PROCEEDINGS OF SCIENCE

Studying the high x frontier with A Fixed-Target ExpeRiment at the LHC

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The opportunities which are offered by a next generation and multi-purpose fixed-target experiment exploiting the proton and lead LHC beams extracted by a bent crystal are outlined. In particular, such an experiment can greatly complement facilities with lepton beams by unravelling the partonic structure of polarised and unpolarised nucleons and of nuclei, especially at large momentum fractions.

XXI International Workshop on Deep-Inelastic Scattering and Related Subject -DIS2013,
22-26 April 2013
Marseille, France

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PoS(DIS 2013)250

1. Introduction

The Large Hadron Collider (LHC) has been providing the most energetic beams ever, delivering proton beams at 3.5 TeV and 4 TeV, and lead beams at 1.38 TeV per nucleon. Projects of detector and accelerator upgrades are being presently discussed, and the idea of colliding the high energy LHC beams with an electron beam is being investigated by the LHeC study group [1].

The LHC complex could be further exploited in a very cost-effective way by recycling the beam loss towards A multipurpose Fixed-Target ExpeRiment, named AFTER [2]. A bent crystal can be used to extract a fraction of the beam loss [3]. Intensity as high as $5 \times 10^8\ p^+ s^{-1}$ can certainly be obtained. This technology was successfully tested at SPS [5], Fermilab [6], Protvino [7] for proton and recently for lead beams at SPS [8]. It has been proposed as a smart alternative for the upgrade of the LHC collimation system and will be tested by the LUA9 collaboration in the years to come [4]. The available energy in the c.m.s. amounts to $\sqrt{s_{NN}} = 72$ GeV in PbA collisions and $\sqrt{s_{NN}} = 115$ GeV in pA collisions. AFTER will benefit from the typical advantages of a fixed-target experiment, notably the outstanding luminosities (Table 1), the high boost between the laboratory and the center-of-momentum frame ($\gamma \simeq 60$ with the 7 TeV proton beam), the versatility of the target species, and the possibility to polarise the target.

Beam	Target	Thickness (cm)	ρ (g cm^{-3})	A	$\mathscr{L}$ (μb^{-1} s^{-1})	$\int \mathscr{L}$ (pb^{-1} y^{-1})
p	Solid H	10	0.088	1	260	2600
p	Liquid H	100	0.068	1	2000	20000
p	Liquid D	100	0.16	2	2400	24000
p	Pb	1	11.35	207	16	160
Pb	Solid H	10	0.088	1	0.11	0.11
Pb	Liquid H	100	0.068	1	0.8	0.8
Pb	Liquid D	100	0.16	2	1	1
Pb	Pb	1	11.35	207	0.007	0.007

Table 1: Integrated luminosities per year (10^7s for p and 10^6s for Pb) obtained with an extracted beam of 5×10^8 p^+/s (3.5 TeV) and of 2×10^5 Pb/s (1.38 TeV) for various targets. The expected yearly luminosities should be way above that of RHIC in the same energy range.

Thanks to the very energetic LHC beams, AFTER will grant access to the target rapidity region i.e. the full backward region, up to $x_F \to -1$ or equivalently $x_2 \to 1$, which is largely uncharted. The x window covered by AFTER will be complementary [2] to those covered by COMPASS, RHIC and their upgrades, which do not go beyond $x \sim 0.3$, and to electron-ion facilities (such as LHeC) that will access the very low values of x, below 10^{-2}. Recently, the importance of large x physics has been emphasized in [9]. As an example, the Fig. 1 shows the current limitations of our knowledge on the nuclear PDF (nPDF). It is worth underlining that the uncertainties at high x are larger than at low x and that they do not decrease with increasing scale, contrary to what is observed at low x. In the following, we will discuss a short selection[1] of opportunities offered by AFTER for the physics at high x.

[1] More details can be found in [2, 10].

PoS(DIS 2013)250

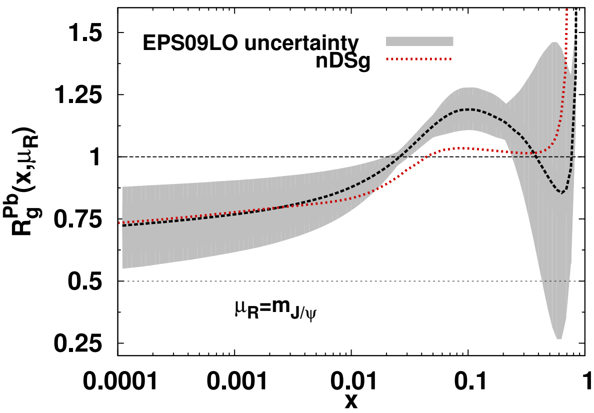

Figure 1: The uncertainty on the nuclear gluon PDF in Pb at the scale of the J/ψ mass.

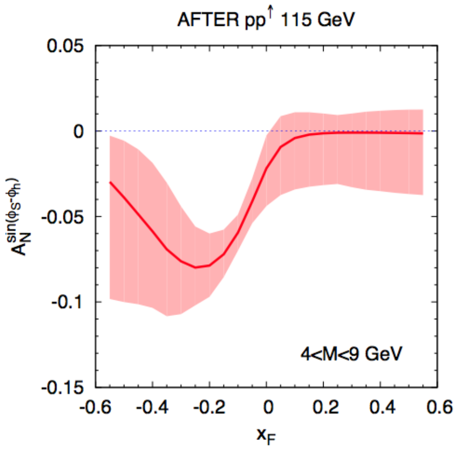

Figure 2: Expected Sivers asymmetry in Drell-Yan measurement at AFTER (no scale evolution). Plot taken from [14], courtesy of U. D'Alesio.

2. Quark distribution at large x

The importance of DY data from fixed-target experiments in global PDF fits is well recognised. By measuring with AFTER DY pair production in both pp and pd collisions in the backward region, the antiquark distributions, $\bar{u}(x)$ and $\bar{d}(x)$, in the nucleons can be accessed at rather low x , complementing the forthcoming studies by E906 [11].

In singly polarised proton-proton collisions, it is also a sensitive probe of the quark Sivers effect and thus of the correlation between the nucleon spin and the transverse momentum k_T of the quark in the nucleon. The study of such correlations are invaluable in the quest to understand the structure of the spin of the nucleons. It has been shown [12] that AFTER is well positioned to measure the quark Sivers effect in DY pair production via such Single-transverse-Spin-Asymmetry (SSA) studies. The domain covered by AFTER in $pp^{\uparrow}$ collisions can basically go up to $x_F \to -1$. In this region, the SSA are sensitive to partons with large momentum fractions in the polarised nucleon, $x^{\uparrow}$. Taking into account the uncertainties obtained in [13], one expects DY asymmetries in the backward region up to 10% in the mass region $4 < M < 9$ GeV (see Fig. 2).

3. Gluon distribution at large x

At high energy, heavy quarkonium production proceeds through gg fusion, whereas isolated photons originate from gq fusion[2]. Both can be used as experimental tools to constrain the gluon PDF and nPDF at large x, which are poorly known (see *e.g.* Fig. 1). A *sine qua non* condition to reach the large x region with these rare probes is a high luminosity, which is precisely what a fixed-target experiment such as AFTER can easily provide [2, 10] in pp and pA collisions. This implies

[2]A recent survey of isolated photon data and their impact on the determination of the gluon PDF can be found in [15].

that AFTER should be designed as a multi-purpose detector, capable of studying quarkonium and isolated photon production. While the use of quarkonia as gluon probe (see *e.g.* [16]) relies on a better understanding of their production mechanisms [17], these would be better constrained thanks to the large quarkonium yields and precise measurements of their correlations, along with the forthcoming LHC results.

In addition, it will be particularly interesting to investigate the gluon content of the neutron and to see whether there is any deviation from that of the proton. A pioneering measurement was done by E866 [18] at Fermilab, using Υ. A unique opportunity to get significant improvements can be offered by AFTER, on two different sides: the precision and also the extension to lower x and Q^2 values by using the J/ψ.

Another question concerns the gluon momentum tomography in the nucleon. Is there any Sivers effect for the gluon? Is there any correlation, pinned down by the Boer-Mulders effect, between the gluon k_T and the gluon linear polarisation?

A first attempt to measure a SSA arising from the gluon Sivers effect was recently carried out by the PHENIX collaboration [19] by looking at J/ψ production in $pp^{\uparrow}$ collisions. Improvements are needed. On top of larger luminosities (by orders of magnitude), AFTER could offer to extend the measurement in various experimental probes sensitive to gluons, such as other quarkonium species (Υ, χ_c, ...), B and D meson [20] production, prompt photon, photon-jet [21] or double photon production [22]. Concerning the Boer-Mulders effect, linearly polarised gluons inside unpolarised protons [23] can be accessed with the study fo low-P_T scalar and pseudoscalar quarkonium[3].

AFTER could also greatly contribute to the knowledge of the gluon nPDF in pA collisions, in good complementarity with LHeC [1] (focusing at low x) and EIC future facilities [25] (at intermediate x). On top of the x dependence, a more precise A dependence is needed. It is easier in a fixed-target setup than in the collider mode thanks to the target versatility. Such results can provide a much better evaluation of the nuclear matter effects on quarkonium and heavy-flavour production, which is a key milestone towards any precision study of the deconfinement at RHIC energies.

4. Heavy quark distribution at large x

The presence of an intrinsic charm component in the nucleon is still the subject of intense debates in the particle and hadron physics community. At large x, whereas compelling indication of intrinsic strangeness has been recently claimed to be found [26], a state-of-the-art global fit [27] has shown that various realisations of intrinsic charm PDFs are allowed by the data. Similarly, the existence of intrinsic bottom is surely worth some investigations (see *e.g.* [28].)

To advance the debate, dedicated measurements are absolutely needed; not only one. Several probes are accessible at AFTER [2, 10], such as backward open charm and beauty production, double quarkonium production, quarkonium plus open heavy flavour production, as well as the production of prompt photon in association with a heavy quark [29, 30]. All these measurements could also be completemented by a new measurement of the charm structure function in DIS.

[3] See [24] for a discussion of the Boer-Mulders effect in heavy flavour production in pp collisions.

5. Summary

A novel testing ground for QCD can be provided by AFTER, a fixed-target facility based on the multi-TeV proton or heavy-ion beams at the LHC extracted by a bent crystal, interacting with a fixed proton, deuteron or nuclear target, possibly polarised. Such a fixed-target mode gives access to outstanding luminosities at c.m.s. energies comparable to RHIC energies. For the first time, AFTER provides a systematic access of the largely uncharted region at $x_F \to -1$ or large x in the target, thus opening high accuracy studies of the quark and gluon content of the nucleon in this region.

Acknowledgements. This research [SLAC-PUB-15718] was supported in part by the French CNRS, grants PICS-06149 Torino-IPNO & PEPS4AFTER2, the Department of Energy, contract DE-AC02-76SF00515 and the Sapore Gravis networking of the I3 Hadron Physics program of the EU 7th FP.

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PoS(DIS 2013)250

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PoS(DIS 2013)250