, M. Schott, [Large effects from small qcd instantons: making soft bombs at hadron colliders](https://arxiv.org/abs/2004.02011), Journal of High Energy Physics 2020 (4). [doi:10.1007/jhep04\(2020\)201](https://doi.org/10.1007/jhep04(2020)201).  
URL [http://dx.doi.org/10.1007/JHEP04\(2020\)201](http://dx.doi.org/10.1007/JHEP04(2020)201)
- [25] V. V. Khoze, D. L. Milne, M. Spannowsky, [Searching for qcd instantons at hadron colliders](https://arxiv.org/abs/1303.6401), Physical Review D 103 (1). [doi:10.1103/physrevd.103.014017](https://doi.org/10.1103/physrevd.103.014017).  
URL <http://dx.doi.org/10.1103/PhysRevD.103.014017>

- [26] H1 Collaboration, Search for qcd instanton-induced processes at herA in the high- $q^2$  domain, Eur.Phys.J. C 76 (2016) 1. [arXiv:1603.05567](#).
- [27] ZEUS Collaboration, S. Chekanov, et al., Inclusive  $K_0(S)K_0(S)$  resonance production in ep collisions at HERA, Phys. Rev. Lett. 101 (2008) 112003. [arXiv:0806.0807](#), [doi:10.1103/PhysRevLett.101.112003](#).
- [28] LHCb Collaboration, R. Aaij, et al., Measurement of the branching fraction of the decay  $B_s^0 \rightarrow K_S^0 K_S^0$ , Phys. Rev. D 102 (1) (2020) 012011. [arXiv:2002.08229](#), [doi:10.1103/PhysRevD.102.012011](#).
- [29] L3 Collaboration, M. Acciarri, et al.,  $k_s^0 k_s^0$  final state in two-photon collisions and implications for glueballs, Physics Letters B 501 (3) (2001) 173 – 182. [doi:https://doi.org/10.1016/S0370-2693\(01\)00116-2](#).
- [30] E. Klempt, A. Zaitsev, Glueballs, Hybrids, Multiquarks. Experimental facts versus QCD inspired concepts, Phys. Rept. 454 (2007) 1–202. [arXiv:0708.4016](#), [doi:10.1016/j.physrep.2007.07.006](#).
- [31] BES Collaboration, Search for  $k_0s k_0s$  in  $j/\psi$  and  $\psi(2s)$  decays, Physics Letters B 589 (1) (2004) 7 – 13. [doi:https://doi.org/10.1016/j.physletb.2004.03.047](#).
- [32] B. Aubert, et al., Search for B decays into  $K_0$  anti- $K_0$ , in: 9th International Symposium on Heavy Flavor Physics, 2001. [arXiv:hep-ex/0109005](#).
- [33] S. Joosten, personal communication (2020).
- [34] ZEUS Collaboration, S. Chekanov, et al., Search for lepton-flavor violation at HERA, Eur. Phys. J. C 44 (2005) 463–479. [arXiv:hep-ex/0501070](#), [doi:10.1140/epjc/s2005-02399-1](#).
- [35] H1 Collaboration, F. Aaron, et al., Search for Lepton Flavour Violation at HERA, Phys. Lett. B 701 (2011) 20–30. [arXiv:1103.4938](#), [doi:10.1016/j.physletb.2011.05.023](#).
- [36] The LHCb Collaboration, Observation of structure in the  $J/\psi$ -pair mass spectrum [arXiv:2006.16957](#).
- [37] ZEUS Collaboration, S. Chekanov, et al., Evidence for a narrow baryonic state decaying to  $K_0(S)$  p and  $K_0(S)$  anti-p in deep inelastic scattering at HERA, Phys. Lett. B 591 (2004) 7–22. [arXiv:hep-ex/0403051](#), [doi:10.1016/j.physletb.2004.04.024](#).
- [38] ZEUS Collaboration, H. Abramowicz, et al., Search for a narrow baryonic state decaying to  $pK_S^0$  and  $\bar{p}K_S^0$  in deep inelastic scattering at HERA, Phys. Lett. B 759 (2016) 446–453. [arXiv:1604.02220](#), [doi:10.1016/j.physletb.2016.06.001](#).
- [39] H1 Collaboration, A. Aktas, et al., Search for a narrow baryonic resonance decaying to  $K_0(s)p$  or  $K_0(s)\text{anti-p}$  in deep inelastic scattering at HERA, Phys. Lett. B 639 (2006) 202–209. [arXiv:hep-ex/0604056](#), [doi:10.1016/j.physletb.2006.06.055](#).

- [40] PARTICLE DATA GROUP Collaboration, M. Tanabashi, et al., [Review of particle physics](#), Phys. Rev. D 98 (2018) 030001. doi:[10.1103/PhysRevD.98.030001](https://doi.org/10.1103/PhysRevD.98.030001). URL <https://link.aps.org/doi/10.1103/PhysRevD.98.030001>
- [41] H1 Collaboration, A. Aktas, et al., Evidence for a narrow anti-charmed baryon state, Phys. Lett. B 588 (2004) 17. arXiv:[hep-ex/0403017](https://arxiv.org/abs/hep-ex/0403017), doi:[10.1016/j.physletb.2004.03.012](https://doi.org/10.1016/j.physletb.2004.03.012).
- [42] ZEUS Collaboration, S. Chekanov, et al., Search for a narrow charmed baryonic state decaying to  $D^{*+} p$  in ep collisions at HERA, Eur. Phys. J. C 38 (2004) 29–41. arXiv:[hep-ex/0409033](https://arxiv.org/abs/hep-ex/0409033), doi:[10.1140/epjc/s2004-02042-9](https://doi.org/10.1140/epjc/s2004-02042-9).
- [43] A. H. Mueller, Parton distributions at very small x-values, Nucl. Phys. B (Proc. Suppl.) 18C (1991) 125–132.
- [44] H. Jung, Aspects of BFKL physics at HERA (2021). arXiv:[2111.09597](https://arxiv.org/abs/2111.09597).
- [45] H1 Collaboration, F. D. Aaron, et al., Measurement of the azimuthal correlation between the most forward jet and the scattered positron in deep-inelastic scattering at HERA, The European Physical Journal C 72 (3). doi:[10.1140/epjc/s10052-012-1910-8](https://doi.org/10.1140/epjc/s10052-012-1910-8).