Spin physics and TMD studies at A Fixed-Target ExpeRiment at the LHC (AFTER@LHC)

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Abstract. We report on the opportunities for spin physics and Transverse-Momentum Dependent distribution (TMD) studies at a future multi-purpose fixed-target experiment using the proton or lead ion LHC beams extracted by a bent crystal. The LHC multi-TeV beams allow for the most energetic fixed-target experiments ever performed, opening new domains of particle and nuclear physics and complementing that of collider physics, in particular that of RHIC and the EIC projects. The luminosity achievable with AFTER@LHC using typical targets would surpass that of RHIC by more that 3 orders of magnitude in a similar energy region. In unpolarised proton-proton collisions, AFTER@LHC allows for measurements of TMDs such as the Boer-Mulders quark distributions, the distribution of unpolarised and linearly polarised gluons in unpolarised protons. Using the polarisation of hydrogen and nuclear targets, one can measure transverse single-spin asymmetries of quark and gluon sensitive probes, such as, respectively, Drell-Yan pair and quarkonium production. The fixed-target mode has the advantage to allow for measurements in the target-rapidity region, namely at large $x^{\uparrow}$ in the polarised nucleon. Overall, this allows for an ambitious spin program which we outline here.

1 Introduction

More than ten years ago, RHIC opened a new era in the study of spin physics at relativistic energies in being the first collider of polarised protons. Thanks to the polarisation of both beams, double-spin asymmetries could be measured (see *e.g.* [1, 2]) and, thanks to its high center-of-mass energy –up to 500 GeV–, the measurements of spin asymmetries in weak boson production could be performed [3, 4].

Unfortunately, neither the Tevatron nor the LHC were designed with the possibility of colliding polarised protons. Nevertheless, it has recently been emphasised that a class of spin-dependent partonic distributions can be studied even in the absence of polarised proton. In fact, the polarised particle is, in this case, the parton in an unpolarised nucleon and a correlation effect arises for nonzero partonic transverse momenta. In the quark case, these quantities are named Boer-Mulders distributions [5]. In principle, the LHC machine can thus also be used to perform spin-related measurements.

Much more can however be done [6] if the multi-TeV proton LHC beams are extracted and sent to a fixed target, the latter being polarised or not. In the former case, one can study a number of target (transverse) spin asymmetries, also called single transverse spin asymmetries (STSA). In the latter case, since the typical conditions of

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Presented at theTransverse Polarisation Phenomena in Hard Processes (Transversity 2014)
China, Italy, June 9 - 13, 2014

This work was supported at SLAC by the US Department of Energy under contract DE-AC02-76SF00515 and HEP.

a fixed-target experiment allow for rather low transverse-momentum measurements, one can perform a number of studies of Boer-Mulders function for the quark sector or of the distribution of polarised gluons in unpolarised nucleons.

In this context, it is useful to recall the critical advantages of a fixed-target experiment compared to a collider one, *i.e.*

- extremely high luminosities thanks to the high density of the target;
- absence of geometrical constraints to access the far backward region in the c.m.s.;
- unlimited versatility of the target species; and
- same energy for proton-proton, proton-deuteron and proton-nucleus collisions.

These first two advantages are particularly relevant for the topics to be discussed here and discussed in [7, 8], whereas the latter two are more relevant for heavy-ion physics previously discussed in [9–11].

2 Beam extraction and target polarisation

The extraction of beams by using the technique of bent-crystal channelling offers an ideal and cost-effective way to obtain a clean and very collimated beam even at TeV energies. This exhibits the asset of not altering the LHC beam performances [12, 13]. A "smart collimator" solution will be tested on the 7-TeV LHC beam by the CERN LUA9 collaboration after the current long shutdown (LS1) [14]; a minimal setup that includes a horizontal and a vertical piezoelectric goniometre with the associated crystal have already been installed in the LHC beampipe in IR7 [15]. Another proposal, to be further investigated, is to "replace" the kicker-modules in LHC section IR6 by a bent crystal [13].

In terms of kinematics, 7 TeV protons colliding on fixed targets release a center-of-mass energy close to 115 GeV ($\sqrt{2E_p m_N}$). The extraction has also been tested for heavy-ion beams, for instance at SPS by the CERN UA9 collaboration [16]. The 2.76 TeV LHC lead beam would for instance allow one to study heavy-ion collisions at a center-of-mass energy per nucleon-nucleon collision close to 72 GeV, exactly half way between RHIC and SPS experiments.

The extraction procedure is as follows: one would position a bent crystal in the halo of the beam such that a few protons (or lead) per bunch per pass are channelled in the crystal lattice. These are consequently deviated by a couple of mrad w.r.t. to the axis of the beam. A significant fraction of the beam loss can then be extracted likewise, with an intensity of 5×10^8 $p^+ s^{-1}$. This corresponds to an average extraction per bunch per revolution of mini-bunches of about 15 p^+ each 25 ns.

Past experiments (see *e.g.* [17]) have shown that the degradation of the crystal is at the level of 6% per 10^{20} particles/cm^2. Such an integrated intensity is equivalent to a year of operation, for realistic impact parameters and realistic beam sizes at the location of the crystal. After a year, the crystal has to be moved by less than a millimetre such that the beam halo hits the crystal on an intact spot. This procedure can be repeated without specific constraints.

Despite the outstanding luminosities which can be obtained, the intensity of the extracted beam is not extremely large. In particular, it does not constrain the choice of the target-polarisation technique. With such a highly energetic beam, one expects a minimum ionisation and a low heating of the target. The expected heating power due to this extracted beam is on the order of 50 μW for a typical 1cm thick target. Temperatures as low as 50 mK can thus be maintained in the target. In the spin-frozen mode, relaxation times can last as long as one month. The damages on the target would typically arise after an irradiation of $10^{15} p^+ \mathrm{cm}^{-2}$ [18]; this corresponds to 1 month of exposition in this case.

Yet, one cannot ignore the major constraint set by the available space in the underground LHC complex. This most likely restricts the choice to polarisation by continuous *Dynamic Nuclear Polarisation* DNP or to a HD target [19]. Both take less space than the frozen-spin machinery. The project AFTER@LHC is a strong motivation to revisit the necessary technology [20]. CERN has a long tradition of DNP for a number of materials such as NH_3 and Li_6D [21]. Experts of DNP can still be found worldwide, while HD target makers are more rare, *e.g.* one at TJNAF (USA) and the other at RCNP (Japan) [22].

The instantaneous and yearly (over 10^7 s) luminosities reachable with the proton beam on targets of various thickness are gathered in table 1. Note that 1m long targets of liquid hydrogen or deuterium give luminosities close to 20 femtobarn^{-1}, as large as the luminosities collected at the LHC at 7 and 8 TeV. Table 1 also gathers the corresponding values for the Pb run of 10^6 s.

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

Figure 1: Instantaneous and yearly luminosities obtained for targets of various thickness with an extracted beam of (a) 5×10^8 p$^+$/s with a momentum of 7 TeV and (b) 2×10^5 Pb/s with a momentum per nucleon of 2.76 TeV.

3 Short selection of highlight studies not related to spin.

Before discussing measurements pertaining to spin and TMD physics, it is instructive to recall what can, in principle, be done to learn more about the spin-independent inner structure of nucleons and nuclei. This section only presents an introductory selection of studies relevant for the discussions of the next sections. A more complete survey of the physics opportunities with AFTER@LHC can be found in [6].

Given the possibility of studying a number of colliding systems, such as proton–proton, proton–deuteron, lead–proton, lead–nucleus, proton–polarised-nucleon and lead–polarised-nucleon, we believe that AFTER@LHC should be designed as a multi-purpose detector. As such, it would *de facto* become a heavy-flavour, quarkonium and prompt-photon *observatory* [6, 9] in pp and pA collisions given the outstanding expected luminosity combined to an access towards low P_T. In turn, thanks also to the complementary forthcoming LHC results, it is sound to expect that the production mechanisms of quarkonia [23] would eventually be constrained thanks to the large quarkonium yields and precise measurements of their correlations.

With 7 TeV protons, the boost between c.m.s. and the lab system is $\gamma^{\rm lab}_{\rm c.m.s.} = \sqrt{s}/(2m_p) \simeq 60$ and the rapidity shift is $\tanh^{-1}\beta^{\rm lab}_{\rm c.m.s.} \simeq 4.8$. With 2.76 TeV lead ions, one has $\gamma^{\rm lab}_{\rm c.m.s.} \simeq 38$ and $\Delta y^{\rm lab}_{\rm c.m.s.} \simeq 4.3$. In both cases, the central-rapidity region in the c.m.s., $y_{\rm cms} \simeq 0$, is thus highly boosted at an angle w.r.t. the beam axis of about one degree in the laboratory frame. One can easily access the entire backward c.m.s. hemisphere, $y_{\rm cms} < 0$, with standard experimental techniques. The forward hemisphere is probably less conveniently accessible; the reduced distance from the (extracted) beam axis requires the use of highly segmented detectors to deal with the large particle density. We thus consider that one can access the region $-4.8 \leq y_{\rm cms} \leq 1$ without specific difficulties. Such an acceptance covers the bulk of most yields and offers the opportunity of high precision measurements in the whole backward hemisphere, down to $x_F \to -1$ for multiple systems. For instance, by studying Υ production at rapidities of the order of -2.4 in the c.m.s., one can access x_F above $\frac{10}{115}e^{2.4} \simeq 0.95$.

The gluon and heavy-quark distributions in the proton, the neutron and nuclei (see *e.g.* [24]) could then be extracted at mid and large momentum fractions, x, by accessing the target-rapidity region. We also note that, in principle, in the nuclear case, the physics at x larger than unity –which necessarily probe nuclear correlation– can be accessed. One could study the scale dependence of nuclear effects in the EMC and Fermi motion region, $0.3 < x < 1$; this may be fundamental to understand the connexion between the EMC effect and the importance of short-range correlations.

In proton-deuteron collisions, unique information on the momentum distribution of the gluons in the neutron can be also obtained with quarkonium measurements along the lines of E866 for Υ [25].

More generally, thanks to its high luminosity, AFTER@LHC offers many other opportunities related to heavy-flavor production, such as quarkonium-associated production (see *e.g.* [26, 27]) or double-charm baryon production [28]. For instance, a very backward measurement of $J/\psi+D$ production [29] could tell us much on the charm quark distribution at large x which is the object of a long-standing debate [30–33].

Finally, let us stress that the large number of quarkonia (approximately 10^9 J/ψ and 10^6 Υ per unit of rapidity per 20 fb^{-1}) to be studied with AFTER@LHC offers the possibility to perform high precision (3-dimensional) measurements of their polarisation [9], which is still the subject of intense debates [34]. In the charmonium case, it is very important to perform measurements on the excited-state polarisation (ψ', χ_c) to avoid to deal with polarisation-dilution effects from their feed-down which preclude one to draw strong conclusions from the RHIC data for instance [35].

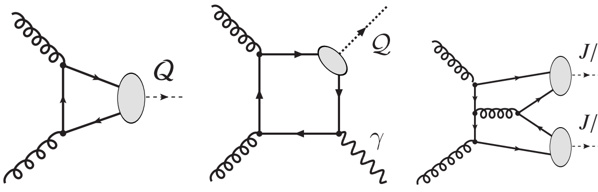
4 Spin studies with unpolarised protons: Boer-Mulders functions and related distributions

4.1 Low-P_T quarkonium production

It has been emphasised in [36] that the study of quarkonium production at low P_T ($P_T \leq M_Q$) can provide information on gluon TMDs, *i.e.* on $f_1^g(x, k_T, \mu)$ and $h_1^{\perp g}(x, k_T, \mu)$, owing to the simplicity of the LO production mechanism (see Fig. 3a). Unfortunately, the sole study of η_Q would not provide enough information to determine these TMDs separately.

Subsequently, the study of η_Q has successfully been carried out in the TMD factorisation at one loop (NLO) in α_s [37] giving confidence that such a factorisation does hold for these particles. On the contrary, it seems not to be the case for P-wave production [38].

With P_T-integrated cross sections for η_c at $y = 0$ as large as 1 nb, such studies can be envisioned. It is however not clear yet down to which P_T they could be carried out. This would depend much on the decay channel, which can be $KK\pi$, $p\bar{p}$, $\gamma\gamma$, ..., and on the detection technique used. Forthcoming simulations will be extremely insightful on this matter. The very first measurement of inclusive η_c hadroproduction by the LHCb collaboration [39] gives us confidence that such a measurement is nowadays possible at least in the $p\bar{p}$ decay channel.



(a) (b) (c)

Figure 3: Typical LO Feynman graphs for (a) η_Q, (b) $\psi+\gamma$ and (c) J/ψ-pair production.

4.2 Back-to-back quarkonium +γ production

In [40], we discussed the possibility of extracting the polarised and unpolarised gluon TMDs, $f_1^g(x, k_T, \mu)$ and $h_1^{\perp g}(x, k_T, \mu)$ through the production of a quarkonium associated with a back-to-back and isolated photon at the LHC,

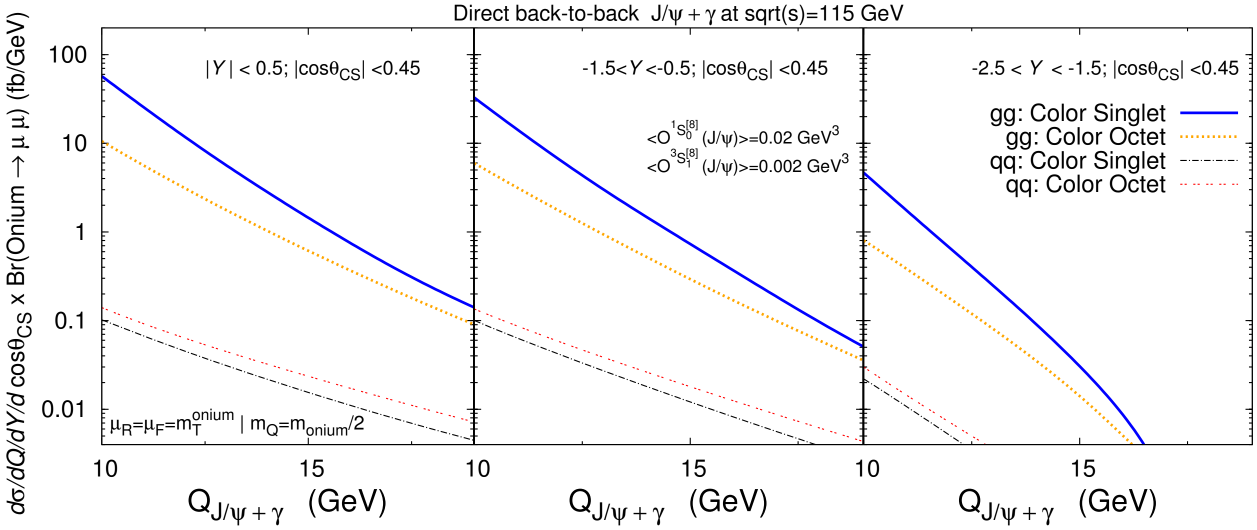


Figure 2: Different contributions to the production of an isolated photon back-to-back with a J/ψ from $g-g$ and $q-\bar{q}$ fusion from the CS and CO channels as a function of the invariant mass of the pair $Q_{(J/\psi+\gamma)}$ for three different rapidity regions (from left to right: $|Y|<0.5$, $-1.5<Y<-0.5$ and $-2.5<Y<-1.5$).

thus with unpolarised protons. Contrary to the inclusive production of quarkonium + photon pair, which has been shown to help to disentangle color-octet (CO) from color-singlet (CS) contributions [41–43], back-to-back production tends to be dominated by CS contributions [44] at least at low transverse momenta. In addition, it is less prone to QCD corrections, which simplifies its theoretical study. In the case of J/ψ and Υ production, the requirement for back-to-back production essentially selects the topologies of graphs Fig. 3b; these are dominated by gluon fusion as expected at high energies for heavy-quark production. If CS contributions are indeed dominant, TMD factorisation should apply and the measurements of the yield as a function of the transverse-momentum imbalance of the pair, q_T, should give, for the first time, a direct access to $f_1^g(x, k_T, \mu)$. Moreover, the study of azimuthally-modulated moments of the yields as function of q_T should allow one to look for a nonzero linear polarisation of gluons inside unpolarised protons by extracting $h_1^{\perp g}(x, k_T, \mu)$.

At the LHC, the study of isolated photons usually imposes to require a minimal transverse momentum, of the order of 10 GeV. At lower energies, it is likely possible to cope with a lower threshold, for instance 4 GeV, thanks to the lower particle multiplicities, especially in the backward region accessible with AFTER@LHC. It is nonetheless legitimate to wonder whether such an observable would still be sensitive to gluons in the region of rather large x values. Let us recall that $x_{1,2} = Q/\sqrt{s}e^{\pm Y}$. Thus, for $Q = 10$ GeV and $Y = -2$, $x_2 \simeq 0.65$. We have checked the gluon-fusion dominance as illustrated by Fig. 2. From left to right, the rapidity Y of the pair is getting more negative. First, the $q\bar{q}$ contribution remains negligible –at most a percent of that from gg. Second, the CS contribution (solid blue curve) remains above the CO one (orange dashed curve) up to $Q \simeq 20$ GeV. At $Q \simeq 10$ GeV, the expected CO contribution is less than a quarter of the CS one and can be disregarded for a first TMD extraction. In fact, it can also simply be removed by isolating the J/ψ as well; this would be required if the measured value of the q_T integrated yield was higher than expected and thus indicative of a larger CO yield. Finally, we wish to stress that we do not expect higher-twist contributions such as intrinsic-charm (IC) quark coalescence [45] to contribute to (back-to-back) $J/\psi + \gamma$ production. As opposed to inclusive J/ψ production for which one has $J/\psi + g$ at LO and for which the color of the non-perturbative IC fluctuations can be bleached by the final-state gluon emission, the emission of the final-state photon is irrelevant; an additional gluon emission is needed for this mechanism to contribute.

In terms of expected counts, since the differential cross section is on the order of tens of fb/GeV, one can reasonably expects a couple of thousands of events per year (*i.e.* per 20 fb^{-1}) with a hydrogen target. This is definitely sufficient to look at the k_T dependence of $f_1^g(x, k_T, \mu)$ as well as to look at the magnitude of $h_1^{\perp g}(x, k_T, \mu)$ at large x.

Another observable where the TMD factorisation should be applicable is J/ψ-pair production. As for $J/\psi+\gamma$ production, the final state (see *e.g.* [27]) can be fully color singlet (see Fig. 3c). Its analysis should also be very well accessible with AFTER@LHC.

5 Spin studies with polarised protons: Single Transverse Spin Asymmetries

5.1 Looking for the gluon Sivers effect and beyond

STSA were computed for η_Q production in the collinear twist-3 approach [46]. In this case, the STSA arises from twist-3 quark gluon correlators $T_F(x, x)$, also known as the Efremov-Teryaev-Qiu-Sterman correlators. In the TMD factorisation, it is due to the well-know Sivers function.

The study of STSA in η_Q production is particularly interesting because of the possible differences – as the sign mismatch first discussed in [47] – between both these approaches, since the Collins effect is not expected to contribute here. Such a measurement is certainly possible with AFTER@LHC with a transversely polarised target. An important point is to be able to carry out such a measurement down to low P_T where both approaches are applicable and can legitimately be compared. In any case, such a measurement would be extremely useful to tell whether or not such a gluon Sivers effect does exist.

The PHENIX collaboration [48] has measured the STSA in J/ψ production at $\sqrt{s} = 200$ GeV. They reported a value of A_N compatible with 0 with a slightly negative central value. More precise data are definitely needed. AFTER@LHC can certainly push far forward the precision limit on such a measurement. It is noteworthy to emphasise the possibility to collide lead ions on a polarised target since a number of theoretical ideas have been proposed lately in the case of $p^\uparrow A$ collisions.

Further measurements can be carried out with a polarised target. By measuring the angular correlations in $\psi + \gamma$ production involving ϕ, the azimuthal Collins-Soper angle and ϕ_{ST}^{qT}, the angle between the q_T of the pair and the transverse polarisation vector of the proton, one gain access to $f_{1T}^{\perp g}$, h_{1T}^{g} and $h_{1T}^{\perp g}$, in addition to f_1^g and $h_1^{\perp g}$ which are accessible without target polarisation.

5.2 Quark Sivers effect

AFTER@LHC is also a good playground to study the quark Sivers effect by measuring STSA in Drell-Yan pair production [49]. Such studies would nicely complement the forthcoming DY STSA measurements in pion-induced reaction at COMPASS [50] and two proposals at Fermilab, P1027 [51] with a polarised beam to study the large $x^\uparrow$ domain and P1039 [52] with a polarised target for lower $x^\uparrow$.

As for now, the main objectives of such measurements is to verify the *prima facie* robust prediction of QCD according which the Sivers function changes sign, when going from semi-inclusive DIS to DY pair production [53].

6 Conclusion

In conclusion, a fixed-target experiment using the LHC beams can provide us with extremely complementary measurements to those made at RHIC and at lower energy fixed target projects, such as COMPASS and P1027 or P1039, which are dedicated to spin physics or TMD extraction.

At high energies, the fixed-target mode is very well adapted for measurements at large x in the target. The latter can be polarised and this opens the path to the study of target-spin asymmetries at large $x^\uparrow$, where they are expected to be the largest. Moreover, as we stressed, a number of spin-related measurements can also be carried without a target polarisation, by taking advantage of the high luminosities and a low-P_T acceptance and by looking at transverse-momentum dependent phenomena, encapsulated in the TMDs.

Acknowledgements. This research [SLAC-PUB-16099] was supported in part by the French CNRS via the grants PICS-06149 Torino-IPNO, FCPPL-Quarkonium4AFTER & PEPS4AFTER2, by the Tournesol 2014 Wallonia-Brussels-France Cooperation Programme, and by the Department of Energy, contract DE-AC02-76SF00515.

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