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Summary of Working Group 7: Future of DIS

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These proceedings give a summary of experimental and theoretical progress, results and a outlook on the future of deep inelastic scattering (DIS) presented in the parallel session of Working Group 7 during the DIS2018 Workshop. Several selected topics, such as electron-ion colliders, high energy DIS facilities, fixed target experiments and other related experimental efforts and theoretical results, have been discussed in this working group.

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1. Introduction

During the DIS2018 workshop, thanks to the speakers and participants as well as the local organizers, the Working Group 7 –"Future of DIS", has organized a rich program, which is featured by 40 presentations and one panel discussion [1] on the intersting physics of DIS, with particular emphasis on future DIS facilities.

This report gives a brief summary of future of DIS facilities and experiments discussed at DIS 2018 in Kobe. Discussions were structured around near future plans of related existing facilities such as (JLAB, LHC, RHIC, KEK) as well as proposed future facilities (CLIC, EIC, LHeC, FCC or VHEeP). A program was structured around following topics: electron-ion collider, high energy ep/eA facilities, fixed target facilities, and DIS related activity at pp, AA, e^+e^- facilities.

2. Electron-Ion Colliders(EIC)

A medium-energy high-luminosity polarized Electron Ion Collider (EIC) was enthusiastically recommended by the US nuclear science advisory committee (NSAC), as the highest priority new facility to be built in the US in the near future. The EIC with its unique capability to collide (un)polarized electrons with (un)polarized protons and light ions, and with various elements of heavy nuclei, will be the ideal and much needed facility to explore the emerging science of nuclear femtography and take us to the next frontier of the Standard Model of nuclear physics [2, 3]. The EIC is a QCD facility to measure structure and dynamic of matter with a main emphasis on studying hadron properties such as hadron mass and spin, 3D imaging of hadrons, emergence of hadrons and probing QCD at extreme parton densities in eA collisions [4, 5, 6].

2.1 EIC accelerator and detector concepts

Two possible configurations for the realization of EIC in US have been presented, eRHIC [7] and JLEIC [8]. These two realizations are making a use of existing pp (RHIC) (Fig. 1) and electron (CEBAF) (Fig. 2) facilities, respectively.

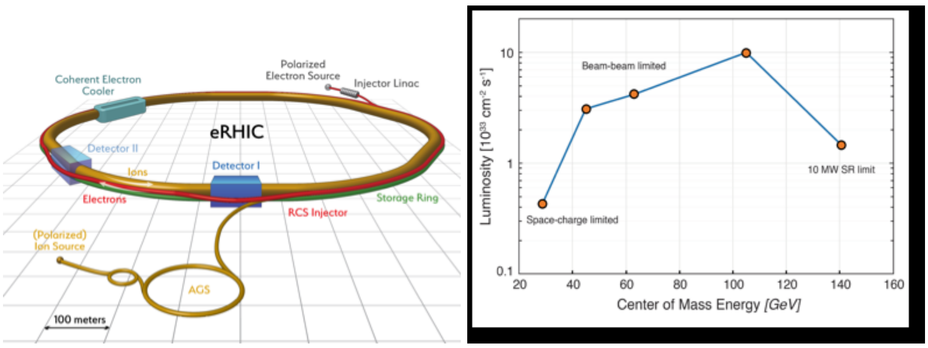

Figure 1: The proposed eRHIC facility and expected luminosity and center of mass coverage.

Both facilities are optimizing their designs to reach the highest possible luminosity of $10^{33}-10^{34} cm^{-2}s^{-1}$ in a broad range ($\sqrt{s} \sim 20-100\,(140)$ GeV) of the center-of-mass energy. The novel technology for bunched beam cooling system has been addressed. The figure-8 shape of JLEIC

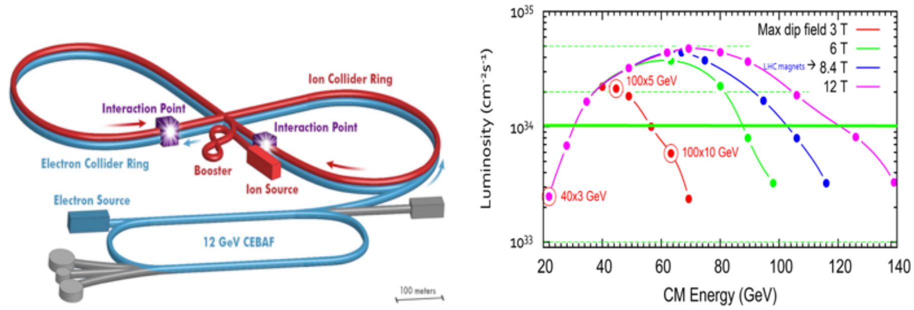

Figure 2: The proposed JLEIC facility and expected luminosity and center of mass coverage.

design allows for preservation and ease of manipulation of the electron polarization and the spin of proton and any light ion species (d, ^3He, Li). Both accelerator designs could accommodate a full-acceptance detector, BeAST and JLEIC, respectively, with complete coverage and geometry tagging in the forward and ultra-forward directions.

The experimental program of the EIC is very diverse. The main goal of the current generic EIC Detector *R&D* Program is to develop detector concepts and technologies that are suitable to carry out the specific EIC scientific program to address open questions in nuclear physics. The broad experimental scope places challenging and unique requirements on detector capabilities, such as, excellent particle identification (PID), vertex detectors, calorimeter, etc. The current status of advancing related detector technologies has been presented [6].

An alternative detector concept [9], TOPSiDE (Fig. 3), proposed for the EIC aims to achieve the best possible momentum/energy resolution exploring the advantages offered by high granularity imaging calorimetry and Particle Flow Algorithms (PFAs). It also includes an ultra-fast silicon sensor, which is necessary for particle identification and position reconstruction. The detector concept, the status of its simulation software, and the first studies performed with a completed simulation tool chain has been presented.

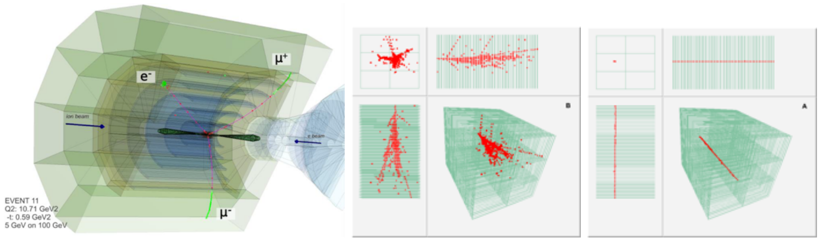

Figure 3: A proposed TOPSIDE detector with a high granularity imaging calorimeter.

Geometry tagging, which is an experimental analysis technique widely used in heavy ion (AA) collisions at RHIC and the LHC, plays also an important role in deep-inelastic scattering for studies of gluon anti-shadowing, parton propagation, attenuation and hadronization in the nucleus, and ultimately for the search for the evidence of gluon saturation effects. The EIC full-acceptance detector, such us at JLEIC, with a full acceptance for forward-going neutrons, protons and nuclear fragments and a high data-taking rate should be ideally suited for such geometry tagging. Recently developed simulation tools, such as BeAGLE, Sartre and GEMC, which help to improve and to tune detectors to study this type of physics, are now available and could be used for simulation studies [10].

High precision measurements at an electron-ion collider demand high precision measurements of hadron polarization. At RHIC, the world's only polarized hadron collider, polarization measurements are performed via two methods: using a polarized hydrogen jet polarimeter (HJET), which has a low rate but provides a source of absolute polarization, or using a proton-carbon polarimeter (pC), which is fast and precise, but needs to be normalized to HJET. The challenges to measure hadron polarization in high collision frequency and luminosity at future electron ion colliders has been discussed [11].

An alternative design of an electron-ion collider was also developed in China (EicC) [12]. In the first phase the EicC running, it is planned to operate $3-5$ GeV polarized electrons and $12-25$ GeV polarized protons (and ions of about 12 GeV per nucleon), achieving a luminosity of $10^{33} cm^{-2}s^{-1}$, with a later upgrade to higher energy and luminosity. The main focus of the EicC physics program is high prescription measurements of sea quarks (1D and 3D structure) inside protons and neutrons, the gluon density, the hadronization mechanism, as well as new physics studies.

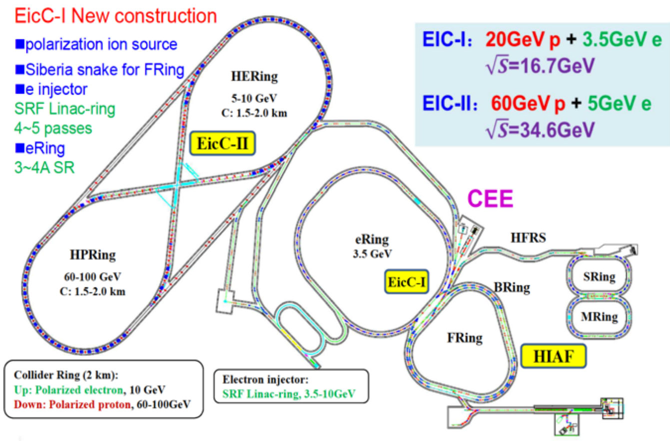

Figure 4: The EIcC design.

The current effort of bringing a polarized positron beam with an energy of 12 GeV to JLab and JLEIC has been discussed. The recent PEPPo (Polarized Electrons for Polarized Positrons) experiment at the Thomas Jefferson National Accelerator Facility (JLAB) opens an easy and low-cost access to a polarized positron beam through the efficient production of polarized positrons from the bremsstrahlung radiation of a MeV polarized electron beam. The application of this technique in the context of the upgraded CEBAF (Continuous Electron Beam Accelerator Facility) and JLEIC projects would allow to investigate new features of deep inelastic and exclusive scatterings [13].

2.2 Physics at EIC

There are many physics opportunities in spin physics which can be explored at the EIC. The underlying parton structure of the exchanged photons and gluon Sivers-functions can be accessed by measuring di-jets events. For the first time, the polarized PDFs for photons can be extracted

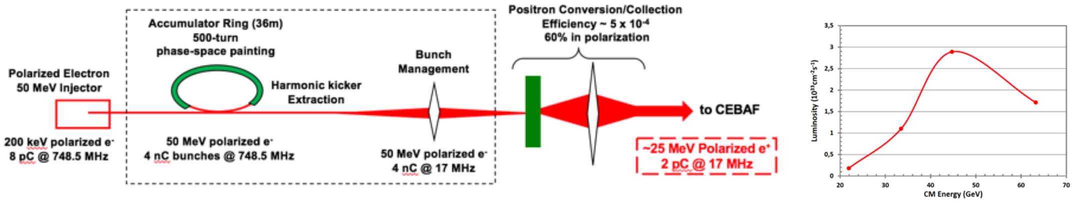

Figure 5: A proposed positron-ion collider at JLAB.

by measuring the double spin asymmetry as a function of x_γ. A tagging method could be used to probe the flavor of the parton content experimentally [14].

A newly published analysis from the HERMES experiment, which extracts new information on the space-time properties of color propagation through fitting to a geometric model of the interaction with a realistic nuclear density distribution has been presented [15]. By comparing p_T broadening and hadron attenuation in nuclei of different sizes, one can measure the length of the process of color propagation at the femtometer scale. This will lead to the first measurement of the color lifetime. Using simple kinematic arguments, one could predict the color lifetime for typical kinematic conditions for 5 GeV measurements at Jefferson lab, for 11 GeV beam at the upgraded Jefferson Lab, and at the energies of the future Electron-Ion Collider.

Heavy flavor production in DIS (open charm, beauty) provides a direct probe of the gluon density in the target. It can be used to determine the unknown nuclear modifications of the gluon density at large x (EMC effect, antishadowing), which reveals the fundamental QCD substructure of nucleon interactions in the nucleus (Fig 6). The demand for a high overall efficiency for charm identification requires a new generation of vertex detectors and particle identification capabilities at the EIC, as well as a high luminosity accelerator facility [16].

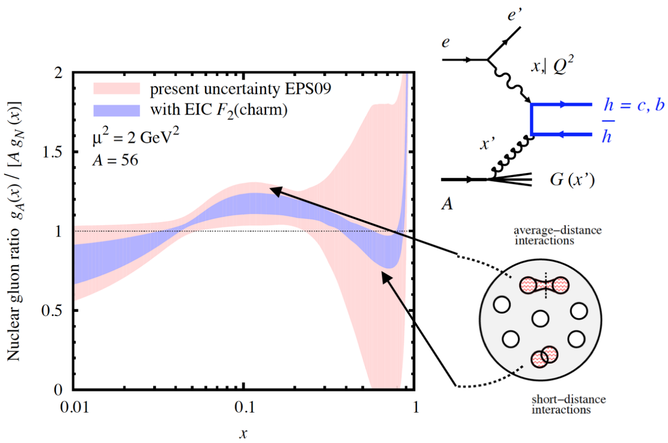

Figure 6: Heavy flavor production in DIS as a direct probe of the gluon density could be used to study nucleon interactions in the nucleus.

The Monte Carlo generator eSTARlight has been presented which was developed to study productions of exclusive vector meson final states, such as ρ, ϕ, J/ψ, ψ' and the Υ for ep and eA collisions has been presented. Exclusive vector meson electroproduction offers a unique opportunity to probe the gluon structure of nuclei to measure nuclear shadowing, and to search for gluon saturation and/or the colored glass condensate at an EIC. Vector mesons are produced over a wide rapidity range (see Fig 7). Therefore, reliable forward and rear instrumentation is essential for this type of physics at the EIC [17].

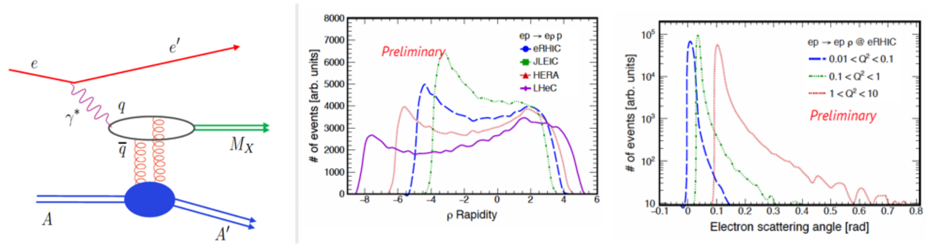

Figure 7: Simulations of vector meson production in DIS at different colliders.

DIS of deuterons with detection of a proton in the nuclear fragmentation region ("spectator tagging") represents a unique method for extracting the neutron structure functions and their spin dependence [18]. Such measurements could be performed at a future EIC with suitable forward detectors. Recent progress in theory and simulation was reported including the development of a theoretical model of nuclear final-state interactions, a calculation of the proton recoil momentum distribution, as determined by initial-state deuteron structure (S and D-waves) and final-state interactions, and simulations of recoil momentum measurements and neutron structure extraction at the EIC.

Pions and kaons are, along with protons and neutrons, the main building blocks of nuclear matter. The distribution of the fundamental constituents, the quarks and gluons, is expected to be different in pions, kaons, and nucleons. The EIC with an acceptance optimized for forward physics could provide access to structure functions over a larger kinematic region. This would allow for measurements to test if the origin of mass is encoded in the difference between gluon distributions in pions, kaons, and nucleons, as well as for measurements that could serve as a test of assumptions used in the extraction of structure functions [19].

3. STAR and PHENIX upgrade

The STAR experiment is planning to upgrade the forward rapidity region ($2.5 < \eta < 4.5$), which is motivated by the exploration of cold QCD physics in the very high and very low regions of Bjorken x. The current design envisions a Calorimeter System (FCS) that integrates parts of the refurbished PHENIX sampling ECal and a hadronic calorimeter (including sandwich iron scintillator plates), as well as a Forward Tracking System (FTS) which is a combination of Silicon mini-strip disks and Small-Strip Thin Gap Chamber (sTGC) wheels. The upgrade will allow studies of the dynamics of partons in cold nuclear matter (CNM) both at low and high x, and of the modification of fragmentation and hadronization of partons through interactions within CNM. Further experiments to study the $2+1$ d momentum and spatial structure of protons and nuclei will become possible, too. Such measurements will provide high precision data that will be essential to enable rigorous universality tests [20] when combined with future results from the EIC.

The proposed sPHENIX [21] detector at RHIC will enhance our understanding of quantum chromodynamics (QCD) by investigating how partons behave in a nuclear environment. This will enable us to explore spin-spin and spin-momentum correlations in the nucleon, and will provide data to investigate effects of non-universality. A potential upgrade to sPHENIX by adding forward instrumentation could significantly enhance these physics capabilities.

4. Very high energy ep/eA colliders

DIS at the high energy frontier allows a diverse and rich physics program covering not only hadronic and nuclear physics, PDFs, and high-x and high Q^2 QCD measurements, but also small-x physics and diffraction, high precision electroweak (EWK), top quark and Higgs boson measurements, and sensitive searches for physics beyond the standard model (BSM).

4.1 Future very high energy ep/eA accelerator and detector concepts

The ring linac colliders *LHeC* [23] and *FCC-eh* are future projects where an electron accelerated in an energy recovering linac (ERL) [24] is collided with a hadron from the LHC (see Fig. 8 upper left). An overview of the ERL is shown at Fig. 8 (lower left). The Powerful ERL for Experiments (PERLE) is planned as a demonstrator providing centre-of-mass energies of the order of 10 MeV [25]. It is important to note, that at the LHeC ep collisions will be produced and measured synchronously and simultaneously to the LHC operation. The scenarios studied here involve an electron beam energy of 60 GeV, and an LHC proton beam of 7 TeV (LHeC) leading to a center-of-mass energy of 1.3 TeV, and an FCC-hh proton beam of 50 TeV (FCC-eh) leading to a center-of-mass energy of 3.5 TeV, respectively. An integrated luminosity of 1 ab^{-1} is assumed for 10 years of running the LHeC, and 2 ab^{-1} is assumed for 25 years of running the FCC-eh. A detailed layout for the LHeC and FCC-eh detectors is shown in Fig. 8 (upper right), and is available in the DELPHES simulation package.

The VHEep [22] is a result of an international community-wide development of a novel accelerator mainly based on plasma wake field technology (AWAKE) (see Fig. 8 lower right), which can accelerate electrons to very high energy (around 3 TeV) using the LHC driver. A similar version, which is known as PEPIC as a demonstration project for VHEep, uses the SPS driver to accelerate electrons. Essentially, it leads to an ultra high energy but low luminosity collider, which can be useful for high energy physics measurements which do not require high luminosities. Its targeted physics objectives are studies of QCD dynamics at extremely small-x and gluon saturation, the measurement of vector meson production and the exploration of the high-energy limit of total cross-sections as well as selected opportunities in the search for BSM physics.

4.2 Physics with the LHeC and FCC-eh

If realized, the LHeC and FCC-eh projects will allow to explore a rich and diverse physics program of *eh* scattering at a new high energy frontier. A few selected highlights of physics studies are presented in the following.

As an example for the broad variety of QCD studies, jets in photoproduction can be used to investigate jet properties, substructure, non-perturbative effects, and much more [26]. Measurements of up-quark, down-quark (therefore being a flavor separator) and gluon PDFs at the LHeC or

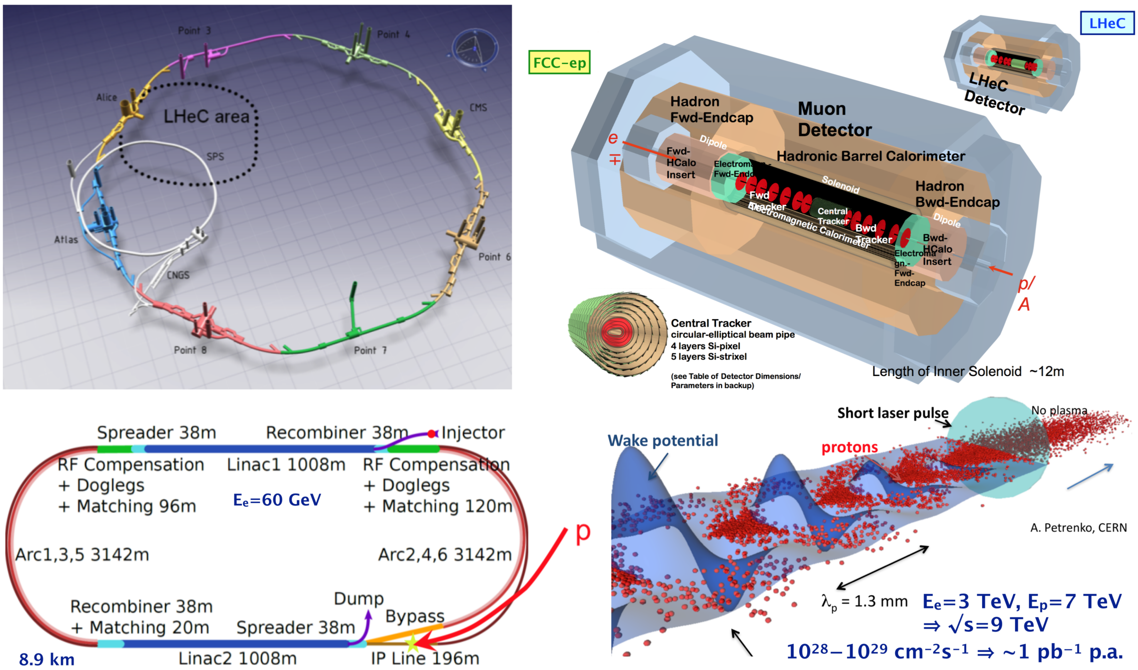

Figure 8: The LHeC accelerator (upper left); the layout of the LHeC and FCC-eh detectors (upper right); the ERL (lower left); acceleration of electrons with AWAKE and the Very High Energy eP collider (lower right).

FCC-eh will represent a huge improvement in precision compared to our current knowledge [27]. The results will be particularly important to test pp factorization, for high-precision Higgs boson measurements, and for searches for BSM physics. An example for an expected gluon PDF measurement at low-x (upper left) and high-x (upper middle) is shown in Fig 9. Very precise measurements of nuclear PDFs are particularly interesting, since they allow to study nuclear effects such as (anti-)shadowing, EMC, Fermi motion, etc. [28]. An example for the expected PDF extraction for Pb nuclei and the ratio for Pb over proton is presented in Fig. 9 (upper right)[1]. Moreover, diffractive parton densities can be measured differentially with high precision [29]. Figure 9 shows expected cross section results as a function of the fractional longitudinal momentum loss of the proton ξ (different plots), the fraction of this momentum taking part in the interaction with the photon β (x-axis), where Bjorken-x is given by $x = \beta\xi$, and for different values of Q^2 (different colors). Such data could be used to test diffractive factorization and the proton vertex factorization ("pomeron structure").

As an example for very high precision EWK measurements, the fermionic couplings of the Z-boson can be measured with a precision better than 1%. Consequently, it also provides a precise measurement dependent on the scale μ [30]. This is shown in Fig. 10 (upper left) for the NC coupling parameter $\rho'_{\mathrm{NC},f}$, defined as $g_A^f = \sqrt{\rho_{\mathrm{NC},f}\,\rho'_{\mathrm{NC},f}}\,I^3_{\mathrm{L},f}$, $g_V^f = \sqrt{\rho_{\mathrm{NC},f}\,\rho'_{\mathrm{NC},f}}\,(I^3_{\mathrm{L},f} - 2Q_f\,\kappa_{\mathrm{NC},f}\,\kappa'_{\mathrm{NC},f}\sin^2\theta_W)$. These results have a high sensitivity to BSM physics, and were shown to be complementary to results from future e^+e^- colliders. The LHeC is also particularly well-suited

[1] the EPPS error bands are biased by the proton PDF put into the extraction.

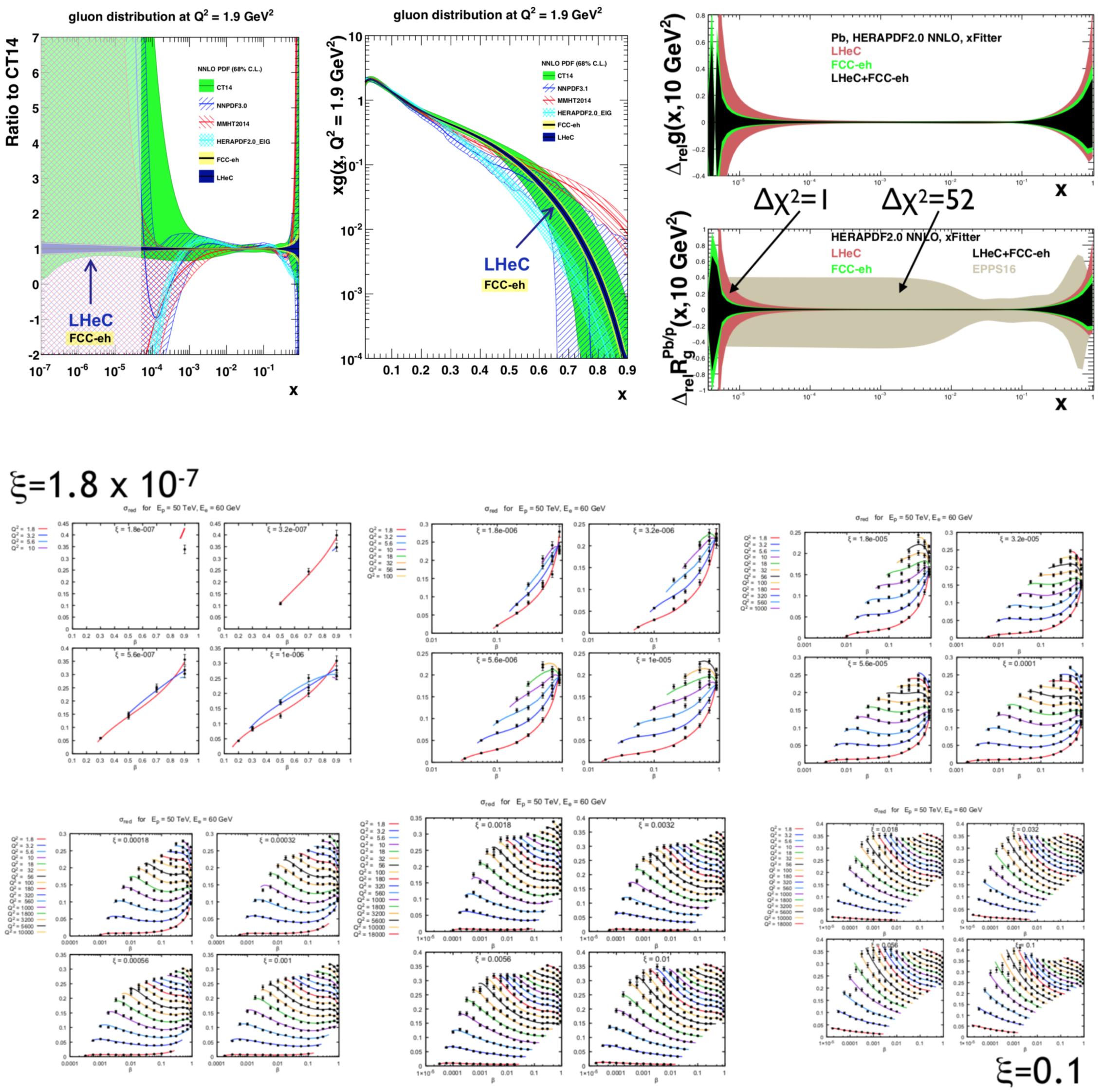

Figure 9: Results of LHeC and FCC-eh, respectively, on gluon PDFs at low (upper left) and high Bjorken-x (upper middle); nuclear PDFs (upper right); diffractive cross sections (lower).

to measure electroweak couplings of top quarks [31], such as both the SM and anomalous Wtb couplings as defined in $L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_V^L P_L - f_V^R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(f_T^L P_L - f_T^R P_R)tW_{\mu}^{-} + h.c.$. The expected accuracies for these couplings are on the percent level, and are shown as a function of the integrated luminosity in Fig. 10 (upper right). It is important to notify that the CKM matrix element V_{tb} can be measured with an uncertainty of better than 1% which exceeds existing measurements from the LHC.

High precision measurements of Higgs boson properties can be performed exploring the $WW \to H$ and $ZZ \to H$ production channels [32]. Many Higgs couplings can be measured with very high precision, and valuable results complimentary to those from pp scattering can be gained. This will make the LHC a Higgs precision facility as can be inferred from the $ep + pp$ combination presented

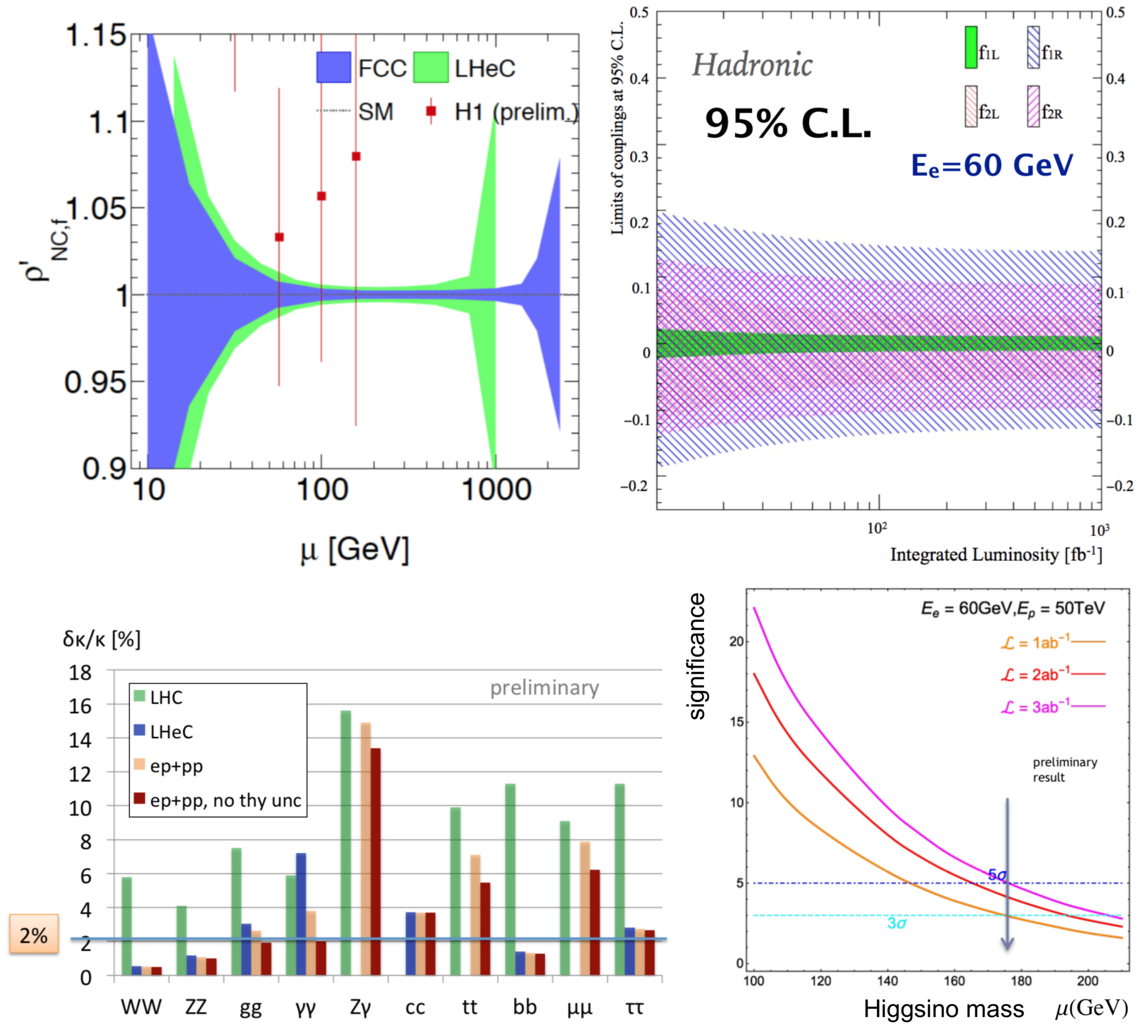

Figure 10: Results of LHeC and FCC-eh, respectively, EWK NC couplings (upper left); *Wtb* couplings (upper right); Higgs boson couplings (lower left); Higgsino pair production (lower right).

in Fig. 10 (lower left), resulting in accuracies below 2% for most of the couplings. Furthermore, many sensitive searches for new phenomena can be performed in *ep* scattering [33], such as for prompt Higgsino pair production in a SUSY model, where the Higgsino is the lightest SUSY particle. The significance at the FCC-eh of such a search as a function of the Higgsino mass is presented in Fig. 10 (lower right).

5. Fixed-target facilities

Jefferson Lab (JLAB) recently completed an upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF) from 6 to 12 GeV [34]. A very high luminosity ($\sim 10^{35} cm^{-2} s^{-1}$) offered by CEBAF makes it a unique facility for high precision studies of a variety of inclusive, semi-inclusive, and exclusive reactions in deep inelastic electron-nucleon and electron-nucleus scattering. The extended kinematic coverage will allow measurements of nucleon and nuclear structure in the valence region, such as Transverse Momentum Dependent Parton Distributions (TMDs) and Generalized Parton Distributions (GPDs), with unprecedented precision [35, 36]. Newly upgraded detectors as well as the polarized target technology in experimental Halls A, B and C will provide ten years of data taking advantage of the upgraded CEBAF beam.

The COMPASS experiment makes use of the CERN SPS high intensity muon and hadron beams to study the nucleon structure and to perform hadron spectroscopy [37]. COMPASS is now planning its future beyond 2020. Measurements will involve semi-inclusive measurements utilizing a transversely polarized deuteron target and proton radius measurements in high-energy elastic muon-proton scattering ($\mu p \rightarrow \mu p$).

AFTER@LHC is a future fixed-target program currently under study, where the LHC beam is scattered with a gas target producing pp, pA, and PbA collisions [38, 39]. This will allow to study, for example, the spin of gluons and quarks inside (un)polarised nucleons.

6. Other related facilities (ee, pp, AA)

The Belle II experiment [40] will be operated at the SuperKEKB energy-asymmetric e^+e^- collider. The accelerator has successfully completed the first phase of commissioning, and data taking with the complete detector is foreseen for February 2019. The design luminosity is $8 \cdot 10^{35}\mathrm{cm}^{-2}s^{-1}$ with an aim to record $5\,\mathrm{ab}^{-1}$ of data by 2020. This will allow to probe new physics regimes, such as of lepton universality in $B \rightarrow D^{(*)}\ell\nu$, dark photon and dark matter searches, and CP Violation in $b \rightarrow s\gamma, b \rightarrow d\gamma$.

CLIC is a linear e^+e^- collider project foreseen to operate in different stages at centre-of-mass energies of 350, 380, 1500, and 3000 GeV [41]. A very rich and wide high energy physics program can be performed. One shining example amongs many others is the high precision measurement of the top quark mass in the quantum field theoretically properly defined 1S scheme with an accuracy of 10 MeV (experimentally) and 50 MeV (theoretically) scanning the top quark pair production threshold.

Results from future e^+e^--, eh-, and hh-colliders deliver complimentary information and will therefore give us a more complete understanding of particle physics in many fields. Fig. 11 (left) presents how accurate different flavor-changing neutral current (FCNC) top quark couplings can be measured at different future colliders and clearly shows the complementarity of the results. Fig. 11 (right) shows the complementarity of results on Higgs boson couplings between the LHeC (dominated by $WW \rightarrow H$ production and therefore delivering higher accuracy on the WWH coupling) and CLIC (dominated by Higgsstrahlung from the Z boson and therefore delivering higher accuracy on the ZZH coupling). The combination from all three different types of colliders will give us a complete picture in elementary particle physics at the high energy frontier.

7. Summary

The physics of DIS represents a very rich and diverse field of research. Many exciting highlights were presented at the DIS 2018 Workshop, and are summarized here. DIS is unique and complementary both in studying the inner structure of nature, and in performing high precision

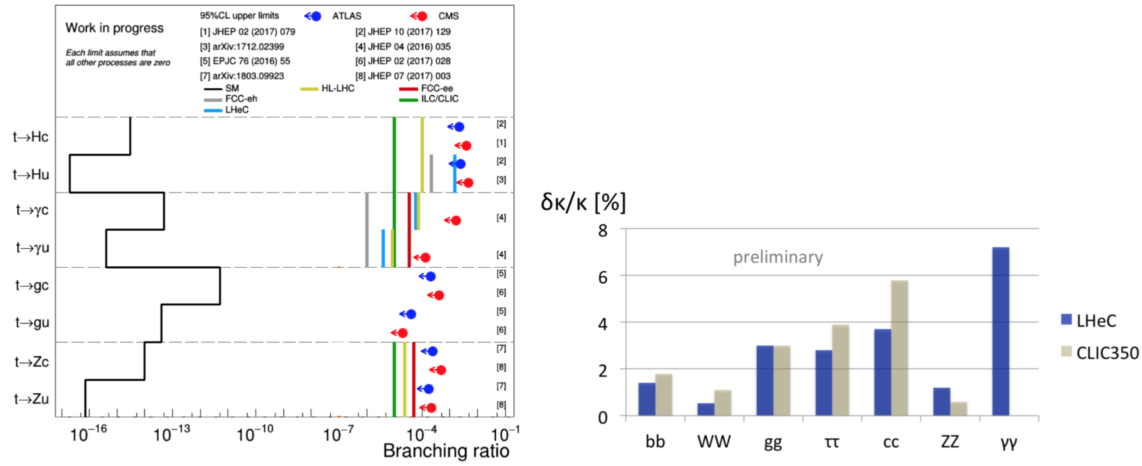

Figure 11: Limits on FCNC top quark decay branching ratios at e^+e^--, eh-, and hh-colliders (left); expected accuracies on Higgs boson couplings at the LHeC and at CLIC ($\sqrt{s} = 350$ GeV).

measurements of particle properties, which lead to high sensitivities for the discovery of new physics.

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