SLAC-PUB-16227

International Journal of Modern Physics: Conference Series

Studies of Transverse-Momentum-Dependent distributions with A Fixed-Target ExpeRiment using the LHC beams (AFTER@LHC)

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We report on the studies of Transverse-Momentum-Dependent distributions (TMDs) at a future fixed-target experiment –AFTER@LHC– using the p^+ or Pb ion LHC beams, which would be the most energetic fixed-target experiment ever performed. AFTER@LHC opens new domains of particle and nuclear physics by complementing collider-mode experiments, in particular those of RHIC and the EIC projects. Both with an extracted beam by a bent crystal or with an internal gas target, the luminosity achieved by AFTER@LHC surpasses that of RHIC by up to 3 orders of magnitude. With an unpolarised target, it allows for measurements of TMDs such as the Boer-Mulders quark distributions and the distribution of unpolarised and linearly polarised gluons in unpolarised protons. Using polarised targets, one can access the quark and gluon Sivers TMDs through single transverse-spin asymmetries in Drell-Yan and quarkonium production. In terms of kinematics, the fixed-target mode combined with a detector covering $\eta_{\rm lab} \in [1,5]$ allows one to measure these asymmetries at large $x^\uparrow$ in the polarised nucleon.

Keywords: TMD; AFTER@LHC; single spin asymmetry; Drell-Yan; quarkonium

PACS numbers:07.90.+c, 21.10.Hw, 13.20.Gd

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This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-76SF00515 and HEP.

1. The AFTER@LHC project

AFTER@LHC[1,2,3,4,5] is a proposal of a future multi-purpose fixed-target experiment (FTE) using the multi-TeV proton or heavy ion beams of the LHC. Such a proposal allows for an exceptional testing ground for QCD at unprecedented laboratory energies and momentum transfers. Important advances in nuclear and hadron physics in the past decades were achieved thanks to FTE: particle discoveries (Ω^-(sss), J/ψ, Υ), first evidence of the creation of a quark-gluon plasma in heavy-ion collisions, discovery of anomalously large single- and double-spin[6,7] correlations in hadron-hadron collisions, etc. Indeed, the fixed-target mode offers several advantages with respect to the collider mode:

- Outstanding luminosities are obtained thanks to the target high density;
- The far backward region in the center-of-mass system (c.m.s), corresponding to an acceptance of $1 \leq \eta_{\rm lab} \leq 5$, is not limited by geometrical constraints;
- A large number of target species can be studied; and
- The c.m.s energy is the same for pp, pd, pA collisions (115 GeV with a proton beam of 7 TeV), and for Pbp, PbA (72 GeV with a Pb beam of 2.76 TeV).

The objective of performing FTE with the p^+ and Pb LHC beams is threefold. First, one wishes to significantly advance our understanding of the large-x gluon, antiquark and heavy-quark content in the nucleon and nucleus. There are many motivations for this:

- The uncertainties of state-of-the-art PDF fits are very large for $x \gtrsim 0.5$. This could be crucial to confirm possible observed excesses in the data at the LHC or Future Circular Collider and to characterise possible Beyond-the-Standard-Model discoveries at these facilities;
- It is equally important for high-energy neutrino and cosmic-rays physics to better constraint the charm-content of the nucleon;
- In the nuclear case, the EMC effect[8] is still an open problem more than two decades after its discovery. The search for a possible *gluon* EMC effect is essential to understand its origin and the connections with short-range correlations in nuclei;
- The understanding of the initial state of heavy-ion collisions, and thus of nuclear PDFs, is also crucial to study the deconfinement of quark and gluons at RHIC and the LHC;
- To further our tests of QCD, the search and study of rare proton fluctuations where one gluon carries most of the proton momentum is extremely appealing.

Second, one wishes to advance our understanding of the dynamics and the spin of *gluons* inside polarised and unpolarised nucleons. This is motivated such as:

- Our understanding of the spin of the nucleon made of partons is still incomplete. A possible missing contribution could arise from their angular momentum.

- It is important to study spin-dependent object, which can also be defined for unpolarised nucleons. One example of these is the distribution of linearly-polarised gluons in unpolarised protons. Once these are known, any hadron collider can in principle be used to do spin physics.
- On the way of studying the parton angular momentum, via transverse-momentum-dependent observables for instance, one would also test fundamental properties of QCD such as the factorisation or universality of initial- and final-state radiations.

Third, one wishes to make a decisive step forward in the study of heavy-ion collisions at ultra-relativisitic energies with measurements towards large rapidities where one of the colliding nuclei is nearly at rest. This is motivated as such:

- In order to better explore the time evolution and longitudinal expansion of the deconfined matter, it is essential to measure new hard probes in the wide longitudinal-momentum range accessible in the fixed-target mode.
- Hard probes studies with the same experiment in asymmetric heavy-ion collisions and in proton-nucleus can provide key insights on the factorisation of cold nuclear matter effect (CNM) in the environment of two heavy ions. If, in some corners of the phase space, such a factorisation is broken, the subtraction of these CNM could simply be impossible.
- In order to use azimutal-asymmetry measurements as a tool to study the properties of the deconfined matter, it is essential to understand their origin. By measuring them up to large rapidities, one can put more stringent constraints on how they are formed, from hydrodynamical origin or from initial-state radiations.

2. Beam extraction with a bent crystal vs. an internal gas target

Two different technological options are currently under investigation to make the highly energetic LHC beams colliding onto a target. First, a bent crystal is positioned in the halo of the LHC beam such that a few protons (or Pb ions) per bunch per pass would be channelled in the lattice of the crystal, and following its curvature, would be deflected by few mrad w.r.t the beam axis. Such an extraction technique is a convenient, efficient and cost-effective way to obtain a clean and well collimated beam, without affecting the LHC performances. This technology was successfully tested for protons at the SPS[9], Fermilab[10], Protvino[11] and for Pb ions at the SPS[12]. It was proposed as a smart alternative for the upgrade of the LHC collimation system and will be tested by the LUA9 Collaboration[13] with the 7 TeV LHC beam, at IR7 after Long Shutdown 1. With a bent crystal, one expects to extract an average of 15 protons each 25 ns (i.e. 5×10^8 $p^+\mathrm{s}^{-1}$) from the LHC-beam losses and about 2×10^5 Pb s^{-1}. It has been shown[14] that one can expect a degradation of the crystal at the level of 6% per 10^{20} particles/cm^2 (about 1 year of operation). To cope with such a degradation, the crystal has to be moved by less than a millimeter each year so that the beam halo hits an intact

Table 1. Expected luminosities obtained for a 7 (2.76) TeV proton (Pb) beam extracted by means of bent crystal and obtained with an internal gas target.

Beam	Target	Thickness (cm)	ρ (g.cm^{-3})	A	$\mathcal{L}$ (μb^{-1}.s^{-1})	$\int\mathcal{L}$ (pb^{-1}.y^{-1})
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	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

Beam	Target	Usable gas zone (cm)	Pressure (Bar)		$\mathcal{L}$ (μb^{-1}.s^{-1})	$\int\mathcal{L}$ (pb^{-1}.y^{-1})
p	perfect gas	100	10^{-9}		10	100
Pb	perfect gas	100	10^{-9}		0.001	0.001

spot of the crystal. This operation can be repeated almost at will. In Tab. 1, the instantaneous and yearly luminosities (assuming 10^7s of p^+ beam and 10^6s of Pb beam per year) are reported for p^+ and Pb beams on targets of various thicknesses. Integrated luminosities as large as 20 fb^{-1} are reached with a 1m-long target of liquid hydrogen, which is as large as the data sample collected at 7 and 8 TeV at the LHC.

Second, the LHC beam goes through an internal gas target installed in one of the existing LHC experiments or in a new one. Such an internal gas target option is currently tested by the LHCb collaboration via a luminosity monitor[16,17,18] (SMOG). A pilot run of p^+ beam (Pb beam) on a Neon gas target was successfully performed in 2012 (2013) at a c.m.s energy of $\sqrt{s_{NN}} = 87$ GeV (54 GeV). SMOG was tested for few hours only in a row during data taking, with non-getterable gases. No decrease of the LHC performances was observed. More studies are needed to confirm that the internal gas target system can be run over extended periods of time, without any interferences on other LHC experiments and to check the behaviour of the gas (e.g. the maximal pressure that can be reached). Assuming a gas pressure[a] of 10^{-9} bar, one can calculate the instantaneous luminosity as follows: $\mathcal{L} = \phi_{\rm beam} \times (\frac{\mathcal{N}_A}{22400} \times \mathrm{P} \times \ell)$ where $\phi_{\rm beam}$ is the p^+ (or Pb) flux in the LHC, P the gas pressure, and ℓ the usable gas zone. In the case of the p^+ beam, $\phi_{\rm beam} = 3.14 \times 10^{18}$ p^+ s^{-1} and for the Pb beam, $\phi_{\rm beam} = 4.6 \times 10^{14}$ Pb s^{-1}. Instantaneous and yearly luminosites expected with an internal gas target are reported in Tab. 1. Provided that the runs can last as long as a year in both cases, luminosities in pA are similar for the bent crystal and for the internal gas target scenario. However in pp, in order to get luminosities as large as 10 fb^{-1} yr^{-1} with the internal gas target, a pressure of 10^{-7} bar is required for the gas, which is challenging. In both scenari, it is technologically possible to polarize the target. For an overview of target polarization techniques see Ref. 19. For the bent-crystal case, the main constraint in the choice of the target polariza-

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[a] We remind that the LHC "vacuum" pressure is 10^{-12} bar.

tion technology is the space available in the underground LHC complex, restricting the possibilities to two choices: continuous Dynamic nuclear Polarisation (DNP), or a HD target[20]. Both are more compact technologies than the frozen-spin one. CERN has expertise in DNP technology using NH_3 or Li_6D materials[21]. Only two groups worldwide are specialized in HD targets: one at TJNAF (USA) and one at RCNP (Japan). Concerning the internal gas target solution, atomic beam source technology, similarly to what is done in HERMES or optical pumping as in SLAC are candidate technologies to polarize the target[19]. One should mention that the fraction of polarizable nuclei over the total number of nuclei is generally larger for polarized gas target.

3. TMD studies

3.1. *Access to the distribution of linearly-polarized gluons in unpolarized protons*

The distribution of linearly-polarized gluons in unpolarized protons is encoded in $h_1^{\perp g}(x,k_T,\mu)$ and can be studied without the need of polarizing the target. Such an effect (known as "Boer-Mulders" effect for the quark case[23]) arises from the correlation between the gluon k_T and its spin. The low-p_T spectra of scalar and pseudo-scalar quarkonia (χ_{c0}, χ_{b0}, η_c, η_b) are affected differently[24] by the linear polarisation of the gluons. Thanks to the large boost ($\gamma \simeq 60$) in the fixed-target mode, AFTER@LHC could access the low-p_T C-even quarkonium. The measurement of the η_c production is a good candidate for such a kind of studies. Recently, the LHCb Collaboration did the first measurement[25] of the η_c hadroproduction, in the $p\bar{p}$ decay channel, for p_T greater than 6 GeV/c. More studies are needed to confirm the feasibility of this measurement at low-p_T with AFTER@LHC.

It has also been proposed[26] that the distribution of linearly-polarized gluons in unpolarized protons could be extracted from the measurement of a quarkonium with a back-to-back isolated photon. It has been shown[27] that this observable is still sensitive to gluons at large x at AFTER@LHC energies. One can expect a differential cross section of the order of tens of fb/GeV. J/ψ-pair production is also interesting for spin related studies with unpolarised protons.

3.2. *Single Transverse Spin Asymmetries with polarized protons*

With a polarized target, one can access the Sivers functions (encoding the correlation between the proton spin and the parton angular momentum) for the quarks and gluons. The existence of a nonzero gluon Sivers effect can be probed by studying single transverse spin assymetries (STSA) in η_Q production, especially at low-p_T, which is a clean gluon-sensitive probe. Quarkonia, such as J/ψ and Υ, are also good probes to look for the gluon Sivers effect. High precision data are needed for such a kind of studies, and the high luminosities reached by AFTER@LHC would definitively help perform STSA studies.

The quark Sivers effect can be probed with the Drell-Yan (DY) process. AFTER@LHC is competitive with DY measurements to be performed at COMPASS[29], Fermilab[30] at large $x^{\uparrow}$, and with the proposal P1039[31] at low $x^{\uparrow}$. An asymmetry up to 10% has been predicted[28] at AFTER@LHC for DY in the backward region, $x_F < 0$. These studies are crucial to test QCD by determining if the quark Sivers function changes sign between Semi-Inclusive DIS and DY pair production.

Finally, we stress the possibility to study STSA in $p^{\uparrow}$A collisions using the Pb beam.

4. Conclusion

AFTER@LHC provides a novel testing ground for QCD. High luminosities are achievable in pp and pA at $\sqrt{s_{NN}} = 115$ GeV as well as Pbp and PbA at $\sqrt{s_{NN}}$ $= 72$ GeV. TMD studies can be performed with and without polarizing the target, thanks to e.g the study of low-p_T quarkonia production. First fast simulations performed with a LHCb-like setup are really promising.

Acknowledgments. This research was supported in part by the French P2IO Excellence Laboratory, the French CNRS via the grants PICS-06149 Torino-IPNO, FCPPL-Quarkonium4AFTER & PEPS4AFTER2 and by the Department of Energy, contract DE-AC02-76SF00515.

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