Physics at High Energy eh and hh Experiments

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1 The Value of Joint DIS and Hadron-Hadron Colliders

The past saw HERA operating together with LEP/SLC and the Tevatron, following a series of muon and neutrino DIS experiments operating together with the SPS $p\bar{p}$ collider, PETRA and PEP. CERN was the host of world leading DIS and hh experiments at once. The current situation of not having a DIS collider operational at the energy scale and luminosity standards of the LHC becomes an obstacle to the exploitation of the LHC. This holds even more so since theory is currently unclear in the path shown forward and experiments at the energy (and precision) frontier have to be pursued as widely different as possible to catch signs for new physics which the incomplete SM hints at.

After almost 10 years of scientific exploitation of the LHC and nearly $200\,\mathrm{fb}^{-1}$ of proton-proton collision data delivered to each of the ATLAS and CMS experiments, the sensitivity of a significant fraction of leading measurements and searches becomes limited by systematic uncertainties. Uncertainties induced by the strong interaction, in particular related to the proton structure, play a prominent role and tend to saturate the physics reach of the experiments. This context will only become more evident when the LHC enters its high-luminosity era. The LHeC is designed to then operate concurrently with the LHC and provides the otherwise missing information on proton structure and dynamics.

Based on the first CDR of the LHeC [1] published in 2012, an update has very recently been presented [2], in which a full chapter is dedicated to the elucidation of how the ep and eA experiment would lead to a more thorough exploitation of the LHC facility physics potential. Examples have been studied and presented on leading problems for the HL-LHC: the challenge for ultra-high precision electroweak measurements, such as on $\sin^2\theta$ and M_W, the search range for high energy scale or mass effects such as Contact Interactions, the combination of the Higgs measurement potential of pp with ep and the resolution of the QCD dynamics underlying the Quark-Gluon Plasma through luminous, high energy electron-ion deep inelastic scattering. Two illustrations, taken from [2], are presented below.

The complementarity, further in the future, of eh and hh scattering is apparent also for the FCC, deserving much deeper study. Clearly with higher energy, rapidity plateau physics at FCC-hh becomes small x physics, the Higgs, for example, being produced at $x \simeq 0.001$ for $\eta = 0$. There is a necessity for DIS to be planned and realised together with a next hadron collider for avoiding the oversight of the LHC planning. It has been shown, for both the LHeC and FCC-eh, that DIS can proceed concurrently with hadron-hadron operation. The FCC-eh has been part of the Future Circular Collider as was presented with the FCC CDR [3]. For the future post-HL-LHC, this will be a major topic, perhaps even earlier if an e^+e^- collider is built in Asia and CERN may directly proceed towards a next hadron collider.

2 Two Examples for the HL-LHC

The Hl-LHC has a great potential for precision electroweak measurements, of which those of M_W and $\sin^2\theta$ are of particular importance. Fig. 1, from [2], compares the ATLAS sensitivity studies of the weak mixing angle to previous measurements from the LHC experiments and to the legacy measurements by the experiments at LEP and SLC and the Tevatron The precision of the measurement of the weak mixing angle in Z-boson events, using 3 ab^{-1} of pp collision data at $\sqrt{s} = 14$ TeV,

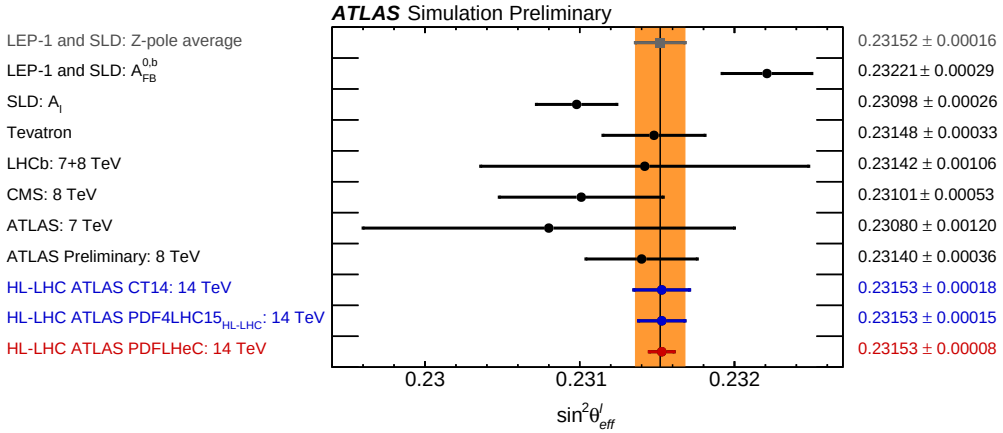

Figure 1: Comparison of measurements or combinations of $\sin^2\theta$ with the world average value (orange band) and the projected uncertainties of measurements at the HL-LHC. For the HL-LHC the central values are set to the world average value and uncertainties are displayed for different assumptions of the available PDF sets.

exceeds the precision achieved in any of the previous single-experiments to date. The LHeC is thus essential in exploiting the full potential of the HL-LHC data for this measurement.

A second example regards Higgs physics at the LHC facility, *ep* and *pp*. The clean final state,

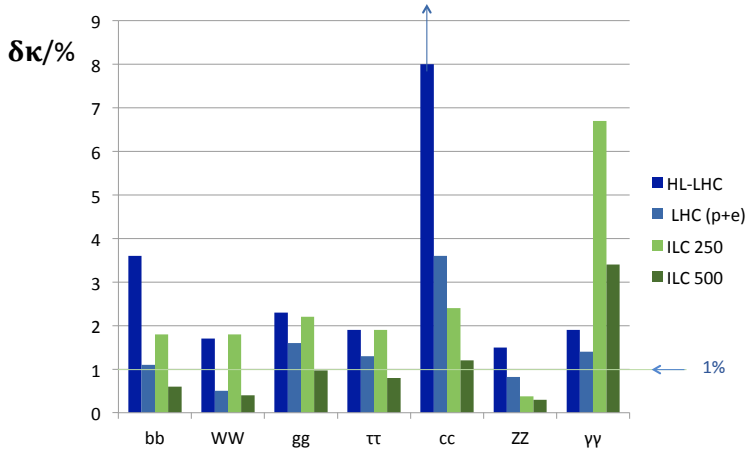

Figure 2: Prospect Higgs results, expressed in the SM kappa framework for the HL-LHC, jointly ep and pp at LHC, the ILC 250 and ILC 500, from [1710.0762]

the unique distinction of ZZH and WWH production and a well controlled theory enable precise measurements of the Higgs boson couplings in *ep*. The joint HL-LHC and LHeC prospects are presented in Fig. 2 for the seven most abundant Higgs decay channels representing 99.8% of the total SM decay width. The substantial improvement of the HL-LHC prospects by the addition of *ep* is evident. It leads to O(1)% precision for all these couplings, with a few % for charm which hardly will be accessible at the LHC. These results are comparable to those envisaged for the ILC. Given the different production mechanisms in *pp*, *ep* and e^+e^- and the high precision required, these are exciting prospects.

The topic of joint HL-LHC and energy frontier DIS physics and experimentation is far from having been resolved or studied in any complete manner. Given the massive engagement of the American community in the HL-LHC programme, this is expected to be of particular interest for the Snowmass process.

References

[1] J. L. Abelleira Fernandez et al. A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector. *J. Phys.*, G39:075001, 2012.

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[3] A. Abada et al. FCC-hh: The Hadron Collider. *Eur. Phys. J. ST*, 228(4):755–1107, 2019.